Application of atomic data to quantitative analysis of tungsten spectra on EAST tokamak

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Outline

• **Background of W spectroscopy in EAST**
  • Upgrade of PFCs on EAST
  • W spectroscopy in EAST

• **W spectra measurement**
  • Hardware development (EUV spectrometers)
  • Line analysis of W spectra at low/high $T_e$
  • Space-resolved measurement of W spectra at high $T_e$

• **Quantitative analysis of W spectra**
  • In-situ absolute intensity calibration
  • Methods for evaluation of W concentration
  • Required atomic data
  • W concentration in steady-state H-mode discharge

• **Summary & Future work**
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Upgrade of Plasma Facing Components on EAST

FW: TZM (Titanium-Zirconium-Molybdenum) alloy
Upper divertor: ITER-like W/Cu monoblock
Lower divertor: SiC/C

Wall conditioning;
- Li coating, Si coating, B coating
- He-GDC, D₂-GDC

Gas puffing for diagnostics; Ar, He

Intrinsic & extrinsic impurities;
- He, Li, B, C, N, O, Si, Ar, Cr, Fe, Ni, Cu, Mo, W...
• ITER has adopted tungsten as the divertor material for the D-T operation.

• Impurity transport of tungsten in long pulse discharges is a crucial issue for both the EAST and ITER.
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Hardware development: EUV spectrometers (1)
(Grazing incidence flat-field spectrometers)

• Two EUV spectrometers at longer wavelength range (20-500Å);
  **EUV_Long**: spectral measurement with fast response
  **EUV_Long2**: space-resolved measurement
  − Slit width: 30μm/100μm (EUV_Long/EUV_Long2 with spatial resolution slit)
  − Varied line spacing groove concave holographic grating: 1200g/mm
  − Back-illuminated CCD (size: 26.6x6.6mm², number of pixels: 1024x255)
    − EUV_Long: 1024 (horizontal) spectral measurement, 255 (vertical) full binning
    − EUV_Long2: 255 (horizontal) spectral measurement, 1024 (vertical) space-resolved measurement

• One EUV spectrometer at shorter wavelength range (10-130Å)
  **EUV_Short**: spectral measurement with fast response
  − Slit width: 30μm
  − Varied line spacing groove concave holographic grating: 2400g/mm
  − Back-illuminated CCD (size: 26.6x6.6mm², number of pixels:1024x255)
    − 1024 (horizontal) spectral measurement
    − 255 (vertical) full binning

• **Pulse motor** for wavelength scan
• **Laser light** for optical alignment
• **Turbo-molecular pump** for vacuum system
Hardware development: EUV spectrometers (2) (Grazing incidence flat-field spectrometers)

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Field of view</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUV_Long 20-500Å</td>
<td>Vertical 30cm, Toroidal 5cm</td>
<td>Time 5ms, Space -</td>
</tr>
<tr>
<td>EUV_Short 10-130Å</td>
<td>Vertical 50cm, Toroidal 4cm</td>
<td>Time 5ms, Space -</td>
</tr>
<tr>
<td>EUV_Long2 20-500Å</td>
<td>Vertical 50cm, Toroidal 7cm</td>
<td>Time ~50ms, Space 2-3cm</td>
</tr>
</tbody>
</table>
Line analysis of W spectra at low $T_e$

• W spectra can not be generally observed in L-mode plasmas at low heating power.

The following W spectra are recorded after sudden drop of tungsten dust from upper divertor.

• $T_e(0)=1.0$keV, $n_e=3.5 \times 10^{19}$m$^{-3}$: USN, L-mode, $P_{LHCD}=0.5$MW, $B_t=2.25$T, $I_p=500$kA, downward $\nabla B$

- Tungsten UTA (unresolved transition array) at 15-70Å is observed by EUV_Short with high spectral resolution.
- UTA at 15-35Å can be compared with CoBIT data.

- $2^{nd}$ order tungsten lines at 90-120Å can be easily identified from UTA with high spectral resolution.
- Quantitative analysis of UTA is difficult.
Line analysis of W spectra at higher $T_e$

- W spectra are always observed with strong intensity in USN H-mode discharges. Additional 4.6GHz LHW and ECRH heating increase the $T_e$ higher than 2.5keV. Then, highly ionized W ions of $W^{40+}$ to $W^{45+}$ can be easily measured with strong intensity. The following W spectra are recorded during ELM-free H-mode phase.

- $T_e(0)=2.6$keV, $n_e=3.7 \times 10^{19}$m$^{-3}$ : USN, $P_{LHW}/P_{ICRH}/P_{ECRH}=2.1/1.4/0.4$MW, $B_t=2.25$T, $I_p=450$kA, downward $\nabla B$

- $W^{40+}$ - $W^{45+}$ lines with strong intensity are identified from the UTA.
- Weak isolated $W^{42+}$ - $W^{45+}$ lines at longer wavelength range are also measured

\[ W^{43+} (E_i=2.210$keV) 4s^24p \quad 4p-4s (61.334, 126.299Å) \]
\[ W^{44+} (E_i=2.354$keV) 4s^2 \quad 4p-4s (60.93, 132.888Å) \]
\[ W^{45+} (E_i=2.414$keV) 4s \quad 4p-4s (62.336, 126.998Å) \]
Space-resolved measurement of W spectra at high $T_e$

USN, $P_{LHW2}/P_{ICRH}/P_{ECRH}=2.2/0.6/0.3$ MW, steady-state ELMy H-mode

- The position of peak intensity for different transition from the W ion with the same ionization stage is a little different, e.g. for $W^{43+}$, $W^{45+}$
- The profiles will be used to check the PEC data
- With absolute intensity calibration and Abel inversion, the tungsten density profile could be calculated

Typical $T_e$ and $n_e$ profile
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In-situ absolute intensity calibration for EUV_Long

- Absolute intensity calibration of the EUV spectrometer is necessary for the quantitative analysis of line emissions and bremsstrahlung continuum.
- Absolute intensity calibration at 20-150Å: comparison of bremsstrahlung continua in EUV and visible ranges.
- Relative intensity calibration at 130-300Å: line pairs of 2p-2s/3p-3s transitions of Li and Na-like ions from EAST.

\[ I_{\text{brem}} = \frac{9.5 \times 10^{-20} \Delta \lambda}{4\pi \lambda} \int \frac{g_{\text{eff}} n_e^2 Z_{\text{eff}}}{T_e^{3/2} \exp(12400/T_e \lambda)} \, \text{dl} \, \text{(photons s}^{-1} \text{m}^{-2} \text{Sr}^{-1})} \]

\[ \varepsilon_{\text{brem}_{\text{EUV}}} = \varepsilon_{\text{brem}_{\text{vis}}} \left( \frac{\lambda_{\text{vis}}}{\lambda_{\text{EUV}}} \right)^2 \frac{g_{\text{eff}} \text{EUV}}{g_{\text{eff}} \text{vis}} \times \exp \left[ -\frac{12400}{T_e} \left( \frac{1}{\lambda_{\text{EUV}}} - \frac{1}{\lambda_{\text{vis}}} \right) \right] \]

Candidate line pairs in EAST plasma:

<table>
<thead>
<tr>
<th>Ion</th>
<th>Ei (eV)</th>
<th>( \lambda ) [Å]</th>
<th>Transition</th>
<th>Intensity ratio</th>
<th>Sensitivity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe XXIV</td>
<td>2046</td>
<td>192.03</td>
<td>1s(^2)2s(^1)S(<em>{12})-1s(^2)2p(^1)P(</em>{32})</td>
<td>1.91</td>
<td>4.38±0.11</td>
</tr>
<tr>
<td>Mo XXXII</td>
<td>1776</td>
<td>127.87</td>
<td>2p(^3)3s(^2)2p(^3)P(_{32})</td>
<td>1.82</td>
<td>5.02±0.13</td>
</tr>
<tr>
<td>Cr XXII</td>
<td>1722</td>
<td>223.02</td>
<td>1s(^2)2s(^1)S(<em>{12})-1s(^2)2p(^3)P(</em>{32})</td>
<td>1.93</td>
<td>3.39±0.11</td>
</tr>
<tr>
<td>Ar XVI</td>
<td>918</td>
<td>353.85</td>
<td>1s(^2)2s(^1)S(<em>{12})-1s(^2)2p(^3)P(</em>{32})</td>
<td>1.97</td>
<td>2.21±0.07</td>
</tr>
<tr>
<td>Fe XVI</td>
<td>489</td>
<td>335.41</td>
<td>2p(^3)3s(^2)2p(^3)P(_{32})</td>
<td>1.95</td>
<td>1.66±0.10</td>
</tr>
</tbody>
</table>

*Ref. “K D Lawson et al 2009 JINST 4 P04013”

EUV spectra have to be checked before the calibration whether the metallic impurity is negligible or not because of its large recombination rate.

There is a wavelength gap between Cr XXII and Ar XVI.
Method for evaluation of W concentration (1): using chord-integrated tungsten line intensity

- W concentration, \( c_W = \frac{N_W}{N_e} \) or \( c_W = \frac{n_W}{n_e} \)

- Evaluation of \( c_W \) from chord-integrated line intensity, e.g. \( I_{W^{44+}}^{44} - I_{W^{45+}}^{45} \)

\[
I_{W^{q+}}^{q+} = \int n_{W^{q+}}(l) PEC_{W^{q+}}^{W^{q+}}(l) n_e(l) \, dl
\]

\[
= \int c_W(l) n_e(l) FA_{W^{q+}}^{W^{q+}}(l) \cdot PEC_{W^{q+}}^{W^{q+}}(l) n_e(l) \, dl
\]

\[
= \int c_W f_{c_W}(l) n_e(l) FA_{W^{q+}}^{W^{q+}}(l) \cdot PEC_{W^{q+}}^{W^{q+}}(l) n_e(l) \, dl
\]

\[
c_W = \frac{I_{W^{q+}}^{q+}}{\int f_{c_W}(l) FA_{W^{q+}}^{W^{q+}}(l) PEC_{W^{q+}}^{W^{q+}}(l) n_e^2(l) \, dl}
\]

\( I_{W^{q+}}^{q+} \): measured chord-integrated line intensity from \( W^{q+} \)

\( n_{W^{q+}} \): density of \( W^{q+} \)

\( PEC_{W^{q+}}^{W^{q+}} \): photon emissivity coefficient of line from \( W^{q+} \)

\( n_e \): electron density

\( c_W(r) \): density profile of \( W \), \( c_W(r) = c_W \cdot f_{c_W}(r) \)

\( f_{c_W} \): normalized density profile of \( W \)

\( FA_{W^{q+}}^{W^{q+}} \): fractional abundance of \( W^{q+} \) under ionization equilibrium

Method for evaluation of W concentration (2): using radiation power loss

- The $c_w$ is analyzed for a target shot.
- Calibration shot with similar $T_e$ profile to the target shot is required; a sudden increase in the radiation power loss caused by $c_w$ increase.
- Radiation power loss is measured by bolometer system.

- Cooling rate (Radiation power coefficient):
  \[ L_W(T_e, n_e) = \sum_q L^{q+}_W(T_e, n_e) N_{Wq+} / N_W \]

- Radiation power loss by W:
  \[ P_W = \int L_W(T_e, n_e) n_e(r) n_W(r) \, dV \]

- For calibration shot:
  \[ L_W^{\text{cali}} = \Delta P_{\text{rad}} / (\Delta I_{W-\text{UTA}}^{\text{cali}} / n_e) \]

- For target shot:
  \[ P_W = L_W^{\text{cali}} \cdot (I_{W-\text{UTA}} / n_e) = \int L_W(T_e, n_e) n_e(r) n_W(r) \, dV \]
  \[ = \int L_W(T_e, n_e) n_e^2(r) c_W f_{cW}(r) \, dV \]
  \[ c_W = L_W^{\text{cali}} \cdot (I_{W-\text{UTA}} / n_e) / \int L_W(T_e, n_e) n_e^2(r) f_{cW}(r) \, dV \]

$c_W(r)$: density profile of W, $f_{cW}(r)$: normalized density profile of W

$I_{W-\text{UTA}}$: chord-integrated intensity of W-UTA at 45-70Å
Method for evaluation of W concentration (3): using space-resolved tungsten line intensity

• Density profile of W ions $n_{wq}(r)$, e.g. for $W^{42+}-W^{45+}$, can be obtained from the space-resolved measurement of impurity line intensity.

• Chord-integrated line intensity, e.g. $I_{wq}^{42+} - I_{wq}^{45+}$

\[
I_{wq}^{q+} = \int \varepsilon_{wq}^{q+} dl = \int n_{wq}(l) PEC_{wq}^{q+}(l)n_e(l)dl
\]

• Multi-channel $I_{wq}^{q+}$ (e.g. 64 channels for EUV_Long2)

$I_{wq}^{q+}$: measured chord-integrated line intensity from $W^{q+}$

$\varepsilon_{wq}^{q+}$: emissivity of line from $W^{q+}$

$n_{wq}^{q+}$: density of $W^{q+}$

$PEC_{wq}^{q+}$: photon emissivity coefficient of line from $W^{q+}$
Atomic data (1):
PEC (photon emissivity coef.) of W lines

- ADAS-IC: with J-resolved fine structure energy levels (arf40_ic series)
- ADAS-LS: with J-unresolved LS levels (arf40_ls series)

![Graphs showing PEC for different W ionization stages and emission lines](image-url)
Data from open-ADAS are used in the set of rate equations.

- Effective ionization coefficient (scd50_w.dat)
- Effective recombination coefficient (acd50_w.dat)

Effect of impurity transport should be considered.
Atomic data (3): Tungsten cooling rate

- D Post et al., At. Data Nucl. Data Tables 20(1977) 397
- Open-ADAS
- T Pütterich et al., Nucl. Fusion 50(2010) 025021

LHD experiment & CR model (line emission)

Original ADPAK model: average ion model

Sasaki and Murakami model

Pütterich calculation

Estimation from bolometer measurement
**W concentration in steady-state ELMy H-mode**

- The evaluated C\textsubscript{w} from W\textsuperscript{42+} is one order of magnitude higher than that from other lines.

- The evaluated C\textsubscript{w} is in the range of 5x10\textsuperscript{-6}-3x10\textsuperscript{-5}.

### Table: Concentration Comparison

<table>
<thead>
<tr>
<th>Method</th>
<th>n\textsubscript{W}(0)/n\textsubscript{e}(0)</th>
<th>N\textsubscript{W}/N\textsubscript{e}</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEC</td>
<td>W\textsuperscript{42+} 129.41Å</td>
<td>1.1x10\textsuperscript{-3}</td>
</tr>
<tr>
<td></td>
<td>W\textsuperscript{43+} 61.334Å</td>
<td>4.5x10\textsuperscript{-5}</td>
</tr>
<tr>
<td></td>
<td>W\textsuperscript{43+} 126.29Å</td>
<td>6.3x10\textsuperscript{-5}</td>
</tr>
<tr>
<td></td>
<td>W\textsuperscript{44+} 60.93Å</td>
<td>1.6x10\textsuperscript{-5}</td>
</tr>
<tr>
<td></td>
<td>W\textsuperscript{45+} 62.336Å</td>
<td>1.9x10\textsuperscript{-5}</td>
</tr>
<tr>
<td></td>
<td>W\textsuperscript{45+} 126.998Å</td>
<td>2.4x10\textsuperscript{-5}</td>
</tr>
<tr>
<td>Cooling rate</td>
<td>AIM</td>
<td>4.3x10\textsuperscript{-5}</td>
</tr>
<tr>
<td></td>
<td>Pütterich</td>
<td>5.3x10\textsuperscript{-5}</td>
</tr>
<tr>
<td></td>
<td>ADAS</td>
<td>9.1x10\textsuperscript{-5}</td>
</tr>
</tbody>
</table>
Summary

• Tungsten spectra have been measured in EAST discharges using newly installed EUV spectrometers. Line analysis of tungsten spectra has been done.

• Two Methods for evaluation of tungsten concentration based on the cooling rate of tungsten ions and the PEC of $W^{42+}$ - $W^{45+}$ ions are introduced with the required atomic data.

• The Cw in steady-state H-mode discharge with RF heating is evaluated to be in a range of $5 \times 10^{-6}$ - $3 \times 10^{-5}$ with different methods, while the evaluated Cw from $W^{42+}$ is one order of magnitude larger than that from other lines.

• Vertical profiles of chord-integrated tungsten line intensity have been measured in steady-state H-mode discharges. Further analysis is being now progressed.

Future work

• To measure and identify the emission lines of W ions in longer wavelength range.

• To make closer collaboration on the tungsten study with atomic physicists.

• To study the tungsten transport with combination of quantitative measurement and simulation.
THANK YOU FOR YOUR ATTENTION