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MEASUREMENT OF THE CENTRAL ION AND ELECTRON TEMPERATURE OF
TOKAMAK PLASMAS FROM THE X-RAY LINE RADIATION
OF HIGH-Z IMPURITY IONS

By

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Measurement of the Central Ion and Electron Temperature of Tokamak

Plasmas from the X-Ray Line Radiation of High Z Impurity Ions*

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ABSTRACT

Hot tokamak plasmas contain small amounts of highly ionized, high Z impurity ions, such as iron and titanium, with charge-state distributions close to the ionization equilibrium of the solar corona. The characteristic X-ray line radiation of these ions represents a unique source of information on the plasma parameters. It is expected to be of vital importance in particular as a diagnostic of the central ion temperature in future large size tokamaks.

This paper describes measurements of the central ion and electron temperature of tokamak plasmas from the observation of the $1s - 2p$ resonance lines, and the associated dielectronic ($1s^2n\ell - 1s2pn\ell$, with $n \geq 2$) satellites, of helium-like iron (Fe XXV) and titanium (Ti XXI). The satellite to resonance line ratios are very sensitive to the electron temperature and are used as an electron temperature diagnostic. The ion temperature is deduced from the Doppler width of the $1s - 2p$ resonance lines. The measurements have been performed with high resolution Bragg crystal spectrometers on the PLT (Princeton Large Torus) and PD α (Poloidal Divertor Experiment) tokamaks. The details of the experimental arrangement and line evaluation are described, and the ion and electron temperature results are compared with those obtained from independent diagnostic techniques, such as the analysis of charge-exchange neutrals and measurements of the electron cyclotron radiation. The obtained experimental results permit a detailed comparison with theoretical predictions.

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I. INTRODUCTION

In recent tokamak experiments, very high plasma temperatures have been obtained by the use of efficient heating techniques, e.g., the injection of intense hydrogen or deuterium beams,¹ and the excitation and damping of plasma waves.² Large volumes of hydrogen plasmas with ion and electron temperatures of $T_i = 1 - 7$ keV and $T_e = 1 - 5$ keV, respectively, and densities of $1 - 5 \times 10^{13} \text{ cm}^{-3}$ can now be maintained in tokamak discharges for several hundred milliseconds. These encouraging experimental results have motivated the design of tokamak fusion test reactors. The prospective dimensions, plasma densities, and temperatures for these devices exceed by far those of present-day tokamaks, and they should be adequate for the demonstration of "fusion breakeven" which will be achieved if the released fusion energy is equal to the energy invested in heating the plasma.

As the dimensions, densities, and temperatures of tokamak plasmas increased, it became obvious that new diagnostic techniques were needed.³⁻⁵ This is true in particular for measurement of the ion temperature in the hot core of tokamak discharges, since the standard methods, i.e., the measurement of the energy distribution of charge-exchange neutrals,⁶ and Doppler-broadening measurements of spectral lines in the VUV (vacuum ultraviolet) region,⁷ prove difficult under these experimental conditions. The charge-exchange diagnostic cannot be used for determination of the central ion temperature when the mean free path for neutral charge exchange is small compared with the diameter of the plasma, and line radiation in the VUV region is primarily emitted from the edge of the plasma, if the central electron temperature is of the order of 1 keV. An exception is the forbidden line of Fe XX,⁸ although this line will also originate from outer regions of the plasma column when the electron temperature exceeds 2 keV. In this paper we

discuss alternative methods for diagnostic of the central ion and electron temperature which are based on observation of the soft X-ray line radiation from helium-like high Z impurity ions, e.g., Fe XXV and Ti XXI. These ions occur in the center of hot tokamak discharges for a wide range of experimental parameters.

The spectra of helium-like ions show, in addition to the characteristic helium lines, a series of satellites close to the $1s - 2p$ resonance lines. These satellites are due to transitions of the type $1s^2n\ell - 1s2pn\ell$ with $n \geq 2$ and are produced by dielectronic capture of electrons with well defined kinetic energies (in the range from 4.69 keV to 6.7 keV, for Fe XXV). The resonance lines are excited by electrons with energies larger than the $1s - 2p$ threshold energies (6.7 keV in Fe XXV). The intensity ratio of the resonance and satellite lines therefore depends strongly on the electron temperature and can be used for electron temperature measurements. In addition, certain satellite to resonance line ratios can be used to measure the relative abundances of the lithium- and helium-like charge states, thus providing a means for diagnostic of the ionization equilibrium and the impurity transport. Most important for hot tokamak plasmas is, of course, the determination of the central ion temperature which is deduced from Doppler-broadening of the K α -resonance lines of Fe XXV and Ti XXI at 1.85 and 2.61 Å. These measurements require Bragg crystal spectrometers of high spectral resolution and intensity for time resolved observations. Competing with Doppler broadening are natural line broadening and the recently discovered dielectronic broadening,^{9,10} a phenomenon peculiar to high temperature plasmas.

Spectra of high Z helium-like ions are also observed in solar flares,¹¹⁻¹⁴ and a detailed theory^{9,15-17} of these spectra has been developed

for diagnostics of the flare parameters. Observations of these spectra in well diagnosed tokamak discharges permit a detailed comparison between experiment and theory and, therefore, are of great interest.

We begin with a brief description of tokamak experiments (Sec. II) and discuss (Sec. III) the parameters, e.g., the electron temperature and density profiles, the charge-state distribution and X-ray line emissivity for helium-like impurity ions, which are relevant for the diagnostic application of these line spectra to tokamak plasmas. Sections IV and V describe the crystal spectrometers and the numerical methods which have been used for evaluation of line profiles. Section VI presents ion and electron temperature results obtained from observation of the Fe XXV- and Ti XXI- spectra on the PLT (Princeton Large Torus) and PDX (Poloidal Divertor Experiment) tokamaks at Princeton. These results are compared with those obtained from different diagnostic techniques, e.g., analysis of the energy distribution of charge-exchange neutrals and measurements of the electron cyclotron emission.

II. THE TOKAMAK

Basically, the tokamak is a ring of hot hydrogen plasma which is confined by a strong toroidal magnetic field inside a vacuum vessel. The plasma is produced by induction of an electric field which causes a current to flow in the toroidal direction. The current serves both to ohmically heat the plasma and to provide MHD equilibrium and stabilization by its poloidal magnetic field.

The stability of a tokamak plasma is a function of the aspect ratio (R/a) of the major (R) and minor (a) radii of the torus. In general, small aspect ratios are desired to obtain a stable plasma and to optimize ohmic heating efficiency. Also, the particle and energy confinement times are

expected to increase in proportion to a^2 . Therefore, short and fat tokamaks are better than long and thin ones. Here we list the parameters of PLT which is one of the largest tokamaks in operation:

major radius:	$R = 140 \text{ cm}$
minor radius:	$a = 40 \text{ cm}$
toroidal magnetic field:	$B_t = 32 \text{ kG}$
plasma current:	$I_p = 500 \text{ kA}$

The duration of a discharge pulse is typically 1 sec. The plasma can be maintained under steady-state conditions for periods of 100 - 300 msec. A schematic of the PLT is shown in Fig. 1.

Tokamaks of comparable dimensions are presently in operation in the U.S. and abroad. The JET (Joint European Torus) and TFTR (Tokamak Fusion Test Reactor) tokamaks which have been designed to achieve "breakeven" in a deuterium tritium plasma, are now under construction and have about twice the linear dimensions of the PLT.

The plasma densities and temperatures in tokamak discharges are nearly constant in the toroidal direction and only vary with radius due to the fact that the ions and electrons move freely along (but not across) the magnetic field lines. In general, the radial density and temperature profiles are peaked near the magnetic axis and decay parabolically or steeper towards the plasma boundary. The peak electron densities and the electron and ion temperatures are typically in the range from $.1 - 1 \times 10^{14} \text{ cm}^{-3}$, and 1 - 3 keV, and 1 - 7 keV, respectively. The maximum temperatures have been obtained in discharges with additional heating by injection of intense deuterium beams¹ or with rf heating.² High purity of the plasma is crucial for the success of

these heating experiments. The tokamak has been reviewed in several articles.^{19,20}

III. IMPURITIES

Tokamak discharges contain small amounts (typically .1%) of impurities, like carbon, oxygen, iron, chromium, nickel, and titanium. These elements enter the plasma from the wall of the vacuum vessel, and are ionized to different states of ionization or charge states. The radiation emitted from impurity ions consists of a bremsstrahlung and recombination continuum and characteristic line spectra, and it contributes significantly to the total energy loss of the plasma. Figure 2 presents a typical spectrum of the soft X-ray radiation emitted from PLT showing the relative contributions of the continuum and line radiation from high Z impurities (Cr, Fe, Ni). The data were observed with the PLT Pulse Height Analysis System, which essentially consists of a pinhole camera and diode detector with an energy resolution of 300 eV.²¹

The line radiation of the various impurity ions affects the plasma in different ways. Low Z elements like carbon and oxygen are fully stripped in the hot center of the discharge, whereas high Z ions like iron and titanium are only partially ionized, the highest state of ionization being the helium-like charge state for typical central electron temperatures of 1-3 keV. Line radiation of low Z ions is, therefore, predominantly emitted from the edge of the plasma, whereas the line radiation of high Z ions is emitted from the center of the discharge. The energy losses associated with the line radiation from high Z ions tend to reduce the temperature in the hot core of the plasma and are therefore a matter of concern. On the other hand, line radiation from low Z ions provides cooling of the plasma periphery. This can, in fact, be

beneficial in that low edge temperatures tend to reduce the influx of high Z wall impurities by reduction of sputtering.⁴

The intensity of the observed impurity line radiation depends on the radial distribution of the different states of ionization. The distribution of the charge states of high Z ions, e.g., Fe XXIV and Fe XXV, is expected to be in equilibrium since the ionization and recombination times are usually small compared with the period of steady-state conditions in tokamak discharges. Moreover, since the electron densities are far below threshold for collisional deexcitation, these ions exist essentially only in their ground states.¹⁵ One may therefore assume that the equilibrium charge-state distribution in tokamak plasmas is close to the so-called coronal equilibrium,²²⁻²⁴ i.e., that the relative abundance of successive ionization states is determined by the ratio of the recombination and ionization rate coefficients, e.g.,

$$n_{\text{Fe XXIV}}/n_{\text{Fe XXV}} = \alpha/S = f(T_e). \quad (1)$$

This equilibrium is a function of the electron temperature (T_e) alone and is usually observed in solar flares. In tokamak plasmas it is, however, only an approximate description since deviations from coronal equilibrium can occur as a result of impurity transport.

Figure 3 shows the fractional abundance for the charge states of iron under coronal equilibrium conditions.²⁵ Each charge state is peaked at an electron temperature ($T_e \approx 1/2 E_i$) which corresponds to about half its ionization potential. In tokamak plasmas with typical (approximately parabolic) temperature profiles and peak temperatures of $T_e \geq 1$ keV, the low states of ionization occur only for a small range of plasma radii. The

helium-like charge state (Fe XXV) is produced in the core of tokamak discharges for (relatively low) central electron temperatures $T_e(0) \geq 1$ keV due to the small ionization potential ($E_i = 2.045$ keV) of lithium-like iron (Fe XXIV). On the other hand, since the ionization potential ($E_i = 8.828$ keV) of Fe XXV is very large, it exists for a wide range of central electron temperatures, being the dominant charge state for $T_e(0)$ in the range from 1.5 to 6 keV and comparable with the fractional abundance of hydrogen-like iron, Fe XXVI, for $T_e(0)$ in the range from 6 to 10 keV. The characteristic line radiation of Fe XXV is therefore well suited for diagnostics of central plasma parameters, both in present-day and in future larger size tokamaks.

An experimental investigation of the charge-state distribution of iron in tokamak plasmas was performed on PLT using a Bragg curved crystal spectrometer.²⁶ These measurements were based on the observation of the characteristic K α -like radiation emitted by the different charge states, and they made use of the fact that, on an average, for each L-shell electron removed between charge states Fe XVII to Fe XXV, the 1s-2p X-ray energy increased by an amount of 40 eV. Figure 4 shows the K α -line spectra obtained for different electron temperatures. Evidently the intensity is shifted to higher states of ionization with increasing electron temperature. For $T_e(0) \geq 1.2$ keV, iron occurs predominately in the helium- and lithium-like charge states. A detailed comparison of these experimental results with calculations by Merts et al.,²⁴ showed that the distribution of the lower charge states was in reasonable agreement with coronal equilibrium predictions. Substantial deviations from coronal equilibrium were found for Fe XXV, however. These deviations can be explained by an outward radial transport of Fe XXV ions on the basis of the fact that the transport time for these ions is small compared to the relevant ionization and recombination

times. In general, the observed deviations from coronal equilibrium become smaller with increasing electron density.²⁷ The assignment of intensity peaks (in Fig. 4) to individual states of ionization gives a simplified picture, since the spectral ranges from neighboring charge states overlap to some extent. However, the spectral lines of the two and three electron systems, e.g., Fe XXV and Fe XXIV, are well resolved. This is important for diagnostic applications.

Figure 5 shows the calculated intensity [in photons/(cm³ sec)] for the 1s-2p transition of Fe XXV as a function of plasma radius for different central electron temperatures assuming parabolic radial electron temperature and density profiles, and coronal equilibrium for the Fe XXV-ions. Due to the strong variation of the excitation rate with electron temperature, the Fe XXV K α -resonance line is predominantly emitted from the center of the discharge, for $T_e(0) = 1 - 4$ keV. For this range of electron temperatures, the observed line spectra of Fe XXV can be used directly as a diagnostic of the central plasma parameters. For higher central electron temperatures the helium-like charge state is burned out in the core of the discharge, so that the emissivity for the K α -resonance line is peaked at the outer plasma radii. Under these conditions, the central plasma parameters can be obtained from observations along different radial chords using Abel inversion.

IV. CRYSTAL SPECTROMETERS

In this section we describe the crystal spectrometers which have been used on PLT and PDX for observation of the satellite spectra of helium-like iron (Fe XXV) and titanium (Ti XXI). These experiments demanded optimization of the spectrometer design for (1) simultaneous observation of different spectral lines, (2) high spectral resolution, and (3) high intensity to enable

time resolved measurements. These requirements led to the choice of focusing bent crystal spectrometers with a position sensitive detector in the Johann configuration.²⁸

Experimental Arrangement

A schematic of a Johann crystal spectrometer and its arrangement on a tokamak is shown in Fig. 6. X-ray photons emitted along chords in the horizontal midplane from impurity ions in the shaded area of the tokamak discharge enter helium filled pipes through a 0.003" thick beryllium window and are Bragg reflected by the crystal onto a position sensitive multiwire proportional counter. Photons of different energies are focused to different points on the Rowland circle and thus to different positions on the detector. The helium atmosphere in the X-ray path reduces photon absorption.

The detector has two planes of approximately 100 anode and cathode wires with 1 mm separation running perpendicular to each other, as illustrated in Fig. 7. An X-ray photon ionizes the P10 gas mixture (90% argon + 10% methane) inside the detector producing an electron avalanche to one of the anode wires. This charge pulse induces an image charge on the cathode wires which is capacitively coupled to a delay line. Standard electronics are used to convert the difference in the arrival times of the charge pulse at the two ends of the delay line into a pulse, whose amplitude is proportional to the position at which the photon struck the detector. These pulses are digitized, stored in the memory of a pulse-height analyzer, and later read by a PDP10 computer.

Since the experiments were performed in an environment with high levels of hard X-ray and neutron background radiation, the detector had to be shielded. Lead (4" thick) was used to shield the detector against the hard X-

ray radiation. Since the 2.5 MeV neutrons emitted from the plasma produce (n, γ)-reactions in the lead shielding, it has been enclosed by a (8" thick) neutron shield of borated (5% Boron) polyethylene. This shielding permitted recording of soft X-ray spectra from deuterium plasmas also during injection of intense (6-8 MW) deuterium beams when the neutron emission from D-D reactions was particularly high, typically about 10^{14} neutrons/sec, corresponding to a flux of 10^8 neutrons/(cm² sec) at the position of the detector.

Spectral Resolution

Following Bragg's law

$$\lambda = 2d \sin\theta, \quad (2)$$

where λ , d , and θ are the wavelength of the X-ray photon, the spacing of the reflecting crystal planes, and the Bragg angle, respectively, the dispersion of a crystal spectrometer is given by

$$\frac{\lambda}{\Delta\lambda} = \frac{1}{\Delta\theta} \tan\theta. \quad (3)$$

The angular resolution ($\Delta\theta$) is mainly determined by the spatial resolution (Δx) of the detector and the crystal-detector distance (D). For the Johann configuration, $D = R \sin\theta$, where $R = 2r$ is the radius of curvature of the crystal, and r is the radius of the Rowland circle. According to Eq. (3) it is advantageous to choose a crystal such that the Bragg angle, θ , is close to 90 degrees.

The spectral resolution can further depend on the intrinsic resolving power of the crystal and on geometrical effects, (1) the specific focusing error of the Johann configuration due to the fact that the crystal surface is tangential to the Rowland circle only at one point, and, more importantly, (2) errors due to the vertical divergence (with respect to the spectrometer plane) of X-ray beams. The Johann aberration (Δ) is given by $\Delta = l^2 \cos \theta / (8R \sin^2 \theta)$, where l is the length of the crystal. Evidently both the Johann defocusing (Δ) and the focusing errors due to the vertical divergence decrease with increasing Bragg angle (θ) and radius (R) of crystal curvature. Since the mosaic spread of a crystal is known to increase occasionally in the bending process, we chose quartz crystals with a very high intrinsic resolving power > 100000 .

In practice, the spectral resolution is limited mostly by the finite spatial resolution of the detector. Its positioning in the Rowland circle is therefore very important. The spatial resolution of the used multiwire proportional counters is .37 mm FWHM for perpendicular incidence of the photons. Therefore, the detector is not placed tangential to the Rowland circle but perpendicular to the reflected beam. This is necessary because the thickness (2 cm) of the sensitive detection volume is relatively large. The focusing error resulting from the displacement of the detector from the Rowland circle decreases with increasing θ , another reason for choosing a large Bragg angle. For the high resolution crystal spectrometers which we used for Doppler broadening measurements, the displacement of the detector from the Rowland circle was comparable with the detector thickness. Optimum focusing can thus be obtained over a small energy interval. However, even for this limited energy range the resolution is affected by the finite thickness of the counter due to the vertical divergence of the reflected beams. It is,

of course, very important to properly align the anode and cathode wires with respect to the directions of the incident photons. This has to be optimized by rotating the detector.

The energy resolution of the crystal spectrometers has been determined experimentally by use of appropriate X-ray lines, after the crystals had been bent to the desired radius of curvature applying the method described by Feser and Faessler.²⁹ Here we mainly discuss the results obtained for the $(22\bar{4}3)$ quartz crystal spectrometer which was used for measurements of the Fe XXV spectra. The crystal was bent to a radius of curvature of 333 cm. To determine the energy resolution of this crystal we used the $L\alpha_1$ and $L\alpha_2$ lines of Holmium (at 6720 eV and 6680 eV) which are close in energy to the Fe XXV $K\alpha$ -resonance line at 6702 eV. Since the natural line width of the Holmium lines is about 6 eV, a special arrangement had to be made to measure the much smaller instrumental width of the spectrometer. A narrow .381 mm (.015") wide slit was placed exactly on the Rowland circle at the focal point for the Holmium $L\alpha_1$ line. In this way only a small central portion of the $L\alpha_1$ -line is Bragg reflected and focused onto the detector. Figure 8a shows the results of this measurement. The experimental points represent an image of the slit which is well approximated by a Gaussian (G_p) of .497 mm FWHM. Following Unsold³⁰ we describe the slit by a Gaussian (G_s) of a FWHM = $2a[(\ln 2)/6]^{1/2}$, where a is the width of the slit, and assume that the image is the result of a convolution with a Gaussian instrumental function (G_I). We obtain a value of .424 mm for the width (FWHM) of the instrumental function. This corresponds to an energy resolution of $\Delta E = .420$ eV at $E = 6700$ eV, or $E/\Delta E = 15000$.

Also shown in Fig. 8b are the results of a measurement of the spatial resolution of the position sensitive detector. For this purpose a collimated Fe^{55} line source (of approximately zero width) was placed directly on the

entrance window of the detector. The collimation was obtained by close contact of two tool bits. The experimental points in Fig. 8b are well approximated by a Gaussian with .369 mm FWHM. This shows that the instrumental width is mostly determined by the finite spatial resolution of the detector.

The energy resolution of the $20\bar{2}3$ quartz crystal, which was used for Doppler broadening measurements of the Ti XXI K α -line at 4.75 keV, has been determined by the same experimental method, except that, in this case, the measurements were performed with the second order Bragg reflection of the tungsten L β_1 -line at 9.670 keV. For this crystal, which was bent to a radius of curvature of 363.5 cm, the obtained spectral resolution ($\lambda/\Delta\lambda$) was 23000.

Intensity

Estimates of the X-ray line intensities as received by the detector from a PLT or PDX discharge have been obtained from an X-ray tracing code for the experimental parameters (i.e., the size of the crystal, the dimensions of the detector window and the beryllium window on the tokamak vacuum vessel, and the distances of the crystal from these windows). Here we consider the basic aspects. Since the tokamak plasma is an extended X-ray source, the intensity is, in principle, independent of the distance of the crystal from the plasma, provided that each crystal element views the plasma with a solid angle which is larger than the width of its rocking curve at the considered Bragg angle. In practice, however, the intensity varies with the distance of the crystal from the plasma in proportion to the vertical divergence of the detected X-rays which is usually limited by the height of the beryllium window on the tokamak vacuum vessel. On the other hand, as mentioned before, a limitation of the vertical divergence may be desirable to reduce focusing errors. The

intensity also depends on Bragg angle θ . For perfect crystals like quartz, the integrated reflectivity increases strongly with θ , if $\theta > 45$ degrees.

It is worth mentioning that the spatial resolution of multiwire proportional counters often deteriorates at very high photon count rates because of space charge effects near the anode wires. This sets an upper limit for the acceptable photon intensities (20,000 counts/sec for our detectors). Because of this count rate limitation we had to reduce the X-ray intensity in certain cases by shielding parts of the crystal. Finally, we mention that the focal points of spectral lines must not fall into the plane of the beryllium window, in order to prevent the observed line intensities being affected by inhomogeneities of the window transmission.

V. EVALUATION OF LINE PROFILES

The profile of a spectral line is described by a Voigt-function, which is the convolution of a Lorentzian and a Gaussian. The Lorentzian describes the natural line broadening, whereas the Gaussian accounts for the Doppler broadening of the spectral line due to the thermal ion motion. This is by far the dominant line broadening mechanism in hot tokamak plasmas. Since the Doppler width is usually large compared with the natural line width, the upper part of the Voigt profile is determined mainly by the Gaussian; whereas, because of exponential decay of the Gaussian, the lower part of the Voigt profile, i.e., the wings, is determined by the Lorentzian.

The ion temperature is, therefore, often evaluated from the fit of a Gaussian to the upper half of the observed line profile. Though this method yields, in principle, a reasonable value for the ion temperature, the statistical error can be rather large because only a limited number of the experimental points are actually used for the fit, and valuable information in

the wings of the observed line profile is ignored; in practice, longer recording times are required if the statistical error is to be reduced to a certain limit. For time resolved measurements it is therefore advantageous to fit the observed spectral lines to actual Voigt-profiles.

For the calculation of Voigt-profiles it is convenient to make use of the close relationship between the Voigt-function and the so-called Plasma Dispersion Function,

$$Z(\xi) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} dt \frac{\exp(-t^2)}{t - \xi}, \quad (4)$$

where $\xi = x + iy$, with $y = \text{Im}\xi > 0$, is a complex variable. The Z -function is of basic importance in the physics of plasma waves and has been extensively studied. The function has been tabulated by Fried and Conte³¹ and several codes for its computation are available. Introducing $\xi = x + iy$ into Eq. (4) one obtains for the imaginary part of $Z(x,y)$

$$\text{Im } Z(x,y) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} dt \exp(-t^2) \frac{y}{(t - x)^2 + y^2} \quad (5)$$

with

$$\frac{1}{\pi} \int_{-\infty}^{\infty} \text{Im } Z(x,y) dx = 1.$$

The Voigt-function is thus most conveniently represented in the form

$$V(x,y) = \frac{A}{\pi} \operatorname{Im} Z(x,y) , \quad (6)$$

with

$$x = \frac{\omega - \omega_0}{\omega_0} \frac{c}{v_i} \quad \text{and} \quad y = \frac{\gamma/2}{\omega_0} \frac{c}{v_i} ,$$

where	c	is the velocity of light,
	$v_i = \sqrt{2kT_i/m_i}$	the thermal ion velocity,
	ω	a frequency within the spectral line,
	ω_0	the center frequency of the spectral line emitted from a stationary ion,
	γ	the natural width (FWHM of the Lorentz profile),
	A	the intensity of the spectral line.

*The variable x represents the ratio of the ion velocity (v) and the thermal ion velocity (v_i).

In order to determine the characteristic line parameters, e.g., the center frequency ω_0 and the thermal ion velocity v_i , from a least squares fit, one needs the partial derivatives of the Voigt-function with respect to x and y . These derivatives are easily obtained with use of a differential equation for $Z'(\xi)$:

$$Z'(\xi) = -2 [1 + \xi Z(\xi)] . \quad (7)$$

One obtains

$$\frac{\partial}{\partial x} \operatorname{Im} Z(x, y) = \operatorname{Im} Z'(F) \quad (8)$$

and

$$\frac{\partial}{\partial y} \operatorname{Im} Z(x, y) = \operatorname{Re} Z'(F) \quad (9)$$

It is therefore sufficient to calculate only the real and imaginary parts of Z . Our line fitting program uses the Eqs. (6)-(9) to find values of A , ω_0 , $\gamma/2$ and v_1 , which minimize χ^2 , given by

$$\chi^2 = \sum_l^M \frac{1}{\sigma_l^2} [D_l - \sum_{p=1}^4 A_p V(\omega_{0p}, \gamma_{p/2}, v_1, l) - B]^2 \quad (10)$$

where D_l is the raw data in the l th position, σ_l is the error, V is the Voigt-function, and B is a constant background. The program allows us to fit up to $p=4$ peaks in a certain spectral region, simultaneously.

VI. EXPERIMENTAL RESULTS

In this section we present spectra of helium-like iron (Fe XXV) and titanium (Ti XXI) and discuss their diagnostic applications for electron and ion temperature measurements in tokamak discharges. Spectra of Fe XXV have been studied on PLT for a wide variety of plasma conditions during the last few years, and these data have permitted a detailed comparison between experiment^{10,18} and theory.^{9,15-17} Here we include some of the experimental results to discuss the characteristic spectral features of helium-like ions, in particular, the electron temperature dependence of intensity ratios. Special emphasis is given to recent results of Doppler-broadening measurements of the Ti XXI K α -resonance line which allowed determination of the central ion temperature in PDX tokamak discharges with additional neutral beam heating.

The most characteristic feature of the spectra emitted from helium-like ions in hot plasmas is the occurrence of satellites to the (1s-2p) resonance line. These satellites are due to transitions of the type 1s2pn l - 1s²n l (with $n \geq 2$), which represent the final step in the process of dielectronic recombination of a helium-like ion. Here we give a brief description of this atomic process. It can be the dominant mechanism of line excitation in hot plasmas and is thus very important for the interpretation and diagnostic application of the observed spectra.

The lithium-like configurations are produced by the process

A free electron of well defined kinetic energy and angular momentum is captured by a helium-like ion into an atomic level with quantum numbers n, l to form an excited lithium-like ion. The 1s2pn l levels are virtually bound

states located in the continuum above the first ionization limit of the lithium-like ion. They can, therefore, decay by autoionization, the reverse process of capture, or by a radiative transition to the $1s^2n\ell$ level. In the latter case, the $1s$ - $2p$ transition is slightly changed in energy by the presence of the "spectator" (n,ℓ) electron in the outer shell, so that the emitted photon gives rise to a satellite near the $1s$ - $2p$ resonance line of the helium-like ion. The wavelength shift of the satellites depends on the main quantum number n of the captured outer shell electron. The $n = 2$ dielectronic satellites are well resolved. However, satellites with $n \geq 3$ are very close to and partially blended with the resonance line.

The unresolved $n \geq 3$ satellites cause an apparent intensity increase and broadening of the resonance line. These effects, which are peculiar to hot plasmas, must be taken into account for evaluation of satellite to resonance line ratios and Doppler broadening measurements. A detailed theory of the dielectronic satellites with $n = 3 - 11$ of the resonance line of Fe XXV has been given recently by Bely-Dubau et al.,⁹ and comparison of this theory with experiment was made by Bitter et al.¹⁰ Both the apparent intensity increase and the dielectronic broadening of the resonance line are very sensitive to the electron temperature.

Since the process of dielectronic capture involves electrons with well defined kinetic energies ($\epsilon = 4.694$ keV for $n=2$ and $\epsilon = 5.815$ keV for $n=3$ in Fe XXV), the satellite intensities are dependent on the energy distribution of the electrons in the plasma and proportional to the abundance of the helium-like ions. The resonance lines are excited by electrons with energies larger than the $1s$ - $2p$ threshold energies (6.7 keV for Fe XXV). The ratios (I_s/I_w) of the intensities of the dielectronic satellites and the resonance line are consequently a function of the electron temperature (T_e) alone, given by¹⁵

$$\frac{I_s}{I_w} = D \frac{\exp(\Delta E/T_e)}{T_e} \quad (11)$$

where ΔE is the ionization energy needed to remove the outer (n, l) electron, and D is a constant mainly determined by the branching ratio of the probabilities for autoionization and radiative decay of the excited lithium-like ion.

Most of the satellites are produced by the described process of dielectronic recombination. Exceptions are the ($1s^2 2s-1s2p2s$) satellites which can also be produced by collisional inner shell excitation of a lithium-like ion in its ground state. For these satellites the intensity ratio (I_s/I_w) is proportional to the relative abundance (n_{Li}/n_{He}) of the lithium- and helium-like charge states,

$$\frac{I_s}{I_w} = S \frac{n_{Li}}{n_{He}} \quad (12)$$

where S is essentially given by the ratio of the oscillator strengths for the $1s \sim 2p$ transitions, e.g., of Fe XXIV and Fe XXV.¹⁵

Figures 9(a) and 9(b) show satellite spectra of Fe XXV obtained for central electron temperatures of 1.65 and 2.30 keV, respectively. The spectra have been observed on PLT using the (2243)-quartz crystal spectrometer with a resolution of $\lambda/\Delta\lambda = 15000$. The electron temperature was determined from the electron-cyclotron radiation emitted by the plasma.³² The raw data for each

of these spectra were recorded during a period of 250 msec of a discharge pulse when the electron temperature was constant (steady-state conditions) and were accumulated typically over ten discharges with nearly identical parameters to reduce the statistical error. The center position, intensity, and width of the spectral lines were determined from a least squares fit of Voigt-functions as described in Section V. In order to determine these line parameters with minimum error, it was necessary to fit groups usually of two neighboring peaks simultaneously. The most prominent peaks have been identified as the helium-like lines w, x, y, z, the lithium-like $n = 2$ satellites t, q, (k, r), j, and the beryllium-like line R. The key letters used for line identification are explained in Table I and agree with Gabriel's notation.¹⁵ The spectra also show a fine line structure between some of the most prominent peaks and on the long-wavelength side of the resonance line w. This structure disappears with increasing electron temperature and is ascribed to weak $n = 2$ satellites, such as a, and to $n = 3$ satellites, respectively.

Table I.

Experimental and theoretical wavelengths of the observed FeXXV spectral lines. The superscripts indicate the references from which the theoretical wavelengths were taken. The experimental wavelengths were normalized to the theoretical value (Ref. 15) of 1.8500 Å for the resonance line w.

(key)	Transition	λ_{exp} (Å)	λ_{theor} (Å)
w	$1s^2(^1S_0) - 1s2p(^1P_1^o)$	1.8500	1.8500 ^a 1.84992 ^b
x	$1s^2(^1S_0) - 1s2p(^3P_2^o)$	1.8552	1.8551 ^a 1.85519 ^b
t	$1s^22s(^2S_{1/2}) - 1s2p2s(^2P_{1/2}^o)$	1.8567	1.8570
y	$1s^2(^1S_0) - 1s2p(^3P_1^o)$	1.8592	1.8591 ^a 1.85947 ^b
q	$1s^22s(^2S_{1/2}) - 1s2p2s(^2P_{3/2}^o)$	1.8608	1.8604 ^c
a	$1s^22p(^2P_{3/2}^o) - 1s2p^2(^2P_{3/2})$	1.8618	1.8618 ^a
k	$1s^22p(^2P_{1/2}^o) - 1s2p^2(^2D_{3/2})$	1.8632	1.8631 ^a
r	$1s^22s(^2S_{1/2}) - 1s2p2s(^2P_{1/2}^o)$		1.8635 ^a
j	$1s^22p(^2P_{3/2}^o) - 1s2p^2(^2D_{5/2})$	1.8657	1.8657 ^a
z	$1s^2(^1S_0) - 1s2s(^3S_1)$	1.8681	1.8677 ^a 1.86801 ^b
β	$1s^22s^2(^1S_0) - 1s2s^22p(^1P_1)$	1.8705	1.8710 ^c
^a Ref. 15		^b Ref. 33	^c Ref. 34

Experimental and theoretical wavelengths are listed in Table I for comparison. For most of the lines the agreement is within the estimated error of $0.0005 \text{ \AA}$ of the theoretical calculations. The experimental accuracy is $0.0001 \text{ \AA}$.

Of great interest for diagnostic applications are the satellites j and q . The satellite j is produced by dielectronic recombination. According to Eq. (11) the intensity ratio (I_j/I_w) can thus be used as a diagnostic for the electron temperature. The satellite q , on the other hand, is produced by collisional inner shell excitation so that, according to Eq. (12), intensity ratio (I_q/I_w) can be used for a measurement of the relative abundance $(n_{\text{Li}}/n_{\text{He}})$ of the lithium- and helium-like ions.

Figure 10 presents the experimental results for I_j/I_w together with predictions of the earlier theory^{15,16} (solid curve) and the most recent theory⁹ (dashed curve) for the experimental values of T_e . The theory of Bely-Dubau et al.⁹ takes into account the apparent intensity increase, $\Delta I_w = \alpha(T_e)I_w$, of the resonance line due to unresolved dielectronic satellites with $n \geq 3$. The experimental results shown in Fig. 10 are in excellent agreement with the most recent theoretical predictions,⁹ indicating that the satellite to resonance line ratio (I_j/I_w) can be used as a diagnostic of the central electron temperature.

On the other hand, the relative abundance $(n_{\text{Fe XXIV}}/n_{\text{Fe XXV}})$ of the lithium- and helium-like charge states derived from the intensity ratio (I_q/I_w) are found to deviate significantly (up to factors of five) from the predictions for coronal equilibrium. These deviations are observed to depend, in particular, on the electron density. They are ascribed to changes of the charge-state distribution due to impurity transport, which is disregarded in the model of coronal equilibrium. Experimentally one finds that coronal equilibrium is approached with increasing plasma density.²⁷

The experimental result that the relative intensities of the dielectronic satellites and the resonance line are in good agreement with the theoretical predictions is explained by the fact that these lines involve only the helium-like charge state, Fe XXV. Their intensity ratios are thus independent of the details of the ionization equilibrium or impurity transport and are uniquely determined by the electron temperature. Therefore, it has been possible to measure the dielectronic recombination rate coefficient of Fe XXV as a function of the electron temperature from the observed total intensity of the dielectronic satellites.³⁵

In the following we present the ion-temperature results which have been obtained from Doppler-broadening measurements of the Ti XXI K α - resonance line. The experiments were performed on PDX using the (2023)-quartz crystal spectrometer with a resolution of $\lambda/\Delta\lambda = 23000$. Figure 11 shows the line spectrum of Ti XXI as observed from ohmically heated PDX discharges with central electron temperatures of ≈ 1 keV. The data were accumulated from approximately ten discharges with similar parameters. The spectrum shows the Ti XXI K α -resonance line (1), the characteristic helium-like intercombination lines (5) and (8), and a series of dielectronic satellites due to transitions of the type $1s^2n\ell-1s2pn\ell$ with $n \geq 2$. The spectral features have been identified with use of the theoretical predictions of Gabriel,³⁶ Vainshtein and Safronova,¹⁷ and Ermolaev and Jones,³³ and are explained in Table II.

Figures 12 and 13 show the results obtained from Doppler broadening measurements of the Ti XXI K α -resonance line. The data have been obtained from PDX discharges with additional neutral beam heating. Four deuterium beams totaling a power of 5 MW (47 kV) were injected into hydrogen discharges with a line averaged density of $4 \times 10^{13} \text{ cm}^{-3}$ for the period from 300-450 msec. Figure 12 shows a time sequence of six out of sixteen line profiles

which have been recorded from each discharge with a time resolution of 25 msec. The data have been accumulated from 20 discharges with nearly identical parameters to reduce the statistical error. The solid curves were obtained from a least squares fit of Voigt-functions to the experimental data as described in Section V. The arrows indicate the range of channels used for the fit. The average in the channels below the lower limit was used for background subtraction. The upper limit was chosen to exclude the $n = 3$ satellites. An enhanced line broadening during neutral beam injection is evident from Fig. 12.

Figure 13 presents the ion-temperature results, deduced from the experimental line profiles, as a function of time. The error bars indicate the statistical error of the experimental results. Corrections are made for the natural line width and the instrumental width. Errors due to the dielectronic line broadening by unresolved $n \geq 3$ satellites have been discussed in detail in Ref. 10. These errors are determined by the electron temperature (which was in the range from 1 to 2 keV for these experiments) and are estimated to be less than 5%. Also shown in Fig. 13 are the results (triangles) from measurements of the energy distribution charge-exchange neutrals (hydrogen atoms) which are in very good agreement with the Doppler ion temperatures.

Table II.

Experimental and theoretical wavelengths of the observed TiXXI spectral lines. The superscripts indicate the references from which the theoretical wavelengths were taken. The experimental wavelengths were normalized to the theoretical value (Ref. 36) of 2.6099 Å for the resonance line w.

Peak	(key)	Transition	λ_{exp} (Å)	λ_{theor} (Å)
1	w	$1s^2(^1S_0) - 1s2p(^1P_1^0)$	2.6099	2.6099 ^a 2.6097 ^b 2.61018 ^c
2			2.6117	
3			2.6134	
4	d13	$1s^23p(^2P_{3/2}) - 1s2p3p(^2D_{5/2})$	2.6142	
5	x	$1s^2(^1S_0) - 1s2p(^3P_2^0)$	2.6184	2.6187 ^a 2.6183 ^b
6	s	$1s^22s(^2S_{1/2}) - 1s2p(^3P)2s(^2P_{3/2})$	2.6195	2.6207 ^a 2.6197 ^b
7	t	$1s^22s(^2S_{1/2}) - 1s2p2s(^2P_{1/2})$	2.6205	2.6214 ^a 2.6205 ^b
8	y	$1s^2(^1S_0) - 1s2p(^3P_1^0)$	2.6223	2.6226 ^a 2.6221 ^b 2.62266 ^c
9	q	$1s^22s(^2S_{1/2}) - 1s2p2s(^3P_{3/2})$	2.6271	2.6272 ^b
	a	$1s^22p(^2P_{3/2}^0) - 1s2p^2(^2P_{3/2})$		2.6295 ^a 2.6296 ^b
10	d	$1s^22p(^2P_{1/2}^0) - 1s2p2s(^2P_{1/2})$	2.6294	2.6297 ^a 2.6299 ^b
	r	$1s^22s(^2S_{1/2}) - 1s2p2s(^2P_{1/2}^0)$		2.6299 ^a 2.6295 ^b
11	k	$1s^22p(^2P_{1/2}^0) - 1s2p^2(^2D_{3/2})$	2.6311 (?)	2.6326 ^a 2.6314 ^b
^a Ref. 36		^b Ref. 17	^c Rel. 33	

In principle, the impurity ion temperature can differ from the temperature of the bulk ion species. An estimate of the expected ion temperature difference can be obtained from a calculation due to R. Goldston:¹ The power coupled from the beam ions to each ion species in the plasma is proportional to $n_i Z_i^2 / \text{mi}$. Thus, while the total power delivered to impurity ions may be small, the power per ion scales as Z_i^2 / mi . At low densities and high ion temperatures, the impurity-hydrogen coupling time becomes long enough so that a temperature difference should develop between the impurity ions and the hydrogenic species. For low-density cases where $Z_{\text{eff}} = 3$, due primarily to carbon, all of the impurity ions are well coupled to each other, and one may write a simple equation governing the impurity temperature, T_x :

$$\frac{dT_x}{dt} = 0 = \frac{T_H - T_x}{\tau_{x-H}} + \left. \frac{dT_x}{dt} \right|_{\text{beam}} + \frac{T_e - T_x}{\tau_{x-e}} - \frac{T_x}{\tau_{Ex}}, \quad (13)$$

where τ_{x-H} and τ_{x-e} are the energy equilibrium times between the impurities and the hydrogenic species, and between the impurities and electrons, respectively. τ_{Ex} is the energy containment time of the impurities.

Taking the dominant impurity to be carbon, and solving this equation for similar parameters of a neutral beam heating experiment on PLT, Goldston found a temperature difference of $T_x - T_H = 800$ eV, assuming a bulk (hydrogen) ion temperature of $T_H = 5$ keV. The evaluation of $T_x - T_H$ is uncertain to within a factor of 2; the possible temperature differential drops dramatically, however, as the density increases and especially as the ion temperature decreases.¹ Experimentally we find that for the parameters of the PDX

experiment the ion temperature differences $T_x - T_H$ are within the error bar (Fig. 13). Note that the charge-exchange diagnostics is still able to determine the central ion temperature for plasma densities of $4 \times 10^{13} \text{ cm}^{-3}$ and plasma radii of 40 cm.

The line profiles in Fig. 12 also show a Doppler shift in addition to the line broadening. Figure 14 presents the observed line shifts as a function of time. The shift appears with the deuterium injection and is observed to some extent even after termination of the injection. It is explained by a toroidal rotation of the plasma due to momentum transfer by the deuterium beams. The crystal spectrometer on PDX views the plasma under a angle of 16.5 degrees with respect to the radial direction, so that the component $v_t \sin(16.5^\circ)$ of the toroidal plasma velocity v_t can be detected. On PDX the neutral beams are injected near-perpendicularly, forming an angle of 14° with the radial direction at the center of the vacuum vessel. The deduced values of $1-2 \times 10^7 \text{ cm/s}$ for the velocity of the toroidal plasma rotation represent a substantial fraction of the tangential component [$v_d \sin(14^\circ) = 4.5 \times 10^7 \text{ cm/s}$] of the beam particle velocity. Measurements of the Doppler shift of the Ti XXI K α -line can be used to determine the momentum confinement time for the Ti XXI-impurity ions.

VII. CONCLUSION

The satellite spectra of helium-like iron and titanium, Fe XXV and Ti XXI, have been used as a diagnostic of the central ion and electron temperature in tokamak discharges. The experimental results are in good agreement with those obtained from different diagnostic methods, i.e., analysis of charge-exchange neutrals and measurements of the electron cyclotron emission, and permit a detailed comparison with theoretical

predictions. Spectra of high Z helium-like ions are observed for a wide range of experimental parameters and are of particular interest as a diagnostic of the central ion temperature both in present-day and in future large size tokamaks. In addition to temperature measurements, the spectra can be used for determination of the charge-state distribution, transport, and momentum confinement of impurity ions in hot plasmas, and they also give valuable information on atomic data, e.g., the dielectronic recombination rate coefficient of helium-like ions. Special emphasis has been given to a discussion of experimental conditions and instrumental requirements.

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- Fig. 1. Model of the PLT (Princeton Large Torus) tokamak. (PPPL-796171)
- Fig. 2. Typical soft X-ray spectrum as observed from a PLT discharge with the Pulse Height Analysis System. The spectrum shows the contributions of the bremsstrahlung and recombination continuum and high Z impurity (Cr, Fe, Ni) line radiation. (PPPL-786492)
- Fig. 3. Fractional abundance of the charge states of iron as a function of electron temperature for coronal equilibrium (C. Breton et al, Ref. 25). (PPPL-82X2025)
- Fig. 4. K α -line spectra of iron observed from PLT discharges with different electron temperatures.²⁶ The intensity is shifted to higher ionization states with increasing electron temperature. (PPPL-773660)
- Fig. 5. Intensity [in photons/(cm³ sec)] of the Fe XXV K α -resonance line as a function of plasma radius. The calculations have been performed for different central electron temperatures, $T_e(0)$, assuming parabolic electron temperature and density profiles, and coronal equilibrium for the Fe XXV charge state. (PPPL-786242)
- Fig. 6. Schematic of the Bragg curved crystal spectrometer. The photo shows the jig used for bending the crystal. (PPPL-773846)
- Fig. 7. Schematic of the multiwire proportional counter and electronics. The detector was built by Grumman Aerospace Corporation. (PPPL-773603)

Fig. 8. Determination of the spectral resolution of the curved ($R = 333$ cm) (2243) quartz-crystal spectrometer. (a) Bragg reflection of the Holmium $L\alpha_1$ -line ($E = 6720$ eV) as observed with a .381 mm (.015") wide slit positioned on the Rowland circle at the focal point for the $L\alpha_1$ -line. The experimental points represent an image of the slit and can be fitted to a Gaussian with .497 mm FWHM. (b) Spatial resolution of the detector observed with an approximate zero width collimated Fe^{55} line source placed on the entrance window of the detector. The experimental points can be fitted to a Gaussian of .369 mm FWHM, indicating that the resolution of the spectrometer is mainly determined by the spatial resolution of the detector. (PPPL-786209; PPPL-786208)

Fig. 9. (a),(b) Dielectronic satellite spectrum of $FeXXV$ as recorded by a multichannel analyzer from PLT for a central electron temperature of 1.65 and 2.30 keV, respectively. The photon energy decreases with increasing channel number. The conversion gain is 0.18 eV/channel. w indicates the $FeXXV$ K α resonance line at 1.8500 Å. Also shown (solid curve) is the result of a least-squares fit of Voigt functions to the raw data of the most prominent peaks. (PPPL-793403)

Fig. 10. Experimental results for the intensity ratio of the dielectronic satellite j and the resonance line w and predictions of both the earlier^{15,16} (solid line) and most recent⁹ (dashed line) theories. The intensity ratios I_j/I_w are plotted vs. the experimental values of T_e as determined from measurements of the electron cyclotron emission.³² (PPPL-793201)

Fig. 11. Dielectronic satellite spectrum of Ti XXI. The spectrum has been observed from ohmically heated PDX discharges with central electron temperatures of ≈ 1 keV, using the curved ($R = 363.5$ cm) (2033)-quartz-crystal spectrometer with a spectral resolution of $\lambda/\Delta\lambda = 23000$. The wavelengths are given relative to the wavelength of the TiXXI $K\alpha$ -resonance line using the theoretical value³⁶ of 2.6099 Å. (PPPL-806817)

Fig. 12. A time sequence of six out of sixteen Ti XXI $K\alpha$ -line profiles observed from PDX discharges with additional ion heating by injection of intense (5 MM, 47 kV) deuterium beams during the period from 300-450 msec. The solid lines represent least-squares fit of Voigt functions. The arrows indicate the limits used for the fit. (PPPL-81X0783)

Fig. 13. Ion temperature results obtained from the observed Ti XXI $K\alpha$ -line profiles (circles) and from measurements of charge-exchange neutrals (triangle) as a function of time. The bars represent the statistical error of experimental results. (PPPL-81X1209)

Fig. 14. Observed Doppler-shift of the Ti XXI $K\alpha$ -line as a function of time. The Doppler-shift is due to a toroidal rotation of the plasma which results from momentum transfer by the injected deuterium beams. (PPPL-81X1337)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

CURVED - CRYSTAL SPECTROMETER

Fig. 6

MULTIWIRE PROPORTIONAL COUNTER AND ELECTRONICS

Fig. 7

Fig. 8a

Fig. 8b

Fig. 9

Fig. 10

DIELECTRONIC SATELLITE SPECTRUM
OF T_i ~~XXI~~ FROM PDX

Fig. 11

Fig. 12

81X1209

Fig. 13

81X1337

Fig. 14