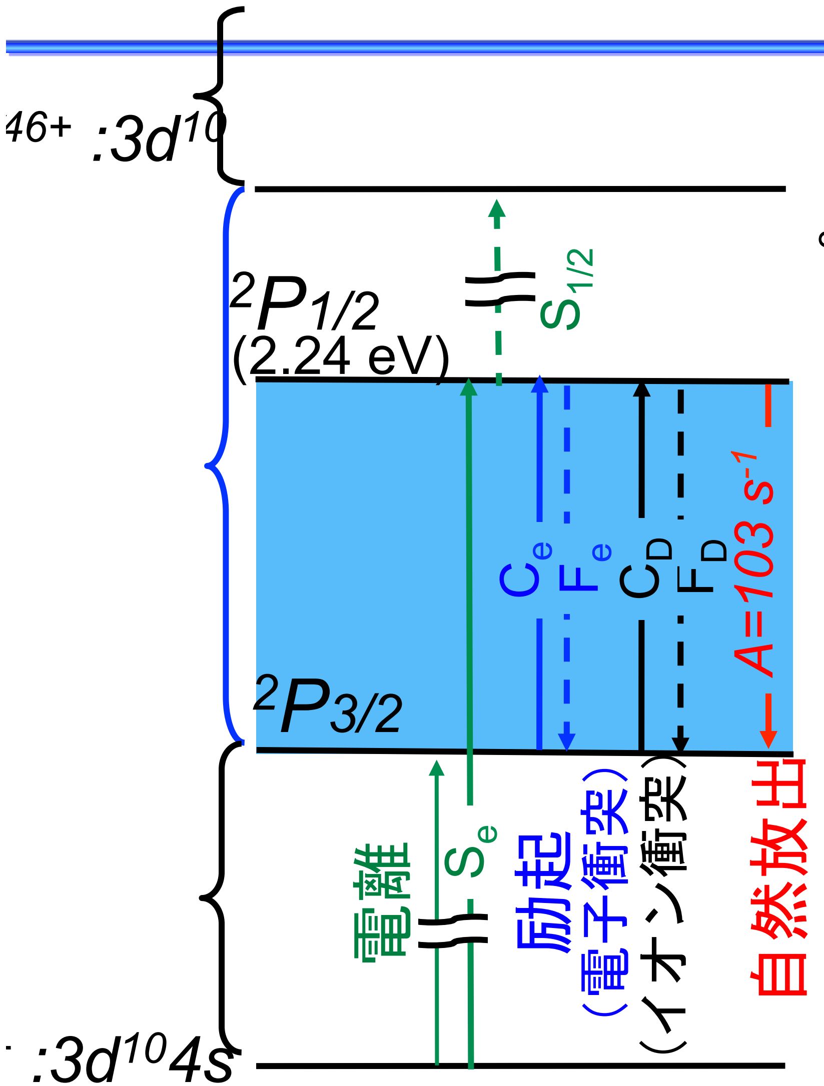
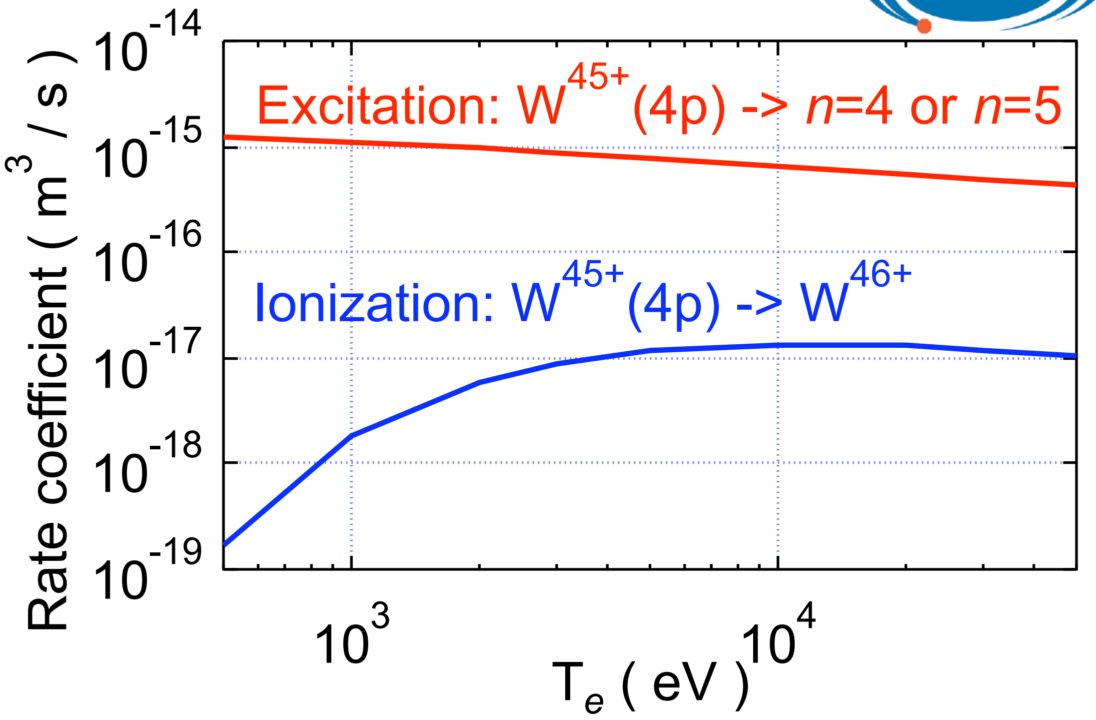
Measurement of W^{44+} and W^{45+} density ratio in JT-60U

T. Nakano and H. Kubo
Japan Atomic Energy Agency

Acknowledge to J. Yanagibayashi at Kyoto Univ.
A. Sasaki at JAEA

Colonal model is valid





S_e

F_e

C_e

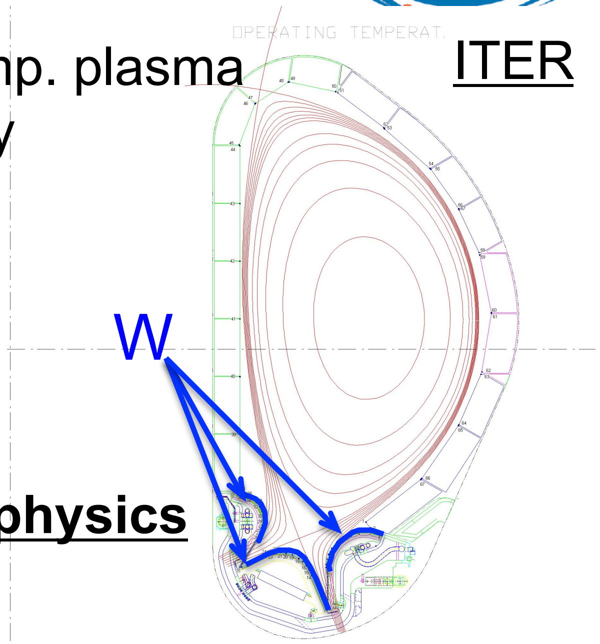
$$\varepsilon_{1/2\rightarrow 3/2} = \frac{A}{F_D n_D + F_e n_e + A + n_e S_{1/2}}\left[\left(n_D C_D + n_e C_e\right) n_{Ar9+} + n_e S_e n_{Ar8+}\right]$$

Introduction: Atomic Physics and Fusion Research

Tungsten as a plasma-facing component

Merit : high melting point => compatible with high temp. plasma
: low hydrogen (T) retention => safety, economy
: low sputtering yield => long lifetime

Demerit : high Z (74)
=> highly radiative(allowable $n_W/n_e < 10^{-5}$)
=> accumulation in the core plasma*)



Highly charged W ions from a view point of atomic physics

Atomic structure, CI, QED, ,,,

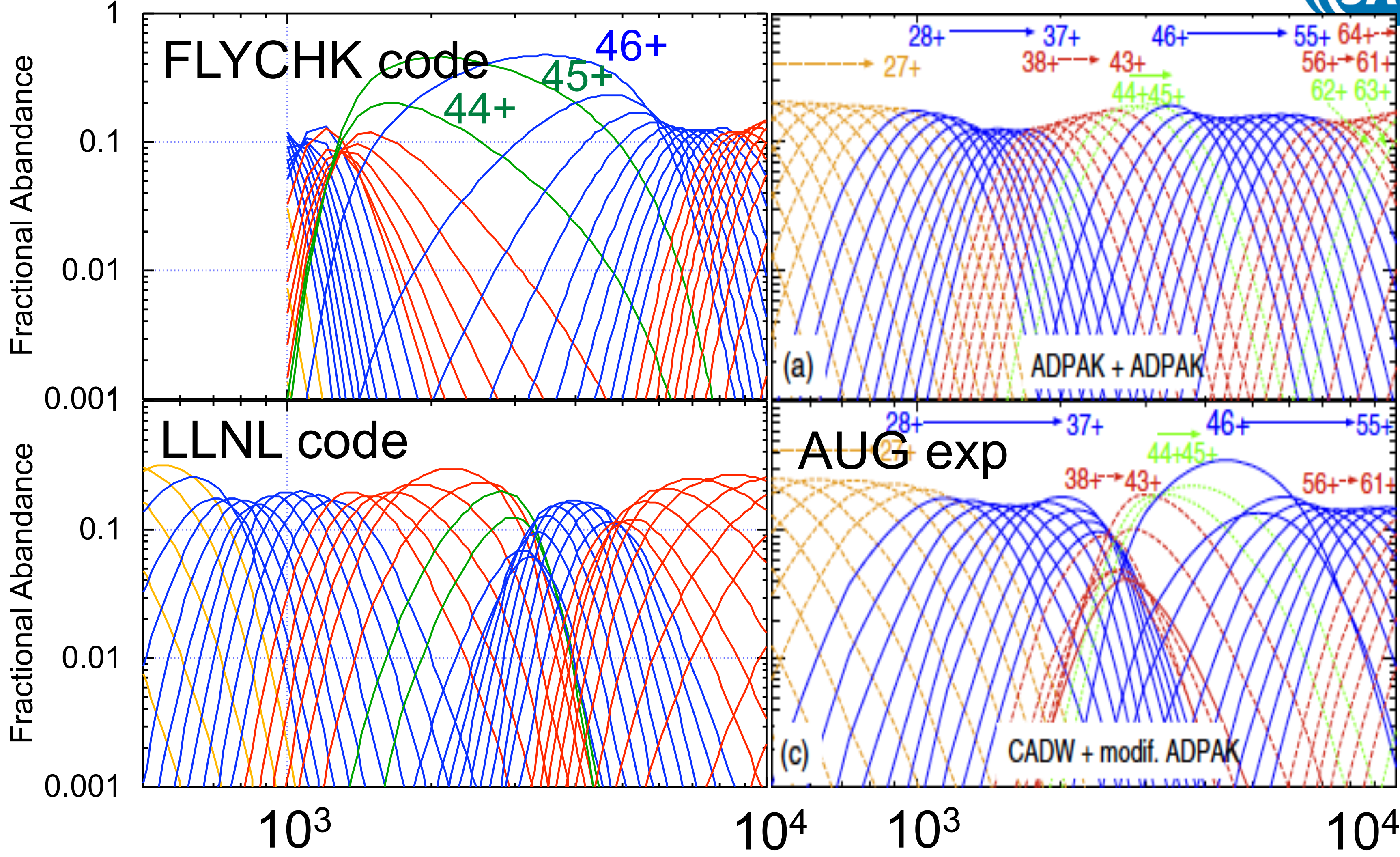
Interface between atomic physics and fusion research

spectral data (wavelength, A coeff.) collisional data (ioniz./recomb coeff.)	⟷	W density (W charge state distribution)

High temp. plasma of JT-60U (> 10 keV) can produce highly charged W ions (> 60+). Studies of atomic physics are possible, contributing to plasma physics.

*) T. Nakano *et al*., Nucl. Fusion **49** (2009) 115024.

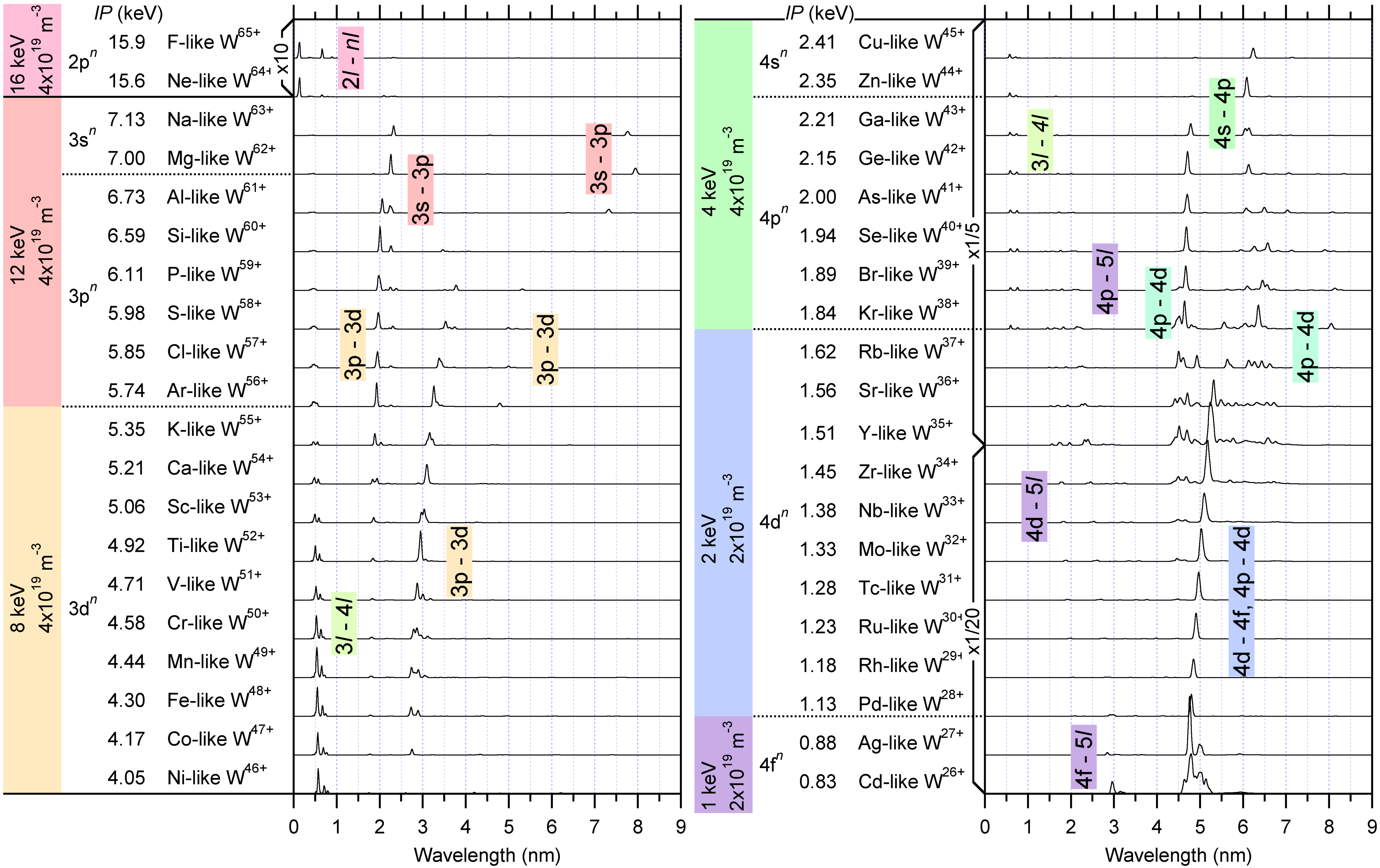
Significant difference in Ionization equilibrium



Experimental validation needed
=>JT-60U plasmas

T Putterich *et al* Plasma Phys. Control. Fusion **50** (2008) 085016

W spectra calculated by FAC

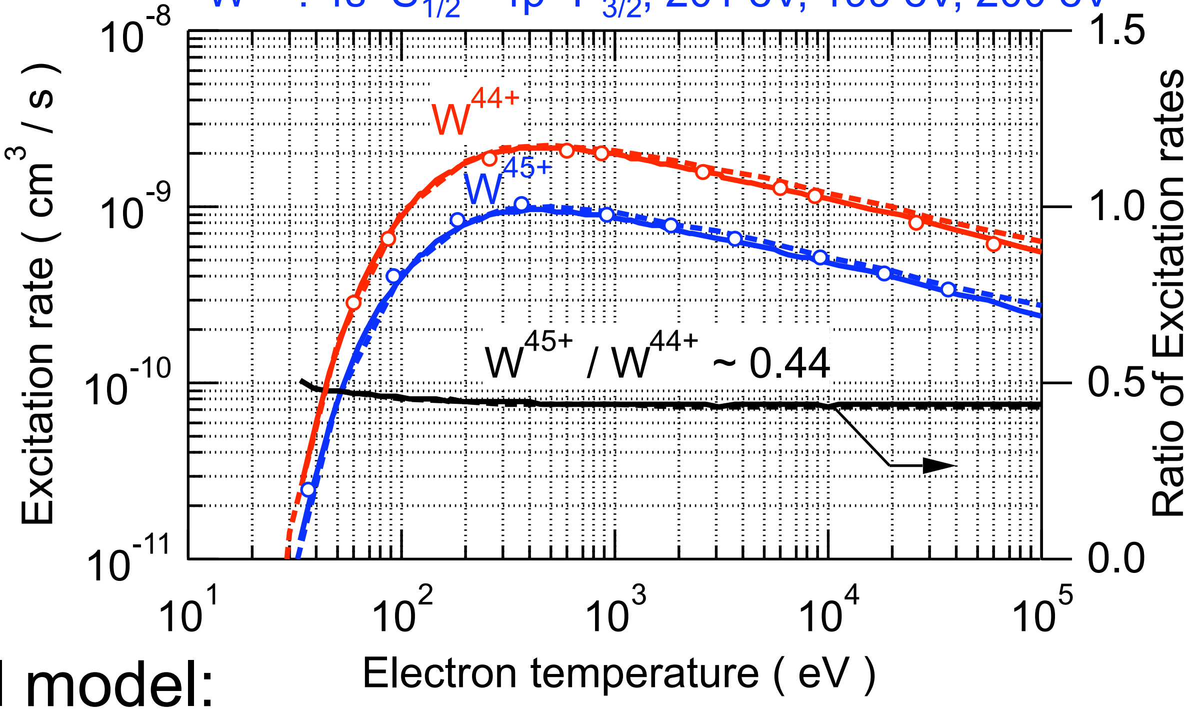


Constant excitation ratio of W^{45+} and W^{44+} for 4s-4p transition

LLNL, FAC, ORNL*

W^{44+}: $4s^2\ ^1S_0$ - $4s4p\ ^1P_1$, 205 eV, 204 eV, 205 eV ~ 6.1 nm

W^{45+}: $4s\ ^2S_{1/2}$ - $4p\ ^2P_{3/2}$, 201 eV, 199 eV, 200 eV ~ 6.2 nm



Coronal model:

$$I^{W45+}(4s \leftarrow 4p) = A(4s,4p) \bullet nW^{45+}(4p) = C^{45+}(4s,4p) \bullet nW^{45+}(4s) \bullet n_e$$

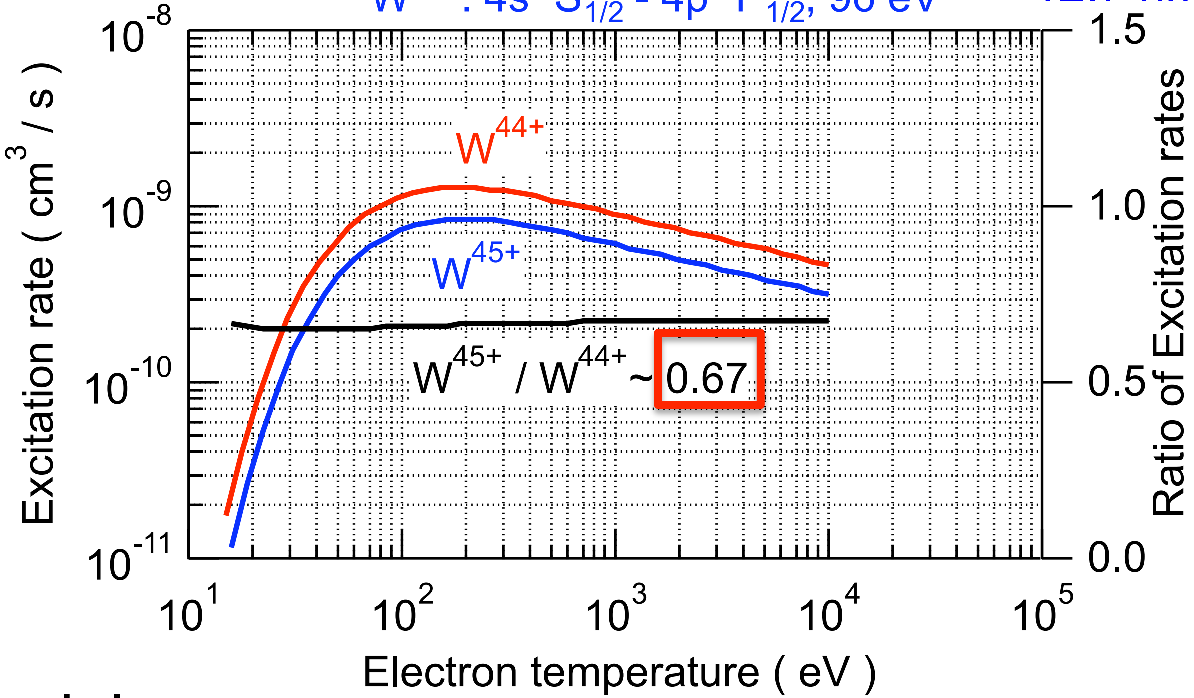
$$I^{W44+}(4s \leftarrow 4p) = A(4s,4p) \bullet nW^{44+}(4p) = C^{44+}(4s,4p) \bullet nW^{44+}(4s) \bullet n_e$$

$$\sim 0.44 \bullet \frac{nW^{45+}(4s)}{nW^{44+}(4s)}$$

Constant excitation ratio of W^{45+} and W^{44+} for 4s-4p transition

W^{44+}: $4s^2\ {}^1S_0$ - $4s4p\ {}^3P_1$, 90.2 eV ~ 13.3 nm

W^{45+}: $4s\ {}^2S_{1/2}$ - $4p\ {}^2P_{1/2}$, 96 eV ~ 12.7 nm



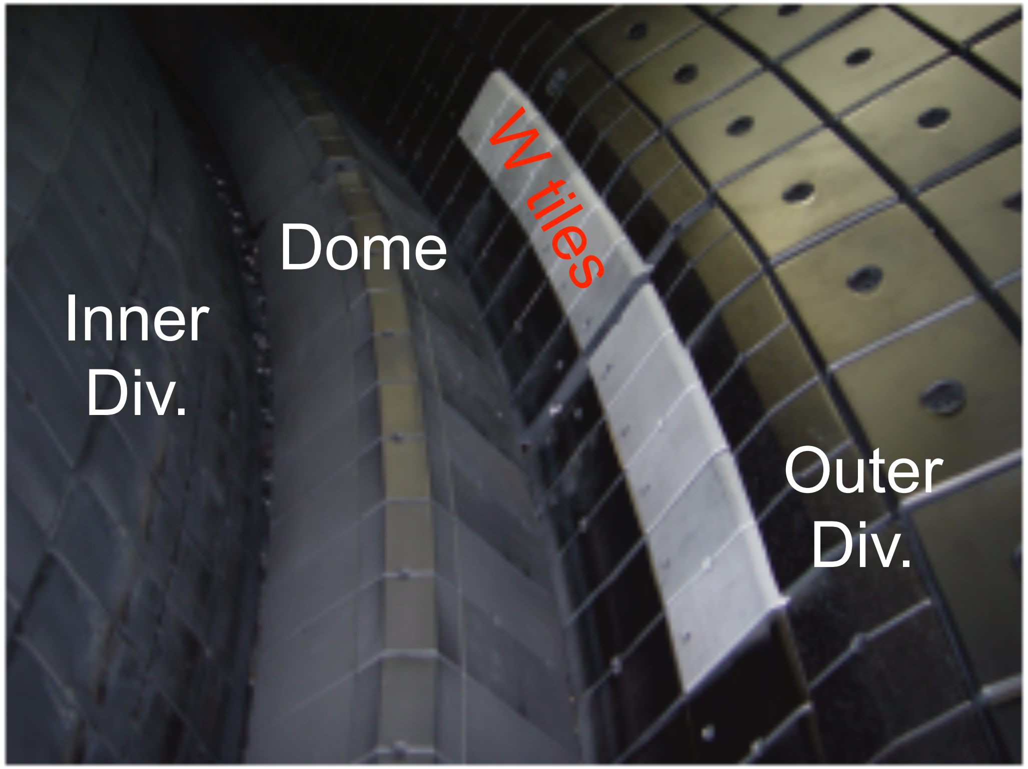
Coronal model:

$$I^{W45+}(4s \leftarrow 4p) = A(4s,4p) \bullet nW^{45+}(4p) = C^{45+}(4s,4p) \bullet nW^{45+}(4s) \bullet n_e$$

$$I^{W44+}(4s \leftarrow 4p) = A(4s,4p) \bullet nW^{44+}(4p) = C^{44+}(4s,4p) \bullet nW^{44+}(4s) \bullet n_e$$

$$\sim 0.67 \bullet \frac{nW^{45+}(4s)}{nW^{44+}(4s)}$$

W divertor plates in JT-60U

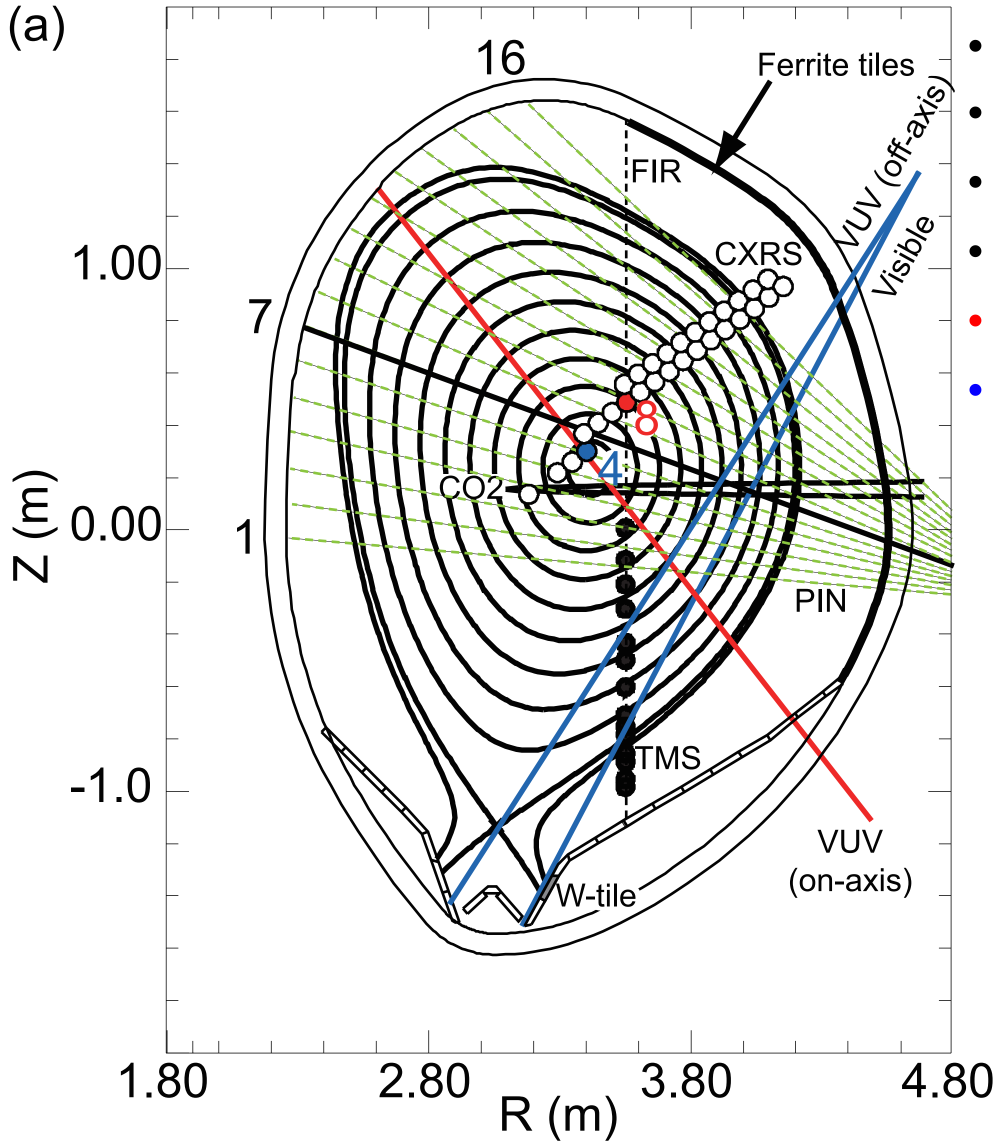


<u>W coated CFC tiles:</u>

50 μm with Re multi-layer

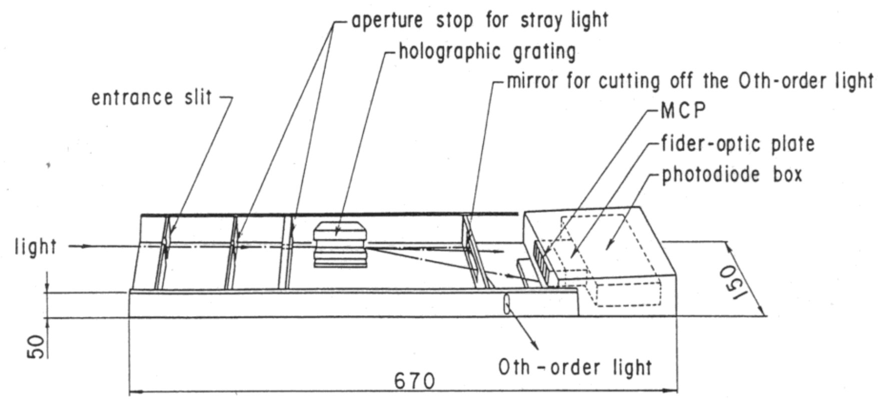
12 tiles (1/21 toroidal length)

Diagnostics



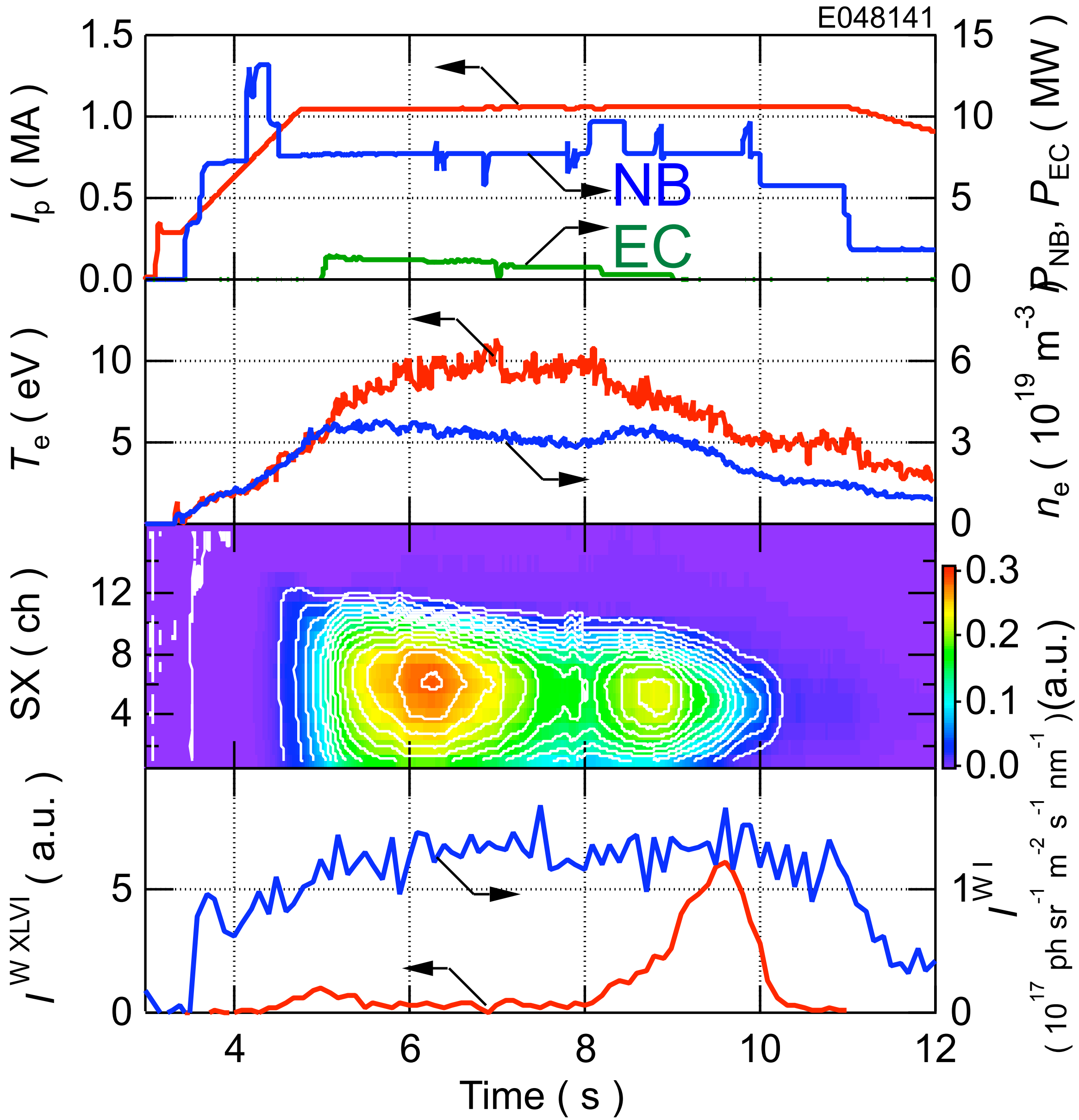
Flat-field grazing incidence spectrometer

- Incident angle: 89°
- Wavelength range : 0.5 - 40 nm
- Wavelength resolution: 0.01 nm @ 5 nm
- Time resolution : 20 ms
- On-axis : for plasma core
- Off-axis : for plasma edge



PIN Soft X-ray (>3keV)
CXRS Toroidal rotation
TMS T_e, n_e
FIR, CO2 line density

Waveform of Reversed Shear discharge with EC injection



Reversed shear discharge:
W accumulation occurs
even with
1. positive toroidal rotation
2. EC injection

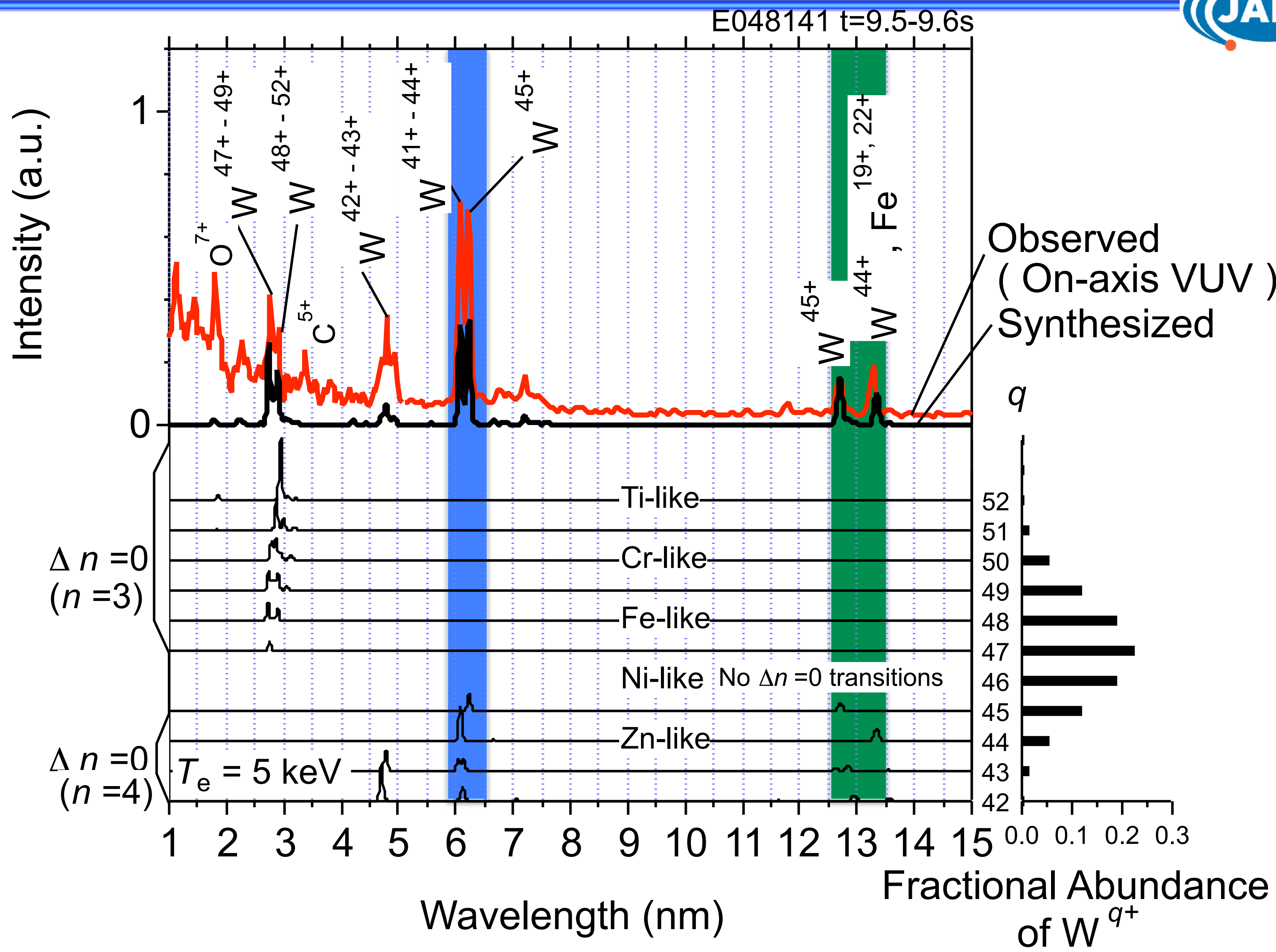
T_e decreases after t=8 s.

Waveform of W^{45+} intensity is NOT similar to that of SX.

During T_e decrease, I^{W45+} increases, and then decreases => T_e scan

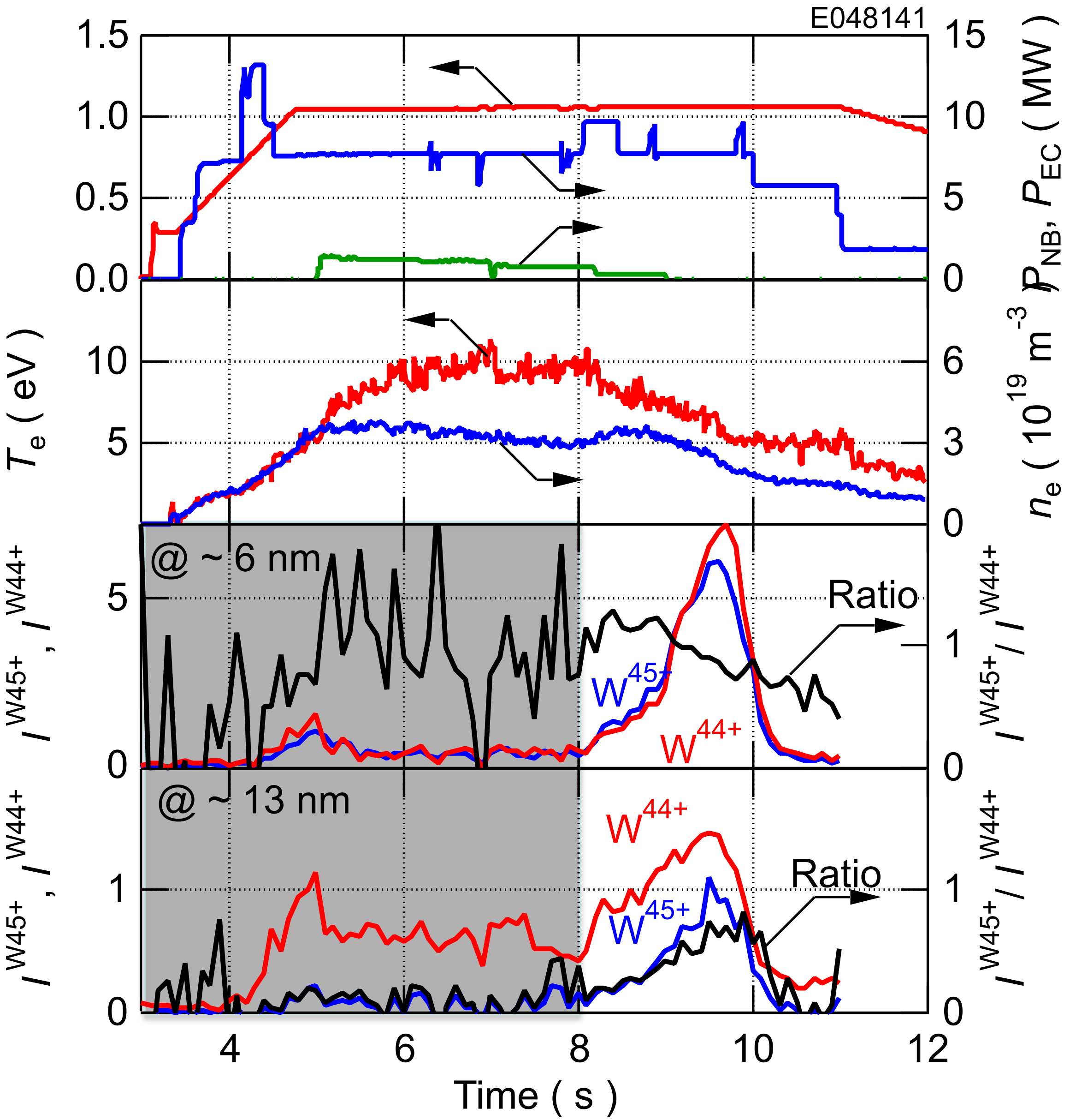
VUV Spectrum

W^{44+} at 6.1 nm blends with $W^{42+,43+}$
W^{44+} at 13.3 nm blends with $Fe^{19+,22+}$



Waveform

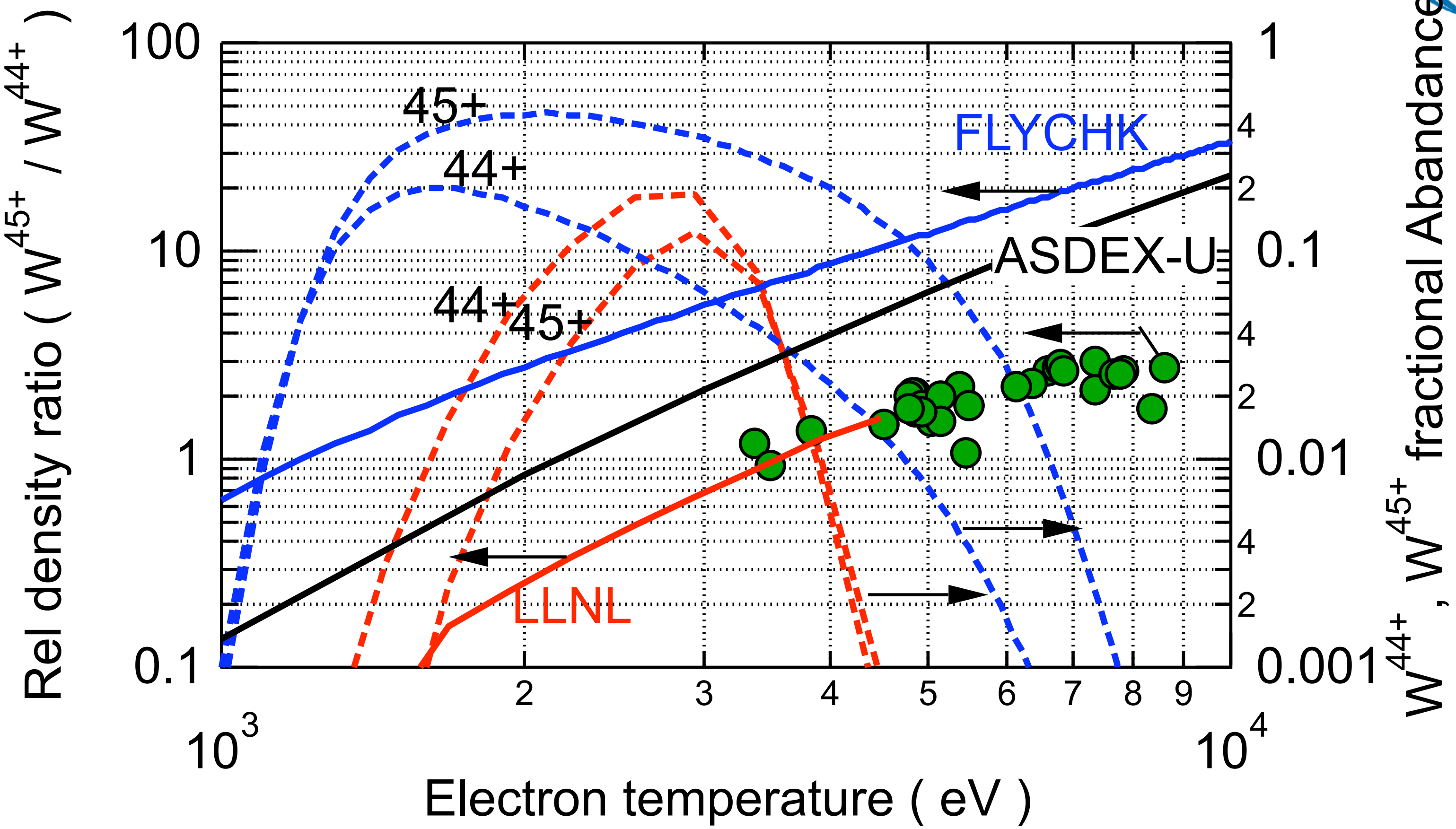
W^{44+} at 6.1 nm blends with $W^{42+,43+}$
W^{44+} at 13.3 nm blends with $Fe^{19+,22+}$



W^{45+}/W^{44+} ratio decreases with decreasing T_e.
used for analysis

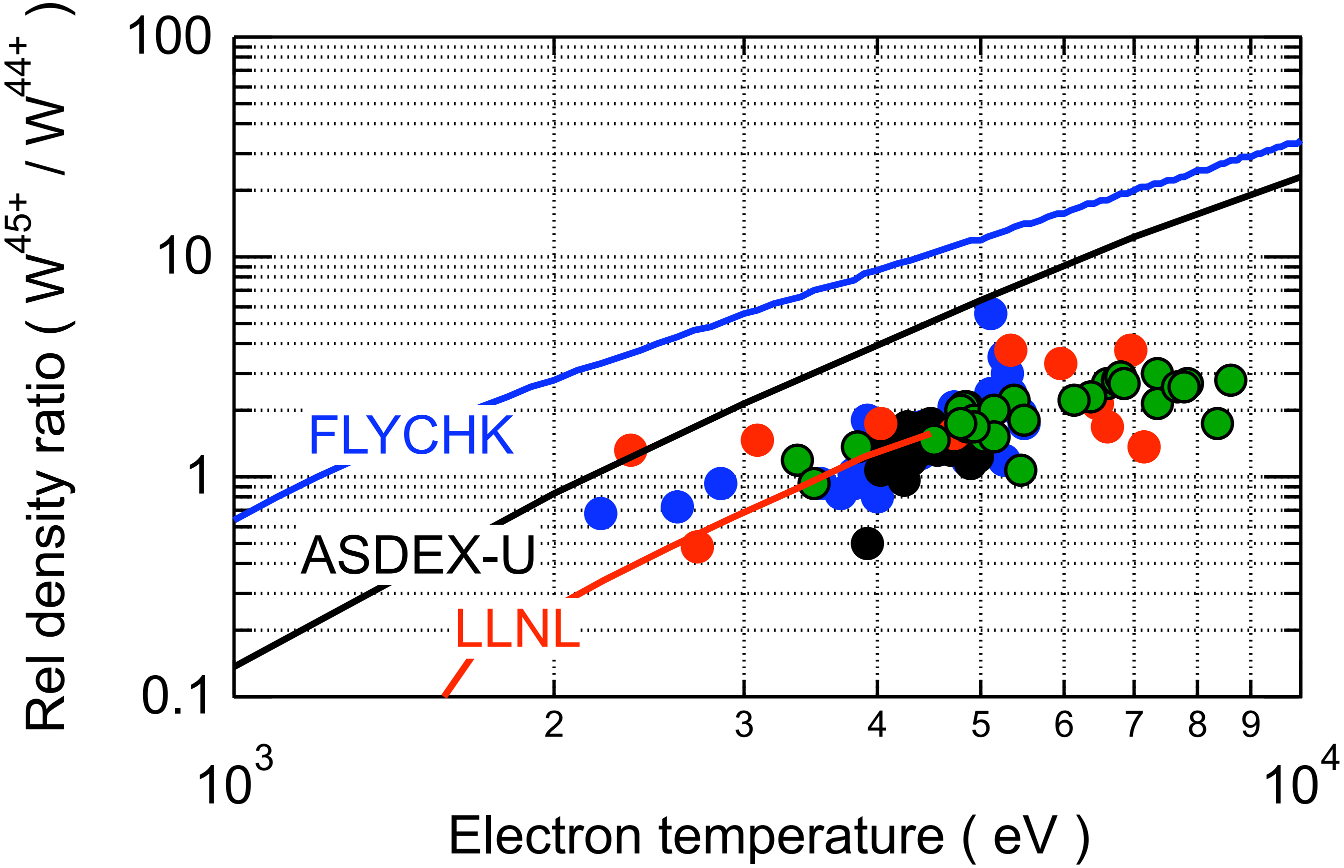
W^{45+}/W^{44+} ratio increases with decreasing T_e.
Blend is obvious at 4-8 s.
Not used for analysis

Measured W^{45+}/W^{44+} closer to LLNL than FLYCHK and AUG results



At high temperature, blend of W^{44+} with $W^{43+, 42+}$ should be low
⇒ high accuracy, better comparison
At low temperature, the blend reduces the W^{45+}/W^{44+} ratio
⇒ T_e-dependence should be weaker

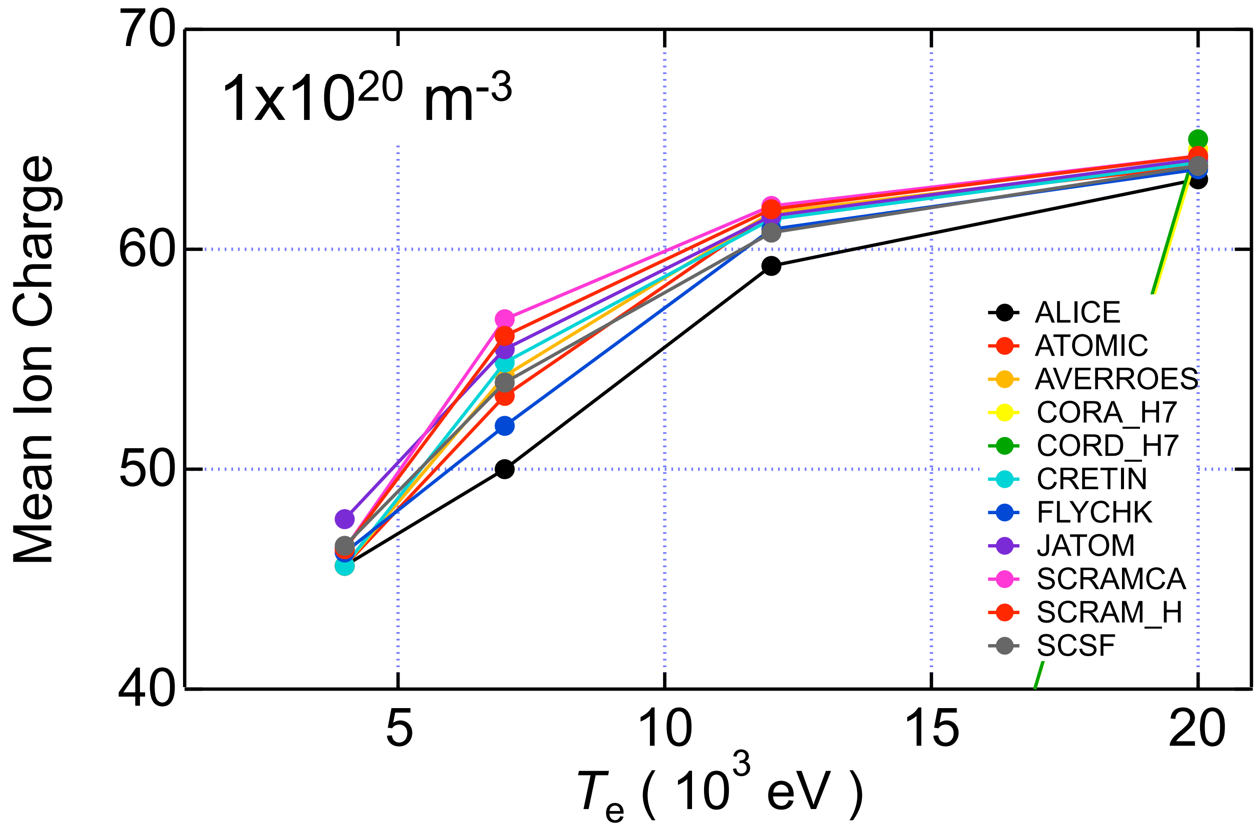
Measured W^{45+}/W^{44+} closer to LLNL than FLYCHK and AUG results



At high temperature, blend of W^{44+} with $W^{43+, 42+}$ should be low
⇒ high accuracy, better comparison
At low temperature, the blend reduces the W^{45+}/W^{44+} ratio
⇒ T_e-dependence should be weaker

Results from the 6th NLTE code comparison workshop

through the courtesy of A. Sasaki

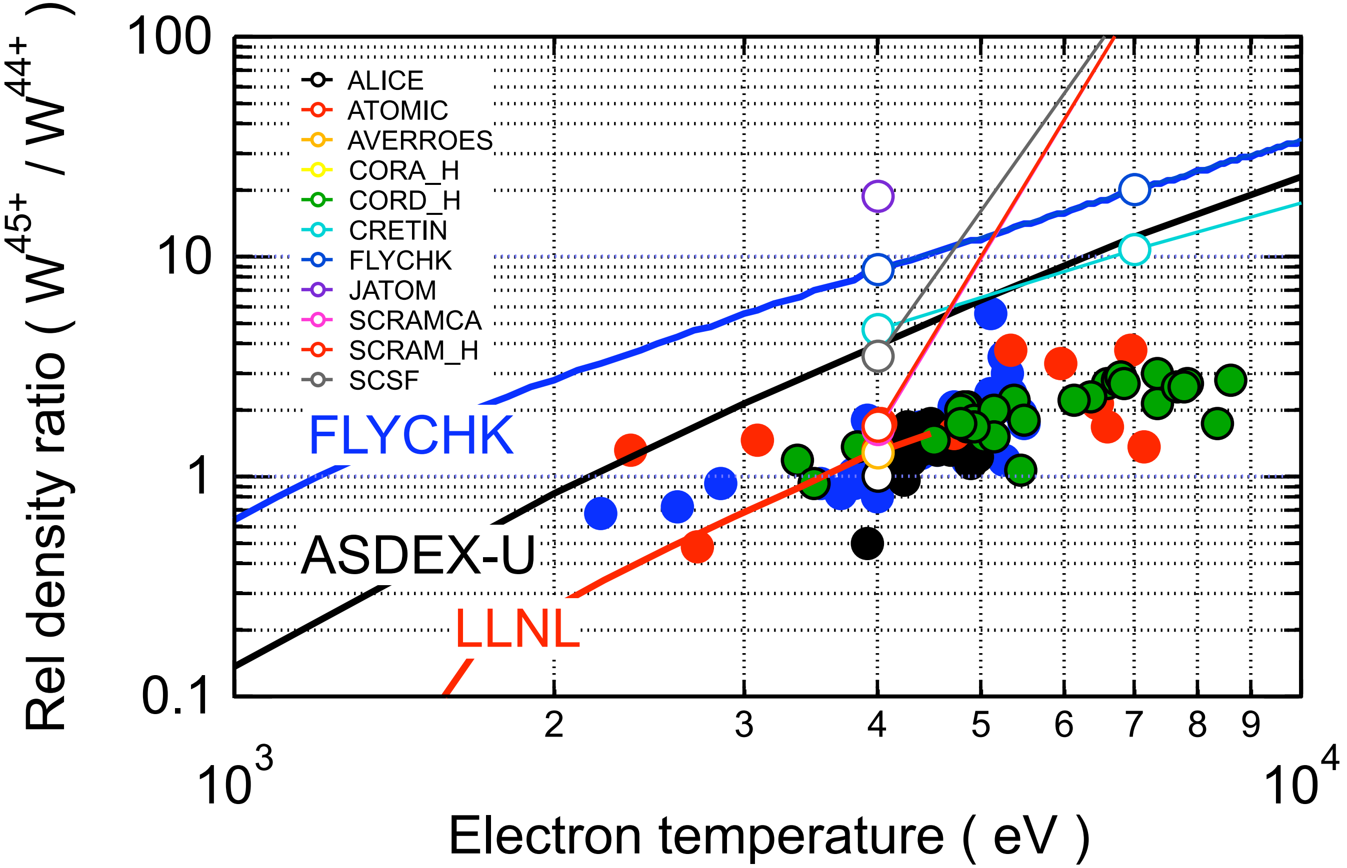


NLTE workshop: code-code comparison under fix conditions

⇒ Difference between codes reduces every meeting

But still big difference at 7 keV

No codes reproduce both the W^{45+}/W^{44+} ratio and the T_e-dependence



Measured W^{45+}/W^{44+} ratio is

4 keV: in the lowest range of the NTLE code results

7 keV: below the NTLE code results

Summary

Analysis of intensity ratio of W^{45+} to W^{44+} line

- W^{45+}/W^{44+} density ratio is directly determined with the W^{44+}/W^{45+} line intensity ratio by coronal model.

Comparison of measured W^{45+}/W^{44+} density ratio with calculated

- LLNL code: close to the measured density ratio but in the T_e range where fractional abundances of $W^{45+,44+}$ are very low.
- FLYCHK code: higher by one order of magnitude
- AUG-EXP: higher by 3 – 4 factors
- NLTE6 codes: don't reproduce both the ratio and T_e-dependence.

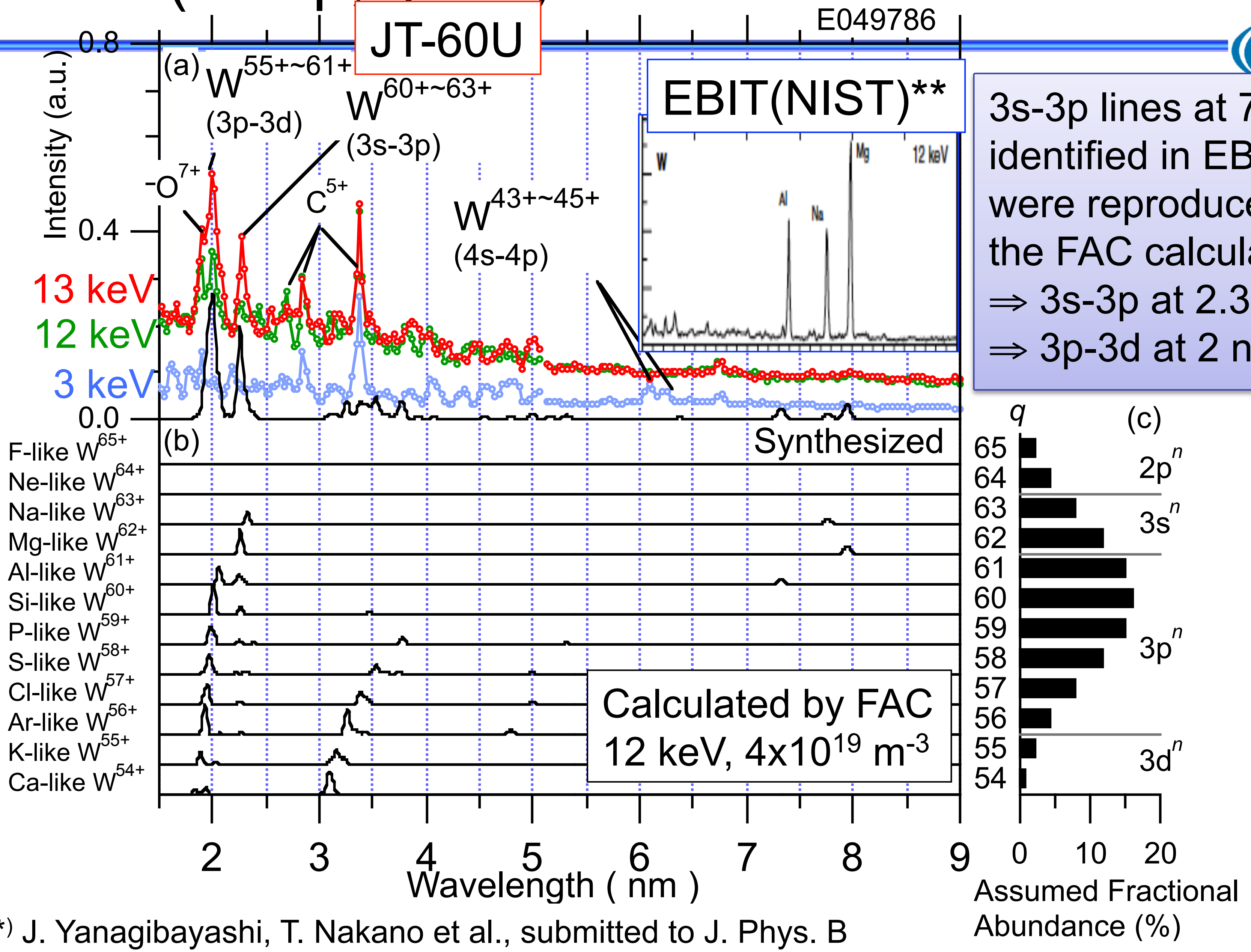
Further study is needed:

Theory: improvement of recombination rates

Experiment: blend free (higher wavelength resolution), EBIT

Thank you!

$W^{\sim 60+}$(3s-3p,3p-3d) at 2 nm identified in JT-60U*)



3s-3p lines at 7-8 nm identified in EBIT** were reproduced by the FAC calculation.

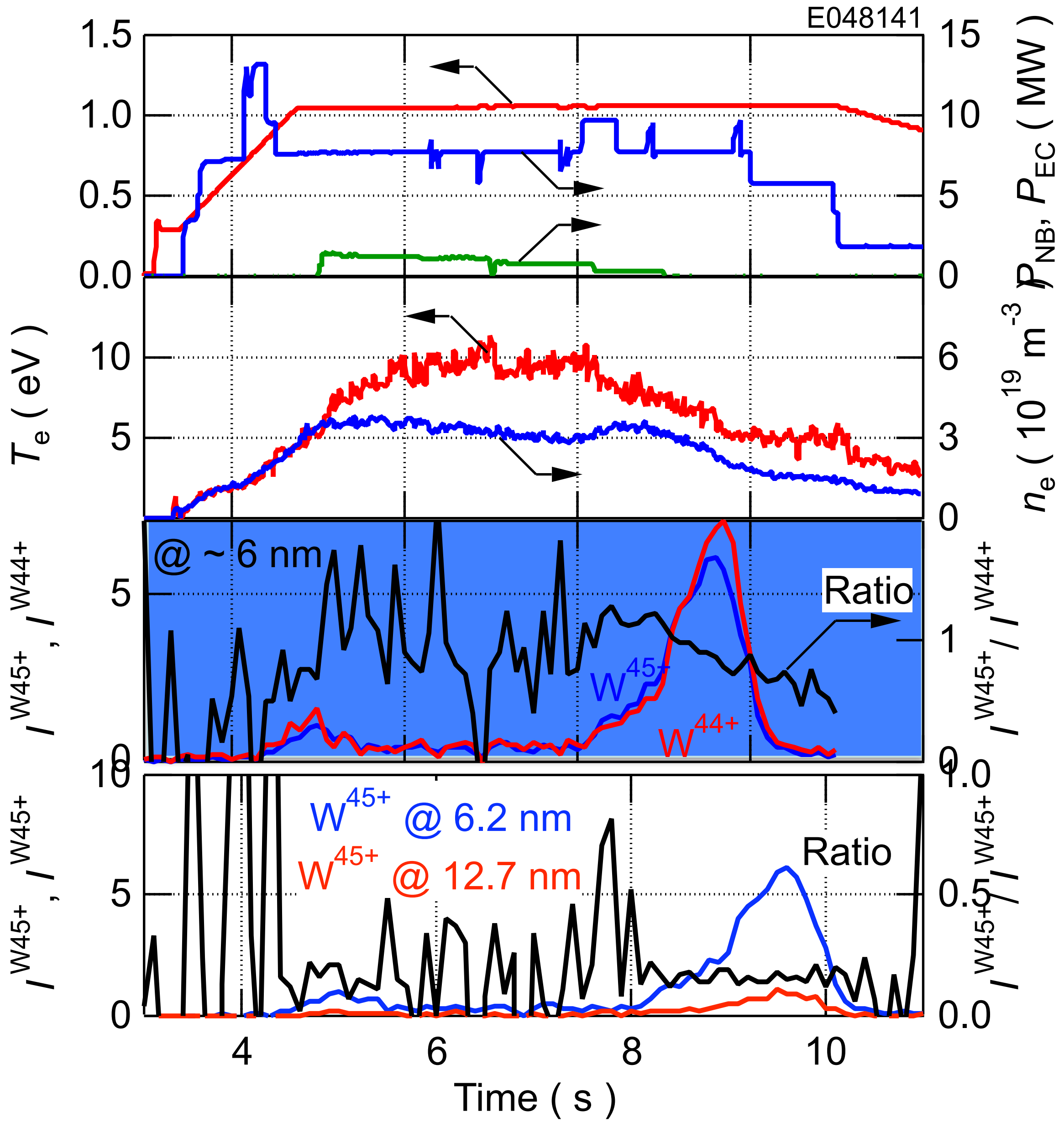
⇒ 3s-3p at 2.3 nm

⇒ 3p-3d at 2 nm

*) J. Yanagibayashi, T. Nakano et al., submitted to J. Phys. B

**)Y. Ralchenko et al J. Phys. B 41 (2008) 021003

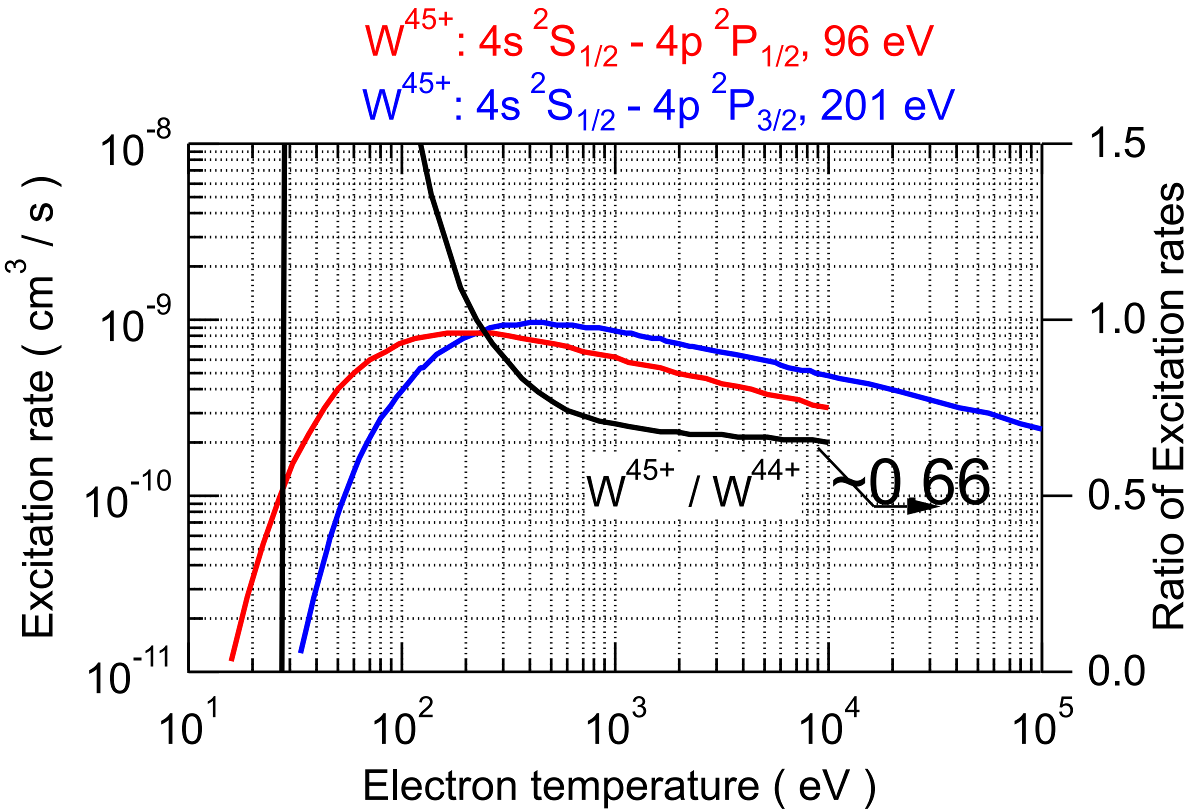
Waveform



~0.161

0.67/0.16 = 4.2

12.7 nm では 6.2 nm の



W45+: 4s 2S1/2 - 4p 2P1/2, 96 eV
W45+: 4s 2S1/2 - 4p 2P3/2, 201 eV
10-8
10-9
10-10
10-11
Excitation rate (cm3 / s)
1.5
1.0
0.5
0.0
Ratio of Excitation rates
W45+ / W44+
~0.66
101
102
103
104
105
Electron temperature (eV)