Low Temperature Tungsten spectroscopy on a Penning Ionization Discharge

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Abstract

Recent experiments on a Penning ionization discharge have used a variety of background gases (He, Ne and Ar) and cathode materials (Al, Cu, CuW alloy). The plasmas produced in such experiments have typical electron densities $\sim 10^{13}$ cm$^{-3}$, bulk electron temperature of a few eV and perhaps a non-Maxwellian tail in electron energy distribution at $\sim 10$s eV. Higher charge states (for example Al III, Al IV, Ne III, Ne IV) may be populated by inner shell ionization of bulk species. These conditions provide a good scenario to study emission from low charge states of W, which could be relevant to the region near the divertor plates on ITER.

The experiment is diagnosed using three different spectrometers which provide an extensive spectral coverage in the EUV, VUV and visible regions. The extensive spectral coverage is useful in monitoring both the bulk electron temperature and the effect of non-Maxwellian electrons.

Charge states of Tungsten up to W IV have been observed in these low temperature plasma experiments. The effect of fast electrons is studied by current scaling experiments.
A Penning discharge relies on confining plasma along an axial magnetic field and quadrupolar electric field. Applications of Penning like confinement scheme include:

- Trapping charged particles
- Ion source
- XUV/EUV source
- Simulating tokamak divertor/scrape off conditions
Penning Ionization Discharge

**Operating characteristics:**

Voltage = 0.5-2.5 kV  
Current = upto 2.5 A  
Background pressure = 3-25 mTorr  
Magnetic field ~ 0.1 T  
$T_e$ ~ 2 eV  
$n_e$ ~ $5 \times 10^{13}$ cm$^{-3}$  
Fast electron population  
Gases – He/Ne/Ar  
Electrodes - Al/Cu/CuW

The experiment operated steadily, limited by electrode sputtering.  
On a Penning like discharge, $T_e$, $n_e$ and population of fast electrons depends on magnetic field, the geometry, etc.
The extensive spectral coverage of the experiment enables diagnosis of effect of bulk electron temperature and also the effect of fast electrons. For e.g., the autoionization lines from Al and Ne show up in EUV/VUV and from W in VUV only.
Transmission grating based imaging EUV spectrometers

D. Kumar et. al, Rev. Sci. Instrum. 81, 10E507 (2010)

Direct photon detection using an ANDOR IKON-M 934[DO] camera also implemented on the spectrometer.
Ne-Al experiments: visible spectrum

Note: Spectra taken at constant background Ne pressure of 5 mTorr. The intensity of Al lines increases with increasing current because of increased sputtering. The intensity of Ne I 3s-3p lines decreases as current is increased to 1.85 Amps. This is an indication of Ne I burn through.
Ne-Al experiments: VUV spectrum

Spectra taken at 6 mTorr background pressure of Ne.
Ne-Al experiments: Bulk electron temperature

The intensity ratios of visible Al II 3s$^2$-3s3p and 3s3p-3s3d transitions confirm that bulk $T_e$ is between 2-2.5 eV even while increasing current.

At such bulk electron temperatures, only low charge states Ne I, Ne II, Al I, Al II, Al III should be measurable (see the equilibrium charge state distribution at $n_e = 10^{13}$ cm$^{-3}$ below)

Experimental data points
Ne-Al experiments: EUV spectrum reveals the presence of fast electrons

- The space resolved EUV spectra was obtained with Ne Gas at 7 m Torr.
- The spectral cut with identified transitions are shown in the next 2 slides.
- While, the Ne IV lines increase in intensity with current, the Ne IV $2s^22p^3-2s2p^4$ transitions at 358, 389 and 469 Angstroms are not observed in the experiment. These transitions are marked in red in the spectrum.

Example of space resolved EUV spectrum obtained by space resolved TGIS with direct photon detection.
Ne-Al experiments: EUV spectrum reveals the presence of fast electrons
Ne-Al experiments: Ne line identification in EUV spectrum

<table>
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<th>( \lambda (\text{Å}) )</th>
<th>Charge State</th>
<th>Transition</th>
<th>Intensity (AU) @1A</th>
<th>Intensity (AU)@1.5A</th>
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Characterization of Penning Ionization Discharge

- Previous work in the group showed that the populating mechanism for Al IV ions is via inner shell ionization - Finkenthal et. al., J. Phys. B. 22 (1989). In this work, we see the intensity of higher charge states of background gas (Ne IV) increases with current.
- Current scaling experiments reveal that changing the plasma current leads to increased population of higher charge states. This can be attributed to an increased Te and/or an increased amount of fast electrons (~10s eV).
- Similar behavior is seen in experiments with CuW electrodes and Ar gas. It provides a unique scenario to study W emission from low charge states (up to W IV), which is relevant to the divertor region of tokamaks. In the following slides W lines were confirmed by comparing the emission to Cu electrodes and Ar gas.
CuW + Ar experiments – visible spectrum

Clear signatures of W I, W II seen in the visible spectrum.
No emission from higher charge states of W was measured in the visible spectrum.
At the bulk Te ~ 2-2.5 eV (from Ne-Al experiments), only Ar I, Ar II, W I, W II, W III are expected to be populated.
Data collected with Ar at 6 mTorr and CuW experiments with changing current. Higher charge states of W (III, IV) are visible and prominent with current scaling.
These graphs show the different scaling behavior of emission from W II, W III, and W IV as current is increased. W IV and most likely W III are expected to be populated by ionization from fast electrons. The emission from W III and W IV are bunched up so that it is not possible to distinguish individual lines.
Conclusions

• A Penning Ionization Discharge (PID) is suitable for studying low $T_e$ spectrum from W, relevant to divertor conditions.
• A PID was operated with $n_e \sim 10^{13} \text{ cm}^{-3}$, and bulk $T_e \sim 2 \text{ eV}$, and fast electrons at 10s of eV.
• W spectrum was obtained by operating the PID with Ar gas and electrodes made of CuW alloy. Low charge states of W (I, II) are prominent in the visible spectrum. Increasing the current populates higher charge states (W III, IV) and the emission lines are visible in VUV.
• The current in the experiments with Ar-CuW was limited by plasma instabilities. Options for increasing the current to populate higher charge states of W V and beyond are being considered.
EXTRA SLIDES
Varying the operating conditions

- It has been shown in other experiments that varying the geometry (diameter of anode plates) and magnetic field effects the bulk electron temperature and population of fast electrons in the plasma. We modified the fast electron population by changing the current (and hence the sheath voltage) in the plasma. This confirmed that the high charge states of cathode ions and background gas ions are populated by inner shell ionization of bulk ions.

- In this poster, we first elucidate this with spectra recorded from experiments with Ne gas and Al electrodes. Next, we use the same concepts to identify presence of high charge states of W from experiments with Ar gas and CuW electrodes.
Ne-Al experiments: Unidentified Ne lines in EUV spectrum

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Scaling of Al line intensities with current

The current scaling of line intensities of Al lines indicate that the populating mechanisms for Al II is excitation from bulk electrons, whereas for higher charge states, is from inner shell ionization by fast electrons.
References

• http://www-amdis.iaea.org/FLYCHK/ZBAR/csd074.php

*Template from NSTX presentation template.*