MASTER

SEPTEMBER 1977

PPPL-1377

IMPURITY MEASUREMENTS IN PLT

BY

H. F. DYLLA

PLASMA PHYSICS
LABORATORY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

This work was supported by U. S. Energy Research and Development Administration Contract EY-76-C-02-3073. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States Government is permitted.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of 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. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, 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.

Printed in the United States of America.

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ * ; Microfiche \$3.00

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-50	\$ 4.00
51-150	5.45
151-325	7.60
326-500	10.60
501-1000	13.60

IMPURITY MEASUREMENTS IN PLT

by

H. F. Dylla

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

PPPL-1377

September 1977

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, 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

IMPURITY MEASUREMENTS IN PLT

H. F. DYLLA

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

ABSTRACT

During the first eighteen months of PLT operation, measurements on impurity-related effects have been obtained using Thomson scattering, visible, vacuum ultra-violet and soft x-ray spectroscopy, mass spectrometry, bolometry, and surface analysis. A brief review is presented of these diagnostic techniques and the present characterization of the discharge cleaning process and impurity related effects in high power discharges.

Prepared for the ERDA report "Impurities in Tokamaks", T.S. Hsu, Editor

Impurity Measurements in PLT

During the first 18 months of PLT operation, measurements on impurity-related effects have been obtained using Thomson scattering, visible, vacuum ultra-violet and soft x-ray spectroscopy, mass spectrometry, bolometry, and surface analysis. A listing of all diagnostics that are in use or planned for near-term impurity studies is given in Table 1. A brief description is presented of the present characterization of the discharge cleaning process and the impurity-related effects observed during high power discharges.

Discharge Cleaning

Two modes of discharge cleaning have been used to condition the PLT vacuum vessel. A comparison of the discharge parameters of the two modes is given in Table 2. The first mode of discharge cleaning investigated was a standard hydrogen tokamak discharge run at lower discharge currents (20-100 kA), lower magnetic fields (1-10 kG), and higher repetition rates ($1/12$ - $1/30$ s⁻¹) than the typical high-power PLT discharge ($> 1/90$ s⁻¹). Such conditions resulted in a discharge typically lasting 10-100 ms with a central electron temperature and density of 100 eV and 10^{13} cm⁻³ respectively. After major vacuum openings, it was generally necessary to discharge clean in this mode for 5-10 days (approximately 10^4) discharges before relatively disruption-free high power discharges could be maintained for several hundred milliseconds. This mode of discharge

cleaning was used on PLT from Dec. 1975 through Feb. 1977, and in general, it had the effect of reducing the carbon impurity level by an order of magnitude, but had little effect on the oxygen impurity level.¹ Z_{eff} values were not reduced below 5-6 for H_2 discharges.

The second mode of discharge cleaning was similar to a mode described by R. Taylor.² A hydrogen discharge was run in a tokamak mode; however, the fill gas pressure was adjusted to yield a partially-ionized plasma with correspondingly low values of the plasma current (2-4 kA), electron density ($1-5 \times 10^{11} \text{ cm}^{-3}$), and electron temperature (2-5 eV). The low power in the resulting discharge (20-30 kW) enabled the repetition rate to be increased to $.5-2 \text{ s}^{-1}$. The first extended application of this type of discharge cleaning in PLT occurred in early February 1977, which resulted in the production of bistable high-power discharges, i.e., discharges characterized by either peaked or hollow electron temperature profiles, depending on the details of the programmed gas injection. Generally, the oxygen impurity level was reduced by a factor of 3-5 after 10^4 low power discharges³, and Z_{eff} was reduced⁴ to values in the range of 1.5-2.5.

A major difference between the two modes of cleaning is seen in the residual gas spectra immediately following each discharge cleaning pulse. The standard cleaning discharges produce primarily CH_4 ($1-5 \times 10^{-7} \text{ torr}$) and CO ($1-10 \times 10^{-7} \text{ torr}$). The time constant of the CH_4 transient was longer than the scaled H_2 pump-out time for the vacuum system; however, the

CO transient disappeared rapidly (< 300 ms), indicating nearly complete pumping of this gas by the wall. In contrast, the low temperature cleaning discharges produced primarily H_2O ($1-2 \times 10^{-6}$ torr) and CH_4 ($1-10 \times 10^{-7}$ torr). The resulting H_2O transient was equal to several pump out times enabling removal of some fraction of the volatile oxygen by the vacuum pumps rather than redeposition onto the wall. The time averaged H_2O partial pressure produced during low-temperature discharge cleaning was observed to decrease with two time-constants.

(See Fig. 1.) The first time constant is of the order of 10^3 pulses and most likely is indicative of the removal of a loosely-bound oxygen adlayer (surface oxide, adsorbed H_2O , etc.); and the second time constant is of the order of 10^4-10^5 pulses and possibly indicates the removal of more tightly bound oxygen from bulk oxide ($FeO-Cr_2O_3$) layers of the stainless steel.

Elemental surface analysis of hydrocarbon covered stainless-steel samples exposed to both types of discharge cleaning showed approximately equal carbon removal rates after 10^3-10^4 pulses.

(See Fig. 2.) In the standard mode the rate of carbon removal was found to be inversely proportional to B_T , which suggests that the unconfined ions are important wall reactants. No significant B_T dependence was found for the low temperature mode which is consistent with the assumption that such a discharge is unconfined and lacking any distinctive current channel. Clean indium thin films exposed to both discharge cleaning procedures showed no metal transport by the low temperature mode, but

occasional transport of both liner (Fe, Cr) and limiter (W) metals by the standard mode.

The mechanisms responsible for the removal of adsorbed carbon and oxygen atoms during discharge cleaning have not been established. However, we infer that chemical processes involving bond-breaking by incident atomic hydrogen and subsequent (atomic and molecular) hydrogen attachment are important. Examples of possible reactions of atomic hydrogen with adsorbed hydrocarbons yielding CH_4 have been given by Rye⁵. The most likely reactions yielding H_2O based on equilibrium constants are empirically:

To summarize: both standard and low temperature discharge cleaning will decrease carbon impurity levels by producing CH_4 which is subsequently easily removed by the vacuum system due to its low sticking probability on the vacuum vessel walls. With regard to decreasing the oxygen impurity level, we find that low temperature discharges are required to produce a molecular product with a sufficiently low sticking probability (H_2O as opposed to O, OH, or CO) to enable removal of gaseous oxygen by the vacuum pumps.

High Power Discharges

Initial operation of PLT in the high power mode (Jan.-Feb., 1976) was characterized by short (< 100 ms) disruptive discharges with large ($n_{\text{I}}/n_{\text{e}} > 20\%$) carbon and oxygen impurity levels.

In later operation (March), stable discharges of 500 kA were obtained for durations of one second⁶. During the quasi-steady state portion of these discharges, the influx rates of H, O, and C were constant and approximately in the ratio 60:10:1 respectively (see Fig. 3). Since the electron density remained roughly constant, the plasma composition probably had the same relationship, implying $\bar{Z} \approx 5-6$ and a ratio of n_p/n_e of 1/3-1/2. No significant radiation from the liner materials (Fe, Cr, Ni) was observed during the initial (Jan.-Mar.) period. However, such radiation did appear after July 1976, but not at levels believed to significantly affect the discharge characteristics (see Fig. 4a). Measurements by VUV spectrometry⁷ and soft x-ray pulse-height analysis⁸ typically yielded Fe densities of $\sim 3 \times 10^{10} \text{ cm}^{-3}$, and Cr and Ni densities of $\sim 1 \times 10^{10} \text{ cm}^{-3}$. During the first year of operation, observations by X-ray PHA of emission lines attributed to W (the limiter material) were limited to runaway discharges (Fig. 4b).

High power discharges obtained during the most recent operating period (Jan.-May 1977) were characteristically bistable with the electron temperature alternating between peaked or hollow profiles, depending on the details of the programmed gas feed and current rise (see Table 3). Radiation up to a level of 1 W cm^{-3} has been measured with bolometry⁹ and soft x-ray 20-200 Å detectors^{10,11}. The source of this radiation has been tentatively ascribed to tungsten (the limiter material). The intensity of radiation at 51 Å, which is a peak in a band of lines ascribed to W XX - W XXXIV^{12,13}, is seen to decrease by an

order of magnitude when a relatively small quantity ($\sim 1\%$ of the fill pressure) of Ne is injected into a discharge during the steady-state portion¹¹ (see Fig. 5). Such a small quantity of Ne should not affect the plasma-wall or plasma-limiter chemistry during the course of one discharge, but is capable of significantly cooling the edge-plasma by line radiation. A cooler edge-plasma temperature would lower the limiter potential which would in turn: (1) decrease limiter sputtering by decreasing the energy of impacting impurity (primarily O) ions on the limiter; or (2) would decrease the vaporization of limiter material by minimizing the probability of vacuum arcs¹⁴ occurring on the limiter surface. Either mechanism would be a source of W in the discharge. Experiments are planned which will correlate spectroscopic measurements with limiter potential and edge-temperature measurements.

The most successful PLT discharges in terms of a high density-confinement time product and minimum impurity content have been produced in pure He (see Table 3). High density operation ($> 10^{14} \text{ cm}^{-3}$) has not yet been possible with pure H_2 (or D_2) discharges. A possible reason for the difference in performance is the edge-cooling which results from the higher radiation of He^+ ions. Other differences to be considered include the lack of chemical reactivity of He with the wall components and the smaller He charge-exchange probabilities.

Surface analysis measurements have confirmed the presence of W in the discharge and have shown that W, along with liner material,

is transported around the torus by the high power discharges. Long-term changes in surface conditions have been monitored by the periodic removal of a variety of sample substrates (stainless steel, alumina, silicon) exposed to PLT discharges at the vacuum vessel wall, and subsequent analysis by Auger electron spectroscopy (AES) and photoelectron spectroscopy (ESCA). Samples were removed from a diagnostic port at the midplane of the torus 170° from the limiter position after three separate exposure intervals. The preliminary results of the subsequent analyses are given in Table 4. The most striking difference between the three groups is the considerably larger quantity of metal (Fe, Cr, Ni, and W) deposited on the samples exposed after Jan. 1977, particularly group B, which was exposed during the first application of the low temperature discharge cleaning (Jan.-Mar. 1977). Examination of the deposited metal films by high resolution ESCA indicated nearly complete oxidation of the Fe, and no evidence of reduction of the nascent Al_2O_3 or SiO_2 oxide layers on the alumina and silicon samples.

Short-term changes in surface conditions and time-resolved measurements of impurity out-fluxes have been obtained with the Surface Analysis Station (SAS) diagnostic^{15,16}. The SAS is capable of exposing a well-characterized metal film (for example, In, Al, or stainless steel) to a given number of discharges at a variable distance behind the limiter radius. Additionally, the sample film can be rotated past an exposure aperture during the course of a series of discharges to record time-resolved

surface changes. In general, when the SAS probe was exposed 2-10 cm outside the limiter radius, only low Z impurities (O, C, Cl) were easily detected. Fig. 6 shows the time-resolved deposition onto the probe when it was positioned 4 cm behind the limiter. Note, in particular, the decreased oxygen outflux which was obtained immediately after low temperature discharge cleaning. With the SAS probe located 1 cm behind the limiter radius, Fe and occasionally W were detected. Fe deposition onto the SAS probe, when exposed at the midplane nearly parallel (8°) to the toroidal magnetic field, was measured at a rate of $1.5 \times 10^{13} \text{ cm}^2 \text{ s}^{-1}$ with the outflux observable 50 ms after the initiation of the discharge, growing to a plateau as the current reaches a plateau and decaying as the current decays (see Fig. 7). W deposition was usually below a sensitivity limit of $4 \times 10^{12} \text{ cm}^2 \text{ s}^{-1}$. With the SAS probe exposed at an angle of 20° (i.e., with an increased solid angle for interception of ion orbits) the deposition rates of both Fe and W were observed to increase an order of magnitude.

We have identified two regimes of interaction of the SAS probe with the plasma: (1) With the probe positioned behind the limiter scrape-off (2-10 cm), and parallel (or nearly parallel) to the toroidal field, the probe is sampling primarily neutral particles (i.e., charge exchange neutrals during the developed segment of the discharge and recombination neutrals at the termination of the discharge. (2) With the probe positioned closer to the limiter scrape-off, or with an increased angle of interception of the toroidal field lines, the probe samples the the ion flux in the edge plasma.

The time behavior of the observed low-Z outflux (e.g., Fig. 6) is similar to the time profile of the VUV emission from the partially ionized atoms within the body of the plasma and is understandable in terms of the same atomic processes. Generally, we observe the low-Z outflux peaking at the beginning and end of the discharge. With the initial ionization a variety of chemical and charge-exchange reactions are probable, and ion confinement is also poor. With the achievement of steady state conditions in the discharge, the burn-out of the low-Z impurities and increased confinement of the discharge decreases the outflux. Finally, with the termination of the discharge, recombination will increase the outflux.

With regard to high-Z impurities, insufficient data has been collected to generally characterize their behavior. However, we draw one important conclusion based on the continual buildup of metallic layers observed on recessed areas of the PLT vacuum vessel (see Table 4), combined with the observation of the time behavior of the Fe outflux (Fig. 7), which shows that the Fe outflux peaks

early (within 50 ms) and continues during the developed segment of the discharge. We conclude that local equilibrium between erosion (by sputtering) and deposition does not occur. There are sources and sinks for the metal impurities. We thus conclude that sputtering of Fe (and possibly W) from the vacuum vessel walls is not responsible for the Fe(W) contamination in the plasma.

More detailed studies are necessary to identify the source and mechanism of introduction of Fe into PLT ohmically-heated discharges. Although the present levels of Fe in the discharge do not seem to have any detrimental effects, this situation may change as high power neutral beam heating experiments increase both the ion temperature and the wall-loading. The more serious high-Z problem is the contamination of the discharge with the limiter material, W. The Ne injection experiments (Fig. 5) indicate that W is entering the discharge directly from the limiter, rather than from the W-containing metallic film on the vacuum vessel wall. We have identified two likely mechanisms for the introduction of W into the discharge, both related to the edge temperature within the limiter scrape-off region: (1) oxygen ion sputtering of the limiter, and (2) vacuum arcs on the limiter surface.

Future experiments related to the W problem include: (1) a further examination of the coupling between the low-Z (O) impurities and W transport through the continued application of low temperature discharge cleaning; (2) gas injection experiments with the purpose of modifying the edge-temperature profile; and (3) tests of graphite as a replacement limiter material.

ACKNOWLEDGEMENTS

The author acknowledges the contributions of the PLT Experimental Group in the compilation of this report, especially K. Bol, N. Bretz, S. Cohen, D. Eames, R. Hawryluk, E. Hinnov, J. Hosea, H. Hsuan, D. Johnson, E. Meservey, N. Sauthoff, W. Stodiek, S. Suckewer, and S. von Goeler.

This work was supported by the U. S. Energy Research and Development Administration Contract EY-76-C-02-3073.

REFERENCES

- [1] DYLLA, H. F., COHEN, S. A., and HINNOV, E.,
Bull. Am. Phys. Soc. Ser. II, 21, (1976) 1160.
- [2] OREN, L., and TAYLOR, R. J., UCLA Rep.
PPG-294 (March 1977).
- [3] SUCKEWER, S., Private Communication.
- [4] BRETZ, N., JOHNSON, D., Private Communication.
- [5] RYE, R. R., Chemical Institute of Canada,
American Chemical Society, (American Chemical
Society, Montreal, 1977) 2nd Joint Conference,
Montreal, (1977) paper COLL 29.
- [6] GROVE, D., et al., in Plasma Physics and Controlled
Nuclear Fusion Research (International Atomic Energy
Agency, Vienna, 1977) Vol. I, 21.
- [7] HINNOV, E., JOHNSON, D., MESERVEY, E., and VON GOELER, S.,
Bull. Am. Phys. Soc. 21 (1976) 1159.
- [8] VON GOELER, S., EAMES, D., GREENBERGER, A., RONEY, W.,
SAUTHOFF, N., STODIEK, W., Bull. Am. Phys. Soc. 21
(1976) 1160.
- [9] HSUAN, H., Private Communication.
- [10] VON GOELER, S., SAUTHOFF, N., Private Communication.
- [11] HINNOV, E., Private Communication.
- [12] ISLER, R. C., NEIDIGH, R. V., and COWAN, R. D.,
Phys. Rev. Letters (to be published).
- [13] HINNOV, E., MATTIOLI, M., Ultra Violet and X-ray
Spectroscopy of Astrophysics and Laboratory Plasmas
5th Colloquium, London (1977).
- [14] MC CRACKEN, G. M., Chemical Institute of Canada,
American Chemical Society, (American Chemical Society,
Montreal, 1977) 2nd Joint Conference, Montreal, (1977)
paper COLL 37.
- [15] DYLLA, H. F., and COHEN, S. A., Nucl. Matter. 63
(1976) 487.
- [16] DYLLA, H. F., and COHEN, S. A., J. Vac. Sci. Technol.
14 (1977) 565.

TABLE I

IMPURITY RELATED DIAGNOSTICS IN USED OR PLANNED FOR PLT

<u>Diagnostic</u>	<u>Schedule</u>	<u>Comments</u>
I. <u>Photon Spectroscopy</u>		
1. Visible	Operational	3 Jarrell Ash 1/2 M Monochrometers. Line scan across major diameter only. Measure H_2 , He, and impurity influxes.
2. Near UV Spectrometer	Operational	Scannable across plasma edge; measure T_i by Doppler broadening.
3. Grazing Incidence UV Bichromomator	Operational	Scannable from 0 - 25 cm; measure impurity densities and influx rates.
4. Soft X-Ray Pulse Height Analyzer	Operational	Scannable from 0 - 40 cm; measure T_e and impurity concentration.
5. Curved-crystal Spectrometer	Operational	Measure ionization status of high Z ions in plasma core.
6. Very Soft X-Ray Detector	Operational	Measure spatial distribution of low energy x-rays
7. Bolometers	Operational	Measure spatial distribution of energy outflux by radiation and charge exchange.
II. <u>Particle Spectroscopy</u>		
1. Diagnostic Neutral Beam	9/01/77	Measure Z_{eff} and q profiles
2. Residual Gas Analyzer	Operational	Measure partial pressures of all gas during and after discharges.
3. Surface Analysis Station	Operational	Measure density and outflux of impurities in the scrape-off region.

	<u>Diagnostic</u>	<u>Schedule</u>	<u>Comments</u>
III.	<u>Miscellaneous Diagnostics</u>		
1.	Langmuir Probes	Operational	Measure n_e and T_e in the scrape-off region.
2.	Surface Analysis Station	Operational	Determine composition of surfaces facing the plasma.
3.	Electron Stimulated Desorption Probes	Operational	Measure amount of loosely-bound gases on tokamak wall.
4.	Ti Gettering Probes	7/01/77	Reduce contamination in plasma.
5.	Impurity Injection	<ul style="list-style-type: none"> • Operational • 6/78 • 7/01/77 	Inject high Z gases with pulse-values Inject metal atoms with laser evaporation Inject carbon pellets with electrostatic acceleration.

TABLE 2
COMPARISON OF DISCHARGE CLEANING PARAMETERS

	<u>Standard Method</u>	<u>New Method</u>
Discharge Duration (s)	.04	.04
Repetition Rate (s^{-1})	1/30	1/2
Magnetic Field (kG)	2	2
Plasma Current (KA)	100	2
Loop Voltage (V)	3	12
Peak Power (kW)	300 kW	24 kW
Peak Power Density (W/cm^2)	.6	.05
Average Power (w)	400	500
Central Electron Density (cm^{-3})	2×10^{13}	2×10^{11}
Central Neutral Gas Density (cm^{-3})	10^{10}	10^{13}
Central Electron Temperature (eV)	100	2-5
Gases Produced after a Discharge	CH ₄ , CO	H ₂ O, CH ₄
Z_{eff}	5-10	1.5-2.0

TABLE 3

DISCHARGE PARAMETERS

	1	2	3	4	5
	D ₂	D ₂	D ₂	D ₂ (Ne)	He
I _p (ma)	.45	.45	.45	.45	.50
t (s)	.45	.45	.45	.45	.75
$\bar{n}_e$ (10^{14} cm^{-3})	.21	.32	.25	.2	.9
n _{eo} (10^{14} cm^{-3})	.25	.50	.4	.3	1.3
t _{eo} (keV)	.7	1.5	3.8	2.0-3.0	1.4
t ₁₀ (keV)	---	1.0	1.2	---	---
τ_{E_e} (ms)	5.0	15.0	16.0	12.0-16.0	50.0-60.0
$\bar{Z}$	2.0-3.0	4.0	8.0-12.0	---	2.0-3.0

1. Hollow T_e Profile
2. Peaked T_e Profile with Increased Gas Injection
3. Air Leak Q_{O2} $\approx 2 \cdot 10^{-5}$ t-l/s
4. D₂ Discharge with ~ 1% Ne Gas Injection
5. He Discharge with He Gas Injection

TABLE 4

LONG-TERM INTEGRATED SURFACE MEASUREMENTS

Samples A[†]

Exposure Time	July - December 1976
Discharges	High T_e , N_e PDC High Power H_2 , D_2 , He
Coverage ($\approx 100 \text{ \AA}$)	20 ml Fe 12 ml W 30 ml C, O

Samples B

Exposure Time	January - March 1977
Discharges	High T_e , N_e PDC Low T_e , N_e , PDC High Power H_2 , D_2
Coverage* ($\sim 900 \text{ \AA}$)	Fe Cr W C O

Samples C

Exposure Time	April - May 1977
Discharges	Low T_e , N_e PDC High Power H_2 , D_2 , He, Ne, CH_4
Coverage* ($\sim 200 \text{ \AA}$)	Fe Cr W C O

[†] Measurements courtesy of Kaminsky, Gruen, and Lam of Argonne National Laboratory.

* Sputtering rate calibrated against the known sputtering rate of 5 keV A+ on TaO.

Figure Captions

- Fig. 1. Equilibrium partial pressure of H_2O in PLT during rapid pulse (.5 pps), low temperature discharge cleaning. After 6000 discharge cleaning pulses .88 torr-liters of O_2 was injected into the torus to quantify the observed H_2O pressure drop with oxygen coverage. The initial rapid drop in H_2O pressure is seen to correspond in order of magnitude to a coverage of one monolayer. Note that not all the injected O_2 was removed by subsequent discharge cleaning.
- Fig. 2. Observed changes in elemental surface composition of a hydrocarbon covered 304 stainless steel substrate exposed to a series of low temperature H_2 discharge cleaning pulses at a repetition rate of .5 pps.
- Fig. 3. Comparison of hydrogen and oxygen light intensities (proportional to influx rates) and average electron density, n_e , before (dashed curves) and after (solid curves) discharge cleaning wall conditioning. Note that in spite of rapid increase of influx rate in the dashed-curve case, n_e does not rise. The discharge depicted by solid curves continued with little further change for another 800 msec. (PPPL 766060).
- Fig. 4. (a) Soft x-ray spectrum of typical discharge following the (July) discharge cleaning period showing Fe, Cr, and Ni $K\alpha$ emission lines.
- (b) Soft x-ray spectrum of runaway discharge which shows tungsten L-lines in addition to the (Fe, Cr, Ni) $K\alpha$ lines.
- Fig. 5. Intensity of a Ne VIII VUV line and a soft-x-ray band (51 Å) attributed to W during a high power D_2 discharge in which ~ 1% Ne is injected after steady-state conditions had been reached.

Fig. 6. Time-resolved measurements of the low-Z impurity outflux from a series of high power PLT discharges. The upper graph shows the averaged outflux of 37 H_2 discharges immediately after 8 hours of low temperature discharge cleaning. The lower graph shows the averaged outflux of 65 D_2 discharges (seeded with a small fraction of Ne) which were not preceded by any discharge cleaning. The measurements were made by repeatedly exposing the same areas of a clean indium sample to the same portions of the .4's long discharges.

Fig. 7. The lower graph shows the time-resolved Fe and C outflux from 20 high power discharges in CH_4 (using a clean Al sample for the substrate). The impurity outflux can be compared with other diagnostic measurements characterizing the discharge which are plotted with the same time scale.

Fig. 1. 773420

Fig.. 2. 773387

Fig. 3. 766060

Shot # 60690

Fig. 4a. 766115

Shot # 57154

Fig. 4b. 766114

Fig. 5. 773675

Fig. 6. 773395

Fig. 7. 773405