Toroidal Mirror Device with Absolute Minimum Field Configuration

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A novel toroidal mirror with an absolute minimum magnetic field configuration (absolute Min-B) using superposition of quadrupole field is proposed. The particle confinement ability of the magnetic configuration is examined and shown to be excellent.

Keywords:
toroidal mirror, axisymmetric magnetic well, absolute minimum field configuration, quadrupole field, particle simulation.

In this paper an axisymmetric magnetic well is proposed which is created by pairs of co-axially placed ring conductors; the conductors of each pair carry the same and oppositely-directed currents.

An example of the coil parameters and numerical conditions are listed in Table 1. An assumed coil current density, $J_{\rm coil}$ ~ 1 [MA/cm^2] or more, is difficult to engineer using existing superconducting coil technology, thus the aim of this paper is to show the potential confinement ability of this magnetic field configuration. Therefore no optimization for the number of coils nor their position have been made. Fig. 1 describes the contours of the constant field strengths $|\boldsymbol{B}|$ (broken lines), and part of the field lines (solid lines) that traverse the region in which the plasma is to be confined. It should be noted that there are four field minima, and that there are two classes of mirror fields. The one is a set of closed field lines created primarily by a single conductor, while the other by two pairs of conductors.

Table 1 Coil parameters and numerical conditions

coil current	$I_{\rm coil}$	25	MA
coil center separation	$d_{\rm coil}$	5	cm
number of coil pairs	$N_{\rm pair}$	5	
deuteron energy	W	10	keV
number of starting points	$N_{\rm start}$	9	
number of pitch angles	$N_{\rm pitch}$	21	
calculation time	$t_{\rm calc}$	2	msec

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The toroidal mirror field configuration proposed here differs from the closed surface field type of the SURMAC (surface magnetic configuration) devices proposed by A.Y. Wong *et al.* [1] which have essentially the former dipolar field lines within the plasma region. Another very similar coil arrangement was proposed by R.W. Moir and R.F. Post [4], in which the axisymmetric field lines are cusp-like ones on the poloidal plane with a field minimum within the region where the plasma is to be confined.

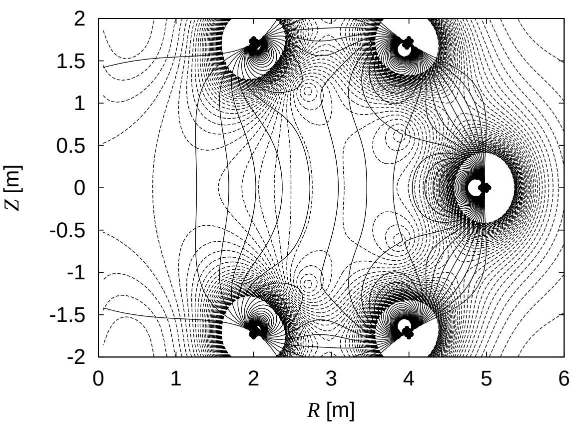

Fig. 1 Plots of flux function (solid lines), and $|\boldsymbol{B}|$ (broken lines) on poloidal plane. There are four field minima in five pairs of conductor coil systems. Field strength at magnetic well perimeter $B_{\rm per} \approx 0.4$ [T].

Table 2 Lost particles marked with √. No lost particle for R_S = 0.5, 1, 1.5, 2, 2.5, and 4.5 m

R_S [m]	Pitch Angel α [deg]																				
	17	31	40	48	55	62	68	74	79	85	90	95	101	107	113	119	126	133	141	150	163
3.0					√						√								√		
3.5										√				√							
4.0	√	√	√	√															√	√	

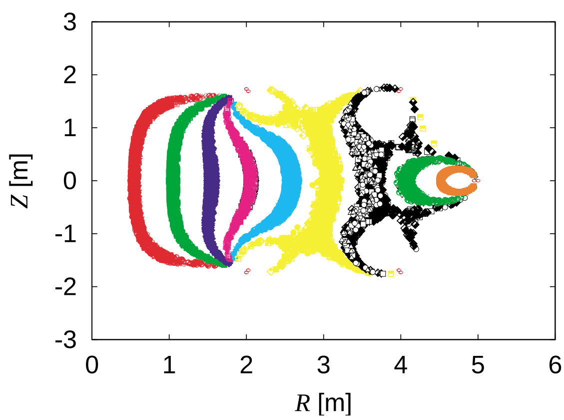

Fig. 2 Poicarè plots of 10 keV deuteron with starting points on R-axis at R_S = 0.5 (red), 1 (green), 1.5 (blue), 2 (purple), 2.5 (cyan), 3 (yellow), 3.5 (black), 4 (green), and 4.5 (orange) m for various pitch angles. Five pairs of conductors are also shown in red.

Since the magnetic field strength in the perimeter of the magnetic well $B_{peri} \approx 0.4$ [Tesla] and the typical Larmor radius $\rho_L \sim$ 1–15 [cm] in the present example, equation of motion, instead of a drift equation, was solved for 10 keV deuteron with pitch angles α, $0 < \alpha < \pi$ [rad] and starting points R_S, $0.5 \le R_S \le 4.5$ [m]. Figure 2 shows the Poincarè plots of a 10 keV deuteron with starting points along the R-axis at R_S = 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, and 4.5 [m] for various pitch angles. Table 2 summarizes the results in which lost particles are checked with √ for each pitch angle α and starting point R_S. The definition of the *lost particles* in the present paper is those that pass through the inter-coil space. No particles are lost when the starting points on the R-axis are at $0.5 \le R_S \le 2.5$ [m] and R_S = 4.5 [m] within a prescribed calculation time of t_{calc} = 2 ms. These particles are trapped by the vertically-formed mirror fields as shown in Fig. 1, and move essentially along the field lines, conserving the second adiabatic invariant, $J = \oint v_{\parallel} dl$, as well as the magnetic moment $\mu = mv_{\perp}^2/2B$. Some particles with the starting points at R_S =3, 3.5, and 4 [m] passed through the narrow inter-coil space, and are regarded as lost particles. Lost particles with R_S = 4 [m] are lost simply because their pitch angles are either $\alpha \approx 0$, or $\alpha \approx \pi$ except α = 163 [deg], i.e., the loss cone loss. On the other hand, the loss of particles with R_S = 3 [m] (yellow points in Fig. 2) and 3.5 [m] (black points) are caused by the *uncorrelated jumps* of the magnetic moments, $\Delta\mu$, each time they pass through one of the four field minima, leading to a diffusion in velocity space [2,3]. In these cases, particle orbits, or the Poincarè plots, extend over much wider regions than the other cases, i.e., R_S = 0.5–2.5 and 4–4.5 [m].

The total number of lost particles in this calculation are 11 out of 189 = 9 (starting points; N_{start}) × 21 (pitch angles; N_{pitch}) within the prescribed calculation time of 2 [msec]. All particles bounce as many as 100–1600 (on average 400) times in 2 [msec] with only one exception: 6 times in the case of R_S = 0.5 [m], α = 90 [deg].

In summary, we have proposed a novel toroidal mirror with an absolute minimum magnetic field configuration (absolute Min-B). The particle confinement ability of the proposed magnetic configuration is examined by means of numerical analysis, and is shown to be excellent with the definition of particle loss adopted here. This definition is employed in order to avoid the deficit of the internal conductor systems, in which a plasma surrounds some of the conductors and the particle loss to the conductor-support system is inevitable. If the definition of particle loss is changed to include those particles that are too close to the coil conductors to leave enough space for cooling and casing, then further analyses will be necessary to obtain more technically realistic results.

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