W-Spectroscopy in Magnetic Confinement Fusion

T. Pütterich[1]

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Outline

- Why is Tungsten of Interest for Fusion Science?
- What is the Setup for Spectroscopic Diagnostics?

- Ionization Equilibrium of Tungsten
- Quick Overview of Strong W-emissions in Fusion Plasmas
- Focus on Quasicontinua Emitted at 10-35 nm (4f-feature)
  and at 5-6 nm (4d-feature)

- Summary & Outlook

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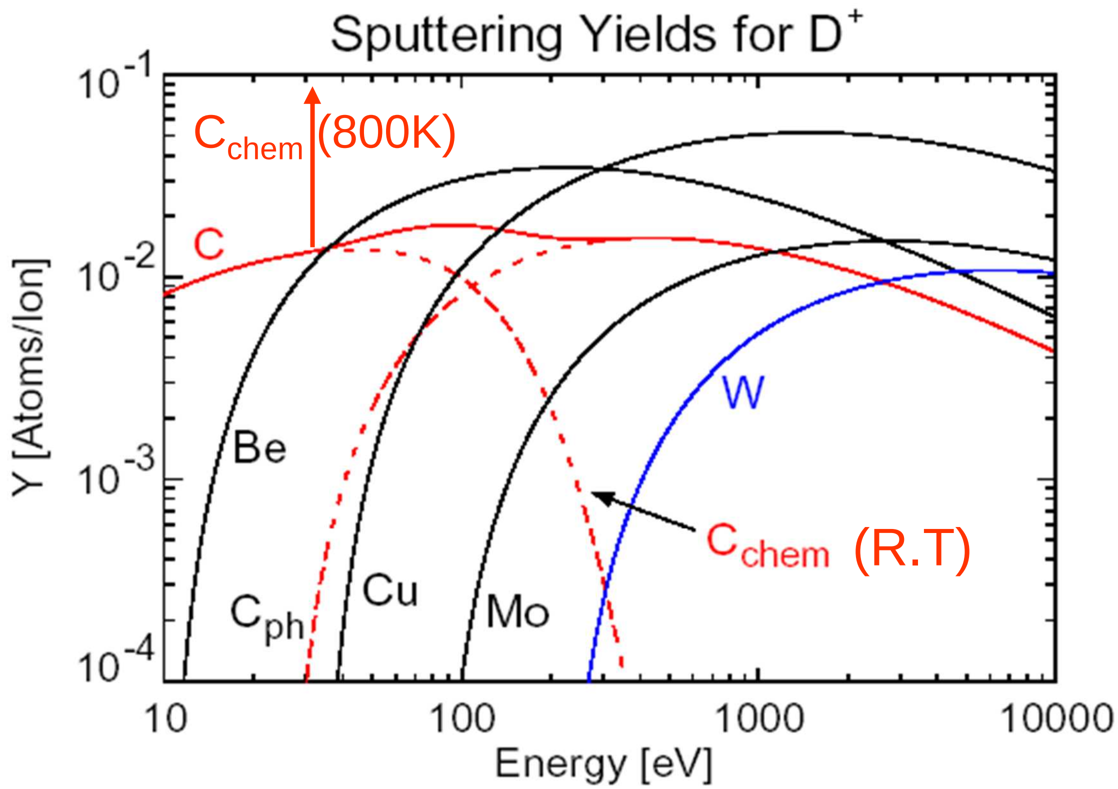
Why is Tungsten of Interest for Fusion Science?

- First wall erosion needs to be very small (Reactor operation 24/7 requires high-Z wall)
- W can handle high heat fluxes (metal with highest melting point)
- Fuel retention in W is small (Co-deposition is no issue)



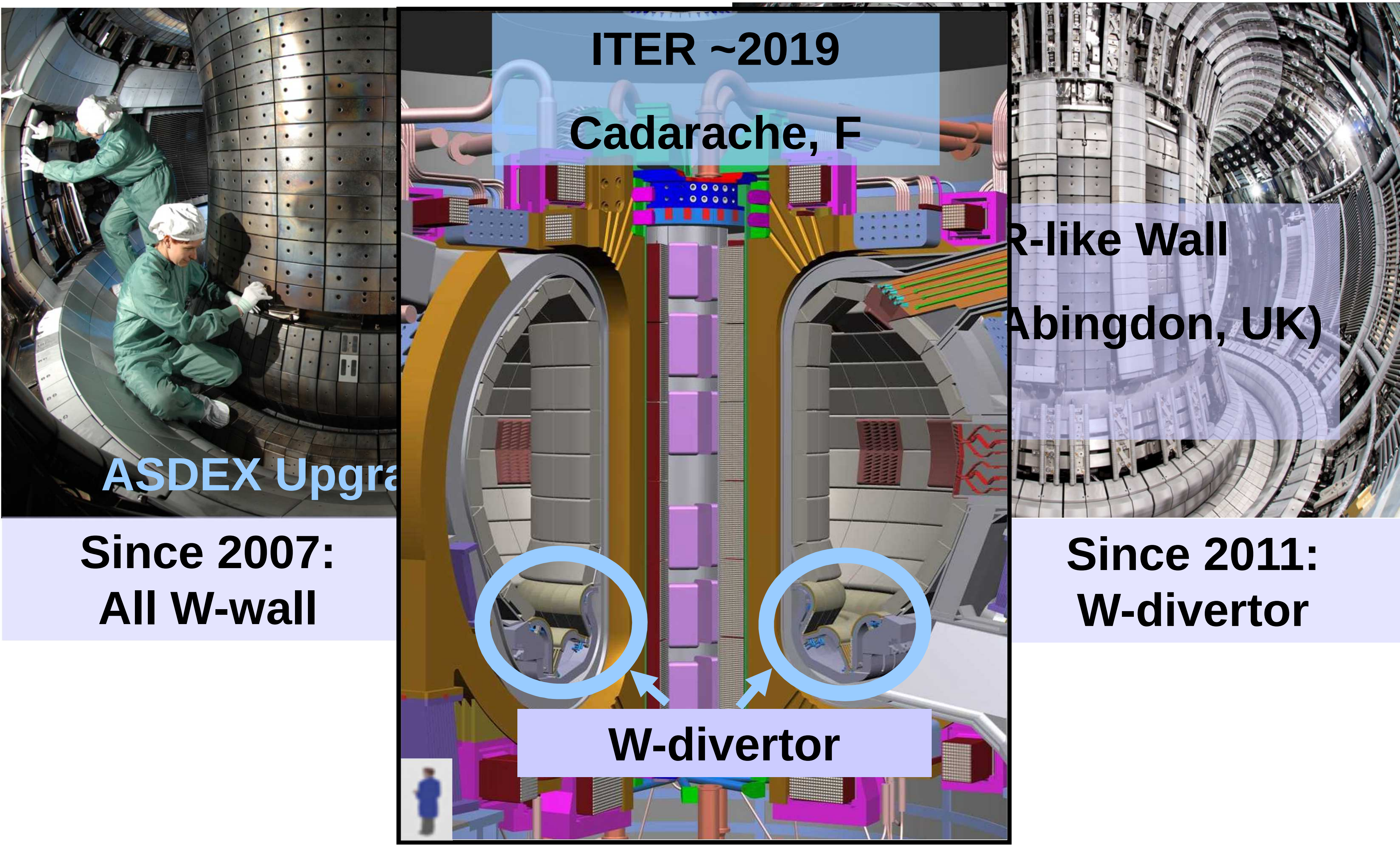
⇒ **W is a plasma impurity**
⇒ **Radiative Cooling due to W demands caution**
⇒ **Diagnostic of W-density important**

Why is tungsten of Interest for Fusion Science?

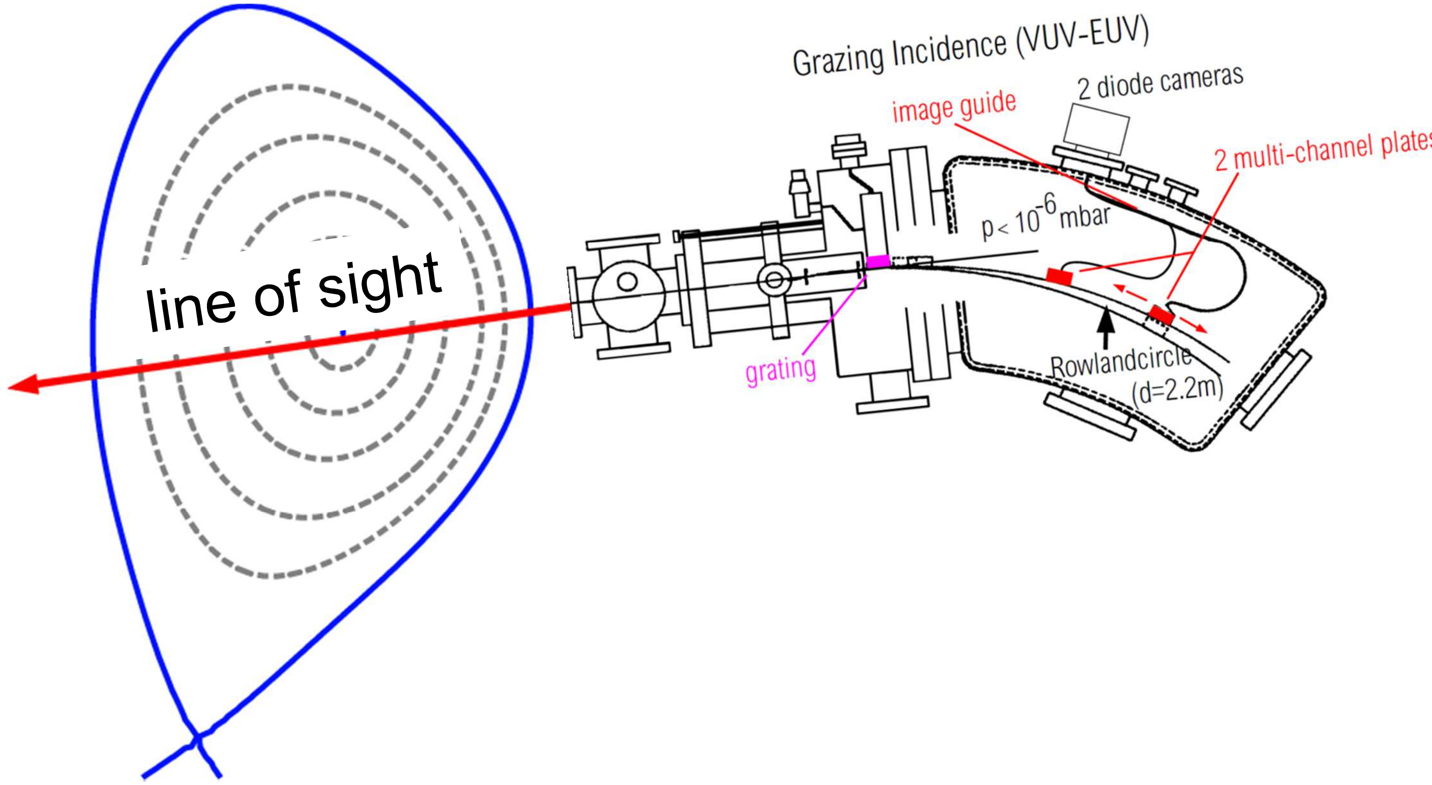
Since 2007:
All W-wall

Since 2011:
W-divertor

Why is tungsten of Interest for Fusion Plasmas?



Setup of Spectroscopic Diagnostics



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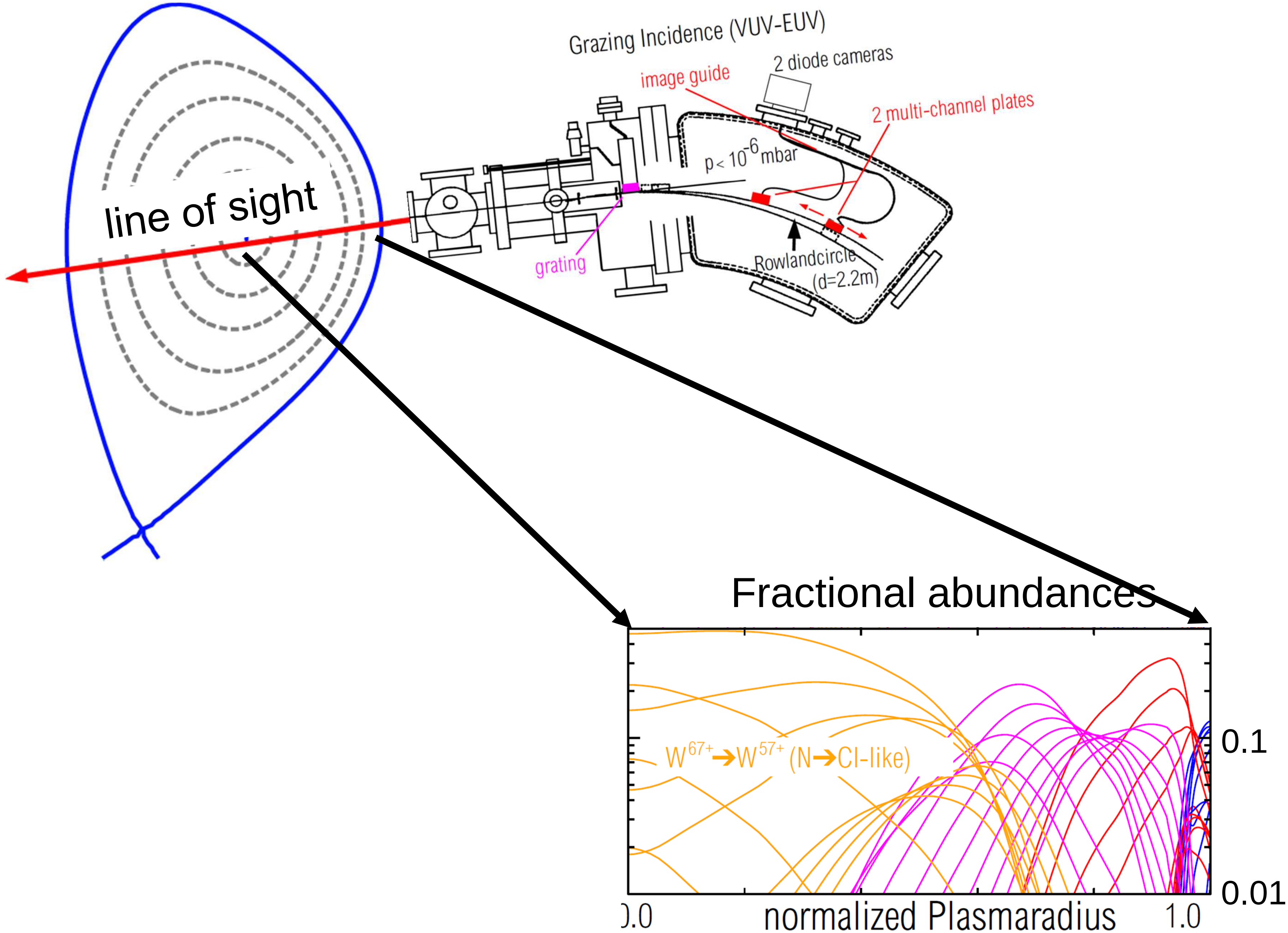

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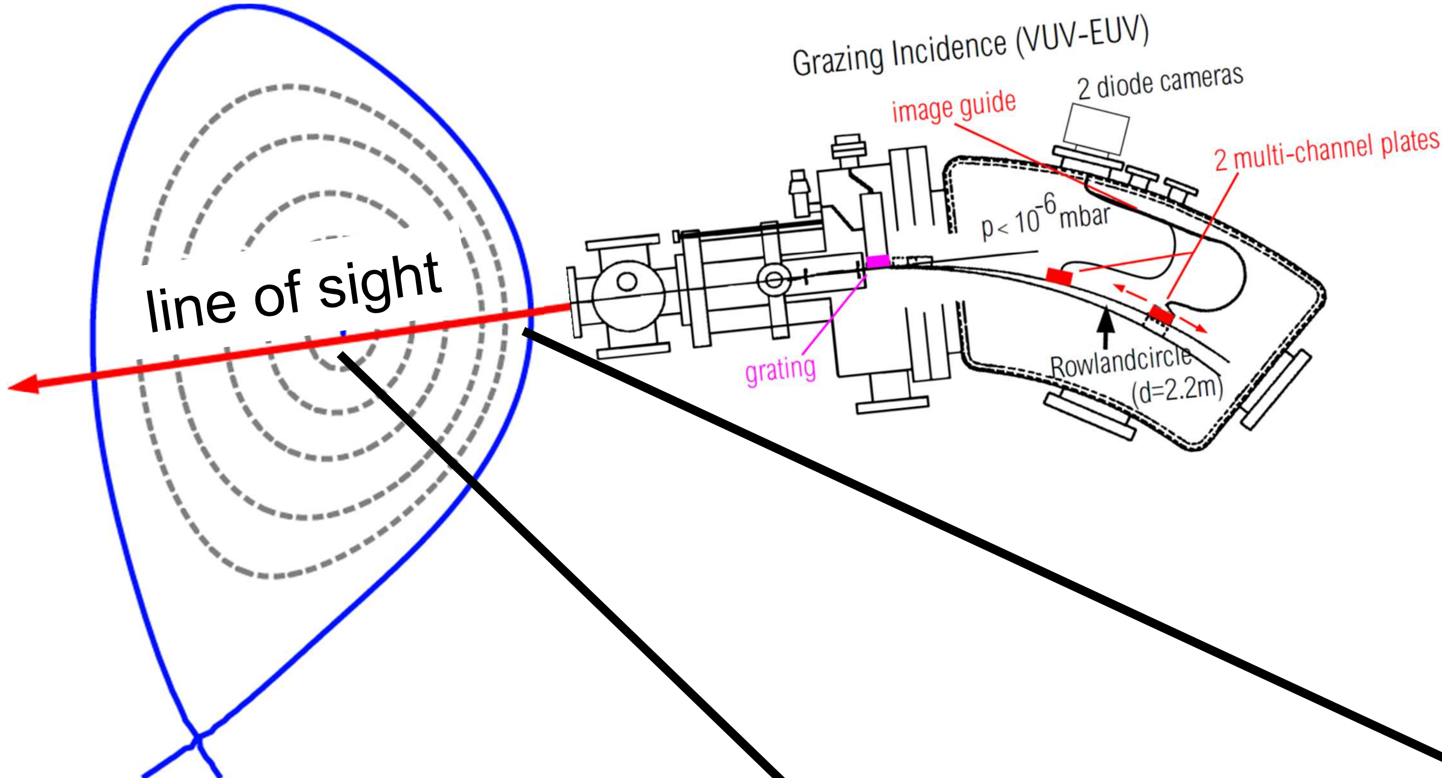
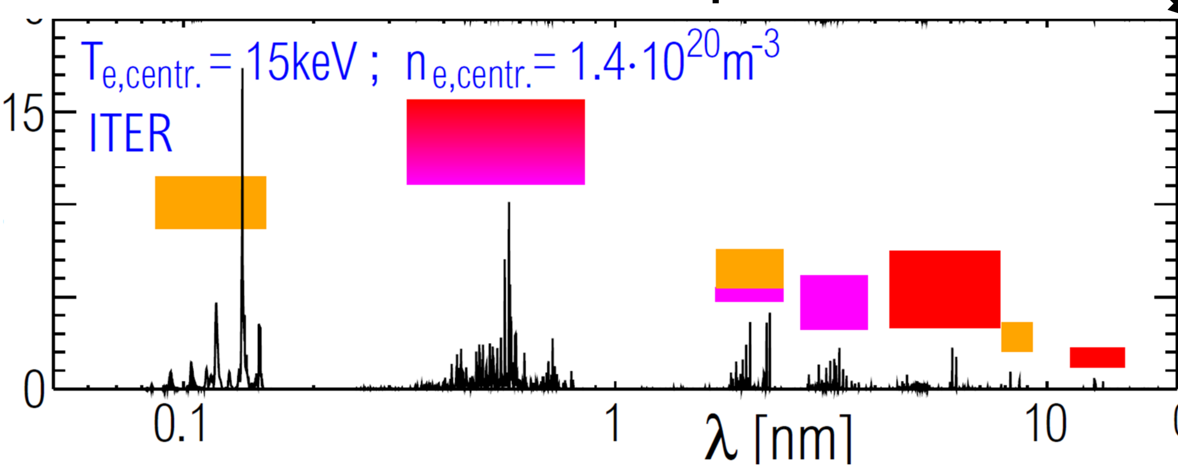
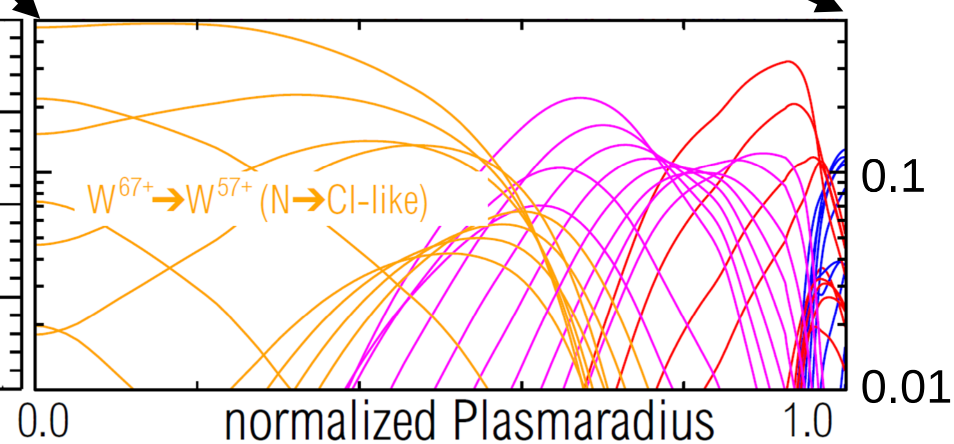


Modelled ITER-spectrum



Fractional abundances



Transport Does not Change Frac. Abundance!

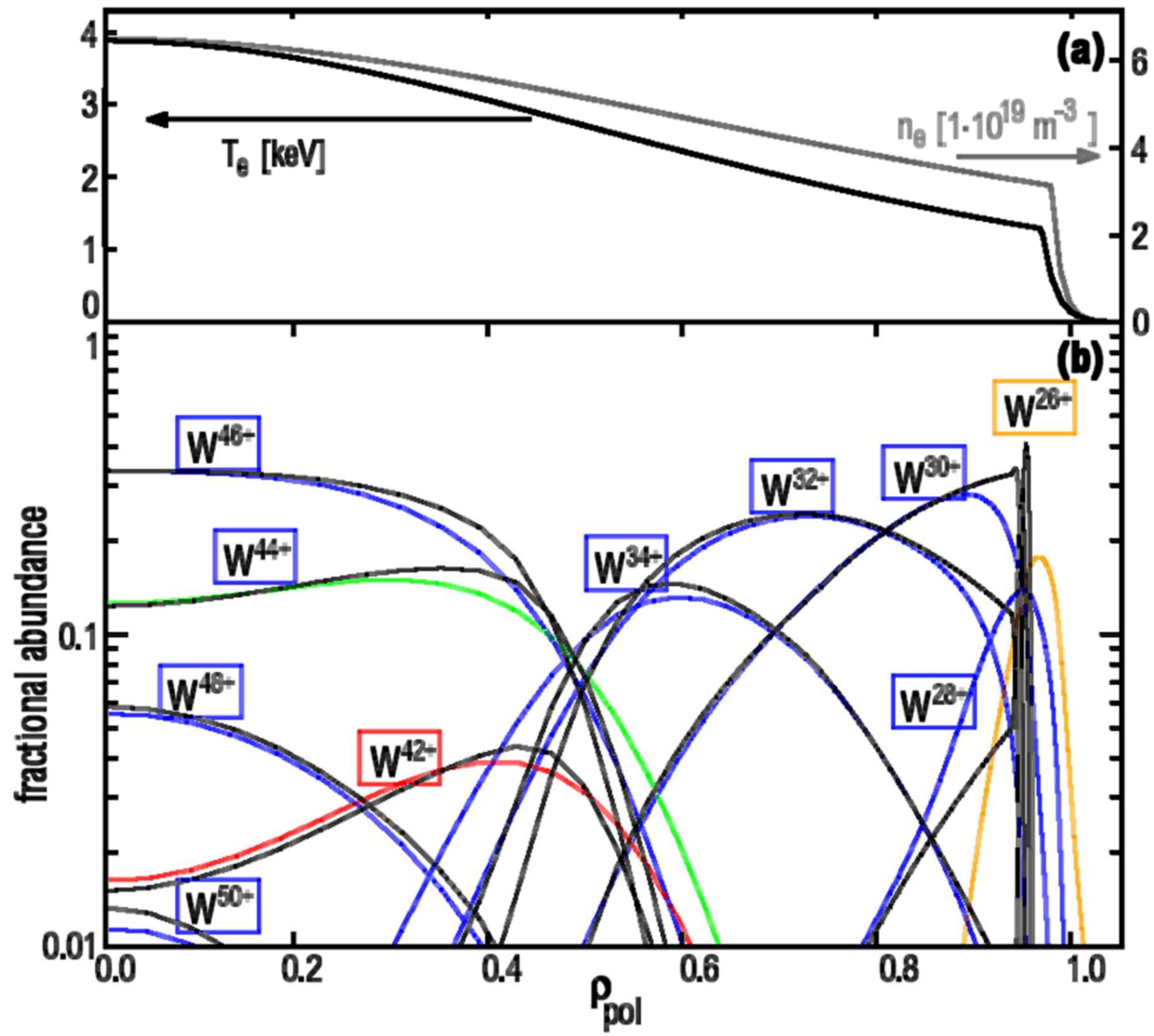
For ionisation equilibrium solve:

$$\frac{\partial}{\partial t} n_Z + \nabla \vec{\Gamma}_Z = n_e \left(n_{Z-1} S_{Z-1} + n_{Z+1} \alpha_{Z+1} - n_Z S_Z - n_Z \alpha_Z \right)$$

weak influence of plasma transport on Frac.abundances

=> Ionization equilibrium is f(T_e)

typical radial plasma profiles in AUG



ionisation shells with (colored) / without (black) transport

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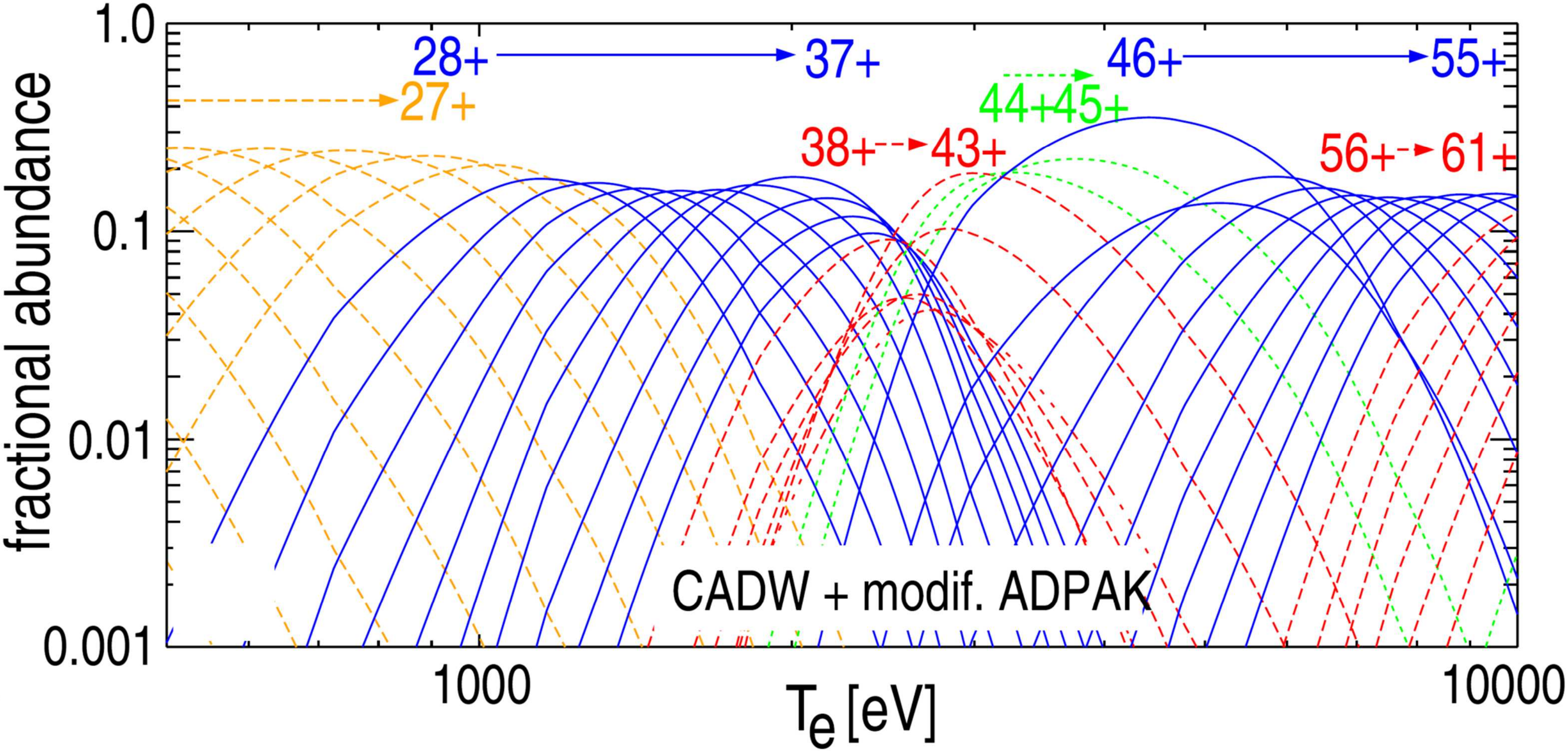
Ionization Equilibrium of W is Complicated

- Many Ions Co-exist
- Ionization-Recombination rates of all ions need to be known
- BUT: Very Detailed Information May be Obtained!

⇨ (Pütterich et.al. PPCF 2008)



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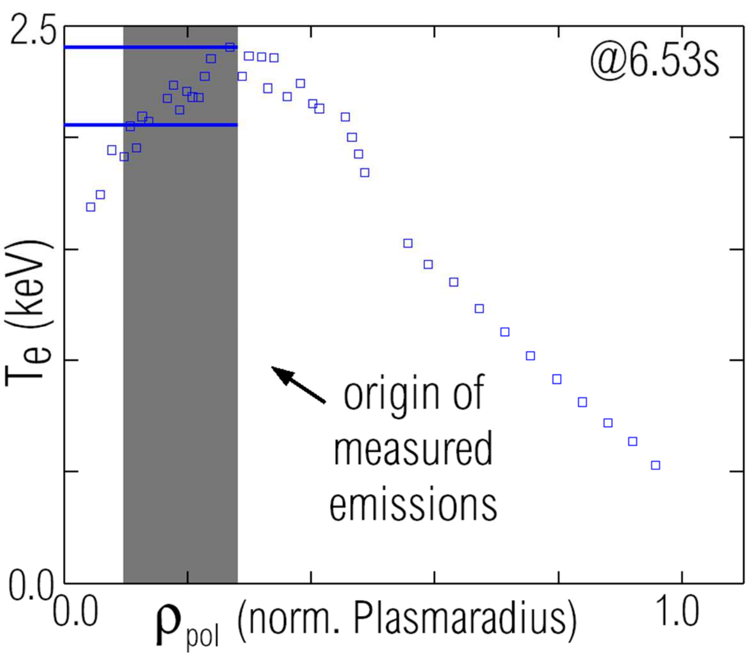
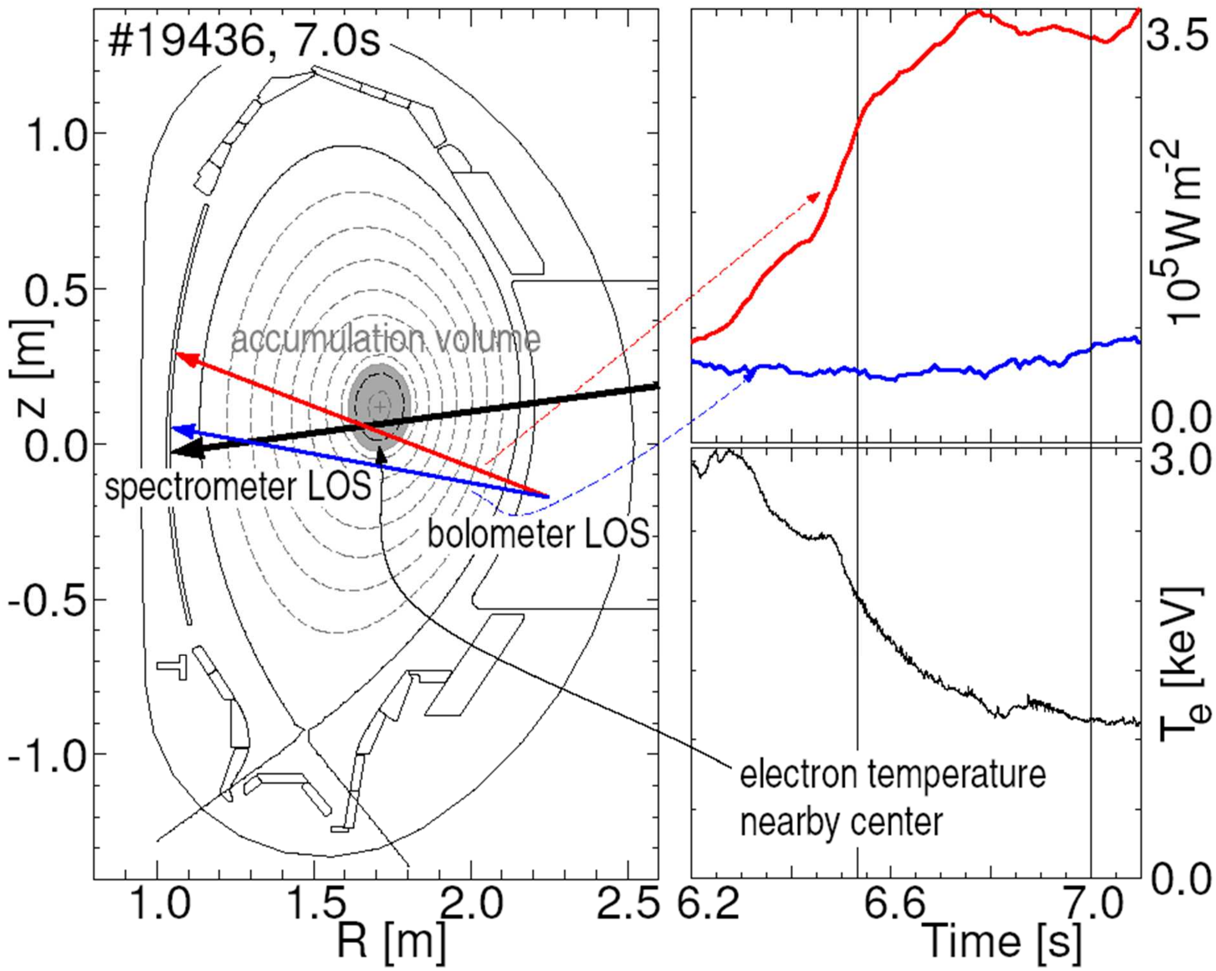
W Spectroscopy in the VUV and SXR

W-accumulation is emphasizing Central Plasma Region

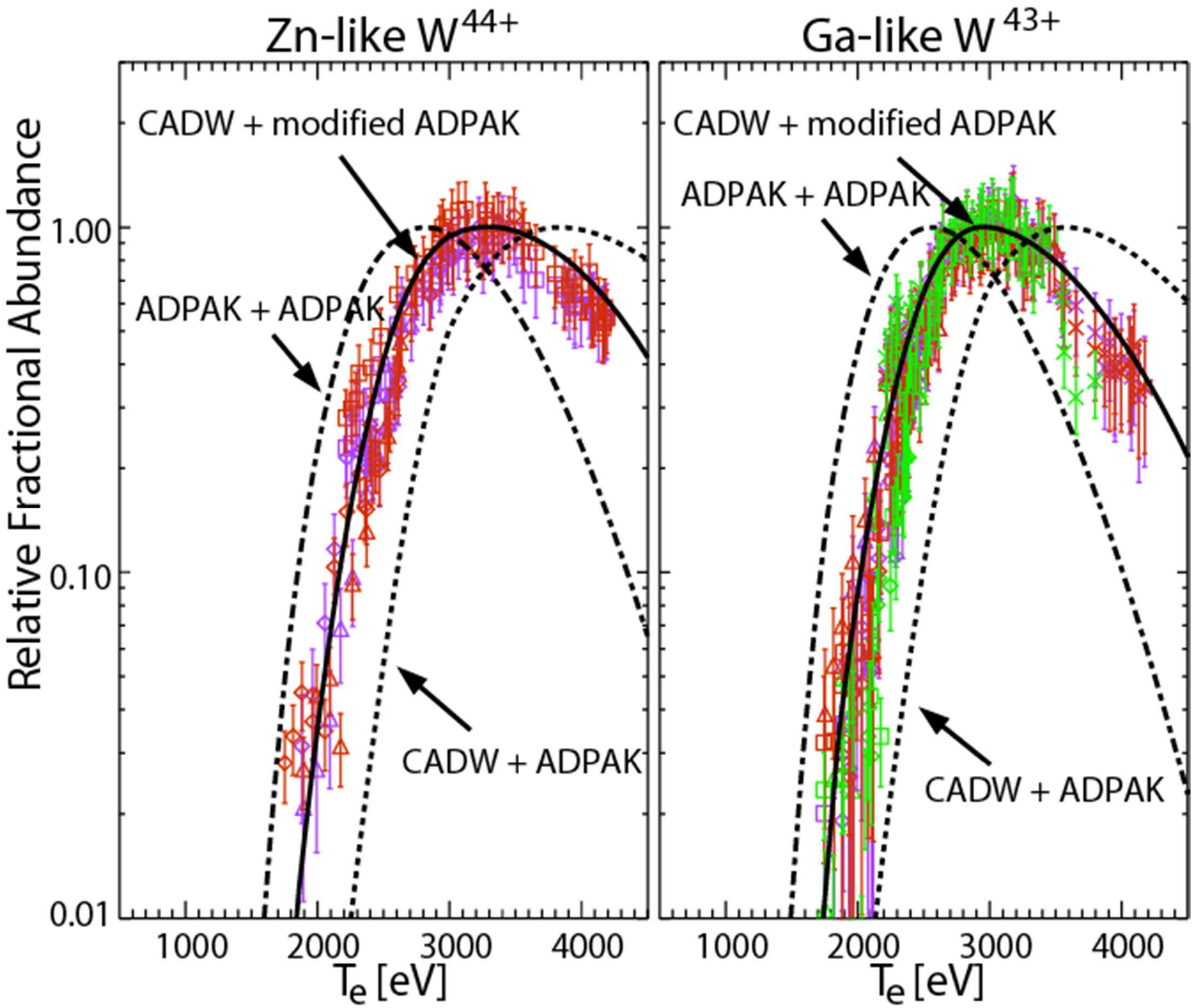
- W can accumulate in plasma centre due to ‚neoclassical' transport
- central concentration can be increased by up to 100 times
- radiation originates from very small volume / radial range

⇒ dominated by very few ionisation states





Ionization Equilibrium is Probed very Accurately by Spectroscopic Measurement



Deduced fractional abundance versus temperature
different discharges: symbols
different spectral lines: colours

Use of CADW ionisation rates (S.D. Loch, PRA 2005) and adjustment of recombination rates allows good description of emissions of W^{24+} - W^{48+}

Pütterich et. al., PPCF50, 085016 (2008)

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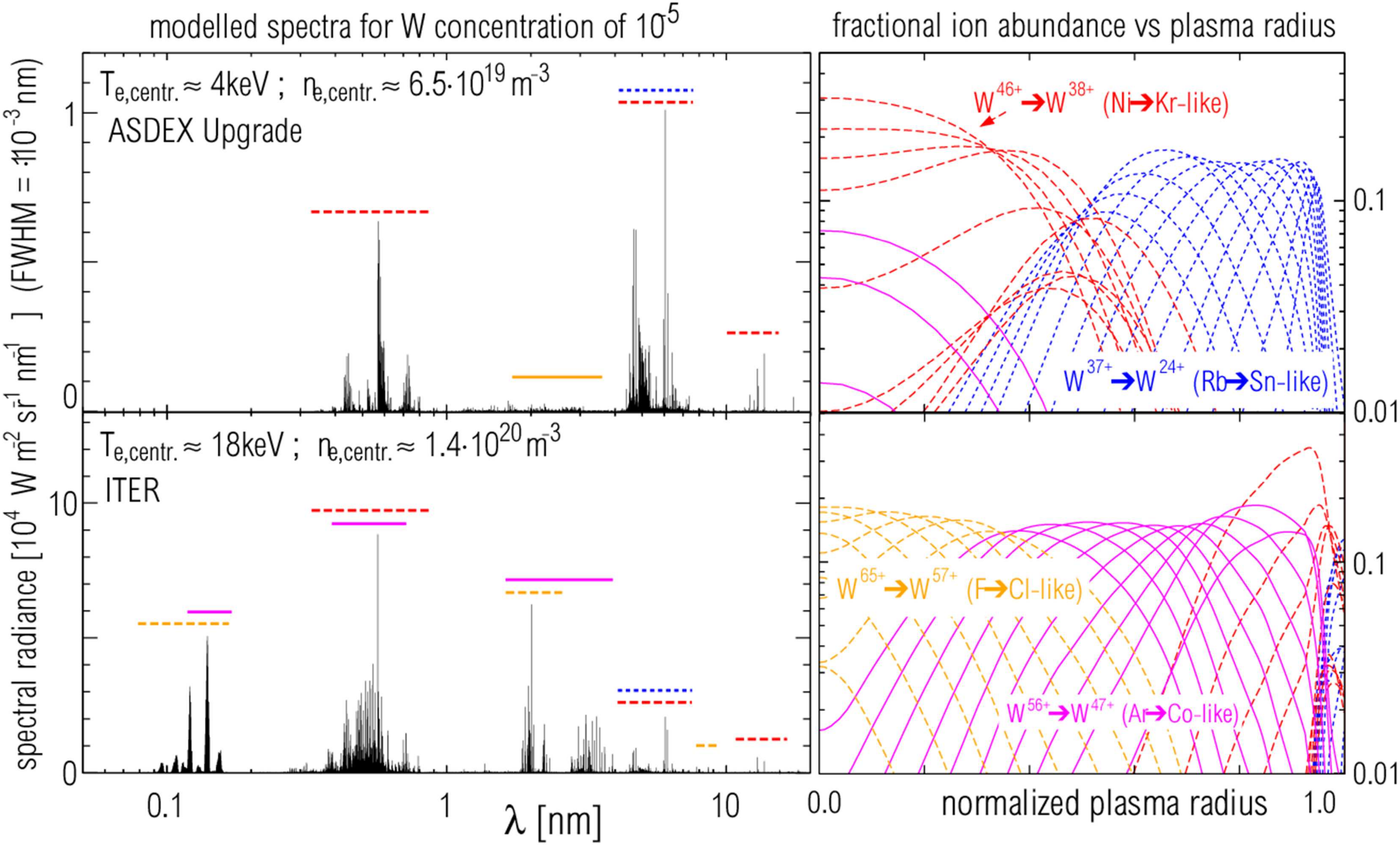
Which Spectral Regions are Interesting?



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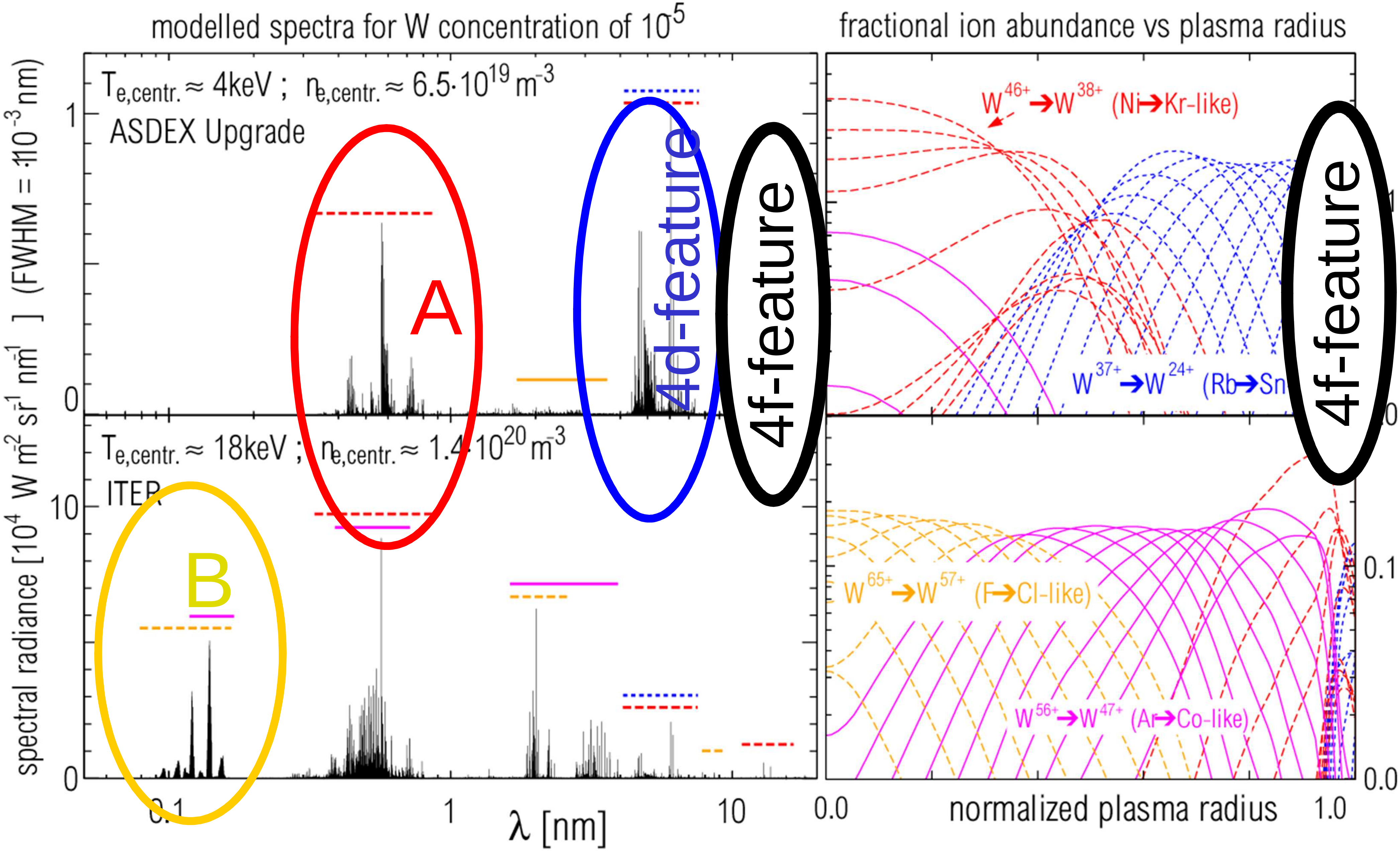
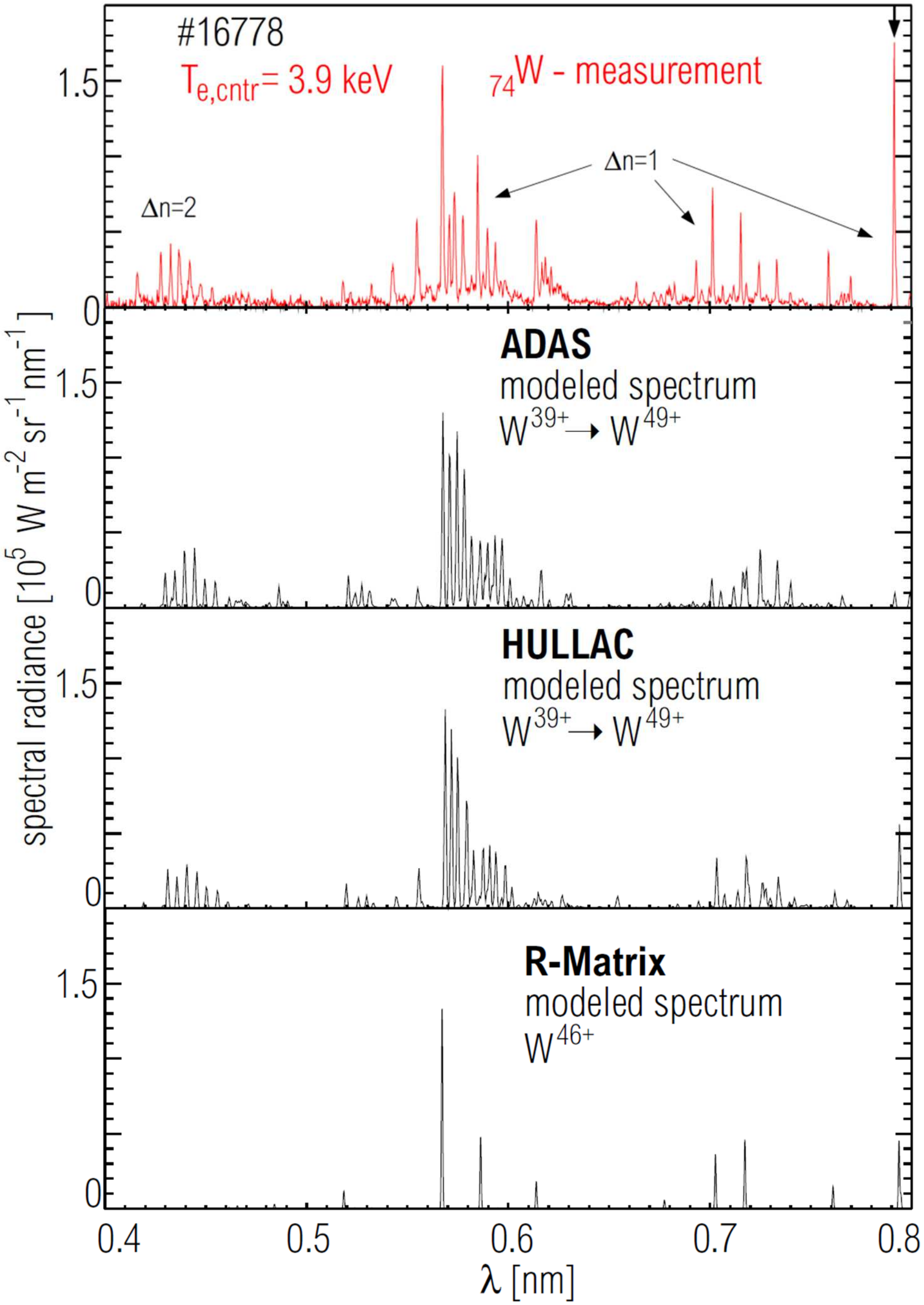


Range A: X-ray Core of AUG, Edge of ITER



- Spectral lines (T_e~2.0-6.0keV)
- W^{39+}-W^{49+}
- Advantages of X-ray spectroscopy
- Accessible with soft X-ray cameras
- ‚mystery line‘ at 0.793nm, with strongest discrepancy

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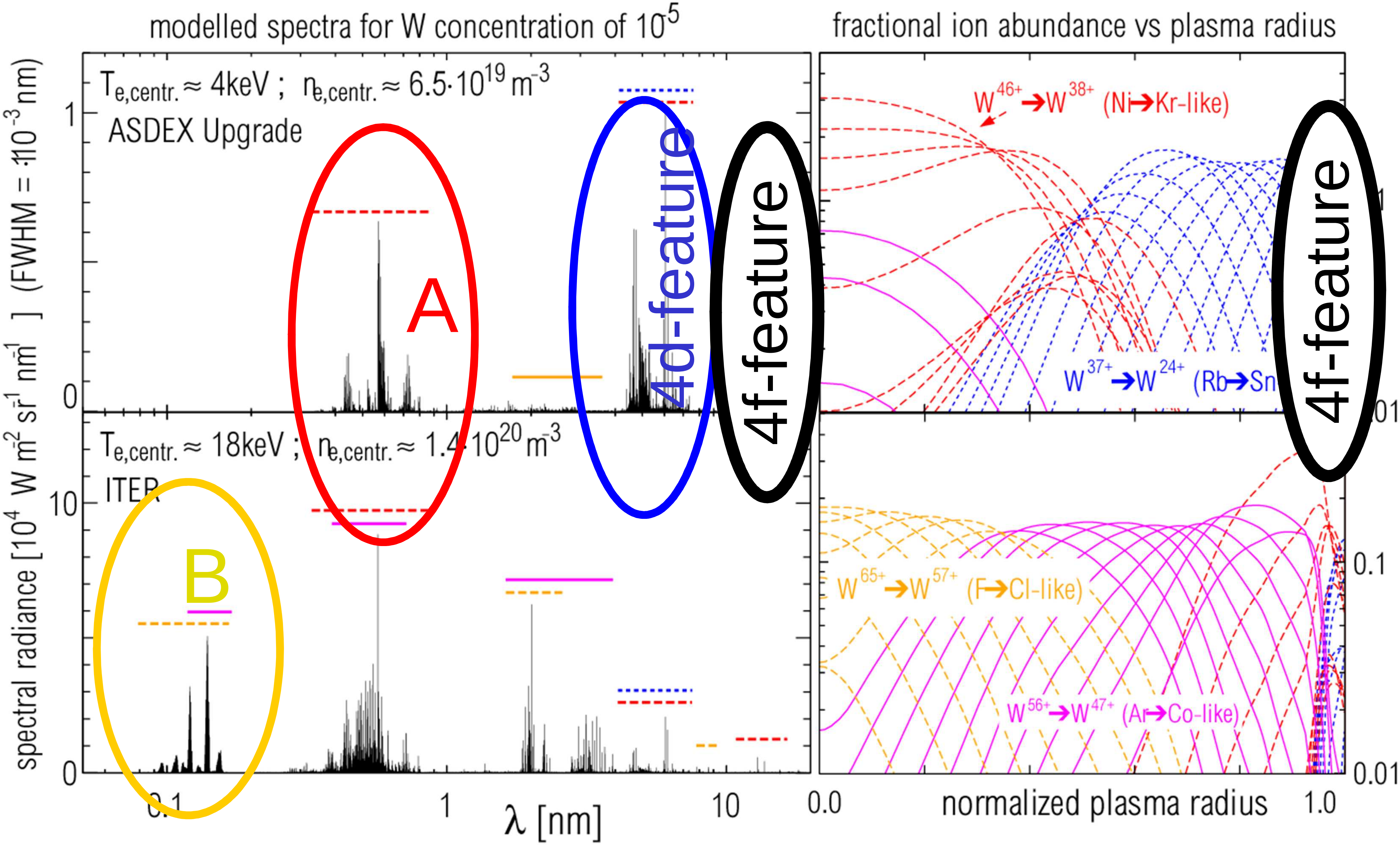
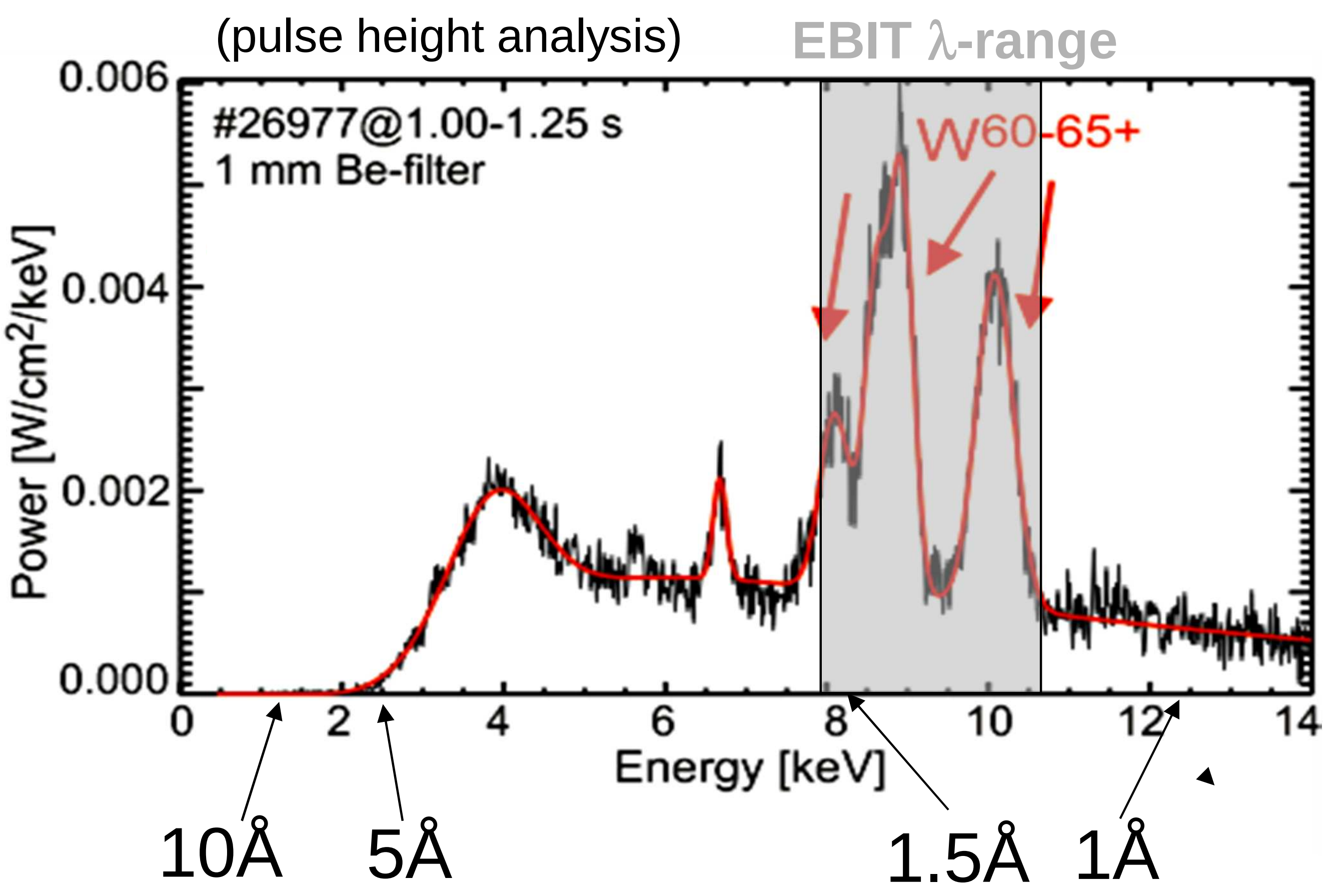


Range B, special plasmas in AUG, core in ITER

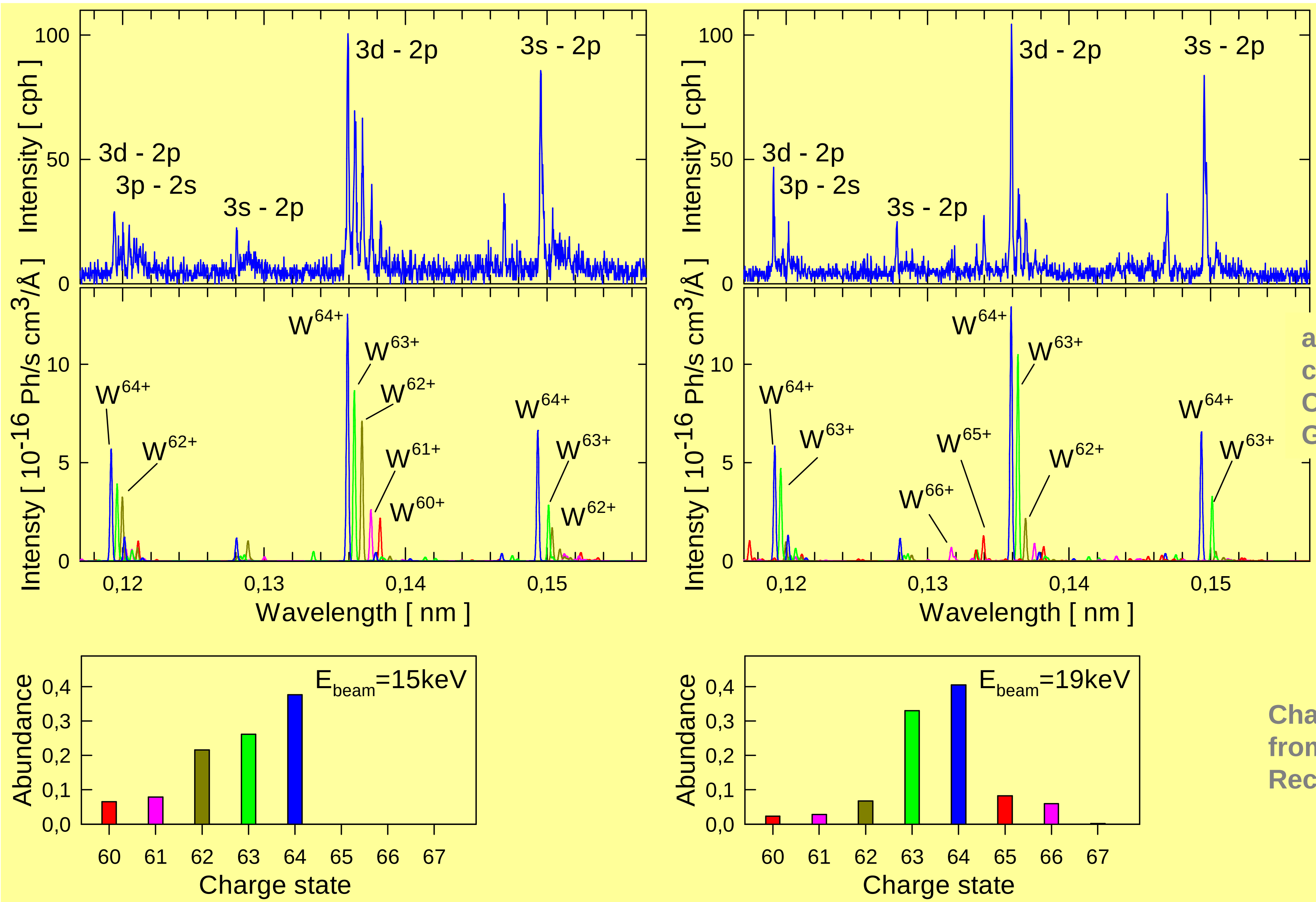
- Observation of spectral lines of >W60+ in ASDEX Upgrade
- Special Discharge with T_e~18keV

X-ray overview ASDEX Upgrade @Te~18keV



Range B, special plasmas in AUG, core in ITER

Electron-Beam Ion-Traps: Prepare W-ions with charge >60+



atomic structure calculations Cowan-code , GRASP + ADAS

Charge state distribution from Radiative Recombination spectrum

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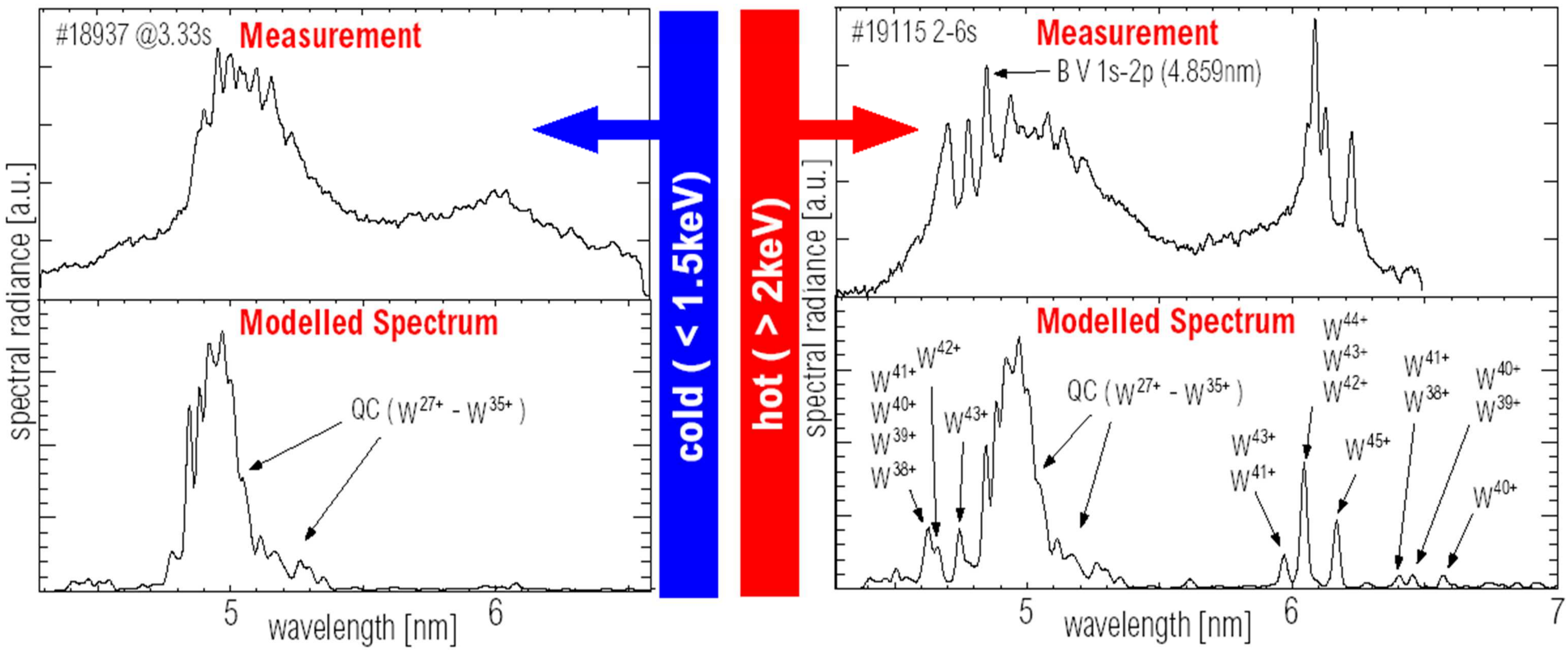
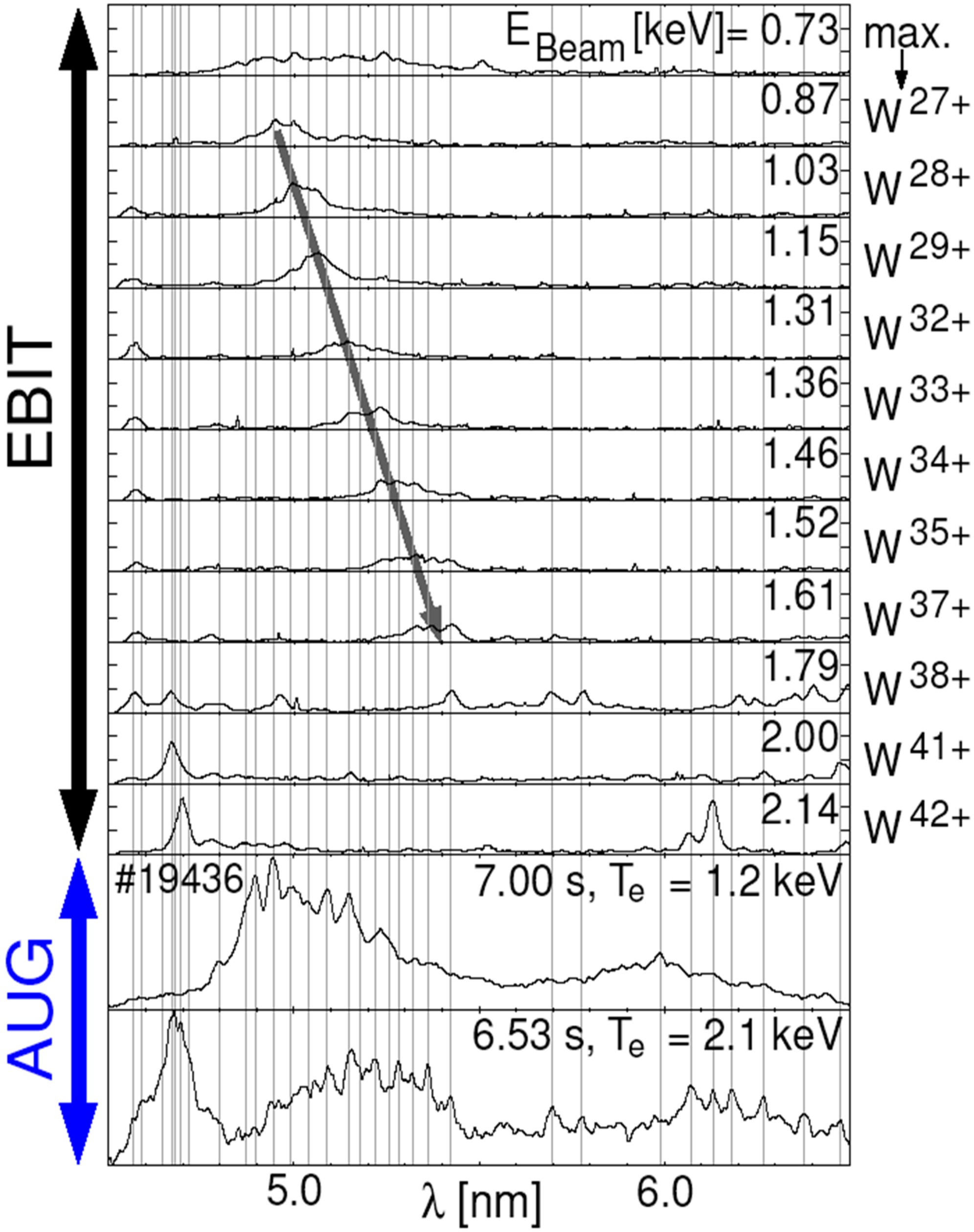
QC: VUV Edge+Core in AUG, Edge in ITER

- Spectral feature (T_e ~ 0.8-1.8keV): ‚Quasicontinuum'
- Spectral lines: T_e~2.0-4.5keV
- Covers Ionization Stages from ~W^{24+}-W^{45+}



5nm: Main Peak is Understood, What about the Neighboring Peak at 6nm?



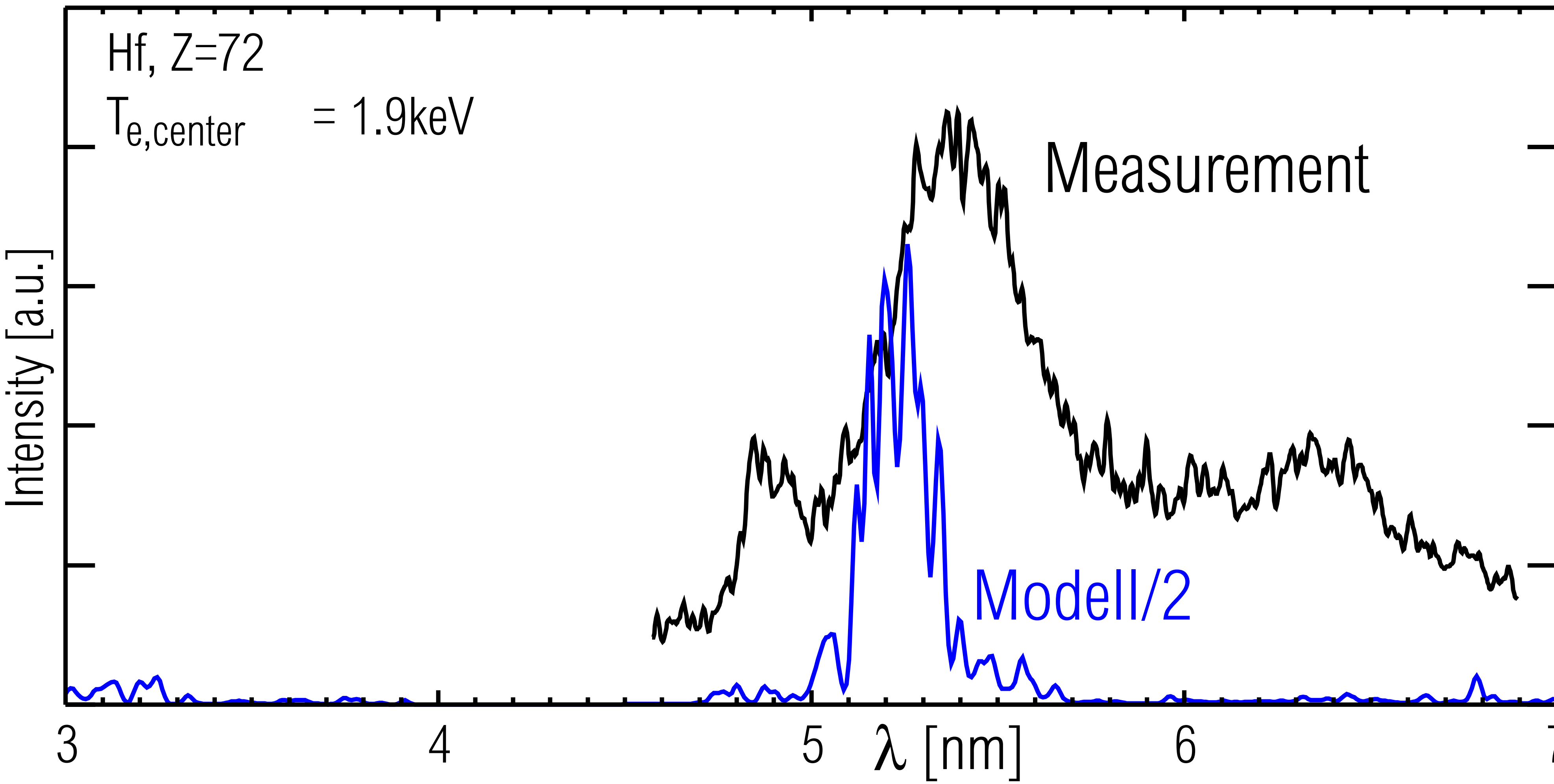
Comparison with EBIT investigations

- EBIT spectra give nice identification of main peak at 5nm, consistently with tokamak spectra
- Emissions of Neighboring 6nm-Peak not Clear
- Electron density effect?

EBIT dens. << tokamak dens.

T. Pütterich et al., J. Phys. B 38 (2005)

VUV Spectra of Various High-Z Elements



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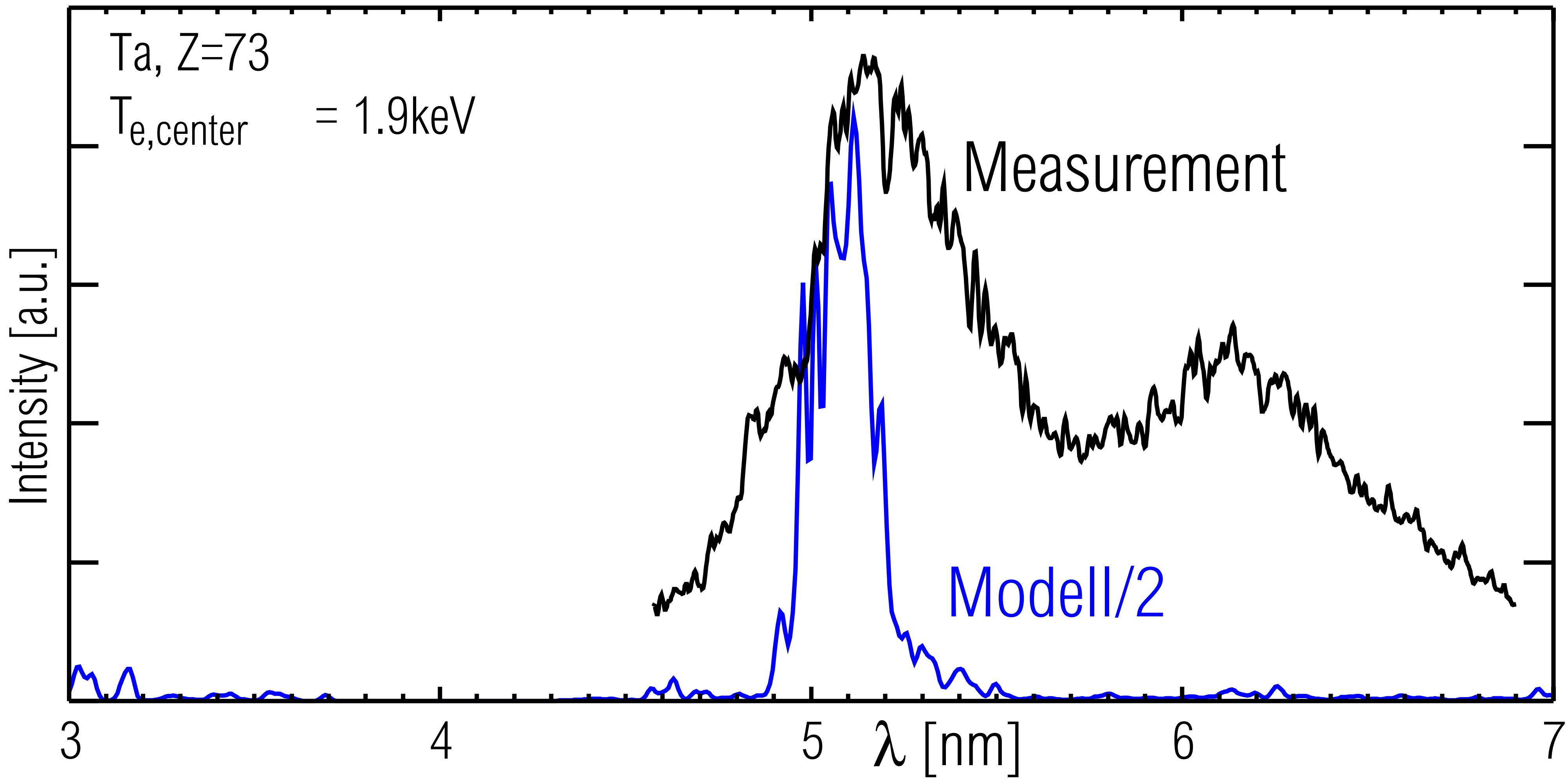

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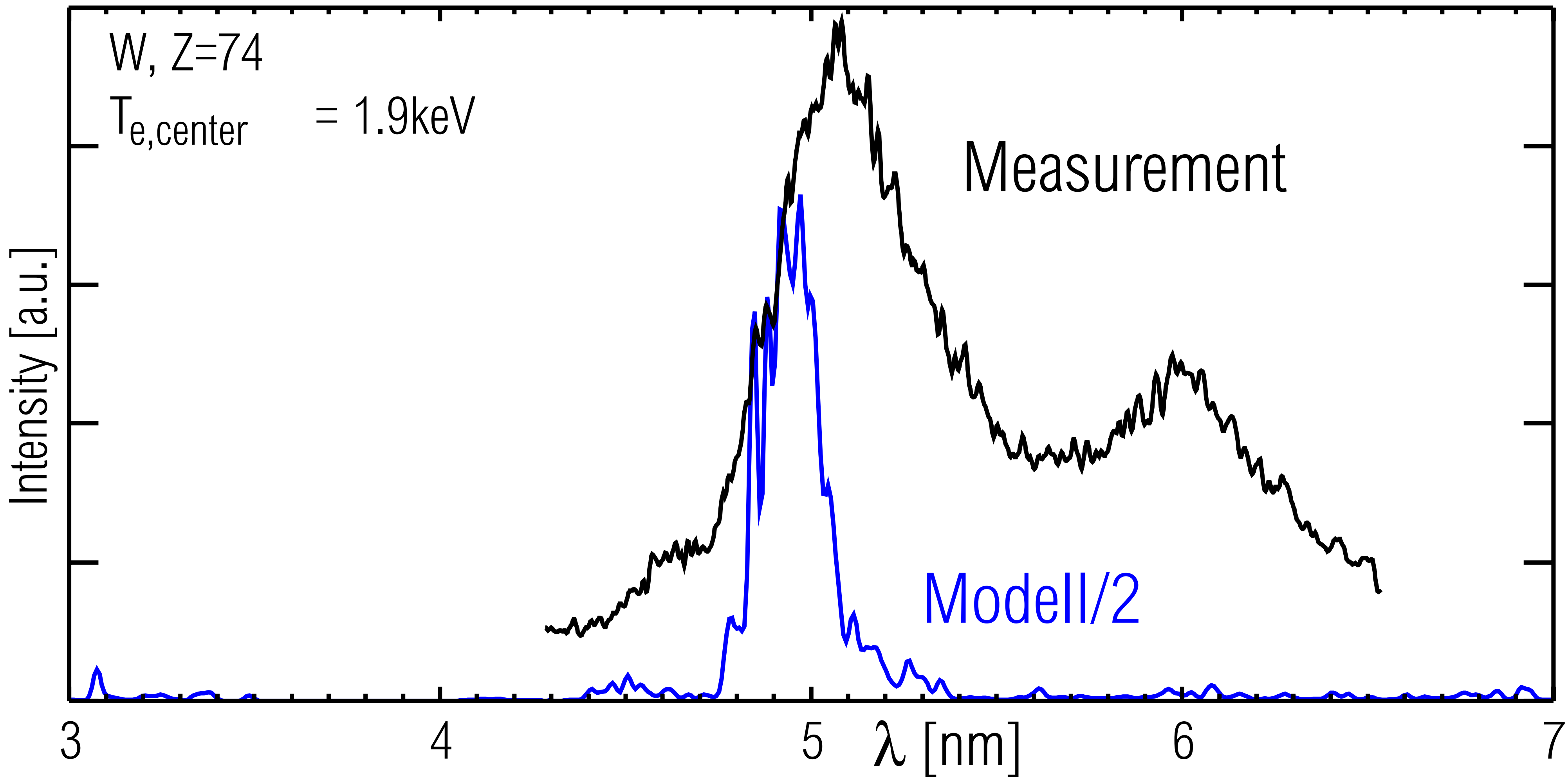

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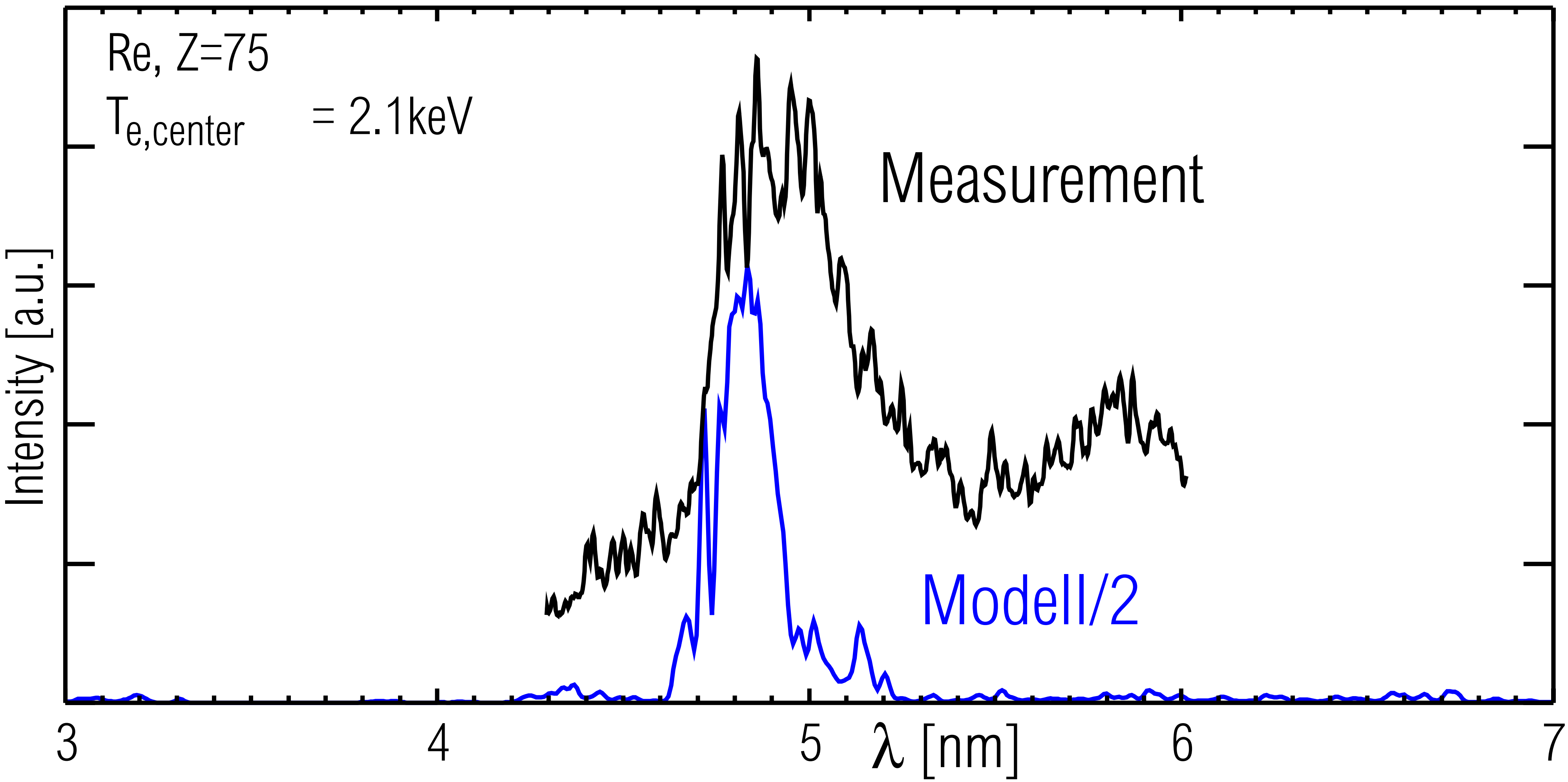

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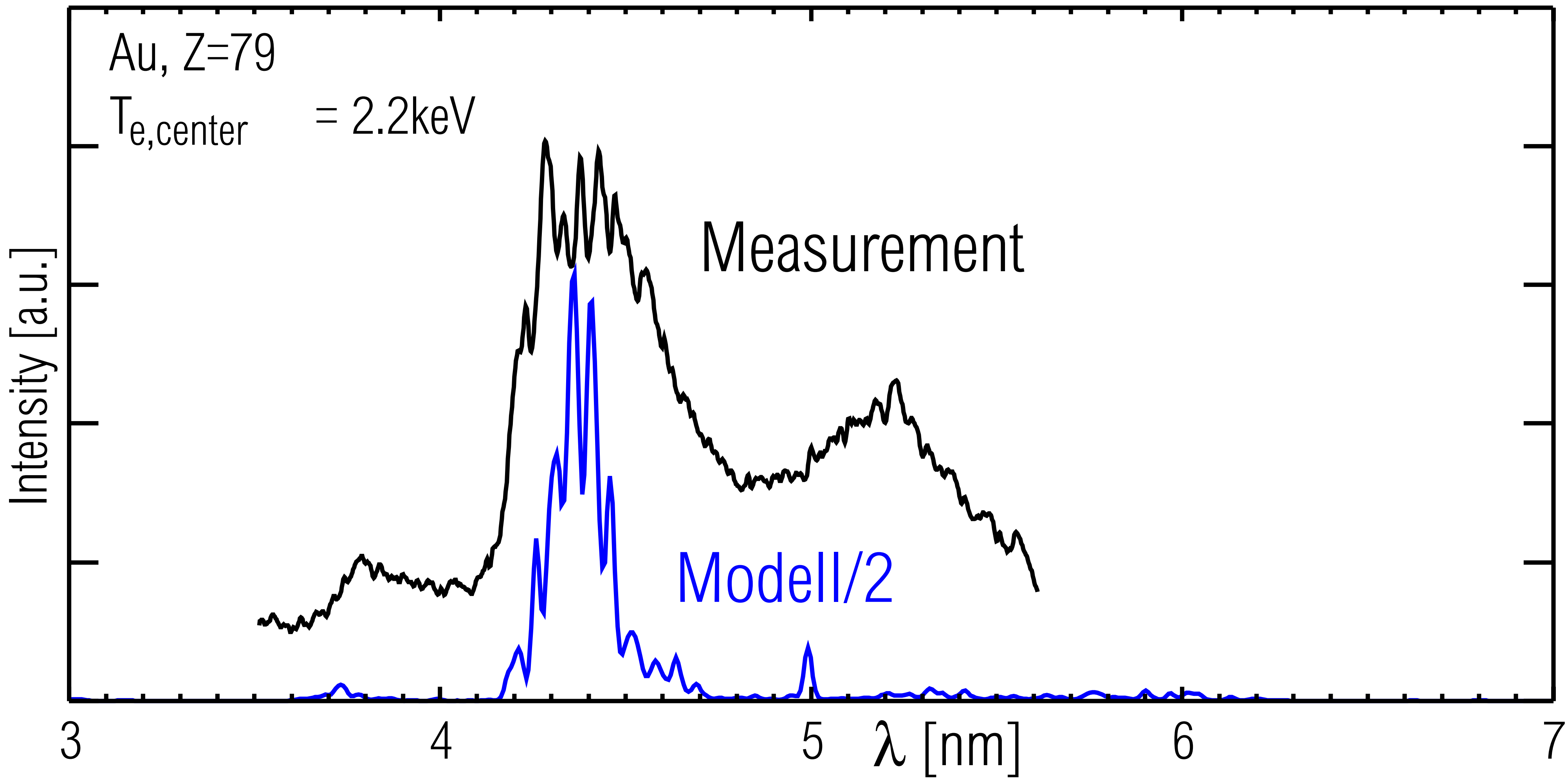

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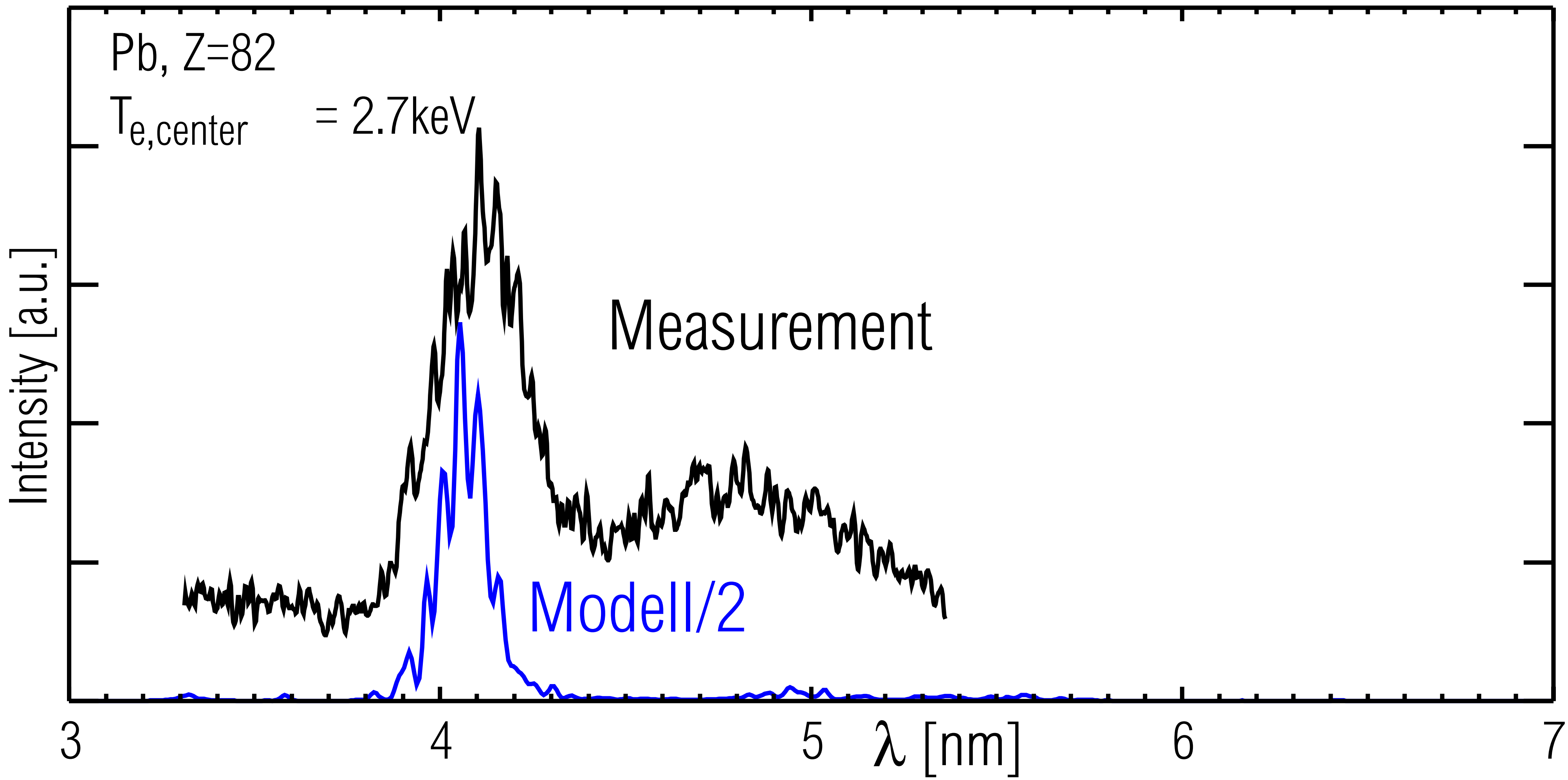

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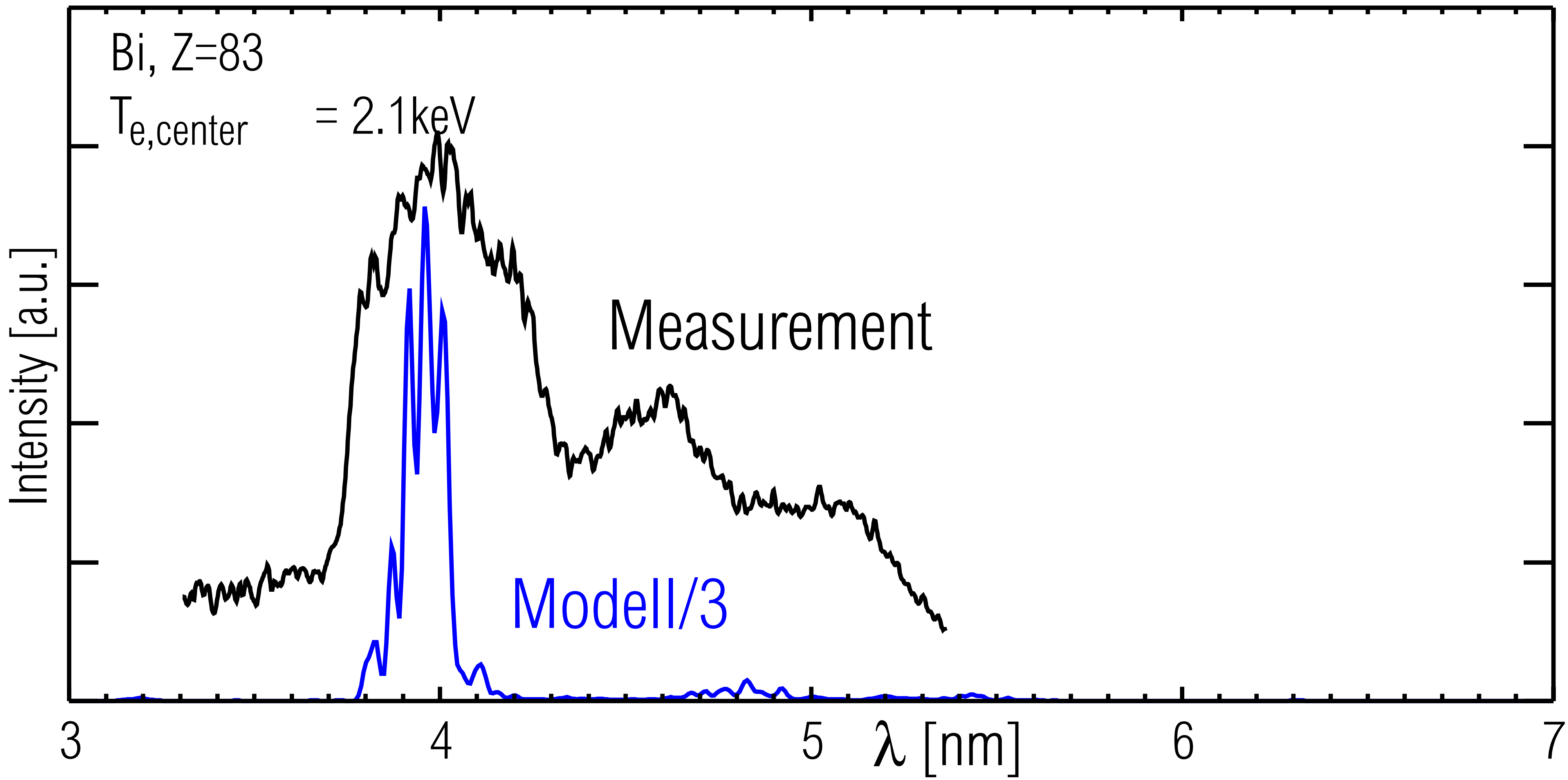

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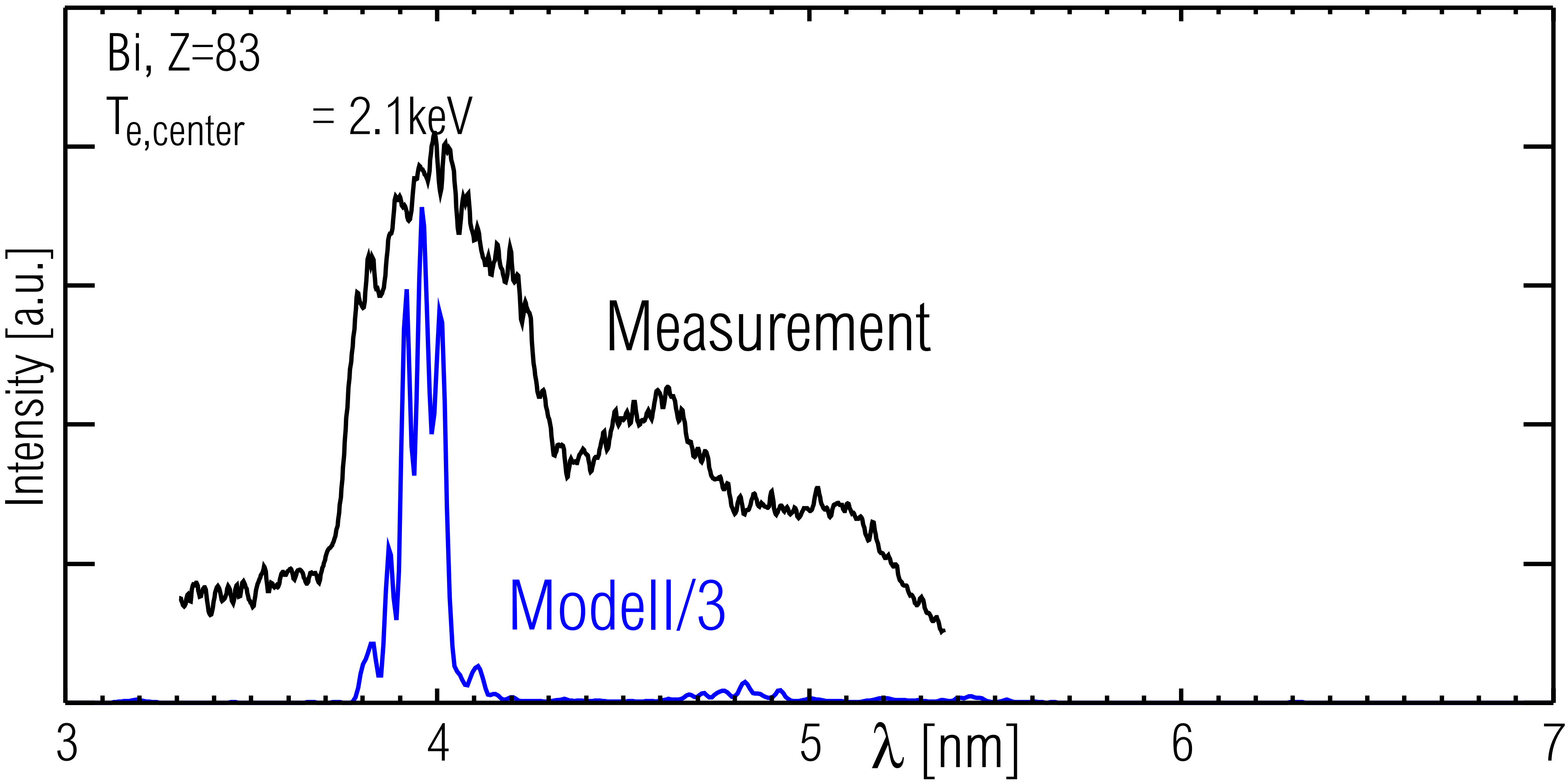
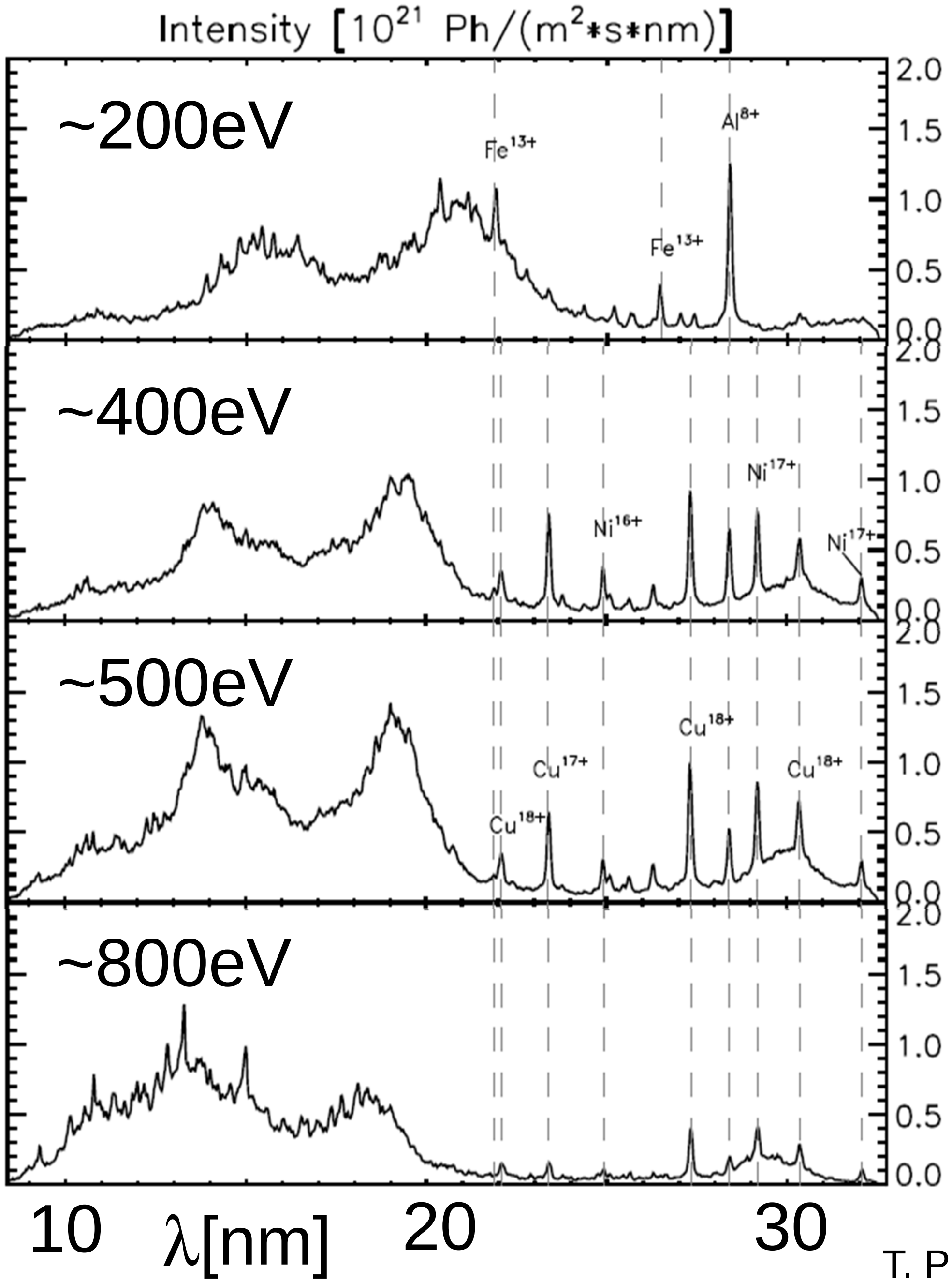


=> Little Peak requires Larger Insight

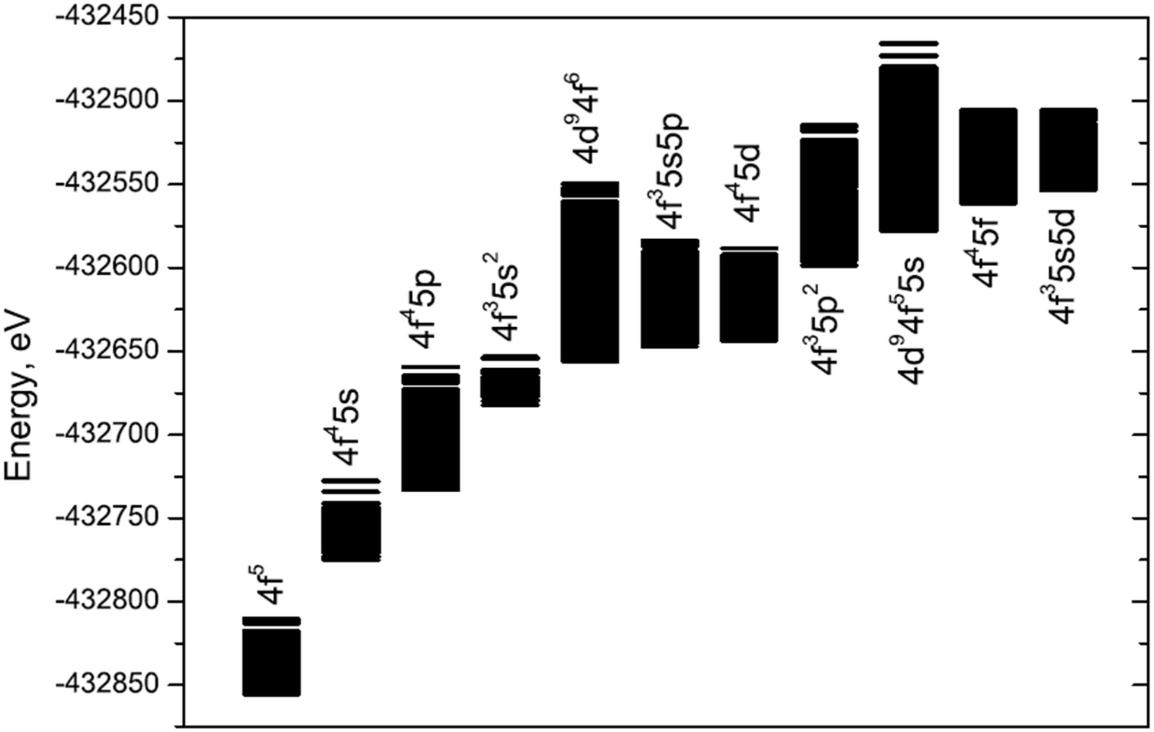
4f-feature – computational demanding

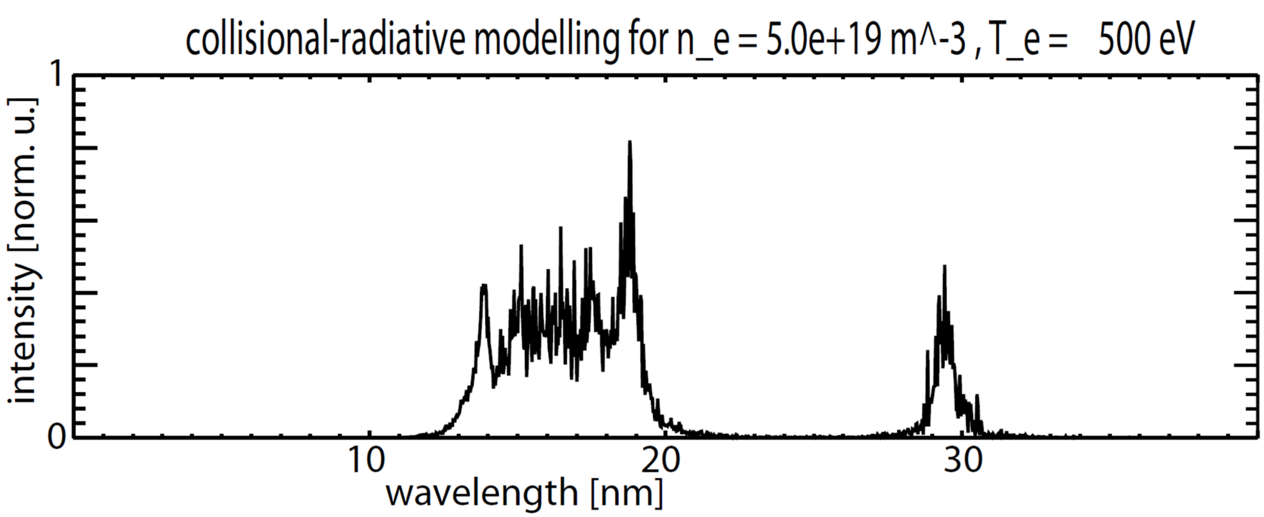


- W-emissions below 1keV from ions below W^{28+}
- Open 4f-shell, very demanding
  - ⇨ $4d^{10}4f^{n}$ => $4d^{9}4f^{n+1}$
  - ⇨ need more configurations, because of severe configuration mixing/interaction
  - ⇨ millions of transitions

PhD thesis, ASDEX Upgrade
A. Janzer

FAC Calculation for W^{23+}

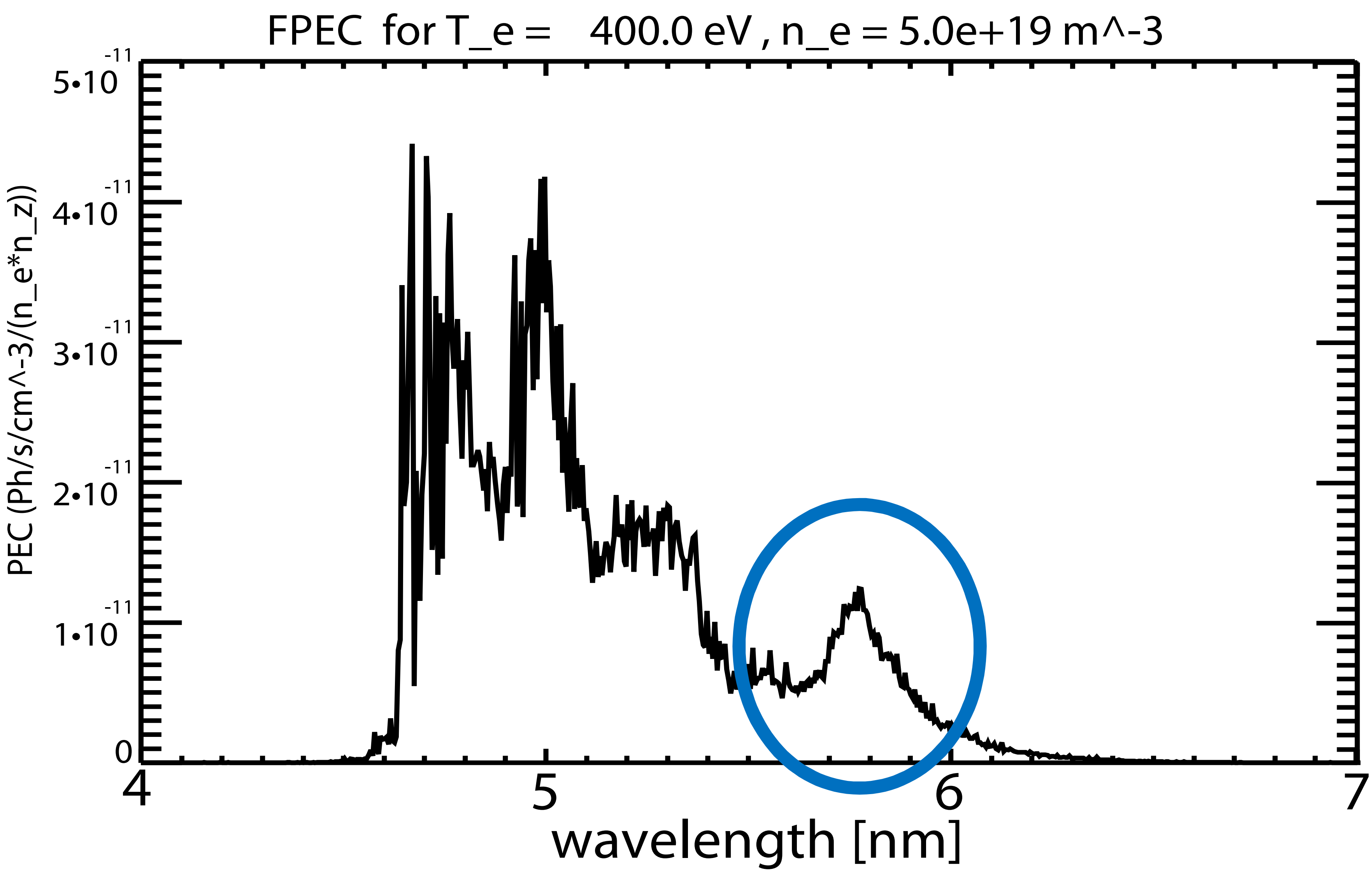




- ~12000 levels
- ~26Mio transitions
- All the configurations influence the modelled spectrum!
  Configuration Mixing important!
- W^{20+} and W^{21+} even more complex
- Need all ions to model tokamak spectrum

FAC Calculation for W^{23+}

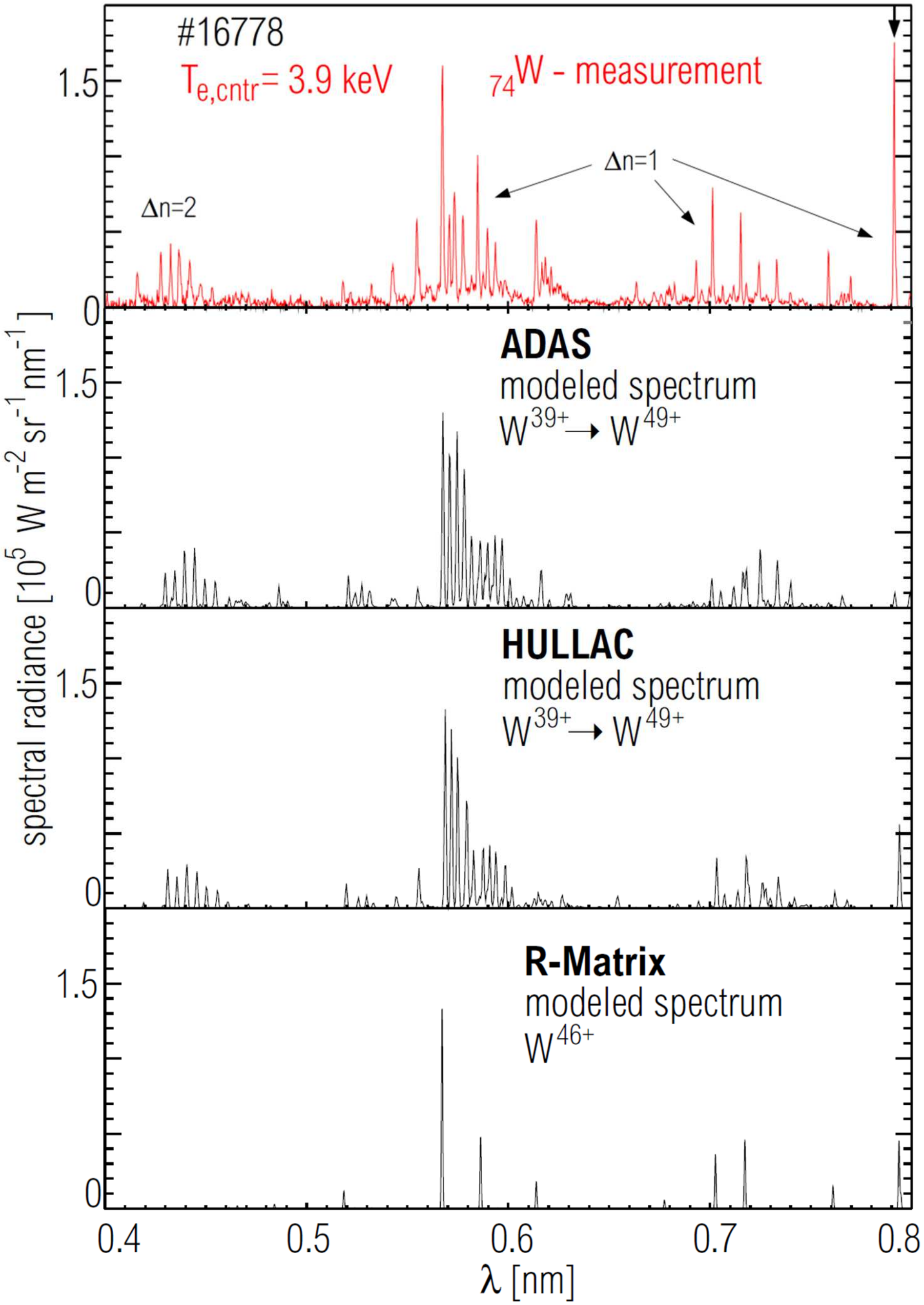
- W23+ - calculation exhibits emission close to 6nm
- Corresponding transitions in W^{27+}-W^{35+}?



Summary & Outlook

- W-content in fusion plasma must be controled
  - ⇨ W-spectroscopy is crucial
- Ionization Equilibrium – tokamaks provide detailed information!
  - ⇨ Transport not important/ Special plasmas allow quasi-local measurem.
- For X-ray and soft X-ray range (W^{40+} - W^{70+}):
  - ⇨ spectra exhibit separate lines
- VUV to EUV range (W^{14+} - W^{45+})
  - ⇨ quasicontinua exist – modelling of quasicontinua require huge structure models (configuration mixing and interaction)
  - ⇨ all further calculations computational demaning
- Outlook: W requires 2D diagnosis (=> cameras integrating spectra)

Range A: X-ray Core of AUG, Edge of ITER



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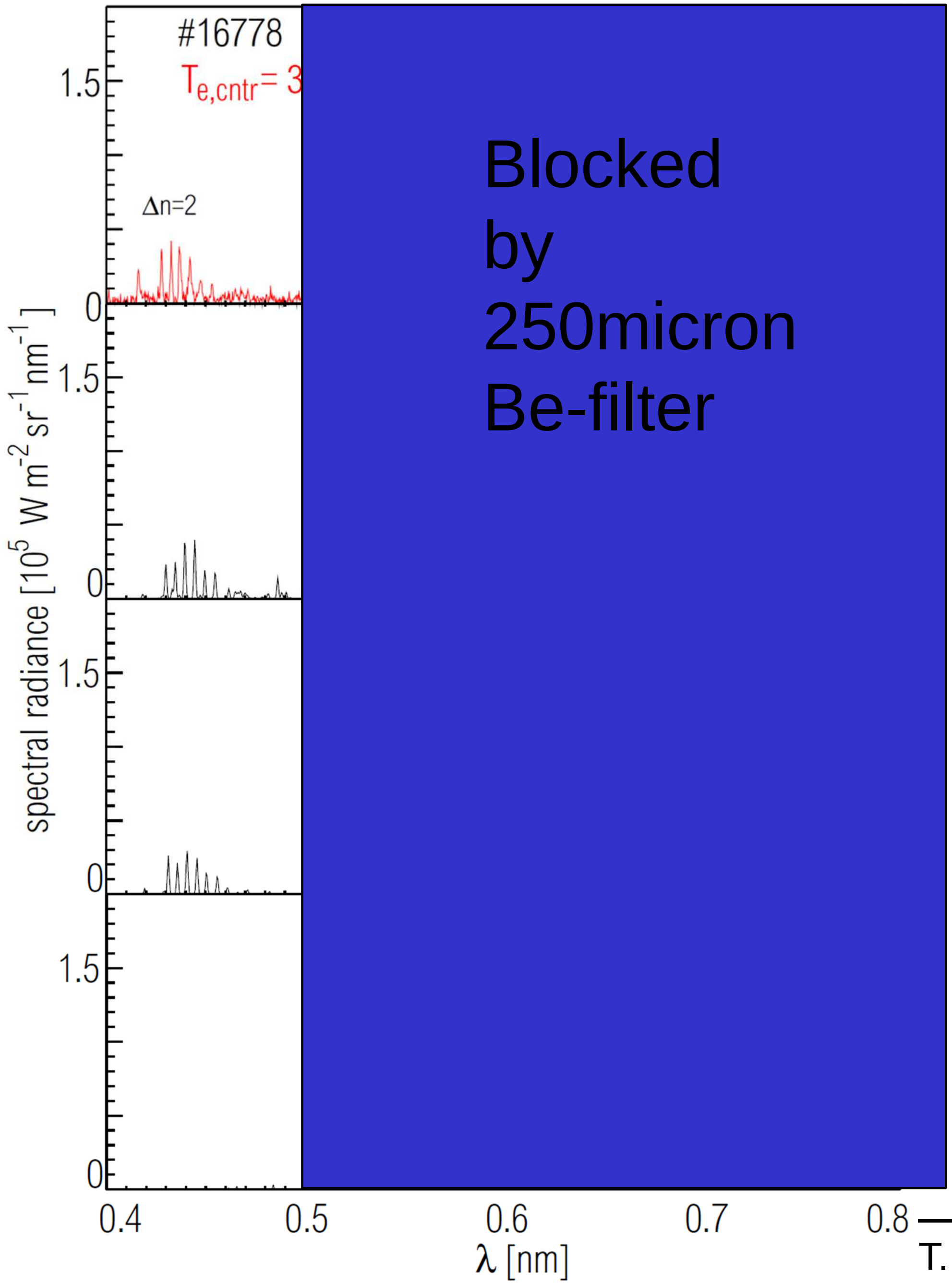

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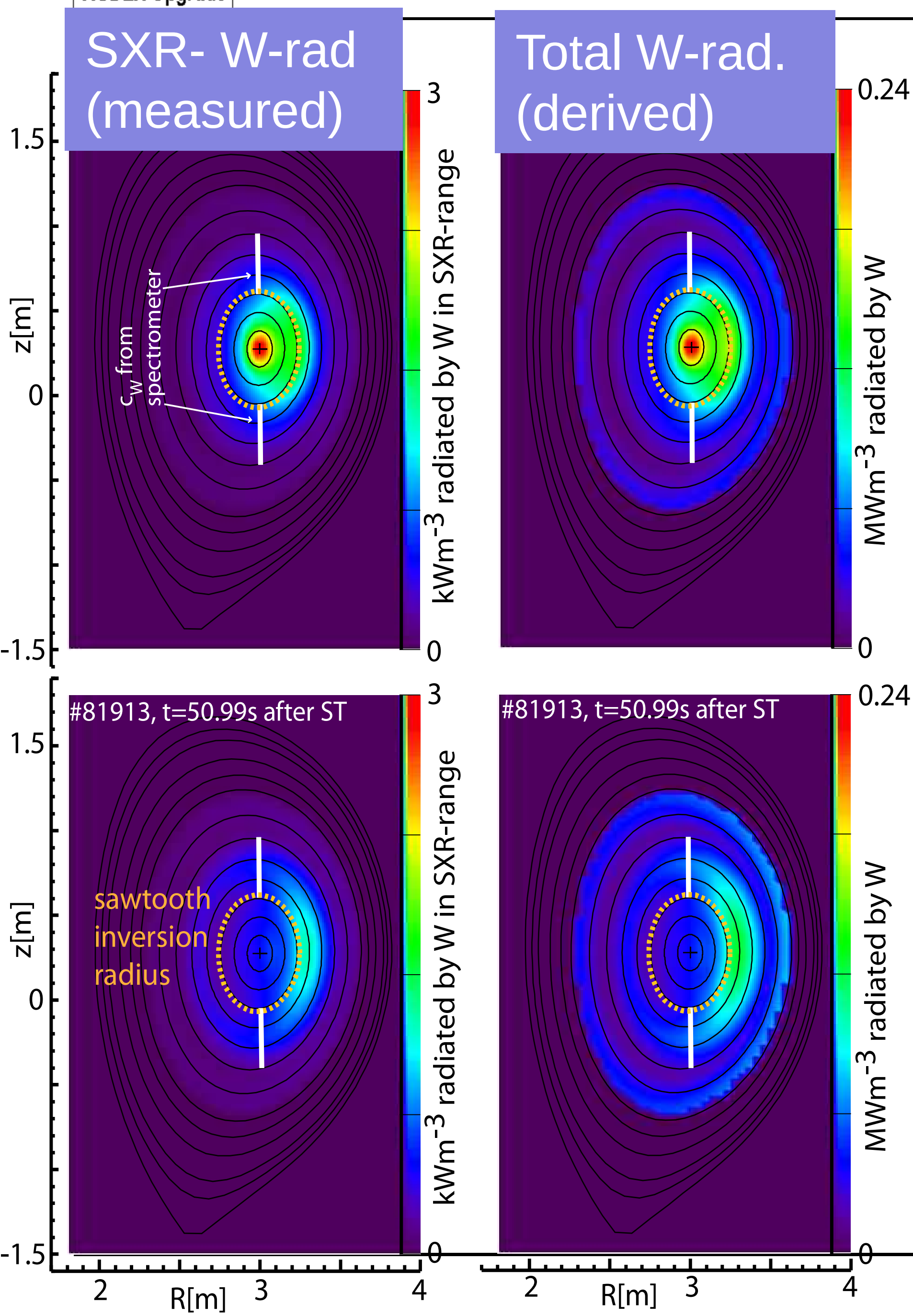
2D deconvolution of integrated SXR-radiation



- Soft X-ray region is used to investigate 2D structure
- Quantitative comparison of spectrometer and cameras
- Integrated SXR-cameras do not give direct information on radiator