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BULK ELECTRONS AND IONS IN A 37 kW DISCHARGE

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ABSTRACT

The power balance of the bulk electrons and ions in discharges with 37 kW of applied microwave power in the ELMO Bumpy Torus (EBT) is examined in a zero-dimensional model using data on the intensity and linewidth of the molecular and atomic hydrogen emission. At least 60% of the applied power is ultimately dissipated by processes involving the neutral particles, including dissociation of molecules, ionization of and radiation from atoms, and heating of cold electrons produced during atomic ionization. The molecular influx rate and the density of atoms are used independently to determine the bulk electron particle confinement time, and an upper bound estimate is made of the diffusional power loss from the bulk plasma electrons. Parameters derived from the basic spectroscopic data presented in this paper include the neutral atom density $2-5 \times 10^{10} \text{ cm}^{-3}$, incident molecular flux $3-5 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$, bulk ion temperature $\approx 3 \text{ eV}$, and particle confinement time $< 1.1 \text{ ms}$. The bulk electron energy confinement time is 0.7 ms or less in the standard operating regime. Published data on the nonthermal electron and ion populations in the plasma are used to evaluate approximately the overall energy flow in the discharge.

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1. INTRODUCTION

In this paper the power balance of an ELMO Bumpy Torus (EBT) discharge with an applied microwave power of 37-58 kW is analyzed using basic atomic and molecular parameters of the plasma to determine the ultimate loss mechanisms for the energy in the bulk plasma electrons. These parameters are derived from data taken during a study of the plasma background light associated with Thomson scattering measurements. With the aid of published data on the nonthermal electron and ion populations in the plasma this analysis is extended to provide an approximate evaluation of the overall power balance for the discharge. This is the first time a detailed analysis of the power balance in EBT has been made using the neutral particle parameters of the plasma. The discussion is limited to a relatively low power discharge; however, the methods and results of this elementary investigation should aid in analyzing the behavior of higher power discharges and in evaluating the prospects of this type of device for plasma heating experiments.

For several years the microwave-heated EBT was considered as a possible approach to nuclear fusion.¹⁻⁸ Until last year, when EBT was shut down, work was under way to design and build a large-scale proof-of-principle experiment which was intended to produce plasmas with the parameters of modern tokamaks.^{9,10} The physical interest of the EBT plasma is enhanced by the fact that none of the particle species present in the plasma is in thermal equilibrium, either by itself or with the other species. Except at very high filling pressures the translational disequilibrium of the neutral atoms in EBT is evident from the Balmer alpha line shape. The relative emission intensities of certain lines of molecular hydrogen show that the molecules are out of rotational equilibrium. Published data have long attested to the nonequilibrium nature of the electrons and ions in EBT. In particular, early Thomson scattering measurements revealed bulk electron densities and temperatures of less than or about $1 \times 10^{12} \text{ cm}^{-3}$ and 150 eV, respectively, at the discharge center for electron cyclotron resonance heating (ECRH) powers of about 20 kW at 18 GHz in the normal operating regime.¹¹⁻¹³ Measurements taken after the machine had been modified as EBT-S to permit ECRH at 28 GHz with powers of up to 200 kW yielded similar electron temperatures and densities according to Thomson scattering.^{13,14} (When operated with 18 GHz resonant microwave power, the machine is referred to as EBT-I.) At the same time, x-ray bremsstrahlung

measurements revealed the presence of electrons with effective temperatures of from several hundred electron volts to above 1 keV.¹⁵⁻¹⁸ These higher energy electrons have customarily been reported as the bulk electron population of the plasma, and several analyses of confinement on EBT have been made on this basis.^{6,7,18} Recent reports have reconfirmed that both groups exist, with a majority of the electrons belonging to the lower temperature group detected in the Thomson scattering measurements.^{13,14,19} (For this reason, the electron population detected by Thomson scattering is referred to as the "bulk electrons" in this paper.) Microwaves generate plasmas easily at low powers^{20,21} and have been shown to provide efficient heating of large, high-temperature plasmas.^{22,23} The failure to achieve higher bulk electron temperatures in EBT is thus puzzling. Until quite recently, the apparent conflict between x-ray and Thomson scattering measurements has obscured studies of the power balance in EBT. It is, therefore, of considerable interest to determine what ultimately happens to the microwave energy applied to this plasma. This paper is an attempt to do this using elementary observations of the plasma combined with some simple assumptions about the plasma geometry and parameters.

A more detailed outline of this paper follows: after a description of the device, spectroscopic data on the atomic and molecular hydrogen emission from the plasma are presented in Sec. II. These data are then used to evaluate the zero-dimensional power balance of the bulk electron plasma (Sec. III). It is possible to determine the ultimate mechanisms for the dissipation of nearly all the energy in the bulk plasma in terms of processes involving atoms and molecules. In a 37 kW EBT-I plasma, the electrons expend a power nearly equal to the applied microwave power through the following mechanisms, of which the first two primarily involve the bulk plasma electrons: (i) reactions with hydrogen atoms and molecules, (ii) Coulomb collisions with cold electrons produced in the plasma by ionization of hydrogen atoms, and (iii) diffusional losses of hot electrons from the plasma. Quantities derived from the spectroscopic data include the density of atomic hydrogen, the incident flux of molecular hydrogen, the ion temperature, and upper bounds on the gross particle and electron energy confinement times of the bulk electron plasma. The energy confinement time is evaluated primarily using the neutral atom density obtained from the H_{α} emission. This approach is based on the fact that the neutral atom population is essentially uniform throughout the plasma. The energy confinement time, ≤ 0.7 ms, is consistent with the particle confinement time, ≤ 1.1 ms, derived from the incident flux of molecules, which is evaluated with the

aid of the observed intensity of molecular line emission. The ion energy balance of the plasma is investigated in Sec. IV using parameters derived from the spectroscopic data. The calculated bulk ion temperature ≈ 3 eV is consistent with the H_{α} line profile observed in EBT-I. Energetic ions, which were observed in charge-exchange measurements and whose energy (>20 eV) has often been reported as the ion temperature of the plasma, are found to correspond to a small fraction of the total ion population in EBT-I and may be produced by a parametric heating mechanism.

The overall power flow for the 37-38 kW EBT-I discharge is discussed in the concluding section of this paper. At high filling pressures the bulk plasma power balance discussed in Secs. III and IV is sufficient to describe the plasma behavior. However, a consistent understanding of the power balance of the discharge as a whole under standard operating conditions requires consideration of the hot electrons. A discussion of the precise relationship between the hot electrons and the bulk electrons is beyond the scope of this paper. It can, however, be assumed that they are heated more directly by ECRH and transfer energy to the colder bulk electrons through Coulomb collisions while undergoing direct loss through diffusion and related transport processes. The ultimate mechanisms for dissipation of most of the applied power in the 37 kW EBT discharge can be identified with the bulk electrons, rather than the hot electron population, because (i) the hot electron population is small and (ii) it contributes to the ultimate power loss from the discharge approximately in proportion to its relative density. In the higher (up to 200 kW) power EBT-S discharges, however, the bulk electrons, whose parameters differ little from those in EBT-I at powers on the order of 30 kW, cannot dissipate more than a small fraction of the applied microwave power. Thus, power balance studies for EBT-S will require another, more detailed, treatment of the hot electrons and the mechanisms by which they lose energy.

II. DATA

The origins of the EBT concept and the construction and operation of the device have been discussed in detail by Glowienka.⁵ In this section a brief description of EBT will be given and the data used in the power balance calculations will be presented.

EBT consisted of twenty-four 50-cm-diam cylindrical aluminum cavities joined toroidally by 22-cm-diam connecting sectors into a torus with a

major diameter of 300 cm. The connecting sectors were surrounded by water-cooled copper windings to make a sequence of 2:1 magnetic mirror traps which generated a closed, bumpy toroidal magnetic field. The magnetic field in the center of the cavities was typically about 5 kG for resonant heating at 18 GHz (in EBT-I) or 7.5 kG for 28 GHz (in EBT-S). This paper deals exclusively with the behavior of discharges in EBT-I. The device was operated in a steady state with microwave power applied equally to each of the twenty-four cavities. The power was not selected as to the direction of the electric field vector of the waves (i.e., ordinary or extraordinary mode), but this was probably not important since the plasma density was far below critical, so that the microwaves could be absorbed in multiple passes. A typical discharge consisted of a toroidal plasma and, in each of the aluminum cavities, a less dense (about one tenth of the density of the toroidal plasma), high-energy (>100 keV/electron) electron annulus^{16,24} with a minor radius of 2-3 cm and a major radius of ≈ 12 cm approximately centered in the cavity midplane. The toroidal plasma had a density of $\approx 10^{12}$ cm⁻³ and consisted of a "bulk" plasma with an electron temperature of around 100 eV measured by Thomson scattering^{11,13,14,16} and a less dense (a quarter or less of the total electron density) "hot" electron component with an effective temperature $T_{eh} \geq 200$ eV determined by soft x-ray bremsstrahlung measurements.^{8,13,15-17} The electron annuli and the hot electron component are neglected in the derivation of the bulk plasma parameters in Secs. III and IV, but are discussed qualitatively in Sec. V.

EBT had three operating regimes, referred to as the C (cold), T (toroidal), and M (mirror) modes, in order of their appearance with decreasing filling pressure.^{5,16} The C-mode had the highest electron densities, an electron temperature $T_e \leq 50$ eV, and almost no electron annuli. The T-mode was the optimum operating regime for the plasma, with all three electron components present: the toroidal plasma, which included the bulk electrons and a hot electron component,^{13,19} as well as high energy electron annuli. The M-mode occurs at the lowest filling pressures for which a discharge can exist and is characterized by a low density, unstable plasma with a large concentration of high energy electrons. Except for some examples from the C-mode, the present discussion is entirely devoted to the T-mode.

Optical measurements were made across the horizontal diameter of one of the aluminum cavities as part of a study by this writer of the plasma background light in the Thomson scattering measurements on EBT-I.²⁵ The data used in this paper come from that study. The Thomson scattering system faced

background plasma light levels that were many orders of magnitude greater than the levels of bremsstrahlung expected from a fully ionized plasma²⁶ at these densities.^{11,13} The plasma emission in the range 600–720 nm was studied in detail and found to consist almost entirely of hydrogen molecular line radiation. Relatively few impurity lines were found, so the discharge can be regarded in the present discussion as a pure hydrogen plasma. The absolute intensity and spectral line shape of the hydrogen Balmer alpha (H_{α}) emission were also measured.

Figure 1 shows the variations with hydrogen filling pressure in the intensity of plasma light at wavelengths of 694, 720, and 656 (H_{α}) nm measured with calibrated photomultipliers and interference filters. (The full-width half-maxima of the filters were 3.0, 13.0, and 1.0 nm, respectively.) The wavelengths 694 and 720 nm have been chosen so as to exclude the strong Al II triplet at $\lambda=704\text{--}706$ nm which was the only significant impurity radiation seen in the wavelength range used for Thomson scattering. Also shown in Fig. 1 is the line-integrated electron density measured with a 70 GHz microwave interferometer during the same experiment. The data of Fig. 1 were taken with 30 kW of 18 GHz ECRH power plus 7–8 kW of supplementary microwave power at 10.6 GHz. (For this reason the discharge analyzed in this paper will be referred to as a "37 kW" discharge.) The line labelled " $\overline{n_N}$ " in Fig. 1 denotes the relative line-integrated density of molecules in the vacuum vessel at the nominal filling pressure p_{H_2} without a discharge, and is proportional to p_{H_2} . The abscissa shows an uncalibrated ionization gauge reading which should be divided by the gauge sensitivity (≈ 0.4) to give the nominal hydrogen pressure at the gauge, which was located at the end of a pipe attached to a flange on the vacuum vessel. In this paper all pressures are given in terms of uncalibrated gauge readings, as has been customary in reports on EBT.

All the quantities plotted in Fig. 1 were measured absolutely. The value 1.0 on the ordinate corresponds to a line-integrated electron density of $\overline{n_e}=3.0\times 10^{13}$ cm⁻³ across the midplane of one of the aluminum cavities. It also corresponds to brightnesses of $B_{H_2}(694)=7.3\times 10^7$ and $B_{H_2}(720)=2.5\times 10^8$ photons/s/cm²/nm at 694 and 720 nm, respectively, and $B_{H_{\alpha}}=2.1\times 10^{11}$ H_{α} photons/s/cm² at a distance of 225 cm from the cavity center viewing through a 7.5-cm-diam window. The error limits in the intensity data are about 20%. Values within that range were obtained on many similar runs with different filter combinations as part of the above-mentioned study of plasma background light in the Thomson scattering measurements. The H_{α} intensity shown here can

be scaled within a factor of 1.5 to the Lyman alpha data (for somewhat different conditions) of Lazar *et al.*,²⁷ when the flatness of the electron and atom density profiles, as well as other factors, are taken into account. The absolute intensities at 694 and 720 nm were confirmed by the relative intensity of the plasma background light compared to the scattered signal in Thomson scattering and by other measurements taken under similar conditions. Qualitatively, the background light increased slightly more than linearly with applied microwave powers of up to 40 kW in EBT-1.²⁵ Thus, the best early Thomson scattering data (ratio of peak scattered intensity to average background intensity ≈ 2) were obtained with microwave powers of about 20 kW. Acceptable data were hard to obtain at 30 kW (intensity ratio below 1), and virtually impossible to obtain at powers of 40 kW or more with the early multipulse Thomson scattering system. Above 40 kW, the hydrogen emission intensity appears to have increased less rapidly with applied power.

Figure 2 shows the H_{α} line shapes obtained with a Fabry-Perot interferometer (FPI) for different discharge conditions.²⁸⁻³⁰ Curve A corresponds to typical T-mode conditions (an intermediate gauge pressure reading of 6-7 μ Torr), curves B and C, to low pressure and moderately high pressure operation (3-4 μ Torr in the M-mode and 18 μ Torr in the C-mode, respectively), and curve D, to high pressure (above 40 μ Torr), very low temperature operation in the C-mode. The resolution of the interferometer is 0.1 $\text{\AA}$ or less in each of the profiles of Fig. 2. The H_{α} line shapes in curves A-D are determined by Doppler broadening. The emitting atoms have energies roughly equal to those of the "Franck-Condon" dissociation product atoms from H_2 , which appear in two groups, with most probable energies of ≈ 0.3 eV and $\approx 3-5$ eV.³¹ Balmer alpha line shapes that include contributions from atoms whose energies are close to the dissociation product energies can be seen in a wide variety of plasmas ranging from capillary tubes to tokamaks.^{29,30} Neither of the two groups of dissociation product atoms is thermalized³¹ and it is evident from Fig. 2 that the atoms in EBT are not thermalized^{29,30} except possibly at very high pressures. (The line shape reported in ref. 28 corresponds to curve D of Fig. 2.) The straight line fits of Fig. 2, curves A-C, are not meant to imply that the wide component of the H_{α} spectrum corresponds to a Maxwellian distribution, since the fits extend over less than an order of magnitude in the intensity. Radiation from atoms at the ion temperature (≈ 3 eV; cf. Sec. IV) can explain the structure near the transition between the wide and narrow components in the spectra of Fig. 2.

Langmuir probe measurements in EBT-I showed that T_e within a few cm of the vessel wall was about 15 eV, rising rapidly to ≥ 30 eV, while early Thomson scattering measurements at low microwave powers in EBT-I (≤ 30 kW) yielded central temperatures between 60 and 150 eV in the T-mode.^{11,16} Subsequent measurements with an improved Thomson scattering system showed that the bulk electron temperature was still in this range for microwave powers of up to 200 kW and that both T_e and n_e had fairly flat spatial distributions over at least the central 20 cm of the plasma column (where the measurements were made).^{13,14} The exact form of the electron kinetic energy distribution is not a critical factor in evaluating the neutral particle parameters because the rates of almost all the reactions involved in the hydrogen chemistry of this plasma are insensitive to T_e (i.e., vary by less than a factor of two for $T_e=40-1000$ eV). The essential information for the following calculations of the bulk electron and ion power balance in EBT-I is the following: (i) the data of Figs. 1 and 2, together with knowledge that (ii) the effective electron temperature is above about 40 eV and (iii) the distributions of T_e and n_e are relatively flat across the plasma.

III. BULK ELECTRON POWER BALANCE

In this section a number of contributions to the power balance of the bulk electrons are evaluated using the spectral intensities shown in Fig. 1. The H_α intensity is first used to obtain the neutral atom density. The energy expended by the plasma electrons in ionization and excitation of H atoms, and in heating the electrons and ions created during ionization can then be calculated. Next, the molecular line emission intensity is used to determine the flux of molecules entering the plasma. A certain amount of energy is also expended in the dissociation of these molecules, but the most important quantity derivable from the molecular flux is the particle confinement (replacement) time for the discharge. Some estimates can also be made of the energy confinement time for the bulk plasma and of the expected energy loss through the plasma boundary (i.e., diffusional losses). These results, together with general information on the power associated with the nonthermal ion and electron populations in the plasma are sufficient to determine the overall energy flow in the discharge (Sec. V).

Plasma parameters derived from the data of Fig. 1 for the T-mode

($p=6-10$ gauge μTorr) are listed in Table I. Quantities that depend on the plasma volume and surface area have been evaluated for an effective torus minor radius $a=15$ cm and a major radius $R=150$ cm, i.e., a plasma volume and surface area of $V_{p1}=6.7 \times 10^5$ cm³ and $\Sigma_{p1}=8.9 \times 10^4$ cm², respectively. The minor radius cannot exceed 11 cm in the mirror throats, but may exceed 15 cm in the 50-cm-diam cavities. Under the assumption of uniform electron parameters, the density of atoms and the entering flux of molecules are independent of the radius, while most of the power and energy terms listed in Table I are proportional to a . The values of T_e given in the table are interpolations based on the maximum and minimum values obtained by Thomson scattering in the T-mode.¹¹ In this section the contribution of the hot electron component is neglected; that is, it is assumed that the fraction η of fast electrons in the total electron population is small ($\eta < 0.2$), as confirmed by the data of Cobble^{13,14} and by calculations of the energy transfer from the hot electrons to the bulk electrons (Sec. V.B.). The effect of this assumption on the parameters listed in Table I is minor in EBT-I and will be discussed briefly in connection with the overall energy balance of the discharge in Sec. V. None of the available data on EBT justify a better precision than about 20% in the estimated effective minor radius of the discharge. This is probably the most serious limit on the precision of the parameters derived in this paper. The estimated error in the derived quantities listed in the table is thus 20-30%, in accordance with the errors associated with the original data from EBT. Nevertheless, a fairly consistent description of the discharge behavior can be obtained, despite the limited accuracy with which any properties of the EBT-I discharge were known. In the following, temperatures and particle energies are given in eV, total plasma energies and powers are given in J and W, respectively, and all other quantities in CGS units except where noted.

A. Hydrogen atoms The Doppler-broadened profiles in Fig. 2 indicate that the velocity of the H atoms is sufficient for them to cross the plasma with little loss. [The mean-free path for loss by ionization³² of atoms whose energies correspond to the narrow peak of the H_{α} profile, i.e., have energies ≈ 0.3 eV, is on the order of 30 cm in EBT.] It can be assumed, therefore, that the atom density n_H is uniform. The measured brightness of H_{α} at a distance $L=225$ cm from the midpoint of the observation cavity is related to the plasma parameters by

$$B_{H\alpha} = \overline{n_e} n_H \langle \sigma_{H\alpha} v \rangle d^2 / 16L^2 \text{ photons/cm}^2/\text{s}, \quad (1)$$

where $\overline{n_e}$ is the line-integrated electron density (Fig. 1) and $d=7.5$ cm is the

viewing window diameter. For $T_e=40-200$ eV the value of the rate coefficient for excitation of H_α by electron impact on H atoms, $\langle\sigma_{H_\alpha}v\rangle$, calculated from the cross-section measurements of Walker and St. John³³ is 1.9×10^{-9} cm²/s to within 5%. (The estimated error in the cross-section measurement is 30%. A comparison with other experimental data for this cross section shows that this rate coefficient may be an upper bound. See the comment following the citation of ref. 33 in this paper.) The resulting values of η_H (minus a 5% correction for H_α produced by electron impact on H_2 and H_2^+ ; see Sec. III.B.) are given in Table I. Also listed in the table is the electron energy content of the "bulk" plasma (again, neglecting the contribution of the "hot" electron component)

$$E_D = 1.5 \bar{n}_e k T_e V_{pl} \text{ J}, \quad (2)$$

where $k=1.602 \times 10^{-19}$ J/eV is the Boltzmann constant and $\bar{n}_e = \bar{n}_e l / (2a)$ is the average electron density.

The H_α emissivity can be scaled to yield the emission rates from all levels of the H atom as well as the ionization rate. When excitation to and radiation from the $n=2-5$ states as well as ionization are included, this power corresponds to an energy of $\epsilon_H \approx 415$ eV per H_α photon (with a calculated range of about 30 eV around this value for the temperatures of interest); roughly equal amounts of energy are dissipated in ionization and radiation.³²⁻³⁵ The total power expended in processes involving electron impact on H atoms, P_H , is then given by

$$P_H = 0.95 k \eta_{H_\alpha} \epsilon_H V_{pl} \text{ W}. \quad (3)$$

Here $\eta_{H_\alpha} = 8B_{H_\alpha} L^2 / (d^2 a)$ photons/cm²/s is the H_α emissivity in the emitting volume. The factor 0.95, as before, accounts for the 5% of the H_α emission produced by electron impact on molecules rather than atoms.

The power transferred to the ions by Coulomb collisions with electrons,

$$P_{ei} = 1.5 \bar{n}_i k T_e V_{pl} / \tau_{ei} \text{ W}, \quad (4)$$

is relatively small. Here $\bar{n}_i = \bar{n}_e$ is the average ion density and $\tau_{ei} = 3.15 \times 10^8 T_e^{3/2} / (\bar{n}_e \ln \Lambda)$ s is the electron-ion equilibration time (the ion temperature $T_i \ll T_e$; cf. Sec. IV), where the Coulomb logarithm $\ln \Lambda = \ln(7.74 \times 10^9 T_e^{3/2} / \bar{n}_i^{1/2}) \approx 16$.³⁶ P_H , in turn, is substantially less than the power P_{He} expended in Coulomb collisional heating of the electrons produced by ionization of hydrogen atoms in the plasma interior. Since the time for newly produced electrons to thermalize to the bulk electron temperature is small (< 100 μ s) compared to the particle replacement time (see below), these electrons will equilibrate to T_e and consume a power

$$P_{He} \approx 1.5 \bar{n}_e n_H k T_e \langle \sigma_{iv} \rangle V_{pl} W, \quad (5)$$

for the discharge as a whole, where $\langle \sigma_{iv} \rangle \approx 3 \times 10^{-8} \text{ cm}^3 \text{ s}^{-1}$ is the ionization rate coefficient.³² This process alone consumes about half of the applied microwave power (Table I).

B. Hydrogen molecules Almost all H_2 molecules are broken up as they enter the plasma. [The mean-free path for room temperature H_2 in this plasma is on the order of 5 cm.^{37,38}] Here we consider an entering flux of H_2 which yields molecular line emission with a certain probability f_m per molecule. This approach is much simpler than trying to average the brightness of the molecular line emission over the plasma volume when n_{H_2} is so obviously nonuniform. The observed brightness of the H_2 line emission in Fig. 1 is given (for $a \ll L$) by

$$B_{H_2} = \Phi_{H_2} f_m a^2 / 8L^2 \text{ photons/cm}^2/\text{s}, \quad (6)$$

where Φ_{H_2} is the entering flux of H_2 molecules ($\text{cm}^{-2} \text{ s}^{-1}$), $f_m = \langle \sigma_m \rangle \Delta \lambda / \langle \sigma_{\text{loss} H_2} \rangle$ is the average number of photons produced in an observation bandwidth $\Delta \lambda$ by a single entering molecule as it is dissociated and ionized, and a factor 2 has been included because molecules are assumed to enter in equal amounts from both sides of the vacuum vessel. Here $\langle \sigma_m \rangle$ is the rate coefficient for emission of molecular lines at a given wavelength per unit wavelength and $\langle \sigma_{\text{loss} H_2} \rangle$ is the total rate coefficient for loss of H_2 by electron impact ionization,³² dissociative ionization,³⁷ and dissociative excitation with product atoms in the $n=1-5$ states.^{37,38} $f_m \approx 1.3 \times 10^{-4}$, 1.2×10^{-4} , and $3.4 \times 10^{-4} \text{ nm}^{-1}$, to within about 20%, for $\lambda=668$, 694, and 720 nm, respectively, when $T_e=20-200 \text{ eV}$. [The probabilities for the last two wavelengths are scaled from published cross-section data for 668 nm³⁹ to the observed intensity of H_2 line emission in the ACT-1 plasma device. In the $T_e < 10 \text{ eV}$ ACT-1 plasma,⁴⁰ excitation is primarily caused by the electrons from an intense 200-400 V electron beam that is used to maintain the plasma. The spectral intensity distribution of a hydrogen plasma in ACT-1 is very similar to that observed in EBT-1 over the interval 500-750 nm.]

The averages of the values of Φ_{H_2} obtained using Eq. (6) and the data of Fig. 1 for 694 and 720 nm are given in Table I. The difference between the fluxes calculated from the data at these two wavelengths is at most 17%. Some of the entering H_2 undergoes dissociative excitation and related processes to produce H_{α} . The fraction of the observed H_{α} signal in Fig. 1 produced by electron impact on H_2 [i.e., dissociative excitation,³⁸] and on H_2^+ [i.e., dissociative recombination^{41,42} and (estimated) dissociative excitation⁴³] as opposed to electron impact on H, is about 5% for filling pressures of 6-10 μTorr .

and has been taken into account in Table I. The density n_{H_2} of molecules at the plasma center is on the order of 10^9 cm^{-3} .

The energy required to dissociate H_2 and H_2^+ to yield H and H^+ as H_2 enters a plasma with $T_e > 40 \text{ eV}$ is approximately 32 eV per molecule. (See the discussion of the next paragraph and Fig. 3.) Therefore, the power required to dissociate the entering H_2 flux and produce the H atoms present in the plasma is

$$P_{H_2} \approx 32 k \Phi_{H_2} \Sigma_{p1} W. \quad (7)$$

In this estimate it is assumed that the flux of H_2 is uniform over the entire plasma surface. The energy expended in the subsequent ionization of the product H atoms and in collisional heating of the protons and electrons obtained from them has already been calculated. The sum

$$P_e = P_{H_2} + P_H + P_{He} + P_{ej}, \quad (8)$$

therefore, represents the total power expended by the bulk plasma electrons to "convert" the entering molecules into thermalized electrons at T_e and ions at T_i . This power has been derived primarily from the neutral atom density in the plasma.

Another estimate of this power may be obtained from the molecular influx as follows: if it is assumed that every molecule entering the plasma is fully dissociated and ionized, and that the product electrons are fully thermalized to the bulk plasma electron temperature, then the total power expended by the bulk electrons in collisions should also be calculable directly from the molecular influx. Consider a hydrogen molecule placed in a large uniform plasma with an electron temperature T_e . The molecule will be broken up in a number of parallel and consecutive reactions including dissociative excitation^{37,38} and dissociative ionization³⁷ of H_2 , molecular ionization,³² dissociative reactions of H_2^+ ,^{41,43,44} ionization of H,³² and so on. The problem of calculating the energy expended in breaking up molecules in a plasma is related to the problem of energy loss by an electron beam entering a gas discussed by Hecps and Green⁴⁵ and by Gerhart.⁴⁶ The average energy needed to dissociate a molecule, for example, will exceed the threshold energy for dissociation because numerous parallel radiative processes may occur, such as ultraviolet band emission from H_2 .⁴⁷ In the present example, the average energy expenditure for the first step in breaking up a single H_2 molecule by molecular ionization, dissociative excitation, and dissociative ionization (to yield H_2^+ , H, and H^+) for $T_e = 1-1000 \text{ eV}$ is shown in Fig. 3 (curve labelled H_2). (Vibrational excitation, which would be significant at very low T_e , has been neglected.) The amount of energy required to break up the average number of product H_2^+ ions

from each molecule by dissociative recombination, excitation, and ionization is shown as the curve labelled H_2^+ . [A von Busch-Dunn vibrational energy distribution, which is close to the Franck-Condon distribution, is assumed for the H_2^+ .⁴³] The energy of 32 eV/molecule in Eq. (7) is obtained from the sum of the curves labelled H_2 and H_2^+ in Fig. 3. The energy required to ionize the average number of atoms created by the complete breakup of an H_2 molecule is shown as the curve labelled H. The average energy required for complete dissociation and ionization of a single H_2 molecule to form two protons and two electrons is given by the sum of these three curves and is plotted in Fig. 3 as the curve labelled "Dissoc.+ioniz." In a large plasma with $T_e \gg T_i$ the electrons obtained from the molecule will thermalize for a further expenditure of $3T_e$ eV. The combined energy expended in dissociation, ionization, and thermalization in a large, cold-ion plasma, ϵ_{H_2} , is shown as the curve labelled "Total" in Fig. 3.

Evidently, almost all molecules entering a plasma as hot and dense as the EBT discharge will be broken up by dissociation and molecular ionization. The resulting H_2^+ will also be broken up into atoms and protons since it is confined for a time comparable to or longer than the loss time. Assuming that the sticking probability for H at the vessel walls is $\ll 1$, then most of the atoms in the discharge will also be ionized. Finally, assuming that they are confined long enough, the electrons produced by ionization of these atoms will be thermalized to T_e . In effect, the molecules entering EBT will behave as if they had been immersed in an infinite plasma: most will undergo complete ionization and the charged particle products will be thermalized. The total power expended by the plasma electrons to carry out these processes can then be found using Fig. 3 and the formula

$$P_m = k \Phi_{H_2} \epsilon_{H_2} \sum p_i \quad W. \quad (9)$$

For the data in Table I, P_m is $\approx 70\%$ of P_e .

A comparison of the density of atoms obtained from the H_{α} intensity (Sec. III.A) and indirectly from the molecular influx confirms the relationship of these estimates (P_e and P_m) of the bulk plasma power expenditure. The molecular influx can be used to estimate the neutral atom density by taking into account the balance between loss of H by volume ionization and adsorption at the vacuum vessel walls, and production of H from the entering H_2 flux. The value of n_H obtained from the molecular flux is about 50% of the value obtained from the H_{α} intensity for the parameters of Table I. Thus, while the molecular emission data provide qualitative support for the conclusions (especially the pressure variations) derived from the more accurate data on atomic line (H_{α}) emission, a

difference of up to a factor of 2 remains. Several effects may contribute to the above difference between P_e and P_m , as well as to the discrepancy in the values of n_H obtained from the atomic and molecular line intensities: (i) the estimates for $\langle\sigma_m v\rangle$ may be high; (ii) if dissociation of H_2 occurs in an edge region with $T_e < 70$ eV, then the number of product atoms per molecule may be greater (approaching 2) than the ≈ 1.3 at the temperatures used in this calculation; (iii) more molecules may enter the plasma from gas feed ports and (per unit area) from wall regions not seen by the detectors; and, (iv) the temperature of the molecules entering the plasma may be higher than room temperature (0.025 eV), so that the mean-free path for H_2 in the plasma would be greater than 5 cm and a smaller fraction of incident H_2 will be broken up. A molecule temperature above 0.075 eV seems improbable since the walls did not melt and the particle densities in EBT were too low to provide much collisional heating of H_2 . It was impossible to determine the temperature of the molecules spectroscopically because the observed intensities of lines near 600 nm in the Q and R branches of the [0,0] band of the Fulcher alpha system ($3p\pi^3\Pi_u \rightarrow 2s\sigma^3\Sigma_g$) did not correspond to a unique rotational temperature for the molecules. Rotational disequilibrium where the upper states have populations in excess of a Boltzmann distribution fit to the lower rotational states is quite common in hydrogen discharges.⁴⁸ A detailed answer to the question of matching the quantities derived from the atomic and molecular spectral intensities would require knowledge of the spatial distributions of H_2 and H. These have been calculated in detail for EBT-S by Davis and Colchin⁴⁹ using Monte-Carlo methods.

C. Particle and energy confinement times The calculated value of P_e in Table I represents consumption of $\approx 60\%$ of the applied microwave power and is a lower bound in terms of experimental data on electron impact production of H_α from H atoms (cf. the note following the citation of ref. 33). The bulk electron energy loss mechanisms described up to this point are local losses associated with the plasma chemistry and do not include explicitly any losses associated with transport at the plasma edge, i.e., diffusion or convection. Such losses have, in fact, been included in P_{He} (Eq. (5)) if the requirements of particle balance are taken into account. For example, the local rate of production of electrons by ionization of H atoms at the plasma center is given by

$$\dot{n}_e = n_e n_H \langle\sigma_i v\rangle \approx 10^{15} \text{ electrons/cm}^3/\text{s}. \quad (10)$$

This implies a local particle confinement (replacement) time at the plasma center (Table I) of

$$\tau_{p,C} = n_e / \dot{n}_e = (n_H \langle\sigma_i v\rangle)^{-1} \text{ s}. \quad (11)$$

The gross particle confinement (replacement) time for electrons or protons in the discharge is given in terms of the incident molecular flux by

$$\tau_p \approx \bar{n}_e / (8\Phi_{H_2}) \quad \text{s} \quad (12)$$

and is listed in Table I. The discrepancy between the densities of H atoms calculated from the H_α data and from the molecular influx [See the discussion following Eq. (9).] shows that the particle confinement times τ_p given in Table I probably are overestimates. On the other hand, $\tau_{p,C}$ [Eq. (11)], which is derived from the atomic line emission intensity, provides a lower limit to τ_p that is within the error limits on the latter quantity.

The relationship between the molecular influx and the plasma properties in the interior of the discharge suggests that the particle replacement time is probably closely related to the overall energy confinement time for the discharge. The diffusional loss (in the general sense of the term, including convection) from the plasma can also now be evaluated. The main problem is to establish how much energy is carried away by each departing charged particle that is replaced in accordance with Eq. (10). In the uniform plasma model used here, each electron leaving the plasma carries away 1.5 T_e eV. Thus the diffusional power loss is given by

$$P_D \approx 3kT_e \Phi_{H_2} \Sigma_{PI} \quad \text{W}, \quad (13a)$$

or equivalently, in terms of the central plasma parameters [using Eq. (12)],

$$P_D \approx 1.5n_e kT_e V_{PI} / \tau_p \quad \text{W}, \quad (13b)$$

where τ_p is determined from the molecular influx. In a plasma with a finite edge region in which the electron temperature varies from its maximum to some lower value, the loss per electron may be smaller, and Eqs. (13) would have to be multiplied by a factor $\alpha < 1$ to account for this. The maximum value of P_D (i.e., for $\alpha=1$), $P_{D(\max)}$, is listed in Table I. Obviously, if τ_p is replaced by $\tau_{p,C}$ (derived from the atom density), P_D is the same as the electron heating power P_{He} . Given the better precision of the H_α data, the latter value may be a better estimate for the diffusional and transport energy loss from the bulk electron component of this plasma. This estimate of the diffusional power loss should be compared to that obtained in the Bohm diffusion limit in which the power loss is given by

$$P_B = E_B / \tau_B \quad \text{W}, \quad (14)$$

where $\tau_B \approx a^2 / D_B$ is the Bohm diffusion time for the plasma, $D_B = ckT_e / 16eB$ is the Bohm diffusion coefficient,^{36,51} and B is the magnetic field in G. The Bohm diffusion power P_B is listed in Table I for a magnetic field $B=5$ kG. (The volume average B is 4-6 kG in the EBT-I configuration.) P_B is somewhat below

the estimate of the maximum transport loss (P_D or P_{He}) at low pressures and the difference becomes much larger at higher pressures. P_{He} is presumably balanced by convection and other transport loss mechanisms besides cross-field diffusion.

The energy confinement time of the bulk plasma electrons is given by

$$\tau_{E,e} \approx E_b / P_e \quad \text{s}, \quad (15)$$

where P_e is the total energy expended by the bulk electrons.

The ratio $\tau_{E,e} / \tau_p$ of the energy and particle confinement times for the bulk electrons is constant to within 10% over the pressure range 6-10 gauge μTorr . The invariance of the confinement time ratio with applied microwave power (or, more precisely, of an analogous quantity derived from data on the fast electrons in EBT-S and incorrectly applied to the discharge as a whole) has been claimed as evidence of neoclassical confinement in EBT.^{6,7,18} In the present discussion, however, the approximate constancy of the confinement time ratio follows theoretically simply from the fact that each cold electron entering the plasma consumes a (roughly) fixed amount of plasma energy and is balanced by an electron that is carrying away a constant fraction of the plasma electron energy as it leaves. Ultimately, experimentally, this constancy follows from the similar slopes of the intensity curves for H_α and molecular light in Fig. 1. Since the bulk plasma energy changes little with applied microwave power [The energy in the hot electron component may be an entirely different matter!], and the luminosity of the plasma increases slowly with power above 40 kW, the confinement time ratio, as calculated here for the bulk plasma, should vary only weakly with the applied power.

IV. ION ENERGY BALANCE

Visible spectrum measurements indicated from the beginning that the ion temperature T_i in EBT was low, but conflicting data were reported from charge-exchange measurements. The main purpose of this discussion of the ion energy balance in EBT-I is to reconcile the two sets of data. The bulk ion temperature is first calculated from the known atom density and energy distribution in the 37 kW EBT-I plasma. The contribution of the ions to the line profiles of Fig. 2 is then found to confirm this value of T_i . An examination of the ion contribution to the line shape is of independent interest for the theory of hydrogen spectral line shapes in plasmas. Finally, the high energy ions detected by charge exchange are examined as part of the overall power balance in the

discharge, and their behavior is compared with other ECRH experiments in an attempt to explain their origin.

A. Bulk ion temperature The ion energy balance in the discharge includes the following source and loss mechanisms: (i) charge exchange on the atoms in the plasma; (ii) ionization of H atoms; (iii) electron-ion collisional heating; and (iv) other less easily accountable processes such as diffusion or convection. Because the Coulomb collisional self-equilibration times for the bulk electrons and (at the temperatures calculated here) ions in this plasma are substantially below the gross particle or energy confinement times, the electrons and ions should be thermalized, possibly at widely different temperatures.³⁶ The terms corresponding to these four local mechanisms in the ion power balance equation are as follows (eV/cm³/s):

$$n_i n_H \langle \sigma_{CX} v \rangle (E_H - 1.5 T_i), \quad (16)$$

$$n_e n_H \langle \sigma_i v \rangle E_H, \quad (17)$$

$$5.7 \times 10^{-8} n_e n_i (T_e - T_i) / T_e^{3/2}, \quad (18)$$

and

$$-1.5 n_i T_i / \tau_{Di}. \quad (19)$$

In the steady-state EBT plasma the sum of Eqs. (16)–(19) is zero. Here $E_H \approx 2.1$ eV is the average energy of the atoms in the plasma (from Fig. 2); n_i , n_e , and n_H are the densities of ions, electrons, and atoms; T_e and T_i are the electron and ion temperatures; $\langle \sigma_{CX} v \rangle$ and $\langle \sigma_i v \rangle$ denote the charge-exchange and ionization rate coefficients;³² and, τ_{Di} is the diffusional loss time for the ions. Terms (16)–(18) set an upper limit on the local value of T_i , but term (19) is fundamentally important in maintaining the balance of particle numbers and will make T_i smaller. The maximum values of T_i ($\tau_{Di} \rightarrow \infty$), denoted by $T_i(\text{max})$, are listed in Table I along with the practical expected values of T_i obtained by setting $\tau_{Di} = \tau_p$ in Eq. (19).

B. Spectral line shape The equilibrium temperature of the ions in the bulk plasma has been shown above to be about 3 eV. Even if diffusional (particle or transport) losses were neglected, the ion temperature could not exceed 10 eV. A 3 eV ion temperature in this plasma is consistent with the H_α line shape observed in EBT-I.^{16,29,30} Measurements of H_α and H_β with a scanning monochromator and with an FPI (Fig. 2) showed no significant Doppler broadening corresponding to temperatures above the calculated $T_i \approx 3$ eV of Table I. The particle balance equations for the neutral atoms in this plasma show that the density of atoms at the ion temperature is between 30 and 50% of the total atom density, regardless of T_i . In particular, the local balance equation for the

density n_{Hf} of fast neutral atoms with an effective temperature determined by charge exchange on a group of hot ions having density n_{if} (as opposed to the density of the bulk ions n_{ib} , where the total ion density $n_i = n_{ib} + n_{if}$) includes terms for the production of these atoms by charge exchange, loss by ionization, and loss by charge exchange on the bulk ions. Assuming a low sticking probability (<0.2 , see ref. 50) for H atoms at the walls, in the steady state the fast atom density would be roughly

$$n_{Hf} = (n_H n_{if} / n_e) [\langle \sigma_{CX} v \rangle / (\langle \sigma_i v \rangle + \langle \sigma_{CX} v \rangle)], \quad (20)$$

where n_H is the given total hydrogen atom density, $\langle \sigma_i v \rangle$ is the electron-impact ionization rate coefficient, and $\langle \sigma_{CX} v \rangle$ is the charge-exchange rate coefficient corresponding to the temperature of the hot ions.³² In the absence of a hot ion component, $n_{if} = n_i$ and this equation yields the density of charge-exchange atoms at the ion temperature. Therefore, if the temperature of the bulk ions, T_i , had been significantly greater than the energy of the atoms seen in the spectrum of Fig. 1, the profile should have had easily detectable wider wings. In the EBT-I plasmas described here, no such wings were detected with a signal amplitude of more than 0.5% of the peak of the H_α profile. That level (about equal to the noise level in the observations) would correspond to fast charge-exchange neutral atom populations at (for example) temperatures of 30 or 10 eV that formed 2.7 or 1.6%, respectively, of the total atom population. (See the discussion of highly energetic ions in Sec. IV.C.)

The contribution to the spectra of Fig. 2 from charge-exchange atoms at the ion temperature can now be examined in more detail. The values of T_i in Table I for $\tau_{Dj} = \tau_p$ lie between the energies of slow and fast dissociation product atoms. If the ions got all their energy from the energy of dissociation product atoms in this plasma, T_i would be roughly 3.5 eV. [That is the solution $T_i = 1.5 E_H$ of the ion energy balance equation obtained from Eqs. (16)-(19) in the limit of infinite T_e and τ_D .] The calculated ion temperature is somewhat lower owing to particle and energy losses. The neutral atom particle balance [Eq. (20)] shows that for the T_i values of Table I, approximately 30% of the total atom density and, therefore, of the H_α intensity in the traces of Fig. 2, curves A-C, is produced by atoms at a temperature T_i . Hence, the line profiles of Fig. 2, curves A-C, are actually made up of emission from three groups of atoms roughly defined as follows: atoms with energies equal to that of slow dissociation products, thermalized atoms at T_i (possibly somewhat lower than the T_i values given in Table I), and atoms with energies equal to that of fast dissociation products. Some thermalization of these atoms may occur because

of reflection at the walls, but since atoms that have lost energy at the walls will tend to be ionized as they cross the plasma and since at least two components can be resolved in traces A-C of Fig. 2, it appears that collisional relaxation is not taking place between the three groups of emitting atoms. The presence of an emitting component at T_i in Fig. 2 (curves A-C) has two effects on the H_{α} line profile: the plateau found in the H_{α} spectrum of fast dissociation product atoms during experiments with electron beam bombardment of hydrogen gas⁵² is smoothed out. Also, the width of the wide component seen in Fig. 2 is somewhat less than that of the fast dissociation product spectrum observed⁵² in the electron beam experiments. (Energy loss in wall collisions will also contribute to both these spectroscopic effects.²⁹) When the discharge conditions were varied over the normal operating range, there was little change in either T_i or (by a factor of about two) in the relative amounts of fast and slow dissociation product atoms in the plasma. Thus, the width of the H_{α} line from EBT is almost independent of the discharge conditions. (At very high pressures, as in Fig. 2, curve D, the line profile contains only a single narrow component. T_e is low in that case, so that few atoms with energies above 1 eV can be produced by dissociation,²⁹ and the width of the profile shows that T_i is low.)

C. Highly energetic ions Charge-exchange measurements were performed on EBT almost from the beginning of machine operation. It was soon found that signals were obtained corresponding to high energy ions in the plasma. "Temperatures" of 30-300 eV or more were derived from fits to the data.^{5,16} A cesium stripping cell has been used in most work on EBT. Published count rate spectra of the neutral particle energy obtained from a cesium cell neutral energy spectrometer for an EBT-I discharge with about 48 kW of applied microwave power show a product of atom density times ion density, $n_i n_H = 6.2 \times 10^{20} \text{ cm}^{-6}$, for an ion population with a fit temperature of 33.5 eV (Ref. 16, p. 28). (Much smaller amounts of ions with fit temperatures of 82 and 680 eV are also shown there.) For the typical ion density of $\approx 1 \times 10^{12} \text{ cm}^{-3}$, this implies $n_H \approx 6 \times 10^8 \text{ cm}^{-3}$, which is almost two orders of magnitude below the neutral atom densities derived from the measured H_{α} intensity for the EBT-I discharges discussed here. In other words, the ions which produced the charge-exchange data form at most 1-3% of the bulk ion population. This interpretation of the charge-exchange data is consistent with the discussion of the H_{α} spectrum given in the preceding section (IV.B). The energy contained in these hot ions is less than 0.5 J and the power lost as they undergo charge exchange is low (<300 W). Some heating of the bulk ions by Coulomb collisions

with the hot ions also occurs. In the present case the upper bound for the power delivered to the bulk ions by collisions with the hot ions is 700 W. This level would lead to a doubling of the ion temperature given in Table I, but this was not observed spectroscopically. Thus, the density of the fast ions was probably on the order of 1% of the bulk ion density in the 37 kW EBT-I plasma, a fraction confirmed by the low level (or absence of) wider wings in the H_α spectrum (cf. the discussion following Eq. (20)). At times the fast ions have been treated as the bulk ions in the plasma in analyses of the plasma behavior in both EBT-I and EBT-S, and their effective energy has been reported as the bulk ion temperature.^{4-7,16} Indeed, it was recently found spectroscopically that at very high powers in EBT-S, atoms with energies on the order of 20 eV made substantially larger contributions to the H_α spectrum than in EBT-I. In that high-power case it thus appears that the fast ion population did form a larger part of the ion energy distribution⁵³ than in EBT-I.

The hot ions in EBT-I could not have been heated by Coulomb collisions with the plasma electrons. In addition, the potential gradient in the plasma measured by means of an ion beam probe corresponded to a smooth potential variation of roughly 200 V over a distance on the order of 8-10 cm.¹⁶ The resultant electric field is not sufficient to heat H ions to these energies, given the high ion-ion collision frequency at low bulk T_i and other effects. How could this plasma have produced any particles detectable by charge-exchange methods at all? It is beyond the scope of the present work to discuss this problem in detail, but ion heating has been observed by Bulyginsky *et al.*, during ECRH on the F1-1 tokamak.²² They found that the thermal charge-exchange energy spectrum characteristic of a $T_i=400$ eV ohmically heated plasma develops a high energy tail (at energies of ≈ 1 keV and above) during ECRH. A parametric mechanism involving the extraordinary wave was proposed by them for the ion heating during ECRH since hot ions were not observed during ECRH using the ordinary wave. Matching of the upper hybrid resonance, with an angular frequency ω_h given by³⁶

$$\omega_h^2 = \omega_p^2 + \omega_c^2, \quad (21)$$

where ω_p and ω_c are the plasma and cyclotron frequencies of the plasma, to the microwave frequency must occur somewhere in the plasma volume for this mechanism to be possible. The upper hybrid resonance is accessible at the typical magnetic fields, densities, and microwave frequencies used in EBT, so that this mechanism may explain, or at least contribute to, the energetic ion population detected by charge exchange.

V. CONCLUSION. POWER BALANCE IN A 37 KW EBT-I DISCHARGE

The power balances for the ions and for the bulk electrons in the T-mode have been examined in detail in this paper. In the first part of this section the power balance in a moderately high pressure (C-mode) plasma is examined. In that mode the nonthermal electron and ion populations are known to be small and the bulk plasma models of Secs. III and IV can be tested directly and are found to be consistent with the plasma behavior. Because the total bulk power consumption P_e of Sec. III (and table I) does not fully match the input microwave power, the relationships of the various nonthermal particles to the power balance in the T-mode plasma are examined in the next section to aid in constructing an overall power balance estimate for the 37 kW EBT-I discharge. The power balance of the discharge as a whole can be consistently explained by assuming that the hot electron component is directly heated by the microwaves and the bulk electrons are heated in Coulomb collisions with the hot electrons. The difference between the applied microwave power and the total power lost through the electron annuli, hot ions, and bulk electrons can be attributed to transport losses from the hot electrons at a level comparable to Bohm diffusion. A summary of the parameters derived from the spectroscopic data for the 37 kW T-mode EBT discharges concludes this paper.

A. C-mode discharge A simple example of the power balance in an EBT-I discharge is provided by a moderately high pressure discharge without significant hot electron or ion populations: the discharge of Fig. 1 at a filling pressure of roughly 20 gauge μTorr . In this plasma there are no hot rings and the x-ray bremsstrahlung detector typically indicated very low effective temperatures if it detected any signal at all,¹⁵ so it can be assumed that there is a single, thermal electron component. The H_α spectrum for this plasma is shown in Fig. 2, curve C. Since $T_e \geq 15$ eV according to probe measurements, the photon yield per entering molecule is roughly independent of the temperature. The data of Fig. 1 for 694 nm and Eq. (6) give a flux of 7.8×10^{15} molecules/cm²/s (9.5×10^{15} for the 720 nm data). Suppose all the microwave power ($P_{\mu W} = 37$ kW) goes into dissociating and ionizing H_2 and heating bulk electrons. Setting $P_m = P_{\mu W}$ in Eq. (9) and taking the effective minor radius of the plasma to be $a = 15$ cm, we find that $\epsilon_{H_2} \approx 250$ eV (205 eV for the 720 nm data). Comparing this value of ϵ_{H_2} with the total energy curve in Fig. 3, we find $T_e \approx 50$ eV (40 eV for the 720 nm data). If the plasma were somewhat more

diffuse ($a > 15$ cm), the resulting temperature would be lower, but still ≥ 20 eV. Thomson scattering measurements for plasmas in the C-mode gave $T_e = 30-40$ eV,¹¹ in fair agreement with the above value. In this plasma the density of hydrogen atoms is close to 1×10^{11} cm⁻³ [Eq. (1)], the particle confinement time is 0.4 ms [Eq. (12)], the total energy confinement time is 0.2 ms [Eq. (15) with $P_e = P_{\mu w}$], and $T_i \approx 2.5$ eV [Eqs. (16)-(19) with $\tau_{Dj} = \tau_p$]. This plasma is well described by the particle and energy balance developed in Sec. III for the bulk plasma electrons.

B. Power balance in the T-mode Power balance estimates including the hot ion and electron populations for the 37-38 kW T-mode discharges with nominal filling pressures of 6-10 μ Torr that have been analyzed in this paper are summarized in Fig. 4. There the numbers denote powers in kW. The lines with arrows that join boxed entries refer to transfer of energy from the microwaves to plasma constituents and among the charged particles in the plasma. The other lines (bulk ion heating by the hot ions is included arbitrarily in this group as it was not observed in the actual discharge) denote final dissipation of the applied power. (Most of the electron loss values are obtained from Table I. The electron heating term P_e is shown in Fig. 4 as balanced by the diffusional and convective energy flow from the bulk plasma.) The input microwave power is divided between heating the electron annuli, the hot ions, and the hot electrons in the toroidal plasma, with most of the power going to the latter and then to the bulk electrons.

ECRH acts more efficiently on electrons with higher energies than the bulk population, that is, on the "hot" electrons.^{13,19} The hot electrons, in turn, transfer energy to the bulk electrons through Coulomb collisions.^{13,36} The magnitude of the possible energy transfer between the hot and bulk electrons can be illustrated by some examples for conditions similar to those under which the measurements discussed in this paper were taken. The equilibration time for a hot electron component at temperature T_{eh} in the field of the bulk electrons is roughly

$$\tau_{eqh} = 3.4 \times 10^5 T_{eh}^{3/2} / ((1-\eta)n_e \ln \Lambda) \text{ s}, \quad (22)$$

where η is the fractional density of hot electrons. The power delivered to the bulk electrons in collisions with the hot electron component is then evaluated using the temperature relaxation equation.³⁶ This power is roughly

$$P_{hb} = 7.2 \times 10^{-25} \eta (1-\eta) n_e^2 V_p \ln \Lambda \times (T_{eh} - T_e) / T_{eh}^{3/2} \text{ W}. \quad (23)$$

Hillis *et al.*,¹⁷ measured a hot electron component with a density $\eta n_e = 2.5 \times 10^{11}$

cm^{-3} and temperature $T_{eh}=450$ eV in an EBT plasma with an applied power of 40 kW at 18 kHz. Assuming that this discharge is similar to the 6 μTorr case of Table I, where $n_e=7.7 \times 10^{11} \text{ cm}^{-3}$ and $T_e=120$ eV, and assuming that the hot and bulk electron populations occupy the same plasma volume, we find $P_{hb}=35$ kW, which is substantially greater than the calculated power dissipation by the bulk electron population. T_{eh} or η , therefore, are probably smaller in our 37 kW case. Figure 1.4 on page 4 of ref. 15 indicates that an x-ray bremsstrahlung temperature $T_{eh} \approx 250$ eV may be more appropriate. The total dissipation P_e of roughly 20 kW by the bulk electrons given in Table I can be provided by P_{hb} from Eq. (23) for $\eta=0.16$. (P_e is balanced by P_{hb} for $T_{eh}=250$ eV and $\eta=0.08$ at a filling pressure of 10 gauge μTorr .)

The assignment of the microwave power to the hot electrons in the first heating step is somewhat arbitrary since some direct rf heating of the lower temperature bulk population may occur, as in the C-mode discharge of Sec. V.A. This "indistinguishability" is indicated in Fig. 4 by a bold arrow which enters the block corresponding to the hot electron component and goes on to the bulk electron box. Because of the rapid energy transfer from the hot electrons to the bulk electrons, the hot electrons maintain the bulk plasma. In this respect they serve a function analogous to that of the fast electron tail in hollow cathode discharges. However, the action of the fast electrons in the two types of discharge is quite different: in a hollow cathode discharge, ionization and electronic excitation are predominantly caused by a hot electron population with an energy of 10 eV or more per particle since the bulk temperature is very low (a few eV) and the rate coefficients corresponding to the bulk electron population are orders of magnitude smaller than those for the fast tail.⁵⁴ In EBT, on the other hand, the rates for electron-impact atomic and molecular processes are essentially the same for the hot and bulk electrons, so that the hot electrons participate in these processes only in proportion to their relative density in the plasma. Calculations for a hot electron population with the parameters of the first example in the preceding paragraph confirm that most of the parameters listed in Table I are changed by no more than 20%. In the present 37 kW case, the apparent power expended in heating cold electrons, P_{He} , may be larger owing to the presence of the hot electrons, but its contribution to the total loss power is balanced by reductions in the other terms. Thus, it is sufficient for the purpose of an overall power balance estimate, such as that of Fig. 4, to assume that the hot electrons contribute to the bulk plasma loss processes in proportion to their density fraction η .

The role of energy losses from the hot electron population (aside from collisions with the bulk electrons as in Eq. (23)), especially in higher power EBT-S discharges, requires a different approach and will be examined elsewhere. However, the problem must now be considered briefly in order to complete the discharge power balance of Fig. 4. Cross-field Bohm diffusion⁵¹ is one possibility, although positive identification of such a diffusion law would require further analysis. As shown above, the power dissipated by the bulk electrons (P_e) can easily be provided by the hot electrons (P_{hb}). This leaves as much as 16 kW of power that must be accounted for beyond the heating requirements of the hot electron annuli and fast ions (described in the next paragraph). For the above examples of hot electron parameters (following Eq. (23)), Bohm diffusional loss (evaluated by Eq. (14) with E_D replaced by $\eta n_e k T_{eh} V_{pl}$, etc.) from the hot electrons can provide a power loss of the required magnitude. Thus, the above example with $\eta=0.32$ and $T_{eh}=450$ eV would yield a Bohm loss of roughly 45 kW, well in excess of the total applied power. It is possible to obtain a computed Bohm loss on the order of 15 kW by reducing the values of η and T_{eh} as in the previous examples. A slight enhancement of the high energy tail of the hot electron kinetic energy distribution (for example, as a result of the dynamics of the ECRH heating process) could also lead to substantially higher Bohm losses than from a thermal distribution at the nominal x-ray temperatures and densities. The estimated diffusional loss (assumed to be Bohm diffusion here) from the hot electrons is indicated in Fig. 4 by an arrow from the hot electron box to that for electron energy loss, from which in turn an arrow indicates an equal hot electron diffusion loss corresponding to a reasonable range of values of η and T_{eh} for the 37 kW discharge. Given that the apparent diffusional and convection losses from the bulk plasma are greater than or equal to the Bohm limit (Sec. III.C.), it is clear from existing data on EBT-S that some energy loss comparable to or in excess of Bohm losses from the hot electrons will have to be invoked to explain the power balance in the high power discharges.

In Fig. 4, the microwave power that is not absorbed by the toroidal electrons (hot and bulk) goes into heating the electron annuli and hot ions and, possibly, into non-plasma rf losses. The high particle energy and long decay times of the annuli formed in ECRH experiments in magnetic mirrors^{16,21} show that they are very well confined compared to the toroidal plasma in EBT. Most of the power delivered to the annuli is lost by Coulomb collisions with the toroidal plasma electrons and ultimately, adds to the power they can spend in

"processing" entering molecules. That power can be estimated using the classical Coulomb collision rate [cf. Eq. (23)]. This and other power losses for the annuli, including drift and scattering on plasma particles, synchrotron radiation, and bremsstrahlung (the mechanism by which they are observed), have been examined by Borowski et al.,²⁴ who also give a relativistic generalization of Eq. (23). As noted in Sec. IV, the hot ions could lose a total power of as much as a few hundred watts through charge exchange (the mechanism by which they are observed) and, in extreme cases, somewhat more through Coulomb collisional heating of the bulk ions. The bulk ions at $T_i \approx 3$ eV lose no more than 0.5 kW by diffusion (included under the "particle transport" entry for the electrons in Fig. 4). No data on rf power losses are available, but at a level of 3 kW or less, they would be sufficient to make up for the apparent discrepancies in the calculations leading to Fig. 4.

C. Summary The results of this paper can be summarized as follows: in a 37 kW T-mode EBT-I discharge, the plasma electrons ultimately lose most of their energy by ionization and excitation of H atoms, dissociation and ionization of entering molecules, ion heating, and, especially, heating of newly formed electrons. The last mechanism also accounts for diffusional, drift, and convective loss as it accounts for the contribution of particle balance to the bulk electron energy. About 60-70% of the microwave power applied to this plasma can be accounted for by these bulk electron loss processes. Spectroscopic data on the emission from hydrogen atoms and molecules in the plasma yielded the plasma parameters used in the power balance estimates. The parameters derived from this data have the following approximate values in the T-mode: hydrogen atom density $3-5 \times 10^{10} \text{ cm}^{-3}$, entering hydrogen molecule flux $3-5 \times 10^{15} \text{ cm}^{-2}\text{s}^{-1}$, and ion temperature 3 eV. The derived bulk electron energy and particle confinement times are 0.5-0.7 ms and $\leq 0.8-1.1$ ms, respectively. The bulk plasma model used here can consistently explain the properties of a moderate-pressure C-mode discharge in which hot electrons are absent. The T-mode plasmas require consideration of the hot electrons that are present in the plasma. The hot electron component, which is more directly heated by the microwaves, can transfer powers on the order of the calculated (bulk electron) dissipation to the bulk electrons by Coulomb collisions. The remainder of the applied power goes into diffusion from the hot electron component, heating the electron annuli and hot ions and, possibly, into non-plasma rf losses. The absolute values of the power losses calculated in this paper have associated errors of 20-30%; however, the basic conclusions about the power balance

derived here remain qualitatively true and consistent over the range of possible values that follow from these errors. Although the discussion given here has been limited to a rather low power EBT-I discharge, the results should be of use in analyzing the power balance in higher power discharges since the bulk plasma parameters are known to change little as the applied power is raised.

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Table I. Bulk Plasma Properties in EBT-1*

Fill pressure	6.0	7.0	8.0	9.0	10.0	$\mu\text{Torr gauge}$
$\overline{n_e}$	2.4	2.6	2.7	2.8	3.0	10^{13} cm^{-2}
T_e	120	108	95	82	70	eV
E_b	15.	15.	14.	12.	11.	J
n_H	4.1	4.4	4.6	5.2	5.3	10^{10} cm^{-3}
P_H	2.6	3.0	3.4	4.0	4.3	kW
P_{ei}	0.46	0.59	0.69	0.80	0.97	kW
P_{He}	19	20.	19	19	18	kW
Φ_{H_2}	2.6	3.3	3.7	4.3	4.8	$10^{15} \text{ cm}^{-2} \text{ s}^{-1}$
P_{H_2}	1.2	1.5	1.7	2.0	2.2	kW
P_e	23	25	25	26	25	kW
P_m	16	18	18	19	19	kW
$\tau_{p,C}$	0.81	0.76	0.72	0.64	0.62	ms
τ_p	1.1	0.99	0.92	0.83	0.78	ms
$P_D(\text{max})$	13	15	15	15	14	kW
P_{Bohm}	10.	9.0	7.3	5.6	4.4	kW
$\tau_{E,e}$	0.66	0.61	0.56	0.47	0.44	ms
$T_i(\text{max})$	8.5	9.0	9.1	9.1	9.4	eV
T_i	3.2	3.3	3.3	3.4	3.4	eV

* Except for those in the first four rows, the parameters listed here are derived from optical measurements on a T-mode discharge with combined microwave powers of 30 kW at 18 GHz and 7-8 kW at 10.6 GHz. These computations apply to a bulk toroidal plasma with an effective minor radius of 15 cm and major radius of 150 cm. The notation is explained in the text.

Figure Captions

Fig. 1. The pressure dependences of the relative intensities of light at 694 nm, 720 nm, and 656 nm (H_{α}), line-integrated electron density, and filling neutral density in an EBT-I discharge with 30 kW of 18 GHz and 7-8 kW of 10.6 GHz microwave power. The absolute values of these parameters are given in the text.

Fig. 2. The H_{α} spectrum from EBT-I under various discharge conditions.

Fig. 3. The average energy expended in breaking up a hydrogen molecule (curve H_2) and in breaking up the H_2^+ and H formed from that molecule (curves H_2^+ and H) inside a large plasma with an electron temperature T_e . Also shown are the total energy expended in dissociating and ionizing the molecule to obtain an ion pair (Dissoc.+Ioniz.) and the total energy to produce an ion pair and heat the product electrons to T_e .

Fig. 4. The power balance for a 37-38 kW EBT-I discharge in the standard operating range (T-mode). The numbers are powers in kW. The arrows denote transfer of energy to and between the charged particle species of the plasma. The values given at the end of line segments denote final dissipation of the applied power.

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Fig. 1

Fig. 2

Fig. 3

85X1594

Fig. 4.

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