**Titanium Density Measurements in the PDX Tokamak
Using TiXVII Forbidden Line**

**S. Suckewer, E. Hinnov, K. Bol, R. Fonck, R. J. Hawryluk,
R. A. Jacobsen, D. M. Meade, M. Okabayashi, G. L. Schmidt,
E. H. Silver and J. C. Linnis**

**Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544**

Abstract

A spectrum line observed at $3834.4 \pm 0.2 \text{ \AA}$ and identified as a $2s^2 2p^2 \text{ } ^3P_2 \rightarrow ^3P_1$ magnetic dipole transition in the TiXVII ground configuration, was used for titanium density measurements in the Poloidal Divertor Experiment (PDX).

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This paper describes the determination of total titanium densities in the central part of the PDX (Poloidal Divertor Experiment) tokamak¹ discharges. The method is based on measurement of the absolute intensity of a newly-identified magnetic dipole line in the TiXVII ion ground term, at 3834.4 Å, i.e., at a wavelength where accurate intensity measurements are relatively simple. Only an approximate knowledge of radial distribution and electron temperature profile is required, and the measurement is insensitive to electron density in the typical tokamak discharge range of 10^{13} - 10^{14} cm⁻³.

Titanium is widely used in tokamaks as a getter to control or modify wall interactions with incident plasma particles,² and also as a construction material¹ for aperture limiters, etc. It is therefore important to have available simple, even if approximate, methods of assessing titanium densities in the plasma. Of course, the forbidden lines of highly ionized titanium, like the corresponding lines of iron, are applicable to a variety of other local diagnostics for the high-temperature interior of tokamak plasmas.³⁻⁶

A spectrum line observed at 3834.4 ± 0.2 Å (in air) in the PLT tokamak discharges was identified as the $2s^2 2p^2 \ ^3P_2 + ^3P_1$ transition in the ground term of TiXVII (Fig. 1). The identification, as described in Ref. 3 for the FeXX case, is based on the time and space behavior of the emissivity in comparison with various titanium ion resonance lines, and on the good

agreement with the theoretical prediction by Kastner et al.⁷ The experimental 3P_2 - 3P_1 level separation is thus $26072 \pm 2 \text{ cm}^{-1}$, and the magnetic dipole radiation transition probability⁷ is 228 sec^{-1} , i.e. sufficiently small for a substantial fraction of the TiXVII to be in the P_2 level at typical tokamak discharge conditions.

Figure 2 shows the temporal behavior of the $\lambda 3834 \text{ \AA}$ line intensity in a PDX tokamak discharge, in comparison with the resonance lines of TiXIX and TiXX and of OVI, measured with a grazing incidence vacuum spectrometer. The inset shows typical oscillograph traces of the $\lambda 3834 \text{ \AA}$ line and the $169 \text{ \AA}$ resonance line of TiXIX. Background intensity (continuum emission, stray light, etc.) was less than 20% for the former, and less than 5% for the latter.

In this experiment PDX was operated as a standard circular discharge, i.e. without the divertor. The minor radius was 40 cm, major radius 140 cm, the plasma current about 360 kA and the toroidal field 20 kG. The line-average electron density (from 2 mm microwave interferometry) and the central (peak) electron temperature (from soft x-ray continuum spectra) are shown in Fig. 2. The electron density rise starting around 180 msec is caused by a programmed (H_2) gas feed during the discharge. During this time, the titanium emission decreases in a manner similar to that observed in previous experiments on PLT.⁸ In the PLT experiments, the decrease in high-Z impurity concentration during the gas influx was attributed to

a decrease in the plasma edge temperature. (When the intensive gas influx ceases, around 400 msec, the titanium concentration begins to rise again. In discharges with less intensive gas influx, where the electron density remains constant the titanium line intensities usually are also constant). Besides titanium, other impurities in the discharge which contribute significantly to Z_{eff} were oxygen and carbon, with concentrations below 1% of $\bar{N}_e$.

The evaluation of the titanium density from the measured absolute brightness of the 3834 Å line consists of two steps: 1) deducing the TiXVII ion density from the emissivity of the line, and 2) relating the TiXVII density to the total titanium density. Although in principle the local emissivities (i.e. Abel-inverted chord brightnesses) of lines of all the titanium ions are needed for this, as well as the local electron density and temperature, an adequate approximate result may be obtained from the following considerations.

In the central ($r \lesssim 10$ cm) part of the plasma, where $T_e \gtrsim 800$ eV, only the states TiXIII-XX occur in appreciable concentration, with only 3-5 of these ionization states constituting most of the total. Furthermore, while the electron density is constant, e.g., 100-200 msec on Fig. 2, the total titanium concentration is also very nearly constant. Therefore, with the intensities (which are proportional to the corresponding ion densities) normalized to unity as in Fig. 2, simple adding the intensities of the measured lines of each of the various

states, TiXIV, -XX, at the time of the TiXVII peak (~ 140 msec) gives a quite good estimate of the total titanium/TiXVII ratio in the central part of the plasma. Experimentally, this ratio was determined to be 5.4 for TiXVII. An analogous procedure for TiXIX yields a total titanium/TiXIX ratio of about 3.1 at the time of the TiXIX peak. Similar ratios may be found for the other states at their peak intensities.

The relative populations of ground configuration states of titanium ions have been calculated by Feldman et al.,⁹ for different electron densities and temperatures, taking into account the electron and proton collisional and radiative transitions between all $n = 2$ levels. From these calculations the 3P_2 level population of TiXVII is very nearly independent of electron density in the 10^{13} - 10^{14} cm^{-3} range and also of electron temperature in the relevant range around 1 keV, with a value in the range $n(^3P_2) \approx 0.41$ - 0.43 of total TiXVII. Thus, the measured absolute intensity, the radiative transition probability, and the approximate knowledge of the radial distribution (i.e. the effective path-length of emitting region) allows evaluation of the TiXVII density and hence of total titanium density. If ℓ is the pathlength of the emitting region (roughly the region where $T_e(r) \gtrsim 800$ eV, so that in our case $\ell \approx 20$ cm), $A(^3P_2 \rightarrow ^3P_1)$, the spontaneous transition probability, and I_{3834} , the measured brightness ($\text{photons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$), then the approximate titanium density at the peak intensity of the

3834 Å line is

$$\bar{N}_{\text{Ti}} \approx 5.4 \frac{4\pi}{\ell} \frac{I_{3834}}{A \cdot n(^3P_2)} \approx 0.56 I_{3834}/\ell \text{ (cm}^{-3}\text{)}$$

where $n(^3P_2)$ is the relative population of the 3P_2 state.⁹ This expression is valid as long as no appreciable fraction of titanium along the line of sight has reached the heliumlike TiXXI state. This restriction may be removed by separately measuring ℓ for the 3834 Å line by radial scanning.

The results of titanium density measurements for two time periods in several discharges of PDX are shown in Table I. With the above mentioned multiplication factors for TiXVII and TiXIX, practically identical results are observed from measurements of the 3834 Å line of TiXVII and the 169 Å line of TiXIX, although the intensity of the latter depends linearly on electron density. Both instruments were calibrated independently for absolute intensity measurements.

The lower-density discharges tend to have high titanium concentrations, probably because of higher temperatures near the limiter radius. The contribution of titanium to the effective ionic charge of the plasma, and hence to plasma resistivity, was comparable or larger than the contribution of oxygen and carbon (~ 0.5 - 0.8% in these discharges). The total Z_{eff} including oxygen and carbon impurities varied from 1.8-3.0 and was in good agreement with values deduced from plasma resistance and electron temperature distribution.

Thus, the simple measurement of the λ 3834 Å line intensity appears to give a good estimate of the titanium density in the discharge, comparable to that achieved by ion resonance line measurements.

Acknowledgements

We wish to thank our colleagues from PLT and PDX for their cooperation in these experiments, and particularly F. Dylla, J. Hosea, E. Meservey, K. Owens, J. Schmidt, and J. Strachan. J. Schivell's support in computer data acquisition is highly appreciated. We would also like to thank R. Mullen for help in preparing the monochromators for measurements needed in our experiments.

We are grateful to U. Feldman from NRL for providing us with his calculations prior to publication.

This report is under contract with U.S. Department of Energy EY-76-C-02-3073.

References

- ¹D. Meade et al., Proc 9th Euro. Conf. on Controlled Fusion and Plasma Physics, Culham, England, September 1979.
- ²K. Bol et al., Proc. 7th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion, IAEA, Innsbruck, Austria, 1978.
- ³Suckewer and R. Hinnov, Phys. Rev. Lett. **41**, 756 (1978).

References

- ⁴H. Eubank et al., Proc. 7th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion, IAEA, Innsbruck, Austria, 1978.
- ⁵S. Suckewer and E. Hinnov, Bull. Am. Phys. Soc. 23, 875 (1978).
- ⁶S. Suckewer and E. Hinnov, Phys. Rev. A., Aug. 1979 (to be published).
- ⁷S. O. Kastner, A. K. Bhatia and L. Cohen, Physica Scripta 15, 259 (1977).
- ⁸R.J. Hawryluk et al., Report PPPL-1534 (1979) to be published in Nuclear Fusion (1979).
- ⁹U. Feldman, G. Doschek, Chung-Chieh Cheng and A. K. Bhatia, J. Appl. Phys. (1979) to be published.

Table 1: Near-central electron and titanium densities and Z_{eff} in four discharges, at different times.

Time: 100-200 msec			Time: 400-500 msec		
$N_e (10^{13} \text{ cm}^{-3})$	$N_{\text{Ti}} (10^{10} \text{ cm}^{-3})$	Z_{eff}	$N_e (10^{13} \text{ cm}^{-3})$	$N_{\text{Ti}} (10^{10} \text{ cm}^{-3})$	Z_{eff}
2.6	4.0	1.9	3.4	2.7	1.8
1.35	5.0	2.4	1.4	5.7	3.0
2.7	4.7	2.0	1.8	4.2	1.8
2.7	4.0	1.9	1.45	4.4	2.6

FIGURE CAPTIONS

Fig. 1. Energy level diagram of the two lowest configurations of TiXVII, showing the location of the 3834 Å transition and the principal transitions (in Å) contributing to the population of the 3P_2 level.

Fig. 2. Time evolution of the intensity of TiXVII 3834 Å line in relation to TiXIX 169 Å and TiXX 309 Å lines, and of OVI 1032 Å line in a PDX discharge. The inset shows oscillograms of the 3834 Å and the 169 Å signals. The early peaks (before 0.1 sec) are caused by background radiation, which has a time behavior roughly similar to OVI. Line-average electron density and near-central electron temperatures are shown with dashed and dashed-dots curves, respectively.

Fig. 1. 793603

Fig. 2. 793622