Ion Temperature Measurement of Tokamak Plasmas by Collective Thomson Scattering of D_2O Laser Radiation

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A D_2O far-infrared laser emitting 0.5 J in 1.4 μs at 385 μm and a heterodyne receiver system comprising a Schottky-barrier-diode mixer with a noise temperature of 8000 K (double sideband) were used in a Thomson scattering experiment to measure the ion temperature of a tokamak plasma during a single laser shot. Series of measurements under reproducible plasma conditions have been carried out in hydrogen, deuterium, and helium plasmas. Their statistical analysis yielded a typical relative error of 25% for a single-shot measurement.

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Collective Thomson scattering of far-infrared radiation (FIR) as a method to measure the ion temperature T_i of a tokamak plasma offers several important advantages: (1) It provides excellent spatial resolution (<10 mm) and hence measures local values of T_i. (2) The temporal resolution is determined by the pulse length of the FIR laser (typically 1 μs) which is shorter than the time scale of most temperature variations of practical interest. (3) It discriminates between majority ions and impurities. (4) Neither restrictive assumptions nor a complex model is required for the evaluation of T_i.

For typical tokamak parameters and scattering angles permitting good spatial resolution, a laser source in the far infrared is required. A suitable choice is the optically pumped D_2O laser with its stimulated Raman transition at 385 μm. At this wavelength, Schottky-barrier-diode mixers allow heterodyne detection with a noise equivalent power (NEP) down to 10^{-19} W/Hz and an IF bandwidth in the GHz range. Long-pulse operation of the laser is important because it will determine the signal integration time which finally limits the signal-to-noise ratio that can be achieved.[1,2]

The first results from collective Thomson scattering using a pulsed D_2O laser were reported in 1983 by Woskoboinikow *et al.*[3] However, because of severe stray light problems and limited signal-to-noise ratio, an ion-temperature measurement was not feasible at that time.

In the following, results from an experiment on the TCA tokamak will be presented, permitting for the first time the evaluation of the ion temperature from the data obtained during a single laser shot.

The experimental setup is shown schematically in Fig. 1. The main components are the D_2O laser resonator, a high-power CO_2 laser for optical pumping, and a heterodyne receiver system with twelve spectral channels. Under typical operating conditions the CO_2 laser delivers 600 J on the $9R(22)$ line in a 1.4-μs single-mode pulse.[4] The D_2O laser has a 4-m-long unstable resonator in an L shape with a wire grid at the vertex to allow efficient coupling of the pump beam. At a filling pressure of 6.5 mbar the FIR laser produces 0.5 J in 1.4 μs.

The D_2O laser emission is focused to a 3-mm waist close to the plasma center via a set of off-axis parabolic mirrors. A conical Pyrex beam dump is used to absorb the laser beam and a deeply grooved Macor-ceramic viewing dump is attached to the tokamak vessel opposite

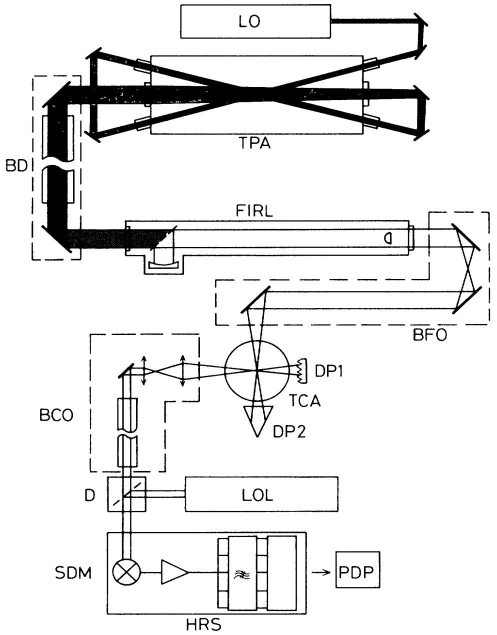

FIG. 1. Configuration of the experimental system. LO: hybrid TEA CO_2 laser oscillator; TPA: triple-pass CO_2 laser amplifier, *e*-beam preionized; BD: beam duct, 70 m long; FIRL: D_2O FIR laser; BFO: beam-focusing optics; TCA: TCA tokamak; DP1: viewing dump, Macor ceramic; DP2: beam-dump, Pyrex cone; BCO: beam collection optics with 7-m-long, dry-nitrogen-filled beam duct; D: diplexer; LOL: local oscillator laser; SDM: Schottky-diode mixer; HRS: heterodyne receiver system.

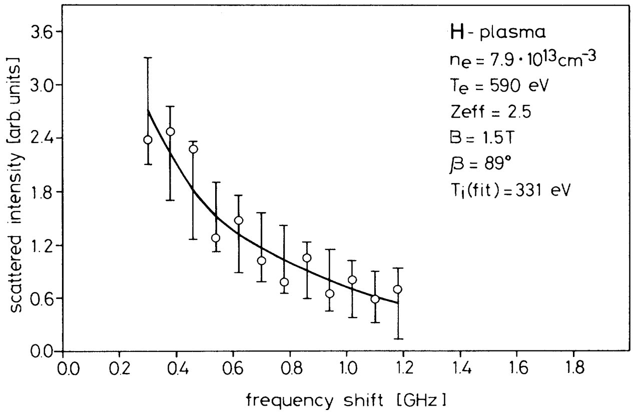

FIG. 2. Single-shot measurement of the scattered light spectrum in an H plasma. The solid curve represents the fitted spectrum for the given plasma parameters. The evaluated ion temperature is $T_i = 330$ eV.

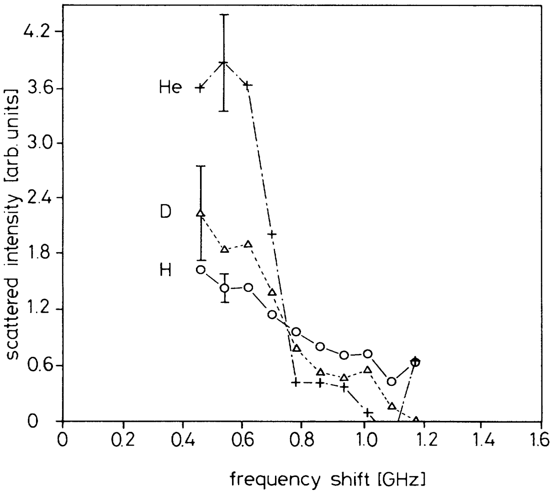

FIG. 3. H, D, and He spectra obtained by averaging seven to ten shots with reproducible plasma parameters.

the output window. The purpose of these two devices is to reduce stray light to an acceptable level. The scattered light is collected at 90° to the incident beam in a solid angle of 4.3×10^{-3} sr.

For detection and spectral analysis of the scattered radiation we use a heterodyne receiver with an optically pumped CD_3Cl FIR laser as a local oscillator. Its emission is combined with the scattered radiation in an optical diplexer and mixed in a Schottky barrier diode. The resulting IF signal, centered around 3.6 GHz, is amplified and split into twelve channels with a bandwidth of 80 MHz each. The signals from the output of the receiver are fed into a CAMAC analog-to-digital converter which comprises a gated integrator.

The collaboration with groups at the University of Duesseldorf and the Max-Planck-Institut für Radioastronomie, Bonn, which provided the Schottky-diode mixer, resulted in a considerable improvement of the sensitivity of our detection system. Calibration of the receiver using black-body sources yielded a system noise temperature of 8000 K (double sideband), equivalent to an NEP of 2.2×10^{-19} W/Hz.

The scattering experiments were carried out in TCA plasmas at electron densities above 5×10^{19} m^{-3}. Under these conditions the signal-to-noise ratio was sufficient to evaluate the ion temperature from data recorded in a single laser shot. The spectrum of scattered radiation of a hydrogen plasma is presented in Fig. 2. The circles represent the measured signals per spectral channel of 80-MHz bandwidth after integration over the 1.4-μs pulse length of the D_2O laser. The solid curve represents the best fit to the data points with the ion temperature and a vertical scaling factor as the only free parameters. The calculation includes the influence of the magnetized electrons which becomes important when the angle between the difference k vector and the magnetic field direction is close to 90°.[5] The effective angle of 89° allows for the averaging over the solid angle of observation (2° half cone angle). Other plasma parameters required by the fitting routine—such as electron density N_e, electron temperature T_e, and effective ion charge Z_{eff}—have been introduced as known quantities. The electron density has been measured by interferometry and the electron temperature by ruby-laser scattering. The Z_{eff} values are not precisely known and therefore typical data for TCA discharges have been used. With these assumptions an ion temperature of $T_i = 330$ eV is found.

From a series of measurements under reproducible plasma conditions we determined the statistical uncertainty of our T_i measurement to be 80 eV, i.e., 20% to

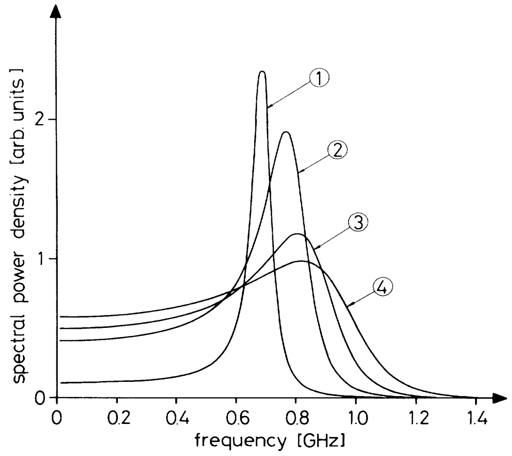

FIG. 4. Calculated spectra for a He plasma for the plasma parameters of Fig. 6 and for different ion temperatures. Curves 1 to 4: $T_i = 100$, 200, 300, and 400 eV. Note that curve 1 ($T_i = 100$ eV) has been reduced by a vertical scaling factor of 3.

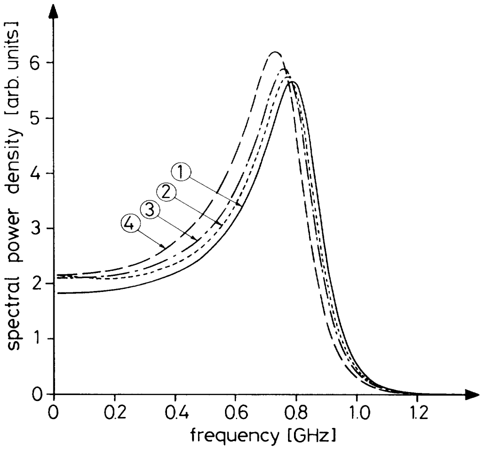

FIG. 5. Effect of impurities. Curve 1: pure He; curves 2 to 4: impurities included with $Z_{\text{eff}}=2.7$, 3.1, and 4.4, respectively. Other parameters as in Fig. 6.

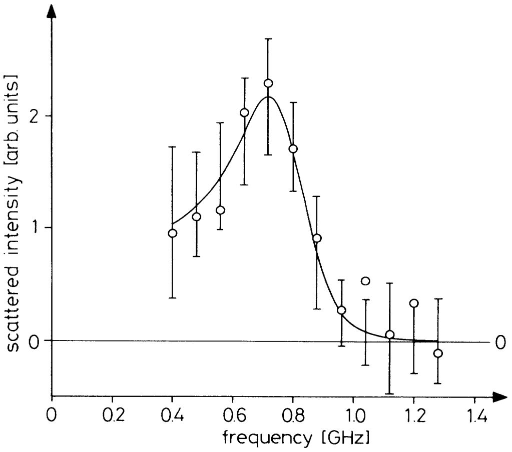

FIG. 6. Measured spectrum for a He plasma in TCA. The solid curve is a least-squares-fitted spectrum for $N_e=7\times10^{19}$ m^{-3}, $T_e=670$ eV, angle $(\mathbf{k},\mathbf{B})=86°$, and $Z_{\text{eff}}=4.4$. The fit yields $T_i=250$ eV.

25% relative error. A comparison of these T_i values with those obtained from a neutral-particle analyzer (NPA) installed on TCA showed a systematic discrepancy. The NPA diagnostic yields T_i values which are 80 to 100 eV higher. This discrepancy was only observed in hydrogen plasmas whereas the results in deuterium showed better agreement. We explain this fact by the present arrangement of the spectral channels of the receiver. In the case of the wider hydrogen spectrum, information about the wing of the spectrum, which is most sensitive to changes in the majority ion temperature, is lost and the result of the fit relies more strongly on the estimate of Z_{eff}.

So far all of our measurements were carried out in Ohmically heated plasmas, which at a given density show very little variation in the ion temperature. In order to demonstrate that the shape of the spectrum varies with plasma parameters in a predicted way, several series of measurements were carried out with hydrogen (H), deuterium (D), and helium (He) as the majority ions. In Fig. 3 the spectra obtained by averaging over a series of about ten reproducible shots in H, D, and He, respectively, are superimposed. Since the ion temperature is roughly the same in all three cases, the width of the spectrum decreases with increasing ion mass.

Changing the scattering geometry such that the angle between **k** and **B** is 86° instead of 89° permitted us to reduce the distortion of the spectrum caused by the magnetized electrons. For a He plasma, theory predicts in this case that the ion-acoustic resonance should be clearly visible as long as $T_e/T_i > 1$ (see Fig. 4). The position and the width of the resonance peak should only be affected weakly by the presence of impurity ions as shown in Fig. 5, where Z_{eff} has been varied from 2.7 to 4.4. For all calculated spectra presented in this paper we assumed a fixed ratio of the impurity concentrations $(\text{C}^{+6}:\text{O}^{+8}:\text{Fe}^{+19}=10:5:1)$. Different values of Z_{eff} were obtained by varying the concentration of each species proportionally.

Figure 6 shows a measured spectrum for a He plasma in TCA recorded in a single laser shot. We observe good agreement with the predictions of theory assuming density fluctuations at the thermal level. In the case of a He plasma with given T_e a variation of T_i leads to a significant change in position and half-width of the resonance peak (see Fig. 4) which allows an unambiguous evaluation of T_i. For the given input parameters (N_e, T_e, Z_{eff}) the fitting routine yields an ion temperature of $T_i=250$ eV with an uncertainty of 20% to 25%. Investigations under study indicate that this precision can be maintained if the uncertainties associated with the other plasma parameters required by the fitting routine (especially T_e) are less than 10%. At present the precision is mainly limited by the signal-to-noise ratio which leads to the error bars given in the figure.

In summary, collective Thomson scattering of FIR laser radiation has been applied to measure the ion temperature of a tokamak plasma. In the experiment carried out at the TCA tokamak a high-power D_2O laser emitting 0.5 J in a 1.4-μs pulse at 385 μm and a heterodyne receiver based on a Schottky-barrier-diode mixer with an NEP of 2.2×10^{-19} W/Hz were used. The observed spectra could clearly be identified as collective scattering from thermal density fluctuations and for the first time the ion temperature could be obtained from data recorded in a single laser shot.

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