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Innovative Design Option for Internal Coils*

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ABSTRACT

For shaping and control of tokamak plasmas it is desirable to have poloidal field coils as close as possible to the plasma. This implies poloidal field coils internal to the toroidal field system. Internal poloidal field coils made of single turn sections are proposed. Interconnects between the different sectors, based on liquid metal contacts, are discussed. The possibility of driving the current in the poloidal field coils by efficient MHD-induced currents (flows of conducting liquid metals across magnetic fields) is explored.

I. INTRODUCTION

Internal PF (poloidal field) coils offer substantial advantages from an operational point of view. The decreased distance between the plasma and the coils decreases the coil currents, resulting in decreased PF system energy and power, and eases plasma control and shaping. However, internal PF systems have the disadvantage of poor assembly/ maintenance operations due to the complex topology, unless the TF (toroidal field) coil or the PF coils are demountable.

Ideally internal poloidal field coils should have moderate power dissipation, low radiation sensitivity and ease of fabrication, assembly and maintenance. Low activation and low impact on tritium breeding would also be desirable. In order to prevent the problem of multiple connections between the coils, it would be preferable if the internal coils consist of a single turn. The choice of single turn design simplifies the design of the segment connections and removes the need for turn-to-turn insulation.

Previous work [1] has suggested the use of integrated blanket toroidal field coils (IBC) with stagnant liquid lithium. Drawbacks of this scheme are the large power dissipation, due to the large electrical resistivity of liquid lithium, and the need for very high current leads and contacts. Coils without leads would facilitate fabrication and design.

Previous work has also considered the possibility of demountable multiple turn poloidal field coils [2]. Demountable coils are toroidally continuous, with mechanical and/or electrical breaks used to sever the coils. Once in sections, the parts can be removed. A problem with this approach is the large number of interconnects between

multiple-turn coil sectors. Multiple-turn coils are necessary with low-current leads.

In this paper we discuss some design options for innovative internal poloidal field coils. Each module contains one or more segments for each coil. Connection between segments is accomplished by flowing liquid metal (lithium). The interaction between the magnetic field and the lithium flow induces an MHD voltage that is used to induce a voltage that drives the current in the coil, eliminating the need for current leads.

Section II motivates the work and discusses possible reactor configurations. Section III presents general calculations on the internal MHD generator. Section IV addresses the issue of efficiency (finite wall resistivity of the insulating channel walls) and the resulting side layers. The results are discussed in Section V. Finally, Section VI summarizes the status of the work.

II. GENERAL CONFIGURATION

Configurations were examined with coils made of copper and flowing liquid metal. The use of normal coils, driven by a discrete in-situ MHD generator, has the following advantages:

    * The use of an MHD generator avoids the need for current leads, which may be a source of difficulty if single turn coil design is desired from the point of view of fabrication, assembly and maintenance.

    * The use of normal coil avoids the cryogenic requirements of superconducting coils at the expense of increased recirculating power fraction.

Either copper or aluminum could be used for the coils. Other conductors could and should be considered (including a mixture of Be spheres and liquid lithium). For the scope of this paper we have assumed that copper is the reference coil material. The presence of the copper or aluminum coil next to the plasma decreases the tritium breeding ratio. The coils may, instead, be placed behind the blanket, decreasing somewhat the efficacy of the coils. Alternatively, by using other conductors (i.e., Be spheres immersed in liquid lithium), the tritium breeding could be left unaffected. In this paper we will only concentrate on the non-nuclear aspects of the MHD-driven coils.

Liquid lithium has been assumed as the liquid metal. In DT reactors lithium must be present in some form. The use of Li as the generator fluid enhances tritium breeding with little activation penalty.

It is possible to arrange the MHD generator in many ways. We have considered both a radial flow-poloidal field interaction (producing a toroidal electric field, as shown in Figure 1a), and a poloidal or radial flow interacting with the toroidal field, resulting in a radial or a poloidal voltage (Figure 1b). In tokamak operating space, the poloidal field is about an order of magnitude smaller than the toroidal field: $B_p \sim aB/Rq$, where B_p and B are the poloidal and toroidal fields, q is the safety factor (q ~ 3) and a and R are the minor and major radius, respectively. Therefore, interacting with the poloidal (vertical) field has the problems that the induced voltages are an order of magnitude smaller than if interacting with the toroidal field, while the pumping power is determined mainly by the toroidal field (so that it is not possible to increase the liquid metal flow to compensate for the smaller induced EMF).

As a consequence, we have chosen the interaction with the toroidal field. Figure 1b shows the geometry. The inner and outer walls of the generator serve as the conductor. In this configuration the generator is contiguous. For engineering simplicity, the coil segments would be in individual pipes, with electrical connections (welded, brazed, etc.) between inner and outer walls, as shown in Figure 1b. Figures 1c and 1d show alternative arrangements, where there are large amounts of copper between discrete generators.

The poloidal field coil is divided into segments -- one per module. It is assumed that a modular maintenance approach [2,3] is used. In this approach, a sector containing one or more toroidal field coils with the blanket, first wall and vacuum vessel associated with the coil/coils, is removed in one operation. A module with an internal poloidal field coil sector is shown in Figure 2. For the case shown in Figure 1b, removal of the sector would require breaking the electrical connections between coil segments.

For the cases shown in Figures 1c and 1d, an MHD generator is used in between sectors to accomplish both the current generation in the coils and the current continuity between coil sectors.

It should also be possible to use this scheme to energize control coils (saddle coils) needed to stabilize kink modes. In this case, the saddle coils can be in one piece. Using the in-situ MHD generator allows the construction of coils without electrical insulation (the coils can be located closer to the plasma) and without the need of current leads. For effective control, the liquid metal flow has to be reversed at a rapid rate, possible with the use of an MHD pump outside the device. The response time of the coils still needs to be determined.

The Lorentz loads of the internal PF coil would be supported by an external support structure (the toroidal field coil or the blanket, for example).

Due to the good thermal contact between the liquid metal and the copper, the copper would probably be at a temperature comparable to that of the liquid metal. This increases the

resistivity and the power dissipation of the system, but it also allows for a straightforward way of cooling the copper.

The presence of the MHD module may introduce non-axisymmetric elements on the PF system. The asymmetry could result in increased transport due to the introduction of islands in the plasma magnetic structure [4]. However, since there are a relative large number of these perturbations (as many as modules), the effect produced by the perturbations is expected to be small.
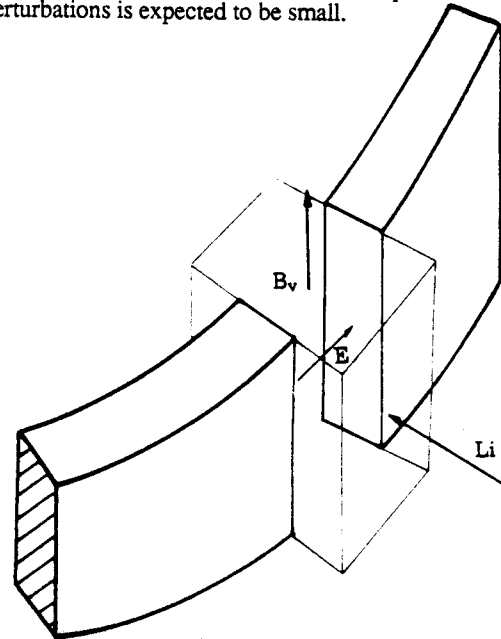

Figure 1. Schematic diagram of possible configurations for MHD-driven coils: (a) radial flow/vertical field (discrete generators); (b) poloidal flow/toroidal field (contiguous generators); (c) poloidal flow/toroidal field (discrete generators); (d) radial flow/toroidal field (discrete generators)
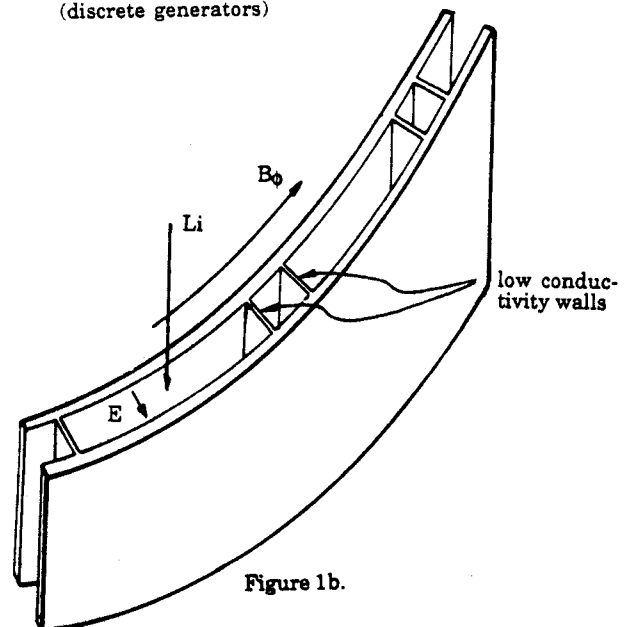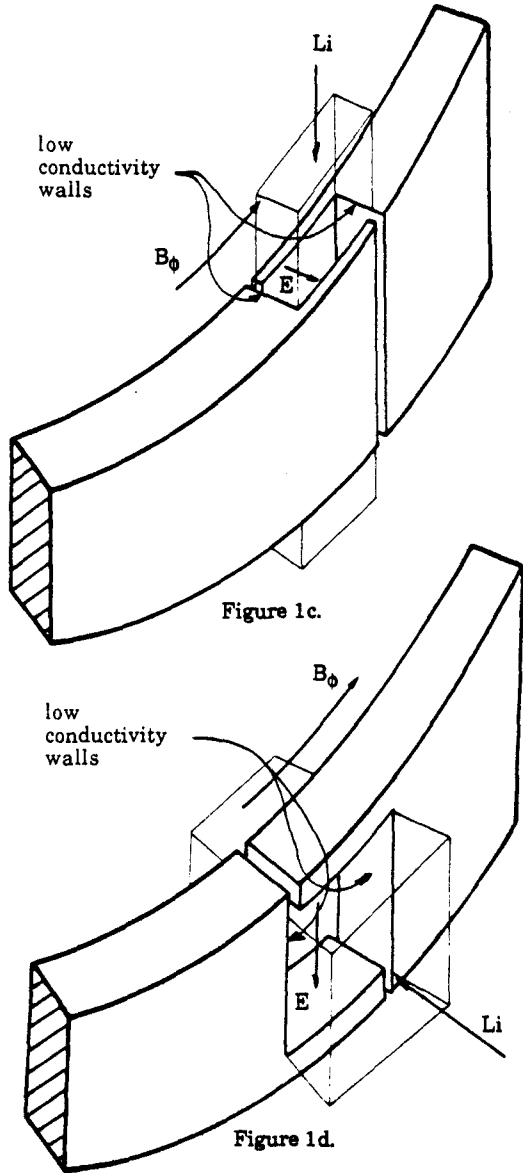

Figure 1b.

Figure 1c.

Figure 1d.

III. MHD COIL CHARACTERISTICS

In this section the generator/coil electrical performance is optimized. For fixed coil current, the resistive power is minimized when the single-turn resistance of the coil, R_Ω, is minimized ($P_\Omega \sim (I_{coil})^2 R_\Omega$). R_Ω includes the internal resistance of the generator.

Using the simplified model shown in Figure 3, the total resistance R_Ω is given by

$$R_\Omega = \frac{\rho_{cu} \, l_{Cu}}{hw} + \frac{\rho_{Li} \, (h-2\delta) N_{Gen}^2}{wl_{Li}} R_{Joint} \quad (1)$$

The first term represents the resistance of the copper sector between generators; the second term represents the resistance of the generators; and the last term represents the resistance of the copper "contacts" between the generator and the

copper sectors. ρ_{cu} and ρ_{Li} are the copper and liquid lithium resistivities, h and w are the poloidal and radial coil dimensions, and 2δ is the maximum thickness of the contact.

The total toroidal length of copper conductor is l_{Cu} while l_{Li} is the total toroidal length of Li-generator ($l_{Li} + l_{Cu} = 2\pi R_{coil}$), N_{Gen} is the number of generators per coil. It is easy to show that

$$R_{Joint} = \frac{\rho_{cu}}{w\delta} \frac{2}{3} l_{Li} \quad (2)$$

Then the product $R_\Omega w$ is

$$R_\Omega w = \frac{\rho_{cu} \, l_{Cu}}{h} + \frac{\rho_{Li} \, (h - 2\delta)}{l_{Li}} N_{Gen}^2 + \frac{\rho_{cu}}{\delta} \frac{2}{3} l_{Li} \quad (3)$$

If the maximum poloidal size of the coil h is constrained, then it is possible to minimize R_w with respect to l_{Li}. Figure 4 shows $R_\Omega w$ as a function of l_{Li}, for R $\sim$ 6 m, ρ_{Li} $\sim$ 4.0 x 10^{-7} Ω m, $\rho_{cu} = 2.5$ x 10^{-8} Ω m, h = 0.8 m, w = 1 m and δ = 0.2 m. It is noted that the resistive power is minimized when l_{Li} is small, i.e., small localized generators.

For a coil carrying 1 MA current, the corresponding minimum power, assuming a radial coil thickness of w = 0.5 m, is about 3 MW. It should be noted that R_Ω is not very sensitive to l_{Li}, since the resistance approximately doubles when l_{Li} $\sim$ $2\pi R_{coil}$ (i.e., $l_{Cu} = 0$). This is to be expected, since for l_{Cu} $\sim$ 0, the copper volume is approximately half that of l_{Cu} $\sim$ $2\pi R_{coil}$ (since δ $\sim$ 0.2 m, h = 0.8 m in Figure 4).
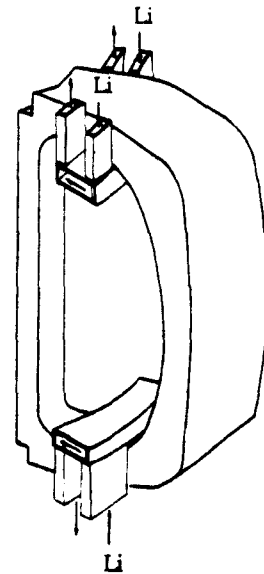

Figure 2. Schematic diagram of toroidal field module with corresponding internal poloidal field coil
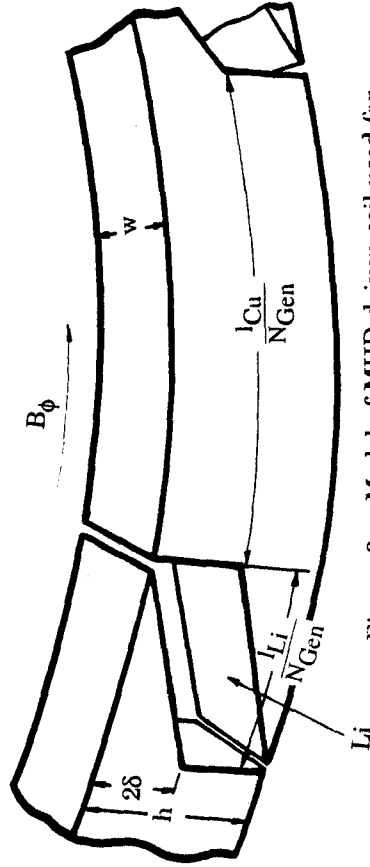
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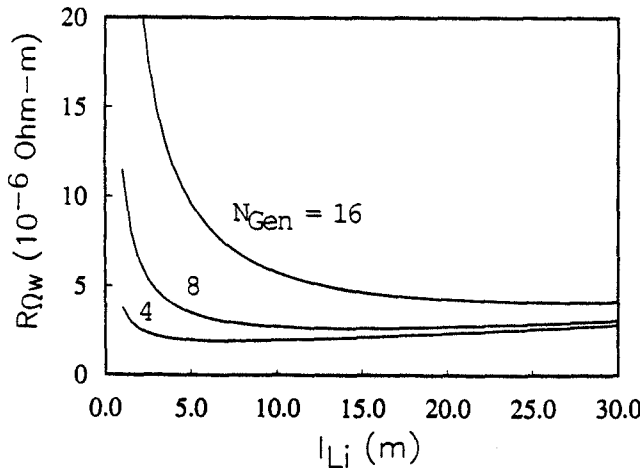Figure 3. Model of MHD-driven coil used for generator optimization.

Figure 4. Product of coil resistance and width (R_{ohm} w) as a function of the total generator length, l_{Li}. N_{Gen} = 4, h = 0.8 m, δ = 0.2 m, R_{coil} = 6 m.

Next we calculate the flowing speed and the flow rate of the liquid lithium. The voltage required to drive the coil is

$$V_{coil} = I_{coil} \, R_\Omega \qquad (4)$$

With N_{Gen} generators, the electrodynamic induced voltage is

$$V_{EMF} = N_{Gen} \, (v \times B) \, (h - 2\delta) \qquad (5)$$

since we have lumped the resistance of the generator in R_Ω. Therefore, the liquid metal speed v is

$$v = \frac{I_{coil} \, R_\Omega}{N_{Gen} \, B \, (h - 2\delta)} \qquad (6)$$

and the flow rate per coil Q is

$$Q = v \, (h - 2\delta) \, l_{Li} = \frac{I_{coil} \, R_\Omega \, l_{Li}}{N_{Gen} B} \qquad (7)$$

Figures 5 and 6 show the flowing speed and the throughput of the liquid lithium as a function of the toroidal length of the MHD generator. These figures are calculated for the same parameters as Figure 4. The velocity has a minimum for relatively low values of l_{Li}, while the throughput is a monotonically increasing function of l_{Li}.

The analysis so far in this section is valid when the height of the coil is held fixed (fixed space for the coil). If instead the amount of copper is fixed (but not the size of the coil) then the power is minimized when $l_{Cu} \sim 0$. This is the case of the contiguous generator, which will be discussed in Section IV.

IV. CALCULATIONS OF CONTIGUOUS GENERATOR

A. Configuration

In-situ coil current generation requires careful consideration of the geometry. The flow is directed through the toroidal field, poloidally through the generator and immediately removed to minimize undesirable MHD pressure losses outside of the generator, as shown in Figure 2.

The emf resulting from the vertical flow and toroidal field is directed radially, and must be turned to produce toroidal currents. This is accomplished by using the electrodes on the generator as the coil conductor (i.e., the load). Figure 7 shows the configuration of the generator and coil. At some point in the circuit, the two electrodes must be joined to form a complete circuit. This cross-over point may be a critical design issue for coils in this configuration.

B. Generator Equations

Estimates of the generator performance are made using a simple, zero-dimensional circuit network analogy. The liquid metal flow induces a net emf proportional to the velocity and magnetic field. Ohm's law in the fluid is given by:

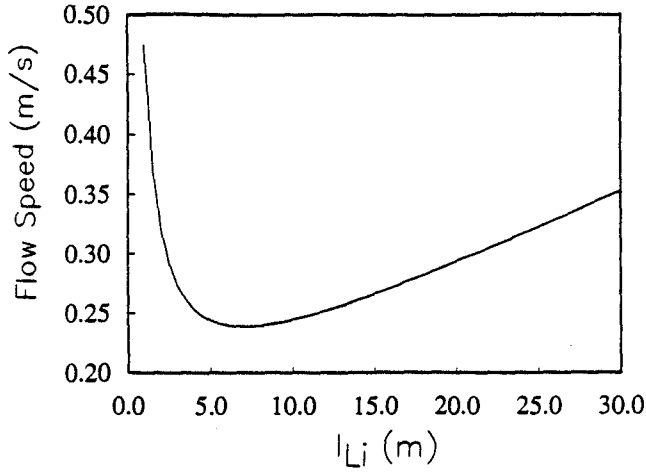$$J_f = \sigma_f \, (vB - \nabla\phi) \qquad (8)$$

Figure 5. Flow speed of the liquid lithium, for the parameters in Figure 4, as a function of the total generator length, l_{Li}.
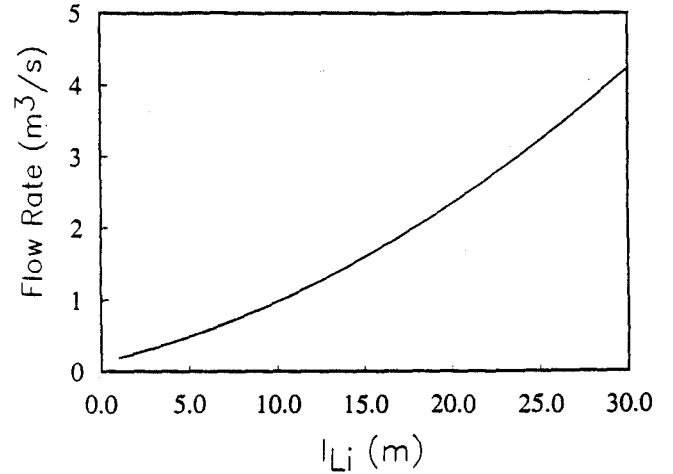
Figure 6. Flow rate of the liquid lithium, for the parameters in Figure 4, as a function of the total generator length, l_{Li}. $N_{Gen} = 4$, h = 0.8 m, $\delta = 0.2$ m, $R_{coil} = 6$ m.
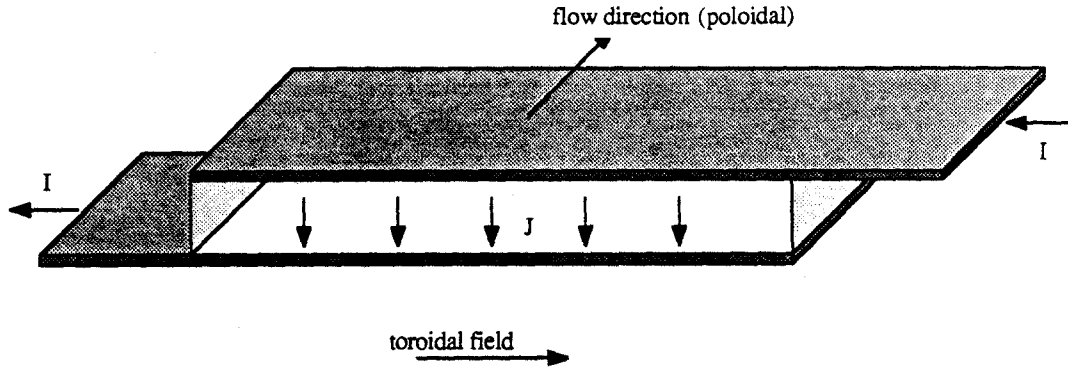

flow direction (poloidal)

I

J

I

toroidal field

Figure 7. MHD-driven coil configuration

$$I_f = J_f \, 2aL \tag{9}$$

where ϕ is the electric potential and the velocity is assumed constant throughout the duct. (Dimensions are shown in Figure 8.) The voltage across the electrodes is $2b\nabla\phi$, which determines the current (I_e) through the external load. In addition, current (I_w) can pass through the side walls (thickness = t) if they are electrically conducting. Current conservation gives:

$$I_f = I_e + I_w \tag{10}$$

Combining eqs. 8-9 with Ohm's law in the walls and the load:

$$I_w = 2Lt \, \sigma_w \, \nabla\phi \tag{11}$$

$$I_e = \frac{2b\nabla\phi}{R_e} \tag{12}$$

where R_e is the load resistance, we obtain:

$$\nabla\phi = \frac{vB}{1+\Phi_w+\Phi_e} \tag{13}$$

Φ_w and Φ_e are the conductance ratios given by:

$$\Phi_w = \frac{\sigma_w \, t}{\sigma_f \, a} \tag{14}$$

$$\Phi_e = \frac{b}{a \, L \, \sigma_f \, R_c} \tag{15}$$

We define a net efficiency as the ratio of power to the load vs. total power dissipated. The total power (P_t) can be obtained by summing the I^2R losses or by evaluating the mechanical work:

$$P_t = 4abv \, \Delta p = 4abvL \, J_f \, B \tag{16}$$

The efficiency thus obtained is given by:

$$\eta = \frac{\Phi_e}{(\Phi_e + \Phi_w)(1 + \Phi_e + \Phi_w)} \qquad (17)$$
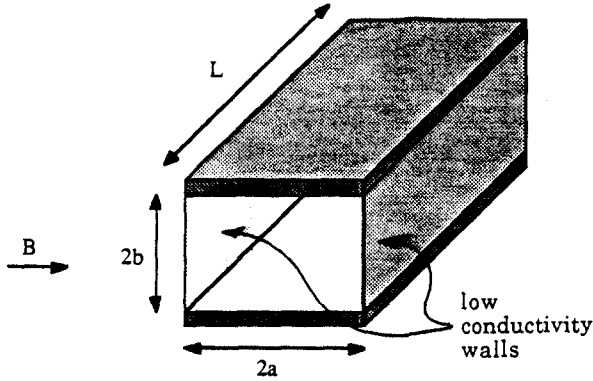

Figure 8. Generator geometry

C. Generator Calculations

We require 1 MA of output into a load consisting of a copper conductor. The conductor is continuous in the toroidal direction at a major radius of 3.5 m. Assuming a coil cross section of 0.3 m², R_e=28μΩ (Δ_{copper} = 0.02 m²) and the load conductance ratio is:

$$\Phi_e = \frac{b/aL}{70} \qquad (18)$$

The channel walls are taken as 5-mm stainless steel, giving

$$\Phi_w = \frac{1}{500 \, a} \qquad (19)$$

If we assume $\Phi_e \ll 1$ and $\Phi_w \ll 1$, then

$$\eta \approx \frac{\Phi_e}{\Phi_w + \Phi_e} = \frac{b/L}{0.14 + b/L} \qquad (20)$$

Finally, we want to maintain a reasonable pressure drop through the generator to minimize pressure stresses. The pressure drop at 5 T is given by:

$$\Delta p = J_f \, B \, L = \frac{I_f \, B}{2a} = \frac{2.5}{a} \text{MPa} \qquad (21)$$

Based on these considerations, we impose the following constraints:

b/aL < 1
a > 1
b/L > 1

These constraints are easy to achieve if a = 2 m or greater. A possible set of design parameters is listed in Table 1, using 4 generators in series. If 12 generators are used in series (one per toroidal sector) without changing any parameters other than "a", then the pressure drop is increased to 1.4 MPa and the flow rate is reduced to 0.75 m³/s.

Table 1. Generator Design Parameters

σ (Li)	=	2.5 x 10⁶ /Ω-m
σ (Cu)	=	40 x 10⁶ /Ω-m
σ (SS)	=	1.0 x 10⁶ /Ω-m
a	=	5.5 m
b	=	40 cm
L	=	20 cm
B	=	5 T
Φ_w	=	3.6 x 10⁻⁴
Φ_e	=	5.2 x 10⁻³
η	=	93.5%
Δp	=	0.45 MPa
<v>	=	7 m/s
Q	=	2.24 m³/s

SIDE LAYERS

Since the load in this case is physically the same as the upper and lower walls, so-called "side-layers" may develop [5]. Side layers are fluid jets which arise due to electric potential mismatches between the fluid and the walls. To estimate the magnitude of the flow in side layers, we compute the electric potential variation along the electrodes and compare to the variation across the duct.

In the fluid, if the magnetic field is roughly constant, then the electric potential also must be constant along field lines. This can be shown easily by taking the curl of the momentum equation:

$$\nabla \times (\nabla p = \underline{J} \times \underline{B}) \qquad (22)$$

Expanding, one obtains:

$$(\underline{B} \cdot \nabla) \underline{J} = 0 \qquad (23)$$

In symmetric ducts, if the current is constant along B, then it must be zero and the potential is constant along B. However, in the electrodes, the current per unit length I_w accumulates from the constant J_f:

$$\frac{dI_w}{dy} = J_f \qquad (24)$$

where y is the toroidal distance along the electrode. The potential in the electrodes is given by:

$$\frac{d\phi}{dy} = \frac{I_w}{\sigma_e \, t} \qquad (25)$$

Since J_f is constant, ϕ varies parabolically. If the potentials in the fluid and wall are equal at the end of the electrode (y = a), then a potential jump exists everywhere else along the side walls:

$$\Delta\phi = \frac{J_f \, (a^2 - y^2)}{2 \, \sigma_e \, t} \qquad (26)$$

This potential jump results in a velocity jet at the wall. The flow rate in the jet is obtained by integrating Ohm's law through the side layer:

$$\int (J/\sigma)\, dz \; = \; \int (v \times B)\, dz - \int (\nabla\phi)\, dz \qquad (27)$$

For constant B, and assuming J is continuous through the boundary layer (and the boundary layer thickness, δ, is very small):

$$\Delta\phi \; = \; B \int v\, dz \qquad (28)$$

We can compare the potential drop in the side layer and the core to determine the ratio of flow in the side layer to that of the core. Using equations (8), (13), and (26), we find:

$$f_{sl} = \frac{\Delta\phi_{sl}}{\Delta\phi_c} \; = \; \frac{\sigma_f}{\sigma_e}(\Phi_w + \Phi_e)\frac{y^2}{2\,t\,b} \qquad (29)$$

For the case above (Table 1), we find the maximum value of $f_{sl} = 4.5$, which indicates that most of the flow is in high-velocity jets near the side walls.

This behavior may result in serious problems with erosion that must be addressed in future work.

V. DISCUSSION

It has been shown that segmented normal internal coils carrying relatively large currents (on the order of 1 MA) can be designed. Use of a single turn facilitates the segment-to-segment connection, while simplifying the turn-to-turn insulator problem. The connection is made using liquid metals. It is possible to use the flow of the liquid metals to induce the voltages required to drive the coil currents.

The liquid metal conduit needs to be insulated from the coils in order to prevent large currents from flowing through the pipes, rather than the coils. Insulating elements between the coils and the pipes would be required.

A way to minimize the side layers is to divide the coil in several sectors, with insulation in-between. Although there will still be side layers, they will be substantially smaller. In addition, the side layers will be decreased further if the metal contacts are not parallel to the toroidal field. Figures 9 and 10 show schematic diagrams of coil concepts that include the considerations mentioned above.

In the future, more careful attention should be placed on the details of the pumping piping/conductor geometries. The efficiency of the system and the current generated have not yet been optimized. The neutronics implication of having the coils near the plasma needs to be evaluated. Finally, an engineering tradeoff study to balance the opposing forces of minimizing the flow speed, the throughput, the pressure drop, the coil proximity to the plasma, and the activation of the coils needs to be done. For the control coils discussed in the introduction, it is necessary to determine the minimum swing time.

VI. CONCLUSIONS

It has been shown that using an MHD generator coupled to liquid-metal connects is an efficient method of producing currents on the order of 1 MA in internal poloidal field coils. These coils could be useful for providing plasma shaping and control. Relatively low liquid metal flow speed (~1 m/s) in the interaction region is required. Use of hybrid coils

(solid and liquid metals) has distinct advantages. The use of the internal MHD generator avoids the need of high current leads and provides current continuity between sectors. The absence of insulation allows locating the coils relatively close to the plasma. Finally, the use of the MHD generator as the connection between coil metal sections allows for a simple scheme of assembly and maintenance.
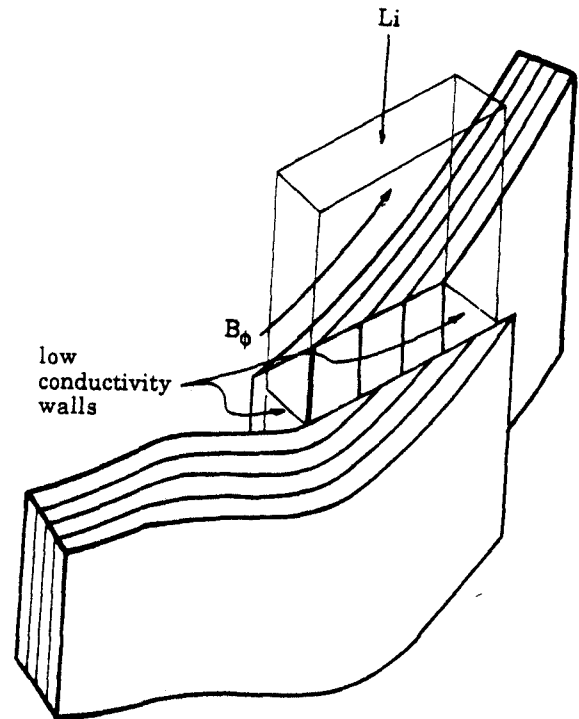

Figure 9. Alternative configuration of case with poloidal flow/toroidal field discrete generators
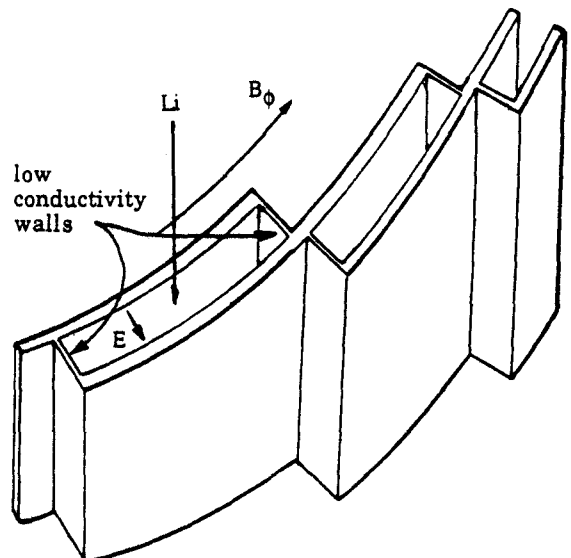

Figure 10. Alternative configuration of case with poloidal flow/toroidal field configuration contiguous generator

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