PARTICLE CONFINEMENT IN EBT REACTORS WITH NONCIRCULAR MIRROR COILS^o

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ABSTRACT

Methods of improving single particle confinement in the vacuum magnetic field of an ELMO Bumpy Torus (EBT) reactor have heretofore focused on enhancement of the effective magnetic aspect ratio through the addition of relatively low current supplementary coils to the basic EBT configuration of toroidally linked circular mirror coils. This method of aspect ratio enhancement is reviewed and compared to the use of noncircular, D-shaped mirror coils. A critical parameter in this evaluation is the required radial thickness δ of the blanket-shield assembly in the coil throat. Results indicate that D-coils represent an attractive alternative to the supplementary coil configurations if future neutronics calculations show that $\delta \leq 1.1$ - 1.2 m gives adequate neutron shielding and acceptable minimal breeding ratio under the coils. D-coils are shown to be extremely effective in synchrotrizing mod-B in the midplane, thereby giving good trapped particle confinement, hot electron ring centering, and reactor volume utilization. In addition, magnetics systems with D-coils are significantly less complicated, with easier assembly, maintenance, and access, than configurations in which there are two supplementary coils per sector.

1. INTRODUCTION

In the ELMO Bumpy Torus (EBT), the spatial position of the hot electron rings (formed near contours of constant $|B|$ in the midplane) is critical to efficient utilization of the magnetic volume within the vacuum chamber because it determines the boundary of the toroidally confined core plasma. Various methods have been proposed for centering the mod-B in the midplane and for improving single-particle confinement in the vacuum magnetic field of a bumpy torus.¹

Methods of improving single-particle confinement in the vacuum magnetic field of an EBT reactor have heretofore focused on enhancement of the effective magnetic aspect ratio through the addition of relatively low current supplementary coils to the basic EBT configuration of toroidally linked circular mirror coils. Recently, the use of semicircular mirror coils has also been considered.² In the work reported here, the parameters (ellipticity and triangularity) that describe the noncircularity are similar to those of typical tokamak D-shaped toroidal field (TF) coils. In a bumpy torus, however, the vertical "straight" leg is optimally located on the outside of the torus rather than on the inside. In a toroidal array of these coils, this orientation results in a partial cancellation of the vertical drift that arises from the toroidicity.

A critical parameter in the assessment of any EBT reactor magnetics configuration is the radial distance δ in the coil throat between the first wall of the reactor chamber and the mirror coil windings. This space is occupied by the first wall, blanket/shield assembly, coil sewer, expansion voids, thermal insulation, etc. In general, $\delta = 1.0$ - 1.5 m is typically required for adequate neutron shielding and acceptable tritium breeding ratio. It is instructive to compare the ratio of δ to the mean coil radius R_c for the present experiment (EBT-I/S) with that for a reactor. In EBT-I/S, δ is just the coil bobbin thickness, and $\delta/R_c = 1/8$. For a reactor with superconducting magnets having $R_c \approx 3.0$ m, $\delta/R_c \approx 1/3$ to $1/2$ for $\delta \approx 1.0$ to 1.5 m. Alpha particle first-orbit losses and efficient plasma volume utilization are primary considerations in an assessment of the impact of large δ/R_c on reactor economics and performance. Without supplementary coils to modify the vacuum magnetic field in the reactor chamber, a large value of δ leads to a large reactor volume (a large mechanical aspect ratio, a large major radius so that the orbits are better centered, or a large minor radius and correspondingly smaller δ/R_c). By taking advantage of the orbit topology and device geometry, a reduction in

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δ/R_c can also be realized with a nonuniform axial distribution of blanket and shield.

Reference 1 showed that the use of symmetrizing (SYM) coils, with circular mirror coils and $\delta = 1.5$ m, resulted in a magnetic field geometry within the reactor chamber in which the midplane mod-B was symmetric across the minor axis at the ring location. The corresponding magnetic aspect ratio enhancement (ARE) factors were approximately 2 (1.5) for trapped (passing) particles. Similar results were obtained with axis-encircling ARE coils. Both ARE and SYM coils improve volume utilization and single-particle confinement by lengthening the magnetic field lines inside the torus relative to those outside; SYM coils are more efficient in terms of magnetic field utilization in a reactor.

Recent studies³ show that noncircular inverse D-coils are extremely effective in symmetrizing (contoring) mod-B (thus contoring the ring and toroidal plasma) in the midplane, thereby giving good trapped particle confinement and reactor volume utilization. While the magnetic system with D-coils is significantly less complicated than that with SYM coils, whether the use of D-coils alone in the basic EBT configuration permits a significant reduction in the size of an EBT reactor is still an open question. Configurations with noncircular tori (square torus, racetrack, etc.) are also under consideration.⁴

Brief summaries of configurations with ARE and SYM coils and noncircular mirror coils are given in the following sections.

2. ARE AND SYM COILS

The supplementary coil technique of aspect ratio enhancement consists of modifying the vacuum magnetic field within the reactor chamber by placing two or more (as required by symmetry) relatively low current supplementary coils in each mirror sector. These coils are in addition to the mirror coils that provide the EBT toroidal field. Two types of supplementary coil configurations have been studied.

Axis-encircling ARE coils (two per sector) typically require $\leq 10\%$ of the ampere-turns in the mirror coils (I_{ARE}), with the polarity of the current opposite to that in the mirror coils. Enhancement of the effective aspect ratio with ARE coils results from two effects: (1) increased mirror ratio and (2) lengthening of the magnetic field lines inside the toroidal minor axis relative to those outside. Those effects come about largely through partial

cancellation of the mirror coil field. Therefore, for operation at a given field strength with ARE coils, the mirror coils must be capable of generating a field that is approximately 3% stronger for each 1% of ARE current than the required field in the absence of ARE coils. To lowest order, the ARE factor for a reactor with ARE coils can be approximated by $f_A \approx (1 + 2I_{ARE})^2 / (1 - 2I_{ARE})$. For example, single-particle confinement in a 24-sector reactor with $I_{ARE} \approx 8-10\%$ of the mirror coil ampere-turns compares favorably with that in a reactor having 42-48 sectors without ARE coils. Although ARE coils are quite effective in improving both single-particle confinement and magnetic field geometry within the reactor chamber, increased size and field requirements of mirror coils result in a costly magnetics system.

The SYM coils serve the same purpose but offer several distinct advantages over ARE coils. SYM coils do not encircle the minor axis of the torus and therefore permit easier assembly and maintenance and better accessibility. In addition, there is no global field calculation, so it is not necessary to operate the mirror coils at higher fields than would be required without SYM coils. They improve single-particle confinement by symmetrizing mod-B across the minor axis in the midplane and lengthening magnetic field lines inside the torus (see Figs. 1 and 2). The required ampere-turns per SYM coil (2 per sector) are roughly twice the value for ARE coils, but the total ampere-turns (SYM + mirror coils) for a given operational field are less for a reactor using SYM coils than for one using ARE coils.

Thus, of the two supplementary coil configurations examined, SYM coils offer the most promise of improving magnetic field geometry and single-particle confinement. Even though the magnetics system is more complicated than that for simple mirror coils, the attendant reduction, by approximately a factor of 2, in the required size of an EBT reactor makes the SYM coil configuration economically attractive. This is particularly true if more detailed neutronics and engineering calculations indicate that the required thickness of the first wall, blanket/shield assembly, dewar, etc., under the coil is $\delta \geq 1.3-1.5$ m.

3. NONCIRCULAR MIRROR COILS

The use of noncircular (specifically, semicircular) mirror coils was recently suggested by the Nagoya Bumpy Torus (NBT) group as a means of improving particle confinement in

Fig. 1. Three-dimensional, finite-beta tensor pressure equilibria in one sector of a reactor without and with SYM coils ($I_{SYM} = 20\%$). The region occupied by the ring (dark dots) and the toroidal core plasma (light dots) is shown. With SYM coils, mod-B across the minor axis is nearly symmetric and the maximum radius of the hot electron rings (as well as the core plasma) is nearly doubled.

the planned NET-II experiment.² Here possible reactor applications of noncircular mirror coils have been examined. Rather than using semicircular coils, the coil shape has been parameterized in the same way as is done for tokamak D-shaped TF coils. In a bumpy torus the vertical "straight" leg of the coil is optimally located outside the toroidal minor axis rather than inside; that is, the coil is reversed from that in tokamak configuration. A typical inverse-D coil for a bumpy torus is shown in

Fig. 2. Variation of ARE factor f_A with SYM coil current I_{SYM} for trapped (T) and passing (P) particles.

Fig. 3. In a toroidal array of these coils, this orientation results in a partial cancellation of the vertical drift that arises from the toroidicity.

To study the effects of mirror coil noncircularity, we consider a system with a given major radius R_T , number of sectors N , mirror ratio M , etc., in which the circular mirror coils are replaced with D-coils with diameter, ellipticity, and triangularity chosen to give the required mirror ratio on axis. For ellipticity and triangularity values of 1.75 and 0.7, respectively, the resulting mean diameter of the D-coils across the equatorial plane is typically about 80% of that for the circular coils. If the mechanical aspect ratio is defined as the major radius of the torus divided by the mean coil radius in the equatorial plane, then the aspect ratio with the D-coil system is about 25% larger than with circular coils. This is evident in the results presented here for passing particles. Defining a quantity to represent the magnetic aspect ratio enhancement of D-coils compared with circular coils is not without ambiguity. For example, the magnetic axis in an infinite aspect ratio D-coil system is outside the geometric center of the coil (defined in the equatorial plane). This means that a finite aspect ratio D-coil torus can have mod-B in the midplane almost perfectly symmetric about the geometric axis, as shown in Fig. 4 for $N = 36$, $M = 2.36$. If the inward shift of the minimum of the longitudinal invariant $r(J_{min})$ is measured relative to the magnetic axis and scaled by the mean coil radius in the equatorial plane, then the ARE factors for trapped and

Fig. 3. Typical inverse-D coil configuration. The mean diameter of the D-coil across the equatorial plane is about 80% of that for the circular coil for a given major radius, number of sectors, and mirror ratio.

passing particles are seen to be ≈ 1.7 and 1.35 , respectively, for $M = 2.36$.

As discussed in Sect. 1, the radial distance δ in the coil throat between the first wall and the mirror coil windings is an important parameter that influences the selection of a magnetics system. The ratio of the area of the largest confined passing particle ($V_{\parallel} = V$) drift orbit to that for trapped particles ($V_{\parallel} = 0$) is compared in Fig. 5 for D-coils and for circular mirror coils (with and without SYM coils) as a function of δ for various reactor sizes with $N = 18, 24, 30$, and 36 coils. In all cases, D-coils are superior to or comparable with simple circular coils.

Fig. 4. Mod-B contours (solid) and magnetic field lines (dashed) in the equatorial plane for devices with 24 (left column) and 36 (right column) sectors. D-coils are shown on the top and circular coils are shown on the bottom.

However, for $\delta \gtrsim 1.0-1.2$ m in the example shown in Fig. 5, the improvement obtained with D-coils is not as large as that obtained with SYM coils.

A commonly used method¹ of characterizing the confinement of single particles in an EBT vacuum magnetic field consists of measuring the inward shift, from the minor axis, of the minimum of the longitudinal adiabatic invariant $J = \oint V_{\parallel} dl$, $[r(J_{\min})]$. In the limit $V_{\parallel} \rightarrow 0$, this shift is given by the radial position of the peak of mod-B in the midplane, $[r_{\max}(\text{midplane mod-B})]$. The magnitude of the inward shift for deeply trapped particles ($V_{\parallel} = 0$) and for extreme passing particles ($V_{\parallel} = V$) is shown in Fig. 6 for D-coils as a function of N . The curve in Fig. 6 shows the N^{-1} dependence of the shift for $V_{\parallel}/V = 0$. On the other hand, the shift for passing particles ($V_{\parallel}/V = 1$) exhibits roughly an $N^{-\alpha}$ dependence with $\alpha = 0.74$ for fixed $M (\approx 2.36)$.

It should be noted that while the dependence of the trapped particle shift upon α is independent of mirror ratio M and coil shape ($\alpha = 1$), the exponent α for passing particles depends on both of these quantities; this dependence is shown in Fig. 7. Note that α is larger for D-coils than for simple circular coils by approximately the ratio of the mean coil diameters in the equatorial plane. A convenient parameterization is

Fig. 5. The ratio of the area of the largest confined passing particle ($V_{\parallel} = V$) drift orbit to that for trapped ($V_{\parallel} = 0$) particles is shown for circular coils [without (a) and with (b) SYM coils] and for D-coils (c) as a function of blanket-shield thickness ($\Delta_{B-S} = \delta$) under the coils for various reactor sizes.

$$\alpha = \beta \tan^{-1}(H/2.7),$$

where $\beta = 1$ for D-coils and $\beta = 0.78$ for circular coils.

In conclusion, noncircular coils or D-coils represent an attractive alternative to the supplementary coil technique of aspect ratio enhancement. If future detailed engineering and neutronics calculations indicate that $\delta < 1.0$ - 1.2 m gives adequate neutron shielding and an acceptable minimal breeding ratio under the coil, then D-coils will certainly compare favorably with systems utilizing SYM coils. If $\delta > 1.3$ - 1.5 m is found to be necessary, then SYM coils would present the most attractive alternative in terms of minimizing reactor size. The D-coil magnetics system is significantly less complicated; hence, assembly, maintenance, and access should not be adversely affected, as they are with configurations in which there are two supplementary coils per sector.

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Fig. 6. Magnitude of inward shift for deeply trapped particles ($V_{\parallel} = 0$) and for extreme passing particles ($V_{\parallel} = V$) for D-coils as a function of number of sectors and major radius.

Fig. 7. The centering of passing particle drift orbits scales with the number of sectors N as $N^{-\alpha}$, where α depends on mirror ratio, M , and coil shape. $\alpha(M)$ for D-shaped coils is seen to be larger than that for circular coils by roughly the ratio of the mean coil diameters in the equatorial plane.

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