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COIL DESIGN FOR THE STRAIGHT FIELD LINE MIRROR

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This paper briefly describes numerical design of 3D super-conduction coils aimed to mimic analytically derived magnetic field for the Straight Field Line Mirror (SFLM) concept. The paper is based on a manuscript for a previous IAEA report, i.e. IAEA-TECDOC-1998.

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INTRODUCTION

The Straight Field Line Mirror (SFLM) concept relies on a quadrupolar magnetic field providing a minimum B field. That is known to provide a pronounced effect on plasma stability. A threat for a non-axisymmetric magnetic field is enhanced neoclassical transport. However, we have derived a magnetic field which is connected with a radial constant of motion which practically eliminates such neoclassical effects. The geometry of the device seems suitable for efficient plasma heating by ion and electron cyclotron heating. Neutron computations predict efficient ways to generate power in a hybrid reactor, with a high power amplification from fission reactions in an annular layer surrounding the plasma confinement region. Reactor safety issues studied so far are favorable, although these studies need to be deepened for reliable predictions. Recent magnetic coil design suggest that a mirror ratio exceeding 10 is possible for the vacuum field. Even higher mirror ratios could be possible with finite beta effects, without violating the minimum B stability criterion or enhancing the flux tube ellipticity. A "fish bone coil design" is developed to enable a convenient stacking of baseball coils on a cylindrical surface, which reproduces the targeted field with a high precision. The coil design is consistent with expanding flux tubes on the two opposite sides beyond the confinement region. A circular shape of the flux surfaces at the end tank facilitates a control of plasma rotation by biasing ring-shaped end plates. Even very small electric potential gradients from the end plates could enhance radial confinement properties substantially. A plan for the near future is to investigate stronger radial electric fields aimed for centrifugal confinement.

REPRODUCTION OF OPTIMIZED MIN B FIELD

A first priority in the magnetic field design is to achieve a minimum B field, which in numerous mirror experiments have demonstrated a striking stabilizing effect on the plasma [1]. Aside from satisfying the minimum B criterion, our design is also optimizing the flux tube ellipticity. This is achieved by selecting a magnetic field where the magnetic drifts are minimized, which is a basis for the SFLM concept [2]. In addition to these properties, we have shown that the optimized field design is connected with a radial constant of motion, which practically eliminates neoclassical transport effects. The radial constant of motion implies that each gyro center moves on a magnetic surface (apart from tiny radial excursions in the micrometer range). The combination of three constant of motion, i.e. the energy, the magnetic moment and finally the radial constant of motion, predict good confinement properties for the single particle motion in the SFLM, along the longitudinal as well as along the transverse directions.

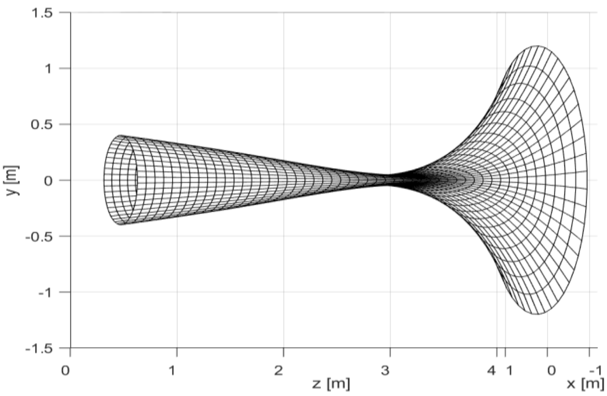

Fig. 1. Magnetic surface for a compact optimized minimum B field. The confinement region has essentially straight and nonparallel magnetic field lines. The shape of the magnetic surface evolves from circular at the mid plane to elliptical near the magnetic field maximum, and regains a circular shape at the expander tank wall, where biased ring-shaped endplates could be placed

Magnetic designs deviating from the optimal would lead to substantially larger ellipticities. From that we may conclude that the impractically large ellipticities would appear if the mirror ratio Rm of the vacuum field exceeds 10 or so. However, with a give minimum B vacuum field, an increase of the plasma beta would increase the mirror ratio, and this is anticipated to evolve without destroying the flute stability or increasing the ellipticity [2]. A mirror ratio above 10 seems possible for a SFLM magnetic field with a finite beta.

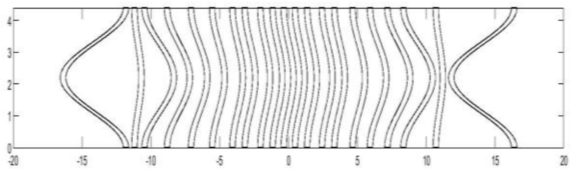

Fig. 2. Coil boundaries versus the arc length at the inner coil radius. The complete winding includes analogous layers of wire currents at constant radii with the same variation versus the cylindrical angle, which facilitates flexible stacking of the coils

A flux tube extending from the mid plane to the expander region is shown in Fig. 1. On the opposite side of the mid plane, the flux tube has an identical shape except that the surface is rotated by 90 degrees around the magnetic axis. The magnetic field could be generated by a set of fish bone coils wounded on a cylindrical surface. The shape of the coils at the inner coil radius versus the arc length around the cylinder is shown in Fig. 2. For a long-thin device, detailed reproduction of the optimized magnetic by the field from the coils can be achieved with mirror ratios exceeding 10. A high precision in the reproduction is required to avoid that field errors generate plasma instabilities or a substantially larger flux tube ellipticity.

For the optimized vacuum magnetic field with a mirror ratio R_m, we may estimate the ellipticy ε_{ell} by (1)

$$\varepsilon_{ell} \sim 4R_m. \qquad (1)$$

An example for the magnetic field design with R_m =10 is shown in Fig. 3. The reproduction in the confinement region is obtained by fitting the coil parameters to mimic two analytically derived target functions, shown by the red curves, for the optimized magnetic field. As seen from Fig. 3, the deviations between the target functions and the corresponding functions from the coils is vanishingly small in the confinement region, which assure a precise reproduction of the target field. The length of the expander region may be shortened by adding correction coils.

There are several implicit engineering constraints for the coil design. There must be a sufficiently wide annular space between the vacuum chamber and the inner coil radius. For a hybrid reactor, this region should contain spent nuclear fuel, coolants, tritium reprocessing, neutron reflectors and shielding etc [3]. The case in Fig. 3 assumes a 70 cm wide such region, and the width could be extended with minor corrections of the coil parameters. The coil geometry is also consistent with holes for the diagnostics and feeding of power for plasma heating near the mirror throats [4], [5]. A special arrangement for ion cyclotron heating is predicted to provide efficient plasma heating [4]. The SFLM magnetic field corresponds also to a favourable “attractor” situation for electron cyclotron heating [5], corresponding to efficient heating of the plasma core. The geometry is furthermore in line with previous neutron computations, where holes in the mantle surface should be avoided to achieve a high power amplification by fission [3]. Within reactor safety requirements [3], our studies suggest that the power amplification by fission could be as high as (2)

$$P_{fission} / P_{fusion} \sim 150 \,. \qquad (2)$$

A fusion power of only 10 MW would then be capable of generating a total power of 1.5 GWth. That is predicted for a 20 m long compact device with a 40 cm plasma radius. The tritium consumption is thus low, and besides, a tritium breeding factor well above unity is predicted, thereby avoiding a huge cost for the fuel. The first wall may withstand more than 30 years of neutron bombardment to exceed a 200 dpa rate.

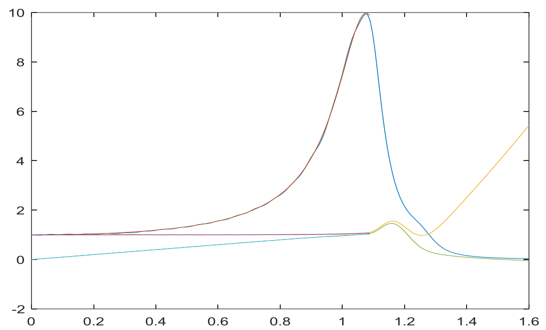

Fig. 3. Plot of the magnetic field strength versus a dimensionless longitudinal length. Also shown are the odd and even target functions (red) for the field reproduction by the coils. The odd function approaches zero near the expander tank wall, where the flux surface regains a circular shape and where ring-shaped end plates could be placed. That arrangement can eliminate the risk for short-circuiting between the end plates

In summary, the coil computations seems consistent with a steady state compact neutron source design aimed for a neutron generation in the range of 10 MW fusion power. Biased end plates placed at the expander tanks could improve radial confinement, even with modest strength of the potential gradients. With stronger potential gradient from the end plates, the design may be suitable for centrifugal confinement scenarios [6], which will be addressed in a near future study.

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РОЗРОБКА КОТУШОК ДЛЯ ПАСТКИ З ПРЯМИМИ СИЛОВИМИ ЛІНІЯМИ

O. Ågren, В.Є. Моісеєнко

Коротко описана чисельна розробка надпровідних тривимірних котушок, спрямованих на імітацію аналітично отриманих магнітних полів для концепції пастки з прямими силовими лініями (SFLM). Стаття заснована на авторському матеріалі для попередньої доповіді МАГАТЕ-TECDOC-1998.