time-independent flow and time-periodic flow occur. In the limiting case of very large aspect ratio for the convection experiment, only time-dependent aperiodic flow is observed when convection is initiated, while for circular couette flow the greatest range of periodic states occurs for large aspect ratio.

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[a]Current address: Bell Laboratories, Murray Hill, N. J. 07974.

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Doppler-Broadening Measurements of X-Ray Lines for Determination of the Ion Temperature in Tokamak Plasmas

M. Bitter, S. von Goeler, R. Horton, M. Goldman, K. W. Hill, N. R. Sauthoff, and W. Stodiek
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
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Ion-temperature results are deduced from Doppler-broadening measurements of the $K\alpha$ ($1s$-$2p$) resonance line emitted from heliumlike iron impurity ions in the hot central core of PLT (Princeton Large Torus) tokamak discharges. The measurements were performed using a high-resolution Bragg-crystal spectrometer with a multiwire proportional counter.

The larger tokamaks of the future require new techniques for the measurement of the ion temperature (T_i) in the hot central core of the plasma since the standard methods become more difficult with increasing plasma diameters and electron temperatures (T_e). Neutral-charge-exchange diagnostics[1] cannot be used for the determination of the central ion temperature when the mean free path for neutral charge exchange is much smaller than the plasma diameter. The line radiation in the vacuum ultraviolet (vuv) region commonly used for Doppler-broadening measurements[2] of T_i is emitted primarily from the edge of the plasma at higher central electron temperatures. An exception is the recently observed[3] forbidden line of Fe XX although this line will also originate from outer regions of the plasma column when the electron temperature exceeds 2 keV. An alternate method, the determination of T_i from a measurement of the neutron yeild,[4] is difficult to interpret if the ion-velocity distribution is not Maxwellian. This may occur, for example, during plasma heating by injection of intense neutral deuterium beams. In this paper we demonstrate that the inner-core ion temperature of a tokamak plasma can be determined from Doppler-broadening measurements of suitable x-ray lines emitted from the plasma.

As T_e increases, a larger fraction of the electromagnetic radiation is emitted in the x-ray region. This radiation consists of a continuous bremsstrahlung spectrum and characteristic line spectra from high-atomic-number impurity ions, which occur in different degrees of ionization or charge states. In a previous experiment[5] we used a germanium Bragg-crystal spectrometer to investigate the $K\alpha$-line spectra of the charge states of iron in Princeton Large Torus (PLT) discharges as a function of T_e. The measured line intensities and wavelengths were in agree-

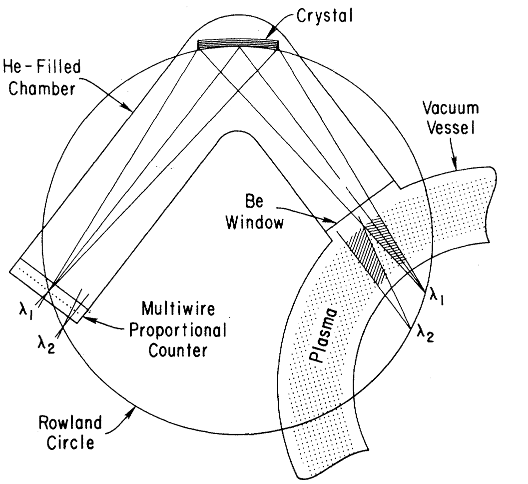

FIG. 1. Quartz-crystal spectrometer in the Johann configuration. X rays emitted from the shaded area of the plasma pass through a beryllium window into a helium-filled tube and are Bragg reflected by the crystal onto the position-sensitive detector. Photons of different energies are focused to different detector points.

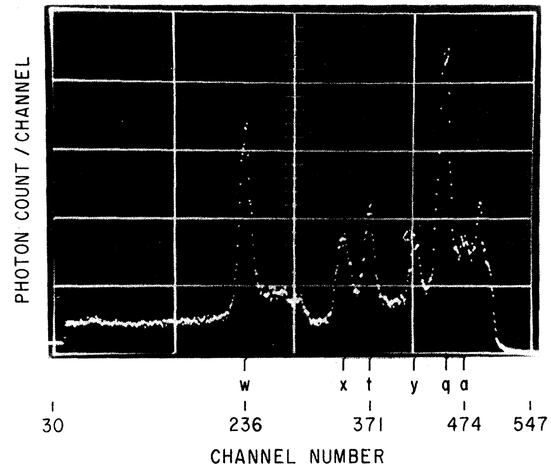

FIG. 2. Satellite line spectrum of the heliumlike iron (Fe XXV) in PLT as recorded by a multichannel analyzer. The photon energy decreases with increasing channel number. The conversion gain is 0.18 eV/channel. w indicates the Fe XXV $K\alpha$ resonance line at 1.85 Å used for Doppler-broadening measurements.

ment with theoretical predictions,[6] based on coronal equilibrium, for the investigated range of electron temperatures from 0.8 to 2.0 keV. For $T_e > 1.2$ keV, the $1s$-$2p$ resonance transition of the heliumlike charge state (Fe XXV) was well excited and appeared as an isolated line at 1.85 Å. These results suggested that this line might be used for Doppler-broadening measurements by means of a Bragg-crystal spectrometer of sufficiently high energy resolution. According to Doppler's law, the energy resolution $(E/\Delta E)$ of the instrument must be better than 3000 for $T_i \sim 1$ keV.

A Bragg-crystal spectrometer, which consists of a 6-in.×1.5-in.×0.030-in. quartz crystal [cut parallel to the $(22\bar{4}\bar{3})$ plane with a $2d$ spacing of 2.028 Å] bent to a radius of curvature of 333 cm in the Johann configuration[7] and of a multiwire proportional counter,[8] with approximately 100 anode wires of ~1 mm spacing, has been used for these measurements.

Figure 1 shows the experimental arrangement. X rays emitted along chords in the horizontal midplane from iron ions in the shaded area of the plasma are Bragg reflected by the crystal and focused onto the position-sensitive detector. Photons of different energies are focused to different detector points. The principles of the spectrometer have been previously[5] described in more detail. Replacement of the germanium crystal by a quartz crystal with an inherent resolving power of $\sim 10^5$ and a dispersion $d\theta/d\lambda = 0.068$ deg/mÅ at 1.85 Å has improved the energy resolution $(E/\Delta E)$ of the instrument from 1700 to 15 000.

Figure 2 presents the $K\alpha$ line spectrum of iron in the neighborhood of the Fe XXV $1s$-$2p$ transition observed with the spectrometer for moderate values of T_e and T_i, 1.1 and 0.9 keV, respectively, and an electron density of 2×10^{13} cm^{-3}. The spectrum was accumulated over fifteen PLT discharges with identical plasma parameters. Gabriel's[9] notation for line identification has been used: w indicates the $K\alpha$ ($1s$-$2p$) resonance line of heliumlike iron, which is observed for Doppler-broadening measurements. The fine satellite line structure on its long-wavelength side is due to transitions of the type $1s^2nl$-$1s2pnl$, for $n>2$.[10] x and y indicate the intercombination lines of the heliumlike iron. t and a are satellites excited through dielectronic recombination, and q results from an inner-shell excitation of the lithiumlike charge state (Fe XXIV). The agreement between the experimental and theoretical[9] wavelengths is illustrated in Table I. Line spectra of the heliumlike and lithiumlike iron have been obtained previously from the study of high-current sparks[11] and the observation of solar flares.[12] The spectrum in Fig. 2 is a high-resolution $K\alpha$ satellite line spectrum of Fe XXV from a large-volume laboratory plasma under conditions close to coronal equilibrium.

Figures 3 and 4 show results obtained from

TABLE I. Experimental and theoretical wavelengths of observed features in the neighborhood of the Fe XXV $1s$-$2p$ transition. The experimental accuracy is $\Delta\lambda = \pm 1\times10^{-4}$ Å. The experimental wavelengths were normalized to the ${}^1S$-${}^1P^0$ theoretical predictions.

	Transition	λ_{theor} (Å)	λ_{exp} (Å)
w	${}^1S$-${}^1P^0$	1.8500	1.8500
x	${}^1S$-${}^3P^0$	1.8551	1.8553
t	${}^2S$-$({}^3P)\,{}^2P^0$	1.8570	1.8567
y	${}^1S$-${}^3P^0$	1.8591	1.8591
q	${}^2S$-$({}^1P)\,{}^2P^0$	1.8604	1.8608
a	${}^2P^0$-${}^2P$	1.8618	1.8618

time-resolved Doppler-broadening measurements of the $K\alpha$ resonance line of the heliumlike iron in PLT discharges. The iron impurity concentration in the predominantly deuterium plasma was only 0.1% of the bulk electron density ($n_e \approx 2\times10^{13}$ cm^{-3}). Auxiliary heating by injection of four neutral hydrogen beams was used. The beams, totaling 1.4 MW, were injected furing the interval from 450 to 580 msec in a 1-sec discharge pulse. A time resolution of 50 msec was obtained by storing data from successive 50-msec intervals of the discharge pulse into sixteen 256-word segments of the memory of a pulse-height analyzer. Figure 3 shows the line profiles of three successive time intervals before (a) and during (b), (c) the hydrogen-beam injection. The solid curves were obtained from a least-squares fit to the experimental data of a Voigt function,[13] taking into account the natural line broadening by a Lorentzian of 0.335 eV full width at half maximum (FWHM).[14] The arrows indicate the range of channels used for the fit. The upper limit has been chosen to exclude the previously mentioned $1s^2nl$-$1s2pnl$ satellite structure. The average in the channels below the lower limit was used for background subtraction. An enhanced line broadening during neutral-beam injection is evident from Figs. 3(b) and 3(c).

Figure 4 presents the ion-temperature results, deduced from the experimental line profiles, as a function of time. Corrections were also made for the instrumental width, assuming a Gaussian broadening of 0.35 eV FWHM. The error bars indicate the statistical error of the experimental data. Note that the apparent drop in T_i before the termination of neutral-beam injection is an artifact of the limited temporal resolution. The datum point shown at 575 msec represents an average over the last 30 msec of beam injection and a period of 20 msec after termination of the injection.

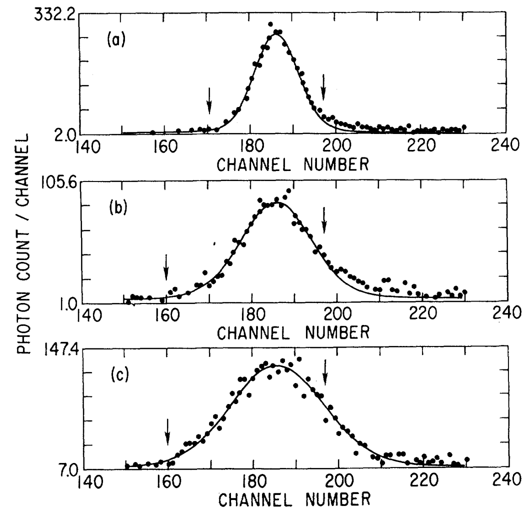

FIG. 3. Line profiles of the Fe XXV $1s^2({}^1S)$-$1s2p\,({}^1P^0)$ resonance transition obtained during time intervals of 50 msec (a) before and (b), (c) during neutral-beam injection. The conversion gain is 0.18 eV/channel. In order to determine the ion temperature, Voigt functions are fitted to the data. Shown are the curve fits for the times (a) 0.425, (b) 0.475, and (c) 0.525 sec of Fig. 4.

In conclusion, the feasibility of Doppler-broadening measurements in the x-ray region has been demonstrated and used for determination of the temperature of impurity ions in tokamak plasmas. The $K\alpha$ resonance line of the heliumlike iron utilized in our experiment is emitted from the central region of PLT plasma discharges. Dop-

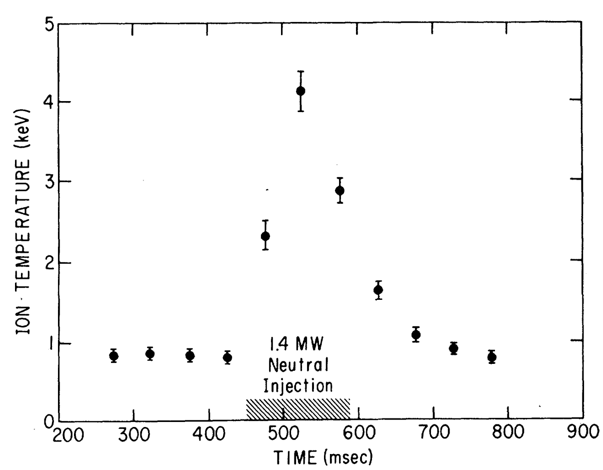

FIG. 4. Ion temperature derived from Doppler broadening of the Fe XXV $K\alpha$ line at 1.85 Å. Each point is taken over an integration time of 50 msec.

pler-broadening measurements of this line may be employed for determining the central ion-impurity temperature for values of T_e up to 10 keV, above which the heliumlike charge state is burned out if the predictions of coronal equilibrium can be extended to tokamak plasmas under these conditions. The quartz-crystal spectrometer described in this paper may be used to obtain high-resolution spectra of the heliumlike and lithiumlike iron as a function of T_e. These would provide improved experimental data for comparison with theoretical codes for excitation, ionization, and recombination rates in tokamak plasmas.

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Saturation of Stimulated Brillouin Backscatter in CO_2-Laser–Plasma Interaction

A. Ng, L. Pitt, D. Salzmann, and A. A. Offenberger

Department of Electrical Engineering, University of Alberta, Edmonton, Alberta T6G 2J1, Canada

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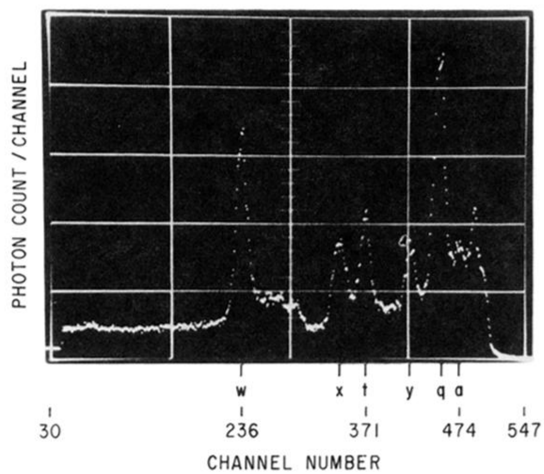
Saturation of stimulated Brillouin scattering has been observed in the interaction of long-pulse CO_2-laser radiation with underdense hydrogen plasma at intensities of $\leq 10^{13}$ W/cm^2. The stimulated Brillouin scattering is strongly modulated with average long-time reflectivity approximately half the peak value. The maximum reflectivity measured was 60% and wave breaking is postulated as the principal saturation mechanism.

A problem of considerable interest and importance to the inertial-confinement fusion concept is the role of stimulated backscatter in potentially reducing the coupling efficiency of laser energy to the target pellet. In particular, theoretical calculations suggest that intense laser radiation interacting with ion waves in the underdense coronal plasma surrounding the target may lead to strong stimulated Brillouin scattering (SBS).[1] In view of the large growth rates, even for relatively short-scale-length plasmas (characteristic of those generated by subnanosecond laser pulses),



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