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**Study of Plasma Confinement
in ELMO Bumpy Torus with
a Heavy-Ion Beam Probe**

Francis M. Bieniosek

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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STUDY OF PLASMA CONFINEMENT IN ELMO BUMPY TORUS
WITH A HEAVY-ION BEAM PROBE

Francis M. Bieniosek

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ABSTRACT

Plasma confinement in ELMO Bumpy Torus (EBT) is generally strongly dependent on an ambipolar electric field. Spatially resolved measurements of the resulting electric space potential ϕ_{sp} have been made in a single plasma cross section by the heavy-ion beam probe. This diagnostic injects a 4-60-keV beam of (usually) Cs^+ ions into the plasma. Measurement of the energy of Cs^{2+} secondary ions leaving the plasma gives a continuous monitor of the local space potential. In addition, the total detected Cs^{2+} ion current is proportional to the product of the local electron density and the ionization rate, which, in turn, is a function of the electron temperature. This signal, $nf(T_e)$, is sensitive to all three electron distributions found in EBT -- those of the cold surface plasma, the warm core plasma, and the hot electron ring.

Measurements have been made on EBT-I (heated at 18 GHz) and on EBT-S (heated at 28 GHz). EBT-I was characterized by positive potentials in the surface plasma of order 100 V and by a nearly symmetric potential well in the core of up to 300 V with respect to the surface potential. EBT-S had a potential structure closely resembling that of EBT-I with well depth and peak potential similar to or greater than that of EBT-I for the same power input.

The radial profile of $nf(T_e)$ through a single chord was measured on EBT-I. The observed profile in the poorly confined C-mode was nearly parabolic to the vacuum wall, whereas the observed profile in the well-confined T-mode was more complicated, in agreement with the

expected confining properties of the hot electron ring.

Studies of the potential structure on EBT-I showed:

- (1) Peak potential and well depth increase as the neutral pressure is lowered and as microwave power input is increased.
- (2) The rim of the potential well follows approximately the expected position of the hot electron ring, but the radial electric field in the core plasma does not noticeably change as the toroidal magnetic field increases over the range of 4000- to 5500-G peak midplane field.
- (3) The radial electric field is large enough to be a significant and possibly dominant factor in plasma confinement in the central plasma region.

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I acknowledge the interest of many members of the EBT experimental group in this work. They have provided invaluable help in my understanding of EBT and in the application of the beam probe to EBT.

Finally, I would like to express my appreciation to Mack McGuffin and Bob Livesey and their crews, who helped look after the physical well-being of the heavy-ion beam probe, and to Vickie Jett, who did the painstaking job of typing this thesis on TEDI.

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PREFACE

This technical memo has the same contents as a thesis entitled "Study of Plasma Confinement in ELMO Bumpy Torus with a Heavy-Ion Beam Probe," which was submitted by F. M. Bieniosek to the Graduate Faculty of Rensselaer Polytechnic Institute in partial fulfillment of the requirements for the degree of Doctor of Philosophy. Having completed all other requirements, the author was awarded this degree at the August 1980 commencement of Rensselaer Polytechnic Institute.

1. INTRODUCTION

The ELMO Bumpy Torus (EBT) concept is one of the leading contenders as a device for magnetic confinement of a fusion plasma. The recent growth in interest in EBT has been accompanied by continued efforts to thoroughly understand the operation of this device. Research is being pursued on the existing small EBT experiment in order to determine the important parameters of the plasma and to address the unanswered physics questions related to the EBT concept.

One of the major diagnostics on EBT is the heavy-ion beam probe. Over the past several years this diagnostic, built and operated by Rensselaer Polytechnic Institute (RPI) for Oak Ridge National Laboratory, has been used to gather data on plasma properties in EBT. The biggest advantage of the heavy-ion beam probe is that it is capable of obtaining direct, spatially localized measurements of the plasma space potential. An ambipolar space potential is important for plasma confinement in the EBT concept. Furthermore, it has been shown that the existing electric field associated with the space potential, as measured by the heavy-ion beam probe, is sufficiently large to be a dominant factor in plasma confinement.

This thesis reports a study of the confinement of plasma in EBT making use of the beam probe's extensive diagnostic capability. A study has been made of the ambipolar space potential structure and of its scaling with pressure, power, and toroidal magnetic field strength. Its dependence on the microwave heating geometry has been investigated, and scaling information from the increased magnetic field

operating mode, EBT-Scale (EBT-S), has been obtained. Further information is available from the total detected signal, which is proportional to the product of the electron density and the ionization rate (a function of the electron temperature). From this signal, information has been obtained on the spatial profiles of the electrons. Several questions concerning EBT operation have been addressed, and a number of new questions have been raised, which point the way toward further study with the ion beam probe.

Section 2 presents a review of the EBT concept, an introduction to the present-day EBT device, and a review of particle beam diagnostic technology. Emphasis is placed on introducing the importance of space potential in bumpy tori and on the ability of the heavy-ion beam probe to measure the space potential. (The EBT device is described in Appendix A.)

Section 3 (with the information presented in Appendices B, C, and D) describes the details of the ion beam diagnostic installed on EBT. Experimental techniques and interpretation of the detected signals are presented.

Section 4 presents the space potential measurement on EBT. In the first part, the technique for interpreting the data is described; in the second part, the measured EBT potential structure is described, and its significance is discussed.

Section 5 describes the information obtained by studying the total signal detected, which is proportional to $nf(T_e)$. Once again, the technique used to interpret the data is described, and the measured

profiles of $nf(T_e)$ are discussed.

Section 6 presents a number of detailed scaling studies. Here, the dependence of the potential structure on the neutral pressure is documented, and a number of experiments studying the dependence of the potential on heating geometry are discussed. The potential structure is shown to be strongly dependent on the specific heating geometry.

Section 7 describes the results of an experiment in which the stability and continuity of the core plasma in the absence of local microwave heating are investigated, and at the same time the sensitivity of the ion beam signal Cs^{3+} to the locally heated hot electrons is shown. The sensitivity of the beam probe to the locally heated hot electrons is used to study the spatial distribution of these electrons.

Section 8 presents a discussion of the significance of this work.

Finally, Sect. 9 presents the conclusions that can be drawn from this work and proposes some areas for future work with the heavy-ion beam probe on EBT. These areas include both upgrading the diagnostic capability and investigating EBT physics.

2. HISTORICAL REVIEW

2.1 THE ELMO BUMPY TORUS

2.1.1 Theory of the Bumpy Torus

Magnetic confinement of plasma is based on the fact that a charged particle tends to gyrate in a helical path along a magnetic field line; the particle is in effect confined to travel in only a single direction. It is an appealing idea to connect the ends of the magnetic field lines together to form a torus. However, a simple torus runs afoul of a critical difficulty: since the magnetic field B is not constant over the cross section, a current density j_y arises perpendicular to both B and ∇B .¹ A simple interpretation of this current is that ions and electrons spiral in opposite directions perpendicular to the magnetic field gradient² (see Fig. 2-1a). This separation of charge then leads directly to a potentially large vertical electric field. Since, in the presence of crossed electric and magnetic fields, charged particles drift² in the direction of $E \times B$, the resulting horizontally outward $E \times B$ drift shifts the entire plasma toward the outer wall. This unfavorable phenomenon was, in fact, observed in the early toroidal device Zeta.¹

Antidotes have traditionally concentrated on causing the toroidal magnetic field lines to spiral and, hence, on inducing sufficient mixing of particles to cancel the toroidal drift. The most well known implementations of this idea are the stellarator,³ which introduces a twist in the field lines by external field coils, and the tokamak,⁴

which has a twist in the field lines due to the poloidal magnetic field from a large toroidal current. The idea is that field lines wind around the torus but never close upon themselves, mapping out magnetic surfaces in the shape of nested tori. A particle spirals along these field lines and traces out a magnetic surface, and the toroidal drift averages out over the magnetic surface.

Other solutions exist to the problem of equilibrium in a toroidal configuration. Since large currents can be a source for driving instabilities, current-free configurations are of special interest. An early study of equilibrium in an idealized current-free toroidal plasma showed that such a system can only be realized if the cross section is bumpy.⁵ A physical realization of this concept has come to be known as the bumpy torus.⁶ In a bumpy torus (see Fig. 2-1b), a radial gradient in the magnetic field strength ($\nabla_r B$), which is a direct result of periodic modulations in the toroidal magnetic field, leads to an azimuthal particle drift ($B \times \nabla B$) around the minor cross section of the torus. For most particles the orbit resulting from the combination of the grad-B and curvature drifts is approximately a circle. The effect of the vertical toroidal drift is simply to shift the center of the circle inward toward the major axis. In this way the toroidal drift is cancelled.

Another mechanism for azimuthal particle drift is provided by a radial electric field. The resulting $E \times B$ rotation of the plasma (see Fig. 2-2) is in the azimuthal direction and may either add to or subtract from the azimuthal grad-B drift. A parabolic potential

profile as shown in Fig. 2-2 corresponds to an azimuthal rotation frequency Ω_{ExB} approximately independent of radius, since the drift velocity (in mks units) is

$$v_{\text{ExB}} = \frac{E}{B} ,$$

and the rotation frequency is

$$\Omega_{\text{ExB}} = \frac{v_{\text{ExB}}}{r} = \frac{E}{rB} .$$

For a parabolic electric potential profile, $\phi = 1/2 kr^2$ or $E = -\nabla\phi = -kr$, the rotation frequency Ω_{ExB} is independent of radius except for the variation of B with radius. Why a radial electric field is a natural consequence of bumpy torus operation is discussed below.

Particle motion in a bumpy torus is a superposition of three periodic motions. First, there is a cyclotron gyration $\omega_c = \frac{eB}{m}$ about a magnetic field line. Second, there is motion along field lines, which takes the form of either bounces between a pair of magnetic mirrors (maxima in the toroidal field strength) or a continuous motion around the entire torus, depending on the particle's pitch angle, $v_{\parallel}/v$, with respect to the magnetic field direction. Third, there is the slow azimuthal drift discussed above, which is due to the bumpiness in the magnetic field lines. The overall particle trajectory may be determined by averaging over the first two types of motion and then

using guiding center drift theory to calculate the overall path to the particle. This theory is based on the conservation of the adiabatic invariants:⁷

$$\mu = W_{\perp} / B , \quad (2-1)$$

$$J = \int p_{\parallel} d\ell , \quad (2-2)$$

where W is the particle's energy and p is the particle's momentum. The integral is taken along a magnetic field line, over a complete bounce period if the particle is trapped, or around the entire torus if the particle is passing. In the drift approximation a particle remains on a surface of constant J , so that by calculating the constant J surfaces, the drift orbits of the particles can also be ascertained. An examination of these orbits^{8,9} shows that the path of the particles may be either a displaced circle or a crescent-shaped orbit (Fig. 2-3), with the amount of the displacement and shape of the orbit dependent on the precise position of the particle in velocity space.

Although in the drift approximation all particles (with reasonable energy) are confined in principle,¹⁰ for any real bumpy torus there will always exist regions of velocity space whose drift orbits intersect the wall.⁹ These regions represent a loss cone, analogous to a magnetic mirror, except that the particles are lost on the relatively slow drift time scale.

However, over much of the cross section of a bumpy torus, most drift orbits are confined, and other loss processes are important. Much attention has been devoted to neoclassical diffusion losses¹¹ which may dominate direct (loss cone) losses.¹² Neoclassical diffusion arises in toroidal magnetic systems because mixing in such systems leads to a larger step size in the diffusion process than that expected in classical (straight system) diffusion. In a bumpy torus the step size is the distance between drift orbits (see Fig. 2-3). Because a particle's orbit is a function of its position in velocity space, a collision between either like or unlike particles that changes their velocity vectors can drastically change the orbits being followed and lead to a random walk diffusion of particles in position. Calculation of the neoclassical diffusion coefficients was done by Kovrizhnykh¹³ in the limit of a large radial electric field. Since, for a particle species j , the radial particle flux Γ_j is related to radial gradients in density n_j , temperature T_j , and electric potential ϕ by

$$\Gamma_j = - \left(D_{nj} \frac{\partial n_j}{\partial r} + D_{tj} \frac{\partial T_j}{\partial r} + n_j \mu_j \frac{\partial \phi}{\partial r} \right), \quad (2-3)$$

where $\mu_j = \frac{Ze}{T_j} D_{nj}$, radial particle fluxes may be calculated from the diffusion coefficients D_{nj} D_{tj} . For example, in the large field limit, Kovrizhnykh gives for D_{nj}

$$D_{nj} = \frac{1}{24} \left(\frac{v_{tj}^2}{\Omega_j} \right) \frac{\Omega_j^2}{v_j^2 + \Omega_j^2} v_j \quad (2-4)$$

Here, v_{tj} is the vertical drift due to toroidicity, v_j is the collision frequency, $v_j = v_{jn} + v_{je} + v_{ji}$, and Ω_j is the azimuthal rotation frequency (the sum of the ∇B and $E \times B$ drifts). It is interesting to note that for $v_j/\Omega_j \ll 1$ (i.e., a "collisionless" plasma) the diffusion coefficient D_{nj} is proportional to $1/\Omega_j^2$. This means that as the radial electric field, and hence Ω_{ExB} , becomes large (in either direction), neoclassical diffusion becomes small, and the plasma particles are increasingly well confined. The physical basis for this behavior is that the step size for neoclassical diffusion, which is proportional to v_{tj}/Ω_j , becomes small as Ω_j becomes large.

Now the fundamental importance of space potential to bumpy torus operation becomes evident. Since, in contrast to axially symmetric (tokamak) systems,¹⁴ like particle collisions give rise to spatial diffusion, electron and ion fluxes are generally not equal, with $E_r = 0$. Hence, in order to maintain charge neutrality, an ambipolar electric field arises to balance the diffusion rates. Usually, v_e is greater than v_i ; therefore, the ambipolar potential can be expected to balance particle losses by increasing ion flux or decreasing electron flux. It may be possible to do so in any of several ways. For example, a large positive potential can electrostatically confine electrons. On the other hand, a negative potential (i.e., $E_r < 0$)

can increase ion diffusion because $E \times B$ and ∇B azimuthal drifts occur in opposite directions for ions, causing reduction of the azimuthal precession Ω and enhancement of the diffusion coefficient D_{ni} . As a result, the ambipolar radial electric field can, in principle, point in either direction.

Most recent work on the bumpy torus concept has concentrated on the EBT. Of great interest is the experimentally measured sign of the electric field in EBT, which, under appropriate conditions, is negative.¹⁵ A number of theoretical models based on neoclassical considerations have recently been developed for EBT. Some earlier point models implied that the potential could only be negative for inverted density profiles.^{16,17} However, recent one-dimensional (1-D) radial calculations¹⁸⁻²⁰ based on more realistic transport coefficients^{19,21} indicate that neoclassical diffusion implies a negative radial electric field for both collisional and collisionless plasmas. The qualitative agreement between experiment and neoclassical theory is encouraging for this view of confinement in a bumpy torus.

As mentioned above, a bumpy torus is by nature a closed-line, current-free configuration. Any perturbation from this ideal state leads to a fundamentally different topology²² in which the magnetic field lines no longer close upon themselves. A direct result is that the basic reflection symmetry of the bumpy torus is lost, thus allowing the presence of a toroidal current. The toroidal current drives a potential drop through the spiraling field lines and drastically changes the structure of the ambipolar field E , as observed on

EBT.²³ Even small magnetic field errors can substantially change particle drift surfaces²⁴ and thereby modify the neoclassical diffusion coefficients, which are dependent on the drift surfaces. As a result, bumpy tori are sensitive to field errors; for example, in EBT, a global field error of $\frac{\Delta B}{B} < 10^{-3}$ is observed to be necessary for current-free operation.²³

2.1.2 Microwave Heated Plasmas

When considered as a fluid, the plasma in the basic bumpy torus is inherently unstable to interchanges. From energy considerations, it is necessary that in the direction of decreasing plasma density the following inequality be true for interchange stability:²⁵

$$\oint \frac{d\ell}{B} < 0 , \quad (2-5)$$

where the integral is taken along a magnetic flux line. If the stability condition is not met, the plasma is unstable because the plasma, which is tied to magnetic tubes of flux, may arrive at a lower energy state by simply interchanging neighboring flux tubes. Because a simple mirror does not satisfy the interchange stability condition, and since a bumpy torus in effect consists of a collection of simple mirrors, one would expect it to be unstable also without an additional stabilizing mechanism.

Research in the properties of microwave heated plasmas in magnetic mirrors has shown experimentally that microwave heating is capable of providing just such a stabilizing mechanism. Microwave heating, which generally couples with the electron cyclotron frequency $\Omega_{ce} = \frac{eB}{m}$ or its harmonics, can produce relatively low density but very high electron temperature plasmas.²⁶ These plasmas tend to take the form of a shell of extremely hot electrons immersed in a cold background plasma of greater density. The TPM machine at Nagoya^{27,28} was observed to have a 150-keV shell of hot electrons at the throat of the hyperboloid-shaped surface of constant magnetic field intensity corresponding to the second harmonic resonance zone for the microwave source. There was also a distribution of cold background plasma $n_c > n_h$. A theory of harmonic resonance heating also indicated localized resonance zones and gave a heating rate comparable to that found in the experiment.²⁹ The ELMO machine at ORNL^{30,31} also had a shell of hot electrons but at a much higher energy (0.5-2 MeV). The heating mechanism for this plasma was probably nonresonant.³²⁻³⁴ In general, off resonant heating has been experimentally observed to change electron pitch-angle distributions.³² For $\omega > \Omega_{ce}$, electrons tend to gain $v_\perp$, whereas for $\omega < \Omega_{ce}$ they gain $v_\parallel$.

Interest in hot electron plasmas of this type is due to the fact that, in a simple analysis, the finite beta from the large energy density of the hot electron ring can reverse the gradient of $\int \frac{d\ell}{B}$ and thereby ensure stability to interchange (Fig. 2-5).¹² Calculations based on a rigid, noninteracting ring model for EBT suggest that this

is indeed the case.³⁵ More sophisticated models that also consider the hot electron component agree with this result³⁶ and show that the hot electron component itself requires a sufficiently large component of cold electrons to remain stable.³⁷

2.1.3 Microwave Heated Bumpy Tori

The promising nature of microwave heating led to its application to EBT,³⁸ which has been in operation since 1975.^{39,40} A description of the EBT experimental results is given in Appendix A. EBT-S is physically the same machine, scaled up to operate at a heating frequency of 28 GHz, rather than the 18 GHz of EBT-I.

A number of future EBT devices⁴¹ have been proposed. The proposed devices are larger bumpy tori with a higher magnetic field, a higher microwave heating frequency, and a denser and hotter plasma than EBT-I. Proposals have been made for ion heating⁴² (for example, ion cyclotron heating and neutral beam heating). Such heating is expected to change the space potential in EBT because of a change in energy balance between ions and electrons.

The only other operating bumpy torus today is the Nagoya Bumpy Torus (NBT)⁴³ at Nagoya, Japan, which is now getting under way. It is similar in design and spirit to EBT, with a lower magnetic field and a lower microwave heating frequency.

2.2 HEAVY-ION BEAM DIAGNOSTICS

There is always a need in fusion energy research for accurate nonperturbing plasma diagnostics. To help meet this need, a number of particle beam diagnostic techniques have been developed.⁴⁴⁻⁴⁶ These techniques have the important advantage that, as long as the magnitudes of the beam particle and energy density are below those of the plasma, local measurements can be made without noticeably perturbing the plasma.

The heavy-ion beam probe described in this work is one of a class of beam probes whose most important feature is the ability to make local measurements of the space potential.⁴⁷ The space potential is a plasma parameter difficult to measure by any other technique. In addition, other information about electron density, electron temperature, and fluctuations is available from the beam probe.

The system used here is derived from the pioneering work of Hickok and Jobes⁴⁸ as extended by Reinovsky.⁴⁹ A beam of positively charged ions (typically, one of the alkali metal ions) is accelerated to a high velocity and injected into the confining magnetic field of the device. Since the particles in the beam obey the Lorentz force equation, they move in a curved path with local radius of curvature R_c :

$$R_c = \frac{mv}{eB} \quad (2-6)$$

As the beam travels through the plasma its density is too low to directly affect the plasma. However, reactions between beam ions and plasma electrons may further ionize some fraction of the beam ions. These ionized beam particles then leave the plasma on trajectories different from that of the primary beam. The reactions of interest to ion beam probing are those which change the beam ion's charge state without affecting its momentum — in particular electron impact ionization,

where R is any probing ion and $n = 2, 3, \dots$. Generally, the dominant ionization mechanism in the operating regimes of present interest is electron impact ionization, with $n = 2$.⁴⁹

The beam probe is capable of making spatially resolved measurements because a suitable detector placed outside the plasma will collect reaction products (or "secondaries") originating inside a small volume in the plasma (see Fig. 2-6). The position of this "emission point" is uniquely determined by the initial position and firing angle of the beam and the position of the detector, since the secondaries are produced in non-momentum-transfer collisions. By varying the energy of the beam and electrostatically sweeping the beam across the plasma, the emission point can be placed at any desired location and, thus, can make it possible to map the entire plasma.

2.2.1 Electron Density and Temperature

As a particle beam passes through a plasma, some portion of the beam will undergo ionizing collisions with hot plasma electrons. The average reaction rate per unit volume is

$$\langle R \rangle = n_b n_e \langle \sigma v \rangle , \quad (2-8)$$

where n_b and n_e are beam ion and plasma electron number densities, σ is the cross section for the reaction in question, and v is the relative speed between beam particle and plasma electron. The resulting attenuation may be used as a measure of integrated line density.⁵⁰

More useful, however, is the detection of the secondary ions themselves since, in this way, spatially resolved information is obtained. Defining

$$\sigma_{\text{eff}} \equiv \frac{\langle \sigma v \rangle}{v_b} , \quad (2-9)$$

the flux of secondary ions reaching a small-aperture detector may be given by

$$\frac{I_s}{I_p} = Z n_e l \sigma_{\text{eff}} , \quad (2-10)$$

where I_s = secondary current in detector,

I_p = primary beam current injected into plasma,

Z = charge state of secondary ion (usually 2),
 n_e = electron density,
 l = length of beam sampled by detector, and
 σ_{eff} = effective ionization cross section. This is a
 function of the ion species used, its
 speed through the plasma, and the electron temperature
 of the plasma.^{49,51}

Measurement of the I_s/I_p ratio yields a result proportional to
 $n_e f(T_e)$, where $f(T_e)$ is a known function. This technique has been used
 to make density measurements.⁵²⁻⁵⁴ A temperature measurement has also
 been made using the same technique by making two I_s/I_p measurements
 with widely differing $f(T_e)$ and then inverting $f(T_e)$.^{55,56}

2.2.2 Space Potential

A number of techniques have been developed for measuring space
 potential with a probing beam.⁵⁷⁻⁵⁹ The technique used here is
 based on the change in charge of a beam ion at the point of
 ionization.^{60,61} Consider a beam ion that undergoes ionization at a
 point where the space potential is ϕ . If its total energy is eV_0 , it
 arrives at the point of ionization with kinetic energy $T = e(V_0 - \phi)$.
 The secondary ion emitted at this point has the same kinetic energy
 (since no momentum has been transferred), but as it returns to ground
 potential outside the plasma, it gains $2e\phi$ in potential energy.
 Therefore, at the detector, it has total energy $e(V_0 + \phi)$. Hence, ϕ =
 space potential can be determined by simply measuring the difference

between the energy of primaries leaving the ion gun and the energy of secondaries arriving at the detector. This measurement can be made with a resolution of a few parts in 10^4 by using a feedback controlled electrostatic energy analyzer.^{62,63}

2.2.3 Magnetic Field

Both spatially resolved and line averaged measurements of magnetic field have been made with beam probes.

In a system with a large current density parallel to symmetric magnetic field lines (tokamak, high current arc), the current density can in principle be determined by making use of the fact that the secondary ion samples not only the electric scalar potential ϕ but also the magnetic vector potential A .⁶⁴ Experimentally, however, this is a difficult measurement to make and has not yet been accomplished.

A second type of magnetic field measurement is useful in devices lacking the necessary spatial symmetry, such as EBT. In this case, a measure of the average beta can be obtained along a particle trajectory.⁶⁴ Any difference between the end points with and without the field perturbation is an indication of finite beta. Although there is no longer any point measurement, the result can be made to fit a cylindrically symmetric model of the field perturbation. Magnetic field measurements have been made with this technique.⁶⁵ Because of the significant beta in EBT, it is an attractive possibility for measuring beta in EBT.

A third method of magnetic field measurement is based on a different concept. As a beam passes through a plasma, it undergoes excitation reactions with plasma electrons. Spectroscopic detection of the line radiation can then be used as a diagnostic to measure, for example, the local electron density.⁶⁶ Furthermore, Zeeman splitting of the spectral line emitted in a magnetic field gives a direct indication of the magnetic field at that point. This phenomenon has been used to measure magnetic field with a neutral Li beam.⁶⁷ A Ba^+ beam has been proposed to measure the beta in EBT-S with this technique.⁶⁸

3. THE HEAVY-ION BEAM PROBE ON EBT

This section describes the heavy-ion beam probe diagnostic system on EBT and the meaning of the detected signal. Further information, especially on the potential measurement, can be found in Sect. 4 and Appendix B.

3.1 BEAM PROBE OPERATION

The heavy-ion beam probe injects a beam of 4- to 60-keV heavy ions into the midplane of a single mirror section. A thermionic ion source⁶⁹ emits a stream of singly charged ions (usually Cs^+). The emitted ions are formed into a beam by cylindrical Pierce electrodes;⁷⁰ the beam is then focused and accelerated by a set of lenses in the ion gun. The ion gun is capable of delivering more than 10 μA of beam focused to 1 cm at a distance of 1 m.

After passing through an aperture (which cuts off stray particles), the beam may be deflected by a pair of electrostatic sweep plates. These plates are capable of deflecting the beam up to $\pm 15^\circ$ and are used to sweep the beam in the midplane across the plasma.

Next, a pair of chop plates is provided to steer the beam out of the midplane. These plates are generally used to chop the beam in conjunction with the synchronous detection system by applying a 3-kHz, 0- to 500-V square wave on one of the plates to deflect the beam out of the plane. The chop plates may also be used to provide a small amount of z-steering, if necessary, to correct for mechanical misalignment.

Diagnostic equipment in the sweep plate chamber includes a Faraday cup for accurately measuring ion emission from the ion gun and a set of wires and cross hairs for aligning and calibrating the system both in the detection plane and in the z-direction.

Both the sweep plate chamber and the detector chamber are screened from microwaves. The shielding is provided by copper screens 1/8 in. thick with a dense honeycomb pattern of holes that allows the beam to pass through. They are curved in a cylindrical shape to allow ions to pass perpendicularly through the holes.

After the ions have passed through the plasma, the electrostatic energy analyzer serves as a detector of both primary and secondary signals. This device,^{62,63} which is central to the space potential measurement, is sketched in Fig. 3-1. A voltage V_a is applied to the top plate of the analyzer, causing the beam of ions of energy $e[V_o + (Z - 1)\phi]$ to be bent down toward the split plate detector. The beam energy is accurately determined by measuring the voltage $V_a + V_b$ required on the top plate to null the difference signal.

The theoretical operation of the analyzer can be described by two parameters: the geometric gain,

$$A_g = \frac{V_o}{V_a} = \frac{V_o + (Z - 1)\phi}{V_a + V_b}, \quad (3-1)$$

and the geometric focusing parameter,

$$\gamma = \frac{2Zy_d}{A_g d} \cong 1, \quad (3-2)$$

where $y_d = y_{d1} + y_{d2}$. Dimensions y_{d1} and y_{d2} are shown in Fig. 3-1. The geometric gain is used to determine the space potential ϕ . It is calibrated by the use of $Z = 1$ primaries, i.e., $A_g = V_o/V_a$. Once A_g is precisely known, ϕ can be determined by measuring the additional top plate voltage V_b needed to center the beam, after compensating for the change in charge state of $Z \neq 1$ secondary ions. The focusing parameter γ is a measure of the angular acceptance properties of the analyzer. γ is set to approximately 1, where the analyzer has an angular acceptance window of as much as 8° (Fig. 3-1).

The beam probe electronic system is described in detail in Appendix C. The beam detection system makes use of the signals from the split plates (four sections) to generate a $nf(T_e)$ signal from the sum and a ϕ_{sp} signal from the up-down difference. (The right-left difference is used to monitor beam displacement out of the plane.) The sum signal is processed with a straightforward amplification; however, the difference signal must be both amplified and fed back to the analyzer top plate. Then, the difference between the top plate voltage and the gun voltage is monitored to give the space potential measurement.

Detected signal levels are generally low, only a few times larger than amplifier noise (about 1 nA) over the bandwidth of the amplifiers. As a result, a narrow bandwidth chopping and detection

system is used to reject the noise. The detection system frequency is set at 3 kHz with a bandwidth of approximately 1 Hz. A phase sensitive detector⁷¹ locks in on the narrow band signal and converts it to a dc level for feeding back to the analyzer. Figure 3-2 illustrates the process. Figure 3-2a shows direct sum and difference signals from Cs²⁺ secondary ions in the absence of chopping. The beam is being swept across the plasma, while staying in the midplane. Although some structure may be observed in the I_{sum} and I_{diff} signals, the amplitudes are not much larger than the amplifier noise. As a result, it is difficult to make meaningful measurements in this way. On the other hand, Fig. 3-2b shows Cs²⁺ sum and difference signals detected from a single point in the plasma as the beam is chopped at 3 kHz. The direct split plate signals are again noisy. However, the filtered signal (sine wave) exhibits very little noise; this is the signal used (after detection) in the feedback loop.

The electronics system and philosophy of operation of the beam probe, especially of the space potential measurement, are given in more detail in Appendix B (Ref. 72).

3.2 THE MEANING OF THE DETECTED SIGNAL

As mentioned in Sect. 2, the signal I_{sum} is directly related to the local electron density at the point of secondary emission. Under ideal conditions,

$$I_{\text{sum}} = Z n_e \ell \sigma_{\text{eff}} I_p, \quad (3-3)$$

where I_p is the primary beam current. In most cases, σ_{eff} can be adequately represented as⁵¹

$$\sigma_{\text{eff}} = \frac{\langle \sigma v \rangle}{v_b} \cong \frac{f(T_e)}{v_b} ; \quad (3-4)$$

i.e., $\langle \sigma v \rangle$ is nearly independent of beam velocity. Conceptually, it is a simple matter to determine $nf(T_e)$ after correcting for the geometric factor Ω and the beam velocity v_b . Some of the contributing parts of the signal I_{sum} are discussed below.

3.2.1 Electron-Impact Ionization

The electron-impact ionization cross sections are calculated from the experimental data. The cross sections for Cs^+ are not as well known as those for Rb^+ .⁷³ Furthermore, in the case of $\text{Cs}^+ + \text{Cs}^{2+}$, the experimental cross section measurements^{74,75} disagree in some ranges (Fig. 3-3). However, Feeney's measurements are preliminary — only preliminary data exist for the $\text{Cs}^+ + \text{Cs}^{3+}$ reaction.⁷⁶ Along with the data, theoretical calculations for the cross sections are plotted in Fig. 3-3, based on the method of Gryzinski.⁷⁷ Gryzinski uses a classical model of the ionization process to derive a simple formula for the cross section. The formula is dependent on the number of electrons available to be ionized and their ionization energy. The cross sections have been calculated in Fig. 3-3 from tabulated ionization energies and with the parameter n (number of available

electrons) chosen to best fit the data. No attempt has been made here to take into account the detailed structure of the probing ion, which may be complicated for cesium, especially in the higher charge states (as shown for rubidium in Ref. 73).

To calculate the effective cross section $\langle\sigma v\rangle/v_b$, the cross sections shown in Fig. 3-3 were integrated over a Maxwellian electron distribution for a fixed beam velocity v_b . Feeney's data were used in the calculation. The scaled Gryzinski curves were then used to extrapolate the effective cross sections out to high electron temperatures, where no experimental cross section data exist. The calculated effective cross sections are plotted in Fig. 3-4 for a $V_{acc} = 10$ kV, Cs^+ beam. The ratio Cs^{2+}/Cs^{3+} may be used as a measure of electron temperature, especially where the ratio is a steep function of temperature. Because of the uncertainty in the experimental numbers, however, these curves cannot be relied upon to give precise temperature measurements.

3.2.2 Charge Exchange

The question of the possibility of other mechanisms for beam ionization or attenuation has been discussed by Reinovsky.⁴⁹ A question of particular interest is that of charge exchange on plasma ions:⁷⁸

Although no data exist for any of the beam probe ions (Rb^+ , Cs^+ , Tl^+),

the measurement has been made for Mg^+ .⁷⁹ Calculated charge exchange cross sections on a Maxwellian ion distribution are compared with the electron impact cross section⁸⁰ for $\text{Mg}^+ \rightarrow \text{Mg}^{2+}$ in Fig. 3-5. In EBT the electron temperature is on the order of 150 eV or greater.⁴⁰ The ions do not have a true Maxwellian distribution, but the bulk of the ions are below 150 eV.⁴⁰ Figure 3-5 indicates that for beam velocities used on EBT (the velocity of a 4.3-kV Mg^+ beam is the same as the velocity of a 10-kV Cs^+ beam) the charge exchange signal would be at least a factor of 10 below the electron impact signal for a Mg^+ beam. Hence, insofar as the alkali metals are similar to magnesium, charge exchange should not be a significant factor in EBT. A more direct argument can be based on the fact that charge exchange has a different dependence on beam velocity than electron impact. Hence, had charge exchange been a major contributor to the Rb^{2+} or Cs^{2+} signals, one would have expected the I_{sum} signal to be qualitatively different for Rb^+ and Cs^+ beams. Since this was, in fact, not observed, it is unlikely that charge exchange contributes more than a few percent of the total signal.

3.2.3 Effective Sampling Length

The total detected signal is linearly dependent on the effective sampling length ℓ . Since ℓ is based on a purely geometric condition, it can be calculated by ion orbit simulations. The factor ℓ is plotted in Fig. 3-6 as the ratio of sample length to analyzer aperture width. It varies significantly across the plasma.

3.2.4 Other Factors

Other factors than those listed in Eq. (3-3) affect the signal I_{sum} . These factors specifically make difficult the determination of $\text{nf}(T_e)$ from the measured signal I_{sum} .

(1) Scaling of I_{sum} with ion gun accelerating voltage is unclear and variable. Not only the emission of the ion gun needs to be taken into account, but also the secondary electron emission at the detector plates. Further, because of its finite size, the beam is distorted by magnetic field gradients. An example of the observed beam distortion is shown in Fig. 3-7. This is a plot of total detected signal at the analyzer for a slightly misaligned system ($\Delta\theta \approx 1^\circ$) as a function of toroidal (z-) steering voltage V_z . Plotted are the signal profiles for a Cs^+ beam and Cs^{2+} secondaries. Also shown is potential comparator output for the secondary signal. Misalignment can be observed in the fact that the peak potential signal (ions flowing into the analyzer at the proper angle) occurs at a nonzero z-steering voltage. Distortion of the beam in the z-direction is evident in the spread-out signal, particularly since the Cs^{2+} signal is more spread out toroidally than the Cs^+ signal. Therefore, not all of the ionized portion of the beam arrives at the small-aperture detector (of which the toroidal width is 1.5 in.). The problem may be remedied to some extent by careful alignment. In practice, the distortion is of marginal importance on the Cs^{2+} signal but is quite important on the Cs^{3+} signal. This is apparently due to the greater sensitivity of the triply charged ions to magnetic field gradients.

(2) There are numerous screens in the path of the beam (such as microwave screens, screens in the analyzer, and plasma suppression screens in the sweep plate chamber); each screen has its own transmission characteristics. Total attenuation due to the screens is approximately a factor of 2. Since this attenuation is a function of the angle of incidence at the screens, the $n_f(T_e)$ profile can only be estimated along a constant or nearly constant angle chord through the plasma.

(3) Beam attenuation may affect the I_{sum} signal. For typical EBT operating conditions, the attenuation from electron impact ionization in passing through the plasma should be in the range 10-30%. Table 3-1 shows the expected voltage ranges and signal attenuation levels in EBT-I and EBT-S for some fairly modest plasma parameters.

Table 3-1

Ion	EBT-I $(n_e l = 2 \times 10^{13} \text{ cm}^{-2},$ $T_e = 100 \text{ eV})$		EBT-S $(n_e l = 3 \times 10^{13} \text{ cm}^{-2},$ $T_e = 100 \text{ eV})$	
	Voltage range (kV)	Beam attenuation (%)	Voltage range (kV)	Beam attenuation (%)
K	15-57	2-4		
Rb	7-26	8-15	15-55	9-16
Cs	4.5-17	12-22	9.5-35	13-24
Tl	3-11	17-30	6-23	19-33

3.3 FLUCTUATIONS

The ion beam probe has been used as a diagnostic tool to measure fluctuations on other plasma devices. A low frequency density fluctuation was observed and identified on the ST tokamak with the help of the ion beam probe.⁸¹ On the RPI arc, beam probe studies were made of both density and potential fluctuations, as well as of the phase angle between them.⁸² This enabled the identification of the fluctuation being studied as a Kelvin-Helmholtz flute mode.⁸³

The necessarily high degree of filtering of the signals from the EBT beam probe makes direct fluctuation measurements of the type made by J. C. Glowienka et al.^{82,83} impossible, but the same information can be obtained by examining the unfiltered signals. In principle, these signals can be used to determine $\tilde{n}$, $\tilde{\phi}$, and the phase angle between the fluctuating signals. The basis for this application is described in Appendix D.

The most immediately apparent observed fluctuation is on the primary beam itself, which exhibits a 50% or more intensity modulation at the detector with even a few watts of microwave power. This poorly understood phenomenon is illustrated in Fig. 3-8, which shows sum and difference signals for both Cs^+ and Cs^{2+} under typical operating conditions. The fluctuations are large on the Cs^+ beam but not at all in evidence above the noise on the Cs^{2+} secondary signal. This implies that the cause of the apparent fluctuation is beam steering.

It is interesting to investigate fluctuations observed on the secondary signal, since the beam steering phenomenon does not seem to manifest itself on the secondaries. Some fluctuations have been observed on the secondary sum and difference signals, especially toward the edge of the plasma. However, without a more thorough understanding of the beam steering, fluctuation measurements are difficult to interpret.

4. THE SPACE POTENTIAL MEASUREMENT

4.1 THE MEASURING TECHNIQUE

This section discusses the technique used to transform the output of the space potential comparator into a meaningful space potential measurement. The process involves, first, correcting the comparator signal so that it yields a true space potential measurement, second, determining where in the plasma the space potential measurement has been made, and third, applying error bars to the data, based on the investigation into sources of error discussed in Appendix B.

4.1.1 Determination of Potential

The potential measurement is derived by measuring the difference between the gun voltage and analyzer voltage required to null the difference signal on the split plates. It is by nature a relative measurement and requires an absolute zero (ground) reference. The zero reference is provided from the analyzer voltage required to null the difference signal on the primary beam. This calibration relies on the voltage-current characteristics of a pair of high voltage comparator resistors. Most of the data presented here were taken with a pair of air-cooled, $10^8\text{-}\Omega$, high voltage comparator resistors. These have since been replaced by more stable, $10^9\text{-}\Omega$ Spellman 100-kV dividers (type HVD 100-1) adjusted at the factory to 0.1%. The Spellman dividers allow operation at the voltage levels required for EBT-S. In all cases, a simple in situ calibration is performed by using the primary-ion beam, which contains not only Cs^+ but also impurity ions

(Rb^+ , K^+ , Na^+). These ions enter the detector at different voltages and, hence, are used to determine zero reference points for different voltage levels on the comparator. This technique is especially useful since other errors that are functions of the gun voltage (for example, misalignment errors) are also corrected. In this way the resistors are calibrated to an accuracy of 0.2% (2 V/kV), which is sufficient for accurate potential measurement (since $\phi_{\text{sp}} \cong 1-3\%$ of V_{gun}).

4.1.2 Determination of Position

The position being sampled in the plasma is determined from the grid map. Usually, the position is known to an accuracy of better than 1 cm. There are two distinct modes of operation of the beam probe. In the first operating mode the ion gun voltage is ramped up from 4 kV through the zero sweep scan (no voltage applied to sweep plates) to produce a canted vertical detector line through the plasma (see Fig. 4-1).

Along this scan variations in entrance angle into the analyzer are minimized. Translating the gun voltage into position is then performed directly with the grid map. Usually, the position is represented as a radius, since the zero sweep scan falls close to the geometric center of the cavity. This scan also passes close to the bottom of the potential well, which is typically shifted 4-5 cm inside the cavity center. The second mode of operation is a point by point method in which the desired emission point is selected and the proper voltages for reaching this point are applied to the gun and sweep plates. The required voltages are calculated from an inversion of the grid

map. The analyzer is mechanically rotated to find the inflection point ($\theta = 30^\circ$) of the angular error curve, and the potential measurement is derived from the analyzer voltage at the inflection point. This technique is most useful when the potential along a particular line (for example, the horizontal line $y = 0$) is desired.

4.1.3 Errors in Measurement

Errors in the potential measurement come from several sources. The most important errors are the following.

(1) The error in establishing a zero reference voltage from the primary beam is approximately 10 V. This comes from spatial gradients in the primary beam which distort the measurement by throwing too much signal onto one plate. A check for this error is available by using doubly and triply ionized secondaries to make a potential measurement after the zero reference has been set with the primaries. Since the 3+ secondaries carry twice as much potential information as the 2+ secondaries, they should give a voltage comparator output twice that for the 2+ secondaries, with respect to the zero reference.

(2) The inherent error in the potential reference point as the gun voltage is changed is 0.2%, or 2 volts per kilovolt of gun voltage, with respect to the calibration point. This error dominates the other errors for $V_{acc} > 15$ kV. Since the error scales linearly with voltage, it is advantageous to operate at the lowest possible voltages, for example, by using heavier Cs^+ ions rather than Rb^+ ions in the beam.

(3) Deviations in entrance angle into the analyzer lead to errors due to the angular sensitivity of the analyzer. In the point by point mode of operation, this error is eliminated by searching for the inflection point of the angular error curve; in the single sweep mode, this error can be kept below 0.1% for a well aimed analyzer on the zero sweep voltage scan. Hence, it is not a dominant error under good operating conditions.

(4) As noted in Appendix D, massive fluctuations in both potential and density can lead to a discrepancy between signal averaged potential, which the beam probe measures, and time averaged (dc) potential. In the absence of any good data on potential fluctuations, it is difficult to put an upper limit on this error. However, the density fluctuations do not seem to be large enough, even given hundreds of volts fluctuating potential, to introduce a significant error in the dc potential measurement, at least in the core plasma.

(5) Other sources of error are small. These would include errors due to contamination of the beam, density gradients in the plasma over the sampled volume, and finite charge density of the beam.

4.2 THE MEASURED POTENTIAL STRUCTURE

There are two operating modes in EBT in which beam probe measurements are possible. The cold, collisional (C-) mode is a high neutral pressure mode in which the plasma is cold and poorly confined and has a high fluctuation level. The toroidal (T-) mode is an intermediate neutral pressure mode in which there is a large amount of

stored energy in the hot electron rings and the core plasma is observed to be stable. The core electrons are warm, and the plasma is well confined. This is the most interesting of the operating modes of EBT. On the other hand, the mirror (M-) mode is a low neutral pressure mode in which the plasma is violently unstable. Beam probe measurements are not possible in this mode.

The potential structure in the C-mode is rather chaotic in nature, with little clear global structure. An example of some potential data from the C-mode along the horizontal line $y = 0$ is shown in Fig. 4-2. These data have been taken on a point by point basis with a Cs^+ beam. In the C-mode the potential is generally small and positive, but larger toward the inside (major axis) than toward the outside. It is not azimuthally symmetric, and the detailed structure is variable. In the structure shown in Fig. 4-2, the plasma is close to the T-mode, so that the potentials are relatively large. A study of the C-T transition is described in Ref. 15.

In the T-mode pressure range, the overall potential structure on EBT is strongly dependent on toroidal magnetic field line closure. Changes in this parameter lead to drastic qualitative changes in the potential structure. However, discussion here is limited to the situation in which the magnetic field errors and toroidal current have been cancelled out,²³ since this is the true bumpy torus (closed-line, current-free) configuration.

An example of a fairly typical T-mode potential structure along the horizontal line $y = 0$ is shown in Fig. 4-3. The current in the toroidal field coils is 5000 A. The expected vacuum field position of the hot electron ring is indicated by the horizontal dashed lines. In the core plasma inside the hot electron ring, there is a deep potential well. The depth of the potential well is larger than the ion temperature and comparable to the electron temperature. Inside the core, the potential has a nearly parabolic shape. The azimuthal rotation frequency Ω_{ExB} (about $9 \times 10^4 \text{ s}^{-1}$ in Fig. 4-2) is larger than Ω_{VB} (about $1 \times 10^4 \text{ s}^{-1}$ for 100-eV particles) for most particles. Consequently, since $\Omega = \Omega_{\text{ExB}} + \Omega_{\text{VB}}$ is an important factor in neoclassical transport [Eq. (2-4)], the ambipolar potential well is important in plasma confinement. The measured potential structure clearly lends support to the idea that the hot electron ring confines a stable core plasma because it forms a deep bowl whose edges are approximately at the position of the ring. Furthermore, in a manner reminiscent of the C-mode, the potential in the surface plasma (outside the hot electron ring) is not in-out symmetric. Due to insufficient signal, potential data are not available for points farther out than those indicated.

Figure 4-4 shows a two-dimensional (2-D) plot of the space potential for a (different) typical T-mode operating condition. This is a hand drawn contour plot of the space potential over the entire plasma cross section in the midplane. It is based on an array of 78 individual data points taken over a period of approximately 3 h.

Although drift in the plasma potential over this period of time is small, it is difficult to indicate the uncertainties in the potential measurement. Actually, the uncertainty is approximately ± 15 V toward the lower edge of the plasma and up to ± 40 V at the top edge of the plasma. As a result it is not certain whether, for example, the 25-V contour was closed toward the top of the plasma, since the inherent error in the measurement may be greater than 25 V in that region.

Furthermore, since the potential measurement could not be made at the edge of the plasma, some potential contours were not followed over the entire cross section. Nevertheless, this plot clearly shows both the deep azimuthally symmetric potential well in the core plasma and the other asymmetric eddies in the potential structure outside the well. These local perturbations may be related to the positions of the toroidal field correction coils, shown in the figure ($\pm I_V$, $\pm I_H$). The marked positions of the hot electron ring and of the last closed drift surface without an electric field for $v_{\parallel}/v = 1$ are intended as a guide to the geometry of the plasma. The indicated position of the hot electron ring corresponds to the expected 18-GHz resonance, and the last closed drift surface is taken from Ref. 39. In fact, the last closed drift surface may more closely resemble the last closed potential contour since, when the $E \times B$ drift dominates the ∇B drift, ions and electrons tend to follow constant potential contours in their drift orbits.

4.3 THE MEANING OF THE POTENTIAL WELL

Summarizing the results of Sect. 4.2, an ambipolar potential well was observed to form when the plasma achieved overall stability. Under these conditions it is axisymmetric in the toroidally passing core plasma and large enough to dominate the azimuthal drift for most particles. Considerable theoretical effort has been expended in attempts to explain this structure.^{18,20} However, it is not yet completely understood.

Electron confinement is easily analyzed in terms of neoclassical calculations.⁸⁴ The electrons are electrostatically repelled by the negative potential, but, according to neoclassical arguments, they are well confined because the step size for radial diffusion becomes small for large Ω_{ExB} . A specific numerical calculation for electron neoclassical transport scaling will be presented in Sect. 6.

Ion confinement is more complicated.⁸⁴ The deep potential well electrostatically confines the ions in addition to the good confining properties of the large azimuthal drift frequency Ω . However, for a small class of ions in the "tail" of the ion distribution, $\Omega \approx \Omega_{\text{ExB}} + \Omega_{\nabla B}$ is not large because, as mentioned in Sect. 2, the poloidal $\mathbf{E} \times \mathbf{B}$ and ∇B drifts are in opposite directions and may cancel each other for some ion energies. In such a case the ion diffusion becomes "resonant"; i.e., the step size for diffusion is large.^{84,85} From the data of Fig. 4-3, it is possible to calculate the ion energy required

to balance these two drifts in the midplane electric and magnetic fields (mirror trapped ions). Since the electric field was only measured in the midplane, this calculation is not possible for any other plasma cross section. The ∇B drift velocity may be written (in mks units) as²

$$v_{\nabla B} = \left(\frac{kT_{\perp}}{e} \right) \frac{\nabla B/B}{B} ,$$

where $kT_{\perp}$ is the perpendicular ion energy $1/2mv_{\perp}^2$. Equating $E \times B$ and ∇B drifts,

$$\left(\frac{kT_{\perp}}{e} \right) = \frac{EB}{\nabla B} .$$

A plot of the radial electric field along the horizontal axis corresponding to Fig. 4-3 is shown in Fig. 4-5. This field is approximately linear over a region in the core plasma $-11 \text{ cm} \leq x \leq +2 \text{ cm}$. The approximate perpendicular ion energy needed to cancel the poloidal drifts is also shown. It shows a broad peak in the core plasma of 1000 to 1400 eV in this central region, which rapidly falls off outside the central region. Unfortunately, no ion temperature information is available for comparison on this particular data run.

The ion confinement is difficult to calculate because the ion energy distribution is not Maxwellian but is instead generally observed to have an enhanced high energy population or tail.⁴⁰ This tail is

near the energy range required to cancel the poloidal $E \times B$ and ∇B drifts. Hence, it is possible that the tail is a determining factor in the existing ion loss rate.⁸⁶

5. THE $nf(T_e)$ MEASUREMENT

The secondary signal I_{2+} collected at the detector is related to the density-cross section product, $nf(T_e)$, at the point of ionization. This section discusses the technique by which the total signal is converted to an estimate of $nf(T_e)$. Essentially, by accounting for the origin of the signal in the plasma, this technique enables the construction of the relative profile of $nf(T_e)$. The calculated profiles will be presented and their behavior discussed.

Although the potential measurement can be made nearly anywhere in the plasma cross section, the $nf(T_e)$ profile measurement has only been done on a single curve through the plasma. This is the canted vertical chord probed for Cs^{2+} with no applied voltage on the sweep plates (see Fig. 4-1). Along this path the angle of incidence, and hence the transmission, of the beam through the microwave screens does not appreciably change. For this reason and because it passes close to both the center of the vacuum chamber and the bottom of the potential well, the zero sweep scan has been chosen as the best suited means for relative $nf(T_e)$ profile measurements.

In practice, the total detected signal is proportional to a number of factors:

$$I_{2+} \sim n_e f'(T_e) \ell(gI_p) . \quad (5-1)$$

Here, n_e is the local electron density; $f'(T_e)$ is the effective cross

section before the correction for cross section scaling is applied, $f(T_e) = (V_{acc}/V'_{acc})^{1/2} f'(T_e)$, where V_{acc} is a nominal, fixed voltage (for example, $V_{acc} = 10$ kV in Fig. 3-4); and ℓ is the length of beam path actually sampled by the detector (see Fig. 3-6). The most difficult part of the equation to determine is in parentheses (gI_p) . Here, g represents the fraction of the beam along the detector's sample length that is actually sampled by the detector. Ideally, all of the beam in this length is observed, but in practice this may not be true because the finite size beam is distorted by magnetic field gradients and because the beam is attenuated in passing through the plasma. The geometric distortion spreads the beam out of the detecting plane. Naturally, the parameter g can depend strongly on detailed beam structure, which, although expected to vary with changing V_{acc} , is difficult to quantify. The total beam current emitted by the ion gun is I_p . This quantity also scales with V_{acc} , and the scaling can be measured with the Faraday cup. However, the scaling changes with beam quality and source output, and in the present system it cannot be measured simultaneously with I_{2+} . Furthermore, the detected current is affected by such factors as secondary emission of electrons from the detector plates, primary beam attenuation, impurity fractions, and primary beam fluctuations. (A more detailed discussion of these effects was presented by Bresnock.⁷⁸⁾

Since the factor (gI_p) is known to scale in some fashion with V_{acc} , one may look for a factor α , such that

$$(gI_p) \sim V_{acc}^\alpha, \quad (5-2)$$

where α is a parameter that can, in principle, be measured. Bresnock measured α by use of the Faraday cup, but because of the inaccuracies involved in that measurement, no definite value for α was determined. In this work measured values for α from the Faraday cup were approximately 0.5. However, the measured value for α was not used. Instead, $nf(T_e)$ measurements were extended to the upper half plane of the plasma cross section, and the value for α was then chosen to ensure up-down symmetry in the measurement. By means of this assumption of up-down symmetry, the difficulties associated with the Faraday cup could be avoided. Typical values for α chosen in this way are in the range 0-0.5, close to the measured values. This technique is capable of representing the gradients in the $nf(T_e)$ profile, which are relatively insensitive to choice of α . No attempt has been made to measure the electron temperature profile, which is sensitive to α .

To illustrate the technique, a pair of examples of the total secondary current I_{2+} collected at the detector as V_{acc} were varied along the zero sweep line as shown in Fig. 5-1. These are scans for a typical T-mode plasma (with a potential well of about 150 V in this case) and a typical C-mode plasma (with no potential well). Some differences can immediately be seen in the shapes of the two profiles. These differences are the results of differences in the profile of either the electron temperature or the electron density, or both.

Now the corrections to the data can be made. Figure 5-2 shows the shape of a typical $nf(T_e)$ profile after corrections have been made for sampling length variations and cross section scaling, with the profile displayed in terms of radius (distance from the center of the vacuum chamber). Negative radius represents those points below the horizontal axis. The current I_{2+} has been assumed to follow the scaling:

$$I_{2+} \sim n_e f(T_e) \ell V_{acc}^{\alpha} .$$

For no gun-emission scaling correction ($\alpha = 0$), the resulting profile (solid curve) is somewhat skewed toward the upper half of the scan. If, on the other hand, a correction $\alpha = 0.5$ is applied (dashed curve), the profile is skewed toward the lower half of the scan. We see that the best choice of α , in order to achieve up-down symmetry, lies somewhere between these two extremes. At the same time, it is clear that the choice of α does not affect the overall indicated scale lengths in the $nf(T_e)$ profiles, only the up-down skewness of the profiles. Since there is no reason to expect a large up-down asymmetry in the plasma, the chosen α can be expected to yield measured $nf(T_e)$ profiles which closely resemble the actual plasma $nf(T_e)$.

Figure 5-3 once again shows the study of typical T- and C-mode profiles of Fig. 5-1 now corrected, assuming up-down symmetry, and normalized to the peak value of $nf(T_e)$. In this case, which is typical of these modes, we see that the relative profile has changed between

the C-mode and the T-mode. The $nf(T_e)$ in the T-mode is concentrated in the center, with a steep gradient at $r \approx 12$ cm, whereas the $nf(T_e)$ in the C-mode is spread more uniformly throughout the cross section of the vacuum chamber.

This change in the $nf(T_e)$ profile is consistent with the idea that, in passing from C-mode to T-mode conditions, the hot electron ring forms at the second harmonic resonance surface for 18 GHz ($r \approx 12$ cm), and the ring in some way contains the core plasma. Outside the central region there is a rapid falloff of $nf(T_e)$ through the hot electron ring, whereas the radial electric field is small in this region. This falloff in $nf(T_e)$ may be due to the loss of stable confinement outside the hot electron ring. The gradient may be in either electron temperature or density, or in both. In any case, because of the presence of the hot electron ring and the radial electric field, it is not surprising that the $nf(T_e)$ profile is more complicated in the T-mode than in the C-mode.

A similar set of comparisons of $nf(T_e)$ profiles is shown in Fig. 5-4. With the microwave power and background neutral pressure fixed, the current in the toroidal magnetic field coils was reduced from its usual value of 4000-5000 A. (The toroidal magnetic field is approximately 1 G/A peak in the midplane; i.e., a 5000-A field current corresponds to a 5000-G peak field in the midplane.) These are plots of the $nf(T_e)$ profile along the single canted vertical path for the toroidal field currents shown. As the magnetic field strength increases, the resonant surface for 18 GHz (3.2 kG) should move

out. These plots show that the $nf(T_e)$ profile did grow larger as expected, indicating that the warm plasma grew with the expanding resonant surface. The observed changes in the shape of the $nf(T_e)$ profile matched corresponding changes in the $\langle n_e \ell \rangle$ measurement from the microwave interferometer. Although only a single chord has been measured, major shifts in the plasma $nf(T_e)$ away from the measured chord can probably be ruled out because no such shifts appeared in the measured potentials (see Sect. 6). It should be pointed out, however, that the constructed $nf(T_e)$ profiles depend on an assumption of up-down symmetry.

The corresponding space potential profiles along the same path are shown in Fig. 5-5. As the changing magnetic field modified the heating geometry, the potential distribution was also modified. The most striking feature here is the shift of the peak potentials with changing magnetic field. These peaks, both top and bottom, fall close to the radii where the $nf(T_e)$ gradient is steepest and where the resonant surface is expected to be. Hence, changes in potential structure closely correspond to changes in the $nf(T_e)$ profile. The variations in the potential structure under these conditions will be discussed in more detail in Sect. 6.

6. STUDY OF POTENTIAL SCALING

6.1 SCALING WITH PRESSURE

The neutral pressure is an important variable in EBT because it is related to the neutral density n_0 in the core. From the neutral density the particle replacement time may be determined; in steady state this is also the particle confinement time³⁹

$$\tau_p = \frac{1}{n_0 \langle \sigma v \rangle} \quad (6-1)$$

Here, $\langle \sigma v \rangle$ is the rate coefficient for ionization of neutrals. Since the neutral pressure is measured at the vacuum wall, it does not perfectly reflect the core neutral density. However, as long as the core neutral density drops when the neutral pressure is reduced, plasma confinement can be expected to improve. With improved confinement, increased electron temperatures would also be expected, and higher temperature plasma should be capable of supporting higher potentials. How do the expected changes in plasma confinement show up in the space potential?

First, it is necessary to define a "well depth" as a measure of the potential structure in the core plasma. Since the edge of the potential well is not azimuthally symmetric, there are many possible definitions for the well depth. Here, the well depth is taken as the difference between the average potential at the two points on the rim of the well where it is swept by the zero sweep scan (approximately $x =$

7 cm, $y = -12$ cm, and $x = 0$, $y = 13$ cm) and the potential at the bottom of the well. This definition is generally used except in those cases in which the $nf(T_e)$ measurement is also made. When the $nf(T_e)$ measurement is made, the analyzer is never rotated, and the lowest potential on the zero sweep scan ($x = -1$, $y = 0$) is used in place of the potential at the well bottom. This approach gives a well depth 0-10% smaller than that calculated by the first method.

The scaling of the potential with pressure is illustrated in Figs. 6-1, 6-2, and 6-3 for three different microwave power levels. The peak potential plotted in these figures is the highest absolute potential observed on the zero sweep scan. The $nf(T_e)$ at center is a measure of the relative total detected signal (from $x = -1$, $y = 0$) with the ion source heater voltage (and hence the ion beam current) held constant. A check of source output showed little change in output over the duration of each set of data. In each case the global field error correction coils were set to minimize the potential in the center.

In general, the observed well depth increased as the background pressure was reduced for all three power cases. The data for 20-kW and 50-kW power input were taken on a different day from the 40-kW case; hence, differences in machine cleanliness may explain slight differences in these plots. In any case, the potentials scaled with power input, but the scaling was not strong. The observed increase in well depth as the neutral pressure was reduced was consistent with the expected increase in confinement time and electron temperature.

The peak potential in all three cases tended to remain constant with respect to pressure except at the T-M transition (which occurs at the low-pressure end of the T-mode). At the T-M transition, the potential was observed to rise everywhere in the core plasma. This rise was difficult to observe because of the instability of the T-M transition, but it can be clearly seen in Fig. 6-2. Such a rise in potential may be an indication of some processes taking place on the surface in the T-M transition, since the electric field increased in the surface plasma rather than in the core plasma.

The $nf(T_e)$ signal at the center (also depicted here) showed little variation throughout the T-mode. Since $f(T_e)$ (cross section) is nearly flat for EBT T_e 's, assuming the changes in plasma conditions do not significantly change the primary beam profile, this may be interpreted as an indication of little change in the core plasma density as the pressure varied in the T-mode. This scaling disagrees with the microwave interferometer, which shows a sharp drop in $\langle n_e \rangle$ at the T-M transition.⁸⁴ The C-mode data point (12×10^{-6} torr) in Fig. 6-2 is also interesting. Here, $nf(T_e)$ is lower than $nf(T_e)$ for the T-mode. This difference supports the expectation that the core electron temperature is significantly lower in the C-mode than in the T-mode. Horizontal shifts in the plasma $nf(T_e)$, which would distort the measured $nf(T_e)$ scaling, are possible but unlikely in the T-mode because the observed change in the position of the potential well bottom is small (see below).

The results of a similar study of the scaling of the potential well in the T-mode for a given power (40 kW at 18 GHz) are shown in Fig. 6-4. In this case the microwave interferometer $\langle n_e \ell \rangle$ signal was used to determine the integrated line density. The line density measured in this way tends to drop as the background pressure drops. However, it may not be indicative of the core density because of changes in the surface plasma. In Fig. 6-4 the well depth $\Delta\phi_{sp}$ and the inward shift of the well bottom are plotted as functions of the line density $\langle n_e \ell \rangle$. In the experiment an increase in the well depth $\Delta\phi_{sp}$ was observed as the line density dropped, but little change was observed in the inward shift x of the well bottom.

Some measurements have been made of the potential structure under EBT-S conditions (28-GHz resonance heating and 7250-A toroidal field current). Since B^2 has doubled in the scale-up from EBT-I to EBT-S, the required voltages and, hence, the inherent errors in the measurement also have doubled. However, from these measurements, it was clear that EBT-S had a potential structure closely resembling that of EBT-I with well depth, peak potential, and position of well bottom similar to those of EBT-I, given the same power input. Since EBT-S can operate at lower pressures than EBT-I, the well depth correspondingly reached higher values than are possible on EBT-I. A well depth of as much as 500 V has been observed on EBT-S. Not enough EBT-S information exists yet to do systematic parameter studies of the type shown in Figs. 6-1 through 6-4.

6.2 DEPENDENCE ON HEATING GEOMETRY

It is possible to change the microwave heating geometry in either of two different ways: by changing the mix of 18-GHz and 10.6-GHz power supplied to the plasma or by changing the toroidal magnetic field (which moves the electron cyclotron resonance surfaces). Observations of changes in the potential structure as the heating geometry changes are discussed below.

6.2.1 Profile Heating

Scaling experiments discussed so far in this section have only considered the use of 18-GHz resonance heating. When 10.6-GHz profile heating is applied to the plasma, the plasma behaves in a somewhat different manner. In particular, the integrated line density $\langle n_e \ell \rangle$ from the microwave interferometer increases,⁸⁴ and the core electron temperature probably decreases slightly.⁸⁷ Ion beam probe observations correspondingly have shown an increase in the core $nf(T_e)$ and, at the same time, a substantial reduction in the potential well depth. A typical case involves an experiment in which 10 kW of 10.6-GHz power was added to 42 kW of 18-GHz power for a plasma at fixed pressure of 6.2×10^{-6} torr. This was in the mid-T-mode, and the error fields were set for no toroidal current. The results were as follows.

Power (kW at 18 GHz/kW at 10.6 GHz)	Relative $nf(T_e)$ at center	$\Delta\phi_{sp}$	ϕ_{peak}	$\Delta\phi_{sp} + \phi_{peak}$
42/0	1.00	205 V	90 V	295 V
42/10	1.35	130 V	130 V	260 V

The drop in $\Delta\phi_{sp}$ as the 10.6-GHz power was applied is not completely understood. From the point of view of electron confinement, since the neutral pressure was held constant, the radial electron diffusion

$$\Gamma_e \cong n_e \mu_e \frac{\partial \phi}{\partial r},$$

should also have remained approximately constant. The observed reduction in the radial potential gradient could then reflect an increase in $n_e D_{ne}/T_e$. However, it is not yet clear how to interpret this observation. It may also be worthwhile to note that when 10.6-GHz power was applied, the well depth and the peak potential varied in such a way that their sum $\Delta\phi + \phi_{peak}$ remained more nearly constant than either of these two quantities individually.

6.2.2 Changing Toroidal Magnetic Field

Another way to change the heating geometry is to move the resonant surfaces by changing the toroidal magnetic field. The results of a set of experiments in which the position of the rim of the potential well along the zero sweep scan was recorded for different magnetic fields in the T-mode are illustrated in Fig. 6-5. In this figure, both the observed radial position of the rim of the potential well and the expected second harmonic resonance surface $\omega = 2\Omega_{ce}$ are plotted as a

function of toroidal field current. The error bars represent the spread in data observed at 5000 A over a large number of T-mode conditions. The observation is that the rim of the potential well followed, but remained slightly inside of, the expected vacuum magnetic field resonance surface.

The results of a related experiment are illustrated in Fig. 6-6. The microwave power input (40 kW at 18 GHz) and the neutral pressure (6.2×10^{-6} torr, which gives a modest T-mode for this power level) were kept constant. There was no net toroidal current. In this figure, the measured potentials at a number of discrete points along the horizontal line $y = 0$ are plotted for each of four toroidal magnetic field cases. The expected positions of the hot electron rings are indicated by the local hatched regions. In each case the potential structure expanded (in a manner similar to that shown in Fig. 5-5) as the magnetic field increased. The expansion of the potential structure was azimuthally symmetric, since it was observed to be similar to other scans through the plasma.

A number of comments can be made about how the potential structure changed in the experiment. Some of these are summarized in Fig. 6-7. In this figure, the difference between the inner peak potential and the well bottom potential, the absolute potential at the inner peak, the approximate width ℓ of the potential well, and the microwave interferometer integrated line density $\langle n_e \ell \rangle$ are plotted as a function of toroidal field current. In the experiment, well depth increased as the magnetic field increased (from 90 V to 300 V), whereas

the peak potential dropped as the magnetic field increased (from 240 V to 65 V). At the same time, the width of the potential structure ℓ and the integrated line density $\langle n_e \ell \rangle$ scaled together, which may imply that the core electron density remained constant.

Although the well depth and peak potential varied dramatically as the magnetic field changed, the sum of these two quantities remained nearly constant. This is reminiscent of the behavior of the potential structure when 10.6-GHz profile heating was added (while keeping neutral pressure constant).

Finally, one may consider in detail the scaling of the most significant parameter in the neoclassical theory, the radial electric field. Figure 6-6 is replotted in Fig. 6-8 with a parabolic fit to the potential structure in the core plasma superimposed on the data. All the potential profiles fit the same curve, which can be described as

$$\phi = 2.9(x - x_0)^2 + \phi(x_0) , \quad (6-2)$$

where x_0 is somewhere in the range -4 to -2 cm. Insofar as the magnetic field is constant (with respect to position), a potential profile of this form represents a rigidly rotating plasma; i.e., Ω_{ExB} is independent of radius over a small region in the core. It is possible to compare the scaling with that of neoclassical theory. Under the assumption that electron diffusion is dominated by the radial electric field, neoclassical diffusion gives

$$\Gamma_e \cong K \left(\frac{n_e}{T_e} \right) \left(\frac{\partial \phi}{\partial r} \right) \left(\frac{v_{Te}}{\Omega_e} \right)^2 \frac{\Omega_e^2}{v_e^2 + \Omega_e^2} v_e . \quad 6-3$$

Since little variation was observed in the global particle replacement time,⁸⁸ the radial diffusion flux Γ_e should have remained constant. Kovrizhnykh¹³ gives a value for K of $1/24$ in the large electric field limit [Eq. (2-4)]. Spong, Harris, and Hedrick²¹ show that K is a strong function of electric field, which increases rapidly as $e\phi/kT_e$ is reduced. In this experiment, the electric field did not change, so K can be considered approximately constant. The scaling of Eq. (6-3) depends on n_e , T_e , ϕ , and the collisionality, v/Ω . Some of this information is available. Equating the distance between potential peaks ℓ and the implied plasma length in the integrated line density $\langle n_e \ell \rangle$ of Fig. 6-7 gives an estimate of average electron density $n_e \cong 5 \times 10^{11} \text{ cm}^{-3}$ for this modest plasma. Using the measured potential profile in the central plasma region and the expressions for collision frequency given by Jaeger and Hedrick,¹⁹ a calculation of the scaling of the neoclassical radial diffusion Γ_e can then be done. Assuming the electron temperature remains constant, this calculation shows a predicted variation of only $\pm 11\%$ in Γ_e over the range 4000 to 5500 G for a constant electron temperature of even as little as 70 eV, which is lower than both typical soft x-ray⁸⁷ and typical Thomson scattering⁸⁹ results. Such a variation is less than the accuracy of the radial electric field measurement — a higher electron temperature

would correspondingly show even less variation over the observed range in magnetic field. Due to uncertainties in plasma parameters and the narrow range of magnetic fields there is insufficient information to completely compare the experiment with neoclassical predictions. Still, the experiment seems to scale in a manner consistent with that predicted by electron neoclassical confinement.

7. STUDY OF THE EFFECTS OF REMOVING MICROWAVE POWER TO THE BEAM PROBE'S CAVITY

An important part of the operation of EBT is the stabilization of the core plasma provided by the hot electron rings. These rings have an electron temperature of about 150 keV in EBT-I.⁴⁰ As noted in Sect. 3 (and shown in Fig. 3-4), the heavy-ion beam probe reaction products Cs^{2+} and Cs^{3+} are sensitive to these electrons, even at a temperature of 150 keV. Of particular interest is the fact that the Cs^{3+} cross section on the hot electrons is approximately the same as the Cs^{3+} cross section on the cold surface plasma electrons. Since the hot electron ring is immersed in just this cold surface plasma, the beam probe should be sensitive to the hot electrons.

It is possible to turn off the 18-GHz microwave power to a given mirror section without affecting the power input to any of the other sections. When this is done, perpendicular energy measurements show that the energy contained in the cavity drops substantially. At the same time, gross stability of the toroidal plasma is not affected, presumably due to the continued presence of the other 23 of 24 electron rings. Since continuity of the electron temperature and density of the toroidally circulating plasma should be maintained along field lines, any substantial change observed in the beam probe signal when power is removed from the cavity may be interpreted as due to the loss of locally heated electrons.

The beam probe measurement described in this section has been taken only along a single chord through the plasma, with 18-GHz power applied, and at a single toroidal magnetic field value (corresponding to 5000-A toroidal field current).

Figure 7-1 shows data taken during a zero sweep scan from 4 kV to 16 kV which was monitoring the Cs^{3+} I_{sum} and ϕ_{sp} signals. Low accelerating voltages correspond to the lower edge of the plasma; high accelerating voltages approach the center of the plasma. (The sharp localized jump in the space potential comparator output at $V_{\text{acc}} = 12.8$ kV is due to noise on the feedback loop and is not plasma related.) Each scan was taken twice to ensure repeatability of the data, both with power to the cavity (E-6) and without power to the cavity. When power was removed from the cavity the $W_{\perp}$ signal on the diamagnetic loop⁹⁰ was observed to drop to about 37% of its previous value in this case. Such a level is comparable to that signal expected only from the rings in the adjacent cavities;⁹⁰ hence, little perpendicular energy remained in cavity E-6.

Two observations can be made about the effect of this experiment on the beam probe signals. First, the space potential profile showed little change (≤ 10 V) when the power to E-6 was turned off. This supports the continuity assumption, that is, that the potential is not directly due to local heating but instead is determined from continuity of the potential along field lines. This result does not necessarily mean that the potential is constant along field lines; rather, it means that it is a global effect of the bumpy torus. The second observation is

twofold: over most of the plasma cross section, the total detected Cs^{3+} signal dropped slightly (about 10%) when power to E-6 was turned off. The Cs^{2+} signal (not shown) showed a similar drop in this case. This drop is interpreted as a small drop in background plasma density, similar to the small (1/24) drop in microwave power to the plasma. However, in a small range from 6 to 8 kV, the Cs^{3+} signal shows a larger (20-50%) drop localized in this region ($r \approx 12-15$ cm). This reduction in signal level was also observed at the upper edge of the plasma. Because Cs^{3+} is more sensitive to hot electrons than Cs^{2+} , the fact that a larger drop was observed on Cs^{3+} than on Cs^{2+} indicates the presence of a localized halo of hot electrons, which are hotter than the background electrons in this region and directly dependent on microwave power in the cavity.

Figure 7-2 plots the space potential profile (from Cs^{2+}) and the relative halo intensity in the Cs^{3+} signal:

$$\text{relative halo intensity} = \frac{I_{3+}(\text{E-6 on}) - I_{3+}(\text{E-6 off})}{I_{3+}(\text{E-6 off})},$$

with the approximately 10% overall background drop subtracted. The expected position of the hot electron ring in the vacuum magnetic field (18-GHz second harmonic resonance surface) is indicated by the hatched vertical line at $r = 12.2$ cm. The rim of the space potential well falls slightly inside the radius of the expected resonance, while at the same time the peak of the relative halo intensity falls slightly

outside that radius. No correction has been made for any distortion in the apparent position of the halo due to a possible electron temperature gradient in the background plasma.

The results of a calculation which may correct for this apparent distortion are shown in Fig. 7-3. A small but detectable difference was also observed on the Cs^{2+} signal profile when the local microwave heating was removed. Comparison of the measured halo profiles from Cs^{2+} and Cs^{3+} allows the correction of the relative halo profile, given an assumed background temperature profile. In Fig. 7-3, the circles come from the Cs^{3+} signal and the squares from the Cs^{2+} signal. Insofar as these two profiles match, a self-consistent background electron temperature profile has been generated. No attempt has been made to obtain better agreement between the two profiles because of the large inaccuracies inherent in the Cs^{2+} data and in the Cs^{3+} cross sections. Nevertheless, this measurement points to a steep electron temperature gradient through the ring region.

Figure 7-3, then, shows a plot of the relative halo density with respect to the background electron density for an assumed background electron temperature as shown. Under these assumptions, the halo falls directly on the expected resonance surface with a radial width of about 3 cm. Finally, although the beam probe itself is not directly sensitive to the temperature of the hot halo electrons, use of the x-ray temperature of the hot electron ring of $T_e = 150$ keV can be made to estimate the halo electron density. For the assumed background temperature and a reasonable guess for the electron density profile

$n_e(\text{peak}) = 1 \times 10^{12} \text{ cm}^{-3}$ [hence $n_e(\text{at ring}) \cong 1/2 n_e(\text{peak}) = 5 \times 10^{11} \text{ cm}^{-3}$
 from the measured $nf(T_e)$ profile], the halo electron density becomes
 $n_h \cong 1/2 n_e(\text{at ring}) = 2.5 \times 10^{11} \text{ cm}^{-3}$, which is similar to the hard
 x-ray $n_r \cong 2 \times 10^{11} \text{ cm}^{-3}$.⁹¹

8. DISCUSSION

This paper has investigated the confinement properties of EBT by employing the spatially resolved measurements of the plasma space potential ϕ_{sp} and of the density-cross section product $nf(T_e)$. For example, a substantial qualitative shift in the plasma properties between the C-mode and the T-mode is seen in the study of the $nf(T_e)$ profiles of Sect. 5 together with the T-mode and C-mode potential profiles of Sect. 4. This shift can be interpreted in terms of a simple plasma model.

In the C-mode there is little radial electric field. Neglecting any temperature gradients, the radial particle diffusion Eq. (2-3) for both species is then simply:

$$\Gamma_r \cong -D_n \nabla_r n = -D_n \frac{\partial n}{\partial r} . \quad (8-1)$$

The source $S = n_e n_o \langle \sigma v \rangle$ of plasma particles from ionization of neutrals is roughly constant throughout the core plasma.^{92,93} In steady state, S is equal to the divergence of the particle flow Γ :

$$\nabla \cdot \partial = S . \quad (8-2)$$

Given this information, a density profile can be obtained. In cylindrical coordinates a solution of Eqs. (8-1) and (8-2), assuming D_n constant, is simply a parabola,

$$n(r) \cong \frac{S}{4D_n} (r_o^2 - r^2) , \quad (8-3)$$

where r_o is the vacuum wall, at which the plasma density must be zero, $n(r_o) = 0$. Comparison of the shape of the measured profile of $nf(T_e)$ in Fig. 5-3 with the parabolic profile of $n(r)$ in Eq. (8-3) shows good agreement. This agreement suggests that the radial diffusion in the C-mode is linked to the radial density gradient, with little contribution from a radial electric field or the hot electron ring.

On the other hand, in the T-mode, the radial electric field and the hot electron ring are both present. Hence, the simple diffusion model for the C-mode no longer holds. In particular, the profile of $nf(T_e)$ is more nearly flat in the central plasma region, so that, if this can be interpreted as flat n_e and T_e profiles, the radial diffusion comes about from some other term. For the electrons, the dominant term may be from the potential gradient, $\frac{\partial \phi}{\partial r}$:

$$\partial_r \cong n_e \mu_e \nabla_r \phi = n_e \mu_e \frac{\partial \phi}{\partial r} . \quad (8-4)$$

In this case, again under simplifying assumptions of n_e , T_e , and D_n roughly constant in the core, a uniform source function S leads to a parabolic potential profile, as observed in the T-mode. Some consequences of this were discussed in more detail in Sect. 6. The observed shift in ϕ_{sp} and $nf(T_e)$ profiles upon entering the T-mode supports the theoretical expectation of diffusion controlled by a radial electric field, as discussed in Sect. 2.

Ion confinement in the T-mode is apparently not as simply related to the electric field, since the negative electric field should draw ions inward. Of the high energy ions which are sufficiently energetic to diffuse out against the electric field, those ions at the resonance $\Omega_{ExB} = \Omega_{VB}$ may dominate radial ion losses, although at the high energies at which the resonance occurs (see Sect. 4) only a small fraction of the ion population remains. And, although the calculation of the ion resonance (see Sect. 4) was done only for the midplane, these are the same ions seen by the charge exchange ion diagnostic.

Measurements have only been made through the midplane between two mirror coils. Although it is clear that the potential is continuous along a field line (from the continuity experiment of Sect. 7), it is not necessarily the same everywhere along the field line. Still, on those field lines which do not intersect the wall, one would not expect a large axial potential drop since this would impede the free flow of charged particles along field lines. Thus, the potential well structure should also appear in the throat.

Another point of interest is that of fluctuations in the space potential. The beam probe, as noted in Sect. 3, is set up to measure dc potential and is not very sensitive to fluctuating potentials. Hence, although no evidence for large potential fluctuations exists, they cannot yet be ruled out. The presence of any large potential fluctuations would not affect the measured dc potentials, but it could affect particle transport.

In general, the measurements described in this work show the existence of a spatially localized ring of hot electrons, inside which exists a warm core plasma with a shallow $n_f(T_e)$ gradient. A large ambipolar electric field is set up by the core plasma, and in view of the difference in potential profile between the C-mode and the T-mode, this field seems to be related to plasma transport processes. The electric field in the T-mode is azimuthally symmetric in the core, but the symmetry is lost farther from the center of the plasma.

9. CONCLUSIONS AND SUGGESTIONS

FOR FUTURE WORK

9.1. CONCLUSIONS

The space potential measurement has been shown to be reliable, with an uncertainty in the measurement of about 10% of the measured potentials. The measurements have shown the existence of a deep potential well in the core plasma, large enough to be a significant factor in plasma confinement, and local asymmetries in the potential structure outside the core plasma.

During the account of the origin of the Cs^{2+} signal in the plasma, the profile of $nf(T_e)$ has been constructed. In this way, variations in the structure of $nf(T_e)$ have been observed. In particular, the profiles in the C-mode were observed to be wider than in the T-mode, and the profile of $nf(T_e)$ was observed to vary as expected when the resonant heating surface was moved.

Scaling studies of the potential structure have shown that the potentials in EBT-S are similar to or larger than the potentials in EBT-I for the same power level. Scaling with pressure in EBT-I has been documented. The increase in the radial electric field as the neutral pressure is lowered is consistent with the expected improvement in plasma confinement.

The effects on the potential of changing the heating geometry have been investigated. The addition of 10.6-GHz profile heating to an 18-GHz plasma reduces the radial electric field. On the other hand, moving the resonance surfaces while keeping both neutral pressure and

microwave power constant dramatically changes the well depth and peak potential but does not greatly change the radial electric field. In general, the parameter which remains most constant when changing the heating geometry is the sum of the well depth and the peak potential.

Observations of Cs^{3+} signals with and without 18-GHz microwave power input to the beam probe cavity show a sensitivity to the local hot electron component. Measurements of this component show that it is spatially localized near the 18-GHz second harmonic resonance surface and is consistent with the hot electron ring observed with the x-ray diagnostic.

9.2 SUGGESTIONS FOR FUTURE WORK

Future work that can be done with the heavy-ion beam probe falls under two categories: improvements to the diagnostic system and experiments to be performed on EBT. Many avenues of work remain in both areas.

The components of the beam probe system have enabled a wide range of measurements of both ϕ_{sp} and $nf(T_e)$. However, a number of improvements can be made. The ion gun, for example, produces a 1-cm-diam, 10- μA ion beam. For more sophisticated measurements, such as a T_e measurement from the $3^+/2^+$ ratio and a beta measurement, beam quality must be improved. In particular, improvements can be made to prevent the backstreaming of electrons in the gun electrodes and to shorten the length of the focusing lens to better match the focal length of the Pierce structure.

An improved analyzer will soon be installed. This analyzer has an externally adjustable entrance slit width and a provision for the focusing adjustment to be made at the detector plates rather than at the entrance slit. The front-end amplifiers are of an improved design and are installed inside the analyzer in order to shorten the length of the signal leads.

Work is currently under way to automate both the data acquisition and system control. A computer controlled beam probe will be able to take data much more efficiently than the current system.

At present, the complete three-dimensional ion beam orbits are not well known. Orbits should be calculated to determine these trajectories. Before these are known it will be difficult to predict the behavior of a misaligned beam probe.

The study of fluctuations in the ion beam probe is very important, but little work has yet been done in this area. The first area to investigate is the large primary fluctuation. One approach to this problem is to investigate the effective average beam attenuation caused by the fluctuations. The fluctuation of beams across the entrance slit causes an effective average signal attenuation by a factor of 2-4, quite a bit larger than that expected only from beam ionization. This should be a relatively sensitive measure of the total amount of beam fluctuation amplitude. Another area of study involves watching the fluctuations over a wide band and monitoring the phase differences among the four detector plates to confirm in which direction the beam is fluctuating.

The halo study described in Sect. 7 is little more than a demonstration of the capabilities of the technique. Elaborations on the method of Sect. 7 involve looking at different positions (Is the halo azimuthally symmetric?) and changing the toroidal field current (Does the halo move as expected?). This study also affords the opportunity to make a measurement of the background electron temperature profile through the halo. To do this, better statistics will be needed, which may be obtained by pulsing the microwave power to the cavity, for example.

A number of comparisons can be done between the potential measurement and the results of other diagnostics. For example, does the well depth scale with the tail ion distribution or the electron temperature and density? More generally, how can the potential structure, which is actually quite complicated, be described most usefully in scaling studies; i.e., to which part of the potential structure should a yardstick be applied? Finally, what is the significance of the sum $\Delta\phi + \phi_{\text{peak}}$, which remains remarkably constant when the heating geometry is modified?

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APPENDIX A

MEASUREMENTS OF PLASMA PARAMETERS IN EBT-I

The schematic layout of EBT is shown in Fig. A-1. EBT operates with a steady-state plasma in a bumpy magnetic field produced by 24 toroidally connected mirrors. Some of the physical parameters of EBT-I are listed in Table A-1.⁴⁰ The upgrade to EBT-S involves increasing the magnetic field to 0.725 T in the midplane (1.45 T in the throat) and adding microwave heating at 28 GHz.

Currently, the diagnostics on EBT include a microwave interferometer for line density measurement, Thomson scattering for electron temperature and density measurement, charge exchange for ion temperature measurement, x-ray diagnostics for electron temperature measurement, spectroscopy for neutral and impurity measurement, and the heavy-ion beam probe.

Table A-1. Physical dimensions and operational parameters of EBT-I

Machine parameters		
Major radius		150 cm
Mean coil radius		18.8 cm
Aspect ratio		9
Magnetic field (midplane, mirror)		0.5 T, 1.0 T
Microwave power (cw)		
Bulk heating		60 kW 18 GHz
Profile heating		30 kW 10.6 GHz
Plasma parameters		
	<u>Toroidal plasma</u>	<u>Hot electron annulus</u>
n	$0.5-2 \times 10^{12} \text{ cm}^{-3}$	$1-4 \times 10^{11} \text{ cm}^{-3}$
T_e	150-600 eV	100-200 keV
T_i	30-150 eV	
β_{max}	0.2-0.6%	10-40%

APPENDIX B

Elmo Bumpy Torus heavy ion probe

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A diagnostic system based on the heavy ion beam probe technique has been developed for the Elmo Bumpy Torus. A variety of singly charged alkali metal ions have been used in the probing beam; detection of multiply charged reaction products allows a continuous spatially resolved monitor of the plasma space potential. Typical spatial resolution is 1 cm^{-3} ; time resolution is on the order of 1 s. The potential measurement is direct and properly referenced to the plasma ground. An investigation into possible sources of error in the measurement points to the conclusion that the uncertainty is an order of magnitude less than the experimentally measured potentials.

INTRODUCTION

The space potential is an important parameter in understanding the particle confinement and overall stability of hot, magnetically confined plasmas. The conventional floating potential measurement utilizing a solid material probe, which provides only an indirect indication of plasma potential, is incompatible with high plasma energy density. A direct, nonperturbing method to determine the space potential using an energetic heavy ion beam has been developed in recent years which can surmount these difficulties.¹⁻³ This technique, which is particularly well suited for space potential measurements, has been used to map the two-dimensional potential profiles of the Elmo Bumpy Torus (EBT) device at ORNL, the results of which are reported elsewhere.⁴

In this paper, we describe the heavy ion beam diagnostic system on EBT with particular attention given to the problems presented by the unique measurement environment of EBT and the solutions which were found to these problems. In Sec. I we describe the concept of heavy ion beam probing. The system is described in detail in Sec. II, and its performance is evaluated in Sec. III.

I. HEAVY ION BEAM PROBING TECHNIQUE

The heavy ion beam probe diagnostic is one of a variety of high temperature plasma probing techniques utilizing ion or neutral beams that have been developed in recent years. The particles interact with the plasma and produce charged reaction products, or in some cases, light.⁵ The technique described here is based on the detection of multiply charged ions created by impact ionization when an energetic beam of singly charged ions is injected into a magnetically confined plasma. A fraction of the beam ions undergo ionizing collisions to produce ions of higher charge states (I^{n+1}) which are separated from the primary (I^{+1}) ions by the confining magnetic field. By proper location of an apertured

detector outside the B field, it is possible to collect the current produced by a particular charge species that originates in a small volume of the primary beam. The amount of I^{n+1} signal (usually $n = 1$) from a particular volume element of the beam is proportional to the effective cross section for the dominant ionization process. The dominant mechanism for ionization in the present operating regime is electron impact; the signal is thus also proportional to electron density.

The energy of the secondary ions leaving the plasma exceeds that of the primary ions by an amount equal to $ne\phi_{sp}$, where ϕ_{sp} is the space potential at the point of ionization. Since electron impact produces negligible momentum transfer, the trajectories of both the I^{+1} and I^{n+1} ions can be determined from the magnetic field structure. The use of the heavy ion beam to obtain accurate measurements of electron density and temperature requires an accounting of all of the beam ions, measured values of absolute cross sections and the assumption of a Maxwellian velocity distribution.⁶ It has not yet been possible to satisfy these requirements with sufficient confidence on EBT. This is not the case with the space potential measurement because it is direct and model independent. If the primary ion energy is eV_G then the secondary ion energy is

$$W_n = ne\phi_{sp} + eV_G \quad (1)$$

and a measurement of the energy difference of primary and secondary ions is a direct measurement of the space potential at a point whose location can be accurately determined by knowledge of the confining magnetic field. The size of the sample volume, i.e., the element of I^{+1} beam from which the I^{n+1} ions originate, sets the limits on spatial resolution. Generally, any point in the cross-sectional plane of the plasma can be sampled in this manner if the density and temperature are sufficient to produce measurable ion current. The intensity of the ion beam necessary to obtain detectable signal is suf-

FIG. 1. EBT magnetic field configuration showing the location of the microwave heated hot electron rings.

ficiently small (tens of microamps) to not perturb the plasma.

II. SYSTEM DESCRIPTION

The design of a heavy ion beam probe diagnostic system requires the specification of the ion species, the range of beam energies, and the physical arrangement of the components. Although most constraints are common to all applications, the unique characteristics of each device (e.g., vacuum access, electron density and temperature, and magnetic field geometry) require that this diagnostic be tailor-made. Figure 1 shows the magnetic field configuration; local depressions due to elec-

FIG. 2. Heavy ion beam probe system hardware with typical primary/secondary ion trajectories.

tron cyclotron resonance heating produced hot electron annuli modify the field in a manner that has been characterized only qualitatively. The ϕ_{sp} measurement is made at the midplane between magnetic coils. Additional information on this plasma device may be found elsewhere.^{7,8}

The configuration of hardware shown in Fig. 2 permits measurements to be made in the entire plasma cross section at the midplane between two magnet coils. The initial beam energies and injection angles required to sample particular locations in the plasma cross section are shown in Fig. 3. This information can be scaled for other ions or magnetic fields by noting that the accelerator voltage required to hold constant the local radius of curvature (mv/qB) of the ion trajectories scales as B^2/m_i .

The intensity of the secondary ($n = 1$) ion current is given by

$$I_s = I^{+1} Z n e l \sigma_{eff}, \quad (2)$$

where l is the projection of the detector aperture on the I^{+1} beam and σ_{eff} is the effective cross section for the particular beam energy and electron temperature assuming a Maxwellian distribution. The detector image length l is the nominal sample length of the measurement. The calculated values of l normalized to the size of the aperture are shown for typical parameters in Fig. 4. The expected secondary ion currents at the detector are shown in Table I for several electron temperatures, assuming n_e is $2 \times 10^{12} \text{ cm}^{-3}$.

Ion beams in the range of 5–50 keV, 1–50 μA currents with a beam diameter of approximately 1 cm are produced by the gun structure shown in Fig. 2. The high voltage electrode structure is similar to many commonly used in electron guns; focusing and accelerating structures of this general type are discussed by Pierce.⁹ The ions are extracted by cylindrical Pierce electrodes

FIG. 3. Map of initial conditions in accelerator voltage and injection angle required to measure ϕ_{sp} in the plasma cross section midway between mirror coils using I^{+1} .

from a thermionic ion emitter loaded with an aluminosilicate compound containing the desired alkali metal.^{10,11} The gun chamber is connected to the remainder of the beam line by a mechanical alignment bellows at the bottom of which an aperture is located to cut off stray ions. A Faraday cup is used to measure total current, a wire grid to measure beam width, and a pair of thin wire cross hairs to align the beam. The beam is directed into the plasma by a pair of electrostatic sweep plates. The sweep plates are calibrated using the focusing ladder and Faraday cup primary beam detectors located on the opposite side of the plasma.

The vacuum chamber containing the sweep plates and the detector chamber are shielded from high power microwave fields on EBT by a 3-mm-thick copper screen consisting of a dense honeycomb pattern of 3-mm-diam holes. The microwave fields are attenuated by about 20 dB while 80% of the ions pass through the screen at normal incidence. To ensure maximum transmission of ions the copper is bent into a cylindrical shape in such a way that the beam passes perpendicularly through the screens. It is also necessary to suppress the cold plasma flux in both places with biased wire grids.

A feedback controlled electrostatic energy analyzer^{3,12,13} is used to determine both the abundance and energy of either the primary (I^{+1}) beam or any of the ionization products (I^{n+1}). Such a device is characterized by a geometric gain (A_g) and a voltage error function (VEF). The separation of the planar electrodes in the analyzer is such that it is necessary to apply only about half of the accelerator voltage to obtain an electric field sufficient to measure the energy of the I^{+1} ions; A_g is thus approximately 2. The analyzer produces an accurate determination of the energy as long as the angle at which the ions pass through the aperture is known. The voltage error function is the deviation of the measured beam energy from the actual energy as a function of this entrance angle. The VEF is determined by the choice of analyzer dimensions as defined in Fig. 5. The VEF predicted for a typical choice of dimensions¹⁴ (cf. Fig. 5)

FIG. 4. Locus of points in plasma cross section for which the sample length l is a constant multiple of the analyzer aperture width w .

TABLE 1. Predicted secondary ion current for maximum required beam energy.

Ion	Energy	$I/I_p = 2n_s l r_{0,0}$ (nA per μ A per mm of sample length)		
		$T_e = 40$ eV	$T_e = 100$ eV	$T_e = 400$ eV
K	51.0	0.23	0.39	0.46
Rb	23.6	0.83	1.40	1.43
Cs	15.0	1.54	2.30	2.12
Tl	9.8	2.42	3.91	5.20

shows that the necessity of knowing the entrance angle can be relaxed if some error in energy measurement is acceptable. Errors are on the order of one part in 10^3 with an analyzer designed to have a 10° angular acceptance window. This window is insufficient to map the entire plasma cross section so that the analyzer may be mechanically rotated in a time short compared to plasma changes. It is possible to use an analyzer with a smaller window to obtain correspondingly smaller errors. Moreover, since the VEF is sensitive to analyzer dimensions, the analyzer entrance aperture is remotely adjustable so that the best VEF can be found under operating conditions.

Unlike beam probe systems used on other plasma devices,¹⁻³ the measurements on EBT are made in steady state. However, to eliminate dc offsets and reduce sensitivity to noise, the beam is chopped at 3 kHz and synchronously detected. Beam chopping is achieved by a pair of electrostatic sweep plates which periodically move the beam out of the plane of the detector (cf. Fig. 2).

FIG. 5. Schematic of parallel plate electrostatic energy analyzer and relative measurement error as a function of entrance angle.

The ion energy is determined by finding the analyzer voltage necessary to equalize the currents on two overlapping collector plates. These two currents are fed through current-to-voltage converters to a difference amplifier which produces an error signal for beam centering. The error signal at 3 kHz passes through tuned notch filter amplifiers and is synchronously detected and filtered to give a feedback signal used to control the analyzer voltage. In effect, the difference current on the split detector plates is connected through a high impedance to the top plate of the analyzer.

The abundance of the ions is measured from the sum of the two split plate signals. However, to be interpreted in terms of density or temperature, the signal must be calibrated by a detailed history of the ions as they pass through the entire system. Cross sections, sample lengths, and transmission coefficients must be known in some detail for this measurement to succeed.

The space potential measurement is free of these difficulties and can be found directly with the comparator circuit shown in Fig. 6. In this circuit, the two $10^8\text{-}\Omega$ resistors are matched and voltage stable. The output voltage of the operational amplifier at (C) is given by

$$V = R_{fc} \left[\frac{V_A}{R_A} (1 + n) \frac{R_{fa}}{3R} - \frac{V_G}{R_G} \right], \quad (3)$$

where R_{fa} and R_{fc} are the feedback resistors of the op-amps at (A) and (C), respectively. From Eq. (1) the analyzer voltage is related to the gun voltage by

$$V_A = \frac{V_G + n\phi_{sp}}{(n+1)A_g}, \quad (4)$$

where the energy of the I^{n+1} ion has been replaced by $e(n+1)A_g V_A$. The comparator is calibrated *in situ* by steering the I^{n+1} beam into the analyzer for which $V_A = V_G/A_g$. The comparator circuit should produce zero output voltage in this case because its purpose is to measure the difference between the initial and final energies of the beam. Resistor R_{fa} is adjusted until this

is the case. Then

$$\frac{V_A}{R_A} = \frac{(n+1)R_{fa}}{3R} = \frac{V_G}{R_G} = \frac{A_g V_A}{R_G}. \quad (5)$$

Thus, to measure the space potential with any of the I^{n+1} ions, the analyzer feedback loop is locked in to center the beam, the appropriate resistor (B) is selected and the output of the comparator becomes

$$V = (R_{fc}/R_G)n\phi_{sp}. \quad (6)$$

The comparator output is therefore proportional to the space potential and is referenced to the same ground as seen by the plasma.

III. SYSTEM PERFORMANCE

The raw ϕ_{sp} data (comparator output) produced on the x-y recorder (cf. Fig. 6) requires little reduction if care is taken to adequately control the sources of error. It is only necessary to use the grid map (Fig. 3) and possibly the sweep plate calibration to determine the locus of measured points corresponding to the voltages of the accelerator and sweep plates to obtain ϕ_{sp} vs position in the plasma. Data is taken by varying the accelerator voltage for fixed sweep angle because in this way the variation in analyzer entrance angle is minimized. Figure 7 shows this variation with respect to 30° for the same conditions as Fig. 3. The constant ion energy lines in these figures are identical so that the initial (sweep) angle can be related to the final (analyzer entrance) angle. On the zero degree sweep line the entrance angle window required to cover about three quarters of the plasma is 2° ; it is therefore possible to scan the bulk of a plasma diameter with minimal error. Other constant sweep voltage lines can be scanned but the required entrance angle window increases with sweep angle (cf. Fig. 7). Scans other than the 0° line are either taken by rotating the analyzer when necessary or adjusting the data for the systematic error introduced by analyzer

FIG. 6. Heavy ion beam probe system electronics for measurements of both space potential and total secondary ion current.

FIG. 7. Map of final conditions of I^{+2} trajectory at the aperture of the analyzer in accelerator voltage and entrance angle referenced to 30° .

entrance angles. A measurement of ϕ_{sp} along the zero sweep line for gun voltage from 6–20 kV is shown in the top curve of Fig. 8. A discussion of the characteristics of similar data and their implications for EBT operation are found in Ref. 4. The total secondary ion current collected on both detector plates is shown in the bottom curve. The dominant reason for the decrease in signal as the accelerator voltage is lowered is the corresponding reduction in the total primary current from the ion gun. At the bottom edge of the plasma, both the ion current and plasma density generally decrease faster than the sample length increases; at that point the signal-to-noise ratio is not sufficient to keep the feedback loop locked in.

Errors can occur in the space potential measurement when the basic assumptions inherent in the design of the system are found to be invalid. All of the potential errors are found to be either sufficiently small to be acceptable or can be effectively minimized by careful operating procedures. The energy of the primary ions (I^{+1}), when leaving the plasma, is assumed equal to the product of the charge ($+e$) and the accelerating voltage (V_G). There are two possible mechanisms for producing a variation of ion energy from this value. The first is in the accelerator which must produce ions of energy within an electron volt or two of this energy. The ions from some sources are characterized by a spread in energy that exceeds one electron volt; thermionic emitters do not have this problem so the beam at least reaches the plasma with the proper energy. The beam ions can also be slowed down and spread in velocity by multiple small angle collisions with plasma electrons but calculations show that this effect is negligible.

Beam ion trajectories are calculated from the vacuum magnetic field only. The confining magnetic field of EBT is modified from vacuum conditions by the hot electron annuli which locally depress the value of B . The detailed structure of the modified field has never been measured, so it is not possible to precisely predict the

trajectories of the primary/secondary ions. However, measurements of the primary beam position with and without plasma and at high and low ring beta show only a small sensitivity to this characteristic of the EBT plasma. While the details of the high beta electron rings are unknown, gross properties such as total energy and approximate position have been measured. Grid maps (cf. Fig. 3) that result from assumed model beta profiles also show that there is less error from ignoring beta than the accuracy with which ion energy and injection angle can be determined. The accelerator voltage is measured with a voltage divider to within 1.0%; this translates into a position error of under 1 cm. The injection angle is also subject to a proportional error. The zero sweep line relies totally on the mechanical alignment of the system; it can be determined to within tolerances that are also well under 1 cm. For other injection angles, position accuracy depends upon the calibration of the electrostatic sweep plates. The focusing ladder, primary ion detector, and electrostatic energy analyzer are used both with and without (where possible) the vacuum magnetic field to determine the constant C in the expression

$$\theta \approx \tan \theta = CV_{sw}/V_G, \quad (8)$$

where V_{sw} is the voltage difference between the two plates. This expression is identical in form to that for ideal small angle electrostatic sweep plates. Only the positions of the focusing ladder wires, primary ion detectors, and analyzer entrance slits go into this determination. A check on the calibration can be made by comparing the predicted analyzer entrance angle with that determined for VEF curves taken both with and without plasma; agreement is found to within 1° or 2° . The overall uncertainty in measurement location resulting from the accuracy of ion energy measurement and sweep plate calibration is determined to be generally less than the maximum dimension of the sample volume

FIG. 8. Raw data for typical plasma conditions showing space potential comparator output and abundance signal as functions of accelerator voltage.

FIG. 9. Experimental voltage error functions taken under typical plasma conditions for three different settings of the entrance aperture location and total current collected on both detector plates as the angular position of the analyzer is varied.

which, at its smallest, is given by the beam diameter. For a typical analyzer entrance aperture width (w) of 6 mm, sample lengths are less than 1 cm as long as l/w is less than 1.5. Spatial resolution is therefore dominated by the beam size.

The angle at which the secondary ions enter the analyzer is assumed to fall within the acceptance window for which ϕ_{sp} measurement errors are less than some value, generally 5–10 V. As discussed above, it is possible to identify the characteristics of the VEF well enough to determine the entrance angle to within at least 2° . Two related assumptions are also necessary here. They are that the actual VEF of the analyzer is known and that theory predicts the behavior of the analyzer sufficiently well to permit the identification of particular characteristics of the VEF with entrance angle. To address these assumptions it is necessary to consider the VEF of the analyzer taken under realistic operating conditions. In Fig. 9, the comparator output is plotted against the analyzer entrance angle referenced to 30° for three different choices of x_d (cf. Fig. 5). All of these curves are raw data taken with a typical plasma. The x input of the x - y recorder was driven with a voltage from a sensor that measures the position of the analyzer. The oscillations in the curves for Rb^{+3} are due to mechanical jitter. Curves of the type labeled 1 and 2 for both primary and secondary ions show no focusing; curve 3 is the type used. Note that the theoretical and experimental curves are very much alike with the exception that the right-left asymmetry of the experimental curves is slightly more pronounced. The inflection point in the bottom curve occurs at 30° . It is possible then to use this information to check the calibration of the sweep plates, as discussed above. Note that for this analyzer configuration there is a maximum error of about 30 V for an 8° window. By constraining measurements to

2° – 3° windows the error can be reduced to 5–10 V. Figure 9 also shows the total current (I_{sum}) to both detector plates; the approximately linear variation of I_{sum} is consistent with the change in effective aperture width as the analyzer is rotated. The small variations in detector current for the Rb^{+3} case are due to the finite size of the primary beam.

The analyzer is assumed to center the beam of ions defined by the entrance aperture. If the beam so formed is uniform, equal currents will fall on the two plates and the action of the analyzer to minimize the difference between the two currents will indeed center the beam. The transimpedance of the feedback loop (Z_f) must be much greater than V_A/I_{sum} if there is to be sufficient current to drive the loop while keeping the currents on the two plates approximately equal.³ This requirement is satisfied by many orders of magnitude since $Z_f > 10^{16}$. Substantial errors could arise if either the primary beam is not uniform or if the plasma density varies significantly across a sample volume. The centering of the beam current would then result in an error in ϕ_{sp} . Careful focusing and aperturing of the beam has eliminated the former possibility. The impact of density gradients on the measurement would be more pronounced in regions where the sample length is long in the direction of ∇n_e and thus an asymmetry in the ϕ_{sp} profiles would result. Estimates of this error are small ($\approx 10^{-3} V_G$ divided by the density scale length in cm), and no asymmetry consistent with this effect has been observed.

Ion sources for Rb^{+} and Cs^{+} beams have been used; both have at times contained impurity ions and thus produced parasitic beams. In particular, the Rb^{+} beams have contained as much as 40% K^{+} and Na^{+} . While Rb^{+} can enter the analyzer at 6.5 kV, the B^2/m_i scaling shows that K^{+} at 14 kV and Na^{+} at 24 kV, can do likewise. If any K^{+} current should fall on either of the detector plates an ambiguity on the ϕ_{sp} measurement will result. When this occurs the only choice is to restrict measurements to the lower half of the plasma. This particular problem was solved by using sources with less than 5% impurities. The existence of Na^{+} and/or K^{+} in the Rb^{+} sources has made it possible to check the ϕ_{sp} measurements in a controlled manner. Rb^{+3} and Cs^{+3} signals have also been used to confirm the accuracy of the ϕ_{sp} profiles. The impurity ions also can provide a test of the stability of the 10^9 - Ω resistors in the comparator circuit. If voltage and temperature are stable, these resistors will keep the comparator output at near zero volts for I^{+1} measurements with all species. This error is hard to control when the resistors are old, not properly cooled, or not kept clean.

The plane defined by the analyzer rotation is the coil midplane wherein the ion trajectories are assumed to lie. An electrostatic energy analyzer is a two-dimensional device. As such, it is insensitive to ion velocity components out of the plane of Fig. 5. A misalignment of the beam probe system will therefore result in a smaller ϕ_{sp} value than actually prevails in the plasma. This effect is clearly seen in Fig. 10, where the total current (I_{sum})

FIG. 10. Total abundance of signal on both detector plates for a Cs^+ primary beam directed into the analyzer and total abundance of current along with space potential comparator output for Cs^{++} as functions of dc bias voltage on the chop plates.

and ϕ_{sp} signals are plotted as functions of the dc voltage on the chop plates. The system is seen to be out of alignment in this case because a finite voltage was necessary to maximize I_{sum} , while a larger voltage was necessary to cause the Cs^{++} ions to maximize the comparator output voltage. When properly aligned both I_{sum} and ϕ_{sp} should be maximum for zero volts on the chop plates. The amount of error in alignment for the conditions of Fig. 10 is about 1° . Measurements made without accounting for this effect result in errors of more than 100 V at the higher accelerating voltages.

The errors discussed above indicate that proper choice of operating procedures permits uncertainty to be readily kept to the order of 10 V. Particular emphasis in application of this diagnostic has been placed on taking data on the zero degree sweep line. For these measurements, the range of analyzer entrance angles, sample lengths, uncertainty in location and alignment, and beam nonuniformities are kept to a minimum. Measurements made elsewhere in the plasma cross section have been made with somewhat larger error. The beam probe sys-

tem has been found to operate satisfactorily on EBT under a great variety of operating conditions. While the potential for the exploitation of this technique for characterizing density, electron temperature, and possibly annular beta has not been realized, the ϕ_{sp} data has contributed significantly to the understanding of high temperature plasma confinement in bumpy tori.

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APPENDIX C

THE BEAM PROBE ELECTRONICS

This appendix describes the electronics system in use on the heavy-ion beam probe. A block diagram of the electronics is shown in Fig. C-1. Shown are the most important high voltage supplies, the high voltage control system, and the beam detection and feedback system. The components are listed in Table C-1. The philosophy of the operation of the system is explained in Appendix B. Other system components are the beam diagnostic systems (Faraday cup, primary dump), the sweep plate and source filament transformers, the high voltage z-deflection supply, and the mechanical servomechanisms (analyzer angle and aperture adjustment).

Table C-1. Guide to electronics

High voltageGun high voltage
suppliesAccelerator

Spellman 60 P 240/RVC/OL/TP

Extractor

Spellman 60 P 240/RVC/OL/TP

Shield

Spellman 40 P 120/RVC/OL/TP

Sweep plate drivers

Two Spellman 5 PN 30/RVC/TP/OL

Deflection plate driver^a

Analyzer high voltage supply

Spellman 40 P 120/RVC/OL/TP

High voltage controlHigh voltage control (gun)^aAnalyzer control (prebias)^aDetection electronicsSplit plate amplifier^aSum and difference amplifier^a

Tuned (filter) amp (4)

Tektronix AF501 bandpass filter

Phase sensitive detector (diff)^aPhase sensitive detector (sum)^aSpace potential comparator^a

Sync pulse generator

Tektronix FG501 function generator

^aCircuit diagrams from "EBT Heavy-Ion Beam Probe Electronics System, April 23, 1980" (unpublished).

APPENDIX D
SPACE POTENTIAL FLUCTUATION MEASUREMENTS WITH A
DC FEEDBACK LOOP

How does one go about measuring fluctuations with a low bandwidth detection system such as exists on EBT? This question may be answered by looking at the finite spatial extent of the incoming beam.

Suppose one has an analyzer which is in a dc feedback mode; i.e., the difference current is fed back and nulled on average. Then, any high frequency fluctuations in space potential are not fed back, and as a result, a difference current appears on the split plates due to these fluctuations.

As the beam energy changes, the beam sweeps across the split plates. For small excursions of ϕ , the entire beam still falls on the split plates, and I_{diff} can be considered to be a linear function of ϕ . The relevant proportionality constant may be estimated based on a finite size model of the ion beam (the beam is assumed to be uniform, monoenergetic, and the same thickness as the entrance slit).

At $\phi = 0$ the ions entering at the midpoint of the entrance slit reach the midpoint of the split plate detector, and the currents on the two plates are precisely balanced. However, when $\phi \neq 0$, the ions striking the center of the split plate detector do not come from the midpoint of the entrance slit but from a point displaced by a distance Δx . Since more ions enter the analyzer on one side of the midpoint than the other, more ions strike one split plate than the other, so that a difference current results. The difference can be written as

$$I_{\text{diff}} = \frac{2\Delta x}{\ell} I_{\text{sum}}, \quad (\text{D-1})$$

where ℓ is the width of the entrance slit.

One can rewrite Δx in terms of ϕ by using the standard analysis of the 30° electrostatic energy analyzer.⁶³ In particular, one needs the trajectory equation (letting charge = 2),

$$x_d = A_g d \sin 2\theta + y_d \cot \theta, \quad (\text{D-2})$$

the definition of the focusing parameter,

$$\gamma = \frac{y_d}{2A_g d \cos 2\beta \sin^2 \beta} = \frac{4y_d}{A_g d} \quad (\text{D-3})$$

(since $\beta = 30^\circ$), and the ratio x_d/y_d ,

$$x_d/y_d = \sqrt{3\left(\frac{2}{\gamma} + 1\right)}. \quad (\text{D-4})$$

Now, a space potential ϕ which is not compensated for by the feedback mechanism may be introduced. The trajectory equation becomes

$$x_d + \Delta x = A_g \left(1 + \frac{\phi}{V_o}\right) d \sin 2\theta + y_d \cot \theta,$$

or

$$\frac{\Delta x}{x_d} = \left(\frac{2}{2 + \gamma} \right) \frac{2}{\sqrt{3}} \left(\frac{\phi}{v_o} \right) \sin 2\theta + \left[\left(\frac{2}{\sqrt{3}} 2\theta - 1 \right) + \frac{\gamma}{2} \left(\frac{1}{\sqrt{3}} \cot \theta - 1 \right) \right] \quad (D-5)$$

For the case of $\theta = \beta = 30^\circ$, this simplifies to

$$\frac{\Delta x}{x_d} = \frac{\phi}{v_o} \left(\frac{2}{2 + \gamma} \right) \quad (D-6)$$

Plugging in for Δx , one arrives at

$$\frac{I_{\text{diff}}}{I_{\text{sum}}} = \frac{\phi}{v_o} \frac{x_d}{\ell} \left(\frac{4}{2 + \gamma} \right) \quad (D-7)$$

Hence, ϕ can be determined from knowledge of certain geometric ratios and the measured ratio $I_{\text{diff}}/I_{\text{sum}}$.

Some observations about this measurement technique are:

(1) Due to vagaries in analyzer geometry, the above analysis can only give an approximate answer for ϕ . Hence, it is necessary, as a check, to experimentally calibrate the analyzer, i.e., to determine experimentally ϕ as a function of $I_{\text{diff}}/I_{\text{sum}}$.

(2) The above analysis assumes a constant entrance angle into the analyzer $\theta = 30^\circ$. However, changes (fluctuations) in the entrance angle can introduce errors in the potential measurement. In particular, the spurious fluctuating potential $\hat{\phi}$ is

$$\frac{\hat{\phi}}{V_0} = \frac{\sqrt{3}}{4} \frac{1}{\sin 2\theta} \left[2 \left(\frac{2}{\sqrt{3}} \sin 2\theta - 1 \right) + \gamma \left(\frac{1}{\sqrt{3}} \cot \theta - 1 \right) \right] . \quad (D-8)$$

Of course, one requires $\phi > \hat{\phi}$. However, since angular fluctuations are not expected, this should turn out to be an unimportant concern.

(3) Although only the dc term in the difference signal is fed back, any fluctuations in the signal will show up in nonlinear terms at dc, introducing an error in the potential measurement. If the modulation of the sum is coherent and has amplitude m , then the dc potential error due to fluctuations not due to feedback

$$\phi_{er} = \int_{f_b}^{f_p} \phi_0(f) \frac{m(f)}{2} \cos \Psi \, df , \quad (D-9)$$

where ϕ_0 is the amplitude of potential fluctuation, Ψ is the phase angle between density and potential fluctuations, f_p is the inherent bandwidth of the beam probe system (about 1 MHz), and f_b is the bandwidth of the feedback loop (about 1 Hz). In EBT, the dc error from this effect should be small.

Experimental work on detection of fluctuations has been directed at verification of the relationship between I_{diff} and ϕ . The experimental calibration was made for both Rb^+ and Rb^{2+} by varying analyzer voltage by a small amount and then measuring the resulting $I_{\text{diff}}/I_{\text{sum}}$. The data show agreement to the scaling expected from measurements of analyzer dimensions for small values of $\phi/V_{\text{gun}} < 0.01$. For larger values of ϕ/V_{gun} , there is a falling off of the increase in $I_{\text{diff}}/I_{\text{sum}}$, as might be expected from the finite detector plate dimensions.

Fig. 2-1

ORNL-DWG 80-2600 FED

Fig. 2-2

ORNL-DWG 80-2599 FED

Fig. 2-3

EBT Mod-B Contours (—), Flux Lines (---), and Heating Geometry (////), (XXXX)

Fig. 2-4

Fig. 2-5

ORNL/DWG/FED - 77346

Fig. 2-6

Fig. 3-1

60 Hz ANGULAR SWEEP ACROSS PLASMA

 $V_{\text{gun}} = 10 \text{ kV}$, Cs^{++} SIGNAL

3 kHz CHOPPED BEAM

 $V_{\text{gun}} = 15 \text{ kV}$, $V_{\text{sw}} = 0$, Cs^{++} SIGNAL

Fig. 3-2

Fig. 3-3

EFFECTIVE CROSS SECTIONS FOR ELECTRON IMPACT IONIZATION

ORNL-DWG 79-3280 FED

Fig. 3-4

Fig. 3-5

Fig. 3-6

Fig. 3-7

3 kHz CHOP, $V_{\text{gun}} = 4 \text{ kV}$, Cs^+ BEAM

3 kHz CHOP, $V_{\text{gun}} = 10.2 \text{ kV}$, Cs^{++}
(CENTER OF PLASMA)

Fig. 3-8

Fig. 4-1

Fig. 4-2

Fig. 4-3

Fig. 4-5

Fig. 5-1

Fig. 5-2

Fig. 5-3

Fig. 5-4

Fig. 5-5

ORNL-DWG 79-3715 FED

Fig. 6-1

ORNL-DWG 79-3645 FED

Fig. 6-2

ORNL-DWG 79-3714 FED

Fig. 6-3

SCALING OF POTENTIAL WELL WITH ELECTRON DENSITY

ORNL DWG 79-3718R FED

Fig. 6-4

Fig. 6-5

Fig. 6-6

VARIATION OF POTENTIAL STRUCTURE WITH MAGNETIC FIELD

ORNL-DWG 79-3717 FED

Fig. 6-7

Fig. 6-8

Fig. 7-1

ORNL-DWG 79-3459 FED

Fig. 7-2

Fig. 7-3

Elmo Bumpy Torus.

Fig. A-1

Fig. C-1

FIGURE CAPTIONS

Fig. 2-1a. A simple torus. A gradient in the toroidal magnetic field B_T leads to charge separation which builds up a vertical electric field E_{cs} . The resulting $E \times B$ drift pushes the plasma outward.

Fig. 2-1b. A bumpy torus. An additional radial gradient $\nabla_r B_T$ leads to azimuthal particle drift and mixing of opposite charged particles. The vertical electric field is, in effect, shorted out.

Fig. 2-2. Bumpy torus with a negative potential. Parabolic potential profile corresponds to an azimuthal rotation frequency Ω_{EXB} approximately independent of radius.

Fig. 2-3. Some typical particle guiding center drift orbits.⁸

Fig. 2-4. Schematic diagram of the microwave heating geometry. An energetic electron population is created on the surface where the second harmonic resonance intersects the midplane.

Fig. 2-5. Effect of hot electron annuli on B and $\oint d\ell/B$.

Fig. 2-6. Schematic representation of a beam probing experiment. Singly charged ions are injected into a magnetically confined plasma and multiply charged ions are produced by electron impact.

Fig. 3-1. Schematic of parallel plate electrostatic energy analyzer and relative measurement error as a function of entrance angle.

Fig. 3-2. Detected secondary signals. (a) 60-Hz angular sweep across plasma. (b) Chopped beam, looking at a single point in the plasma.

Fig. 3-3. Electron impact cross sections for a Cs^+ ion.

Fig. 3-4. Effective electron impact cross sections for a 10-kV Cs^+ ion beam.

Fig. 3-5. Effective electron impact and charge exchange cross sections for a Mg^+ ion beam.

Fig. 3-6. Contour plot of beam probe sample length normalized to analyzer aperture width.

Fig. 3-7. Signal profiles as a function of z -steering voltage V_z for Cs^+ and Cs^{2+} signals.

Fig. 3-8. Cs^+ and Cs^{2+} signals, showing apparent beam steering on primaries, which is washed out on secondaries.

Fig. 4-1. Spatial positions of ion beam probe scans for a Cs^+ beam and a 5000-A toroidal field current.

Fig. 4-2. Typical C-mode potential profile along $y = 0$.

Fig. 4-3. Typical T-mode potential profile along $y = 0$.

Fig. 4-4. Measured constant-potential contour plot in EBT.

Fig. 4-5. Radial electric field E and perpendicular ion energy T_i needed to balance ∇E and $E \times B$ drifts in the midplane. Accuracy of the core electric field measurement is about $\pm 30\%$.

Fig. 5-1. Typical experimental secondary current profile in C-mode and T-mode.

Fig. 5-2. Effect of gun-emission scaling parameter α .

Fig. 5-3. Typical C-mode and T-mode $nf(T_e)$ profiles. Local hatched regions correspond to expected position of hot electron ring.

Fig. 5-4. Moving the resonant heating surface changes the $nf(T_e)$ profile.

Fig. 5-5. Space potential profiles along the same path as the $nf(T_e)$ profiles of Fig. 5-4.

Fig. 6-1. Space potential and $nf(T_e)$ scaling for 20 kW at 18 GHz.

Fig. 6-2. Space potential and $nf(T_e)$ scaling for 40 kW at 18 GHz.

Fig. 6-3. Space potential and $nf(T_e)$ scaling for 50 kW at 18 GHz.

Fig. 6-4. Scaling of space potential well depth and inward shift of well bottom as a function of integrated line density.

Fig. 6-5. Position of the rim of the potential well on a single scan, in comparison to the vacuum resonance position $\omega = 2\Omega_{ce}$, as a function of toroidal field current.

Fig. 6-6. Potential profile along $y = 0$ for four different toroidal magnetic field values. The vacuum field resonance location $\omega = 2\Omega_{ce}$ is indicated by the local hatched regions.

Fig. 6-7. Variation of potential structure with magnetic field.

Fig. 6-8. Potential profile is parabolic in the core plasma. The radial electric field does not change with magnetic field.

Fig. 7-1. Effect on Cs^{3+} signals of removing microwave power to the beam probe cavity (E-6).

Fig. 7-2. Radial profile of space potential and relative halo intensity of Cs^{3+} signal.

Fig. 7-3. Radial profile of space potential and relative halo density, corrected for an assumed halo temperature (150 keV) and an assumed background electron temperature profile (as shown).

Fig. A-1. Schematic layout of EBT.

Fig. C-1. Block diagram of the electronics system in use on the heavy-ion beam probe.

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