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**Electron Heating and Confinement
Measurements in EBT-S Using
Thomson Scattering**

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MASTER

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ELECTRON HEATING AND CONFINEMENT MEASUREMENTS
IN EBT-S USING THOMSON SCATTERING

L. Bighel and J. A. Cobble

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ABSTRACT

Thomson scattering of ruby laser light was used to measure electron temperatures and densities in the ELMO Bumpy Torus-Scale (EBT-S) at Oak Ridge National Laboratory. The measurements were made primarily during May 1980, although some were taken during January 1980. The scattering system, which was designed for very low electron density measurements, features a 14-J ruby laser, a high-throughput spectrometer, and 15% quantum efficiency photomultipliers. The measured electron densities lie in the range $5 \times 10^{11} \text{ cm}^{-3}$ to $2.2 \times 10^{12} \text{ cm}^{-3}$ with electron temperatures from 50 to 500 eV. The radial profiles of T_e and n_e are reasonably flat over an 8-cm region from the plasma center outward. The dependence of T_e and n_e on microwave power input and on background pressure is discussed. The electron data are used to derive approximate values of the energy confinement time.

1. INTRODUCTION

The initial ELMO Bumpy Torus (EBT-I) has been described in the literature,^{1,2} and some Thomson scattering measurements on EBT-I have been reported.^{3,4} The ELMO Bumpy Torus-Scale (EBT-S) differs from EBT-I in two respects: the magnetic field on axis in EBT-S is higher in the ratio of 1.45:1, and the basic electron cyclotron heating frequency in EBT-S is 28 GHz versus 18 GHz for EBT-I. The 28-GHz microwaves are generated by a cw Varian gyrotron and are fed to the EBT-S cavities via an overmoded waveguide system.⁵ The 18-GHz power from klystron amplifiers is used for profile heating in EBT-S. During May 1980, EBT-S operated with Varian gyrotron No. 12. The earlier experimental runs during December 1979 and January 1980 were made with Varian gyrotron No. 7. Although still at a developmental stage, the gyrotrons were operated at continuous high-power output for long periods, at times in excess of one hour.

The laser scattering measurements were generally made in the stable T mode of operation,¹ with background pressures typically reaching 4 to 6×10^{-6} torr of hydrogen and with 28-GHz power output from the gyrotron P_{μ} in the range of 30 to 60 kW.

The electron densities in EBT-S are at the lower end of the range of applicability of incoherent Thomson scattering with ruby laser sources. Great care was therefore taken to maximize the detected scattered signal within the limits of EBT geometry and available ruby laser energy. The scattering system is described in Sect. 2 along with comments on the statistical reliability of the laser data.

The electron temperature and density profile measurements are discussed in Sect. 3. In Sects. 4 and 5, various experimental scaling trends are examined, leading to an expression for the energy confinement time $\tau_{Ee} \propto P_{\mu}$ for stable T-mode operation.

2. THOMSON SCATTERING SYSTEM

The scattering arrangement is shown schematically in Fig. 1. The Holobeam laser oscillator-amplifier unit is capable of delivering 14-J

Fig. 1. Thomson scattering apparatus on EBT-S.

pulses of 25-ns duration FWHM and normally generates (12 ± 1) J at one shot per minute for 100 to 200 shots per day. The beam is focused into the plasma to a 3-mm diameter along a horizontal midplane diameter by a 75-cm focal length lens. Scattered light, reflected off a mirror through a set of coated, aberration-corrected lenses, is collected in an F/3.5 Minuteman polychromator. Fiber-optics bundles carry the dispersed light to Varian 192 M series phototubes (quantum efficiency is $\sim 15\%$) in six discrete wavelength channels from 694 to 740 nm. Stray light rejection is achieved with the use of a ruby absorption filter.⁶

The laser and polychromator are in fixed, mechanically stable positions. Radial scans of the plasma are performed by small mirror rotations that preserve conjugate planes of the stationary lens system. An elongated observation window with water flowing between two plates of glass allows maximum transmission of scattered light while preventing the escape of microwaves from the machine. A corresponding observation dump is used to reduce laser light reflections into the polychromator. The beam itself is deposited on a water-cooled black glass oriented at Brewster's angle.

The scattering angle for the measurements reported is a variable that depends on the plasma position observed. Measurements of plasma space potential indicate that the approximate plasma center is 4 cm inboard of the cavity geometric center. The 8-cm scans from this point outward correspond to scattering angles of 75° to 69° . The design is such that roughly twice this range may be employed.

The photomultiplier signals are photographed on fast oscilloscopes. Figure 2 shows a set of scattered signals and the PIN photodiode laser monitor. There is no detectable stray light (indicated by no-plasma laser shots) in any of the five Thomson scattering channels, but plasma radiation is evident. The plasma light is due mainly to line radiation⁷ from molecules at the plasma surface. There is a minor contribution from aluminum impurities, and for EBT plasma conditions, bremsstrahlung is negligible. The main source of error is the poor statistics of the scattered signals. For example, the number of photoelectrons emitted from the photocathode of the middle channel is typically about four for every 10^{12} electrons/cm³.

Fig. 2. Oscilloscope traces of five photomultiplier channels and the photodiode signal for a typical laser shot. The poor statistics and plasma background light are evident.

To discriminate against plasma background, direct peak readings of carefully timed oscilloscope signals were used. The logarithmic intensities of individual channels are plotted against the square of the channel wavelength shift. Temperature is deduced from the slope of an unbiased, least-squares-best-fit line with appropriate blue shift corrections. In Fig. 3, several measurements taken one minute apart are shown. These are for constant plasma conditions during a typical EBT-S run: constant pressure, power, and resolution volume. The effects of plasma light on the data must be taken into account in determining the best fit for T_e .

The absolute values of n_e are determined by calibrating the system with Rayleigh scattering off nitrogen in the 694-nm channel with the ruby filter removed. A typical Rayleigh run is shown in Fig. 4. The density calibrations are done periodically at the extremes and in the middle of the 8-cm region; they show little variation and differ by about 10% as a function of radius.

3. ELECTRON TEMPERATURE AND DENSITY RESULTS

The typical operational procedure for an EBT-S diagnostic run is as follows:

1. The torus is filled with approximately 10^{-5} torr of hydrogen.
2. Next, 5-10 kW of 18-GHz power is added.
3. The 28-GHz gyrotron is brought up to the desired power value and allowed to stabilize.
4. The background pressure is reduced to the desired value, typically 4×10^{-6} torr.
5. The toroidal field error is adjusted to give low fluctuations (quiescent plasma) on the microwave interferometer signal.
6. The diagnostics run commences and continues as long as required or until the gyrotron crowbars (typically 30 min).

The ruby laser can be fired approximately once a minute, generating about six scattered spectra for each of five radial positions during a 30-min run.

Fig. 3. Logarithmic intensities of four individual channels plotted against the square of the channel wavelength shift for three consecutive laser shots on EBT-S.

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Fig. 4. Signal in the 6943 Å channel as a function of nitrogen pressure in EBT-S.

Some discussion is required about the statistical variations in the quality of scattered spectra under the extreme conditions of low n_e . Examples taken for analysis are the data obtained during four runs in EBT-S on May 14, 1980. Of a total of 113 laser shots, 101 had discernible scattered signals above plasma noise. Figure 5 shows a histogram of the number of spectra as a function of the total number of detected photons per spectrum for the 101 spectra.

Of these, 68 spectra were selected for determining T_e and n_e ; 11 were two-point spectra; 44 had a correlation coefficient of $r \geq 0.95$; eight had $0.85 \leq r \leq 0.95$; and five had $0.75 \leq r \leq 0.85$. The lengths of the four runs on May 14, 1980, were 25, 48, 24, and 36 min at 28-GHz power levels of 49, 54, 62, and 30 kW, respectively. The individual values of T_e and n_e for the 54-kW run are shown as a function of radial position in Fig. 6. Also shown are the means and standard deviations. There is considerable spread in the values of T_e and n_e . The averaged values of these parameters at each radial position have large error bars. The results described below are generally averages over two to eight laser shots with only a few single-shot data points.

Figures 7 and 8 show radial profiles of T_e and n_e for several 28-GHz microwave power levels at constant background pressure and with 5 to 10 kW of 18-GHz profile heating. Within the large error bars, the profiles are reasonably flat over the 8-cm range for all values of microwave power. The values of T_e and n_e averaged over the profile are used to derive empirical scaling laws in Sect. 4.

In a different series of experiments the 28-GHz power was kept constant while the background pressure of H_2 was varied. The scattering measurements in this case were all taken at the one radial position near the plasma center ($r = -4$ cm). The values of T_e and n_e used for scaling with pressure are averages of up to three spectra for each pressure setting.

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Fig. 5. Histogram of the number of spectra as a function of the total number of detected photons (in all channels) per spectrum for 101 laser shots (May 14, 1980).

Fig. 6. Measured values of T_e and n_e as a function of radius during one run on EBT-S with $P_{28} = 54$ kW, $P_{18} = 10$ kW, and 4×10^{-6} torr of H_2 . The open circles are the arithmetic means with standard deviations as error bars.

Fig. 7. Radial profiles of T_e for several values of 28-GHz microwave power at $4-5 \times 10^{-6}$ torr of hydrogen.

Fig. 8. Radial profiles of n_e for several values of 28-GHz microwave power at $4-5 \times 10^{-6}$ torr of hydrogen.

4. SCALING OF T_e AND n_e WITH MICROWAVE POWER AND WITH BACKGROUND PRESSURE

The two EBT-S parameters that are easily adjustable externally are hydrogen background pressure and microwave power. Experimental scaling of T_e and n_e with pressure involves keeping constant the gyrotron power and staying in the T mode where the fluctuation level is low. Scaling with microwave power at constant pressure, also in the T mode, is at this time limited only by a self-imposed power limit on gyrotron No. 12. It is expected that higher power levels will be available from gyrotron No. 5 in the not-too-distant future.

Figures 9 and 10 show T_e and n_e at $r = -4$ cm as a function of background pressure for 30 kW of 28-GHz microwave power. The central electron density exhibits a broad plateau at $(1.3 \pm 0.2) \times 10^{12} \text{ cm}^{-3}$ between 5 and 15×10^{-6} torr. At pressures below and above this range, there are indications of a fall in n_e .

The central electron temperature increases with decreasing pressure as predicted by theory.⁸ The temperature rises from about 50 eV at 2×10^{-5} torr to 150 eV at 3×10^{-6} torr.

The behavior of n_e (radially averaged over the 8-cm range) with microwave power at constant pressure is shown in Fig. 11. The electron density increases approximately as the square root of microwave power over the available range of P_μ , as predicted by theory.⁸

Figure 12 shows how the value of T_e (radially averaged over the 8-cm range) scales with P_μ at constant pressure. The empirical dependence is $T_e \propto P_\mu^{3/2}$ over the available range of microwave power. This dependence is in agreement with the results from January 1980, shown in Fig. 13, which were taken with a different gyrotron and microwave distribution system. The systematic difference between the May and the January results can be partly explained in terms of the differences in the microwave systems and the uncertainties in the measurement of microwave power input to the plasma. There is also less complete laser data from the runs in January than from those in May. This is a consequence of two facts: gyrotron No. 7 gave shorter average runs than gyrotron No. 12 and the radial scanning facility for Thomson scattering was not available in January.

Fig. 9. T_e as a function of background pressure for a fixed value of microwave power.

Fig. 10. n_e as a function of background pressure for a fixed value of microwave power.

Fig. 11. n_c as a function of total 28-GHz microwave power (May 1980).

5. ENERGY CONFINEMENT

The electron energy confinement time can be defined as follows:

$$\tau_{Ee} = \frac{\int (3/2) n_e k T_e dV}{P_{\mu c}},$$

where $P_{\mu c}$ is the amount of microwave power that heats the core electrons in EBT at the fundamental electron cyclotron frequency.

The laser scattering measurements of T_e and n_e provide radial profile information over an 8-cm region outward from the plasma center. Assuming azimuthal symmetry and an effective radius of 9.4 cm⁹ for the core plasma, the volume-integrated core electron energy can be estimated.

The microwave power that heats the core plasma must be accounted for by subtracting losses. System transmission losses — as in the miter bends, mode conversion, the mode filter, and the manifold — amount to approximately 30%. Some small percentage is lost to microwave traps in the cavities (e.g., the water windows for laser detection and the laser beam dump). With profile power neglected, ring heating accounts for another 10% of total gyrotron power. This is determined from measurements of ring temperature, density, lifetime, and estimates of ring volume.¹⁰ The fraction that goes to the core may be taken to be the ratio of the volume of the core plasma to the total plasma volume in the fundamental resonance region. This fraction is about 12%⁹ of the total gyrotron output. This estimate has been verified by calculating the electron power balance for several measured plasma parameters in EBT-S.¹¹ It was shown that the total power loss from the electrons via heat and particle diffusion, electron-ion heat transfer, ionization, and radiation was roughly equal to the estimated microwave power input.

In Fig. 14, τ_{Ee} is shown as a function of total gyrotron power P_{μ} for T-mode operation assuming a constant 12% coupling to the core. The uncertainties in the values of τ_{Ee} (not shown on the graph) are compounded from the uncertainties in the 2-D T_e and n_e profiles, the effective plasma radius, the estimate of $P_{\mu c}$, and the neglect of core heating by

Fig. 12. T_e as a function of total 28-GHz microwave power (May 1980).

Fig. 13. T_e as a function of total 28-GHz microwave power (January 1980).

Fig. 14. Electron energy confinement time as a function of total 28-GHz microwave power (May 1980).

the rings. Notwithstanding the large level of uncertainty, τ_{Ee} shows reasonably linear dependence on P_μ , with values ranging from 2 ms at 30 kW to 4 ms at 60 kW.

6. SUMMARY

The Thomson scattering measurements presented in this report were made on EBT-S during May 1980 and during January 1980.

1. The measured electron temperature ranges from 50 eV to 500 eV for electron densities in the range 5×10^{11} to $2.2 \times 10^{12} \text{ cm}^{-3}$.
2. The temperature and density profiles are quite flat over an 8-cm region outward from the plasma center.
3. For constant microwave power the temperature scales approximately inversely as background pressure, and the density is constant over a wide pressure range with a falloff at very high and at very low pressures.
4. The following empirical scalings with microwave power at constant pressure were observed:

$$T_e \propto P_\mu^{3/2} ,$$

$$n_e \propto P_\mu^{1/2} ,$$

and

$$\tau_{Ee} \propto P_\mu .$$

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