27
11-4-77
25 DUTIS

MASTER

ORNL/TM-6075

Effects of Global Field Errors on ELMO Bumpy Torus

B. H. Quon
R. A. Dandl
P. L. Colestock
H. Ikegami

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$4.00; Microfiche \$3.00

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, contractors, subcontractors, or their employees, makes any warranty, express or implied, nor assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product or process disclosed in this report, nor represents that its use by such third party would not infringe privately owned rights.

Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

EFFECTS OF GLOBAL FIELD ERRORS ON ELMO BUMPY TORUS

B. H. Quon and R. A. Dandl

P. L. Colestock
Rensselaer Polytechnic Institute

H. Ikegami
Nagoya University, Japan

Date Published - October 1977

NOTICE This document contains information of a preliminary nature.
It is subject to revision or correction and therefore does not represent a
final report.

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

NOTICE
This report was prepared as an account of work
sponsored by the United States Government. Neither
the United States nor the United States Energy
Research and Development Administration, nor any of
their employees, nor any of their contractors,
subcontractors, or their employees, makes any
warranty, express or implied, or assumes any legal
liability or responsibility for the accuracy, completeness
or usefulness of any information, apparatus, product or
process disclosed, or represents that its use would not
infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

leg

ABSTRACT

The plasma sensitivity to magnetic field error effects has been tested experimentally using externally introduced global field errors in the ELMO Bumpy Torus (EBT). A critical field $(\delta B_r/B)_{cr} \sim 0.6-1 \times 10^{-3}$ was observed, below which the plasma is essentially free from convective cells, toroidal currents, and instabilities. The 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.

The microwave-heated, closed-line ELMO Bumpy Torus¹ (EBT) is most attractive in that it does not require a toroidal current and hence can eliminate a class of current-driven drift modes and MHD instabilities. However, the ideal current-free closed-line toroidal system can be sensitive to magnetic perturbations, which can cause field lines to spiral out of the confinement region and to connect the plasma to the system wall. Deleterious field error effects,² such as anomalous diffusion, instabilities, and convective cells, have been observed to impair many closed-line devices with inherently large field error or plasma asymmetry. Experiments³ in EBT, on the other hand, have shown the validity of the premise that the microwave-heated high β annular electrons can provide macroscopic plasma stability⁴ in a steady-state bumpy torus. The system field error in EBT has been measured⁵ to be relatively small, and EBT thus far has shown no perceptible difficulties with field error effects.

However, this optimistic conclusion for EBT would not apply if the global field correction scheme were less effective. In the experiments described below, we have extended this field correction to superimpose externally introduced field error on EBT in order to study the plasma sensitivity to field error effects. We have observed a critical field, $\delta B_r/B \cong 0.6-1 \times 10^{-3}$, below which the plasma is essentially free from toroidal current, plasma instabilities, and convective cells. For larger field errors, the plasma potential symmetry was observed to be

modified. The plasma was observed to carry a net toroidal current with an amplitude proportional to field errors. Enhanced plasma fluctuations with frequency in the range of the drift waves manifested themselves when the net toroidal current became sufficiently large (>200 A).

The presence of a net toroidal current in EBT is an interesting phenomenon and deserves a careful investigation. The main physical feature is as follows. The radial ambipolar field can have a small component along the perturbed field lines, $E_{\parallel} \cong E_r (\delta B_r / B)$, so that a parallel current can be driven through the finite plasma conductivity in the presence of a field error

$$J_{\parallel} \cong \pm \frac{E_r}{\eta_{\parallel}} \frac{\delta B_r}{B}, \quad (1)$$

where $\eta_{\parallel}$ is the Spitzer resistivity. Because of the toroidal geometry, a net toroidal current can result from integrating Eq. (1) over the cross section,

$$I_{\text{toroidal}} = \int J_{\parallel} d\sigma \cong \frac{\pi a^2}{3} \left(\frac{a}{R} \right) \left\langle \frac{E_r}{\eta_{\parallel}} \right\rangle_r \frac{\delta B_H}{B}, \quad (2)$$

where a is the minor radius and R is the major radius of the torus, the symbol $\langle \rangle_r$ represents an average over the radial dimension, and δB_H is the horizontal component of the field error. This simple global relationship suggests that the ambipolar field can be strongly affected by field

errors and that the net toroidal current can be nulled by a global field compensation. Alternatively, the toroidal current amplitude can serve as a useful reference for field corrections.

The global field correction in EBT employs two pairs of current loops wound alongside the toroidally linked cavities, as schematically shown in Fig. 1. When current (I_H and I_V) is applied to these loops, a horizontal and a vertical field can be generated 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 stabilities and confinement with field errors as a parameter. The net toroidal current is measured by integrating the electromotive force induced on two large pickup coils (Fig. 1). A 70-GHz microwave interferometer is used to obtain the averaged plasma density and density fluctuations. The two-dimensional plasma potential profile on the minor cross section is measured in the midplane of a single mirror using a heavy ion (rubidium) beam probing technique.⁶ All these measurements are performed with the help of synchronized electronic systems, such as lockin amplifiers, in steady state and are designed for maximum accuracy.

The detailed dependence of the toroidal current on the externally introduced field error is shown in Fig. 2 for several gas filling pressures. This dependence was found to be nearly linear for $p \sim 1-1.5 \times 10^{-5}$ Torr, as predicted from Eq. (2). For lower pressure, $p \sim 5-10 \times 10^{-6}$ Torr, the toroidal current was found to be significantly reduced for a range of field errors. According to Eq. (2), the deviation from

the linear dependence may suggest the occurrence of changes in the plasma potential profile in such a way that the averaged radial electric field $\langle E_r \rangle_r$ is significantly reduced. It has been observed from the plasma potential profile measurement that in this lower pressure range a negative potential well is developed in the center plasma core, surrounded by a positive potential barrier near the annular electron rings.⁷ The formation of this negative well reverses the radial field direction in the center region and consequently reduces the averaged value $\langle E_r \rangle_r$. Our measurements of toroidal current and ambipolar potential thus conform to the simple global relationship proposed by Eq. (2).

We now focus our attention on the two-dimensional potential profiles measured at pressure $p_0 \cong 6 \times 10^{-6}$ Torr with a microwave power of ~ 50 kW. Figure 3(a) shows a radially symmetric potential well measured with a global field correction such that the toroidal current is minimized. The remarkable symmetry in the potential profile excludes any possible formation of convective cells and is favorable to a neoclassical ambipolar transport.⁸ This desired symmetry breaks down when the global field correction is turned off. As shown in Fig. 3(b), the central plasma potential seems to be short-circuited to ground through the outer system wall.

The effects of magnetic field errors on plasma stability and confinement in EBT are demonstrated in Fig. 4. The net toroidal current, the averaged plasma density, the averaged density fluctuation amplitude, and the plasma potential measured at the center and near the annular are

plotted together with the horizontal field error as functions of the current I_H applied to the field correction coil. There is a remarkable correlation between these measurements -- they change promptly as the field error scans across a critical value. By locating the probable global field error as indicated by the arrow in the $\delta B_H/B$ curve, the critical field is estimated to be $(\delta B_H/B)_{cr} \cong 0.6-1 \times 10^3$. We observed that within this critical field (1) the plasma carries very small net toroidal current ($I_{toroidal} \lesssim 5$ A), (2) the average plasma density is relatively high (by $\sim 30\%$), (3) the plasma is free from fluctuations ($\overline{\delta n}/\bar{n} \lesssim 2 \times 10^{-3}$, dominant at $\Delta f < 20$ kHz), and (4) there is a large ambipolar field which is consistent with the potential profile shown in Fig. 3(a). Outside this range, a large toroidal current (up to 200 A) is observed to coexist with an enhanced fluctuation level, and the ambipolar field becomes small. The increase of the average plasma density suggests an improvement of plasma confinement; however, an accurate estimate of this would require detailed measurements of the charged and neutral particle profiles, which are currently being undertaken in EBT.

The observed phenomena appear to be consistent with a neoclassical estimate for field error effects on radial diffusion. Including the field error effect on the radial loss velocity,

$$W \cong V_o \sin \theta + V_{||} \frac{\delta B_r}{B}, \quad (3)$$

where $V_o \cong (kT/m)(1/\omega_c R)$ is the vertical drift velocity due to the toroidal field geometry and θ is the azimuthal coordinate, we can obtain an effective diffusion rate by using the time-independent drift kinetic equation⁹ as

$$D^* \cong \frac{V_o^2}{2} \frac{\nu}{\nu^2 + \Omega^2} + \frac{V_o^2}{3} \sum \left(\frac{\delta B_{m,n}}{B} \right)^2 \frac{\nu}{\nu^2 + (m\Omega)^2 + (nV_{||}/R)^2}, \quad (4)$$

where $\delta B_{m,n}$ is the (m, n) th Fourier component of the radial field error, ν is the relevant collision frequency, and Ω is the precession frequency of charged particles due to the bumpy magnetic field and the $E \times B$ drift. The first term of Eq. (4) is the usual neoclassical diffusion¹⁰ rate due to the toroidal effect, while the second term is contributed by the radial magnetic perturbation.¹¹ The most important field error effect comes from the global $n = 0, m = 1$ component. By comparing this term with the toroidal effect, we obtain a critical field

$$\left(\frac{\delta B_r}{B} \right)_{cr} \cong \sqrt{3/2} \rho/R. \quad (5)$$

This result yields a critical field of $(\delta B_r/B)_{cr} \sim 10^{-3}$ for ions in EBT. Although the numerical value should be obtained with more accurate averaging over the bumpy toroidal field, it is nevertheless quite close to the experimental value.

In this investigation, the use of externally introduced global field errors on EBT has permitted a study of plasma sensitivity to field error effects. Within the critical field, the plasma behaviors are not significantly altered. The presence of toroidal currents and plasma fluctuations and the quenching of the ambipolar field with larger global field errors may signify a new kind of anomalous transport. These results thus warrant further studies in the next generation of EBT plasmas,³ in which small collisionality is anticipated.

We wish to acknowledge helpful discussions with N. H. Lazar, K. Connor, and R. L. Hickok (Rensselaer Polytechnic Institute). We also acknowledge the assistance of the EBT Technical Staff. This research was sponsored by the Department of Energy under contract with Union Carbide Corporation. One of the authors (P.L.C.) is under subcontract from Rensselaer Polytechnic Institute.

References

- ¹R. A. Dandl, H. O. Eason, G. E. Guest, C. L. Hedrick, H. Ikegami, and D. B. Nelson, in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 5th Conf. Tokyo, 1974) II, IAEA, Vienna, 141; R. A. Dandl, H. O. Eason, and H. Ikegami (to be published in Nucl. Fusion).
- ²J. A. Schmidt, Phys. Rev. Lett. 24, 721 (1970); T. Jernigan, J. Rudmin, and D. M. Meade, Phys. Rev. Lett. 26, 1298 (1971); T. Ohkawa, Phys. Rev. Lett. 27, 177 (1971); S. Yoshikawa, Nucl. Fusion 13, 433 (1973); J. C. Sprott, Phys. Fluids 16, 1157 (1973); J. R. Drake, J. R. Greenwood, G. A. Chatelier, and A. Samain, Phys. Fluids 20, 148 (1977).
- ³R. A. Dandl *et al.*, Research Program for Plasma Confinement and Heating in ELMO Bumpy Torus, Oak Ridge National Laboratory Report No. ORNL/TM-4941 (1975).
- ⁴G. E. Guest, C. L. Hedrick, and D. B. Nelson, Phys. Fluids 18, 871 (1975).
- ⁵H. Ikegami and R. A. Dandl have measured a horizontal field error $\delta B_H/B \cong 1.5 \times 10^{-4}$ in EBT using an electron beam probing technique (1974).
- ⁶P. L. Colestock *et al.*, paper presented at the IEEE 1977 International Conference on Plasma Science, Troy, New York, May 23-25, 1977.
- ⁷P. L. Colestock, K. A. Connor, R. L. Hickok, and R. A. Dandl, submitted to Phys. Rev. Lett.

⁸C. L. Hedrick *et al.*, Oak Ridge National Laboratory Report No. ORNL/TM-5490 (1977), submitted to Nucl. Fusion; E. F. Jaeger *et al.*, Oak Ridge National Laboratory Report No. ORNL/TM-6013 (1977).

⁹B. B. Kadomtsev and O. P. Pogutse, Nucl. Fusion 11, 67 (1971).

¹⁰L. M. Kovrizhnykh, Zh. Eksp. Teor. Fiz. [Sov. Phys.-JETP] 29, 475 (1969).

¹¹D. M. Meade and R. J. Fonck, Phys. Fluids 16, 1654 (1973).

Figure Captions

Fig. 1. Schematic diagram of the global field correction system on EBT. The correction loops are 50 cm from the minor axis. Each of these loops 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. 2. Dependence of the net toroidal current on magnetic field errors introduced by the external loop current (I_H) for different gas filling pressures. I_V (≈ 20 A) is held fixed. The large current reduction for a range of field errors at low pressure suggests a change in the plasma potential profile.

Fig. 3. The plasma potential profiles measured by using a rubidium ion beam probe (15 kV). 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. 4. 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.

Fig. 1

Fig. 2

ORNL/DWG/FED-77345

Fig. 3

ORNL DWG FED-77342

Fig. 4

INTERNAL DISTRIBUTION

1. F. W. Baity, Jr.	48. J. N. Luton
2. D. B. Batchelor	49. O. B. Morgan, Jr.
3. F. Bieniosek	50. D. B. Nelson
4. J. D. Callen	51. H. Postma
5. K. Carpenter	52. B. H. Quon
6. J. A. Cobble	53. M. W. Rosenthal
7. F. L. Culler	54. D. A. Spong
8-36. R. A. Dandl	55. N. A. Uckan
37. R. A. Dory	56. T. Uckan
38. H. O. Eason, Jr.	57. T. L. White
39. J. C. Glowienka	58-60. Laboratory Records
40. G. R. Haste	61. Laboratory Records - ORNL RC
41. C. L. Hedrick, Jr.	62. Fusion Energy Division Reports Office
42. M. Hesse	63. Document Reference Section
43. S. Hiroe	64-65. Central Research Library
44. E. F. Jaeger	66-67. Fusion Energy Division Library
45. G. G. Kelley	68. ORNL Patent Office
46. S. Kuo	
47. N. H. Lazar	

EXTERNAL DISTRIBUTION

69. Dr. Charles Baker, Fusion Engineering Department, General Atomic Company, P.O. Box 81608, San Diego, CA 92138
70. Dr. Jack W. Beal, Office of Confinement Systems, M/S G-234, Division of Magnetic Fusion Energy, Department of Energy, Washington, DC 20545
71. Dr. John F. Clarke, Division of Magnetic Fusion Energy, Department of Energy, Washington, DC 20545
72. Dr. Patrick L. Colestock, Princeton Plasma Physics Laboratory, P.O. Box 451, C-Site, Princeton, NJ 08540
73. Dr. T. Consoli, Centre d'Etudes Nucléaires de Grenoble, B. P. 85 Centre de Tri, 38041 Grenoble Cedex, Grenoble, France
74. Dr. R. C. Davidson, Applied Plasma Physics Branch, M/S G-234, Division of Magnetic Fusion Energy, Department of Energy, Washington, DC 20545
75. Dr. S. O. Dean, Office of Confinement Systems, M/S G-234, Division of Magnetic Fusion Energy, Department of Energy, Washington, DC 20545
76. Dr. James F. Decker, Applied Plasma Physics Branch, M/S G-234, Division of Magnetic Fusion Energy, Department of Energy, Washington, DC 20545
77. Dr. David A. Dingee, Manager, Fusion Program, Battelle-Northwest, Battelle Blvd., Richland, WA 99352
78. Dr. William R. Ellis, Jr., Advanced Fusion Systems Branch, Division of Magnetic Fusion Energy, M/S G-234, Department of Energy, Washington, DC 20545
79. Dr. T. K. Fowler, L-382, University of California, Lawrence Livermore Laboratory, P.O. Box 808, Livermore, CA 94550

80. Dr. M. Fujiwara, Institute of Plasma Physics, Nagoya University,
Nagoya 464 Japan
81. Dr. H. P. Furth, Princeton University, Plasma Physics Laboratory,
P.O. Box 451, Princeton, NJ 08540
82. Dr. Roy W. Gould, Department of Applied Physics, California
Institute of Technology, Pasadena, CA 91109
83. Dr. Gareth E. Guest, General Atomic Company, P.O. Box 81608, San
Diego, CA 92138
84. Dr. E. G. Harris, Department of Physics, University of Tennessee,
Knoxville, TN 37916
85. Dr. R. L. Hickok, Electrophysics Division, Rensselaer Polytechnic
Institute, Troy, NY 12181
86. Dr. R. L. Hirsch, Science and Technology Department, 1251 Avenue of
the Americas, New York, NY 10020
87. Dr. H. Ikegami, Institute of Plasma Physics, Nagoya University,
Nagoya, 464 Japan
88. Dr. Howard R. Jory, Varian Associates, 611 Hansen Way, Palo Alto,
CA 94303
89. Dr. A. Kadish, Division of Magnetic Fusion Energy M/S G-234,
Department of Energy, Washington, DC 20545
90. Dr. Edwin E. Kintner, Division of Magnetic Fusion Energy, M/S G-234,
Department of Energy, Washington, DC 20545
91. Dr. Nicholas A. Krall, Science Applications, Inc., 1200 Prospect
Street, Box 2351, La Jolla, CA 92037
92. Dr. Kenneth G. Moses, Chief, Reactor Engineering Branch, Office
of the Assistant Director for Technical Projects, Division of
Magnetic Fusion Energy, Department of Energy, Washington, DC 20545
93. Dr. Erol Oktay, Division of Magnetic Fusion Energy, M/S G-234,
Department of Energy, Washington, DC 20545
94. Dr. Robert E. Price, Division of Magnetic Fusion Energy, M/S G-234,
Department of Energy, Washington, DC 20545
95. Dr. David J. Rose, Department of Nuclear Engineering, Massachusetts
Institute of Technology, Cambridge, MA 02139
96. Mr. H. Stanley Staten, Engineering Design and Component Development
Branch, D and T Program, Division of Magnetic Fusion Energy, M/S
G-234, Department of Energy, Washington, DC 20545
97. Dr. A. Straprans, Varian Associates, 611 Hansen Way, Palo Alto, CA
94303
98. Dr. L. D. Stewart, Princeton Plasma Physics Lab., P.O. Box 451,
Princeton, NJ 08540
99. Dr. R. S. Symons, Varian Associates, 611 Hansen Way, Palo Alto,
CA 94303
100. Dr. J. M. Williams, Division of Magnetic Fusion Energy, M/S G-234,
Department of Energy, Washington, DC 20545
101. Dr. Herbert H. Woodson, Department of Electrical Engineering, The
University of Texas at Austin, Austin, TX 78712
102. Director, Research and Technical Support Division, Department of
Energy, Oak Ridge Operations, Oak Ridge, TN 37830
- 103-129. Technical Information Center, P.O. Box 62, Oak Ridge, TN 37830