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MASTER

SCALING IN ELMO BUMPY TORUS (EBT)*

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1. INTRODUCTION

The steady-state plasma in the ELMO Bumpy Torus (EBT) is confined in a "bumpy" magnetic field produced by joining 24 magnetic mirror cells into a large aspect ratio torus. Heating power is provided by continuous wave (cw) microwave sources at 28 GHz, 18 GHz, and 10.6 GHz. The magnetic field is adjusted to bring either the 28 GHz or the 18 GHz microwaves into local electron cyclotron resonance in the toroidal plasma. The two cases are referred to as EBT-S (for Scale) and EBT-I, respectively. The toroidal plasma has been shown to be macroscopically stabilized by the magnetic field modification resulting from diamagnetic annuli of energetic electrons which form in each cell as a result of the microwave heating.

The EBT-S configuration employs a 28 GHz cw gyrotron tube, developed by Varian Associates, for the purpose of scaling the plasma parameters with applied microwave frequency. Operation of the machine in the EBT-S configuration has been for a limited time to date, so experimental documentation of the plasma in EBT-S is a prime objective of the experimental group. Documentation of the plasma parameters in the EBT-I mode is more complete.

2. MEASUREMENT OF PLASMA PARAMETERS IN EBT-I

The plasma parameters in the EBT-I mode have been measured by a variety of diagnostic techniques. The results of a typical data run in the macrostable regime (T-mode) of operation are listed in Table 1.

These parameters do not represent the maximum values of any of the parameters, but rather the case for which the greatest amount of diagnostic information is available. As the ambient pressure is reduced

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(lower collisionality), both the density and electron temperature (and, consequently, the energy lifetime) are observed to increase (see Figs. 1 and 2). In addition, the ion temperature and the potential well depth also are greater at lower collisionality.

The two measurements of electron temperature (soft x-ray and laser scattering) differ significantly. The laser scattering spectrum for the case given in Table 1 is shown in Fig. 3. The analysis of this spectrum indicates an uncertainty of ±75 eV in the temperature determination. The uncertainty in the soft x-ray measurement is estimated to be in the neighborhood of ±50%.

For calculation of the energy lifetime, 10-25% of the applied microwave power was assumed to be absorbed by the plasma electrons.

TABLE 1. Results of a typical EBT-I run

MACHINE PARAMETERS

Parameter	Value	
Magnetic field	5 kG midplane	10 kG mirror
Major radius	150 cm	
Minor radius, midplane	12 cm	
Plasma volume	300 liters	
Magnetic aspect ratio	9:1	
Microwave power	40 kW at 18 GHz + 6 kW at 10.6 GHz	
Ambient pressure	5.5×10^{-6} torr (outside cavity)	

PLASMA PARAMETERS

Parameter	Diagnostic	Value
Line averaged density, n_e	Microwave interferometer	$6\pm2\times10^{11}$ cm^{-3}
Electron temperature, T_e	Soft x-ray detector	315 eV
	Thomson scattering	120±75 eV
Ion temperature, T_i	Charge exchange	63 eV
Potential well depth, $\Delta\phi$	Heavy ion beam probe	80 V
Energy lifetime, τ		1-2.5 msec

3. EBT SCALING LAWS

The basic plasma parameters in EBT [density (n), electron temperature (T_e), and confinement time (τ)] are predicted to scale in the following manner. The plasma density is limited by microwave cutoff, so the maximum attainable density increases as the square of the microwave frequency. Since the magnetic field required to bring the applied microwave power into resonance increases linearly with the frequency, then the density scales as the magnetic field squared ($n \propto B^2$). A limited number of measurements at 28 GHz support this scaling.[2] The electron temperature, as determined by the soft x-ray detector, has been observed to increase proportional to the square root of the applied microwave power ($T_e \propto P^{1/2}$). The confinement time exhibits two different scaling relations, depending on the regime of collisionality (ν/Ω) in which the plasma operates.

$$\tau \propto \begin{cases} T_e^{-7/2}, & \nu/\Omega \gg 1 \\ T_e^{3/2}, & \nu/\Omega \ll 1 \end{cases}$$

4. RADIAL TRANSPORT CALCULATIONS WITH CONSTANT EDGE NEUTRAL FLUX

Recently, one-dimensional radial transport equations for EBT have been solved assuming a constant flux of cold neutrals at the plasma edge, independent of toroidal plasma parameters.[3] This boundary condition provides a negative feedback mechanism which limits thermal excursions and allows steady-state solutions at low collisionality. Such a boundary condition is appropriate if reflux from the wall occurs on a time scale slow compared to an energy containment time. Experiments[1] indicate that a time on the order of tens of minutes is required for the plasma to reach equilibrium with the wall. Once equilibrium is reached, pumping is balanced by a slight gas feed of about 3×10^{-2} torr liter/sec. This feed rate is small compared to the flux of neutrals required to sustain the plasma, which is about 1 torr liter/sec in the present calculations. The source of these neutrals is assumed to be wall reflux.[1]

The one-dimensional radial transport equations used in these calculations incorporate a self-consistent electric field.[4,5,6] The transport coefficients are assumed to be approximately neoclassical and include lowest order effects of velocity space regions where poloidal drift frequencies are small.[5,7]

Experimental results are often plotted versus ambient neutral pressure as given by ion gauges. For comparison with such data, the numerical results are plotted as a function of $p_o = n_o kT_o$, where n_o is the density of cold neutrals at the plasma edge and $kT_o = E_o \sim 0.5$ eV. Note that p_o is similar to but not equal to the ion gauge pressure. In the collisionless regime (low neutral pressure), the parametric dependence on edge neutral pressure is similar to that observed experimentally; i.e., density, temperature, and potential all increase with decreasing neutral pressure. Compare Fig. 4 with Figs. 1 and 2. Experiments apparently do not observe the collisional scaling at high neutral pressures since the electron ring beta is not sufficient to stabilize the toroidal plasma in this regime. In order to obtain solutions matching the measured plasma parameters with the present diffusion coefficients, the power input to the plasma must be taken to be nearly an order of magnitude less than the experimental estimate. This implies an energy lifetime which is an order of magnitude higher than the experimental estimate, namely ~10 msec.

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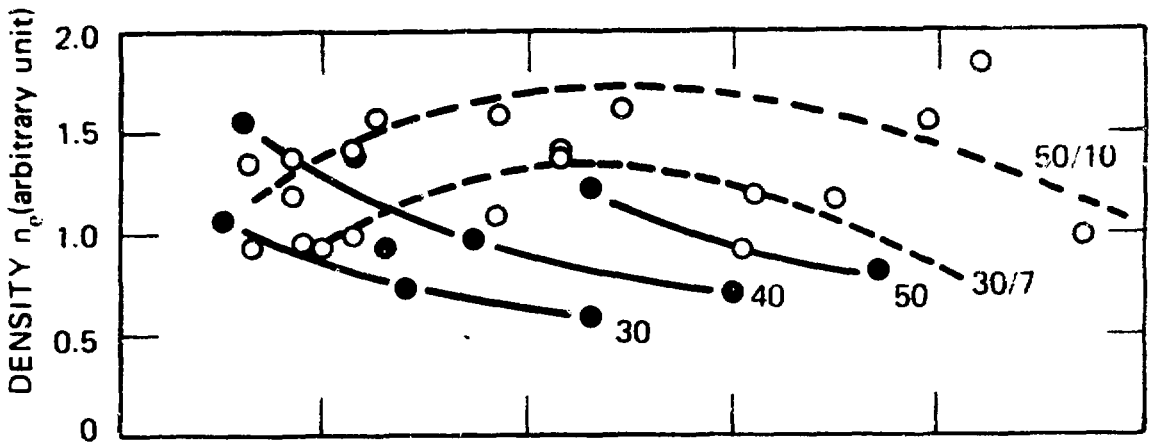


Fig. 1

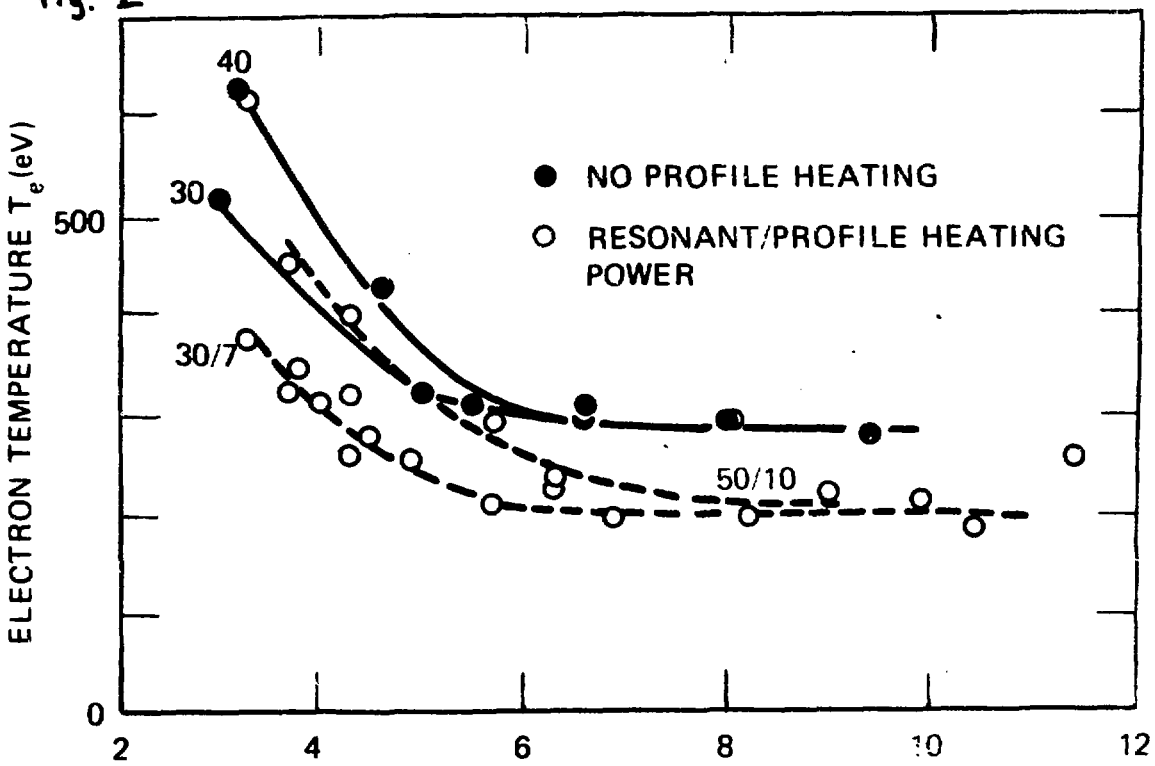
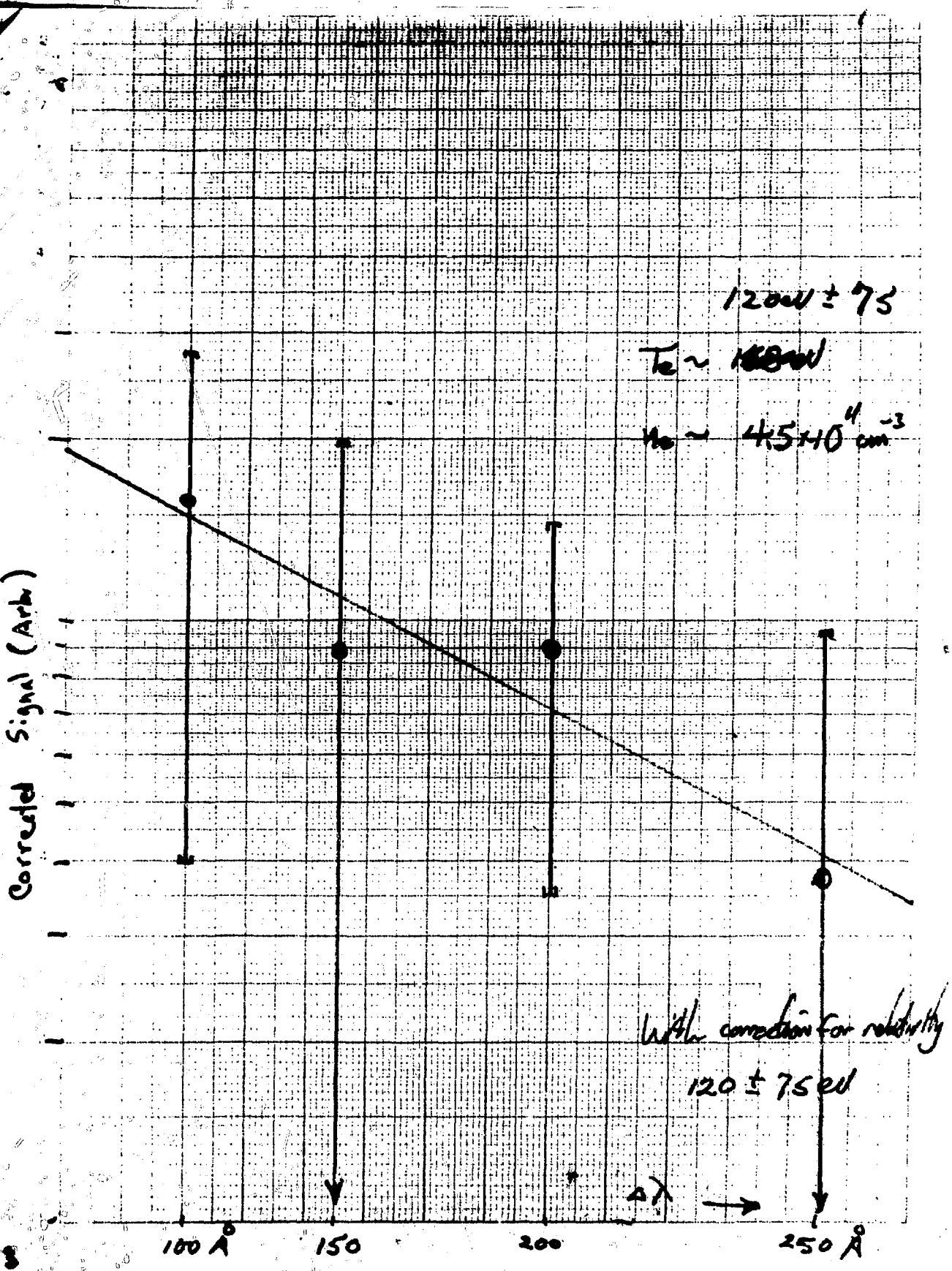


Fig. 2.


120eV ± 75
Te ~ 160eV
ne ~ 4.5×10^4 cm^-3
Corrected Signal (Arb)
With correction for relativity
120 ± 75 eV
Δλ
100 Å
150
200
250 Å

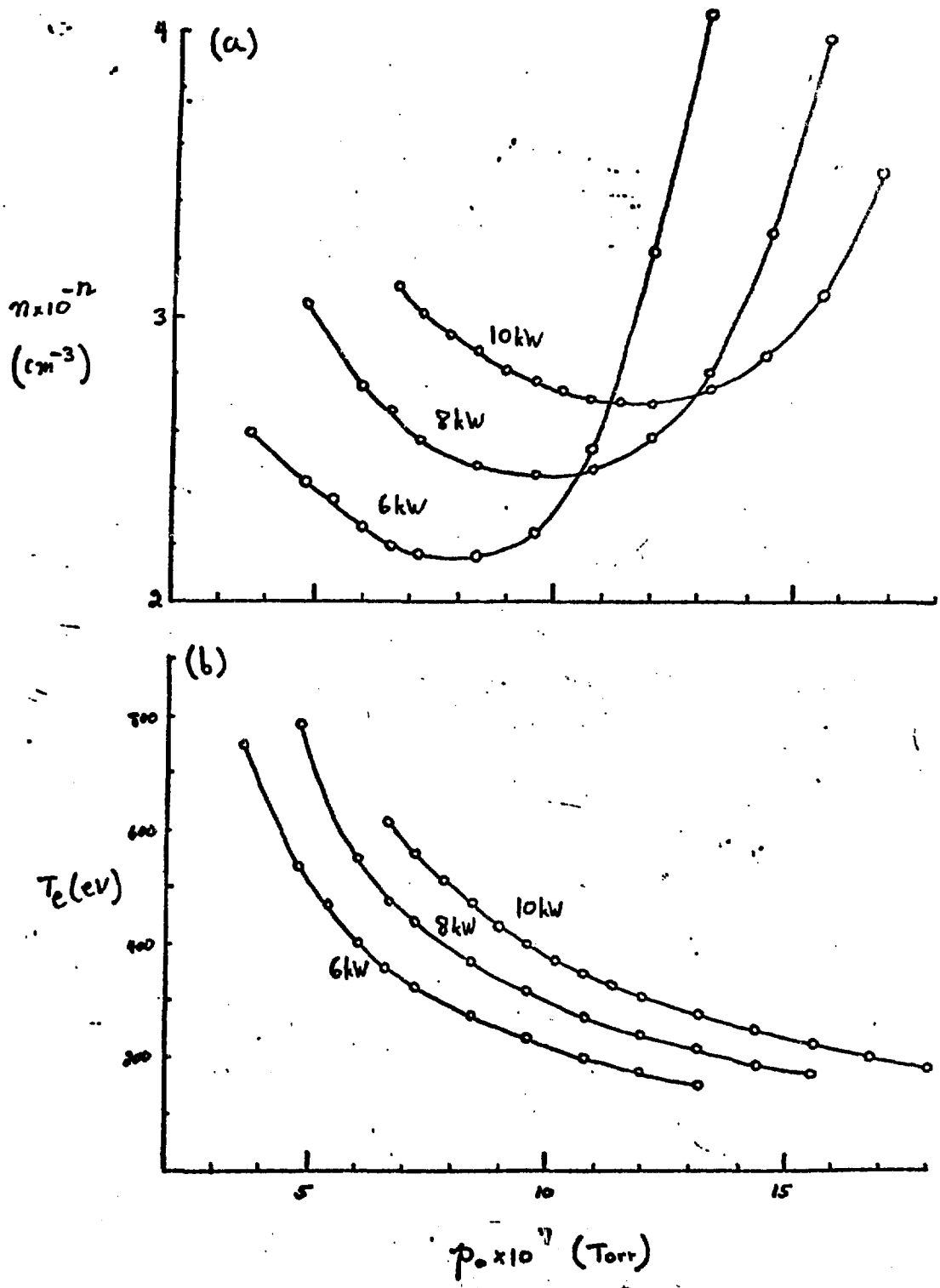

(a)
4
3
2
$n \times 10^{-n}$
(cm^{-3})
10kW
8kW
6kW
(b)
800
600
400
200
T_e(eV)
10kW
8kW
6kW
5
10
15
$p_0 \times 10^{n}$ (Torr)

Fig. 4.

Fig 3