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# CONTENTS

ABSTRACT ........................................... v
1. INTRODUCTION .................................. 1
2. BUMPY TORUS EXPERIMENTS .................. 2
   2.1 Operating Regime and Parameters of EBT ........ 2
   2.2 Properties of the Hot Electrons ............... 10
   2.3 Stability of the Bulk Plasma ................. 12
   2.4 2-D Potential Contours ....................... 14
   2.5 Asymmetry of Potential Contours (Equilibrium) . 16
   2.6 Local Convective Power Loss ................. 17
   2.7 Confinement Times ........................... 20
3. SUMMARY ........................................ 22

ACKNOWLEDGMENTS ............................... 23

REFERENCES .................................... 25
ABSTRACT

Experiments were conducted in the ELMO Bumpy Torus (EBT) from 1973 until 1984. A number of papers have been published on various aspects of the final two years of the EBT experiments. This report summarizes the final experimental conclusions and discusses issues that were not resolved.
1. INTRODUCTION

The ELMO Bumpy Torus (EBT) experiment [1-3] was terminated in September 1984. Previous summaries of results were published by Dandl et al. in 1978 [2] and by Colchin et al. in 1982 [3]. During the last two years of operation, experiments were aimed at improving plasma parameters and understanding EBT plasma physics. The results of these experiments have been published in a number of papers. This work gives an integrated summary of the conclusions of these papers, which represent the final results of the EBT experiment.

During the period from 1982 through 1984, many improvements in diagnostics added to the understanding of EBT plasma physics. First, Thomson scattering results could be obtained at densities below $10^{18}$ m$^{-3}$ as the result of improved handling of stray and plasma light [4,5]. Second, new diagnostics made it possible to measure the electron ring dimensions [6]. Third, improvements to the heavy-ion beam probe made possible the measurement of two-dimensional (2-D) potential contours [7]. Fourth, several new diagnostics were implemented for the determination of the neutral density, giving an improved measurement of the particle confinement time [8].

Experimental details are given in Section 2. The basic physics issues are those of MHD (flute mode) plasma stability, plasma transport, equilibrium, and the effects of plasma fluctuations. The principal conclusions of Section 2 are as follows.

1. Plasma potential contours in the C-mode (high ambient pressure) were streamlines, which is the classical non-equilibrium (i.e. non-force-balanced) state of a toroidal confinement system [9]. In contrast to this, central potential contours in the T-mode (lower ambient pressure) were nested, implying that particles were confined. However, the stored energy in the T-mode was only twice as large as that in the non-equilibrium C-mode, which suggests that plasma in the T-mode suffered from some form of anomalous transport [10] (see Section 2.1).

2. Stability of EBT plasmas to MHD (flute) instabilities was originally predicted on reversing the magnetic field gradient at the location of the hot electron rings [11]. To achieve such stability, the diamagnetic energy density of the hot electrons must be large enough to reverse the magnetic field gradient. Measurements of the ring thickness, width, and stored energy [6] prove that this did not occur (see Section 2.2).

3. The effect of plasma fluctuations on plasma performance was studied [10]. Broadband, low-frequency density fluctuations seem to be correlated with lower
plasma density and lower stored energy, making it appear likely that transport was affected by turbulence. However, the associated power loss was less than 20% of the microwave power input, implying that instabilities were not the dominant cause of plasma transport (see Section 2.3).

(4) 2-D potential contours measured during T-mode operation showed nested contours at the plasma center with open contours outside [12]. In the outer region, plasma loss could occur convectively as plasma streamed along the open potential contours [13] (see Sections 2.4 and 2.5).

(5) The global energy confinement time, a measure of the average confinement for inner and outer (convective) loss regions, was found to be approximately 100 μs and did not exceed 200 μs even if the energy of the warm (non-Maxwellian) electrons was included [14]. This confinement time is comparable with the $\vec{E} \times \vec{B}$ drift time across the plasma [13] and with the particle confinement time measured by a diagnostic neutral beam [8] (see Sections 2.6 and 2.7).

Experiments were carried out in close cooperation with the EBT plasma theory community, and relevant plasma theory publications are referenced in each section. Results from excellent work [15] by the Nagoya Bumpy Torus (NBT) group have not been included.

2. BUMPY TORUS EXPERIMENTS

Several aspects of the EBT experiments are summarized in this section. The number of figures associated with each topic has been minimized to avoid overlap with the original articles. More detailed information is available in the references.

2.1 Operating Regime and Parameters of EBT [4,5,8,9,14,16,17]

The original concept of the EBT [1] was to produce MHD stability by the use of magnetic wells dug by the diamagnetism of energetic electron annuli. Electron cyclotron heating (ECH) was employed both to produce the hot electron annuli and to heat the bulk plasma. The hot electron annuli were formed at the second electron cyclotron harmonic resonance zone, the $|B|$ surface of which is ring-shaped. Reference [18] gives a summary of the origins of the EBT concept and the construction of the device.
The EBT device consisted of 24 simple mirrors joined end-to-end so as to form a torus with closed field lines but with no rotational transform. The mirror ratio of each cell was 1.9:1. When operated with up to 60 kW of 18 GHz applied power and with a central midplane magnetic field of 0.5 T, the device was called EBT-I [2]. In this configuration, the ECH power fed into individual cavities could be controlled. This flexibility was not readily available in the EBT-Scale (EBT-S) configuration, where up to 200 kW of 28 GHz applied microwave power could be applied along with a central magnetic field of 0.73 T. Both EBT-I and EBT-S were operated in steady state. The field lines, resonance layer, and other structures are shown in Fig. 1. Limitations on the magnetic field constrained the rings to slightly smaller radii in EBT-S than in EBT-I. The diagnostics and their locations are shown in Fig. 2.

FIG. 1. One sector of the EBT device. This view shows 1 of 24 vacuum cavities and 2 mirror coils in the plane of the minor toroidal axis. Dashed lines: magnetic field lines. Solid lines: contours of |B|. Numbers on the |B| contours, when multiplied by 0.71, give the field strength in tesla. The number 1.4 corresponds to 1.0 T, which is the location of the fundamental electron cyclotron resonance in EBT-S. The second harmonic resonance is on the 0.7 contour.
FIG. 2. Location of diagnostics around the EBT device, as seen from above.

EBT operating regimes [16] were mainly governed by the ambient hydrogen pressure. When the hydrogen pressure \( p_0 \) was decreased while the microwave power \( P_\mu \) was kept constant, the plasma behavior as a function of pressure could be classified into three operating modes. C-mode operation was characterized by the absence of hot electron rings, by open potential contours, and by a high-density, low-temperature, noisy plasma. As \( p_0 \) was reduced, hot electrons appeared, nested potential contours were formed, and the electron temperature of the bulk plasma increased. This regime was called the T-mode. At still lower pressure, potential contours remained nested, but the density dropped and the stored energy of the hot electron rings increased, exciting the hot electron interchange mode [16]. This was called the T-M transition.

The presence of closed potential contours at the transition between C- and T-modes made a critical change in confinement, as reflected in the plasma properties. Figure 3 shows the line density as a function of the neutral pressure. Note
FIG. 3. The evolution of plasma parameters upon transition from the C-mode to the T-mode. Line electron density as a function of the ambient pressure. The pressure at the T-C transition is shown by a dashed line.

that absolute pressures are quoted throughout this paper; they are a factor of two higher than the gauge pressures commonly quoted in the references. Below a neutral pressure of 27 \( \mu \text{torr} \) (in EBT-I), the line density remained constant as the neutral pressure was lowered. Above that critical pressure, the line density increased proportionally with the neutral pressure. Thus, there was a definite pressure at which the transition from the C-mode to the T-mode occurred. Figures 4(a)–4(d) show the potential contours for pressure variations in the vicinity of the transition pressure \[9\]. For a pressure of 32 \( \mu \text{torr} \) (deep C-mode), the potential contours were open streamlines, which is the classical non-equilibrium state of a toroidal system without rotational transform. At pressures of 28 \( \mu \text{torr} \) and higher, all the potential contours remained open. At 26 \( \mu \text{torr} \) the first contour became closed, and further decreases in the neutral pressure increased the area of the closed contours. Therefore, closure of the first potential contour signaled the transition into the T-mode.

The particle confinement time \[8\] increased continuously from the C-mode to the T-M transition but decreased if the ambient pressure was further reduced. The plasma density and temperature, as measured by Thomson scattering \[4,5\], are shown in Fig. 5. Several experiments have confirmed that the electron distribution function was non-Maxwellian \[14\]. It consisted of a main cold component
FIG. 4. Potential contours near the T-C transition are displayed for four different pressures: (a) 32 μtorr, (b) 28 μtorr, (c) 26 μtorr, and (d) 16 μtorr. The machine axis was located at $z = x = 0$ and the magnetic axis was at $z = 0$, $x = -2.5$ cm. (Fig. 2 of Ref. [9].)

($n_e < 1.0 \times 10^{12}$ cm$^{-3}$, $T_e < 100$ eV), a mirror-confined tenuous warm component with a density of 5–20% of the total and an energy of 200–800 eV, and hot electrons (with energies $\leq 1$ MeV) associated with the rings. The cold component was collisional and relatively isotropic, while the warm component was collisionless and anisotropic. The majority of the warm particles were mirror trapped. These warm electrons were generated when the ambient pressure was below that of the T-C transition and signaled the formation of centrally nested potential contours [9]. The non-Maxwellian distribution function was driven by the ECH heating power.
FIG. 5. The dependence of the electron temperature and density on the ambient gas pressure. Each data point represents the average of at least ten shots. Error limits are the result of photon statistics. The ambient pressure at the T-C transition was 24 μtorr; at the T-M transition, the pressure was 10 μtorr. (Fig. 5 of Ref. [5].)

Performance limits for EBT plasmas may be obtained by examining plasma parameters both as a function of the ambient neutral pressure with differing magnetic fields and during the “ring modifier” and “ring killer” experiments [17]. The data are shown in Fig. 6. During the ring killer and ring modifier experiments, 24 small limiters were installed near the second electron cyclotron resonance zone to
FIG. 6. Line integral electron density as a function of ambient gas pressure for (a) three values of the midplane magnetic field (microwave heating power was 100 kW) (Fig. 14 of Ref. [17]) and (b) normal EBT-S operation and the ring killer and ring modifier experiments (microwave heating power was 150 kW) (Fig. 7 of Ref. [17]).

either kill or modify the hot electrons. Line densities were similar when the magnetic field was low [Fig. 6(a)] and when the ring killers were in place [Fig. 6(b)]. This is the lower limit of the line density and represents the base plasma performance of EBT. This limit is independent of the microwave power in the range
50–150 kW. As the magnetic field was increased, the line density increased in the T-mode at constant ambient pressure.

The data of Fig. 7 show that a similar trend holds for the stored energy density [10], where the higher (lower) temperatures correspond to the lower (higher) ambient pressures. The central stored energy density was nearly the same for the ring killer and ring modifier experiments, in the C-mode, and at low magnetic

FIG. 7. Electron density as a function of temperature for several operating modes. These data were taken at \( r = 0 \) by Thomson scattering. The magnetic field scan, the C-mode scan, and the T-mode scan were carried out at an applied power of 150 kW. The ring killer and ring modifier experiments were carried out at an applied power of 100 kW. Magnetic field scan data are labeled by field strength. Data on the right side of the graph are for ambient pressures in the C-mode. (Fig. 10 of Ref. [10].)
field. These values represent the base stored energy density for EBT. This lower limit was valid for a range of applied ECH power from 100 to 150 kW.

Under typical T-mode conditions in EBT-S with 100 kW of gyrotron power, the plasma parameters were $n_e \approx 8 \times 10^{17}$ m$^{-3}$, bulk electron temperature $\geq 40$ eV, hot electron temperature $\approx 400$ keV, hot electron stored energy $\approx 20$ J/annulus, and ion temperature $T_i < 20$ eV [3]. Unless otherwise noted in this paper, the plasmas discussed are in the T-mode of operation with 100 kW of applied ECH power.

2.2 Properties of the Hot Electrons [6,16,19–22]

The principal physics issues regarding the hot electron rings are: (1) whether the hot electron stored energy was large enough to reverse the magnetic field gradient, thereby providing MHD (flute mode) stabilization, and (2) whether the hot electron rings were themselves stable.

In order to evaluate the stored energy density in the rings, it is necessary to know their spatial extent. The width of the rings was determined by a horizontal array of five NaI detectors, which measured bremsstrahlung radiation from the hot electrons [19]. The ring width was measured to be 10–12 cm (FWHM). The ring thickness was estimated by dropping small stainless steel pellets through the rings and measuring the change in the rings' diamagnetism, thick target X-ray signals, and 95 GHz synchrotron radiation signals [6]. As shown in Fig. 8, the X-ray and synchrotron signals give a ring thickness of 5–7 cm. These X-ray and synchrotron measurements of ring thickness are consistent with diamagnetic determinations. The measured stored energy was 20–30 J, which is not large enough to reduce the magnetic field gradient [6,23] to a local zero. A maximum stored energy of 90 J was obtained when microwaves were launched from the high magnetic field region of the torus [20]; this is also insufficient to reverse the magnetic field gradient. Attempts to increase the stored energy using multiple-frequency heating led to no substantial improvement in the ring stored energy [21], in contrast to the results from simple mirror experiments [24]. From these considerations, it is reasonable to conclude that the hot electrons were not localized in a narrow region, which implies a dilution in their stored energy density and in their ability to deform the MHD-unfavorable magnetic field curvature inherent in the mirror cells of EBT.
FIG. 8. Experimental data obtained from the pellet dropper experiment during typical EBT-S T-mode operating conditions. The derivative of the 95 GHz synchrotron radiation signal and the X-ray intensity are plotted as functions of the cavity radius. The locations of the cavity walls and the vacuum field resonances are shown as shaded areas. The ring thickness was determined to be \( \approx 6 \) cm (FWHM). The vertical distance of the pellet is determined from the pellet's flight time. (Fig. 6 of Ref. [6].)

The hot electron rings can themselves be unstable [25], leading to energy loss and a diminution of their diamagnetism. Three types of unstable hot electron modes were observed experimentally. The whistler instability [26] was characterized by microwave bursts emitted when the plasma was in the T-mode. A second mode [22] was characterized by an oscillation frequency of 100 MHz, which was observed throughout the T-mode. The third instability [16] was the hot electron
interchange mode [25], which was found near the T-M transition and was characterized by large (18 MHz) magnetic fluctuations (where, for comparison, the ion cyclotron frequency is \(\approx 8\) MHz at the ring position and the hot electron precession frequency is \(\approx 3\) MHz). Experimentally it was found that a minimum hot-electron-to-ion density of 0.2 was required for onset (where the previously quoted value of 0.5 [16] has been revised downward to account for the rings being larger than formerly supposed). It was important for the hot electron interchange mode to be stable because the interchange mode prohibited lowering the pressure to obtain higher bulk plasma temperatures.

2.3 Stability of the Bulk Plasma [10,17]

Since the hot electrons in EBT-S did not have sufficient energy density to modify the vacuum magnetic field so as to form an MHD-stable configuration, the plasma might have been expected to be flute-unstable. Surprisingly [10,17], only broadband turbulence \(\tilde{n}_e l/n_e l\) (peak to peak) \(\approx 5\%\) with frequencies up to 500 kHz was observed during normal operation. Shallow pressure gradients in the interior of the plasma suggest that the bulk plasma was at least partially stabilized by compressibility [10], although other stabilization mechanisms, such as charge uncovering [27] or finite Larmor radius effects [28], may also have played a role. Compressibility requires that the radial pressure profile be shallower than \((\int dl/B)^{-\gamma}\), where \(\gamma\) is the ratio of specific heats. The product \(n_e(r)T_e(r)\), as measured by Thomson scattering, is nearly constant, implying a flat pressure profile. This result was supported by \(n_e(r)\) and \(T_e(r)\) measurements made by the heavy-ion beam probe [7].

Coherent modes (see Fig. 9) were observed under other than normal operating conditions, such as at low pressure, at low magnetic field \((B < 0.6\) T), and during the ring killer experiments. The presence of flute modes in the ring killer experiments can be explained by steep density gradients necessarily introduced at the radius of the rings by stainless steel limiters in each cavity. Similar explanations hold for the appearance of the flute mode under other conditions. The density profile steepened as the ambient pressure was reduced [29], and the pressure profile at lower magnetic fields [10] violated the \((\int dl/B)^{-\gamma}\) criterion.

While looking for coherent modes, experimenters always observed broadband density fluctuations \(\tilde{n}_e l\). These fluctuations were systematically studied by varying the pressure and the magnetic field [10]. Generally speaking, the higher the
density and the magnetic field, the lower the fractional fluctuation level $\tilde{n}/n$. At high magnetic field ($B = 0.73$ T), $\tilde{n}/n$ decreased from 0.1 at the T-C transition to 0.05 in the upper T-mode. In the C-mode the fractional fluctuation level was independent of magnetic field strength, but it increased at lower pressure as the magnetic field was reduced. In order to evaluate the effects of turbulent transport, it is necessary to know the phase relations of density fluctuations with potential fluctuations. These phase relations were not measured. In the T-mode, heavy-ion beam probe fluctuation measurements indicated $e\tilde{\phi}/kT_e \geq 0.1$, although it was not possible to eliminate certain noise sources, which could have enhanced the measured potential fluctuation level [30].
These observations seem to indicate that plasma transport was governed by fluctuations. However, limiter data indicated that fluctuations carried away less than 20% of the absorbed microwave power (some indications, as in Fig. 9 of Ref. [10], give 5%). The bulk of the power was convected out of the plasma, as is discussed in Section 2.6. Effects of fluctuations on plasma transport were not entirely negligible. For example, the power incident on the limiter increased as the fluctuation level increased.

2.4 2-D Potential Contours [7,9,10,13,14,17]

Much of the crucial physics of EBT plasmas can be determined from an examination of the 2-D potential contours [31] displayed in Figs. 3 and 4. Figure 4(a) shows that potential contours in the C-mode are nearly horizontal, leading to a vertical electric field. Thus in the C-mode, the plasma is not confined. Figure 4(d) shows that the topology of the potential contours changes dramatically as the neutral pressure is lowered to the T-mode. The central potential contours become nested circles, which implies a radial electric field and hence a confined plasma. Data for these figures were taken in EBT-I. The same general tendencies persisted in EBT-S [9,10], except that the absolute value of the potential depth was somewhat larger.

It is interesting to determine the conditions [32] necessary for the evolution of the potential from the C-mode to the T-mode. The first requirement [10] for the formation of closed potential contours is that key particles complete closed drift orbits, overcoming the $\vec{E}_v \times \vec{B}$ drift due to the non-equilibrium vertical field $\vec{E}_v$ present in the C-mode. This requirement is satisfied when the poloidal $\nabla \vec{B}$ drift is faster than the $\vec{E}_v \times \vec{B}/B^2$ drift,

$$W/Br\nabla B > E_v/B$$

where $W$ is the energy of the key particles and $r\nabla B$ is the scale length associated with the radial magnetic field gradient of the mirror field.

A second requirement for the existence of axis-encircling particles is that the key particles complete a closed drift orbit before being scattered, or that $\tau_{\text{precession}} < \tau_{\text{scattering}}$. For EBT parameters the critical energy is about 300 eV. Higher energy particles were "collisionless" and could execute closed drift orbits before being scattered.
The key particles were most likely warm electrons with an energy of \( \approx 1 \) keV. The evidence for this observation comes from experiments in which a limiter was introduced onto field lines just inside the second cyclotron harmonic resonance region. The nested potential contours disappeared and the soft X-ray signal at 1 keV decreased by a third, while the cold electron temperature and the hard X-ray signal remained unchanged [33]. Another observation supporting the hypothesis that warm electrons were the key particles is that warm electrons were detected at the T-C transition as the closed potential contours began to form.

The presence of closed potential contours made a critical change in the confinement. As mentioned in Section 2.1, closure of the potential contours signaled the transition into the T-mode. Further decreases in the neutral pressure increased the area of the last closed potential contour, but [as shown in Fig. 4(d)] the closed contours could not be made to cover the entire plasma cross section. Optimum plasma performance was obtained with the maximum magnetic field (0.73 T in EBT-S) at a pressure just above the T-M transition. In this case, the last closed contour had one-quarter the area enclosed by the second cyclotron harmonic surface and one-eighth the area of the entire plasma cross section.

Two caveats should be noted for measured potentials. First, potentials were measured only in the midplane. It is usually assumed that the potential was continuous along field lines (i.e. \( E_z = 0 \)), and there is indirect evidence to support this assumption. For example, the average density at the midplane and that at the throat were similar [14]. Also, when the power was turned off in the cavity in which the potential measurements were made, the potential distribution remained virtually unchanged. Thus, loss of the locally trapped plasma component in cavities where the power was turned off did not greatly affect the potential distribution, which was determined by the plasma in power-fed cavities.

The second caveat is that 2-D potential measurements required several minutes for data acquisition. Thus, the potentials shown in Fig. 4 are time averaged. The structure of the potential on shorter time scales is not known.

The ultimate importance of these potential measurements is that they determine the electric field structure, which plays a role in plasma transport. The densities and electron temperatures that were present with a variety of different potential structures are summarized in Table I. It is clear from these data that \( n_e T_e \) does not vary by more than \( \approx 50\% \) regardless of the type of potential contour. It may be noted from Fig. 4(d) that the potentials are higher on the inside.
### TABLE I. ELECTRON DENSITY, TEMPERATURE, ELECTRIC FIELD STRENGTH, AND POTENTIAL STRUCTURE FOR VARIOUS EXPERIMENTAL SITUATIONS IN EBT
(From Table I of Ref. [10])

| Case | Potential shape | \(|E|\) (V/cm) | \(n_e\) \(10^{11}\) cm\(^{-3}\) | \(T_e\) (eV) | \(n_eT_e\) ratio |
|------|-----------------|---------------|-----------------|-----------|----------------|
|      | Magnetic field scan |              |                 |           |                |
| 1    | 7.25 kG         | Well          | >30             | 8.3       | 60             | 1.0           |
| 2    | 5.8 kG          | No closed contour | <10           | 5.8       | 62             | 0.72          |
| 3    | 5.2 kG          | Hill           | >30             | 3.0       | 90             | 0.54          |
|      | Pressure scan   |               |                 |           |                |               |
| 4    | Low \(p_0\)     | Well          | \(\approx50\)   | 6.0       | 90             | 1.0           |
| 5    | High \(p_0\)    | No equilibrium | \(\approx10\)   | 6.0       | 50             | 0.56          |
|      | Error field     |               |                 |           |                |               |
| 6    | No correction current | No closed contour | <10   | 8.4       | 67             | 1.15          |
| 7    | Correction current | Well          | 30              | 9.8       | 50             | 1.0           |
|      | Limiter scan\(^a\) |               |                 |           |                |               |
| 8    | Out             | Well          | 30              | 13.6      | 113            | 1.0           |
| 9    | Just outside ring | Symmetric well | >30           | 12.9      | 148            | 1.24          |
| 10   | Just inside ring | No closed contour | 0   | 11.1      | 100            | 0.72          |
| 11   | Fully inserted  | No closed contour | 0   | 11.7      | 97             | 0.74          |

\(^a\)The electron temperatures for cases 8-11 are \(\approx50\)% higher than those for the other cases because of an inability to accurately quantify the background light level in the limiter scans.

and are not centered with respect to the (grounded) cavity. This gives rise to a horizontal electric field that induces particle convection, as discussed in the following sections.

### 2.5 Asymmetry of Potential Contours (Equilibrium) [9,13]

The aforementioned potential asymmetry played a major role in plasma confinement. In the C-mode, where all of the potential contours were open, the confinement time was determined by
\[ \tau = \langle \ell \rangle B / E \]

where \( \langle \ell \rangle \) is the average length of the path along a potential contour before encountering a wall. For typical values of \( \langle \ell \rangle = 0.1 \text{ m} \), \( E = 2.5 \text{ kV/m} \), and \( B = 1 \text{ T} \), \( \tau \) is 40 \( \mu \text{s} \). In the T-mode, although potential contours were closed near the axis, the majority of the plasma cross section consisted of open contours, so that convective loss dominated plasma transport. A Monte Carlo calculation [34] showed that convective loss in the region of closed potential contours was still rapid.

Information about the plasma equilibrium (i.e., force balance) can be gleaned from the position of the plasma. The peaks of the density, electron temperature, pressure (Fig. 10), and potential profiles [Fig. 4(d)] all lie near the magnetic axis, which is shifted inward 2--3 cm in major radius from the machine axis. This is also the center of the drift orbits of warm electrons, which are thought to be key players in determining the potential [9]. At the plasma center, cold isotropic (bulk) electrons are the main contributors to the plasma pressure. In this region, equilibrium theory suggests that without the hot electron rings the plasma pressure center should be at the center of the \( \oint dl / B \) surfaces [35,36], which are shifted 9--10 cm inward from the machine axis. This is contrary to the experimentally observed shift of 2--3 cm.

At least two theoretical treatments [32,37,38] attempt to explain the potential asymmetry. In the first [32], a horizontal electric field acts on the plasma to produce a radial inward force that balances the outward ballooning force of the bulk plasma [9]. The horizontal electric field in this electrostatic equilibrium [37] is conceptually equivalent to the vertical magnetic field necessary for tokamak equilibrium. In the second treatment [38], the toroidal gradient of the magnetic field results in a poloidal asymmetry of the warm electrons and a corresponding asymmetry in the potential. The plasma center is taken as that of the hot electron rings.

2.6 Local Convective Power Loss [13]

The loss of plasma particles by convection due to the asymmetric electric field has been mentioned previously. The symmetric and horizontal asymmetric electric fields cancel each other in two places near the electron rings: one is inside and the other is outside the major radius at the midplane. Inside this area lie
FIG. 10. Midplane Thomson scattering profiles of the electron temperature and density. The pressure was $p_0 = 16 \mu\text{torr}$ and there was 150 kW of applied microwave power. Abel-inverted data from a scanning microwave interferometer are also plotted. (Figs. 5 and 7 of Ref. [14].)

the closed potential contours. The mixture of areas of open and closed potential contours implies a mixture of areas of differing plasma confinement, which are somehow combined to produce an average power loss. Plasma parameters are compared for various potential structures and values of the radial electric field in Table I. The stored energy is relatively constant (to within $\approx 50\%$) independent of the potential structure or the strength of the radial electric field [10]. This trend
is also seen in Fig. 7. The data of Fig. 7 show that the stored energy is a weak function of the collision frequency. It is also a weak function of the fluctuation level, as discussed in Section 3. This suggests that EBT plasma transport is not governed by classical processes but is due to other mechanisms, such as a gross electric field convection.

Limiter measurements [13,39] give a quantitative estimate of the local power transported to the wall in each cavity. Of the 100 kW output by the gyrotron, only 13 kW was observed on a limiter just outside the second harmonic electron cyclotron resonance. In order to ascertain where the remaining power was going, experiments were conducted in EBT-I, where the power distribution into individual cavities could be easily controlled [13]. The limiter power is plotted in Fig. 11 as a function of the cavity from which the microwave power was removed. Data are plotted for four ambient pressures. The results indicate that the power to

![Diagram](image_url)

**FIG. 11.** Power incident on a limiter as the power fed to cavities was turned off in one cavity at a time. The power to the limiter when all the cavities were fed is indicated on the vertical axis at the left. (Fig. 3 of Ref. [13].)
the limiter was independent of the cavity in which the power was shut off, un-
less the power was removed from the limiter cavity itself. In the latter case there
was an additional power loss representing the local power loss. These data sug-
egest that, in the T-mode, ≈70% of the power was lost locally and the rest of the
power traveled toroidally. This is consistent with the EBT-S data. In estimating
the local power loss, radiation losses have been subtracted.

In previous discussions, ion transport has not been addressed. Ions are lost at
the same rate as electrons along open potential contours.

2.7 Confinement Times [4,5,8,10,13,14,17,40–43]

According to neoclassical transport theory [44], the particle confinement time
is the upper limit of the energy confinement time. Three methods were used in
EBT to determine the particle confinement time [8]. The first method used the
spectroscopic measurement of atomic hydrogen line emission. The second in-
volved the charge-exchange decay of energetic ions injected into the plasma by
a diagnostic neutral beam. The results of these two diagnostics showed similar
trends (Fig. 12) while differing by a factor of 2–3.

The third method employed H_α laser fluorescence [43]. The results lie close
to those of the H_α spectroscopic measurement (100 kW). Typical particle confine-
ment times deduced from diagnostic neutral beam data taken in the mid-T'-mode
in EBT-S were ≈300 μs. The neutral density and the neutral density profile have
been evaluated using Monte Carlo calculations [40], with results that are consis-
tent with those of the diagnostic neutral beam.

The energy confinement can be determined from a knowledge of the absorbed
microwave power and radial profiles of the density and temperature. The rela-
tively low plasma density in EBT made routine Thomson scattering profile mea-
surements difficult [4]. Although this precluded a precise determination of the
energy confinement time, crude estimates for the standard 100 kW case can be
made. The transmission loss from the gyrotron tube to the cavity was 20% [41].
The best estimate [42] of the power used to heat the hot electrons is ≈16 kW or
15–20%. The power lost through ionization and radiation was calculated to be
5 kW using the formula $E_{\text{atom}} \cdot \int n_i dV/\tau_p$, where $E_{\text{atom}} \approx 60$ eV is the power lost
per electron for each ion loss [45], $\tau_p$ is the global particle confinement time, and
$\int n_i dV$ is the total number of ions in the plasma. Subtracting these power losses
FIG. 12. The particle confinement time $\tau_p$ determined by spectroscopy (solid lines) and by fast ion decay measurements (circles) as a function of ambient pressure. Data are shown for 50, 100, and 150 kW of gyrotron power. (Fig. 5 of Ref. [8].)
from the 100 kW of gyrotron output power leaves $65 \pm 5$ kW for the total plasma absorption.

Electron density and temperature profiles [14] were measured for several standard conditions. For an ion temperature of $\approx 10$ eV and an ion density profile similar to that of the electrons, the bulk stored energy was found to be $6 \pm 1$ J. When the stored energy of the warm electrons was included, the stored energy did not exceed 12 J. Thus, the global energy confinement time was in the range 100-200 $\mu$s.

When the vertical drift velocity due to the horizontal electric field, $E_h/B$, exceeds the $T/\Omega$ vertical drift velocity due to the toroidal gradient in the magnetic field, the potential asymmetry dictates particle behavior. The critical electric field is $E_h = 50$ V/m for $T = 75$ eV. The observed horizontal electric field is $E_h \approx 500$ V/m [13]. If the plasma is lost due to $E_h \times B$ drifts, the flight time at the mirror throat is 200 $\mu$s. Similar times were calculated [46] for the loss of bulk electrons within closed potential contours into the loss cone. Thus, estimates of the particle confinement time, the energy confinement time, the $E_h \times B$ flight time, and the loss of bulk plasma into loss cones are in reasonable agreement.

3. SUMMARY

The important results of Section 2 can be summarized as follows.

1. The stored energy of the hot electrons was insufficient to significantly modify the local magnetic field gradient and therefore failed to produce a magnetic field configuration that was stable (in the simplest sense) against flute modes.
2. Coherent flute modes were not normally observed in the core plasma. This stability is most likely attributable to a shallow pressure profile (compressibility).
3. Broadband plasma fluctuations were always observed during normal operation. However, the power loss associated with these fluctuations accounted for less than 20% of the power loss due to other transport mechanisms.
4. 2-D potential contours showed that all contours were open in the C-mode but that in the T-mode there were closed potential contours at the plasma center.
5. Although central potential contours were nested in the T-mode, the area of these nested contours constituted only one-quarter of the area bounded by the second electron cyclotron harmonic resonance zone and one-eighth of the whole plasma cross section.
In the T-mode the outer potential contours were asymmetric, giving rise to a net horizontal electric field. The particle drift induced by this horizontal electric field was an order of magnitude larger than that resulting from the toroidal field gradient.

Most of the power input was lost in the cavity into which the power was fed; power did not circulate toroidally. This observation is consistent with convective loss of power caused by open potential contours.

A rough estimate gives overall energy confinement times of 100–200 µs. The particle confinement time is ≈ 300 µs. These times are consistent with the flight time along the open potential contours.

The T-mode energy confinement time in the region of good closed potential contours is not known experimentally, but calculations imply loss of bulk plasma into loss cones at loss rates similar to those due to the horizontal electric field.

Confinement was not studied in a mode with strong (ring) MHD stabilization. The ability of a ring-stabilized system to contain significant plasma pressure and the transport properties of such a plasma remain open questions.

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REFERENCES


[7] 2-D potential contours in EBT were measured by L. Solensten and J.R. Goyer; see GOYER, J.R., Ph. D. thesis, Rensselaer Polytechnic Institute, Troy, New York (1985). The first measurement of 2-D potential contours was published in Ref. [31]. Recent results were reported in Refs [9,10,13,17].


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