Conf- 741105--1

The ELMO Bumpy Torus (EBT) Experiments*

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The bumpy torus has received very much less attention than other toroidal confinement schemes, primarily because of anticipated MHD instabilities and superbanana losses. [Several theoretical papers have pointed out its difficulty with the interchange stability criterion.]

In an attempt to circumvent these instabilities and permit studies of plasma confinement, we have constructed the ELMO Bumpy Torus (EBT), a specific toroidal array closely modeled after stable, steady-state, high-beta, hot-electron plasmas produced earlier in the ELMO open-ended trap by electron-cyclotron heating. The EBT is expected to derive MHD stability from the average minimum-B generated by the high-beta, mirror-confined, hot-electron shells typical of the ELMO plasma. Such annular hot-electron plasmas have been experimentally generated in each mirror section of EBT with only the outermost edges of the annuli line-tied against flutes by cold-plasma conduction to chamber walls.

We are encouraged by the observed stability in the present EBT, as well as in straight and canted-mirror experiments, as long as the pressure exceeds a critical value. Although this stability is ascribed to some form of line-tying, there is evidence to indicate that conducting end plates may not be necessary. It is possible that the stabilization stems from the electrostatic confinement of a cold-electron component produced by ionization of the ambient background gas [1].

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*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

Bumpy torus confinement of single particles has been shown by a number of authors [2] for a wide range of magnetic parameters. The neoclassical diffusion coefficient is given approximately by [3,4]

$$D \simeq \frac{1}{2} \langle v_T^{\,2} \rangle \frac{\nu}{\Omega^2 + \nu^2} \quad ,$$

where Ω is the precessional frequency, v_T is the toroidal drift velocity, and ν is the effective collision frequency. The plasma confinement time of EBT in a collisionless, neoclassical regime can be approximately given by

$$\tau = \left(\frac{R}{a}\right)^2 \tau_{ei} \quad ,$$

where R/a is the aspect ratio of the torus. Because the character of the particle drift surfaces is independent of mass, no distributed space charge difficulties seem likely, so that we can discuss the equilibrium from the standpoint of a charge-neutral guiding-center-fluid. We cannot, however, ignore the plasma currents which are expected to modify the magnetic field significantly. The effects are studied experimentally since it is difficult to obtain a unique pressure profile theoretically from first principles. Part of our program is therefore to optimize the vacuum field and to develop the analytical and experimental techniques for study and control of the equilibrium.

A schematic of EBT is shown in Fig. 1. The 24 coils are arranged in the bumpy torus configuration so as to give a mirror ratio of 2:1 with 15° cant angle between the planes of adjacent coils. This requirement is based upon experiments in the canted-mirror facility in which total stored plasma energy was observed to decrease by only 25% for 15° as compared to 50% for 22.5° cant angle. The major radius of the torus is 150 cm with an aspect ratio 10:1. The radius of the cavity sections enclosing hot-electron annuli is 30 cm with a maximum midplane magnetic mirror field of 6500 gauss.

The plasma is formed and heated by two 18-GHz klystron amplifiers with 30 kW (cw) divided into 24 equal parts in order to provide separate power feed to each individual mirror region of the torus. Resonant power feed to each mirror region is necessary for balanced excitation, because of the strong plasma absorption of power at the electron-cyclotron frequency. Each klystron feeds alternate mirror regions in order to maintain over-all power feed balance. A significant feature of the microwave technology is the degree of control of plasma parameters, such as density, temperature, amount of hot electrons, and consequently the location of drift surfaces, by the use of resonant and off-resonant frequencies. Two traveling-wave amplifiers at 55 GHz with 10 kW cw generate the off-resonant power which is almost entirely absorbed by the hot-electron annulus.

The average plasma density was determined by microwave interferometry and by measuring the perpendicular energy by diamagnetic loops coupled to the hot-electron shells; radial profiles, by skimmer probes; bremsstrahlung analysis allowed estimation of the hot-electron temperature and density; and Langmuir probes are used to determine the cold-plasma temperature and density profiles.

Magnetic field errors are known to destroy plasma confinement in closed-line devices, such as bumpy tori and multipoles, by causing the magnetic field lines to spiral out and strike the wall. In order to estimate the amount of error field in EBT, the shift of a pulsed electron beam trajectory caused by an artificially imposed error field was measured. Assuming the error field to be due to the asymmetry of the toroidal coil assembly to be uniformly distributed over the entire toroidal axis, the error field, relative to the toroidal field strength was measured to be about 1.5×10^{-4}. A more complete analysis of plasma losses due to error fields shows them to be the dominant loss mechanism in EBT for a plasma of density less than 10^{12} cm^{-3} with the electron temperature 100 eV.

Preliminary experimental results were obtained with four out of the 24 cavities energized with 18 GHz resonant power (full power operation will be under way in mid-March).

The diamagnetic signals, which show the stored energy per cavity to increase linearly with the microwave power input, indicate that macrostable annular plasmas have been formed in each of four cavities with betas around 0.5.

The steady-state, hot-electron component is estimated to have a temperature of about 300 keV, forming a shell structure with a diameter of about 25 cm at the midplane. Average plasma density is measured from the microwave interferometer to be 1×10^{12} cm^{-3} and, after turn-off of the microwave heating power, plasma density remains at 10^{12} cm^{-3} for about 1 msec (Fig. 2) then decrease to 3×10^{11} cm^{-3} in the next 1 msec, and about 7 or 8 msec later it again decays abruptly. At this time a dudden burst of x-rays was observed, as shown in Fig. 2, indicating the destruction of the hot-electron shells. These observations indicate some stabilization effects from the high-beta annulus with only four cavities energized.

The cold-electron temperature as measured by Langmuir probes indicate that the plasma outside the hot-electron shell has a temperature of about 4 eV filling the region adjacent to the wall. The electron temperature shows a steep change across the hot-electron shell, that is, 10 V/cm, and the temperature of the toroidal plasma just on the inner edge of the hot-electron shell is observed to be more than 20 eV. The electron temperature of toroidally-confined plasma cannot be conveniently measured by this probe method. We are preparing to use soft x-ray detectors to measure the temperature of this component.

The electron density radial profile measured by the ion saturation current also delineated the confined plasma inside the hot-electron shell from the unconfined cold plasma outside the shell.

Expected Information by June

We expect to obtain the following experimental information by June.

- By controlling the microwave power and gas pressure, we hope to study the transport mechanisms of the EBT plasma from the medium collisional regime into the collisionless regime.
- We also expect to control the plasma pressure in the hot-electron shell and to some extent its geometry so that MHD stabilization can be optimized. These results could provide insight into stable, high-beta toroidal confinement.

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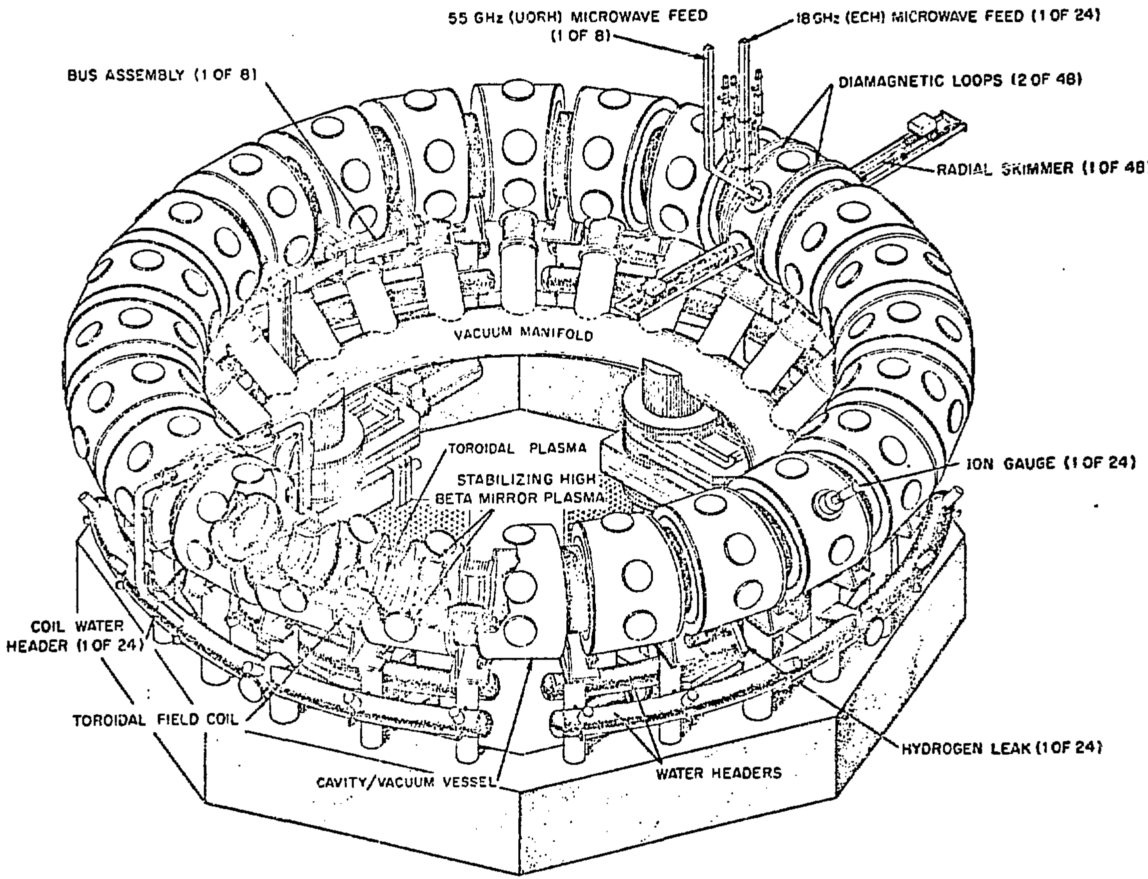

FIG. 1. **Elmo Bumpy Torus.**

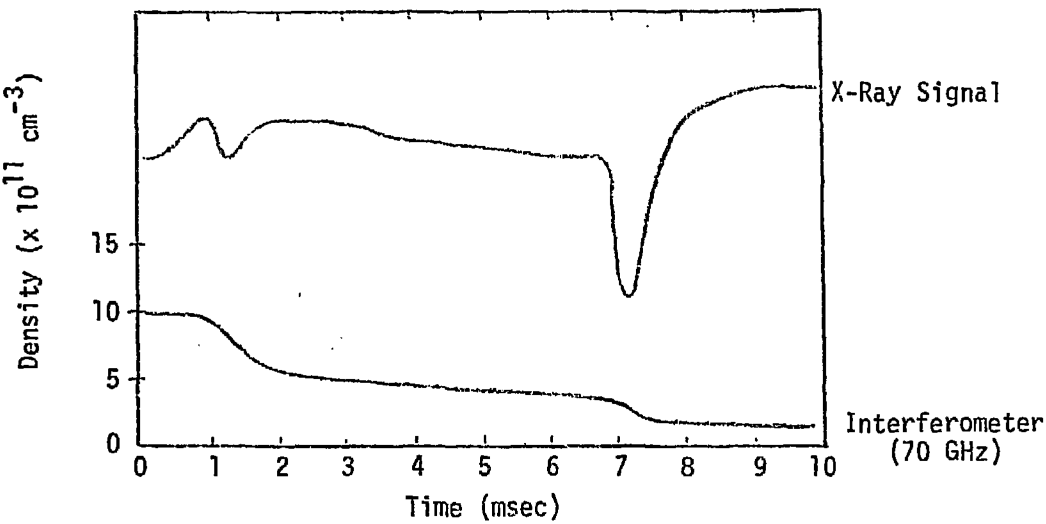

FIG. 2. Plasma density decay indicating high-beta annulus stabilization effect. The upper trace is x-ray signal detected by a small ionization chamber inserted on the inner wall of one of the four energized chambers (resonant power 18 GHz at 6 kW and off-resonant power 55 GHz at 2 kW). The lower trace is the 70 GHz microwave interferometer signal. Steady hydrogen gas feed at 3×10^{-6} Torr.