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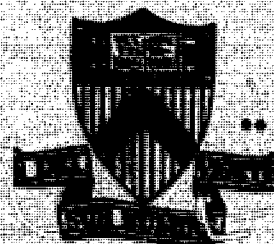
OBSERVATION OF A FORBIDDEN LINE  
OF FeXX AND ITS APPLICATION  
FOR ION TEMPERATURE MEASUREMENTS  
IN THE PLT TOKAMAK

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Observation of a Forbidden Line of FeXX and Its  
Application for Ion Temperature Measurements In  
The PLT Tokamak

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ABSTRACT

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A spectrum line in the PLT tokamak discharges, with wavelength measured as  $2665.1 \pm 0.3\text{\AA}$ , has been identified as the  $2s^2 2p^3 \ ^2D_{5/2} \rightarrow \ ^2D_{3/2}$  magnetic dipole transition in the FeXX 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  $2665\text{\AA}$  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 space distribution measurements in tokamaks have been restricted to the relatively abundant oxygen and carbon impurities<sup>1,2</sup>, which become stripped and hence unobservable at temperature  $\gtrsim 0.7$  keV.

In this paper, we report the first observation and diagnostic application of a FeXX forbidden line in tokamak discharges. This line, from transition  $2s^2 2p^3 \ ^2D_{5/2} + \ ^2D_{3/2}$  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  $2665.1 \pm 0.3 \text{ \AA}$ , corresponding to the  $^2D$  level separation of  $37511 \pm 4 \text{ cm}^{-1}$ . The simple LS-coupling magnetic dipole radiative transition probability (which should be adequate to better than a factor 2) is  $570 \text{ sec}^{-1}$ . The identification of the line is based on the time and space 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 FeXXI at about 2300Å and 1354Å have been also observed in the ATC and PLT tokamaks, but not yet with sufficient intensity and reproducibility to allow accurate wavelength determination or consistent use for plasma diagnostics, mostly because of interfering radiation of other origin in the spectral neighborhood.

The energy levels and wavelengths of the ground configurations of FeXX 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<sup>3,4</sup>. The lines 1354.1Å of FeXXI, 845.1Å of FeXXII, and 974.8 of FeXVIII have been observed in solar flares<sup>5</sup>, the others are mostly deduced from differences of far UV lines from laser-produced plasmas<sup>6,7</sup>, or from ab initio calculations (except of course the coronal green line<sup>8</sup> of FeXIV). Magnetic dipole transition probabilities and wavelengths have been calculated by Cowan<sup>9</sup> and Kastner, et al.<sup>10</sup>. In general, the directly observed wavelengths are accurate to about  $\pm .1\text{\AA}$ , whereas the interpolated or calculated wavelengths are uncertain to at least several Ångstroms.

Figure 2 shows the temporal behavior of the  $\lambda 2665\text{\AA}$  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  $45^\circ$ . The intensities are measured on an absolute scale, although for illustration we have normalized them to peak values. The  $2665\text{\AA}$  line is measured with an IM Ebert-Fastie spectrometer, 1200 line/mm grating in the fourth order. A typical sample of the actual signal, together 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  $2665\text{\AA}$  line are clearly appropriate to FeXX, 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 FeXX 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  $2665\text{\AA}$  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. In this respect also the  $2665\text{\AA}$  line is appropriate to FeXX.

From the intensities of the resonance lines and the electron density, the FeXX ion concentration near the  $2665\text{\AA}$  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<sup>11,12</sup> and the radiative lifetimes<sup>9,10</sup>, the population of the  $^2D_{5/2}$  state under the experimental conditions is calculated to be about 20% of the total FeXX population. The measured intensity (near the peak) of  $1.2 \times 10^{13}$  photons/cm<sup>2</sup>-sr-sec of the 2665Å line is in very good agreement with this estimate.

Figure 3 shows the vertical brightness distribution of the 2665Å line, with a CV line distribution superimposed for comparison [The discharge conditions here differed somewhat from those pertaining to Fig. 2: the temperature was lower,  $T_e(o) \approx 1.2$  keV versus  $\sim 2$  keV in Fig. 2, and  $n_e(o)$  about double that of Fig. 2]. The CV line distribution corresponds to a quasicylindrical shell of radiation located at about  $r \approx 28-30$  cm (where  $T_e \approx 200$  eV), whereas the 2665Å line has a strongly centrally peaked distribution, as is expected for the  $\sim 1.5$  keV ionization potential of FeXX. 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 2665Å line. [The apparatus, measurement techniques, etc., for the radial brightness distributions have been described in Ref. 13].

With the space and time behaviour, as well as the wavelength and absolute intensity all consistent with the  $^2D_{5/2} - ^2D_{3/2}$  transition of FeXX, we consider the identity of the 2665.1Å 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<sup>1</sup> from Doppler broadening of the line in a PLT tokamak discharge with auxiliary neutral beam heating<sup>14</sup>. The neutral beams injected approximately 1 MW power from 300-400 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  $\lambda 2665\text{\AA}$  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<sup>14</sup>, under similar discharge conditions. The advantages of Doppler temperature measurements are that the radial location of the measurement is, at least in principle, more definitively 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 for 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 the future large tokamaks, since its addition and removal is easily controllable.

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Figure Captions

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

Fig. 2. Time behavior of the  $\lambda 2665\text{\AA}$  line and several iron ion resonance lines in a PLT tokamak discharge. Inset shows the  $\lambda 2665\text{\AA}$  signal relative to neighboring background radiation from carbon and oxygen impurities.

Fig. 3. Chord distribution of the  $\lambda 2665\text{\AA}$  line and background, compared with the CV light distribution in the same discharge. Aperture limiter at  $\pm 40$  cm.

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  $\lambda 2665\text{\AA}$  line. Insets show some measured spectral contours before, at the end, and after neutral beam injection.

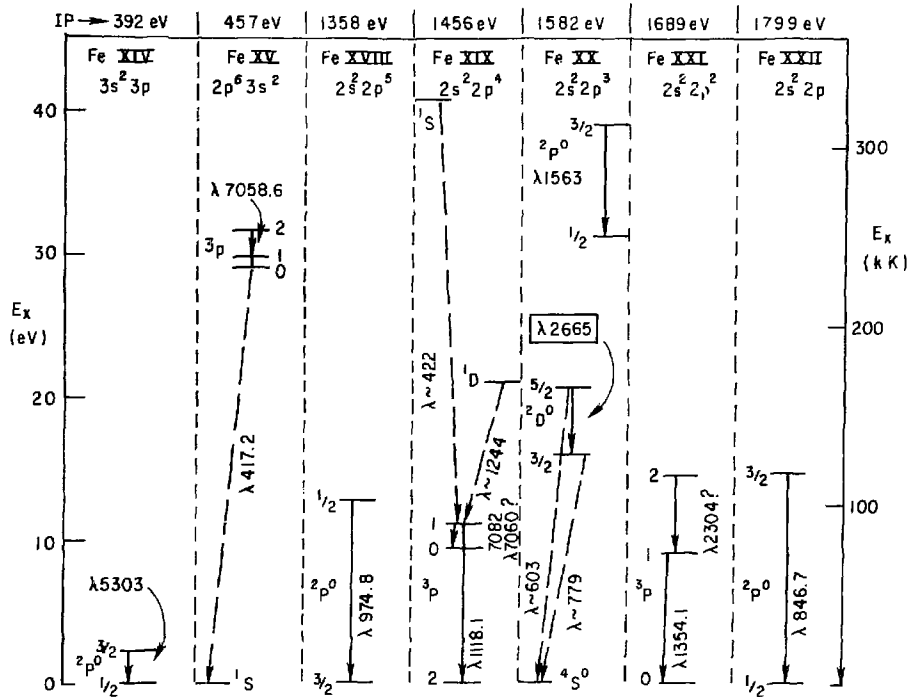


Fig. 1. 783742

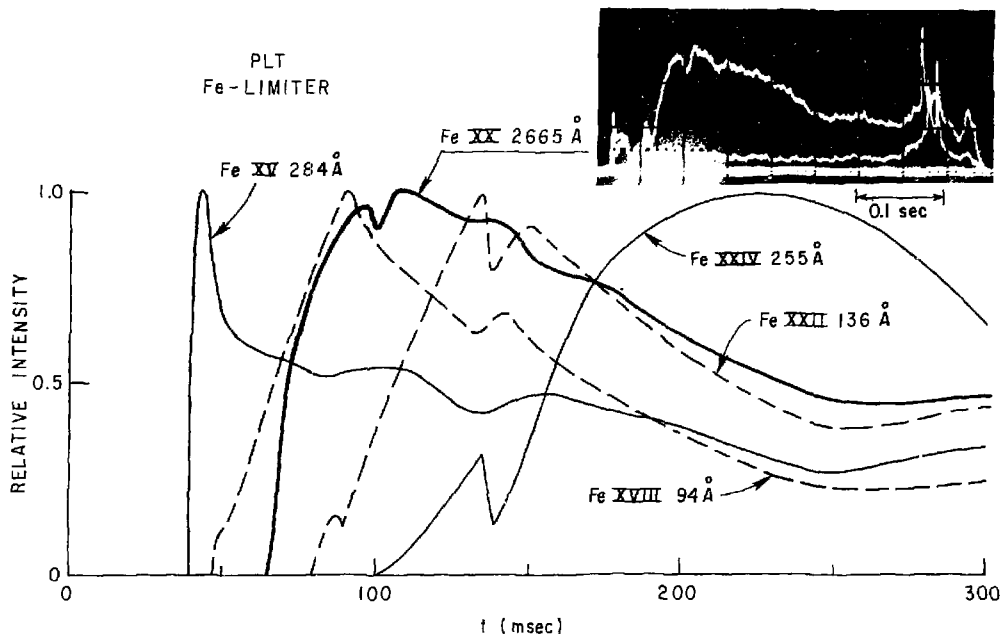


Fig. 2. 783762

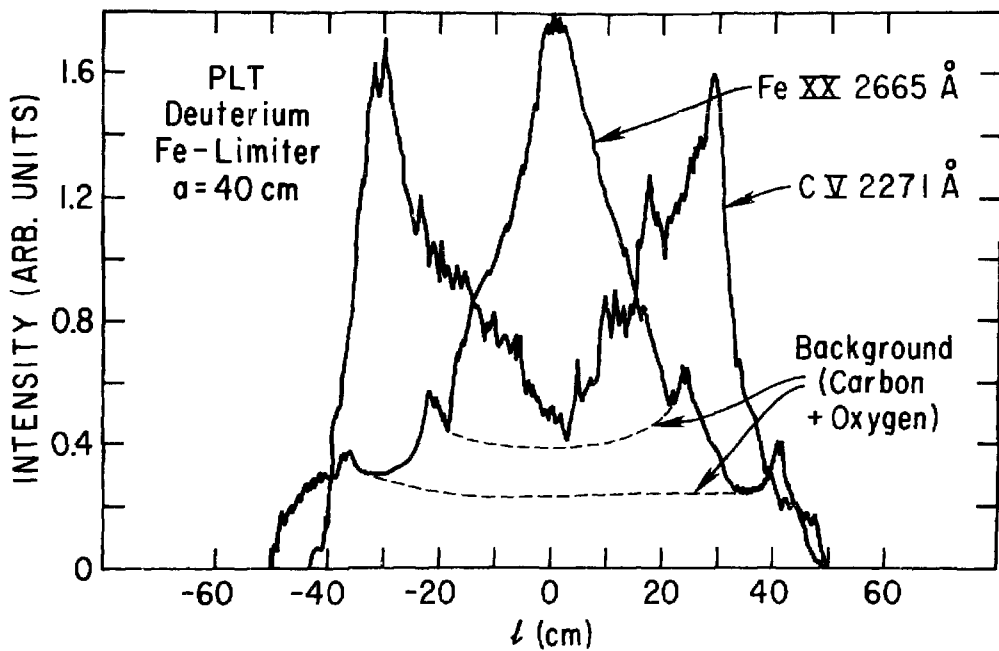


Fig. 3. 783743

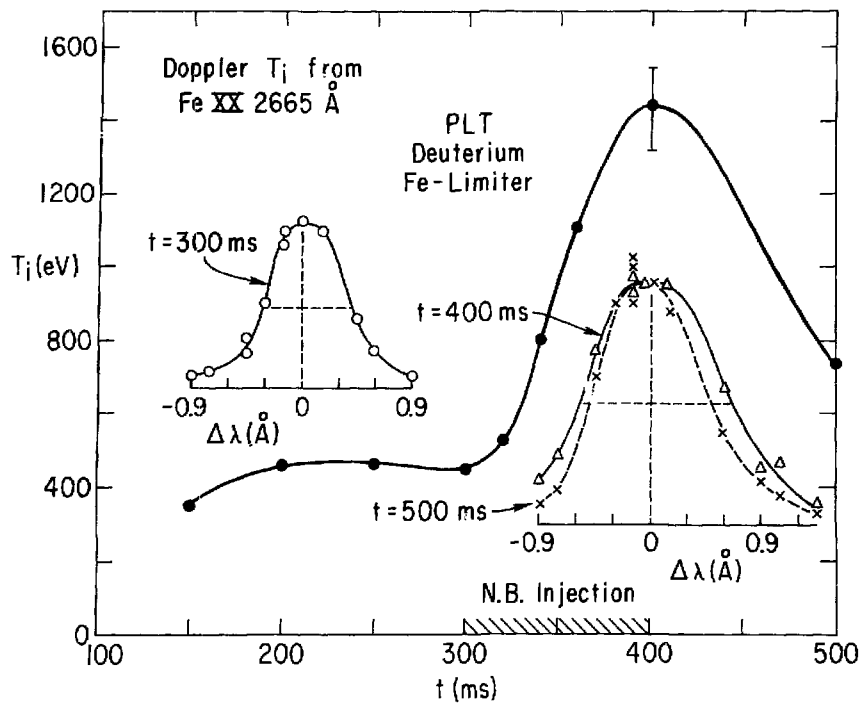


Fig. 4. 783747