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MEASUREMENTS IN THE TMX-U TANDEM MIRROR

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INITIAL SIMULTANEOUS THOMSON-SCATTERING MEASUREMENTS
IN THE TMX-U TANDEM MIRROR

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ABSTRACT

In this report, we briefly describe the TMX-U Thomson-scattering systems; we compare TMX-U velocity-distribution measurements with computer modeling; and we present and discuss our first simultaneous measurements of end-plug and central-cell electron temperatures.

INTRODUCTION

This document contains a summary of the initial Thomson-scattering electron temperature (T_e) measurements on the TMX-U. Independent Thomson-scattering systems were used to obtain simultaneous measurements in the east end plug (at the potential peak) and in the central cell (at the midplane). All of the experimental operations covered in this report examined thermal barrier start-up. These experiments were characterized by low densities in both the central cell and end plugs, which make Thomson-scattering measurements difficult because of the low scattered light levels; nevertheless, we observed evidence of non-Maxwellian electron distributions that were predicted by computer modeling of our electron-cyclotron-resonance-heated (ECRH) plasmas.

Our experiments also showed that ECRH produced energetic, mirror-confined electrons.¹ Each end plug has two 28-GHz gyrotrons, each delivering over 100 kW of power to the resonance locations. This power heats the electrons

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much faster than their Coulomb-scattering rate. Such strong ECRH heating produces the non-Maxwellian electron distribution functions that are required for thermal barrier formation. Diamagnetic-loop, x-ray, and electron-cyclotron-emission diagnostics,^{2,3} all indicate that a large fraction of the plug electrons have a mean energy of 30 to 100 keV, with the distribution continuing beyond 100 keV.⁴ The plug Thomson-scattering system measures only the lower energy electrons. We call these the warm, end-plug electrons. These electrons control the plasma potential and particularly the central-cell, ion-confining potential. Our early experiments demonstrate the need for microwave heating at the potential peak to maintain the plugging of axial end losses.⁴

On shots with simultaneous T_e measurements in the central cell and east end plug, we usually observe that the end-plug, warm-electron temperature exceeds the central-cell electron temperature. The end-plug, warm-electron temperature can be as high as 5 to 10 times that of the central cell. In contrast, measurements in our previous TMX experiment (without ECRH) showed smaller differences between the end-plug and central-cell temperatures.⁵

DESCRIPTION OF SYSTEMS

There are two independent Thomson-scattering systems operating on TMX-U, the locations of these systems are shown in Fig. 1. Each of these systems is similar to the systems that we used on TMX.⁶ Figure 2 is a layout of TMX-U east-plug system components. The central cell system is very similar to the east plug system. The main difference between these new systems and the ones used on TMX is the use of forward angle scattering ($\sim 42^\circ$) on TMX-U rather than the usual 90° scattering used on Thomson-scattering diagnostics. For a given temperature, this smaller angle narrows the Doppler width of the scattered light spectrum, allowing higher temperatures to be measured by a polychromator without an excessive wavelength spread. Also, a narrower distribution improves the signal-to-noise ratio in the presence of background plasma light.

In both east plug and central cell systems, we use a 12-J, single-pulse ruby laser. The central-cell viewing optics can image three radial positions: $R = 0, 8,$ and 15 cm; however, to date, we have made T_e measurements only at $R = 0$. The east plug system images a single point at $R = 0$ cm. In both

Figure 1. Location of the Thomson-scattering systems on TMX-U as related to magnetic field B , potential ϕ , and density n_e .

Figure 2. Components of the east-plug Thomson-scattering system.

systems, each viewing optic chain is followed by a polychromator that separates the scattered light into 10 wavelength channels. The light in each channel is measured by a photomultiplier (PM) tube. The output of the PM tubes is read by a computer or can be recorded on film from oscilloscope cameras.

Figures 3 and 4 are examples of measured spectra from the end plug and central cell. These measurements are from different days and under different experimental conditions. Like much of the TMX-U data, a non-Maxwellian feature is evident in these figures. As shown in these figures, we often approximate the distribution function as a sum of two Maxwellian components, although, in reality, the distribution is probably a more complex, continuous function.

COMPARISON BETWEEN MEASUREMENTS AND COMPUTER MODELING

A Monte Carlo code⁷ has been modified to produce electron distributions based on the parameters of our experimental, ECRH-heated plasmas. Figure 5 is a plug electron distribution for a plasma with parameters similar those in our July 15, 1983, experiments. As seen in this figure, this distribution is anisotropic and non-Maxwellian; therefore, it is no longer possible to describe the plasma by an electron temperature. However, temperatures, or mean energies, can be assigned to portions of the distribution. Figure 6 is an enlargement of the low energy portion of the distribution of Fig. 5, and also details the locations of the wavelength (energy) channels of our east-plug, Thomson-scattering system. As evident from Fig. 6, Thomson-scattering can measure only a small fraction of the total distribution, and the 677-eV portion is only about 10% of the total distribution. This is one of the difficulties in making plug Thomson-scattering measurements on TMX-U. The electron density of the total distribution of Fig. 5 is $2 \times 10^{11} \text{ cm}^{-3}$, which matches our experiments in July 1983. This means that the portion of the distribution that could be seen by Thomson-scattering would have a density of $\sim 2 \times 10^{10} \text{ cm}^{-3}$ --too low for a measurement. Our systems were designed to measure electron density, $n_e \geq 1 \times 10^{12} \text{ cm}^{-3}$, $50 \leq T_e \leq 1500 \text{ eV}$. However, on another day when the plug density was higher, we did measure a non-Maxwellian distribution (Fig. 3) that is similar to the $f(E_{\parallel})$ distribution function shown in Fig. 6.

Figure 3. East-plug Thomson-scattering electron temperature measurements showing a non-Maxwellian distribution.

Figure 4. Central-cell Thomson-scattering electron temperature measurements with a non-Maxwellian distribution.

Figure 5. End-plug electron distribution functions, $f(E_{\perp})$, $f(E_{\parallel})$, produced by a Monte Carlo code, for an ECRH heated plasma similar to those of the July TMX-U experiments.

Figure 6. Low energy portion of the distribution functions, $f(E_{\perp})$, $f(E_{\parallel})$ of Fig. 5. Also shown are the Thomson-scattering energy (wavelength) channels in the end plug.

Monte Carlo code modeling of our central-cell plasmas can also show non-Maxwellian electron distributions at low densities for $n_e = 1 \times 10^{11} \text{ cm}^{-3}$ (Fig. 7). In this case, the higher energy tail is due to plug electrons that have enough energy to cross the thermal barrier into the central cell. The plug electrons have had enough collisions to have a perpendicular energy component, but not enough to relax to a single Maxwellian distribution. The $f(E_\perp)$ distribution in Fig. 7 can be compared with Fig. 4--a sample central-cell Thomson-scattering measurement that has a similar non-Maxwellian character. Power balance in TMX-U indicates that a central-cell bi-Maxwellian distribution, with a significant tail, cannot exist for $n_e > 3 \times 10^{11} \text{ cm}^{-3}$.

INITIAL SIMULTANEOUS CENTRAL-CELL AND EAST PLUG T_e MEASUREMENTS

Table 1 lists our simultaneous central-cell and east-plug T_e measurements, which are plotted in Fig. 8. Because of the low densities ($3 \times 10^{11} < n_e < 2 \times 10^{12} \text{ cm}^{-3}$) and the spreading of the electron distribution, the error bars on these measurements are quite large. At best, these temperatures are accurate only to about a factor of two. Many of these measurements show a large difference between end-plug (T_{ep}) and central-cell (T_{ec}) electron temperatures, larger than can be attributed to the error bars. On TMX, we often measured $T_{ep} \simeq 2T_{ec}$ (Fig. 9). However, several of the TMX-U measurements exhibit $T_{ep} > 2T_{ec}$, which we attribute to the ECRH heating in the plug region. The variation in the electron temperature along a field line is consistent with the presence of a thermal barrier.

In this data there is no clear correlation between a large T_{ep}/T_{ec} ratio and end plugging. Only two of these shots showed evidence of plugging on the east end at the time of the T_e measurement. It is possible that low densities cause some of these central-cell plasmas to have a higher temperature tail that is below the sensitivity limit of our Thomson-scattering system. This possibility would reduce the effective temperature ratio.

From our initial data in Table 1, we have begun to develop a statistical data base. For example, in the shots with the 10-kG ECRH system on, 73% had $T_{ep} > 160 \text{ eV}$ and $T_{ep} > 2T_{ec}$. Similarly for shots without the 10-kG ECRH, 66% had $T_{ep} < 160 \text{ eV}$ and $T_{ep} < 2T_{ec}$. The two shots with end plugging had the highest end-plug electron temperatures--0.66 and 0.68 keV. The central-cell electron temperature, in the experiments reported here, is

Figure 7. Central-cell electron distribution functions, $f(E_{\perp})$, $f(E_{\parallel})$, produced by a Monte Carlo code, for an ECRH heated plasma, similar to that of Fig. 5.

Table 1. List of simultaneous central-cell and east-plug T_e measurements that are plotted in Fig. 8.

Date (1983)	Shot no.	$T_{ec}(eV)$	$T_{ep}(eV)$	ECRH 5-KG	ECRH 10-KG	East-end plugging
10-11	3	76	84	Yes	No	No
	14	21	19	No	No	No
	23	32	199	No	Yes	No
10-14	20	63	80	Yes	No	No
	25	70	150	Yes	No	No
	30	40	103	Yes	No	No
10-18	31	56	359	Yes	No	No
	15	63	34	Yes	No	No
	23	55	52	Yes	No	No
10-19	22	30	139	Yes	No	No
	26	215	173	Yes	No	No
	14	180	251	Yes	No	No
10-31	15	37	78	No	No	No
	16	29	210	Yes	No	No
	17	27	247	Yes	Yes	No
11-1	18	42	578(T_{a11})	Yes	Yes	No
	20	68		Yes	Yes	No
	25	102		Yes	Yes	Yes
11-2	32	40	26	Yes	Yes	No
	33	47	166	Yes	Yes	No
	8	431	575	Yes	Yes	No
11-2	9	134	115	Yes	Yes	No
	12	29	203	Yes	Yes	No

Table 1. (continued)

Date (1983)	Shot no.	T_{ec} (eV)	T_{ep} (eV)	ECRH 5-kG	ECRH 10-kG	East-end plugging
11-4	4	108	326	Yes	Yes	No
	5	302	679	Yes	Yes	Yes
	10	116	287	Yes	No	No
	12	24	92	Yes	Yes	No
	16	72	252	No	Yes	No
	22	68	121	Yes	Yes	No
	24	33	169	Yes	Yes	No
	36	147	217	Yes	Yes	No
	37	19	575	Yes	No	No

Figure 8. Comparison of simultaneous east-plug and central-cell Thomson-scattering electron temperature measurements on TMX-U.

Figure 9. Comparison of simultaneous east-plug and central-cell Thomson-scattering measurements on the TMX experiment.

generally below 0.2 keV, although values as high as 0.30 and 0.44 keV are shown in Fig. 8. This figure also indicates that T_{ep} is always greater than T_{ec} , considering the error bars on these measurements.

Because of the density of these experiments ($n_e \leq 2 \times 10^{12} \text{ cm}^{-3}$), there is up to a factor of two uncertainty in these initial measurements. Even given a factor of two uncertainty, these data show that TMX-U is operating with higher electron temperatures than the previous TMX device,⁵ which operated without ECRH.

Simultaneous Thomson-scattering measurements will continue to be used to monitor the difference in temperature between the end plug and central cell, which is an important feature of the thermal-barrier concept. This feature will be explored in future TMX-U experiments at higher densities in which more accurate and detailed measurements will be possible. In addition, the high-density experiments will allow more detailed comparisons with our theoretical models.

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