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Observation of a Forbidden Line of Fe XX and Its Application for Ion Temperature Measurements in the Princeton Large Torus Tokamak

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A spectrum line in the Princeton Large Torus (PLT) tokamak discharges, with wavelength measured as 2665.1 ± 0.3 Å, has been identified as the $2s^2 2p^3\,{}^2D_{5/2} \to {}^2D_{3/2}$ magnetic dipole transition in Fe XX ground configuration. A variety of localized spectroscopic diagnostics, e.g., ion temperature and density distribution measurements in the high-temperature interior of the plasma, are feasible by means of forbidden lines of this type. The 2665-Å line has been used to measure near-central ion temperature in a discharge with auxiliary neutral-beam heating.

Special interest in forbidden lines of highly ionized atoms in plasma diagnostics arises for two reasons. One reason is that the radiation originates usually from a fairly localized region, where the ionization potential of the ion is roughly comparable to the local electron temperature. The other is that this radiation occurs at relatively long wavelengths, where optics (mirrors, perhaps windows and lenses) can be effectively used, thus allowing employment of versatile spectroscopic techniques. In the past, spectroscopic ion temperature and spatial distribution measurements in tokamaks have been restricted to the relatively abundant oxygen and carbon impurities,[1,2] which become stripped and hence unobservable at temperature ≳0.7 keV.

In this paper, we report the first observation and diagnostic application of a Fe XX forbidden line in tokamak discharges. This line, from the transition $2s^2 2p^3\,{}^2D_{5/2} \to {}^2D_{3/2}$ in the ground configuration, had not been directly observed before, although its approximate location was, of course, predictable. The wavelength (in air) was measured as 2665.1 ± 0.3 Å, corresponding to the ^2D-level separation of 375 11 ± 4 cm^{-1}. The simple *LS*-coupling magnetic dipole radiative transition probability (which should be adequate to better than a factor 2) is 570 sec^{-1}. The identification of the line is based on the temporal and spatial variation of the observed emissivity in the discharge, and the approximate agreement with the expected wavelength and intensity, as described below. Forbidden iron lines of Fe XXI at about 2300 and 1354 Å have been also observed in the adiabatic toroidal compressor (ATC) and Princeton Large Torus (PLT) tokamaks, but not yet with sufficient intensity and reproducibility to allow accurate wavelength determination or consistent use for plasma dignostics, mostly because of interfering radiation of other origin in the spectral neighborhood.

The energy levels and wavelengths of the ground configurations of Fe XX and neighboring iron ions are shown in Fig. 1. The energy levels and their scaling in isoelectronic sequences, and the observed lines, have been described by Edlen.[3,4] The lines at 1354.1 Å of Fe XXI, at 845.1 Å of Fe XXII, and at 974.8 Å of Fe XVIII have been observed in solar flares,[5] the others are mostly deduced from differences of far-uv lines from laser-produced plasmas,[6,7] or from *ab initio* calculations (except, of course, the coronal green line[8] of Fe XIV). Magnetic dipole transition probabilities and wavelengths have been calculated by Cowan[9] and Kastner, Bhatia, and Cohen.[10] In general, the directly observed wavelengths are accurate to about ±0.1 Å, whereas the interpolated or calculated wavelengths are uncertain to at least several angstroms.

Figure 2 shows the temporal behavior of the

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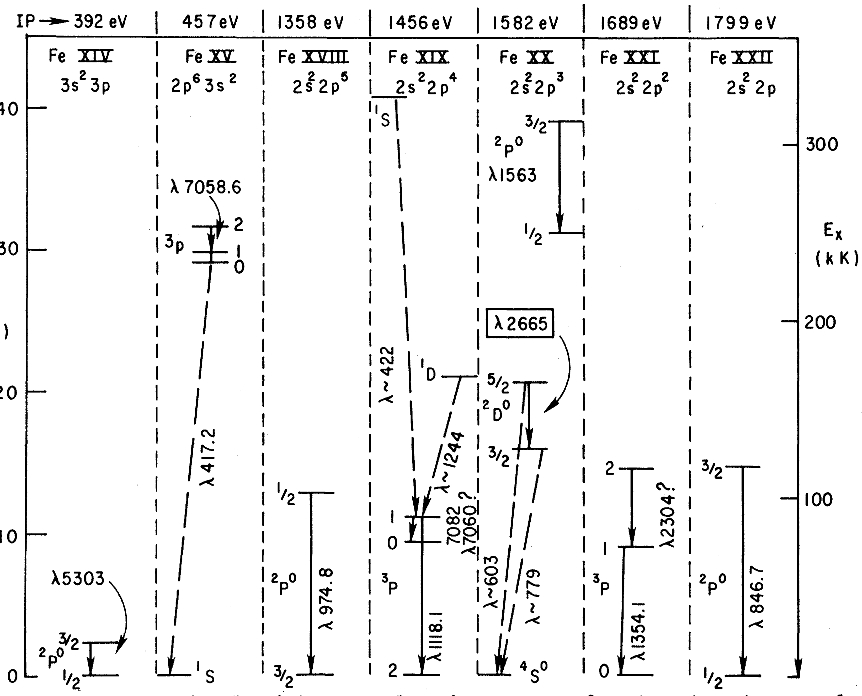

FIG. 1. Energy levels of the ground configurations of various iron ions, and wavelengths (in angstroms) corresponding to the indicated transitions. The top row gives the ionization potential of the ion, also a rough indication of the electron temperature region in the plasma where the ion is likely to be located.

λ = 2665 Å line intensity in a PLT tokamak discharge, in comparison with a succession of iron-ion resonance lines measured with a grazing-incidence spectrometer. All measurements are taken in the equatorial plane of the torus, with the toroidal separation of the two instruments about 45°. The intensities are measured on an absolute scale, although for illustration we have normalized them to peak values. The 2665-Å line is measured with an 1-M Ebert-Fastie spec-

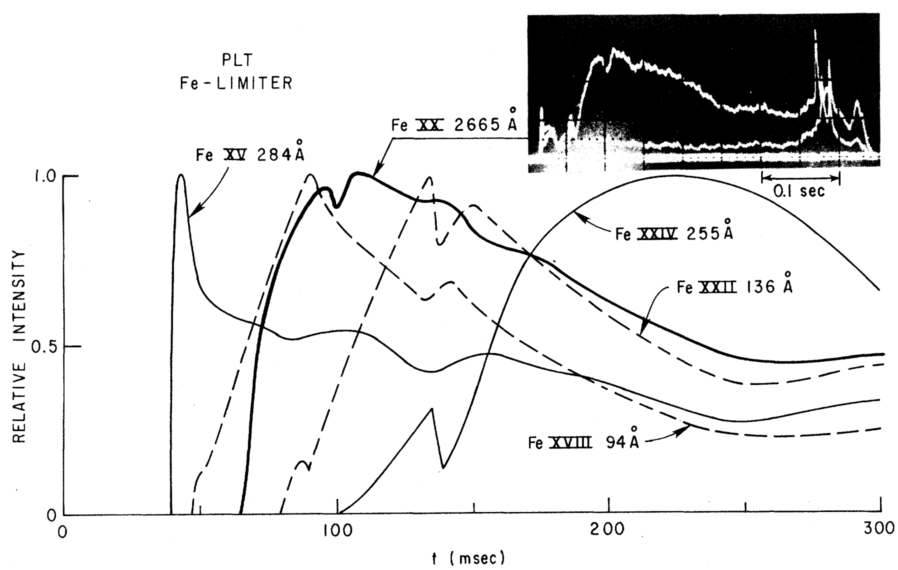

FIG. 2. Temporal behavior of the λ = 2665 Å line and several iron-ion resonance lines in a PLT tokamak discharge. Inset shows the λ = 2665 Å signal relative to neighboring background radiation from carbon and oxygen impurities.

trometer, 1200-line/mm grating in the fourth order. A typical sample of the actual signal, with background radiation of neighboring weak carbon or oxygen lines, is shown in the inset.

The discharge starts at 20 msec in the scale of the figure, and the (central) electron density rises nearly linearly from about $1.3\times 10^{13}/\text{cm}^3$ at 50 msec to $3\times 10^{13}/\text{cm}^3$ at 200 msec. The appearance and peaking times of the 2665-Å line are clearly appropriate for Fe XX, in comparison with the other ion lines. The somewhat different early-time shape is probably due to different electron density dependence of the emission: The radiative lifetimes of the ^2D states of Fe XX are not very much shorter than collisional lifetimes (as is the case in the other lines depicted in Fig. 2); so with increasing density the relative intensity of the 2665-Å line may be progressively reduced. At about 135 msec the discharge suffered an internal disruption (which reproduced quite well from discharge to discharge) that lowers and broadens the electron temperature radial profile. As a result, the ion lines pertaining to the highest temperatures (highest ionization potentials) drop, whereas those of lower states increase slightly. Also in this respect the 2665-Å line is appropriate for Fe XX.

From the intensities of the resonance line and the electron density, the Fe XX ion concentration near the 2665-Å line peak is found to be nearly $7\times 10^{10}/\text{cm}^3$ for these particular discharges with high Fe concentration. From the pattern of the energy levels and approximately known collisional rate coefficients, it appears that the dominant population mechanism of the ^2D states is the direct transition from the ground state ($2p^3\,^4S$) rather than, e.g., pumping through higher-energy states. With the help of extrapolated collision cross sections[11,12] and the radiative lifetimes,[9,10] the population of the $^2D_{5/2}$ state under the experimental conditions is calculated to be about 20% of the total Fe XX population. The measured intensity (near the peak) of 1.2×10^{13} photons/cm^2 sr sec of the 2665-Å line is in very good agreement with this estimate.

Figure 3 shows the vertical brightness distribution of the $\lambda = 2665$ Å line, with a C V line distribution superimposed for comparison. [The discharge conditions here differed somewhat from those pertaining to Fig. 2: The temperature was lower, $T_e(0)\approx 1.2$ keV versus ~2 keV in Fig. 2, and $n_e(0)$ about double that of Fig. 2.] The C V line distribution corresponds to a quasicylindrical shell of radiation located at about $r = 28-30$ cm (where T_e ≈ 200 eV), whereas the $\lambda = 2665$ Å line has a strongly centrally peaked distribution, as is expected for the ~1.5-keV ionization potential of Fe XX. The shoulder distributions of the latter trace belong to some interfering lines of lower states of carbon or oxygen, with quite different time as well as space dependence from the $\lambda = 2665$ Å line. (The apparatus, measurement techniques, etc., for the radial brightness distributions have been described by Suckewer, Hinnov, and Schivell.[13])

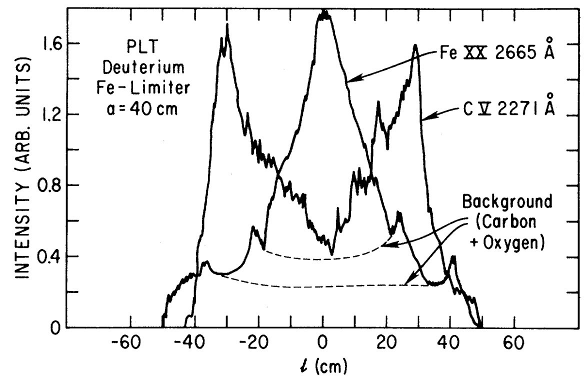

FIG. 3. Chord distribution of the $\lambda = 2665$ Å line and background, compared with the C V light distribution in the same discharge. Aperture limiter is at ± 40 cm.

With the space and time behavior, as well as the wavelength and absolute intensity all consistent with the $^2D_{5/2}$-$^2D_{3/2}$ transition of Fe XX, we consider the identity of the $\lambda = 2665.1$ Å line definitely established.

As a first application of this line for plasma diagnostics, we show in Fig. 4 the results of near-central ion temperature measurements[1] from Doppler broadening of the line in a PLT tokamak discharge with auxiliary neutral-beam heating.[14] The neutral beams injected approximately 1-MW power from 300 to 400 msec into a discharge with Ohmic-heating power input about 0.7 MW. Figure 4 shows the consequent ion temperature behavior at radial locations determined by the radiation pattern of the $\lambda = 2665$ Å line (similar to that in Fig. 3). The insets show the measured line profiles just before and at the end of the beam injection, and 100 msec later. These measurements are in good agreement with ion temperatures determined from charge-exchanged neutral deuterium energy spectra and collimated neutron counts,[14] under similar discharge conditions. The advantages of Doppler temperature measurements are that the radial location of the measurement is, at least in principle, more definitely

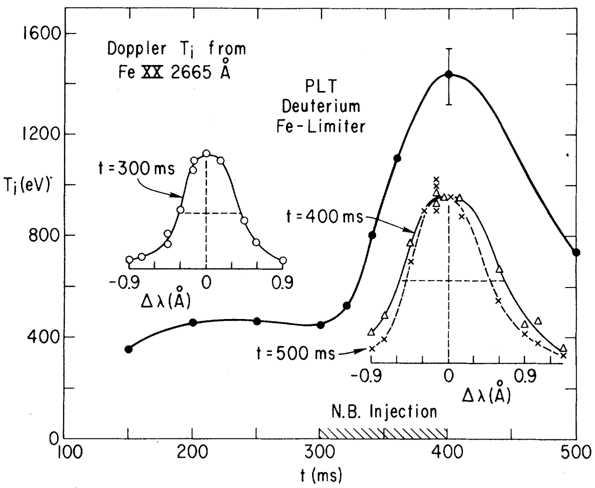

FIG. 4. Ion temperature near the center of a PLT discharge with neutral-beam heating (300–400 msec) measured from the Doppler contours of the $\lambda = 2665$ Å line. Insets show some measured spectral contours before, at the end, and after neutral-beam injection.

determinable, and the results do not depend on the plasma composition (e.g., electron/deuteron or hydrogen/deuteron ratios) or minor deviations from Maxwellian distributions.

Besides local ion temperature measurements in hot plasma interiors, the long-wavelength forbidden lines of heavy ions are useful many other localized diagnostics. Measurement of plasma motions, e.g., rotations, is an obvious extension of the Doppler temperature measurement. But perhaps the most important in tokamak experiments is the possibility of determination of spatial distribution of the various ion concentrations, which can lead to direct measurement of cross-field ion transport rates. The ion concentrations follow directly from local absolute emissivity measurements, since the transition probabilities can be calculated with relatively good accuracy, and the populations of near-ground levels can be related to each other fairly reliably, in plasmas of known electron density.

Evidently, iron ions (and the associated chromium and nickel from stainless steel walls or limiters) are useful for such diagnostics in the 1–2-keV electron temperature range. Corresponding transitions in somewhat heavier elements that could be added in small quantities to the discharge would extend the temperature range upward. In this respect krypton is a particularly useful element in the diagnostics of future larger tokamaks, since its addition and removal is easily controllable.

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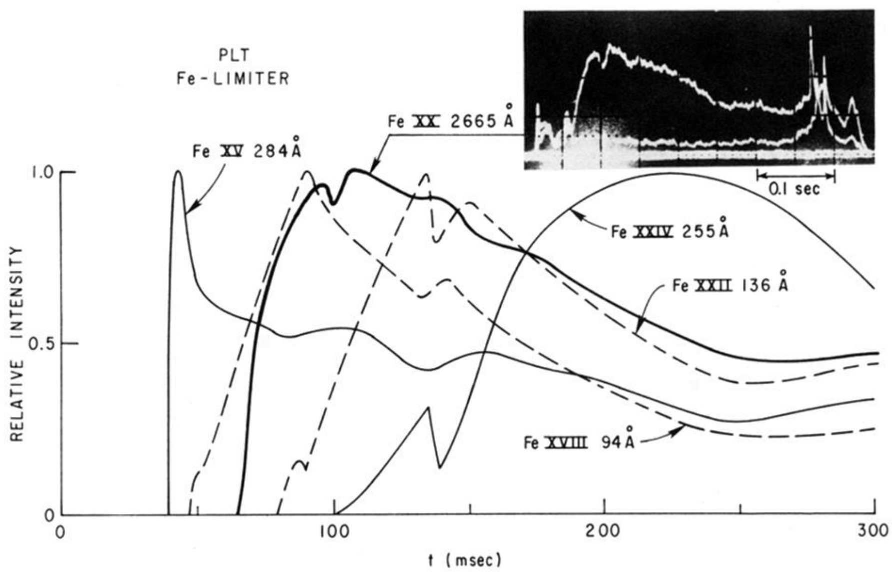

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