A Study of tungsten spectra using Large Helical Device and Compact Electron Beam Ion Trap in NIFS

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ICAMDATA-8

8th International Conference on Atomic and Molecular Data and Their Applications

National Institute of Standards and Technology, Gaithersburg, Maryland, USA

30 September - 4 October 2012

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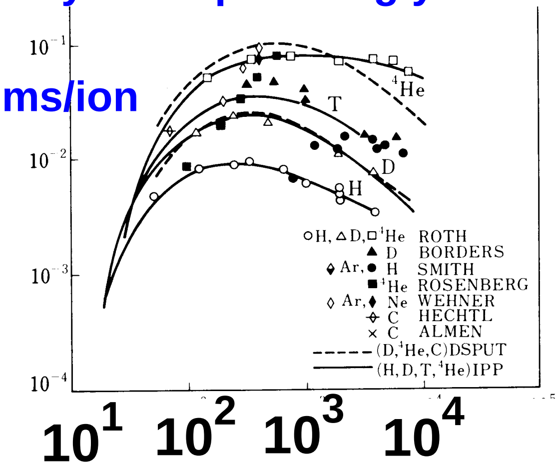
Introduction (I): W in fusion devices

- ITER decided to use W for divertor region instead of carbon.

- Erosion of W
  - 1000 times smaller at 100eV
  - Chemical sputtering of C is bigger than physical sputtering at 800°C.
  - Large erosion increases DUST.

Physical sputtering yield: C

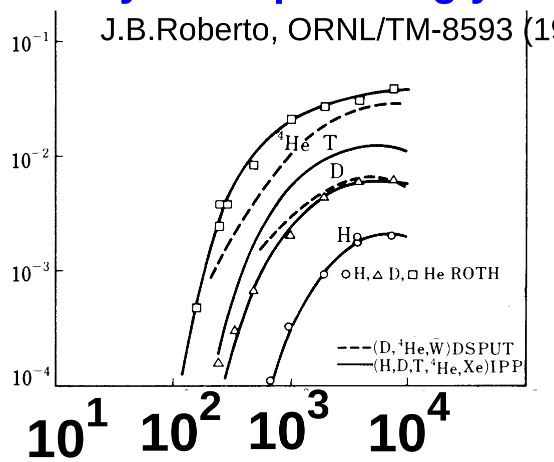
atoms/ion



Ion energy (eV)

Physical sputtering yield: W

J.B.Roberto, ORNL/TM-8593 (1983).

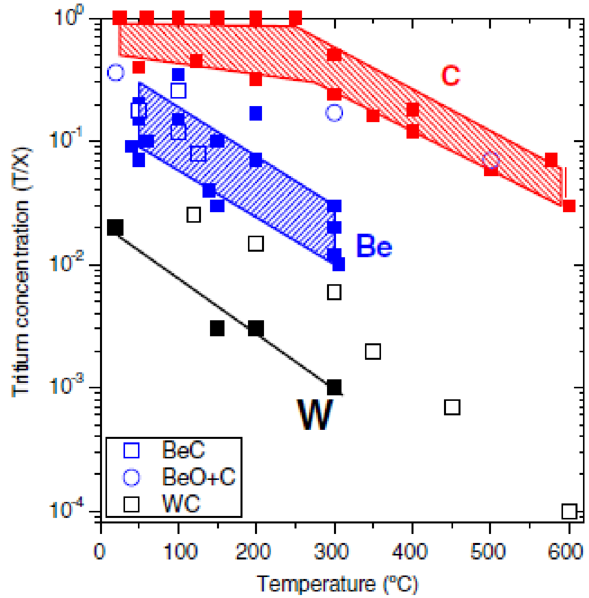


Ion energy (eV)

- Tritium retention of W
  - 1000 times smaller at 300°C.
  - Tritium is absorbed by DUST and cooling water.

Tritium retention (tritium/atom)

J.Roth et al., PPCF 50(2008)103001.

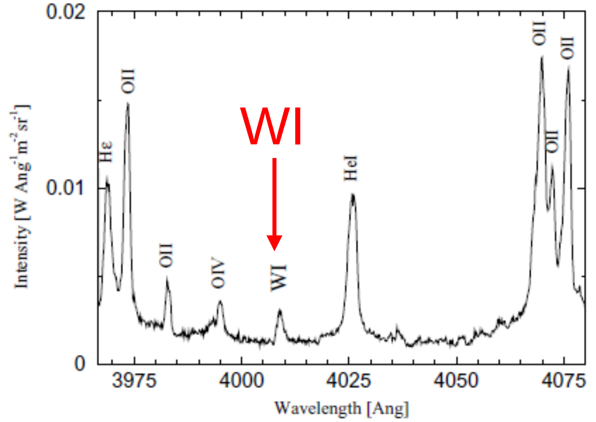


- Demerits
  - Changed into highly radioactive material.
  - Breakable at high temperature.
  - Large radiation loss.

Introduction (II): W diagnostics

- Spectroscopy is only a tool for the study of W transport in fusion plasmas.
- At present the spectral line useful for W diagnostics is only one;

WI (W^{0+}): 4009Å in visible range



- It is quite important to study the W line in fusion research;

  - What kinds of W lines exist in plasmas? (identification of W lines)
  - Which line is useful for the diagnostics of fusion plasma?
  - What is the reliability of existing wavelengths and rate coefficients?

(Study on atomic structure of high-Z elements in relativistic system is of course important)

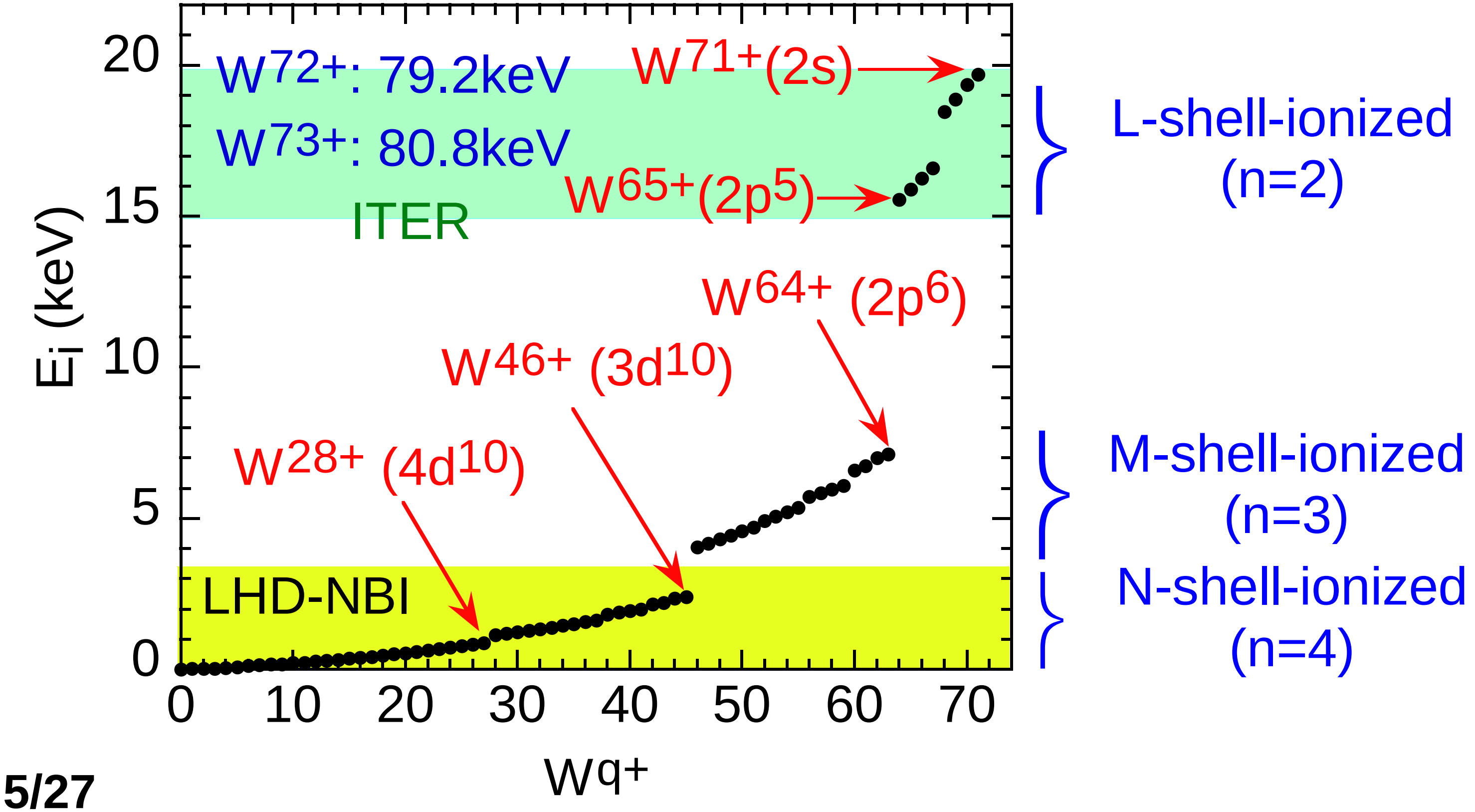
- W study in fusion research is really necessary for a great help of atomic physicists.
- Zn-like WXLV (W^{44+}: $4s^2$), which has a similar configuration of He-like ion, is one of candidates applicable to the fusion plasma diagnostics.

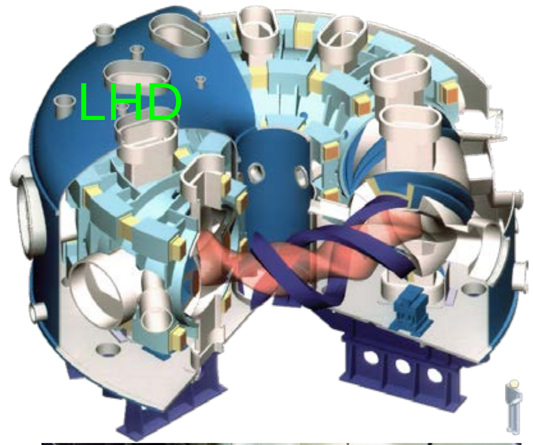
- Preliminary result on W^{44+} is presented with possible quantitative analysis.

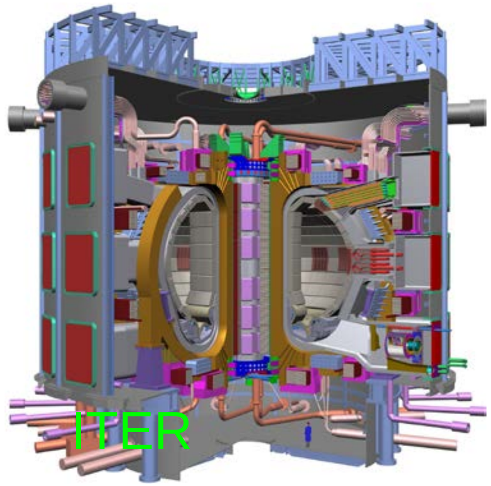
Introduction (III): Max. charge state of W

- LHD
  - NBI (neutral beam injection): T_e<4keV (max. q: W^{46+})
  - ECH (electron cyclotron heating) T_e<20keV

- ITER (max. q: W^{64+} - W^{72+})
  - $T_e \sim T_i \sim$10-20keV at $n_e \sim 10^{14}$cm^{-3}

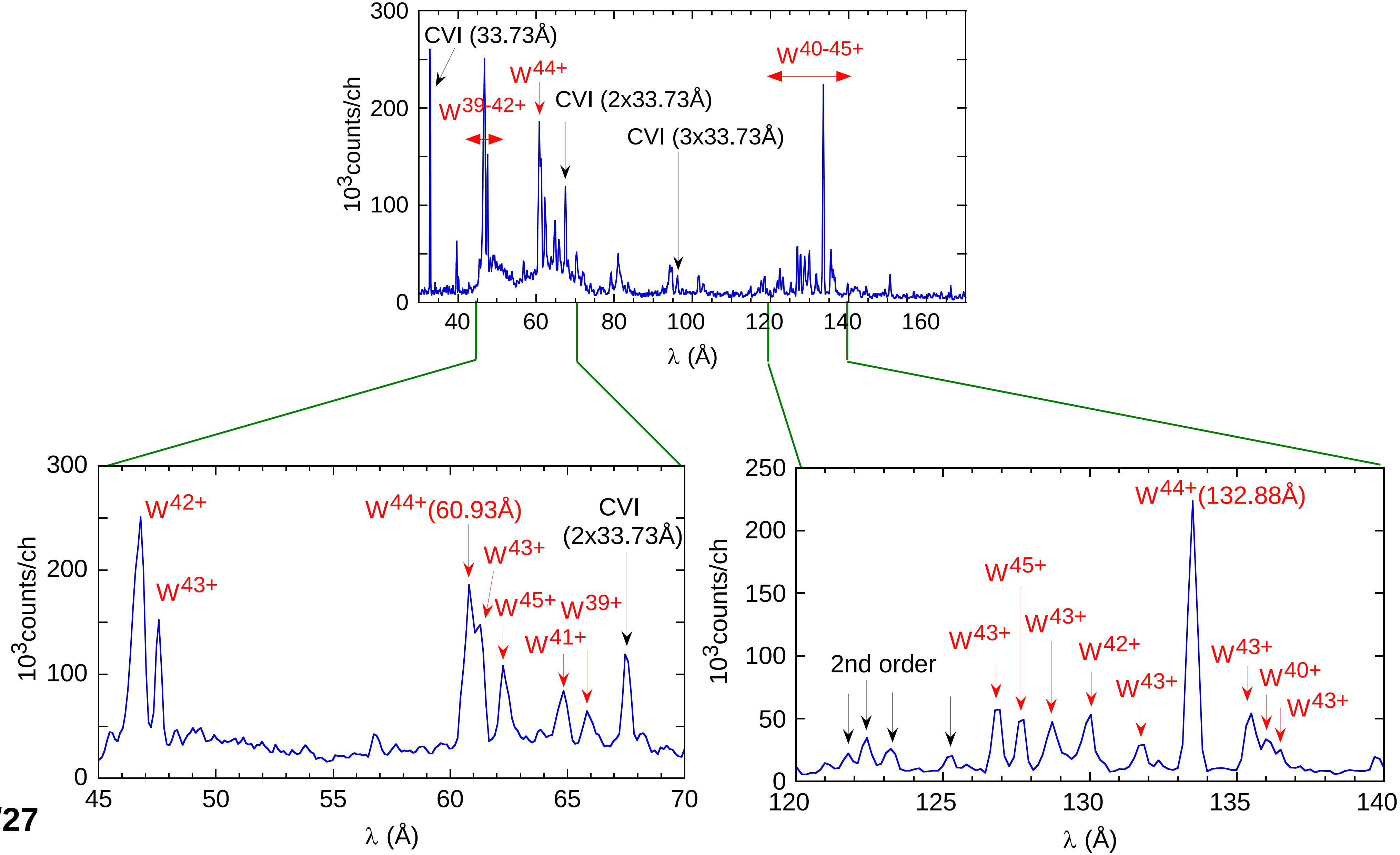






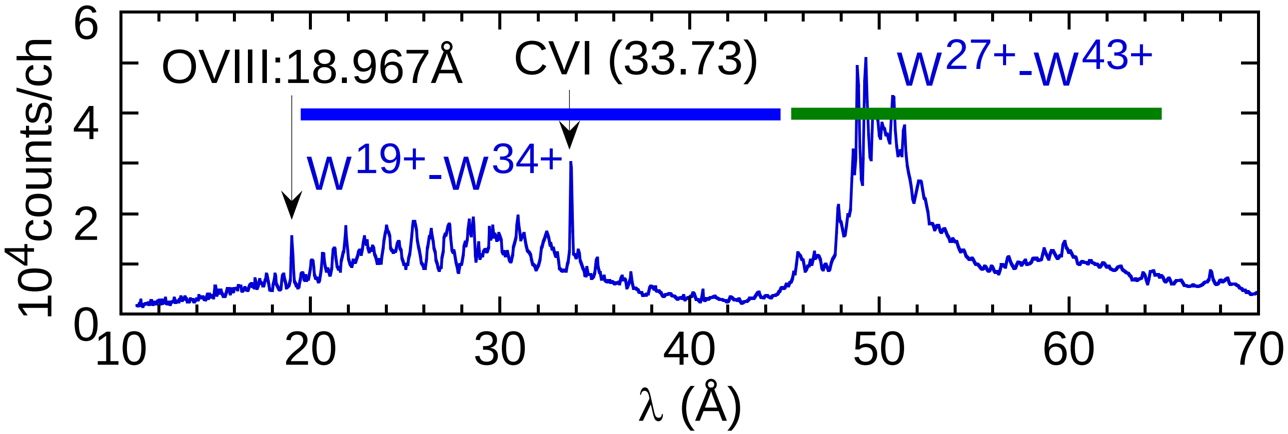
W EUV spectra from LHD in 40-140Å

- 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).



- W^{12+} (E_i=0.258keV) $4s^2 4p^6 4d^{10} 4f^{14} 5s^2$ → Not simple configuration
- W^{15+} (E_i=0.362keV) $4s^2 4p^6 4d^{10} 4f^{11} 5s^2$
- W^{17+} (E_i=0.421keV) $4s^2 4p^6 4d^{10} 4f^{11}$
- W^{19+} (E_i=0.503keV) $4s^2 4p^6 4d^{10} 4f^9$ → 6g-4f (20-40Å), 5g-4f (20-45Å)
- W^{28+} (E_i=1.132keV) $4s^2 4p^6 4d^{10}$ → 5f-4d (18-30Å), 5g-4f (20-45Å), 4f-4d (45-65Å)
- W^{38+} (E_i=1.830keV) $4s^2 4p^6$ → 4d-4p (60-70Å)

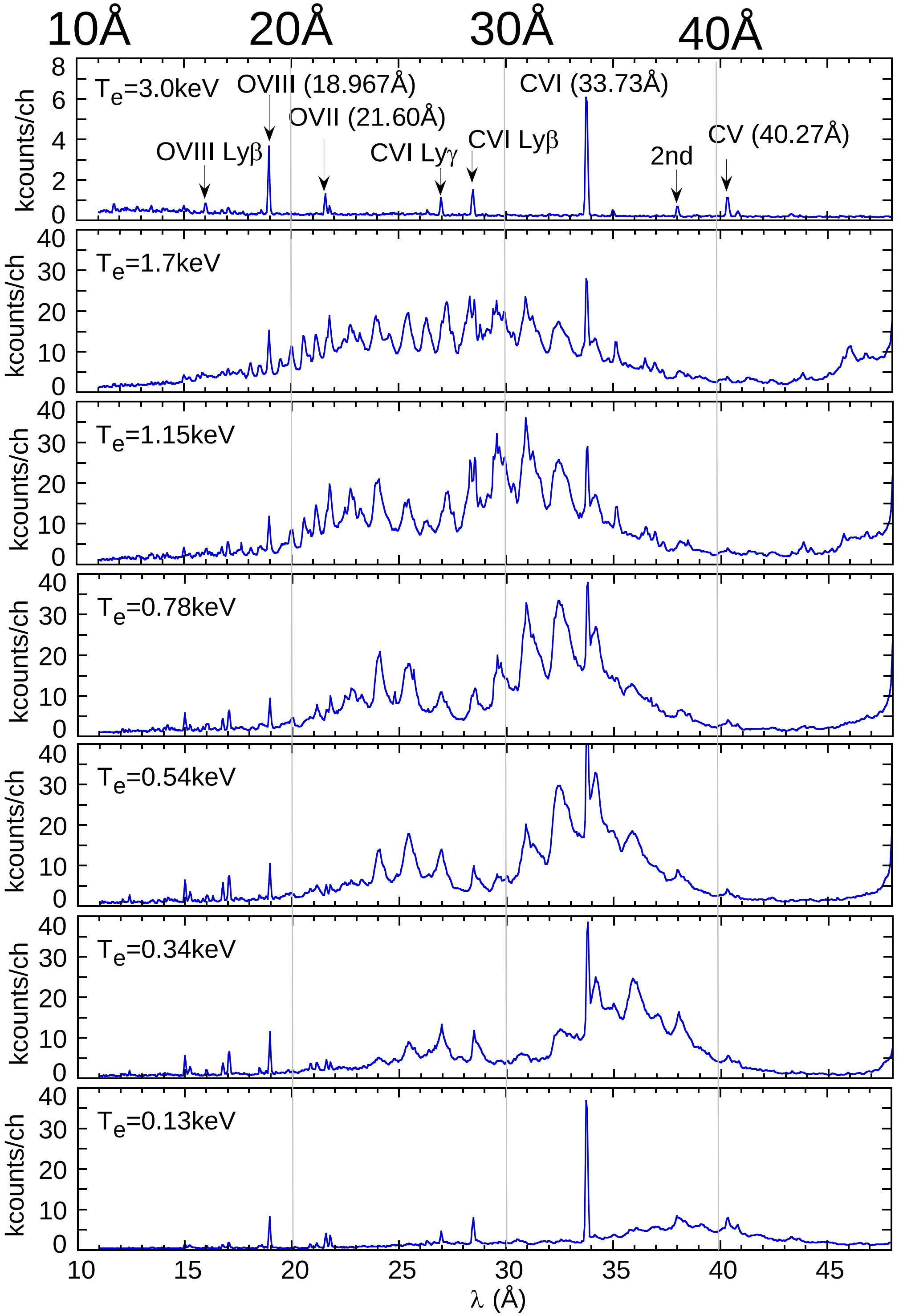
- W^{44+} (E_i=2.354keV) $4s^2$ → 4p-4s (60.93, 132.9Å) →
- W^{45+} (E_i=2.414keV) $4s$ → 4p-4s (62.336, 126.998Å) →

Simple configuration

W^{19+}-W^{34+} in 15-45Å

- 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 15-35Å is analyzed based on EUV spectra from CoBIT.

CoBIT: Compact EBIT



W^{27+}-W^{43+} in 45-70Å

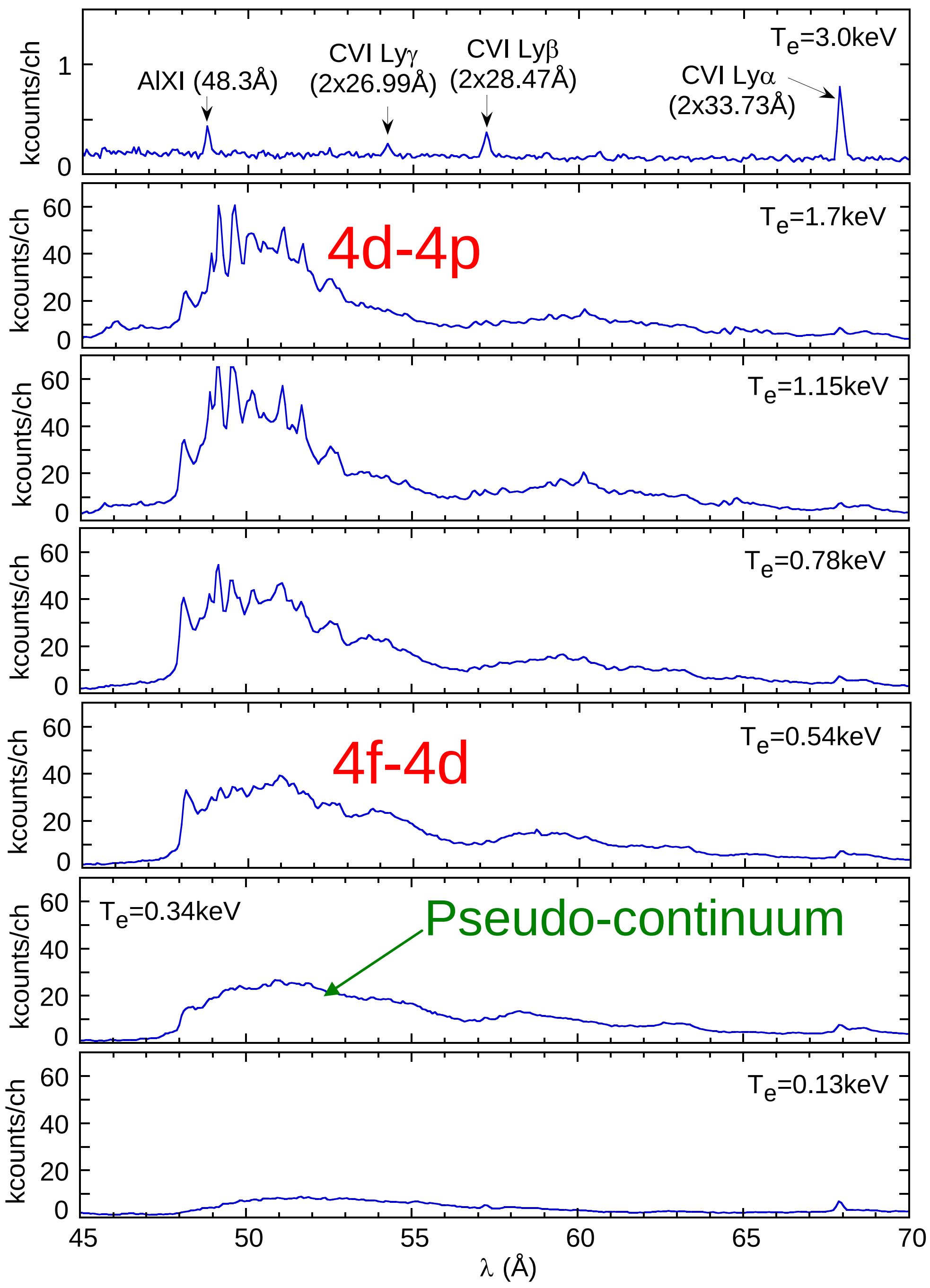
- 4f-4d transition array: W^{19+}-W^{27+}
  E_i=0.503-0.881keV
  Lower T_e range

- 4d-4p transition array: W^{27+}-W^{43+}
  E_i=0.881-2.210keV
  Higher T_e range

- Spectral lines are visible when 4d electrons are partially ionized.
  (E_i=1.132keV for W^{28+} $4s^2 4p^6 4d^{10}$)

- Pseudo-continuum in low T_e discharges will come from 4f-4d transition.

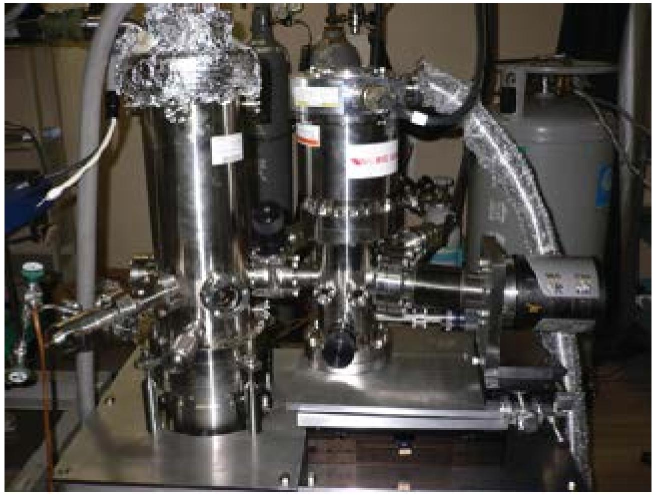
- Application to plasma diagnostics is entirely difficult in these transitions.

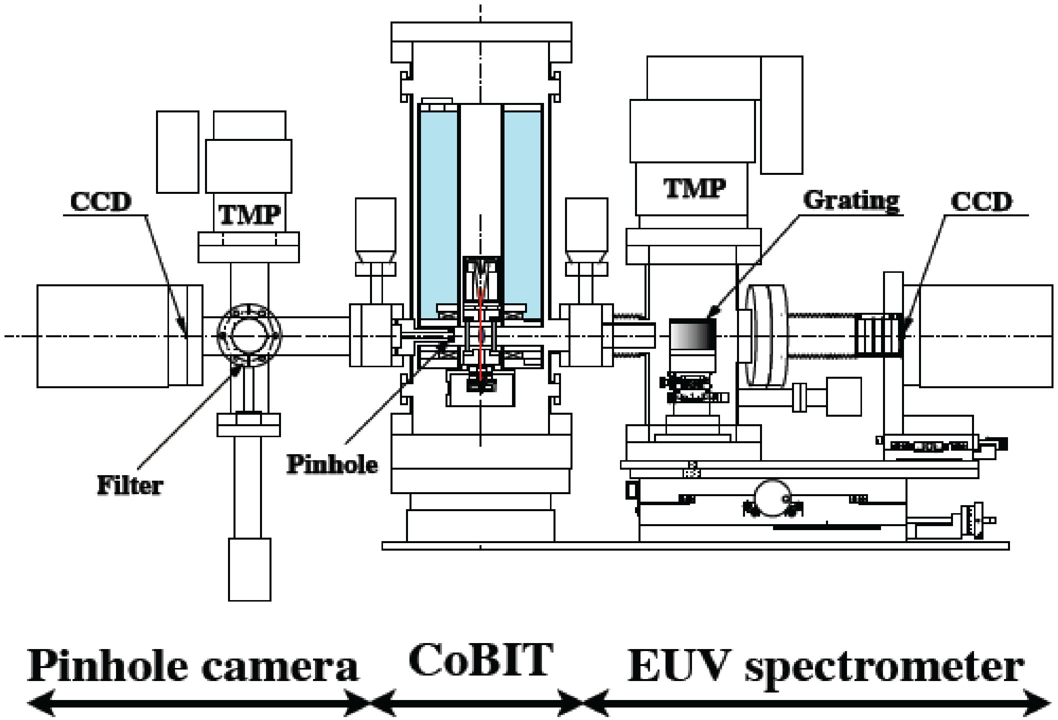


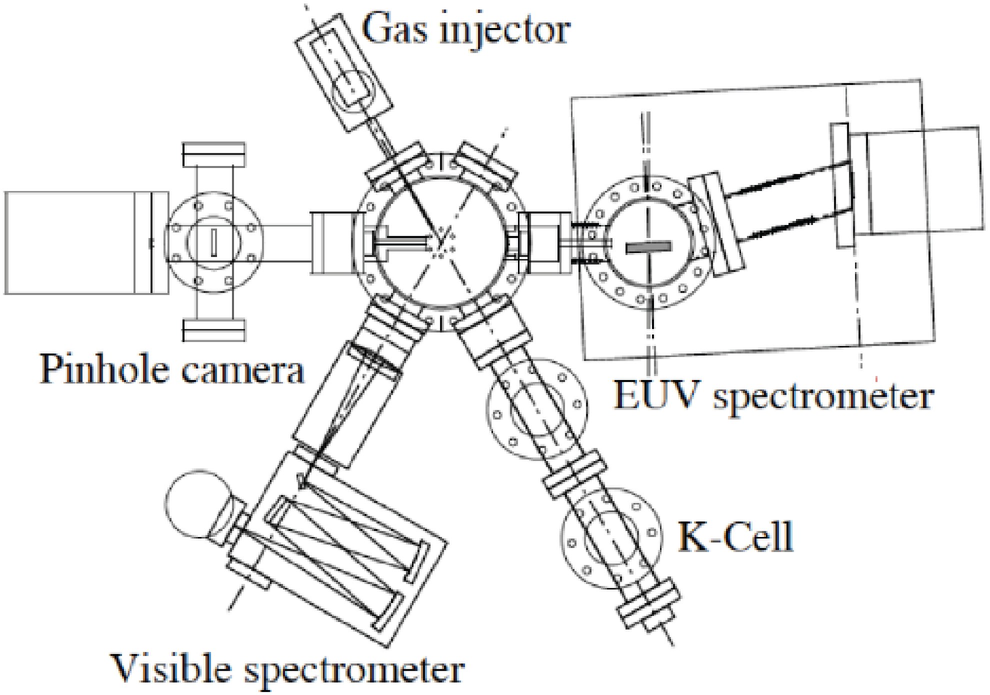
CoBIT (compact EBIT) in NIFS

CoBIT is very compact and easier operatable ion source.

- Electron energy: 0.1-3keV
- Electron current: 10-20mA
- Max. magnetic field: 0.2T operated with Lq. N_2

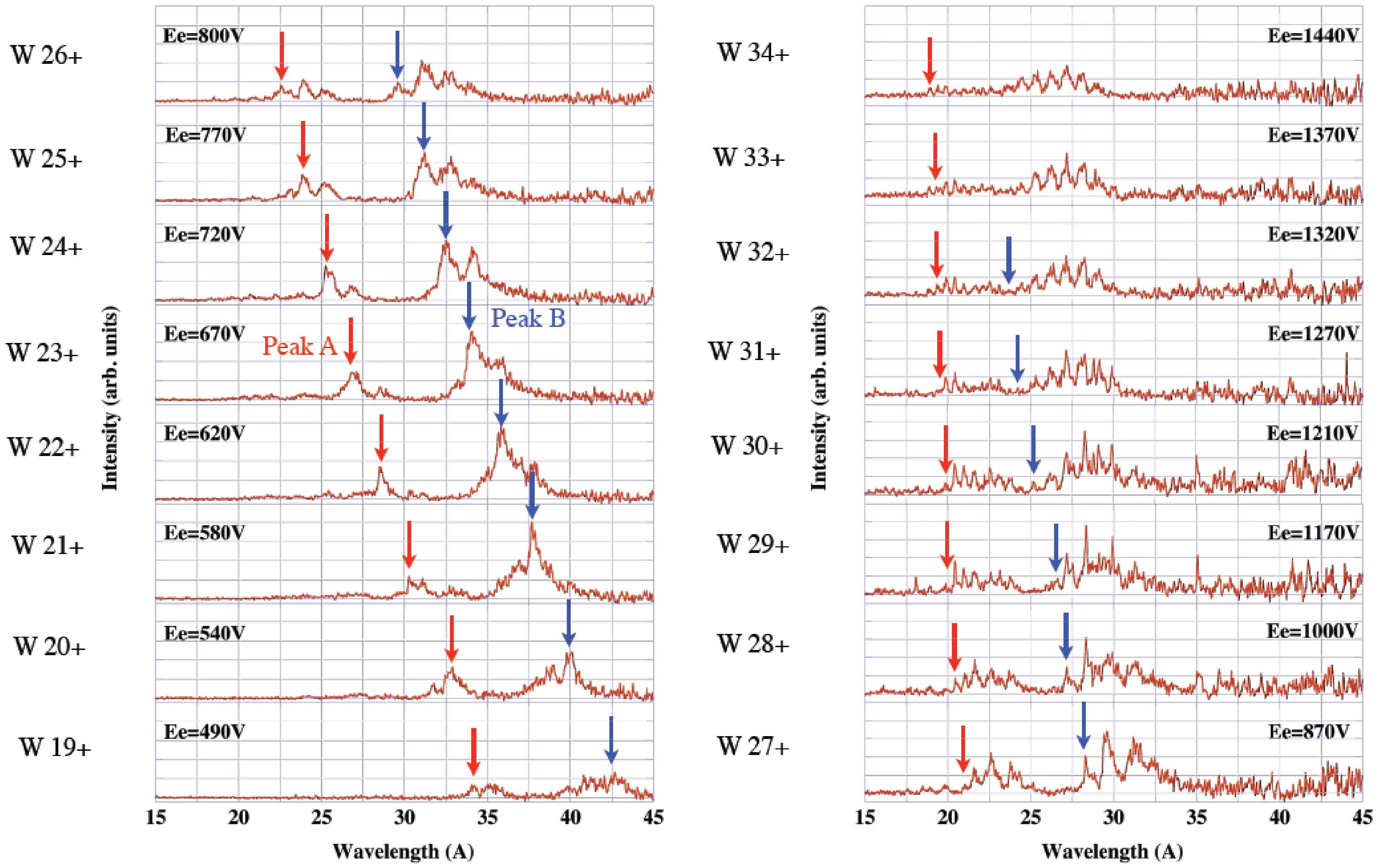






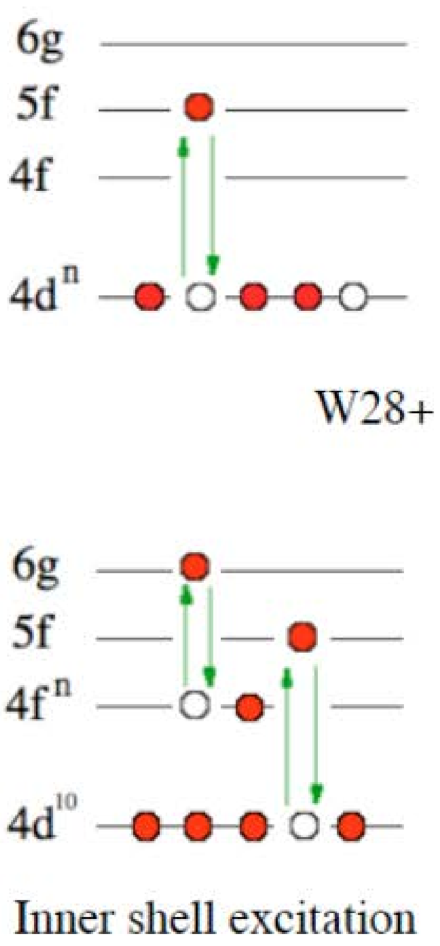
W EUV spectra from CoBIT

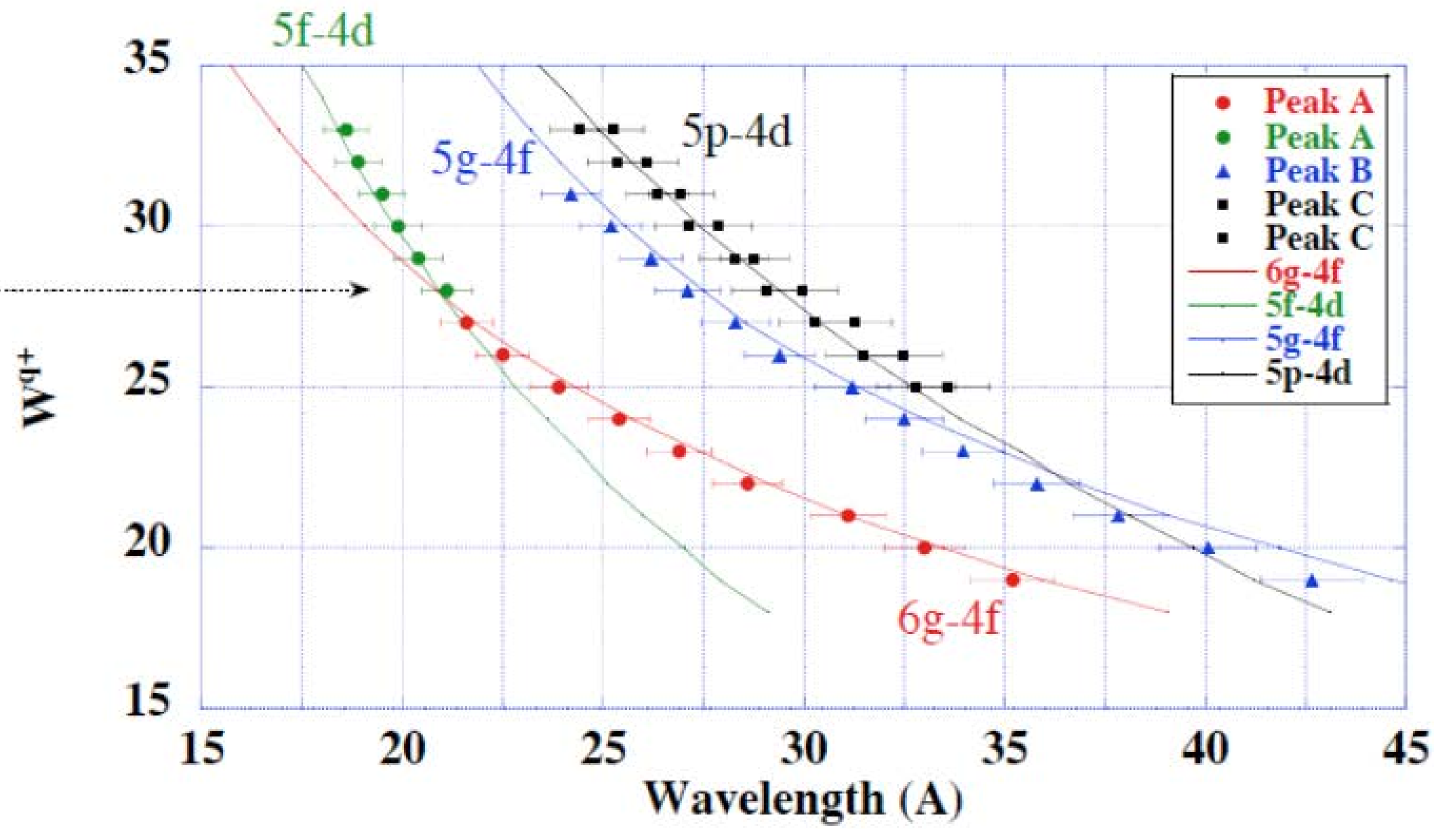
- W spectra are observed with line peak shift for W^{19+} to W^{34+} ions when E_e is changed.



Line peak shift for each transition

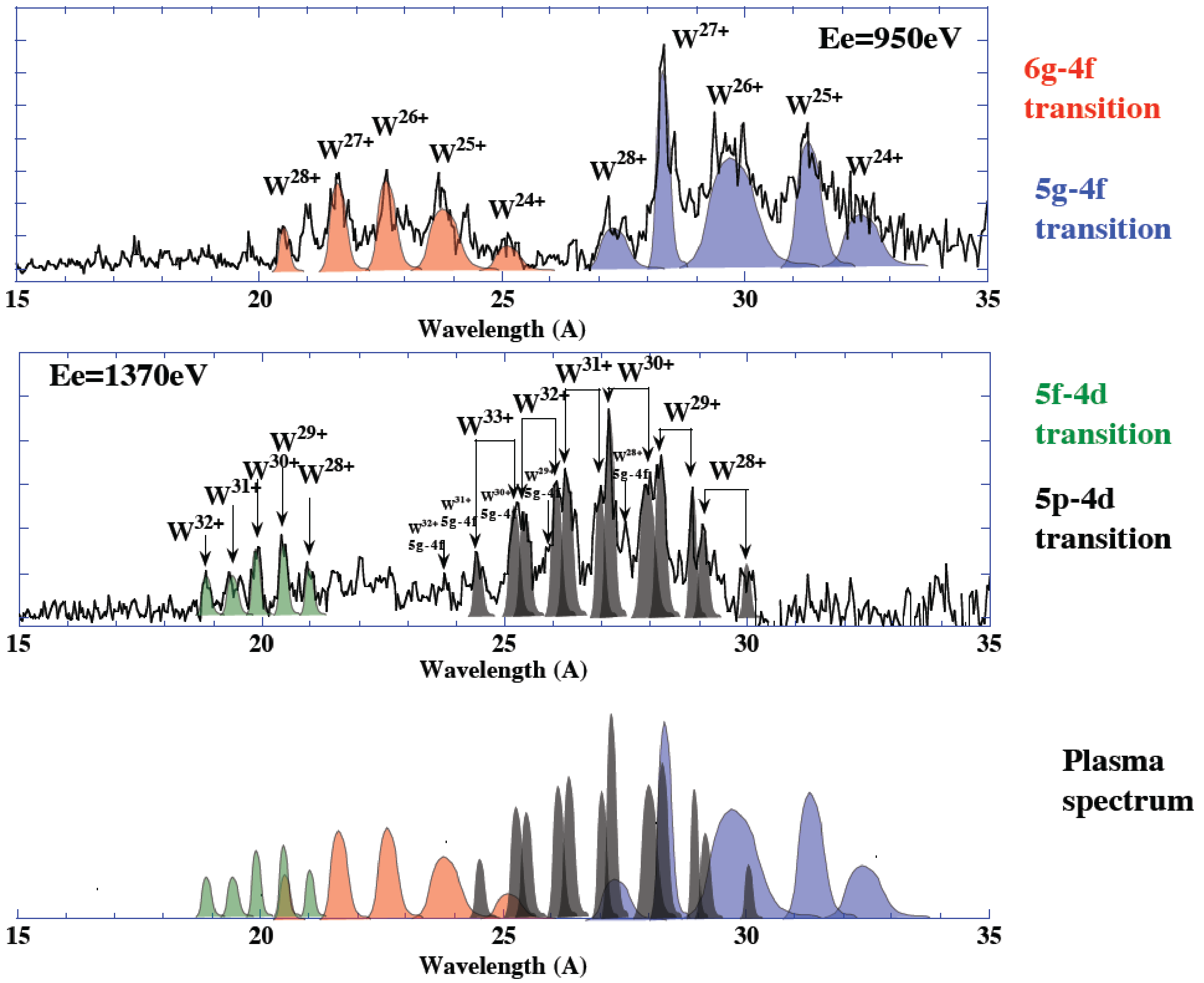
- Peak shift is well explained by C-R model developed with HULLAC code in configuration mode
- Configuration mode: configuration average energy and total angular momentum *J*





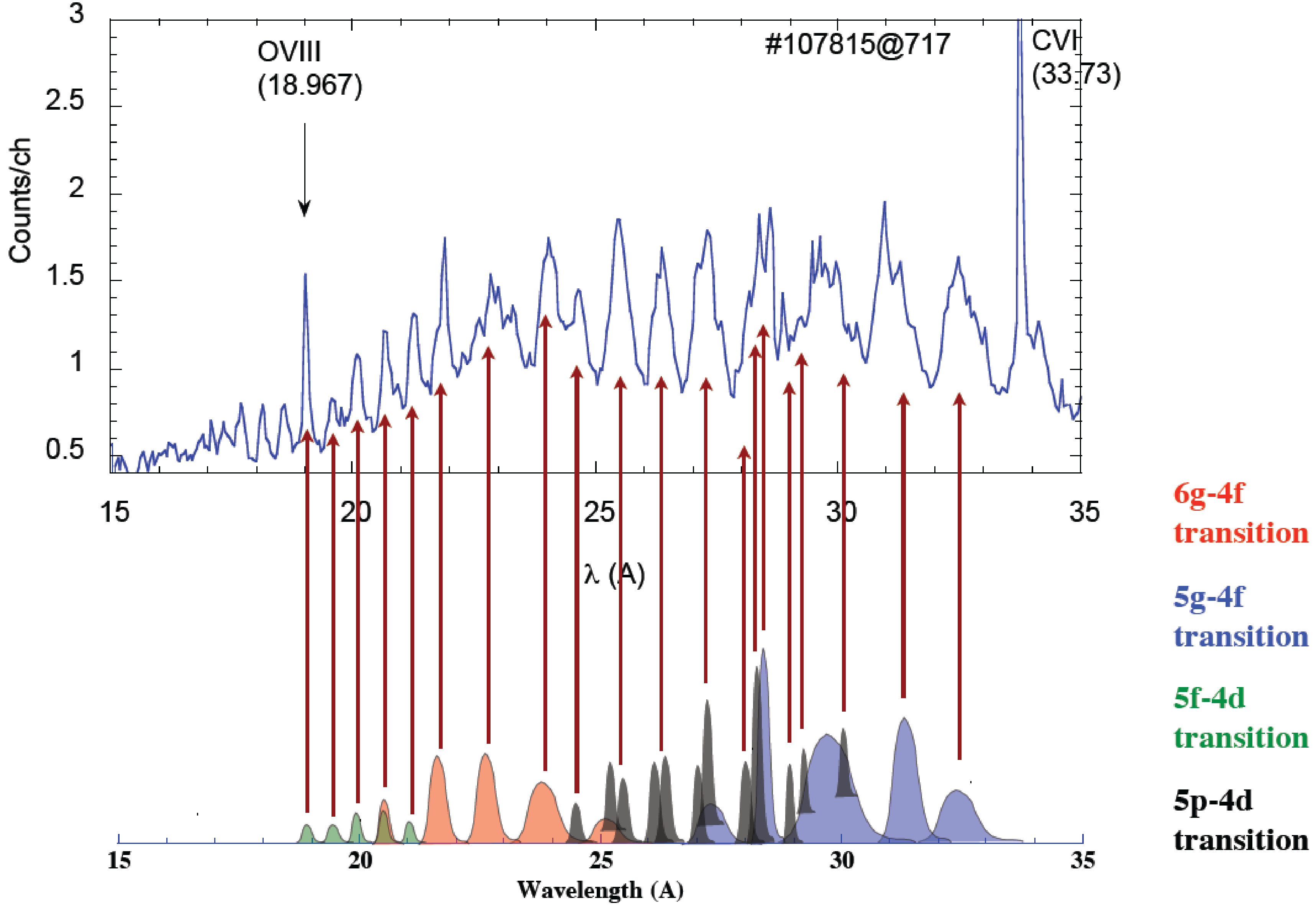
LHD spectrum analysis from CoBIT (I)

- Two CoBIT spectra with different energies of E=950 and 1370eV are considered.
- Analyzed spectral lines are superposed to simulate LHD spectrum.



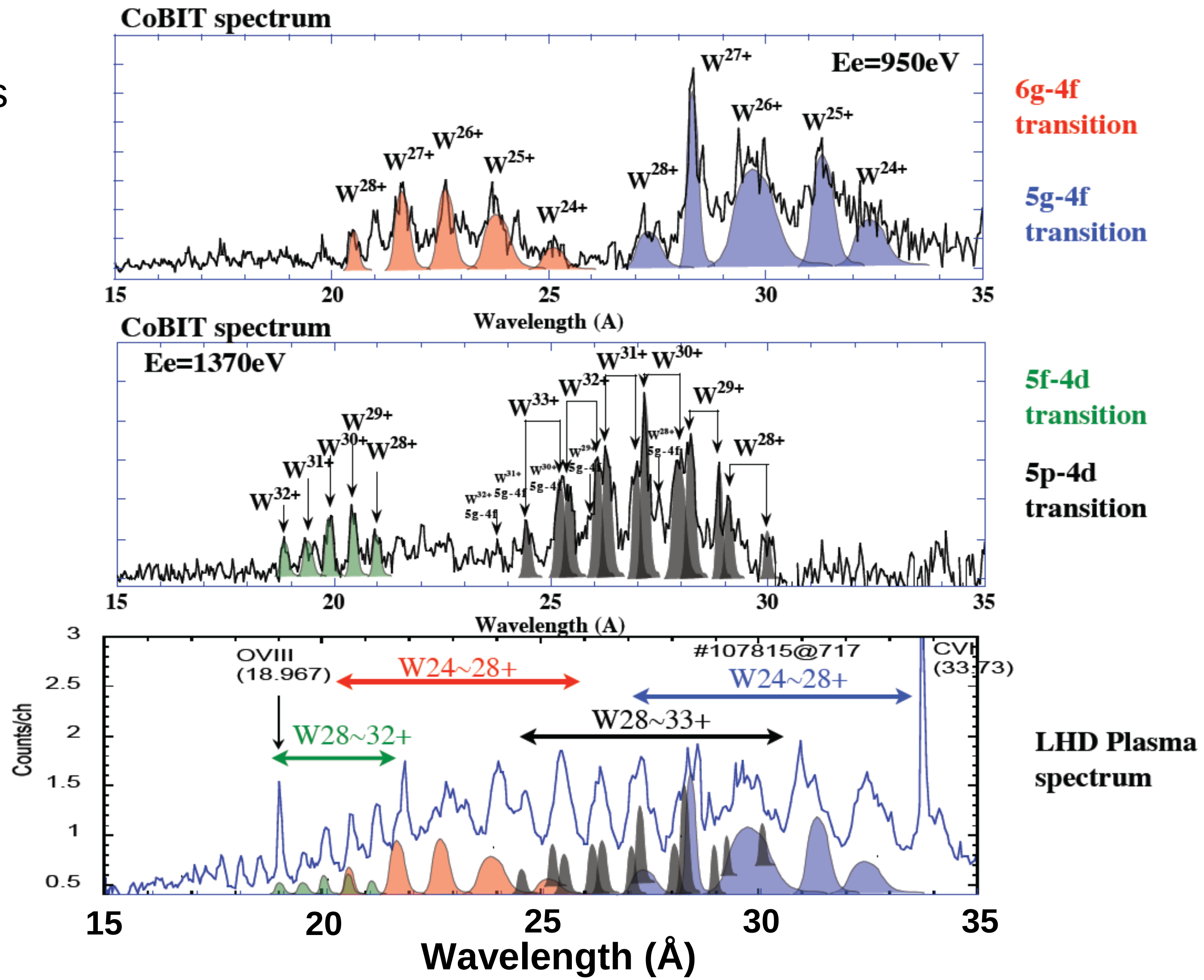
LHD spectrum analysis from CoBIT (II)

- Superposed CoBIT spectrum is compared with LHD spectrum.
- Basic structure of LHD spectrum can be well explained by CoBIT spectrum.



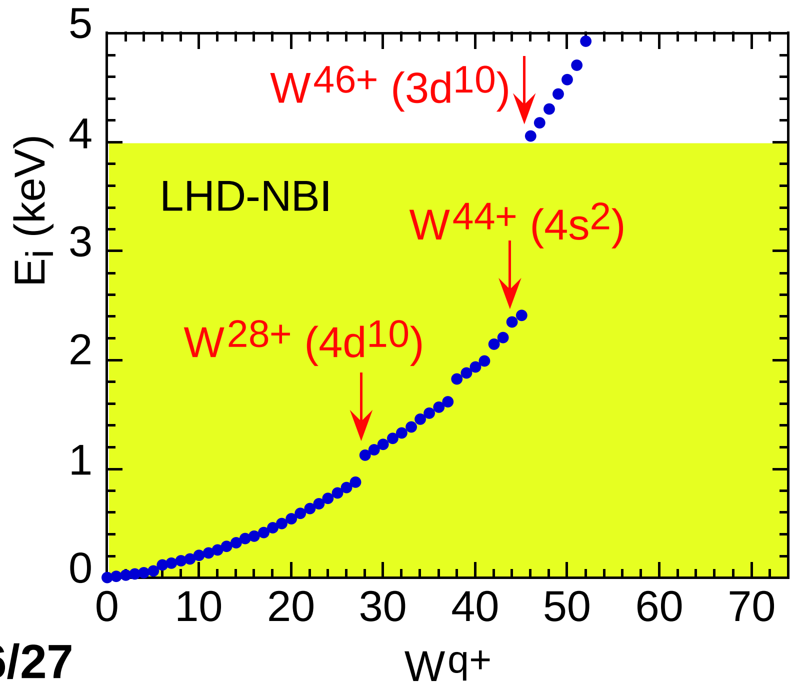
LHD spectrum analysis from CoBIT (III)

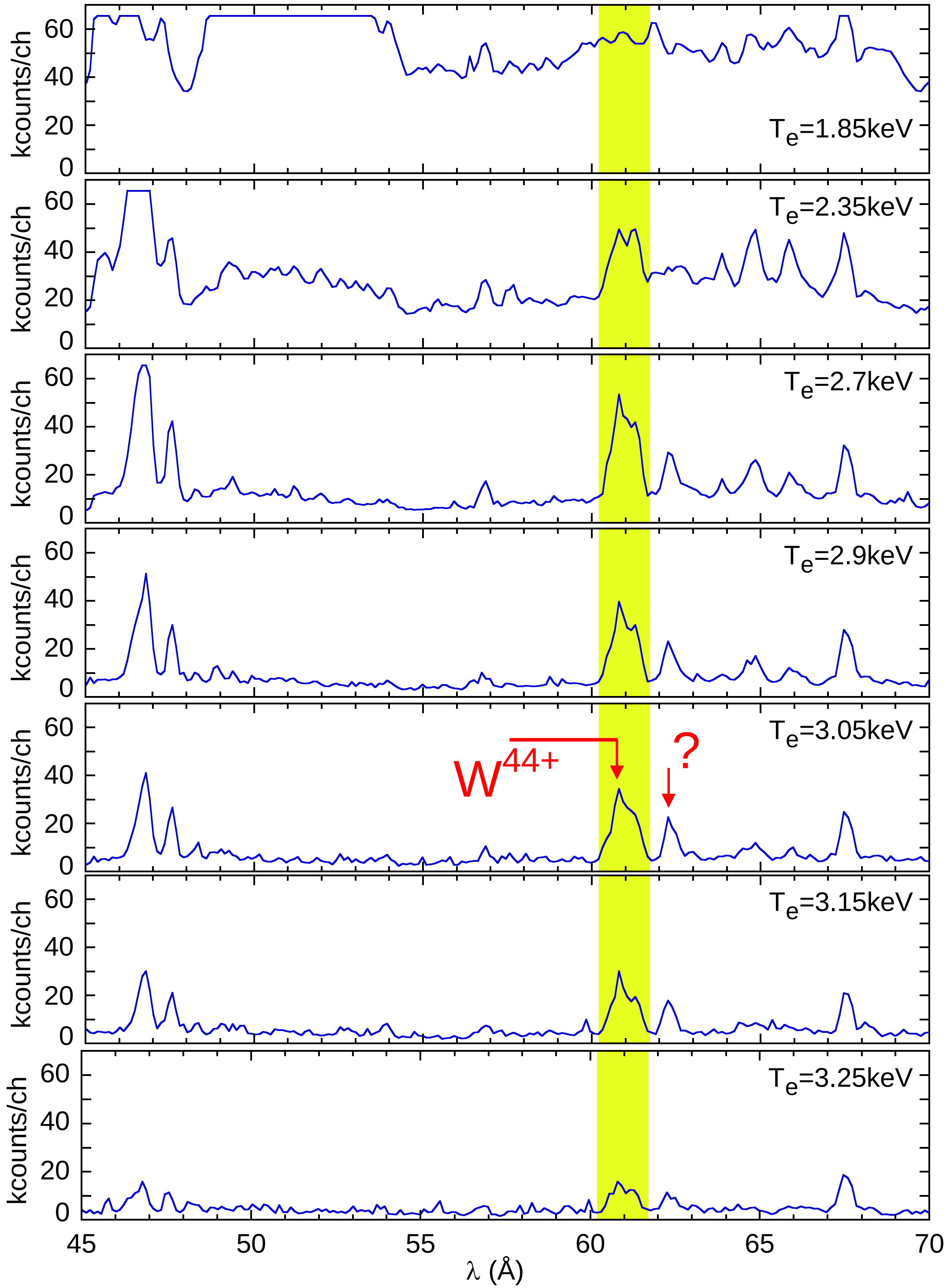
- LHD spectrum in 15-35Å range composes of
  5f-4d of W^{28+}-W^{32+} ions
  6g-4f of W^{24+}-W^{28+} ions
  5p-4d of W^{28+}-W^{33+} ions
  5g-4f of W^{24+}-W^{28+} ions



W^{44+} 4p-4s

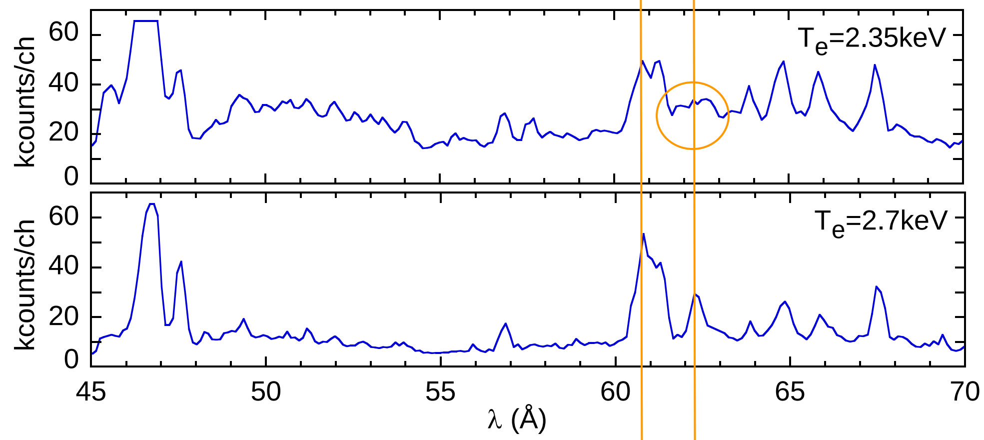
- W^{44+} is visible when $T_e \geq 2.35$keV.
- W^{46+} is the highest ionization stage in NBI discharges of LHD.
- W spectrum from W^{44+} and W^{45+} at plasma core is simple.

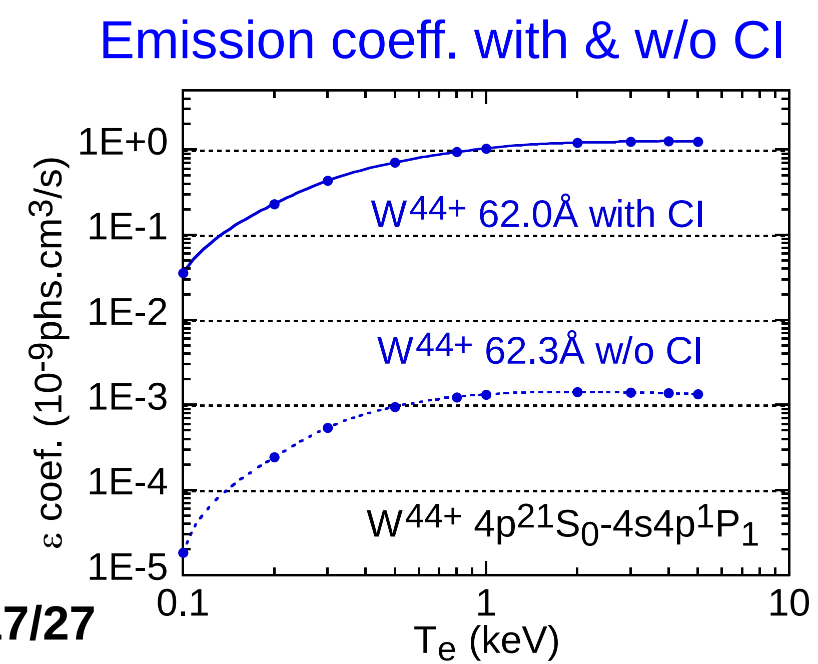


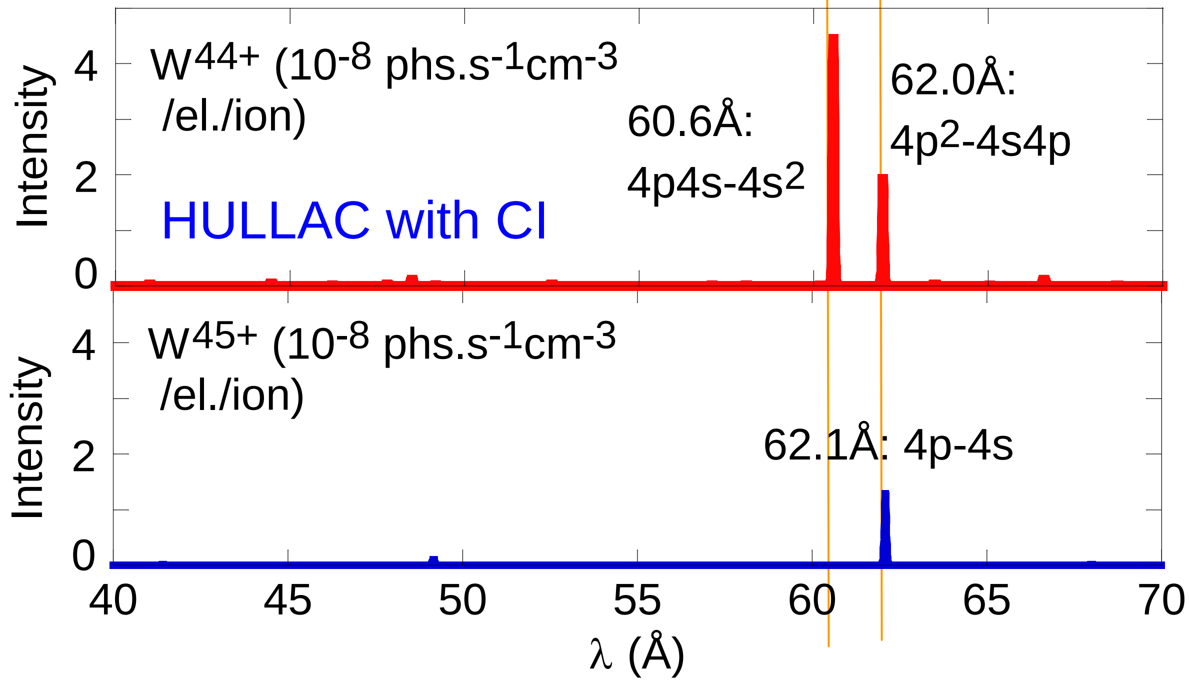


HULLAC code calculation of W^{44+} spectra

- W^{44+} spectra near 60Å are calculated by HULLAC code.
- Configuration interaction between $4s^2\,{}^1S_0$ and $4p^2\,{}^1S_0$ enhances intensity of W^{44+} line $4p^2\,{}^1S_0$ and $4s4p\,{}^1P_1$ at 62.0Å.
- W^{44+} is not observed at 62.0Å in T_e=2.35keV whereas W^{44+} appears at 60.6Å.
- W^{45+} at 62.1Å is visible when T_e is higher (=2.7keV).
- Effect of configuration interaction is not so large for W^{44+} $4p^2$ - 4s4p line at 62.0Å.







Impurity transport code calculation

- Local impurity density, n_q, is determined by continuity equation in cylindrical geometry.

$$\frac{\partial n_q}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_q\right) - \left(\alpha_q + \beta_q\right) n_e n_q + \beta_{q+1} n_e n_{q+1} + \alpha_{q-1} n_e n_{q-1}$$

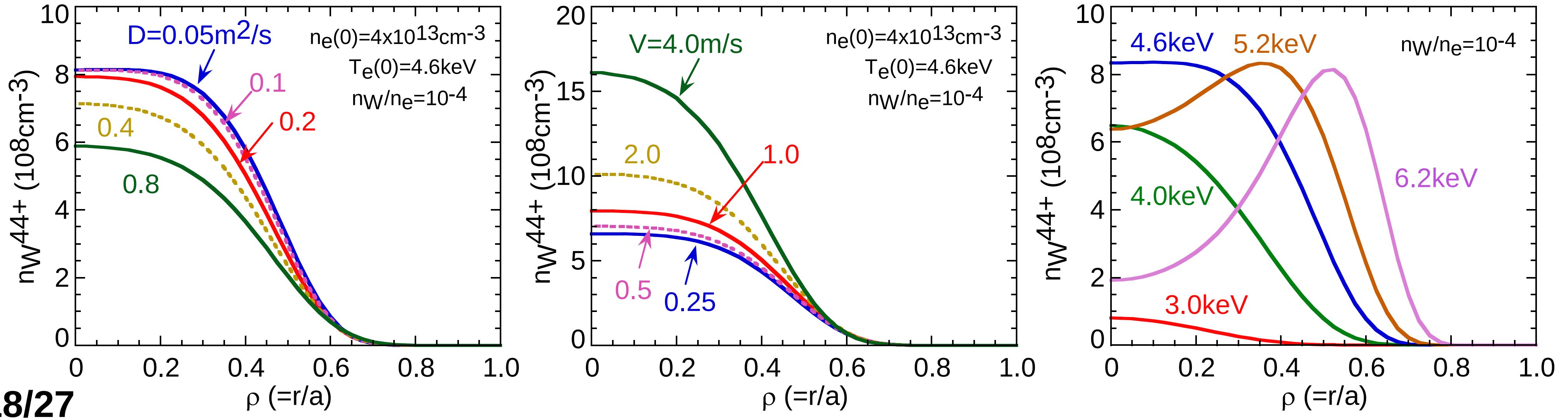
(α, β : ionization and recombination rate coefficients used ADPAK code)

- Radial impurity flux, Γ_q, is expressed by diffusive/convective model;

$$\Gamma_q = -D\frac{\partial n_q}{\partial r} + n_q V$$

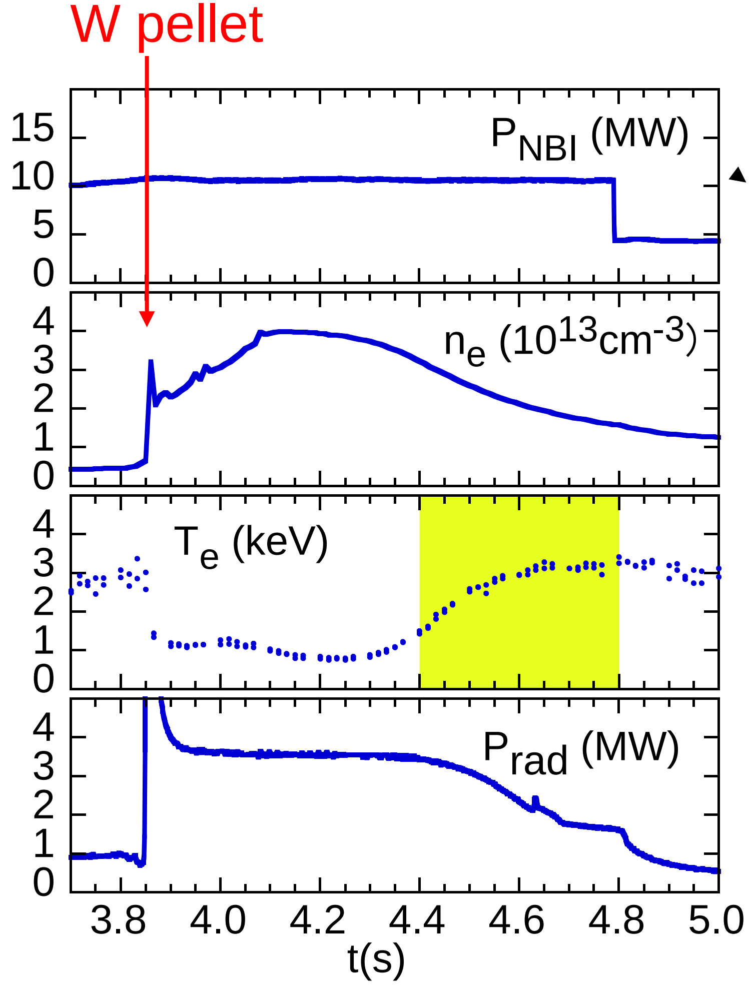
(D, V : diffusion coefficient and convective velocity)

- W^{q+} distribution at plasma core is not sensitive to reasonable D and V ranges.
- It is much affected by the reliability of ionization and recombination rates.

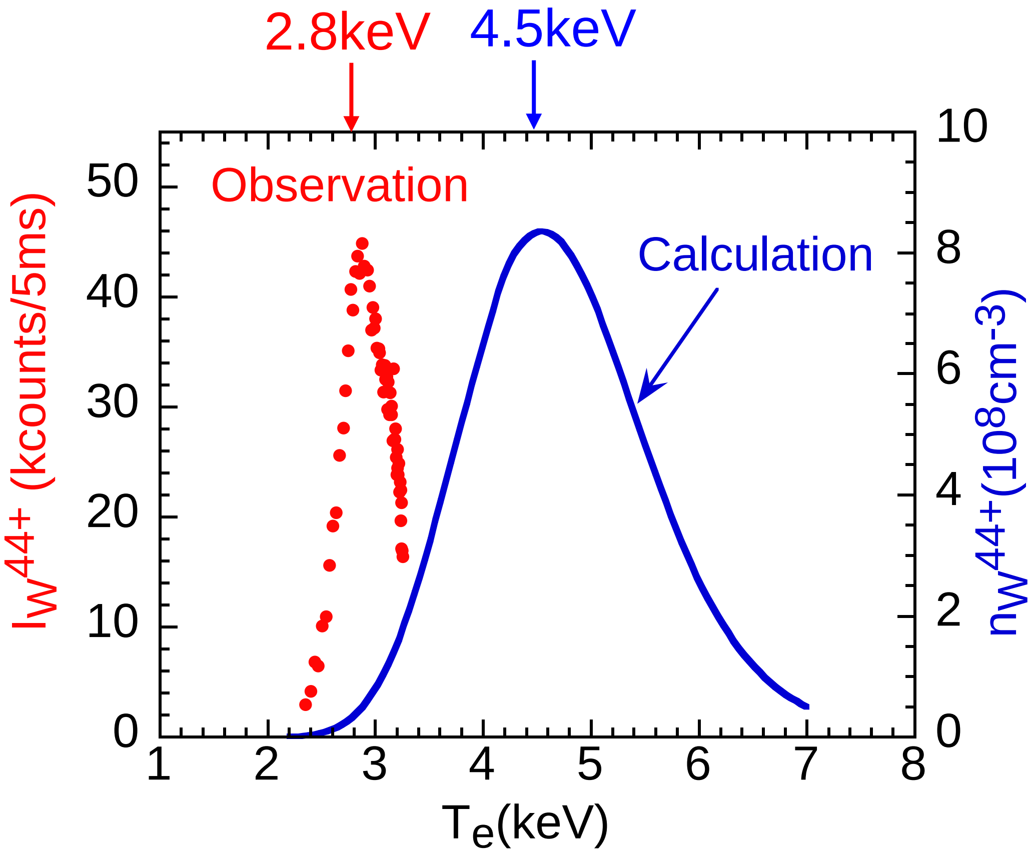


Temperature dependence of W^{44+} line

- T_e dependence of W^{44+} line intensity is analyzed using T_e recovery phase after W pellet injection ($4.4 \le t \le 4.8$s).
- Peak intensity of W^{44+} is observed at T_e=2.8keV, whereas the peak abundance of W^{44+} is predicted at T_e=4.5keV by the impurity transport code calculation.

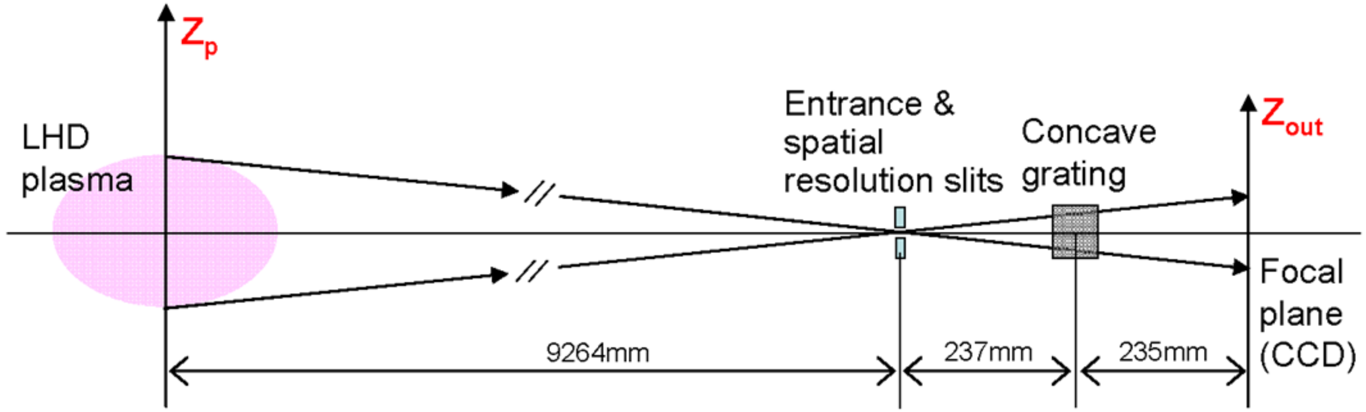


Difference suggests wrong rate coeff.

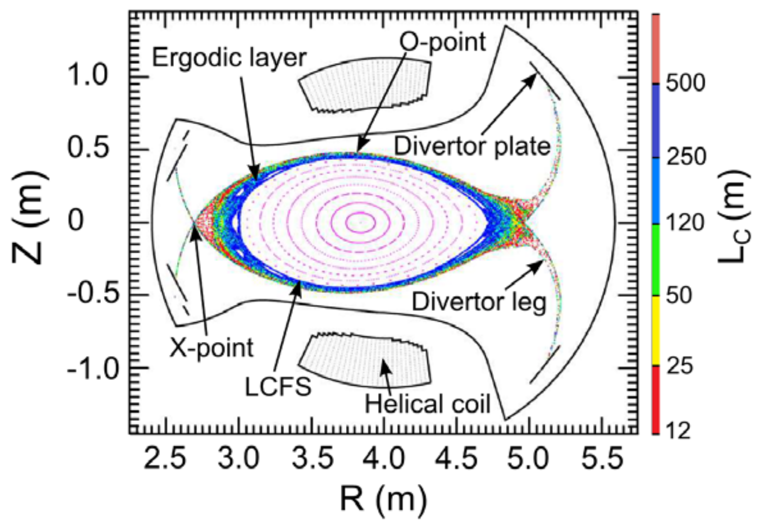


Radial profile of W^{44+} emission

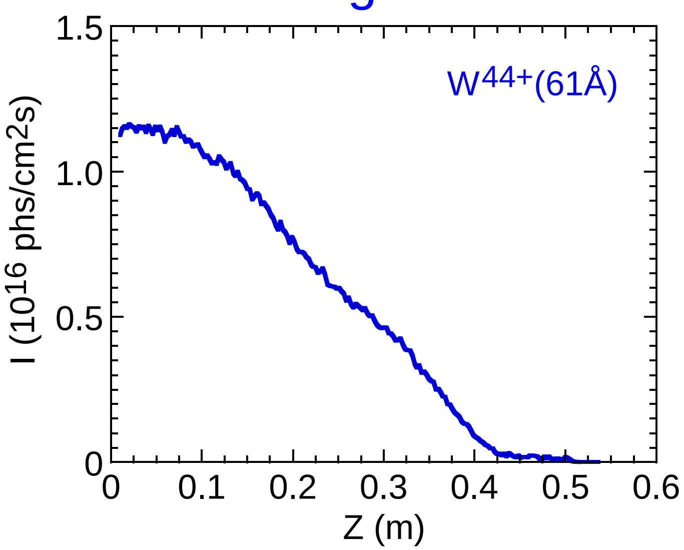
- Vertical profile of W is measured with a space-resolved EUV spectrometer.



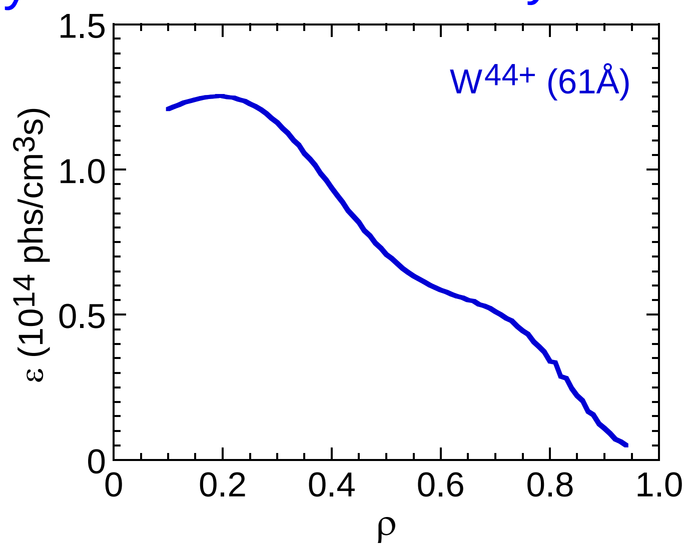
- Vertical profile is reconstructed into local emissivity as a function of ρ.
  Normalized radius: ρ=r/<a>, plasma volume: $V_p=2\pi R\times\pi\langle a\rangle^2$
  <a>, R, r: minor radius, major radius and radial position of cylindrical torus



Chord-integrated intensity



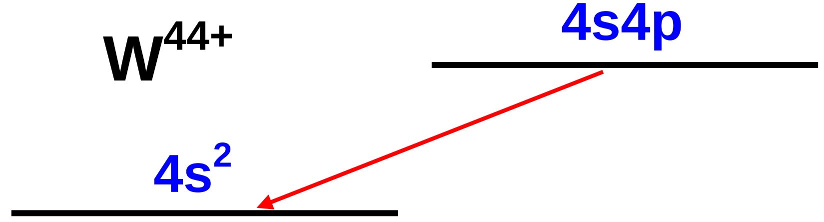
Local emissivity

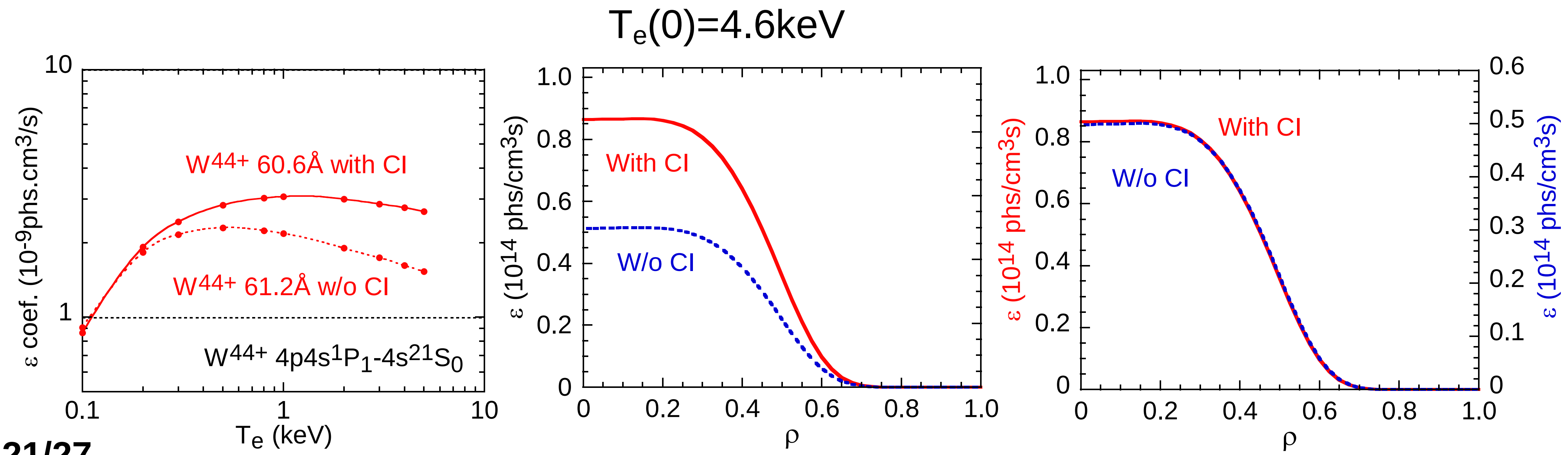


Effect of CI on W^{44+} emission coefficient

- Configuration interaction (CI) of W^{44+} line gives a clear difference in the emission coefficient.
- Emission coefficient with CI is about 70% larger than that without CI.
- But radial emissions of W^{44+} give a very similar profile between the two cases.
- Wavelength of W^{44+} clearly changes between the two cases.

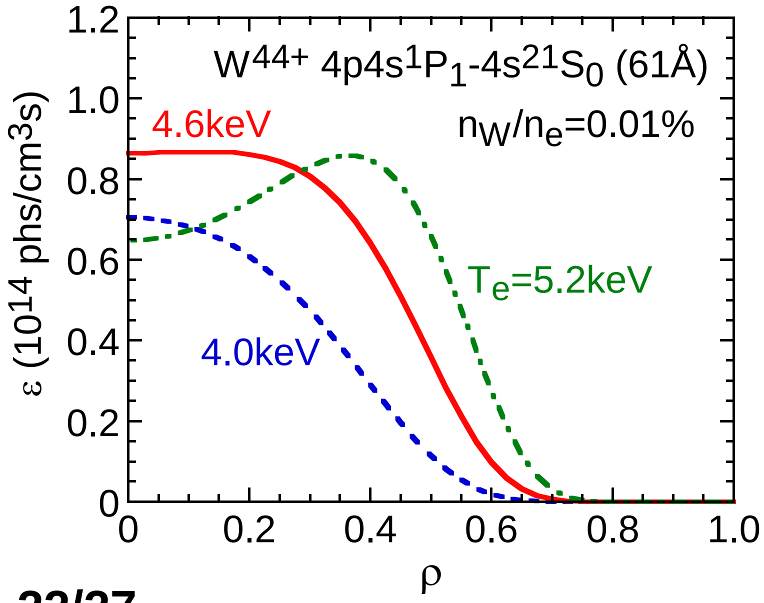
  HULLAC with CI: 60.6Å
  HULLAC w/o CI: 61.2Å
  EBIT, tokamak: 60.87, 60.93Å
  LHD: (60.81Å)

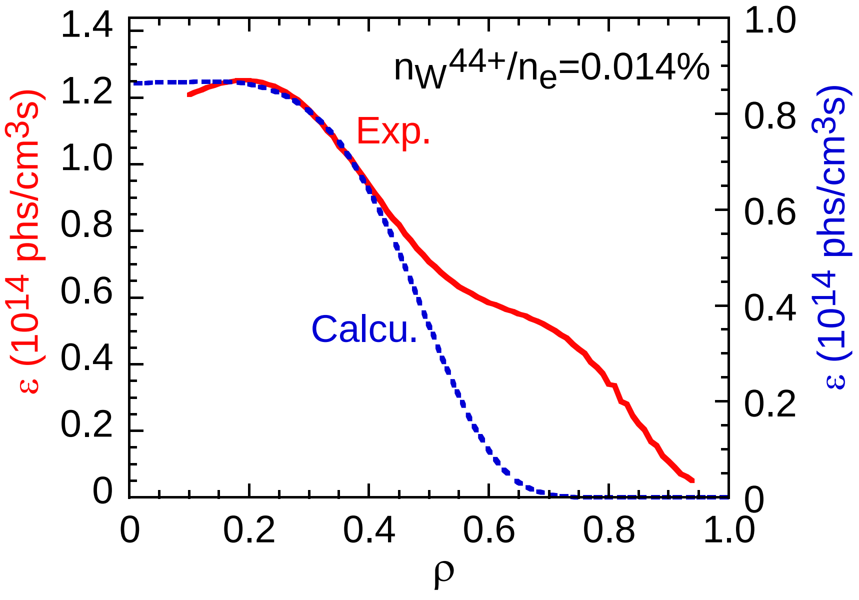


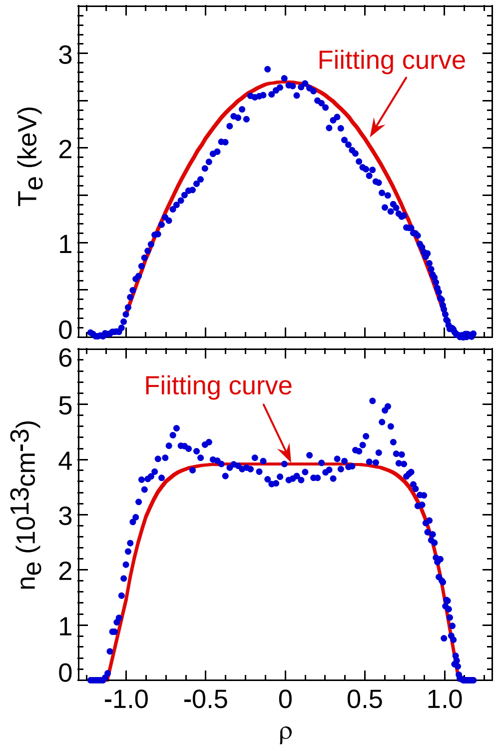


Quantitative analysis of W^{44+}

- Uncertainty of recombination rate coefficient is ignored in the analysis.
- W^{44+} profile calculated from impurity transport code agreed with experimental profile only in the plasma core.
- It suggests W^{44+} line is blended with W line from lower ionization stage.
- Analysis indicates the density of W^{44+} ion, $n(W^{44+})$:
  $n(W^{44+})/n_e=1.4\text{x}10^{-4}$ with CI, $n(W^{44+})/n_e=2.4\text{x}10^{-4}$ w/o CI.
- Total W density: $n_W/n_e=8.8\text{x}10^{-4}$ with CI, $n_W/n_e=1.5\text{x}10^{-3}$ w/o CI
- Total radiation from W is estimated to be roughly 5MW from average ion model.





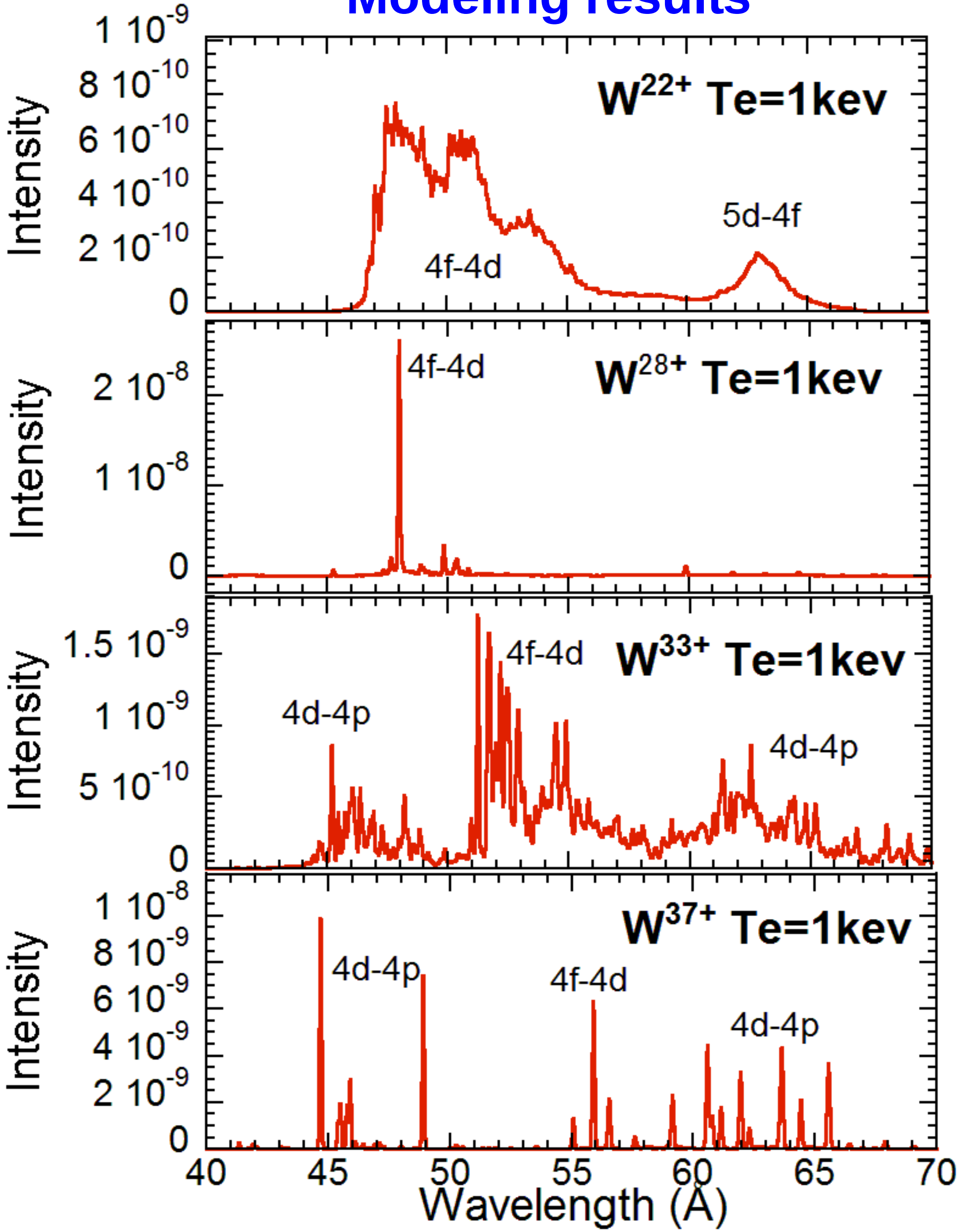


Spectral modeling for W ions

- Modeling of W ions is attempted for EUV spectra at 40-70Å.
- Collisional-radiative model has been constructed for W^{q+} ions with q=20 - 45.
- Maxwellian electron velocity distribution is assumed.
- Atomic data are calculated by HULLAC code.
- Excited fine structure levels with n up to 6 (l<5) are considered;
  2,000 - 26,000 levels examined for one ion.
- Recombination processes are not included.
- UTA at 45-55Å: 4d-4p and 4f-4d transitions
  UTA at 55-65Å: 4d-4p, 4f-4d, and 5d-4f transitions of W^{q+} with q<38.

- Modeling of W including recombination has been also developed to calculate ionization balance, while spectral modeling is difficult.

Modeling results



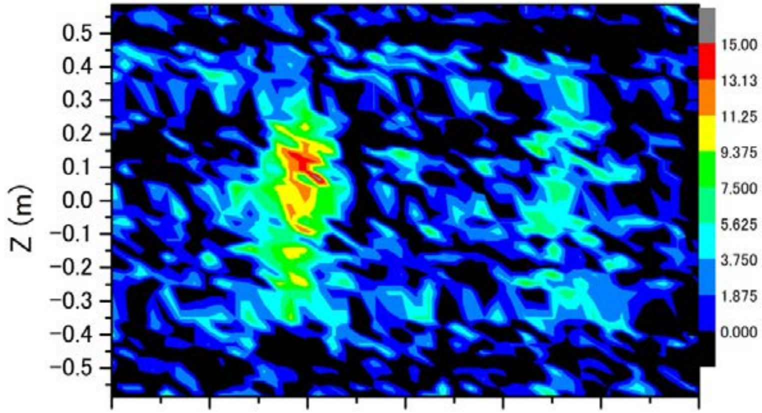
Observation of M1 transition from W^{26+}

- **M1 transition is identified as $4s^2 4p^6 4d^{10} 4f^2\ {}^3H_5 - {}^3H_4$ at ground state of W^{26+} ion.**

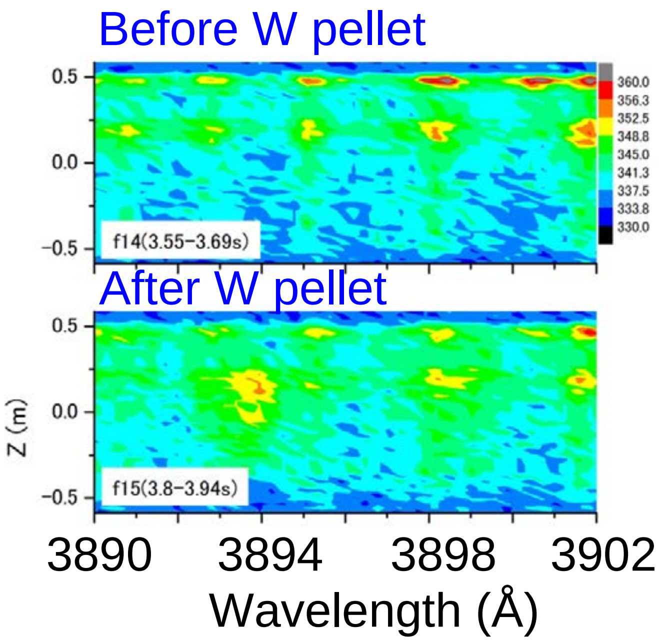
Present results	Previous experiment (EBIT)	Theory
3893.7(4)Å	3894.1(6)Å[a], 3893.5(3)Å[b]	3884.3Å[c] (MCDF)
3899.1(4)Å	Not available	Not available

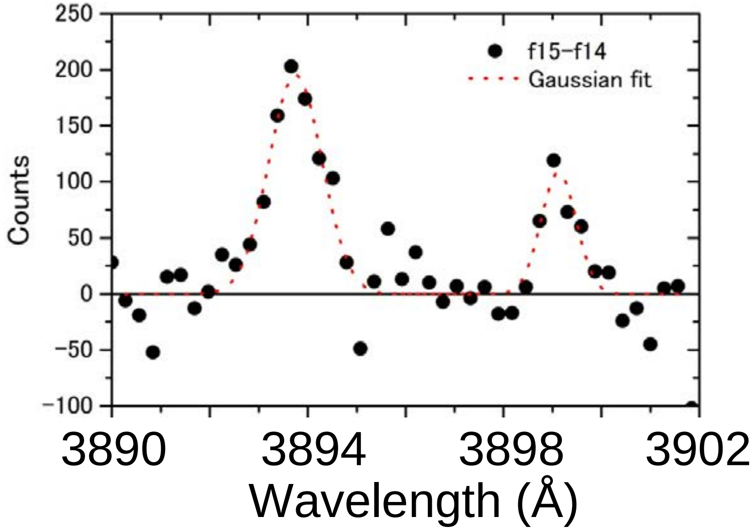
[a]CoBIT, A.Komatsu et al. Phys.Scr. **T144** (2011) 014012, [b]Tokyo-EBIT, H. Watanabe et al. Can.J.Phys. **90** (2012) 497, [c]grasp2K, X.-B.Ding et al. J.Phys.B **44** (2011) 145004.

- Wavelength is determined by Gaussian fitting.
- Central emission at 3894Å indicates a visible line from highly charged ion.
- M1 is useful for diagnostics and atomic structure modeling.



- 1.3m Czerny-Turner spectrometer;
  1800 grooves/mm
  Δλ=0.45Å
  40 optical fiber array
- CCD exposure: 140ms

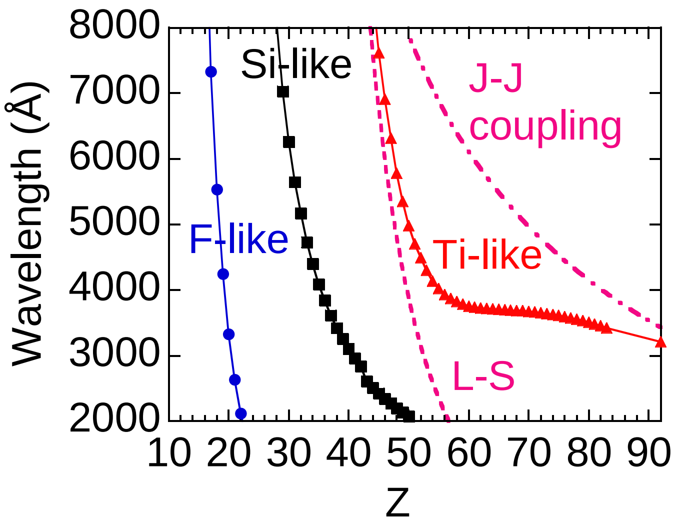




Importance of M1 transition

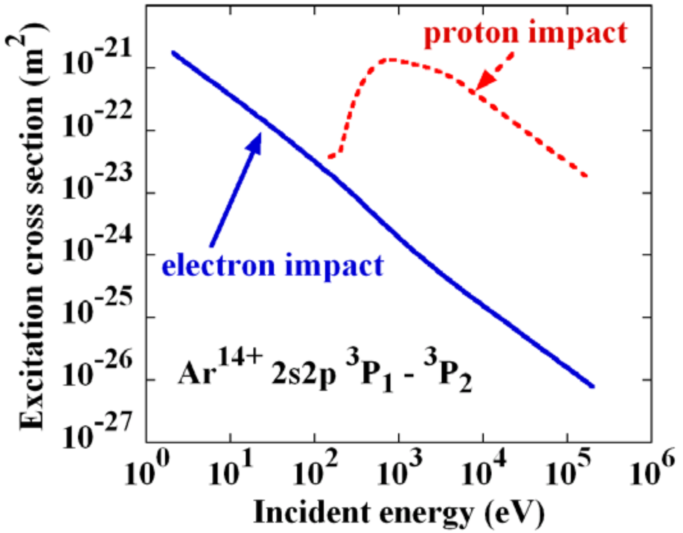
Atomic physics

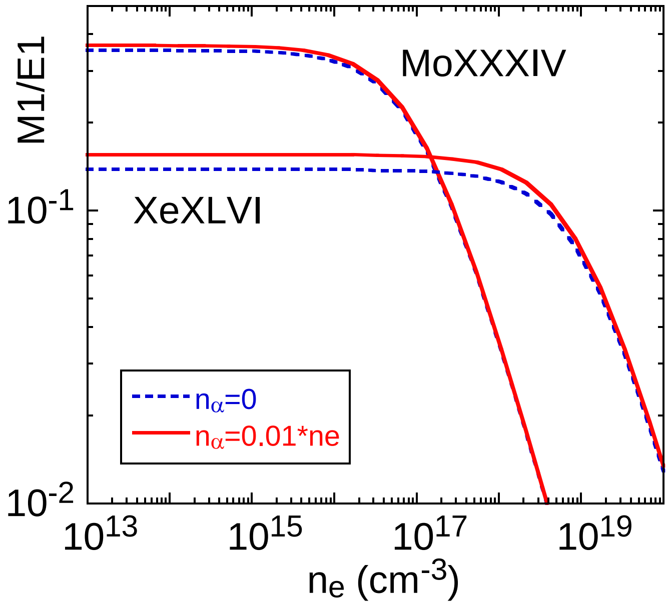
• Strong relativistic effect in high-Z elements
• Transition from L-S coupling to J-J coupling
• Reconstruction of atomic structure of high-Z ions is possible based on M1 transition observation.

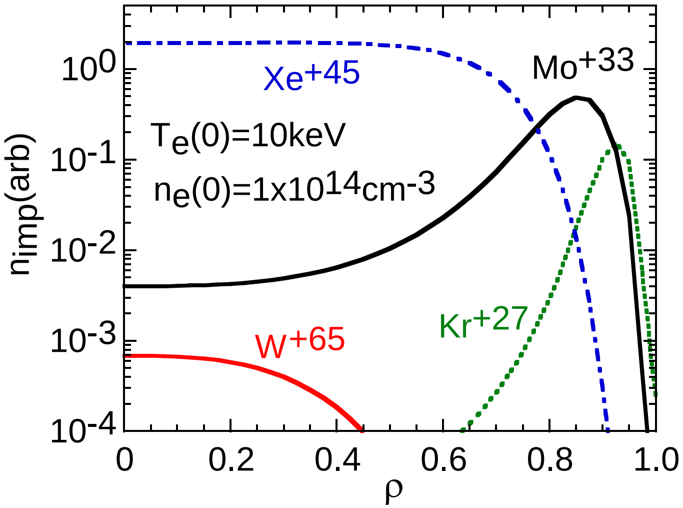


Diagnostics of alpha particle for ITER burning plasmas

• M1 intensity is sensitive to high-energy ions.
• Ratio of E1 to M1 for F-like ions is calculated for a-particle diagnostics of ITER.
• Enhancement of M1 intensity by proton collision is very large due to high T_i.
• Small effect of proton impact and large effect of α-particle impact are necessary for M1.





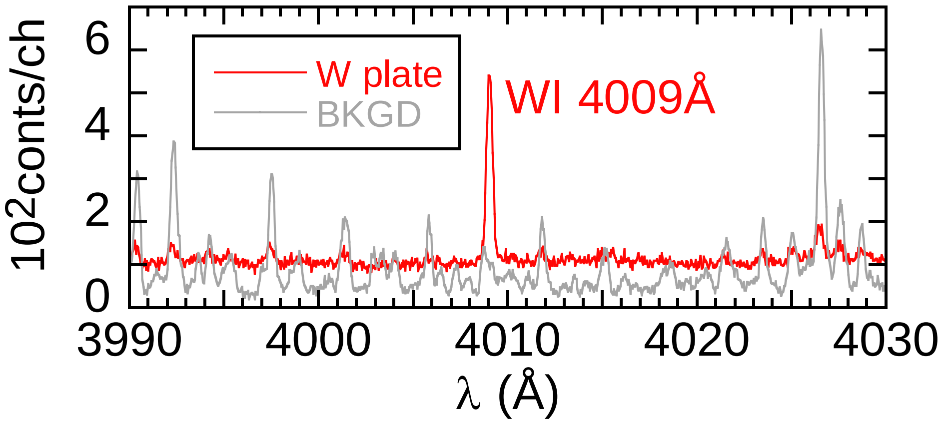


Visible spectroscopy of W

W visible line from LHD

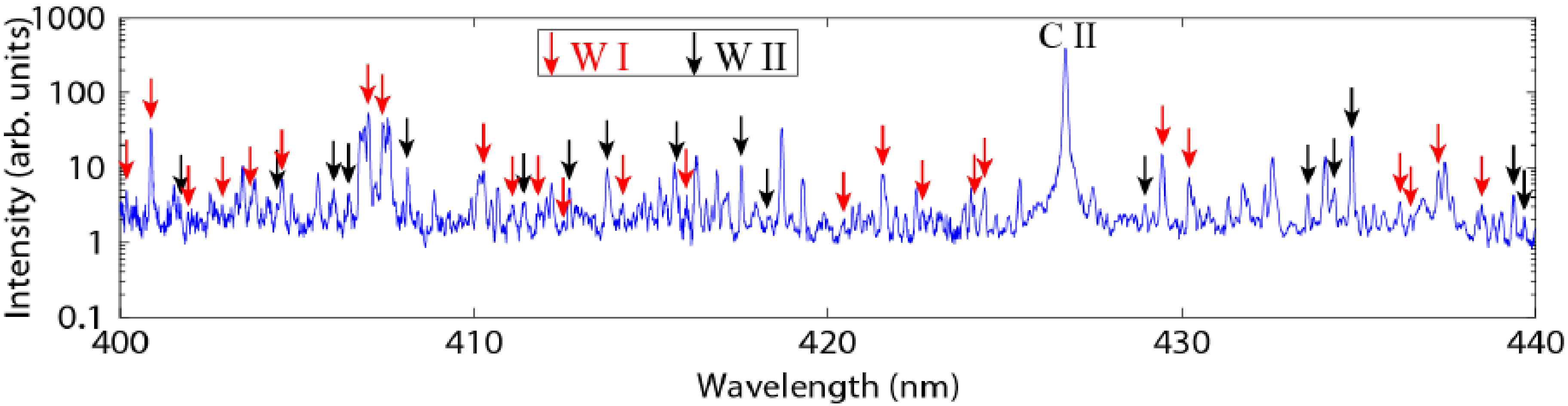
- W plate inserted into plasma edge boundary

Red: Direct observation of W plate at 4.5-U port
Gray: BKGD emission from divertor region at 10-O port



W visible lines from ablation cloud of impurity pellet

- Ablation cloud of cylindrical carbon pellet with W ($1.2mm^L x 1.2mm^\phi$, $100 \leq V_p \leq 300$m/s)
  Parameters: T_e=2.5eV, n_e=$5x10^{16}cm^{-3}$ for CII, T_e=3.0eV, n_e=$5x10^{14}cm^{-3}$ for CIII
- Several lines denoted with arrows are identified by NIST data table.
- WI line at 4009Å is not strong.



Summary

- W spectroscopy in LHD has started from FY 2011.
- W spectra from LHD have been observed in visible, VUV and EUV ranges.

- UTA spectrum in 15-35Å is well analyzed based on CoBIT spectra.
- Radial profile of Zn-like W^{44+} is quantitatively analyzed with HULLAC code.
- W density to electron density of 8.8×10^{-4} is reasonably obtained as initial trial.
- The present result indicates that W^{44+} and W^{45+} can be used for plasma diagnostics.

- Modeling of W spectra has been also started by considering 20,000 sublevels.
- Modeling including recombination effect also begins to study.
- M1 transition is observed from W^{26+} ion.
- A large number of visible W lines are observed from pellet ablation cloud.

For more reliable analysis of W;

- Improvement of ionization and recombination rates
- Modeling of W spectra to explain the experiment
- More accurate wavelength calculation
- Further line identification in the whole wavelength range of 10-7000Å

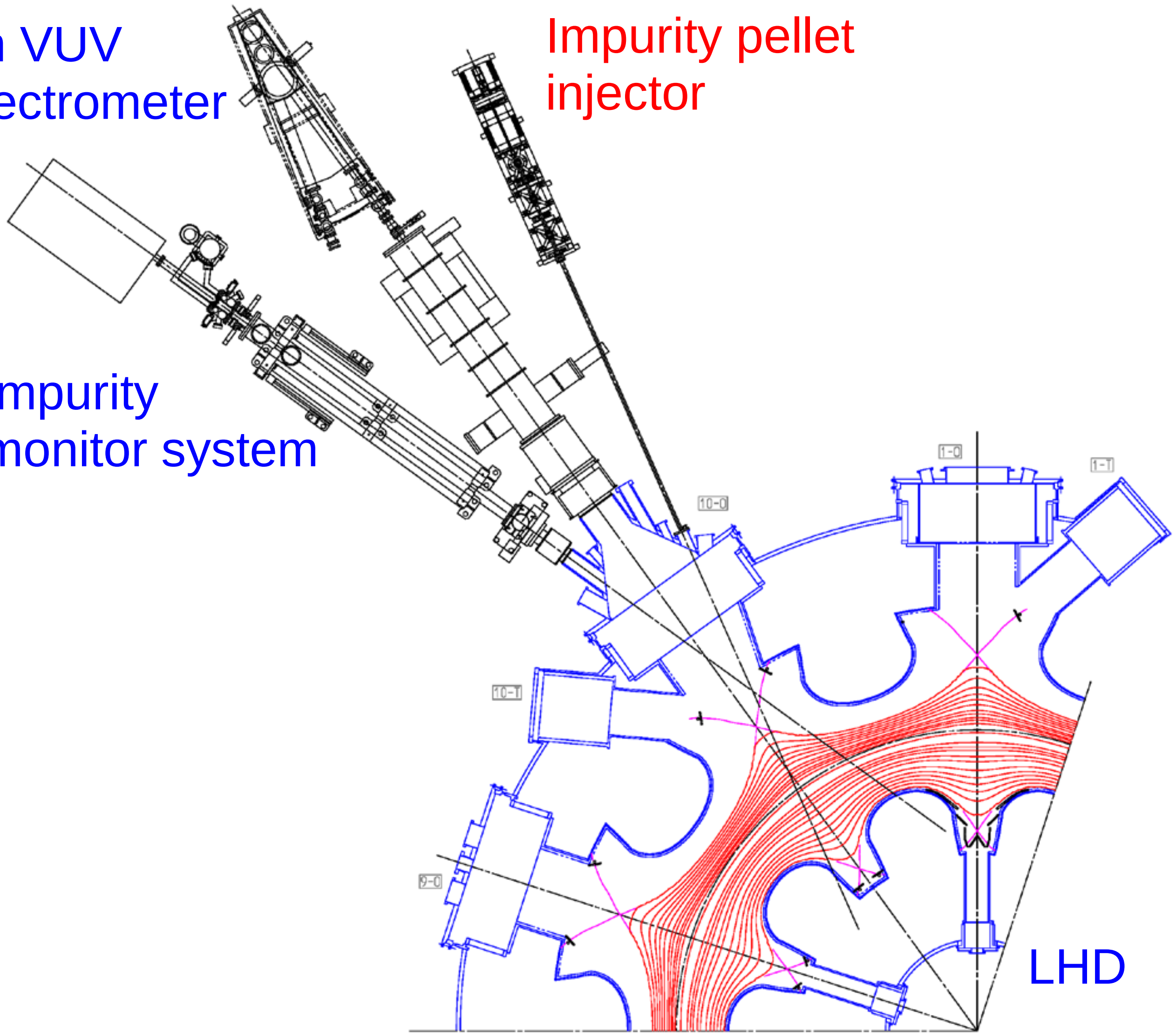
Impurity pellet injection

- Various cylindrical impurity pellets have been injected to LHD for confinement improvement and diagnostic use.

3m VUV spectrometer

Impurity pellet injector

Impurity monitor system



LHD

$6 \le Z \le 74$

$0.3mm \le L \le 2.0mm$