METHODS AND SYSTEMS FOR STELLARATOR OPERATION AND MAINTENANCE

CROSS-REFERENCE

[0001] This application claims the benefit of U.S. Provisional Application No. 63/550,457 filed February 6, 2024, U.S. Provisional Application No. 63/635,973 filed April 18, 2024, U.S. Provisional Application No. 63/550,477 filed February 6, 2024, U.S. Provisional Application No. 63/635,994 filed April 18, 2024, which applications are incorporated herein by reference.

BACKGROUND

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

SUMMARY

[0003] In one aspect, the present disclosure provides a high-temperature superconducting (HTS) coil. The coil may comprise an HTS tape. The coil may comprise an infill material disposed surrounding said HTS tape. The infill material may have a melting point below a damage temperature threshold of the HTS tape.

[0004] In another aspect, the coil may further comprise a plurality of struts disposed in contact with the HTS tape. The plurality of struts may be configured to support the HTS tape.

[0005] The melting point of the infill material may be at least about 50% lower than a damage temperature threshold of the HTS tape. The HTS coil may not comprise a jacket material around the HTS tape. The coil may further comprise a spine material disposed in contact with the HTS tape configured to provide support for the HTS tape. The spine material may be hollow. The spine material may be adapted for a flow of a coolant. The spine material may comprise copper. The temperature sufficient to melt the infill material may be at most about 136 degrees Celsius. The infill material may comprise bismuth, metal, tin, indium, gallium, or any combination

thereof. The infill material may comprise a bismuth-based eutectic alloy. In some cases, the infill material comprises an insulation material.

[0006] In one aspect, the present disclosure provides a plasma reactor. In some cases, the plasma reactor comprises a first set of magnetic field generating coils. In some cases, the plasma reactor comprises a neutron absorbing layer. In some cases, the plasma reactor comprises a second set of magnetic field generating coils. In some cases, said neutron absorbing layer is disposed between said first set of magnetic field generating coils and said second set of magnetic field generating coils.

[0007] In some cases, the first set of magnetic generating coils or said second set of magnetic generating coils are superconducting magnetic field generating coils.

[0008] In some cases, the superconducting magnetic field generating coils are high temperature superconducting magnetic field generating coils.

[0009] In some cases, the neutron absorbing layer comprises water.

[0010] In some cases, the neutron absorbing layer is at most about 1 meter thick.

[0011] In some cases, a material used to generate said first set of magnetic field generating coils is different from a material used to generate said second set of magnetic field generating coils.

[0012] In some cases, the first set of magnetic coils and said second set of magnetic coils are collectively at least a portion of a stellarator.

[0013] In some cases, the neutron absorbing layer comprises one or more hollow members.

[0014] In some cases, the one or more hollow members are tubes.

[0015] In some cases, the first set of magnetic field generating coils are configured to generate a fine control over a magnetic field.

[0016] In some cases, the second set of magnetic field generating coils are configured to generate a gross control over a magnetic field.

[0017] In some cases, the neutron absorbing layer comprises lithium.

[0018] In some cases, the neutron absorbing layer is configured to protect said second set of magnetic field generating coils.

[0019] In some cases, the first set of magnetic field generating coils is positioned at most about 2 meters from a plasma of said plasma reactor.

[0020] In some cases, the first set of magnetic field generating coils can be removed from said plasma reactor without removal of said second set of magnetic field generating coils.

[0021] In some cases, the first set of magnetic field generating coils provides at most about 1% of the magnetic field provided by said second set of magnetic field generating coils.

[0022] In some cases, the first set of magnetic field generating coils has an operational lifetime of at least about 10 years.

[0023] In some cases, the second set of magnetic field generating coils has an operational lifetime of at least about 40 years.

[0024] In another aspect, the present disclosure provides a method of forming a plasma reactor. In some cases, the method comprises forming a first set of magnetic field generating coils. In some cases, the method comprises placing a neutron absorbing layer around said first set of magnetic field generating coils. In some cases, the method comprises forming a second set of magnetic field generating coils around said neutron absorbing layer.

[0025] High-temperature superconducting (HTS) materials have revolutionized magnetic coil systems, offering significant advantages in efficiency and performance for applications such as stellarators. However, the technology may face certain challenges, such as in the durability and maintenance of HTS tape coils. HTS coils may be vulnerable to quench events, where a sudden loss of superconductivity leads to rapid heating and potential damage. This risk may be exacerbated by the high costs and technical difficulties associated with repairing or replacing HTS tapes. Current HTS coil designs may also face challenges with limitations in flexibility and adaptability. For example, the intricate and rigid structures of these coils may make them difficult to modify or repair without compromising integrity or performance. This lack of

adaptability may restrict the ability to upgrade or repair systems, leading to, for example, increased waste and costs as entire coils may need to be replaced, rather than repaired.

[0026] Additionally, the manufacturing and assembly processes for HTS coils may be complex and sensitive, using precise conditions to reduce damage to the superconducting tapes. Any deviation during these processes can lead to inefficiencies or failures in the system. Furthermore, the use of traditional soldering materials in HTS coil systems may pose a problem due to their high melting points, which may be close to the critical temperatures at which HTS tapes can be damaged. This narrow temperature margin may complicate repair and maintenance activities, as the risk of damaging the tapes may be high.

[0027] The environmental impact of HTS coil systems may also face certain challenges. The difficulty in repairing and recycling components may contribute to material waste, as damaged coils may be discarded, rather than repaired or reused.

[0028] Advantageously, the HTS coil system disclosed herein may be capable of being repaired. This system may significantly reduce operational downtime and costs associated with the maintenance and replacement of HTS coils, especially in critical applications like stellarators. The ability to efficiently repair and replace HTS tapes after quenching events or for aftermarket upgrades extends the lifespan of magnetic coil systems, decrease waste, and promote sustainable practices. This advancement represents a significant step forward in the reliability and environmental sustainability of HTS coil technologies, offering a practical solution to the current challenges faced in their maintenance and lifecycle management.

Hybrid Fusion Systems

[0029] 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.

[0030] 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

[0031] 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.

[0032] 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.

[0033] 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

[0034] 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

[0035] 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

[0036] 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.

[0037] 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.

[0038] 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.

[0039] 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

[0040] 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

[0041] 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.

[0042] 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.

[0043] 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

[0044] 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

[0045] 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.

[0046] 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 ˆfunctionality and safety.

Vacuum Systems

[0047] 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.

[0048] 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

[0049] 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

[0050] 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.

[0051] 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.

[0052] 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:

[0053] 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.

[0054] 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.

[0055] 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.

[0056] 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

[0057] 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.

[0058] 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.

[0059] 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.

[0060] 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

[0061] 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.

[0062] 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.

[0063] 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.

[0064] 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

[0065] 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

[0066] 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.

[0067] 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.

[0068] 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

[0069] 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.

[0070] 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

[0071] 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.

[0072] 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.

[0073] 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

[0074] 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.

[0075] 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.

[0076] 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

[0077] 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

[0078] 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.

[0079] 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.

[0080] 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

[0081] 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.

[0082] 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

[0083] 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

[0084] 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

[0085] 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.

[0086] 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.

[0087] 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.

[0088] 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

[0089] 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.

[0090] 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.

[0091] 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

[0092] 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.

[0093] 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

[0094] 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.

[0095] 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.

[0096] 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.

[0097] 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

[0098] 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.

[0099] 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.

[0100] 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.

[0101] 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.

[0102] 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

[0103] 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.

[0104] 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.

[0105] 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.

[0106] 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

[0107] 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.

[0108] 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.

[0109] 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.

[0110] 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

[0111] 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.

[0112] 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.

[0113] 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.

[0114] 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

[0115] 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.

[0116] 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.

[0117] 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.

[0118] 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

[0119] 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.

[0120] 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.

[0121] 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.

[0122] 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.

[0123] 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.

[0124] 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.

[0125] 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

[0126] 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.

[0127] 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.

[0128] 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

[0129] 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.

[0130] 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.

[0131] 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

[0132] 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.

[0133] 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.

[0134] 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

[0135] 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

[0136] 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.

[0137] 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.

[0138] 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.

[0139] 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.

[0140] 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

[0141] 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.

[0142] 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.

[0143] 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

[0144] Coils may generate complex magnetic fields confine highly charged plasma produced during fusion.

[0145] 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

[0146] 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.

[0147] 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

[0148] 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.

[0149] 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

[0150] 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.

[0151] 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

[0152] 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.

[0153] 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.

[0154] 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

[0155] 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

[0156] 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.

[0157] Magnetic fields may be optimized to regulate the behavior of high-energy particles, such as neutrons..

[0158] 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.

[0159] 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

[0160] 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.

[0161] 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

[0162] 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

[0163] 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

[0164] 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.

[0165] 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

[0166] Waste products may be gradually extracted during cycles. Waste products may also be eliminated 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.

[0167] 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.

[0168] 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

[0169] 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.

[0170] 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

[0171] 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.

[0172] 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

[0173] 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.

[0174] 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.

[0175] 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

[0176] 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

[0177] 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

[0178] 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

[0179] 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

[0180] 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

[0181] 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.

[0182] 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.

[0183] 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.

[0184] 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.

[0185] AI may provide real-time plasma control by regulating magnetic fields in microseconds, facilitating optimal confinement and averting disruptions or instabilities in the plasma.

INCORPORATION BY REFERENCE

[0186] 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

[0187] 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:

[0188] FIG. 1 illustrates an example of a jacketless HTS cable system, per one or more embodiments herein;

[0189] FIG. 2 illustrates an example of a cable channel, per one or more embodiments herein;

[0190] FIG. 3 illustrates an example of a low-temperature infill, per one or more embodiments herein;

[0191] FIG. 4 illustrates an example of a method of manufacture, per one or more embodiments herein;

[0192] FIG. 5 illustrates an example of a repair method, per one or more embodiments herein;

[0193] FIG. 6 illustrates an example of a close-fitting modular tiered-lifespan coils for a stellarator system, per one or more embodiments herein; and

[0194] FIG. 7 illustrates an example of a close-fitting coil, per one or more embodiments herein.

DETAILED DESCRIPTION

[0195] Embodiments of the present disclosure will be described more fully hereinafter with reference to the accompanying drawings in which like numerals represent like elements throughout the several figures, and in which example embodiments are shown. Embodiments of the claims may, however, be embodied in many different forms and should not be construed as

limited to the embodiments set forth herein. The examples set forth herein are non-limiting examples and are merely examples among other possible examples.

Repairable Superconducting Magnetic Coils for Stellarator Systems

[0196] Provided herein are methods and systems used with a repairable stellarator, including maintaining magnetic coils, such as HTS tape coils, and allowing for deconstruction and reconstruction of one or more components of the repairable stellarator. The methods and systems may facilitate the removal and replacement of HTS tapes post-quench events or for aftermarket purposes. This may be facilitated by melting off a low-temperature infill. This maintenance-friendly approach renders the coils repairable, thereby extending their usable life and reducing waste. Further provided herein are methods of forming a stellarator coil with improved volume utilization percentages from a cable bent into a tapered helical shape.

[0197] FIG. 1 illustrates a jacketless HTS cable system. This system may be comprised of a spine 102. The spine may be a critical component of the high-temperature superconducting (HTS) tape suspension system. The materials for the spine 102 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 106.

[0198] In some cases, construction methods for the spine 102 may vary to accommodate the system's design and operational scalability. The spine 102 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 102 to specific application needs. This may enhance the system's adaptability and efficiency.

[0199] The choice of a hollow annealed copper tube, as described in some embodiments herein, may facilitate 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 stacks 106 to remain within certain superconducting temperature ranges. 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.

[0200] In some cases, the design of the spine 102 may reduce mechanical stress on the HTS tape stacks 106. The spine may be configured to safeguard integrity and superconducting properties of the HTS tape stacks 106 during installation and use. Accordingly, the design of the spine 102 may enhance the reliability and performance of the suspension system.

[0201] In some cases, struts 104, which may function as the primary support structure in the spatial configuration of the HTS tape stack 106, may serve to sustain placement and alignment of the HTS tape stack 106 throughout the coil. Attached along the spine 102, the struts 104 may be spaced at intervals that can 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 104 can be positioned further apart, reducing the density of support and thus allowing the HTS tape stack 106 greater freedom to move and align within the coil's architecture. Conversely, for tighter bends the struts 104 are placed closer together to provide more support to reduce strain or damage.

[0202] In some cases, the adaptability of the strut placement may be complemented by the variety of shapes that the struts 104 may form. In some embodiments, the struts may be shaped symmetrically or asymmetrically around a central axis. This versatility may enable the struts 104 to support the HTS tape stack 106 effectively, whether the coil includes broad arcs or sharp angles. The design of the struts 104 provides a reliable anchor for the HTS tape stack 106. The struts may maintain the tape's proximity to the spine 102.

[0203] In some cases, through strategic placement and diverse shaping, the struts 104 may contribute to the stability of the HTS tape stack 106. For example, the struts 104 may provide support for the HTS tape stack 106 during the manufacturing process, as well as in the operational environment, where the HTS tape stack 106 may undergo various mechanical stresses. The design of the struts 104 may help to secure the position and orientation of the HTS tape stack 106, without compromising structural integrity. In this design, the HTS tape stack 106's placement is uniquely defined in relation to the spine 102, which may form the central axis of the coil system. The HTS tape stack 106 is meticulously wound around the spine 102, with struts 104 employed as intermediary supports to maintain a separation between the HTS tape stack 106 and the spine 102. This configuration may help position the HTS tape stack 106 for preserving the tape's superconducting qualities, while accommodating the coil's various geometrical configurations.

[0204] In some cases, one or more HTS tape stacks 106 may be strategically positioned within the coil system to improve magnetic field generation and control. These HTS tape stacks 106 may include layers of high-temperature superconducting tape arranged to achieve certain electromagnetic properties. For example, the design may ensures that each HTS tape within the stack 106 is aligned and secured to increase superconducting efficiency while reducing electrical resistance. The HTS tape stacks 106 may be useful in the operation of the system, providing the necessary magnetic flux density required for certain applications. The placement of HTS tape stacks 106 within the system may facilitate easy access and removal for maintenance or

replacement purposes. This design consideration may enable repair of the magnetic coil system, addressing one of the challenges with other systems. By enabling the HTS tape stacks 106 to be replaceable, the system may enhance the longevity and reliability of the magnetic coils, creating a more sustainable solution.

[0205] In some cases, the system may include a cable channel 108 that may be a groove or channel built into the coil plate. The cable channel 108 may allow the coil plate to support and position the cable system. The flexibility of the spine 102 may provide more flexibility in the design possibilities for the cable channel 108 because the cables can be bent into shape without specialized equipment. This may enable creating various coil shapes to improve the magnetic field. A complete cable channel 108 may use two coil plates with corresponding grooves to be fixed together around the cable system. The space in the cable channel 108 may then be filled with a low-temperature infill such as Cerrolow 136 or a Pb-Sn solder, or a custom blend of In-Pb-Bi-Sn-Cd-Sb.

[0206] FIG. 2 illustrates the cable channel 108. In some cases, a first coil plate 200 and a second coil plate 202 are affixed to one another such that the grooves in each coil plate align to form the cable channel 108. The coil plates 200 and 202 may serve as a mold that defines the placement and alignment of the HTS tape stacks 106 within the magnetic coil system. Each cable channel 108 within the coil plates 200 and 202 may be configured to hold the HTS tape stacks 106 in a certain spatial arrangement. This holding may improve performance of the HTS tape stacks 106, as spatial positioning influences the uniformity of the magnetic fields the HTS tape stacks 106 generate.

[0207] In some cases, during the assembly process, the HTS tape stacks 106 may be positioned into the coil channel 108, where the HTS tape stacks 106 are secured in place by the casting a low-temperature alloy within the coil channels 108. This alloy may have a melting point that does not compromise the integrity of the HTS tape stacks 106 and solidifies to form a supportive matrix around the HTS tape stacks 106. The solidification of the alloy within the coil channel

108 may secure the HTS tape stacks 106, maintaining configuration of the HTS tape stacks 106, even under the mechanical stresses of operation. The coil channel 108, therefore, may be important to the assembly and long-term functionality of the magnetic coil system. For example, the coil channel may enable embedding the HTS tape stacks 106 in an environment that maintains positioning. The coil channel 108 thus contributes to the structural stability of the HTS tapes stacks 106, without compromising accessibility of the HTS tape stacks 106 for future maintenance or repair.

[0208] FIG. 3 illustrates low-temperature infill 110. The low-temperature infill may generally be an alloy of metals with a melting point lower than the temperature at which an HTS tape stack 106 is damaged or burns. For example, Cerrolow 136 may be used, which has a melting temperature of 136°F or 57.8°C. Cerrolow may also be available with melting points ranging from 117°F to 203°F based on varying ratios of metals, bismuth, lead, tin, and indium. Another example may utilize Indalloy with melting points ranging from 140°F to 338°F, gallium, Rose's metal, Wood's metal, Field's metal, or other alloys comprising any of bismuth, lead, tin, cadmium, indium, gallium, antimony, thallium, etc. Another example may utilize high-entropy alloys, alloys amenable to the formation of bulk metallic glass, or low-temperature superconducting alloys. In another example, the low-temperature infill may comprise one or more mix-ins such as copper powder, synthetic diamond powder, carbon fiber, fiberglass, chopped Kevlar, silica powder, silica beads, seed crystals, metallic glass fragments, etc., to adjust or improve any of the low-temperature infill's thermal conductivity, electrical conductivity, or structural strength.

[0209] In some cases, identifying a composition of the low-temperature infill may utilize machine learning algorithms or artificial intelligence models to identify elemental ratios or additives, such as synthetic diamond powder, silica powder, etc. This identification may also utilize computer models and simulations, small-scale and large-scale physical experimentation, end-use demonstrations, etc. to evaluate candidate compositions. Likewise, the performance of

the low-temperature infill may be improve for one or more of its electrical conductivity, thermal behavior, and structural characteristics, which may be customized to specific regions or use cases, such as the low-temperature infill may have a composition optimized for electrical conductivity so the coils may shunt excess current to resistors, grounds, or other power drains.

[0210] In some cases, in contrast, regions not near functional areas may be optimized for thermal properties such as thermal conductivity and capacity. The compositions of the low-temperature infill may additionally be selected based upon their coefficient of thermal expansion at operational temperatures, which may range from cryogenic temperatures to elevated temperatures which may occur during a quench event. Similarly, the compositions of the low-temperature infill may be evaluated for performance at operational cryogenic temperatures and for the crystalline structure or lack thereof in the cast alloy. The low-temperature infill may be cast or otherwise formed around a coil, providing structural support and to provide improved thermal conductivity.

[0211] In some cases, the plate assembly or casting mold may be heated using hot water or cooled with an ice-water bath to control the temperature to achieve the desired crystal structure, suspension of non-metallic infill, etc. The water may be substituted with other fluids having a certain boiling point and viscosity, such as glycerin or oil, to control and stabilize the temperature of the plate assembly, casting mold, and low-temperature infill being cast. The low-temperature infill being cast may be cooled slowly to generate larger grains or quickly to generate smaller grains. The low-temperature infill may be quenched rapidly with a cryogen to create bulk metallic glass or amorphous structures. The pressure may be controlled during the casting process to produce thixotropic or other non-Newtonian behaviors. Some issues, such as air bubbles, may be removed by lengthening the casting process, using a vacuum to extract air, increasing the pressure during the cooling process to reduce the size of air bubbles in a solid state, or providing holes to allow air to escape which may be plugged after the casting process, or allowed to remain partially or completely filled with the low-temperature infill. The casting

process may utilize vibration, such as at ultrasonic frequencies, to aid mixing and removal of air bubbles, and may further utilize a process of multiple heating and cooling cycles to achieve a desired structure.

[0212] In some cases, the low-temperature infill may be cast in layers, which may include the use of multiple molds to achieve desired properties. In such cases, each layer may comprise a different low-temperature infill composition. When the low-temperature infill is heated to its melting point temperature, the temperature may remain constant while the low-temperature infill undergoes a phase transition from solid to liquid. The temperature may not rise until the entire mass of the low-temperature infill within a region of heating has transitioned to the liquid phase, after which the temperature may begin to rise. In some cases, the liquid low-temperature infill may facilitate improved heat removal via convective heat flux. Because the phase transition temperature, or melting point, of the low-temperature infill may be below the temperature at which the HTS Tape stack 106 will burn or otherwise be damaged, a heat capacity increase of 40% over the traditional lead and tin alloy solders may provide additional time and total heat capacity, which can be absorbed by the low-temperature infill before the HTS Tape stack 106 is damaged. In some cases, the low-temperature infill may additionally conduct current away from the HTS tape stack 106 if the HTS tape stack 106 warms beyond the critical point and loses its superconducting properties. In such cases, the conductivity of the low-temperature infill may be greater than the non-superconducting HTS tape stack 106, or the low-temperature infill may have a lower resistance than the HTS Tape stack 106. The low-temperature infill may additionally be used to provide component protection to components other than coils and the HTS tape stack 106 in a stellarator, such as serving as a heat sink for external dump resistors. The low-temperature infill may additionally provide a demountable joint method. The low-temperature infill may further provide a method of remotely connecting or disconnecting electrical components within the vacuum vessel of the stellarator, without using leads to transfer current out of the cryostat.

[0213] FIG. 4 illustrates a method of manufacture 112. The process begins with the construction of the spine 102. The spine 102 may be constructed at operation 400 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.

[0214] In some cases, struts 104, 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 402. The struts 104 may then be soldered in place with a propane torch. In some cases, the struts may be spaced at 3 cm intervals with a 100 mm pitch. In some cases, the struts 104 may be held in place with solder bumps that allow the struts 104 to pivot. This may provide a way for the struts 104 to relieve strain on the HTS tape stacks 106 during the bending process. The spine 102 may then be cleaned with isopropyl alcohol.

[0215] In some cases, operation 404 includes laying the HTS tape stack 106 along the struts 104. This can be done in a variety of ways, such as laying the stack in a helical pattern along the struts 104 while interstitially tying the stack to the spine 102 with a tin copper wire. In some cases, the stack may be wrapped in copper foil continuously or at intervals to hold it 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 106 has been laid, the assembly should be cleaned with isopropyl alcohol. In some embodiments, the HTS tape stacks 106 may be made of several segments that are soldered together. In this case, the HTS tape stacks 106 may be soldered together with a solder that has a higher melting point than the low-temperature infill but still well below the burn point of the HTS tape stacks 106, for example, 138°C. The assembled cable would then be bend into the plate.

[0216] In some cases, the assembly may be cast at operation 406 into the coil. The assembly may be loaded into the coil plate. Once the assembly is sealed in the plate, Cerrolow can be melted and fed in through a pour hole. The low melting point of Cerrolow will allow it to fill the space between the spine 102, struts 104, HTS tape stacks 106, and any other optional elements,

such as cooling channels or integrated sensors. The Cerrolow will then be cooled to cast the coil assembly in place with the coil assembly still in place. As used herein, the term "Cerrolow" may refer to a low melting temperature solder material. The low temperature solder material may comprise one or more metals. The one or more metals may comprise bismuth. The solder material may comprise lead, indium, tin or other elements.

[0217] FIG. 5 illustrates the repair method 114. The process begins with identifying at operation 500 a coil that has been damaged in a quench event. In some cases, an operator can visually inspect the system for signs of physical damage, such as discoloration or deformation of the HTS tapes or the surrounding structure. This can be indicative of a quench event where excessive heat may have compromised the HTS tape stack 106. By running electrical tests, such as measuring the resistance of the coil segments, the operator can detect inconsistencies that may identify damaged areas. An increase in resistance may indicate that a quench event has caused deterioration in the HTS tape stacks 106.

[0218] In some cases, once an HTS tape stack 106 that has sustained damage due to a quench event is isolated within the coil system, the coil assembly may be heated at operation 502. The repair procedure may gently heate the entire system to a controlled temperature of around 60 degrees Celsius. The temperature may be higher provided the temperature is below the temperature of the other low-temperature infill used on internal joints. This specific temperature may be sufficient to melt the low-temperature alloy used as infill, which may secure the HTS tape stacks 106 in place within the coil channels 108. By melting the infill, the system avoids exposing the HTS tapes to temperatures that may harm the superconducting properties of the HTS tapes. This may be done by submerging the entire coil assembly into a hot water bath, where the temperature may be controlled to be sufficient for melting the low-temperature infill, without affecting the HTS tapes.

[0219] In some cases, this method may leverage the specific melting point of the chosen infill alloy to liquefy the infill alloy, thereby freeing the HTS tape stacks for removal or repair.

Alternatively, the structural support plate system can be designed with strategically placed holes incorporated to allow for the injection of hot liquid, such as glycerin or oils, directly into the areas where the low-temperature infill needs to be melted. This targeted approach ensures that only the infill melts while the HTS tape stacks 106 remain intact. A drainage port is also included to remove the liquefied infill from the system, which helps in the repair and replacement of the HTS tape stacks 106. Drainage ports may be fitted with a filtering or separation system to capture material during the melt.

[0220] In some cases, optionally, at operation 504, specific solder joints may be heated to remove segments of HTS tape stacks 106 that have been soldered together. This process may loosen the tape stack, allowing it to be freed from the encapsulating material.

[0221] In some cases, the HTS tape stacks 106 may be extracted at operation 506. The now-loosened HTS tape stack 106 may be extracted by physically manipulating the tape. This can involve tools or techniques appropriate for handling delicate superconducting materials without causing further damage. The HTS tape stacks 106 may be an expensive component of the coil, so the repair may seek to salvage as much of the HTS tape as possible from the quenched coil.

[0222] In some cases, a quench damaged coil may have the HTS tape stacks 106 replaced at operation 508. The salvaged HTS tape stacks 106 may have additional segments of HTS tape soldered in so that it is the proper length for the coil being repaired. In some cases, the damaged coil may be rebuilt with a new HTS cable. In quench events that cause enough damage to the coil that the coil cannot be rebuilt, at least a portion of the HTS tape stacks 106 may be salvageable for use in building new coils.

[0223] In some cases, the assembly may be loaded into the coil plate. Once the assembly is sealed in the plate, Cerrolow can be melted and fed in through a pour hole. The low melting point of Cerrolow may allow the Cerrelow to fill the space between the spine 102, struts 104, HTS tape stacks 106, and any other optional elements, such as cooling channels or integrated

sensors. The Cerrolow will then be cooled to recast the repaired coil assembly in place at operation 510.

Close-Fitting Modular Tiered-Lifespan Coils for Stellarator Systems

[0224] Provided herein are methods and systems for a stellarator system which integrates a modular sacrificial coil set. The modular sacrificial coil set may be engineered to address neutron radiation and magnetic field precision in stellarators. The methods and systems may place a collection of coils in proximity to the neutron source within a fusion reactor. These coils may be easily replaceable after a specific period to manage the effects of neutron irradiation. The methods and systems may enable the targeted replacement of coil sections most affected by neutron exposure. The methods and systems may reduce the need for comprehensive reactor overhauls, thus minimizing downtime and maintenance expenses. The methods and systems for modular coils may be compatible with existing stellarator designs, allowing for straightforward incorporation with minimal structural adjustments. The methods and systems may use lower-current, non-superconducting coils positioned inside the blanket layer for precise magnetic field control, simplifying superconducting coil designs and relaxing accuracy requirements. The methods and systems may maintain optimal reactor performance levels by preserving magnetic field integrity, thereby supporting continuous, efficient operation.

[0225] FIG. 6 illustrates a system for close-fitting modular tiered-lifespan coils for a stellarator system. The stellarator system 602 may be a type of magnetic confinement fusion device designed to achieve controlled nuclear fusion for the generation of energy. The stellarator system 602 may utilize magnetic fields to confine and control hot plasma, sustaining the conditions necessary for nuclear fusion reactions. The stellarator system 602 may include a torus-shaped vacuum vessel 612, superconducting coils 610 for magnetic confinement, diagnostic systems 618 for monitoring and control, a cooling system 616 for managing heat generated during fusion, and a power supply 614 for sustaining the magnetic fields. The stellarator system 602 may also include close-fitting coils 606 or inner copper coils situated

within the blanket 608, for generating magnetic fields for plasma confinement. The close-fitting coils 606 may increase the accuracy of the magnetic field. The close-fitting coils 606 may achieve a uniform neutron flux distribution within the fusion reactor.

[0226] In some cases, the system may include a plasma 604. The plasma 604 may be a state of matter in which atoms may be stripped of their electrons, resulting in a mixture of positively charged ions and free electrons. Ionized gas consisting of charged particles may be the fuel for a fusion reaction, during which atomic nuclei fuse to release energy. In the stellarator system 602, the plasma 604 may be confined and manipulated by a complex magnetic field structure to achieve the necessary conditions for sustained fusion reactions. Variations in shape and position contribute to the geometrical effects of a magnetic field. These geometrical effects may impact the distribution of neutron flux. Forms of the plasma 604 may range from elongated to bullet-shaped. Variations in form may influence the neutron flux distribution across the system. The neutron flux distribution may impact the performance and longevity of components, including the close-fitting coils 606. The system may create the plasma 604 by introducing fuel into the vacuum vessel. The fuel may include a mixture of hydrogen isotopes, like deuterium and tritium.

[0227] In some cases, the system may include a vacuum vessel. The vacuum vessel may create a low-pressure environment to prevent collisions between gas molecules. The low-pressure environment may ensure the fuel particles have sufficient space to undergo fusion reactions. External heating systems may be employed to increase the temperature of the introduced gas. External heating systems may include radio-frequency or neutral beam heating. The heating process may transform the gas into a plasma state where electrons may be separated from nuclei.

[0228] The superconducting coils 610 located outside the blanket 608 may generate a magnetic field that may confine and shape the plasma 604. The magnetic field may prevent the plasma 604 from coming into direct contact with the vessel walls. The magnetic field may maintain stability of the plasma 604. The close-fitting coils 606, positioned near the plasma 604, may fine-tune the magnetic field for optimal plasma confinement. The modularity of the close-fitting

coils 606 may facilitate easy adjustments and maintenance. The combination of the superconducting coils 610 and the close-fitting coils 606 may facilitate a stable and well-controlled magnetic field within the plasma 604 region. With the plasma 604 in a confined and stabilized state, controlled fusion reactions may occur within the plasma 604. The isotopes of hydrogen, deuterium, and tritium may undergo fusion and may release energy in the form of heat. The generated heat may be extracted from the plasma 604 using a heat exchange system. The extracted heat may then be utilized to produce steam, which may drive turbines to generate electricity.

[0229] The blanket 608 surrounding the plasma 604 may both breed tritium and absorb the fusion-produced neutrons to shield components of the stellarator. Neutrons produced during the fusion reactions may interact with lithium in the blanket 608, converting it into tritium. Tritium may be used as a fuel for the fusion reaction. The shielded components may include superconducting magnets. A diagnostic system 616 may monitor the conditions of the plasma 604. The diagnostic system 616 may provide real-time data on temperature, density, and other parameters of the plasma 604 to maintain optimal fusion conditions.

[0230] In some cases, the system may include a plurality of close-fitting coils 606. The close-fitting coils 606 may be positioned close to the plasma. The close-fitting coils 606 may assist in shaping and confining the plasma within the toroidal structure. The close-fitting coils 606 may be strategically designed and placed to generate a magnetic field that can increase control and stabilize the plasma during fusion reactions. The close-fitting coils 606 may be positioned within the blanket 608. The close-fitting coils 606 may be able to fix the field error of the magnetic field produced by the superconducting coils 610. The close-fitting coils 606 may be constructed from high-conductivity materials to facilitate the smooth flow of electric current. High-conductivity materials may include copper. The close-fitting coils 606 may be demountable, facilitating easy replacement of the close-fitting coils 606 and sustained functionality of the stellarator system 602.

[0231] The precise positioning of the close-fitting coils 606 may provide optimal magnetic confinement of the plasma 604. The close-fitting coils 606 may shape the magnetic field to maintain stability within the reactor. Stability may prevent plasma 604 instabilities that may hinder the fusion process. The close-fitting coils 606 may minimize field errors within the plasma 604 confinement region. Field errors can arise from imperfections in the magnetic field geometry, and the close-fitting coils 606 may be designed to counteract such errors, ensuring a more uniform and controlled magnetic field. The close-fitting coils 606 may fine-tune the magnetic field within the stellarator system 602 by maintaining the stability, shape, and position of the plasma 604 during the fusion process. The close-fitting coils 606 may be positioned very close to the plasma 604, allowing for precise control of the magnetic field with high fidelity. The close proximity enables the close-fitting coils 606 to have a more direct influence on the behavior of the plasma 604, contributing to improved stability and confinement.

[0232] In some cases, the close-fitting coils 606 may be non-superconducting. The close-fitting coils 606 may not rely on superconducting materials that require extremely low temperatures for operation. Non-superconducting coils may be more tolerant of higher temperatures. Non-superconducting coils may dissipate heat more effectively, allowing for a modest amount of dissipation without losing functionality. The close-fitting coils 606 may operate at lower currents compared to the superconducting coils 610 responsible for the overall magnetic field. The lower current may allow for a modest amount of dissipation within these coils and may be suited to handle the associated heat generation.

[0233] The close-fitting coils 606 may fine-tune the magnetic field strength, adjusting with an accuracy within 1/100 of the total field strength. The proximity of the close-fitting coils 606 to the plasma 604 may facilitate influence on the magnetic field in a way that complements the broader magnetic field generated by the superconducting coils 610. Utilizing the close-fitting coils 606 for the fine-tuning aspect of magnetic field generation may substantially relax the geometric complexity and accuracy parameters of the superconducting coils. Superconductor

coils 610 farther from the plasma may be designed with simpler shapes, reducing manufacturing challenges and costs.

[0234] The close-fitting coils 606 may enhance the overall efficiency and performance of the stellarator system 602 by providing a precise and locally controlled magnetic field close to the plasma 604. The close-fitting coils 606 may be constructed from high temperature materials and may include surface alloys. High temperature materials may survive stellarator environmental conditions and may include refractory metals. Surface alloys may provide enhanced properties and may include carbon or nitrogen. The materials may be selected based on resilience against neutron irradiation impacts.

[0235] In some cases, the system may include a blanket 608. The blanket 608 may be about one meter thick. The thickness of the neutron absorbing blanket may be about 0.1 m to about 2 m. The thickness of the neutron absorbing blanket may be about 0.1 m to about 0.25 m, about 0.1 m to about 0.5 m, about 0.1 m to about 0.75 m, about 0.1 m to about 0.9 m, about 0.1 m to about 1 m, about 0.1 m to about 1.1 m, about 0.1 m to about 1.25 m, about 0.1 m to about 1.5 m, about 0.1 m to about 2 m, about 0.25 m to about 0.5 m, about 0.25 m to about 0.75 m, about 0.25 m to about 0.9 m, about 0.25 m to about 1 m, about 0.25 m to about 1.1 m, about 0.25 m to about 1.25 m, about 0.25 m to about 1.5 m, about 0.25 m to about 2 m, about 0.5 m to about 0.75 m, about 0.5 m to about 0.9 m, about 0.5 m to about 1 m, about 0.5 m to about 1.1 m, about 0.5 m to about 1.25 m, about 0.5 m to about 1.5 m, about 0.5 m to about 2 m, about 0.75 m to about 0.9 m, about 0.75 m to about 1 m, about 0.75 m to about 1.1 m, about 0.75 m to about 1.25 m, about 0.75 m to about 1.5 m, about 0.75 m to about 2 m, about 0.9 m to about 1 m, about 0.9 m to about 1.1 m, about 0.9 m to about 1.25 m, about 0.9 m to about 1.5 m, about 0.9 m to about 2 m, about 1 m to about 1.1 m, about 1 m to about 1.25 m, about 1 m to about 1.5 m, about 1 m to about 2 m, about 1.1 m to about 1.25 m, about 1.1 m to about 1.5 m, about 1.1 m to about 2 m, about 1.25 m to about 1.5 m, about 1.25 m to about 2 m, or about 1.5 m to about 2 m. The thickness of the neutron absorbing blanket may be about 0.1 m, about 0.25 m, about 0.5 m,

about 0.75 m, about 0.9 m, about 1 m, about 1.1 m, about 1.25 m, about 1.5 m, or about 2 m. The thickness of the neutron absorbing blanket may be at least about 0.1 m, about 0.25 m, about 0.5 m, about 0.75 m, about 0.9 m, about 1 m, about 1.1 m, about 1.25 m, or about 1.5 m. The thickness of the neutron absorbing blanket may be at most about 0.25 m, about 0.5 m, about 0.75 m, about 0.9 m, about 1 m, about 1.1 m, about 1.25 m, about 1.5 m, or about 2 m. The blanket 608 may encase the plasma 604 and close-fitting coils 606. The blanket 608 may create a barrier between the plasma 604 and surrounding components. The blanket 608 may house the close-fitting coils 606, which may be positioned near the plasma 604 for fine-tuning the magnetic field. These coils may be located within the blanket, ensuring close proximity to the plasma 604 for effective control.

[0236] The blanket 608 may also breed tritium for fuel and may shield the superconducting coils 610 from neutron flux. The blanket 608 may be composed of materials that are effective in breeding tritium and provide substantial neutron shielding. Tritium breeding may be achieved by incorporating specific materials within the blanket 608 that may capture neutrons and produce tritium through nuclear reactions. The blanket 608 may act as a shield against the neutron flux generated during the fusion process. Neutron shielding may protect the superconducting coils 610 from degradation. Neutron exposure may lead to damage and may eventually destroy superconductivity. In some embodiments, the blanket 608 materials may be compatible with tritium breeding requirements. These materials may capture neutrons and produce tritium as part of the fusion fuel cycle. The blanket 608 may also provide structural support to the overall fusion reactor system. The blanket 608 may be capable of withstanding harsh conditions within the reactor, including high temperatures, radiation, and the mechanical stresses associated with plasma confinement.

[0237] In some cases, the system may include a plurality of superconducting coils 610. The superconducting coils 610 may generate a strong and stable magnetic field for confining the plasma 604 during the fusion reaction. The superconducting coils 610 may also contribute to

controlling the shape and position of the plasma 604 during the fusion reaction. The superconducting coils 610 may be positioned or located on the outer side of the blanket 608 and thus may be exposed to neutron flux generated by the fusion reactions. Thus, the blanket 608 may provide the superconducting coils 610 with a layer of protection from the neutron flux generated by the fusion process. Neutron shielding mechanisms, possibly provided by the blanket 608, may protect the superconducting coils 610 from degradation and loss of superconductivity.

[0238] The superconducting coils 610 may comprise high-temperature superconducting materials. Thus, the superconducting coils 610 may carry large currents without resistance. High-temperature superconductors may maintain superconductivity at temperatures achievable with cryogenic cooling systems. The superconducting coils 610 may be configured to create a complex and precise magnetic field required for stellarator confinement. The geometry and arrangement of the coils may be designed to achieve optimal plasma 604 stability and control. The superconducting coils 610 may require cryogenic cooling to maintain the low temperatures necessary for superconductivity. Advanced cooling systems may include liquid or gaseous helium or other cryogenic fluids. These advanced cooling systems may be employed to achieve and maintain the required temperatures.

[0239] In some cases, the fine-tuning of the magnetic field may be achieved by the close-fitting coils 606 or the non-superconducting coils located closer to the plasma 604. The close-fitting coils 606 may contribute to adjustments within the range of less than 1/100th of the total field strength. The superconducting coils 610 may primarily provide the base magnetic field strength. The superconducting coils 610 may last for longer operational lifetimes, potentially in the range of 40 to 80 years. The superconducting coils 610 may be integrated into the broader reactor system, including connections to power supplies, cooling systems, and control mechanisms.

[0240] In some cases, there may be HTS coils that are manufactured to be replaceable. These replaceable coils may be located so as to encounter the majority of the neutron flux from the

plasma. These coils may be smaller and separable from the larger outer HTS coils. The expected lifetime of these internal coils may be less than the lifetime of the fusion power plant (FPP) and may be intended to be replaced. These replaceable coils may include materials to capture neutrons or to mitigate the impacts of the neutron flux. These replaceable coils may have meaningful differences from the outer coils. The replaceable coils may be of different cable, superconducting materials, insulators, geometries, quench detection schemes, and/or quench protection schemes from the outer coils. These replaceable coils may include internal diagnostics for the remaining useful lifetime. These internal diagnostics may include a number of sacrificial in-situ coupons, sensors, or other indicators. The system may include programmatic maintenance to determine and extend the useful lifetime of the sacrificial coils and components. The programmatic standards may include certification requirements for extension of an OEM warranty, maintenance contracts, serviceability, or other post sale support by the OEM. The replaceable coils may have options for improved performance with replacement coils. The replacement coils may be customizable or optimizable. The replacement coils may be modular or repairable. The replacement coils may be the basis for the useful lifetime determination of the FPP. Replacement of the replacement coils may extend the useful lifetime of the FPP. The external non-replaceable coils may determine the useful lifetime of the FPP.

[0241] In some cases, the system may include a power supply 612. The power supply 612 may be an electrical system designed to deliver controlled and precisely regulated electrical power to different components within the stellarator system 602. The power supply 612 may supply energy to create and sustain the magnetic confinement of the fusion plasma 604. The power supply 612 may deliver auxiliary power for diagnostic systems 616. The power supply 612 may support other operational requirements.

[0242] In some cases, the system may include a cooling system 614. Thecooling system 614 may be designed to absorb, transport, and dissipate heat generated during the fusion process. The cooling system 614 may facilitate the temperature regulation of critical components,

including superconducting magnets, plasma-facing materials, and associated systems. The cooling system 614 may maintain structural integrity and optimal performance.

[0243] In some cases, the system may include a diagnostic system 616. The diagnostic system 616 may include an array of instruments and techniques dedicated to monitoring and analyzing key parameters, behaviors, and conditions within the stellarator system 602. The diagnostic system 616 may provide essential data for assessing reactor performance. The diagnostic system 616 may facilitate reactor safety. The diagnostic system 616 may facilitate research and development activities.

[0244] The diagnostic system 616 may fix a magnetic field error produced by the superconducting coils 610 by adjusting the magnetic field through the close-fitting coils 606 using a 3D hall probe. The 3D hall probe may be a sensor that responds to the magnetic field, providing quantitative data about its characteristics. The 3D hall probe may be positioned at specific locations within the stellarator system 602 where field adjustments may be required or needed. The locations may be selected based on simulation results, initial magnetic field mapping, or previous diagnostic data indicating areas of concern. The 3D hall probe may be activated to measure the magnetic field strength and direction at its location. The data collected from the 3D Hall probe and the magnetic field parameters may be used to identify any deviations from the desired magnetic field configuration. The magnetic field parameters may include strength, orientation, and local variations. The measured magnetic field data may compared with the target or desired magnetic field configuration. Discrepancies between the actual and desired fields may be indicative of field errors that need correction. The data may be analyzed to identify the sources and causes of field errors. The sources and causes of field errors may include variations in coil currents, misalignments, or other factors affecting the magnetic field. The field errors may be corrected by fine-tuning the close-fitting coils 606. Fine-tuning the close-fitting coils 606 may involve altering the currents in specific coils, modifying shapes of specific coils, or employing other control strategies to achieve the desired field configuration.

[0245] In some cases, the system may include a control system 618. The control system 618 may include an integrated set of components, devices, and software. The control system 618 may collectively manage and regulate the operation of the stellarator system 602. The control system 618 may utilize sensors and the diagnostic system 616 to monitor the behavior of the plasma 604 and the condition of the coils. The control system 618 may utilize an array of sensors to measure the magnetic field in real time. The sensors may include 3D hall effect sensors. Additional diagnostics may measure plasma density, temperature, and neutron flux. Overall, diagnostics may provide comprehensive data on the state of the reactor.

[0246] The control system 618 may control the superconducting coils 610, including the HTS tape coils which may generate the primary magnetic field necessary to confine the plasma. The control system 618 may control the operation of the close-fitting coils 606, or modular sacrificial coils. the The close-fitting coils 606 or modular sacrificial coils may be positioned for fine-tuning the magnetic field. The close-fitting coils 606 or modular sacrificial coils may be turned on or off. The power and strength of the coils may be adjusted in terms of power and strength to modify the magnetic field in localized regions around the plasma.

[0247] The control system 618 may leverage artificial intelligence and machine learning algorithms. These algorithms may process input from the diagnostic system 616 and adjust the magnetic field in real-time. By analyzing data like the efficiency of plasma confinement as measured by 3D hall effect sensors, the control system 618 may identify any deviations from optimal conditions. Based on the sensor data, the control system 618 may dynamically adjust which close-fitting coils 606 are active, including power and strength levels. Dynamic adjustment may allow for fine-tuning of the magnetic field in specific regions, thus counteracting inefficiencies or instabilities detected in the plasma. The control system 618 may operate in concert with the superconducting coils 610. Adjustments made by activating or deactivating the close-fitting coils 606 may complement the larger magnetic fields created by the superconducting coils 610. These adjustments may maintain plasma confinement and stability.

[0248] The control system 618 may utilize AI algorithms that may predict how changes in coil activation will affect plasma behavior, allowing for proactive adjustments that optimize performance. Over time, the control system 618 may learn from historical data to improve predictive accuracy. The AI algorithm may simulate various configurations and operational scenarios to identify the most effective coil designs. The AI algorithm may identify arrangements for maximizing plasma 604 efficiency and reactor lifespan. The control system 618 may adapt to changes in reactor conditions over time. The control system 618 may learn from each operational cycle to enhance the decision-making processes which facilitate continuous operation of the reactor at peak efficiency. These enhancements may bring human intervention required for routine adjustments to a minimum.

[0249] FIG. 7 illustrates the close-fitting coils integrated into the system. The illustration displays a cross-sectional view of the stellarator system 602, including a plasma 702, the close-fitting coils 704, the blanket 706, and the superconducting coils 708. These elements may be in locations or positions in relation to one another similar to those depicted. The plasma 702 may located in the center of the system. The close-fitting coils 704 may be positioned around the first wall. The first wall may enclose the plasma 702. The close-fitting coils 704 may be positioned within the first wall or outside the first wall, or a combination of both. The blanket 706 may enclose the plasma 702. The blanket 706 may enclose the close-fitting coils 704. The vacuum vessel may be positioned inside the blanket 706 or outside of the blanket 706. The superconducting coils 708 may be positioned around the blanket 708.

[0250] The plasma 702 may be similar to the plasma 604. The plurality of close-fitting coils 704 may be similar to the close-fitting coils 606. The blanket 706 may be similar to the blanket 608 The superconducting coils 708 may be similar to the superconducting coils 610.

[0251] In some cases, the close-fitting coils 704 may be manufactured as separate, replaceable units. Thus, the close-fitting coils 704 may provide easy removal and replacement without a major overhaul of the whole stellarator system102. The close-fitting coils 704 may be

categorized based on expected lifespan. Lifespan of the coils may be determined by exposure to radiation and neutron flux. Short lifespans may be 10 years, while long lifespans may be 40 to 80 years. Coils positioned in high-radiation zones, closest to the plasma 702, may be consumable components with shorter lifespans. The superconducting coils 708 may have a longer lifespan in comparison.

[0252] 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.

Certain Definitions and Additional Considerations

[0253] 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.

[0254] 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.

[0255] 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.

[0256] 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.

[0257] 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.

[0258] 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.

[0259] 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.

[0260] 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.

[0261] 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.

[0262] 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.

[0263] 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.

[0264] 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.

[0265] 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.

[0266] 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.

[0267] 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.

[0268] 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.

[0269] 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.

[0270] 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.

[0271] 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.

[0272] 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.

CLAIMS

WHAT IS CLAIMED IS:

1. A high-temperature superconducting (HTS) coil, comprising:
   (a) an HTS tape; and
   (b) an infill material disposed surrounding said HTS tape, wherein said infill material has a melting point below a damage temperature threshold of said HTS tape.
2. The HTS coil of claim 1, further comprising a plurality of struts disposed in contact with said HTS tape, wherein said plurality of struts are configured to support said HTS tape.
3. The HTS coil of claim 1, wherein said melting point of said infill material is at least about 50% lower than said damage temperature threshold of said HTS tape.
4. The HTS coil of claim 1, wherein said HTS coil does not comprise a jacket material around said HTS tape.
5. The HTS coil of claim 1, further comprising a spine material disposed in contact with said HTS tape configured to provide support for said HTS tape.
6. The HTS coil of claim 5, wherein said spine material is hollow.
7. The HTS coil of claim 6, wherein said spine material is adapted for a flow of a coolant.
8. The HTS coil of claim 5, wherein said spine material is copper.
9. The HTS coil of claim 1, wherein said temperature sufficient to melt said infill material is at most about 136 degrees Celsius.
10. The HTS coil of claim 1, wherein said infill material comprises bismuth, metal, tin, indium, gallium, or any combination thereof.
11. The HTS coil of claim 1, wherein said infill material comprises a bismuth-based eutectic alloy.
12. The HTS coil of claim 1, wherein said infill material comprises an insulation material.
13. A method of forming an HTS coil, comprising:

(a) providing an HTS tape and a plurality of struts disposed in a mold, wherein said mold has a void with a same shape as said HTS coil, and wherein said plurality of struts are configured to support said HTS tape within said mold;

(b) injecting an infill material into said void of said mold, thereby forming said HTS coil comprising said HTS tape, said plurality of struts, and said infill material, wherein said infill material has a melting point less than a damage temperature threshold of said HTS tape.

14. A method of repairing an HTS coil, comprising:

(a) providing a damaged HTS coil comprising an HTS tape and an infill material;

(b) heating the damaged HTS coil to a temperature sufficient to melt said infill material but below a damage temperature threshold of said HTS tape to generate a heated HTS coil; and

(c) forming said heated HTS coil to repair said damaged HTS coil.

15. A plasma reactor, comprising:

a first set of magnetic field generating coils, a neutron absorbing layer, and a second set of magnetic field generating coils, wherein said neutron absorbing layer is disposed between said first set of magnetic field generating coils and said second set of magnetic field generating coils.

16. The plasma reactor of claim 15, wherein said first set of magnetic generating coils or said second set of magnetic generating coils are superconducting magnetic field generating coils.

17. The plasma reactor of claim 16, wherein said superconducting magnetic field generating coils are high temperature superconducting magnetic field generating coils.

18. The plasma reactor of claim 15, wherein said neutron absorbing layer comprises water.

19. The plasma reactor of claim 15, wherein said neutron absorbing layer is at most about 1 meter thick.

20. The plasma reactor of claim 15, wherein a material used to generate said first set of magnetic field generating coils is different from a material used to generate said second set of magnetic field generating coils.
21. The plasma reactor of claim 15, wherein said first set of magnetic coils and said second set of magnetic coils are collectively at least a portion of a stellarator.
22. The plasma reactor of claim 15, wherein said neutron absorbing layer comprises one or more hollow members.
23. The plasma reactor of claim 22, wherein said one or more hollow members are tubes.
24. The plasma reactor of claim 15, wherein said first set of magnetic field generating coils are configured to generate a fine control over a magnetic field.
25. The plasma reactor of claim 15, wherein said second set of magnetic field generating coils are configured to generate a gross control over a magnetic field.
26. The plasma reactor of claim 15, wherein said neutron absorbing layer comprises lithium.
27. The plasma reactor of claim 15, wherein said neutron absorbing layer is configured to protect said second set of magnetic field generating coils.
28. The plasma reactor of claim 15, wherein said first set of magnetic field generating coils is positioned at most about 2 meters from a plasma of said plasma reactor.
29. The plasma reactor of claim 15, wherein said first set of magnetic field generating coils can be removed from said plasma reactor without removal of said second set of magnetic field generating coils.
30. The plasma reactor of claim 15, wherein said first set of magnetic field generating coils provides at most about 1% of the magnetic field provided by said second set of magnetic field generating coils.
31. The plasma reactor of claim 15, wherein said first set of magnetic field generating coil has an operational lifetime of at least about 10 years.

32. The plasma reactor of claim 15, wherein said second set of magnetic field generating coils has an operational lifetime of at least about 40 years.

33. A method of forming a plasma reactor, comprising:

(a) forming a first set of magnetic field generating coils;

(b) placing a neutron absorbing layer around said first set of magnetic field generating coils; and forming a second set of magnetic field generating coils around said neutron absorbing layer.

34. The method of claim 33, wherein said first set of magnetic generating coils or said second set of magnetic generating coils are superconducting magnetic field generating coils.

35. The method of claim 34, wherein said superconducting magnetic field generating coils are high temperature superconducting magnetic field generating coils.

36. The method of claim 33, wherein said neutron absorbing layer comprises water.

37. The method of claim 33, wherein said neutron absorbing layer is at most about 1 meter thick.

38. The method of claim 33, wherein a material used to generate said first set of magnetic field generating coils is different from a material used to generate said second set of magnetic field generating coils.

39. The method of claim 33, wherein said first set of magnetic coils and said second set of magnetic coils are collectively at least a portion of a stellarator.

40. The method of claim 33, wherein said neutron absorbing layer comprises one or more hollow members.

41. The method of claim 40, wherein said one or more hollow members are tubes.

42. The method of claim 33, wherein said first set of magnetic field generating coils are configured to generate a fine control over a magnetic field.

43. The method of claim 33, wherein said second set of magnetic field generating coils are configured to generate a gross control over a magnetic field.
44. The method of claim 33, wherein said neutron absorbing layer comprises lithium.
45. The method of claim 33, wherein said neutron absorbing layer is configured to protect said second set of magnetic field generating coils.
46. The method of claim 33, wherein said first set of magnetic field generating coils is positioned at most about 2 meters from a plasma of said plasma reactor.
47. The method of claim 33, wherein said first set of magnetic field generating coils can be removed from said plasma reactor without removal of said second set of magnetic field generating coils.
48. The method of claim 33, wherein said first set of magnetic field generating coils provides at most about 1% of the magnetic field provided by said second set of magnetic field generating coils.
49. The method of claim 33, wherein said first set of magnetic field generating coils has an operational lifetime of at least about 10 years.
50. The method of claim 33, wherein said second set of magnetic field generating coils has an operational lifetime of at least about 40 years.
51. The method of claim 33, wherein said first set of magnetic field generating coils can be removed from said plasma reactor without removal of said second set of magnetic field generating coils.
52. The method of claim 33, wherein said first set of magnetic field generating coils provides at most about 1% of the magnetic field provided by said second set of magnetic field generating coils.
53. The method of claim 33, wherein said first set of magnetic field generating coils has an operational lifetime of at least about 10 years.

54. The method of claim 33, wherein said second set of magnetic field generating coils has an operational lifetime of at least about 40 years.