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**Unconventional Heating
Experiments in EBT**

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FUSION ENERGY DIVISION

UNCONVENTIONAL HEATING EXPERIMENTS IN EBT

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CONTENTS

ABSTRACT	v
1. INTRODUCTION	1
2. DEFINITION OF HEATING GEOMETRIES	3
2.1 STANDARD RESONANCE CONFIGURATION	3
2.2 NONSTANDARD HEATING SCHEMES	3
3. RESULTS	5
3.1 FR EXPERIMENTS	5
3.2 SCRATCH EXPERIMENTS	7
4. CONCLUSIONS	9
REFERENCES	11
FIGURE CAPTIONS	12

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ABSTRACT

The magnetic design of EBT-I/S provides a flexible environment in which to examine various ring and core plasma electron cyclotron heating (ECH) scenarios. The heating occurs when the ECH power, available at three discrete frequencies, 10.6, 18, and 28 GHz, is in resonance with local harmonics of the electron cyclotron frequency. The resonance locations can be moved in a continuous fashion in the cavity sectors by changing the toroidal magnetic field over the range of 0-1.4 T. In an EBT, the bumpy magnetic equilibrium is stabilized by the high beta, hot electron rings formed in the field bumps by proper choice of microwave heating frequency and magnetic geometry. The most commonly used heating geometry for ECH is the standard resonance configuration (SR) wherein a fundamental resonance exists across the mirror coil throats for bulk plasma heating and a second harmonic resonance exists in an annular region in the cavity midplane for ring heating. Reported here are the results of two nonstandard heating experiments. In one, the fundamental ECH resonance at either 10.6 or 18 GHz was placed at the usual ring position in an attempt to generate rings solely with fundamental heating; this is the fundamental resonance configuration (FR). In a second experiment, an attempt was made to heat the ring and core separately by forming the ring as above with 10.6 GHz and then heating the core with the fundamental and second harmonic of 28 GHz; this is the separately coupled ring and toroidal core heating configuration (SCRATCH). In both cases, the hot electron annuli were formed and stabilized the core plasma as in the SR experiments. In FR, the rings form at the second harmonic and no

significant potential structures were found. In SCRATCH, either a potential well or a potential hill could be formed. In both heating regimes, significant ion heating above that found in standard heating experiments was found.

1. INTRODUCTION

The ELMO Bumpy Torus (EBT)¹ is a steady-state, microwave-heated toroidal plasma device consisting of 24 mirror sections with a mirror ratio of 1.9:1, a major radius of 150 cm, and a mirror throat radius of 11 cm. Heating occurs when the electron cyclotron heating (ECH) power, available at three discrete frequencies (10.6, 18, and 28 GHz), is in resonance with local harmonics of the electron cyclotron frequency. The resonance locations can be moved in a continuous fashion throughout the cavity sectors by changing the toroidal magnetic field over the range of 0-1.4 T.

Reported here are the results of two nonstandard heating experiments. In one, the fundamental ECH resonance at either 10.6 or 18 GHz was placed at the usual ring position in an attempt to generate rings solely with fundamental heating; this is the fundamental resonance configuration (FR). In a second experiment, an attempt was made to heat the ring and core separately by forming the ring as above with 10.6 GHz and then heating the core with the fundamental and second harmonic of 28 GHz; this is the separately coupled ring and toroidal core heating configuration (SCRATCH²). In both cases, the hot electron annuli were formed and stabilized the core plasma as in the standard heating experiments. In FR, no significant potential structures were found; in SCRATCH, either a potential well or a potential hill could be formed. In both heating regimes, significant ion heating above that found in standard heating experiments was found. Section 2 provides the definitions for the various heating geometries; Sect. 3 lists the

experimental results, and Sect. 4 offers several conclusions about these two new modes of operating EBT.

2. DEFINITION OF HEATING GEOMETRIES

2.1 STANDARD RESONANCE CONFIGURATION

The conventional heating procedure in EBT, the standard resonance configuration (SR), makes use of a fundamental resonance mod-B contour spanning each magnet near the throat and a second harmonic resonance mod-B contour located in the field bumps. Typical resonance locations for SR in EBT-I/S are plotted in the equatorial plane in Fig. 1. In this manner, a warm electron core of order hundreds of electron volts is generated by the fundamental resonance, and those warm electrons passing through the second harmonic resonance are heated to energies of order hundreds of kilo electron volts to form the mirror-trapped, hot electron annuli necessary for EBT stability. The ions are weakly heated by the electrons through collisions.

2.2 NONSTANDARD HEATING SCHEMES

The ability to vary the magnetic field and/or the microwave frequency provides the opportunity to investigate entirely new heating geometries. The fundamental resonance configuration (FR) seeks to generate the hot electron annuli with a fundamental resonance placed at the ring location, as shown in Fig. 2. The higher harmonics are located outside the ring region and can couple energy to electrons, but present heating theories³ predict much lower coupling for higher harmonic heating unless the higher harmonic heating zones coincide with a region of already heated (relativistic) electrons. If the rings could be formed by the fundamental heating and could provide

stabilization for a separately heated core plasma, the microwave frequency requirements for a reactor could be reduced.

An attempt to heat the ring and core plasmas independently (SCRATCH) makes use of rings formed by FR and a core heated by a higher frequency ECH source with its fundamental and second harmonic resonance zones located inside the core plasma, as illustrated in Fig. 3. The desired locations of the higher frequency heating zones shown on Fig. 3 are impossible to obtain in EBT-I/S because the actual (on-axis) mirror ratio (1.873 to 1) is lower than the design (on-axis) mirror ratio (2 to 1). The net effect is to shift the fundamental heating zone closer to the coil (mod-B contour $C = 2.02$ on Fig. 1) so that it no longer spans the magnet throat and to shift the second harmonic heating zone so that it spans the two coils (mod-B contour $C = 1.01$ on Fig. 1). The lower frequency heating zones remain virtually unchanged because of the layer gradient in the field. Again, present theories suggest that higher harmonics do not play a significant heating role.

With various mixtures of microwave frequencies and magnetic fields possible, a shorthand has been developed to identify the type of heating geometry in EBT. The steady-state microwave power in kilowatts is denoted as X/X/X for heating at 28, 18, and 10.6 GHz, respectively. A 4-digit number following the ECH frequencies identifies the toroidal field (TF) magnet current. Table 1 lists the various possibilities. The values for the TF coil current are nominal values. The details for locating the resonant mod-B contours for arbitrary currents are found in Fig. 4.

3. RESULTS

3.1 FR EXPERIMENTS

The first FR experiments were conducted on the Nagoya Bumpy Torus (NBT); the principal results⁴ were that the rings formed and were found to stabilize a toroidal core plasma over an operating range defined by pressure and power with identifiable C-, T-, and M-modes of operation. In addition, the line-averaged density in FR was approximately twice that found in SR for comparable power. The NBT experiments utilized 8.5-GHz ECH and 3200 A in the TF coils for a midplane-on-axis field of about 0.32 T.

Experiments were conducted in EBT-I FR and EBT-S FR; however, detailed plasma parameter measurements are available only in the higher density EBT-S FR. A plot of line-integrated density $n_e \ell$ as a function of pressure, using 50-kW ECH for EBT-I SR, EBT-S SR, and EBT-S FR, is shown in Fig. 5a. The stored energy $W_{\perp}$ is shown in Fig. 5b for the same conditions. The signatures of the C-, T-, and M-modes of operation are clearly seen in FR, albeit at higher pressure. The ring stored energy does not drop as fast in FR as in SR with increasing pressure. Figure 6 shows a plot of ring stored energy, ring temperature, and density for 30-kW and 50-kW ECH in EBT-S FR versus pressure. Typical of EBT-I/S SR operation, the ring temperature in T-mode is fairly constant and the ring density varies inversely with pressure.

Notably lacking in Fig. 5a is a plot of potential well depth⁵ in T-mode. As shown in Fig. 7, a quasi-spatial scan of plasma potential obtained with a heavy ion beam probe using a Cs^{1+} primary beam shows a nearly flat profile near zero volts. A detailed look at the Cs^{2+} and Cs^{3+} secondary signals indicates that there is little ring formation at the fundamental resonance; most of the ring is formed at the second harmonic resonance, as in SR operation. The details of the beam probe's sensitivity to hot electrons have been documented elsewhere.⁶ The low secondary ion current or sum signal in the core region indicates a hollow density profile and/or extremely cold core electrons ($T_e < 10$ eV). Conventional electron temperature diagnostics suggest a very cold core, and multichord microwave interferometry indicates a relatively flat density profile inside the ring.

In sharp contrast to the electrons, the ions appear to be heated above levels obtained in EBT-S SR. Shown in Fig. 8 are distribution functions for an EBT-S SR 100/0/0 at a pressure of 5.5×10^{-6} torr and an EBT-S FR 0/50/0 at 7×10^{-6} torr. Despite the lower power and higher pressure, a significant ion tail population exists. In an attempt to heat the ions separately with fast wave ion cyclotron heating (ICH), majority heating of hydrogen and minority heating of hydrogen in a deuterium majority were tried at low power but with little success. Higher power and higher frequency experiments are planned in the near term.

3.2 SCRATCH EXPERIMENTS

SCRATCH experiments were conducted in an attempt to independently heat the ring and core plasmas. In all experiments, ECH at 10.6 GHz was used to establish the rings using 0, 10, 20, and 30 kW, and various levels of ECH at 28 GHz were used to heat the core using up to 110 kW. The plots of line-integrated density $n_e \ell$ and ring stored energy W_1 versus pressure shown in Fig. 9 show that conditions can be established in which the standard hierarchy⁵ of C-, T-, and M-modes characteristic of EBT's is found. Ring densities and temperatures remain fairly constant as a function of pressure at fixed power. At fixed pressure, ring densities (of order 10^{11} cm^{-3}) increase with power, whereas ring temperatures vary from about 100 keV with 10.6-GHz power alone to about 500 keV with 28-GHz power alone. The mechanism that determines the ring temperature with combinations of 10.6 and 28 GHz power is not understood. A plot of $n_e \ell$ versus 28-GHz power at various levels of 10.6-GHz power, as shown in Fig. 10, shows $n_e \ell$ increasing with increasing 10.6-GHz power at constant 28-GHz power, but also shows $n_e \ell$ decreasing with 28-GHz power while 10.6-GHz power constant. Shown for reference is an EBT-S SR. From Figs. 9 and 10, it is evident that there is no decoupling of ring and core heating. As in FR, the ions are heated above levels in EBT-S SR for comparable powers, as shown in Fig. 11. In SCRATCH, it is those ions nearer to the bulk of the distribution that appear to be heated. Calibration problems with the charge exchange analyzer prevent ascribing an actual temperature, although the heating is clear.

SCRATCH differs sharply from FR in that definite potential structures exist. In Fig. 12 are plotted two potential profiles, one showing a positive potential hill and the other, the traditional EBT potential well. The difference between the two is the amount of ring heating power at 10.6 GHz. This is the first experimental evidence of a large positive potential in an EBT T-mode. The beam probe also supplies indirect evidence of a warmer electron component from the relative signal levels compared to FR. Conventional electron temperature diagnostics indicate temperatures of order 100 eV, consistent with the beam probe signal levels.

4. CONCLUSIONS

It is significant that rings are formed and stabilize a core plasma, yielding the familiar C-, T-, and M-modes, for both FR and SCRATCH. It is also fairly clear that these heating geometries are not strong candidates to supplant the traditional SR operation. In FR, it appears that the larger line densities can be attributed to a larger line length. Second harmonic heating dominates ring formation in both SR and FR. FR may still provide an interesting vehicle for ICH studies with higher frequencies and higher powers. Both FR and SCRATCH provide interesting contrasts in ion heating that are not understood. SCRATCH may provide valuable insights into potential formation and its effect on transport.

10

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2. This acronym was first suggested in February 1981 by L. Bighel (now deceased).
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5. See Ref. 1, Fig. 4a.
6. F. M. Bieniosek and K. A. Conner, paper G-4 presented at the Second EBT Ring Physics Workshop, San Diego, California, December 1-3, 1981 (proceedings to be published).

FIGURE CAPTIONS

- Fig. 1. Typical resonance locations for SR heating in EBT-I/S, plotted in the equatorial plane.
- Fig. 2. Resonance locations for FR heating, plotted in the equatorial plane.
- Fig. 3. Resonance locations for SCRATCH, plotted in the equatorial plane.
- Fig. 4. Generalized method for locating resonant mod-B contours in the equatorial plane for EBT-I/S.
- Fig. 5a. Line-integrated density $n_e \ell$ as a function of pressure using 50-kW ECH for EBT-I SR, EBT-S SR, and EBT-S FR.
- Fig. 5b. Average annulus stored energy per ring W_l as a function of pressure using 50-kW ECH for EBT-I SR, EBT-S SR, and EBT-S FR.
- Fig. 6. Ring stored energy, temperature, and density as a function of pressure for 30 kW and 50 kW in FR.
- Fig. 7. Quasi-spatial scan of plasma potential in FR. Structure found between 25 and 35 cm is caused by small errors in the electronics and in the alignment.
- Fig. 8. Comparison of ion energy distribution functions for EBT-S SR (100/0/0, 5.5×10^{-6} torr) and EBT-S FR (0/50/0, 7×10^{-6} torr).
- Fig. 9. Line-integrated density $n_e \ell$ and ring stored energy W_l as a function of pressure and power mixtures in SCRATCH.
- Fig. 10. Line-integrated density $n_e \ell$ as a function of 10.6-GHz and 28-GHz power in SCRATCH. Shown for reference (black squares) is an EBT-S SR.
- Fig. 11. Comparison of ion energy distribution for EBT-S SR (100/0/0, 5.5×10^{-6} torr) and SCRATCH (50/0/0, 6×10^{-6} torr).
- Fig. 12. Comparison of two plasma potential profiles in SCRATCH: 50/0/10 and 50/0/20.

SR

ORNL-DWG 81-22202 FED

Fig. 1

FR

ORNL-DWG 81-22205

FED

Fig. 2

SCRATCH

ORNL-DWG 84-22200

FED

Fig. 3

Fig. 4

Fig. 5(a)

Fig. 5(b)

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

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