METHODS AND SYSTEMS FOR FORMING STELLARATOR COILS AND SUPERCONDUCTING TAPES

CROSS-REFERENCE

[0001] This application claims the benefit of U.S. Provisional Application No. 63/550,338 filed February 6, 2024, U.S. Provisional Application No. 63/550,342 filed February 6, 2024, U.S. Provisional Application No. 63/550,467 filed February 6, 2024, U.S. Provisional Application No. 63/550,485 filed February 6, 2024, U.S. Provisional Application No. 63/550,488 filed February 6, 2024, U.S. Provisional Application No. 63/550,490 filed February 6, 2024, U.S. Provisional Application No. 63/635,977 filed April 18, 2024, U.S. Provisional Application No. 63/649,830 filed May 20, 2024, U.S. Provisional Application No. 63/649,826 filed May 20, 2024, U.S. Provisional Application No. 63/658,669 filed June 11, 2024, which applications are incorporated herein by reference.

BACKGROUND

[0002] A stellarator is a plasma device that relies primarily on external magnets to confine a plasma. Scientists researching magnetic confinement fusion aim to use stellarator devices as a vessel for nuclear fusion reactions.

SUMMARY

[0003] In one aspect, disclosed herein is a method of forming reinforced superconducting tape for a stellarator coil, comprising: (a) pre-straining at least some of a reinforcement while said reinforcement is at a first temperature above a cryogenic temperature, thereby forming a pre-strained reinforcement; (b) pre-straining at least some of superconducting tape while said superconducting tape is at a second temperature above a cryogenic temperature, thereby forming pre-strained superconducting tape; and (c) affixing said pre-strained superconducting tape to said pre-strained reinforcement, thereby forming a reinforced superconducting tape. In some embodiments, pre-straining said at least some of said reinforcement at (a) comprises pre-tensioning said at least some of said reinforcement. In some embodiments, pre-straining said at least some of said superconducting tape at (b) comprises pre-compressing said at least some of said superconducting tape. In some embodiments, affixing said pre-strained superconducting tape to said pre-strained reinforcement at (c) comprises affixing said pre-strained superconducting tape to said pre-strained reinforcement reel-by-reel. In some embodiments, affixing said pre-strained superconducting tape to said pre-strained reinforcement at (c) comprises soldering said pre-strained superconducting tape to said pre-strained reinforcement. In

some embodiments, said reinforcement comprises tungsten. In some embodiments, said reinforcement comprises a potassium and tungsten alloy. In some embodiments, said reinforcement comprises rhenium. In some embodiments, said reinforcement comprises tantalum. In some embodiments, said reinforced superconducting tape comprises a modulus at least about twice as high as steel.

[0004] In one aspect, disclosed herein is a method of forming a stellarator coil, the method comprising: shaping a cable into a helical cable; and compressing at least a portion of the helical cable about an axis parallel to a central axis of the helical cable to form the stellarator coil. In some embodiments, shaping the cable into the helical cable is performed by a free-form bender. In some embodiments, the free-form bender comprises a Computer Numerical Control (CNC) bender. In some embodiments, shaping the cable into the helical cable comprises twisting the cable along its length. In some embodiments, the helical cable has a tapered helical shape. In some embodiments, the helical cable has a constant pitch. In some embodiments, the helical cable has a variable pitch. In some embodiments, the helical cable has a constant coil angle. In some embodiments, the helical cable has a variable coil angle. In some embodiments, the helical cable and the stellarator coil have a clockwise chirality. In some embodiments, the helical cable and the stellarator coil have a counter-clockwise chirality. In some embodiments, the helical cable, the stellarator coil, or both has about 3 turns to about 100 turns. In some embodiments, the helical cable is compressed by hand. In some embodiments, the helical cable is compressed by machine. In some embodiments, compressing the helical cable comprises compressing a first portion of the helical cable and compressing a second portion of the helical cable. In some embodiments, compressing the helical cable further comprises re-compressing the first portion, the second portion, or both. In some embodiments, the first portion comprises about 5% to about 95% of the length of the helical cable. In some embodiments, the method further comprises: extending at least the first portion of the helical cable; and recompressing at least the first portion of the helical cable to form the stellarator coil. In some embodiments, a ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil is about 10:1 to about 10,000:1. In some embodiments, the stellarator coil is substantially flat. In some embodiments, the stellarator coil has a paraboloid shape. In some embodiments, the stellarator coil has a hyperbolic paraboloid shape. In some embodiments, the portion of the helical cable is compressed between a tool having a first face that is substantially flat and a second face parallel to the first face. In some embodiments, the portion of the helical cable is compressed between a tool having a parabolic first face and a second face offset from the first face. In some embodiments, the portion of the helical cable is compressed between a

tool having a hyperbolic parabolic first face and a second face offset from the first face. In some embodiments, a ratio between a distance between consecutive turns of the stellarator coil and the thickness of the cable is about 0.01:1 and about 0.9:1. In some embodiments, the method further comprises heat treating the stellarator coil. In some embodiments, the method further comprises weakening a hinge section of the cable before step (a) or step (b). In some embodiments, weakening comprises annealing, cutting, fatiguing, or any combination thereof.

[0005] Another aspect provided herein is a stellarator coil formed by a method of: shaping a cable into a helical cable; and compressing at least a portion of the helical cable about an axis parallel to a central axis of the helical cable to form the stellarator coil. In some embodiments, shaping the cable into the helical cable is performed by a free-form bender. In some embodiments, the free-form bender comprises a Computer Numerical Control (CNC) bender. In some embodiments, shaping the cable into the helical cable comprises twisting the cable along its length. In some embodiments, the helical cable has a tapered helical shape. In some embodiments, the helical cable has a constant pitch. In some embodiments, the helical cable has a variable pitch. In some embodiments, the helical cable has a constant coil angle. In some embodiments, the helical cable has a variable coil angle. In some embodiments, the helical cable and the stellarator coil have a clockwise chirality. In some embodiments, the helical cable and the stellarator coil have a counter-clockwise chirality. In some embodiments, the helical cable, the stellarator coil, or both has about 3 turns to about 100 turns. In some embodiments, the helical cable is compressed by hand. In some embodiments, the helical cable is compressed by machine. In some embodiments, compressing the helical cable comprises compressing a first portion of the helical cable and compressing a second portion of the helical cable. In some embodiments, compressing the helical cable further comprises re-compressing the first portion, the second portion, or both. In some embodiments, the first portion comprises about 5% to about 95% of the length of the helical cable. In some embodiments, the stellarator coil is further formed by: extending at least the first portion of the helical cable; and recompressing at least the first portion of the helical cable to form the stellarator coil. In some embodiments, a ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil is about 10:1 to about 10,000:1. In some embodiments, the stellarator coil is substantially flat. In some embodiments, the stellarator coil has a paraboloid shape. In some embodiments, the stellarator coil has a hyperbolic paraboloid shape. In some embodiments, the portion of the helical cable is compressed between a tool having a first face that is substantially flat and a second face parallel to the first face. In some embodiments, the portion of the helical cable is compressed between a tool having a parabolic first face and a second face offset from

the first face. In some embodiments, the portion of the helical cable is compressed between a tool having a hyperbolic parabolic first face and a second face offset from the first face. In some embodiments, a ratio between a distance between consecutive turns of the stellarator coil and the thickness of the cable is about 0.01:1 and about 0.9:1. In some embodiments, the stellarator coil is further formed by heat treating the stellarator coil. In some embodiments, the stellarator coil is further formed by weakening a hinge section of the cable before step (a) or step (b). In some embodiments, weakening comprises annealing, cutting, fatiguing, or any combination thereof.

[0006] In an aspect, the present disclosure provides a method of bending a coil, comprising (a) providing a cable comprising a cable core and a cable jacket to a bending apparatus, wherein said cable jacket comprises a cable jacket segment, wherein said bending apparatus has a maximum working length, and a length of said cable core is longer than said maximum working length, and a length of said cable jacket segment is shorter than said maximum working length; (b) using a feeder portion of said bending apparatus, moving said cable jacket segment and said cable core through a bending head of said bending apparatus, thereby bending said cable jacket and said cable core into a portion of said coil; (c) providing an additional cable jacket segment around said cable core, wherein said additional cable jacket segment has a length shorter than said maximum working length; and (d) using said feeder portion of said bending apparatus, moving said cable jacket and said cable core through said bending head of said bending apparatus to bend said cable jacket and said cable core into an additional portion of said coil.

[0007] In some embodiments, the method further comprises (i) coupling said additional cable jacket segment to said cable jacket or said cable core. In some embodiments, (i) comprises coupling said additional cable jacket segment to said cable jacket and said cable core. In some embodiments, said moving of (b) or (d) comprises pushing using said feeder portion. In some embodiments, said coupling of (i) comprises one or more of ultrasonic soldering, fusing, heat-based soldering, press fitting, or any combination thereof. In some embodiments, the method further comprises repeating (c) – (d) one or more times. In some embodiments, said bending apparatus is a computer numerical control (CNC) bending apparatus. In some embodiments, said feeder portion pushes either said cable jacket segment or said additional cable jacket segment with at least a mandrel configured to fit over said cable core. In some embodiments, said mandrel is a clamping mandrel. In some embodiments, said clamping mandrel is a c-shaped mandrel. In some embodiments, said clamping mandrel is configured to clamp onto said cable jacket segment or said additional cable jacket segment. In some embodiments, said clamping mandrel is configured to clamp behind said cable jacket segment or said additional cable jacket segment. In some embodiments, said bending apparatus exerts a force on said mandrel, and

wherein said mandrel transmits said force primarily to said cable jacket. In some embodiments, said mandrel has a thickness of at least about a thickness of said cable jacket segment or said additional cable jacket segment. In some embodiments, said thickness of said mandrel is measured at a contact point between said mandrel and said cable jacket segment or said additional cable jacket segment. In some embodiments, said mandrel is configured to engage via at least friction with said cable jacket segment or said additional cable jacket segment. In some embodiments, the method further comprises one or more grooves on said cable jacket segment or said additional cable jacket segment configured to engage with said mandrel via friction between a member of said mandrel and said one or more grooves. In some embodiments, said cable jacket segment or said additional cable jacket segment is cut perpendicular to the axis of the cable core. In some embodiments, said mandrel comprises one or more teeth configured to engage with said cable jacket segment or said additional cable jacket segment. In some embodiments, said mandrel is a steel mandrel. In some embodiments, said cable jacket comprises copper. In some embodiments, said cable jacket comprises titanium. In some embodiments, said cable jacket comprises steel. In some embodiments, said cable core comprises one or more high temperature superconducting (HTS) tapes. In some embodiments, said cable core comprises one or more HTS stacks. In some embodiments, said cable core has a length of at least about 6 meters (m). In some embodiments, said maximum working length of said bending apparatus is about 4 m. In some embodiments, a diameter of said cable core is at least about 19 millimeters (mm). In some embodiments, a diameter of said cable core is at most about 50 mm. In some embodiments, a thickness of said cable jacket segment or said additional cable jacket segment is at least about 1.5 mm. In some embodiments, a thickness of said cable jacket segment or said additional cable jacket segment is at most about 5 mm.

[0008] In an aspect, the present disclosure provides a cable comprising a cable core and a cable jacket, wherein said cable jacket is formed of at least two pieces, wherein said cable core is a single cable core disposed in said at least two pieces, and wherein said cable is non-planar.

[0009] In some embodiments, said at least two pieces of said cable jacket are fused together. In some embodiments, said at least two pieces of said cable jacket are soldered together or welded together. In some embodiments, said cable core is a conductor on a round core (CORC) cable. In some embodiments, said cable core comprises one or more high temperature superconducting tapes. In some embodiments, said cable core comprise an insulated, partially transposed, extruded, and roll-formed (VIPER) cable. In some embodiments, said cable jacket comprises copper. In some embodiments, an interface between said at least two cable pieces comprises a flat interface. In some embodiments, said cable jacket comprises grooves. In some

embodiments, said cable is bent into at least a portion of a stellarator coil. In some embodiments, said cable is a non-planar spiral.

[0010] In an aspect, the present disclosure provides a cable comprising a cable core and a cable jacket, wherein said cable jacket is formed of at least two pieces, wherein said cable core is a single cable core disposed in said at least two pieces, and wherein said cable core comprises a high temperature superconductor tape.

[0011] In another aspect, the present disclosure provides a cable comprising a cable core and a cable jacket, wherein said cable jacket is formed of at least two pieces, wherein said cable core is a single cable core disposed in said at least two pieces, and wherein said cable jacket comprises copper or stainless steel.

[0012] In another aspect, the present disclosure provides a system for stabilizing HTS tapes in a superconducting coil. In some cases, the system comprises a thermally and electrically conductive spine. In some cases, the system comprises a plurality of thermally and electrically conductive struts. In some cases, a first strut and a second strut of the plurality of struts are positioned with (i) a distance between the first and second struts, and (ii) an angle of rotation perpendicular to the spine. In some cases, the distance between the first and second struts and the angle of rotation perpendicular to the spine are based at least in part on a final bend radius of the coil. In some cases, the system comprises at least one HTS tape, mechanically supported by the first strut and the second strut.

[0013] In some cases, the first strut and the second strut of the plurality of thermally and electrically conductive struts each comprise one or more apertures for one or more cooling channels.

[0014] In some cases, the one or more cooling channels run parallel to the spine and through the first and the second struts.

[0015] In some cases, the angle of rotation of the strut with respect to the spine is configured to change as an external bend radius of the coil changes.

[0016] In some cases, a distance between the first strut and the second strut is configured to change as an external bend radius of the coil changes.

[0017] In another aspect, the present disclosure provides a method of forming a high temperature superconducting (HTS) coil. In some cases, the method comprises providing one or more HTS tapes along a spine of the HTS coil. In some cases, at least one HTS tape of the one or more HTS tapes is supported by a first strut and a second strut. In some cases, the method further comprises coupling the HTS tape to the first strut and the second strut while the HTS coil is in a first configuration; and bending the HTS coil into a second configuration, which results in

a change in one or both of (i) the distance between the first strut and the second strut, and (ii) a rotation angle around the spine of the first strut and/or the second strut.

[0018] In some cases, the change in one or both of (i) the distance between the first strut and the second strut, and (ii) a rotation angle around the spine of the first strut and/or the second strut minimizes a strain on the HTS tape.

[0019] In some cases, one or both of the first strut and the second strut are configured to rotate around the spine of the HTS coil.

[0020] In some cases, the HTS tape is configured to translate relative to the first strut and/or the second strut.

[0021] In some cases, during bending of the HTS coil into a second configuration, a bend radius of the HTS tape within the coil is either increased or decreased.

[0022] Fusion energy devices can produce a large flux of high energy neutrons that provide a difficult operating environment. These high energy neutrons can impart damage to the materials surrounding a plasma, which can be particularly damaging for carbon polymer electrical insulation materials, as the damage from the neutrons can generate conductive pathways through the insulation. These conductive pathways can cause electrical shorts, damaging the materials that the insulation was designed to protect. Using ceramic based insulations can provide resilience to the neutron flux and increase the mean time between failures of the insulation, and therefore the system at large.

[0023] In an aspect, the present disclosure provides a system, comprising: a high-temperature superconducting (HTS) tape; and a ceramic insulator in contact with said HTS tape, wherein the ceramic insulator is configured to insulate said HTS tape. In some embodiments, said HTS tape and said ceramic insulator are configured as a magnet coil. In some embodiments, said magnet coil is a portion of a stellarator. In some embodiments, said ceramic insulator is configured in a single piece comprising a channel configured to hold said HTS tape. In some embodiments, said ceramic insulator is a powder. In some embodiments, a thermal contraction rate of said HTS tape and said ceramic insulator are different by at most about 10%.

[0024] In another aspect, the present disclosure provides a magnetic coil, comprising: a high-temperature superconducting (HTS) tape; and an insulator disposed around the HTS tape, wherein the insulator is resilient to neutron bombardment damage.

[0025] In some embodiments, the insulator has an improved resilience to neutron bombardment as compared to a polymeric insulation. In some embodiments, the insulator comprises one or more channels configured to form the HTS tape into the magnetic coil. In some embodiments, the ceramic is at least about 80% of the insulator. In some embodiments, the ceramic is at least

about 99% of the insulator. In some embodiments, the insulator is an electrical insulator. In some embodiments, the insulator is a thermal insulator. In some embodiments, the HTS tape is coiled, and wherein the insulator supports the HTS tape. In some embodiments, the insulator comprises one or more of an oxide, a carbide, a nitride, or any combination thereof. In some embodiments, the insulator is aluminum oxide or titanium oxide. In some embodiments, the HTS tape is a portion of a stellarator. In some embodiments, the magnetic coil further comprises generating a magnetic coil using the insulated HTS tape. In some embodiments, the HTS tape is an HTS tape stack. In some embodiments, the HTS tape stack comprises at least about 3 HTS tapes. In some embodiments, the insulator comprises a tube comprising a wall defining an interior portion of the tube and an insulator comprising a ceramic disposed between the HTS tape and the wall of the tube. In some embodiments, the insulator is configured to, after exposure to a high energy neutron source for 1,000 hours, not generate percolative conductive carbon chains within the insulator.

[0026] In another aspect, the present disclosure provides a magnetic coil, comprising: a high-temperature superconducting (HTS) tape; and an insulator disposed around the HTS tape, wherein the insulator comprises a ceramic.

[0027] In some embodiments, the insulator comprises one or more channels configured to form the HTS tape into the magnetic coil. In some embodiments, the ceramic is at least about 80% of the insulator. In some embodiments, the ceramic is at least about 99% of the insulator. In some embodiments, the insulator is an electrical insulator. In some embodiments, the insulator is a thermal insulator. In some embodiments, the HTS tape is coiled, and wherein the insulator supports the HTS tape. In some embodiments, the insulator comprises one or more of an oxide, a carbide, a nitride, or any combination thereof. In some embodiments, the insulator is aluminum oxide or titanium oxide. In some embodiments, the HTS tape is a portion of a stellarator. In some embodiments, the magnetic coil further comprises generating a magnetic coil using the insulated HTS tape. In some embodiments, the HTS tape is an HTS tape stack. In some embodiments, the HTS tape stack comprises at least about 3 HTS tapes. In some embodiments, the insulator comprises a tube comprising a wall defining an interior portion of the tube and an insulator comprising a ceramic disposed between the HTS tape and the wall of the tube. In some embodiments, the insulator is configured to, after exposure to a high energy neutron source for 1,000 hours, not generate percolative conductive carbon chains within the insulator.

[0028] In another aspect, the present disclosure provides a stellarator, comprising: a ceramic insulator comprising a high-temperature superconducting (HTS) tape disposed therein.

[0029] In some embodiments, the insulator comprises one or more channels configured to form the HTS tape into the magnetic coil. In some embodiments, the ceramic is at least about 80% of the insulator. In some embodiments, the ceramic is at least about 99% of the insulator. In some embodiments, the insulator is an electrical insulator. In some embodiments, the insulator is a thermal insulator. In some embodiments, the HTS tape is coiled, and wherein the insulator supports the HTS tape. In some embodiments, the insulator comprises one or more of an oxide, a carbide, a nitride, or any combination thereof. In some embodiments, the insulator is aluminum oxide or titanium oxide. In some embodiments, the HTS tape is a portion of a stellarator. In some embodiments, the stellarator further comprises generating a magnetic coil using the insulated HTS tape. In some embodiments, the HTS tape is an HTS tape stack. In some embodiments, the HTS tape stack comprises at least about 3 HTS tapes. In some embodiments, the insulator comprises a tube comprising a wall defining an interior portion of the tube and an insulator comprising a ceramic disposed between the HTS tape and the wall of the tube. In some embodiments, the insulator is configured to, after exposure to a high energy neutron source for 1,000 hours, not generate percolative conductive carbon chains within the insulator.

[0030] In another aspect, the present disclosure provides a method, comprising: (a) providing a high-temperature superconducting (HTS) tape; and (b) disposing the HTS tape in an insulator, wherein the insulator is a ceramic insulator.

[0031] In some embodiments, prior to (b), the insulator is formed using additive manufacturing, milling, or a combination thereof. In some embodiments, the disposing comprises use of powder coating, sol gel deposition, or a combination thereof. In some embodiments, the insulator comprises a tube disposed around the HTS tape, wherein the tube is filled with ceramic insulation. In some embodiments, the method further comprises baking the HTS tape and the insulator. In some embodiments, the HTS tape is a part of an HTS cable. In some embodiments, the insulator comprises one or more channels configured to form the HTS tape into the magnetic coil. In some embodiments, the ceramic is at least about 80% of the insulator. In some embodiments, the ceramic is at least about 99% of the insulator. In some embodiments, the insulator is an electrical insulator. In some embodiments, the insulator is a thermal insulator. In some embodiments, the HTS tape is coiled, and wherein the insulator supports the HTS tape. In some embodiments, the insulator comprises one or more of an oxide, a carbide, a nitride, or any combination thereof. In some embodiments, the insulator is aluminum oxide or titanium oxide. In some embodiments, the HTS tape is a portion of a stellarator. In some embodiments, the method further comprises generating a magnetic coil using the insulated HTS tape. In some embodiments, the HTS tape is an HTS tape stack. In some embodiments, the HTS tape stack

comprises at least about 3 HTS tapes. In some embodiments, the insulator comprises a tube comprising a wall defining an interior portion of the tube and an insulator comprising a ceramic disposed between the HTS tape and the wall of the tube. In some embodiments, the insulator is configured to, after exposure to a high energy neutron source for 1,000 hours, not generate percolative conductive carbon chains within the insulator.

[0032] In one aspect disclosed herein is a method of fabricating at least a portion of a superconducting tape stack for a stellarator coil, comprising: (a) applying, a first layer of the superconducting tape stack on a substrate; and (b) applying, a second layer of the superconducting tape stack on the first layer of the superconducting tape stack, thereby forming the at least the portion of the superconducting tape stack.

[0033] In some embodiments, the first layer or the second layer of the superconducting tape stack is a superconducting tape.

[0034] In some embodiments, the superconducting tape is a high-temperature superconductor (HTS) tape.

[0035] In some embodiments, the first layer is applied to a curved surface of the substrate. In some embodiments, applying the first layer in (a) comprises determining, using a first dispensing device, a strain of the first layer.

[0036] In some embodiments, the method comprises determining the strain of the first layer while ap-plying the first layer to the substrate.

[0037] In some embodiments, the method comprises adjusting, using a first dispensing device, the strain of the first layer while applying the first layer to the substrate. In some embodiments, applying the second layer at (b) comprises determining, using a second dispensing device, a strain of the second layer.

[0038] In some embodiments, determining the strain of the second layer occurs during the application of the second layer at (b).

[0039] In some embodiments, the method comprises adjusting, using a first dispensing device, the strain of the second layer while applying the second layer to the first layer.

[0040] In some embodiments, the method comprises adjusting the strain of the first layer based at least in part on a comparison of the strain of the first layer against a strain threshold.

[0041] In some embodiments, the strain threshold is one or both of a tension strain of about 0.4% or a compression strain of about 1%.

[0042] In some embodiments, a first dispensing device comprises: (i) a bobbin configured to hold the first layer, (ii) a deflector configured to deflect at least a portion of the first layer during applying at (a), (iii) a motor configured to rotate the bobbin, and (iv) a PID controller configured

to obtain a determination of the strain of the first layer and provide a command signal to the motor to adjust the strain of the first layer.

[0043] In some embodiments, a second dispensing device comprises: (i) a bobbin configured to hold the second layer, (ii) a deflector configured to deflect at least a portion of the second layer during applying at (b), (iii) a motor configured to rotate the bobbin, and (iv) a PID controller configured to obtain a determination of the strain of the second layer and provide a command signal to the motor to adjust the strain of the second layer.

[0044] In some embodiments, at least after applying the second layer at (b): (i) a dispensed amount of the first layer is different than a dispensed amount of the second layer, and (ii) a first end of the first layer substantially aligns with a first end of the second layer; and (iii) a second end of the first layer substantially aligns with a second end of the second layer.

[0045] In some embodiments, the substrate comprises a magnetic material.

[0046] In some embodiments, the substrate comprises a corner.

[0047] In some embodiments, the method comprises at least after the applying at (b) applying, using a third dispensing device that is different from a first dispensing device and a second dispensing device, reinforcement layer to one or both of the first layer of the superconducting tape or the second layer of the superconducting tape, thereby reinforcing the stack corresponding to the superconducting tape.

[0048] In some embodiments, the reinforcement layer comprises copper.

[0049] In some embodiments, an applied strain of the first layer of the superconducting tape at least after the applying at (a) is different than an applied strain of the second layer of the superconducting tape at least after the applying at (b).

[0050] In some embodiments, one or both of the applied strain of the first layer of the superconducting tape or the applied strain of the second layer of the superconducting tape comprises tension strain.

[0051] In some embodiments, one or both of the applied strain of the first layer of the superconducting tape or the applied strain of the second layer of the superconducting tape comprises compression strain.

[0052] In some embodiments, the applied strain of the first layer of the superconducting tape is greater than the applied strain of the second layer of the superconducting tape.

[0053] In some embodiments, the first layer of the superconducting tape comprise a first material and the second layer of the superconducting tape comprises a second material, and wherein the first material has a greater durability to strain than the second material.

[0054] In some embodiments, an environmental temperature of the first layer of the superconducting tape at least after the applying at (a) is different than an environmental temperature of the second layer of the superconducting tape at least after the applying at (b).

[0055] In some embodiments, the environmental temperature of the first layer of the superconducting tape is greater than the environmental temperature of the second layer of the superconducting tape.

[0056] In some embodiments, the first layer of the superconducting tape comprises a first material and the second layer of the superconducting tape comprises a second material, and wherein the first material has a greater durability to high temperature than the second material.

[0057] In some embodiments, (a) is performed using a first dispensing device. In some embodiments, (b) is performed using a second dispensing device.

[0058] In another aspect disclosed herein is a system for fabricating at least a portion of a superconducting tape stack for a stellarator coil, comprising: (a) a first dispensing device configured to apply a first layer of the superconducting tape stack on a substrate; and (b) a second dispensing device, wherein the second dispensing device is configured to apply a second layer of the superconducting tape stack on the first layer of the superconducting tape, thereby forming the at least the portion of the superconducting tape stack.

[0059] In some embodiments, the first dispensing device is configured to: (i) determine a strain of the first layer of the superconducting tape while applying the first layer of the superconducting tape; and (ii) adjust the strain of the first layer of the superconducting tape while applying the first layer of the superconducting tape.

[0060] In some embodiments, a first dispensing device is configured to adjust the strain of the first layer of the superconducting tape at based at least in part on determining the strain of the first layer of the superconducting tape satisfies a threshold.

[0061] In some embodiments, the threshold is one or both of a tension strain of about 0.4% or a compression strain of about 1%.

[0062] In some embodiments, a first dispensing device is configured to one or both of determine the strain of the first layer of the superconducting and adjust the strain of the first layer of the superconducting tape at using a PID controller.

[0063] In some embodiments, a first dispensing device comprises: (i) a bobbin configured to hold the layer of the superconducting tape, (ii) a deflector configured to deflect at least part of the first layer of the superconducting tape during applying the first layer of the superconducting tape, (iii) a motor configured to rotate the bobbin, and (iv) the PID controller configured to

obtain a determination of the strain of the first layer of the superconducting tape and provide a command signal to the motor to adjust the strain of the first layer of the superconducting tape.

[0064] In some embodiments, a second dispensing device comprises components that are substantially the same as each of the components of a first dispensing device.

[0065] In some embodiments, one or both of the first dispenser or the second dispenser is configured such that: (i) a dispensed amount of the first layer of the superconducting tape is different than a dispensed amount of the second layer of the superconducting tape, and (ii) both a first end of the first layer of the superconducting tape substantially aligns with a first end of the second layer of the superconducting tape and a second end of the first layer of the superconducting tape substantially aligns with a second end of the second layer of the superconducting tape.

[0066] In some embodiments, the superconducting tape is high temperature superconducting (HTS) tape.

[0067] In some embodiments, the curved substrate comprises a magnetic material.

[0068] In some embodiments, the curved substrate comprises a corner.

[0069] In some embodiments, the system comprises a third dispenser that is different from a first dispensing device and a second dispensing device, wherein the third dispenser is configured to apply reinforcement layer to one or both of the first layer of the superconducting tape or the second layer of the superconducting tape, thereby reinforcing the stack corresponding to the superconducting tape.

[0070] In some embodiments, the reinforcement layer comprises copper.

[0071] In some embodiments, one or both of the first dispenser or the second dispenser are configured such that an applied strain of the first layer of the superconducting tape is different than an applied strain of the second layer of the superconducting tape.

[0072] In some embodiments, one or both of the applied strain of the first layer of the superconducting tape or the applied strain of the second layer of the superconducting tape comprises tension strain.

[0073] In some embodiments, one or both of the applied strain of the first layer of the superconducting tape or the applied strain of the second layer of the superconducting tape comprises compression strain.

[0074] In some embodiments, the applied strain of the first layer of the superconducting tape is greater than the applied strain of the second layer of the superconducting tape.

[0075] In some embodiments, the first layer of the superconducting tape comprise a first material and the second layer of the superconducting tape comprises a second material, and wherein the first material has a greater durability to strain than the second material.

[0076] In some embodiments, one or both of the first dispenser or the second dispenser are configured such that an environmental temperature of the first layer of the superconducting tape is different than an environmental temperature of the second layer of the superconducting tape.

[0077] In some embodiments, the environmental temperature of the first layer of the superconducting tape is greater than the environmental temperature of the second layer of the superconducting tape.

[0078] In some embodiments, the first layer of the superconducting tape comprise a first material and the second layer of the superconducting tape comprises a second material, and wherein the first material has a greater durability to high temperature than the second material.

[0079] In some embodiments, the second dispensing device is different from the first dispensing device.

[0080] High-temperature superconducting (HTS) tapes are critical components in the construction of stellarator coils used in fusion energy systems. A key challenge in the utilization of HTS tapes is their susceptibility to mechanical strain during the manufacturing process and operational use. The rigidity of existing stabilization systems often restricts the ability to bend HTS tapes into the complex geometries required without inducing damage. This limitation arises from the direct contact between HTS tapes and the bulky conductive substrates, which provides little room for the tapes to move or shift, increasing the risk of mechanical failure.

[0081] Another issue pertains to the cooling of HTS tapes and the integration of diagnostic sensors. Effective cooling is essential for maintaining the superconducting properties of the tapes, yet the space constraints within current stabilization systems limit the inclusion of adequate cooling channels or strips. Furthermore, the integration of sensors for monitoring the performance and health of the tapes is challenging, as there is insufficient space to incorporate them without impacting the tapes' structural integrity or superconducting function.

[0082] The manufacturing process of HTS tapes for use in stellarator coils involves intricate design and precise assembly to ensure the tapes' performance and longevity. Current methods require extensive machinery for bending and shaping, which increases complexity and cost. Additionally, scalability is a concern; the ability to produce HTS tapes for larger or differently configured systems often necessitates a complete redesign of the stabilization framework, hindering efficient production scaling and the ability to meet diverse design specifications.

[0083] Therefore, it would be useful to have a stabilization system for HTS tapes that allows for enhanced mechanical flexibility, enabling the tapes to be shaped into complex geometries without incurring damage. Such a system should facilitate integrated cooling solutions and the incorporation of diagnostic sensors without compromising the structural integrity of the superconducting properties of the tapes. Additionally, a more efficient manufacturing process that reduces the reliance on heavy machinery and allows for scalable production to accommodate various design requirements would be highly beneficial. This system would address the need for improved handling and operational stability of HTS tapes in the construction of stellarator coils, ultimately contributing to the advancement of fusion energy technology.

Hybrid Fusion Systems

[0084] Fusion systems may be integrated with an additional power system, including hybrids between fusion and fission. Hybrid fusion systems, including a stellarator-mirror (SM) hybrid, may facilitate optimizing stellarator functionality and advancing the business model. SM hybrids combine fusion and fission and may be referred to as fusion-fission hybrids. Fusion-fission hybrid methodology may employ uranium-238, a resource that can sustain global energy generation for a prolonged duration (about 100,000 years), as a principle fuel. A benefit of uranium-238 can include its subcritical configuration, which employs an external neutron source such as a plasma neutron generator, to regulate neutron reactions. Fusion-fission hybrids may both enhance safety through the substitution of delayed neutron actions and increase flexibility of control systems.

[0085] Furthermore, fusion-fission hybrid models may incorporate fuel recycling to preserve isotopic equilibrium and convert fission byproducts into valuable co-products instead of deeming them waste. Fuel recycling may substantially improve the safety and control capabilities of a stellarator by adhering to nuclear non-proliferation standards.

Magnetic Materials

[0086] In some aspects, the systems described herein may comprise novel magnet materials. These materials may be utilized in plasma confinement devices. Magnetic material advancements may optimize plasma confinement in a stellarator, thus enhancing the stellarator's operation and business model. Stellarator magnets preserve the form and stability of the plasma.

[0087] Permanent magnets may be applied to shape stellarator designs in a way that reduces a need for intricate three-dimensional coils to confine plasma. This method may streamline and reduce the cost of stellarator construction. For example, the MUSE stellarator features optimized

magnetic configurations. Optimization may involve systematic arrangement and orientation of magnets in order to generate intended magnetic fields to confine the plasma efficiently.

[0088] Progressions in magnetic materials and design methodologies may improve stellarator effectiveness, security, and economic viability, enhancing their appeal as a viable alternative for fusion energy production. Advancements in stellarator magnet technology not only serve to optimize operational processes but also potentially mitigate construction and operational expenses, thereby bolstering the sustainability of the business model.

Cables

[0089] Advancements in stellarator cables and connectors may prioritize resistance to high forces and enhanced structural integrity, as well as improved current carrying capacity of the cables at operational conditions (e.g., at field and at temperature). Adjustments may be made to field angle, field temperature, lower field, lower temperature, pending center optimization, in order to improve current capacity. These adjustments may help preserve stability and safety within the intricate magnetic confinement systems found in stellarators. Stellarator operational dependability may be enhanced by cables and connectors constructed from robust and long-lasting materials. Improved operational dependability may reduce operational expenses, minimize maintenance demands, and diminish the probability of mechanical malfunctions. Thus, improved cables and connectors may contribute to the economic viability and overall efficiency of stellarator-based fusion energy generation.

Neutron-Multiplier Materials

[0090] Tritium may be used as the primary fuel for fusion reactors. Materials capable of producing tritium efficiently while minimizing neutron flux during the fusion process may be used as neutron-multiplier materials in stellarators. Self-sufficiency of neutron-multiplier materials contributes to the production of tritium. Tritium breeding blanket material compositions may be optimized, with the dual objectives of enhancing tritium production and effectively managing the heat generated throughout the procedure. This methodology may improve the viability and profitability of stellarators for tritium production, suggesting that the revenue generated by tritium surpasses the expenses associated with the materials. Heat transfer and structural integrity may impact breeding blankets design and efficiency of tritium production. Optimizing breeding blanket design may augment stellarators' operational efficiency and positively contribute to their business model by ensuring steady and adequate fuel provision.

Neutron-Resistant Materials

[0091] Materials that exhibit minimal damage when exposed to high levels of neutrons may be used for internal components of stellarators. Neutron-resistant materials may improve stellarator functionality and economic viability, particularly regarding cost, environmental impact, upkeep, and security. Stellarator internal components constructed from neutron-resistant materials may better withstand intense neutron bombardment from fusion reactions.

[0092] The formidable neutron flux generated by fusion reactions may encourage designs which guard stellarator magnets against intense neutron bombardment. A breeding blanket infused with lithium may both safeguard the magnets and capture neutrons to produce tritium. A blanket approximately 1 to 1.5 meters thick may capture most neutrons; however, increased distance from the plasma may necessitate stronger magnets. The use of stronger magnets may increase overall machine size, which may affect a stellarator's overall cost and footprint.

[0093] Intricate magnetic fields present in stellarators necessitate the placement of the magnets with the utmost precision, which may increase expenses associated with construction. Attaining the precise tolerances required for positioning these components may be challenging, especially for construction of large-scale devices.

[0094] The size and complexity of the breeding blanket and magnet systems may be reduced by deploying materials that are more resistant to neutron bombardment without sacrificing functionality or structural integrity. Increased resistance may not only enhance stellarator operational effectiveness, but may also decrease stellarator construction and maintenance expenditures as well as stellarator physical footprints.

Shielding Materials

[0095] Shielding materials designed for fusion systems may protect a stellarator's constituents, particularly the magnets, against the intense neutrons generated during fusion processes. The neutrons may induce substantial degradation and harm to the structural materials. Effective shielding may preserve stellarator integrity and may guarantee long-term operational stability and safety. Desirable shielding materials may be capable of efficiently absorbing or deflecting energetic neutrons while preventing structural degradation or excessive radioactivity. Improved shielding materials may enhance overall design of stellarators, by facilitating footprint reduction, safety improvement, and maintenance cost savings due to increased component durability and lifespan. Thus, improved shielding materials may facilitate the economic viability of stellarators as a sustainable energy source.

Activation Materials

[0096] When exposed to neutrons, activation materials transform into radioactive waste with minimal effort. Low-activation materials may exhibit low susceptibility to neutron

bombardment, a frequent occurrence in the stellarator environment of fusion reactors. Low-activation materials may be applied in stellarators to enhance functionality as well as financial implications, environmental impact, upkeep, and safety.

[0097] Components capable of withstanding high neutron bombardment while maintaining structural stability may be desirable in operating fusion reactors. Considerations may include the degradation of wall surfaces due to neutron bombardment and the subsequent plasma-wall surface conditions. Materials suitable for withstanding high neutron bombardment may include SiC/SiC composites, ferritic/martensitic steels, and vanadium alloys. These materials may provide design alternatives for coolants and temperatures, and may be optimal even without the low activation criteria.

[0098] Considerations including material erosion and the disposal of irradiated materials as low-level radioactive waste may be mitigated through thoughtful material selection. In some cases, material degradation may occur if chrome steel is exposed to a typical neutron flux in a reactor, causing neutron activation in the chrome steel and resulting in the formation of chromium-51/51. In some cases, materials used for construction of components of systems described herein may comprise low-activation materials (e.g., beryllium or graphite). Alternatively, materials used for construction of components of systems described herein may comprise high-Z materials (e.g., tungsten). Additionally, molybdenum may be used. Components fabricated, coated or comprising Molydenum may exhibit a lower propensity to undergo radioactive transformation. Tin, lithium, and gallium liquids may also function as low-activation materials. Careful material selection for stellarators may improve operational efficiency, by facilitating decreased maintenance and replacement frequency, and may enhance safety and environmental concerns, by minimizing radioactive waste production.

High-Temperature Superconductors

[0099] High-temperature superconductors (HTS) may be implemented in reactor coils. HTS materials may be used to generate more vital magnetic fields, which contribute to the confinement of plasma in fusion reactors. Adopting HTS in stellarator coils may lead to compact and efficient reactor designs, potentially reducing the overall reactor size and cost. Reduced reactor size and cost may enhance the economic viability and feasibility of the fusion process, thereby promoting the progress of stellarator technology as an environmentally friendly energy alternative.

Sensors & Monitors

[0100] Stellarator sensors and monitors may enhance operation and overall design, encompassing factors including cost, footprint, maintenance, and safety. In some cases, XUV

(Extreme Ultraviolet) diagnostics may be utilized to observe a multitude of plasma characteristics, including the emission of boron, carbon, nitrogen, and oxygen. XUV sensors may enhance precision in regulating and comprehending the fusion process by furnishing comprehensive data regarding plasma conditions and interactions. Enhanced precision may enhance stellarator performance and safety and may reduce operational expenses and reactor dimensions by implementing more optimized designs.

[0101] Stellarator sensors may include electrostatic probes for determining plasma density and potential, interferometers for quantifying radiated power, bolometers for assessing ion and electron temperature, and magnetic sensors for evaluating the strength and configuration of the magnetic field. Each sensor type may provide distinct perspectives on distinct facets of plasma behavior, and may be deliberately positioned in diverse positions throughout the stellarator to amass exhaustive data. This data may be utilized to enhance ˇfunctionality and safety.

Vacuum Systems

[0102] An optimized stellarator vacuum system may reduce expenses, environmental impact, upkeep requirements, and safety apprehensions. Meticulously engineered vacuum systems may establish and sustain ultra-high vacuum conditions involved in plasma confinement. An optimized vacuum system may reduce plasma contamination, consequently enhancing plasma stability and performance. Compact and efficient vacuum systems may decrease the energy consumption and overall size of stellarators. Dependable and robust vacuum systems may preserve integrity of the plasma environment and may prevent introduction of impurities, thereby contributing to reactor safety and practical implementation.

[0103] The system may comprise a vacuum system (e.g., sub-system). Ultra-high vacuum conditions may facilitate maintaining plasma stability and reducing the risk of contamination. These conditions may contribute increased safety, decreased operational expenses, and enhanced performance.

Coil Structure

[0104] Structures associated with coils and magnets may be used to generate magnetic fields in fusion systems. Improving stellarator coil structure may reduce costs, footprint, maintenance, and safety concerns while enhancing operation. Coil configurations may be globally optimized via algorithmic and/or stochastic means. Algorithms may prioritize generating coil sets that exhibit resilience to random errors, thus enhancing the dependability and effectiveness of magnetic field production. Bayesian and stochastic optimizers may be employed to determine promising coil configurations. Algorithmic development may streamline and enhance the

intricate three-dimensional coil systems found in stellarators, which may lead to economical and effective fusion reactors.

Heating Systems

[0105] Optimization of the heating systems of systems described herein may reduce costs, footprint, maintenance, and safety concerns and may improve stellarator operation. The heating system may comprise high-power gyrotrons which utilize electron cyclotron resonance heating (ECRH). The high-power gyrotrons may give the plasma heat greater than or equal to about 1 MW, 2 MW, 3 MW, 5 MW, 7 MW, 10 MW, 12 MW, 15 MW, 20 MW or greater. The substantial heating capability may enable the elevated plasma temperatures at which fusion may occur. Furthermore, the system may comprise a neutral beam injection and/or an ion cyclotron resonance heating (ICRH) system, which individually or taken togehter may enhance its heating capabilities by around 8 megawatts for around 10 seconds. In addition, an enhanced diverter and a water-cooling system may prolong fusion experiments and may improve stellarator performance.

[0106] Implementing these sophisticated heating systems may enhance the performance of the plasma and may enable extended operational phases. Heating systems may be useful when conducting experiments investigating and comprehending plasma behaviors under different conditions. Thus, sophisticated heating systems may contribute to advancing scientific knowledge regarding plasma physics and enhancing stellarator design and efficiency. Such enhancements may facilitate stellarator technology as an alternative for future fusion power plants.

[0107] The heaters utilized in stellarators may attain extremely high temperatures which may enable plasma confinement and fusion reactions by applying fundamental physics principles. A concise synopsis of the physics underlying these heating systems follows:

[0108] Electron Cyclotron Resonance Heating (ECRH): ECRH may utilize the resonance between the cyclotron frequency of the electrons in the plasma and the electromagnetic waves generated by the gyrotron. When the frequency of these microwaves coincides with the natural gyro-frequency of the electrons in the magnetic field, the electrons may receive an efficient energy transfer, which may cause the plasma to heat. ECRH may regulate plasma temperature profiles and stability by enabling the targeting of specific regions of the plasma.

[0109] Neutral Beam Injection (NBI): NBI may inject high-energy neutral atoms into the plasma. After entering the plasma, these neutral atoms may undergo ionization and may initiate interactions with the ions and electrons of the plasma, thereby transferring energy and causing

the plasma to heat. NBI may not only elevate plasma temperature but may also contribute to overall confinement quality by aiding in maintaining plasma density.

[0110] Ion Cyclotron Resonance Heating (ICRH): Analogous to ECRH, ICRH relates to the principle of resonance between plasma ions and radio frequency (RF) waves. Aligning the frequency of the radio frequency (RF) waves with the cyclotron frequency of particular ion species present in the plasma may enable an effective energy transfer to the ions, thus heating the plasma.

[0111] These heating techniques may aid in the attainment of the requisite conditions for nuclear fusion through the elevation of plasma temperature and energy. These heating techniques may also enable optimizing stellarator performance and investigating diverse plasma behaviors.

Cooling Systems

[0112] Improved cooling systems may reduce costs and enhance operation of stellarators. Specifically, cooling systems may be used to maintain temperatures of magnets within stellarators and may be used to sustain plasma confinement. Sophisticated cooling methodologies may enhance the stellarator's operability and stability, diminishing the system's overall dimensions and intricacy. Subsequently, cooling systems may reduce the initial construction and ongoing maintenance costs associated with stellarators. Additionally, enhanced cooling mechanisms may bolster stellarator durability and longevity, thereby augmenting operational dependability and cost-effectiveness.

[0113] Superconducting magnets in stellarators may be used to generate the magnetic fields required to confine the plasma. Liquid helium may be employed to maintain these magnets at superconducting temperatures, thus creating conditions which may necessitate efficient cooling. Other cryogens which may be used may include hydrogen, nitrogen, neon, argon, fluorine, oxygen, and methane. Cryogens used for cooling may be utilized in a vacuum, with various isotopes and phases. A dependable and efficient cooling system for the magnets may enable stable operation of the reactor and the magnetic field.

[0114] Cooling systems may also be used to cool the diverter or other plasma-facing components. The diverter may manage the heat and plasma exhaust from the fusion process. Adequate cooling of the diverter may control the high heat flux and may prevent structural damage to the reactor.

[0115] Cooling systems may also be used to cool breeding blankets—substantial layers comprised of lithium—which may be utilized in a stellarator to capture neutrons generated during fusion reactions. Sufficient cooling of these blankets may preserve functionality and integrity.

Fueling

[0116] Similar to other fusion devices, the fueling process of a stellarator may include generating and sustaining a plasma state conducive to fusion reactions. In a stellarator, external coils may be employed to produce a helical magnetic field. The helical magnetic field may encircle the plasma in the form of a toroidal donut. This magnetic confinement may facilitate maintaining elevated plasma temperature and density for fusion reactions.

[0117] A stellarator may operate on hydrogen isotopes, including deuterium and tritium, as fuel. These isotopes may be subjected to high temperatures after introduction into the plasma. Electrons may be extracted from the nuclei at these temperatures. These extractions may result in the formation of a plasma state. Stellarator magnetic fields may confine and stabilize plasma These magnetic fields may also prevent plasma from contacting the reactor walls.

[0118] Hydrogen isotope nuclei in a plasma state may be in motion at high velocities. Nuclei in a plasma state may undergo fusion reactions through collisions with sufficient force which overcome inherent electrostatic repulsion. Such reactions may be utilized to produce large quantities of energy during the fusion process.

[0119] Precise manipulation of plasma conditions and magnetic fields may be utilized to fuel and maintain plasma in a stellarator. Enhanced confinement efficiency and plasma state stability and duration may also improve stellarator performance.

Blankets/Tritium Processing

[0120] Helium-cooled pebble bed (HCPB) breeding blankets may be utilized for tritium processing in the operation and design of stellarators. The use of HCPB breeding blankets may employ pressurized helium gas as a coolant. The use of HCPB breeding blankets may further utilize lithium ceramic as a tritium breeder. Tritium processing may incorporate a purge gas system to facilitate efficient breeding and extraction of tritium. HCPB breeding blanket designs may be characterized by design optimizations. Such optimizations may emphasize safeguarding components against nuclear irradiation. Optimizations may also emphasize extracting high-grade heat for electricity generation. Optimizations may further emphasize ensuring fuel self-sufficiency.

Wall Diverter Exhaust Enhancements

[0121] Enhancements to stellarator wall diverter exhaust systems may improve cost-effectiveness, operational efficiency, and safety. A wall divertor may be located at the radical periphery of the plasma. Stellarator diverters may serve as an exhaust system. Wall divertor exhaust systems may regulate the elimination of particles and heat from the stellarator. These systems may also facilitate the interaction between plasma and reactor walls. A diverter may

clean the plasma environment by accumulating and subsequently pumping out helium ash, a byproduct of the fusion process. A clean plasma environment may sustain uninterrupted stellarator operation.

[0122] Diverter design innovations may enhance stellarator performance. The design of a novel Diverter design may incorporate the theoretical and experimental intricacies of plasma physics and the materials implicated. Both magnetic field configuration and material selection may influence diverter function.

[0123] Development of stellarator diverter concepts may entail the execution of synchronized experiments across multiple stellarator facilities and the creation of computational instruments for analysis. Developments may minimize turbulence by optimizing the plasma core. Developments may also integrate a suitably shaped and designed diverter into the apparatus. Such developments may ensure that plasma and exhaust systems operate in unison.

Magnet Design

[0124] Stellarator magnet design development, including those utilizing permanent magnets, may enhance stellarator operation, cost, footprint, maintenance, and safety. Permanent magnets may resemble the magnets found on refrigerator doors, but possess significantly greater strength. Stellarator design may be streamlined through the use of permanent magnets. Permanent magnets may replace the intricate and expensive twisted magnetic coils traditionally used to confine the superhot plasma in stellarators. The use of permanent magnets may diminish the expense and intricacy associated with stellarator fabrication.

[0125] For example, the MUSE permanent magnet stellarator aims to develop stellarator geometries optimized in place of intricate 3D coils. Permanent magnets have been investigated in this context as a potential practical solution; numerous studies describe techniques for determining magnet distributions for optimized stellarator configurations. A shift from conventional, intricate modular coil designs to more efficient methodologies utilizing permanent magnets may facilitate the creation and assembly of more economical and efficient stellarators.

Magnetic Field Optimization

[0126] Optimizing stellarator magnetic fields may improve operation, cost-effectiveness, footprint, maintenance, and safety of stellarators. Optimizations may improve plasma confinement and stability, both of which may influence stellarator operational efficiency. Optimizing the magnetic field may involve carefully balancing various computational methods and physical constraints.

[0127] Optimizing a stellarator magnetic field may include applying various magnetic field representations, including the Stepped Pressure Equilibrium Code (SPEC) and the Variational

Moments Equilibrium Code (VMEC). Constraints such as nested magnetic surfaces may render VMEC unsuitable for representing magnetic islands and chaos. However, VMEC has been extensively implemented in the stellarator community and functions by minimizing the magnetohydrodynamic (MHD) energy. In comparison, SPEC may depict islands and chaos. SPEC may accomplish this depiction by dividing the toroidal domain into nested annular regions without restricting magnetic surfaces within each region. The use of both VMEC and SPEC during optimization may facilitate manipulation of magnetic islands and utilization of calculations predicated on the existence of magnetic surfaces. The combined use of VMEC and SPEC may mitigate the presence of chaotic regions and magnetic islands, which may otherwise negatively impact plasma confinement. Thus, adopting this dual strategy may achieve a more thorough optimization procedure.

[0128] Plasma stability and energy confinement may be improved by regulation of parasitic plasma currents via magnetic design. Such improvements may derive from careful engineering and refinement of the magnetic field. Thus, magnetic field optimization may improve stellarator-based fusion systems' overall functionality and sustainability.

Quench Protection

[0129] Quench event safeguarding is a critical element concerning the efficiency and security of the fusion system regarding stellarator operation. Quenching may denote an expeditious deterioration of superconductivity within a magnet. Improper management of such deterioration may result in substantial harm. Effective quench protection systems may ensure the safe operation of stellarators and may prevent damage.

[0130] Inverse Biot-Savart methods reproduce current distributions in magnet cables. These methods may safeguard against and detect quench conditions in fusion magnets. This methodology may be utilized with superconducting fusion magnets constructed from ReBCO CORC® cables or other high-temperature superconductors. Such systems may utilize voltage or temperature measurements to initiate protective mechanisms. Protective mechanisms may include current extraction processes. Discerning anomalies in the current distribution at cable terminations may identify quench events and may facilitate responses which safeguard the magnet system against potential harm.

[0131] Protection heaters and coupling loss-induced quenching (CLIQ) may protect magnets against quench. Protection heaters may be employed to enlarge the normal zone rapidly when a quench is detected in low-temperature superconductor (LTS) accelerator magnets. However, the substantial enthalpy margin may hinder use of high-power protection heaters in high-temperature superconductor (HTS) magnets. CLIQ may be employed to discharge a capacitor to

generate heat in the bulk of the cable conductor. This discharge may generate oscillatory currents and accompanying coupling losses. While efficacious in LTS magnets, implementation of CLIQ in HTS magnets may yet be optimized. A blend of voltage and non-voltage techniques may be used to enhance quench protection system detection sensitivity and redundancy for HTS magnets.

Diagnostics/Maintenance

[0132] Sophisticated monitoring and diagnostic equipment may optimize stellarator safety, performance, and operational efficiency. This equipment may include predictive maintenance systems. These systems may facilitate real-time monitoring and analysis of stellarator components and conditions. Such real-time monitoring may facilitate prompt interventions and early identification of potential issues. Integration of these technologies may enable maintenance of optimal operational conditions. Such integration may also reduce overall costs and environmental footprint of stellarators by preventing damage and prolonging component life. Advancing diagnostic and predictive maintenance systems may improve stellarator dependability and sustainability as a viable fusion power source.

Efficient Operation

[0133] Enhancing stellarator efficiency may entail optimizing diverse facets encompassing stellarator design and operation. Such facets may include mitigation of neoclassical transport losses. Neoclassical transport losses may contribute substantially to plasma depletion in stellarators. The optimized shape of the Wendelstein 7-X (W7-X) stellarator may mitigate neoclassical transport. This mitigation may facilitate the W7-X in attaining elevated temperatures while maintaining heating power. The W7-X optimized shape may diminish plasma loss and enhance fuel utilization efficiency.

[0134] Stellarator configuration may involve harmonizing numerous physical parameters and engineering limitations. Harmonization may lead to exceptional quasi-axisymmetry, minimized alpha-particle losses, and stability to linear ideal modes of MHD. However, harmonization may also result in heightened intricacy in the plasma configuration. The ARIES-CS project is an integrated study examining these trade-offs to optimize compact stellarator power plants. Strategies which may overcome the difficulties associated with stellarator operation and design may include cost-optimization systems and development of modular coils.

[0135] Developing stellarators that maintain high-performance plasma and exhibit efficiency in cost, energy consumption, and maintenance may involve blending theoretical investigations and experimental findings.

Continuous Operation

[0136] Practical fusion energy may involve continuous stellarator operation. Stellarator design permits steady-state operation with minimal recirculating power demands. Thus, stellarators may function without interruption and without the plasma disturbances typical in tokamaks. The Wendelstein 7-X (W7-X) in Germany, one of the largest stellarators of its kind, demonstrates such uninterrupted function. The U.S. Department of Energy has financially supported energy projects at W7-X to conduct additional research on ion-heat transport, electric field measurement, and plasma confinement enhancement. These initiatives may enhance the performance and dependability of stellarators, which may enable the use of stellarators as fusion power plants in the future.

[0137] Maintaining continuous operation in fusion systems like stellarators may involve advanced plasma confinement, stable magnetic fields, efficient heat and particle management, material durability, integration of control and diagnostic systems, and energy conversion and extraction., (1) Advanced plasma confinement may efficiently confine plasma to optimize the fusion reactions. (2) Magnetic fields which are both stable and intricate may promote prolonged plasma stability. (3) Efficient management of heat and particles generated by the fusion process may be improved by the development of advanced diverters and other systems. (4) Durabile materials capable of withstanding prolonged exposure to extreme conditions may be employed within the reactor. (5) Control and diagnostic systems may be integrated to oversee and modify the parameters of the reactor to achieve maximum efficiency. (6) Efficient mechanisms may be employed to convert and extract the electrical energy generated during fusion reactions.

Advanced Manufacturing

[0138] The progression of additive manufacturing may influence the evolution of stellarators. Additive manufacturing techniques may produce stellarator components such as coil supports, especially when dealing with complex geometries. Monolithic coil supports for stellarators may be manufactured additively by layering composites on a substrate. Additive manufacturing may meet the necessary precision, stiffness, and strength standards for stellarator components. Advanced manufacturing techniques may be feasible in the presence of moderate to strong magnetic fields. Implementing additive manufacturing techniques of stellarator components may decrease expenses and enhance production efficiency. These improvements may augment stellarator viability and effectiveness.

Compact and Modular Designs

[0139] Compact and modular stellarator designs may improve the practicality and effectiveness of these fusion systems. Compact hybrid configurations featuring two or three field periods may provide favorable stability and quasiaxial symmetry. Stability and symmetry may facilitate

sufficient transport within a magnetic fusion reactor. A combination of helical fields and bootstrap currents may enable compact or modular designs to perform rotational transformations efficiently at low aspect ratios. Moreover, these configurations may exhibit stability against ballooning modes. These configurations may also possess the capability to attain elevated beta limits, which may facilitate efficient fusion reactions. Thus, modular and compact stellarators may increase the accessibility and practicability of fusion energy.

Safety and Environmental Benefits

[0140] Compared to tokamak fusion reactors, stellarators may present a multitude of environmental and safety benefits which may enhance functionality and overall influence. Stellarators may maintain plasma without being dependent on induced plasma currents. Plasma maintenance may contribute significantly to the stellarator security and stability. Plasma disruptions may present an obstable in tokamak design. In comparison, stellarator mitigation of the likelihood of plasma disruptions may enhance the safety and dependability of stellarators for uninterrupted operation.

[0141] Additionally, the safety profile of stellarators may be enhanced by their design flexibility. Stellarators may enable a greater variety of plasma control options, which can result in more stable and effective operation. Furthermore, stellarators may employ robust electromagnetic coils to produce torsional magnetic fields. Use of these coils may involve high accuracy and may provide substantial regulation of plasma characteristics.

[0142] The overarching objectives of fusion energy may include supplying a clean, renewable, and virtually limitless energy source. Stellarators may be provide environmental advantages within these objectives. Fusion energy, which may encompass stellarator-generated energy, may aid in mitigating climate change and may contribute to a varied energy portfolio. Stellarators may provide a more environmentally friendly substitute for conventional energy sources by facilitating fusion reactions without producing persistent radioactive waste.

[0143] Ongoing scientific and technical endeavors in stellarator technology, backed by reputable organizations such as the Department of Energy (DOE) and the International Atomic Energy Agency (IAEA), may optimize designs for fusion energy. Such designs may encompass optimizing magnetic fields responsible for regulating plasma in stellarators. Such designs may also encompass formulating designs and methodologies which augment operational efficiency while minimizing ecological footprints.

Power Generation Applications

[0144] Stellarator design and operation improvements may enhance fusion energy as a viable power source. The German Wendelstein 7-X (W7-X) stellarator enhances performance and

extends the duration of fusion experiments by installing a water-cooling system and an improved diverter for managing high-performance heat. The W7-X may verify that power plants may utilize optimized stellarators.

[0145] Stellarators present some benefits compared to tokamaks in the field of fusion research. Stellarators may enable increased design flexibility, reduced power consumption for plasma maintenance, and simplified plasma control mechanisms. However, design improvements may overcome stellarator complexity, specifically regarding the design of magnetic field coils. Improvements in plasma theory and high-performance computing may assist in optimizing stellarator designs, such as the W7-X and the HSX (Helically Symmetric Experiment) in Wisconsin. Such designs may develop magnetic fields that effectively regulate plasma in stellarators and may contribute to comprehension of fundamental plasma theory.

[0146] A diverter may remove helium ash to ensure the continuous operation of a clean plasma. Diverters may act as an integral component in the interface between the hot plasma and the reactor walls. Diverter design may involve substantial experimental and theoretical effort due to its intricate nature. A divertor system described herein may streamline the plasma core, minimize turbulence, and incorporate a productive exhaust system.

Heat Generation Applications

[0147] The heat produced by stellarators may be applied in industrial processes and power generation. Industrial processes may include material processing, metallurgy, chemical manufacturing, or other operations requiring high temperatures. Fusion reactor high-grade heat may be converted into steam for conventional industrial operations. Fusion reactor high-grade heat may also be directly implemented in processes which involve elevated temperatures. Thus, fusion reactions may be substituted for the use of fossil fuels and may contribute to mitigating carbon emissions.

[0148] Reliable and continuous operation of fusion technology may facilitate the development of heat-harvesting technologies for industrial purposes. Advancements in fusion research may extend beyond electricity generation.

Neutron Production Applications

[0149] Plasma confinement and heating to facilitate fusion reactions may contribute to neutron generation in a stellarator. Stellarators may utilize magnetic fields to confine plasma in the form of a toroid. Stellarator design and operational conditions may impact the rate and efficiency of neutron production resulting from fusion reactions occurring within the plasma.

[0150] Improving the generation of neutrons may involve the optimization of magnetic confinement to maintain the required conditions of high-temperature plasma. Advancements in

stellarator design, including enhanced coil configurations and improved plasma heating methods, may augment plasma confinement and stability. Consequently, these advancements may augment neutron production.

[0151] Sophisticated computational models and simulations may be utilized to examine diverse facets of stellarator operation, such as the configurations of the magnetic field and the behavior of the plasma. These models may facilitate increasing the efficiency of neutron production.

[0152] Stellarator designs which are adaptable and sustain stable plasma while consuming less energy may result in operational and financial gains for fusion systems. By optimizing magnetic fields that regulate plasma, these designs may offer a secure and practical approach to generating neutrons in fusion processes.

Medical Applications

[0153] Stellarators may be designed to produce and regulate high-temperature plasmas to maintain fusion reactions. Technology and discoveries derived from stellarator research may indirectly benefit medical applications, specifically in fields associated with nuclear and radiation medicine.

[0154] Radiation Therapy: Fusion and plasma physics research developments may contribute to improving radiation therapy technologies. Gaining insight into the dynamics of high-energy particles and radiation within stellarators may contribute to advancing radiation therapy methods. These therapy methods may become more accurate and productive in the context of cancer treatment.

[0155] Production of Medical Isotopes: Fusion systems like stellarators may generate medical isotopes. These medical isotypes may be utilized in therapeutic and diagnostic contexts. Such isotopes may be used in imaging and treatment procedures in nuclear medicine.

[0156] Radiation-Resistant Materials: Materials devised for stellarators may endure high temperatures and radiation and may be modified for medical applications. Radiation-resistant materials may be utilized in medical devices and implants.

[0157] Neutron Imaging: Stellarators utilized in fusion systems may generate neutrons. Neutrons may be utilized in the fields of medical imaging and cancer treatment. Neutron imaging presents specific benefits compared to conventional X-ray imaging. Additionally, specific forms of cancer can be targeted through neutron therapy.

Precision Requirements

[0158] Stellarator coils may be utilized to generate the complex magnetic fields which confine plasma in a stellarator fusion device. The intricate three-dimensional configurations of these coils may involve a significant level of precision in both design and manufacturing. Precision

related to stellarator coils may facilitate optimal plasma confinement and stability. The design, fabrication, and upkeep of stellarator coils may involve extreme precision to improve stellarator operation, reduce costs, enhance maintenance, and reduce device footprint profiles.

[0159] Stellarator Operation Improvements: Accurate coil geometry may enable a stellarator to produce an intended magnetic field configuration. Coil accuracy levels may directly influence the effectiveness of plasma confinement. Coil accuracy may also influence the caliber of the fusion reactions. Coil accuracy may also contribute to overall stellarator performance. Advancements in manufacturing technologies and design methodologies may lead to improved alignment accuracy. These improvements may enhance plasma confinement and stability, ultimately facilitating more efficient fusion processes.

[0160] Achieving Cost Reduction: The intricate design and precise parameters involved in manufacturing and assembling stellarator coils may contribute excessive expenses to stellarator construction.. The overall cost of stellarator construction and operation may be diminished through design and fabrication techniques that enhance efficiency. Such techniques may include employing advanced computational modeling, 3D printing components, and deploying materials that are simple to shape and assemble.. Labor and material costs may be reduced by optimizing coil designs. Such optimizations may facilitate more straightforward assembly or may reduce the number of unique components.

[0161] Enhanced Maintenance and a Reduced Footprint: Precise coil design and fabrication may contribute to more compact stellarator configuration. Compact configurations may further diminish overall footprints of stellarators. A more space-efficient stellarator in a compact design may enable integration into pre-existing facilities. Furthermore, precision-engineered, readily accessible, and replacable coils may streamline maintenance protocols. Streamlined maintenance protocols may augment stellarator safety and durability.

Material Stress

[0162] Operational heat and magnetic fields may place significant strain on stellarator component materials. Such material stress may encourage meticulous attention to detail during the design, production, and upkeep stages.

[0163] Enhanced Stellarator Performance: Addressing material stress in stellarators may enhance operational efficiency. Stellarator operations may increase longevity and effectiveness by incorporating composite materials or alloys specifically engineered to endure elevated temperatures and stresses. Further, cooling technologies and heat management systems may alleviate the consequences of thermal stress, resulting in enhanced fusion processes and more consistent plasma confinement.

[0164] Safety, Cost, Footprint, and Maintenance: Effective material stress management may affect stellarators' costs, footprints, and maintenance. Materials with increased resistance to stress may decrease operational expenses by eliminating frequent component replacements and extensive maintenance. Compact designs that effectively handle material stress may result in diminished footprints. Diminished footprints may then in turn increase the viability of stellarators across diverse environments. Materials with a greater capacity to withstand operational stresses may inherently enhance safety by mitigating the likelihood of system failures. System failures may otherwise result in system shutdowns or hazardous environments.

[0165] Interdisciplinary developments may enhance the management of material stress in stellarators. Such developments may involve materials science, thermal dynamics, and plasma physics. Interdisciplinary development may further stellarator technology toward practical and economically viable fusion energy production.

Magnetic Field Optimization

[0166] Optimization of the magnetic field within stellarators may increase energy generation efficiency and enhance reactor performance as a whole. In contrast to tokamak designs, stellarator design may generate precise magnetic fields. These precise fields may be capable of effectively confining plasma amidst inherent symmetries. The toroidal and poloidal components of these magnetic fields may be balanced to generate flux surfaces. These flux surfaces may confine the plasma throughout the numerous plasma circuits around the apparatus.

[0167] Optimizations which minimize neoclassical energy transport may be utilized to optimize magnetic fields. The magnitude of neoclassical energy transport may be impacted by the geometry of the magnetic field. Stellarators generate both toroidal and poloidal components of the magnetic field. These components may be generated externally through coils specifically engineered to induce the required spiraling of the field. Neoclassical energy transport may be reduced by minimizing time-averaged radial drifts encountered by localized particles. This minimization maybe achieved by optimizing these fields and decreasing the effective helical ripple. The Wendelstein 7-X (W7-X) design strives to minimize neoclassical energy transport by manipulating magnetic field geometry.

[0168] Optimization may relate not only to the magnetic field but also to the configuration and design of the coils responsible for producing it. Computational design may influence configuration and design of the coils. Thus, computational design may provide a cost-effective method for exploring the stellarator design space. Computational models may direct the development process towards configurations that offer enhanced confinement and stability for the plasma by commencing with an optimized initial state.

[0169] Thus, optimization efforts may enhance the stability and confinement of the plasma to improve the operation of stellarators. Such optimization efforts may also address concerns regarding cost, footprint, maintenance, and safety. Enhanced stellarator maintenance, reduced coil system complexity and size, and improved magnetic field efficiency may facilitate efficient, economic, sustainable, and secure fusion energy sources.

Conductor Material

[0170] Cryogenic superconductors may contribute to stellarator development and function. These cryogenic superconductors may conduct electricity at extremely low temperatures with no resistance. Such superconductors may produce the intense magnetic fields used for plasma confinement in stellarators. High-temperature superconducting (HTS) materials, including REBCO (Rare Earth-Barium-Copper Oxide), may enhance stellarator operations and decrease expenses in multiple respects.

[0171] Enhanced Stellarator Performance: HTS materials may generate more robust and consistent magnetic fields. Such fields may facilitate the efficient confinement of plasma. Compared to conventional superconductors, HTS materials may possess elevated critical temperatures and magnetic field strengths. Such characteristics may facilitate cooling systems with greater efficiency and may diminish the energy needed to sustain the superconducting state. Thus, HTS materials may improve plasma stability and higher fusion power output.

[0172] Long-Term Cost Reduction: Despite the initial high cost of HTS materials and associated cooling systems, the exceptional efficiency and performance associated with these materials may reduce operational expenditures. HTS materials may enable more compact coil designs and decrease cooling requirements, thereby reducing stellarator device size and complexity. Consequently, reduced device size and complexity may result in cost savings associated with construction and maintenance.

[0173] Enhanced Maintenance and a Smaller Footprint: Incorporating HTS materials into the stellarator design may result in a more compact formation. Compact formations may diminish physical dimensions and potentially streamlining integration with pre-existing infrastructure. Furthermore, the increased dependability and prolonged operational lifespan of HTS coils may decrease maintenance demands and expenses. These decreases may bolster overall security and longevity of the system.

Structural Support

[0174] The structural support of stellarators may directly influence the efficiency, cost, footprint, maintenance, and safety of fusion devices. Support mechanisms may allow stellarator

coils and other functional structures to endure the stresses caused by magnetic fields, thermal loads, and the physical weight of the components.

[0175] Various manufacturing techniques may be employed to produce stellarators of small to medium dimensions. Manufacturing techniques may include additive manufacturing or 3D printing. In contrast to conventional fabrication methods such as cutting, casting, forging, and welding, these approaches may present distinct benefits, particularly when constructing sophisticated, intricate modular stellarators. 3D printing may preserve complex component positioning accuracy while also reducing costs. Geometrically simple assembly configurations achieved with 3D printing may maintain high precision while reducing device costs.

[0176] Manufacturing techniques may also adjust material thicknesses by forming a continuous monolithic coil structural shell that conforms to modular coils. In conjunction with additive manufacturing, this strategy may reduce the capital expenditures associated with stellarator construction. Utilizing computer-aided design files to generate distinct configuration may produce components similar to the intended form. Producing components with minimal deviations from the original designs may diminish extensive machining processes. Components with minimal deviations may also curtail manufacturing expenses while optimizing structural support.

[0177] Like any engineering structure, structural support may preserve stellarator functionality and integrity. To ensure that structures can withstand internal forces such as gravity and lateral forces such as wind or earthquakes, engineering may employ a variety of supports that transfer such loads to the ground in a safe manner. Fixed supports may be utilized for this purpose. Fixed supports may be characterized by extreme rigidity which prevents any motion of the abutting structure. Undesirable motion of the structures may include translations and rotations. Fixed supports may include poles or columns inserted into concrete. Such fixed supports may establish a sturdy linkage for edifices that demand slight deflection or “play” to safeguard adjacent materials.

[0178] Pinned or hinged supports may also be utilized to transfer external loads to the ground in a safe manner. Pinned support may function like a hinge by permitting rotational motion but limiting translational changes. Structures like door leaves, which rotate about a vertical axis without horizontal or vertical displacement, may benefit from pinned support.

[0179] Further, roller supports may be utilized to permit thermal expansion and contraction. Roller supports may resist only perpendicular forces commonly found in large bridges, thus preventing damage from expansion or contraction caused by temperature changes.

[0180] Structural support in stellarators may facilitate designing and constructing intricate coil systems and other functional structures which may confine the plasma. Appropriate forms of structural reinforcement may be deployed to support the complex geometries and critical placement requirements of stellarator components. Fixed supports may be employed to firmly fasten the base of stellarator coils. In contrast, pinned or hinged supports may permit adjustments or movements executed during maintenance without jeopardizing overall structural stability. Roller supports may be utilized in structural components that require thermal expansion accommodation.

Magnetic Field Shaping Elements

[0181] Stellarators may employ magnetic fields to confine plasma. Electromagnetic coils may be implemented to generate these magnetic fields. Coil configuration, placement, and constituent materials may influence coil efficacy. Prominent stellarators such as the Wendelstein 7-X in Germany, the Helically Symmetric Experiment (HSX) in the United States, and the Large Helical Device in Japan may illustrate the varied methodologies employed in a magnetic field configuration.

[0182] Permanent magnets may be employed to simplify stellarator design. This approach may decrease the intricacy and expense conventionally linked to twisted magnetic coils. Powerful permanent magnets may be used to generate a significant portion of the magnetic fields required for plasma confinement. The use of permanent magnets may eliminate complex coil systems, which could result in more cost-effective and uncomplicated construction processes.

[0183] Optimized coil geometry and magnetic field shaping may increase the efficiency of particle confinement. Numerical methods may be developed to compute particle distribution. The influence of plasma-generated electric currents on the magnetic field may be investigated. Stellarators may be designed to achieve optimal confinement. Finally, plasma turbulence and its consequences for heat and particle losses may be investigated.

Power Supply and Control Systems

[0184] The design, construction, and testing of electrical power supply components in the TJ-II stellarator in Spain may influence power supply system advancements. The flywheel synchronous generators may satisfy the essential criteria for stellarator operation. Augmenting the effectiveness and dependability of stellarator power systems may result in operational enhancements, cost reductions, and safety improvements.

[0185] Power supplies may supply energy to support the operation of control systems and maintain plasma confinement. Stellarators, such as the Wendelstein 7-X located in Germany, may employ sophisticated power supply systems to regulate the intricate magnetic fields used

for for plasma confinement. The use of permanent magnets may simplify stellarator design, potentially reducing the complexity and expense of magnetic coil systems. Robust permanent magnets may generate a proportion of the magnetic fields required for plasma confinement. The use of permanent magnets may avoid the use of complex and costly twisted magnetic coils.

[0186] Plasma turbulence may result in inefficiencies in plasma confinement and energy dissipation. Schola Computational models may be employed to comprehend and mitigate plasma turbulence in stellarator-type plasmas. The Gyrokinetic Electromagnetic Numerical Experiment (GENE) code, initially designed for tokamak systems, has been expanded to include stellarators. GENE code simulations may reduce plasma turbulence by over 50%. Such reductions in turbulence may enhance plasma confinement efficiency and reduce the operational expenses of forthcoming stellarator power plants.

Thermal Management

[0187] The design and operation of stellarators may involve thermal management. Superconductor cryogenic conditions may contribute to stellarator functionality. These cryogenic conditions may be preserved through effective management of thermal energy produced by stellarators. Thermal management in stellarators may control the heat produced by the apparatus while preserving the cryogenic condition of superconductors.

[0188] The application of high-temperature superconductors (HTS) to stellarators may boost performance and efficiency. Higher temperature operation of HTS materials compared to conventional superconductors may reduce cooling requirements and simplify thermal management systems. Magnetic fields, which may be used for plasma confinement in stellarators, may be generated by these materials with a reduced footprint and energy consumption.

[0189] Thermal management systems may regulate the heat load from external and plasma sources. These systems may also preserve the superconductors below critical temperature. Thermal management may also protect cooling system integrity in intense magnetic fields. Cooling mechanisms, such as cryogenic liquid helium or nitrogen, may extract thermal energy from the superconducting coils.

Assembly

[0190] Stellarator designs may incorporate precisely shaped and positioned magnetic coils to generate the three-dimensional magnetic fields which may confine plasma. In contrast to tokamaks, the stellarator configuration may deviate from toroidal symmetry. This deviation may lead to more complex configurations of magnetic coils to guarantee efficient plasma containment without a plasma current.

Integration with Other Systems

[0191] Stellarator designs may involve operational, financial, environmental, upkeep, and safety-related considerations. These considerations may facilitate stellarator-based fusion energy as a feasible component of the overall energy portfolio.

[0192] Improvements to stellarator operation may incorporate optimizing magnetic field configurations to enhance plasma confinement and stability. Sophisticated computational models may be developed to optimize the design of magnetic coils. Optimized designs may minimize energy losses and enhance plasma confinement effectiveness. Integration of real-time temperature monitoring and quench protection systems may enable secure device function even in the most extreme conditions, thereby improving overall operational stability.

[0193] Cost and Physical Footprint: Resilient, effective, and low-maintenance magnetic coils may decrease stellarator expenses and ecological impact. Compact power conversion systems may employ supercritical CO2 in combined cycles for electricity production. Compact power conversion systems may be incorporated into stellarator design to enhance thermal efficiency and diminish the scale of the infrastructure.

[0194] Safety and Maintenance: Safety enhancements may prevent accidents. Such enhancements may include sophisticated diagnostics and control systems that may react to deviations in plasma behavior. Modular designs may enhance the efficiency of maintenance processes by facilitating convenient access to components that require repair or replacement. Energy usage and generation monitoring may be incorporated with safety systems to achieve efficiency while maintaining safety standards.

[0195] Integrating a stellarator with power grid utilities may be enhanced by implementing innovative grid technologies. Such technologies may enable dynamic balancing of energy supply and demand. Innovative integration may include developing energy storage or conversion systems that manage the intermittent nature of fusion energy production. By facilitating smooth integration with the electrical grid, sophisticated control systems may promote fusion power as a dependable and consistent energy source.

Plasma Creation

[0196] Stellarators may maintain plasma without requiring constant external power to propel plasma currents, unlike tokamaks. Stellarator plasma stability may facilitate consistent and uninterrupted operation. Such operation may decrease operational intricacy and expenses associated with fusion power generation. Stellarators may be engineered to be adaptable, allowing for adjustments. These adjustments may result in enhanced confinement and diminished energy dissipation. Neoclassical transport, a significant source of energy loss, may

be mitigated through optimized stellarator designs. This optimization may attain elevated temperatures and confinement underlying the practical generation of fusion energy.

[0197] Furthermore, in contrast to tokamaks, stellarators may function in an intrinsic steady-state manner. Steady-state operation may improve safety and alleviate maintenance difficulties typically associated with fusion reactors. Additionally, steady-state operation may diminish needs for intricate systems to control disruptions and instabilities. Thus, steady-state operation may diminish financial burdens and reduce expenses.

[0198] Plasma theory and high-performance computing may facilitate stellarator designs. Theory and computing may aid in comprehending and optimizing magnetic fields that regulate plasma. Stellarator technology that is safe, clean, and renewable may be a viable alternative for fusion power plants.

Magnetic Confinement

[0199] Coils may generate complex magnetic fields confine highly charged plasma produced during fusion.

[0200] Stellarators may regulate fusion of highly charged plasma with magnetic confinement. This confinement may be achieved with intricate magnetic coil arrangements. Stellarators have a distinct advantage over tokamaks by preserving plasma stability without a substantial toroidal current. This level of stability may avoid the use of external current drivers, thus decreasing energy consumption and operational expenses. Stable and prolonged plasma confinement within stellarators may also facilitate sustained fusion reactions. Materials and magnetic field optimizations may enhance complex coil design performance and efficiency. Comprehension of plasma behavior and development of robust materials and potent magnets may facilitate stellarators as a feasible alternative for fusion power plants.

Stability and Control

[0201] Stellarators may incorporate design parameters, including applying 150 million degrees Celsius heating to a plasma, confining the plasma by a meticulous configuration of magnetic coils, and driving the coils by superconductors. Enhanced stability and control in stellarator design may sustain the high-temperature plasma utilized for fusion. Computational optimization may yield stellarator configurations that may enhance turbulent transport reduction, include effective non-resonant diverters, and improve transport of energetic particles. Sophisticated algorithms may refine the plasma boundary and may provide quasi-symmetry and homogeneity. Thus, plasma stability may enhance stellarator performance and stability. Quasi-helical symmetric designs, optimized for particular performance metrics, may be implemented to

improve performance and stability. Such metrics may include diminished deviation from quasi-symmetry and enhanced confinement and stability characteristics.

[0202] Stellarator stability and control may also be enhanced by three-dimensional Monte Carlo codes of plasma transport in island diverters. This methodology may enable comprehensive simulation of plasma dynamics in intricate magnetic configurations. These simulations may offer valuable insights into enhancing diverter designs to manage heat loads and regulate particles efficiently. Technological advances of this nature may facilitate refinement of stellarator designs to attain stable and efficient fusion energy production.

Energy Extraction

[0203] Fusion heat may be converted to a liquid state to extract energy from a fusion reactor. Heat may converted to a liquid state by producing steam. Energy extraction methods may be utilized to enhance stellarator operations or mitigate concerns related to cost, footprint, maintenance, and safety. Stellarator designs present unique challenges, including the administration of the high-energy neutrons generated during fusion reactions. A breeding blanket, commonly composed of lithium-containing material, may be employed to capture these neutrons. Breeding blankets safeguard the magnets which sustain magnetic confinement of the plasma. The breeding blanket layer must be sufficiently thick to capture the majority of neutrons. If the majority of neutrons are not captured, the magnets may be pushed further away from the plasma. The further the magnets are from the plasma, the more powerful the magnets may become as the device scales up. These stringent placement tolerances may contribute to the intricate nature of stellarator magnets and may pose significant financial and manufacturing obstacles.

[0204] Stellarator design may integrate various plasma heating techniques before ignition to extract energy. Such techniques may include current heating for preliminary warm-up, neutral particle beam injection, and high-frequency electromagnetic waves. High-frequency electromagnetic waves may be analogized to microwave heating. High-frequency electromagnetic waves may be utilized to generate and enhance an ion beam injected into the plasma after neutralization to prevent deflection caused by the magnetic field. This method effectively warms the plasma by transferring kinetic energy to the plasma particles via collisions.

Gas Introduction

[0205] To ionize a substance, the gas may be introduced into the stellarator while maintaining internal conditions. Gas introduction may be manipulated to optimize the restriction and preservation of plasma at exceedingly high temperatures utilized for fusion reactions. The

process of gas introduction into a stellarator, followed by plasma formation via ionization, may influence operational stability and efficiency. Maxwell–Boltzmann statistics suggest that certain particles may attain the elevated energies required for fusion reactions, even at lower bulk gas temperatures. These reactions may generate substantial amounts of energy, which may aid in sustaining the gas at the necessary temperature for fusion to continue.

[0206] The magnetic confinement capabilities of a stellarator may facilitate introducing and managing gas within the apparatus. Gas introduction, ionization, and subsequent plasma heating and containment may support operational enhancements and advancements that may establish stellarator-based fusion as a feasible and environmentally sustainable energy alternative.

Ionization

[0207] Gas introduced into a stellarator may be heated to induce ionization. The gas may reach a critical temperature for fusion to occur. Thus, gas ionization may facilitate attaining and maintaining ideal plasma conditions.

[0208] Enhancing the efficiency and regulation of gas ionization in stellarators may facilitate the optimization of fusion reactions. Advancements in stellarator design may employ sophisticated optimization methodologies, which may augment ionization efficiency substantially. Manipulation of plasma conditions and optimized magnetic field configurations may result in elevated ion temperatures and enhanced confinement, thus facilitating effective ionization and fusion.

[0209] Department of Energy funded stellarator research aims to surmount the obstacles that arise from ionization and plasma control. This research may advance magnetic fields that improve plasma stability, enhance the efficiency of stellarators in ionizing gas, and sustain the elevated temperatures essential for fusion. Such research may utilize computational tools to investigate novel design methodologies, which may influence the capacity to attain the intended ionization rates and thermal conditions for sustainable fusion reactions.

Neutral Beam Injection

[0210] High-energy neutral particles may be introduced into a magnetic confinement field to induce ionization in the neutral particles. Ionized injected neutral atoms may impart kinetic energy to plasma particles via collisions. This kinetic energy may heat the plasma, thus facilitating fusion. Stellarators such as Wendelstein 7-X may increase plasma heating via Neutral Beam Injection (NBI) by injecting high-energy neutral particles. NBI may generate plasma temperature and aid in plasma fueling via ionizing injected neutral atoms. NBI may contribute to establishing fusion conditions, demonstrating a capacity to enhance stellarator functionality and the security and effectiveness of fusion energy production.

High-Energy Neutrons

[0211] Primary modes of interaction between high-energy neutrons and matter may include elastic and inelastic collisions with nuclei. These collisions may generate charged particles, secondary neutrons, and gamma rays. In a stellarator setting, secondary particles may be generated by high-energy neutrons interacting with matter. These particles may impact the structural integrity of the materials comprising the reactor as well as the overall efficiency of the fusion process. Addressing the interaction of high-energy neutrons in stellarators with materials and plasma may enhance stellarator functionality, safety, and cost-effectiveness.

[0212] Magnetic fields may be optimized to regulate the behavior of high-energy particles, such as neutrons.

[0213] Advanced materials and magnetic configurations that reduce energetic particle losses and mitigate the effects of neutron radiation on reactor components may optimize particle confinement and manage neutron interactions. Detecting resonances that may result in particle losses during the design stage may produce effective confinement and reduce challenges associated with neutrons.

[0214] Stellarator performance may be improved by reducing neutron-induced damage and augmenting neutron confinement. These improvements may decrease expenses and provide compact physical appearance. In turn, these improvements may simplify stellarator upkeep and improved safety profiles. These developments may enhance overall effectiveness and security, increasing feasibility of extended periods of stellarator operation.

Collision with Reactor Walls

[0215] Neutrons colliding with the breeding blanket positioned within the reactor walls may produce tritium. Tritium may serve as supplementary fuel for the reactor. Thus, stellarator reactor design and operation may consider management of neutrons. Capturing these neutrons efficiently to produce tritium may augment stellarator fuel supply, which may improve operational efficiency.

[0216] Advanced materials and design strategies may be employed to reduce maintenance needs, enhance reactor safety, and mitigate neutron-induced damage in light of interactions between neutrons with reactor materials. Thus, design principles and material science techniques may enhance stellarator overall performance and cost-efficiency.

Heat Utilization

[0217] Heat may be harvested from nuclear fusion reactions utilizing heat exchangers embedded in the blanket. These heat exchanges may convert the heat to liquid that flows through the exchangers. This liquid may then be utilized to produce electricity, for instance, through

turbines. Utilizing this heat may transform the enormous energy generated by fusion reactions into practical electrical power. Thus, stellarators ay enhance operational effectiveness and positively contribute to generating sustainable energy.

Neutron Handling and Material Durability

[0218] Fusion may produce elastic neutrons. These elastic neutrons may be utilized to generate energy, but may also have long-term degradation effects on the materials comprising the reactor. Issues associated with neutron handling and material durability may be addressed by development of materials and concepts that are intrinsically stable and able to operate continuously. Stability and continuous operation may be improved by enhancing energy confinement duration and reducing neoclassical losses. These improvements may improve reactor performance and resilience to energetic neutrons. . . These advancements may decrease the environmental impact of stellarators, enhance safety measures, and streamline maintenance procedures.

Energy Transfer

[0219] Energy may transferred to a liquid that flows through the blanket and is subsequently utilized to power generators to produce electricity. Power generators may include turbines. Employing heat exchangers integrated into the blanket may facilitate the efficient transfer of heat generated during fusion reactions to a working fluid. Subsequently, the heated fluid may be employed to drive turbines, which produce electrical energy. This procedure may demonstrate the potential of stellarators to enhance operational efficiency and generate energy.

[0220] Liquid lithium-based walls may be incorporated into stellarator structures to overcome obstacles in fusion energy generation associated with neutron management and material longevity. These liquid walls may prevent the transfer of almost all neutron energy to solid materials, which could potentially induce radioactivity. Stellarators may utilize thick, fluid-filled walls to regulate the heat produced during fusion efficiently. These fluid-filled walls may enable the extraction of heat to drive turbine-driven electricity generation. By preventing material degradation over time, this method may improve sustainability and safety and increase energy transfer efficiency.

Extraction of Waste Products

[0221] Waste products may be gradually extracted during cycles. Waste products may also be elimitated when a stellarator may be cycled down between cycles. Fusion reactors may generate inert helium as their primary output, rather than hazardous byproduct gases that necessitate further processing. Stellarators, may integrate sophisticated techniques for waste product management. These waste product management techniques may emphasize secure and effective

elimination of inert helium, the principal byproduct of fusion processes. In contrast to traditional nuclear reactors, stellarators and fusion reactors may operate without emitting perilous waste gases. Operation without such waste may mitigate environmental and safety apprehensions linked to waste management. The extraction of waste products in stellarators may involve cycling down the reactor to eliminate waste between cycles or utilizing systems designed to draw off waste gradually during operation cycles. Elimination of waste may contribute to safe and continuous operation of the reactor.

[0222] Stellarator operational methodology, distinct from that of tokamaks and other fusion reactor designs, may utilize magnetic fields to confine the plasma. Stellarator operational methodology may generate conditions for fusion reactions without relying on induced plasma currents. This methodology may enhance the potential of stellarators to facilitate more straightforward plasma control and potentially more effective waste management procedures.

[0223] Additionally, technological developments like innovative first-wall designs and dual coolant lithium lead breeding blankets may improve operational efficiency and material durability. These advancements may enhance heat extraction and regulate neutron flux, both of which may impact the materials of the reactor gradually. In particular, incorporating sophisticated materials and cooling mechanisms may alleviate the deterioration induced by the energetic neutrons produced during fusion. These materials may prolong reactor lifespan and diminish maintenance demands. Optimized stellarator operation and waste management may facilitate stellarators as a means of fusion energy generation that is secure, effective, and ecologically sustainable.

Handling and Treatment of Neutron-Irradiated Material

[0224] A breeding blanket may contain a significant amount of neutron-irradiated material because it absorbs neutrons to produce additional tritium for use as fuel. Structural and functional properties of a reactor may deteriorate gradually due to neutrons interacting with other structures. Induced radiation may result from the activation of neutrons by materials exposed to neutron irradiation; therefore, improved systems and methods described herein may be advantageous for maintaining and decommissioning a fusion reactor.

[0225] In stellarators, the treatment and handling of neutron-irradiated materials may preserve the integrity and safety of the reactor. In addition to absorbing neutrons to produce additional tritium, a breeding blanket may degrade gradually due to neutron impact. To mitigate induced radiation caused by neutron activation, neutron-irradiated materials may be managed meticulously, including implementing precautions during maintenance and decommissioning stages.

Momentum and Collision

[0226] The ionized particles that make up the plasma in a stellarator may collide with supplementary fuel, thereby sustaining the fusion reaction. Similarly, neutrons produced from these reactions may breed tritium by colliding with the breeding blanket, which may then supply additional fuel to the reactor, or with fluid in heat exchangers, which may then extract energy that may be converted to electricity. The momentum and collision mechanisms involving ionized particles and neutrons may maintain fusion reactions and extract energy during stellarator operations. The aforementioned dual function of neutrons may contribute to practical energy extraction and to sustaining the fusion process.

[0227] Stellarators may confine plasma in a toroidal (doughnut-like) shape using complex electromagnetic coils rather than induced plasma currents. The use of complex electromagnetic coils represents a departure from tokamak designs. Magnetic confinement may facilitate the regulation of the plasma particles and may establish optimal circumstances for fusion reactions. Efforts to manage heat and particle confinement in stellarators may include reducing neoclassical transport, a form of heat loss induced by collisions that expel heated particles from their orbits. In some cases, a stellarator system described herein may exhibit substantial reductions in neoclassical transport through the use of optimized magnetic field designs. Optimized magnetic field designs indicate that stellarators may be optimized to increase fusion reaction efficiency and energy extraction to generate electricity.

Heating Metal Hydrides

[0228] When heated, hydrogen gas may be liberated from metal hydrides. Due to their heating-activated hydrogen storage and release mechanism, metal hydrides may be viable candidates for energy storage applications, including stellarator fusion reactors. Accordingly, hydrogen storage by metal hydrides may enhance stellarator operations, costs, footprints, maintenance, and safety considerations. The process by which metal hydrides emit hydrogen gas when heated may be utilized to regulate fuel supply in a fusion reactor or for alternative power generation.

[0229] Efficient utilization of metal hydrides may involve optimizing hydrogen storage performance, managing heat generated during hydrogen absorption and desorption processes, and accounting for corrosion, degradation, and cost. Sophisticated thermal management methodologies may augment the operational efficiency and security of hydrogen storage systems based on metal hydride. Such methodologies encompass the advancement of novel materials and structures to enhance hydrogen storage capacity and the formulation of inventive strategies to regulate the thermal components effectively.

[0230] Investigations into using metal hydrides in conjunction with solar technologies may focus on metal hydrides' potential for thermal energy storage (TES) purposes in high-temperature power generation. This methodology facilitates uninterrupted power production by storing solar energy heat in high-temperature (HT) metal hydrides, which may subsequently be utilized to produce electricity, potentially even during periods of low solar activity. Dual-bed metal hydride systems demonstrate the versatility of metal hydrides in energy storage and generation by incorporating low-temperature (LT) and high-temperature (HT) hydrides. Such developments demonstrate how metal hydrides may contribute to the sustainability of energy systems.

Radiation Protection Measures

[0231] A blanket situated within the reactor may act as a primary means of radiation protection. Fuel in fusion reactors possesses only a low level of radioactivity and may not regarded as exceedingly hazardous. Optimization of stellarator operation and efficiency may prioritize reducing neoclassical losses and enhancing energy confinement. Design improvements resulting from enhanced comprehension of neoclassical transport and plasma stability may enable the development of steady-state operational designs. Such improvements may mitigate radiation-related issues by decreasing the likelihood of plasma instabilities, which may otherwise result in elevated radiation levels. Constant, interruption-free operation may increase safety and reduce the expense and complexity of radiation protection measures.

Plasma Purification

[0232] Plasma may be purified after use in the reactor by extracting small quantities of helium from the plasma, separating the helium, and reintroducing the plasma into the reactor. In stellarators, the process of plasma purification may involve the removal of helium from the plasma while reintroducing the fuel. Plasma purification may preserve plasma quality and reactor efficiency. Both effective management of plasma-wall interactions and precise assembly of a stellarator may impact plasma purification and overall stellarator operation.

Helium Separation

[0233] When helium is extracted from the plasma, a portion of the fuel may be extracted and separated before being reintroduced into the reactor. Membrane gas separation technologies, whose selectivity demonstrates potential in the retrieval and purification of helium, may augment helium separation in stellarators. Incorporation of membrane gas separation into stellarator operations may effectively isolate helium from the fusion process, enabling fuel reintroduction while guaranteeing helium retrieval for subsequent applications. Streamlining the

management of mixed gas streams may enhance safety, reduce expenses, and improve operational efficiency.

Pumping Out

[0234] The process of pumping out, also known as ash removal, may involve the removal of waste gases from stellarators. Pumping-out procedures in stellarators may involve removing ash or waste gases, usually during a cycle-down of a reactor. Pumping-out preserves the safety and effectiveness of the reactor by ensuring that only the elements required for fusion reactions are present. Initial experiments involving expansive stellarator configurations may signify progression in the manipulation and upkeep of plasma by encompassing efficient management of waste gases. Enhancements to stellarator operation demonstrate the potential for environmentally friendly and secure nuclear energy sources, emphasizing the usefulness of an effective waste gas management system.

Safety Systems

[0235] Safety systems may focus primarily on containing plasma during a reactor cycle down in case of a failure, such as quenching. Stellarator safety systems may be engineered to regulate plasma containment in the event of a malfunction, thereby facilitating safe cycling down of the reactor. Methodologies devised for magnetic confinement fusion, including implementing "baseball" coil arrangements and Ioffe bars, focus on enhancing containment and mitigating other challenges, including flute instability. The present disclosure enhances the safety of stellarators by improving plasma containment and control, facilitating prevention and management of potential failures.

Integration of AI

[0236] In one aspect, the systems described herein may comprise computer systems comprising an Artificial Intelligence (AI) or Machine Learning algorithm (collectively referred to herein as "AI"). AI may identify optimal operational parameters that maximize energy extraction while maintaining adequate safety margins. AI may be utilized to develop predictive models that utilize training data to detect occurrences like quenching events. These predictive models may facilitate proactive modifications that avert offlineing of a reactor.

[0237] AI may be applied to stellarator operations in optimizing operational parameters to increase safety and efficiency. AI algorithms may forecast disruptions, such as quenching events, facilitating proactive adaptations by operators. Proactive adaptations may avert avoidable reactor downtimes and optimize energy extraction while maintaining safe operational margins. The present disclosure addresses the intricate plasma dynamics in stellarators and may improve the stability and efficiency of fusion energy generation.

[0238] AI algorithms may determine the most efficient operational parameters by analyzing vast datasets from previous operations, thereby increasing energy output and decreasing wear on reactor components.

[0239] AI may provide predictive maintenance recommendations as an automated safety measure, ensuring that all components operate within safe parameters. AI may analyze operational data to identify when components are likely to fail or require maintenance, thus preventing unanticipated downtimes.

[0240] AI may provide real-time plasma control by regulating magnetic fields in microseconds, facilitating optimal confinement and averting disruptions or instabilities in the plasma.

[0241] In another aspect, disclosed herein is a system comprising one or more computer processors and computer memory coupled thereto. The computer memory comprises machine executable code that, upon execution by the one or more computer processors, implements any of the methods disclosed above or elsewhere herein.

[0242] In another aspect, disclosed herein is a non-transitory computer-readable media comprising machine-executable code comprising one or more instructions that, upon execution, implements any of the methods disclosed above or elsewhere herein on a computer, wherein said computer is configured to execute said one or more instructions.

[0243] Additional aspects and advantages of the present disclosure will become readily apparent to those skilled in this art from the following detailed description, wherein only illustrative embodiments of the present disclosure are shown and described. As will be realized, the present disclosure is capable of other and different embodiments, and its several details are capable of modifications in various obvious respects, all without departing from the disclosure. Accordingly, the drawings and description are to be regarded as illustrative in nature, and not as restrictive.

INCORPORATION BY REFERENCE

[0244] All publications, patents, and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication, patent, or patent application was specifically and individually indicated to be incorporated by reference. To the extent publications and patents or patent applications incorporated by reference contradict the disclosure contained in the specification, the specification is intended to supersede and/or take precedence over any such contradictory material.

BRIEF DESCRIPTION OF THE DRAWINGS

[0245] The novel features of the disclosure are set forth with particularity in the appended claims. A better understanding of the features and advantages of the present disclosure will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which the principles of the disclosure are utilized, and the accompanying drawings of which:

[0246] FIG. 1A illustrates a side-view illustration of an exemplary helical cable, per one or more embodiments herein;

[0247] FIG. 1B illustrates a perspective-view illustration of an exemplary helical cable, per one or more embodiments herein;

[0248] FIG. 2 illustrates a perspective-view illustration of an exemplary flat stellarator coil, per one or more embodiments herein;

[0249] FIG. 3 illustrates a perspective-view illustration of an exemplary parabolic stellarator coil, per one or more embodiments herein;

[0250] FIG. 4 illustrates an illustration of compressing the helical cable to form an exemplary flat stellarator coil, per one or more embodiments herein;

[0251] FIG. 5 illustrates an illustration of compressing the helical cable to form an exemplary parabolic stellarator coil, per one or more embodiments herein;

[0252] FIG. 6 illustrates an example of a layering of superconducting tape and reinforcement, per one or more embodiments herein;

[0253] FIG. 7 shows a flowchart of an example method of bending a coil, per one or more embodiments herein;

[0254] FIG. 8 shows an example of a set of operations of a freeform bender, per one or more embodiments herein;

[0255] FIGs. 9A – 9D shows an example of a multipart mandrel, per one or more embodiments herein;

[0256] FIG. 10 illustrates an example of a system for stabilizing HTS taps, per one or more embodiments herein;

[0257] FIGS. 11A – 11B illustrate an example of jacket types, per one or more embodiments herein;

[0258] FIG. 12 illustrates an example of variable strut spacing, per one or more embodiments herein;

[0259] FIG. 13 illustrates an example of integrated cooling, per one or more embodiments herein;

[0260] FIG. 14 illustrates an example of alternative strut shapes, per one or more embodiments herein;

[0261] FIG. 15 illustrates an example of a method of manufacture, per one or more embodiments herein;

[0262] FIGs. 16A – 16B show an example of a shell-tape insulation configuration, per one or more embodiments herein;

[0263] FIG. 17 shows an example of a preformed ceramic insulation, per one or more embodiments herein;

[0264] FIG. 18 illustrates an example of two bobbins, each dispensing one layer of superconducting tape onto a curved substrate, per one or more embodiments herein;

[0265] FIG. 19 illustrates an example of a dispenser dispensing one layer of superconducting tape onto a curved substrate, per one or more embodiments herein; and

[0266] FIG. 20 shows a computer system that is programmed or otherwise configured to implement methods provided herein, per one or more embodiments herein.

DETAILED DESCRIPTION

Superconducting Tape Reinforcement

[0267] Superconducting materials may include high temperature superconductors (HTS) and low temperature superconductors (LTS). In one example, HTS materials may include cuprate superconductors, which may be ceramics based on cuprates (compounds containing a copper oxide group), such as BSCCO, or ReBCO (where Re is a rare earth element, commonly Y or Gd). In another example, HTS materials may include iron pnictides (e.g., FeAs and FeSe) and magnesium diboride (MgB_2).

[0268] ReBCO may be manufactured as a tape. For example, the tape may be approximately 100 microns thick and include a substrate. The substrate may include, for example, an electropolished nickel-molybdenum alloy (e.g., approximately 50 microns thick) with a series of buffer layers known as the buffer stack. The buffer stack may be approximately 0.2 microns thick.

[0269] The substrate may provide a mechanical backbone that can be fed through a manufacturing line and permit growth of subsequent layers. The buffer stack may provide a biaxially textured crystalline template upon which to grow the HTS layer, and may prevent chemical diffusion of elements from the substrate to the HTS. Each of these layers described may collectively form HTS tape.

[0270] In some cases, HTS tapes may be arranged into HTS cables. An HTS cable may include one or more HTS tapes. In some cases, the one or more HTS tapes may be connected lengthwise via conductive material (e.g., copper). In some cases, the HTS tapes may be stacked (e.g., arranged such that the HTS layers are parallel). In some cases, the HTS tapes may have some other arrangement, which may vary along the length of the HTS cable.

[0271] Some examples of HTS cables may include single HTS tapes and HTS pairs. In some cases, HTS pairs may include a pair of HTS tapes arranged such that the HTS layers are parallel. In some cases, HTS cables comprising more than two HTS tapes may be configured with at least some of the HTS tapes in HTS pairs. In some cases, stacked HTS tapes may comprise various arrangements of HTS pairs. In some cases, HTS cables may comprise one or both of substrated HTS tape or exfoliated HTS tape.

[0272] In some cases, HTS field coils may be constructed by winding or by assembling several sections. For example, HTS field coils may be wound coils by wrapping an HTS cable in a spiral (e.g., a continuous spiral). In some cases, HTS coils may be insulated. For example, the HTS coils may be insulated via one or more electrical insulating materials between the turns of the HTS coils. In some cases, insulated HTS coils may be used in applications with large, rapid changes in magnetic field, such as plasma control in fusion magnets. In other cases, HTS coils may be uninsulated. In other cases, HTS coils may be partially insulated.

[0273] The high-temperature superconducting materials may be used in fusion energy applications, such as plasma chambers (e.g., stellarators, tokamaks, etc.). For example, in a stellarator, large magnet coils may be made from HTS tapes. In some cases, HTS tape may form an HTS cable in a stellarator conductor shape. Bobbins may be used to apply the HTS materials (e.g., HTS tapes or HTS coils) during assembly of the stellarator.

Examples of Superconducting Tape Reinforcement

[0274] HTS tape may be durable to a maximum of about 0.4% strain in tension. Although, in some cases, about 0%, about 0.1%, about 0.2%, or about 0.3% strain in tension may result in better performance. Further, HTS tape may be durable to a maximum of about 1% strain in compression. Although, in some cases, about 0%, about 0.1%, about 0.2%, about 0.3%, about 0.4%, about 0.5%, about 0.6%, about 0.7%, about 0.8%, or about 0.9% strain in compression may result in better performance.

[0275] The systems, the methods, and the techniques disclosed herein provide reinforcing for superconducting tape (e.g., HTS tape). For example, the superconducting tape may be reinforced using tungsten to achieve a higher modulus while addressing thermal expansion challenges. The

systems, the methods, and the techniques disclosed herein may include managing the strain on superconducting tape across various temperatures. Managing strain may be of particular importance in stellarators given the complex shapes in stellarators (e.g., as illustrated in **FIGs. 3-5**) formed by stellarator coils (e.g., as illustrated in **FIGs. 1A-2**). For example, these various temperatures may include high temperatures, room temperature, and cooling conditions. Accordingly, the systems, the methods, and the techniques disclosed herein may thereby improve durability of the superconducting tapes when undergoing differential expansion from room to cryogenic temperatures. Therefore, the systems, the methods, and the techniques aim to streamline the manufacturing of long cable lengths without individually laying tapes, thereby improving efficiency of production and reducing strain-related issues in stellarator coil applications.

[0276] In some cases, the systems, the methods, and the techniques disclosed herein help overcome certain challenges associated with superconducting (e.g., HTS) tape shrinkage in stellarators. For example, by affixing the HTS tape to a reinforcement member (e.g., a reinforcement), HTS tape shrinkage as the stellarator environment cools to cryogenic temperatures may be reduced (e.g., substantially eliminated). In some cases, HTS tape may have shrinkage of about 0.3% when cooling from room temperature to cryogenic temperatures (e.g., less than about -100 °F, less than about -150 °F, less than about -200 °F, less than about -250 °F, etc.). Such shrinkage may be measured in, for example, one or more of: length, width, thickness, surface area, volume, etc. Alternatively, or in addition, the reinforcement may have a shrinkage that is less than the shrinkage of the HTS tape when both are cooled to cryogenic temperatures. For example, the reinforcement may be tungsten, which has a shrinkage of about 0.1%.

[0277] In some cases, the reinforcement may comprise tungsten. In some cases, the reinforcement may comprise potassium alloyed tungsten. In some cases, the reinforcement may comprise rhenium. In some cases, the reinforcement may comprise tantalum. In some cases, the reinforcement may comprise carbon fiber (e.g., high modulus carbon fiber). In some cases, the reinforcement may comprise titanium. In some cases, the reinforcement may comprise one or more of: vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, zirconium, niobium, molybdenum, technetium, ruthenium, rhodium, palladium, silver, cadmium, hafnium, osmium, iridium, platinum, gold, mercury, rutherfordium, dubnium, seaborgium, bohrium, or hassium. In some cases, the reinforcement may comprise an alloy or combination comprising one or more of any of the elements or materials named in this paragraph or elsewhere herein.

[0278] In some cases, the systems, the methods, and the techniques disclosed herein may include pre-straining the reinforcement. For example, pre-straining the reinforcement may

include pre-tensioning the reinforcement. In another example, pre-straining the reinforcement may include pre-compressing the reinforcement. Pre-straining the reinforcement at room temperature prior to cooling to cryogenic temperatures may help to reduce (e.g., substantially eliminate) failures in the reinforcement. In some cases, a reinforcement comprising tungsten may be pre-strained (e.g., pre-tensioned or pre-compressed) to about 0.2%, about 0.3%, about 0.4%, about 0.5%, about 0.6%, about 0.7%, about 0.8%, about 0.9%, about 1.0%, etc.

[0279] In some cases, by pre-straining the reinforcement when at room temperature, the strain on the reinforcement once the reinforcement is cooled to cryogenic temperatures may be reduced. For example, a reinforcement comprising tungsten that is pre-tensioned at room temperature to between about 0.2% and about 1.0% may result in a compression strain between about 0% and about 0.8% when the reinforcement is cooled to cryogenic temperatures.

[0280] In some cases, in addition or in alternative to pre-straining the reinforcement (e.g., at room temperature), the superconducting (e.g., HTS) tape may be pre-strained (e.g., at room temperature). Pre-straining the HTS tape at room temperature prior to cooling to cryogenic temperatures may help to reduce (e.g., substantially eliminate) failures in the HTS tape. Without pre-straining, HTS tape may be liable to fail in tension. Pre-compression of the HTS tape may help to reduce (e.g., substantially eliminate) tension failures in the HTS tape.

[0281] In some cases, while the reinforcement may be pre-tensioned to reduce compression strain under cooling, the superconducting (e.g., HTS) tape may be pre-compressed to reduce tension strain under cooling. In some cases, HTS tape may be pre-strained (e.g., pre-compressed or pre-tensioned) to about 0.2%, about 0.3%, about 0.4%, about 0.5%, about 0.6%, about 0.7%, about 0.8%, about 0.9%, about 1.0%, etc. For example, by pre-compressing the HTS to about 1.0%, the HTS tape may be able to endure about twice the force (e.g., Lorentz force) than the HTS tape can endure without pre-compression.

[0282] In some cases, after pre-straining one or both of the reinforcement or the superconducting (e.g., HTS) tape, the reinforcement and the superconducting tape may be attached to one another. This attachment may be achieved, for example, by soldering the reinforcement and the superconducting tape together. **FIG. 6** illustrates an example of a layering of superconducting tape **610** and reinforcement **620**. In some cases, the reinforcement and the superconducting tape may be soldered together reel-by-reel. Accordingly, the soldering may form a coil in which the reinforcement is attached to the superconducting tape. This coil may then be unrolled (e.g., from a bobbin) and applied in the stellarator as reinforced superconducting tape.

[0283] In some cases, pre-straining the reinforcement or the HTS tape may improve the modulus of the reinforced superconducting tape substantially. For example, this pre-straining may improve modulus of the reinforced superconducting tape to about twice that of steel based on the higher modulus of the reinforcement; meaning for a given force (e.g., a given Lorentz force), there will be half the strain as with steel. Advantageously, this improved modulus of the reinforced superconducting tape may enable achieving a higher field. For example, this improved modulus of the reinforced superconducting tape may enable achieving a field strength about 50% greater than without pre-straining. These higher field strengths may improve performance (e.g., efficiency) of the stellarator.

[0284] In some cases, the reinforcement may dominate the strain in the reinforced superconducting tape due to the reinforcement's high modulus. For example, a reinforcement including tungsten may have low to zero strain, while the HTS tape may be slightly (e.g., about 1%) compressed. In some cases, the reinforced superconducting tape may have a thickness of about 0.1 microns, about 0.2 microns, about 0.3 microns, about 0.4 microns, about 0.5 microns, about 0.6 microns, about 0.7 microns, about 0.8 microns, about 0.9 microns, about 1 micron, about 5 microns, about 10 microns, about 15 microns, about 20 microns, about 25 microns, about 30 microns, about 35 microns, about 40 microns, about 45 microns, about 50 microns, etc.

[0285] In some cases, a first portion of the reinforcement or the HTS tape may not be pre-strained and a second portion of the reinforcement or the HTS tape may be pre-strained. By pre-straining the second portion of the reinforcement or the HTS tape, without pre-straining the first portion of the reinforcement or the HTS tape, efficiency (e.g., cost efficiency, energy efficiency, material efficiency, etc.) may be improved. For example, the first portion of the reinforcement or the HTS tape may be identified as corresponding to sections of a stellarator that induce less strain on the superconducting tape. Conversely, the second portion of the reinforcement or the HTS tape may be identified as corresponding to sections of a stellarator that induce more strain on the superconducting tape.

[0286] Advantageously, the systems, the methods, and the techniques disclosed herein for creating reinforced superconducting tape may improve neutron capturing abilities with high absorption spectra. Further advantageously, the systems, the methods, and the techniques disclosed herein for creating reinforced superconducting tape may be applied to areas in a stellarator with a high field gradient (e.g., about 10 Tesla, about 25 Tesla, about 50 Tesla, etc.) that introduce torsion across the reinforced superconducting tape. Further advantageously, the systems, the methods, and the techniques disclosed herein may enable the reinforced superconducting tape to serve as a shunting material. Further advantageously, the systems, the

methods, and the techniques disclosed herein may improve thermal properties of the reinforced superconducting tape.

Stellarator Coils and Methods of Forming Thereof

[0287] Provided herein are systems, methods, and techniques disclosed herein to help overcome certain challenges associated with superconducting (e.g., HTS) tape shrinkage in stellarators. For example, by affixing the superconducting tape to a reinforcement, superconducting tape shrinkage as the stellarator environment cools to cryogenic temperatures may be reduced. This shrinkage may cause strain, which may be reduced by pre-straining one or both of the superconducting tape or the reinforcement prior to affixing the superconducting tape to the reinforcement.

[0288] In one aspect, disclosed herein is a method of forming a stellarator coil. In some embodiments, the method comprises: shaping a cable into a helical cable; and compressing at least a portion of the helical cable about an axis parallel to a central axis of the helical cable to form the stellarator coil.

[0289] In another aspect, disclosed herein are methods of forming a stellarator coil with improved volume utilization percentages from a cable bent into a tapered helical shape.

[0290] Thick cables and tubes can be formed into a wide variety of shapes by hand or by bending machines. However, shaping coils thereby requires a minimum gap between adjacent cable turns. For example, cable with a 2 cm diameter coiled using a bending machine having a minimum 8 cm gap distance has only a 25% volume utilization.

[0291] As such, provided herein are methods of forming coils that overcome the current limitations of bending machines. In order to create a stellarator (or tokamak) coil without any gap between successive turns, the coil is first created in an extended (e.g., helical) stage using a CNC bending machine. Then, the helical shape is compressed (by machine or by hand) along the axis of the helix until the coils align with the plane of the plate. The methods herein enable the formation of stellarator coils with a reduced ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil to improve its volume utilization. In some embodiments, volume utilization is calculated as a percentage by volume of the stellarator coil that is composed of the cable (i.e., not empty space). In some embodiments, volume utilization is calculated as a percentage by volume of the stellarator coil that is composed of the wires within the cable (i.e., not empty space or wire jackets).

[0292] In some embodiments, shaping the cable into the helical cable comprises twisting the cable along its length. In some embodiments, shaping the cable into the helical cable is

performed by hand. In some embodiments, shaping the cable into the helical cable is performed by a manual bending tool. In some embodiments, shaping the cable into the helical cable is performed by a free-form bender. In some embodiments, shaping the cable into the helical cable is performed by a Computer Numerical Control (CNC) free-form bender. Free-form benders translate a cable along its axis of symmetry (e.g., length) toward a bending tool, which imparts force to bend the cable. In some embodiments, in the Computer Numerical Control (CNC) bender, the translation of the cable and/or the movement of the bending tool of the free-form is computer controlled.

[0293] In some embodiments, per **FIGS. 1A-1B**, the helical cable **100** has a tapered helical shape. In some embodiments, as shown, the helical cable **100** has a base outer diameter **111** that is larger than a tip outer diameter **112**, and a height **121**. In some embodiments, per **FIG. 2**, the dimensions and/or shape of the helical cable **100** reduces a ratio between the diameter of the cable **130** and an average gap **114** between successive turns of the cable in the stellarator coil **200** to improve its utilization percentage.

[0294] In some embodiments, the helical cable **100** has a constant pitch **122**, wherein a distance between consecutive turns in a first direction along the center axis of the helical cable **100** is constant. In some embodiments, the helical cable **100** has a variable pitch, wherein a distance between consecutive turns in the first direction increases from the base to the tip. In some embodiments, the helical cable **100** has a variable pitch, wherein a distance between consecutive turns in the first direction decreases from the base to the tip. In some embodiments, the pitch is measured as a mean, median, or mode pitch between the turns of the helical cable **100**.

[0295] In some embodiments, the helical cable **100** and the stellarator coil **200** have a clockwise chirality. In some embodiments, the helical cable **100** and the stellarator coil **200** have a counter-clockwise chirality. In some embodiments, a first segment of the helical cable **100** and the stellarator has a clockwise chirality, wherein a second segment of the helical cable **100** and the stellarator has a counter-clockwise chirality.

[0296] In some embodiments, the helical cable **100** has a coil angle **113** defined as a conical angle tangent to the outer surfaces of the coils. In some embodiments, the helical cable **100** has a coil angle **113** defined as a mean, median, or mode conical angle tangent to the outer surfaces of the coils. In some embodiments, the helical cable **100** has a constant coil angle **113**, wherein the conical angle at the base of the helical cable **100** is equal to the conical angle at the tip of the helical cable **100**. In some embodiments, a helical cable **100** with a constant coil angle **113** enables In some embodiments, the helical cable **100** has a variable coil angle **113**, wherein the conical angle at the base of the helical cable **100** is greater than the conical angle at the tip of the

helical cable **100**. In some embodiments, the helical cable **100** has a variable coil angle **113**, wherein the conical angle at the base of the helical cable **100** is less than the conical angle at the tip of the helical cable **100**.

[0297] In some embodiments, the coil angle **113**, the pitch, and their variability or consistency along the length of the helical cable **100** are specifically selected to reduce the force required to overcome the plastic and/or elastic deformation of the spring during the compression of the helical cable **100** to form the stellarator coil **200**. In some embodiments, the coil angle **113**, the pitch, and their variability or consistency along the length of the helical cable **100** are specifically selected to reduce the force required to overcome any friction between overlapping or coincident surfaces of the cable that interact during the compression of the helical cable **100** to form the stellarator coil **200**. In some embodiments, the coil angle **113**, the pitch, and their variability or consistency along the length of the helical cable **100** are specifically selected to reduce the force required to overcome the radial expansion in diameter of a coil when displaced by a subsequent coil during the compression of the helical cable **100** to form the stellarator coil **200**. In some embodiments, the coil angle **113**, the pitch, and their variability or consistency along the length of the helical cable **100** are specifically selected to reduce a ratio between the diameter of the cable and an average gap **114** between successive turns of the cable in the stellarator coil **200** to improve its utilization percentage.

[0298] In some embodiments, the coil angle **113**, the pitch, their variability or consistency along the length of the helical cable **100**, or any combination thereof are specifically selected to reduce the force required to overcome the plastic and/or elastic deformation of the spring during the compression of the helical cable **100** to form the stellarator coil **200**. In some embodiments, the coil angle **113**, the pitch, their variability or consistency along the length of the helical cable **100**, or any combination thereof are specifically selected to reduce the force required to overcome any friction between overlapping or coincident surfaces of the cable that interact during the compression of the helical cable **100** to form the stellarator coil **200**. In some embodiments, the coil angle **113**, the pitch, their variability or consistency along the length of the helical cable **100**, or any combination thereof are specifically selected to reduce the force required to overcome the radial expansion in diameter of a coil when displaced by a subsequent coil during the compression of the helical cable **100** to form the stellarator coil **200**. In some embodiments, the coil angle **113**, the pitch, their variability or consistency along the length of the helical cable **100**, or any combination thereof are specifically selected to reduce a ratio between the diameter of the cable and an average gap **114** between successive turns of the cable in the stellarator coil **200** to improve its utilization percentage.

[0299] In some embodiments, the height, the number of turns, or both of the helical cable **100** are specifically selected to reduce the force required to overcome the plastic and/or elastic deformation of the spring during the compression of the helical cable **100** to form the stellarator coil **200**. In some embodiments, the height, the number of turns, or both of the helical cable **100** are specifically selected to reduce the force required to overcome any friction between overlapping or coincident surfaces of the cable that interact during the compression of the helical cable **100** to form the stellarator coil **200**. In some embodiments, the height, the number of turns, or both of the helical cable **100** are specifically selected to reduce the force required to overcome the radial expansion in diameter of a coil when displaced by a subsequent coil during the compression of the helical cable **100** to form the stellarator coil **200**. In some embodiments, the height, the number of turns, or both of the helical cable **100** are specifically selected to reduce a ratio between the diameter of the cable and an average gap **114** between successive turns of the cable in the stellarator coil **200** to improve its utilization percentage.

[0300] In some embodiments, the shape of the helical cable **100** is determined by reverse-modeling engineering. Reverse-modeling engineering may simulation the deformation of the helical cable **100** in revers to determine the shape required to form the final stellarator coil **200**. In some embodiments, the helical shape is formed and measured to tolerance using laser metrology and/or correction factors. In some embodiments, the shape of the helical cable **100** is reverse-modeled to reduce a ratio between the diameter of the cable and an average gap **114** between successive turns of the cable in the stellarator coil **200** to improve its utilization percentage.

[0301] In some embodiments, the helical cable **100** is compressed by hand. In some embodiments, the helical cable **100** is compressed by machine. In some embodiments, the helical cable **100** is compressed by a Computer Numerical Control (CNC) machine. In some embodiments, compressing the helical cable **100** comprises compressing a first portion of the helical cable **100** and compressing a second portion of the helical cable **100**. In some embodiments, compressing the helical cable **100** further comprises re-compressing the first portion, the second portion, or both. In some embodiments, the stellarator coil **200** is further produced by extending at least the first portion of the helical cable **100** and recompressing at least the first portion of the helical cable **100** to form the stellarator coil **200**. In some embodiments, compressing and recompressing the helical cable **100** reduces a ratio between the diameter of the cable and an average gap **114** between successive turns of the cable in the stellarator coil **200** to improve its utilization percentage.

[0302] In some embodiments, per **FIG. 2**, the stellarator coil **200** is a flat stellarator coil **200**. In some embodiments, the flat stellarator coil **200** is substantially flat, wherein its thickness varies by at most about 50 %, 40 %, 30 %, 20 %, 10 %, or less, including increments therein, of the thickness of the cable. In some embodiments, the flat stellarator coil **200** is substantially flat, wherein its height varies by at most about 50 %, 40 %, 30 %, 20 %, 10 %, or less, including increments therein, of the thickness of the cable. In some embodiments, per **FIG. 4**, the flat stellarator coil **200** is formed by compressing the helical cable **100** between a first primary tool having a substantially flat face and a second primary tool also having a substantially flat face. In some embodiments, a height of the face of the first primary tool, the second primary tool, or both, varies by at most about 50 %, 40 %, 30 %, 20 %, 10 %, or less, including increments therein, of the thickness of the cable. In some embodiments, the face of the first primary tool **410**, the second primary tool, or both **420**, comprises a spiral groove, a retaining ring, a clip, a magnet, or any combination thereof to direct the cable during compression. In some embodiments, the face of the first primary tool **410**, the second primary tool **420**, or both, comprises a spiral groove, a retaining ring, a clip, a magnet, or any combination thereof to direct the cable during compression. In some embodiments, the methods and tools to form the flat stellarator coil **300** herein prevent damage to the cable's outer and/or inner components.

[0303] In some embodiments, per **FIG. 3**, the stellarator coil is a paraboloid stellarator coil **300**. In some embodiments, the stellarator coil **200** has a hyperbolic paraboloid shape. In some embodiments, as shown, the hyperbolic paraboloid is curved about a 1st axis **310** in a first direction coincident with the center of the stellarator coil **200** and about a second axis **320** in a second direction opposite the first direction. In some embodiments, per **FIG. 5**, the parabolic stellarator coil **300** is formed by compressing the helical cable **100** between a first secondary tool **510** having a parabolic face and a second secondary tool **520** having a matching parabolic face. In some embodiments, the face of the first secondary tool **510**, the second secondary tool **520**, or both, comprises a spiral groove, a retaining ring, a clip, a magnet, or any combination thereof to direct the cable during compression. In some embodiments, the methods and tools to form the parabolic stellarator coils **300** herein prevent damage to the cable's outer and/or inner components.

[0304] In some embodiments, the method further comprises heat treating the stellarator coil **200**. In some embodiments, heating treating the stellarator coil **200** is performed at a temperature of about 25 to about 200 degrees Celsius. In some embodiments, heating treating the stellarator coil **200** is performed for a time of about 0 to about 60 minutes. In some embodiments, heating treating the stellarator coil **200** is performed at a temperature over about 0 to about 500 cycles.

[0305] In some embodiments, the method further comprises weakening a hinge section of the cable before step (a) or step (b). In some embodiments, weakening comprises annealing, cutting, fatiguing, or any combination thereof. In some embodiments, the helical cable deforms about the hinge region as it is compressed, to more precisely form the shape of the stellarator coil. In some embodiments, the hinge section comprises a gap in the cable and/or its jacket. In some embodiments, the hinge section has a width less than the minimum diameter of the bending tool. In some embodiments, weakening a hinge section of the cable reduces a ratio between the diameter of the cable and an average gap between successive turns of the cable in the formed stellarator coil to improve its utilization percentage.

[0306] In some cases, the cable can be formed in other configurations besides a helix. For example, the cable can be formed in adjacent windings formed together (e.g., a double pancake coil). The double pancake coil may comprise a single cable forming two adjacent windings coiling in opposite directions. In some cases, the cable can be formed as a layer winding coil. For example, the layer winding coil can comprise a plurality of coils wound such that the coils are adjacent to one another.

[0307] In some embodiments, the helical cable, the stellarator coil, or both has about 3 turns to about 100 turns. In some embodiments, the helical cable, the stellarator coil, or both has about 3 turns to about 5 turns, about 3 turns to about 10 turns, about 3 turns to about 20 turns, about 3 turns to about 30 turns, about 3 turns to about 40 turns, about 3 turns to about 50 turns, about 3 turns to about 60 turns, about 3 turns to about 70 turns, about 3 turns to about 80 turns, about 3 turns to about 90 turns, about 3 turns to about 100 turns, about 5 turns to about 10 turns, about 5 turns to about 20 turns, about 5 turns to about 30 turns, about 5 turns to about 40 turns, about 5 turns to about 50 turns, about 5 turns to about 60 turns, about 5 turns to about 70 turns, about 5 turns to about 80 turns, about 5 turns to about 90 turns, about 5 turns to about 100 turns, about 10 turns to about 20 turns, about 10 turns to about 30 turns, about 10 turns to about 40 turns, about 10 turns to about 50 turns, about 10 turns to about 60 turns, about 10 turns to about 70 turns, about 10 turns to about 80 turns, about 10 turns to about 90 turns, about 10 turns to about 100 turns, about 20 turns to about 30 turns, about 20 turns to about 40 turns, about 20 turns to about 50 turns, about 20 turns to about 60 turns, about 20 turns to about 70 turns, about 20 turns to about 80 turns, about 20 turns to about 90 turns, about 20 turns to about 100 turns, about 30 turns to about 40 turns, about 30 turns to about 50 turns, about 30 turns to about 60 turns, about 30 turns to about 70 turns, about 30 turns to about 80 turns, about 30 turns to about 90 turns, about 30 turns to about 100 turns, about 40 turns to about 50 turns, about 40 turns to about 60 turns, about 40 turns to about 70 turns, about 40 turns to about 80 turns, about 40 turns to about

90 turns, about 40 turns to about 100 turns, about 50 turns to about 60 turns, about 50 turns to about 70 turns, about 50 turns to about 80 turns, about 50 turns to about 90 turns, about 50 turns to about 100 turns, about 60 turns to about 70 turns, about 60 turns to about 80 turns, about 60 turns to about 90 turns, about 60 turns to about 100 turns, about 70 turns to about 80 turns, about 70 turns to about 90 turns, about 70 turns to about 100 turns, about 80 turns to about 90 turns, about 80 turns to about 100 turns, or about 90 turns to about 100 turns, including increments therein. In some embodiments, the helical cable, the stellarator coil, or both has about 3 turns, about 5 turns, about 10 turns, about 20 turns, about 30 turns, about 40 turns, about 50 turns, about 60 turns, about 70 turns, about 80 turns, about 90 turns, or about 100 turns. In some embodiments, the helical cable, the stellarator coil, or both has at least about 3 turns, about 5 turns, about 10 turns, about 20 turns, about 30 turns, about 40 turns, about 50 turns, about 60 turns, about 70 turns, about 80 turns, or about 90 turns. In some embodiments, the helical cable, the stellarator coil, or both has at most about 5 turns, about 10 turns, about 20 turns, about 30 turns, about 40 turns, about 50 turns, about 60 turns, about 70 turns, about 80 turns, about 90 turns, or about 100 turns.

[0308] In some embodiments, the first portion comprises a part of the length of the helical cable of about 5 % to about 95 %. In some embodiments, the first portion comprises a part of the length of the helical cable of about 5 % to about 10 %, about 5 % to about 20 %, about 5 % to about 30 %, about 5 % to about 40 %, about 5 % to about 50 %, about 5 % to about 60 %, about 5 % to about 70 %, about 5 % to about 80 %, about 5 % to about 90 %, about 5 % to about 95 %, about 10 % to about 20 %, about 10 % to about 30 %, about 10 % to about 40 %, about 10 % to about 50 %, about 10 % to about 60 %, about 10 % to about 70 %, about 10 % to about 80 %, about 10 % to about 90 %, about 10 % to about 95 %, about 20 % to about 30 %, about 20 % to about 40 %, about 20 % to about 50 %, about 20 % to about 60 %, about 20 % to about 70 %, about 20 % to about 80 %, about 20 % to about 90 %, about 20 % to about 95 %, about 30 % to about 40 %, about 30 % to about 50 %, about 30 % to about 60 %, about 30 % to about 70 %, about 30 % to about 80 %, about 30 % to about 90 %, about 30 % to about 95 %, about 40 % to about 50 %, about 40 % to about 60 %, about 40 % to about 70 %, about 40 % to about 80 %, about 40 % to about 90 %, about 40 % to about 95 %, about 50 % to about 60 %, about 50 % to about 70 %, about 50 % to about 80 %, about 50 % to about 90 %, about 50 % to about 95 %, about 60 % to about 70 %, about 60 % to about 80 %, about 60 % to about 90 %, about 60 % to about 95 %, about 70 % to about 80 %, about 70 % to about 90 %, about 70 % to about 95 %, about 80 % to about 90 %, about 80 % to about 95 %, or about 90 % to about 95 %, including increments therein. In some embodiments, the first portion comprises a part of the length of the

helical cable of about 5 %, about 10 %, about 20 %, about 30 %, about 40 %, about 50 %, about 60 %, about 70 %, about 80 %, about 90 %, or about 95 %. In some embodiments, the first portion comprises a part of the length of the helical cable of at least about 5 %, about 10 %, about 20 %, about 30 %, about 40 %, about 50 %, about 60 %, about 70 %, about 80 %, or about 90 %. In some embodiments, the first portion comprises a part of the length of the helical cable of at most about 10 %, about 20 %, about 30 %, about 40 %, about 50 %, about 60 %, about 70 %, about 80 %, about 90 %, or about 95 %.

[0309] In some embodiments, a ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil is about 1:4 to about 10,000:1. In some embodiments, a ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil is about 10:1 to about 20:1, about 10:1 to about 50:1, about 10:1 to about 100:1, about 10:1 to about 200:1, about 10:1 to about 500:1, about 10:1 to about 1,000:1, about 10:1 to about 2,000:1, about 10:1 to about 5,000:1, about 10:1 to about 10,000:1, about 20:1 to about 50:1, about 20:1 to about 100:1, about 20:1 to about 200:1, about 20:1 to about 500:1, about 20:1 to about 1,000:1, about 20:1 to about 2,000:1, about 20:1 to about 5,000:1, about 20:1 to about 10,000:1, about 50:1 to about 100:1, about 50:1 to about 200:1, about 50:1 to about 500:1, about 50:1 to about 1,000:1, about 50:1 to about 2,000:1, about 50:1 to about 5,000:1, about 50:1 to about 10,000:1, about 100:1 to about 200:1, about 100:1 to about 500:1, about 100:1 to about 1,000:1, about 100:1 to about 2,000:1, about 100:1 to about 5,000:1, about 100:1 to about 10,000:1, about 200:1 to about 500:1, about 200:1 to about 1,000:1, about 200:1 to about 2,000:1, about 200:1 to about 5,000:1, about 200:1 to about 10,000:1, about 500:1 to about 1,000:1, about 500:1 to about 2,000:1, about 500:1 to about 5,000:1, about 500:1 to about 10,000:1, about 1,000:1 to about 2,000:1, about 1,000:1 to about 5,000:1, about 1,000:1 to about 10,000:1, about 2,000:1 to about 5,000:1, about 2,000:1 to about 10,000:1, or about 5,000:1 to about 10,000:1, including increments therein. In some embodiments, a ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil is about 10:1, about 20:1, about 50:1, about 100:1, about 200:1, about 500:1, about 1,000:1, about 2,000:1, about 5,000:1, or about 10,000:1. In some embodiments, a ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil is at least about 10:1, about 20:1, about 50:1, about 100:1, about 200:1, about 500:1, about 1,000:1, about 2,000:1, or about 5,000:1. In some embodiments, a ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil is at most about 20:1, about 50:1, about 100:1, about 200:1, about 500:1, about 1,000:1, about 2,000:1, about 5,000:1, or about 10,000:1. In some

cases, the gap may have a size of at most about 0.01, 0.05, 0.1, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 50, 100, or more millimeters.

[0310] In some embodiments, a ratio between a distance between consecutive turns of the stellarator coil and the thickness of the cable is about 0.01:1 to about 15:1. In some embodiments, a ratio between a distance between consecutive turns of the stellarator coil and the thickness of the cable is about 0.01:1 to about 0.025:1, about 0.01:1 to about 0.05:1, about 0.01:1 to about 0.075:1, about 0.01:1 to about 0.1:1, about 0.01:1 to about 0.2:1, about 0.01:1 to about 0.4:1, about 0.01:1 to about 0.6:1, about 0.01:1 to about 0.9:1, about 0.025:1 to about 0.05:1, about 0.025:1 to about 0.075:1, about 0.025:1 to about 0.1:1, about 0.025:1 to about 0.2:1, about 0.025:1 to about 0.4:1, about 0.025:1 to about 0.6:1, about 0.025:1 to about 0.9:1, about 0.05:1 to about 0.075:1, about 0.05:1 to about 0.1:1, about 0.05:1 to about 0.2:1, about 0.05:1 to about 0.4:1, about 0.05:1 to about 0.6:1, about 0.05:1 to about 0.9:1, about 0.075:1 to about 0.1:1, about 0.075:1 to about 0.2:1, about 0.075:1 to about 0.4:1, about 0.075:1 to about 0.6:1, about 0.075:1 to about 0.9:1, about 0.1:1 to about 0.2:1, about 0.1:1 to about 0.4:1, about 0.1:1 to about 0.6:1, about 0.1:1 to about 0.9:1, about 0.2:1 to about 0.4:1, about 0.2:1 to about 0.6:1, about 0.2:1 to about 0.9:1, about 0.4:1 to about 0.6:1, about 0.4:1 to about 0.9:1, or about 0.6:1 to about 0.9:1, including increments therein. In some embodiments, a ratio between a distance between consecutive turns of the stellarator coil and the thickness of the cable is about 0.01:1, about 0.025:1, about 0.05:1, about 0.075:1, about 0.1:1, about 0.2:1, about 0.4:1, about 0.6:1, or about 0.9:1. In some embodiments, a ratio between a distance between consecutive turns of the stellarator coil and the thickness of the cable is at least about 0.01:1, about 0.025:1, about 0.05:1, about 0.075:1, about 0.1:1, about 0.2:1, about 0.4:1, or about 0.6:1. In some embodiments, a ratio between a distance between consecutive turns of the stellarator coil and the thickness of the cable is at most about 0.025:1, about 0.05:1, about 0.075:1, about 0.1:1, about 0.2:1, about 0.4:1, about 0.6:1, or about 0.9:1.

[0311] In some embodiments, a ratio between the diameter of the cable and a pitch of the helical cable is about 0.1:1 to about 10:1. In some embodiments, a ratio between the diameter of the cable and a pitch of the helical cable is about 0.1:1 to about 0.5:1, about 0.1:1 to about 1:1, about 0.1:1 to about 2:1, about 0.1:1 to about 4:1, about 0.1:1 to about 6:1, about 0.1:1 to about 8:1, about 0.1:1 to about 10:1, about 0.5:1 to about 1:1, about 0.5:1 to about 2:1, about 0.5:1 to about 4:1, about 0.5:1 to about 6:1, about 0.5:1 to about 8:1, about 0.5:1 to about 10:1, about 1:1 to about 2:1, about 1:1 to about 4:1, about 1:1 to about 6:1, about 1:1 to about 8:1, about 1:1 to about 10:1, about 2:1 to about 4:1, about 2:1 to about 6:1, about 2:1 to about 8:1, about 2:1 to about 10:1, about 4:1 to about 6:1, about 4:1 to about 8:1, about 4:1 to about 10:1, about 6:1 to

about 8:1, about 6:1 to about 10:1, or about 8:1 to about 10:1, including increments therein. In some embodiments, a ratio between the diameter of the cable and a pitch of the helical cable is about 0.1:1, about 0.5:1, about 1:1, about 2:1, about 4:1, about 6:1, about 8:1, or about 10:1. In some embodiments, a ratio between the diameter of the cable and a pitch of the helical cable is at least about 0.1:1, about 0.5:1, about 1:1, about 2:1, about 4:1, about 6:1, or about 8:1. In some embodiments, a ratio between the diameter of the cable and a pitch of the helical cable is at most about 0.5:1, about 1:1, about 2:1, about 4:1, about 6:1, about 8:1, or about 10:1.

[0312] In some embodiments, the helical cable has a coil angle of about 15 degrees to about 80 degrees. In some embodiments, the helical cable has a coil angle of about 15 degrees to about 20 degrees, about 15 degrees to about 25 degrees, about 15 degrees to about 30 degrees, about 15 degrees to about 35 degrees, about 15 degrees to about 40 degrees, about 15 degrees to about 45 degrees, about 15 degrees to about 50 degrees, about 15 degrees to about 55 degrees, about 15 degrees to about 60 degrees, about 15 degrees to about 65 degrees, about 15 degrees to about 80 degrees, about 20 degrees to about 25 degrees, about 20 degrees to about 30 degrees, about 20 degrees to about 35 degrees, about 20 degrees to about 40 degrees, about 20 degrees to about 45 degrees, about 20 degrees to about 50 degrees, about 20 degrees to about 55 degrees, about 20 degrees to about 60 degrees, about 20 degrees to about 65 degrees, about 20 degrees to about 80 degrees, about 25 degrees to about 30 degrees, about 25 degrees to about 35 degrees, about 25 degrees to about 40 degrees, about 25 degrees to about 45 degrees, about 25 degrees to about 50 degrees, about 25 degrees to about 55 degrees, about 25 degrees to about 60 degrees, about 25 degrees to about 65 degrees, about 25 degrees to about 80 degrees, about 30 degrees to about 35 degrees, about 30 degrees to about 40 degrees, about 30 degrees to about 45 degrees, about 30 degrees to about 50 degrees, about 30 degrees to about 55 degrees, about 30 degrees to about 60 degrees, about 30 degrees to about 65 degrees, about 30 degrees to about 80 degrees, about 35 degrees to about 40 degrees, about 35 degrees to about 45 degrees, about 35 degrees to about 50 degrees, about 35 degrees to about 55 degrees, about 35 degrees to about 60 degrees, about 35 degrees to about 65 degrees, about 35 degrees to about 80 degrees, about 40 degrees to about 45 degrees, about 40 degrees to about 50 degrees, about 40 degrees to about 55 degrees, about 40 degrees to about 60 degrees, about 40 degrees to about 65 degrees, about 40 degrees to about 80 degrees, about 45 degrees to about 50 degrees, about 45 degrees to about 55 degrees, about 45 degrees to about 60 degrees, about 45 degrees to about 65 degrees, about 45 degrees to about 80 degrees, about 50 degrees to about 55 degrees, about 50 degrees to about 60 degrees, about 50 degrees to about 65 degrees, about 50 degrees to about 80 degrees, about 55 degrees to about 60 degrees, about 55 degrees to about 65 degrees, about 55 degrees to about 80 degrees, about 60

degrees to about 65 degrees, about 60 degrees to about 80 degrees, or about 65 degrees to about 80 degrees, including increments therein. In some embodiments, the helical cable has a coil angle of about 15 degrees, about 20 degrees, about 25 degrees, about 30 degrees, about 35 degrees, about 40 degrees, about 45 degrees, about 50 degrees, about 55 degrees, about 60 degrees, about 65 degrees, or about 80 degrees. In some embodiments, the helical cable has a coil angle of at least about 15 degrees, about 20 degrees, about 25 degrees, about 30 degrees, about 35 degrees, about 40 degrees, about 45 degrees, about 50 degrees, about 55 degrees, about 60 degrees, or about 65 degrees. In some embodiments, the helical cable has a coil angle of at most about 20 degrees, about 25 degrees, about 30 degrees, about 35 degrees, about 40 degrees, about 45 degrees, about 50 degrees, about 55 degrees, about 60 degrees, about 65 degrees, or about 80 degrees.

Extended Length Bending

[0313] In some cases, the present disclosure provides methods and systems for generating a coil. The coil can comprise a cable comprising a cable jacket and a cable core. The cable jacket may comprise a plurality of cable jacket segments. The coil may be longer than a maximum working lengths of a bending apparatus used to generate the coil.

[0314] **FIG. 7** shows a flowchart of an example method 700 of bending a coil, according to some embodiments. In an operation 710, the method 700 may comprise providing a cable comprising a cable core and a cable jacket to a bending apparatus. The cable jacket may comprise a cable jacket segment. The bending apparatus may have a maximum working length, and a length of the cable core may be longer than the maximum working length, and a length of the cable jacket segment may be shorter than the maximum working length. The bending apparatus may be a computer numerical control (CNC) bending apparatus. Examples of bending apparatuses include, but are not limited to, CNC bending apparatuses (e.g., a Jneu freeform bender, etc.), rotary draw bending apparatuses, roll bending apparatuses, manual bending apparatuses (e.g., an apparatus that comprises a user operated bending system), or the like. In some cases, the core may be a hollow core. The hollow core can be configured to, for example, carry coolant through the cable.

[0315] The cable jacket segment or the additional cable jacket segment may comprise one or more of, for example, non-magnetic metals (e.g., copper, titanium, aluminum, etc.), other metals (e.g., iron, steels, stainless steels, etc.), alloys, polymers, or the like, or any combination thereof. In some cases, the cable core comprises one or more high temperature superconducting (HTS) tapes. The cable core can comprise one or more HTS tape stacks. The cable core may comprise

one or more other superconducting architectures. In some cases, the cable core, cable jacket segment, or maximum working length of the bending apparatus are each independently at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, or more meters long. The diameter of the cable core may be at least about 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 25, 30, 35, 40, 45, 50 or more millimeters.

[0316] In an operation 720, the method 700 may comprise using a feeder portion of the bending apparatus to move the cable jacket segment and the cable core through a bending head of the bending apparatus, thereby bending the cable jacket and the cable core into a portion of the coil. In some cases, the moving the cable jacket segment comprises pushing the cable jacket segment using the feeder portion. For example, the feeder portion can engage with the cable jacket segment and push the cable jacket segment through the bending head.

[0317] In an operation 730, the method 700 may comprise providing an additional cable jacket segment around the cable core. The additional cable jacket segment may have a length shorter than the maximum working length.

[0318] In an operation 740, the method 700 may comprise coupling the additional cable jacket segment to the cable jacket and/or the cable core. The coupling may comprise, for example, welding, soldering (e.g., ultrasonic soldering, heat soldering, etc.), engagement of one or more physical couplers (e.g., teeth, grooves, threads, etc.), fusing (e.g., melting the additional cable jacket segment and the cable jacket or the cable core), press fitting (e.g., pressing together for a friction fit), or the like, or any combination thereof.

[0319] The feeder portion can push either the cable jacket segment or the additional cable jacket segment with at least a mandrel configured to fit over said cable core. The feeder portion can use the mandrel to provide enhanced contact and greater force transfer versus not using the mandrel. The mandrel can be a clamping mandrel (e.g., comprising a plurality of portions configured to clamp to a jacket segment or over the cable core). The clamping mandrel can enable placement of the mandrel onto a cable core that does not have access to the end of the cable core. For example, the clamping mandrel can be placed in the middle of a cable core. The clamping mandrel can be configured to clamp onto the cable jacket segment or the additional cable jacket segment. For example, the clamping mandrel can have an internal diameter sufficient to permit the clamping mandrel to engage with the cable jacket segment or the additional cable jacket segment. In some cases, the clamping mandrel can be configured to clamp behind the cable jacket segment or the additional cable jacket segment. For example, the clamping mandrel can clamp around the cable core and be configured to press against the cable jacket segment, thereby transferring the movement of the feeder portion to the cable jacket segment. The mandrel may

comprise one or more of metals (e.g., iron, copper, aluminum, etc.), alloys (e.g., steel, bronze, etc.), plastics (e.g., polymers, polyethylene, polypropylene, polylactic acid, etc.), or the like, or any combination thereof.

[0320] The bending apparatus may exert a force on the mandrel. The mandrel can transmit the force primarily to the cable jacket. For example, the bending apparatus can be configured to interface with the cable jacket through the mandrel. In some cases, the mandrel can transmit the force entirely to the cable jacket. For example, the force applied by the feeder portion can be transmitted to the cable jacket through the mandrel. The mandrel can have a thickness of at least about a thickness of the cable jacket segment or the additional cable jacket segment. For example, the mandrel can be made of a material such that the overall thickness of the mandrel on the cable core is equivalent to the thickness of the cable jacket segment or the additional cable jacket segment. The mandrel may be larger than the cable jacket segment or the additional cable jacket segment. The mandrel may be smaller than the cable jacket segment or the additional cable jacket segment. The thickness of the mandrel can be measured at a contact point between the mandrel and the cable jacket segment or the additional cable jacket segment. Having a mandrel with a same thickness as the cable jacket segment or the additional cable jacket segment can result in force transfer from the mandrel to the cable jacket segment or the additional cable jacket segment without deforming the cable jacket segment or the additional cable jacket segment.

[0321] The mandrel can be configured to engage with the cable jacket segment or the additional cable jacket segment through at least, for example, friction, one or more physical interfaces (e.g., grooves, teeth, pegs, slots, etc.), or the like, or any combination thereof. The mandrel may comprise one or more protruding members (e.g., teeth), intruding members (e.g., grooves), or a combination thereof. The presence of members on the mandrel or the cable jacket segment or the additional cable jacket segment can enhance the force transfer from the mandrel to the cable jacket segment or the additional cable jacket segment, thereby improving the efficiency of the feeder portion. The cable jacket segment or the additional cable jacket segment may be cut perpendicular to the long axis of the cable core. For example, the ends of the cable jacket segment or the additional cable jacket segment can have a plane perpendicular to the long plane of the cable core. The cable jacket segment or the additional cable jacket segment may be cut at an angle of at least about 10, 20, 30, 40, 45, 50, 60, 70, 80, 90, or more degrees from the long axis of the cable core. The cable jacket segment or the additional cable jacket segment may be cut such that one end of the cable jacket segment and one end of the additional cable jacket segment flush fit together. In some cases, a cable jacket segment can be fed backwards through

the bending head, and the mandrel can then push the cable jacket segment through the bending apparatus. For example, a straight portion of a cable jacket can be loaded backwards through the bending head to load the cable jacket into the bending apparatus. Such a loading can enable further bending of cable jackets that already have a bent portion or another geometry that can prevent loading through the back of the bending apparatus.

[0322] The thickness of the cable jacket segment or the additional cable jacket segment may be at least about 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, or more millimeters. The thickness may be related to the material of the cable jacket segment or the additional cable jacket segment. For example, a harder material may have a thinner thickness than a softer material.

[0323] In an operation 750, the method 700 may comprise using the feeder portion of the bending apparatus to move the cable jacket and the cable core through the bending head of the bending apparatus to bend the cable jacket and the cable core into an additional portion of the coil.

[0324] In some cases, operations 710 – 750 may be repeated one or more times. Repeating operations 710 – 750 can generate coils with overall lengths much greater than the maximum working length of the bending apparatus, which can, in turn, enable new coil geometries and densities. For example, a coil can be produced for a larger end use than would otherwise be available. In this example, the coil may also have increased coil density due to the inclusion of additional coil material within the coil.

[0325] In some aspects, the present disclosure provides a cable comprising a cable core and a cable jacket. The cable jacket can be formed of at least two pieces. The cable jacket can be formed of at least about 2, 3, 4, 5, 6, 7, 8, 9, 10, or more pieces. The cable core can be a single cable core disposed in the at least two pieces. The cable can be non-planar. For example, the cable can be in a three-dimensional shape (e.g., a coil, spiral, etc.). The cable can be made non-planar through use of, for example, a bending apparatus as described elsewhere herein. The cable may be bent into at least a portion of a stellarator coil.

[0326] The at least two pieces of the cable jacket can be fused together. The fusing may be as described elsewhere herein. For example, the at least two pieces can be soldered, welded, fused, etc. The cable core can be a cable core as described elsewhere herein. For example, the cable core can be a conductor on a round core (CORC) cable. The cable core may comprise one or more superconducting (e.g., high temperature superconducting) tapes. The cable core may comprise a vacuum pressure impregnated, insulated, partially transposed, extruded, and roll formed (VIPER) cable. Examples of VIPER cables can be found in N. Riva *et al.* "Development

of the first non-planar REBCO stellarator coil using VIPER cable," 2023 *Supercond. Sci. Technol.* **36** 105001, DOI: 10.1088/1361-6668/aced9d which is incorporated by reference in its entirety. In some cases, the cable jacket can comprise a VIPER cable jacket.

[0327] The cable jacket may comprise, for example, non-magnetic metals (e.g., copper, aluminum, titanium, etc.), metal alloys (e.g., brass, etc.), polymers, or the like, or any combination thereof. The cable jacket may comprise one or more members configured to engage the cable jacket to the cable core or to a mandrel. Examples of members include, but are not limited to grooves, teeth, etc. An interface between the at least two cable pieces may comprise an interface as described elsewhere herein (e.g., a flat interface, a screw interface, etc.).

Example 1 – Operation of a freeform bending using multiple cable jackets

[0328] **FIG. 8** shows an example of a set of operations of a freeform bender, according to some embodiments. In operation 1, a first cable jacket segment can be placed on the cable core, and a feeder portion can be butted up against the first cable jacket segment. The feeder portion can then push the first cable jacket segment through the bending head in operation 2, resulting in a portion of a coil. In operation 3, the feeder portion can be retracted to permit the loading of an additional cable jacket segment in operation 4. The feeder portion can then feed the additional cable jacket segment through the bending head, thus enlarging the at least a portion of the coil.

[0329] **FIGs. 9A – 9D** shows an example of a multipart mandrel, according to some embodiments. The mandrel 900 can comprise a first portion 901 and a second portion 902. The first portion 901 can be configured to mount to a bending apparatus, thereby enabling force transfer between the bending apparatus and the cable or cable jacket. The second portion 902 may be configured to couple to the first portion 901 to form the mandrel 900, and can enable concentric force to be applied to the cable jacket during a feeding process of the bending apparatus.

Suspending HTS Tapes

[0330] Provided herein are methods and systems used for stabilizing high-temperature superconducting (HTS) tapes, including using a structure composed of a thin spine and struts to suspend the HTS tapes. The methods and systems allow manual bending of the wires to conform to specific shapes without the need for a bending unit, leveraging flexibility to accommodate the HTS tapes laid across the spine, akin to a suspension bridge. This flexibility may allow the tapes significant room to shift and bend, naturally minimizing stress during the bending process. The tapes, once in place, may be directly laid into grooves on support plates, providing a mold-like

structure for the tapes. Copper strips within the tape stack may aid in cooling. The structure may allow for additional components, such as sensors, without interfering with the bending process. The methods and systems may be designed for scalability; the spine may be extended without machinery, and may be adapted for use with different materials to enhance structural strength or thermal conductivity.

[0331] FIG. 10 illustrates a system for stabilizing HTS tapes. This system may comprise a spine 1002. The spine may be a critical component of the high-temperature superconducting (HTS) tape suspension system. The materials for the spine 1002 may include, but are not limited to, for example, an 8 AWG solid copper wire or a hollow annealed copper tube. The spine may have an outer diameter greater than or equal to about 1 millimeter (mm), 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9 mm, 10mm, 12mm, 15mm, 20mm or greater. The spine may have an out diameter less than or equal to about 20 mm, 15 mm, 12 mm, 10 mm, 9 mm, 8 mm, 7 mm, 6 mm, 5 mm, 4 mm, 3 mm, 2 mm, 1 mm, or less. An outer diameter of the spine may be between any two values described herein, for example between about 4 mm and about 6 mm. The diameter may be chosen based upon the application. Materials of the spine (e.g., 8 AWG solid copper wire or hollowed annealed copper tube) may have excellent thermal conductivity and structural integrity, useful for the effective support and cooling of HTS tapes.

[0332] In some cases, construction methods for the spine 1002 may vary to accommodate system design requirements and operational scalability. The spine 1002 may be assembled by soldering individual sections together to achieve a certain length. Alternatively, or in addition, the spine may be assembled by employing a continuous piece that extends the full length of the coil. This flexibility in construction may allow for tailoring the spine 1002 to specific application needs. This may enhance the system's adaptability and efficiency.

[0333] The choice of a hollow annealed copper tube, as described in some embodiments herein, may facilitate the integration of advanced cooling solutions. Coolant may flow directly through the tube. Coolant flowing through the tube may improve the system's ability to manage heat, enabling the HTS tape stack 1200 remain within an optimal superconducting temperature range. For example, the HTS tape stack may be cooled to a temperature of less than or equal to about 30 degrees Celsius, about 40 degrees Celsius, about 50 degrees Celsius, about 55 degrees Celsius, about 60 degrees Celsius, about 65 degrees Celsius, about 70 degrees Celsius, about 75 degrees Celsius, about 80 degrees Celsius, about 90 degrees Celsius, or about 100 degrees Celsius.

[0334] In some cases, the design of the spine 1002 may reduce mechanical stress on the HTS tape stack 1200. The spine may be configured to safeguard integrity and superconducting

properties during installation and use. Accordingly, the design of the spine 1002 may enhance the reliability and performance of the suspension system.

[0335] In some cases, struts 1004, which may function as the primary support structure in the spatial configuration of the HTS tape, may serve to sustain placement and alignment of the HTS tape stack 1200 throughout the coil. Attached along the spine 1002, the struts 1004 may be spaced at intervals that may be adjusted according to the curvature of the coil. For example, struts may be spaced where the distance between a first strut and a second strut is about 1 centimeter (cm) to about 20 cm. The distance may be about 1 cm to about 2 cm, about 1 cm to about 3 cm, about 1 cm to about 4 cm, about 1 cm to about 5 cm, about 1 cm to about 6 cm, about 1 cm to about 7 cm, about 1 cm to about 8 cm, about 1 cm to about 9 cm, about 1 cm to about 10 cm, about 1 cm to about 15 cm, about 1 cm to about 20 cm, about 2 cm to about 3 cm, about 2 cm to about 4 cm, about 2 cm to about 5 cm, about 2 cm to about 6 cm, about 2 cm to about 7 cm, about 2 cm to about 8 cm, about 2 cm to about 9 cm, about 2 cm to about 10 cm, about 2 cm to about 15 cm, about 2 cm to about 20 cm, about 3 cm to about 4 cm, about 3 cm to about 5 cm, about 3 cm to about 6 cm, about 3 cm to about 7 cm, about 3 cm to about 8 cm, about 3 cm to about 9 cm, about 3 cm to about 10 cm, about 3 cm to about 15 cm, about 3 cm to about 20 cm, about 4 cm to about 5 cm, about 4 cm to about 6 cm, about 4 cm to about 7 cm, about 4 cm to about 8 cm, about 4 cm to about 9 cm, about 4 cm to about 10 cm, about 4 cm to about 15 cm, about 4 cm to about 20 cm, about 5 cm to about 6 cm, about 5 cm to about 7 cm, about 5 cm to about 8 cm, about 5 cm to about 9 cm, about 5 cm to about 10 cm, about 5 cm to about 15 cm, about 5 cm to about 20 cm, about 6 cm to about 7 cm, about 6 cm to about 8 cm, about 6 cm to about 9 cm, about 6 cm to about 10 cm, about 6 cm to about 15 cm, about 6 cm to about 20 cm, about 7 cm to about 8 cm, about 7 cm to about 9 cm, about 7 cm to about 10 cm, about 7 cm to about 15 cm, about 7 cm to about 20 cm, about 8 cm to about 9 cm, about 8 cm to about 10 cm, about 8 cm to about 15 cm, about 8 cm to about 20 cm, about 9 cm to about 10 cm, about 9 cm to about 15 cm, about 9 cm to about 20 cm, about 10 cm to about 15 cm, about 10 cm to about 20 cm, or about 15 cm to about 20 cm. The distance may be about 1 cm, about 2 cm, about 3 cm, about 4 cm, about 5 cm, about 6 cm, about 7 cm, about 8 cm, about 9 cm, about 10 cm, about 15 cm, or about 20 cm. The distance may be at least about 1 cm, about 2 cm, about 3 cm, about 4 cm, about 5 cm, about 6 cm, about 7 cm, about 8 cm, about 9 cm, about 10 cm, or about 15 cm. The distance may be at most about 2 cm, about 3 cm, about 4 cm, about 5 cm, about 6 cm, about 7 cm, about 8 cm, about 9 cm, about 10 cm, about 15 cm, or about 20 cm. In some cases, a first struct spacing may be used at a first location. A second strut spacing may be used at a second location. The first strut spacing may be different from the second strut spacing.

For gentle bends, the struts 1004 may be positioned further apart, reducing the density of support and thus allowing the HTS tape greater freedom to move and align within the coil's architecture. Conversely, for tighter bends, the struts 1004 may be placed closer together to provide more support to reduce strain or damage.

[0336] In some cases, the adaptability of the strut placement may be complemented by the variety of shapes that the struts 1004 may form. In some embodiments, the struts may be shaped symmetrically or asymmetrically around a central axis. This versatility may enable the struts 1004 to support the HTS tape stack 1200 effectively, whether the coil includes broad arcs or sharp angles. The design of the struts 1004 may provide a reliable anchor for the HTS tape stack 1200. The struts may maintain the tape's proximity to the spine 1002.

[0337] In some cases, through the strategic placement and diverse shaping, the struts 1004 may contribute to the stability of the HTS tape stack 1200. For example, the struts 1004 may provide support for the HTS tape stack 1200 during the manufacturing process, as well as in the operational environment, where the HTS tape stack 1200 may undergo various mechanical stresses. The design of the struts 1004 may help secure the position and orientation of the HTS tape stack 1200, without compromising structural integrity. In this design, the placement of the HTS tape stack 1200 is uniquely defined in relation to the spine 1002, which may form the central axis of the coil system. The HTS tape stack 1200 may be wound around the spine 1002, with struts 1004 employed as intermediary supports to maintain a separation between the HTS tape stack 1200 and the spine 1002. This configuration may help position the HTS tape stack 1200 for preserving the tape's superconducting qualities while accommodating the coil's various geometrical configurations.

[0338] In some cases, a jacket 1006, which may be a protective and/or structural component, may encase the HTS tape stack 1200 and spine 1002 assembly within the coil system. The jacket 1006 may provide mechanical protection, thermal insulation, and/or environmental isolation for the superconducting elements. The jacket 1006 may minimize exposure to detrimental conditions and/or may help the HTS tape stack 1200 to operate at optimal efficiency.

[0339] In some cases, the jacket 1006, may be tailored for various application requirements. In some cases, a modified gooseneck embodiment may provide structural flexibility and may allow for intricate coil geometries without compromising the integrity of the HTS tape stack 1200. In some cases, Kapton sleeves may provide a lightweight solution which prioritizes electrical insulation and thermal management by isolating the superconducting tape. In some cases, the jacket 1006 may contain copper foil material, providing additional electrical pathways in case of current surges. In some cases, strips (e.g. copper strips) may be integrated into the jacket 1006

to act as heat sinks. The strips may quickly dissipate heat from the HTS tape stack 1200 to the low temperature infill. In other embodiments, the jacket 1006 may be cast directly into the coil plates, which may provide a durable and streamlined design. Casting the jacket 1006 directly into the coil plates may enhance the coil's overall functionality and reliability by integrating the protective structure with the cooling channels and sensor systems.

[0340] FIG. 11A illustrates an HTS tape suspension system utilizing a modified gooseneck jacket 1102 laid in a channel in one half of a coil plate 1100. In some cases, the unique design of the gooseneck jacket 1102 may be manually bent into desired shapes and configurations without the need for specialized bending machinery. The manual bending of the gooseneck jacket 1102 may provide significant flexibility in designing coil shapes, which may allow for custom fits in various applications and may prevent damage to the HTS tape stack 1200 during the bending and installation process. The manual bending of the gooseneck jacket 1102 may also greatly simplify the process of shaping the coils, allowing for precise geometries included in stellarator applications without the complexity and expense of custom bending tools. The ability to manually adjust the shape of the gooseneck jacket 1102 directly on the coil plate 1100 streamlines the installation process, allowing for the spatial parameters of the HTS tape stack 1200 to be met while maintaining structural integrity.

[0341] FIG. 11B illustrates a jacket-less HTS tape suspension system 1104 being cast directly into the coil plate 1100, which bypasses the need for a separate jacket component. In some cases, embedding the HTS tape suspension system directly into the structure of the coil plate effectively integrates the suspension system with the coil's foundational structure. In some cases, a direct casting technique may simplify the manufacturing process by reducing the number of components and steps required to assemble the superconducting coil. Simplifying the manufacturing process may be particularly advantageous in the construction of stellarators where precision and reliability are paramount.

[0342] In some cases, the jacket-less HTS tape suspension system 1104 may enhance cooling efficiency by improving thermal contact between the HTS tape stack 1200 and the cooling infrastructure of the coil plate. In some cases, the jacket-less HTS tape suspension system 1104 may minimize mechanical stress on the HTS tapes. The HTS suspension system may providea platform that may be tailored to the tapes' dimensions and cooling parameters. The platform may be stable and/or immobile. Direct integration may also provide a compact and robust coil design, which may reduce the susceptibility of the HTS tapes to external disturbances and enhancing the overall performance of the stellarator's magnetic confinement system. A cable

with no jacket may allow for greater current density by fitting more HTS tapes into the same coil design.

[0343] In some cases, once the jacket-less HTS tape suspension system 1104 is shaped into the coil plate 1100, solder may be used to secure the jacket-less HTS tape suspension system 1104 in place. Solder may be melted and filled around the jacket-less HTS tape suspension system 1104, which may provide a robust mechanical bond and enhance thermal conductivity between the components. The soldering step may provide a stable, conductive path for cooling and electrical currents by maintaining the positional integrity of the HTS tapes within the coil plate. In some cases, the solder may contribute to the efficiency and reliability of the superconducting coil in stellarator applications by reinforcing the structural cohesion of the system and minimizing electrical resistance at the interface. The use of solder may optimize performance of the HTS tapes under operational conditions by creating precise control over the mechanical and thermal properties of the system.. In some cases, a Kapton sleeve may be used as the jacket 1006. The thin-walled tubes in a Kapton sleeve may crinkle when bent while maintaining their structural integrity. With a melting point of 500°C, a Kapton sleeve may be filled with Pb-Sn solder or a low-temperature infill. Kapton sleeves as jackets 1006 may provide excellent cryogenic and electrical performance.

[0344] FIG. 12 illustrates variable strut spacing. Stellarator coils may have a wide variety of bend radii. In some cases, the direct access to the core of the cable provided by the present disclosure may allow for the distance between the struts 1004 to be variable. Variability in the spacing of the struts 1004 may allow the pitch angle of the path of the HTS tape stack 1200 to vary along the length of the coil. A tighter pitch angle may have a greater tolerance for tighter bending radii in anticipated sections of the coil, such as section 1204. The struts 1004 may be spaced further apart in straighter sections of the coil, such as in section 1202 and section 1206. Variable strut spacing may utilize less HTS tape in a given section of coil.

[0345] FIG. 13 illustrates an HTS tape system with integrated cooling. Cooling may allow the HTS tapes to remain below their critical temperature, thus maintaining the operational efficiency and longevity of the HTS tapes. In some cases, cooling may be integrated into the system through direct contact cooling, where the HTS tape stack 1200 may be in physical contact with cooling channels or surfaces that may efficiently dissipate heat. These cooling channels or surfaces may be incorporated into the design of the spine 1002 or the coil, allowing for effective thermal management without compromising the structural integrity of the system. Different strut designs may be utilized to support this cooling process. FIG. 13A illustrates a side view of an HTS suspension system. In some cases, cooling channels 1300 can be twisted into the coil along

the struts 1004, using the off-axis suspension points from the HTS tape stack 1200. FIG. 13B illustrates a cross-section of the HTS suspension system depicted in FIG. 13A. FIG. 13C illustrates the struts 1004 with hollow interiors, which in some cases may act as cooling channels 1300, providing a direct cooling effect to the HTS tape stack 1200 suspended between the struts 1004. Strut designs may incorporate materials with high thermal conductivity which may facilitate the transfer of heat from the HTS tape stack 1200 to the cooling elements of the system. Strut designs may be tailored based on the specific cooling parameters, balancing factors such as cooling efficiency, mechanical stability, and manufacturability. FIG. 13D illustrates how cooling channels 1300 can be incorporated into the struts 1004 by shaping the dividers 1302 to cradle the cooling channels 1300. Innovative strut configurations may enhance the overall cooling strategy. For instance, adjustable or modular struts may be designed to optimize the spacing between HTS tapes, which may improve airflow or coolant circulation around the tapes. Optimization of the spacing between HTS tapes may allow for dynamic thermal management and may accommodate varying operational loads and environmental conditions.

[0346] FIG. 14 illustrates alternative strut shapes. The parameters of a coil may determine variations in the design of the struts 1004. The struts may be designed to allow for the placement of sensors that may move freely during the bending process without damaging the HTS tape stack 1200. The sensors may become secure when cast in Cerrolow or otherwise soldered in place. In some cases, deformable tabs 1400 may be incorporated into the HTS tape channel in the strut 1004. These deformable tabs 1400 may bend should the HTS tape be pulled during stress, thus relieving the stress on the HTS tape before the HTS tape bends and creases. Example strut 1402 may have off-axis HTS tape channels, which have a greater bend radius at the same distance diameter. Example strut 504 may fit as many HTS tape stacks as possible in the given space. Increasing the tapes by 50% and running the same amount of current may result in the same current density throughout the coil while running below the quench current.

[0347] In some cases, the variety struts 1004 may be manufactured with laser cutting, water cutting, or punch cutting, among other potential manufacturing methods. Different strut shapes may also allow for the incorporation of diagnostic tools, such as integrated strain gauges, temperature sensors, voltage taps, Hall sensors, and any other small scientific instrument within the infill and within the space between the tape stack, the struts 1004, and the cooling channels 1300.

[0348] FIG. 15 illustrates a method of manufacture 116. The process may begin with the construction of the spine 1002. The spine 1002 may be constructed at operation 1500 from a

hollow annealed copper tube of roughly 4-6mm outer diameter that is the length of the coil. In other cases, a solid wire, such as 8AWG, may be used in place of the copper tube.

[0349] In some cases, struts 1004, which may have been sliced from a custom extrusion and either punch-cut from a die or laser cut or waterjet cut from a sheet, may then be affixed at operation 1502. The struts 1004 may then be soldered in place with a propane torch. In some cases, the struts may be spaced at 3cm intervals with a 100mm pitch. In some cases, the struts 1004 may be held in place with solder bumps that allow the struts 1004 to pivot. This may provide a way for the struts 1004 to relieve strain on the HTS tape stack 1200 during the bending process. The spine 1002 may then be cleaned with isopropyl alcohol.

[0350] In some cases, operation 1504 includes laying the HTS tape stack 1200 along the struts 1004. This may be done in a variety of ways, such as laying the stack in a helical pattern along the struts 1004 while interstitially tying the HTS tape stack 1200 to the spine 1002 with a tin copper wire. In some cases, the HTS tape stack 1200 may be wrapped in copper foil continuously or at intervals to hold the HTS tape stack 1200 together. This copper wrapping could be perforated to create small heat sinks that would facilitate a more rapid transfer of heat from the tape stack to the Cerrolow cast. Once the HTS tape stack 1200 has been laid, the assembly may be cleaned with isopropyl alcohol. Then the coil is put into the jacket (if used), shaped by hand into the casting plate, and cast via the LTI process.

[0351] The functions performed in the processes and methods may be implemented in differing order. Furthermore, the outlined steps and operations are only provided as examples, and some of the steps and operations may be optional, combined into fewer steps and operations, or expanded into additional steps and operations without detracting from the essence of the disclosed embodiments.

[0352]

Ceramic High Temperature Superconductor Insulation

[0353] The present disclosure can provide insulations materials for high temperature superconductors.

[0354] Superconducting materials may include high temperature superconductors (HTS) and low temperature superconductors (LTS). In one example, HTS materials may include cuprate superconductors, which may be ceramics based on cuprates (compounds containing a copper oxide group), such as bismuth strontium calcium copper oxide (BSCCO), or ReBCO (where Re is a rare earth element, commonly Y or Gd). In another example, HTS materials may include

iron pnictides (e.g., FeAs and FeSe), magnesium diboride (MgB2), thallium barium calcium copper oxide (TBCCO), mercury barium calcium copper oxide (HBCCO), or the like.

[0355] ReBCO may be manufactured as a tape. For example, the tape may be approximately 50, 75, 100, 150, 250, or 300 microns thick and include a substrate. The substrate may include, for example, an electropolished nickel-molybdenum alloy (e.g., approximately 50 microns thick) with a series of buffer layers known as the buffer stack. The buffer stack may be approximately 0.2 microns thick. Other examples of substrates include, but are not limited to silver, gold, magnesium, aluminum, alloys thereof, or the like.

[0356] The substrate may provide a mechanical backbone that can be fed through a manufacturing line and permit growth of subsequent layers. The buffer stack may provide a biaxially textured crystalline template upon which to grow the HTS layer, and may prevent chemical diffusion of elements from the substrate to the HTS. Each of these layers described may collectively form HTS tape.

[0357] In some cases, HTS tapes may be arranged into HTS cables. An HTS cable may include one or more HTS tapes. In some cases, the one or more HTS tapes may be connected lengthwise via conductive material (e.g., copper). In some cases, the HTS tapes may be stacked (e.g., arranged such that the HTS layers are parallel). In some cases, the HTS tapes may have some other arrangement, which may vary along the length of the HTS cable.

[0358] Some examples of HTS cables may include single HTS tapes and HTS pairs. In some cases, HTS pairs may include a pair of HTS tapes arranged such that the HTS layers are parallel. In some cases, HTS cables comprising more than two HTS tapes may be configured with at least some of the HTS tapes in HTS pairs. In some cases, stacked HTS tapes may comprise various arrangements of HTS pairs. In some cases, HTS cables may comprise one or both of substrated HTS tape or exfoliated HTS tape.

[0359] In some cases, HTS field coils may be constructed by winding or by assembling several sections. For example, HTS field coils may be wound coils by wrapping an HTS cable in a spiral (e.g., a continuous spiral). In some cases, HTS coils may be insulated. For example, the HTS coils may be insulated via one or more electrical insulating materials between the turns of the HTS coils. In some cases, insulated HTS coils may be used in applications with large, rapid changes in magnetic field, such as plasma control in fusion magnets. In other cases, HTS coils may be uninsulated. In other cases, HTS coils may be partially insulated. The HTS coil may be supported by the insulation.

[0360] The high-temperature superconducting materials may be used in fusion energy applications, such as plasma chambers (e.g., stellarators, tokamaks, etc.). For example, in a

stellarator, large magnet coils may be made from HTS tapes. In some cases, HTS tape may form an HTS cable in a stellarator conductor shape. Bobbins may be used to apply the HTS materials (e.g., HTS tapes or HTS coils) during assembly of the stellarator.

[0361] The HTS tapes of the present disclosure can be a portion of a magnetic coil system. For example, the HTS tapes can be formed into coils and used to generate magnetic fields. The magnetic coil systems may be used in nuclear fusion systems such as, for example, stellarators. The HTS tapes can provide high field strengths configured to contain a plasma within the nuclear fusion system.

[0362] An HTS tape can be placed into an insulator configured to insulate the HTS tape (e.g., electrically, thermally, etc.). Electrical insulation of the HTS tape can provide for enhanced functioning of the HTS tape by reducing shorts as well as providing a consistent local environment for the HTS tape. The insulator can also provide support to the HTS tape (e.g., provide structure for the HTS tape, lessening the strain on the tape).

[0363] The insulator can comprise one or more ceramic materials. Examples of ceramic materials include, but are not limited to, aluminum oxide, magnesium silicate, aluminum silicate, titanium oxides, zirconium oxides, silicon oxides, silicon nitride, beryllium oxide, boron carbide, titanium diboride, aluminum nitride, magnesium aluminum oxide, composites (e.g., Accura Bluestone ®), or the like, or any combination thereof. The ceramic material may have a high dielectric standoff, low surface tracking (e.g., low surface voltage breakdown), thermal contraction rate similar to or matched with the HTS tape, high mechanical strength, or the like, or any combination thereof. For example, a ceramic with a thermal contraction rate similar to that of the HTS tape between room temperature and cryogenic temperatures can reduce the strain put onto the HTS tape during the cooling of the HTS tape to its operating temperature. Further, the ceramic may have a high resistance to neutron flux (e.g., be resilient to neutron bombardment). The ceramic may have a high resistance to other ionizing radiation (e.g., gamma rays, x-rays, etc.). Such resistances can improve the longevity of the insulator in nuclear fusion applications.

[0364] In some cases, the ceramic insulator is formed prior to contact with the HTS tape. Examples of forming methods include milling (e.g., subtractive manufacturing of the ceramic), additive manufacturing (e.g., three-dimensional printing), casting, molding, or the like, or any combination thereof. The ceramic insulator may be fired. For example, the insulator may be fired in a furnace to set the ceramic. The ceramic insulator may not be fired. For example, ceramic powder can be used without firing. In some cases, the ceramic insulator is added between the HTS tape and an external shell. For example, an external shell in the form of a tube

can have the HTS tape placed within the tube, and the ceramic insulator can be subsequently added to insulate the HTS tape. In this example, the insulation can be added as a powder (e.g., resulting in a tube filled with loose powder) or flowed in (e.g., resulting in a tube filled with a solid insulation and the HTS tape). In some cases where the insulation is a powder, the external shell with the ceramic powder disposed therein can be evacuated (e.g., placed under vacuum), thereby providing additional thermal insulation to the HTS tape. In some cases where the insulation is powder, the ceramic can be compacted by compressing the external shell. The external shell can comprise iron, steel, copper, titanium, tantalum, tungsten, or the like, or any combination thereof. In some cases, the insulation can be added to the external shell as a powder and reacted (e.g., sintered, baked, welded, soldered, etc.) to form a single ceramic insulator comprising the HTS tape. The tube may comprise a neutron resilient material. For example, the tube can be configured to block the neutron flux from impacting the insulation contained within the tube. In this example, the insulation may not be as resilient as the tube can provide a majority of the neutron flux resistance. In another example, neutron bombardment resistant insulation can be placed within a neutron bombardment resistant tube, thereby providing an improved neutron bombardment resistance.

[0365] FIGs. 16A – 16B show an example of a shell-tape insulation configuration, according to some embodiments. HTS tape 1602 can be oriented within external shell 1603 such that the HTS tape is insulated by insulation 1601. The insulation can provide thermal and electrical insulation to the HTS tape. The insulation can be a powder (e.g., a plurality of small particles). The insulation can be a solid insulation (e.g., a single piece of insulation). Prior to or subsequent to the addition of the insulation, the HTS tape and the external shell can be bent or otherwise formed (e.g., into a magnet coil). For example, the HTS tape and an external shell can be bent to form a coil. In this example, the insulation may be a powdered insulation that freely forms to the new coil shape. In some cases, the shell, the insulation, or the HTS tape may comprise a channel. The channel can be configured to, for example, permit flow of a coolant.

[0366] FIG. 17 shows an example of a preformed ceramic insulation, according to some embodiments. The ceramic insulator 1701 can comprise a channel 1702 configured to house an HTS tape. For example, the ceramic insulator can be three dimensionally printed to form the insulator and the channel. The ceramic insulation can be configured with a variety of different channels (e.g., at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more channels) to provide a variety of HTS tape configurations.

[0367] In some cases, the present disclosure provides a magnetic coil comprising an HTS tape and an insulator disposed around the HTS tape. The insulator may be resilient to neutron

bombardment damage. For example, the insulator may be configured such that exposure to a neutron source (e.g., a stellarator plasma) does not significantly degrade the insulator. The degradation may comprise, for example, deterioration of the mechanical properties (e.g., breaking or cracking of the insulation, reduced tolerance to stress or strain, etc.), deterioration of the electrical properties (e.g., reduced insulation effectiveness, increased conductivity, etc.), or the like, or any combination thereof. The exposure to the neutron source may be, for example, exposure to a radioactive neutron source, exposure to a plasma neutron source, etc. The insulator may have an improved resilience to neutron bombardment as compared to a polymeric insulation (e.g., polyethylene, polypropylene, polytetrafluoroethylene, polystyrene, etc.). For example, a polymeric insulation can, under neutron bombardment, suffer breakages in the carbon containing molecules of the insulation which can, in turn, result in electrically conductive species being generated in the polymeric insulation. In this example, the formation of the conductive species can generate electrically conductive pathways in the insulation which can, in turn, short through the insulation. The insulator may be at least about 1, 5, 10, 50, 100, 500, 1,000, or more times more resilient to neutron bombardment than the polymeric insulation. Metrics of improved resilience can include, but are not limited to, mean time between failure, maximum acceptable neutron flux, etc. The insulator may, after exposure to a high energy neutron source (e.g., a stellarator, etc.) for at least about 10, 50, 100, 500, 1,000, 5,000, 10,000, or more hours, not generate percolative conductive carbon chains within the insulator.

[0368] In some cases, the insulator can comprise a ceramic. The ceramic may be a solid ceramic. The ceramic may comprise an insulating ceramic material. Examples of ceramics include, but are not limited to, silicon oxides, aluminum oxides, titanium oxides, zirconium oxides, beryllium oxides, titanium oxides, magnesium oxides, barium titanium oxides, silicon carbide, silicon nitride, boron nitride, aluminum nitride, boron carbide, titanium borides, or the like, or any combination thereof. The ceramic may comprise a plurality of different materials configured as insulators. For example, a ceramic may comprise a plurality of different oxide materials chosen to tune the properties of the ceramic. The ceramic may be resilient to increased temperature used as a part of a baking or annealing operation on the HTS tape. For example, the ceramic may maintain structural and electrical properties even after being heated to elevated (e.g., greater than about 200 degrees Celsius) temperatures. The insulator may comprise at least about 40, 50, 60, 70, 80, 90, 95, 99, 99.9, or more percent ceramic.

[0369] The insulator may be formed using, for example, additive manufacturing techniques (e.g., three-dimensional printing, stereolithography, selective laser sintering, multi-jet fusion binder jetting, or the like), milling, sol gel deposition, or the like, or any combination thereof.

The sol gel deposition may comprise forming a sol gel comprising a precursor to the insulator, depositing the insulator onto, for example, an HTS tape stack (e.g. comprising at least about 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 30, 50, or more HTS tapes), and heating the deposited sol gel to dry the sol gel into the insulator. In this way, a conformal coating of insulator can be applied to the HTS tape stack in a facile manufacturing process.

[0370] The insulator may be an electrical insulator. For example, the insulator may be an electrical insulator at ambient temperatures, cryogenic temperatures, or a combination thereof. The insulator may be a thermal insulator. The insulator may not be a thermal insulator. For example, the insulator may be electrically insulating but not thermally insulating. The insulator may not be thermally insulating at cryogenic temperatures.

[0371] Though described herein with respect to HTS tape morphologies, the present disclosure can also be used for other HTS structures. For example, HTS wires, HTS cables, etc. can all be insulated using the insulations of the present disclosure. Additionally, the insulators of the present disclosure can be utilized with low temperature superconductors (LTS) or regular conductors. For example, an LTS tape can be insulated by the insulation of the present disclosure. Similarly, the insulation of the present disclosure can be used for other electrical components placed in high neutron flux areas. For example, the insulation can insulate electrical wires, sensors, capacitors, transistors, etc. that are used in high neutron flux applications.

Reel-to-Reel Superconducting Tape Deposition

[0372] Provided herein are systems, methods, and techniques for using independent bobbins for dispending each layer of superconducting tape to a stellarator coil. The systems, the methods, and the techniques disclosed herein may utilize the independent bobbins to lay down superconducting tapes simultaneously to form a cohesive stack upon the superconducting cable. Accordingly, the systems, the methods, and the techniques disclosed herein may also streamline the application of superconducting tapes in coil manufacturing.

Examples of Reel-to-Reel HTS Tape Deposition

[0373] In some cases, unrolling superconducting tapes (e.g., HTS tapes) onto a magnet, may present certain challenges with buckling or separating of the superconducting tape. For example, certain challenges arise when unrolling HTS tape onto a curved shape or shape with corners. Stellarators have complex shapes (e.g., as illustrated in **FIGs. 3-5)** with many curves, formed by stellarator coils (e.g., as illustrated in **FIGs. 1A-2)**.

[0374] At least in part due to the larger radius on an outside edge of a curved shape than an inside edge, layers of HTS tape on the inside of the curved shape may end up with a longer

length than layers of HTS tape on the outside of the curved shape. This divergence in length may increase with increasing size of the curved shape. Stellarators, which follow a curved shape, may use one or more kilometers of HTS tape, thereby resulting in a notable divergence in length of layers of the HTS tape.

[0375] In some cases, divergence in length of tape (e.g., due to variation in radii between the inside edge and outside edge of a curved magnet), may create strain on the HTS tape. HTS tape may be durable to a maximum of about 0.4% strain in tension. Although, in some cases, about 0%, about 0.1%, about 0.2%, or about 0.3% strain in tension may result in better performance. Further, HTS tape may be durable to a maximum of about 1% strain in compression. Although, in some cases, about 0%, about 0.1%, about 0.2%, about 0.3%, about 0.4%, about 0.5%, about 0.6%, about 0.7%, about 0.8%, or about 0.9% strain in compression may result in better performance.

[0376] The systems, the methods, and the techniques disclosed herein help reduce (e.g., substantially eliminate) the divergence in length of the layers of the superconducting tape and strain in the layers of the superconducting tape (e.g., as discussed above). The systems, the methods, and the techniques disclosed herein may provide for reel-to-reel manufacturing to deposit superconducting tapes in stacks to form superconducting cables. The systems, the methods, and the techniques disclosed herein may utilize independent bobbins for each of the layers of the superconducting tape. The systems, the methods, and the techniques disclosed herein may utilize the independent bobbins to lay down superconducting tapes simultaneously to form a cohesive stack upon the superconducting cable. Accordingly, the systems, the methods, and the techniques disclosed herein may also streamline the application of HTS tapes in coil manufacturing.

[0377] In some cases, to reduce (e.g., substantially eliminate) divergence in length of the layers of the HTS tape (e.g., due to variation in radii between the inside and outside edges of a curved magnet), the systems, the methods, and the techniques disclosed herein may use a plurality of independent bobbins. Each bobbin of the plurality of individual bobbins may include a layer of the HTS tape. Accordingly, when each of the layers of the HTS tape are applied to the substrate (e.g., a curved magnet), the layers of the HTS tape layer on one another to form a stack. By having each layer of the HTS tape on a bobbin of the plurality of individual bobbins, different amounts of each layer may be unrolled such that each layer lines up lengthwise with the other layers.

[0378] **FIG. 18** illustrates an example of two bobbins, each dispensing one layer of superconducting (e.g., HTS) tape onto a curved substrate. As illustrated, the upper most layer of

superconducting tape will have a slightly longer application path as it is applied atop the lower most layer of superconducting tape. Accordingly, by having two separate bobbins, different amounts of each of the two layers may be unrolled, ensuring a uniform length of the two layers.

[0379] In some cases, each of the layers of the HTS tape that layer to form the stack in the HTS tape may have a different strain durability. Advantageously, using the plurality of individual bobbins, each with a layer of the HTS tape, may enable applying different strains to each layer. For example, layers with higher durability to strain in tension may be loaded with higher strain in tension than layers with lower durability to strain in tension.

[0380] In some cases, each of the layers of the HTS tape that layer to form the stack in the HTS tape may have a different response to environmental conditions. Advantageously, using the plurality of individual bobbins, each with a layer of the HTS tape, may enable applying each layer according to different microenvironments. For example, layers with higher temperature durability may be applied to a microenvironment in a stellarator with higher temperatures (e.g., closer to a fusion event) than layers with lower temperature durability.

[0381] In some cases, using the plurality of individual bobbins, each with a layer of the HTS tape, may reduce strain on each of the layers. For example, as the layers of the HTS tape are unrolled, the layers may slide past (e.g., at least partially contacting) each other. In cases when the layers are unrolled from a single bobbin, the layers may pull and tug at each other, creating strain. This strain may increase when length of HTS tape deposition is increased (e.g., to kilometers in length, as used in a stellarator). This strain may also increase when the substrate is more curved or has more corners. By using the plurality of individual bobbins, each with a layer of the HTS tape, the systems, the methods, and the techniques disclosed herein may help reduce strain as the layers of the HTS tape are unrolled by reducing (e.g., substantially eliminating) layers pulling and tugging at each other. For example, pulling and tugging may be reduced by using the plurality of individual bobbins to create space between each of the layers during unrolling.

[0382] In some cases, as the layers of the HTS tape are unrolled onto the substrate from the plurality of individual bobbins, the layers of the HTS tape layer on top of one another to form a stack. This stack may form the HTS tape. In some cases, a flat stack configuration of layers may include a copper layer around one or more layers or the flat stack overall. In some cases, the copper layer may serve to improve the durability of the stack to strain. For example, the copper layer may be loaded to a higher strain (e.g., tension or compression). In some cases, the techniques for applying HTS tapes in coil manufacturing may have certain similarities to rope or cable-making techniques.

[0383] As described, in some cases, the systems, the methods, and the techniques disclosed herein may enable loading each layer on each individual bobbin with a different amount of strain. In some cases, the amount of strain for each layer may be controlled (e.g., by a digital or mechanical controller). In some cases, the controller may be a PID controller. The PID controller may control, based on feedback, a motor configured to dispense a layer of the HTS tape. The feedback may include one or more of: a strain of a layer, a tension of a layer, a compression of a layer, a rate of unrolling a layer, etc. In cases in which the feedback include a strain (e.g., tension or compression) of a layer, the strain may be measured by hardware. For example, the strain of the layer may be measured by a spring arm that creates a bend in the tape as the tape is unrolled. Based on the deflection of the bend, the strain of the layer of the HTS tape may be determined. In another example, a mechanical controller may be configured to (e.g., using one or more springs) maintain or adjust a strain in the layer of the HTS tape. Accordingly, using the plurality of individual bobbins, each with a layer of the HTS tape, may enable controlling strain in the layers of the HTS tape as the layers are deposited onto a substrate.

[0384] **FIG. 19** illustrates an example of a dispenser dispensing one layer of superconducting (e.g., HTS) tape onto a curved substrate. As illustrated, the dispenser includes a bobbin in addition to a motor and controller. As the layer of superconducting tape is dispensed from the dispenser, a deflector may be used to determine strain on the superconducting tape. The deflector may include a spring arm that may deflect the tape downward. The amount of deflection (illustrated as measured from the lower most point of deflection up to the dotted horizon line) may be used to determine the strain of the superconducting tape (e.g., where a smaller deflection distance indicate a greater strain than a larger deflection distance). In some cases, a different technique or device may be used to determine the strain of the superconducting tape.

[0385] As described, in some cases, the systems, the methods, and the techniques disclosed herein may include dispensing a plurality of layers from a plurality of bobbins. In one example, each bobbin of the plurality of bobbins may hold one roll of one layer of the plurality of layers. In another example, each bobbin of the plurality of bobbins may hold two or more layered rolls of layers of the plurality of layers.

Computer Systems

[0386] The present disclosure provides computer systems that are programmed to implement methods of the disclosure. FIG. 20 shows a computer system 2001 that is programmed or

otherwise configured to operate a bending apparatus according to the methods of the present disclosure. The computer system 2001 can regulate various aspects of the present disclosure, such as, for example, the operation of a bending apparatus. The computer system 2001 can be an electronic device of a user or a computer system that is remotely located with respect to the electronic device. The electronic device can be a mobile electronic device.

[0387] The computer system 2001 includes a central processing unit (CPU, also "processor" and "computer processor" herein) 2005, which can be a single core or multi core processor, or a plurality of processors for parallel processing. The computer system 2001 also includes memory or memory location 2010 (e.g., random-access memory, read-only memory, flash memory), electronic storage unit 2015 (e.g., hard disk), communication interface 2020 (e.g., network adapter) for communicating with one or more other systems, and peripheral devices 2025, such as cache, other memory, data storage and/or electronic display adapters. The memory 2010, storage unit 2015, interface 2020 and peripheral devices 2025 are in communication with the CPU 2005 through a communication bus (solid lines), such as a motherboard. The storage unit 2015 can be a data storage unit (or data repository) for storing data. The computer system 2001 can be operatively coupled to a computer network ("network") 2030 with the aid of the communication interface 2020. The network 2030 can be the Internet, an internet and/or extranet, or an intranet and/or extranet that is in communication with the Internet. The network 2030 in some cases is a telecommunication and/or data network. The network 2030 can include one or more computer servers, which can enable distributed computing, such as cloud computing. The network 2030, in some cases with the aid of the computer system 2001, can implement a peer-to-peer network, which may enable devices coupled to the computer system 2001 to behave as a client or a server.

[0388] The CPU 2005 can execute a sequence of machine-readable instructions, which can be embodied in a program or software. The instructions may be stored in a memory location, such as the memory 2010. The instructions can be directed to the CPU 2005, which can subsequently program or otherwise configure the CPU 2005 to implement methods of the present disclosure. Examples of operations performed by the CPU 2005 can include fetch, decode, execute, and writeback.

[0389] The CPU 2005 can be part of a circuit, such as an integrated circuit. One or more other components of the system 2001 can be included in the circuit. In some cases, the circuit is an application specific integrated circuit (ASIC).

[0390] The storage unit 2015 can store files, such as drivers, libraries and saved programs. The storage unit 2015 can store user data, e.g., user preferences and user programs. The computer

system 2001 in some cases can include one or more additional data storage units that are external to the computer system 2001, such as located on a remote server that is in communication with the computer system 2001 through an intranet or the Internet.

[0391] The computer system 2001 can communicate with one or more remote computer systems through the network 2030. For instance, the computer system 2001 can communicate with a remote computer system of a user. Examples of remote computer systems include personal computers (e.g., portable PC), slate or tablet PC's (e.g., Apple® iPad, Samsung® Galaxy Tab), telephones, Smart phones (e.g., Apple® iPhone, Android-enabled device, Blackberry®), or personal digital assistants. The user can access the computer system 2001 via the network 2030.

[0392] Methods as described herein can be implemented by way of machine (e.g., computer processor) executable code stored on an electronic storage location of the computer system 2001, such as, for example, on the memory 2010 or electronic storage unit 2015. The machine executable or machine readable code can be provided in the form of software. During use, the code can be executed by the processor 2005. In some cases, the code can be retrieved from the storage unit 2015 and stored on the memory 2010 for ready access by the processor 2005. In some situations, the electronic storage unit 2015 can be precluded, and machine-executable instructions are stored on memory 2010.

[0393] The code can be pre-compiled and configured for use with a machine having a processer adapted to execute the code, or can be compiled during runtime. The code can be supplied in a programming language that can be selected to enable the code to execute in a pre-compiled or as-compiled fashion.

[0394] Aspects of the systems and methods provided herein, such as the computer system 2001, can be embodied in programming. Various aspects of the technology may be thought of as "products" or "articles of manufacture" typically in the form of machine (or processor) executable code and/or associated data that is carried on or embodied in a type of machine readable medium. Machine-executable code can be stored on an electronic storage unit, such as memory (e.g., read-only memory, random-access memory, flash memory) or a hard disk. "Storage" type media can include any or all of the tangible memory of the computers, processors or the like, or associated modules thereof, such as various semiconductor memories, tape drives, disk drives and the like, which may provide non-transitory storage at any time for the software programming. All or portions of the software may at times be communicated through the Internet or various other telecommunication networks. Such communications, for example, may enable loading of the software from one computer or processor into another, for example, from a management server or host computer into the computer platform of an application server. Thus,

another type of media that may bear the software elements includes optical, electrical and electromagnetic waves, such as used across physical interfaces between local devices, through wired and optical landline networks and over various air-links. The physical elements that carry such waves, such as wired or wireless links, optical links or the like, also may be considered as media bearing the software. As used herein, unless restricted to non-transitory, tangible "storage" media, terms such as computer or machine "readable medium" refer to any medium that participates in providing instructions to a processor for execution.

[0395] Hence, a machine readable medium, such as computer-executable code, may take many forms, including but not limited to, a tangible storage medium, a carrier wave medium or physical transmission medium. Non-volatile storage media include, for example, optical or magnetic disks, such as any of the storage devices in any computer(s) or the like, such as may be used to implement the databases, etc. shown in the drawings. Volatile storage media include dynamic memory, such as main memory of such a computer platform. Tangible transmission media include coaxial cables; copper wire and fiber optics, including the wires that comprise a bus within a computer system. Carrier-wave transmission media may take the form of electric or electromagnetic signals, or acoustic or light waves such as those generated during radio frequency (RF) and infrared (IR) data communications. Common forms of computer-readable media therefore include for example: a floppy disk, a flexible disk, hard disk, magnetic tape, any other magnetic medium, a CD-ROM, DVD or DVD-ROM, any other optical medium, punch cards paper tape, any other physical storage medium with patterns of holes, a RAM, a ROM, a PROM and EPROM, a FLASH-EPROM, any other memory chip or cartridge, a carrier wave transporting data or instructions, cables or links transporting such a carrier wave, or any other medium from which a computer may read programming code and/or data. Many of these forms of computer readable media may be involved in carrying one or more sequences of one or more instructions to a processor for execution.

[0396] The computer system 2001 can include or be in communication with an electronic display 2035 that comprises a user interface (UI) 2040 for providing, for example, an interface for the programming an monitoring of a bending apparatus. Examples of UI's include, without limitation, a graphical user interface (GUI) and web-based user interface.

[0397] Methods and systems of the present disclosure can be implemented by way of one or more algorithms. An algorithm can be implemented by way of software upon execution by the central processing unit 2005. The algorithm can, for example, translate a computer model of a coil into operating instructions for a bending apparatus.

Certain Definitions and Additional Considerations

[0398] Unless otherwise defined, all technical terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs.

[0399] Whenever the term "at least," "greater than," or "greater than or equal to" precedes the first numerical value in a series of two or more numerical values, the term "at least," "greater than" or "greater than or equal to" applies to each of the numerical values in that series of numerical values. For example, greater than or equal to 1, 2, or 3 is equivalent to greater than or equal to 1, greater than or equal to 2, or greater than or equal to 3.

[0400] Whenever the term "no more than," "less than," or "less than or equal to" precedes the first numerical value in a series of two or more numerical values, the term "no more than," "less than," or "less than or equal to" applies to each of the numerical values in that series of numerical values. For example, less than or equal to 3, 2, or 1 is equivalent to less than or equal to 3, less than or equal to 2, or less than or equal to 1.

[0401] Certain inventive embodiments herein contemplate numerical ranges. When ranges are present, the ranges include the range endpoints. Additionally, every sub range and value within the range is present as if explicitly written out.

[0402] The term "about" or "approximately" may mean within an acceptable error range for the particular value, which will depend in part on how the value is measured or determined, e.g., the limitations of the measurement system. For example, "about" may mean within 1 or more than 1 standard deviation, per the practice in the art. Alternatively, "about" may mean a range of up to 20%, up to 10%, up to 5%, or up to 1% of a given value. Where particular values are described in the application and claims, unless otherwise stated the term "about" meaning within an acceptable error range for the particular value may be assumed.

[0403] As used herein, "or" is intended to mean an "inclusive or" or what is also known as a "logical OR," wherein when used as a logic statement, the expression "A or B" is true if either A or B is true, or if both A and B are true, and when used as a list of elements, the expression "A, B or C" is intended to include all combinations of the elements recited in the expression, for example, any of the elements selected from the group consisting of A, B, C, (A, B), (A, C), (B, C), and (A, B, C); and so on if additional elements are listed. As such, any reference to "or" herein is intended to encompass "and/or" unless otherwise stated.

[0404] It will be understood that when an element such as a layer, region, or substrate is referred to as being "on" or extending "onto" another element, it may be directly on or extend directly onto the other element or intervening elements may also be present. In contrast, when an

element is referred to as being "directly on" or extending "directly onto" another element, there are no intervening elements present. Likewise, it will be understood that when an element such as a layer, region, or substrate is referred to as being "over" or extending "over" another element, it may be directly over or extend directly over the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly over" or extending "directly over" another element, there are no intervening elements present. It will also be understood that when an element is referred to as being "connected" or "coupled" to another element, it may be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present.

[0405] Relative terms such as "below" or "above" or "upper" or "lower" or "horizontal" or "vertical" may be used herein to describe a relationship of one element, layer, or region to another element, layer, or region as illustrated in the Figures. It will be understood that these terms and those discussed above are intended to encompass different orientations of the device in addition to the orientation depicted in the Figures.

[0406] It will be understood that, although the terms "first," "second," "third," etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element may be termed a second element, and, similarly, a second element may be termed a first element, without departing from the scope of the present disclosure.

[0407] While preferred embodiments of the present invention have been shown and disclosed herein, it will be obvious to those skilled in the art that such embodiments are provided by way of example only. It is not intended that the invention be limited by the specific examples provided within the specification. While the invention has been described with reference to the aforementioned specification, the descriptions and illustrations of the embodiments herein are not meant to be construed in a limiting sense. Numerous variations, changes, and substitutions will now occur to those skilled in the art without departing from the invention. Furthermore, it shall be understood that all aspects of the invention are not limited to the specific depictions, configurations or relative proportions set forth herein which depend upon a variety of conditions and variables. It should be understood that various alternatives to the embodiments of the invention disclosed herein may be employed in practicing the invention. It is therefore contemplated that the invention shall also cover any such alternatives, modifications, variations, or equivalents. It is intended that the following claims define the scope of the invention and that

methods and structures within the scope of these claims and their equivalents be covered thereby.

[0408] It should be noted that various illustrative or suggested ranges set forth herein are specific to their example embodiments and are not intended to limit the scope or range of disclosed technologies, but, again, merely provide example ranges for frequency, amplitudes, etc. associated with their respective embodiments or use cases. Where values are described as ranges, it will be understood that such disclosure includes the disclosure of all possible sub-ranges within such ranges, as well as specific numerical values that fall within such ranges irrespective of whether a specific numerical value or specific sub-range is expressly stated.

[0409] It should be understood that, unless a term is expressly defined in this patent, there is no intent to limit the meaning of that term, either expressly or by implication, beyond its plain or ordinary meaning, and such term should not be interpreted to be limited in scope based at least in part on any statement made in any section of this patent (other than the language of the claims). To the extent that any term recited in the claims at the end of this patent is referred to in this patent in a manner consistent with a single meaning, that is done for sake of clarity only so as to not confuse the reader, and it is not intended that such claim term be limited, by implication or otherwise, to that single meaning.

[0410] Throughout this specification, plural instances may implement components, operations, or structures described as a single instance. Although individual operations of one or more methods are illustrated and described as separate operations, one or more of the individual operations may be performed concurrently, and nothing requires that the operations be performed in the order illustrated. Structures and functionality presented as separate components in example configurations may be implemented as a combined structure or component. Similarly, structures and functionality presented as a single component may be implemented as separate components. These and other variations, modifications, additions, and improvements fall within the scope of the subject matter herein.

[0411] Additionally, certain embodiments are disclosed herein as including logic or a number of routines, subroutines, applications, or instructions. These may constitute either software (e.g., code embodied on a machine-readable medium) or hardware. In hardware, the routines, etc., are tangible units capable of performing certain operations and may be configured or arranged in a certain manner. In example embodiments, one or more computer systems (e.g., a standalone, client or server computer system) or one or more hardware modules of a computer system (e.g., a processor or a group of processors) may be configured by software (e.g., an application or

application portion) as a hardware module that operates to perform certain operations as disclosed herein.

[0412] In various embodiments, a hardware module may be implemented mechanically or electronically. For example, a hardware module may comprise dedicated circuitry or logic that is permanently configured (e.g., as a special-purpose processor, such as a field programmable gate array (FPGA) or an application-specific integrated circuit (ASIC) to perform certain operations. A hardware module may also comprise programmable logic or circuitry (e.g., as encompassed within a general-purpose processor or other programmable processor) that is temporarily configured by software to perform certain operations. It will be appreciated that the decision to implement a hardware module mechanically, in dedicated and permanently configured circuitry, or in temporarily configured circuitry (e.g., configured by software) may be driven by cost and time considerations.

[0413] Accordingly, hardware modules may encompass a tangible entity, be that an entity that is physically constructed, permanently configured (e.g., hardwired), or temporarily configured (e.g., programmed) to operate in a certain manner or to perform certain operations disclosed herein. Considering embodiments in which hardware modules are temporarily configured (e.g., programmed), each of the hardware modules need not be configured or instantiated at any one instance in time. For example, where the hardware modules comprise a general-purpose processor configured using software, the general-purpose processor may be configured as respective different hardware modules at different times. Software may accordingly configure processor, for example, to constitute a particular hardware module at one instance of time and to constitute a different hardware module at a different instance of time.

[0414] Hardware modules may provide information to, and receive information from, other hardware modules. Accordingly, the described hardware modules may be regarded as being communicatively coupled. Where multiple of such hardware modules exist contemporaneously, communications may be achieved through signal transmission (e.g., over appropriate circuits and buses) that connect the hardware modules. In embodiments in which multiple hardware modules are configured or instantiated at different times, communications between such hardware modules may be achieved, for example, through the storage and retrieval of information in memory structures to which the multiple hardware modules have access. For example, one hardware module may perform an operation and store the output of that operation in a memory device to which it is communicatively coupled. A further hardware module may then, at a later time, access the memory device to retrieve and process the stored output. Hardware modules may also initiate communications with input or output devices, and may

operate on a resource (e.g., a collection of information). Elements that are described as being coupled and or connected may refer to two or more elements that may be (e.g., direct physical contact) or may not be (e.g., electrically connected, communicatively coupled, etc.) in direct contact with each other, but yet still cooperate or interact with each other.

[0415] The various operations of example methods disclosed herein may be performed, at least partially, by one or more processors that are temporarily configured (e.g., by software) or permanently configured to perform the relevant operations. Whether temporarily or permanently configured, such processors may constitute processor-implemented modules that operate to perform one or more operations or functions. The modules referred to herein may, in some example embodiments, comprise processor-implemented modules.

[0416] Similarly, the methods or routines disclosed herein may be at least partially processor-implemented. For example, at least some of the operations of a method may be performed by one or more processors or processor-implemented hardware modules. The performance of certain operations may be distributed among the one or more processors, not only residing within a single machine, but deployed across a number of machines. In some example embodiments, the processor or processors may be located in a single location (e.g., within a home environment, an office environment or as a server farm), while in other embodiments the processors may be distributed across a number of locations.

[0417] The performance of certain operations may be distributed among the one or more processors, not only residing within a single machine, but deployed across a number of machines. In some example embodiments, the one or more processors or processor-implemented modules may be located in a single geographic location (e.g., within a home environment, an office environment, or a server farm). In other example embodiments, the one or more processors or processor-implemented modules may be distributed across a number of geographic locations.

EMBODIMENTS

[0418] Embodiment 1. A method of forming a reinforced superconducting tape, comprising: (a) providing a reinforcement member and a superconducting tape; (b) pre-straining at least a portion of said reinforcement member or said superconducting tape; and (c) affixing said superconducting tape to said reinforcement member, thereby forming said reinforced superconducting tape.

[0419] Embodiment 2. The method of Embodiment 1, wherein said portion of said reinforcement member or said superconducting tape is pre-strained during (c).

[0420] Embodiment 3. The method of Embodiment 1, wherein (b) further comprises pre-straining at least a portion of said reinforcement member and said superconducting tape.

[0421] Embodiment 4. The method of Embodiment 1, wherein said pre-straining of (b) is at a temperature different from an operational temperature of said reinforced superconducting tape.

[0422] Embodiment 5. The method of Embodiment 4, wherein said temperature is greater than an operational temperature of said reinforced superconducting tape.

[0423] Embodiment 6. The method of Embodiment 5, wherein said operational temperature of said reinforced superconducting tape is less than or equal to about -100 degrees Celsius.

[0424] Embodiment 7. The method of Embodiment 3, further comprising pre-straining said at least said portion of said reinforcement member at a first temperature, and pre-straining said at least said portion of said superconducting tape at a second temperature.

[0425] Embodiment 8. The method of Embodiment 7, wherein said first temperature is different from said second temperature.

[0426] Embodiment 9. The method of Embodiment 7, wherein said first temperature and said second temperature are greater than an operational temperature of said reinforced superconducting tape.

[0427] Embodiment 10. The method of Embodiment 1, wherein said pre-straining in (b) comprises applying a tension to said at least said portion of said reinforcement member or said superconducting tape.

[0428] Embodiment 11. The method of Embodiment 10, wherein a strain value of said tension is between about 0.2% and about 1.0%.

[0429] Embodiment 12. The method of Embodiment 1, wherein said pre-straining in (b) comprises applying a compression to said at least said portion of said reinforcement member or said superconducting tape.

[0430] Embodiment 13. The method of Embodiment 12, wherein a strain value of said compression is between about 0.2% and about 1.0%.

[0431] Embodiment 14. The method of Embodiment 1, wherein affixing said superconducting tape to said reinforcement member in (c) comprises affixing said superconducting tape to said pre-strained reinforcement member in a reel-to-reel process.

[0432] Embodiment 15. The method of Embodiment 1, wherein affixing said superconducting tape to said reinforcement member in (c) comprises soldering said superconducting tape to said reinforcement member.

[0433] Embodiment 16. The method of Embodiment 1, wherein said reinforcement member comprises tungsten.

[0434] Embodiment 17. The method of Embodiment 1, wherein said reinforcement member comprises an alloy comprising potassium and tungsten.

[0435] Embodiment 18. The method of Embodiment 1, wherein said reinforcement member comprises rhenium.

[0436] Embodiment 19. The method of Embodiment 1, wherein said reinforcement member comprises tantalum.

[0437] Embodiment 20. The method of Embodiment 1, wherein said reinforced superconducting tape comprises a modulus at least about twice as high as steel.

[0438] Embodiment 21. The method of Embodiment 1, wherein said superconducting tape is configured to be operate under a maximum of about 0.4% strain in tension.

[0439] Embodiment 22. The method of Embodiment 1, wherein said reinforced superconducting tape is configured to be operate under a maximum of about 0.8% strain in tension.

[0440] Embodiment 23. The method of Embodiment 7, wherein one or both of said first temperature and said second temperature are greater than about 0 degrees Celsius.

[0441] Embodiment 24. The method of Embodiment 1, wherein said first temperature is the same as said second temperature.

[0442] Embodiment 25. The method of Embodiment 1, further comprising: (d) cooling said reinforced superconducting tape to a cryogenic temperature of less than about -100 degrees Celsius, wherein during said cooling of said reinforced superconducting tape, said reinforced superconducting tape undergoes less shrinkage when cooled to said cryogenic temperature than a superconducting tape that does not comprise said reinforcement member.

[0443] Embodiment 26. The method of Embodiment 1, wherein said reinforced superconducting tape is installed in a stellarator.

[0444] Embodiment 27. The method of Embodiment 26, wherein at least a portion of said stellarator is cooled to a temperature of less than about -100 degrees Celsius.

[0445] Embodiment 28. The method of Embodiment 1, wherein said superconducting tape is high-temperature superconducting (HTS) tape.

[0446] Embodiment 29. A method of forming a stellarator coil, the method comprising: (a) shaping a cable into a helical cable; and (b) compressing at least a portion of the helical cable about an axis parallel to a central axis of the helical cable to form the stellarator coil.

[0447] Embodiment 30. The method of Embodiment 29, wherein shaping the cable into the helical cable is performed by a free-form bender.

[0448] Embodiment 31. The method of Embodiment 30, wherein the free-form bender comprises a Computer Numerical Control (CNC) bender.

[0449] Embodiment 32. The method of Embodiment 29, wherein shaping the cable into the helical cable comprises twisting the cable along its length.

[0450] Embodiment 33. The method of Embodiment 29, wherein the helical cable has a tapered helical shape.

[0451] Embodiment 34. The method of Embodiment 29, wherein the helical cable has a constant pitch.

[0452] Embodiment 35. The method of Embodiment 29, wherein the helical cable has a variable pitch.

[0453] Embodiment 36. The method of Embodiment 29, wherein the helical cable has a constant coil angle.

[0454] Embodiment 37. The method of Embodiment 29, wherein the helical cable has a variable coil angle.

[0455] Embodiment 38. The method of Embodiment 29, wherein the helical cable and the stellarator coil have a clockwise chirality.

[0456] Embodiment 39. The method of Embodiment 29, wherein the helical cable and the stellarator coil have a counter-clockwise chirality.

[0457] Embodiment 40. The method of Embodiment 29, wherein the helical cable, the stellarator coil, or both have about 3 turns to about 100 turns.

[0458] Embodiment 41. The method of Embodiment 29, wherein the helical cable is compressed by hand.

[0459] Embodiment 42. The method of Embodiment 29, wherein the helical cable is compressed by machine.

[0460] Embodiment 43. The method of Embodiment 29, wherein compressing the helical cable comprises compressing a first portion of the helical cable and compressing a second portion of the helical cable.

[0461] Embodiment 44. The method of Embodiment 43, wherein compressing the helical cable further comprises re-compressing the first portion, the second portion, or both.

[0462] Embodiment 45. The method of Embodiment 43 or Embodiment 44, wherein the first portion comprises about 5% to about 95% of the length of the helical cable.

[0463] Embodiment 46. The method of Embodiment 43, further comprising: (a) extending at least the first portion of the helical cable; and (b) recompressing at least the first portion of the helical cable to form the stellarator coil.

[0464] Embodiment 47. The method of Embodiment 29, wherein a ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil is about 10:1 to about 10,000:1.

[0465] Embodiment 48. The method of Embodiment 29, wherein the stellarator coil is substantially flat.

[0466] Embodiment 49. The method of Embodiment 29, wherein the stellarator coil has a paraboloid shape.

[0467] Embodiment 50. The method of Embodiment 29, wherein the stellarator coil has a hyperbolic paraboloid shape.

[0468] Embodiment 51. The method of Embodiment 29, wherein the portion of the helical cable is compressed between a tool having a first face that is substantially flat and a second face parallel to the first face.

[0469] Embodiment 52. The method of Embodiment 29, wherein the portion of the helical cable is compressed between a tool having a parabolic first face and a second face offset from the first face.

[0470] Embodiment 53. The method of Embodiment 29, wherein the portion of the helical cable is compressed between a tool having a hyperbolic parabolic first face and a second face offset from the first face.

[0471] Embodiment 54. The method of Embodiment 29, wherein a ratio between a distance between consecutive turns of the stellarator coil and the thickness of the cable is about 0.01:1 and about 0.9:1.

[0472] Embodiment 55. The method of Embodiment 29, further comprising heat treating the stellarator coil.

[0473] Embodiment 56. The method of Embodiment 29, further comprising weakening a hinge section of the cable before step (a) or step (b).

[0474] Embodiment 57. The method of Embodiment 56, wherein weakening comprises annealing, cutting, fatiguing, or any combination thereof.

[0475] Embodiment 58. A stellarator coil formed by a method of: (a) shaping a cable into a helical cable; and (b) compressing at least a portion of the helical cable about an axis parallel to a central axis of the helical cable to form the stellarator coil.

[0476] Embodiment 59. The stellarator coil of Embodiment 58, wherein shaping the cable into the helical cable is performed by a free-form bender.

[0477] Embodiment 60. The stellarator coil of Embodiment 59, wherein the free-form bender comprises a Computer Numerical Control (CNC) bender.

[0478] Embodiment 61. The stellarator coil of Embodiment 58, wherein shaping the cable into the helical cable comprises twisting the cable along its length.

[0479] Embodiment 62. The stellarator coil of Embodiment 58, wherein the helical cable has a tapered helical shape.

[0480] Embodiment 63. The stellarator coil of Embodiment 58, wherein the helical cable has a constant pitch.

[0481] Embodiment 64. The stellarator coil of Embodiment 58, wherein the helical cable has a variable pitch.

[0482] Embodiment 65. The stellarator coil of Embodiment 58, wherein the helical cable has a constant coil angle.

[0483] Embodiment 66. The stellarator coil of Embodiment 58, wherein the helical cable has a variable coil angle.

[0484] Embodiment 67. The stellarator coil of Embodiment 58, wherein the helical cable and the stellarator coil have a clockwise chirality.

[0485] Embodiment 68. The stellarator coil of Embodiment 58, wherein the helical cable and the stellarator coil have a counter-clockwise chirality.

[0486] Embodiment 69. The stellarator coil of Embodiment 58, wherein the helical cable, the stellarator coil, or both has about 3 turns to about 100 turns.

[0487] Embodiment 70. The stellarator coil of Embodiment 58, wherein the helical cable is compressed by hand.

[0488] Embodiment 71. The stellarator coil of Embodiment 58, wherein the helical cable is compressed by machine.

[0489] Embodiment 72. The stellarator coil of Embodiment 58, wherein compressing the helical cable comprises compressing a first portion of the helical cable and compressing a second portion of the helical cable.

[0490] Embodiment 73. The stellarator coil of Embodiment 72, wherein compressing the helical cable further comprises re-compressing the first portion, the second portion, or both.

[0491] Embodiment 74. The stellarator coil of Embodiment 72 or Embodiment 73, wherein the first portion comprises about 5% to about 95% of the length of the helical cable.

[0492] Embodiment 75. The stellarator coil of Embodiment 72, further formed by: (a) extending at least the first portion of the helical cable; and (b) recompressing at least the first portion of the helical cable to form the stellarator coil.

[0493] Embodiment 76. The stellarator coil of Embodiment 58, wherein a ratio between the diameter of the cable and an average gap between successive turns of the cable in the stellarator coil is about 10:1 to about 10,000:1.

[0494] Embodiment 77. The stellarator coil of Embodiment 58, wherein the stellarator coil is substantially flat.

[0495] Embodiment 78. The stellarator coil of Embodiment 58, wherein the stellarator coil has a paraboloid shape.

[0496] Embodiment 79. The stellarator coil of Embodiment 58, wherein the stellarator coil has a hyperbolic paraboloid shape.

[0497] Embodiment 80. The stellarator coil of Embodiment 58, wherein the portion of the helical cable is compressed between a tool having a first face that is substantially flat and a second face parallel to the first face.

[0498] Embodiment 81. The stellarator coil of Embodiment 58, wherein the portion of the helical cable is compressed between a tool having a parabolic first face and a second face offset from the first face.

[0499] Embodiment 82. The stellarator coil of Embodiment 58, wherein the portion of the helical cable is compressed between a tool having a hyperbolic parabolic first face and a second face offset from the first face.

[0500] Embodiment 83. The stellarator coil of Embodiment 58, wherein a ratio between a distance between consecutive turns of the stellarator coil and the thickness of the cable is about 0.01:1 and about 0.9:1.

[0501] Embodiment 84. The stellarator coil of Embodiment 58, further formed by heat treating the stellarator coil.

[0502] Embodiment 85. The stellarator coil of Embodiment 58, further formed by weakening a hinge section of the cable before step (a) or step (b).

[0503] Embodiment 86. The stellarator coil of Embodiment 57, wherein weakening comprises annealing, cutting, fatiguing, or any combination thereof.

[0504] Embodiment 87. A method of bending a coil, comprising: (a) providing a cable comprising a cable core and a cable jacket to a bending apparatus, wherein said cable jacket comprises a cable jacket segment, wherein said bending apparatus has a maximum working length, and a length of said cable core is longer than said maximum working length, and a length of said cable jacket segment is shorter than said maximum working length; (b) using a feeder portion of said bending apparatus, moving said cable jacket segment and said cable core through a bending head of said bending apparatus, thereby bending said cable jacket and said cable core

into a portion of said coil; (c) providing an additional cable jacket segment around said cable core, wherein said additional cable jacket segment has a length shorter than said maximum working length; and (d) using said feeder portion of said bending apparatus, moving said cable jacket and said cable core through said bending head of said bending apparatus to bend said cable jacket and said cable core into an additional portion of said coil.

[0505] Embodiment 88. The method of Embodiment 87, further comprising, prior to (d), (i) coupling said additional cable jacket segment to said cable jacket or said cable core.

[0506] Embodiment 89. The method of Embodiment 88, wherein (i) comprises coupling said additional cable jacket segment to said cable jacket and said cable core.

[0507] Embodiment 90. The method of Embodiment 88, wherein said coupling of (i) comprises one or more of ultrasonic soldering, fusing, heat-based soldering, press fitting, or any combination thereof.

[0508] Embodiment 91. The method of Embodiment 88, wherein said moving of (b) or (d) comprises pushing using said feeder portion.

[0509] Embodiment 92. The method of Embodiment 88, further comprising repeating (c) – (d) one or more times.

[0510] Embodiment 93. The method of Embodiment 88, wherein said bending apparatus is a computer numerical control (CNC) bending apparatus.

[0511] Embodiment 94. The method of Embodiment 88, wherein said feeder portion pushes either said cable jacket segment or said additional cable jacket segment with at least a mandrel configured to fit over said cable core.

[0512] Embodiment 95. The method of Embodiment 94, wherein said mandrel is a clamping mandrel.

[0513] Embodiment 96. The method of Embodiment 95, wherein said clamping mandrel is a c-shaped mandrel.

[0514] Embodiment 97. The method of Embodiment 95, wherein said clamping mandrel is configured to clamp onto said cable jacket segment or said additional cable jacket segment.

[0515] Embodiment 98. The method of Embodiment 95, wherein said clamping mandrel is configured to clamp behind said cable jacket segment or said additional cable jacket segment.

[0516] Embodiment 99. The method of Embodiment 94, wherein said bending apparatus exerts a force on said mandrel, and wherein said mandrel transmits said force primarily to said cable jacket.

[0517] Embodiment 100. The method of Embodiment 94, wherein said mandrel has a thickness of at least about a thickness of said cable jacket segment or said additional cable jacket segment.

[0518] Embodiment 101. The method of Embodiment 100, wherein said thickness of said mandrel is measured at a contact point between said mandrel and said cable jacket segment or said additional cable jacket segment.

[0519] Embodiment 102. The method of Embodiment 94, wherein said mandrel is configured to engage via at least friction with said cable jacket segment or said additional cable jacket segment.

[0520] Embodiment 103. The method of Embodiment 102, further comprising one or more grooves on said cable jacket segment or said additional cable jacket segment configured to engage with said mandrel via friction between a member of said mandrel and said one or more grooves.

[0521] Embodiment 104. The method of Embodiment 94, wherein said cable jacket segment or said additional cable jacket segment is cut perpendicular to the axis of the cable core.

[0522] Embodiment 105. The method of Embodiment 94, wherein said mandrel comprises one or more teeth configured to engage with said cable jacket segment or said additional cable jacket segment.

[0523] Embodiment 106. The method of Embodiment 94, wherein said mandrel is a steel mandrel.

[0524] Embodiment 107. The method of Embodiment 88, wherein said cable jacket comprises copper.

[0525] Embodiment 108. The method of Embodiment 88, wherein said cable jacket comprises titanium.

[0526] Embodiment 109. The method of Embodiment 88, wherein said cable jacket comprises steel.

[0527] Embodiment 110. The method of Embodiment 88, wherein said cable core comprises one or more high temperature superconducting (HTS) tapes.

[0528] Embodiment 111. The method of Embodiment 88, wherein said cable core comprises one or more HTS stacks.

[0529] Embodiment 112. The method of Embodiment 88, wherein said cable core has a length of at least about 6 meters (m).

[0530] Embodiment 113. The method of Embodiment 88, wherein said maximum working length of said bending apparatus is about 4 m.

[0531] Embodiment 114. The method of Embodiment 88, wherein a diameter of said cable core is at least about 19 millimeters (mm).

[0532] Embodiment 115. The method of Embodiment 114, wherein a diameter of said cable core is at most about 50 mm.

[0533] Embodiment 116. The method of Embodiment 88, wherein a thickness of said cable jacket segment or said additional cable jacket segment is at least about 1.5 mm.

[0534] Embodiment 117. The method of Embodiment 116, wherein a thickness of said cable jacket segment or said additional cable jacket segment is at most about 5 mm.

[0535] Embodiment 118. A cable comprising a cable core and a cable jacket, wherein said cable jacket is formed of at least two pieces, wherein said cable core is a single cable core disposed in said at least two pieces, and wherein said cable is non-planar.

[0536] Embodiment 119. The cable of Embodiment 118, wherein said at least two pieces of said cable jacket are fused together.

[0537] Embodiment 120. The cable of Embodiment 119, wherein said at least two pieces of said cable jacket are soldered together or welded together.

[0538] Embodiment 121. The cable of Embodiment 118, wherein said cable core is a conductor on a round core (CORC) cable.

[0539] Embodiment 122. The cable of Embodiment 118, wherein said cable core comprises one or more high temperature superconducting tapes.

[0540] Embodiment 123. The cable of Embodiment 118, wherein said cable core comprise an insulated, partially transposed, extruded, and roll-formed (VIPER) cable.

[0541] Embodiment 124. The cable of Embodiment 118, wherein said cable jacket comprises copper.

[0542] Embodiment 125. The cable of Embodiment 118, wherein an interface between said at least two cable pieces comprises a flat interface.

[0543] Embodiment 126. The cable of Embodiment 118, wherein said cable jacket comprises grooves.

[0544] Embodiment 127. The cable of Embodiment 118, wherein said cable is bent into at least a portion of a stellarator coil.

[0545] Embodiment 128. The cable of Embodiment 118, wherein said cable is a non-planar spiral.

[0546] Embodiment 129. A cable comprising a cable core and a cable jacket, wherein said cable jacket is formed of at least two pieces, wherein said cable core is a single cable core disposed in said at least two pieces, and wherein said cable core comprises a high temperature superconductor tape.

[0547] Embodiment 130. A cable comprising a cable core and a cable jacket, wherein said cable jacket is formed of at least two pieces, wherein said cable core is a single cable core disposed in said at least two pieces, and wherein said cable jacket comprises copper or stainless steel.

[0548] Embodiment 131. A system for stabilizing high temperature superconducting (HTS) tapes in a superconducting coil, comprising: a thermally and electrically conductive spine; a plurality of thermally and electrically conductive struts, wherein a first strut and a second strut of the plurality of struts are positioned with (i) a distance between said first and second struts, and (ii) an angle of rotation perpendicular to said spine, wherein said distance between said first and second struts and said angle of rotation perpendicular to said spine are based at least in part on a final bend radius of said coil; and at least one HTS tape mechanically supported by said first strut and said second strut.

[0549] Embodiment 132. The system of Embodiment 131, wherein said first strut and said second strut of said plurality of thermally and electrically conductive struts each comprise one or more apertures for one or more cooling channels.

[0550] Embodiment 133. The system of Embodiment 131, wherein said one or more cooling channels run parallel to said spine and through said first and said second struts.

[0551] Embodiment 134. The system of Embodiment 131, wherein said angle of rotation of said strut with respect to said spine is configured to change as an external bend radius of said coil changes.

[0552] Embodiment 135. The system of Embodiment 131, wherein a distance between said first strut and said second strut is configured to change as an external bend radius of said coil changes.

[0553] Embodiment 136. A method of forming a high temperature superconducting (HTS) coil, comprising: (a) providing one or more HTS tapes along a spine of said HTS coil, wherein at least one HTS tape of said one or more HTS tapes is supported by a first strut and a second strut; (b) coupling said HTS tape to said first strut and said second strut while said HTS coil is in a first configuration; and (c) bending said HTS coil into a second configuration, which results in a change in one or both of (i) the distance between said first strut and said second strut, and (ii) a rotation angle around said spine of said first strut and/or said second strut, wherein said second configuration is different from said first configuration.

[0554] Embodiment 137. The method of Embodiment 137, wherein said change in one or both of (i) the distance between said first strut and said second strut, and (ii) a rotation angle around said spine of said first strut and/or said second strut minimizes a strain on said HTS tape.

[0555] Embodiment 138. The method of Embodiment 137, wherein one or both of said first strut and said second strut are configured to rotate around said spine of said HTS coil.

[0556] Embodiment 139. The method of Embodiment 137, wherein said HTS tape is configured to translate relative to said first strut and/or said second strut.

[0557] Embodiment 140. The method of Embodiment 137, wherein during (c) a bend radius of said HTS tape within said coil is either increased or decreased.

[0558] Embodiment 141. A magnetic coil, comprising: a high-temperature superconducting (HTS) tape; and an insulator disposed around said HTS tape, wherein said insulator is resilient to neutron bombardment damage.

[0559] Embodiment 142. The magnetic coil of Embodiment 141, wherein said insulator has an improved resilience to neutron bombardment as compared to a polymeric insulation.

[0560] Embodiment 143. The magnetic coil of Embodiment 141, wherein said insulator comprises one or more channels configured to form said HTS tape into said magnetic coil.

[0561] Embodiment 144. The magnetic coil of Embodiment 141, wherein said ceramic is at least about 80% of said insulator.

[0562] Embodiment 145. The magnetic coil of Embodiment 144, wherein said ceramic is at least about 99% of said insulator.

[0563] Embodiment 146. The magnetic coil of Embodiment 141, wherein said insulator is an electrical insulator.

[0564] Embodiment 147. The magnetic coil of Embodiment 141, wherein said insulator is a thermal insulator.

[0565] Embodiment 148. The magnetic coil of Embodiment 141, wherein said HTS tape is coiled, and wherein said insulator supports said HTS tape.

[0566] Embodiment 149. The magnetic coil of Embodiment 141, wherein said insulator comprises one or more of an oxide, a carbide, a nitride, or any combination thereof.

[0567] Embodiment 150. The magnetic coil of Embodiment 149, wherein said insulator is aluminum oxide or titanium oxide.

[0568] Embodiment 151. The magnetic coil of Embodiment 141, wherein said HTS tape is a portion of a stellarator.

[0569] Embodiment 152. The magnetic coil of Embodiment 141, further comprising generating a magnetic coil using said insulated HTS tape.

[0570] Embodiment 153. The magnetic coil of Embodiment 141, wherein said HTS tape is an HTS tape stack.

[0571] Embodiment 154. The magnetic coil of Embodiment 153, wherein said HTS tape stack comprises at least about 3 HTS tapes.

[0572] Embodiment 155. The magnetic coil of Embodiment 141, wherein said insulator comprises a tube comprising a wall defining an interior portion of said tube and an insulator comprising a ceramic disposed between said HTS tape and said wall of said tube.

[0573] Embodiment 156. The magnetic coil of Embodiment 141, wherein said insulator is configured to, after exposure to a high energy neutron source for 1,000 hours, not generate percolative conductive carbon chains within said insulator.

[0574] Embodiment 157. A magnetic coil, comprising: a high-temperature superconducting (HTS) tape; and an insulator disposed around said HTS tape, wherein said insulator comprises a ceramic.

[0575] Embodiment 158. The magnetic coil of Embodiment 157, wherein said insulator comprises one or more channels configured to form said HTS tape into said magnetic coil.

[0576] Embodiment 159. The magnetic coil of Embodiment 157, wherein said ceramic is at least about 80% of said insulator.

[0577] Embodiment 160. The magnetic coil of Embodiment 159, wherein said ceramic is at least about 99% of said insulator.

[0578] Embodiment 161. The magnetic coil of Embodiment 157, wherein said insulator is an electrical insulator.

[0579] Embodiment 162. The magnetic coil of Embodiment 157, wherein said insulator is a thermal insulator.

[0580] Embodiment 163. The magnetic coil of Embodiment 157, wherein said HTS tape is coiled, and wherein said insulator supports said HTS tape.

[0581] Embodiment 164. The magnetic coil of Embodiment 157, wherein said insulator comprises one or more of an oxide, a carbide, a nitride, or any combination thereof.

[0582] Embodiment 165. The magnetic coil of Embodiment 164, wherein said insulator is aluminum oxide or titanium oxide.

[0583] Embodiment 166. The magnetic coil of Embodiment 157, wherein said HTS tape is a portion of a stellarator.

[0584] Embodiment 167. The magnetic coil of Embodiment 157, further comprising generating a magnetic coil using said insulated HTS tape.

[0585] Embodiment 168. The magnetic coil of Embodiment 157, wherein said HTS tape is an HTS tape stack.

[0586] Embodiment 169. The magnetic coil of Embodiment 168, wherein said HTS tape stack comprises at least about 3 HTS tapes.

[0587] Embodiment 170. The magnetic coil of Embodiment 157, wherein said insulator comprises a tube comprising a wall defining an interior portion of said tube and an insulator comprising a ceramic disposed between said HTS tape and said wall of said tube.

[0588] Embodiment 171. The magnetic coil of Embodiment 157, wherein said insulator is configured to, after exposure to a high energy neutron source for 1,000 hours, not generate percolative conductive carbon chains within said insulator.

[0589] Embodiment 172. A stellarator, comprising: a ceramic insulator comprising a high-temperature superconducting (HTS) tape disposed therein.

[0590] Embodiment 173. The stellarator of Embodiment 172, wherein said insulator comprises one or more channels configured to form said HTS tape into said magnetic coil.

[0591] Embodiment 174. The stellarator of Embodiment 172, wherein said ceramic is at least about 80% of said insulator.

[0592] Embodiment 175. The stellarator of Embodiment 174, wherein said ceramic is at least about 99% of said insulator.

[0593] Embodiment 176. The stellarator of Embodiment 172, wherein said insulator is an electrical insulator.

[0594] Embodiment 177. The stellarator of Embodiment 172, wherein said insulator is a thermal insulator.

[0595] Embodiment 178. The stellarator of Embodiment 172, wherein said HTS tape is coiled, and wherein said insulator supports said HTS tape.

[0596] Embodiment 179. The stellarator of Embodiment 172, wherein said insulator comprises one or more of an oxide, a carbide, a nitride, or any combination thereof.

[0597] Embodiment 180. The stellarator of Embodiment 179, wherein said insulator is aluminum oxide or titanium oxide.

[0598] Embodiment 181. The stellarator of Embodiment 172, wherein said HTS tape is a portion of a stellarator.

[0599] Embodiment 182. The stellarator of Embodiment 172, further comprising generating a magnetic coil using said insulated HTS tape.

[0600] Embodiment 183. The stellarator of Embodiment 172, wherein said HTS tape is an HTS tape stack.

[0601] Embodiment 184. The stellarator of Embodiment 183, wherein said HTS tape stack comprises at least about 3 HTS tapes.

[0602] Embodiment 185. The stellarator of Embodiment 172, wherein said insulator comprises a tube comprising a wall defining an interior portion of said tube and an insulator comprising a ceramic disposed between said HTS tape and said wall of said tube.

[0603] Embodiment 186. The stellarator of Embodiment 172, wherein said insulator is configured to, after exposure to a high energy neutron source for 1,000 hours, not generate percolative conductive carbon chains within said insulator.

[0604] Embodiment 187. A method, comprising: (a) providing a high-temperature superconducting (HTS) tape; and (b) disposing said HTS tape in an insulator, wherein said insulator is a ceramic insulator.

[0605] Embodiment 188. The method of Embodiment 187, wherein, prior to (b), said insulator is formed using additive manufacturing, milling, or a combination thereof.

[0606] Embodiment 189. The method of Embodiment 187, wherein said disposing comprises use of powder coating, sol gel deposition, or a combination thereof.

[0607] Embodiment 190. The method of Embodiment 187, wherein said insulator comprises a tube disposed around said HTS tape, wherein said tube is filled with ceramic insulation.

[0608] Embodiment 191. The method of Embodiment 187, further comprising baking said HTS tape and said insulator.

[0609] Embodiment 192. The method of Embodiment 187, wherein said HTS tape is a part of an HTS cable.

[0610] Embodiment 193. The method of Embodiment 187, wherein said insulator comprises one or more channels configured to form said HTS tape into said magnetic coil.

[0611] Embodiment 194. The method of Embodiment 187, wherein said ceramic is at least about 80% of said insulator.

[0612] Embodiment 195. The method of Embodiment 194, wherein said ceramic is at least about 99% of said insulator.

[0613] Embodiment 196. The method of Embodiment 187, wherein said insulator is an electrical insulator.

[0614] Embodiment 197. The method of Embodiment 187, wherein said insulator is a thermal insulator.

[0615] Embodiment 198. The method of Embodiment 187, wherein said HTS tape is coiled, and wherein said insulator supports said HTS tape.

[0616] Embodiment 199. The method of Embodiment 187, wherein said insulator comprises one or more of an oxide, a carbide, a nitride, or any combination thereof.

[0617] Embodiment 200. The method of Embodiment 199, wherein said insulator is aluminum oxide or titanium oxide.

[0618] Embodiment 201.The method of Embodiment 187, wherein said HTS tape is a portion of a stellarator.

[0619] Embodiment 202. The method of Embodiment 187, further comprising generating a magnetic coil using said insulated HTS tape.

[0620] Embodiment 203. The method of Embodiment 187, wherein said HTS tape is an HTS tape stack.

[0621] Embodiment 204. The method of Embodiment 203, wherein said HTS tape stack comprises at least about 3 HTS tapes.

[0622] Embodiment 205. The method of Embodiment 187, wherein said insulator comprises a tube comprising a wall defining an interior portion of said tube and an insulator comprising a ceramic disposed between said HTS tape and said wall of said tube.

[0623] Embodiment 206. The method of Embodiment 187, wherein said insulator is configured to, after exposure to a high energy neutron source for 1,000 hours, not generate percolative conductive carbon chains within said insulator.

[0624] Embodiment 207. A method of fabricating at least a portion of a superconducting tape stack for a stellarator coil, comprising: (a) applying, a first layer of said superconducting tape stack on a substrate; and (b) applying, a second layer of said superconducting tape stack on said first layer of said superconducting tape stack, thereby forming said at least said portion of said superconducting tape stack.

[0625] Embodiment 208. The method of Embodiment 207, wherein said first layer or said second layer of said superconducting tape stack is a superconducting tape.

[0626] Embodiment 209. The method of Embodiment 208, wherein said superconducting tape is a high-temperature superconductor (HTS) tape.

[0627] Embodiment 210. The method of Embodiment 207, wherein said first layer is applied to a curved surface of said substrate.

[0628] Embodiment 211. The method of Embodiment 207, wherein applying said first layer in (a) comprises determining, using a first dispensing device, a strain of said first layer.

[0629] Embodiment 212. The method of Embodiment 211, further comprising determining said strain of said first layer while applying said first layer to said substrate.

[0630] Embodiment 213. The method of Embodiment 211, further comprising adjusting, using a first dispensing device, said strain of said first layer while applying said first layer to said substrate.

[0631] Embodiment 214. The method of Embodiment 207, wherein applying said second layer in (b) comprises determining, using a second dispensing device, a strain of said second layer.

[0632] Embodiment 215. The method of Embodiment 214, wherein determining said strain of said second layer occurs during said application of said second layer in (b).

[0633] Embodiment 216. The method of Embodiment 215, further comprising adjusting, using a first dispensing device, said strain of said second layer while applying said second layer to said first layer.

[0634] Embodiment 217. The method of Embodiment 211, further comprising adjusting said strain of said first layer based at least in part on a comparison of said strain of said first layer against a strain threshold.

[0635] Embodiment 218. The method of Embodiment 217, wherein said strain threshold is one or both of a tension strain of about 0.4% or a compression strain of about 1%.

[0636] Embodiment 219. The method of Embodiment 211, wherein said first dispensing device comprises: (i) a bobbin configured to hold said first layer, (ii) a deflector configured to deflect at least a portion of said first layer during applying in (a), (iii) a motor configured to rotate said bobbin, and (iv) a PID controller configured to obtain a determination of said strain of said first layer and provide a command signal to said motor to adjust said strain of said first layer.

[0637] Embodiment 220. The method of Embodiment 214, wherein said second dispensing device comprises: (i) a bobbin configured to hold said second layer, (ii) a deflector configured to deflect at least a portion of said second layer during applying in (b), (iii) a motor configured to rotate said bobbin, and (iv) a PID controller configured to obtain a determination of said strain of said second layer and provide a command signal to said motor to adjust said strain of said second layer.

[0638] Embodiment 221. The method of Embodiment 207, wherein, at least after applying said second layer in (b): (i) a dispensed amount of said first layer is different than a dispensed amount of said second layer, and (ii) a first end of said first layer substantially aligns with a first end of said second layer; and (iii) a second end of said first layer substantially aligns with a second end of said second layer.

[0639] Embodiment 222. The method of Embodiment 207, wherein said substrate comprises a magnetic material.

[0640] Embodiment 223. The method of Embodiment 207, wherein said substrate comprises a corner.

[0641] Embodiment 224. The method of Embodiment 207, further comprising, at least after said applying in (b): (c) applying, using a third dispensing device that is different from a first

dispensing device and a second dispensing device, a reinforcement layer to one or both of said first layer of said superconducting tape or said second layer of said superconducting tape, thereby reinforcing said stack corresponding to said superconducting tape.

[0642] Embodiment 225. The method of Embodiment 224, wherein said reinforcement layer comprises copper.

[0643] Embodiment 226. The method of Embodiment 207, wherein an applied strain of said first layer of said superconducting tape at least after said applying in (a) is different than an applied strain of said second layer of said superconducting tape at least after said applying in (b).

[0644] Embodiment 227. The method of Embodiment 226, wherein one or both of said applied strain of said first layer of said superconducting tape or said applied strain of said second layer of said superconducting tape comprises tension strain.

[0645] Embodiment 228. The method of Embodiment 226, wherein one or both of said applied strain of said first layer of said superconducting tape or said applied strain of said second layer of said superconducting tape comprises compression strain.

[0646] Embodiment 229. The method of any one of Embodiments 235-228, wherein said applied strain of said first layer of said superconducting tape is greater than said applied strain of said second layer of said superconducting tape.

[0647] Embodiment 230. The method of Embodiment 207, wherein said first layer of said superconducting tape comprises a first material and said second layer of said superconducting tape comprises a second material, and wherein said first material has a greater durability to strain than said second material.

[0648] Embodiment 231. The method of Embodiment 207, wherein an environmental temperature of said first layer of said superconducting tape at least after said applying in (a) is different than an environmental temperature of said second layer of said superconducting tape at least after said applying in (b).

[0649] Embodiment 232. The method of Embodiment 231, wherein said environmental temperature of said first layer of said superconducting tape is greater than said environmental temperature of said second layer of said superconducting tape.

[0650] Embodiment 233. The method of Embodiment 207, wherein said first layer of said superconducting tape comprises a first material and said second layer of said superconducting tape comprises a second material, and wherein said first material has a greater durability to high temperature than said second material.

[0651] Embodiment 234. The method of Embodiment 207, wherein (a) is performed using a first dispensing device.

[0652] Embodiment 235. The method of Embodiment 207, wherein (b) is performed using a second dispensing device.

[0653] Embodiment 236. A system for fabricating at least a portion of a superconducting tape stack for a stellarator coil, comprising: (i) a first dispensing device configured to apply a first layer of said superconducting tape stack on a substrate; and (ii) a second dispensing device, wherein said second dispensing device is configured to apply a second layer of said superconducting tape stack on said first layer of said superconducting tape, thereby forming said at least said portion of said superconducting tape stack.

[0654] Embodiment 237. The system of Embodiment 236, wherein a first dispensing device is further configured to: (a) determine a strain of said first layer of said superconducting tape while applying said first layer of said superconducting tape; and (b) adjust said strain of said first layer of said superconducting tape while applying said first layer of said superconducting tape.

[0655] Embodiment 238. The system of Embodiment 237, wherein a first dispensing device is configured to adjust said strain of said first layer of said superconducting tape at based at least in part on determining said strain of said first layer of said superconducting tape satisfies a threshold.

[0656] Embodiment 239. The system of Embodiment 238, wherein said threshold is one or both of a tension strain of about 0.4% or a compression strain of about 1%.

[0657] Embodiment 240. The system of any one of Embodiments 236-239, wherein a first dispensing device is configured to one or both of determine said strain of said first layer of said superconducting and adjust said strain of said first layer of said superconducting tape at using a PID controller.

[0658] Embodiment 241. The system of Embodiment 240, wherein a first dispensing device comprises:

[0659] (i) a bobbin configured to hold said layer of said superconducting tape, (ii) a deflector configured to deflect at least part of said first layer of said superconducting tape during applying said first layer of said superconducting tape, (iii) a motor configured to rotate said bobbin, and (iv) said PID controller configured to obtain a determination of said strain of said first layer of said superconducting tape and provide a command signal to said motor to adjust said strain of said first layer of said superconducting tape.

[0660] Embodiment 242. The system of Embodiment 241, wherein a second dispensing device comprises components that are substantially the same as each of the components of a first dispensing device.

[0661] Embodiment 243. The system of any one of Embodiments 236-242, wherein one or both of said first dispenser or said second dispenser is configured such that: (i) a dispensed amount of said first layer of said superconducting tape is different than a dispensed amount of said second layer of said superconducting tape, and (ii) both a first end of said first layer of said superconducting tape substantially aligns with a first end of said second layer of said superconducting tape and a second end of said first layer of said superconducting tape substantially aligns with a second end of said second layer of said superconducting tape.

[0662] Embodiment 244. The system of any one of Embodiments 236-243, wherein said superconducting tape is high temperature superconducting (HTS) tape.

[0663] Embodiment 245. The system of any one of Embodiments 236-244, wherein said curved substrate comprises a magnetic material.

[0664] Embodiment 246. The system of any one of Embodiments 236-245, wherein said curved substrate comprises a corner.

[0665] Embodiment 247. The system of any one of Embodiments 236-246, further comprising: (iii) a third dispenser that is different from a first dispensing device and a second dispensing device, wherein said third dispenser is configured to apply reinforcement layer to one or both of said first layer of said superconducting tape or said second layer of said superconducting tape, thereby reinforcing said stack corresponding to said superconducting tape.

[0666] Embodiment 248. The system of Embodiment 247, wherein said reinforcement layer comprise copper.

[0667] Embodiment 249. The system of any one of Embodiments 236-248, wherein one or both of said first dispenser or said second dispenser are configured such that an applied strain of said first layer of said superconducting tape is different than an applied strain of said second layer of said superconducting tape.

[0668] Embodiment 250. The system of Embodiment 249, wherein one or both of said applied strain of said first layer of said superconducting tape or said applied strain of said second layer of said superconducting tape comprises tension strain.

[0669] Embodiment 251. The system of Embodiment 249, wherein one or both of said applied strain of said first layer of said superconducting tape or said applied strain of said second layer of said superconducting tape comprises compression strain.

[0670] Embodiment 252. The system of any one of Embodiments 249-251, wherein said applied strain of said first layer of said superconducting tape is greater than said applied strain of said second layer of said superconducting tape.

[0671] Embodiment 253. The system of Embodiment 252, wherein said first layer of said superconducting tape comprise a first material and said second layer of said superconducting tape comprises a second material, and wherein said first material has a greater durability to strain than said second material.

[0672] Embodiment 254. The system of any one of Embodiments 236-253, wherein one or both of said first dispenser or said second dispenser are configured such that an environmental temperature of said first layer of said superconducting tape is different than an environmental temperature of said second layer of said superconducting tape.

[0673] Embodiment 255. The system of Embodiment 254, wherein said environmental temperature of said first layer of said superconducting tape is greater than said environmental temperature of said second layer of said superconducting tape.

[0674] Embodiment 256. The system of Embodiment 255, wherein said first layer of said superconducting tape comprise a first material and said second layer of said superconducting tape comprises a second material, and wherein said first material has a greater durability to high temperature than said second material.

[0675] Embodiment 257. The system of Embodiment 236, wherein said second dispensing device is different from said first dispensing device.

CLAIMS

WHAT IS CLAIMED IS:

1. A method of forming a reinforced superconducting tape, comprising:
   (a) providing a reinforcement member and a superconducting tape;
   (b) pre-straining at least a portion of said reinforcement member or said superconducting tape; and
   (c) affixing said superconducting tape to said reinforcement member, thereby forming said reinforced superconducting tape.
2. The method of claim 1, wherein said portion of said reinforcement member or said superconducting tape is pre-strained during (c).
3. The method of claim 1, wherein (b) further comprises pre-straining at least a portion of said reinforcement member and said superconducting tape.
4. The method of claim 1, wherein said pre-straining of (b) is at a temperature different from an operational temperature of said reinforced superconducting tape.
5. The method of claim 4, wherein said temperature is greater than an operational temperature of said reinforced superconducting tape.
6. The method of claim 5, wherein said operational temperature of said reinforced superconducting tape is less than or equal to about -100 degrees Celsius.
7. The method of claim 3, further comprising pre-straining said at least said portion of said reinforcement member at a first temperature, and pre-straining said at least said portion of said superconducting tape at a second temperature.
8. The method of claim 7, wherein said first temperature is different from said second temperature.
9. The method of claim 7, wherein said first temperature and said second temperature are greater than an operational temperature of said reinforced superconducting tape.
10. The method of claim 1, wherein said pre-straining in (b) comprises applying a tension to said at least said portion of said reinforcement member or said superconducting tape.
11. The method of claim 10, wherein a strain value of said tension is between about 0.2% and about 1.0%.
12. The method of claim 1, wherein said pre-straining in (b) comprises applying a compression to said at least said portion of said reinforcement member or said superconducting tape.

13. The method of claim 12, wherein a strain value of said compression is between about 0.2% and about 1.0%.
14. The method of claim 1, wherein affixing said superconducting tape to said reinforcement member in (c) comprises affixing said superconducting tape to said pre-strained reinforcement member in a reel-to-reel process.
15. The method of claim 1, wherein affixing said superconducting tape to said reinforcement member in (c) comprises soldering said superconducting tape to said reinforcement member.
16. The method of any one of the preceding claims, wherein said reinforcement member comprises tungsten.
17. The method of claim 1, wherein said reinforcement member comprises an alloy comprising potassium and tungsten.
18. The method of claim 1, wherein said reinforcement member comprises rhenium.
19. The method of claim 1, wherein said reinforcement member comprises tantalum.
20. The method of claim 1, wherein said reinforced superconducting tape comprises a modulus at least about twice as high as steel.
21. The method of claim 1, wherein said superconducting tape is configured to operate under a maximum of about 0.4% strain in tension.
22. The method of claim 1, wherein said reinforced superconducting tape is configured to operate under a maximum of about 0.8% strain in tension.
23. The method of claim 7, wherein one or both of said first temperature and said second temperature are greater than about 0 degrees Celsius.
24. The method of any one of the preceding claims, wherein said first temperature is the same as said second temperature.
25. The method of any one of the preceding claims, further comprising:

    (d) cooling said reinforced superconducting tape to a cryogenic temperature of less than about -100 degrees Celsius, wherein during said cooling of said reinforced superconducting tape, said reinforced superconducting tape undergoes less shrinkage when cooled to said cryogenic temperature than a superconducting tape that does not comprise said reinforcement member.
26. The method of claim 1, wherein said reinforced superconducting tape is installed in a stellarator.
27. The method of claim 26, wherein at least a portion of said stellarator is cooled to a temperature of less than about -100 degrees Celsius.

28. The method of claim 1, wherein said superconducting tape is high-temperature superconducting (HTS) tape.
29. A system for forming reinforced superconducting tape for a stellarator coil, comprising:
    (a) a first pre-straining device configured to pre-strain at least a portion of a reinforcement member or a superconducting tape; and
    (b) an affixment device configured to (i) maintain said pre-strain on said at least said portion of said reinforcement member or said superconducting tape, and (ii) affix said superconducting tape to said reinforcement member, thereby forming said reinforced superconducting tape.
30. A method of forming a stellarator coil, the method comprising:
    (a) shaping a cable into a helical cable; and
    (b) compressing at least a portion of the helical cable about an axis parallel to a central axis of the helical cable to form the stellarator coil.
31. A method of bending a coil, comprising:
    (a) providing a cable comprising a cable core and a cable jacket to a bending apparatus, wherein said cable jacket comprises a cable jacket segment, wherein said bending apparatus has a maximum working length, and a length of said cable core is longer than said maximum working length, and a length of said cable jacket segment is shorter than said maximum working length;
    (b) using a feeder portion of said bending apparatus, moving said cable jacket segment and said cable core through a bending head of said bending apparatus, thereby bending said cable jacket and said cable core into a portion of said coil;
    (c) providing an additional cable jacket segment around said cable core, wherein said additional cable jacket segment has a length shorter than said maximum working length; and
    (d) using said feeder portion of said bending apparatus, moving said cable jacket and said cable core through said bending head of said bending apparatus to bend said cable jacket and said cable core into an additional portion of said coil.
32. A cable comprising a cable core and a cable jacket, wherein said cable jacket is formed of at least two pieces, wherein said cable core is a single cable core disposed in said at least two pieces, and wherein said cable is non-planar.
33. A cable comprising a cable core and a cable jacket, wherein said cable jacket is formed of at least two pieces, wherein said cable core is a single cable core disposed in said at

least two pieces, and wherein said cable core comprises a high temperature superconductor tape.

34. A cable comprising a cable core and a cable jacket, wherein said cable jacket is formed of at least two pieces, wherein said cable core is a single cable core disposed in said at least two pieces, and wherein said cable jacket comprises copper or stainless steel.

35. A system for stabilizing high temperature superconducting (HTS) tapes in a superconducting coil, comprising:

a thermally and electrically conductive spine;

a plurality of thermally and electrically conductive struts, wherein a first strut and a second strut of the plurality of struts are positioned with (i) a distance between said first and second struts, and (ii) an angle of rotation perpendicular to said spine,

wherein said distance between said first and second struts and said angle of rotation perpendicular to said spine are based at least in part on a final bend radius of said coil; and

at least one HTS tape mechanically supported by said first strut and said second strut.

36. A method of forming a high temperature superconducting (HTS) coil, comprising

(a) providing one or more HTS tapes along a spine of said HTS coil, wherein at least one HTS tape of said one or more HTS tapes is supported by a first strut and a second strut;

(b) coupling said HTS tape to said first strut and said second strut while said HTS coil is in a first configuration; and

(c) bending said HTS coil into a second configuration, which results in a change in one or both of (i) the distance between said first strut and said second strut, and (ii) a rotation angle around said spine of said first strut and/or said second strut, wherein said second configuration is different from said first configuration.

37. A magnetic coil, comprising:

a high-temperature superconducting (HTS) tape; and

an insulator disposed around said HTS tape, wherein said insulator is resilient to neutron bombardment damage.

38. A magnetic coil, comprising:

a high-temperature superconducting (HTS) tape; and

an insulator disposed around said HTS tape, wherein said insulator comprises a ceramic.

39. A stellarator, comprising:

a ceramic insulator comprising a high-temperature superconducting (HTS) tape disposed therein.

40. A method, comprising:

(a) providing a high-temperature superconducting (HTS) tape; and

(b) disposing said HTS tape in an insulator, wherein said insulator is a ceramic insulator.

41. A method of fabricating at least a portion of a superconducting tape stack for a stellarator coil, comprising:

(a) applying a first layer of said superconducting tape stack on a substrate; and

(b) applying a second layer of said superconducting tape stack on said first layer of said superconducting tape stack, thereby forming said at least said portion of said superconducting tape stack.

42. A system for fabricating at least a portion of a superconducting tape stack for a stellarator coil, comprising:

(a) a first dispensing device configured to apply a first layer of said superconducting tape stack on a substrate; and

(b) a second dispensing device, wherein said second dispensing device is configured to apply a second layer of said superconducting tape stack on said first layer of said superconducting tape, thereby forming said at least said portion of said superconducting tape stack.