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ASIPP

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

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19 Dec. 2016

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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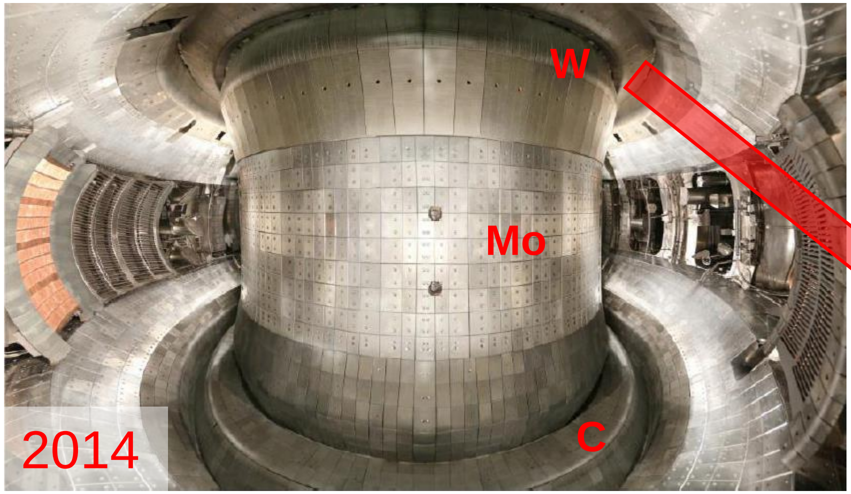
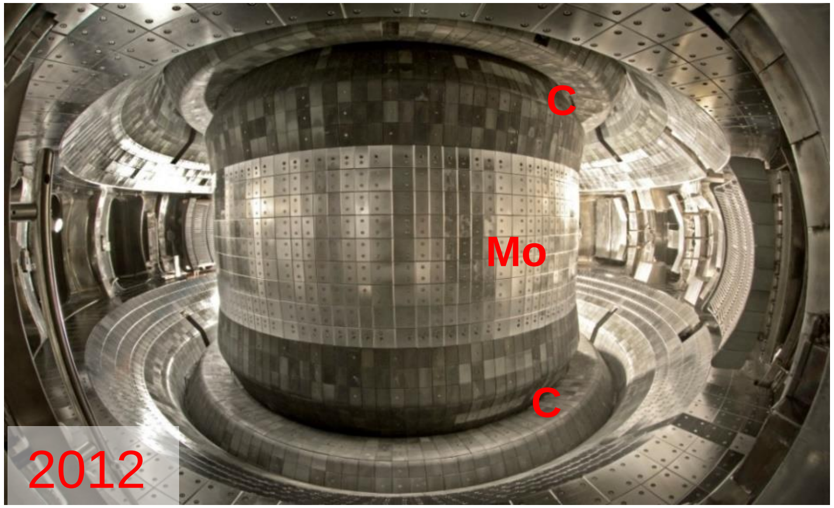
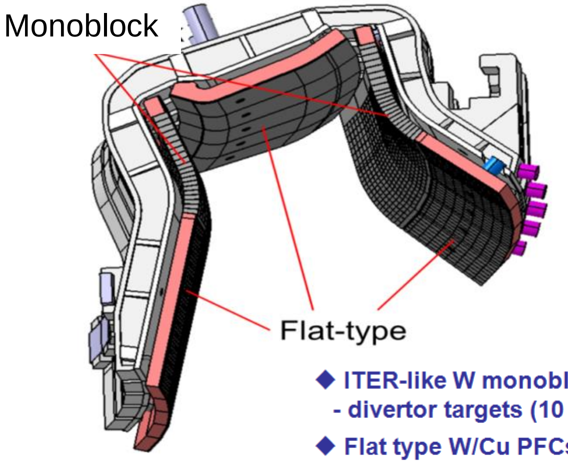
Upgrade of Plasma Facing Components on EAST





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

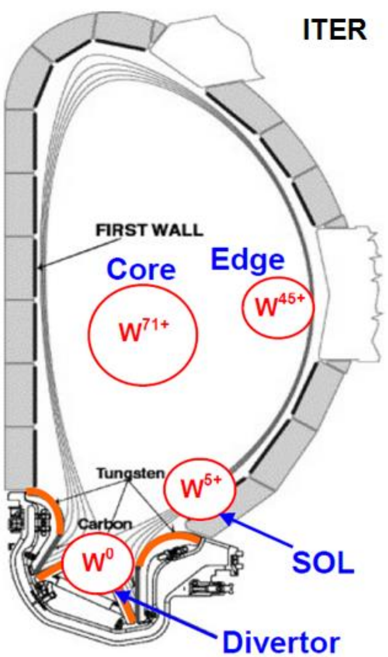


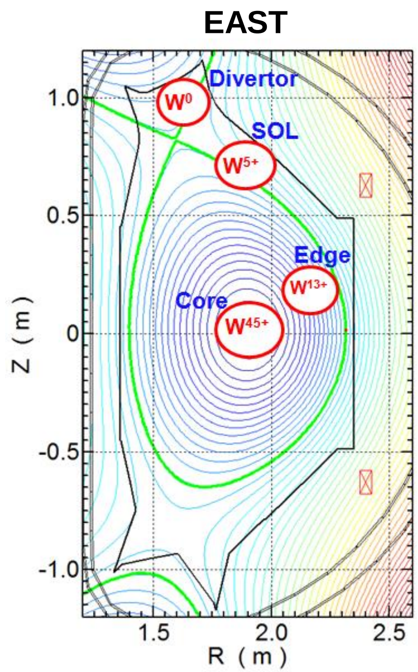
- **Wall conditioning;**
  Li coating, Si coating, B coating
  He-GDC, D_2-GDC
- **Gas puffing for diagnostics;** **Ar, He**

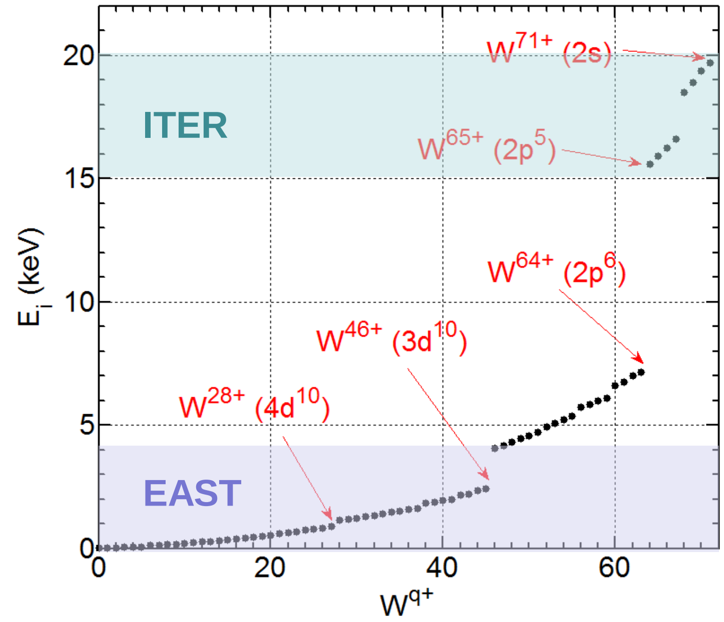
Intrinsic & extrinsic impurities;
He, Li, B, C, N, O, Si, Ar, Cr, Fe, Ni, Cu, Mo, W…

W spectroscopy in EAST

- 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.







W spectroscopy

	ITER (T_{e0}~15-20keV)	EAST (T_{e0}~4keV)
Visible	Divertor (e.g. W^{0+}-W^{2+}) Sputtering at div. plates	Divertor (e.g. W^{0+}-W^{2+}) Sputtering at div. plates
VUV	SOL (e.g. W^{3+}-W^{6+}) Influx at SOL	SOL (e.g. W^{3+}-W^{6+}) Influx at SOL
EUV	Edge (e.g. W^{19+}-W^{45+}) Influx at edge; W density	Edge (e.g. W^{7+}-W^{13+}) Influx at edge
EUV & X-ray	Core (e.g. W^{65+}-W^{71+}) W density	Core (e.g. W^{19+}-W^{45+}) W density

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Hardware development: EUV spectrometers (1)
(Grazing incidence flat-field spectrometers)

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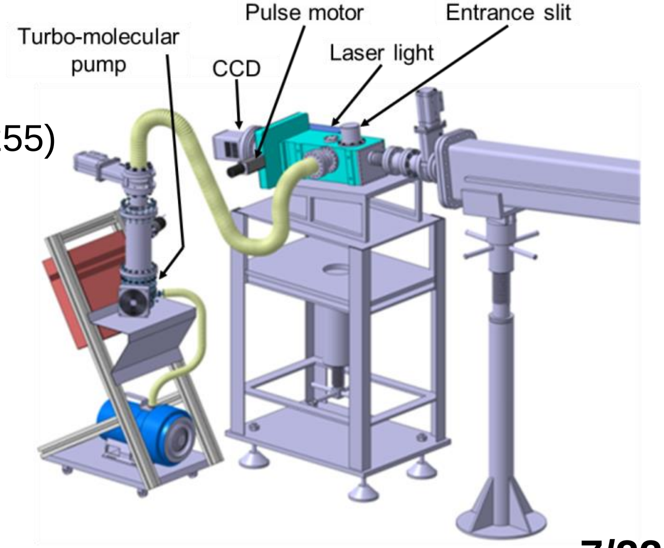
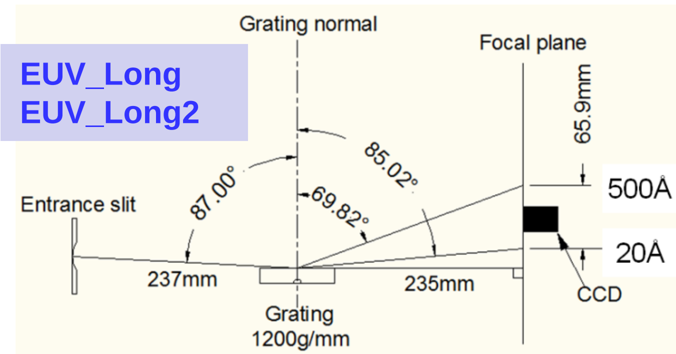
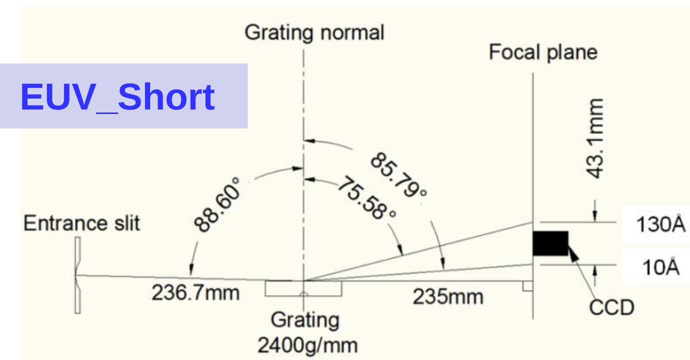
- **Two EUV spectrometers at longer wavelength range (20-500Å);**
  EUV_Long: spectral measurement with fast response
  EUV_Long2: space-resolved measurement
  - Slit width: 30μm/100μm (EUV_Long/EUV_Long2 with spatial resolution slit)
  - Varied line spacing groove concave holographic grating: 1200g/mm
  - Back-illuminated CCD (size: 26.6x6.6mm^2, 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: 26.6x6.6mm^2, 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**

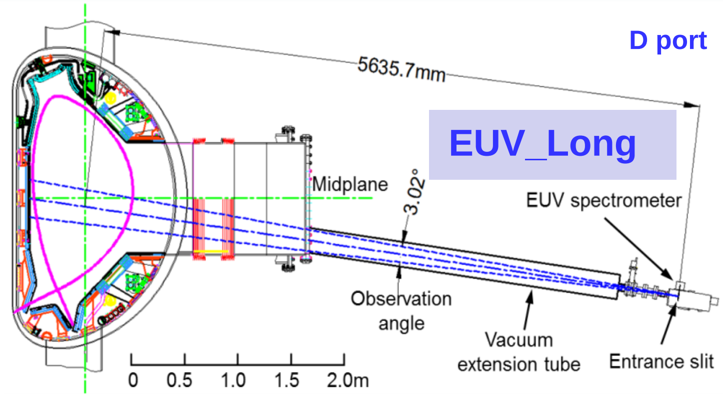


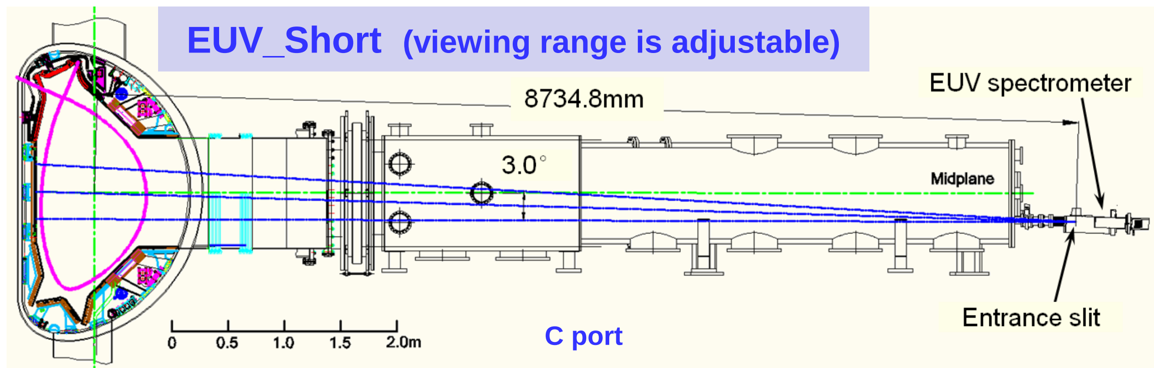
Hardware development: EUV spectrometers (2)
(Grazing incidence flat-field spectrometers)

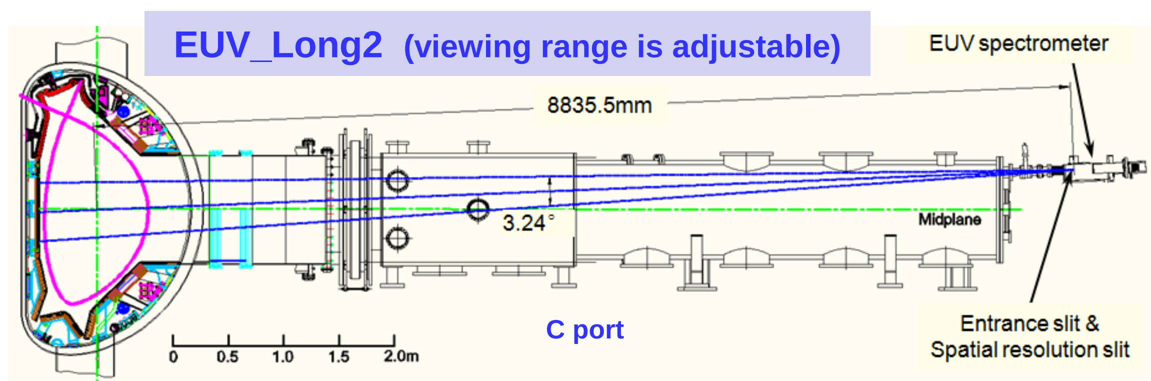




Wavelength	Field of view		Resolution		
	Vertical	Toroidal	Time	Space	Spectrum
EUV_Long 20-500Å	30cm	5cm	5ms	-	0.22@200Å
EUV_Short 10-130Å	50cm	4cm	5ms	-	0.1@20Å
EUV_Long2 20-500Å	50cm	7cm	~50ms	2-3cm	0.22@200Å



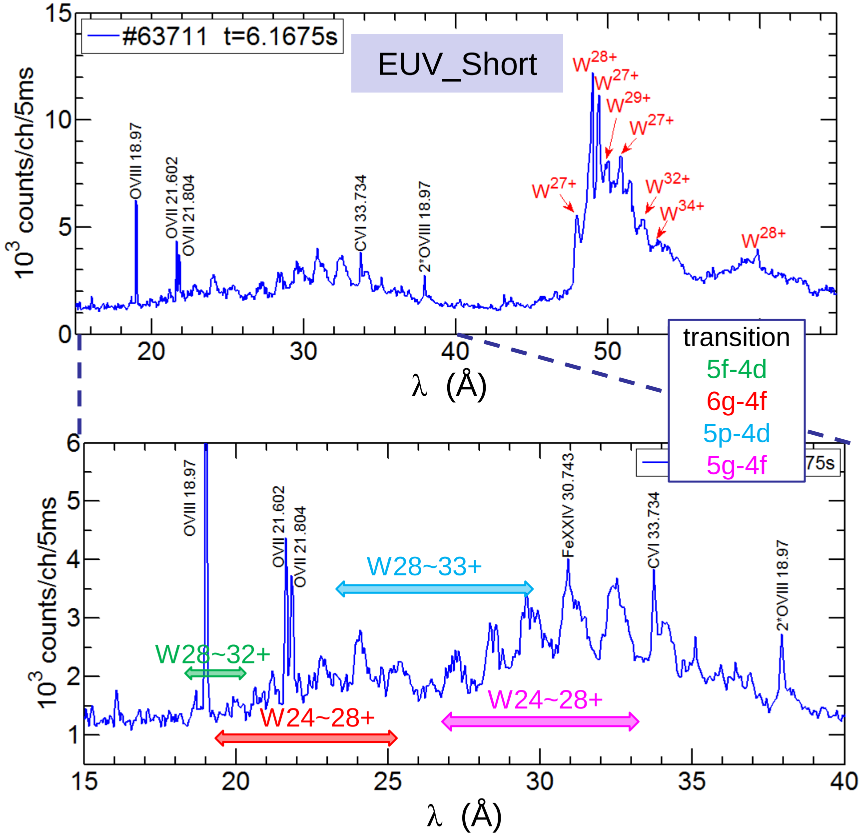


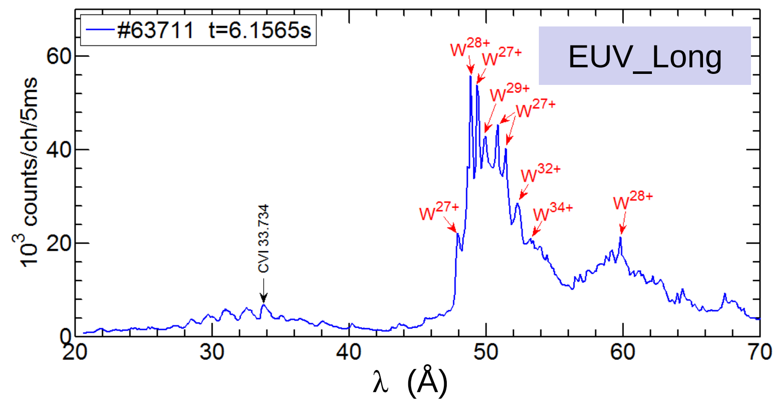


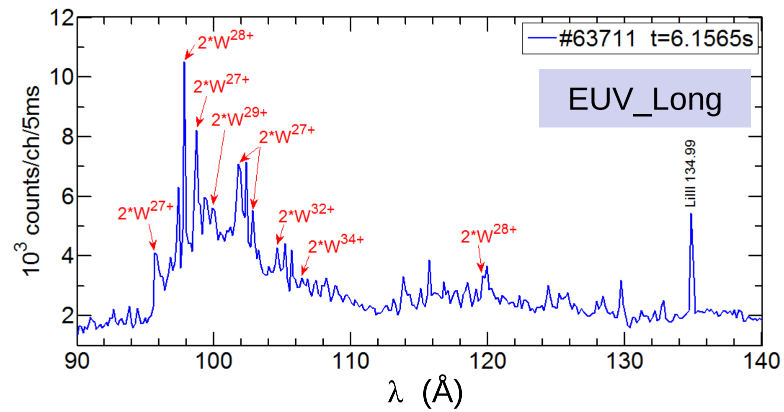
Line analysis of W spectra at low T_e

- 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.
- $T_e(0)$=1.0keV, n_e=3.5x10^{19}m^{-3}: USN, L-mode, P_{LHCD}=0.5MW, B_t=2.25T, I_p=500kA, downward ∇B





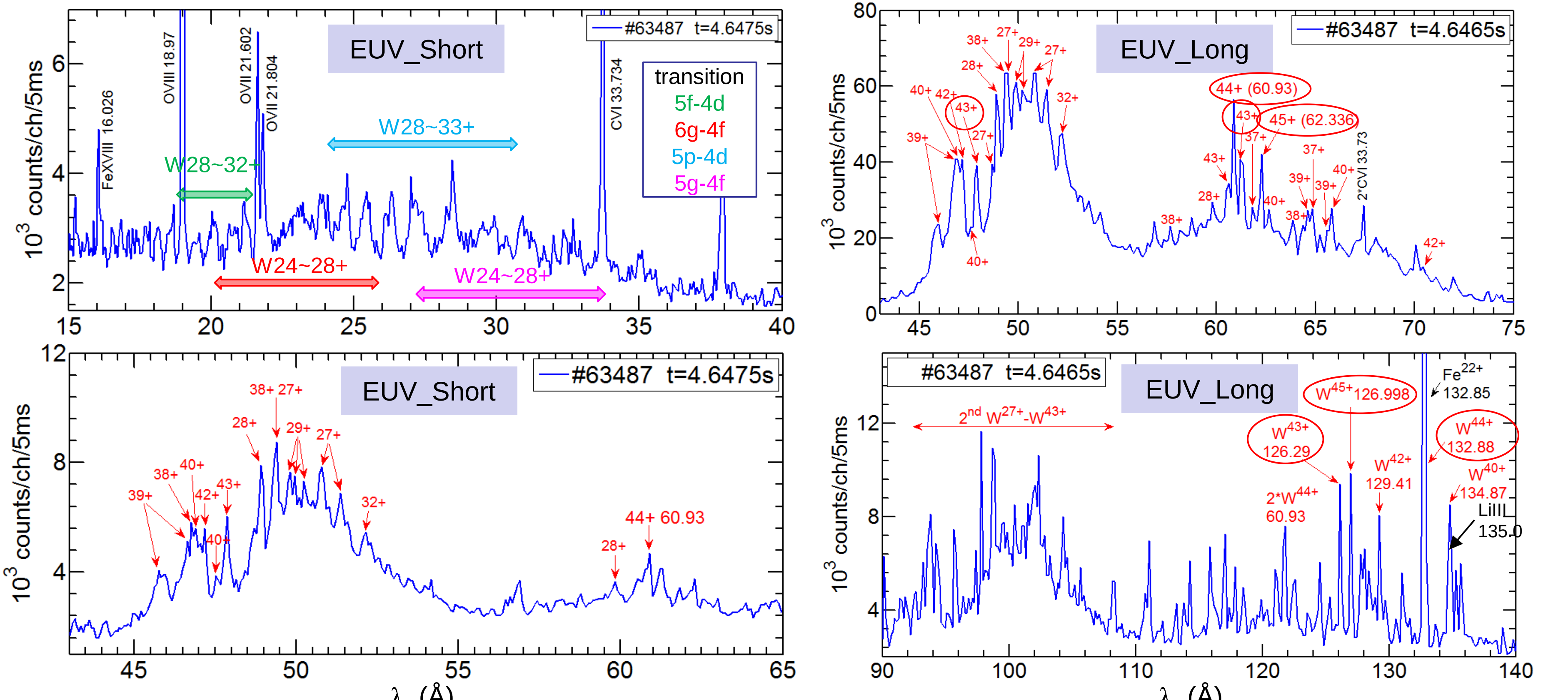


- Tungsten UTA (**u**nresolved **t**ransition **a**rray) at 15-70Å is observed by EUV_Short with high spectral resolution.
- UTA at 15-35Å can be compared with CoBIT data.

- 2nd 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.
- $T_e(0)$=2.6keV, $n_e=3.7\times10^{19}m^{-3}$: USN, $P_{LHW}/P_{ICRH}/P_{ECRH}$=2.1/1.4/0.4MW, B_t=2.25T, I_p=450kA, downward ∇B



W^{43+} (E_i=2.210keV)	$4s^24p$	4p-4s (61.334, 126.29Å)
W^{44+} (E_i=2.354keV)	$4s^2$	4p-4s (60.93, 132.88Å)
W^{45+} (E_i=2.414keV)	4s	4p-4s (62.336, 126.998Å)

- 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

Space-resolved measurement of W spectra at high T_e

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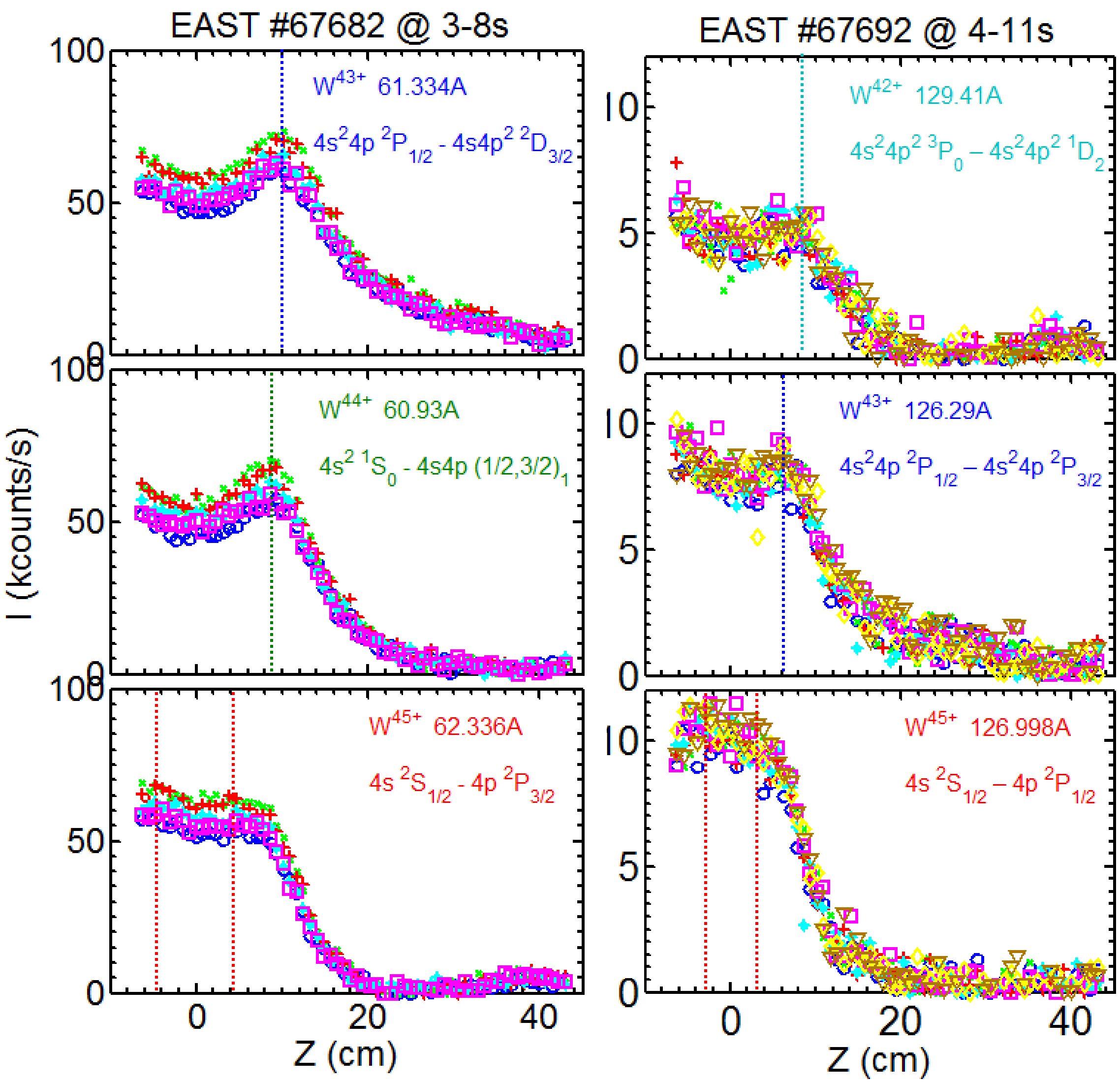
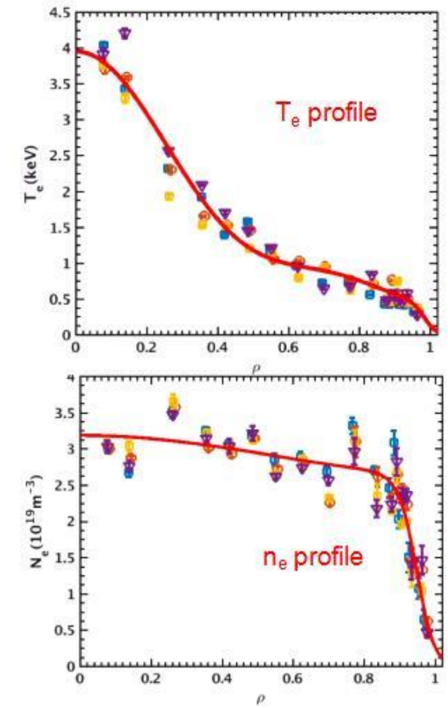
USN, $P_{LHW2}/P_{ICRH}/P_{ECRH}$=2.2/0.6/0.3MW, steady-state ELMy H-mode



- 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

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- 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.

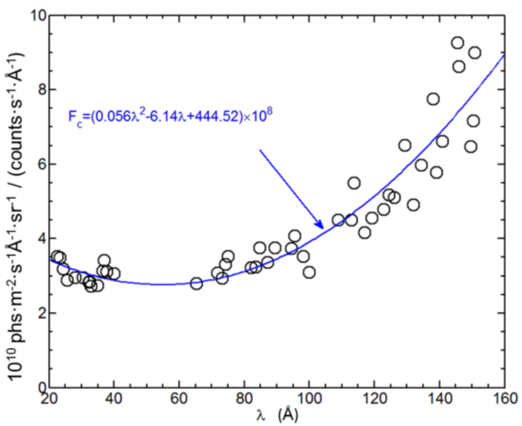
Candidate line pairs in EAST plasma:

Ion	Ei (eV)	λ [Å]	Transition	Intensity ratio		Sensitivity ratio
				Modeled*	Measured	
Fe XXIV	2046	192.03	$1s^22s\ ^2S_{1/2}$-$1s^22p\ ^2P_{3/2}$	1.91	4.38±0.11	0.436
		255.11	$1s^22s\ ^2S_{1/2}$-$1s^22p\ ^2P_{1/2}$			
Mo XXXII	1776	127.87	$2p^63s\ ^2S_{1/2}$-$2p^63p\ ^2P_{3/2}$	1.82	5.02±0.13	0.363
		176.65	$2p^63s\ ^2S_{1/2}$-$2p^63p\ ^2P_{1/2}$			
Cr XXII	1722	223.02	$1s^22s\ ^2S_{1/2}$-$1s^22p\ ^2P_{3/2}$	1.93	3.39±0.11	0.569
		279.74	$1s^22s\ ^2S_{1/2}$-$1s^22p\ ^2P_{1/2}$			
Ar XVI	918	353.85	$1s^22s\ ^2S_{1/2}$-$1s^22p\ ^2P_{3/2}$	1.97	2.21±0.07	0.891
		389.07	$1s^22s\ ^2S_{1/2}$-$1s^22p\ ^2P_{1/2}$			
Fe XVI	489	335.41	$2p^63s\ ^2S_{1/2}$-$2p^63p\ ^2P_{3/2}$	1.95	1.66±0.10	1.175
		360.76	$2p^63s\ ^2S_{1/2}$-$2p^63p\ ^2P_{1/2}$			

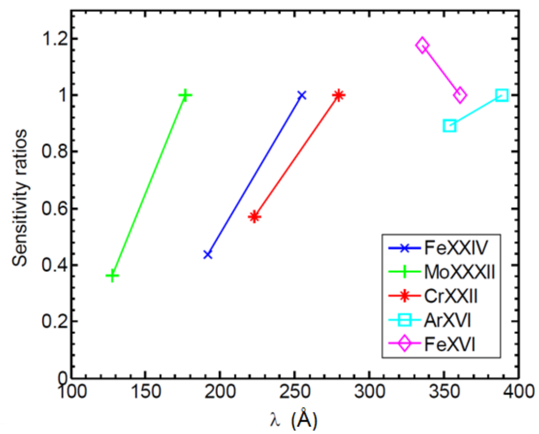
* Ref. "K D Lawson et al 2009 JINST 4 P04013"

$$I_{brem} = \frac{9.5\times10^{-20}\Delta\lambda}{4\pi\lambda}\int\frac{g_{ff}n_e^2Z_{eff}}{T_e^{1/2}\exp(12400/T_e\lambda)}dl\ \ (\text{photons s}^{-1}\text{ m}^{-2}\text{ Sr}^{-1})$$

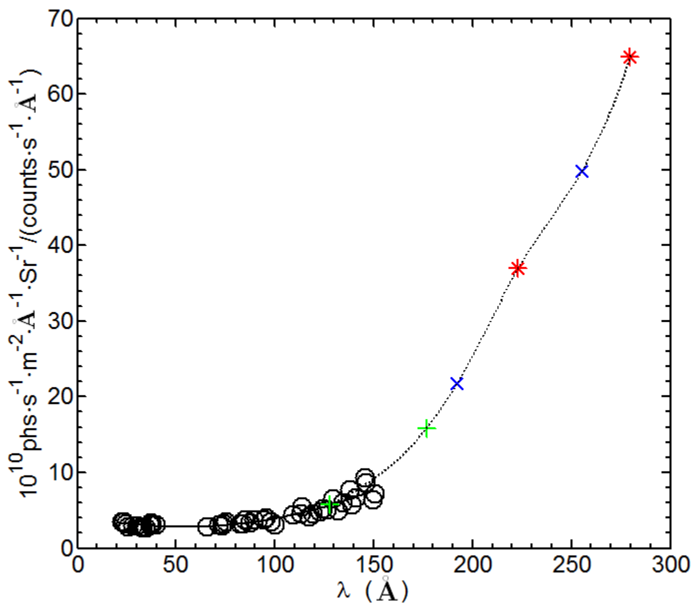
$$\varepsilon_{brem\_EUV} = \varepsilon_{brem\_vis}\left(\frac{\lambda_{vis}}{\lambda_{EUV}}\right)^2\frac{g_{ff\_EUV}}{g_{ff\_vis}}\times\exp\left[-\frac{12400}{T_e}\left(\frac{1}{\lambda_{EUV}}-\frac{1}{\lambda_{vis}}\right)\right]$$



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

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- W concentration, $c_W = N_W / N_e$ or $c_W = n_W / n_e$
- Evaluation of c_W from chord-integrated line intensity, e.g. I^{W44+}-I^{W45+}

$$I^{W^{q+}} = \int n_{W^{q+}}(l) \mathrm{PEC}^{W^{q+}}(l) n_e(l) \mathrm{d}l$$

$$= \int c_W(l) n_e(l) FA^{W^{q+}}(l) \cdot PEC^{W^{q+}}(l) n_e(l) dl$$

$$= \int c_W f_{c_W}(l) n_e(l) FA^{W^{q+}}(l) \cdot PEC^{W^{q+}}(l) n_e(l) dl$$

$$c_W = I^{W^{q+}} / \int f_{c_W}(l) FA^{W^{q+}}(l) PEC^{W^{q+}}(l) n_e^2(l) \mathrm{d}l$$

I^{Wq+} : measured chord-integrated line intensity from W^{q+}

n_{Wq+} : density of W^{q+}

PEC^{Wq+} : photon emissivity coefficient of line from W^{q+}

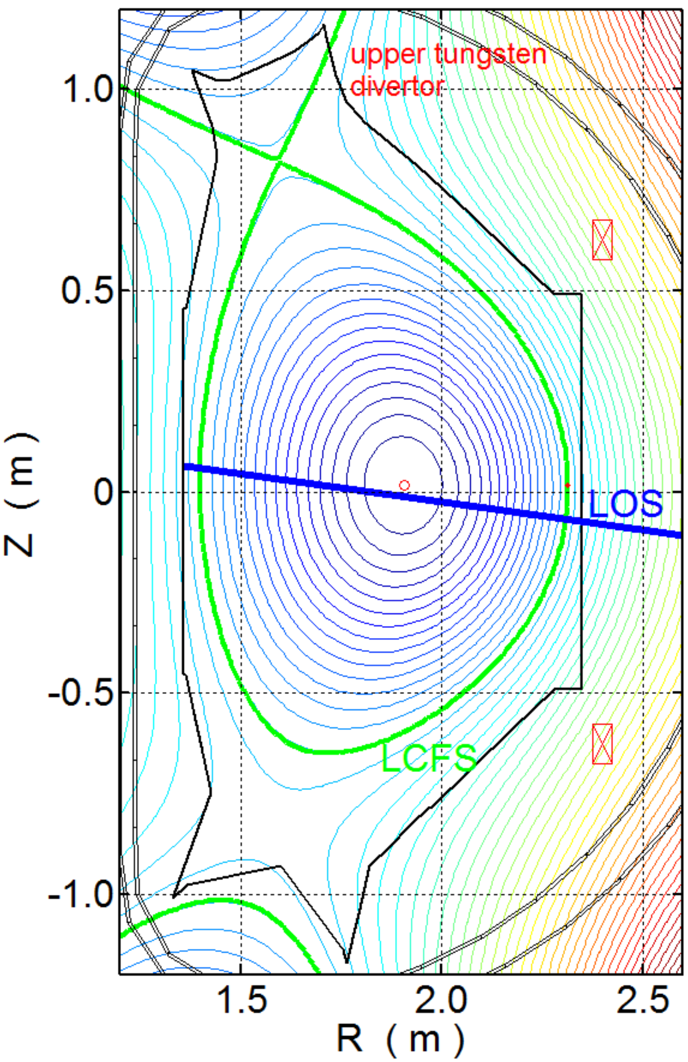
n_e : electron density

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

f_{Cw} : normalized density profile of W

FA^{Wq+} : fractional abundance of W^{q+} under ionization equilibrium

EAST plasma with USN

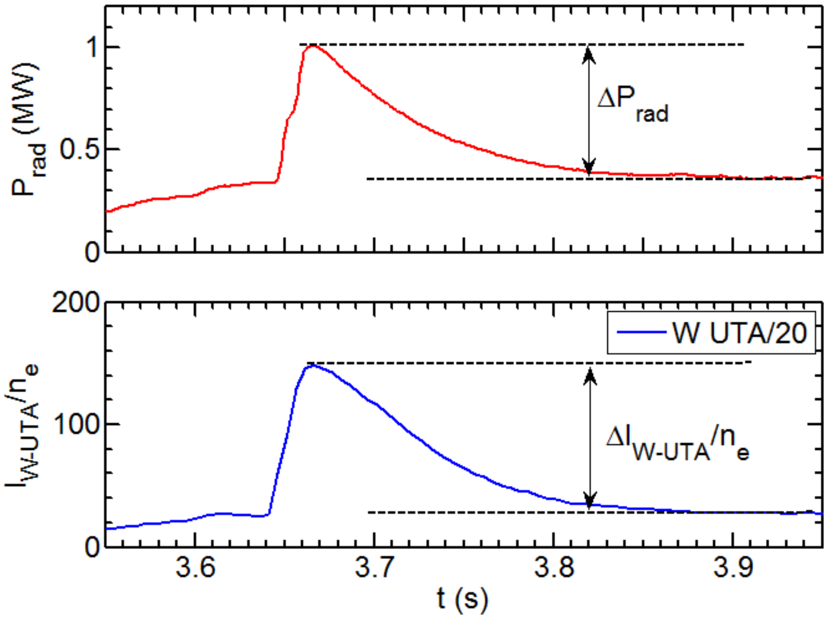


T. Nakano et al., J. Phys. B 48 (2015) 144023

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.

calibration shot EAST #63873



- Cooling rate (Radiation power coefficient):

$$L_W(T_e, n_e) = \sum_q L_W^{q+}(T_e, n_e) N_{W^{q+}}/N_W$$

- Radiation power loss by W:

$$P_W = \int L_W(T_e, n_e) n_e(r)\, n_W(r) \mathrm{d}V$$

- For calibration shot:

$$L_W^{Cali} = \Delta P_{rad}^{Cali} / (\Delta I_{W-UTA}^{Cali}/n_e)$$

- For target shot:

$$P_W = L_W^{Cali} \cdot (I_{W-UTA}/n_e) = \int L_W(T_e, n_e) n_e(r)\, n_W(r) \mathrm{d}V$$
$$= \int L_W(T_e, n_e) n_e^2(r)\, c_W f_{c_W}(r) \mathrm{d}V$$
$$c_W = L_W^{Cali} \cdot (I_{W-UTA}/n_e) / \int L_W(T_e, n_e) n_e^2(r)\, f_{c_W}(r) \mathrm{d}V$$

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

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^{W42+}-I^{W45+}

$$I^{W^{q+}} = \int \varepsilon_{W^{q+}}\,\mathrm{d}l = \int n_{W^{q+}}(l)\mathrm{PEC}^{W^{q+}}(l)n_e(l)\mathrm{d}l$$

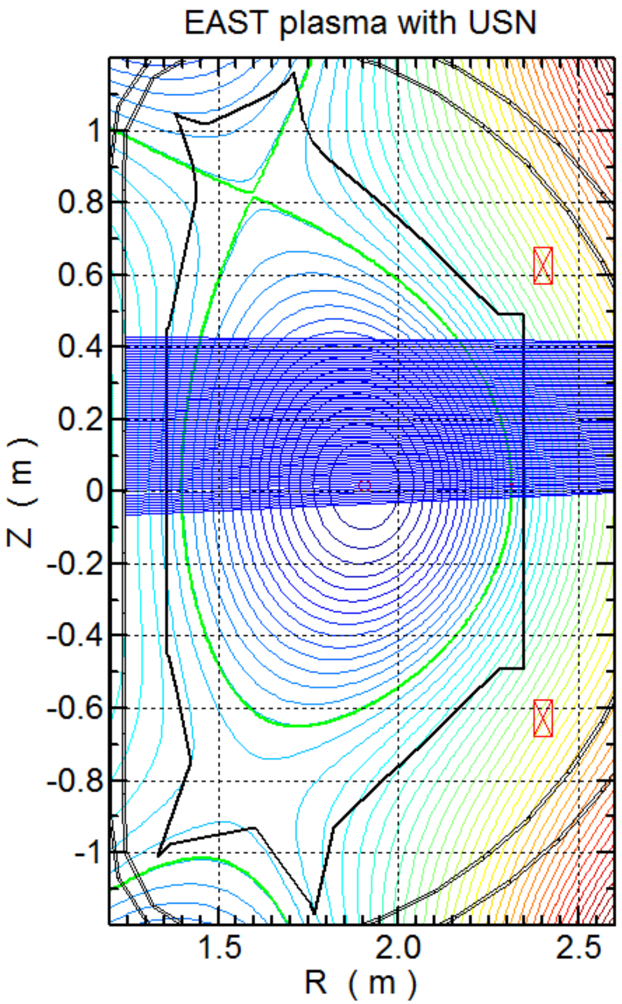
- Multi-channel I^{Wq+} (e.g. 64 channels for EUV_Long2)

EFIT
Abel Inversion

$\varepsilon_{wq+}(r)$

$T_e(r)$, n_e (r), $PEC(T_e,n_e)$

$n_{wq+}(r)$



I^{Wq+} : measured chord-integrated line intensity from W^{q+}

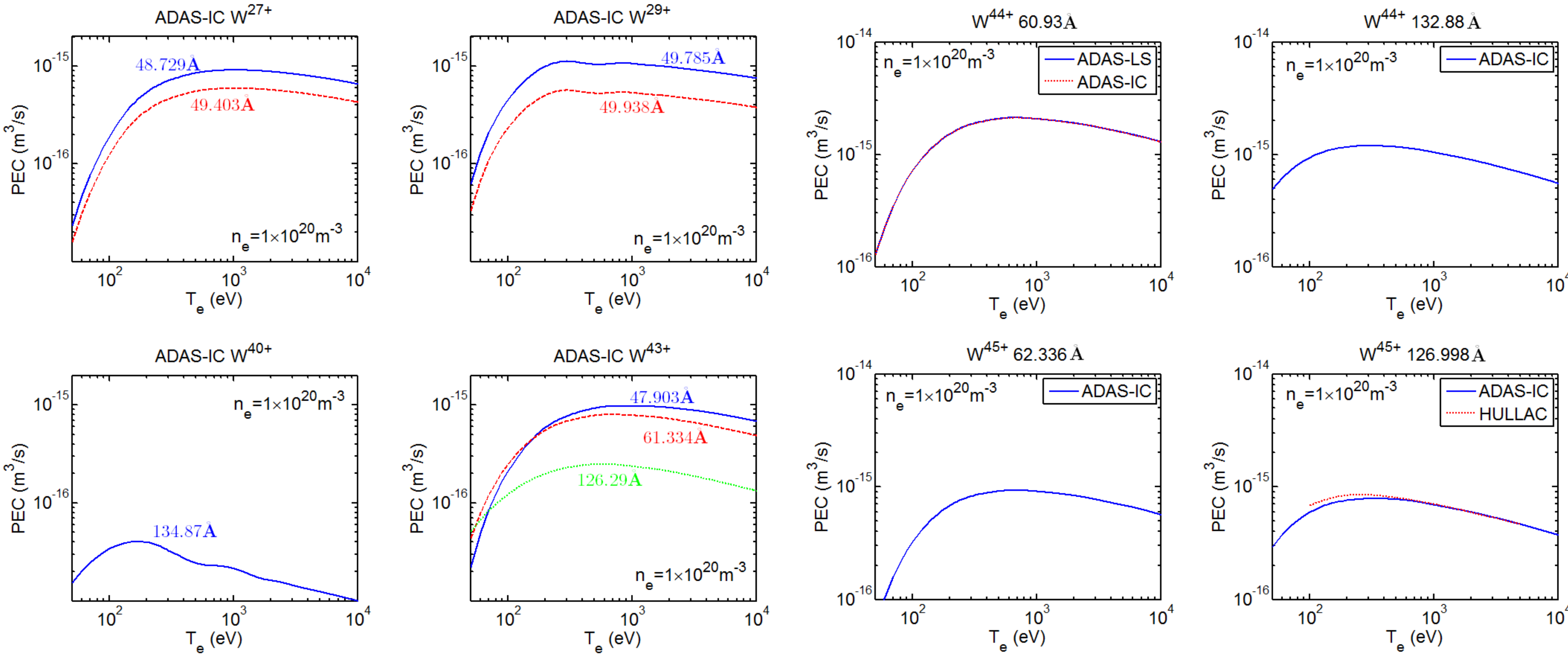
ε_{wq+}: emissivity of line from W^{q+}

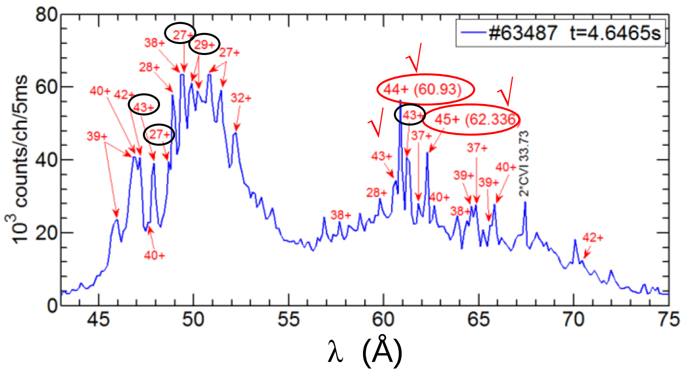
n_{Wq+} : density of W^{q+}

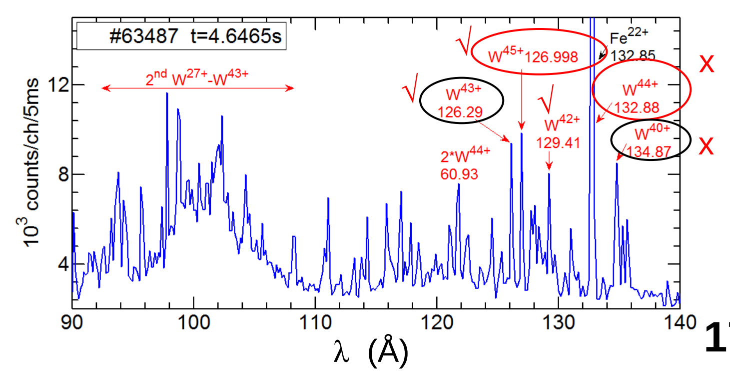
PEC^{Wq+} : photon emissivity coefficient of line from W^{q+}

Atomic data (1): PEC (photon emissivity coef.) of W lines

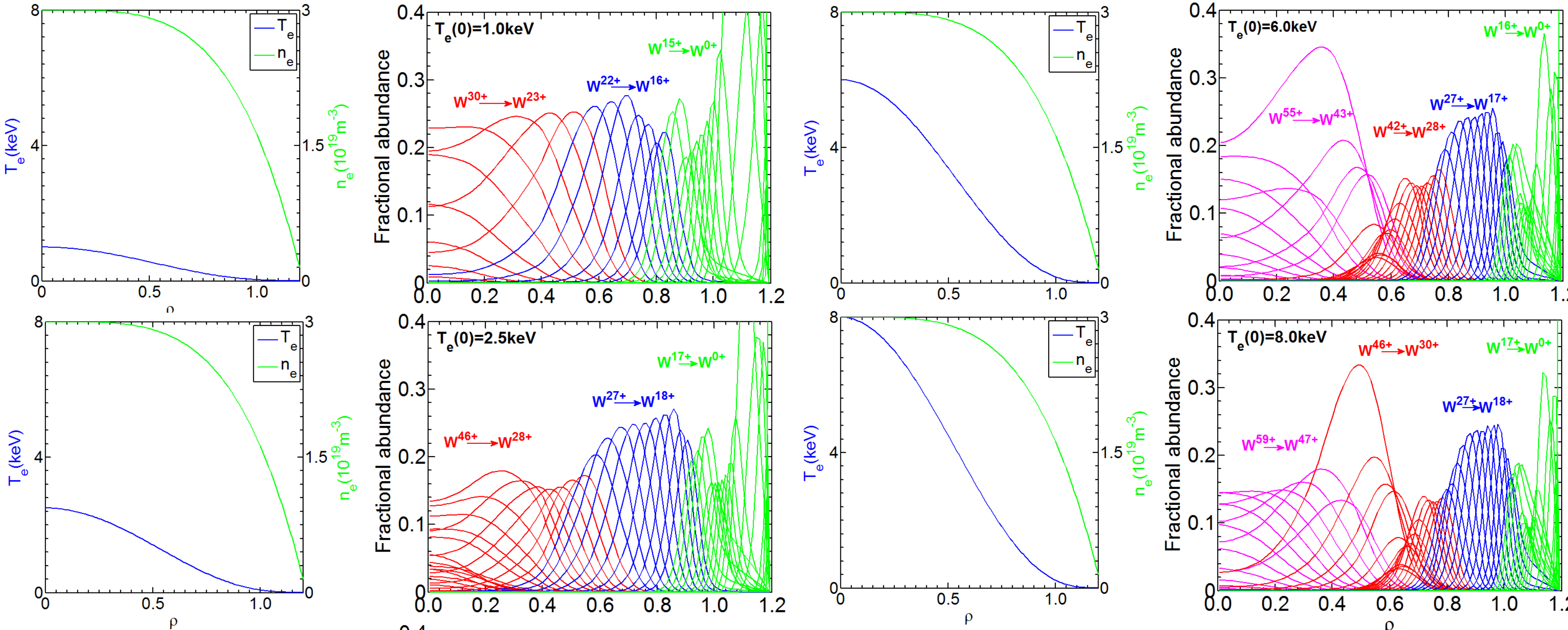
- ADAS-IC: with J-resolved fine structure energy levels (arf40_ic series)
- ADAS-LS: with J-unresolved LS levels (arf40_ls series)

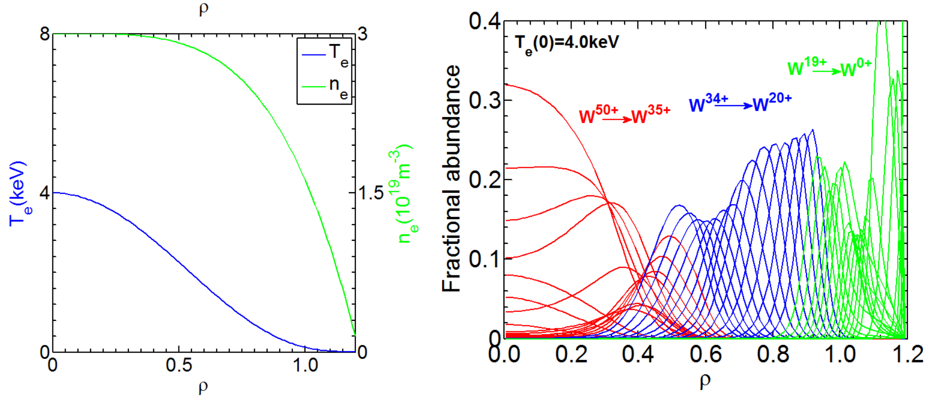






Atomic data (2): Fractional Abundance of W^{q+} ions

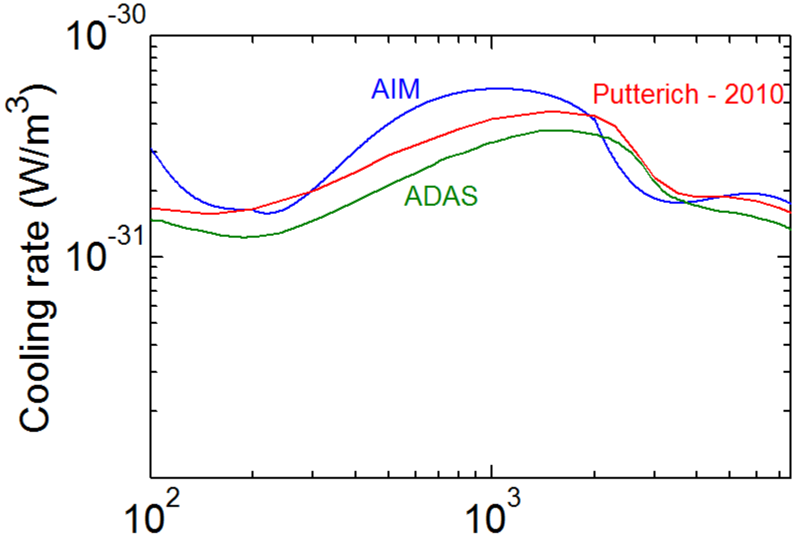




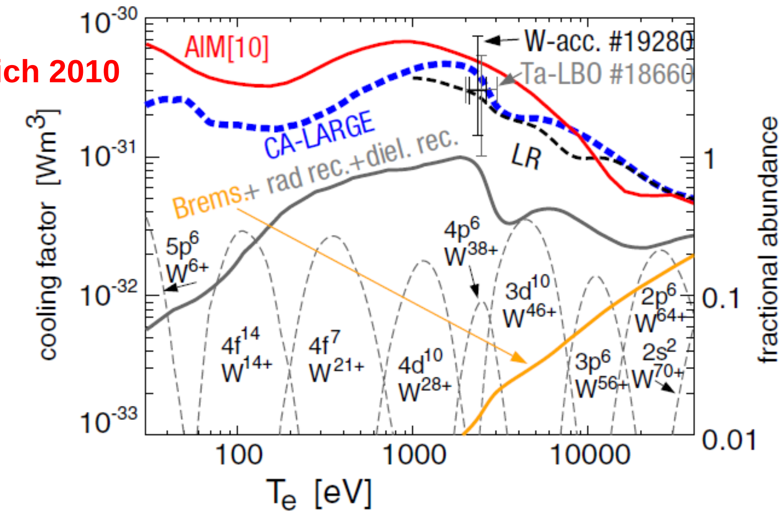
- **Data from open-ADAS are used in the set of rate equations.**
  - Effective ionization coefficient (scd50_w.dat)
  - Effective recombination coefficient (acd50_w.dat)
- **Effect of impurity transport should be considered.**

Atomic data (3): Tungsten cooling rate

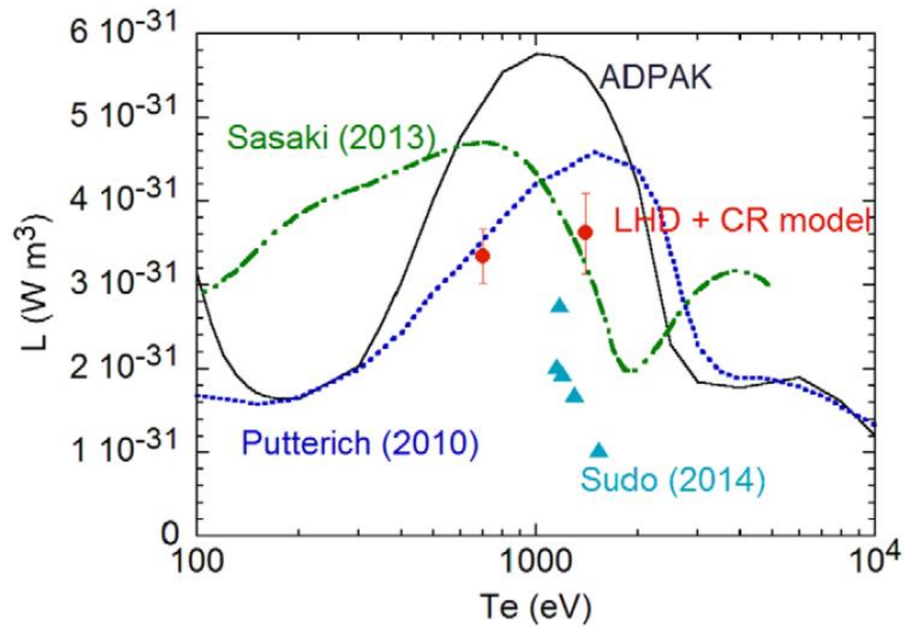
D Post et al., At. Data Nucl. Data Tables 20(1977) 397
Open-ADAS
T Pütterich et al., Nucl. Fusion 50(2010) 025021



Pütterich 2010



I Murakami et al., Nucl. Fusion 55(2015) 093016



LHD experiment & CR model (line emission)

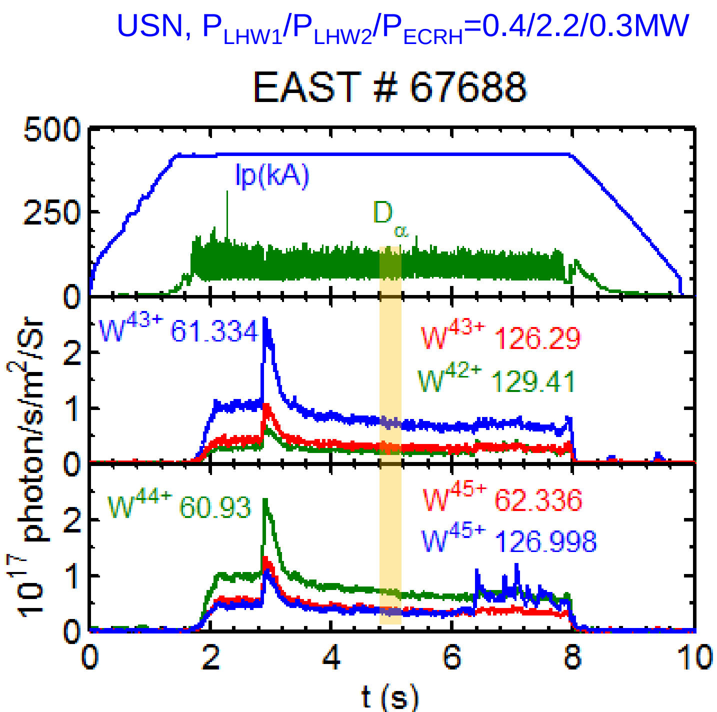
Original ADPAK model: average ion model

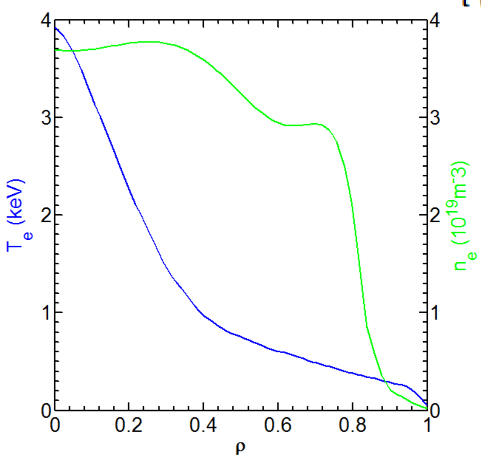
Sasaki and Murakami model

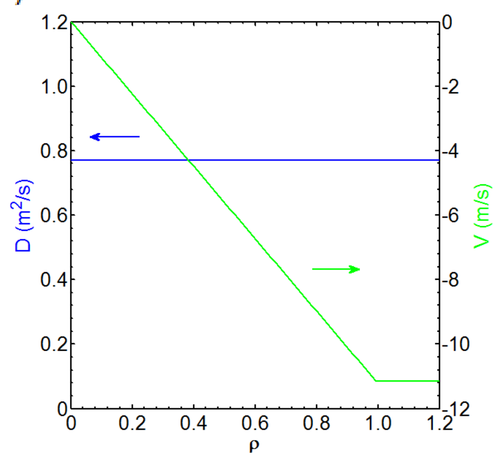
Pütterich calculation

Estimation from bolometer measurement

W concentration in steady-state ELMy H-mode







Method		$n_W(0)/n_e(0)$	N_W/N_e
PEC	W^{42+} 129.41Å	1.1×10^{-3}	3.9×10^{-4}
	W^{43+} 61.334Å	4.5×10^{-5}	1.6×10^{-5}
	W^{43+} 126.29Å	6.3×10^{-5}	2.3×10^{-5}
	W^{44+} 60.93Å	1.6×10^{-5}	5.6×10^{-6}
	W^{45+} 62.336Å	1.9×10^{-5}	6.7×10^{-6}
	W^{45+} 126.998Å	2.4×10^{-5}	8.8×10^{-6}
Cooling rate	AIM	4.3×10^{-5}	1.5×10^{-5}
	Pütterich	5.3×10^{-5}	1.9×10^{-5}
	ADAS	9.1×10^{-5}	3.2×10^{-5}

- The evaluated Cw from W^{42+} is one order of magnitude higher than that from other lines
- The evaluated Cw is in the range of 5×10^{-6}-3×10^{-5}

Summary & Future work

ASIPP

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 5×10^{-6} - 3×10^{-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