Exploration of emission spectra from highly charged tungsten impurity ions in X-ray wavelength range of 3.7–4.0 Å in the Large Helical Device for fusion plasma diagnostics

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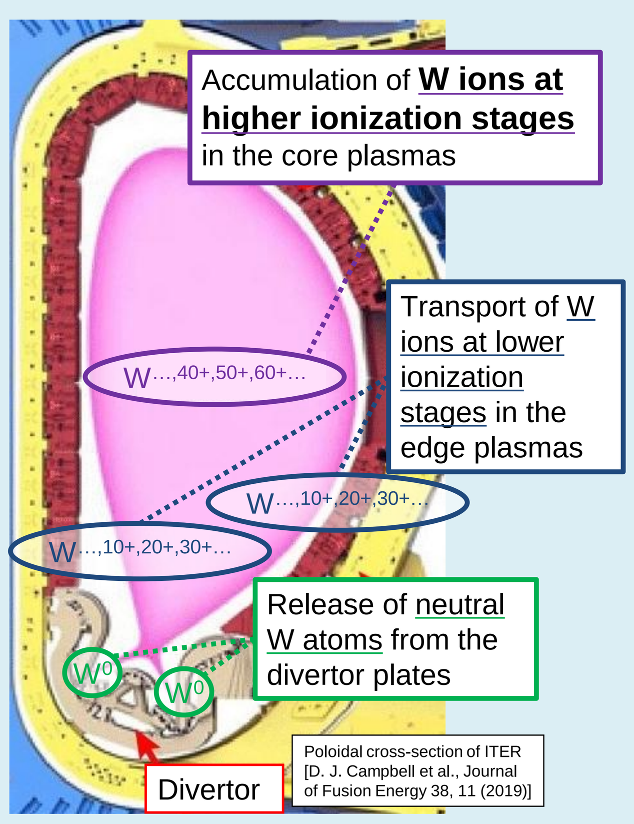
Summary

- **Spectroscopic measurements of tungsten ions have been conducted in the Large Helical Device (LHD) using tungsten pellets to investigate high-Z impurity transport in fusion plasmas and to expand the spectral database.**
- **Numerous emission lines with W^{42+}–W^{47+} are newly observed in the X-ray wavelength range of 3.7–4.0 Å.** **W^{47+} 3.7691 Å represents a new charge state region for the LHD experiment.**
- **Possibility of simultaneous measurement for W emission intensity, ion temperature, T_i, and electron temperature, T_e, have been demonstrated as follows.**
  - **W^{47+} line intensity is useful as an indicator of tungsten impurities in the electron temperature region around 4 keV.**
  - **In T_i measurement using Doppler broadening of W^{46+} 3.8784 Å, accurate evaluation of the instrument function, $\Delta\lambda_{Ins}$, is extremely important.**
  - **W^{46+} 3.8784 Å / 3.8956 Å ratio is useful for T_e measurement.**

1. Introduction

- **Tungsten (W) is regarded as a leading candidate material for the plasma facing component in ITER and future fusion reactors.**



Production and transport processes of the tungsten impurity ions in the magnetically-confined torus plasmas.

Characteristics of tungsten:
- High melting point
- Low sputtering rate
- Large radiation loss due to high Z

… It is very important to investigate the behavior of tungsten in high temperature plasmas in order to control tungsten transport and establish reliable operation scenarios for fusion reactors.

W emission line measurement by spectroscopy:
(Charge states and main emission wavelength range)

- Neutral W atoms: Visible spectroscopy
- W ions at lower ionization stages: VUV spectroscopy
- W ions at higher ionization stages: EUV and **X-ray** spectroscopy

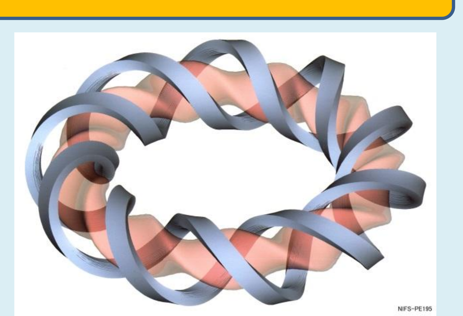
… Simultaneous measurement of a wide range of wavelengths and charge states is required for a comprehensive understanding of the tungsten impurity behavior.

Spectroscopic studies of emissions released from tungsten ions combined with a pellet injection technique have been conducted in the Large Helical Device (LHD) for contribution to the tungsten transport study in tungsten divertor fusion devices and for expansion of the experimental database of tungsten line emissions.

2. Experimental Setup

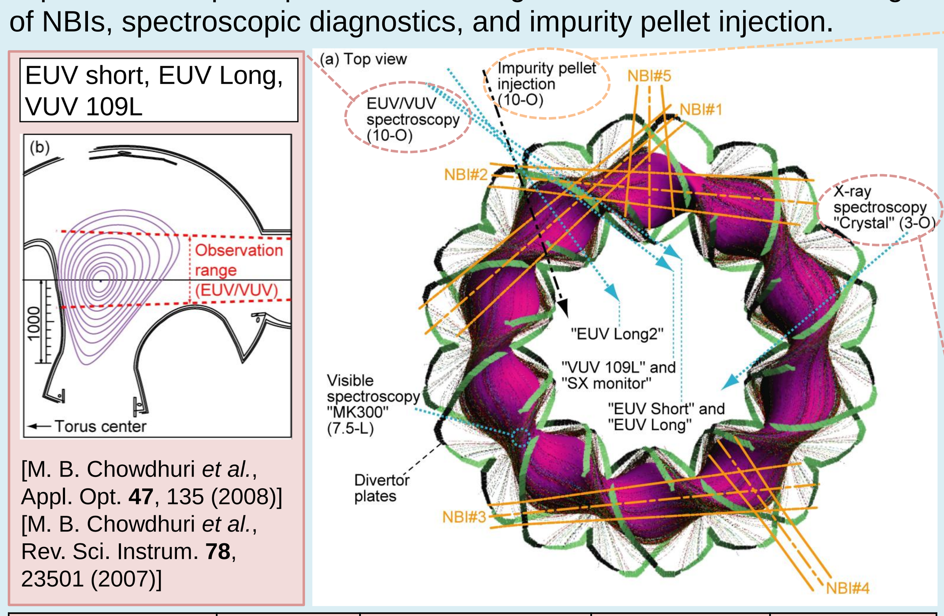
Large Helical Device

- A superconducting plasma confinement device with a heliotron magnetic configuration
- R = 3.6 m, $<a>$ = 0.64 m, B_t < 3 T. T_e < 5 keV in this study
- toroidal/poloidal period number = 10/2
- Heating: ECH (electron cyclotron heating), NBI (neutral beam injection)
  - negative ion source (n-NBI): NBI#1, #2, #3
  - positive ion source (p-NBI): NBI#4, #5



W pellet injection & spectroscopy

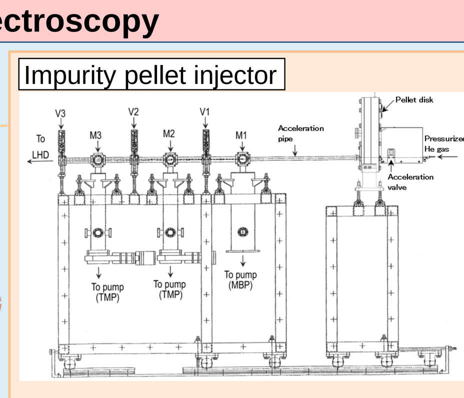
Top view of shape of plasma in LHD together with schematic drawings of NBIs, spectroscopic diagnostics, and impurity pellet injection.



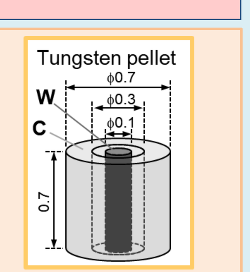
[M. B. Chowdhuri *et al.*, Appl. Opt. **47**, 135 (2008)]
[M. B. Chowdhuri *et al.*, Rev. Sci. Instrum. **78**, 23501 (2007)]

Spectrometer	Type	Grating (g/mm)	λ range (Å)	dλ/dx (Å/mm)
EUV Short	Grazing incidence	2400	5 – 130	1.2 – 4.3
EUV Long	Grazing incidence	1200	50 – 500	4.0 – 11.0
VUV 109L	Normal incidence	1200	300 – 1050	32.7

Impurity pellet injector



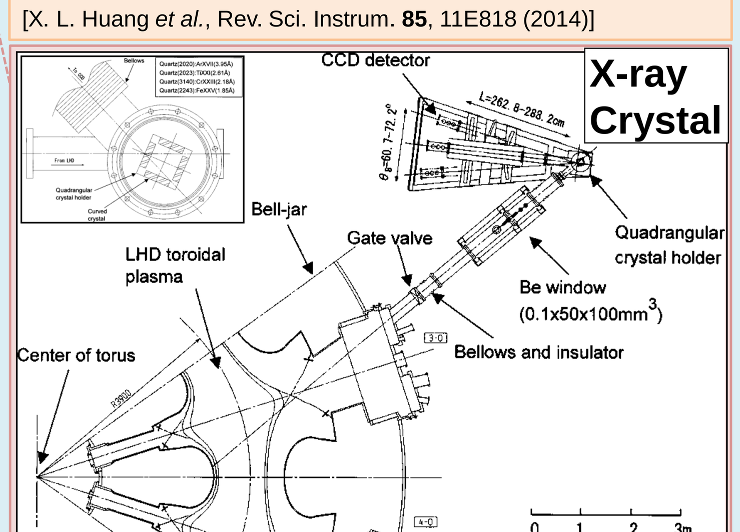
Tungsten pellet



W wire in a C pellet: l 0.7 mm × ϕ0.1 mm ~3.5×10¹⁷ W atoms

[X. L. Huang *et al.*, Rev. Sci. Instrum. **85**, 11E818 (2014)]

X-ray Crystal



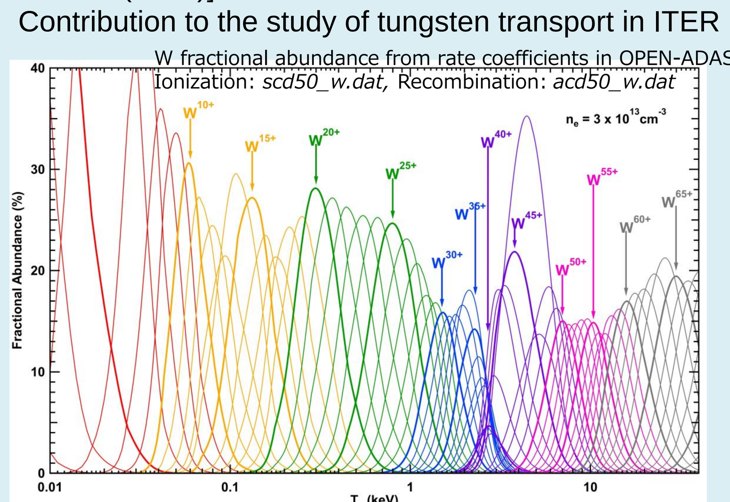
Crystal for Ar XVII (3.9492 Å)	
Quartz	(2020)
Lattice spacing 2d (Å)	4.2554
Curvature radius 2R (mm)	1500
Bragg angle θ_B (deg.)	68.13
Wavelength λ range (Å)	3.7 – 4.0
Dispersion dλ/dx (10^{-3} Å/mm)	1.6 – 1.1

Detector CCD: 1024 × 256 pixels, pixel size 26 × 26 μm²

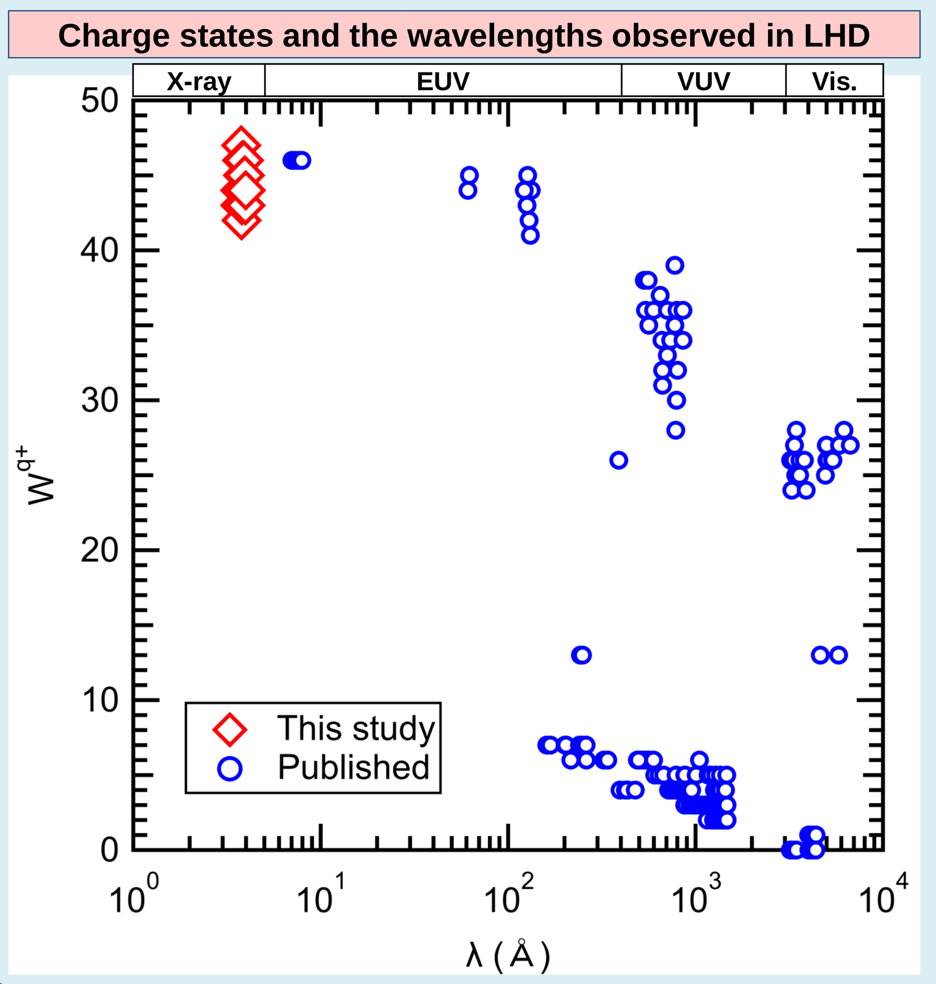
[S. Morita and M. Goto, Rev. Sci. Instrum. **74**, 2375 (2003)]

- Simultaneous charge range and wide charge state range measurement [T. Oishi *et al.*, Nuclear Fusion **64**, 106011 (2024)]
- Contribution to the study of tungsten transport in ITER

W fractional abundance from rate coefficients in OPEN-ADAS
Ionization: *scd50_w.dat*, Recombination: *acd50_w.dat*

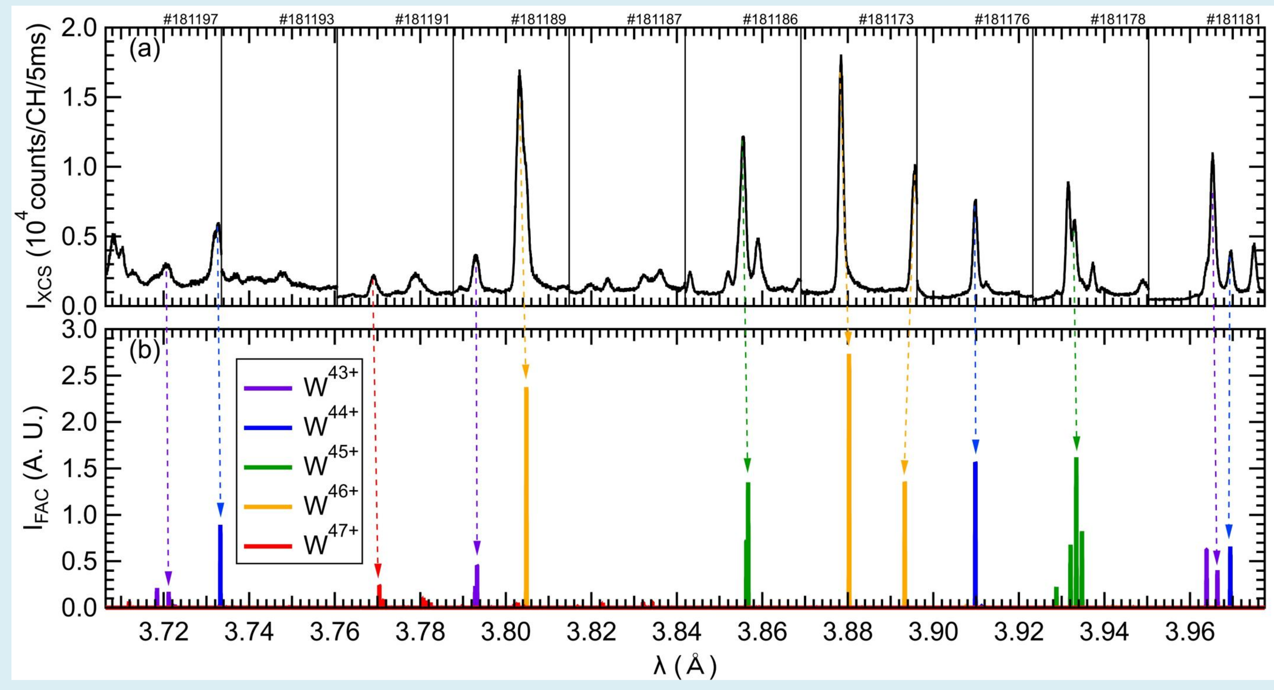


Charge states and the wavelengths observed in LHD



3. Measurement Results

3-1. Newly observed W^{43+}–W^{47+} X-ray spectra in 3.7–4.0 Å



λ_{XCS} (Å)	λ_{FAC} (Å)	W^{q+}	Lower level	Upper level	Ref.
3.7204	3.7212	43+	$3d^{10}4s^24p$	$3d^94s^24p7f$	C-Mod
3.7323	3.7332	44+	$3d^{10}4s^2$	$3d^94s^27f$	C-Mod
3.7691	3.7704	47+	$3d^9$	$3d^86f$	C-Mod
3.7783	3.7778	42+	$3d^{10}4s^24p^2$	$3d^94s^24p^27f$	C-Mod
3.7930	3.7933	43+	$3d^{10}4s^24p$	$3d^94s^24p7f$	C-Mod
3.8033	3.8048	46+	$3d^{10}$	$3d^96f$	NIST
3.8555	3.8567	45+	$3d^{10}4s$	$3d^94s6f$	NIST
3.8784	3.8805	46+	$3d^{10}$	$3d^96f$	C-Mod
3.8956	3.8941	46+	$3d^{10}$	$3d^95d$	C-Mod
3.9098	3.9098	44+	$3d^{10}4s^2$	$3d^94s^26f$	NIST
3.9330	3.9334	45+	$3d^{10}4s$	$3d^94s6f$	NIST
3.9655	3.9664	43+	$3d^{10}4s^24p$	$3d^94s^24p6f$	C-Mod
3.9751	3.9694	44+	$3d^{10}4s^2$	$3p^53d^{10}4s^25d$	C-Mod

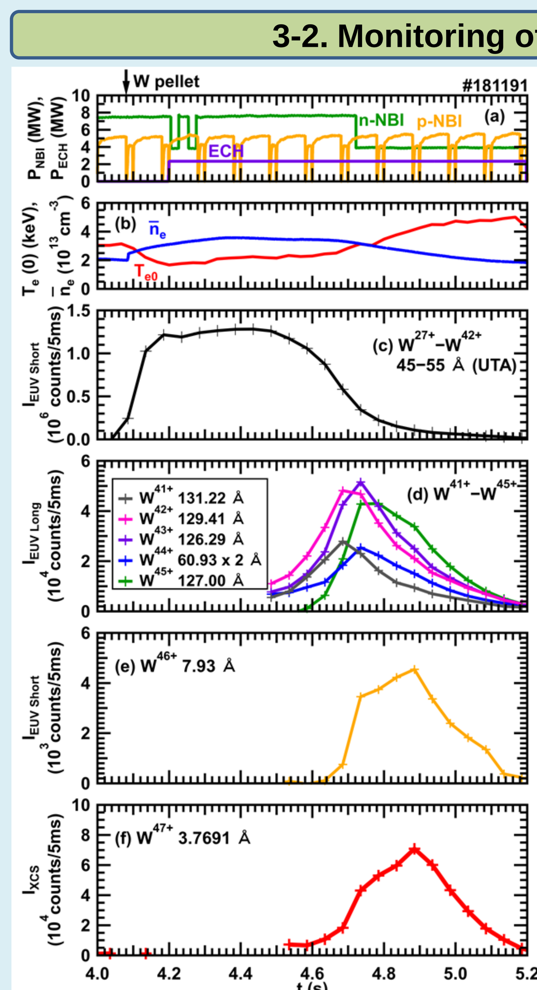
[NIST] A. Kramida et al., NIST Atomic Spectra Database (version 5.12), https://physics.nist.gov/asd (2025, Sep. 22), National Institute of Standards and Technology, Gaithersburg, MD.
[C-Mod] J. E. Rice et al., J. Phys. B: At. Mol. Opt. Phys. **54**, 095701 (2021)]

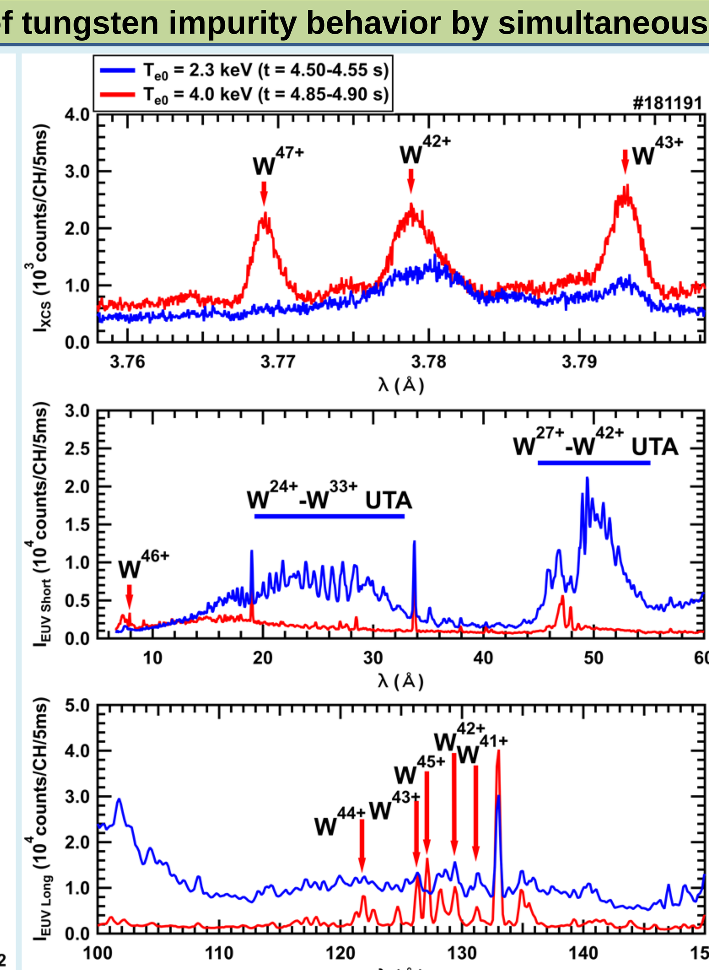
λ_{XCS} (Å) for newly observed but unidentified W lines
3.7082, 3.7101, 3.7129, 3.7477, 3.8199, 3.8239, 3.8324, 3.8359, 3.8431, 3.8520, 3.8590, 3.8686, 3.9123, 3.9290, 3.9316, 3.9346, 3.9373, 3.9396

- H working gas, H neutral beams, R_{ax} = 3.6m, B_t = 2.75 T (CCW in the top view)
- Spectra of W ions measured by an **X-ray crystal spectrometer (XCS)** during the time period when T_{e0} was around 4 keV.
- 10 discharges were merged to cover the 3.7−4.0 Å wavelength range.
- Identification of charge states by comparison with calculations using **Flexible Atomic Code (FAC)** [M.F. Gu, Astrophys. J., **582** (2003) 1241.]
  - Calculation of energy levels, spontaneous emission coefficients, and collision cross sections
  - Solve CR model with n_e, T_e to output emission spectrum

⇒ Numerous emission lines with **W^{42+}–W^{47+}** are newly observed. **W^{47+} 3.7691 Å ($3p^63d^9$–$3p^63d^86f$)** represents a new charge state region for the LHD experiment.

3-2. Monitoring of tungsten impurity behavior by simultaneous measurement of multiple charge states



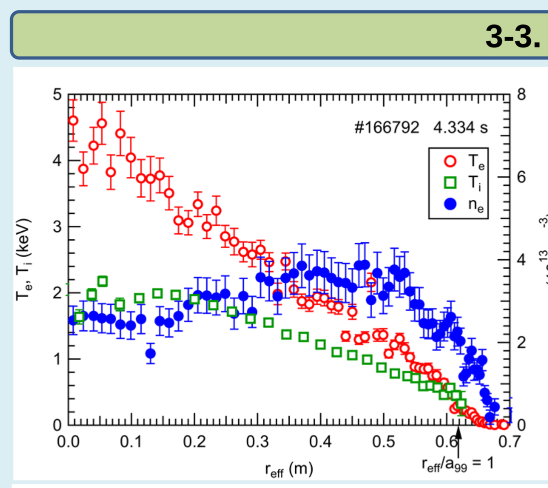


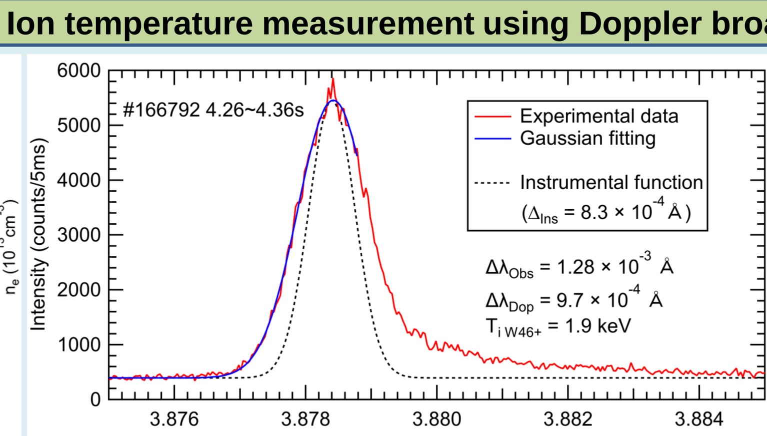
- Temporal evolution of (a) heating power of ECH and NBI, (b) T_{e0} and n_e, emission intensities of (c) UTA (unresolved transition array) spectra consisting of the charge range from W^{27+} to W^{42+}, (d) line spectra from W^{41+} to W^{45+}, (e) W^{46+}, and (f) W^{47+}.
- (c-e) and (f) are observed in the EUV and X-ray wavelength ranges, respectively (right-hand side panels)

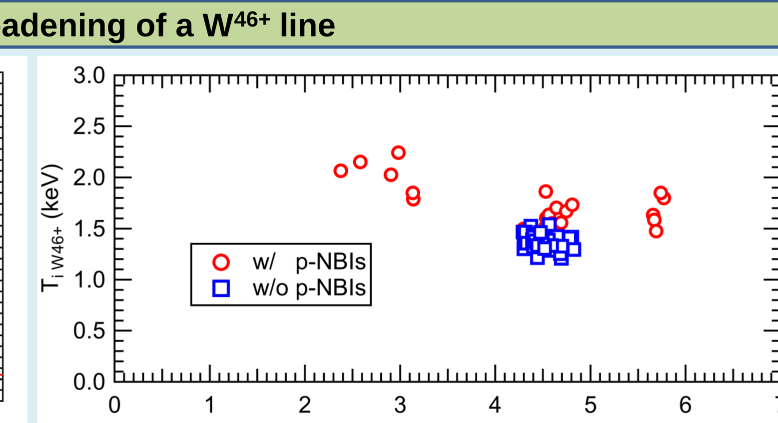
- T_{e0} increases from 1.7 keV to 5.0 keV
- For T_{e0} < 3 keV, the UTA at 45-55 Å of W^{27+}–W^{42+} serves as an indicator of tungsten impurities
- After t = 4.5 s, the UTA intensity decreases, and the W^{41+}–W^{47+} emission lines sequentially appear
- At t = 4.9 s, **W^{47+}** has a maximum value with **T_{e0} = 4.3 keV**

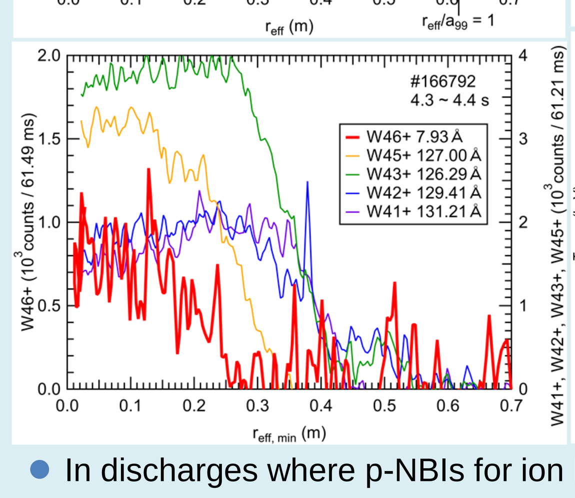
⇒ **W^{47+}** is useful as an indicator of tungsten impurities in the electron temperature region around **4 keV**.

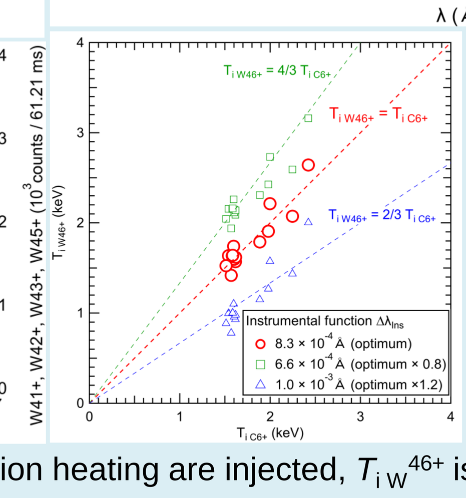
3-3. Ion temperature measurement using Doppler broadening of a W^{46+} line











- W^{46+} is localized in the plasma core in LHD… Doppler broadening in the spectrum reflects the ion temperature, T_i, in the plasma core.
- Observed wavelength broadening $\Delta\lambda_{Obs}$, **instrument function $\Delta\lambda_{Ins}$**, Doppler broadening $\Delta\lambda_{Dop}$ → W^{46+} ion temperature $T_{i\,W}{}^{46+}$

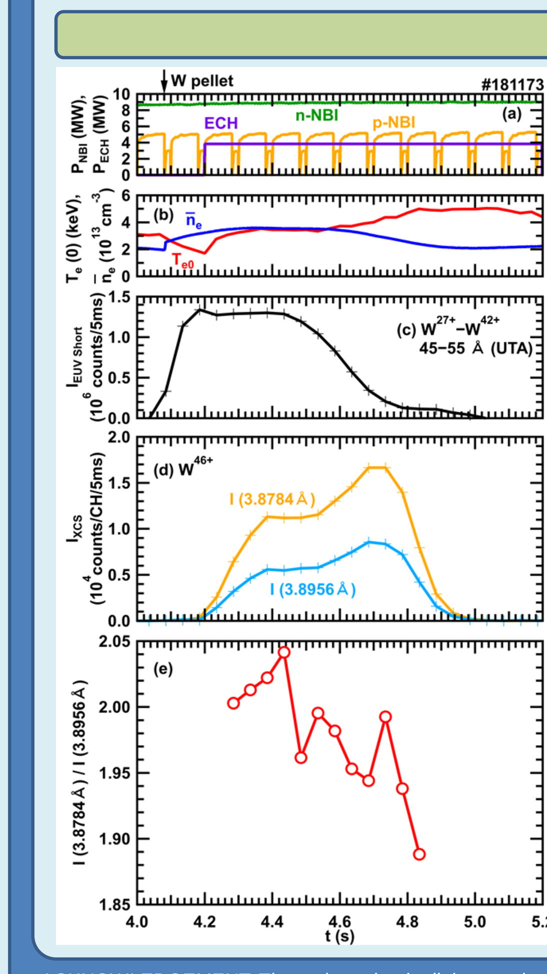
$$\Delta\lambda_{Dop}{}^2 = \Delta\lambda_{Obs}{}^2 - \Delta\lambda_{Ins}{}^2$$
$$T_{i\,W46+} = 1.68 \times 10^8 M_{i\,W46+} (\Delta\lambda_{Dop} / \lambda_0)^2$$

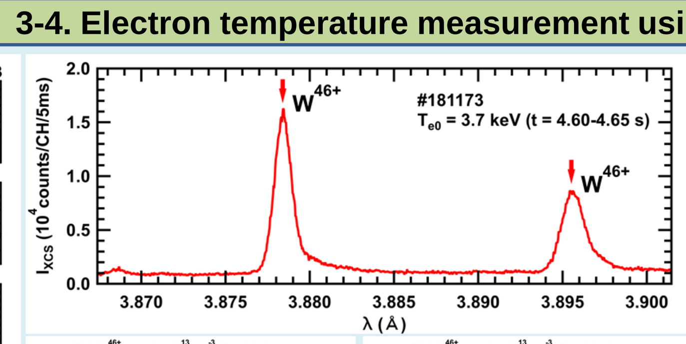
- **The optimal value of $\Delta\lambda_{Ins}$** was determined such that **$T_{i\,W}{}^{46+}$** becomes equal to the central ion temperature measured by charge-exchange recombination spectroscopy, **$T_{i\,C}{}^{6+}$**.

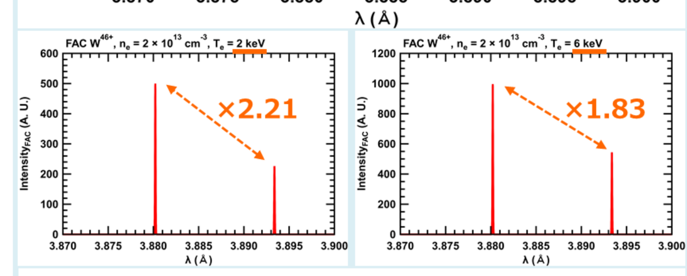
- In discharges where p-NBIs for ion heating are injected, $T_{i\,W}{}^{46+}$ is approximately 0.2 to 0.3 keV higher compared to discharges without p-NBIs.

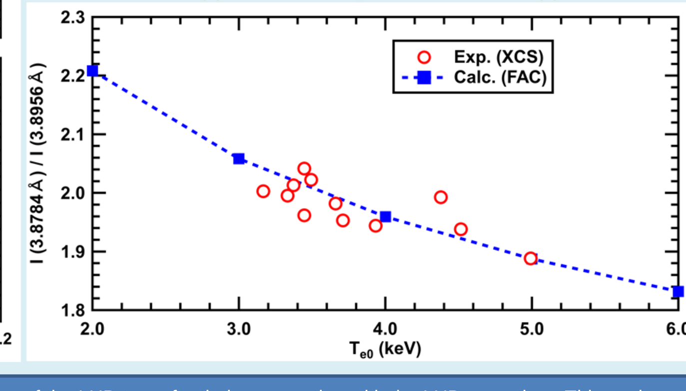
⇒ In **T_i measurement** using **Doppler broadening of W^{46+}**, **accurate evaluation of $\Delta\lambda_{Ins}$** is extremely important.

3-4. Electron temperature measurement using a W^{46+} line intensity ratio









- Temporal evolution of (a) heating power of ECH and NBI, (b) T_{e0} and n_e, emission intensities of (c) W^{27+} to W^{42+} UTA, (d) W^{46+} 3.8784 Å and 3.8956 Å lines, and (f) line intensity ratio between the two W^{46+} lines.
- As T_e increases, the **line intensity ratio between W^{46+} 3.8784 Å ($3p^63d^{10}$−$3p^63d^96f$) and W^{46+} 3.8956 Å ($3p^63d^{10}$−$3p^53d^{10}5d$)** decreases.
- FAC calculations reproduce the observed T_e dependence of the line intensity ratio.
- In the electron density range of 10^9–10^{15} cm^{-3}, no density dependence of the line intensity ratio is observed (confirmed by FAC calculations).

⇒ **W^{46+} 3.8784 Å / 3.8956 Å ratio** is useful for **T_e measurement**.

X-ray spectroscopy measurements have successfully demonstrated the possibility of simultaneously measuring the W impurity emission intensity, ion temperature, and electron temperature.

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