Low Temperature Tungsten and other fusion relevant element spectroscopy on a Penning Ionization Discharge

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53rd APS DPP meeting
14th-18th Nov, 2011
Abstract

Complete Tungsten divertor operation is being planned on many tokamaks including Tore Supra and ITER. Thus, low temperature tungsten spectroscopy is important for aiding the divertor diagnostics on larger machines. A Penning Ionization Discharge (PID) operated at the Johns Hopkins University produces steady state plasmas with $T_e \sim$ several eV, $n_e \sim 10^{13}$ cm$^{-3}$ and a fast electron fraction at tens of eV. Bi-Maxwellian distributions, but with different electron temperatures are found in the divertor plasmas of tokamaks as well.

The two significant populating mechanisms for higher charge states in the PID are: (a) collisional excitation from bulk electrons, and (b) inner shell ionization from the fast electrons. The PID is diagnosed in a wide wavelength range, from XUV to visible, to differentiate the two populating mechanisms. W is introduced in the PID by the sputtering of W cathodes or those made of CuW alloy. Spectral emission from charge states of W (up to W III) has been observed in the experiment. This poster will describe results elucidating the populating mechanism of W ions.

Supported by USDOE.
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 photometric source
- Simulating tokamak divertor/scrape off conditions
**Operating characteristics:**

Voltage = 0.5-2.5 kV  
Current = upto 2.5 A  
Background pressure = 3-25 mTorr  
Magnetic field ~ 0.2 T  
$T_e$ ~ 1-3 eV  
$n_e$ ~ $10^{13}$ cm$^{-3}$  
Fast electron population  
Gases – He, Ne, Ar  
Electrodes - C, Al, Cu, CuW, W

The experiment operated steadily, limited by electrode sputtering.  
In 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 XUV and from W should show up in VUV.
Transmission grating based imaging XUV and VUV spectrometers

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

Direct photon detection using ANDOR IKON-M 934[DO] and Princeton Instruments PIXI XO 400 B camera also implemented on the spectrometer.
Ne-Al experiments: Scaling with $I_p$ in the 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 slightly as current is increased to 1.85 Amps. This may be attributed to increase in $T_e$. Al II lines show similar trend as Al II resonance lines in VUV spectrum (next slide).
Ne-Al experiments: scaling with $I_p VUV$ spectrum

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

At such bulk electron temperatures, only low charge states Ne I, Ne II should be measurable (see the equilibrium charge state distribution at $n_e = 10^{13}$ cm$^{-3}$ below). However the presence of Ne III and Ne IV lines in XUV and increase of their intensity with current indicate either an increase in bulk $T_e$ or the presence of fast electrons.

The intensity ratios of visible Al II 3s$^2$-3s3p and 3s3p-3s3d transitions confirm that bulk $T_e$ is between 2.5-2.9 eV even while increasing current.
Ne-Al experiments: XUV spectrum reveals the presence of fast electrons

- The space resolved XUV 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 Å are not observed in the experiment.

Example of space resolved EUV spectrum obtained by TGIS with direct photon detection (ANDOR).
Ne-Al experiments: Ne III, IV emission appears in the XUV spectrum with the increase in $I_p$.

Increase in Ne III, IV emission may be attributed to an increasing $T_e$. 

$\text{Al IV}$

$\text{Al III} + \text{Ne IV 2p-3d}$

$\text{Ne IV - Line } #1$

$\text{Ne IV - Line } #2$

$\text{Ne IV - Line } #3$

$\text{Ne III - Line } #4$

$\text{Ne III - Line } #5$

$\text{Ne II - Line } #6$

$\text{Ne II - Line } #7$

$\text{Ne II - Line } #8$

$\text{Ne II - Line } #9$

$\text{Ne II - Line } #10$

$\text{Ne II - Line } #11$

$\text{Ne II - Line } #12$

$\text{Ne II - Line } #13$

$\text{Ne II - Line } #14$

$\text{Ne II - Line } #15$

$\text{Ne II - Line } #16$

$\text{Missing Ne IV line}$

$\text{Missing Ne IV line}$

$\text{Increase in Ne III, IV emission may be attributed to an increasing } T_e$. 

APS 2011 – Low $T_e$ Tungsten spectroscopy on a Penning Discharge, Kumar
### Ne-Al experiments: Ne line identification in XUV spectrum

<table>
<thead>
<tr>
<th>( \lambda (\text{\AA}) )</th>
<th>Charge State</th>
<th>Transition</th>
<th>Intensity (AU)@1Å</th>
<th>Intensity (AU)@1.5Å</th>
<th>Intensity (AU)@2Å</th>
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<tr>
<td>1</td>
<td>Ne IV</td>
<td>2s2p^4-2s2p^3d</td>
<td>240</td>
<td>400</td>
<td>505</td>
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<td>2</td>
<td>Ne IV</td>
<td>2s^22p^3-2s^22p^2s</td>
<td>210</td>
<td>350</td>
<td>380</td>
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<tr>
<td>3</td>
<td>Ne IV</td>
<td>2s^22p^3-2s^22p^23s</td>
<td>220</td>
<td>350</td>
<td>480</td>
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<tr>
<td>4</td>
<td>Ne III</td>
<td>2s^22p^4-2s^22p^3d</td>
<td>210</td>
<td>330</td>
<td>270</td>
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<tr>
<td>5</td>
<td>Ne III</td>
<td>2s^22p^4-2s^22p^23s</td>
<td>215</td>
<td>305</td>
<td>240</td>
</tr>
<tr>
<td>6</td>
<td>Ne III</td>
<td>2s^22p^4-2s^22p^23s</td>
<td>310</td>
<td>470</td>
<td>380</td>
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<tr>
<td>7</td>
<td>Ne III</td>
<td>2s^22p^4-2s^22p^23s</td>
<td>240</td>
<td>360</td>
<td>220</td>
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<tr>
<td>8</td>
<td>Ne III</td>
<td>2s^22p^4-2s2p^5</td>
<td>430</td>
<td>660</td>
<td>300</td>
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<td>9</td>
<td>Ne III</td>
<td>2s^22p^4-2s2p^5</td>
<td>430</td>
<td>680</td>
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<td>10</td>
<td>Ne II</td>
<td>2s^22p^5-2s^22p^43d</td>
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<td>730</td>
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<td>490</td>
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<td>340</td>
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<td>12</td>
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<td>2s^22p^5-2s^22p^43s</td>
<td>350</td>
<td>400</td>
<td>-</td>
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<tr>
<td>13</td>
<td>Ne II</td>
<td>2s^22p^5-2s^22p^43s</td>
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<td>830</td>
<td>270</td>
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<tr>
<td>15</td>
<td>Ne II</td>
<td>2s^22p^5-2s^22p^43s</td>
<td>680</td>
<td>920</td>
<td>370</td>
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<tr>
<td>16</td>
<td>Ne II</td>
<td>2s^22p^5-2s2p^6</td>
<td>3100</td>
<td>3760</td>
<td>1040</td>
</tr>
</tbody>
</table>
Low $T_e$ Tungsten spectroscopy

- W is introduced in the plasma by operating the PID with Ar gas and W electrodes (or CuW electrodes). Ar gas is used instead of Ne as the increased mass causes W sputtering into the plasma.
- While the operation with Ne gas provides a bulk $T_e \sim 2.5$ eV, operation of PID with Ar gas provides a slightly lower $T_e \sim 1$ eV.
- W spectroscopy at such low $T_e$ is relevant to the boundary where W is introduced into the magnetic fusion devices.
- Low charge states of W are difficult to model and have not been studied extensively in experiments or theory. W I and W II oscillator strengths were determined in a hollow cathode discharge (Kling et al. 1998, 1999). We report measurements of W III, and possibly W IV emission in a 1 eV plasma. W III (and possibly W IV) lines were identified by comparison with measurements on a sliding spark discharge (Iglesias et al. 1985, 1989).
CuW + Ar experiments – visible spectrum

High resolution optical spectrum confirms presence of W I, W II. No emission from higher charge states of W was measured in the visible spectrum.
At the bulk $T_e \sim 1$ eV, only $\text{Ar I-II, W I-III}$ are expected to be populated.
W III emission is observed mostly in the 1600-2000 Å region. Example of Δn=0 transitions shown with increasing $I_p$. Some unidentified transitions and transitions which can possibly be attributed to W IV were also observed in the discharge. Enabling, higher $T_e$ should lead to higher charge states of W.
The C-He discharge is an example that low Z plasma facing components can be monitored on the Penning. Absence of CIII emission indicate $T_e \sim 1$ eV.
The plasma spectroscopy group at JHU specializes in developing SXR, XUV, VUV diagnostics.

Transmission grating based spectrometers with CCD detection (Princeton Instruments PIXIS) have been tested with XUV (d=2000 Å) and VUV (d=1 µm) gratings.

The spectrometers operate in a survey mode. Binning the pixels on the detector exploits the trade off between high spectral resolution and high spatial/time resolution. See the XUV spectrum from Ne-Al operation of Penning on the next slide.
No binning
3 s exposure

15x spatial binning
10 ms exposure

15x spatial binning
15x spectra binning
1 ms exposure
TGIS upgrade for NSTX 2011: fast readout

Image readout using a lens coupled CCD camera enables Time response ~ 10 ms. Sample spectra from PID with 10 ms exposure is shown above.

Ne I 736 Å
Ne II 461 Å
Conclusions

- A Penning Ionization Discharge (PID) is suitable for studying low $T_e$ spectrum from W, relevant to divertor and near wall conditions.
- The PID was operated with $n_e \sim 10^{13} \text{ cm}^{-3}$, and bulk $T_e \sim 2 \text{ eV}$, and possibly fast electrons at 10s of eV. A wide range of elements have been studied under these conditions – C, Ne, Al, Ar, Cu, W.
- W spectrum was obtained by operating the PID with Ar gas and electrodes made of W (or 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) and the emission lines are visible in VUV.
- The current in the experiments with Ar-W was limited by plasma instabilities. Current in a Penning discharge is determined by cross field diffusion of electrons to the anode. Modifying the magnetic field and/or the anode geometry may lead to higher currents. Increasing the current may populate higher W charge states.
- For better bulk $T_e$ estimates, construction of a Langmuir probe is planned.
- It is not clear why Ar discharges with similar I-V characteristics have smaller $T_e$ than Ne discharges.
EXTRA SLIDES
References


*Template from NSTX presentation template.*