Recent Progress on Tungsten Spectroscopy
And Its Data Analysis in Large Helical Device


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IAEA Technical Meeting on Atomic, Molecular and Plasma Material Interaction Data for Fusion Science and Technology
Daejeon Convention Center (DCC), Daejeon, Korea
15 - 19 December 2014

This work was partially supported by the LHD project (NIFS14ULPP010), JSPS KAKENHI Grant Number 23340183 and the JSPS/SRF/NSFC All Friendship Program in the field of Plasma Physics (NSFC No.11305145, SRF No. No.2012KA5000445).

Introduction (I): Requirement for W diagnostics and transport study in ITER

- The following requirement can be solved in LHD.
  1. W diagnostics
     - Line identification
       - Visible: divertor plasma (e.g., W\(^{5+}\))
       - VUV: SOL plasma (e.g., W\(^{5+}\))
       - EUV: edge plasma (e.g., W\(^{5+}\))
     - X-ray: core plasma (e.g., W\(^{5+}\))
     - Density measurement
     - Visible: sputtering at divertor plates
     - VUV: influx at SOL
     - EUV: W density at plasma edge
     - X-ray: W density at plasma core
  2. W transport study
     - Calculation of accurate ionization equilibrium
       - Ionization and recombination coefficients

LHD can accept W pellet injection

- Thin W wire in cylindrical carbon or plastic
- W size: 0.03 - 0.2mm\(^2\) in diameter
- W weight: 9.55x10\(^{-3}\) g - 4.25x10\(^{-2}\) g
- W particles (N\(_W\)): 3.13x10\(^{15}\) - 1.39x10\(^{16}\)
- W average density (N\(_W\)/V\(_LHD\)): 1.04x10\(^{17}\) - 4.64x10\(^{17}\) cm\(^{-3}\)
- V\(_LHD\) LHD plasma volume, N\(_W\)/V\(_LHD\)=0.6x10\(^{17}\) cm\(^{-3}\)

Remarkable benefit of LHD for W spectroscopy:
- Discharge can self-recover, even if T\(_e\) is close to zero.
- LHD can produce the brightest W light source.
- W spectra can be measured at a variety of T\(_e\).

W EUV spectra from LHD in 40-140Å

- W spectra observed with 1200g/mm EUV spectrometer (50-500Å).

W EUV spectra from LHD in 10-70Å

- W spectra observed with 2400g/mm EUV spectrometer (10-100Å).

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Introduction (II): Max. charge state of W

- LHD (neutral beam injection): T\(_e\)=4keV (max. q: W\(^{45+}\))
- ECH (electron cyclotron heating) T\(_e\)<20keV

ITER (max. q: W\(^{39+}\), W\(^{40+}\))
  - T\(_e\), T\(_{99}\)~10-20keV at n\(_e\)>10\(^{11}\)cm\(^{-3}\)
  (Observation of W\(^{39+}\) & W\(^{40+}\) lines is difficult)

W ion behavior after W pellet injection

- After W pellet injection, higher ionization stages of W ions appear as a function of time.
physica scripta by t. oishi et al.,
results will be soon submitted to

are partially ionized \( W^{27+} \).

spectral lines are visible when 4d electrons are partially ionized \( W^{27+} \).

higher \( T_e \) range

\( E=0.881-2.210 \text{keV} \).

4d-4p transition array: \( W^{27+}, 4s^24p3d^{27} \).

lower \( T_e \) range

\( E=0.503-0.881 \text{keV} \).

4f-4d transition array: \( W^{27+}, 4s^24p3d^{27} \).

extreme low \( T_e \) range

pseudo-continuum from 4f-4d transition.

higher \( T_e \) range

\( E=0.54-1.7 \text{keV} \).

4f-4d transition array: \( W^{27+}, 4s^24p3d^{27} \).

polarization also confirmed m1 line: \( W^{27+}, 4s^24p3d^{27} \).

line identification in visible range (i)

w\( ^{19+} , w^{34+} \) in 15-45\( \AA \)

- electron temperature \( (T_e) \) dependence of euv spectra from lhd.
- spectral shape changes largely.
- spectra are composed of \( w^{19+} \) to \( w^{34+} \) ions?
- typical spectrum in 15-35a is analyzed based on euv spectra from cobit.
- cobit: compact ebit

line identification in vuv range (i)

- 3m normal incidence vuv spectrometer
- \( d_x/d_x=0.037\text{Å/pixel} = 2.85 \text{ Å/mm} \) ccd: 13um/pixel \( \times 1024 \) pixels
- euv: no w spectrum at just after pellet.

line identification in vuv range (ii)

495-600\( \text{Å} \)

- our identification agrees with nifs database within 0.1\( \text{Å} \).
- w\( ^{3}ii \) \( (w^{3}) \) is dominant in this wavelength range.

line identification in vuv range (iii)

600-705\( \text{Å} \)

- w\( ^{7}i \) \( (w^{7}) \) is bright.

line identification in visible range (ii)

705-810\( \text{Å} \)

- \( w^{27} \) \( (w^{27}) \) is dominant in this wavelength range.

- \( 810-12200 \text{Å} \)
  - \( w \) \( (w^{27}) \)
  - \( w\) \( (w^{27}) \)
  - \( w\) \( (w^{27}) \)
  - \( w\) \( (w^{27}) \)
  - \( w\) \( (w^{27}) \)

- are dominantly observed.

line identification in visible range (iii)

- \( w^{27} \) m1: \((4f^{2})h_{f}^{-1}h_{i}^{-1} \)
  - centrally peaked profile of visible line confirmed m1 transition

- w\( ^{27} \) m1: \((4f^{2})h_{f}^{-1}h_{i}^{-1} \)
  - centrally peaked profile of visible line confirmed m1 transition

- polarization also confirmed m1 line: \( w^{27} \) 6693\( \text{Å} \).

10/25

12/25

14/25

16/25

9/25

13/25

15/25
Line identification in Visible range (II)

- W plate inserted into plasma edge boundary
- W pellet ablation cloud directly observed
- Ablation cloud: T > 16eV, 10^5 cm^-3
- Several lines denoted with arrows are identified by NIST data table
- W line at 4008Å is not strong

W^{44+} & W^{45+} with simple configuration

- W^{44+}: 4sp P\rightarrow 4s^2 4s^2 (60.93 Å)
  4s^2 P\rightarrow 4s^2 4s^2 (60.93 Å)
- W^{45+}: 4p^2 4s S\rightarrow 6s^2 (126.998 Å)
  4s^2 P\rightarrow 4s^2 4s^2 (126.998 Å)

W (Z=74) density measurement

- Configuration with one or two electrons at outer shell possible for n_\text{in}
  measurement

W^{44+} 4s^2 4s^2 60.93 Å

- Density analysis (I): W^{44+} 4s^2 60.93 Å
  - Local impurity density: n_\text{in} is determined by continuity equation in
    cylindrical geometry.
  - Radial impurity flux: \Gamma_\text{in} is expressed by diffusive/convective model.
  - ADPAK original used in the present study.
- Ionization & recombination coefficients necessary for impurity transport code

W (Z=74) density measurement

- Chord-integrated intensity
- Local emissivity

Density analysis (II): W^{45+} 4p-4s 126.998 Å

- W^{45+} 4p-4s 126.998 Å
  - Estimated W^{45+} 4p-4s 126.998 Å density at plasma center is very similar to
    W^{44+} density at 60.93 Å.

Ionization & recombination coefficients evaluation (I)

- From radial profiles
  - Coefficients can be evaluated from radial profiles of W spectrum and T_c.
  - Problems:
    - W spectrum blended with other ions.
    - Difficulty in Abel inversion.
    - Either recombination or ionization is worse?

Ionization & recombination coefficients evaluation (II)

- From time behavior during T_c recovery phase
  - T_c dependence of W^{44+} is analyzed during T_c recovery phase after W pellet
    injection.
  - Peak intensity of W^{44+} is observed at T_c=2.8keV, whereas the peak abundance of
    W^{44+} is predicted at T_c=4.5keV by the impurity transport code calculation.
Summary

- The brightest W light source can be given by LHD plasmas with W pellet injection.
- W spectra have been successfully observed in EUV, VUV and visible ranges.
  (10: EUV: 600 Å, 300: VUV: 3000 Å, 2500: Visible: 7000 Å)
  - EUV spectra identified for W^{19+} - W^{26+} ions
  - UTA spectrum at 15-35 Å is well analyzed with CoBIT spectra.
  - W^{26+} VUV line found as a new tool for W influx measurement
  - Several W and WII spectra identified and compared with NIST data.
  - Several M1 transitions found in visible and VUV ranges, e.g. W^{26+} 3893.7 Å
- W density measurement is attempted for Zn-like W^{44+} and Cu-like W^{45+} ions.
  W^{44+} density is reasonably obtained as n(W^{44+})/n_e = 1.4x10^{-4}.
- W^{44+} and W^{45+} are applicable to W density measurement.
  - Experimental evaluation of ionization and/or recombination rate coefficients is being attempted with two methods;
  - Radial profile measurement of W ion emissions
  - Temporal behavior of W ion emissions during T_e recovery phase
- Collaboration with our data in LHD highly welcomes.