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**Influence of Global Magnetic
Perturbations on Plasma Behavior
in ELMO Bumpy Torus**

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INFLUENCE OF GLOBAL MAGNETIC PERTURBATIONS
ON PLASMA BEHAVIOR IN ELMO BUMPY TORUS

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ABSTRACT

The sensitivity of plasma confinement to magnetic field error effects has been tested experimentally using externally introduced global field errors on the ELMO Bumpy Torus (EBT). Below a critical error field $(\delta B_r/B)_{cr}$ of $\sim 0.6-1 \times 10^{-3}$ the plasma was observed to be essentially free from convective cells, toroidal currents, and instabilities. This observed critical value is comparable to a neoclassical critical field error $(\delta B_r/B)_{cr} \cong \rho/R$, the ratio of the ion Larmor radius to the major radius of the torus.

1. INTRODUCTION

The microwave-heated, closed-line ELMO Bumpy Torus (EBT) [1] differs from most toroidal geometries in that it does not require a toroidal current or external rotational transform windings. The reactor advantages result from the elimination of both the toroidal current and current-driven magnetohydrodynamic (MHD) instabilities which may unacceptably limit confinement in these devices. Previous theoretical studies have shown that equilibria [2] do exist in the bumpy torus configuration, that single particles [3] can trace out closed drift surfaces and be absolutely confined, and that a plasma can be MHD stable [4] because of the average minimum B created by the energetic electron rings. Because of the absence of a rotational transform, ($\ell/2\pi = n/m = 0$), the only resonant magnetic perturbation is global ($n = 0$) and there should be no difficulty with the formation of magnetic islands on the constant pressure surfaces [5]. However, global field perturbations can be deleterious to such an ideal, current-free, closed-line system. Steady-state magnetic field errors can, for example, cause the field lines to spiral out of the confinement region and to connect the plasma to system walls. In view of the current interest in the ELMO Bumpy Torus as an alternative to the tokamak reactor concept, a set of experiments has been conducted at Oak Ridge National Laboratory to investigate the plasma confinement sensitivity to magnetic field error effects using externally introduced global magnetic field perturbations. We have observed a critical error field, $(\delta B/B)_{cr} \approx 0.6-1 \times 10^{-3}$, below which the steady-state plasma configuration is not

significantly altered. The plasma is essentially free from toroidal current, plasma instabilities, and convective cells. For larger field errors, the ambipolar plasma potential symmetry was observed to be modified and the plasma was observed to carry a net toroidal current with amplitude proportional to field error. Enhanced plasma fluctuations in the drift wave frequency range were observed when the net toroidal current was sufficiently large (≥ 200 A). These changes in the global plasma behavior resulting from strong error fields suggested a topological change of plasma equilibrium.

In Section 2 we first stress the important effects of global field errors to bumpy torus confinement from the viewpoint of single particle orbits. In Section 3 we include a brief description of the ELMO Bumpy Torus device and its experimentally determined parameters. The error field experimental observations are presented in Section 4, and discussions of these experimental results are given in Section 5.

2. MOTIONS OF SINGLE-CHARGED PARTICLES

IN A PERTURBED BUMPY TORUS

The effect of field errors on a bumpy torus had been investigated by J. C. Sprott [6] using a computer code that calculated both the magnetic lines of force and particle drift trajectories in a perturbed field. From somewhat similar calculations we obtain the plot of the two trajectories for a given initial position as shown in Fig. 1 with a vertical field error of $\delta B/B \sim 4 \times 10^{-4}$. The field line spirals upward, while the drift surface is enlarged and displaced further toward the major axis. Particles whose drift surface intersects the limiting

system wall are lost on a drift time scale, thus resembling a mirror geometry loss cone. Therefore, global field errors generally enlarge the effective loss cone in a bumpy torus and would be expected to give an enhanced diffusion.

However, a more important concern is: what extent is the equilibrium configuration in EBT topologically changed under the influence of field errors? This effect is shown in Fig. 2, where the limiting drift surfaces for particles moving in opposite directions along the field lines are shown. Notice that in the presence of a global field error these two drift surface projections are quite different, resulting in plasma anisotropy in the parallel particle distribution and consequent overflowing of the parallel current. The area between the two drift surface projections in Fig. 2, for example, tends to confine those particles moving in the opposite direction of the magnetic field.

The above single-particle pictures may be overly pessimistic when collisions occur inside a drift time $2\pi/\Omega$, where Ω is the poloidal precession frequency, giving a Maxwellian particle distribution so that the plasma equilibrium configuration is not greatly altered. It is expected then that field errors will set a low collisionality limit on EBT confinement, as is indicated in the experiments described below.

3. EXPERIMENTAL ARRANGEMENTS

The physical dimensions and operating parameters of EBT are listed in Table I, and a schematic diagram of the facility is shown in Fig. 3. The magnetic field is produced by 24 toroidally linked mirrors with

individual mirror ratios of 2:1. Each mirror sector is connected by an aluminum vacuum cavity and the enclosed plasma is generated and heated by microwave power coupled to each cavity. The magnetic field coils were designed and constructed so that field errors due to spiral winding, bus bars, and interconnecting current leads are largely canceled. By using an electron beam probe in vacuum, we measured a global field error of $\delta B/B \sim 1.5 \times 10^{-4}$, which mostly results from the uncompensated earth field and ferromagnetic materials in the surroundings. Two pairs of current carrying loops were wound alongside the toroidally linked cavities to produce a horizontal and a vertical field in an arbitrary plane perpendicular to the minor axis. These fields can be used to reduce or enhance the system global field error, thus permitting studies of plasma stability and confinement with field errors as a parameter. The net toroidal plasma current, which is an important characteristic of the experiments to be described, is measured by integrating the electromotive force induced on two large pickup coils as shown in Fig. 3. A 70-GHz interferometer is used to obtain the averaged plasma density and density fluctuations. The two-dimensional ambipolar plasma potential profile is measured in the midplane of a single mirror by means of a heavy ion (rubidium) beam probing technique [7]. Other diagnostics such as soft x-ray measurements, charge exchange neutral particle ion temperature measurements, visible and vacuum ultraviolet spectroscopy, Thomson scattering, etc., are also used for plasma studies in various operating conditions.

These studies have shown the toroidal plasma in EBT to be macroscopically stable in the presence of the minimum averaged B

configuration created by the microwave-heated high beta electron annuli [1]. Optimization of the plasma parameters occurs when magnetic field errors are globally canceled by the compensation coils. In the macrostable regime where the plasma parameters have been measured over a sufficient range of operating conditions, these parameters are: $n_e \sim 1-2 \times 10^{12} \text{ cm}^{-3}$, $T_e \sim 150-600 \text{ eV}$, $T_i \sim 30-100 \text{ eV}$. The spatial potential profiles show a poloidally symmetric negative potential well whose depth is comparable to the electron temperature, about -300 to +100 volts in the center and up to +200 eV at the position of the annulus. The density fluctuation is found to be less than 0.2%, and there is no evidence of static potential fluctuation or convective cells. The overall energy confinement time is estimated to be 2-8 msec, compared favorably with the neoclassical theoretical prediction [8,9]. The plasma electron collisionality ν/Ω was found to range from 1 to 0.3. The low collisionality may necessitate electrons being non Maxwellian with respect to their parallel motions, as mentioned previously in Section 2.

4. EXPERIMENTAL RESULTS

4.1. Parallel current in EBT under the influence of global field errors

The net toroidal current in EBT has been measured by using both toroidal pickup coils and Rogowski coils surrounding the plasma. The detailed dependence of the toroidal current on externally introduced field errors is shown in Fig. 4 for several gas filling pressures. This dependence was found to be nearly linear for $p \sim 1-1.5 \times 10^{-5} \text{ torr}$. For lower pressure, $p \sim 5-10 \times 10^{-6} \text{ torr}$, the toroidal current was found to reduce to the minimum for a range of field errors, limited by

some critical field error value, $(\delta B/B)_{cr} \sim 0.6-1 \times 10^{-3}$. Outside this range, the toroidal current rapidly increases up to several hundred amperes. When the induced field errors I_h , I_v are scanned two-dimensionally as in Fig. 5, a plateau of minimum net toroidal current was found in the toroidal current. This interesting feature suggests that field errors cause the net toroidal current, although the EBT plasma under some conditions tends to remain current-free until field errors become very large. In order to confirm this conjecture, we have used four independent current pickup coils located on the outer surface at four different poloidal angles $\theta \approx 60^\circ$, 150° , 240° , and 330° . The characteristics obtained from each of these pickup coils are plotted in Fig. 6. It was found from these measurements that, for error fields larger than the critical value, all four toroidal current signals are of the same sign and increase to large amplitudes simultaneously showing a unidirectional current which changes direction with field error sense. In the region of small net toroidal current, $\delta B/B \leq (\delta B/B)_{cr}$, the amplitudes of all signals reduce to small values, thus confirming the conjecture that an essential current-free configuration was maintained. However, there is some detailed structure on the small residue current in this range of field errors: a) each of these signals seems to vary sinusoidally and cross zero once as the horizontal field error sweeps through this range, and b) the signs of each signal appear to be consistent with that expected from a diffusion-driven current (as discussed in Section 5).

4.2. Change of spatial potential profile by global field errors

The parallel currents observed have been found to be closely related to the ambipolar potential profile in EBT. Figure 7(a) shows a poloidally symmetric potential well as measured in the minimum toroidal current region. This desired symmetry breaks down when the global field compensation is turned off, as in Fig. 7(b). Here the central plasma potential seems to be short-circuited to ground through the system wall. The two-dimensional maps are generated assuming vertical symmetry from the horizontal scan and measurements in the lower half plane.

A sequence of radial potential profiles is presented in Fig. 8(a) together with the net toroidal current vs field error in Fig. 8(b). The potential profiles are measured along a canted vertical path defined by the heavy ion beam through the bottom half of the plasma. These figures illustrate a remarkable correlation as follows. In the region of minimum net toroidal current (between cases 3 and 4) the potential profiles remain nearly the same and are consistent with the typical two-dimensional profile [Fig. 7(a)] which shows a deep potential well. Outside this region, in both directions, the potential well was found to be reduced as field errors and the net toroidal current increase. Cases 1 and 5 show similar potential profiles at opposite extremes of toroidal current. At one extreme, cases 1 and 2 show the deepening of the well with decreasing toroidal current; at the other extreme, case 5 shows an abrupt shift in the potential profile as toroidal current increases.

4.3. Density fluctuations vs field errors

The macroscopic stability of plasma has been demonstrated by the low density fluctuation level observed in EBT. The line-averaged density fluctuation in the low frequency range ($\Delta f \sim 20$ kHz) was estimated as $\delta n/n \sim 0.2\%$ from the 70-GHz microwave interferometer. These fluctuations were found, using a movable rf probe, to be located mostly in the surface plasma. The fluctuation level as function of field error is shown in Fig. 9 together with the line-averaged plasma density, toroidal current, and space potential measured at two points. The fluctuation level was found to be greatly increased by the field error-induced toroidal current. The line-averaged density was found to drop by $\sim 30\%$ as the low frequency fluctuations became manifest upon applying the critical error field.

There is also experimental evidence of a large relaxation oscillation occurring in the plasma when the current is sufficiently large (≥ 200 A). This fluctuation resembles those observed when the gas filling pressure is brought to the lowest limit where stable EBT operation is no longer maintained. In this limit the plasma collisionality is smallest ($\nu/\Omega \sim 0.03$). The fluctuation presumably has to do with the stabilization effect of the electron annuli. However, small field errors in this range can hardly affect the mirror confined energetic electrons; the large relaxation oscillations may also have to do with plasma anisotropy, as discussed in Section 2. The detailed spectrum of these instabilities has not yet been obtained.

5. DISCUSSION

Although the experiments described above demonstrate the effects of global field errors on the behavior of plasma in EBT, a complete theoretical treatment of these effects is beyond the scope of this paper. However, we attempt some physical interpretation in order to make these observed effects comprehensible.

For the origin of parallel current the following physical model may be applicable. The ambipolar radial electric field can have components along the perturbed field lines $E_{||} \approx \bar{E} \cdot (\delta\bar{B}/B)$, so that a parallel current can be driven through the finite plasma conductivity.

$$J_{||} \approx \frac{\bar{E}}{\eta_{||}} \cdot \frac{\delta\bar{B}}{B} \approx \frac{E_r}{\eta_{||}} \frac{\delta B_r}{B} \quad (1)$$

In this case the plasma potential itself acts like a voltage source which is charged up by the ambipolar particle loss. Since this current relates to charge particles (electrons) leaving the plasma to the system wall, it will be reduced if many of these particles are returned to the plasma column by their drift motion. Particularly, when the drift surfaces of these particles remain closed within the column there should be no parallel current of this type. Equation (1) correlates the linear dependence of current amplitude on the field error as in Fig. 4 where all particles have effectively open drift surfaces in the collisional limit. In the range of small collisionality, most of the particles have closed drift surfaces until the field errors are large enough so that these closed drift surfaces intersect the system wall. The transition occurs when the inward displacement of this drift surface is comparable to the plasma radius:

$$\Delta x \approx \frac{v_y + v_{||}(\delta B r/B)}{\Omega} \sim a \quad (2)$$

where $v_y \approx (-kT/eB)1/R$ is the vertical drift velocity due to toroidal geometry, $v_{||}$ is the particle parallel velocity, Ω is the poloidal precession frequency due to mirror gradient and curvature, and R is the major radius. A simple calculation using Eq. (2) gives the critical field error:

$$\frac{\rho_e}{R} \leq \left(\frac{\delta B}{B} \right)_{cr} \leq \frac{\rho_e}{a} \quad (3)$$

which is in the experimentally observed range of $(\delta B/B)_{cr} \approx 0.6-1 \times 10^{-3}$ for typical EBT plasma parameters.

The residual parallel current is also related to field error, as shown in Fig. 6. This may be explained by a diffusion-driven current:

$$J_{||} = \frac{(2\bar{\Gamma} \times \bar{B})_{||}}{n\eta_{||}} \approx \frac{2\Gamma_r \delta B_{\theta}}{n\eta_{||}} \quad (4)$$

Here Γ_r is the radial diffusion flux and δB_{θ} is the poloidal component of the error field. This current is driven by the Lorentz force due to the radial particle flux and resembles the bootstrap current in tokamaks.

Note that $\delta B_{\theta} \approx -\delta B_H \sin\theta$ for the experimental condition described in Section 4. The sinusoidal behavior of Eq. (4) is evident in Fig. 6.

The ratio of the current described by Eq. (4) to that described by Eq. (1) is about the ratio of the diffusion velocity to the $E \times B$ drift velocity, which is about 10^{-2} to 1 in our experiment.

$$\frac{2\Gamma_r}{n} : \frac{E}{B} \sim 10^{-2} : 1 \quad (5)$$

compared qualitatively with the observed amplitudes. Note that Eqs (1) and (4) can be combined to give

$$E_{||} + (\bar{v} \times \bar{B})_{||} = J_{||} \eta_{||} \quad (6)$$

which is the usual Ohm's law, as is expected.

The potential asymmetry which develops with toroidal current appears to be related to the vertical drift of electrons whose drift surfaces intersect the system wall. Notice that the current carries electrons out of the plasma and therefore tends to reduce the negatively charged potential. While the steady-state plasma behavior remains qualitatively the same for a range of small field errors, $|\delta B/B| \leq (\delta B/B)_{cr}$, the plasma equilibrium conditions appear to deviate significantly from the ideal EBT configuration outside this limit.

The effects of global field errors on particle and energy transport can be estimated from the drift kinetic equation.

$$(\bar{V}_{||} + \bar{V}_D) \cdot \frac{\partial f}{\partial \underline{x}} = C(f) \quad (7)$$

Using

$$\bar{V}_{||} = V_{||} (\bar{B} + \delta \bar{B})/B \quad (8)$$

and neglecting the toroidal variation along the field lines, Eq. (7) reduces to the following form:

$$\Omega \frac{\partial f}{\partial \theta} - C(f) \approx -(V_y \sin \theta + V_{||} \delta B_r/B) \frac{\partial f}{\partial r} \quad (9)$$

where Ω is the precessional frequency and V_y is the vertical drift velocity. The transport coefficients [10] can then be calculated with a chosen model collision operator. The results obtained in the strong electric field limit are compared with the results of Spong [10] and

Kovrizhnykh [11] in Table II. These coefficients are defined as follows:

$$\Gamma_r = -D_n \frac{dn}{dr} - D_{Tdr} \frac{dT}{dr} - \mu_{ndr} \frac{dp}{dr} \quad (10)$$

$$Q_r = -K_n \frac{dn}{dr} - K_{Tdr} \frac{dT}{dr} - \mu_{Tdr} \frac{dp}{dr} \quad (10)$$

$$\mu_n = \frac{en}{\kappa T} D_n, \quad \mu_T = \frac{en}{\kappa T} K_n$$

where Γ_r and Q_r are the radial particle and energy flux respectively.

For $\delta B/B \approx \rho_e/R$, the transport coefficients are found to be comparable to the neoclassical value. Numerically, the heat conductivity K_T is found to be less sensitive to field error than the particle diffusion rate D_n . This indicates that the energy confinement time in EBT can be nearly the same over the entire range of field error $|\delta B/B| < (\delta B/B)_{cr} \sim 0.6-1 \times 10^{-3}$. Measurements of energy confinement time in EBT with the available diagnostics seem to support this contention.

Finally, we wish to point out that even though a global field error of $\delta B/B \sim \rho_e/R$ is rather small, relatively simple external field windings permit adequate compensation of EBT in its steady-state mode with no serious field error difficulties in a desirable range of plasma collisionality.

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FIGURE CAPTIONS

FIG. 1. The drift orbit (circles) and the field line (triangles) for a perturbed bumpy torus with a vertical field error $\delta B/B \sim 0.4\%$. The plot shows a minor cross section of the torus in a mirror midplane with distances normalized to $R = 24$.

FIG. 2. The limiting drift surfaces of a particle moving in opposite directions with respect to the magnetic field; the area between these two surfaces confines only those particles moving in the reverse direction along the field lines.

FIG. 3. Schematic diagram of the global field correction system on EBT. The correction loops are 50 cm from the minor axis. Each loop consists of a 20-turn coil capable of carrying a current up to 30 A. The major radius of the torus is 150 cm.

FIG. 4. Toroidal current vs horizontal field error for several gas filling pressures. The vertical field error is unchanged.

FIG. 5. Toroidal current vs horizontal field error — family of curves with vertical field error as a parameter, showing the remarkable minimum toroidal current plateau in the characteristic surface.

FIG. 6. Detailed current variation detected by four extra current pickup coils located at 60° , 150° , 240° , and 330° poloidal angle. The zero lines are provided for comparison.

FIG. 7. The plasma potential profiles measured by using a rubidium ion beam probe. The flat outer regions are provided for zero reference. Curve (a) is the horizontal scan across the minor axis; plot (a) is the two-dimensional profile generated using a spline fit to data obtained

with a proper field correction on EBT. Curve (b) and plot (b) are measured without field corrections.

FIG. 8(a). A sequence of potential profiles measured along a line defined by the primary heavy ion beam (data taken under slightly different plasma conditions from Fig. 7).

FIG. 8(b). The net toroidal current vs field error measured at the same conditions as Fig. 8(a). Points indicate the corresponding field error values for each potential profile in Fig. 8(a).

FIG. 9. Correlations of several parameters measured simultaneously as the horizontal field error scans in the range of $\pm 1-2 \times 10^{-3}$. The probable system global error is estimated to be 3×10^{-4} , as indicated by the arrowhead.

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TABLE I. NOMINAL EBT PARAMETERS

Present EBT	
Magnetic field	6.5 kG midplane — 13 kG mirror
Magnetic field power	10 MW
Torus volume	$\cong 1,351$ liters
Major radius	150 cm
Aspect ratio	$\approx 10:1$
<u>cw microwave power</u>	
ECH microwave source	60 kw cw — 18 GHz
LORH microwave source	30 kW cw — 10.6 GHz

TABLE II. COMPARISON OF NEOCLASSICAL TRANSPORT COEFFICIENTS
WITH FIELD ERROR TRANSPORT COEFFICIENTS

	D_n	D_T	K_n	K_T
	$\left(\frac{v_o^2 v}{v^2 + \Omega^2} \right)$	$\left(\frac{v_o^2 v_n}{v^2 + \Omega^2} \right)$	$\left(\frac{v_o^2 v kT}{v^2 + \Omega^2} \right)$	$\left(\frac{v_o^2 v_n}{v^2 + \Omega^2} \right)$
Kovrizhnykh, Spong	$\frac{1}{24}$	$\frac{2}{24}$	$\frac{7}{48}$	$\frac{101}{48}$
$\frac{\langle \delta B \rangle}{\langle B \rangle} \sim \frac{1}{\sqrt{3}} \frac{\rho}{R}$	$\frac{1}{24}$	$\frac{1}{24}$	$\frac{5}{48}$	$\frac{10}{48}$

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Fig. 1. The drift orbit (circles) and the field line (triangles) for a perturbed bumpy torus with a vertical field error $\delta B/B \sim 0.4\%$. The plot shows a minor cross section of the torus in a mirror midplane with distances normalized to $R = 24$.

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Fig. 3. Schematic diagram of the global field correction system on EBT. The correction loops are 50 cm from the minor axis. Each loop consists of a 20-turn coil capable of carrying a current up to 30 A. The major radius of the torus is 150 cm.

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Fig. 4. Toroidal current vs horizontal field error for several gas filling pressures. The vertical field error is unchanged.

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Fig. 5. Toroidal current vs horizontal field error — family of curves with vertical field error as a parameter, showing the remarkable minimum toroidal current plateau in the characteristic surface.

Fig. 6. Detailed current variation detected by four extra current pickup coils located at 60° , 150° , 240° , and 330° poloidal angle. The zero lines are provided for comparison.

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Fig. 7. The plasma potential profiles measured by using a rubidium ion beam probe. The flat outer regions are provided for zero reference. Curve (a) is the horizontal scan across the minor axis; plot (a) is the two-dimensional profile generated using a spline fit to data obtained with a proper field correction on EBT. Curve (b) and plot (b) are measured without field corrections.

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Fig. 8(a). A sequence of potential profiles measured along a line defined by the primary heavy ion beam (data taken under slightly different plasma conditions from Fig. 7).

Fig. 8(b). The net toroidal current vs field error measured at the same conditions as Fig. 8(a). Points indicate the corresponding field error values for each potential profile in Fig. 8(a).

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Fig. 9. Correlations of several parameters measured simultaneously as the horizontal field error scans in the range of $\pm 1-2 \times 10^{-3}$. The probable system global error is estimated to be 3×10^{-4} , as indicated by the arrowhead.

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