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(54) ELECTROMAGNETIC COIL

(57) The present inventive concept relates to an electromagnetic coil (10) having a transversal cross-section (11) comprising a channel (20) for a cooling fluid, wherein said electromagnetic coil (10) comprises a plurality of cross-connections (26) for said cooling fluid, each cross-connection (26) of said plurality of cross-connections (26) running between the channels (20) of two

windings (12) of said electromagnetic coil (10), wherein said plurality of cross-connections (26) are circumferentially displaced with respect to each other so as to form a staircase-shaped flow path (30) for said cooling fluid between the windings (12) of said electromagnetic coil (10).

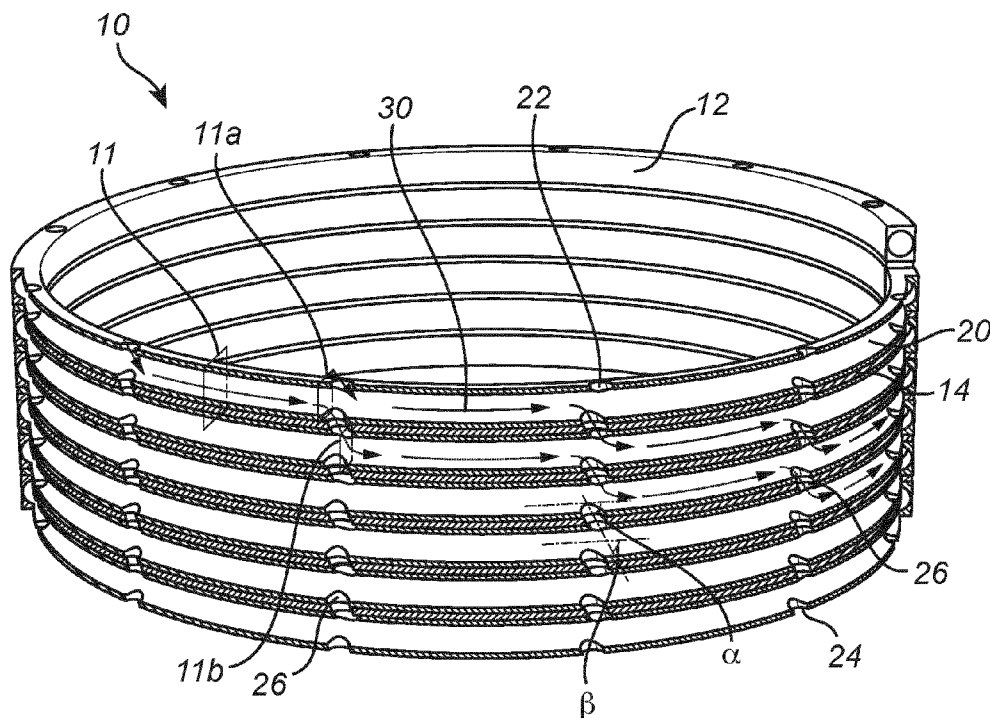


Fig. 2

Description

Field of technology

[0001] The present disclosure relates an electromagnetic coil, to a plasma confinement device comprising an electromagnetic coil, and to a method of cooling an electromagnetic coil.

Background

[0002] Great efforts are being made to design a reactor for controlled fusion on earth. The most promising fusion process is between the hydrogen isotopes deuterium (2H) and tritium (3H). In the deuterium-tritium fusion process, a 4He alpha particle, having a kinetic energy of about 3.5 MeV and a neutron, having a kinetic energy of about 14.1 MeV, are created.

[0003] For fusion to occur, nuclei must be in the form of a plasma having a temperature in the order of 150 million kelvins. Providing confinement for such a plasma remains a major challenge.

[0004] Plasma confinement involves confining the charged particles of the plasma. There are several different known magnetic configurations for plasma confinement. A well-known design is the magnetic mirror, or magnetic mirror machine. Therein, particles follow magnetic field lines, typically running substantially longitudinally through the magnetic mirror machine, and are reflected in areas of increasing magnetic flux density at the respective ends of the device.

[0005] Other examples of plasma confinement devices are the tokamak, and the biconic cusp. Further examples of plasma confinement devices are disclosed in published patent application WO 2021/094372.

[0006] Common to most plasma confinement devices is the generation of strong electromagnetic fields using electromagnetic coils. During the operation of such devices, and other systems comprising electromagnetic coils, the coils generate heat due to the flow of electric current, which may overheat the coils and limit their performance. Therefore, there is a need for an efficient cooling system that can maintain the temperature of the coils within a safe operating range.

[0007] The use of superconducting coils may allow for higher current densities, and thus stronger magnetic fields, than what is possible using conventional, resistive, conductors. However, a disadvantage of superconductor coils, and superconductor materials in general, is the need of low temperatures for the materials to become superconducting. In particular, temperatures close to the absolute zero may be needed, which results in high operating costs. In practice, while superconductor materials used in fusion experiments may intrinsically allow for current densities in the order of 50 A/mm², engineering considerations may limit the practically achievable current density, taking the whole cable area into account, to the order of 10-20 A/mm². Such engineering considera-

tions may be that conventional cooling systems take up a lot of space, e.g. due to heat shields, and that superconducting components must be surrounded by copper layers to cope with breakdown of the superconducting property due to material defects, high temperatures, high magnetic fields, etc. Meanwhile, traditional copper and/or aluminium windings in electromagnetic coils may have current densities up to 3 A/mm² without any active cooling, up to 5 A/mm² when using conventional air cooling methods, and up to 10 A/mm² when using conventional liquid-based cooling methods. Thus, using superconductors may only marginally provide higher current densities than conventional, resistive, conductors.

[0008] Conventional electromagnetic coils being subject to a cooling process may have a duct running helically through the electromagnetic coil along a centre of each winding, thereby forming a channel for cooling fluid to flow in, wherein a first winding has an inlet and a last winding has an outlet. However, the cooling fluid may heat up, boil, and/or lose its cooling capabilities before reaching said outlet. Thus, there is a need to improve the cooling methods of non-superconductor electromagnetic coils in order to obtain greater current densities running through the windings in electromagnetic coils that may approach current densities practically achievable using superconductors.

Summary

[0009] It is an object of the present disclosure to solve, or at least mitigate, the above problems.

[0010] To this end, according to a first aspect, there is provided an electromagnetic coil having a transversal cross-section comprising a channel for a cooling fluid, wherein said electromagnetic coil comprises a plurality of cross-connections for said cooling fluid, each cross-connection of said plurality of cross-connections running between the channels of two windings of said electromagnetic coil, wherein said plurality of cross-connections are circumferentially displaced with respect to each other so as to form a staircase-shaped flow path for said cooling fluid between the windings of said electromagnetic coil.

[0011] Thus, a plurality of such staircase-shaped flow paths may be formed in the electromagnetic coil. Hereby, the flow capacity for the cooling fluid is multiplied as compared to a conventional coil providing only a single flow path for the cooling fluid along the windings of the electromagnetic coil.

[0012] The transversal cross-section should be understood as any slice of the electromagnetic coil perpendicular or substantially perpendicular to a main direction of current flow of a winding of the electromagnetic coil, thus revealing an internal arrangement of the channel in the windings. For example, the transversal cross-section may be a slice of the electromagnetic coil along the length of the electromagnetic coil. For example, the transversal cross section could be vertical.

[0013] A cross-connection should be understood as a passage and/or shortcut for the cooling fluid to travel between the channels of the two windings of the electromagnetic coil. Thus, the plurality of cross-connections may allow for the cooling fluid to flow between the two windings of the electromagnetic coil. For example, a cross-connection may be a tube or a channel configured to cross-connect a portion the channel of one winding with another portion of the channel of another winding of the electromagnetic coil.

[0014] Thus, a cross-connection may be a direct physical connection between the channels of the two windings. In other words, the cross-connection may allow for the fluid to bypass a normal or conventional path of the fluid through the channel and/or allow for faster fluid communication between the channels of the windings.

[0015] The plurality of cross-connections may allow for the cooling fluid to rapidly flow from a first end to a second end of the electromagnetic coil. In other words, the cross-connections may guide the cooling fluid from one end to another of the electromagnetic coil and/or through each winding of the electromagnetic coil.

[0016] The plurality of cross-connections being circumferentially displaced with respect to each other may be understood as the cross-connections being located at different angular positions around the windings so as to create the staircase-shaped flow paths.

[0017] Naturally, the windings of the electromagnetic coil may be circular or substantially circular and/or the electromagnetic coil may have a cylindrical shape. However, the electromagnetic coil may be a rectangular electromagnetic coil and/or have a shape of a rectangular block. The terminology of being 'circumferentially displaced' may apply to any shape. The plurality of cross-connections may be circumferentially displaced along a rim and/or a periphery of the electromagnetic coil. In other words, circumferentially displaced may refer to a displacement or shift that occurs around or along a boundary or perimeter of a shape. The circumferential displacement may describe a displacement that occurs around the entire edge of a shape.

[0018] The cooling fluid flowing in a staircase-shaped flow path may provide a rapid through-flow of the cooling fluid. The staircase-shaped flow path may allow for the cooling fluid to cool the electromagnetic coil throughout the complete flow path. Each step of the staircase-shaped flow path may correspond to the cooling fluid's ascent, descent, and/or travel between adjacent windings of the electromagnetic coil. The tread of each step may run along a portion of the channel in each winding of the electromagnetic coil. Each cross-connection may consequently be comparable to the riser portion of each step of the staircase-shaped flow path.

[0019] The terms 'staircase-shaped' and 'staircase-pattern' may be interpreted as a structure and/or pattern that ascends at an incline with a series of flat platforms or steps along the channel, which are arranged one after the other, with interspersed cross-connections.

[0020] The steps may be arranged in a pattern such that the cooling fluid may climb or descend the electromagnetic coil in an efficient manner. In other words, the cooling fluid may efficiently ascend or descend from one level, i.e. winding, to another through the cross-connection.

[0021] The shape of the staircase may vary depending on the design, some featuring steps may be of equal size, while others may have steps that vary in size or shape. The overall shape of the staircase may typically be angular, i.e. the incline of the steps may create a gradual upward or downward slope.

[0022] It is appreciated that the current may flow in a spiral-pattern through the electromagnetic coil via the entirety of each winding, whereas the cooling fluid may flow in a staircase-pattern through the electromagnetic coil via portions of each winding of the electromagnetic coil and the cross-connections thereof.

[0023] It is to be understood that the electromagnetic coil may be formed by, and/or comprise, any plurality of windings. The terms 'winding' and 'windings' may further not necessarily be interpreted as to form a cohesive or continuous element. The windings may be joint or disjoint. In other words, the windings may form one body, or a winding may be a separate body configured to be connected to another winding such that current and cooling fluid may flow through each winding.

[0024] Thus, for example, the windings may be comprised in an elongate spiral-shaped conductor along which the channel for the cooling fluid runs. Alternatively, for example, the windings may be single (e.g., circular) windings electrically connectable in parallel and each comprising a channel for the cooling fluid not connected to the channels of other windings except for at one or more cross-connections.

[0025] That the transversal cross-section of the electromagnetic coil comprises a channel for a cooling fluid, may mean that each winding of the electromagnetic coil comprises a channel for the cooling fluid running along the length of the windings.

[0026] Through the present inventive concept, improved cooling for the electromagnetic coil may be provided by an increased flow of the fluid without significantly decreasing the conductive area of electromagnetic coil or increasing the resistive heating of the electromagnetic coil. The improved cooling may further improve the electromagnetic coil performance and efficiency by maintaining a safe operating temperature, increasing lifespan, reducing maintenance needs, enhancing safety, and offering flexible design options. It may further enable higher power output without overheating, prevent thermal cycling and fatigue, reduce repair and replacement frequency, and mitigate the risk of fire and other hazards.

[0027] The channel for the cooling fluid may be a duct integrated in the windings of the electromagnetic coil. The channel may be arranged to maximize a contact surface between the cooling fluid and the electromagnetic coil. The channel may be an extruded channel. The

channel may form a circular or elliptical duct in the windings of the electromagnetic coil. However, it is to be understood that the channel may have any shape, the channel may e.g. have a quadratic shape or a plurality of segmentally different shapes.

[0028] The plurality of cross-connections for the cooling fluid may be holes, channels, and/or ducts.

[0029] A cross-connection of the plurality of cross-connections may run between the channels of two adjacent windings of the electromagnetic coil. In other words, the the cooling fluid may flow between the channels of adjacent windings of the electromagnetic coil. This may be a particularly simple way of implementing the present inventive concept.

[0030] A cross-connection of said plurality of cross-connections may depart from, and/or join, a channel at an acute angle.

[0031] As the angle from which a cross-connection departs from or joins the channel should be understood the angle between a direction of flow of the cooling fluid in the cross-connection and a direction of flow of the cooling fluid in the channel.

[0032] With an acute angle should be understood and angle larger than zero degrees and smaller than 90 degrees.

[0033] For example, all of the cross connections of the plurality of cross-connections may depart from and/or join a corresponding channel at an acute angle. In other words, a cross-connection, some cross-connections, or all cross-connections, may form an acute angle with a channel of the windings or at least one winding of the electromagnetic coil.

[0034] The acute angle may guide the cooling fluid into an adjacent winding such that a flow-out rate of the cooling fluid may be optimized. The acute angle of a cross-connection may influence the flow of the fluid through the electromagnetic coil. The acute angle may affect the velocity, pressure, and efficiency of the fluid flow. The acute angle may guide the fluid to flow in a direction along an intended flow path. The acute angle may govern how the fluid enters and/or exits the plurality of cross-connections. The acute angle may define a flow path of the fluid. The acute angle may be aligned with a desired flow direction such that a smoother passage with minimal disruption to the fluid's momentum is attained. The acute angle may provide the staircase-shaped flow path of the cooling fluid. The angle of the acute angle may be adapted to the size of the electromagnetic coil.

[0035] The acute angle may be between 10 and 50 degrees, preferably between 20 and 40 degrees, and even more preferably between 25 and 35 degrees. Hereby, the acute angle may be substantially in agreement with the fluid's flow direction such that turbulence, Eddies, currents, and/or reverse fluid flow may be avoided or mitigated. Thus disruptions causing inefficiencies in flow of the fluid, pressure drops, and/or flow restrictions, which may increase a vaporization tendency of the fluid, may be avoided or mitigated.

[0036] The acute angle of a cross-connection may affect a pressure distribution within the fluid, thus an acute angle smaller than 25 degrees or larger than 35 degrees may create areas having high pressure gradients which may cause localized pressure losses and/or flow separation such that the cooling of the electromagnetic coil is decreased and/or the electromagnetic coil is damaged due to excessive pressure differences.

[0037] The magnitude of the acute angle may affect a velocity profile of the fluid. A smooth, gradual, or acute angle between 25 and 35 degrees, may allow for a uniform velocity distribution of the fluid across the electromagnetic coil. An angle smaller than 25 degrees, or smaller than 10 degrees, may cause velocity disparities, resulting in regions of the channel of the electromagnetic coil having different velocities causing an uneven distribution of the fluid and/or an increased turbulence. In particular, a too small angle may result in abrasion of the cross-connections, thus resulting in the cross-connections becoming larger.

[0038] A cross-connection of the plurality of cross-connections may depart from and/or join a channel at a right angle. In other words, the angle between the cross-connections and the channels may be 90 degrees. For example, all of the cross connections of the plurality of cross-connections may depart from and/or join a corresponding channel at a right angle. This may result in an electromagnetic coil that is easier to manufacture.

[0039] The right angle may allow for the cooling fluid to flow between channels of windings in a straight manner. It is appreciated that a set of the plurality of cross-connections may depart from and/or join a channel at a right angle, while another set of the plurality of cross-connections may depart from and/or join a channel at an acute angle. The electromagnetic coil may comprise a combination of right-angled and acute-angled cross-connections.

[0040] The electromagnetic coil having a channel from which a cross-connection of said plurality of cross-connections departs, may be sealed at a location adjacent to and past said cross-connection, said channel preferably being sealed by means of a plug. The plug may be a non-conductive plug. Sealing of the channel may force and/or guide the cooling fluid to flow into a cross-connection and/or a channel of an adjacent winding, thus forcing and/or guiding the cooling fluid to flow in the staircase-pattern, fully separating flow paths of the electromagnetic coil, which may improve cooling. The sealing of the channel, e.g. by means of the plug, may be positioned past a cross-connection in a direction of the flow of the cooling fluid.

[0041] A first winding of the electromagnetic coil may have a plurality of inlets configured to receive the cooling fluid from a fluid reservoir in fluid contact with the plurality of inlets of the first winding. The fluid reservoir may be a water reservoir. The cooling fluid may comprise anti-boiling and/or boiling-point increasing additives. The cooling fluid may cool the electromagnetic coil without

having the cooling fluid boiling. The cooling fluid may comprise anti-freezing and/or freeze-point decreasing additives.

[0042] The fluid reservoir may be configured to provide cooling fluid to the electromagnetic coil with cooling fluid momentum sufficient for guiding and/or forcing the cooling fluid to flow through the electromagnetic coil in a staircase-pattern. Each inlet may be configured to receive the cooling fluid. Each inlet may correspond to and/or initiate a staircase-shaped flow path for the cooling fluid. The cooling fluid flowing in through an inlet or a cross-connection of a winding may by the momentum of the cooling fluid flow through the winding and to a successive, or a next, cross-connection such that the cooling fluid enters the channel of a successive winding of the electromagnetic coil in a direction of the flow of the cooling fluid.

[0043] The flow rate through the electromagnetic coil may be proportional to the number of inlets, consequently, the cooling fluid may be distributed evenly across the electromagnetic coil and remove heat from all parts of the electromagnetic coil. The plurality of inlets may be configured to receive a cooling fluid via a high-pressure pump. The high-pressure pump may provide a consistent flow rate through the electromagnetic coil and ensure that the cooling fluid is distributed evenly across the plurality of inlets. The high-pressure pump may further overcome resistance or pressure drops occurring within the electromagnetic coil due to its complex geometry.

[0044] A last winding of the electromagnetic coil may comprise a plurality of outlets configured to output the cooling fluid from the electromagnetic coil. The plurality of outlets may be in fluid contact with the fluid reservoir and/or another fluid reservoir. The cooling fluid heated by the electromagnetic coil may be reused, repurposed, and/or transferred to an external heat exchanger and/or radiator.

[0045] The inlets and the outlets of the electromagnetic coil may enable the cooling fluid to cycle through the electromagnetic coil. The electromagnetic coil and the at least one fluid reservoir may be comprised by a system configured to cool and/or provide cooling fluid configured to be received by the plurality of inlets. Each inlet of the plurality of inlets may correspond to and/or be associated with an outlet. The flow path of the cooling fluid between an inlet and an outlet may form a staircase-shaped flow path.

[0046] The outlets and inlets may be positioned on the same winding. In other words, the staircase shaped flow path may be a descending and ascending staircase shaped flow path. The cooling fluid in a flow path may be configured to firstly ascend through the electromagnetic coil in a staircase-shaped pattern and then ascend through the electromagnetic coil in a staircase-shaped pattern or in a straight manner, upright manner, or inclined manner. In other words, the staircase-shaped flow path may constitute a descending staircase-shaped flow path and an ascending staircase-shaped flow path that

come together to form a V-shape or a split-level staircase corresponding to two flights of stairs that meet at a landing and then continue in opposite directions. Thus the cooling fluid intake and outtake may be on a same side or portion of the electromagnetic coil.

[0047] The cooling fluid may be a cooling liquid. The cooling fluid may, for example, be an refrigerant, oil, and/or water. The cooling fluid may advantageously be water due to the high thermal capacity, low viscosity, availability, and the low cost of water. However, the cooling fluid may be any fluid suitable for absorbing heat. The electromagnetic coil may be a resistive coil. In other words, the electromagnetic coil may be a non-superconducting coil. The electromagnetic coil may be an electromagnetic coil prone to generating heat and/or overheating, and thus in need of cooling. This may be a particularly beneficial application of the present inventive concept.

[0048] The electromagnetic coil may have a first cross-connection between a first winding and a second winding aligned with a second cross-connection between said second winding and a third winding. In other words, each cross-connection may be vertically aligned with another cross-connection. A set of cross-connections may be aligned along a straight line, thereby encouraging a sequential flow of the fluid, and/or preventing a backflow of the fluid.

[0049] The first cross-connection and the second cross-connection may be substantially aligned and/or aligned with an offset. The first cross-connection and the second cross-connection may be aligned to allow and/or guide the cooling fluid to flow in a staircase-pattern. However, the first cross-connection and the second cross-connection may be aligned to allow and/or guide the cooling fluid to flow through the electromagnetic coil in a significantly straight manner. The first cross-connection and the second cross-connection may be aligned such that the cooling fluid is guided and/or enabled to flow partly helically and partly staircase-shaped through the channels of the windings of the electromagnetic coil. The first cross-connection and the second cross-connection may be aligned to guide and/or enable the cooling fluid to flow mainly, or solely, in a staircase-pattern. The first and second cross-connections may be any two cross-connections.

[0050] The electromagnetic coil may further have at least a subset of cross-connections, in said plurality of cross-connections, being circumferentially evenly distributed along the electromagnetic coil. In other words, at least some cross-connections may be evenly distributed along a periphery of the electromagnetic coil. The cross-connections between a first winding and a second winding may be evenly or unevenly distributed, the cross-connections between a second winding and a third winding may be evenly or unevenly distributed, etc.

[0051] The evenly distributed cross-connections may allow for a coherent flow of the fluid and/or provide evenly distributed fluid throughout the electromagnetic coil.

[0052] The electromagnetic coil may further be an extruded profile. The channel, cross-connections, and/or plugs may form part of the extruded profile.

[0053] An extruded profile may offer cost-effectiveness due simplified and automated mass production. An extrusion process may provide dimensional control in the manufacturing of the electromagnetic coil, resulting in uniformity and minimized variations. The extrusion may allow for smooth surface finishes of the channel cross-connections, and/or plugs, thereby eliminating a need for additional timely and/or costly finishing operations.

[0054] The extrusion may allow for tolerance control by enabling precise measurements and small tolerances for meeting specific design requirements and/or ensuring compatibility with connecting parts, such as hoses or pipes. Other features such as mounting holes, slots, or connectors may further be integrated in the extruded profile such that separate components are minimized allowing for easy and/or efficient assembly of the electromagnetic coil.

[0055] The channel of the electromagnetic coil may be internal to the electromagnetic coil. The channel may be internal to the windings of the electromagnetic coil. Internal may mean that the channel exists within the structure of the windings. In other words, the channel is located inside the windings. The internal channel may be a hollow space or pathway enclosed within the winding structure of the electromagnetic coil. The channel may be a duct. The channel may run through a centre of the windings of the electromagnetic coil. However, it is to be understood that the channel may run along an edge or outer surface of the windings. The channel may be an open channel with respect to the electromagnetic coil. The channel may be confined by the electromagnetic coil and/or an outer layer, coat, and/or sheet surrounding the electromagnetic coil.

[0056] According to a second aspect, there is provided a plasma confinement device comprising the electromagnetic coil of the first aspect. The plasma confinement device may be a magnetic mirror machine. The plasma confinement device may be configured to provide a stable enclosure of plasma and/or create a stable fusion process. The plasma confinement device may be an open-field-line plasma confinement device. The plasma confinement device may comprise two magnet systems facing each other in an axial direction, with a space in-between where a plasma may be confined. Each magnet system may have at least two electromagnetic coils according to the first aspect, where the current direction and magnitude create an annular plasma confinement area with a magnetic field.

[0057] Hereby, improved stable fusion processes and/or stable plasma confinement may be obtained by the improved cooling of the resistive coils subject to high currents.

[0058] According to a third aspect, there is provided a method for cooling an electromagnetic coil, comprising running a cooling fluid through said electromagnetic coil,

said electromagnetic coil having a transversal cross-section comprising a channel for a cooling fluid, wherein said electromagnetic coil comprises a plurality of cross-connections for said cooling fluid, each cross-connection of said plurality of cross-connections running between the channels of two windings of said electromagnetic coil, wherein said plurality of cross-connections are circumferentially displaced with respect to each other so as to form a staircase-shaped flow path for said cooling fluid between the windings of said electromagnetic coil.

[0059] Running the cooling fluid through the electromagnetic coil may comprise using a pump. The pump may be a high-pressure pump, such that a consistent flow rate and pressure of the cooling fluid through the coil may be maintained. The high-pressure pump may also overcome, or mitigate, any resistance or pressure drops that may occur within the coil due to its complex geometry.

[0060] The flow rate of the cooling fluid may be adjusted based on the number of inlets of the electromagnetic coil. For example, more inlets may increase the flow rate and maintain a consistent and efficient cooling of the electromagnetic coil. Conversely, fewer inlets may allow for decreasing the flow rate such that overcooling and/or waste of energy may be avoided or mitigated.

[0061] The method may implement various types of cooling fluids and pumps depending on the specific requirements of the application of the electromagnetic coil. For example, the cooling fluid may be water, oil, or a refrigerant, and the pump may be an electric pump, a hydraulic pump, or a pneumatic pump.

[0062] It is to be understood that the terminology used herein is for descriptive purpose only, and is not intended to be limiting. It must be noted that, as used in the specification and the appended claim, the articles "a", "an", "the", and "said" are intended to mean that there are one or more of the elements unless the context clearly dictates otherwise. Thus, for example, reference to "a unit" or "the unit" may include several devices, and the like. Furthermore, the words "comprising", "including", "containing" and similar wordings does not exclude other elements or steps.

Brief description of the drawings

[0063] The above, as well as additional objects, features and advantages of the present disclosure, will be better understood through the following illustrative and non-limiting detailed description of preferred embodiments, with reference to the appended drawings, where the same reference numerals will be used for similar elements, wherein:

Fig. 1 is a perspective view of an electromagnetic coil.

Fig. 2 is a partially translucent perspective view of an electromagnetic coil with indicated cooling fluid flow path and cooling fluid flow direction.

Fig. 3A shows a transversal cross-section of a wind-

ing of the electromagnetic coil comprising a channel. Fig. 3B shows a transversal cross-section of two windings at a location of a cross-connection of the electromagnetic coil.

Fig. 4 shows a translucent cross-sectional perspective view of an electromagnetic coil with simulated flow lines of a cooling fluid.

Fig. 5 shows a plasma confinement device comprising the electromagnetic coil of any one of Fig. 1-4.

Figs 6A and 6B show respective cross-sectional view of cross-connections between channels of adjacent windings of the electromagnetic coil.

Detailed description

[0064] In the following detailed description, some embodiments of the present inventive concept will be described more fully with reference to the accompanying drawings, in which preferred and/or exemplary variants of the inventive concept are shown. This inventive concept may, however, be embodied in many different forms and should not be construed as limited to the variants set forth herein; rather, these variants are provided for thoroughness and completeness, and fully convey the scope of the inventive concept to the skilled person. It is further to be understood that features of the different embodiments are exchangeable between the embodiments and may be combined in different ways, unless anything else is specifically indicated. Like reference numerals refer to like elements throughout the description.

[0065] Initially an electromagnetic coil 10 having a cooling system will be described with references to Figs. 1-4. The electromagnetic coil 10 will be described without specifying in what context the electromagnetic coil 10 is installed. However, the electromagnetic coil 10 may be used in a number of different applications and application areas. An example of this will be described below with reference to Fig. 5 in which an electromagnetic coil 10 is installed in a plasma confinement device 100. The described example is however to be considered as non-limiting, meaning that the electromagnetic coil 10 may equally well be used in any suitable circumstances.

[0066] Fig. 1 shows an electromagnetic coil 10 comprising six windings 12 of an electrically conducting material such as copper and/or aluminum alloy, however, it is to be understood that the electromagnetic coil 10 may have any number of windings 12. The electromagnetic coil may e.g. have a diameter of 5-15 meters, and a height or length of 1-5 meters. The electromagnetic coil 10 may be a resistive, non-superconducting, coil prone to generating heat and/or overheating. However, the electromagnetic coil 10 may be any type of electromagnetic coil 10. Throughout the application, the electromagnetic coil 10 is depicted to have circular windings 12 forming a cylindrical coil, however, the electromagnetic coil 10 may have any suitable shape, the electromagnetic coil 10 may, e.g., have quadratic or rectangular windings 12 forming a coil having a rectangular block shape.

[0067] The electromagnetic coil 10 may comprise a non-conductive material 14 arranged between each winding 12. The non-conductive material 14 may be a material having substantially lower conductivity than the conducting material of the electromagnetic coil 10. The non-conductive material 14 may be an insulating material. The non-conductive material 14 may be a non-conductive layer and/or coating. The non-conducting material 14 may, e.g., be: Mylar (polyester film) having high dielectric strength, low moisture absorption, and good temperature resistance; Nomex (aramid paper) being a strong and heat-resistant material that is commonly used in high-temperature applications; Teflon (polytetrafluoroethylene or PTFE) being a highly inert and stable material with electrical insulation properties; Kapton (polyimide film) being a versatile and durable material capable of withstand high temperatures and harsh environments; and/or glass fiber having a high thermal stability and mechanical strength. However, the non-conductive material 14 may be any suitable material, the non-conductive material 14 may e.g. be air.

[0068] Another, or the same, non-conductive material may further be used for leakage sealing between the windings 12, thus preventing leakage of the cooling fluid. Such a non-conductive sealing material may be rubber (e.g. nitrile, Viton®) or Kalrez®.

[0069] Here, the electromagnetic coil 10 is further seen to comprise a transversal cross-section 11 having a channel 20, wherein the channel 20 runs through a center of each winding 12. In other words the channel 20 here forms a duct running through each winding 12. The channel 20 may be an extrusion through the windings 12 of the electromagnetic coil 10. However, the channel may not necessarily be limited to run through the center of the windings 12, the channel 20 may be an open channel 20 and/or from a groove in the windings 12. The channel 20 may be configured to receive and/guide a cooling fluid through the electromagnetic coil 10.

[0070] The electromagnetic coil 10 of Fig. 1 comprises a spiral-shaped conductor comprising the several windings 12. Thus, the channel 20 for the cooling fluid may run through the whole electromagnetic coil. Alternatively, for example, the windings may be single (e.g., circular) windings electrically connectable in parallel and each comprising a channel for the cooling fluid not connected to the channels of other windings except for at one or more cross-connections (cf. below).

[0071] Moreover, the channel 20 may not necessarily comprise open ends. In other words, the transverse ends of the channel 20 may be stops and/or plugs. Alternatively, the ends of the electromagnetic coil 10 constituted by the transversal end of the of the first and last windings 12, respectively, may be configured to be connected to other electromagnetic coils 10. In particular, one end of a first electromagnetic coil 10 may comprise a female interconnection member configured to receive a male interconnection member of a second electromagnetic coil 10, and/or the other end of the electromagnetic coil

10 may comprise a male interconnection member configured to receive a female interconnection member of a third electromagnetic coil 10. In other words, the electromagnetic coil 10 may be an electromagnetic coil module. The interconnected electromagnetic coil modules may consequently allow of connection of a channel 20 of a first electromagnetic coil 10 with a channel 20 of second electromagnetic coil 10.

[0072] The channel 20 may, for example, have a diameter or width of 3-20 centimeters.

[0073] Further in Fig. 1, the channel 20 of the electromagnetic coil 10 comprises a plurality of inlets 22 arranged at a top portion of the first winding 12. However, the plurality of inlets 22 may be arranged at any suitable portion of the electromagnetic coil 10. The inlets 22 may be openings or ports configured to allow the cooling fluid to enter the electromagnetic coil 10 and flow through its internal channel 20. The inlets 22 may e.g. have a diameter or width of 3-20 centimeters.

[0074] Here, the plurality of inlets 22 are evenly distributed along the circumference of the first winding 12 of the electromagnetic coil 10. However, it is to be understood that the plurality of inlets 22 may be unevenly and/or irregularly distributed along the circumference of the electromagnetic coil. The plurality of inlets 22 may be configured to receive a cooling fluid from a fluid reservoir in fluid contact with the plurality of inlets 22 of the first winding 12.

[0075] In Fig. 2, a partially translucent view of an electromagnetic coil 10 is seen. The electromagnetic coil 10 comprises a plurality of windings 12 distanced by a non-conductive material 14, each winding 12 having a transversal cross-section 11 comprising a channel 20 running through the center of each winding 12, and a first winding 12 comprising a plurality of inlets 22.

[0076] Fig. 3A, the transversal cross-section 11 of the winding 12 of the electromagnetic coil 10 is shown to comprise the channel 20. In particular, the winding 12 is here seen to have a transversal cross-section 11 comprising the channel 20 which runs through a center of the winding 12.

[0077] Here, the transversal cross-section 11 is a vertical slice of the winding 12 of the electromagnetic coil 10. In other words, the transversal cross-section 11 is here perpendicular to an elongation or length of the winding 12. In other words, the transversal cross-section 11 may be a slice of the winding 12 of the electromagnetic coil 10 perpendicular, or substantially perpendicular, to a main direction of current flow of a winding 12 of the electromagnetic coil 10. However, the transversal cross-section 11 may be any slice of the electromagnetic coil 10, e.g. along a length of the electromagnetic coil 10. The transversal cross-section 11 may, e.g., have the dimensions of 5-15 cm by 15-25 cm.

[0078] Turning back to Fig. 2, the electromagnetic coil 10 is here further seen to comprise a plurality of outlets 24 arranged at a bottom portion of a last winding 12 of the electromagnetic coil 10, however, the outlets 24 may be

arranged at any suitable location of the electromagnetic coil 10. The outlets 24 are evenly distributed along the circumference of the electromagnetic coil 10, however, it is to be understood that the outlets 24 may be unevenly distributed and/or irregularly arranged along the circumference of the electromagnetic coil 10. Moreover, the outlets 24 are here seen to be substantially aligned with the inlets 22, however, the outlets 24 and the inlets 22 may be non-aligned. Each, or an, outlet 24 may be equidistant to two arbitrary and/or neighboring inlets 22. The inlets 22 and outlets 24 may form an acute angle to their corresponding channel 20, however, the inlets 22 and outlets 24 may form any angle with their respective channel 20. The outlets 24 may further be configured to be fluidly connected to a fluid reservoir.

[0079] Fig. 2 further depicts a plurality of cross-connections 26 configured to fluidly connect the channel 20 of each winding 12 with a channel 20 of at least one neighboring and/or adjacent winding 12. In other words, each cross-connection 26 run between the channels 20 of two windings 12 of the electromagnetic coil 10. The cross-connections 26 may be formed by extrusions in the windings 12 of the electromagnetic coil 10. The cross-connections may have a diameter or width of 3-20 centimeters.

[0080] Fig. 3B shows a transversal cross-section 11a (cf. Fig. 2) of the winding 12 of the electromagnetic coil 10 leaving the channel 26 in a downward direction and a transversal cross-section 11b (cf. Fig. 2) of the winding 12 of the electromagnetic coil 10 joining the channel 20 from above.

[0081] Turning back to Fig. 2, each cross-connection 26 is here seen to be formed by a hole, i.e. channel access-point, of each winding 12 being aligned with a hole, i.e. channel access-point, of another winding 12. It is to be understood that also the non-conductive material 14 here comprises a hole and/or any construct allowing fluid to flow through the cross-connections 26 connecting the channels 20 of the windings 12.

[0082] The cross-connections 26 are further seen to be evenly distributed along the circumference of the electromagnetic coil 10. However, the cross-connections 26 may be unevenly distributed and/or irregularly arranged along the circumference of the electromagnetic coil 10. Alternatively, at least a subset of the cross-connections 26 may be circumferentially evenly distributed along the electromagnetic coil 10.

[0083] With reference to Fig. 2, the cross-connections 26 depart from, and join, the channels 20 at respective angles α and β . In other words, a cross-connection 26 may depart from one channel 20 at one angle α and join another channel 20 at another angle β .

[0084] In the example of Fig. 2, angles α and β are equal, i.e., have the same magnitude. Further, α and β are both acute angles, however, it is to be understood that the angle α or β may not be acute. In other words, the angle α may be acute while the angle β may form any angle with the channel 20, and vice versa.

[0085] However, the angles α and β may be the same or different for all cross-connections 26. It is to be understood that a subset of the cross-connections 26 may have an acute angle α and/or β different from the acute angle α and/or β of another subset of the cross-connections 26. The acute angle α and/or β may be between 10 and 50 degrees, between 20 and 40 degrees, between 25 and 35 degrees. However, the cross-connections 26 may form any suitable angle α and/or β with the channels 20, the angle α and/or β may e.g. be a right-angle. The angle α and/or β between the cross-connections 26 and the channels 20 may be the same as the angle between the inlets 22 and/or outlets 24 and their respective winding 12 channel 20. All cross-connections 26 may form the same, different, partly the same, or partly different angles α and/or β to the channels 20.

[0086] Figs 6A and 6B illustrate examples of the angles α and β in more detail. In Fig. 6A, the angles α and β are seen to be the same. However, as seen in Fig. 6B, some angles α and β may be different in relation to each other. In particular, the cross-connections 26 here depart from, and joins, the channels 20 of two adjacent windings 12 at different angles α , β .

[0087] Turning back to Fig. 2, it is also seen that the cross-connections 26 form straight channels, i.e. ducts, however, the cross-connections 26 may have a curvature and/or be bent. The cross-connections 26 may particularly have an arc-shape.

[0088] It is further depicted here that a center of each cross-connection 26 is substantially aligned with a center of another cross-connection 26 between any two windings 12. In other words, a first cross-connection 26 between a first winding and a second winding is aligned with a second cross-connection 26 between the second winding and a third winding. However, the cross-connections 26 may be non-aligned and/or arranged in any suitable manner, the cross-connections 26 may be equidistant to neighboring cross-connections 26 of the same and/or a different winding 12.

[0089] In Fig. 2, the electromagnetic coil is also shown having a staircase-shaped flow path 30 of the cooling fluid is further depicted. In particular, the cross-connections 26 are circumferentially displaced with respect to each other so as to form a staircase-shaped flow path 30 for the cooling fluid between the windings 12 of the electromagnetic coil 12. Fig. 2 particularly shows two staircase-shaped flow paths 30, however, it is to be understood that the electromagnetic coil 10 may comprise a plurality staircase-shaped flow paths 30. The staircase shaped flow paths 30 may be parallel or substantially parallel. The staircase-shaped flow paths 30 may allow for a cooling fluid to flow through the entirety of the electromagnetic coil 10 and/or the channels 20 of the electromagnetic coil 10. In other words, the staircase-shaped flow paths 30 may jointly cover the whole electromagnetic coil 10 and/or allow for the cooling fluid to flow through a majority of the electromagnetic coil 10.

[0090] The cross-connections 26 are angled with the

acute angles α and β such that the fluid may flow and/or be guided towards a successive cross-connection 26 according to the staircase-shaped flow path 30.

[0091] Even though not shown in Fig. 2, there may be a seal, plug, or barrier arranged in connection with the cross-connections 26. In particular, the channel 20 from which a cross-connection 26 departs, may be sealed at a location adjacent to, and past, the cross-connection 26. In other words, there may be a seal in connection with each or some cross-connections 26 such that the cooling fluid is guided and/or forced to take the staircase-shaped flow path 30. The seal may be a non-conductive seal. The seal may be positioned past a cross-connection 26 in the direction of the flow of the cooling fluid indicated by the arrows on the staircase-shaped flow path 30. In other words, each staircase-shaped flow path 30 may not necessarily mix or interfere with other staircase-shaped flow paths 30. Each staircase-shaped flow path 30 may be sealed-off from the other staircase-shaped flow paths 30.

[0092] Fig. 4 shows a perspective cross-sectional translucent view of the electromagnetic coil 10. In particular, Fig. 4 depicts simulated flow lines 32 of the cooling fluid. The simulated flow lines 32 here show that the cooling fluid flows in a staircase-shaped flow path 30. The cooling fluid may flow in the staircase-shaped flow path 30 due to its momentum and/or dynamic pressure achieved by a high input pressure of the cooling fluid through the inlets 22 of the electromagnetic coil 10.

[0093] The cooling fluid may be water, oil, a refrigerant, or any other fluid that has a high specific heat capacity and thermal conductivity. The cooling fluid may be any suitable liquid. The cooling fluid may have a relatively high density, e.g. in comparison to air or water, such that a greater momentum of the cooling fluid is obtained and a defined staircase-shaped flow path 30 is achieved.

[0094] The cooling fluid may further be guided and/or forced to flow in a staircase-shaped flow path 30 due to seals and/or plugs (not shown) positioned in the channel 20 in connection with the transitions of the cooling fluid from one winding 12 to another winding 12 through the cross-connections 26.

[0095] Fig. 5 shows a plasma confinement device 100 having a housing 102 comprising the electromagnetic coil 10 of any one of Figs. 1-4. The plasma confinement device 100 is here a magnetic mirror machine configured to provide a stable enclosure of plasma and/or create a stable fusion process. The plasma confinement device 100 may be an open-field-line plasma confinement device. The plasma confinement device 100 comprises a plasma vessel 104, as well-known per se in plasma fusion technology. The plasma confinement device 100 further comprises a magnet system 110 with a space in-between where a plasma may be confined. The magnet system 110 may comprise the least one electromagnetic coil 10, where the current direction and current magnitude create an annular plasma confinement area with a magnetic field.

Claims

1. An electromagnetic coil (10) having a transversal cross-section (11) comprising a channel (20) for a cooling fluid, wherein said electromagnetic coil (10) comprises a plurality of cross-connections (26) for said cooling fluid, each cross-connection (26) of said plurality of cross-connections (26) running between the channels (20) of two windings (12) of said electromagnetic coil (10), wherein said plurality of cross-connections (26) are circumferentially displaced with respect to each other so as to form a staircase-shaped flow path (30) for said cooling fluid between the windings (12) of said electromagnetic coil (10). 5
2. The electromagnetic coil (10) of claim 1, wherein a cross-connection (26) of said plurality of cross-connections (26) runs between the channels (20) of two adjacent windings (12) of said electromagnetic coil (10). 10
3. The electromagnetic coil (10) of any one of claims 1-2, wherein a cross-connection (26) of said plurality of cross-connections (26) departs from and/or joins a channel (20) at an acute angle (α). 15
4. The electromagnetic coil (10) of claim 3, wherein said acute angle (α) is between 10 and 50 degrees, preferably between 20 and 40 degrees, and even more preferably between 25 and 35 degrees. 20
5. The electromagnetic coil (10) of any one of claims 1-2, wherein a cross-connection (26) of said plurality of cross-connections (26) departs from or joins a channel (20) at a right angle. 25
6. The electromagnetic coil (10) of any one of claims 1-5, wherein a channel (20) from which a cross-connection (26) of said plurality of cross-connections (26) depart is sealed at a location adjacent to and past said cross-connection (26), said channel (20) preferably being sealed by means of a plug. 30
7. The electromagnetic coil (10) of any one of claims 1-4, wherein a plurality of inlets (22) of a first winding (12) of the electromagnetic coil (10) are configured to receive the cooling fluid from a fluid reservoir in fluid contact with the plurality of inlets (22) of the first winding (12). 35
8. The electromagnetic coil (10) of any one of claims 1-7, wherein the cooling fluid is a cooling liquid. 40
9. The electromagnetic coil (10) of any one of claims 1-8, wherein the electromagnetic coil (10) is a resistive coil. 45
10. The electromagnetic coil (10) of any one of claims 1-9, wherein a first cross-connection (26) between a first winding (12) and a second winding (12) is aligned with a second cross-connection (26) between said second winding (12) and a third winding (12). 50
11. The electromagnetic coil (10) of any one of claims 1-10, wherein at least a subset of cross-connections (26) in said plurality of cross-connections (26) are circumferentially evenly distributed along said electromagnetic coil (10). 55
12. The electromagnetic coil (10) of any one of claims 1-11, said electromagnetic coil (10) being an extruded profile.
13. The electromagnetic coil (10) of any one of claims 1-12, wherein said channel (20) is internal to said electromagnetic coil (10).
14. A plasma confinement device (100) comprising the electromagnetic coil (10) of any one of claims 1-13.
15. A method of cooling an electromagnetic coil (10), comprising running (1000) a cooling fluid through said electromagnetic coil (10), said electromagnetic coil (10) having a transversal cross-section (11) comprising a channel (20) for a cooling fluid, wherein said electromagnetic coil (10) comprises a plurality of cross-connections (26) for said cooling fluid, each cross-connection (26) of said plurality of cross-connections (26) running between the channels (20) of two windings (12) of said electromagnetic coil (10), wherein said plurality of cross-connections (26) are circumferentially displaced with respect to each other so as to form a staircase-shaped flow path (30) for said cooling fluid between the windings (12) of said electromagnetic coil (10).

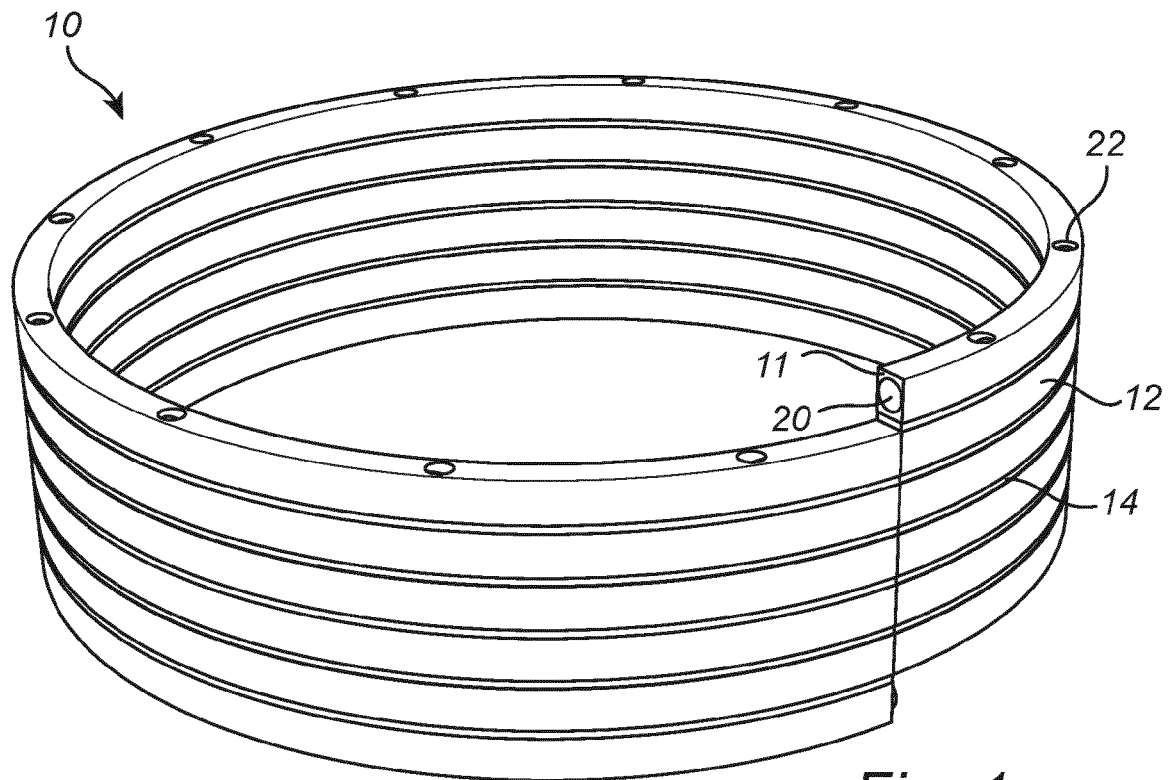


Fig. 1

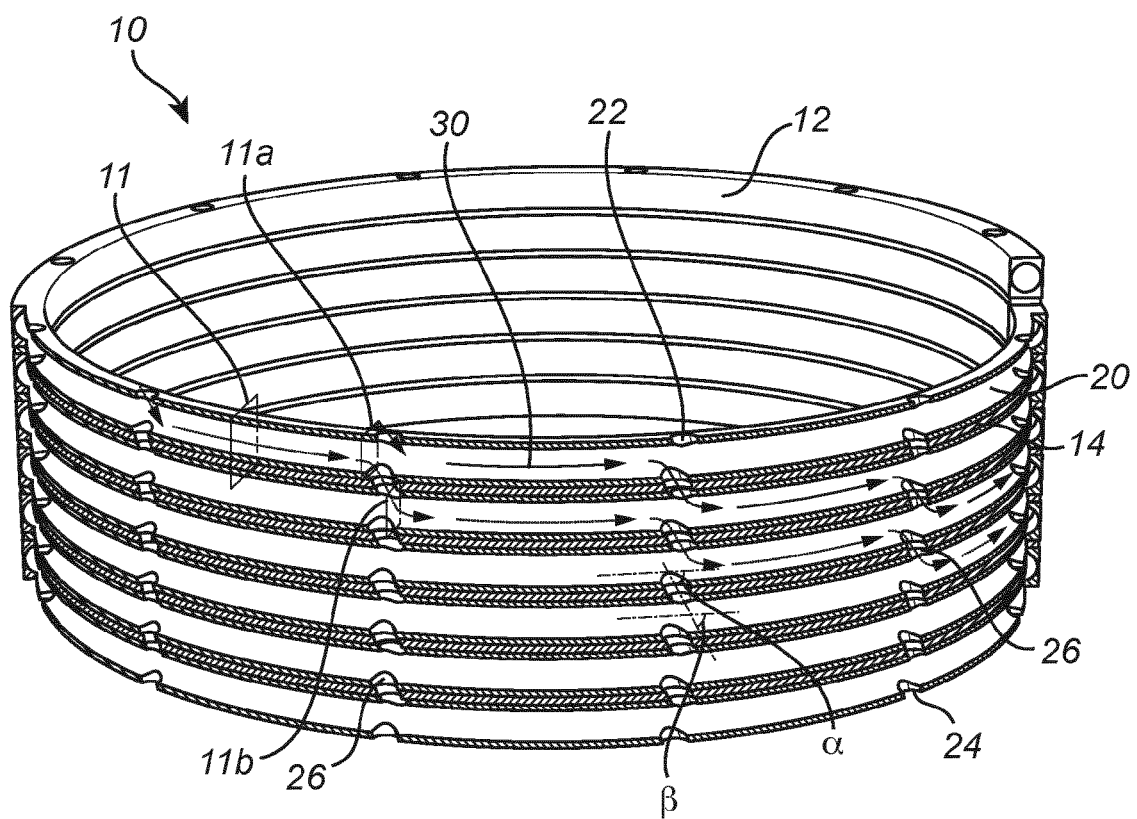
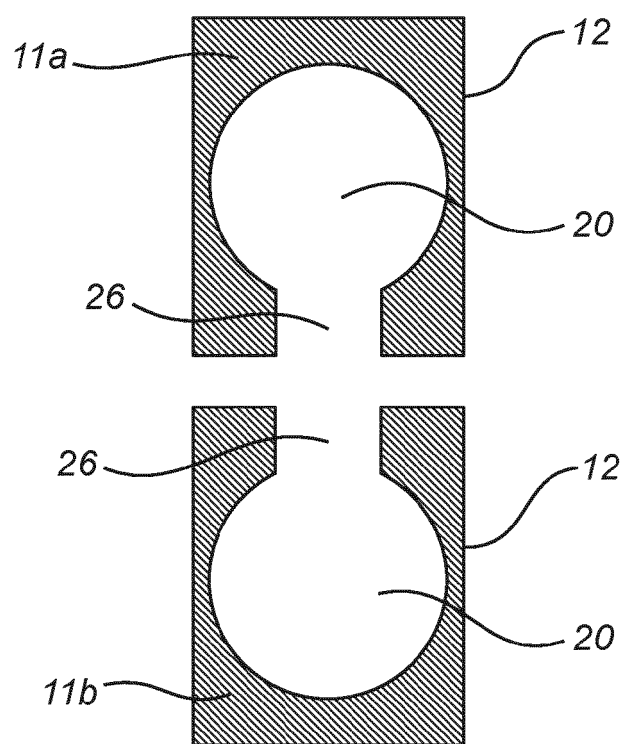
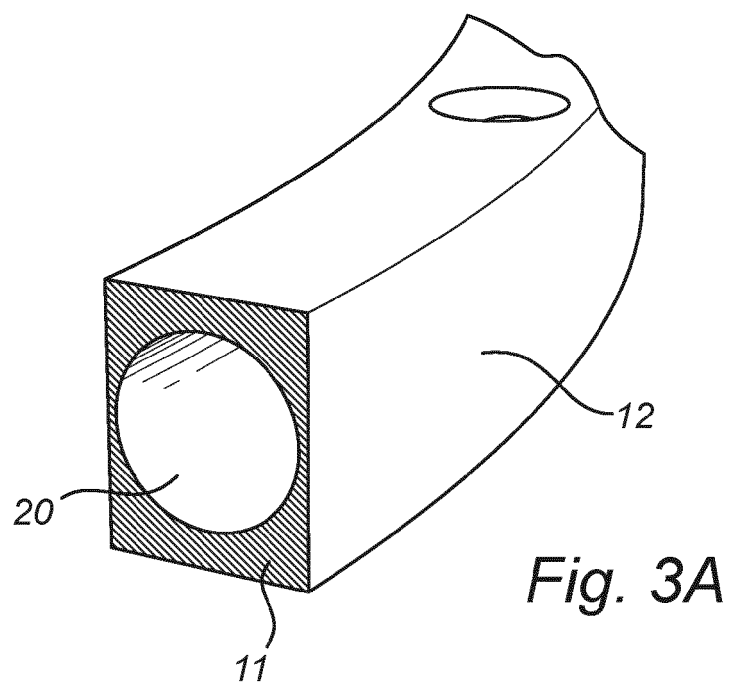
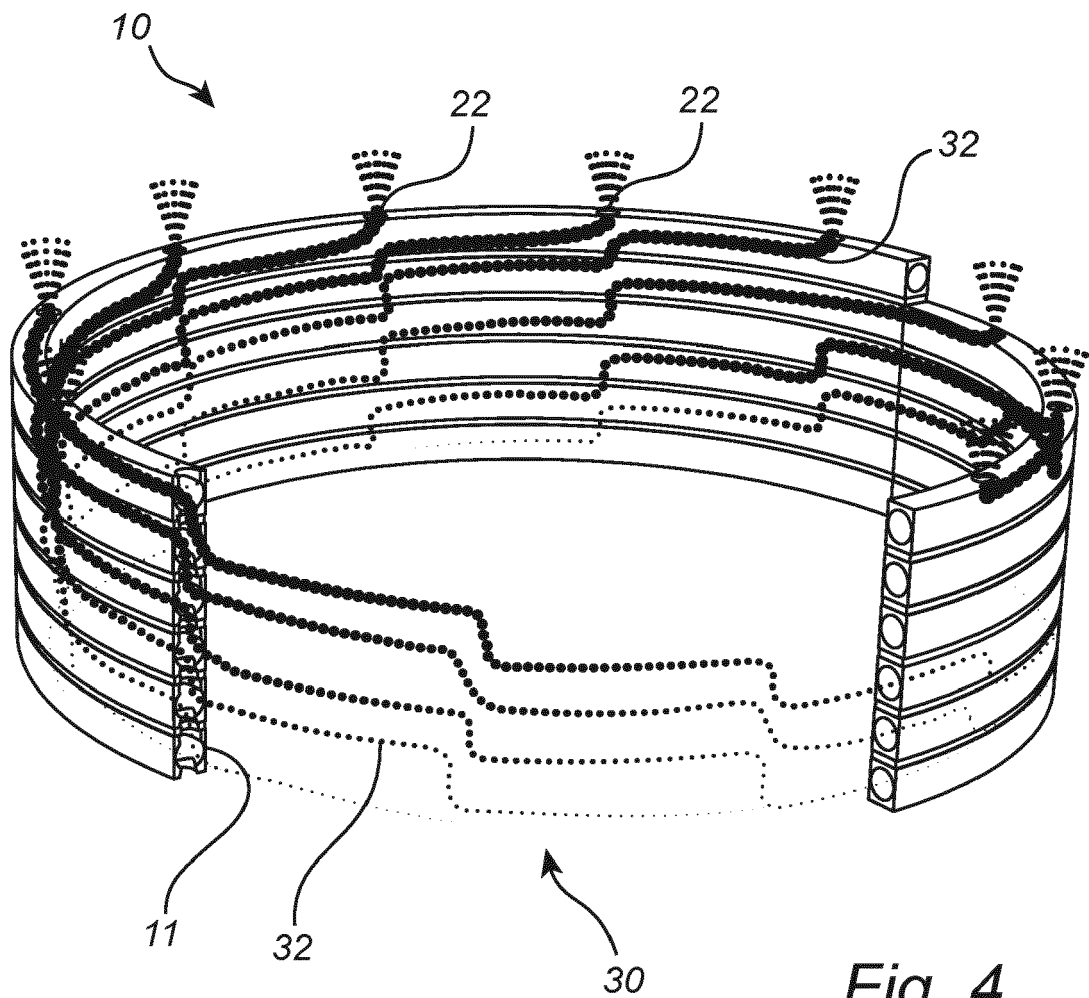


Fig. 2





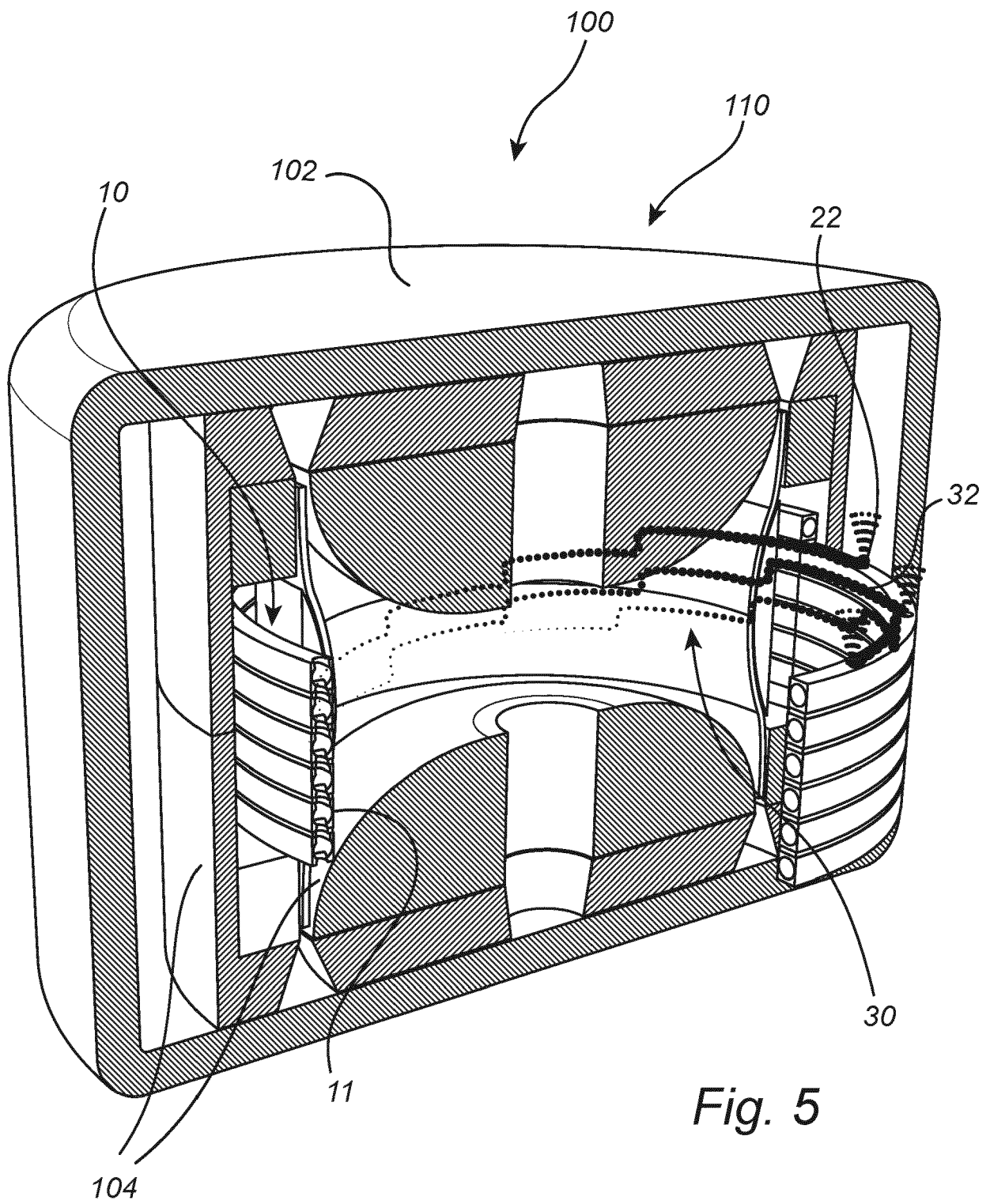
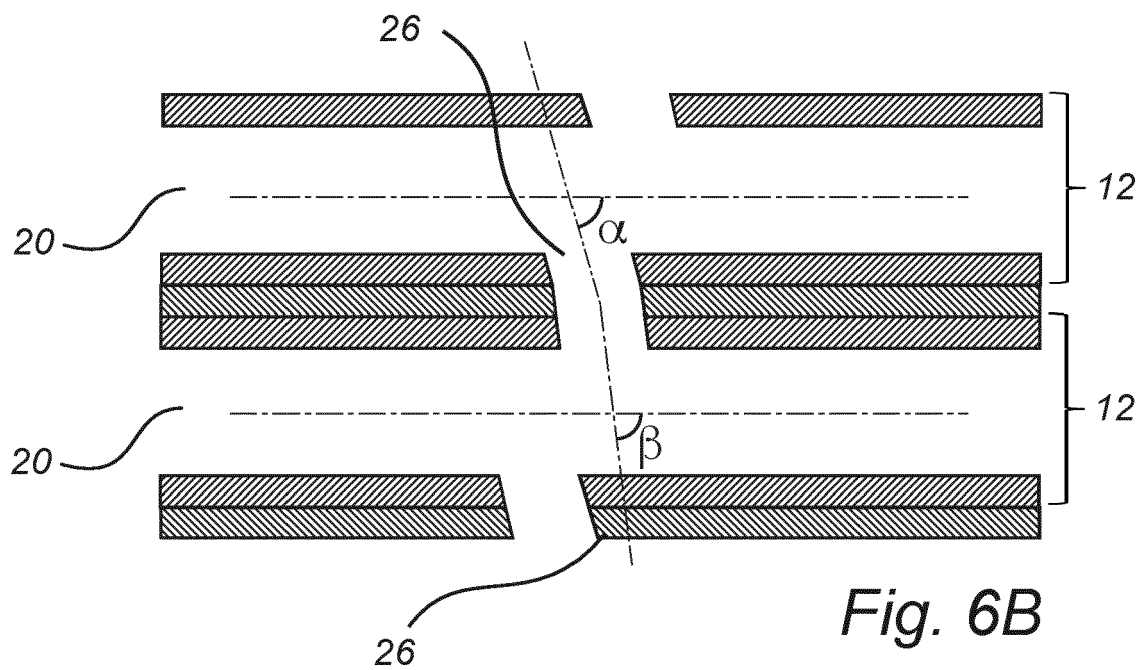
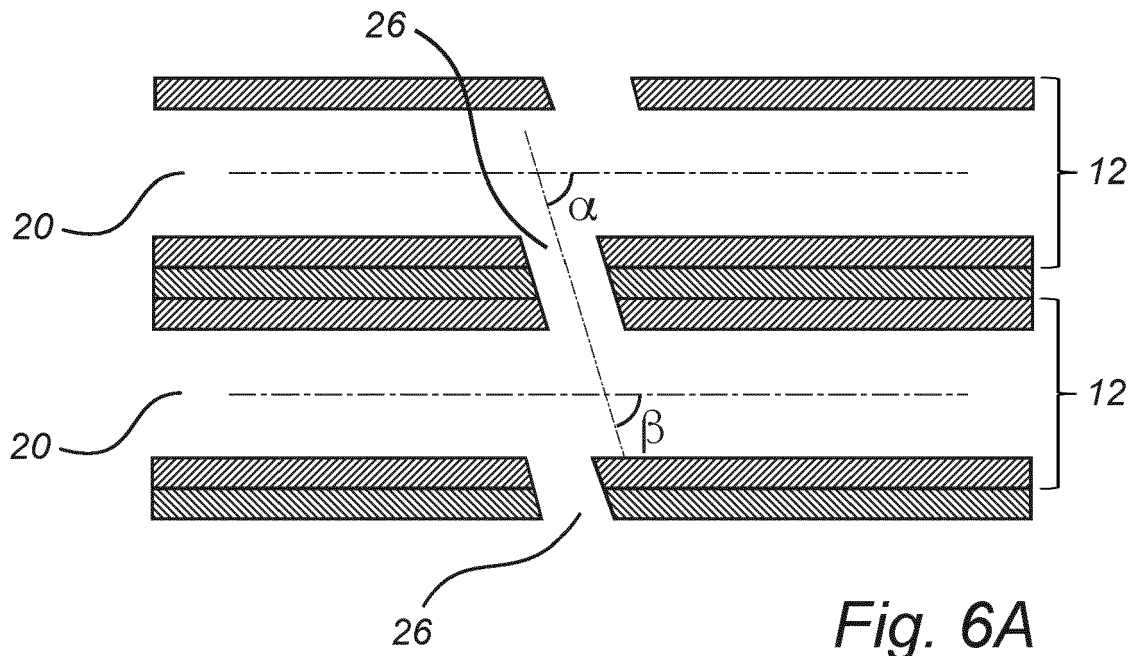


Fig. 5





EUROPEAN SEARCH REPORT

Application Number

EP 23 18 3628

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A	* abstract *; figures 1-8 * * column 4, line 24 - column 5, line 39 * * column 1, lines 6-21 *	3, 4, 6	H01F27/28 G21B1/05
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Place of search		Date of completion of the search	Examiner
Munich		20 December 2023	Reder, Michael
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