CONF-780905--4

RESULTS FROM THE ELMO BUMPY TORUS IN A THEORETICAL CONTEXT*

C. L. Hedrick, R. A. Dandl, R. A. Dory, H. O. Eason, G. E. Guest, G. R. Haste, H. Ikegami, E. F. Jaeger, N. H. Lazar, D. G. McAlees, D. H. McNeill, D. B. Nelson, L. W. Owen

Oak Ridge National Laboratory, Oak Ridge, Tennessee USA

Abstract: Theoretical and experimental results from the ELMO Bumpy Torus will be discussed with particular emphasis on macroscopic stability and transport.

The ELMO Bumpy Torus (EBT) is a steady state device [1] composed of a linked set of twenty four 2-to-1 mirrors, arranged to form a torus with plasma heated by microwave power. The plasma has two basic components; a mirror confined, high beta, hot electron plasma, forming hollow annuli between each pair of coils; and a moderate temperature toroidal plasma that threads each of the electron annuli. Experiments carried out during the past year have demonstrated the validity of the basic EBT premise: that plasma currents produced by the high-beta hot-electron annuli can provide macroscopically stable plasma confinement by creating average minimum-B. EBT has also exhibited confinement of particles and energy for 10's of milliseconds, high plasma purity, and no perceptible difficulties with field errors or convective cells. This paper summarizes the principal experimental and theoretical features of the EBT research program.

Stability

Three distinct, reproducible modes of operation, the C-, T- and M-Modes are observed at successive lower ambient gas pressure. The C-Mode has a relatively high level of density fluctuations while the T-Mode is quiet. Theory predicts that when the hot electron component beta is in excess of about 15%, the local gradient in magnetic intensity should reverse and satisfy the relevant stability criteria. Experimentally the transition between the C- and T-Modes occurs for beta on the order of 15%.

Ideal MHD and guiding center theory would predict that the macroscopic modes of most importantance are pressure driven ballooning modes. These theories are not applicable to the annuli themselves, since ω_d, $\omega_* > \Omega_i$. A more correct, but geometrically simplified Vlasov analysis shows that the annuli are stabilized when the poloidal drift frequency of the electrons exceeds the ion cyclotron frequency. If the annuli are considered to be rigid an MHD variational stability analysis of the toroidal core plasma shows that ballooning modes can only occur if the beta of the toroidal core exceeds a critical value comparable to the beta in the annuli. These results confirm that the present values of beta for the toroidal core are not limited by gross stability requirements.

Transport and Heating

In the EBT plasma, electrons are heated by microwave power at frequencies of 18 GHz and 10.6 GHz. The 18 GHz is resonant (electron cyclotron frequency) for constant B surfaces on each side of the mirror midplanes, while the 10.6 GHz source can provide lower off-resonant heating as well as profile heating. Ions are heated by Coulomb collisions with hot electrons. In the T-Mode, typical values of the plasma parameters are n_e(toroidal) $\sim$ 1-5 $\times$ $10^{12}/\text{cm}^3$; T_e(toroidal) $\approx$ 150 eV; T_i(toroidal) $\approx$ 75 eV; τ > 30 msec; n_e(annulus) $\cong$ 2.5 $\times$ $10^{11}/\text{cm}^3$; T_e(annulus) $\cong$ 250 keV; $\beta \cong 0.4$.

For a theoretical estimate of operating conditions in the quiet T-Mode, a simple point model has been developed in which radial variations are characterized by typical scale lengths. We assume a neoclassical lifetime for ions as derived by Kovrizhnikh [2] for the bumpy torus. To maintain charge neutrality, the loss rate of electrons must equal that for ions, requiring an ambipolar electric field in the radial direction. If the rate at which electrons transfer energy to ions is that of classical Coulomb collisions, the electron and ion temperatures and particle lifetimes can be calculated as functions of charged particle density.

The results for a density of 2×10^{12} cm^{-3} suggest ion and electron temperatures of 60 and 150 eV and particle lifetimes of about 20 msec. For weak ambipolar electric fields, the calculated particle lifetimes exhibit a strong inverse dependence on ion temperature, characteristic of the collisional regime. Higher electric fields and higher poloidal drift frequencies are required to attain the collisionless regime where confinement time increases with ion temperature.

While this model gives results which are consistent with typical parameters in the T-Mode, more detailed knowledge is needed of electron dynamics, ambipolar fields, diffusion coefficients and microwave power deposition to permit an unambiguous comparison with experiment. To upgrade the theory accordingly, we have devised a strategy based on the following circular relations:

1. Equilibrium magnetic fields depend on the pressure profile.
2. Guiding-center drift orbits depend on the equilibrium magnetic field and ambipolar electric fields.
3. Transport rates, which together with sources and sinks determine the profile, depend on the guiding center drift orbits.

3D equilibrium codes have been developed and are being improved and operated to gain insight into the effect of finite beta on guiding-center drift orbits. The effect of finite-beta and electric fields on guiding-center drifts is significant. To determine the resulting effect on transport phenomena and study the effects of microwave heating, a kinetic model of transport has been formulated using a Fokker-Planck equation to determine the radial dependence of the distribution function and ambipolar electric field. This is being implemented. Ultimately the loop represented by 1), 2) and 3) above will be closed with transport and the pressure profiles then being determined self-consistently.

The fluid-model computer codes developed in support of the tokamak program at Oak Ridge will have relevance to EBT, especially for questions of neutral and impurity effects. The EBT experiments have demonstrated the importance of the reflux of gas from the cavity wall in determining the source of particles required to maintain the plasma. The dominant source of fresh ion-electron pairs is energetic neutral hydrogen, recirculated at the wall. Experiments provide estimates of the principal impurities; these suggest that impurity ions drift to a wall (and are collected there) faster than they can diffuse inward, thus providing the observed high purity of the EBT toroidal plasma.

A central research objective unifies all the experimental and theoretical work on EBT reported here: to gain a working understanding of any mechanisms responsible for the loss of particles and energy from the system. Given the encouraging confirmation of the arguments advanced in proposing the EBT experiment, [3] we contemplate a sequence of devices to confirm the present scaling. The next step calls for a moderate increase in magnetic field to perform scaling experiments using the existing torus. The second step would involve a large increase in the magnetic field and a new torus. These steps require development (already underway) of appropriate high frequency microwave power sources.

References

*Research sponsored by the U. S. Energy Research and Development Administration under contract with Union Carbide Corporation.

[1] R. A. Dandl, et al, "The ELMO Bumpy Torus Program", ORNL-TM-4941 (June 1975) and references cited therein.

[2] L. M. Kovrizhnikh, Sov. Phys. - JETP 29, 475 (1969).

[3] R. A. Dandl, et al, "The ELMO Bumpy Torus Experiment", ORNL-TM-3694 (November 1971).