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Summary of Thomson-Scattering Data From the Tandem Mirror Experiment (TMX)

Abstract

We provide a synthesis of our Thomson-scattering measurements of electron temperature (T_e) and density (n_e) for the Tandem Mirror Experiment (TMX). TMX operated in two modes—high and low T_e. When performing in the high T_e mode (in general >100 eV), heating the central-cell ions with neutral beams raised T_e in the end plug. We achieved a maximum T_e of 260 eV in the east end plug. Specifically, our experiments demonstrated that in the end plug, the radial T_e profiles were flat to r = 5 cm; the ratio of potential (ϕ_p) to T_e ranged between four and six. In addition, we found that although T_e in the central cell was generally comparable to that in the plug, it was often not constant along a magnetic field line. Under some conditions a non-Maxwellian electron distribution may have been present.

Introduction

This final report on Thomson-scattering summarizes the electron temperature (T_e) and density (n_e) data gained from the two Thomson-scattering systems used on the Tandem Mirror Experiment (TMX), a machine that operated at Lawrence Livermore National Laboratory (LLNL) from 1979-80. A detailed description of the electron power flow for a few well-documented operating conditions, based on these Thomson-scattering measurements has been previously described by Grubb.[1,2]

The TMX[3,4] consisted of a long central cell or solenoid plugged at each end by minimum-B mirror cells (Fig. 1). High-density plasmas were maintained in the end plugs by the injection of neutral beams at energies between 15 and 18 keV. (For some experiments a small amount of higher-energy beam current—approximately 32 keV—was injected into the plugs.) A plasma with lower energy and density was contained in the central cell. This central-cell plasma was fueled by gas input either from the two gas boxes located near the transition coils or from the puffer located on the central-cell midplane.

Whereas the TMX proposal[5] predicted a T_e of 200 eV in the end plugs, during the actual operation of TMX we achieved above 200 eV on 15 occasions (see Table 1). We place the "official" high-electron temperature in the plugs at 260 eV,[3] although there were two even higher shots. We have confidence in this 260 eV value, considering the probable errors in the measurements. However, as discussed below, TMX did not always achieve these high-electron temperatures, and T_e was not always constant along magnetic field lines.

There were two independent Thomson-scattering systems on TMX[6]—one located on the midplane of the east end plug, and another located on the midplane of the central cell (Fig. 2). We could measure with the east-plug system at radial positions of r = 0, 5, 10, and 15 cm. This system was in use during the entire operation of TMX. The central-cell system, which could measure at only r = 0 cm, was installed shortly before the shutdown of TMX. Thus, a very limited amount of data is available from the central-cell system, and we must base many of our conclusions on the information gained from the instrument on the east end plug.

The electron temperature, obtained with a given amount of input neutral-beam power, can be greater in one end plug of a tandem mirror than in a single mirror. In fact, the TMX east end plug often achieved electron temperatures three to four times higher than those of 2XIIB (a similar single-cell mirror machine that operated at LLNL from 1976-78) when 2XIIB operated with neutral-beam input power comparable to one of the TMX end plugs. Since TMX had a large-volume plasma in the central cell, such an increase in T_e indicates a hundredfold improvement in electron energy confinement.[7] This escalation was possible because of two conditions: the TMX central cell supplied the low-energy

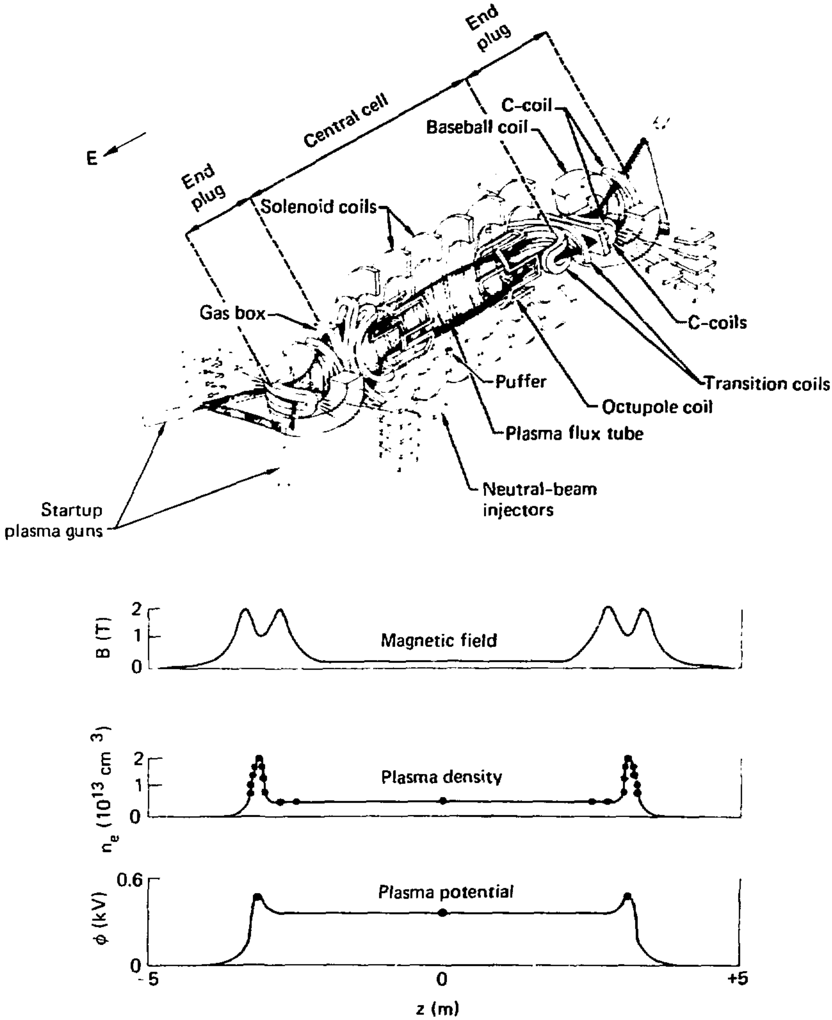

Figure 1. TMX magnet geometry and axial profiles.

Table 1. Summary of TMX electron temperature (T_e) measurements > 150 eV.[a]

Date	Shot no.	T_e(eV)
7-20-79	10	162
	18	166
7-25-79	27	171
9-17-79	22	219
	27	187
	28	157
	29	182
9-21-79	35	273
	43	152
	44	192
9-25-79	13	154
	54	166
	55	209
	57	192
9-26-79	16	229
	17	174
	22	260
	35	155
	55	153
9-28-79	22	194
	29	187
	36	182
	38	189
	39	188
	43	173
	48	206
	50	158
	51	156
	52	169
	53	152

Date	Shot no.	T_e(eV)
9-28-79	57	172
	58	164
	59	155
10-5-79	22	170
10-9-79	9	167
	15	164
11-5-79	10	200
	11	164
	12	196
	14	191
	15	170
	62	196
11-21-79	30	163
	34	165
	35	163
	36	163
	38	176
	42	169
	43	187
11-27-79	40	162
	51	168
11-28-79	49	156
	51	156
11-30-79	20	174
	40	197
	41	171
	42	177
	44	189
	47	213

Date	Shot no.	T_e(eV)
12-5-79	32	179
	34	184
	35	199
	45	220
12-6-79	17	162
	32	177
	40	151
	70	155
12-11-79	29	152
	34	164
	37	171
	40	159
	42	159
	48	178
	53	196
	54	195
	55	174
12-12-79	41	162
12-13-79	80	155
	81	168
2-7-80	23	176
	24	156
	26	222
2-8-80	14	161
3-28-80	19	170
5-23-80	43	157
	59	189

Date	Shot no.	T_e(eV)
5-27-80	6	173
	66	151
7-9-80	27	232
	28	159
	30	172
7-18-80	49	155
8-14-80	10	190
	11	199
	39	341
8-18-80	24	185
8-19-80	8	156
	37	153
	46	227
	49	166
	50	176
	54	152
	63	167
	68	194
	69	244
	87	172
	93	204
	95	177
	96	173
	97	163
	98	224
8-22-80	44	190
	71	177

[a]All measurements were in the east plug at radius ~ 0 cm.

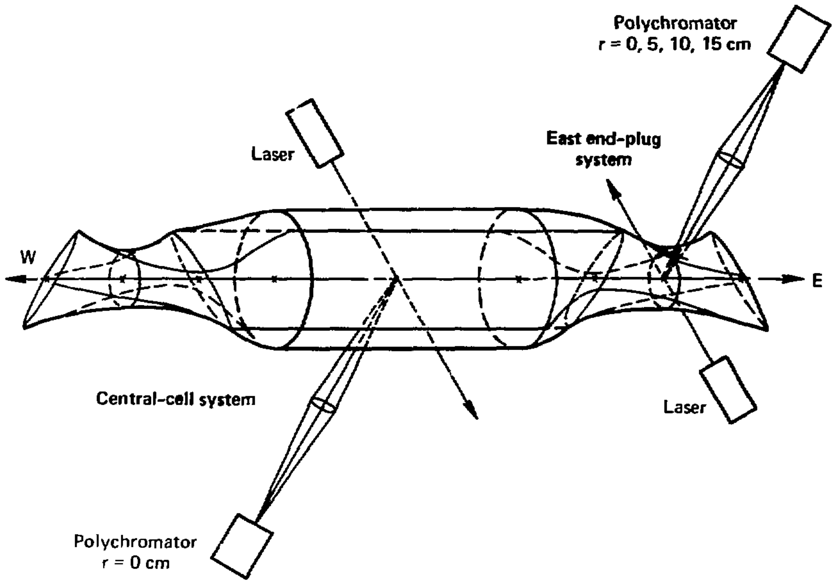

Figure 2. Location of the two TMX Thomson-scattering systems on TMX with respect to the magnetic field lines. Polychromators and lasers are two of the components of each system.

plasma required for end-plug microstability, and the plasmas were decoupled from the end walls of the plugs.[8]

TMX had two general modes of operating: one was the high T_e mode (in general >100 eV) described above, and the second was a lower T_e mode in which the T_e scalings were close to those observed in the 2XIIB experiment. Table 1 lists all TMX shots in the plug with a T_e above 150 eV. These shots occurred for various combinations of experimental operating parameters such as beam current, gas fueling, and magnetic field.

While it was not always completely clear what caused the experiment to operate in the high and low modes, several mechanisms have been tentatively identified. TMX was observed to drop from the high T_e to the lower T_e mode when the central cell received too much fueling gas from either the gas boxes or the central-cell puffer. Also, a vacuum leak in the west-plug region caused lower electron temperatures in the east plug. (For details, see the following sections on Electron Temperature Scaling and the Comparison of Temperature Measurements in the Plug and Central Cell.) These results, along with observations by Pickles, (as reported by Correll[9] and the TMX Group[10]) indicate that ultimately, T_e was dependent upon vacuum conditions.

This summary report employs 18 representative figures to depict the pertinent data gathered by the two Thomson-scattering systems on TMX. As appropriate, we have compared our findings to those of single-cell mirrors. In the final section we summarize the information we will apply to our next-generation machine, TMX Upgrade. This new experiment will begin operation in the spring of 1982.

Radial Profiles of Temperature and Density

Radial profiles of the electron temperature (T_e) in the east end plug are shown in Fig. 3 for both puffer and gas-box fueling. These data are from shot-by-shot scans taken during operation in a high T_e mode. Note that in this figure the gas-box profile is relatively flat to r = 5 cm; in contrast, the puffer profile has dropped slightly at 5 cm. Both profiles drop sharply between 5 and 10 cm. We also checked at 15 cm, but there was not enough plasma at that radius to measure.

Figure 4 illustrates radial profiles of both T_e and density (n_e) in the plug and compares these with our T_e and n_e measurements in the central cell. The temperature and density points for each shot are paired vertically. For this scan, the plug measurements at r = 0 and 5 cm were made simultaneously and are matched left-to-right. Because the plug system at r = 10 cm was not calibrated for density, those data are not available.

In this scan illustrating puffer fueling (Fig. 4), both T_e and n_e are flat to 5 cm. The error bars on each measurement are determined from fits to the scattered wavelength spectrum—measured by the photomultiplier tube (PM) channels—that are $\pm\sigma$ (standard deviation) from the best Gaussian fit. The statistical σ for each PM is measured after each shot and is used as a weighting factor in the fitting.[6]

Radial measurements of density profiles in the east plug by other diagnostics show that T_e scales radially as $(n_e)^2$.[11]

Comparison of Temperature and Density Measurements Before and After Beam Turnoff

Experiments were conducted in which neutral beams in the east plug were turned off earlier than those in the west end [Fig. 5(a)]. Note that

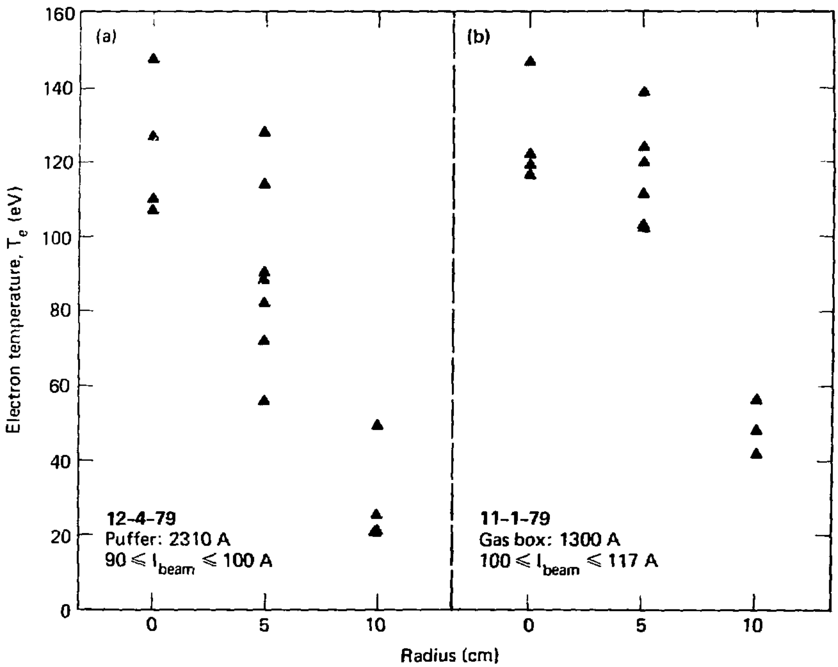

Figure 3. Radial profiles of the east-plug electron temperature (T_e) contrasting gas fueling by (a) the puffer in the central cell with (b) the gas boxes near the transition coils.

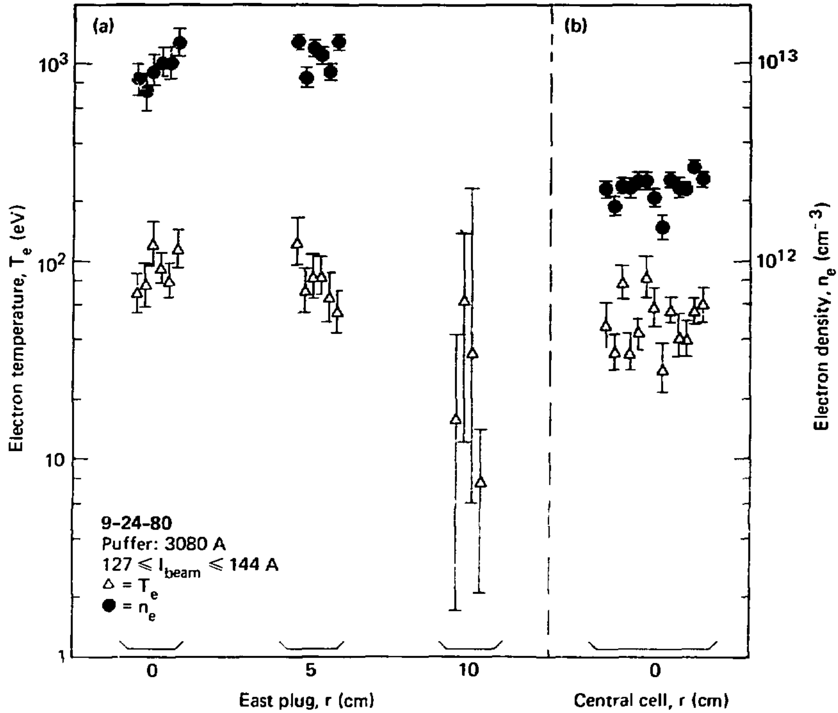

Figure 4. Radial profiles of (a) east-plug electron temperature (T_e) and density (n_e) compared to (b) central-cell measurements for indicated values of puffer fueling and neutral-beam heating. To avoid overlapping data, measurement (T_e) points were offset.

density (n_e) in the east plug ($r = 0$ cm) begins to drop within 1 ms of the east beam turnoff. However, at the same time the electron temperature (T_e) has not changed; this implies that the plug potential (ϕ_p) is also still high. At 5 ms after beam turnoff, n_e has continued to drop, and T_e has also dropped considerably.

The results of this temporal behavior of T_e and n_e can be seen in the current lost from the east end [Fig. 5(b)], as measured by an end-loss analyzer.[12] Most of this end-loss current can be traced to escaping central-cell ions. In the steady-state operation of the east plug ($t = 10$ to 15 ms), the ϕ_p is greater than the central-cell potential (ϕ_c), and the central-cell ions are electrostatically confined. At 1 ms after beam turnoff, T_e (and presumably ϕ_p) has not changed, although n_e has begun to decrease. The central-cell ions are still confined, and the end-loss current has dropped because rf fluctuation levels have decreased.[13,14] After 3 ms, T_e drops, and ϕ_p is no longer high enough to confine the central-cell ions; this causes a large end-loss current. This T_e data corroborates other evidence for the plugging effect of a tandem mirror.[3,15]

Figure 6 shows shot-by-shot radial profiles of T_e for a similar experiment in which the east-plug beams were terminated at $t = 24$ ms and the

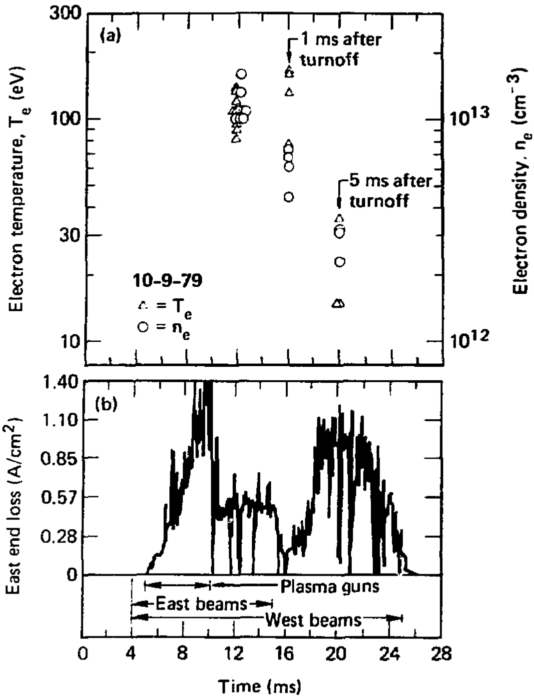

Figure 5. Comparison of (a) time variation of east-plug electron temperature T_e and n_e to (b) loss of current from the east end plug density. The radius is 0 cm.

west-plug beams at t = 28 ms. At r = 0 and 5 cm, T_e is similar at both t = 16 and 25 ms. But at r = 10 cm, T_e at 25 ms has dropped from its steady-state value. This fall demonstrates that after the input power to the plasma is terminated, electrons located at larger radii lose energy more rapidly than those in the core of the plasma. As in the previous experiment (Fig. 5), n_e at r = 0 cm has already dropped a factor of three at 1 ms after beam turnoff.

We now turn to our experiments dealing with T_e alone as well as those that concern potential and distribution.

Electron Temperature Scaling

In an experiment using constant gas fueling by the puffer (1540 A equivalent), the electron temperature (T_e) in the plug (r = 0 cm) was measured while the input beam currents (I_{beam}) to the plugs were varied. In Fig. 7 we have plotted these high T_e mode measurements and, for comparison, the same measurements (under similar conditions) from 2XIIB. The electron temperature in the single-cell 2XIIB was proportional to I_{beam}, whereas in TMX it was independent of I_{beam} for the high mode. In addition, T_e in TMX was several

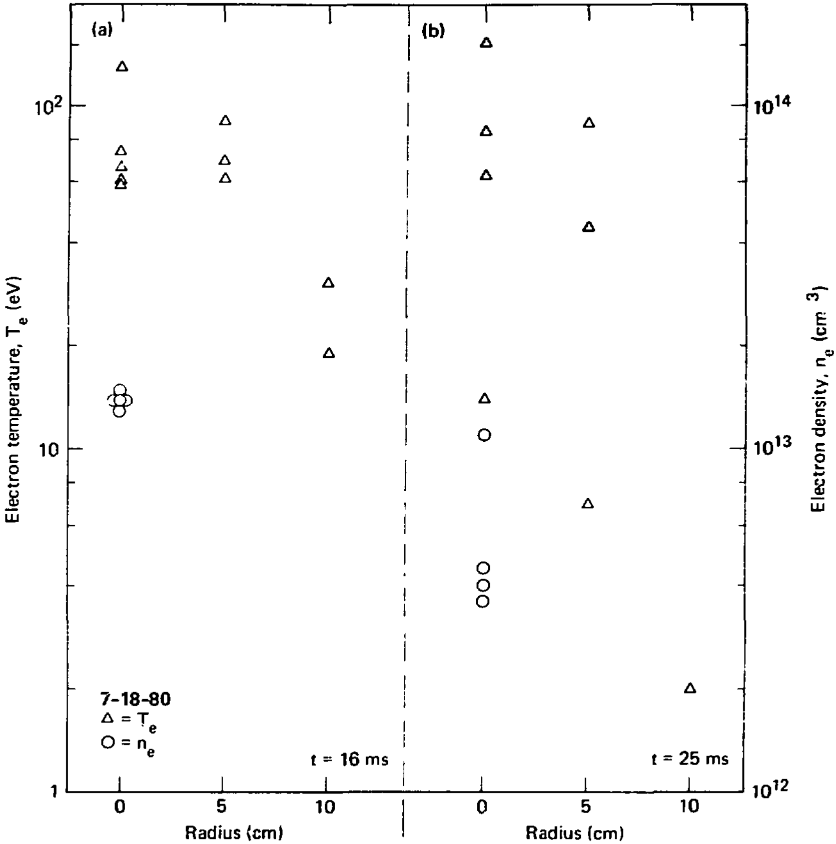

Figure 6. East-plug radial profiles of electron temperature (T_e) at (a) 16 ms vs T_e at (b) 25 ms. The east beams were turned off at 24 ms.

times higher than could be obtained in 2XIIB with a comparable I_{beam}.

These differences in T_e scaling with I_{beam} between TMX and its forerunner, 2XIIB, arise from the requirement of providing low-energy plasma to control the drift-cyclotron loss-cone (DCLC) instability in a minimum-B mirror cell. In 2XIIB, this low-energy plasma was ultimately supplied by the neutral-beam current, making T_e proportional to I_{beam}.[16] But in TMX, this stabilizing plasma for the end plugs was supplied by axial losses from the central cell, which allowed the plug T_e to be independent of I_{beam}.[13]

Figure 8 indicates how the shift between the high and the low T_e modes is caused by changes in the amount of fueling gas introduced into the central cell by the puffer. For this experiment on Sept. 17, 1979, all the other machine parameters

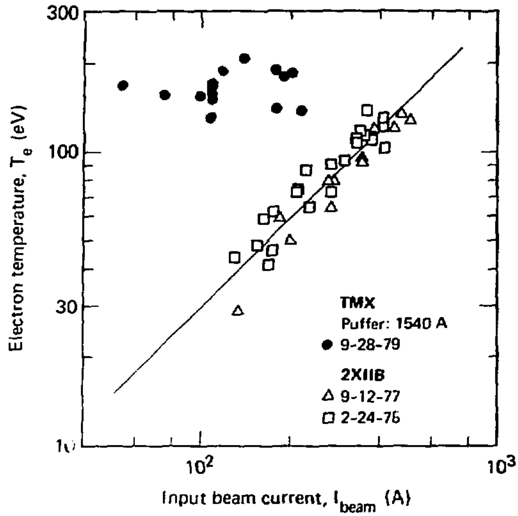

Figure 7. East-plug electron temperature (T_e) vs east-plug beam current (I_{beam}). Measurements are compared with the same ones from the single-cell machine, 2XIIB, at r = 0 cm.

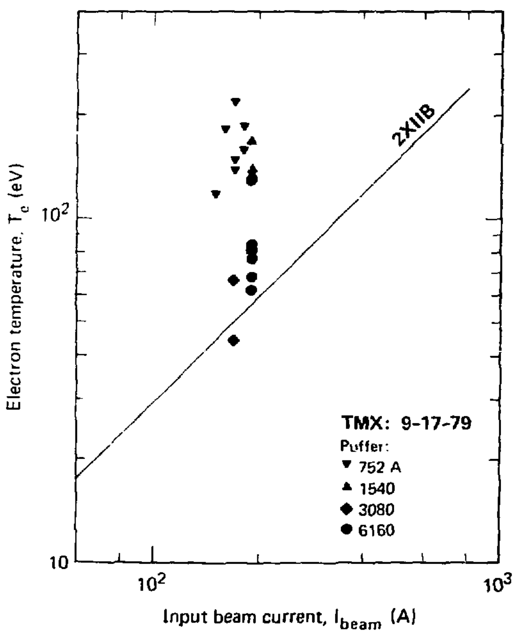

Figure 8. Variation in electron temperature (T_e) in the east plug (r = 0 cm) as the gas fueling from the central-cell puffer was increased.

were held constant. Thus, we can see that large amounts of fueling gas can restrict T_e in the TMX plug to the 2XIIB regime. Operation of TMX near the 2XIIB scaling suggests that, under these conditions, the central-cell axial losses are not providing the low-energy plasma necessary to stabilize the DCLC in the plug. However, on other occasions the TMX plugs operated near the 2XIIB scaling regardless of the amount of gas introduced. TMX researchers have concluded that this was probably related to vacuum conditions in the machine.[10]

Comparison of Temperature Measurements in the Plug and Central Cell

To determine if T_e was constant along magnetic field lines, we compared simultaneous measurements of temperature in the east end plug and the central cell. In Fig. 9 we have contrasted plug and central-cell T_e at r = 0 cm for various TMX operating conditions. TMX was running in the lower T_e mode for most of these shots. Overall,

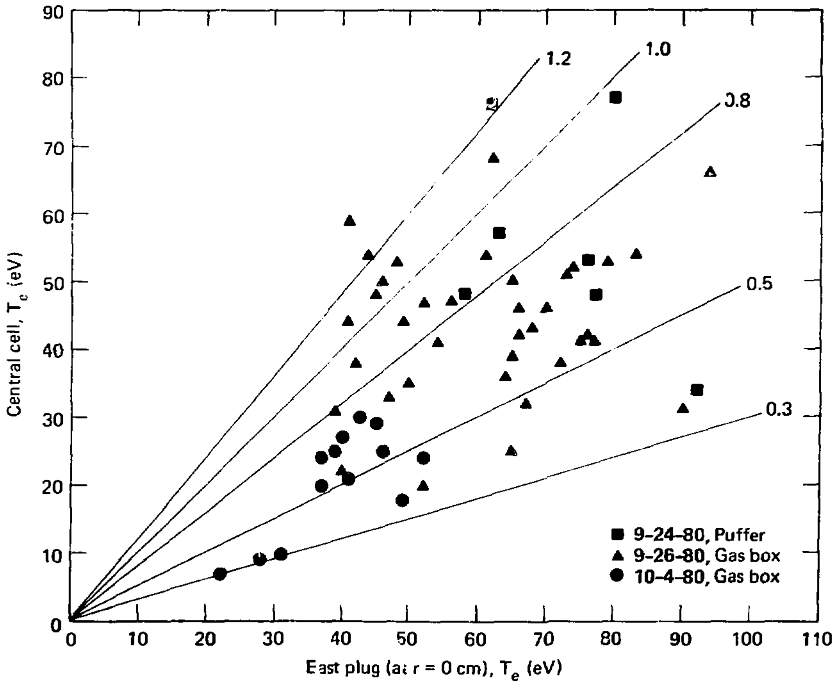

Figure 9. Comparison of simultaneous electron temperature measurements in the east plug (r = 0 cm) and the central cell under various TMX operating conditions. The diagonal lines show ratios of T_e (central cell) to T_e (plug).

central-cell T_e is comparable to that in the east plug. The existence of central-cell temperatures above 50 eV indicates that there are no large energy losses due to impurities trapped in the central cell.[17] Figure 9 also shows that the ratio of T_e in the central cell to that in the plug can range from 0.3 to 1.2; thus, T_e is often not constant along a given magnetic field line. This may be due to some isolation between plug and central-cell electrons that allows a gradient in the electron temperatures.

Figure 10 compares simultaneous east-plug and central-cell electron temperatures (at r = 0 cm), which were taken on the day (9-29-80) when one of the coils in the west plug developed a vacuum leak. As can be seen, this caused the east plug to drop from the high T_e to the lower T_e operating mode. Even with the resulting low temperatures, T_e was usually not constant along a field line.

The radial profiles of T_e at r = 0 and 5 cm in the east plug and at r = 0 cm in the central cell are shown in Fig. 11 for the same shots as in Fig. 10. The temperatures at each position generally track each other. The point density profiles (n_e) for these shots are given in Fig. 12. For comparison, the point densities obtained by unfolding line-density measurements (Gaussian fits) from neutral-beam attenuation[12] are also plotted. The rise in central-cell n_e due to the air leak in the west plug can be seen; however, the east-plug densities are little affected by this rise and are relatively flat to a 5-cm radius. The higher central-cell densities are associated with the lower electron temperatures. This maximum central-cell density is similar to the density that would result from a gas-box fueling of approximately 7000 A equivalent.

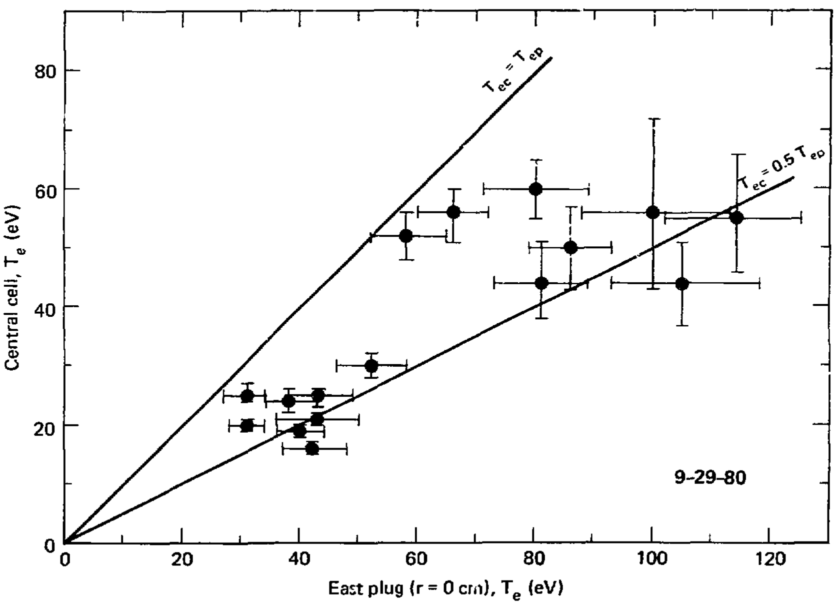

Figure 10. Comparison of simultaneous east-plug (T_{ep}) and central-cell (T_{ec}) electron temperature measurements with gas-box fueling only. The group of lower temperatures is associated with a vacuum leak in the west-plug region.

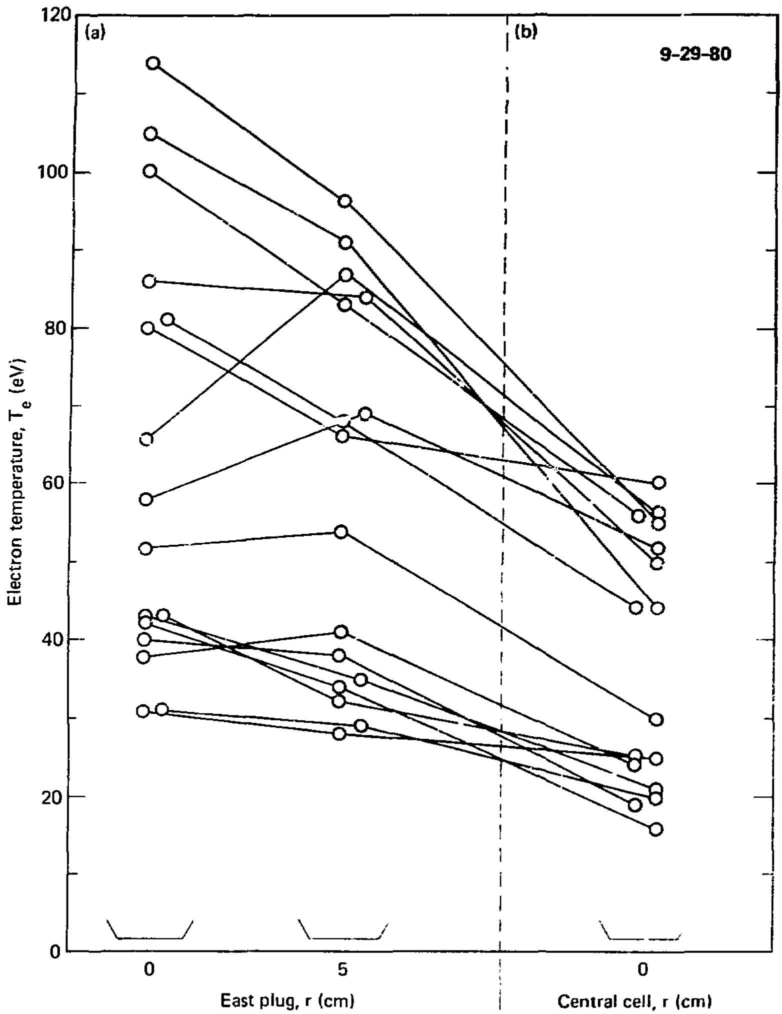

Figure 11. Electron temperatures (T_e) at two radii in the (a) TMX east plug compared to (b) central-cell electron temperatures. The solid lines connect simultaneous measurements, although the points have been offset for clarity. These data are for the same shots as Fig. 10.

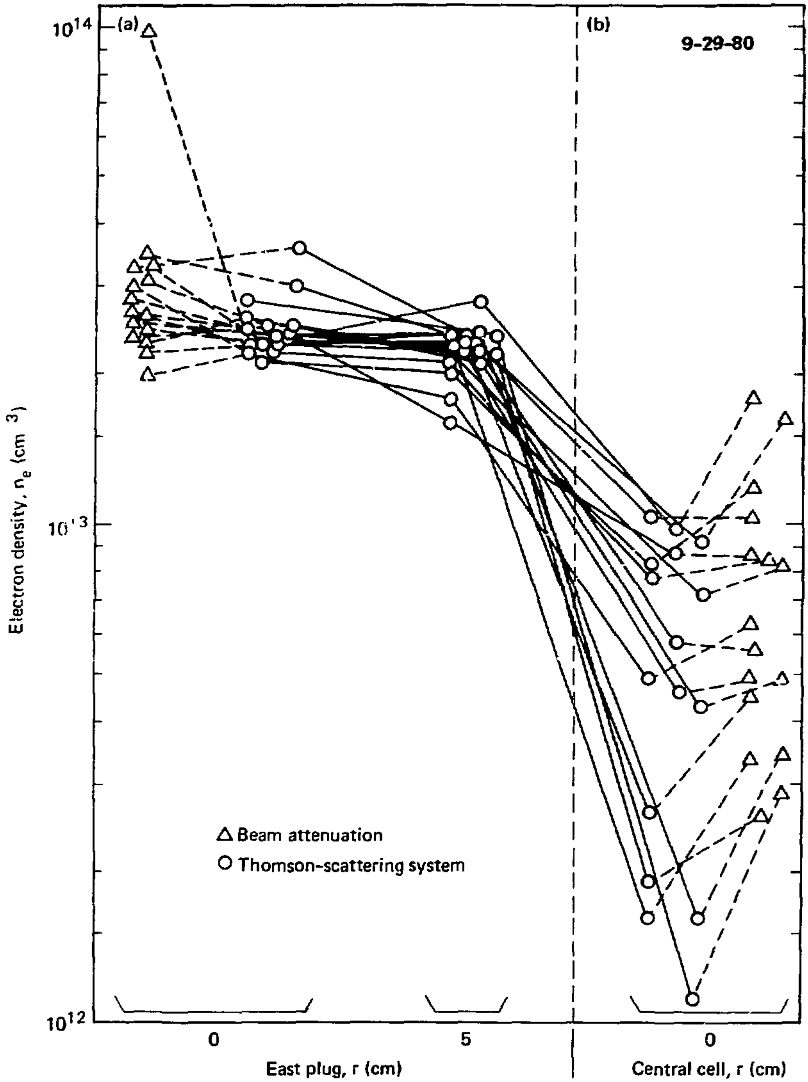

Figure 12. Plasma densities (n_e) at two radii in the (a) TMX east plug compared to (b) central-cell densities. Also shown are densities obtained from beam-attenuation measurements. These data are for the same shots as Fig. 10; they are offset for clarity. The higher central-cell densities correspond to the lower electron temperatures of Fig. 11.

Effect of Central-Cell Beam Heating on Electron Temperatures

We measured certain effects of heating the central-cell ions with neutral beams (Fig. 13). For this experiment we used a neutral-beam current between 45 and 60 A in the central cell, and a beam current in each plug between 110 and 140 A. Under these conditions, T_e in the east plug ($r = 0$ cm), which was in the high T_e mode, was raised by the central-cell heating [Fig. 13(a)] as was the central-cell diamagnetic loop signal [Fig. 13(b)].[12] The second Thomson-scattering system was not installed in the central cell at this time. However, measurements by a vacuum ultraviolet spectrometer[15] indicate that the central-cell T_e was also raised by heating with neutral beams.[18]

Figure 14 gives the results of a second central-cell heating experiment. Here, the gas fueling rate was also varied. The decrease in temperature in the east plug from the high T_e to the lower T_e mode, proportional to the increase in fueling rate, is evident. The heating of central-cell ions has little effect on the temperature in the plug when it is operating in the lower T_e mode.

Correlation of Potential and Electron Temperature

Radial profiles of the east-and-west-plug plasma potentials (ϕ_p), as measured by end-loss analyzers, plus the east-plug electron temperature (T_e) are plotted in Fig. 15. This data is for the

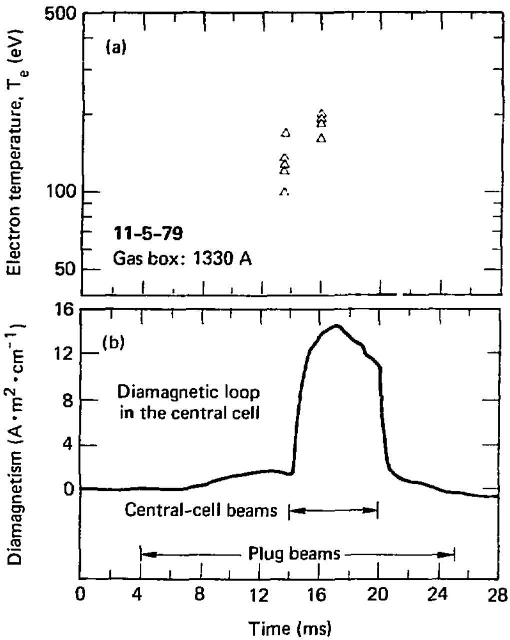

Figure 13. Some effects of neutral-beam heating of the central-cell ions including (a) analysis of east-plug ($r = 0$ cm) electron temperature before and during heating and (b) the central-cell diamagnetic loop signal (b).

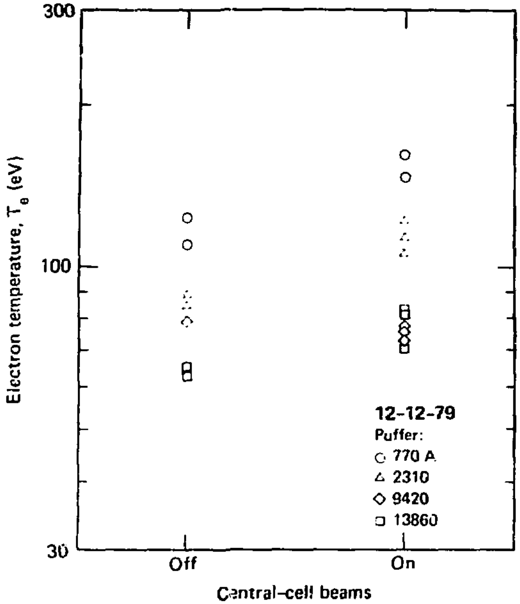

Figure 14. Analysis of east-plug (r = 0 cm) electron temperatures with and without central-cell neutral-beam heating for four gas-fueling rates.

lower T_e mode of operation. All radial positions are plotted at an equivalent position on the plug midplane by mapping the magnetic field lines. Each point in this plot is an average over several shots, and the error bars represent the standard deviation. The east and west plugs have comparable plasma potentials, and the ϕ_p and T_e profiles have a similar shape.

A shot-by-shot comparison of the ϕ_p and T_e in the east plug is given in Fig. 16 for two radii. Note that the low points are from the day (9-29-80) that a vacuum leak occurred in the west-plug region (see the preceding section on temperature measurements in the plug and central cell). Under these conditions the ratio of ϕ_p/T_e decreases to two; for normal operation, the ϕ_p/T_e ratio usually ranges between four and six at both r = 0 and 5 cm.

We also measured the central-cell plasma potential (ϕ_c) with the heavy-ion beam probe.[12] Figure 17 shows a radial profile of ϕ_c compared to T_e in both the central cell and east plug using an average over several shots. Here the central-cell radial positions are plotted at corresponding positions on the plug midplane. For these shots in the central cell, the ratio of ϕ_c/T_e at r = 0 cm is approximately eight.

Non-Maxwellian Electron Distribution

On some occasions the Thomson-scattered light spectra have shown what may be a non-Maxwellian electron distribution. Non-Maxwellian electron distributions have previously been observed in the Alcator experiment.[19] Figure 18(a) is a single-shot, scattered light spectrum taken with the plasma in the central cell in equilibrium. The lines are weighted, least-square fits to the selected points, to form a

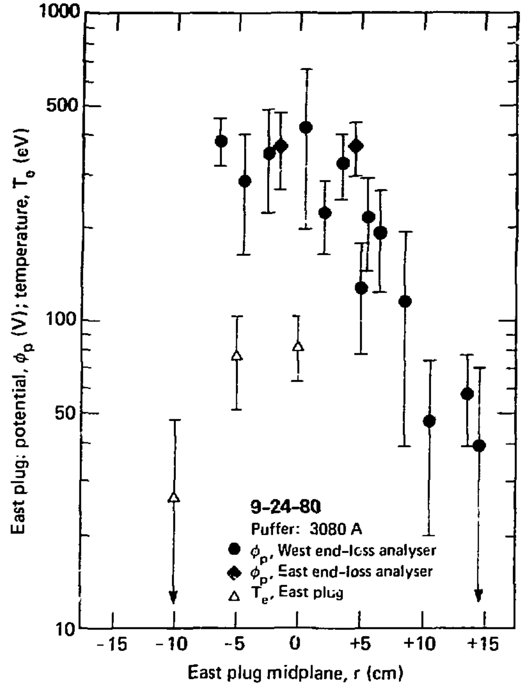

Figure 15. Radial profiles of the east-and-west-plug plasma potentials (ϕ_p) and the east-plug electron temperature (T_e).

bi-Maxwellian distribution. Here the evidence for a hot tail in the distribution function rests upon one point. Additional wavelength channels, which were not available when these data were taken, would be necessary to obtain more conclusive evidence. However, for most shots the spectrum is best fitted by a single straight line that indicates a normal Maxwellian electron distribution.

As a further check for a non-Maxwellian distribution, simultaneous east-plug and central-cell spectra are plotted in Fig. 18(b). These were taken 5 ms after the east-plug beams had been terminated and the plasma potential in the plug no longer blocked the central-cell ions. Under this condition the east plug and the central cell basically have a common plasma. These spectra show a relatively uniform electron temperature and density as would be expected. This also shows that the two Thomson-scattering systems have equivalent calibrations. The plug has a definite high-energy tail, and the central cell indicates one also.

Our measurements of central-cell potentials would match theory more closely if a higher energy tail were present on the central-cell electron distribution.[20] While such an electron distribution is not definitely shown in our measurements, it would not be inconsistent with our data.

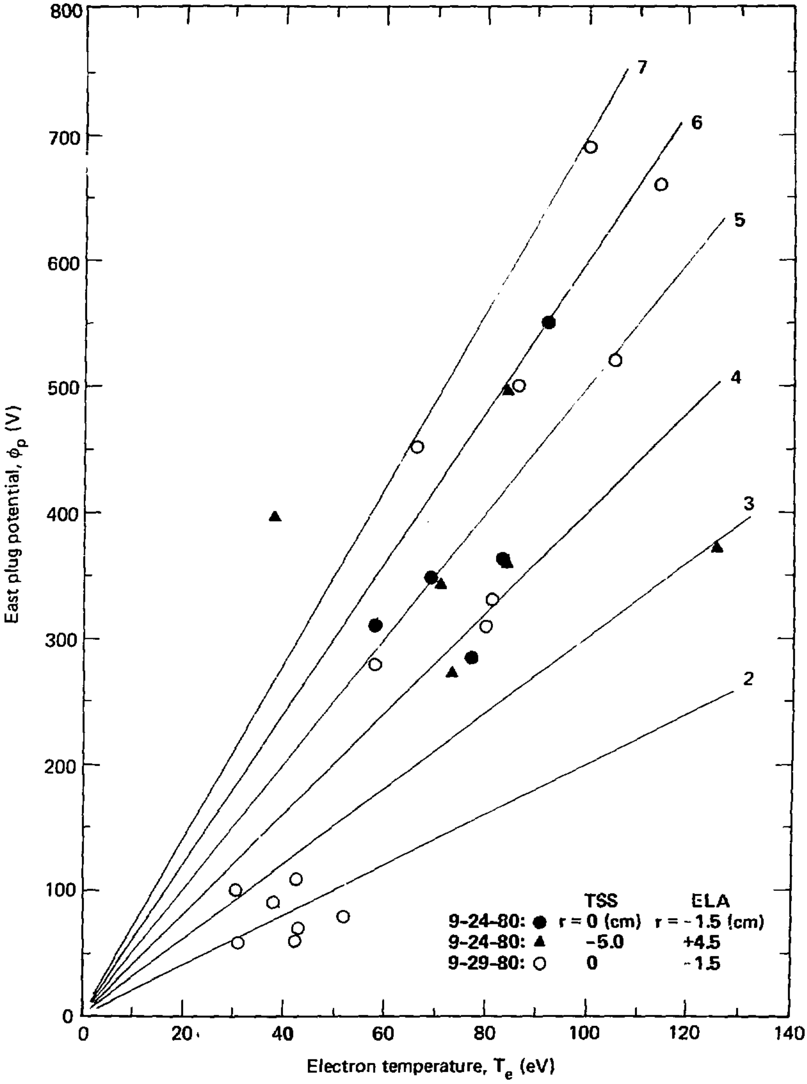

Figure 16. A shot-by-shot comparison of the east-plug electron temperature (T_e) and plasma potential (ϕ_p) at two radii. The diagonal lines show the ratio of ϕ_p/T_e. (TSS = Thomson-scattering system; ELA = end-loss analyzer).

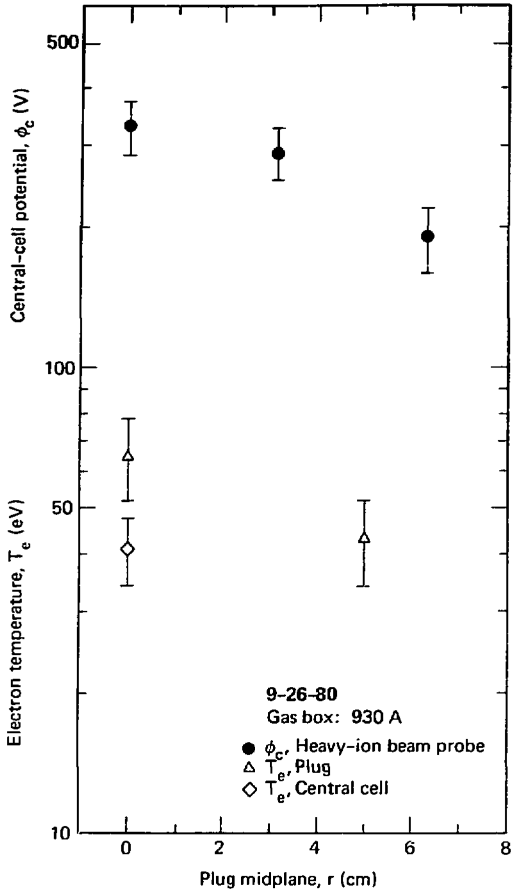

Figure 17. Comparison of the central-cell plasma potential (ϕ_c) and the plug and central-cell electron temperatures.

Summary

Our Thomson-scattering measurements show that the TMX end plugs can operate in two electron temperature modes: a high T_e mode in which the electron temperature can reach 260 eV—three to four times higher than in a single-cell mirror for comparable input beam current—and a lower T_e mode that is similar to a single-cell mirror. Our initial research suggests that any shift between the two modes may be connected to vacuum conditions. Also, we noted that when heating the central-cell ions with neutral beams (during the high T_e mode), the temperature in the plug elevated.

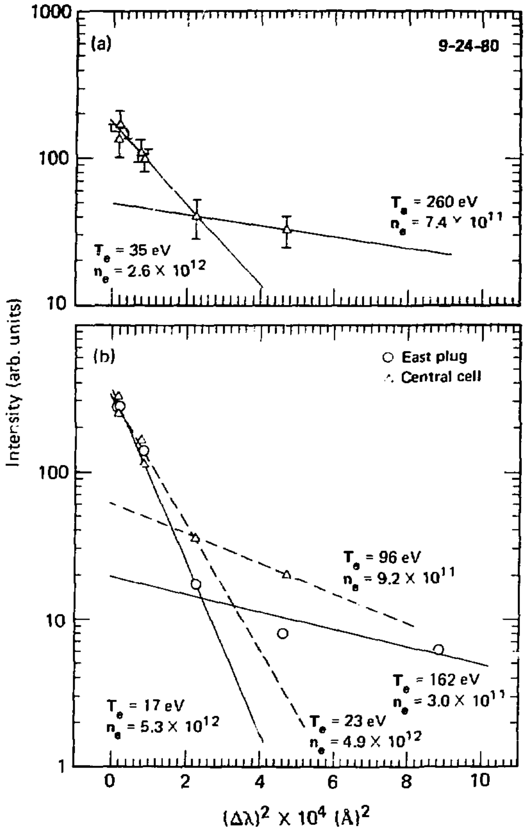

Figure 18. Thomson-scattered light spectra indicating a bi-Maxwellian electron distribution: (a) central-cell spectrum with plasma in equilibrium and (b) simultaneous east-plug and central-cell spectra taken 5 ms after the east-plug beams were terminated. ($\Delta\lambda$ is the shift from the laser wavelength.) The dashed lines are fits to the central-cell spectrum, and the solid lines are fits to the east-plug spectrum.

Radial profiles of the plug electron temperature generally follow a density-squared radial profile (as determined from other diagnostics) and are relatively flat to $r = 5$ cm. Furthermore, the radial profile of the potential has a shape similar to the T_e profile. In correlating potential (ϕ_p) and temperature (T_e), we have found that the ratio of ϕ_p/T_e in the plug ranges between four and six.

A comparison of T_e in the plug and central cell shows that the electron temperature in the two regions is comparable, but that often T_e is not constant along a magnetic field line. In addition, we found that under some conditions there is an indication that a non-Maxwellian electron distribution may be present in both the end plug and the central cell.

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