A SUPERCONDUCTOR CONNECTOR ASSEMBLY, BLADDER AND METHODS OF CONNECTION AND DISCONNECTION

FIELD OF THE INVENTION

The present disclosure relates to a superconductor connector assembly, bladder and methods of connection and disconnection. In particular, although not exclusively, the present disclosure relates to the application of the superconductor connector assembly, bladder and methods of connection and disconnection to a nuclear fusion reactor.

BACKGROUND OF THE INVENTION

A tokamak is a nuclear fusion reactor that may confine a mix of deuterium and tritium in plasma form by a magnetic field with a toroidal geometry. A spherical tokamak is a compact version, in which the radius at the centre of the toroid is minimised. Such a compact arrangement is still topologically a toroid, but it is referred to as a spherical tokamak due to its spherical appearance.

Figure 1 shows a cutaway view of a previously-proposed tokamak arrangement. Superconducting magnet assemblies 1, 2, 3 are disposed around a toroidal vacuum vessel 4. Superconducting magnet assemblies 1, 2, 3 may be formed from superconducting cables.

Superconducting magnet assembly 1 comprises toroidal field coils which extend around a section of the toroidal vacuum vessel 4. A plurality of such toroidal field coils may be provided and may be distributed about a circumference of the toroidal vacuum vessel 4. The toroidal field coils provide a magnetic field with field lines circulating around the centre of the toroidal vacuum vessel 4 and help to contain the plasma.

Superconducting magnet assembly 2 comprises poloidal field coils which extend about the circumference of the toroidal vacuum vessel 4. A plurality of such poloidal field coils may be provided and they may be distributed along a central axis of the toroidal vacuum vessel 4. The poloidal field coils help to shape and stabilise the plasma.

Superconducting magnet assembly 3 comprises a central solenoid that extends through the centre of the toroidal vacuum vessel 4. The central solenoid may induce a current in the plasma so as to heat the plasma.

A benefit of the spherical tokamak is its compact nature, which is expected to reduce the capital cost. Other benefits include attractive plasma physics features. A key efficiency parameter, called beta, is the ratio of the thermal energy density stored in the plasma to that stored in the confining magnetic

field. A spherical tokamak can accommodate much higher values of beta than a conventional tokamak because of the high ratio of plasma current to magnetic field it can contain.

However, the more compact arrangement of the spherical tokamak presents challenges. For example, there may not be sufficient space for shielding to allow the magnet assemblies 1, 2, 3 to survive the full life of the reactor. The magnetic assemblies and their superconducting cables may therefore require replacement during the life of the reactor. It is therefore desirable to allow ready access to the magnet assemblies.

To this end, it has previously been proposed to provide the superconducting cables with disconnectable, easily demountable, or remountable joints that permit disassembly of the magnet assemblies. However, previously-proposed superconducting cable joints are not easily disconnected, e.g. by remote-handling means. Such remountable electrical connections also require very low resistance as this can significantly impact on their superconducting performance. It is known to apply contact pressure through mechanical clamping such as bolts to reduce contact resistance, however, it is very difficult to ensure adequate and even pressure across the whole connector assembly.

SUMMARY OF THE INVENTION

According to a first specific aspect, there is provided a superconductor connector assembly configured to electrically connect a first superconductor cable and a second superconductor cable at a cryogenic temperature, the superconductor connector assembly comprising:

at least one first superconducting cable terminal, e.g. for receiving the first superconductor cable;

at least one second superconducting cable terminal, e.g. for receiving the second superconductor cable; and

a bladder configured to contain a liquid that expands when frozen as the superconductor connector assembly is cooled to the cryogenic temperature, wherein the bladder is positioned such that expansion of the bladder holds (e.g. compresses) the first and second superconducting cable terminals together at an electrical interface therebetween.

The bladder may comprise at least one resilient feature, e.g. on or along at least one side wall of the bladder. The resilient feature may be configured to compress as the liquid freezes and partially expand as the superconductor connector assembly is cooled below the freezing point of the liquid. The bladder may comprise at least one resilient feature along one or both of the side walls of the bladder. The resilient feature may comprise a compressible bridge portion over an opening in a cross-section of the side wall of the bladder. The bladder side wall may comprise a plurality of resilient features. The bladder side wall may be scalloped between neighbouring resilient features. At least one of the bladder side or internal walls may be corrugated so as to form a plurality of the resilient features.

The bladder may comprise at least one bladder cavity. The bladder may comprise a plurality of bladder cavities. The bladder cavities may be disposed alongside one another between walls of the bladder. The bladder may comprise a mesh inside the bladder cavity, e.g. to provide sites for crystal formation during the freezing process.

The bladder may comprise a reinforcing wall alongside the bladder cavity. The reinforcing wall may be disposed between neighbouring bladder cavities. The reinforcing wall may have greater rigidity than side walls of the bladder. The rigidity of the reinforcing wall may assist in placing bladder into the desired location.

The bladder may comprise excess material along at least one edge of the bladder. The excess material may form a bellows arrangement that permits expansion of the bladder. A seam may be provided along at least one edge of the bladder.

A thickness of a side wall of the bladder may vary across a surface of the bladder to provide a desired pressure profile across the surface of the bladder when the bladder has expanded.

The first superconducting cable terminal and the second superconducting cable terminal may be configured to be provided alongside one another. At least a portion of one of the first and second superconducting cable terminals may be provided between the bladder and at least a portion of the other of the first and second superconducting cable terminals. The bladder and first and second superconducting cable terminals (or portions thereof) may be provided between rigid walls of the superconductor connector assembly, e.g. to provide a reaction force to hold the first and second superconducting cable terminals together.

The liquid may comprise water, such as a solution of water. The liquid may comprise a eutectic mixture. The liquid may form ice when frozen. The bladder may be pre-filled with the liquid and sealed, e.g. prior to placement in the superconductor connector assembly. The bladder may thus form a passive component. Alternatively, the bladder may comprise an inlet for filling the bladder with the liquid, e.g. when installed in the superconductor connector assembly. The bladder may be filled with the liquid until a desired pressure has been attained. In this case, the bladder may be an active component.

Components of the superconductor connector assembly may be formed from materials that are not activated (e.g., not induced to be radioactive) in a radioactive environment. The first and second superconducting cable terminals may be formed from copper, such as oxygen free high conductivity copper. The bladder may be at least partially formed from a metallic film, such as stainless steel. The bladder may be at least partially formed from a woven composite material. The bladder may be configured to control the expansion of the bladder in one or more directions or locations. The bladder may act as an electrical insulator at the cryogenic temperature. The bladder may electrically insulate neighbouring components from one another.

The bladder may be configured such that expansion of the bladder causes the first and second superconducting cable terminals to be compressed together at the cryogenic temperature.

The bladder may be configured to expand to fill voids or intolerances. Once frozen the bladder may provide a solid shim to hold the first and second superconducting cable terminals and the electrical interface in place. The superconductor connector assembly may further comprise a surrounding part surrounding at least the first and second superconducting cable terminals. The surrounding part may be configured to thermally contract more than the first and second superconducting cable terminals so that the first and second superconducting cable terminals are compressed together at an operating temperature of the superconductor connector assembly.

The first and second superconducting cable terminals may interlock with respect to one another. For example, one (or both) of the first and second superconducting cable terminals may comprise a protruding portion and the other (or both) of the first and second superconducting cable terminals may comprise a receiving portion. The receiving portion may be configured to receive the protruding portion. The electrical interface may be provided by opposing surfaces on the protruding portion and the receiving portion.

The superconductor connector assembly may comprise a plurality of first superconducting cable terminals and a plurality of second superconducting cable terminals. For example, the superconductor connector assembly may comprise a plurality of pairs of first and second superconducting cable terminals. The pairs of the first and second superconducting cable terminals may be distributed in a circular arrangement. The pairs of the first and second superconducting cable terminals may be equiangularly distributed in the circular arrangement. Each pair of the first and second superconducting cable terminals may form a truncated sector of the circular arrangement. The surrounding part may surround the pairs of the first and second superconducting cable terminals distributed in the circular arrangement. Each pair of the first and second superconducting cable terminals may be configured to connect ends of a superconducting toroidal field cable together.

At least one of the first and second superconducting cable terminals may comprise a conducting portion and an insulating portion. The conducting portion may provide at least part of the electrical interface. An insulating portion of the first and second superconducting cable terminals may be provided at least at an interface between neighbouring pairs of the first and second superconducting cable terminals.

The dimensions of the components of the superconductor connector assembly may permit assembly of the superconductor connector assembly at room temperature (~298K). The first and second superconducting cable terminals may be compressed together at cryogenic temperatures, e.g., below approximately 100K.

The superconductor connector assembly may be for a nuclear reactor, such as a nuclear fusion reactor, in particular a Tokamak reactor. The reactor may comprise the superconductor connector

assembly. The superconductor connector assembly may be used in other superconductor applications, such as MRI, NMR, particle accelerators or any other application requiring superconductor connectors.

The superconductor connector assembly may provide an excellent electrical connection between the first and second superconductor cables, e.g., thanks to the contact pressure that may be obtained between the first and second superconducting cable terminals and without compromising the superconducting performance. The compressive stress may not be transferred to the first and second superconductor cables, which may otherwise degrade their superconducting properties.

The superconductor connector assembly may also provide a compact arrangement. Such a compact arrangement may be beneficial in a nuclear fusion reactor that may require a dense arrangement of superconducting cables to generate the necessary magnetic fields. The superconductor connector assembly may also readily permit disassembly and reassembly during maintenance of the reactor. The compact arrangement may leave enough space between each superconductor connector assembly for the connections to be robotically de-mounted and re-mounted.

According to a second specific aspect, there is provided an assembly comprising the above-mentioned superconductor connector assembly, the first superconductor cable and the second superconductor cable.

According to a third specific aspect, there is provided a superconducting toroidal field coil assembly comprising the above-mentioned superconductor connector assembly, e.g. comprising the plurality of pairs of first and second superconducting cable terminals. Each pair of the first and second superconducting cable terminals may be configured to connect ends of a superconducting toroidal field cable together. The superconductor connector assembly may be provided centrally (or non-centrally) with respect to a toroidal vessel, e.g., for a nuclear fusion reactor.

According to a fourth specific aspect, there is provided a bladder for a superconductor connector assembly electrically connecting at least one first superconducting cable terminal and at least one second superconducting cable terminal at a cryogenic temperature, wherein the bladder is configured to contain a liquid that expands when frozen as the superconductor connector assembly is cooled to the cryogenic temperature, wherein the bladder is configured such that expansion of the bladder holds (e.g. compresses) the first and second superconducting cable terminals together at an electrical interface therebetween.

According to a fifth specific aspect, there is provided a method of electrically connecting a first superconductor cable terminal and a second superconductor cable terminal of a superconductor connector assembly configured to operate at a cryogenic temperature, the superconductor connector assembly further comprising a bladder containing a liquid that expands when frozen, wherein the method comprises:

cooling the superconductor connector assembly to the cryogenic temperature such that the liquid contained in the bladder is frozen, the expansion of the bladder causing the first superconducting cable

terminal and the second superconducting cable terminal to be held (e.g. compressed) together at an electrical interface therebetween.

The method may further comprise filling the bladder with the liquid prior to cooling.

According to a sixth specific aspect, there is provided a method of electrically disconnecting a first superconductor cable terminal and a second superconductor cable terminal of a superconductor connector assembly configured to operate at a cryogenic temperature, the superconductor connector assembly further comprising a bladder containing a liquid that expands when frozen, wherein the method comprises:

raising the temperature of the superconductor connector assembly from the cryogenic temperature such that frozen liquid contained in the bladder melts, the contraction of the bladder causing the first superconducting cable terminal and the second superconducting cable terminal to be released (e.g. decompressed).

These and other aspects will be apparent from and elucidated with reference to the embodiment(s) described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments will now be described, by way of example only, with reference to the following drawings, in which:

Figure 1 is a cutaway schematic view of a previously-proposed tokamak nuclear fusion reactor;

Figure 2 is a perspective view of a superconducting toroidal field coil assembly according to an example of the present disclosure;

Figure 3 is a sectional perspective view of the superconductor connector assembly according to an example of the present disclosure;

Figure 4 is a sectional plan view of the superconductor connector assembly according to the example of the present disclosure;

Figure 5 is a sectional plan view of part of the superconductor connector assembly according to the example of the present disclosure;

Figures 6a and 6b (collectively Figure 6) are sectional plan views of part of the superconductor connector assembly according to the example of the present disclosure, with Figure 6a showing the first and second superconducting cable terminals disassembled and Figure 6b showing the first and second superconducting cable terminals assembled together;

Figure 7 is a perspective view of a bladder according to an example of the present disclosure;

Figure 8 is a side view of the bladder according to the example of the present disclosure;

Figure 9 is a side sectional view of the bladder according to the example of the present disclosure;

Figure 10 is a partial sectional perspective view of the bladder according to the example of the present disclosure;

Figures 11a, 11b, 11c and 11d (collectively Figure 11) are sectional views of the bladder according to the example of the present disclosure with Figures 11a, 11b, 11c and 11d respectively depicting the bladder prior to filling with a liquid, after filling the liquid, after freezing the liquid; and after further cooling;

Figure 12 is a perspective view of a bladder according to a further example of the present disclosure;

Figure 13 is a perspective view of part of the superconducting toroidal field coil assembly with the bladder according to the further example of the present disclosure;

Figure 14 is a flowchart depicting a method of electrically connecting the superconductor connector assembly according to an example of the present disclosure; and

Figure 15 is a flowchart depicting a method of electrically disconnecting the superconductor connector assembly according to an example of the present disclosure.

DETAILED DESCRIPTION OF EMBODIMENTS

With reference to Figures 2 to 4, a superconductor connector assembly 100 according to the present disclosure may be provided in a superconducting toroidal field coil assembly 200. The superconducting toroidal field coil assembly 200 may correspond to the superconducting magnet assembly 1 depicted in Figure 1. The superconductor connector assembly 100 may connect all of the superconducting toroidal field cables 202 together with a single connector assembly. The superconductor connector assembly 100 may operate at a cryogenic temperature, such as below approximately 100K or even below 20K. The superconductor connector assembly 100 may be provided centrally with respect to a toroidal vessel 4, e.g., for a nuclear fusion reactor, such as a Tokamak reactor. In particular, the superconductor connector assembly 100 may be provided at the top of the toroidal vessel 4.

Figure 3 depicts the different paths of first and second superconducting cables 102, 104 emanating from the superconductor connector assembly 100. The first and second superconducting cables 102, 104 correspond to first and second ends of a particular superconducting toroidal field cable 202, 204. First and second ends of the superconducting toroidal field cable 202, 204 may extend from the same side of the superconductor connector assembly 100. The first end of the superconducting toroidal field cable 202 (i.e., first superconducting cable 102) may initially extend vertically downwards, but may

then rotate substantially 90 degrees and extend horizontally across the top of the toroidal vessel 4. The second end of the superconducting toroidal field cable 204 (i.e., second superconducting cable 104) may continue vertically downwards, e.g., through a centre of the toroidal vessel 4.

Although Figures 2 and 3 depict the superconductor connector assembly 100 provided at the top of the toroidal vessel 4, it is also envisaged that the superconductor connector assembly 100 may be additionally or alternatively provided at the bottom of the toroidal vessel 4. Also, Figure 3 shows the first and second superconductor cables 102, 104 extending from the same side of the superconductor connector assembly 100. However, it is also envisaged that the first and second superconductor cables 102, 104 may extend from opposite sides of the superconductor connector assembly 100.

With reference to Figure 4, the superconductor connector assembly 100 will now be described. The superconductor connector assembly 100 comprises a plurality of pairs of first and second superconducting cable terminals 110, 120. A surrounding part 130 collectively surrounds the pairs of first and second superconducting cable terminals 110, 120. Each pair of first and second superconducting cable terminals 110, 120 comprises a first superconducting cable terminal 110 and a second superconducting cable terminal 120 that are provided alongside one another and are configured to be electrically coupled together to form an electrical connection. Each of the first and second superconducting cable terminals 110, 120 receives a corresponding superconducting cable 102, 104. Accordingly, each pair of the first and second superconducting cable terminals 110, 120 may electrically connect together the superconducting cables 102, 104 that are connected to that pair of first and second superconducting cable terminals 110, 120. However, as will be described in more detail below, neighbouring pairs of first and second superconducting cable terminals 110, 120 may be electrically isolated from one another.

As best shown in Figure 4, the pairs of the first and second superconducting cable terminals 110, 120 may be distributed in a circular arrangement, for example with each pair of the first and second superconducting cable terminals 110, 120 forming a truncated sector of the circular arrangement. (Each pair of the first and second superconducting cable terminals 110, 120 may be substantially trapezium shaped, e.g., with a curved surface that faces the surrounding part 130.) The pairs of the first and second superconducting cable terminals 110, 120 may be equiangularly distributed in the circular arrangement. The surrounding part 130 surrounds the pairs of the first and second superconducting cable terminals 110, 120. The surrounding part 130 may have a substantially annular cross-section. The pairs of the first and second superconducting cable terminals 110, 120 may also collectively have a substantially annular cross-section.

Although the above-described superconductor connector assembly 100 comprises a plurality of pairs of the first and second superconducting cable terminals 110, 120, it is also envisaged that the superconductor connector assembly may comprise a single pair of first and second superconducting cable terminals, e.g. for applications other than for a toroidal field coil assembly. The first and second superconducting cable terminals may be provided alongside one another, e.g. in a non-circular

arrangement. It is also envisaged that the superconductor connector assembly may not be provided centrally, e.g. with respect to the superconducting toroidal field cables 204. For example, individual superconducting toroidal field cables 204 may be provided with a corresponding superconductor connector assembly and/or the superconductor connector assembly may be provided at a radially outboard position.

The dimensions of the first and second superconducting cable terminals 110, 120 (and the surrounding part 130) may permit assembly of the superconductor connector assembly 100, e.g., at a standard room temperature (approximately 298K). However, the surrounding part 130 may be configured to thermally contract more than the first and second superconducting cable terminals 110, 120, so that the first and second superconducting cable terminals are pressed together at the operating temperature of the superconductor connector assembly 100. The surrounding part 130 may be formed from aluminium. As the surrounding part 130 contracts, the pairs of the first and second superconducting cable terminals 110, 120 may be compressed together (e.g., in a circumferential direction) and the first and second superconducting cable terminals 110, 120 within each pair may also be urged towards one another. However, it is also envisaged that the surrounding part may contract at the same rate as the first and second superconducting cable terminals 110, 120.

Figures 5 and 6 show a pair of the first and second superconducting cable terminals 110, 120. The first and second superconducting cable terminals 110, 120 are configured to cooperate with one another to form an electrical contact therebetween. As depicted, the first and second superconducting cable terminals 110, 120 may interlock with respect to one another. For example, the first superconducting cable terminal 110 may comprise a protruding portion 116 and the second superconducting cable terminal 120 may comprise a receiving portion 128 configured to matingly receive the protruding portion 116. In addition, the second superconducting cable terminal 120 may comprise a pair of further protruding portions 126a, 126b and the first superconducting cable terminal 110 may comprise a pair of further receiving portion 118a, 118b configured to matingly receive the pair of further protruding portions 126a, 126b. The pair of further protruding portions 126a, 126b may be provided either side of (and may at least partially define) the receiving portion 128 of the second superconducting cable terminal 120. Likewise, the pair of further receiving portions 118a, 118b may be provided either side of the protruding portion 116 of the first superconducting cable terminal 110. As a result of this configuration and as depicted in Figure 6b, the first and second superconducting cable terminals 110, 120 may matingly interlock with respect to one another.

As shown, the protruding portion 116 (and corresponding receiving portion 128) may be longer than the further protruding portions 126a, 126b (and the further receiving portion 118a, 118b). However, it is also envisaged that they may have the same length.

Opposing contact surfaces on the protruding portion 116 and the receiving portion 128 may form an electrical interface. Likewise, opposing contact surfaces on the pair of further protruding portions 126a, 126b and the pair of further receiving portion 118a, 118b may also form an electrical interface. In

this way, a large contact area for the electrical interface may be provided. Electrical resistance at the interface may thus be reduced.

The protruding portion 116 and/or further protruding portions 126a, 126b may extend in a substantially radial direction of the superconductor connector assembly 100. Likewise, the opposing contact surfaces may also extend in a substantially radial direction of the superconductor connector assembly 100. As a result, the electrical interface may be substantially perpendicular to the circumferential direction of the superconductor connector assembly 100. This orientation may maximise the contact pressure between the opposing electrical contact surfaces. This again may reduce the electrical resistance at the interface.

Referring still to Figure 6, the first superconducting cable terminal 110 may comprise at least one conducting portion 119a and an insulating portion 119b. Likewise, the second superconducting cable terminal 120 may comprise at least one conducting portion 129a and an insulating portion 129b. The conducting portions 119a, 129a may provide at least part of the electrical interface. For example, side walls of the protruding portions 116, 126a, 126b and recesses 118a, 118b, 128 may comprise the conducting portions 119a, 129a. By contrast, the insulating portions 119b, 129b may be provided at least at an interface between neighbouring pairs of the first and second superconducting cable terminals 110, 120, e.g., such that neighbouring pairs may be insulated from one another. As best shown in Figure 6b, the insulating portions 119b, 129b may form a carrier for the respective conducting portions 119a, 129a. The conducting portions 119a, 129a may be formed from an electrically conducting material, such as copper, in particular an oxygen free high conductivity copper. The insulating portions 119b, 129b may be formed from an electrically insulating material (e.g. at cryogenic temperatures), such as stainless steel.

The first superconducting cable terminal 110 may comprise first openings 112 for receiving respective first superconductor cables 102 (or strands of the first superconductor cable 102) and the second superconducting cable terminal 120 may comprise second openings 122 for receiving respective second superconductor cables 104 (or strands of the second superconductor cable 104). In particular, the conducting portion 119a of the first superconducting cable terminal 110 may comprise the first openings 112. Likewise, the conducting portion 129a of the second superconducting cable terminal 120 may comprise the second openings 122. The openings 112, 122 may be arranged in rows, e.g., with a row of openings 112, 122 for each of the opposing contact surfaces. The first and/or second openings 112, 122 may be circular, e.g., to receive circular cable types (such as CORC™), or substantially square/rectangular to receive CICC (cable-in-conduit) or stacked tape type arrangements. Figure 6a shows the first and second superconductor cables 102, 104 in place, whereas they have been omitted from Figure 6b. In addition to the openings 112, 122, the first and second superconducting cable terminals 110, 120 may also comprise coolant passageways 114, 124.

The first and second openings 112, 122 may be the same size as or wider than the ends (or strands) of the respective first and second superconductor cables 102, 104 (e.g. at standard room temperature and/or at the operating temperature of the superconductor connector assembly 100). The first

and second superconductor cables 102, 104 may be soldered into the first and second openings, e.g., with a solder 114, 124, such as an Indium based or eutectic solder. The solder 114, 124 may be soft (relative to the first and second superconducting terminals 110, 120) to minimise the compressive stress in the terminals 110, 120 being translated to the superconducting cables 102, 104. For example, the solder may (at the operating temperature of the superconductor connector assembly 100) have a Young's modulus or hardness value less than the material of the first and second superconducting cable terminals 110, 120. In particular, the solder may have a Young's modulus or hardness that is an order of magnitude less than the material of the first and second superconducting cable terminals 110, 120.

Although separate first and second superconducting cable terminals 110, 120 have been described, it is also envisaged that the first and second superconducting cable terminals 110, 120 could be portions of a single piece item with said portions forming an electrical interface. It is also envisaged that the conducting portions 119a, 129a may be regarded as the first and second superconducting cable terminals 110, 120 respectively.

Referring still to Figures 5 and 6, the superconductor connector assembly 100 may further comprise at least one bladder 180. (Figure 6 shows the bladder 180 in schematic form.) The bladder 180 is configured to contain a liquid that expands when frozen as the superconductor connector assembly 100 is cooled to its operating temperature. The bladder 180 is positioned such that expansion of the bladder holds the first and second superconducting cable terminals 110, 120 together at an electrical interface therebetween. The liquid may comprise water, such as a solution of water, which expands when frozen. The liquid may thus form ice when frozen. The liquid may comprise a eutectic mixture, e.g. to lower the freezing temperature of the liquid.

At least a portion of one of the first and second superconducting cable terminals 110, 120 may be provided between the bladder 180 and at least a portion of the other of the first and second superconducting cable terminals 110, 120. The bladder 180 and corresponding portions of the first and second superconducting cable terminals 110, 120 may be provided between rigid walls of the superconductor connector assembly 100. In the particular example shown, a pair of bladders 180 is provided between respective rows of conductor openings 122 in the second superconducting cable terminal 120, e.g. within the protruding portions 126a. The bladders 180 may extend substantially radially. Each bladder 180 may also partially engage the insulating portion 129b. When the bladders 180 expand, the side walls of the insulating portions 119b, 129b may provide a reaction force to compress the first and second superconducting cable terminals 110, 120 together. It is also envisaged that a bladder 180 may additionally or alternatively be provided behind conductor portions 119a (e.g. between rows of conductor openings 112) in the first superconducting cable terminal 110.

Expansion of the bladder 180 as the liquid freezes may cause the lateral spacing (e.g., in the circumferential direction) behind the conducting portions 129a to increase. This in turn may increase the contact pressure between the opposing electrical contact surfaces. Such an arrangement may provide a compression force on the electrical interface along the length of the electrical interface. The bladder 180

advantageously conforms to the shape of the components surrounding the bladder and provides a large and uniform pressure when the liquid has frozen. A good electrical contact between and across the first and second superconducting cable terminals 110, 120 is thus provided.

The bladder 180 may otherwise be configured to expand to just fill voids or intolerances within the superconductor connector assembly 100. Once frozen the bladder 180 may provide a solid shim to hold the first and second superconducting cable terminals 110, 120 and the electrical interface in place. In other words, the bladder 180 may simply form a solid shim without providing a significant or substantial compressive force. The first and second superconducting cable terminals 110, 120 may however be held together at least by friction. A majority of the compressive force between the first and second superconducting cable terminals 110, 120 may instead be provided by the relative contraction of the above-described surrounding part 130.

Referring now to Figures 7 to 11, the bladder 180 will be described in more detail. The bladder 180 may be approximately cuboid in shape. For example, the bladder 180 may be substantially planar, e.g. with a width and length that are at least an order of magnitude greater than its thickness. However, other shapes and relative sizes are contemplated, for example, the bladder may conform to a particular shape within the superconductor connector assembly 100.

As shown in Figures 9 to 11, the bladder 180 may comprise at least one bladder cavity 181 for receiving the liquid and walls of the bladder 180 may define the cavity 181. For example, the bladder 180 may be formed from a metallic film, such as stainless steel, and the film may enclose the cavity 181. The bladder 180 may also be formed from a woven composite material. The bladder 180 may be formed from a combination of the metallic film and a woven material. The bladder 180 may comprise a plurality of bladder cavities 181. For example, Figures 9 and 10 show an example with two such cavities 181, whereas Figure 11 shows an example with four cavities 181. Other numbers of cavities are contemplated. The bladder cavities 181 may be disposed alongside one another between side walls of the bladder, e.g. with a layer of the metallic film between neighbouring cavities 181. Although not depicted, the bladder 180 may comprise a mesh inside the bladder cavity 181. The mesh may provide sites that promote crystal formation during the freezing process. The use of a woven composite material may allow tuning of the strength properties in various regions and provide control over how the bladder may expand in one or more directions.

Referring still to Figures 9 to 11, the bladder 180 may comprise a reinforcing wall 182 provided alongside one or more of the bladder cavities 181. In particular, the reinforcing wall 182 may be disposed between neighbouring bladder cavities 181. As depicted, the reinforcing wall 182 may be centrally disposed, however, it is also envisaged that the reinforcing wall may be provided to one side of the bladder. The reinforcing wall 182 may have greater rigidity than other walls of the bladder 180. The rigidity of the reinforcing wall 182 may assist in placing the bladder 180 into the desired location.

As best shown in Figure 11, the bladder 180 may comprise excess material 183 along at least one edge of the bladder. Each bladder cavity 181 may comprise such excess material 183. The excess material 183 may form a bellows arrangement that permits expansion of the bladder 180. For example, the excess material 183 may unfold as the bladder 180 expands (during filling and/or freezing of the liquid). A seam may be provided along at least one edge of the bladder 180, e.g. to join walls of the bladder together.

The bladder 180 may be configured (e.g. has sufficient liquid) such that when the liquid has just frozen, the bladder exerts a greater pressure on the surrounding components than is required to ensure a good electrical connection. The superconductor connector assembly 100 may be configured to withstand such a peak pressure at the freezing point. The pressure exerted by the bladder 180 may then reduce with further cooling due to the contraction of the frozen liquid, but the bladder 180 may be configured such that the remaining exerted pressure is sufficient to maintain the required pressure between the first and second superconducting cable terminals 110, 120.

The bladder 180 may optionally comprise at least one resilient feature 184 on at least one side wall of the bladder. As shown, the bladder 180 may comprise the resilient feature on only one side of the bladder, however, it is also contemplated that both sides of the bladder 180 may comprise at least one resilient feature. Also, although the depicted bladder 180 has the resilient features on an external surface of the bladder 180, it is also contemplated that the resilient feature 184 may be provided internally within the bladder. It is also envisaged that the bladder may not comprise any such resilient features, e.g. as shown in Figure 12.

The resilient feature 184 may be configured to compress as the liquid freezes and expands. The resilient feature 184 may then partially expand as the superconductor connector assembly is cooled below the freezing point of the liquid. The resilient feature 184 may thus continue to exert a force despite the subsequent contraction of the bladder 180 due to further cooling below the freezing temperature of the liquid. The resilient feature 184 may be configured to compress by an amount that is greater than the amount of contraction caused by further cooling of the bladder (and surrounding components). In this way, the bladder 180 may continue to exert a force on the first and second superconducting cable terminals 110, 120 once the superconductor connector assembly 100 is at its cryogenic operating temperature. The resilient feature 184 may be omitted, e.g. if a surrounding part 130 is providing a majority of the compressive force.

As best shown in Figures 8 to 11, at least one of the bladder side walls may be corrugated so as to form a plurality of the resilient features 184. For example, the resilient feature 184 may comprise a compressible bridge portion 185 over an opening 186 in a cross-section of the side wall of the bladder. The bladder side wall may comprise a plurality of such resilient features 184. The bladder side wall may be scalloped between neighbouring resilient features 184. Although Figures 8 to 11 show the corrugated resilient feature 184 being provided on an external surface of the bladder, it is also envisaged that such a corrugation could be provided internally within the bladder 180.

Figure 11 depicts a sectional view of the bladder 180 across its thickness and shows the progression of the bladder 180 during cooling (the first and second superconducting cable terminals 110, 120 have been omitted for clarity). Figure 11a shows the bladder prior to filling with the liquid, although it should be noted that the bladder 180 may be provided pre-filled. Figure 11b shows the bladder 180 filled with the liquid and prior to cooling. The bladder 180 may be filled via an optional inlet 187 that is in fluidic communication with each of the cavities 181. The temperature of the superconductor connector assembly 100 may then be reduced and Figure 11c shows the bladder 180 just after the liquid in the bladder has frozen and expanded. At this point, the resilient features 184 have been compressed as a result of the expanding liquid. Figure 11d shows the bladder 180 once the superconductor connector assembly 100 has been cooled to its cryogenic operating temperature. In this state, the frozen liquid has contracted slightly, but the resilient component 184 has expanded to at least partially compensate for this contraction. The bladder 180 thus still exerts a force on the surrounding components. The reverse process may occur when the superconductor assembly 100 warms up, e.g. after use or for maintenance.

The bladder 180 may be configured to control (e.g. vary) the expansion of the bladder in one or more directions or locations. The expansion of the bladder 180 may be controlled in one or more directions, e.g. by one or more of: varying surface thicknesses of the bladder; providing internal supports or surface features, or varying the strength of the weave (in the composite material example) to tune how the bladder behaves when expanding. This may allow the bladder to expand in one or more desired locations or directions in preference to other locations or directions. In particular, a thickness of the bladder wall may be varied across a surface of the bladder to vary the rate of expansion across the surface of the bladder and/or control the pressure applied by the bladder across the surface of the bladder. For example, the bladder 180 may be tuned to expand at a greater rate at the radially outer regions of the bladder than the radially inner regions of the bladder, e.g. when installed in the circular superconductor connector assembly 100 depicted in Figure 2 to 4. The bladder 180 may be tuned to provide a desired pressure profile, e.g. a substantially uniform pressure, across the surface of the bladder when the bladder has expanded.

As mentioned above, the bladder 180 may be pre-filled with the liquid and sealed, e.g. prior to placement in the superconductor connector assembly 100. The bladder 180 may thus form a passive component. Alternatively, and with reference to Figure 12, a bladder 280 according to a further example, may comprise an inlet 287 for filling the bladder 280 with the liquid, e.g. when installed in the superconductor connector assembly 100. The bladder 280 may be filled with the liquid until a desired pressure has been attained. In this case, the bladder 280 may be an active component.

Figure 13 shows the bladder 280 installed in the central solenoid 290 of a tokamak reactor. A plurality of the bladders 280 extend substantially radially and are circumferentially distributed about the solenoid 290. The bladders 280 are sandwiched between conductor potions of a second superconducting cable terminal 220. A first superconducting cable terminal (not shown) may engage the second

superconducting cable terminal 220, e.g. in a manner similar to that descried above. It is also envisaged that the bladder 180 may be used in the arrangement shown in Figure 13.

As mentioned above, the superconductor connector assembly 100 may be used in a nuclear fusion reactor. Accordingly, components of the superconductor connector assembly 100 may be formed from materials that are not activated (e.g., not induced to be radioactive) in a radioactive environment. However, it is also envisaged that the superconductor connector assembly 100 may be used in other superconductor applications, such as MRI, NMR, particle accelerators or any other application requiring superconductor connectors. It will therefore be appreciated that other materials (i.e. those that may be induced to be radioactive) may be used in such non-nuclear applications.

With reference to Figure 14, the present disclosure relates to a method 300 of electrically connecting the first superconductor cable terminal 110 and the second superconductor cable terminal 120 of the superconductor connector assembly 100 (and thereby electrically connect the first superconductor cable 102 and the second superconductor cable 104). The method 300 comprises cooling 320 the superconductor connector assembly to the cryogenic temperature such that the liquid contained in the bladder 180 is frozen. The expansion of the bladder 180 causes the first superconducting cable terminal 110 and the second superconducting cable terminal 120 to be compressed together at the electrical interface therebetween. The method 300 may optionally comprise, prior to cryogenically cooling 320 the superconductor connector assembly, filling 310 the bladder with the liquid prior to cooling.

With reference to Figure 15, the present disclosure relates to a method 400 of electrically disconnecting the first superconductor cable terminal 110 and the second superconductor cable terminal 120 of the superconductor connector assembly 100 (and thereby electrically disconnect the first superconductor cable 102 and the second superconductor cable 104). The method 400 comprises raising 410 the temperature of the superconductor connector assembly 100 from the cryogenic temperature such that frozen liquid contained in the bladder 180 melts. The contraction of the bladder 180 causes the first superconducting cable terminal 110 and the second superconducting cable terminal 120 to be decompressed.

Variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the principles and techniques described herein, from a study of the drawings, the disclosure and the appended claims. In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope.

CLAIMS

1. A superconductor connector assembly configured to electrically connect a first superconductor cable and a second superconductor cable at a cryogenic temperature, the superconductor connector assembly comprising:

at least one first superconducting cable terminal;

at least one second superconducting cable terminal; and

a bladder configured to contain a liquid that expands when frozen as the superconductor connector assembly is cooled to the cryogenic temperature, wherein the bladder is positioned such that expansion of the bladder holds the first and second superconducting cable terminals together at an electrical interface therebetween.

2. The superconductor connector assembly of claim 1, wherein the bladder comprises at least one resilient feature, the resilient feature being configured to compress as the liquid freezes and partially expand as the superconductor connector assembly is cooled below the freezing point of the liquid.

3. The superconductor connector assembly of claim 2, wherein the bladder comprises at least one resilient feature on one or both of the side walls of the bladder.

4. The superconductor connector assembly of claim 2 or 3, wherein the resilient feature comprises a compressible bridge portion over an opening in a cross-section of the side wall of the bladder.

5. The superconductor connector assembly of any of claims 2 to 4, wherein the bladder side wall comprises a plurality of resilient features and the bladder side wall is scalloped between neighbouring resilient features.

6. The superconductor connector assembly of any of claims 2 to 5, wherein at least one of the bladder side or internal walls is corrugated so as to form a plurality of the resilient features.

7. The superconductor connector assembly of any of the preceding claims, wherein the bladder comprises at least one bladder cavity.

8. The superconductor connector assembly of claim 7, wherein the bladder comprises a plurality of bladder cavities.

9. The superconductor connector assembly of claim 8, wherein the bladder cavities are disposed alongside one another between walls of the bladder.

10. The superconductor connector assembly of any of claims 7 to 9, wherein the bladder comprises a mesh inside the bladder cavity.

11. The superconductor connector assembly of any of claims 7 to 10, wherein the bladder comprises a reinforcing wall alongside at least one of the bladder cavities.

12. The superconductor connector assembly of any of the preceding claims, wherein the bladder is pre-filled with the liquid and sealed.

13. The superconductor connector assembly of any of claims 1 to 11, wherein the bladder comprises an inlet for filling the bladder with the liquid, e.g. when installed in the superconductor connector assembly.

14. The superconductor connector assembly of any of the preceding claims, wherein the bladder is at least partially formed from a metallic film, such as stainless steel.

15. The superconductor connector assembly of any of the preceding claims, wherein the bladder is at least partially formed from a woven composite material.

16. The superconductor connector assembly of any of the preceding claims, wherein the bladder is configured to control the expansion of the bladder in one or more directions or locations.

17. The superconductor connector assembly of any of the preceding claims, wherein the liquid comprises water, such as a solution of water.

18. The superconductor connector assembly of any of the preceding claims, wherein the liquid comprises a eutectic mixture.

19. The superconductor connector assembly of any of the preceding claims, wherein the bladder is configured such that expansion of the bladder causes the first and second superconducting cable terminals to be compressed together at the cryogenic temperature.

20. The superconductor connector assembly of any of the preceding claims, wherein the bladder is configured to expand to fill voids or intolerances and once frozen provide a solid shim to hold the first and second superconducting cable terminals and the electrical interface in place.

21. The superconductor connector assembly of any of the preceding claims, wherein the superconductor connector assembly further comprises a surrounding part surrounding at least the first and second superconducting cable terminals, the surrounding part being configured to thermally contract more than the first and second superconducting cable terminals so that the first and second superconducting cable terminals are compressed together at an operating temperature of the superconductor connector assembly.

22. The superconductor connector assembly of any of the preceding claims, wherein a thickness of a side wall of the bladder varies across a surface of the bladder to provide a desired pressure profile across the surface of the bladder when the bladder has expanded.

23. The superconductor connector assembly of any of the preceding claims, wherein the superconductor connector assembly comprises a plurality of pairs of first and second superconducting cable terminals, the pairs of the first and second superconducting cable terminals being distributed in a circular arrangement.

24. A superconducting toroidal field coil assembly comprising the superconductor connector assembly of claim 23, wherein each pair of the first and second superconducting cable terminals is configured to connect ends of a superconducting toroidal field cable together.

25. A bladder for a superconductor connector assembly electrically connecting at least one first superconducting cable terminal and at least one second superconducting cable terminal at a cryogenic temperature, wherein the bladder is configured to contain a liquid that expands when frozen as the superconductor connector assembly is cooled to the cryogenic temperature, wherein the bladder is configured such that expansion of the bladder holds the first and second superconducting cable terminals together at an electrical interface therebetween.

26. A method of electrically connecting a first superconductor cable terminal and a second superconductor cable terminal of a superconductor connector assembly configured to operate at a cryogenic temperature, the superconductor connector assembly further comprising a bladder containing a liquid that expands when frozen, wherein the method comprises:

cooling the superconductor connector assembly to the cryogenic temperature such that the liquid contained in the bladder is frozen, the expansion of the bladder causing the first superconducting cable terminal and the second superconducting cable terminal to be held together at an electrical interface therebetween.

27. The method of claim 26 further comprising filling the bladder with the liquid prior to cooling.

28. A method of electrically disconnecting a first superconductor cable terminal and a second superconductor cable terminal of a superconductor connector assembly configured to operate at a cryogenic temperature, the superconductor connector assembly further comprising a bladder containing a liquid that expands when frozen, wherein the method comprises:

raising the temperature of the superconductor connector assembly from the cryogenic temperature such that frozen liquid contained in the bladder melts, the contraction of the bladder causing the first superconducting cable terminal and the second superconducting cable terminal to be released.