Coil design for the SFLM Hybrid

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INTRODUCTION

A fusion-fission hybrid reactor is a combination of a fusion reactor and a fast fission reactor suggested for energy production, breeding of fissile material or transmutation of radioactive waste from fission plants. A primary goal for hybrid reactors is transmutation of TRU (TRansUranic) elements. Both TRU elements and FP (Fission Products) contribute to the total radiotoxicity in the spent nuclear fuel, but after 400 years the radiotoxicity from the FP is well below that of natural uranium. For the TRU content, the corresponding time is more than 300 000 years. TRU elements are transmuted by fission, which produces energy.

In the SFLM Hybrid study [1], a theoretical concept design of a mirror-based hybrid reactor is being developed. In this paper, two different superconducting coil system designs for the SFLM Hybrid are described. The first coil set is a semi-planar coil set with two layers of coils that has been published in detail in Ref [2]. The second coil set is a non-planar one-layer coil set aimed for a weaker magnetic field and is published in detail in Ref [3].

The fusion driver is a quadrupolar single-cell mirror with magnetic expanders at the mirror ends. The geometry of the device is given in figure 1. The coils are not allowed to intersect each other or the magnetic expanders, and are located outside the fission mantle. There should also be space available for influx and outflux of liquid lead/bismuth coolant through the coil system, which are located at the ends of the fission mantle outside the recirculation region.

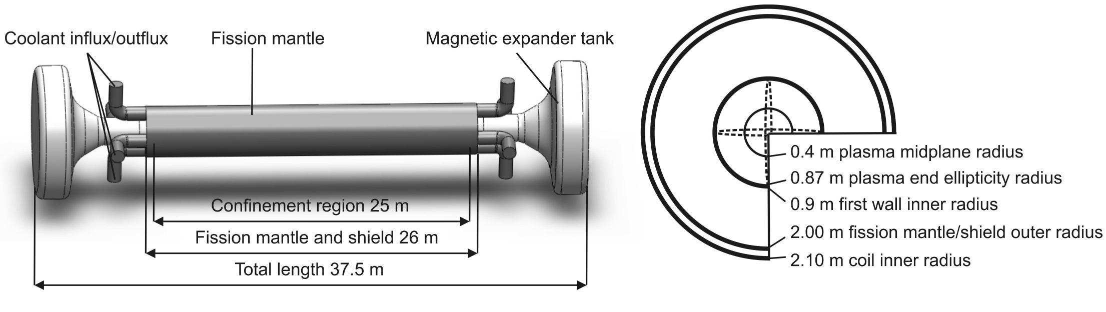

Figure 1. The hybrid reactor without coils, where the coolant outflux/influx, the fission mantle and the vacuum chamber with magnetic expanders are shown.

VACUUM MAGNETIC FIELD PROPERTIES

The vacuum magnetic field properties are described in Ref [2], and is briefly described here. The magnetic field is expressed in the long-thin approximation with $\lambda = a/c$ as small parameter, where a is the plasma radius and $2c$ is the length of the confinement region. The magnetic field has the components

$$B_x = \frac{x}{2}(g - \tilde{B}'), \quad B_y = -\frac{y}{2}(g + \tilde{B}'), \quad B_z = \tilde{B} + \frac{x^2}{4}\frac{d(g - \tilde{B}')}{dz} - \frac{y^2}{4}\frac{d(g + \tilde{B}')}{dz}$$

to order $o(\lambda^3)$ where $\tilde{B}$ is the magnetic field on the z axis and g represents the quadrupolar field. Some properties of the vacuum magnetic field is examined to select a suitable field based on the functions $\tilde{B}(z)$ and $g(z)$. The flute stability criterion [4] and the flux tube ellipticity ε_{ell} is given by [2]

$$W_1 \cos^2\theta_0 + W_2 \sin^2\theta_0 \ \geq\ 0, \quad W_{1,2}(z_{end}) = \int_{-z_{end}}^{z_{end}} \frac{pdz}{\tilde{B}(z)} e^{2\int_0^z h_{1,2}(z')dz'} [h_{1,2}^2(z) + \frac{dh_{1,2}(z)}{dz}] \ \geq\ 0$$

$$h_1(z) = \frac{g - \tilde{B}'}{2\tilde{B}}, \quad h_2(z) = -\frac{g + \tilde{B}'}{2\tilde{B}}, \quad \varepsilon_{ell}(z) = Max[e^{2G(z)}, e^{-2G(z)}], \quad G(z) = \int_0^z dz' \frac{g}{2\tilde{B}}$$

where p is the plasma pressure and θ_0 is the polar angular flux coordinate. A representative sloshing ion pressure profile has been used in this work.

The magnetic field profile selected for the device is a combination of the Straight Field Line Mirror (SFLM) [5] in the central region, concatenated at $z = \pm 8.75$ m with another field to end the mirror and specify the expanders. The $\tilde{B}(z)$, $g(z)$, $W_1(z)$, $\varepsilon_{ell}(z)$ and $p(z)$ functions for the selected field is shown in figure 2. The field is flute stable, has a reasonably low maximum ellipticity (about 20), has low field gradients and has a mirror ratio of 4.

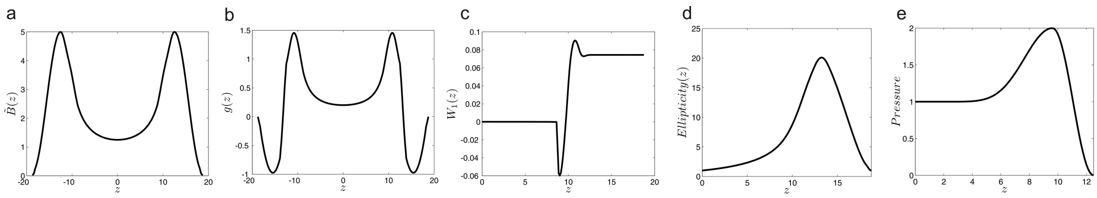

Figure 2. Some properties of the vacuum magnetic field for the SFLM hybrid.

SEMI-PLANAR COIL SET FOR 2 T MIDPLANE B

A semi-planar coil set has been designed for a case where the midplane magnetic field $B_0 = 2$ T. With this field, a midplane $\beta \approx 0.20$ would be required to give a neutron production of about 7.1×10^{18} neutrons/s, corresponding to about 20 MW fusion power. This coil set has been published in detail in Ref [2]. The coil set consists of two layers of coils, where an inner layer of “Ioffe bars” produces the quadrupolar field and an outer layer of circular coils produces the axisymmetric field. To roughly dimension the coils, a current density of 1.5

kA/cm^2 for the winding package has been used and 10 % additional width on each side for structure material, which is roughly taken from the Nb_3Sn ITER TF coils [6].

The coil set is optimized using a local optimization method, where a cost function to minimize is specified. The cost function adds cost from field inaccuracy and current consumption. The coils are parameterized using position and current, and the number of coils is fixed in the optimization. Since each coil layer only contributes to one of the functions $g(z)$ and $\tilde{B}(z)$, the optimization problem is separated into two optimization problems, one for $g(z)$ and one for $\tilde{B}(z)$ (see Ref [2] for details). The resulting coil set is shown in figure 3. It shows the inner quadrupolar coil set and the entire coil set.

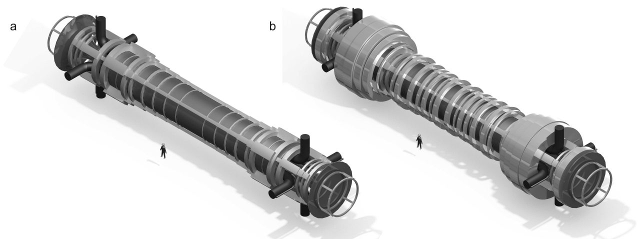

Figure 3. The semiplanar coil set without (a) and with (b) the circular coils.

3D COIL SET FOR 1.25 T MIDPLANE B

To reduce the cost of the coil system and to make it more practical, another design has been made. *B* is now downscaled to 1.25 T at the midplane and with a 3D coil geometry the coils can now be fitted into one layer instead of two. To maintain the neutron production, the maximum midplane β is now increased from about 0.2 to about 0.5. The coil geometry used is best described by looking at the lateral surface that the coil is located on. The coil midline is at a constant radius from the z axis, and the coil layout on one half of that circumferential surface is shown in figure 4a. The coils can be parameterized using the current *I* and the distances *L*, *r*, *a* and *z* where *z* is the coil center position in *z*, *r* is the coil inner radius, *a* is the turn radius for the coil midline and *L* is the coil midline extension in *z*. The parameterization is quite well separated, where *I* controls the coil overall contribution to the magnetic field components and *L* roughly controls $g/\tilde{B}$. This type of coils can be fitted into each other like a pile of glasses, which makes it easier to prevent the coils from intersecting in numerical optimization and to fit them in, as long as *L* does not vary too much between adjacent coils. The coils are dimensioned by using a winding package current density of 2.6 kA/cm^2 and 10 % extra width on all sides for structure material, which is roughly in accordance with the JT-60SA coils [7]. The optimization of the coil set has so far been done by hand by changing the parameters *L*, *z* and *I*, setting $a = 1$ m and $r = 2.10$ m. The resulting coil set is shown in 3D in figure 4b and consists of 30 coils. For more details, see Ref [3].

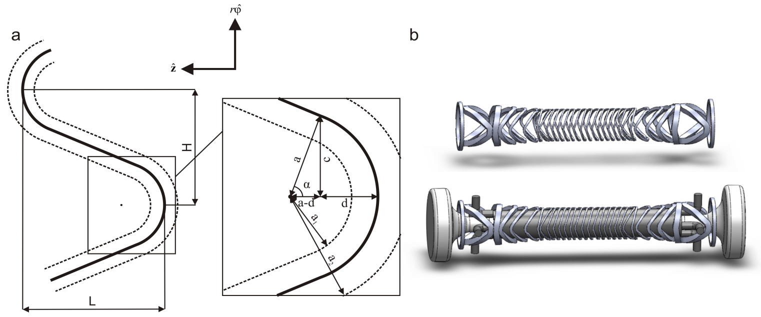

Figure 4. In (a), half of the coil circumferential surface is shown. In (b), the 3D coil set is shown both with and without the vacuum chamber, fission mantle and coolant influx/outflux.

DISCUSSION AND CONCLUSIONS

To select a suitable magnetic field, flute stability is most important. To restrain the maximum flux tube ellipticity is also important, since a high ellipticity shrinks the plasma volume in a cylindrical vacuum chamber. Neoclassical/resonant transport is also of some interest, but has not been fully addressed yet. The semi-planar two-layer coil set produces a strong magnetic field, and it would be hard (but maybe possible) to find a non-intersecting single layer 3D coil set that reproduces this field since the coils would be thick. There are however some questions regarding maximum magnetic field, rounding of coils etc. for these semi-planar coils that has not been checked. For the 3D coils, the lower magnetic field (1.25 T at midplane) and higher $\beta \approx 0.5$ makes better use of the magnetic field. The geometry of the coil system makes it possible to produce both the axisymmetric and the quadrupolar field with a single layer of coils, which makes the coils and overall current use smaller. Also, the lower field enables the use of the considerably cheaper superconductor NbTi instead of Nb_3Sn for most of the coils. There is however a need to analyze the impact of the high plasma β concerning stability. Such an analysis will suggest a modification of the field and the coil system.

To conclude, two alternative coil systems have been presented, one with semiplanar coils for a midplane magnetic field of 2 T and another with 3D coils for a 1.25 T midplane field. The 3D coils seem to be the better choice. Both coil systems reproduce the magnetic field with satisfying accuracy.

References

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