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THOMSON SCATTERING DIAGNOSTIC FOR THE MICROWAVE TOKAMAK EXPERIMENT

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ABSTRACT

The Thomson-scattering diagnostic system (TSS) on the Microwave Tokamak Experiment (MTX) at LLNL routinely monitors electron temperature (T_e) and density. Typical measured values at the plasma center under clean conditions are 900 ± 70 eV and 1 to 2 X 10^{14} (±30%) cm^{-3}. The TSS apparatus is compact, with all elements mounted on one sturdy, two-level optics table. Because of this, we maintain with minimum effort the alignment of both the ruby-laser input optics and the scattered-light collecting optics. Undesired background signals, e.g., plasma light as well as ruby-laser light scattered off obstacles and walls, are generally small compared with the Thomson-scattered signals we normally detect. In the MTX T_e region, the TSS data are definitely fitted better when relativistic effects are included in the equations. Besides determining the temperature of the Maxwellian electron distribution, the system is designed to detect electron heating from GW-level free-electron laser (FEL) pulses by measuring large wavelength shifts of the scattered laser photons. TSS data suggest that we may indeed be able to detect these electrons, which can have energies up to 10 keV, according to computer simulation.

INTRODUCTION

One of the basic diagnostics on the Microwave Tokamak Experiment (MTX)[1] at the Lawrence Livermore National Laboratory (LLNL) is the Thomson-scattering system (TSS). It routinely measures electron temperature (T_e) and density during plasma discharges. These data provide a reference point for the more comprehensive but time-averaged measurements of T_e by the electron-cyclotron-emission diagnostic,[2] which is more difficult to calibrate. The TSS measurements of density complement the far-infrared-interferometer density measurements.[3]

By mounting all the TSS equipment compactly on one sturdy, two-level optics table, we have avoided problems of maintaining alignment that have plagued certain more-complex Thomson-scattering arrangements. We are able to maintain with minimum effort the alignment of both the ruby-laser input optics and the scattered-light collecting optics. Alignment checks separated in time by several weeks give reproducible results.

Besides determining the temperature and density of the Maxwellian electron distribution, our TSS apparatus is designed to detect electron heating from GW-level free-electron laser (FEL) pulses injected into the MTX plasma. The investigation of electron heating by high-peak-power FEL pulses is the chief goal at MTX, where preparations for this experimentation are under way.

I. APPARATUS

Figure 1 shows the layout of the TSS apparatus. To economize, equipment from the tandem-mirror experiments TMX and TMX-U is being reused, including the ruby laser (with 35-ns-FWHM pulse and 10-J output energy) and the spectrometer, light pipes, and photomultiplier tubes.[4] A unique aspect of our equipment is its compactness. The ruby-laser input system is mounted on a 3.66 X 0.76 X 0.61-m granite optics table, while the collecting-optics system is mounted on a 2.44 X 0.76 X 0.11-m honeycomb optics table placed above the laser system and fastened securely to the granite slab. There is no mechanical or electrical coupling between the TSS equipment and the MTX machine. These features facilitate the reproducible aiming of the laser beam through the plasma viewing point of the collection optics. The spatial filter shown in Fig. 1 eliminates many of the poorly focused components of the laser beam, thus reducing the scattering off apertures and other obstacles near the plasma.

The data-collecting system consists of two mirrors and eight lenses (two are cylindrical) to gather, focus, and transport the light, followed by analyzing and recording components. A polarizing-cube beamsplitter along the optics path reduces the unwanted plasma light, passes the polarized Thomson-scattered light, and allows tungsten-lamp calibration light to enter from the side. An image (2 mm wide X 10 mm high) of the observed plasma volume (7 mm wide X 10 mm high X 7 mm deep) is formed by the collection optics at the entrance slit to the spectrometer. This modified Czerny-Turner spectrometer has a diffraction grating to disperse the wavelength band formed in the Thomson-scattering process. The dispersed wavelengths fall on an array of 14 rectangular fiber-optics light pipes of different widths, which then conduct the light to 14 photomultiplier tubes (PMT). The PMT signals are routed to analog-to-digital (A/D) recorders, the stored contents of which are read into the MTX computer data base.

In practice, we make three sets of measurements within a 2-μs period during a plasma discharge, integrating the light for 100 ns each time. The plasma background light is recorded during the first and third measurements. (To obtain the laser light scattered off apertures and other obstacles, we make a separate measurement without plasma present.) During the second measurement with plasma, the laser is fired and the resulting Thomson-scattered light is recorded in addition to the other signals just mentioned. Thus, a subtraction can be made to obtain just the Thomson-scattered light.

Correct timing is an important part of this diagnostic. When GW-level FEL pulses are injected into the MTX plasma, the timing of the ruby-laser firing will be even more critical than usual because it must be accurately coordinated with the firing of the FEL. We will look for electron heating at about 100 ns after the FEL pulse, the approximate time needed for the heated electrons to drift one-third of the way around the tokamak torus to the location of the TSS. Because of the jitter in the relative timing between the FEL and tokamak, the TSS laser timing must be synchronized to the FEL firing. The special and accurate timing system to be used here was designed specifically for the TSS measurements, and it has subsequently been selected for use with other elements of the MTX diagnostic system.[5] The jitter of the TSS laser firing, once it receives the command to fire, is in the acceptable range of 10 to 15 ns.

Our TSS equipment allows a measurement at one spatial point and one time during each plasma discharge. We can do a radial scan over a series of shots by rotating a mirror. Two beam lines through the plasma are available for the laser beam, extending the radial range of measurement.

II. EXPERIMENTAL RESULTS

In Fig. 2(a), we give an example of TSS recorded signals for the 14 data channels. The lower (usually two) lines shown for each channel are the first and third data samples, taken with plasma present but without firing the laser. The top of the histogram bar for each channel represents the second sample, taken when the laser fired, and is labeled with the channel number. Channel 3 includes the ruby-laser wavelength (694 nm). Its data are not useful in the subsequent analysis because of the large obstacle-scattered signal. All channels have the plasma background signal small compared with the Thomson-scattered signal except for channel 7 (and 14). The channel 7 signal includes the H-alpha wavelength, a strong plasma signal; even so, channel 7 provides useful Thomson-scattering data after the plasma background light is subtracted off. We position just enough of the data channels at wavelengths longer than the ruby wavelength to satisfactorily define the peak of the Thomson-scattered distribution. (The quantum efficiency of the PMTs is falling rapidly with increasing wavelength in that region.)

Figure 2(b) displays the data in the same way as in Fig. 2(a), but during these measurements no plasma was present. Thus, these signals result from laser light scattering off apertures and obstacles. Only the ruby wavelength channel 3 has a sizable signal. In the data analysis, these signals are subtracted from the second sample of the Fig. 2(a) data.

Analysis of the Fig. 2 data produces the reduced results, with standard-deviation error bars, plotted in Fig. 3. Immediately after a plasma shot, the gain of each channel is automatically measured with the calibration light mentioned earlier. When these individual calibrations are applied to the somewhat-random-looking data shown in Fig. 2, and the various background signals are subtracted off, we obtain the much smoother variation in Fig. 3. The solid curve shows a least-squares fit to the data obtained assuming an electron Maxwellian distribution. The fitting equation is a Gaussian with a relativistic correction that moves the peak to wavelengths shorter than the ruby wavelength.[6] These data yield 1206 $\pm$ 68 eV for T_e and 1.6 X 10^{14} ($\pm$30%) cm^{-3} for the density. The standard-deviation errors are typical for our measurements. (The TSS density value is calculated by integrating the area under the entire scattered-light curve defined by the data of Fig. 3, with the density calibration obtained from Rayleigh scattering of the laser beam off argon gas in the MTX vacuum chamber.[7])

III. CONCLUDING REMARKS

Figure 4 shows MTX plasma data and also residual-signal results obtained (with no injected FEL beam) in the wavelength-shift region where we expect to see the effects of FEL electron heating. This plot is like that in Fig. 3 except that it is a semilog scale and the wavelength-shift region is extended to shorter wavelengths. Two sets of overlapping plasma data are shown, obtained at two rotation settings of the spectrometer diffraction grating to extend the wavelength span. The solid curve at the right is the fit to the one set of data, as in Fig. 3. The dashed line at the left is estimated from computer-simulation calculations of electrons heated by the FEL beam up to energies as high as 10 keV. When compared with our residual-signal results in this region (after all known background signals are subtracted off, leaving only plasma and uncorrected effects), it appears that measurements of the FEL-heated electrons with our Thomson-scattering apparatus may be possible for anticipated FEL and plasma parameters.

Thus, in addition to the MTX Thomson-scattering equipment performing well in its primary function of providing reliable T_e and electron-density measurements for basic MTX plasma conditions, it appears possible that its usefulness can be extended to measurements concerning the basic role of the MTX experiment, that of heating electrons with a high-power FEL beam. This indeed would be a significant contribution to the experiment.

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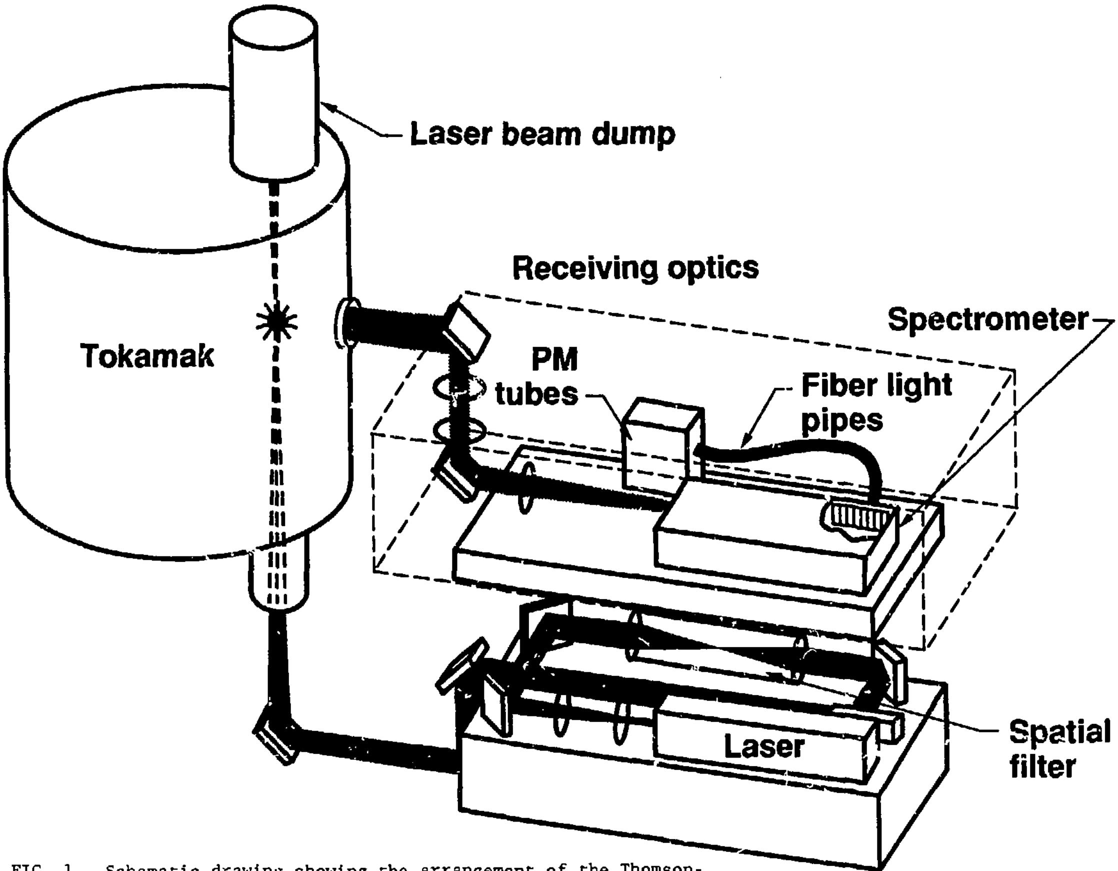

FIG. 1. Schematic drawing showing the arrangement of the Thomson-scattering equipment on MTX. For simplicity, the polarization cube and several of the lenses mentioned in the text are not shown.

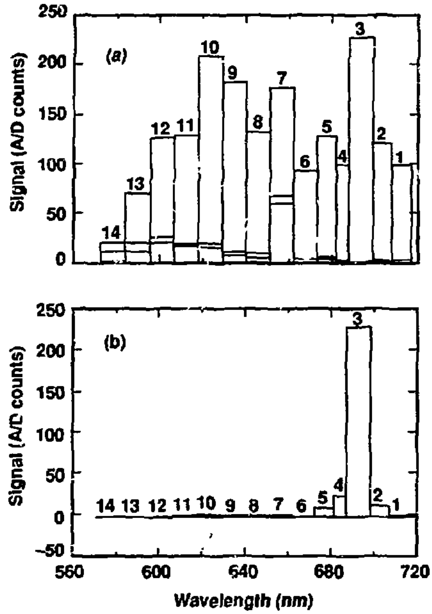

FIG. 2. (a) An example of 14 channels of raw data from the TSS recorded during an MTX plasma discharge. Signal zero levels have been subtracted. The term "A/D counts" in the vertical scale label refers to the data-recorder digital readings. Numbers of photoelectrons from the PMT cathodes are higher by a factor of about 10. (b) The same data display as in (a), except that no plasma was present during these measurements.

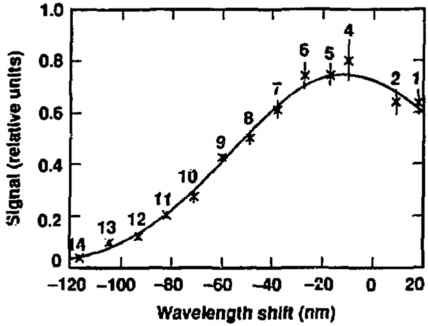

FIG. 3. TSS results (with standard-deviation errors) obtained after reducing the data shown in Fig. 2, including adjusting for the gain of each channel. The wavelength shift of the horizontal scale is with respect to the ruby wavelength at 694 nm. The curve is a least-squares fit to a Gaussian with a relativistic correction, with a peak displaced in wavelength from the ruby wavelength to best fit the data and yielding T_e = 1206 ± 68 eV.

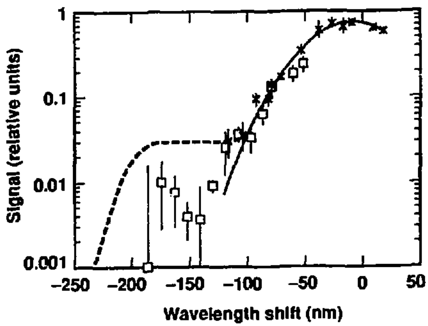

FIG. 4. On the right we show a standard set of reduced TSS data (the x's) from MTX, with a fit as in Fig. 3 (T_e = 857 ± 62 eV). Toward the left are residual-signal measurements (the squares) averaged over three MTX plasma discharges, extending into the wavelength-shift region where we would expect to see the results of FEL electron heating (FEL beam not present for these data). The curve at the left (dashed line) is estimated from computer-simulation calculations of electrons heated up to 10 keV by the FEL beam, assuming a 3-GW, 30-ns FEL pulse injected into an MTX plasma of 2 X 10^{14} cm^{-3} density. This curve shows the signal level we might observe, compared with our residual-signal measurements.