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OBSERVATIONS OF MULTIPLY IONIZED
TUNGSTEN RADIATION IN THE PLT
DISCHARGES

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OBSERVATIONS OF MULTIPLY IONIZED TUNGSTEN RADIATION
IN THE PLT DISCHARGES

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ABSTRACT

Spectral and spatial distributions of radiation bands with peaks at 33, 51 and $60 \text{ \AA}$, ascribed to $4d - 4f$ transitions of tungsten ions in the range about W XX - W XXXV, have been measured in discharges of different electron temperatures.

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The observations described in this paper were carried out in the PLT tokamak [1] at Princeton. The plasmas are produced by a toroidal current in a toroidal magnetic field, approximately 450 k-amperes and 32 k-gauss, respectively, in the present experiments. The major radius, R , of the torus is 132 cm, minor radius, a , 40 cm. The minor radius is determined by a massive tungsten rail aperture limiter at one toroidal location. The discharge is produced in hydrogen or deuterium, but the plasma contains usually several per cent oxygen and carbon impurities (desorbed from the walls at the beginning of the discharge), of the order of 0.1% Fe, Cr and Ni ions, and so far undetermined amount of tungsten ions. A discharge typically lasts 0.5-1.0 sec., most of which time it is in a quasisteady state, i.e., its characteristics (temperature, density, etc.) change slowly in the time scale of the energy replacement time, $\tau_E \equiv \text{plasma energy/power input}$, ($\tau_E \approx 5-50$ msec, depending on plasma conditions). The average electron densities in the present experiments were in the range $3-5 \times 10^{13} \text{ cm}^{-3}$, with the radial distributions more-or-less parabolic within the limiter radius. The electron temperature $T_e(r)$ usually exhibits a profile peaked in the center, with $T_e(0)$ ranging from 0.6 keV to over 2 keV. However, often a lower-temperature discharge develops a central depression, with maxima of 0.6-0.8 keV at $r \approx 15-20$ cm and $T_e(0)$ as low as 200-300 eV. The radial current density and power input density distribution

is thought to follow the temperature distribution fairly closely. The consequent ohmic heating power input has maxima in the neighborhood of 1 watt/cm^3 , with total power input during the quasisteady phase about one megawatt.

The great complexity of the tungsten spectra in its first 40-45 states of ionization precludes the possibility of emission of very prominent lines that could be readily used for quantitative analysis of the tungsten concentration in the usual manner. Nevertheless, recent observations in the ORMAK device [2], laser-produced plasmas [3,4], a theoretical study of the expected spectra [5], and extrapolations from isoelectronic sequences [6] indicate that during the entire stripping of the $n = 4$ shell groups of fairly strong lines should appear in the neighborhood of 50-60 Å. If the emission characteristics of such groups or bands of radiation become sufficiently well understood it may be possible to use the entire bands for the study of the behavior of tungsten or other very heavy elements in hot plasmas, or at least for the quantitative measurements of radiative energy losses by these elements.

Figure 1 shows samples of the radiation bands ascribed to tungsten ions, in two different types of discharges (characterized by the radial temperature profiles shown in the inset), of the PLT tokamak. These spectra were obtained on a shot-to-shot scan, with a photoelectric detector in a grazing incidence (85°) spectrometer, instrumental bandwidth 1.25 Å. A spectrometer was calibrated

for absolute intensity measurements at 40 Å and 88 Å (branching ratios of C V and Ne VIII lines, respectively), with interpolations and extrapolations at other wavelengths. Scattered light from the grating (important at wavelength positions below 40 Å) has been separately measured and subtracted in the figure.

The radial profiles of electron temperature and density, and the volume emissivity of the peak at 51 Å of the tungsten radiation in similar two discharges, are shown in Fig. 2. In both cases the electron densities and temperatures were nearly constant (within $\approx 10\%$) for at least 50 msec before and after the time of the measurement.

The electron temperature range, about 400-1600 eV, where the tungsten bands originate gives an indication of the range of ionization potentials of the tungsten ions emitting this radiation. These states should be near but probably slightly below coronal equilibrium values. According to a recent calculation [7] of the expected ionization states, the emission must span the range from about W XX to W XXXV, i.e., throughout the stripping of the 4f and part of the 4d subshells. The observed radiation may therefore be ascribed to transitions of the type $4d^r 4f^{s-1} - 4d^{r-1} 4f^s$, and the remarkably small variation of the spectrum with temperature (Fig. 1) may be taken as evidence that the 4d subshell (ionization potentials 1200-1600 eV) is indeed

not entirely stripped by $T_e = 1600$ eV. Yet, it is evident from Fig. 2(b) that a large fraction of the tungsten radiation arises from the same or even slightly narrower region as Fe XXIII (ionization potential 1950 eV) observed in the same discharge. The coexistence of ions with such disparate ionization potentials must be due to an efficient recombination mechanism of the W ions.

The explicit density dependence of the radiation is probably $\propto n_e^2(r)$ (i.e., corresponding to a radially constant fraction of tungsten concentration). The radial light distribution on Fig. 2(b) then indicates in the 51 Å band of radiation efficiency increasing with temperature up to at least 1500 eV. Since the excitation rate coefficient at about 2-6 times threshold energy should be nearly independent of T_e , the radiation efficiency must be increasing with the ionization state. Radial scans off the spectral peak, e.g. at 58 Å indicate somewhat less radially peaked profiles, in qualitative agreement with the narrowing of the spectral distributions at higher T_e (Fig. 1). The 33 Å band may also be slightly broader radially than the 51 Å peak (hence pertaining to lower temperature).

In the case of the hollow discharge (Fig. 2(a)), the relatively high emissivity near the center is probably due to deviations from coronal equilibrium caused by radial

drift of the ions (estimated velocities $(1-2) \times 10^3$ cm/sec), i.e., the states of ionization are somewhat below equilibrium outside T_e maximum, and above inside.

An emission of 10^{14} photons/cm³-sec-Å at the 51 Å maximum corresponds to an emissive power for the three bands of about 50-60 mW/cm³. Thus the total radiated power is comparable to the power input densities. Comparison of the radiation magnitudes in Fig. 2(a) and (b) at $r \approx 15-20$ cm suggests a tungsten concentration some 3-4 times higher in the hollow discharge case. (The absolute concentrations are estimated from probable excitation rates to be of the order $10^{10} - 10^{11}$ cm⁻³). Indeed it appears that the high tungsten concentration is a necessary condition for developing the hollow temperature profile by providing the necessary heat sink in the center of the discharge.

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Fig. 1. Observed tungsten spectra pertaining to the two electron temperature profiles shown in the inset.

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Fig. 2. Radial distributions of electron density and temperature (right scales) and the 51 Å band peak intensity (left scale) during the quasisteady phase of (a) hollow and (b) peaked-temperature discharges. Also shown is the distribution of Fe XXIII ion in the latter discharge.