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1	Provisional Cover Sheet (SB16)	Princeton-96601-SB16.pdf	2032464 ba50327d6856a0bcb6f78ef9f69628863a38bfb9	no	4
Warnings:					
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2	Specification	Princeton-96601-Application.pdf	295119 15ebcc869569e0ce9d13db4c7c7aa8dfcf02f1b2	no	21
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Provisional Application for Patent Cover Sheet

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c)

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Title of Invention	SINGLE-TORUS-LIQUID-METAL-COIL FUSION DEVICE TO OBTAIN ALL STELLARATOR AND TOKAMAK CONFIGURATIONS
Attorney Docket Number (if applicable)	Princeton - 96601

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● The address corresponding to Customer Number	○ Firm or Individual Name
Customer Number	14333

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

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DOE Grant Nos. DE-AC02-09-CH11466 and DE-SC0022005

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Applicant asserts small entity status under 37 CFR 1.27 or applicant certifies micro entity status under 37 CFR 1.29

● Applicant asserts small entity status under 37 CFR 1.27
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Signature	/Thomas F. Meagher/			Date (YYYY-MM-DD)	2023-10-20
First Name	Thomas	Last Name	Meagher	Registration Number (If appropriate)	29831

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SINGLE-TORUS-LIQUID-METAL-COIL FUSION DEVICE TO OBTAIN ALL STELLARATOR AND TOKAMAK CONFIGURATIONS

[0001] STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under Grant Nos. DE-AC02-09-CH11466 and DE-SC0022005 awarded by the Department of Energy. The government has certain rights in the invention.

[0003] DETAILED DESCRIPTION

[0004] Disclosed herein is a single-torus-liquid-metal-coil fusion device to obtain all stellarator and tokamak configurations.

[0005] Disclosed is a method for the design of fusion devices (tokamaks and stellarators) that achieve magnetic confinement of plasmas with electromagnetic coils made of a single torus coil. Torus single coil design allows archiving all the possible magnetic field configurations which is very useful for comparing the performance of different stellarators. Current on the torus is unconstrained, and flows along the surface. The conductive torus itself can be made from large 2D super conducting sheets that are not yet commercially available, or a solid metal conductor such as copper. However, this design allows a way to use liquid metal inside a shell as the coil as well. It is an improvement to the current design of tokamaks and stellarators.

[0006] Conventionally, the magnetic field of fusion devices is generated by running electric currents through a set of separate coils. The disclosed approach is to build a single toroidal shell or a set of plates that form a toroidal shell, with liquid metal inside the shell. An electric current is to be applied in the liquid metal inside the shell, and this current would generate a magnetic field that achieves the confinement desired for the device. This approach allows the design of a toroidal confinement system that does not require the construction of separate coils, but merely the installation of voltage sources at specific locations of the toroidal shell.

[0007] The disclosed approach would allow the implementation of different configurations of magnetic fields in a single device. This would be advantageous as it would allow the study of different magnetic confinement concepts on a midsize device without the need for the construction of new sets of coils. Furthermore, for the construction of stellarators, it would avoid the need for complex and convoluted shapes for the coils. Additionally, the disclosed approach does not require superconducting magnet technology, nor the development of new technology for implementation.

[0008] The disclosed approach offers further advantages for reactor operation, as it could operate as a cooling system – tritium breeder - coil set combination in a single liquid-metal system. This combination of systems leads to significant reductions in manufacturing costs, both for research facilities and for future fusion power plants.

[0009] The disclosed combined liquid metal system can generate magnetic fields, breed tritium as the fuel for the fusion reaction, and transfer heat for electricity generation. Liquid metal systems have been suggested as heat carriers [1] and tritium breeding [2] but not for magnetic field generation or a combination of all these systems. The disclosed approach has potential advantages, *inter alia*, in reduced complexity and construction costs, flexibility to test different magnetic confinement concepts.

[0010] An immediate application of the disclosed approach would be for a single test reactor to compare different stellarator designs in a single machine. All the possible stellarator magnetic configurations can be achieved without any modification to the hardware but by only changing the voltage on power supplies that feed to the system.

[0011] Another application would be for liquid-metal electromagnetic coils of magnetic-confinement-fusion devices. These coils could also serve as tritium breeders and neutron shields.

Other uses in the future could include industrial applications that require any magnetic field configuration, such as magnetic induction furnaces and magnetic resonance imaging.

[0012] Conventionally, the magnetic field of fusion devices is generated by running electric currents through a set of separate solid coils. Current designs and previously built magnetic confinement devices do not offer modularity for different magnetic configurations in a single device. The disclosed approach is to build a single toroidal shell. While 2D superconducting sheets are not commercially available yet, a single toroidal shell can be constructed with copper to generate an unconstrained flowing current in it. The disclosed approach allows liquid metal inside the shell. An electric current is to be applied in the liquid metal inside the shell, and this current would generate a magnetic field that achieves the confinement desired for the device.

[0013] The disclosed approach aims to reproduce magnetic confinement configurations: tokamaks and stellarators. For the case of a tokamak, toroidal and poloidal fields are generated by running electric currents in the poloidal and toroidal direction on the liquid metal coil. For stellarators, the liquid metal coil would allow the implementation of voltage sources at different positions on the liquid metal coil with different voltage inputs to generate the magnetic field desired. While conventional stellarators require complex shapes for the electromagnetic coils in order to achieve confinement, the disclosed approach would simply have a single toroidal liquid-metal coil, which is much simpler. Moreover, the disclosed device is advantageous as it would be able to yield different stellarator configurations without the need of new sets of coils or to change the shape and size of the coils, only modifications in the voltage inputs are required. This would be advantageous for stellarator optimization studies.

[0014] In addition, the liquid-metal-coil system offers low-cost construction of coils that do not encounter several of the engineering issues of solid coils: high mechanical stress from Lorentz forces and thermal expansion. Moreover, the liquid-metal coil around the plasma could also work as a neutron shield (if liquid lithium is used). Furthermore, the use of liquid lithium in this system as a coating/thin film flow on the reactor walls would allow low recycling of hydrogen isotopes [3]. Finally, the toroidal shell could also be modular by cutting it into smaller sections (multiple liquid-metal coils). The latter would be helpful as it would allow the separation of liquid-metal chambers for magnetic field purposes.

[0015] Overall, the disclosed approach offers simplicity for construction, as it would not need superconducting coils or cryocoolers for their operation. Also, there is no need for the development of new superconducting-magnet technology, as it would only need a toroidal liquid metal coil and pumps to purge liquid metal out of the system when necessary.

[0016] There are several liquid-metal candidates for fusion applications: lithium, lead-lithium (Pb-Li alloy), tin and gallium alloys (such as gallium indium tin eutectic). The size of the reactor is a function of the maximum electrical current density that is permissible in the liquid metal coil, and the maximum heat flux load/ohmic heating allowed on the heat transfer system of the coil. There is little information about the maximum current density for liquid metals, given that it is defined as a temperature constraint to avoid overheating. For all liquid metal options aforementioned, the maximum current density is assumed to be that of gallium-indium-tin eutectic (~10-20 MA/m^2) [4].

[0017] For illustration purposes of a test machine, the parameters of the National Compact Stellarator Experiment (NCSX) are used. This device was designed to have a major radius of 1.4 m, minor radius of 0.32 m and to operate with a toroidal magnetic field of 1.7 T. A safety factor of 3.5 is assumed for the estimation of a poloidal magnetic field of 0.11 T. Tin is chosen as the material for the coils. The electrical conductivity of tin is 8.7 MS/m, and the melting point is 232˚C in the open atmosphere. The operational current density in the liquid metal is fixed at 10 MA/m^2. For the aforementioned parameters, the size, power requirements and critical aspects were calculated and are shown in Figure 2.

[0018] The plots shown in Figure 2 indicate that for an NCSX-like test machine, a coil thickness of 20 cm would be required. The ohmic power to generate the magnetic fields is ~ 20 MW. Moreover, if all the ohmic heating is assumed to be used to melt the solid tin coils, it would take ~ 1.3 min to melt them. In reality it would take more time as some heat would be transferred to the surroundings. The latter indicates that there would be plenty of time to run tests and measurements before melting the solid-tin coils. The peak magnetic field in the coil would be 7.5 T. Moreover, the plots in Figure 2 also indicate there is room for improvements in case any of the operational parameters need to be modified.

[0019] Furthermore, the construction of a liquid metal coil poses several advantages for structural integrity. Lorentz forces that usually bend solid coils and disimprove their performance would no longer be an issue for a liquid metal conductor. While there would be a Lorentz force applied on the liquid metal, no net reshaping of the coil is expected. The main structural damage expected would be on the substrate that supports the liquid metal coil from neutron bombardment from the burning plasma and also from Lorentz forces applied to the duct where liquid metal flows. However, cost reductions are expected given that this system offers modularity for testing different magnetic configurations.

[0020] The heat-carrier system of the liquid-metal-coil is expected to handle the heat flux load on the first wall and the ohmic heating generated by driving currents through them. The peak heat-flux load at the divertor targets is the most critical load and a divertorlets system is suggested [5-6]. The disclosed approach would be implemented to handle this heat load while avoiding liquid metal overheating with low-hydrogen recycling conditions. A simple diagram of the divertorlets system in a tokamak is shown in Figure 3.

[0021] For a liquid lithium or lead-lithium alloy coil system, isotope separation (deuterium and tritium) from lithium could be achieved with the Magnetic Centrifuge for LiH-Li separation For deuterium and tritium extraction from liquid lithium (DTX, patent disclosure M-924 [7]). This device is a hydrogen isotope concentrator with no moving parts. It is based on the density difference between liquid lithium and different lithium hydrides: LiH/LiD/LiT. The magnetic centrifuge uses Lorentz forces to induce centrifugal motion, only the concentrate needs to be pumped out of the reactor for further separation. Overall, this will reduce lithium inventory and pumping requirements.

[0022] The disclosed approach would not require new manufacturing methods besides the ones that are already used for the construction of magnetic confinement devices. The disclosed approach is to build a single toroidal shell or a set of plates that form a toroidal shell, with liquid metal inside the shell. An electric current is to be applied in the liquid metal inside the shell, and this current would generate a magnetic field that achieves the confinement desired for the device. It is aimed to avoid the need for superconducting technology. However, it could be implemented to add more flexibility to the design.

[0023] Electric currents in the liquid metal would be applied by installing a set of negative and positive voltage leads around specific boundaries of the toroidal shell. The disclosed approach allows the design of a toroidal confinement system that does not require the construction of separate coils, but merely the installation of voltage sources at specific locations of the toroidal shell. Moreover, the modification of the location of the voltage sources would also be possible, which would allow the implementation of different configurations of magnetic fields with just a single device. This would be advantageous as it would allow the study of different magnetic confinement concepts (tokamaks and stellarators) on a midsize device without the need for the construction of new sets of coils. Additionally, it would reduce the cost and avoid the complexity of the manufacturing of discrete coils for stellarators. Further, it relaxes the mechanical stresses on the stellarator coils, which are known to have an impact on superconducting coils.

[0024] For illustration purposes, different implementation examples of a liquid-metal coil are shown below.

[0025] 1. Installation of voltage sources along a toroidal cut (see Figure 4): for this configuration, electric current leads would be installed on two toroidal extrusions and voltages would be applied according to operational parameters desired.

[0026] 2. Installation of voltage sources along a toroidal cut and several poloidal cuts (see Figure 5): for this configuration, electric current leads would be installed on toroidal and poloidal extrusions. The locations of the poloidal cuts would also be determined and the electric voltages would be applied according to operational parameters desired.

Approaches #1 and #2 both rely on minimizing the normal component of the magnetic field on the plasma boundary. The solution is found through an error minimization by varying the voltage inputs on the winding surface and their specific locations. Further computer simulations and calculations of mechanical stress are required to guarantee structural integrity of the solid substrate that supports the liquid metal coils.

The governing equations that are implemented to design this concept are as follows. The plasma enclosed by the winding surface has a plasma current j_p across the volume of the plasma. This current generates a magnetic field B_p with a normal component to the plasma surface.

$$B_p \cdot n_{\Gamma_p} \neq 0,$$

where Γ_p stands for the plasma surface. The total field on the plasma surface B_T and B_p are known and they correspond to a plasma equilibrium. A plasma equilibrium is defined by the force balance, as follows:

$$j_p \times B_T = \nabla p$$

where p is a pressure profile that is provided to compute the plasma equilibrium. Our goal is to achieve $B_T \cdot n = 0$. The common procedure for this consists of generating a secondary magnetic field B_w with a winding surface that satisfies the following:

$$B_T \cdot n = (B_p + B_w) \cdot n = 0$$

The current K on the winding surface will generate this magnetic field, and it is calculated through Biot-Savart's Law:

$$B_w = \mu \int_\Gamma K' \times a \, d\Gamma'$$

where Γ stands for the winding surface and μ is the vacuum permeability. The apostrophe notation is used to indicate functions evaluated using the variable of integration. Additionally, $a = \frac{r-r'}{|r-r'|^3}$. The constraint for this method is that the calculation of K has to be made through the definition of a physical current. First, the current on the winding surface must satisfy Ohm's Law:

$$K = \sigma \nabla_\Gamma V$$

where V is a scalar function, $V = V(\theta, \zeta)$, where θ, ζ are the coordinates on the winding surface. σ represents the electrical conductivity of the liquid metal on the winding surface. The gradient operator is defined as $\nabla = \nabla_\Gamma + \nabla_\perp$, where $\nabla_\perp = n(n \cdot \nabla) = n\partial_n$.

The surface Γ is parameterized through the (θ, ζ) coordinates. Thus, the vector normal to Γ is defined as $n = \frac{e^\rho}{|e^\rho|} = \frac{e_\theta \times e_\zeta}{|e_\theta \times e_\zeta|}$, where $e^\rho, e^\theta, e^\zeta$ are the directional vectors in covariant coordinates, and $e_\rho, e_\theta, e_\zeta$ are the directional vectors in contravariant coordinates. Thus, the gradient operator is defined as $\nabla = e^\rho \frac{\partial}{\partial \rho} + e^\theta \frac{\partial}{\partial \theta} + e^\zeta \frac{\partial}{\partial \zeta}$, where (ρ, θ, ζ) are the space coordinates. Thus $\nabla_\Gamma = \nabla - \nabla_\perp = [e^\theta - n(n \cdot e^\theta)] \frac{\partial}{\partial \theta} + [e^\zeta - n(n \cdot e^\zeta)] \frac{\partial}{\partial \zeta}$

The second constraint is that this current has to satisfy electric charge conservation, which implies the following:

$$\nabla_\Gamma \cdot K = \sigma \nabla_\Gamma^2 V = 0$$

where ∇_Γ^2 represents the Laplace-Beltrami operator for a surface: $\nabla_\Gamma^2 = \nabla_\Gamma \cdot \nabla_\Gamma$.

V is defined with a double Fourier series expansion with unknown coefficients. These coefficients are found through an error minimization:

$$\left(B_p + \int_{\Gamma} \sigma \nabla'_{\Gamma} V' \times a \, d\Gamma'\right) \cdot n \rightarrow 0$$

$$\nabla_{\Gamma}^{2} V \rightarrow 0$$

There is no guarantee that the previous set of constraints will be satisfied to an error threshold that is acceptable for a specific design. For these cases, surface optimization of the plasma boundary must also be implemented. This last step consists of changing the shape of the plasma boundary in order to satisfy our design constraints and also find a surface that is in agreement with a plasma equilibrium.

[0028] A sample result for Approaches #1 and #2 is shown in Figure 6. The procedure consists of changing the shape of the plasma boundary, as shown in Figure 6b, as well as the surface current on the winding surface, shown in Figure 6a. The magnitude of the normal component of the magnetic field on the resulting plasma boundary is also shown in Figure 6b. These preliminary results still require the force balance constraint, which will be implemented in future designs, and the surface current does not exactly satisfy the Laplace equation, which can be achieved in the future by further optimization.

[0029] 3. Installation of current sources at different locations on a grid on the winding surface (see Figure 7): for this configuration, electric current leads would be installed at different points on a grid. The values of the voltages applied at each of these grid points would be determined according to the operational parameters desired.

[0030] The aim of external coils is to obtain the vacuum magnetic field required by stellarators. Thus, any stellarator can be obtained with a single torus coil.

Approach # 3 needs modifications to the previous equations shown for the design procedure. For Approach #3, the constraint for Ohm's Law for K is enforced as follows:

$$K = \sigma\nabla_{\Gamma}V,$$

V is generated by a superposition of current sources on Γ that are represented by dirac-delta distributions in this model. This source is referred to as a scalar function $f(\theta, \zeta)$, where $\nabla_{\Gamma} \cdot K = f(\theta, \zeta)$. Thus, we have the following:

$$\nabla_{\Gamma} \cdot K = \sigma\nabla^{2}_{\Gamma}V = f$$

Electric charge conservation must be satisfied, which requires sources and sinks to sum to zero. In a real scenario, the "current source" would consist of wires connected perpendicular to the winding surface. The power supplies will provide positive and negative current to input and return coils, conservation is automatically satisfied. One would put small quantized voltage or current supplies and put many of them in parallel to achieve different current input to different points on the surface.

B_w is calculated through a modified version of Biot-Savart's Law

$$B_w = \mu\sigma\int_{\Gamma}(\nabla'_{\Gamma}V') \times a\, d\Gamma'$$

V is defined as a double Fourier series expansion with unknown coefficients. These coefficients are found through an error minimization:

$$[B_p + \sigma\int_{\Gamma}(\nabla'_{\Gamma}V') \times a\, d\Gamma'] \cdot n \rightarrow 0$$

This is a one-to-one linear equation between V and B_n. As long as the normal component B_n of the magnetic field is physical (no net magnetic flux out of the surface), one can find an electric potential field V that minimizes B_n. The aim of external coils is to obtain the vacuum magnetic field required by stellarators. Thus, any stellarator can be obtained with a single torus coil.

[0031] A sample result for Approach #3 is shown in Figure 8. The procedure consists of having a fixed plasma boundary, shown in Figure 8a). Then, a set of grid points on the winding surface (see Figure 7) will be assigned continuously varying current sources to reproduce the desired magnetic field (Figure 8a), resulting in the surface current density on the axisymmetric, circular toroidal winding surface (8b) which minimizes the normal component of the magnetic field on the surface (Figure 8c).

4. Installation of voltage sources along a toroidal/poloidal cuts and local current sources/sinks with a surface varying effective resistivity for the coil: for this configuration, electric current leads would be installed on toroidal and poloidal extrusions, same as in Approach #3 . The locations of the poloidal cuts would also be determined and the electric voltages would be applied according to operational parameters desired. However, there is more freedom added to the design by changing the local "effective resistivity" of the liquid metal.

In a real scenario, the liquid metal shell would have a finite thickness and the three-dimensional current distribution j is described by Ohm's Law as follows:

$$j = \sigma \nabla V$$

where $\nabla \cdot j = 0 \rightarrow \nabla^2 V = 0$. Integrating j along the thickness t of the liquid metal shell allows us to simplify the analysis with a surface current K, as follows:

$$\int j dt = K = \sigma_\Gamma \nabla_\Gamma \phi$$

where σ_Γ is the effective conductivity for the surface current, which varies along the surface Γ. For the design stage with this approach, $\nabla_\Gamma \cdot K$ must be enforced through the following equation:

$$\nabla_\Gamma \sigma_\Gamma \cdot \nabla_\Gamma \phi + \sigma_\Gamma \nabla_\Gamma^2 \phi = 0$$

Now, there is no constraint on ϕ to satisfy the Surface-Laplace's Equation $\nabla_\Gamma^2 \phi = 0$. $\nabla_\Gamma^2 \phi$ is allowed to vary freely and the design only requires to find a σ_Γ scalar function that satisfies the desired constraint $\nabla_\Gamma \cdot K$. Finally, the objective functions for minimization are as follows:

$$[B_p + \int_\Gamma (\sigma_\Gamma \nabla_\Gamma \phi') \times a\, d\Gamma'] \cdot n \rightarrow 0$$

$$\nabla_\Gamma \sigma_\Gamma \cdot \nabla_\Gamma \phi + \sigma_\Gamma \nabla_\Gamma^2 \phi \rightarrow 0$$

There are several methods to achieve a surface variation σ_Γ:

> 4.1 Local variation of the thickness of the conductive shell/liquid metal shell: the local effective conductivity σ_Γ is inversely proportional to the local thickness of the conductor along the electric current path. Thus, we can change its thickness t to satisfy the constraint $\nabla_\Gamma \sigma_\Gamma \cdot \nabla_\Gamma \phi + \sigma_\Gamma \nabla_\Gamma^2 \phi = 0$. The local thickness of the liquid metal shell can be modified by introducing a layer of insulating material, like alumina (highlighted in yellow in Figure 9). This would allow the modification of the thickness of the coil without the need of constructing a new support for the liquid metal shell, only adding new layers of insulating material would be necessary.

[0033] 4.2 Installation of non-electrically-conductive structures inside the conductive shell/liquid metal shell: The non-electrically-conductive structures could consist of small alumina pins or simply electrically-insulated metallic components. These structures could also be advantageous to improve the robustness of the frame that supports the conductive shell/liquid metal shell itself.

[0034] 4.3 Attachment of high-electrical-conductivity components at different locations on the winding surface (see Figure 10): these components would be external to the conductive shell/liquid metal shell and they could be installed on top or bottom of the outer side of the shell depending on the configuration choice. These components would have electrical contact with the current that generates the magnetic field desired. The size of these components and their locations on the winding surface would be placed accordingly to minimize the normal component of the magnetic field.

[0035] 4.4 A combination of approaches 4.1, 4.2 and/or 4.3.

[0036] 5. Installation of voltage sources along a toroidal/poloidal cuts and local current sources/sinks on a case-specific designed conductive shell/liquid metal shell: This approach is similar to the conventional design of stellarator coils. The shape of the single coil would be chosen in order to achieve the minimization of the normal component of the magnetic field on the plasma boundary. The case-specific designed winding surfaces could be constructed using 3D-printed metallic components.

[0037] 6. High-temperature solid superconducting coils in combination with a liquid-metal coil: this design would allow a relaxation on the magnetic field generated by the liquid-metal coil. The toroidal magnetic field would be generated with high-temperature superconducting coils, and the poloidal field would be generated by the liquid-metal coil.

[0038] As a note, the pressure in a liquid-metal flow is the sum of gravitational and Lorentz forces, which both vary over the winding surface. Gravitational pressure is highest at the bottom. Lorentz force ($j \times B$) will not be uniform because of the required electric current distribution across the surface. These pressure differences across the winding surface could also be used to pump the liquid metal flow in and out through external ports.

[0039] The design presented is a continuous port placement to adapt the electric current distribution, which needs to be taken into account in the engineering design. Also, an infinitesimally thin surface current was assumed for the analysis presented. However, three-dimensional computational analysis is required for each of the previously mentioned implementation options. Additionally, mechanical stress studies are required for the design of the solid substrate that supports the liquid-metal coil.

[0040] The liquid metal version of the disclosed single coil design is limited primarily in the magnetic field intensity it could generate for several reasons. Electrically conductive materials present a maximum current density they could carry, which constrains the maximum electric current applicable on a conductor with a specific cross section. The latter sets a limit on the magnetic field intensity to be generated.

[0041] Additionally, the heat released from the plasma sets a limit on the minimum size the device could have to avoid melting of solid components and overheating of the liquid metal. Increasing the area of the inner walls of the reactor reduces the heat flux load, but bigger devices lead to more expensive manufacturing costs. Moreover, increasing the reactor size also leads to a reduction of the magnetic field intensity for a given applied electric current on the liquid metal coil set. Moreover, the power required to drive currents in the liquid metal coil sets another limitation in the design, as this power should not surpass the output expected from the device.

[0042] An important goal of the disclosed approach is to achieve a commercially viable fusion reactor for electricity production with increased efficiency, with reduced costs for manufacturing and flexibility to render different magnetic confinement setups. However, it can be used for any machine that needs a specific magnetic field configuration. Unlike high-temperature superconducting coils, a liquid-metal coil could generate magnetic fields in any particular shape and intensity required with a single shape for the coil. In particular, this can be useful for medicine and biological applications with strong magnetic fields (for example magnetic resonance imaging).

[0043] References: Other methods for handling heat on the walls of a tokamak reactor through liquid metal systems have been presented. However, the combination of magnetic field coil set - cycle power plant - tritium breeder in a single liquid metal system is not known to have been presented previously. The divertorlets concept has been published previously and the respective references are shown below:

[0044] 1. J W Coenen et al 2014 Phys. Scr. 2014 014037. https://doi.org/10.1088/0031-8949/2014/T159/014037

[0045] 2. Rubel, M. Fusion Neutrons: Tritium Breeding and Impact on Wall Materials and Components of Diagnostic Systems. J Fusion Energ 38, 315–329 (2019). https://doi.org/10.1007/s10894-018-0182-1

[0046] 3. Majeski, R. (2010, May). Liquid metal walls, lithium, and low recycling boundary conditions in tokamaks. In AIP Conference Proceedings (Vol. 1237, No. 1, pp. 122-137). American Institute of Physics.

[0047] 4. Park YG, An HS, Kim JY, Park JU. High-resolution, reconfigurable printing of liquid metals with three-dimensional structures. Sci Adv. 2019 Jun 21;5(6):eaaw2844. doi: 10.1126/sciadv.aaw2844. PMID: 31245538; PMCID: PMC6588379.

[0048] 5. A. E. Fisher, Z. Sun, and E. Kolemen, “Liquid metal ‘divertorlets’ concept for fusion reactors,” Nuclear Materials and Energy, vol. 25, p. 100855, Dec. 2020, doi: 10.1016/j.nme.2020.100855.

[0049] 6. F. Saenz, Z. Sun, A. E. Fisher, B. Wynne, and E. Kolemen, “Divertorlets concept for low-recycling fusion reactor divertor: experimental, analytical and numerical verification,” Nucl. Fusion, vol. 62, no. 8, p. 086008, Aug. 2022, doi: 10.1088/1741-4326/ac6682.

[0050] 7. M-924. Princeton Plasma Physics Laboratory. (n.d.). Retrieved March 20, 2023, from https://www.pppl.gov/m-924#:-:text=m-924

[0051] 8. G. Komarzyniec, “Cooperation of an Electric Arc Device with a Power Supply

System Equipped with a Superconducting Element,” Energies, vol. 15, no. 7, p. 2553, Mar. 2022, doi: 10.3390/en15072553.

[0052] 9. Osamah Nawfal Oudah and Raad Hameed Majeed 2019 J. Phys.: Conf. Ser. 1234 012114, doi: 10.1088/1742-6596/1234/1/012114

[0053] 10. Lewis, H. Ralph, and Paul M. Bellan. "Physical constraints on the coefficients of Fourier expansions in cylindrical coordinates." Journal of Mathematical Physics 31.11 (1990): 2592-2596.

[0054] The references listed herein are part of the application and are incorporated by reference in their entirety as if fully set forth herein.

* * *

What is claimed:

1. A method for operating a fusion device, comprising:

applying an electric current to a liquid metal coil disposed in a toroidal shell; and

allowing the current to generate a magnetic field that achieves a target level of confinement for the fusion device,

wherein the liquid metal coil is configured to be disposed around a plasma confined by the single toroidal shell.

2. The method of claim 1, further comprising providing a different stellarator configuration by adjusting a voltage input to the liquid metal.

3. The method of claim 1, wherein the liquid metal comprises lithium, lead, tin, gallium, or a combination thereof.

4. The method of claim 1, further comprising providing a cooling fluid thermally communicating with the liquid metal coil.

5. The method of claim 1, further comprising allowing divertorlets within the single toroidal shell to aid in managing a peak heat-flux load.

6. The method of claim 1, further comprising allowing the fusion device to breed tritium as the fuel for the fusion reaction.

7. The method of claim 1, further comprising transferring heat from the fusion device to generate electricity.

8. A single torus coil for fusion devices, comprising:

a toroidal shell; and

a liquid metal coil disposed within the shell;

wherein the liquid metal coil is configured to be disposed around a plasma confined by the toroidal shell.

9. The single torus coil of claim 8, further comprising one or more divertorlets in thermal communication with the liquid metal coil.

10. The single torus coil of claim 8, further comprising a cooling fluid in one or more cooling channels, the cooling fluid being in thermal communication with the liquid metal coil, the cooling fluid being disposed within the toroidal shell, outside the liquid metal coil.

11. The single torus coil of claim 8, wherein the toroidal shell is a single toroidal shell.

12. The single torus coil of claim 8, wherein the toroidal shell comprises a plurality of plates forming a single toroidal shell.

13. The single torus coil of claim 8, wherein the single torus coil is comprised of conductive metal.

14. The single torus coil of claim 8, wherein the single torus coil is free of superconducting materials.

15. The single torus coil of claim 8, further comprising at least one superconducting coil.

16. A system, comprising:

a single torus coil of claim 8; and

one or more power controllers, configured to control a voltage or current flowing to the liquid metal coil.

ABSTRACT

Disclosed is a method for the design of fusion devices (tokamaks and stellarators) that achieve magnetic confinement of plasmas with electromagnetic coils made of a single torus coil. Torus single coil design allows archiving all the possible magnetic field configurations which is very useful for comparing the performance of different stellarators. The conductive torus itself can be made from large 2D super conducting sheets that are not yet commercially available, or a solid metal conductor such as copper. However, this design allows a way to use liquid metal inside a shell as the coil as well. An electric current is to be applied in the liquid metal inside the shell, and this current would generate a magnetic field that achieves the confinement desired for the device. This approach allows the design of a toroidal confinement system that does not require the construction of separate coils, but merely the installation of voltage sources at specific locations of the toroidal shell. The disclosed approach offers further advantages for reactor operation, as it could operate as a cooling system – tritium breeder - coil set combination in a single liquid-metal system. This combination of systems leads to significant reductions in manufacturing costs, both for research facilities and for future fusion power plants.

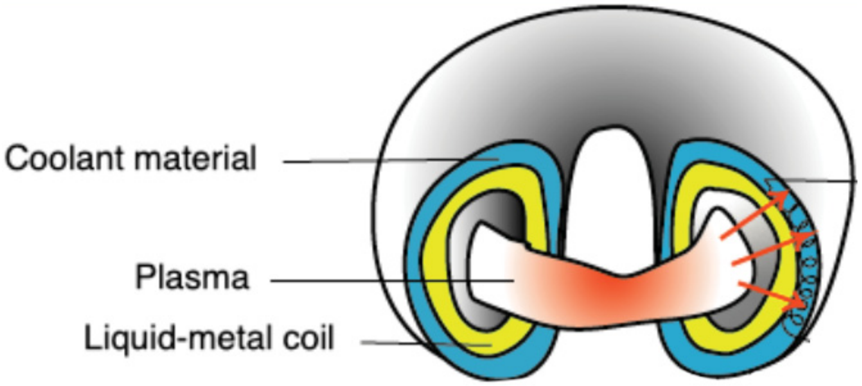


Figure 1. Magnetic-confinement test device with a liquid-metal coil

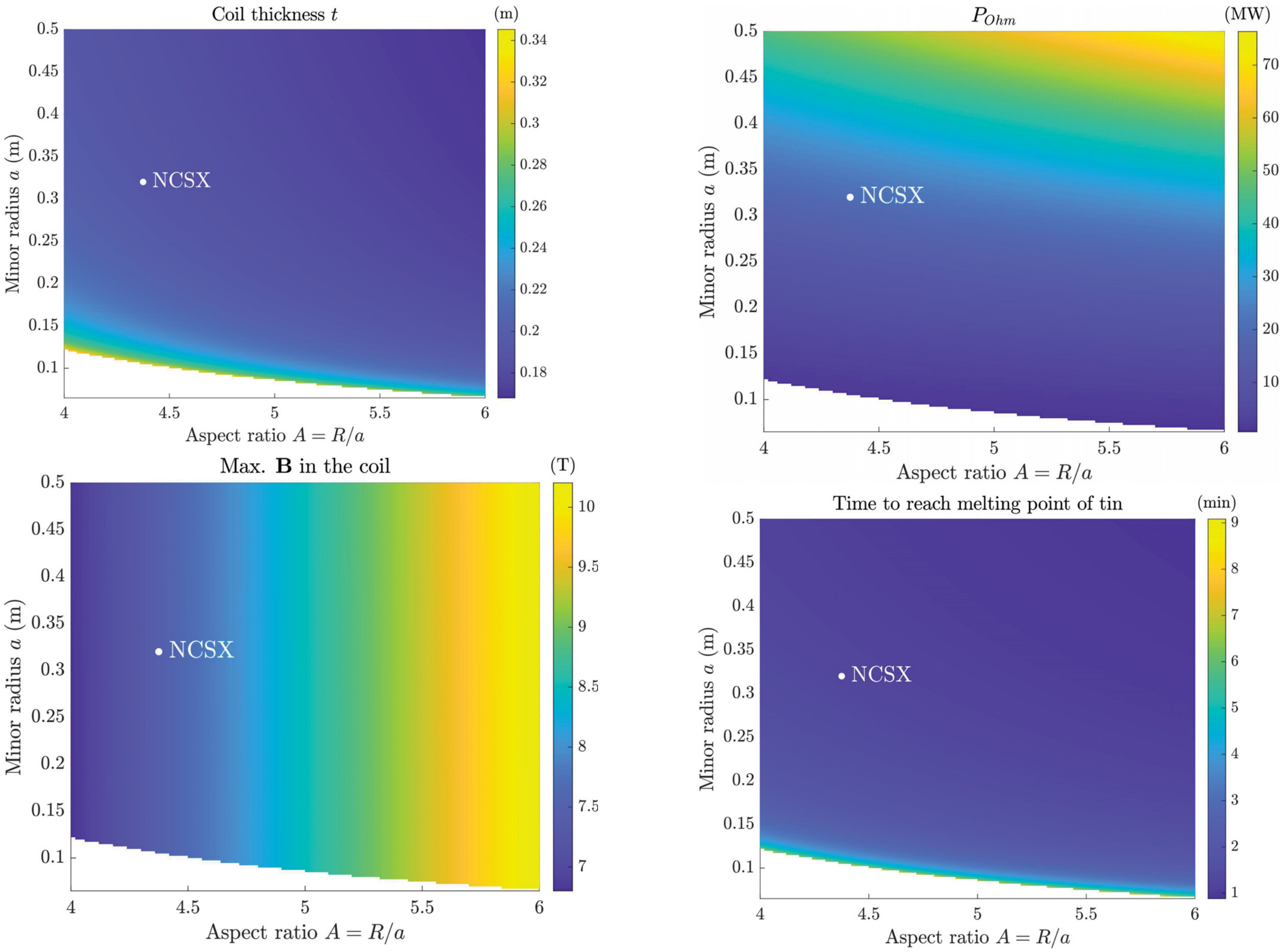


Figure 2. Range of operational parameters for a NCSX-like test machine.

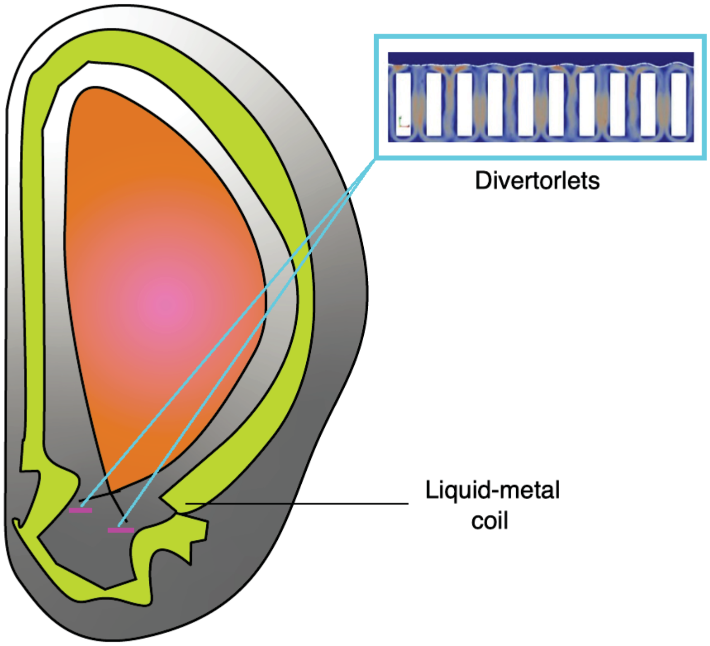


Figure 3. Cross section of a tokamak with divertorlets as the divertor targets

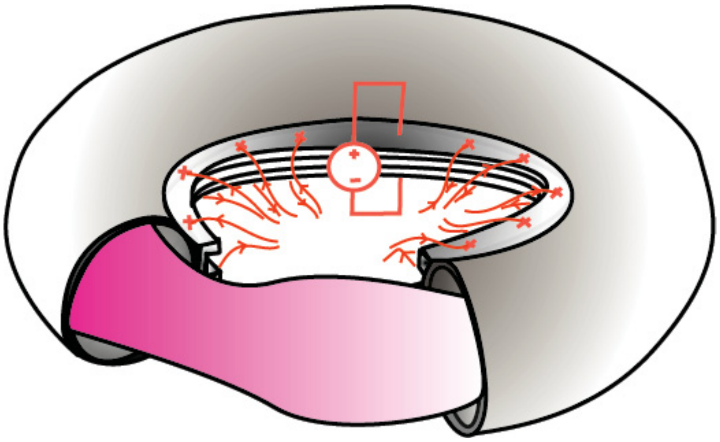


Figure 4. Toroidal cut for voltage inputs on a liquid-metal coil around a confined plasma. Green contours in the figure simply represent arbitrary current paths on the liquid-metal winding surface; there is no need for a set of discrete coils

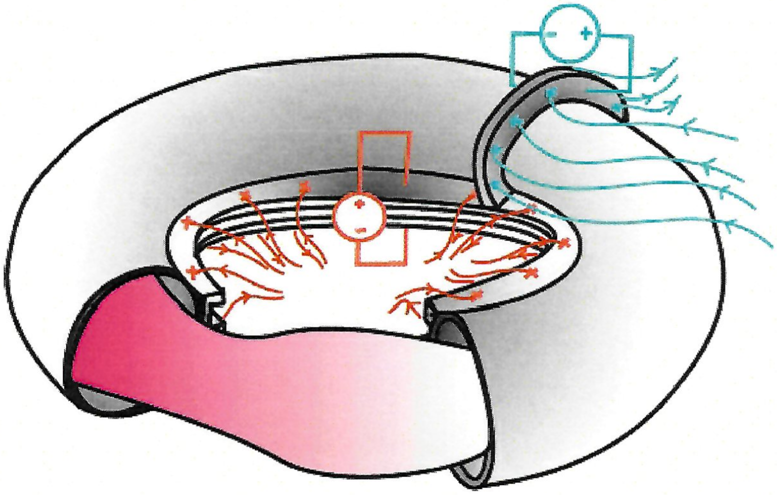
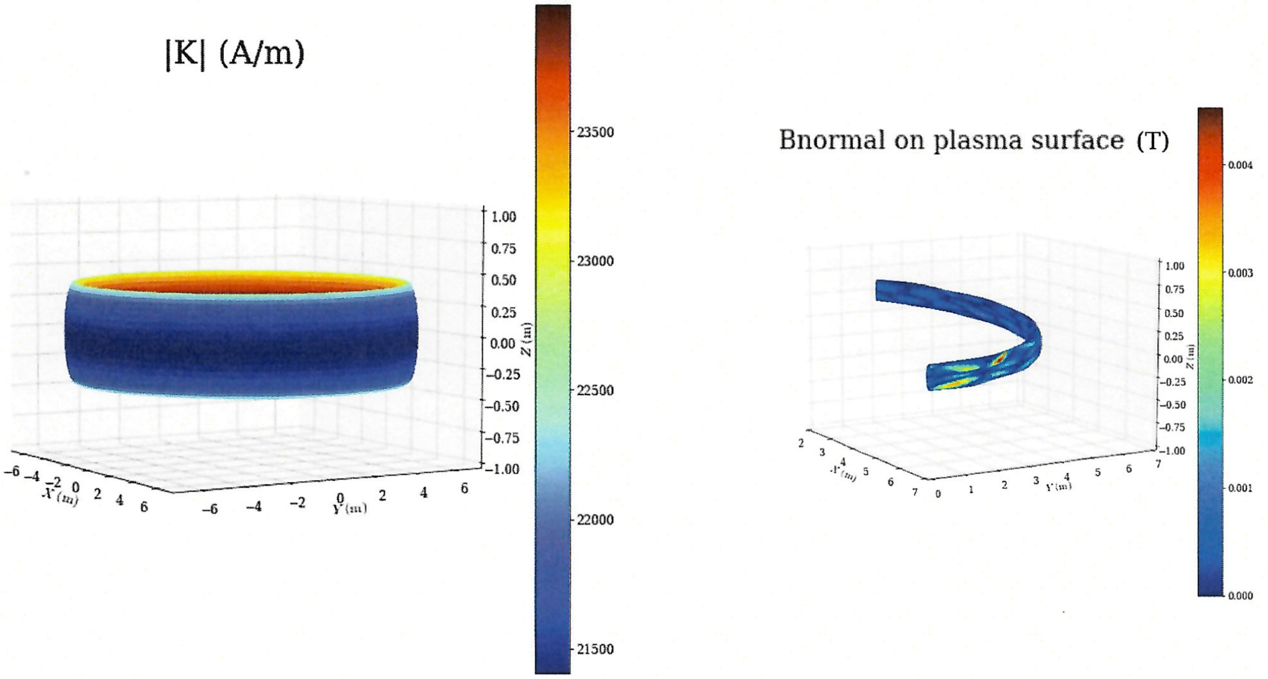


Figure 5. Toroidal and poloidal cuts for voltage inputs on a liquid-metal coil around a confined plasma. Green contours in the figure simply represent arbitrary current paths on the liquid-metal winding surface; there is no need for a set of discrete coils.



a) Current distribution on winding surface

a) Normal component of the magnetic field on a section of the plasma surface

Figure 6. Surface minimization of the normal component of the magnetic field through shape variation of the plasma surface and voltage inputs along a contour on the winding surface.

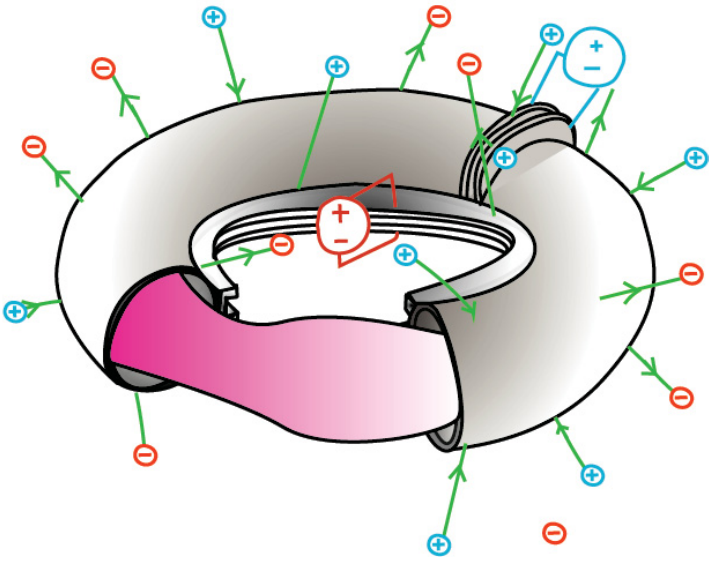
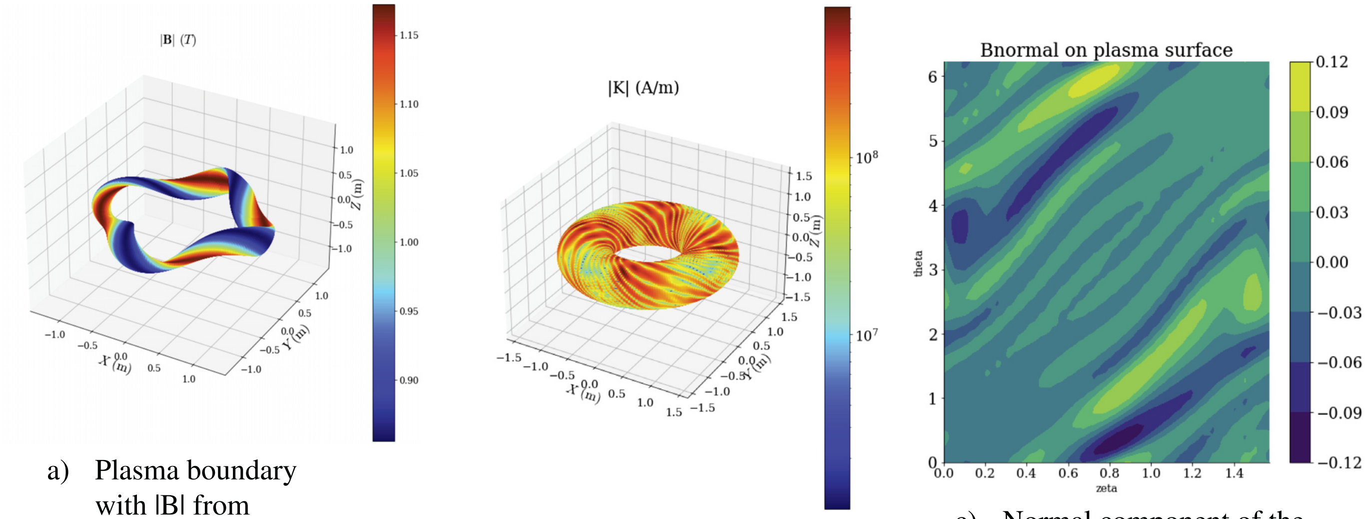


Figure 7. Voltage inputs on a grid of points on the winding surface. Green contours in the figure simply represent arbitrary current paths on the liquid-metal winding surface; there is no need for a set of discrete coils.



a) Plasma boundary with |B| from plasma equilibrium

b) Surface current magnitude on winding surface.

c) Normal component of the magnetic field on the plasma surface.

Figure 8. Surface minimization of the normal component of the magnetic field through localized voltage inputs on a point grid on the winding surface.

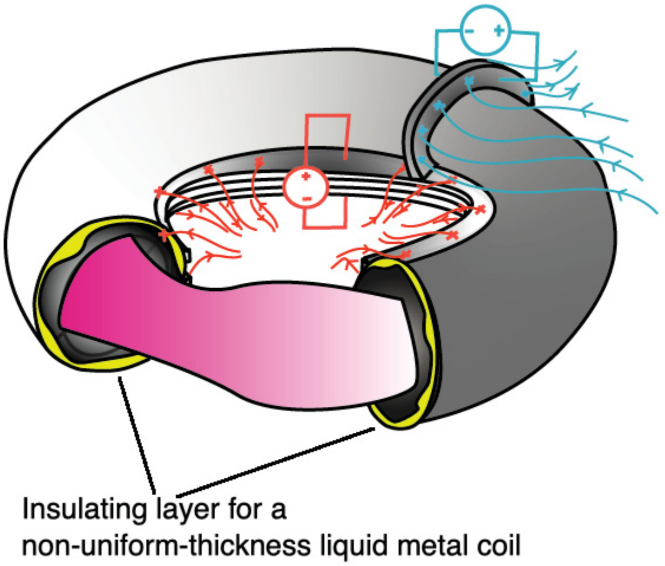


Figure 9. Variation of the local thickness of liquid metal shell/conductive shell for the winding surface.

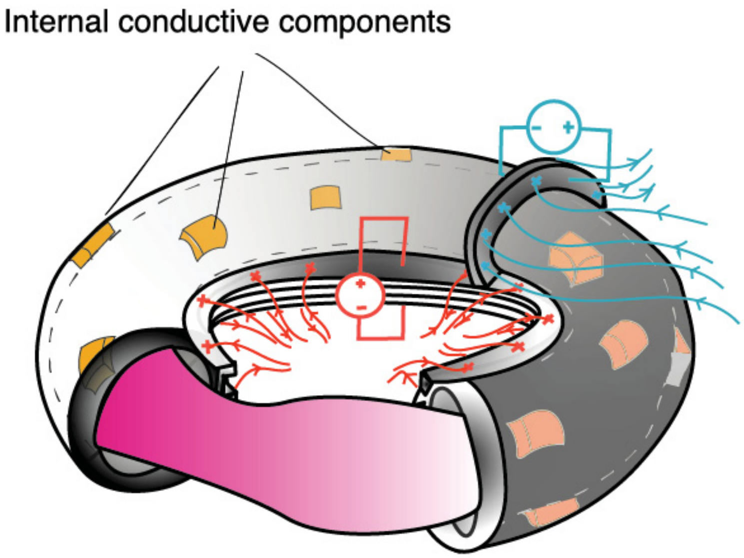


Figure 10. Variation of the local effective conductivity by installing external conductive components on the winding surface.

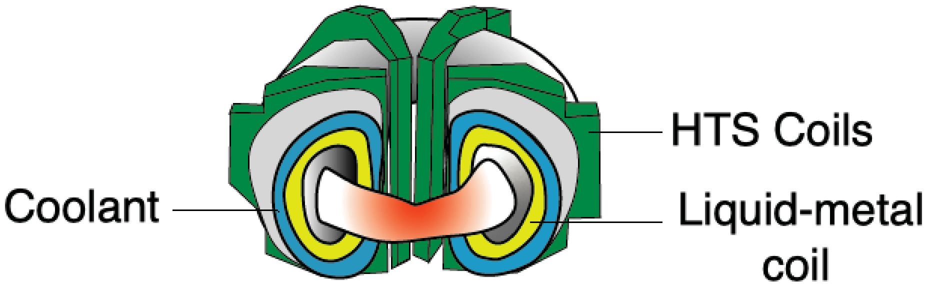


Figure 11. Toroidal and poloidal cuts for voltage inputs on a liquid-metal coil around a confined plasma. HTS coils are separate from the liquid-metal coil. HTS coils are highlighted in green, and the liquid metal coil is highlighted in yellow.

(Updated 6.29.2023-WRR)