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Iron Radiation in Tokamak Discharges*

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Abstract:

Iron ion resonance-line intensity measurements are described as a representative sample of spectroscopic diagnostics of tokamak plasmas. A brief outline of the tokamak discharge characteristics is followed by a description of the spectrometer, and its calibration for absolute intensity measurements in the vacuum ultraviolet wavelength region. Then iron ion resonance lines in the wavelength range 90-360 Å, from ionization states FeXV through FeXXIV, are shown as observed in the PLT tokamak. A discussion of the principal excitation processes leading to the emission of these lines in tokamak-type plasmas, and of the appropriate atomic cross-sections and rate coefficients, is then followed by quantitative measurements of these emissions in time and space in a PLT tokamak discharge. The results are interpreted in terms of iron ion concentrations, their behavior in the discharge, and their implications to radiative energy loss, contributions to electrical resistivity, and ion confinement times in the plasma.

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1. Introduction

Iron has been one of the persistent constituents of tokamak plasmas, [1,2], together with smaller quantities of chromium and nickel. Although from the point of view of radiative energy losses the presence of iron has not been overwhelming important, it has many actual or potential application for plasma diagnostics. It is therefore fortunate that iron spectra are relatively well known [3]. Iron is one of the prominent elements in astronomical light sources, particularly solar flares [4,5], and iron spectra have been extensively investigated in laser-produced plasmas [6].

With the progressive elimination of heavier Mo, W, and Au as tokamak construction materials, the importance of iron in tokamak plasmas is certain to increase. Furthermore, most of the diagnostics aspects of iron spectra (wavelengths of resonance lines, collisional transition rate coefficients, etc.) are readily extendable to neighboring elements, e.g., Ti, Cr, Ni, Cu, that also are likely to be encountered in tokamaks.

In this paper we present some observations of iron ion resonance lines, from FeXVI to FeXXIV in the PLT tokamak discharges.

2. Characteristics of the Discharge

The PLT discharge may be regarded as a quasi-cylindrical plasma with a radius $a = 40$ cm, that may be viewed at right angles along different chords. The plasma consists of hydrogen, with 1-3% oxygen and carbon impurities, and small amounts of iron and other metals. In the discharges under consideration, the electron densities and temperatures remained nearly constant for about 0.3 seconds, with the radial density distribution approximately parabolic, and central value $n_e(0)$ about $2.7 \times 10^{13} \text{ cm}^{-3}$. The electron temperature distribution was considerably narrower, with central peak 1.6 keV. Under these conditions the line profiles are almost exclusively determined by Doppler broadening, with $\Delta\lambda_D/\lambda \approx 2 \times 10^{-4}$. The plasma is optically thin to all the resonance lines under consideration. And most importantly, practically all the radiation is the result of electron collisional excitation from the ion ground state. Typical resonance-line excitation times are of the order of 10^{-5} sec — much longer than radiative lifetimes of excited states, and much shorter than recombination times or particle confinement times.

3. The Spectrometer

The measurements were made with a Spex grazing incidence spectrometer, equipped with a Jobin-Yvon holographically ruled gold-coated grating, with

2400 groove/mm, 1 meter radius at 85° incidence, and two Bendix (now Galileo) magnetic electron multipliers with tungsten photocathodes. The spectral resolution (first order) was approximately $0.8 \text{ \AA}$ over the entire range. The spectrometer was calibrated in situ for absolute intensity measurements by means of the line-ratio method [7], with results shown in Fig. 1, for the two channels. The long-wavelength components were measured with a 1/2-meter Jarrell-Ash Ebert-Fastie spectrometer, which in turn had been calibrated against a black body. The two spectrometers viewed simultaneously the same volume of plasma, with the appropriate elements either present spontaneously or added for this purpose. The ordinate in Fig. 1 is such that 10^{12} photons/ $\text{cm}^2\text{-sr-sec}$ plasma brightness produces a collector current of 10^{-12} amperes, if the photomultiplier voltage is 1500 volts.

The spectrometer slits are horizontal, i.e., parallel to the plasma axis, and field of view may be scanned by rotating the spectrometer about the entrance slit. The total range of the scan is about 20 cm, i.e., from the center out to about 1/2 the plasma radius (the view is limited by plasma positioning field coils), with spatial resolution about 2 cm.

4. Observed Iron Ion Resonance Lines

Fig. 2 shows the observed intensities of the strongest resonance lines from FeXVIII to FeXXIV. These intensities are measured at their temporal maxima, which appear successively according to the ionization potentials during the discharge, in a discharge where the electron density was approximately constant, and they probably give a quite accurate measure of the relative collisional excitation rates. In general, the measurements accuracy is better for the stronger and more isolated lines. Some of the lines (e.g., the $\lambda 132.9$ line of FeXXIII and $\lambda 132.8$ of FeXX) could be distinguished only from their different temporal behavior, and in such cases the intensity of the weaker line is less accurate. The lines of FeXVIII-XX are displaced in the figure to minimize crowding, but the lengths of the lines refer to the same ordinate scale.

5. Excitation Rate Coefficients

Since the resonance lines are emitted almost exclusively as a result of collisional excitation from the ground state, the volume emissivity (photons/ $\text{cm}^3\text{-sec}$) is the product of the known electron density, n_e , the ground-state ion density, n_i , of the particular state of ionization of the element, and the appropriate excitation rate coefficient, S_x . The rate coefficients for several of the strongest iron ion lines are shown in Fig. 3.

These are based on the oscillator strengths calculated by Armstrong et al. [8] and Weiss [9], and near-threshold Gaunt factors by Rely [10] and Blaha [11]. The latter, although obtained through a simple approximation, have been found quite reliable by more elaborate calculations in special cases, and in any case the near-threshold uncertainties in the excitation cross-sections only affect the rate coefficients appreciably at low temperatures (to the left of the maxima).

The ions of a particular species tend to be located in the plasma where the electron energy (temperature) is nearly comparable to their ionization potential and therefore much larger than the excitation potential of the $A_n = 0$ resonance lines (i.e., the appropriate S_x are typically about a factor 5 to the right of the maxima in Fig. 3). Thus the coefficients for these lines vary slowly with electron temperature, in addition to being insensitive to the principal uncertainties of the calculated cross-sections.

6. Observed Behavior of the Iron Ion Lines

Fig. 4 shows the time behavior of the brightness of FeXVI, XXIII and XXIV resonance lines, measured in the central plane of the PLT tokamak in a discharge characterized at the top of the figure. The scales of the different lines are chosen roughly in proportion to the excitation rate coefficients. The appearance time of each ion is determined by the ionization time at the prevailing plasma temperature and density. In the earlier states of ionization, such as FeXVI, with ionization potentials substantially lower than the eventual peak temperature, the emission goes through a pronounced maximum, and settles to a fairly constant plateau after most of the iron in the central part of the discharge is ionized to higher states. The radiation from higher states generally varies relatively slowly in time. The minimum at ~ 130 msec is something unusual (although well reproducible in this particular series of discharges) apparently resulting from an internal instability that temporarily dropped the central temperature by several hundred eV, without disturbing the outer regions of the plasma.

The spatial variations of the FeXXIII and XXIV lines, measured along chords at different distances from the plasma center, are shown in Fig. 5. Within experimental uncertainties, both of these shapes remained constant from 100-350 msec, except during the minimum, at which time there was a distinct broadening of the profile, as indicated. In the same discharge, a FeXXII line indicated a nearly flat profile from the center to about

17 cm with a rapid drop further out. FeXVI brightness showed no variation radially to the limit of observation at about 30 cm, except during the initial peak (~ 40 msec) at which time it had a shallow central maximum.

7. Interpretation of the Results

With the assumption of cylindrical symmetry the observed chord brightness distributions may be converted to radial distributions of local emissivity (Abel inversion), and the local ion densities can then be established from the known rate coefficients and the measured electron density. The results (at a particular time) for three iron ions, as well as the measured electron temperature and density distribution are shown at the top of Fig. 6, whereas the bottom of Fig. 6 shows the time variation of the central densities of FeXXIII and XXIV. In the case of FeXVI, the shape and precise location of the density profile are based on some modelling calculations. Only the area under the curve, and its location at $r > 20$ cm, are directly measured quantities.

The distribution of the various states of ionization in the plasma of given electron temperature and density, is determined by the rates of ionization and recombination, and the radial ion motions. The rapid variation of ionization time with electron temperature and the state of ionization imply that only a few (typically 3-5) successive states can coexist in appreciable numbers. Further, if in the center of the discharge the helium-like [FeXXV] concentration were large ($> [FeXXIV]$) we should also expect $[FeXXIV] > [FeXXIII]$ contrary to observation (Fig. 6 bottom). We therefore conclude that $[FeXXIV]$ is not larger than the observed concentrations, although it could be comparable, especially around the 300 msec times. On the other hand, the central $[FeXXIII]$ was found comparable to that of FeXXIV, and the concentrations of still earlier states were much smaller, as indeed would be expected from their short ionization times (< 1 msec). Thus, the two states shown in Fig. 6 constitute about one half the total central iron concentration, and this total concentration does not change substantially in time (although changes $< 3 \times 10^{11}/\text{cm}^3\text{-sec}$ cannot be precluded).

From the size of $[FeXVI]$, which also should constitute about 1/3-1/4 of the local iron concentration, it may be concluded that the iron concentration also remains at least approximately homogeneous in space, suggesting rapid mixing of the plasma, perhaps by turbulent convection.

The total iron concentration is in the neighborhood of $3 \times 10^{10}/\text{cm}^3$ — a value that makes only a modest contribution to the plasma resistivity

(dominated by the much larger oxygen impurity). The total radiative energy losses by iron are less than 10% of the local power input ($P_{in} \approx 1 \text{ W/cm}^3$ near the center).

The best available ionization and recombination rates imply that the iron ionization states are significantly below coronal equilibrium values [12,13], and suggest radial ion motions about $1-2 \times 10^3 \text{ cm/sec}$. Radial drifts of this magnitude are consistent with the homogeneity of the plasma composition, and result in ion confinement times comparable to the electron energy replacement times ($\tau_E \equiv \text{electron energy/power input} \sim 10-20 \text{ msec}$).

The most critical shortcoming in the interpretation of the observed light profiles is the factor-of-two type uncertainty of the ionization and recombination rates. However, it appears feasible to evaluate these rates experimentally from systematic measurements of such profiles in tokamak discharges, including radiation from similar transitions in other elements (Cr, Ni, Ti, etc.), in discharges with different electron temperatures and densities. Once the atomic rates are accurately known, the ion light measurements would provide a powerful and versatile tool of plasma diagnostics, not only for the type of information discussed here, but a number of other applications, some of which are described in the paper by von Goeler on x-ray diagnostics.

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Figure Captions

Fig. 1. Wavelength dependence of the two u-v spectrometer channels and the line pairs used for calibration.

Fig. 2. Intensities of observed resonance lines of iron ions, each measured at its maximum during the discharge in the PLT tokamak.

Fig. 3. Rate coefficients for excitation by electron collision for the indicated iron ion resonance lines.

Fig. 4. Top: Ohmic heating current, peak electron density and temperature (o from Thomson scattering, • from x-ray continuum) in a PLT discharge. Bottom: Time variation of the absolute intensities of FeXXVI, XXIII and XXIV resonance lines.

Fig. 5. Intensity variation with distance from the central plane of FeXXIII and XXIV lines, compared with variation expected from assumed radial distributions. The contours were constant in time, except during the minima (~ 130 msec) where the radial profile broadened as shown in the inset, for FeXXIII.

Fig. 6. Top: Radial distributions of iron ion densities deduced from the measured intensities, and of electron density and temperature (from Thomson scattering) Bottom: Central densities of FeXXIII and XXIV versus time.

FIGURE 1

FIGURE 2

FIGURE 3

Figure 4

FIGURE 5

FIGURE 6