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Thomson-Scattering Systems on TMX

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ABSTRACT

This report summarizes the criteria and designs that were used for the two TMX Thomson-scattering systems. It describes the optical, mechanical, electronic, and computer analysis features of these installations. A brief discussion of general Thomson-scattering principles and sensitivity limits is given. Also included are some plasma electron temperature and density measurements from TMX that were obtained through the use of these systems.

I. INTRODUCTION

Electron temperature T_e is one of the most important parameters that characterize a plasma. Its measurement is necessary to describe plasma operating conditions such as: energy loss rates, power balance, plasma stability, and particle transport. It is also used to determine the rate coefficients for spectroscopic analysis. At the present time Thomson scattering is the most accurate and useful method of measuring T_e in a plasma. The advantages of this technique are: (1) it can give a direct measurement of electron temperature T_e and also electron density n_e in a small region of the plasma at a specified time, (2) it provides both spatial and temporal resolution of T_e and n_e , and (3) it does not significantly perturb the plasma under most conditions. In recent years Thomson scattering has become a standard diagnostic technique for many plasma experiments.¹⁻¹⁵

The TMX (tandem mirror) plasma experiment^{16, 17} at LLNL has a long central-solenoid cell terminated by minimum-B-type mirror coils (baseball) that plug each end (Fig. 1). High-density plasmas are maintained in the end plugs by neutral-beam injection at high energies. A plasma with lower energy and density is contained in the solenoid. Since the plasmas in the end plugs and the central cell are different, it is desirable to measure T_e in each region. Therefore, two independent Thomson scattering systems, one in an end plug and one in the central cell, were installed on TMX (Fig. 2). The design of the system is based on experience gained from operating the Thomson scattering system⁵ on the 2X11B plasma experiment.

II. PRINCIPLES AND GENERAL CONSIDERATIONS

A. Theory

The Thomson scattering technique^{18, 19} uses a laser beam of monochromatic λ_i photons that is directed through the plasma. A small fraction of these photons interact with the plasma electrons and are scattered. The cross section for this Thomson scattering is small ($\sigma_T = 6.66 \times 10^{-25} \text{ cm}^2$),

therefore, an intense, well-collimated beam from a laser is required to provide a sufficient number of photons that are scattered by an angle θ (the angle between the laser beam and the center of the viewing optics). Because the plasma electrons have thermal motion, the scattered photons are shifted from the laser wavelength by the Doppler effect. An analysis of this wavelength shift can give information on the velocity of plasma electrons.

Fig. 1. TMX (Tandem Mirror Experiment) magnet geometry and axial profiles.

Fig. 2. Schematic diagram showing the location of the TMX Thomson-scattering systems with respect to the magnetic field lines.

If the scattering wavelength λ is much less than the Debye wavelength λ_D , the electrons are scattered by uncorrelated electron motion. This condition can be expressed by

$$\alpha \equiv 1/|\vec{k}| \lambda_D \ll 1, \quad (1)$$

where $\vec{k} = \vec{k}_i - \vec{k}_s$, the wave-number shift (Fig. 3). The subscripts i and s refer to incident and scattered wave numbers, respectively.

When this is satisfied, the Doppler-shifted wavelength profile represents the electron velocity distribution in the direction of $\vec{k}$. If $a \ll c$, then

$$\lambda \approx \lambda_1 [2 \sin(\theta/2)]^{-1}, \quad (2)$$

where $a^2 \approx 2k T_e m_e^{-1}$, c is the speed of light, and

Fig. 3. Wavenumber vector diagram for Thomson scattering.

$$\alpha = \frac{1.08 \times 10^{-4} \lambda_i (\text{cm})}{\sin(\theta/2)}$$

$$\times \left[\frac{n_e (\text{cm}^{-3})}{T_e (\text{eV})} \right]^{1/2} \quad (3)$$

In TMN, when

$$10 \leq T_e \leq 300 \text{ eV},$$

$$1 \times 10^{12} \leq n_e \leq 3 \times 10^{13} \text{ cm}^{-3},$$

$$\theta = 100^\circ, \text{ and}$$

$$\lambda_i = 6943 \text{ \AA} \text{ (using a ruby laser)}$$

then

$$\alpha = < 0.02$$

satisfying the above requirement.

For a plasma with a Maxwellian electron velocity distribution (most plasmas) and a low electron temperature ($< 1 \text{ keV}$), the observed scattered wavelength profile will be a simple Gaussian with its peak at the laser wavelength. It will be of the form¹⁹

$$P_s(\lambda_s) d\Omega d\lambda_s = \frac{P_i L r_0^2 n_e c}{2a\lambda_i \sin(\theta/2) \sqrt{\pi}}$$

$$\times \exp \left[- \frac{(\Delta\lambda)^2 c^2}{4a^2 \lambda_i^2 \sin^2(\theta/2)} \right]$$

$$\times d\Omega d\lambda_s \quad , \quad (4)$$

where

P_s is the scattered power,
 Ω is the scattering solid angle intercepted by the viewing optics,
 λ_s is the wavelength of the scattered light,
 P_i is the laser power,
 L is the viewed length of the laser beam,
 r_0 is the classical electron radius,
 $\Delta\lambda$ is $\lambda_s - \lambda_i$.

The halfwidth of this profile at the 1/e amplitude point is given by

$$\Delta\lambda_{1/e} (\text{\AA}) = 3.95 \times 10^{-3}$$

$$\times \lambda_i (\text{\AA}) \sin(\theta/2) [T_e (\text{eV})]^{1/2} \quad . \quad (5)$$

The total number of photons N_s scattered into Ω can be obtained by integrating Eq. (4) to give

$$N_s \approx W_i r_0^2 n_e L \Omega / h \nu_i \quad , \quad (6)$$

where W_i is the laser energy, h is Planck's constant, and ν_i is the laser frequency.

From Eqs. (5) and (6) it can be seen that the width of the scattered spectrum is a direct function of T_e and the total collected intensity is proportional to n_e . For a plasma with a high electron temperature ($> 1 \text{ keV}$), relativistic effects must be included and the profile of the scattered spectrum is altered.¹⁹⁻²¹

B. Measurement

The profile of the scattered spectrum is determined by separating the light collected by the viewing optics into wavelength channels. This separation is done with either a diffraction grating (polychromator) or a series of optical bandpass filters. In each of these channels the number of collected photons is measured by a photomultiplier (PM) tube or equivalent detector. Relative gains, from the PM tubes and amplifiers, are determined by a calibration; the signals from each channel are then normalized to the same gain. The normalized output from the PM tubes has the same profile as the power spectrum of the scattered light [Eq. (4)]. These output data are sent to a computer that performs the normalization and calculates the T_e . The data can also be reduced by hand from oscilloscope traces of the PM tube signals. To do this, the logarithm of the normalized signal from each channel is plotted versus $(\Delta\lambda)^2$ and Eq. (5) is used to determine T_e (Fig. 4). If the total system has been calibrated for density (Section II-D), n_e can also be obtained from these data either by the computer or by hand.

C. SYSTEM SENSITIVITY

The output of a photomultiplier tube depends on the number of scattered photons N_{sc} received by that channel and the quantum efficiency η of the photocathode. Since the conversion from photons to photoelectrons is governed by Poisson statistics this may be written as¹⁹

$$N_{se} = N_{sc} \eta \pm (N_{sc} \eta)^{1/2} \quad , \quad (7)$$

Fig. 4. Plot of signal amplitude vs wavelength shift for various electron temperatures. Also shown are the PM channel wavelength assignments for the TMX Thomson-scattering systems.

where N_{sc} is the number of photoelectrons emitted. The signal-to-noise ratio for a channel is then

$$S/N = N_{sc}/(N_{sc})^{1/2} = (N_{sc})^{1/2}. \quad (8)$$

Thus, from Eqs. (6) and (8), S/N can be improved by: (1) increasing the laser power, (2) increasing the plasma density, (3) improving the transmission of the viewing optics, and (4) using PM tubes with a higher quantum efficiency. The accuracy of Thomson scattering data and the resulting practical measurement limit are determined by S/N .

From Eq. (6) and the TMX parameters [10-] ruby laser, $L \approx 1$ cm, $\Omega = 0.033$ sr (with f4.9 viewing optics) and $n_e = 1 \times 10^{13}$ cm $^{-3}$], the expected total number of collected photons is $N_s = 9.5 \times 10^5$. This agrees with the magnitude of the signals that we observe, and shows that the overall sensitivity is usually not the limit of our ability to make measurements.

In addition to the Thomson scattered photons, the viewing optics also collect photons from plasma radiation. This includes Bremsstrahlung, recombination, and line radiation. An estimate

of the expected number of photons from Bremsstrahlung N_B gives $N_B < 10^{-3} N_s$, which is negligible. However, on both the 2XII B and TMX experiments we have observed that the ratio of N_B to N_p (the number of plasma radiation photons collected) ranges between two and ten depending upon the impurity conditions in the experiment. This is similar to what had been observed on the T3-A experiment.³

The amount of plasma radiation present places limits on the ability of a Thomson scattering system to make measurements. When plasma radiation is included, Eq. (8) becomes

$$S/N = \frac{(N_{sc}\eta)^{1/2}}{\left(1 + \frac{N_{pc}}{N_{sc}}\right)^{1/2}}, \quad (9)$$

where N_{pc} is the number of plasma radiation photons received by a PM channel. Therefore, the presence of plasma radiation in a channel sets an effective sensitivity limit for that channel. Also, a strong N_2 line at 6468 Å in TMX (Fig. 5) rendered one of our photomultiplier channels unusable. For the TMX plasmas some plasma radiation appeared

Fig. 5. Impurity line spectra from TMX central-cell plasma over a period of two days.

in most of the PM channels and was the limiting factor on our ability to make measurements. Because the scattered radiation is plane polarized, while the plasma radiation is not, an improvement in the N_s to N_p ratio by a factor of 2 can be obtained by using a polarizing element in the viewing optics. Also, N_s/N_p is inversely proportional to the plasma diameter since the viewing optics receive plasma radiation generated along a chord through the plasma while the scattering volume is constant. Since N_p is approximately constant when the plasma is in a state of equilibrium, the level of N_p , as seen by each PM tube, can be sampled near the time of the scattering measurement and can be subtracted from the total signal of that tube.

From Eq. (4) the peak of the scattered power spectrum can be written as

$$P_s(\lambda_s) \propto \frac{P_i n_e d \lambda_s}{\lambda_i \sin(\theta/2) \sqrt{T_e}} \quad (10)$$

Therefore, for channels near the laser wavelength, there is an effective upper limit on T_e (for a given n_e and P_i) to keep above a minimum, usable S/N. Figure 6 shows some TMX Thomson scattering T_e and n_e measurements near a minimal S/N. Here the density values have been normalized to a laser energy of 10 J (to give an equivalent

Fig. 6. Thomson-scattering T_e and n_e measurements from TMX. The line indicates the limit for measurements with the plug system.

number of photons) since some of these measurements were made with a laser energy of only 3 J. The line is $n_e(T_e)^{-1/2}$ which is a constant number of photons per unit wavelength at the peak of the profile. Assuming a constant plasma radiation level, this line represents the practical sensitivity limit of our measurements with the plug system. Usable parameter space lies to the right of this line, with S/N also increasing to the right. From Eq. (10) this line could be moved to the left either by increasing the laser power or by lowering λ_i or θ . A smaller θ can also improve N_s/N_p as it compresses the scattered spectrum in $\Delta\lambda$ while the plasma radiation spectrum remains constant. The central-cell points (Fig. 6) that lie to the left of the line show the effect of using PM tubes with a higher quantum efficiency. The plug system had PM tubes with quantum efficiencies from 2 to 4%; PM tubes of the central-cell system had quantum efficiencies from 10 to 20%.

Another possible limit on sensitivity is the amount of stray laser light reflected into the viewing optics and seen by the PM tubes. This is more of a concern with channels near the laser wavelength and depends upon the rejection efficiency of the polychromator or filter system. However, careful design of the laser optics (Sections VI-B and -C) can minimize this problem. For our systems, the channels next to the channel that contained the laser wavelength showed no laser light. Even in the laser wavelength channel the amount of laser light was low enough that it could be subtracted and the signal from that channel could be used in the T_e measurement. The amount of stray laser light seen by the various channels can be checked by firing the laser under normal conditions, except with no plasma present.

D. DENSITY CALIBRATION

As is shown in Eq. (6), the total number of photons collected is proportional to plasma density. The Thomson scattering system can be calibrated for absolute density by substituting a gas of known density for the plasma and measuring the

total light collected. This Rayleigh scattering of light from a gas has the same radiation characteristics as Thomson scattering. The ratio of cross sections from Rayleigh and Thomson scattering (σ_R/σ_T) is known for several gases¹⁹; nitrogen is the one often used. Because the viewed volume and all of the optics are the same, the ratio of Rayleigh-to-Thomson scattering signal can be expressed as

$$\frac{N_R}{N_T} = \frac{W_{iR} n_g \sigma_R}{W_{iT} n_e \sigma_T} \quad (11)$$

where N is the total light collected, W_i is the laser energy, n_g is the gas density, and R and T refer to Rayleigh and Thomson scattering, respectively. Since the calibration gas is at room temperature, the Doppler shift will be very small and all of the Rayleigh scattered light will be essentially at the laser wavelength. To use this calibration the relative laser energy must be monitored for the calibration and for each plasma measurement.

Both Thomson scattering systems on TMX were calibrated by filling the vacuum tanks with N_2 to several pressures between 10 and 75 Torr. The total scattered light was measured at each pressure by the PM tube on a channel at the laser wavelength. The calibration pressure must be high enough that the Rayleigh signal is much greater than the stray laser light signal on that channel and also so the absolute pressure can be measured accurately. The pressures we used gave signals that would saturate the PM tube and, therefore, required the use of a calibrated neutral-density filter in the optical chain. This factor was then included in the calibration constant. To minimize the error due to the scattering of light from dust particles, the tanks were allowed to sit overnight at 75 Torr before any calibrations were taken. The tanks were then pumped in steps to give measurements at lower pressures. Any subsequent change in alignment of the optical system or the laser can change the calibration constant by changing either the viewed volume or the optical transmission of the system.

III. BASIC DESIGN CRITERIA

For the TMX experiment it was desired to know the radial T_e and n_e profiles in the plug plasmas. Based on our experience with the Thom-

son scattering system on the 2XIIB experiment, we decided to use conventional optics rather than a more complex system such as that in use at

Princeton.² The viewing optics of the plug system were designed to simultaneously image five 1-cm segments of the laser path through the plasma. These segments corresponded to plasma radial positions (R) of -5 , 0 , 5 , 10 and 15 cm. Because of the ports available on the vacuum tank, the scattering angle θ was 100.22° for the $R = 0$ position and was slightly different for the other radial positions. The optical system was also designed to utilize three polychromator and PM tube sets to make simultaneous measurements at any three of these radial positions (Fig. 7). Only two polychromators were actually installed. The radial position viewed by each polychromator could be shifted by changing mirrors in the optical path.

The central-cell system was simpler as its optics imaged only the $R = 0$ position and therefore had one polychromator and PM set. The scattering angle of the central-cell system was 89.99° .

These TMX Thomson scattering systems were designed to measure temperatures between 10 and 350 eV. The Gaussian spectral profiles corresponding to temperatures in this range are shown in Fig. 4. This type of plot is useful for determining how to divide the expected scattered spectra into wavelength channels. The number and arrangement of the channels for the TMX system was based on experience from 2XIIB. To calibrate the system for absolute density (Section II-D) one channel was needed on λ_i . For the low temperatures, several narrow channels near the laser wavelength were necessary. To have enough channels for reasonable measurement required channels on both sides of λ_i for accuracy in this range. Generally channels are placed on the shorter wavelength side since PM tubes have higher quantum efficiencies in this region. For higher temperatures, progressively wider channels were used at larger $\Delta\lambda$ to compensate for the

Fig. 7. Schematic diagram of the TMX plug Thomson-scattering system.

Fig. 8. Photomultiplier channel wavelength assignments and light pipe dimensions.

lower numbers of scattered photons at these wavelengths. The resulting channel placement is also shown in Fig. 4; the wavelength positions are shown in Fig. 8. A gap was placed around the D_α line at 6563 Å.

The expected electron temperatures and densities ($1 \times 10^{12} \leq n_e \leq 3 \times 10^{13} \text{ cm}^{-3}$) required the use of the highest energy, pulsed lasers available [Eq. (10)]. Ruby lasers ($\lambda_i = 6943 \text{ Å}$) with a pulse width of 20 to 40 ns and energies from 10 to 12 J are readily obtained. They are

commonly used in this application and were chosen for our systems. Also, the wavelength of the ruby laser is in a region that is relatively free of strong plasma radiation (Fig. 5). Neodymium glass and YAG lasers ($\lambda = 10600 \text{ Å}$), with their higher energies, lie in a wavelength region that is not suitable for PM tubes. Doubled Nd-glass and YAG lasers ($\lambda_i = 5300 \text{ Å}$)²² were in the development stage and were not considered when these systems were being designed.

IV. MECHANICAL DESIGN

The Thomson scattering system located on the TMX plug (Fig. 9) was composed of two subsystems: the laser beam line components and the scattered-light-viewing components. The overall configuration (vertical view tube and almost horizontal laser path) was chosen to reduce the light from the neutral-beam injectors (Fig. 1) that would be collected by the viewing system. This arrangement allowed for good accessibility to the various components by placing them on top of the vacuum vessel (Fig. 10).

For overall system stability the laser, beam transport boxes, distribution box, polychromators, and PM tube boxes were all rigidly mounted to the vacuum vessel by a stainless-steel box-beam and I-beam frame. The view tube, laser input arm, and beam dump were mounted directly on the vacuum vessel. The alignment stability of the system was quite good. Realignment was required

only after the vacuum vessel was rolled apart for general TMX maintenance or after an earthquake (January 24, 1980).

The system was designed to allow final alignment of all components while TMX was under vacuum. The view tube, mounted on a gimbal and connected to the tank with a bellows, was aligned by jacking screws. Adjustments to the laser input arm and its mirror were by bellows-type vacuum feedthroughs. The laser beam dump had a bellows vacuum seal and could translate $\pm 2.5 \text{ cm}$ either vertically or horizontally on linear bearings. It could also be tilted $\pm 5^\circ$ in either plane. For alignment purposes, a mechanical flag could be rotated into the center of the plasma region. It defined the main alignment point and both the laser and view tube could be aligned to the same spot on this flag.

Fig. 9. Location of components for the TMX plug Thomson-scattering system.

All of the components located inside the vacuum system had heat shields to minimize thermal gradients caused by the liquid nitrogen-cooled liners or the titanium sublimators used for vacuum pumping. The inner ends of the input arm, beam dump, and view tube each had a mechanical shutter to prevent titanium from striking any of the optics. These tight-fitting shutters, open only during a plasma shot, helped to keep the optics clean and maintain their optical efficiency. The interior sections of the input arm, beam dump, and view tube were vented to the main vacuum system through 20-micron filters in

the walls of their solid housings. All of the optics and components of these units were cleaned and assembled in a Class-1000 clean room.

The central-cell Thomson scattering system was similar to the plug system except that the view tube was located on the bottom of the TMX and looked up. Its distribution box, polychromator, and PM tube box were located under the vacuum vessel. This was necessary because other diagnostics were located on the top of the central cell. The laser and its transport boxes were located on top of the vacuum vessel and the laser path through the plasma was almost horizontal.

Fig. 10. View of TMX during construction showing the plug Thomson-scattering system. The polychromators and PM tubes are not installed.

V. LASERS

A. PLUG SYSTEM

The commercially-manufactured Q-switched ruby laser in the plug system was originally designed to produce four 10-J pulses during a plasma shot. However, its operation in that mode was never satisfactory and, therefore, it was used as a single-pulse 10-J laser. Its pulse width was 20 to 40 ns full width, half maximum (FWHM); the beam divergence was 1.5 mrad full angle, half energy (FAHE) after its beam was expanded to 5-cm diameter.

The oscillator head had a 15.2-cm by 0.95-cm-diam ruby rod. Its beam diameter was limited to 0.64 cm by an aperture on the head. The three amplifier heads each had a 12.7-cm by 1.91-cm-diam rod. To match the diameter of the amplifier rods, the oscillator beam was expanded by a factor of 3 before entering the first amplifier. Following the final amplifier the beam was expanded 2.7 times to produce a parallel 5-cm-diam beam. This expansion was done to prevent damage to the turning mirrors in the beam path. On the 2XIIB

system we found that the damage threshold to our mirrors was approximately 1 J/cm^2 . Because of the way the amplifier rods were pumped, the expanded beam is hollow. Figure 11 is an imprint from the expanded beam striking a piece of burn paper (photographic paper that has been exposed and developed).

To align the laser beam, a helium-neon (HeNe) laser was introduced into the system through the rear cavity mirror of the oscillator (Fig. 12). Its beam was expanded to match the diameter of the ruby laser beam and could easily be made colinear with the ruby beam by adjusting the two turning mirrors. The oscillator energy was monitored by measuring the fraction of the ruby beam that leaked through the rear cavity mirror with a vacuum photodiode. The energy monitor was calibrated by firing the oscillator and comparing the signal from the photodiode with the signal from a calorimeter placed after the front cavity mirror.

It was found that the TMX magnetic field degraded the operation of the plug laser's oscillator

Fig. 11. Full-size burn-paper imprint of the expanded laser beam. The crossed lines are from alignment reticles.

head. The field in this region (~ 0.02 T) was transverse to the ruby rod. A carbon-steel box around the oscillator head was necessary to prevent this from occurring.

B. CENTRAL-CELL SYSTEM

The Q-switched ruby laser used in the central-cell system was also manufactured commercially. It was a 12-J single-pulse laser with a pulse width of 25 ns (FWHM) and a beam divergence of 2 mrad (FAHE) at a beam diameter of 1.91 cm. The oscillator head had a 15.2-cm by 1.59-cm-diam ruby rod. It had a single amplifier head with a 15.2-cm by 1.91-cm-diam rod. There was no beam expander between the oscillator and amplifier. Following the amplifier, the beam was expanded to 5-cm diameter as in the plug system. The oscillator power monitor and the HeNe alignment laser in this system were similar to those used with the plug laser.

Fig. 12. Schematic of the oscillator section of the plug laser. Also shown is the helium-neon beam-alignment laser.

VI. BEAM-LINE COMPONENTS

A. BEAM TRANSPORT

Figure 13 shows the beam transport components for the plug system. The total energy of the laser was monitored by measuring the small fraction of the beam that leaked through the first turning mirror. This beam sample was diffused by deflecting it from a magnesium-oxide disk before it entered the vacuum photodiode detector. Diffusing the beam sample minimized measurement errors that would be caused by the hollow nature of the main laser beam in this region (Fig. 11). The energy monitor was calibrated for absolute energy by firing the laser and comparing the photodiode signal with the signal from a calibrated calorimeter. It was the energy measurement from this detector that was used in the plasma density measurements (Section II-D).

Three turning mirrors were required in the beam transport section to preserve the correct polarization (normal to the viewing system axis) of the laser beam as it traversed the plasma. Each of these mirrors was a dielectric interference coating supported on a 1.91-cm by 9.78-cm-diam Bk-7 glass substrate. The coating was 99.8% reflecting for a wavelength of $6943\text{\AA}$ at an incident angle of 45° . These mirrors, along with the other laser beam-line components, were ultra-low scatter (ULS) with $<5\text{\AA}$ RMS surface roughness and $<10^{-5}$ total integrated scattering after coating. The mirrors were mounted on commercial mirror holders and optical rails that allowed both translation and tilt.

Following the second turning mirror were two alignment reticles (Fig. 13) mounted on an optical rail. They were used to define a reference beam axis. The laser beam could be centered on these reticles by adjusting the first and second turning mirrors. A superimposed image of their cross hairs is seen in Fig. 11. The beam could easily be returned to this reference axis after any changes to the laser or its realignment, so realignment of the following components in the laser path was not necessary. This is a very useful feature of the system.

Although more compact, the beam transport section of the central-cell system was similar to that of the plug section. Because the axis of the central-cell laser was parallel to the TMX axis, its transport section contained four turning mirrors to preserve the correct polarization.

Fig. 13. Layout of the beam-transport section of the plug Thomson-scattering system.

B. INPUT ARM

The input arm assembly, which was identical in both the plug system and central-cell system, is shown in Figs. 14 and 15. To reduce the number of optical surfaces, the beam lens doubled as a vacuum window. This 9.27-cm-diam plano-convex lens fabricated from Bk-7 had antireflection (AR) coatings ($<0.1\%$ reflectivity) on both surfaces. Its 272-cm focal length gave a narrow cone angle and allowed measurements to be made at various radial points in the plasma. The isolation valve allowed the lens to be changed, if necessary, without taking the main vacuum system to air. The turning mirror was the same as the mirrors in the transport section except for its elliptical shape and different beam input angle.

Details of the beam collimation for the input arm and beam dump are shown in Fig. 16. Each collimator was fabricated from a dye glass that absorbed radiation in the wavelength region near $6943\text{\AA}$. The sizes of the collimators and their knife edges were designed to reduce the amount of scattered laser beam that could enter the

Fig. 14. Laser beam input arm assembly.

viewing optics (Section II-C). Antireflection coatings and the ULS surfaces also contributed to the reduction of beam scatter.

C. BEAM DUMP

Details of the laser beam dump, identical in both systems, are shown in Fig. 17. The collimators were similar to those in the input arm. The image of the laser aperture is at the aperture

Fig. 15. Laser beam input arm.

of the first dump collimator (Fig. 16) to ensure that all diffracted laser light falls on the dump. The dump pieces were fabricated from the same absorbing dye glass as the collimators. The main dump piece (Fig. 16) was set at Brewster's angle for maximum transmission. The secondary dump absorbed most of the beam that was reflected from the main dump. The total collimating and dump system was very efficient in controlling the laser beam (Section II-C).

The fiber optic bundle, behind the center of the main dump, was connected to a combination photodiode detector and high-intensity lamp unit. The photodiode could be used as a general monitor on the laser alignment by measuring the amount of beam transmitted through the center of the dye glass when the laser was fired. The lamp could also be used to check the laser beam alignment. With the lamp on and one of the alignment reticles installed in the beam transport section, a blue spot (color of the dye glass) could be seen by looking down the laser optical chain from a position near the output of the laser. If the optics were correctly aligned, the cross hairs of the reticle would appear centered on the spot from the dump.

D. LASER BEAM ALIGNMENT

The alignment of the laser beam in each system was done with the HeNe laser beam and then checked by firing the ruby laser into a burn

Fig. 16. Schematic of the laser beam collimation and dump components.

Fig. 17. Laser-beam dump assembly.

paper at various locations. The beam was first centered on the two reticles in the transport section as described above. Then the last turning mirror was adjusted to the center of the beam on an alignment reticle at the focusing lens (Fig. 14).

An alignment telescope looked through a vacuum window and the turning mirror of the input arm. It could view the end of the input arm, the alignment flag, and the beam dump. When TMX was under vacuum, the alignment flag and

the beam dump could be illuminated by a spotlight shining through an auxiliary window on the input arm assembly (Fig. 15). With this telescope the beam could be centered on the alignment flag by adjusting the rotation (horizontal plane) and tilt (vertical plane) of the input arm mirror. This set the laser path through the plasma. The input arm and the mirror rotated together. Their alignment in this plane had been adjusted with a bench setup when the input arm was assembled. The tilt of the mirror and the input arm was independently adjustable. The input arm tilt was aligned by

centering a target, marked on the inner surface of the input arm shutter, on the HeNe beam.

The optical path of the alignment telescope was made colinear with the laser beam by adjusting the position and tilt of the telescope and its turning mirror (Fig. 15). This telescope was then used to align the beam dump. The dump assembly was translated to center the fiber-optic light spot described above on the telescope axis and was rotated to center the target marked on the dump shutter.

VII. VIEWING AND DETECTION COMPONENTS

A VIEW TUBE

The large diameter of the vacuum vessel in the plug region required the use of a series of relay lenses in the viewing optics. The plug system view tube is shown in Fig. 9; a layout of its optical components is shown in Fig. 18. These optics were designed to image a 20-cm section of the laser path through the plasma. This allowed simultaneous measurements at more than one radial position in the plasma. The strong curvature and astigmatism over the total field was not significant in the 1.5-cm segments used by each polychromator. The sagittal focus was parallel to the entrance slits of the polychromators.

For maximum light input, the objective lens was as large in diameter as possible (125 mm) and was placed as near the plasma as practical. It had an input cone of $f/4.9$. The first relay lens had a 150-mm diameter to prevent vignetting. The

requirement to image points 10 cm off axis made it necessary to use 300-mm-diam field lenses. To minimize aberrations, the vacuum window was placed between the last pair of relay lenses. The output cone of this assembly was made $f/6$ to match the polychromator input optics. The view tube optics had a magnification factor of 1.5.

All the lenses were commercially available and, except for the field lenses, were air-spaced acromats. Both surfaces of each optical component were AR coated ($<0.3\%$ reflection in a broad band). The total transmission of this assembly with 22 optical surfaces was quite good (Fig. 19).

The viewing optics of the central-cell system were designed to image only one position in the plasma. Because of this and the smaller diameter of the vacuum vessel, a single air-space acromat was used in its view tube. The input cone of this lens was also $f/4.9$ and its surfaces were AR coated.

Fig. 18. Layout of the optics in the plug-system view tube.

Fig. 19. Overall optical transmission of the plug-system view tube.

No special viewing dump was used in these systems. In each case the viewed tank wall was located far from the plasma. These walls were roughened to prevent specular reflections and were naturally blackened by titanium sublimation for vacuum pumping.

B. IMAGE DISTRIBUTION

Five 1-cm segments of the laser path are imaged by the view tube at aperture-stop slits in the image distribution box. The purpose of the aperture stop is to reduce unfocused, stray plasma radiation originating outside of the laser path. The location of these stops was set by finding the real image of marks placed at the desired positions on a string attached along the laser path. In addition, the image of the HeNe beam on the alignment flag was centered in the $R = 0$ -cm (plasma center) aperture stop. This was the reference that was later used to check the view tube alignment. A polarizing sheet was placed at each of these slits to discriminate against background plasma light (Section II-C).

A photograph of the plug distribution box is shown in Fig. 20; Fig. 21 is a schematic of its components. Only two polychromators were actually installed. Image separation mirrors were used to direct the desired position image through a pair of relay lenses to a polychromator. These

lenses were AR-coated 125-mm-diam acromats and were set to produce a 1:1 image of the aperture slit on the entrance slit of the polychromator. Since the polychromator entrance slit (2 mm by 15 mm) was smaller than the aperture-stop slit, it became the defining aperture of the system.

Because of the efficiency of the beam collimating and dump components (Section VI-C), it was not necessary to use a notch filter, at the laser wavelength, in the viewing optics. However, a high-pass filter (yellow) was placed before the polychromator entrance slit to block short wavelength plasma light that could appear in second order.

A similar, but smaller, image distribution box was used in the central-cell system. It contained a single aperture-stop slit.

C. CALIBRATION SOURCE

A calibration lamp source, similar in both systems, was used to normalize the gains of the various PM tubes and amplifiers. This light was introduced into the viewing optical chain by a beam splitter in the distribution box (Fig. 21) and, therefore, used the polychromators and much of the same optics as the scattered light. The plasma side of the beam splitter was AR coated and its tilt direction, with respect to polarization, was chosen to minimize the losses to the scattered light coming from the plasma.

A linear-filament quartz-iodide lamp, which had been calibrated for spectral emission, was the

Fig. 20. Plug-system image distribution box.

Fig. 21. Schematic diagram of the image distribution and the calibration lamp source for the plug system.

source. For spectral stability it operated continuously and a mechanical shutter was opened, after each plasma shot, for calibration of the PM channels. Separate achromatic lenses focused a portion of the lamp filament onto each aperture stop in the distribution box. A calibrated neutral-density filter was placed below the shutter to reduce the intensity of the calibration source to the same general level as the Thomson-scattered light.

The calibration assembly (Fig. 22) also contained a gas-discharge lamp that could be directed into the optical chain with a movable mirror. Its spectral lines were used to calibrate the polychromators and PM channels for wavelength.

D. POLYCHROMATORS

The three polychromators in these systems were commercial 600-mm Czerny-Turner-type monochromators (Fig. 23) that we modified. The modifications were: (1) the focal length of the collimating mirror was shortened, (2) the output focusing mirror was widened, and (3) the output slit was replaced with a fiber-optic light-pipe assembly that defined the channels and interfaced the PM tubes. The design widths and spacing of the polychromator end of the light pipes are shown in Fig. 8. These light pipes had transmissions between 47 and 64%. The holographic diffraction gratings in the polychromators were

Fig. 22. Plug-system calibration lamp source.

109 by 109 mm and had 1200 grooves per mm. This gave a dispersion at $7000\text{\AA}$ of $11.5\text{\AA}$ per mm at the entrance to the light pipes.

The grating rotation dial on the polychromators was calibrated for absolute wavelength at the center of the laser wavelength PM channel, No. 4, by using appropriate spectral lines from argon, neon, and hydrogen discharge tubes. With this calibrated dial and the hydrogen-alpha line ($6562.79\text{\AA}$), the wavelength, with respect to channel 4, for the half-amplitude points at the edge of each PM channel was determined. For each PM channel, this absolute wavelength calibration was close to the design values.

E. PHOTOMULTIPLIER TUBES

One of the polychromators used a set of PM tubes from the 2XIIB Thomson scattering

system. These tubes had multialkali photocathodes with quantum efficiencies between 2 and 4% at $7000\text{\AA}$ and electron gains of 10^8 . The other polychromators had newer tubes with transparent gallium-arsenide photocathodes and quantum efficiencies between 10 and 20%. They had electron gains of only 10^6 and, therefore, required amplifiers to provide suitable signal levels (Section VIII-D). To prevent saturation by background plasma light, each PM tube was gated on for $2\text{ }\mu\text{s}$ when the laser fired (Section VIII-C). The magnetic field, at the photomultiplier tube locations, was approximately 0.02 T. Each PM tube had a cylindrical magnetic shield and each set of ten tubes was enclosed in a carbon-steel box (Fig. 24). The amplifiers, where required, were also contained in these boxes. Each light pipe was mechanically clamped to the end of a PM tube and optical grease provided the light coupling.

The calibration lamp and a set of calibrated neutral-density filters were used to determine the saturation level of each PM tube. The high voltage on each PM tube was adjusted so the tube always operated below this limit.

Fig. 23. Schematic drawing of a polychromator and photomultiplier tube assembly.

Fig. 24. Photomultiplier tube set.

VIII. ELECTRONICS AND SIGNAL HANDLING

A. GENERAL OPERATION AND TIMING

A functional block diagram for the automatic operation of the TMX central-cell system is shown in Fig. 25. The pulses to charge the laser, open the shutters, and fire the laser came from the master TMX timing system. The generation of the PM-tube gates and the operation of the calibration lamp shutter was controlled by the autocalibrator (Section VIII-B). The PM signals were interfaced to a computer (Section VIII-E) for automatic analysis and could also be recorded with oscilloscope cameras for hand analysis. To avoid reflection problems, all pulse and signal coax cables were operated as 50- Ω terminated lines.

The firing sequence began with a $t = -5$ -ms pulse from the TMX timer. The first digital delay was set to compensate for the delays built into the laser so that it would fire at $t = 0$ if the second digital delay was set to zero. This second delay selected the measurement time during the plasma shot: typically $t = 16$ ms. The typical length of a

plasma shot was 25 ms. The pulse to fire the laser Q-switch triggered a section in the autocalibrator that generated the 2- μ s-wide PM tube gate. Cable delays were added to fine tune this timing and approximately center the laser firing time in this gate time.

The output signal from each PM tube was split five ways, one to a scope and four to a computer, by a fan-out that preserved the 50- Ω termination in each direction. This fan-out unit also contained linked 50- Ω T-pad-type attenuators on each output except the one for the scope. The separation of the computer part of each PM signal into four parts provided separate measurements of the Thomson-scattered signal (prompt) and three samples of the plasma radiation (Section IV-C) signal (delayed 1, 2, 3) on each shot. The three plasma radiation samples allowed rejection, by the computer, of noise spikes on this radiation.

The four computer outputs from each PM channel went to separate analog-to-digital (A/D) converter modules that were gated at different times. These modules were commercial 12-channel

Fig. 25. Electronics block diagram for the central-cell Thomson scattering system.

charge-sensitive A/D converters with a 32-deep memory on each channel. Each A/D channel effectively integrated and stored the signal received during its gate time. The 100-ns-wide gate for the prompt module was generated by a discriminator. This commercial discriminator module was triggered by the signal from the photodiode that measured the total laser energy (Section VI-A). Cable delays were used to center the arrival of the scattered-light signal within the time of the prompt module gate. The gate pulses to the modules measuring the plasma radiation samples were further delayed by 100 ns each. With this arrangement the scattered signal and three

plasma radiation sample signals for each PM channel were stored and could be read by the computer at a later time. The output of the laser-energy photodiodes were also recorded on channels of the prompt A/D module. The discriminator setting, and the enable pulse (from the PM gate) to the discriminator was to prevent noise pulses from triggering this unit at the wrong time.

The plug system was the same as described above except that it had a second set of four A/D modules for the second polychromator and PM tube set. The gates for these modules were the same as those for the first set.

B. AUTOCALIBRATOR

The autocalibrator unit generated the PM gates and oscilloscope triggers. However, its main function was to control the relative calibration of each PM channel. At approximately 350 ms following the laser firing (the plasma shot was over) it gated the A/D modules to measure the zero level of each A/D channel. Then it opened the calibration lamp shutter and, at approximately 150-ms intervals, it gated the PM tubes and the A/D modules fifteen times. This sequence produced fifteen measurements of the calibration lamp signal on each A/D channel (prompt and delayed) that were also stored in their memory. These provided a direct measurement of the photon statistics of each PM tube and was used by the computer to compute a standard deviation for each channel (Section IX-A). The average of these measurements, for each channel, was the gain normalization factor for all the PM output signals of that channel. This calibration was performed for each plasma shot and removed any errors that would be caused by drifts in gains. For these calibrations, the time of the prompt A/D module gate within PM gate was set to be the same as the time of the laser firing within this gate in case the gain of any PM tube varied during its gating.

C. PHOTOMULTIPLIER-TUBE GATING

To gate the PM tubes (Section VII-E) a special tube base containing the dynode voltage divider string with gating circuitry was designed and constructed. The schematic diagram for the high-quantum efficiency tubes (Section VII-E) is shown in Fig. 26. The gating circuitry for the lower-quantum efficiency tubes was functionally similar, but with certain modifications to accommodate differences in tube properties. The resistor chain divides the high voltage (~ 3500 V) between each of the tube elements while the capacitors store sufficient charge to keep the dynode voltages constant during the 2- μ s-gated period when the current drain is relatively high.

Under normal operation, both switches are in the gated position. In this mode, with no gate signal, dynodes 4 and 8 are at a more negative potential than dynodes 3 and 7, respectively. This produces an electric field in the tube that opposes the flow of electrons and effectively turns off the tube. When a negative gate signal is applied, turning on transistors Q1 and Q2, the proper

voltages are applied to allow current to flow in the PM tube. Proper operation of this gating circuitry is dependent on the characteristics of the switching transistors. These particular PNP transistors were chosen for their high emitter-collector standoff voltage. Capacitors C1 and C2 were selected to accommodate the base resistance of the transistor and the drive capabilities of the gate signal.

When calibrating the grating rotation dial on the polychromators (Section VII-D), the PM tubes were operated in the continuous mode with the switches in the CW position. In this way the gating circuitry is bypassed. To limit the average anode current to its allowable level, in this mode of operation, a high impedance (~ 1 M Ω) series element was inserted between the anode and input of the measurement instrument. For normal operation in the gated mode, the anode was terminated in 50 Ω .

D. PHOTOMULTIPLIER-TUBE AMPLIFIERS

For the sets of PM tubes having a gain of only 10^0 (Section VII-E), an additional amplifier was added between the PM tube and the A/D converters. The linear amplifier used was a 12-channel NIM packaged unit with fixed gain of 10 and having a 200-MHz bandwidth. Two of the lower-level channels required gains of 100 that was achieved by connecting two of the amplifier channels in series. Although we used a commercially available NIM module we did not install it in a NIMBIN, but instead made a special installation inside of the PM tube enclosure box.

E. COMPUTER INTERFACE

After the shot, the data stored in the memory of the A/D converter modules were transferred to the TMX computer system. Figure 27 is a block diagram of the interface system. The photoisolator modules were the standard units used on all diagnostic interfaces to the TMX computer system. In collecting the data, we utilized the address scan mode of the crate controller interface. This feature allows block transfers of data initiated by a single computer command. A CAMAC command with $N = 1$, $A = 0$, $F = 2$, and a word count of 144 would cause the controller to transfer the first word of the 32-deep ADC memory from each

Fig. 27. Block diagram of the computer interface system.

channel ($A = 0 - 11$) of each module ($N = 1 - 12$). Using the $F = 2$ command for the ADC modules would clear the output word of the first-in-first-out (FIFO) memory and shift out the next word for the following read command. In this way, by

reissuing the same command, the next layer of 144 data words would be transferred. This was done 17 times to read out the data from the 17-gated intervals of each PM tube (Section VIII-B).

IX. DATA REDUCTION

A. ERROR ANALYSIS

The total photon flux (F) into a given PM tube for a Thomson scattering measurement, can be expressed as

$$F = CV \quad (12)$$

where V is the output read by the computer from the charge-sensitive A/D converter (Section VIII-A) and is proportional to the number of photoelectrons emitted by the tube photocathode. The calibration constant C includes the photocathode quantum efficiency and all of the gain factors for that channel. A relative C for each channel is measured after each plasma shot by using the calibration lamp (Sections VII-C and VIII-B) and can be written as

$$C = \frac{F_c}{\bar{V}_c} \quad (13)$$

where:

F_c = calibration lamp photon flux into the PM tube and
 $\bar{V}_c$ = the average of the A/D outputs from the fifteen calibration measurements.

While F_c is not absolutely calibrated,

$$\frac{F_c}{W} S = K \quad (14)$$

where K is constant for all of the channels of a polychromator. Here W is the wavelength width of the channel and S is the relative spectral output per wavelength for the calibration lamp. Since all PM output signals are referenced to the calibration lamp intensity, the calibration of the system for density (Section II-D) effectively calibrates this K in terms of plasma density.

From Eq. (12), the percent error in F may be expressed by²³

$$\left(\frac{\sigma_F}{F} \right)^2 = \left(\frac{\sigma_C}{C} \right)^2 + \left(\frac{\sigma_V}{V} \right)^2 \quad (15)$$

where σ is a standard deviation. Because the photon-electron conversion in a PM tube is governed by Poisson statistics, and assuming that the percent error of a single scattering measurement is approximately the same as the percent error in the calibration lamp measurements, a constant can be obtained

$$\frac{\sigma_V}{\sqrt{V}} \approx \frac{\sigma_{V_c}}{\sqrt{\bar{V}_c}} = \text{constant} \quad (16)$$

From Eq. (13) the percent error in C can be written as²³

$$\frac{\sigma_C}{C} \approx \frac{\sigma_{V_c}}{\bar{V}_c} = \frac{\sigma_{V_c}}{\sqrt{N_c}} \frac{1}{\bar{V}_c} \quad (17)$$

where N_c is the number of calibration measurements. By using Eqs. (16) and (17), Eq. (15) becomes

$$\left(\frac{\sigma_F}{F} \right)^2 = \frac{\left(\frac{\bar{V}_c}{V} + \frac{1}{N_c} \right)}{(N_c - 1)} \times \left[\frac{\sum_i V_{ci}^2}{\bar{V}_c^2} - N_c \right] \quad (18)$$

where i is an index on the calibration lamp measurements.

B. COMPUTER ANALYSIS

The computer reduction of Thomson scattering data was performed between plasma shots by

Fig. 28. Typical TMX Thomson-scattering data reduction.

the TMX diagnostic computer system.²⁴ Background shots (no plasma present) were regularly taken on TMX for various diagnostic systems. These were used by the Thomson scattering systems to record any stray laser light (Section II-C) received by a PM channel. Following each background and plasma shot the computer read, and stored in arrays, the data from the memory of all the A/D modules (Section VIII-E).

For each PM tube, the appropriate A/D channel baseline was subtracted from each separate output signal (prompt, delayed, and calibration). The computer then applied the averages of the sets of calibration lamp measurements as a gain normalization factor to the corresponding prompt and delayed signals and also calculated the errors in each of these signals from Eq. (18). Any delayed signal that was greater than 2σ above the lowest of the three delayed signals, was considered to be a noise spike and was rejected. The average of the remaining delayed signals was subtracted from the prompt signal and the result was normalized to the total laser power.

The computer performed all of the above calculations on both the plasma shot and the appropriate background shot. The value from the background shot (stray laser light) was subtracted

from the value for the plasma shot and the final result was proportional to the Thomson scattered photon flux that entered the PM tube of that channel. The total error for each channel was calculated from the errors of each contributing signal as

$$\sigma^2 = \sum_i \sigma_i^2 \quad (19)$$

where i indexes prompt and delayed for both the plasma and background shots.

From these results for each PM channel, the computer fits a two-parameter (T_e , n_e) Gaussian to the points by the grid-search method of least squares.²³ Each point used in the fit was weighted by its calculated error σ from Eq. (19). Fits at $+\sigma$ and $-\sigma$ from the best fit, were also obtained to provide the total errors in the measurement of T_e and n_e . A typical output from this computer analysis is shown in Fig. 28. When this data was taken, two PM tubes (channels 1 and 9) were saturating and they, along with the laser wavelength (channel 4), were not included in the analysis. The error bars on each point show the error determined from Eqs. (18) and (19).

X. RESULTS

Thomson scattering measurements from some of the TMX experiments are given in Figs. 29-34. Figure 29 shows a shot-by-shot radial profile of the electron temperature in the east plug for gas-box operation of TMX.^{16, 17} This profile is relatively flat out to $R = 5$ cm, then is down by a factor of 2 or 3 at 10 cm. The comparison of simultaneous east-plug ($R = 0$) and central-cell electron temperatures in Fig. 30 shows that the central-cell T_e is generally comparable to that in the east plug. The existence of central-cell temperatures of 50 eV and above indicates that there are no large energy losses due to impurities trapped in the central cell. This plot also shows that because these temperatures often differ by a factor of 2, there can be some isolation between the central-cell and end-plug electrons. The smaller error bars on the central-cell temperatures are due to the higher quantum efficiency of the central-cell PM tubes (see Section II-C).

On the day that the data in Fig. 30 were obtained, one of the coils in the west plug developed an air leak. However, even with the

resulting low temperatures the electrons were isolated. The radial profiles of T_e at $R = 0$ and 5 cm in the east plug and at $R = 0$ in the central cell for these same shots are shown in Fig. 31. It can be seen that the temperatures generally track each other. The point density profiles for these shots are given in Fig. 32. For comparison, the densities obtained by unfolding line-density measurements from beam attenuation²⁴ (Gaussian fits) are also plotted. The rise in the central-cell n_e due to the air leak in the west plug can be seen. The east-plug densities are little affected by this rise and are relatively flat out to a 5 cm radius. The higher central-cell densities are associated with the lower electron temperatures. These data show that poor vacuum conditions can result in lower T_e . The background gas pressure during a shot may also be affected by wall conditions.

In Fig. 33, the radial plug potentials (ϕ)—measured by electrostatic end-loss analyzers²⁴—are compared with the radial electron temperatures in the east plug measured on the same series of shots. Here, measurements from several shots

at each position are averaged and the error bars are the standard deviations of the measurements. These data are from central-cell gas purifier operation of TMX. It can be seen that the ratio of ϕ to T_e for the plug is approximately five.

The central-cell potentials were measured by the heavy-ion-beam-probe (HIBP).²⁴ Figure 34 shows a comparison of some of these measurements with electron temperature measurements in both the central cell and east plug. Here, the central-cell potentials are plotted at an equivalent magnetic field line position in the midplane of the plug. The central-cell potential and the plug electron temperature have similar profiles.

Fig. 29. A shot-by-shot radial profile of the electron temperature in the east plug.

Fig. 30. A comparison of simultaneous central cell and east plug ($R = 0$) electron temperatures. The lines represent T_e (central cell) equals T_e (plug), and T_e (central cell) equals $0.5 T_e$ (plug). The group of lower temperatures is associated with a vacuum leak in the west plug.

Fig. 31. Electron temperatures at two radii in the TMX east plug compared to central-cell electron temperatures. The solid lines connect simultaneous measurements. These data are from the same shots as Fig. 30.

Fig. 32. Plasma densities at two radii in the TMX east plug compared to central-cell densities. Also shown are densities obtained from beam attenuation measurements. These data are for the same shots as Fig. 30.

Fig. 33. A comparison of radial plug potentials with plug radial electron temperatures. Potentials obtained with electrostatic end-loss analyzers. ● refers to ϕ , west end-loss analyzer, ◆ to the ϕ , east end-loss analyzer, and Δ to T_e , east plug.

Fig. 34. The central-cell radial-potential profile, measured by the heavy-ion-beam probe, compared with central-cell and east-plug electron temperatures.

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