Tungsten Spectroscopy for Fusion Plasmas

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Tungsten Spectroscopy for Fusion Plasmas

- Rationales for W as a Plasma Facing Material
- W in ITER and Other Devices
- Spectroscopic Diagnostic of Fusion Plasmas
- W Spectroscopy in the Visible and UV
  (Influx Measurements)
- W Spectroscopy in the VUV and SXR
  (Density Measurements)
- Conclusions and Outlook

Rationales for W as plasma facing material

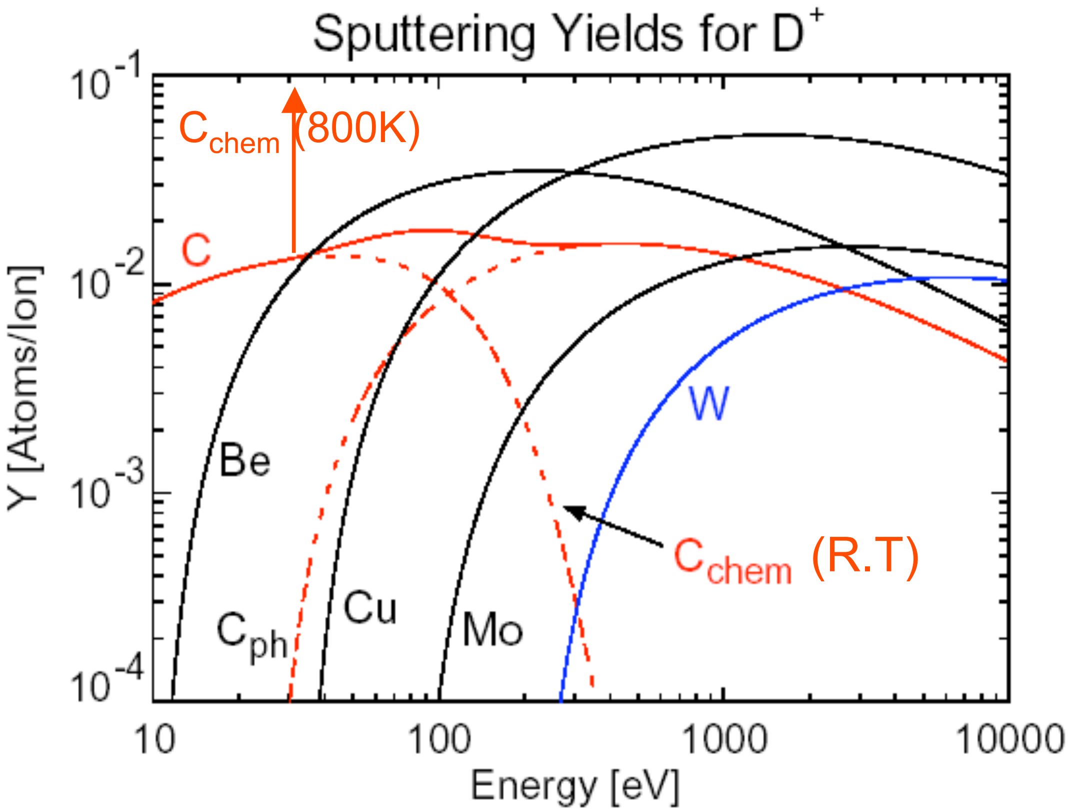
Low erosion rates:

→ low power loss by dilution / radiation originating from impurities

→ long lifetime of PFCs

→ low dust production

→ low T co-deposition



Rationales for W as plasma facing material

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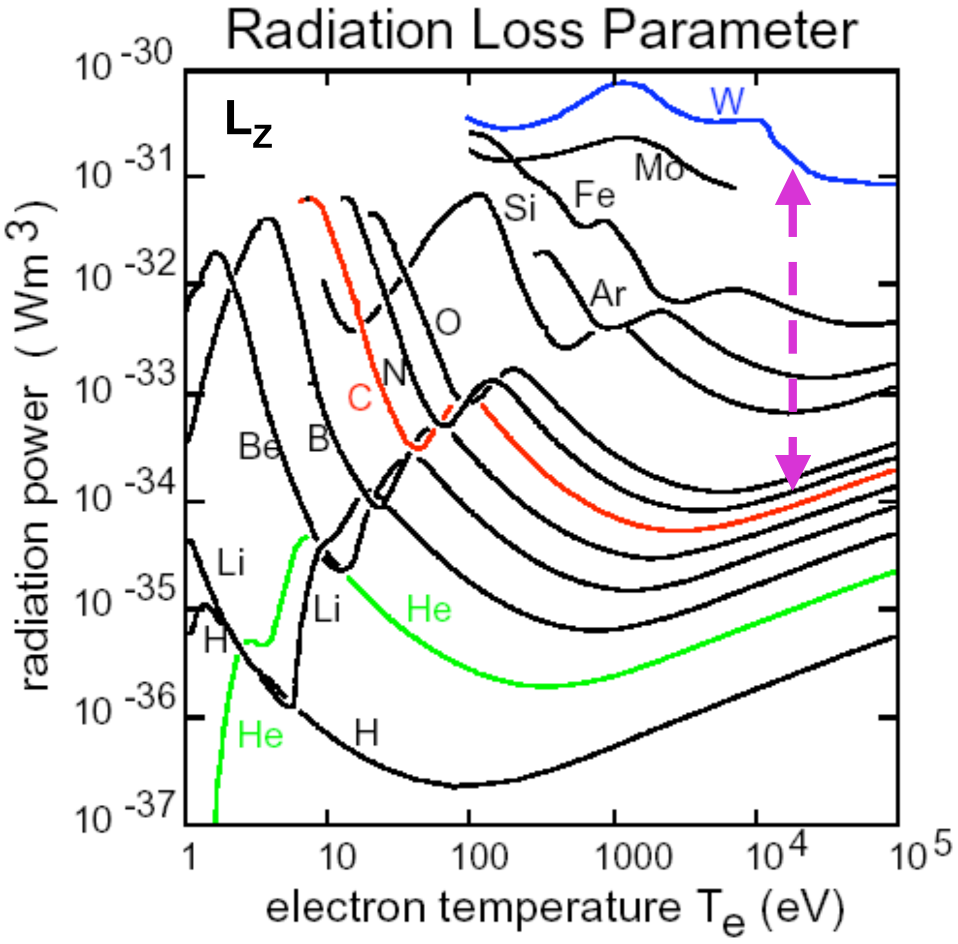
Low atomic number

→ low radiation loss parameter



Losses through

dilution (low-Z) : $n_{DT} = n_e(1 - Zn_Z)$

radiation (high-Z) : $P_{rad} / V = L_Z \, n_Z \, n_e$

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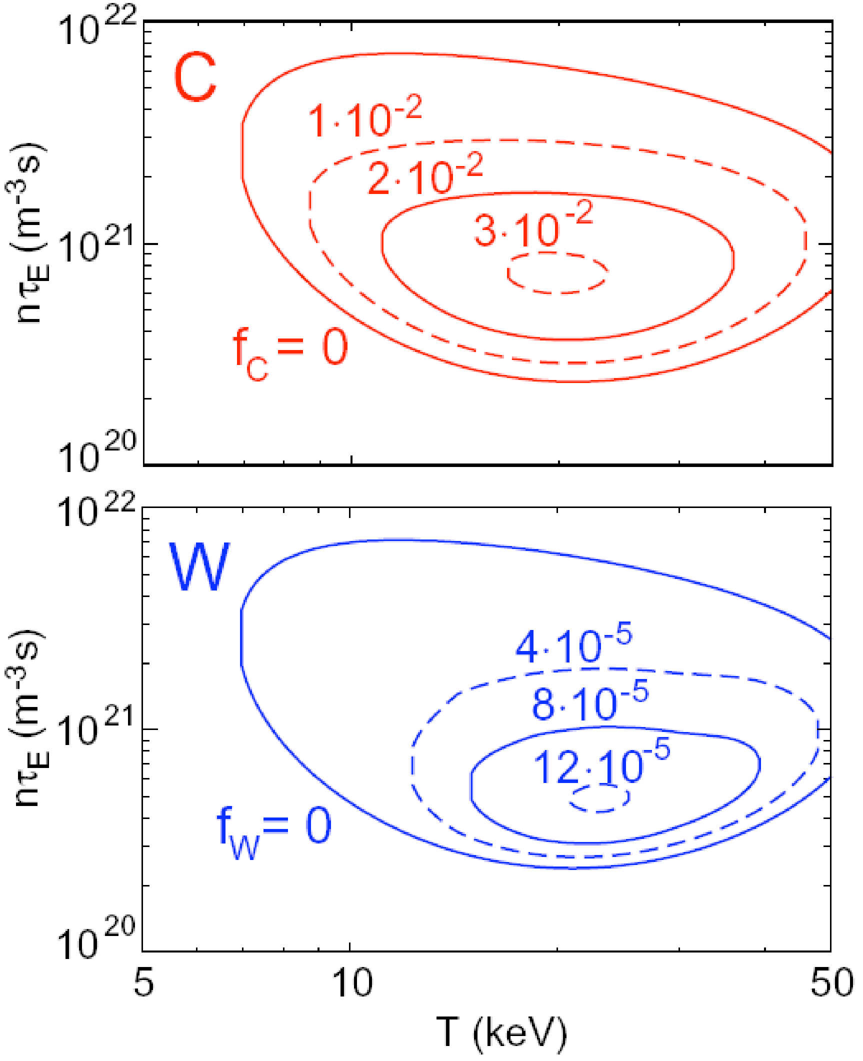

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W in ITER and other devices

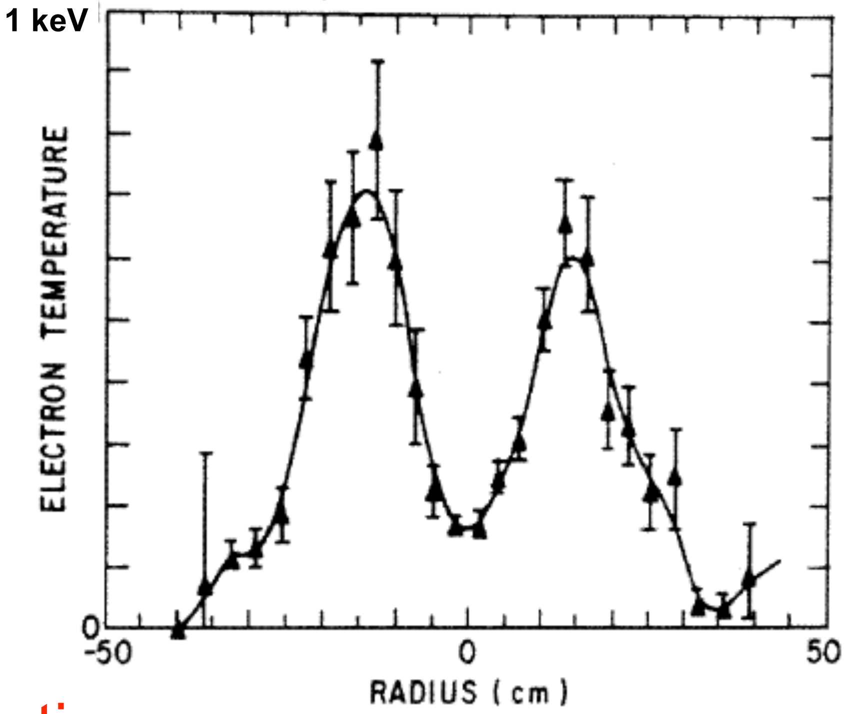
Early devices

Most of the fusion devices in the 70‘ties started with high-Z PFCs (limiters):

(Alcator A,C)
(FT)
ORMAK
PLT

(DIVA)

temperature profile in PLT during W accumulation

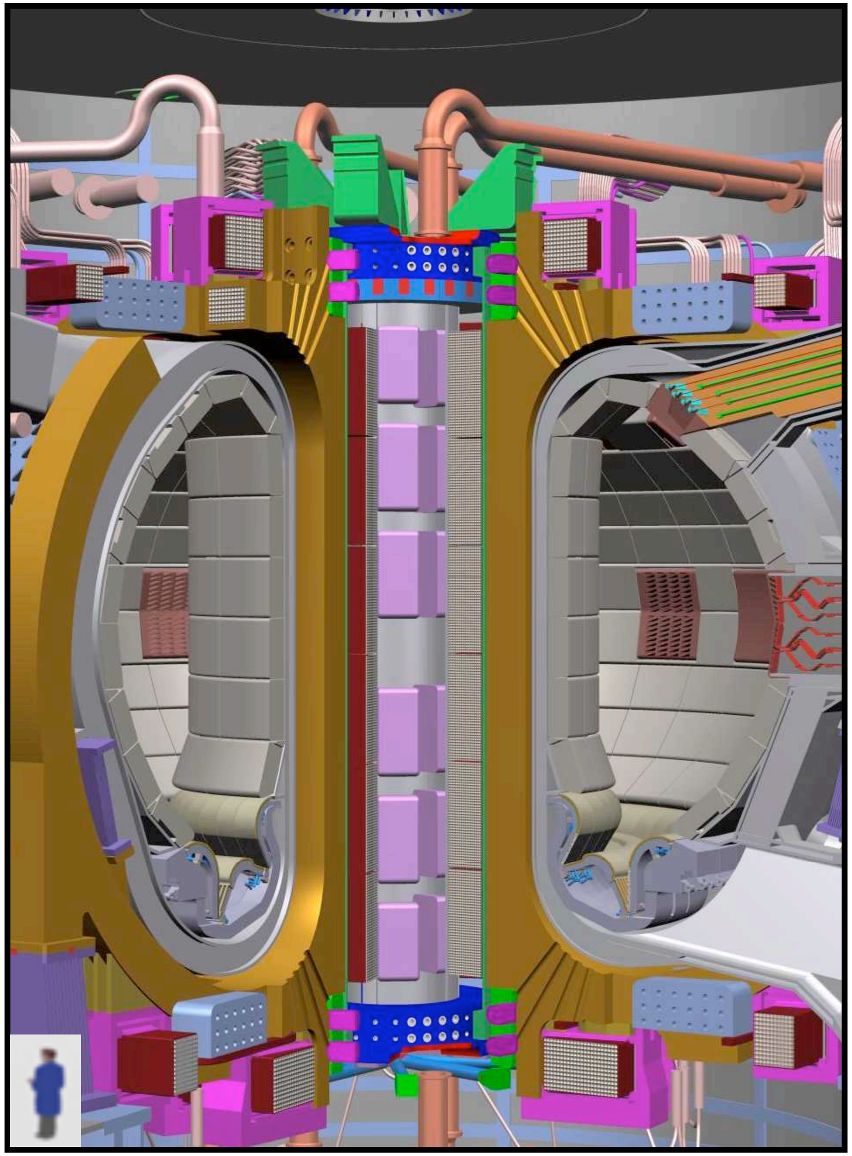


high-Z contamination / accumulations strongly deteriorated performance

⇒ all devices with moderate current densities use low-Z PFCs

W in ITER and other devices

ITER Design Parameters



- dimensions: R=6.2 m, a=2 m
  2 x JET, 4 x AUG (linear)
- plasma heating 150 MW
  5 x JET, AUG
- discharge duration: 400s
  10 x JET, 40 x AUG
- energy content: 350 MJ
  50 x JET, 300 x AUG
- fluency / discharge: 4e26/m^2
  100 x JET, 200 x AUG

⇒ plasma surface interaction /
plasma facing materials
are central issues

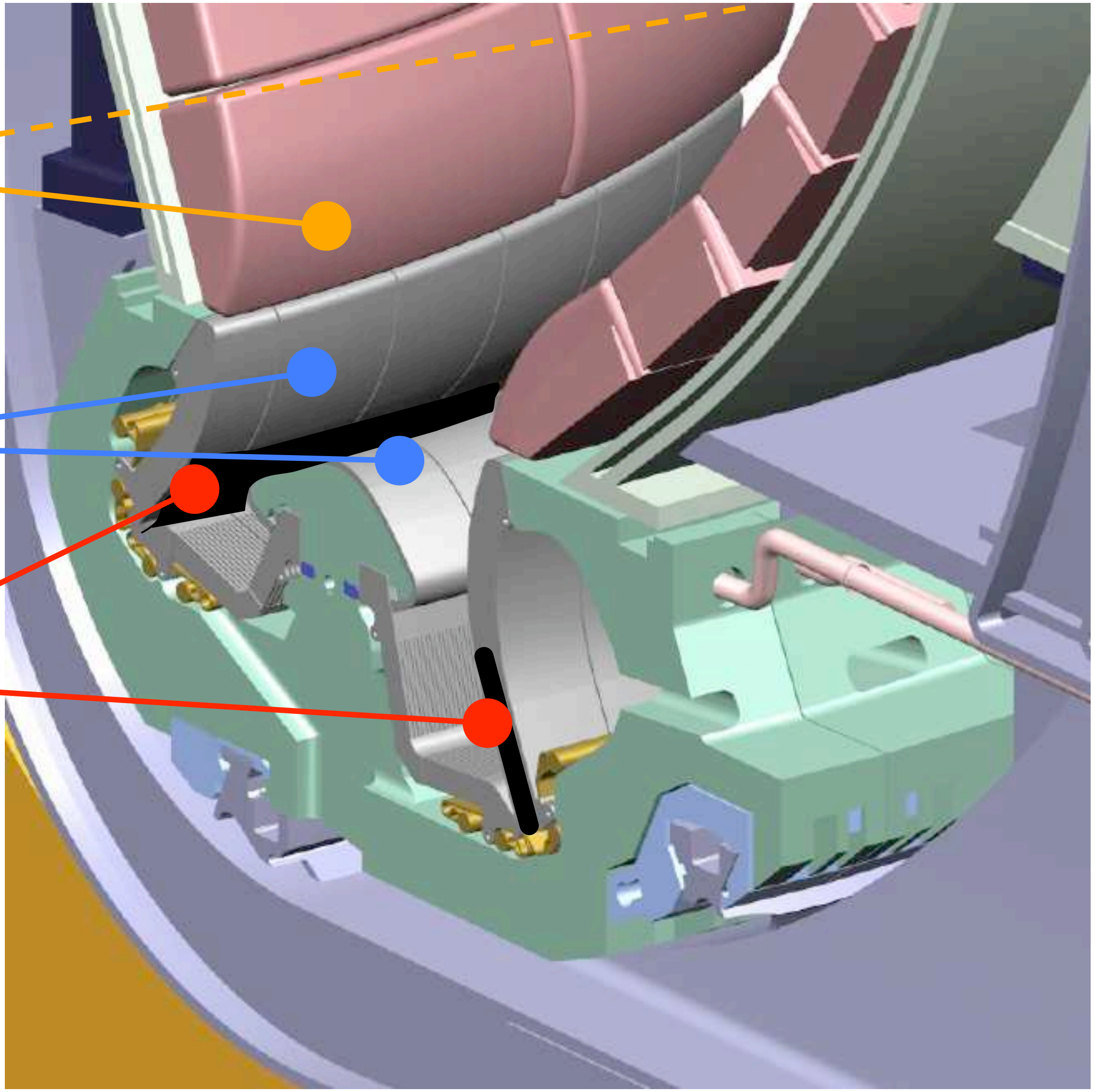
W in ITER and other devices

Plasma facing materials in ITER

Be: main chamber,
port-limiter,
baffles
($\sim 700 m^2$)

W: upper part
target, dome
($\sim 100 m^2$)

CFC: lower part
target
($\sim 50 m^2$)



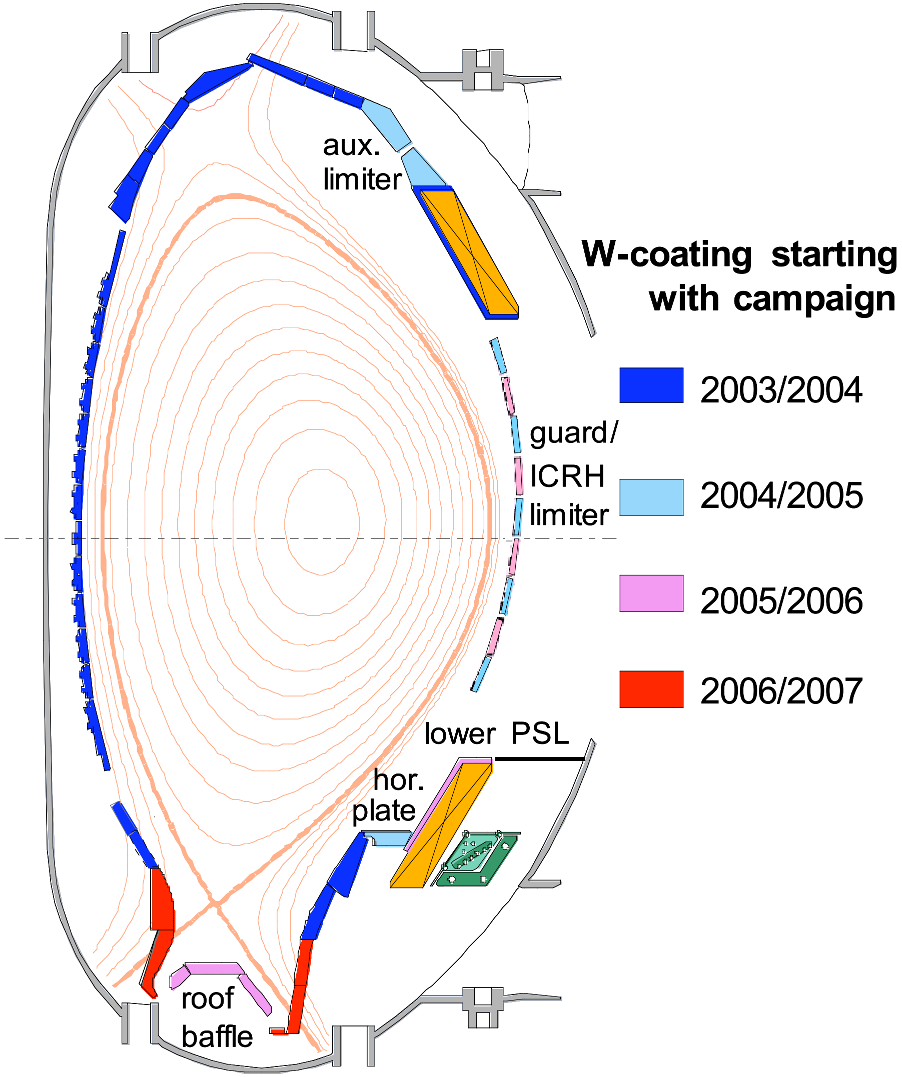
W in ITER and other devices

Steps in ASDEX Upgrade towards a full W device

Steady increase of area of main chamber W PFCs since 1999

Rationales:

- risk minimisation
- physics investigations
- partitioning of installation time
- production capacity



W in ITER and other devices
Steps in ASDEX Upgrade towards a full W device

Steady increase of area
of main chamber W PFCs
since 1999

‘05/’06 campaign:

⇒ 36 m² (85% of PFCs)

‘07 campaign

W divertor

⇒ full W device

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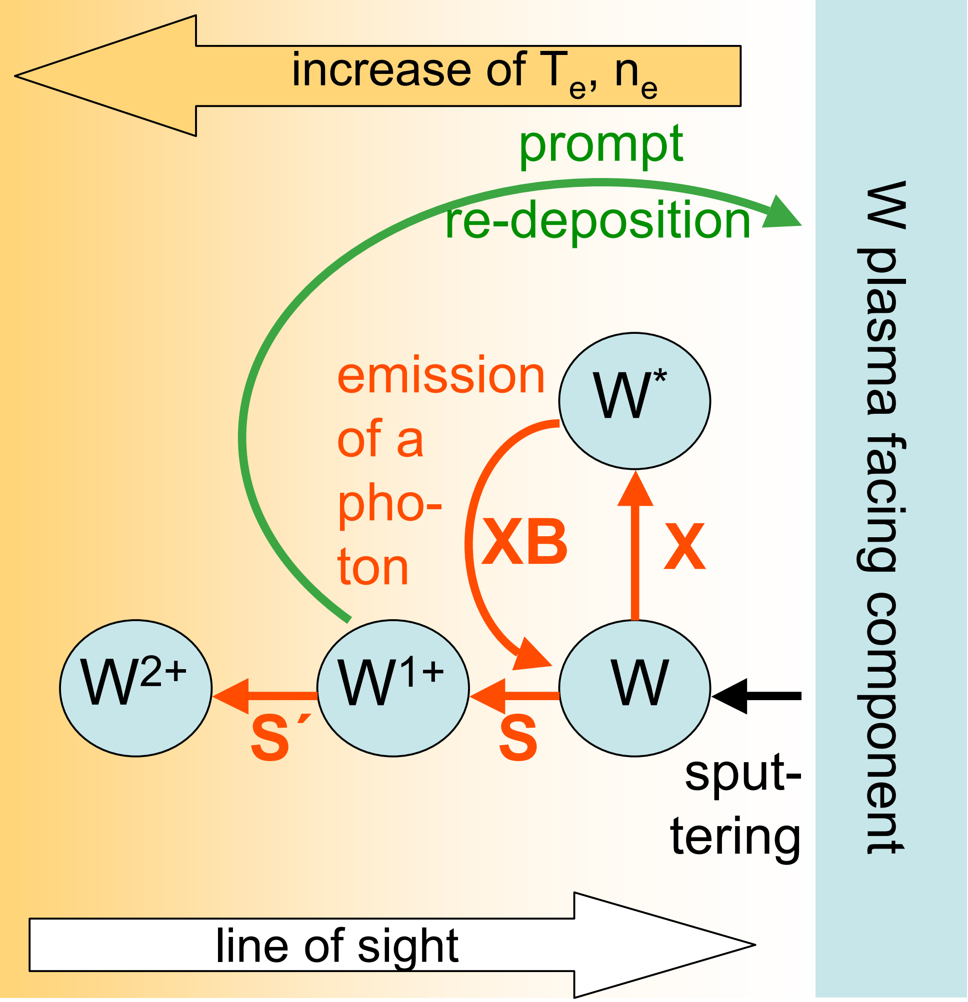
Spectroscopic diagnostic of fusion plasmas

S/XB method for influx measurements

schematic view of processes involved in
W-flux measurements



increase of T_e, n_e

prompt re-deposition

emission of a photon

W^*

XB

X

W^{2+}

W^{1+}

W

S´

S

sputtering

W plasma facing component

line of sight

prerequisite:
recombination negligible

- influx

$$\Gamma_{Z+1} = \int_{los} n_e n_Z S \, dx$$

- photon flux

$$\Gamma_\gamma = \int_{los} n_e n_Z XB \, dx$$

$$\Rightarrow \Gamma_{Z+1} / \Gamma_\gamma \approx S/(XB)\,(x_0)$$

S: ionisation, X: excitation
B: branching ratio

Spectroscopic diagnostic of fusion plasmas

Ionisation shells in the central plasma

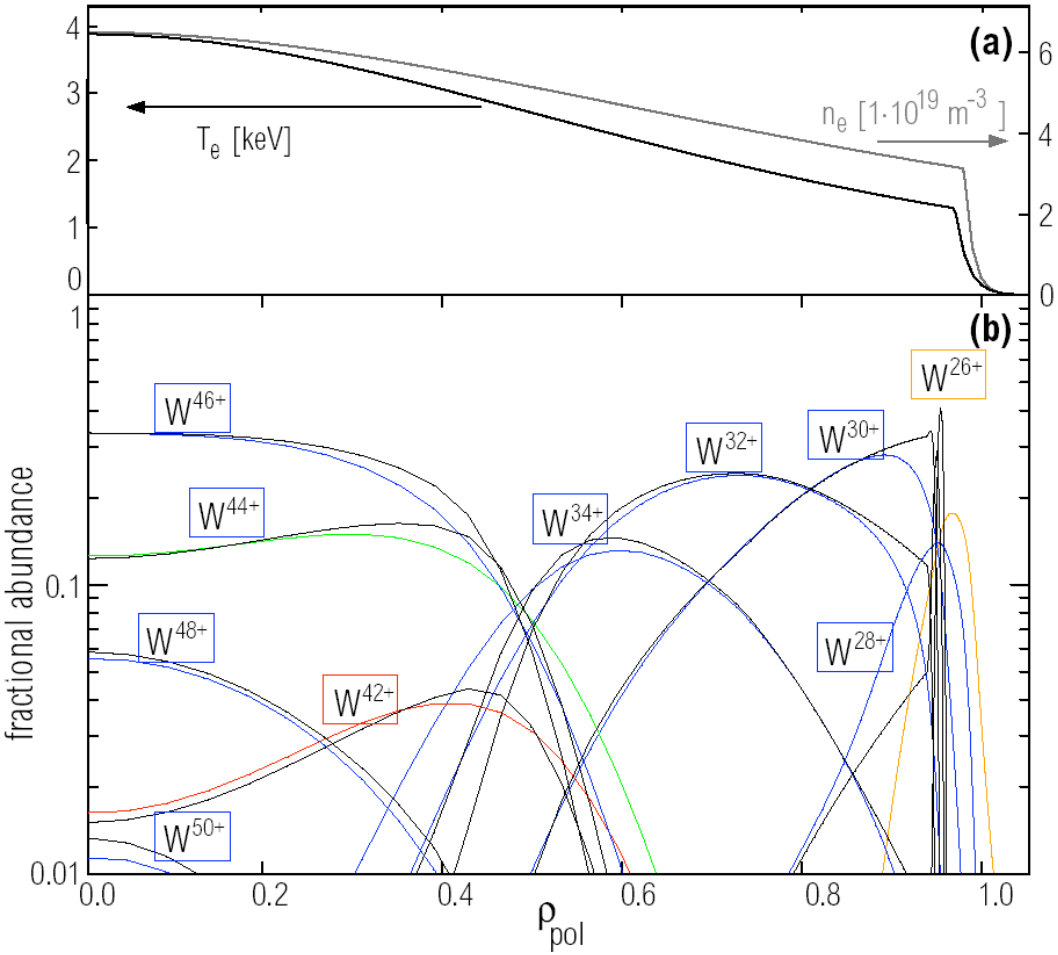
ionisation equilibrium governed by Coronal approximation

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

weak influence of plasma transport on shell structure

$$\vec{\Gamma}_Z = D_Z \nabla n_Z + v_Z n_Z$$

typical radial plasma profiles



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

Spectroscopic diagnostic of fusion plasmas
Impurity concentrations from LOS measurements

Comparison of measured I_M and calculated I_C intensities

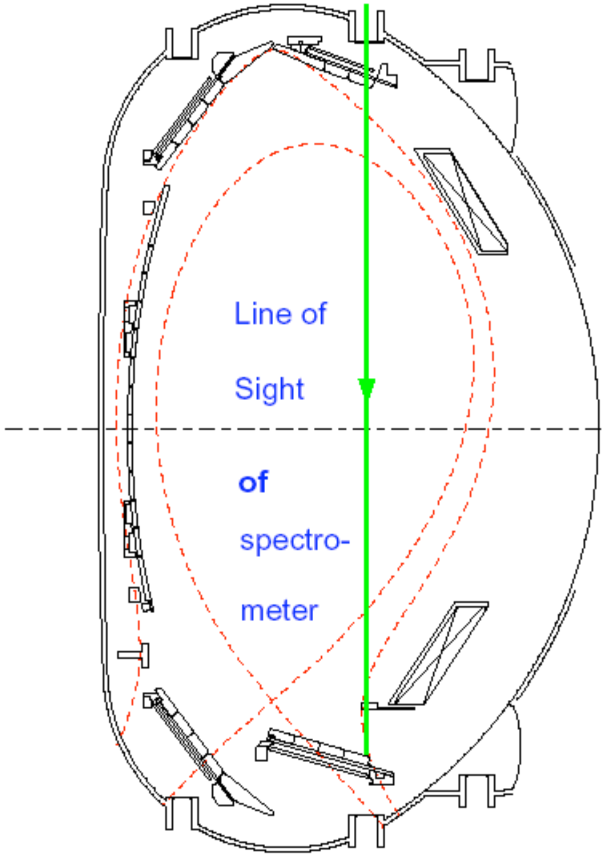
$$I_c = \frac{1}{4\pi}\int_\ell h\nu n_x n_e \langle \sigma v_e \rangle dl$$

n_x density of impurity in ionisation state x
n_e electron density
$<\sigma\upsilon>$ excitation rate coefficient

$$n_x = C_{imp} \cdot f_x \cdot n_e$$

f_x fractional abundance of the impurity ionisation state x
C_{imp} impurity concentration

C_{imp} only valid within the emission shell!



$$C_{imp} = \frac{4\pi \cdot I_m}{\int_\ell h\nu f_x n_e^2 \langle \sigma v_e \rangle dl}$$

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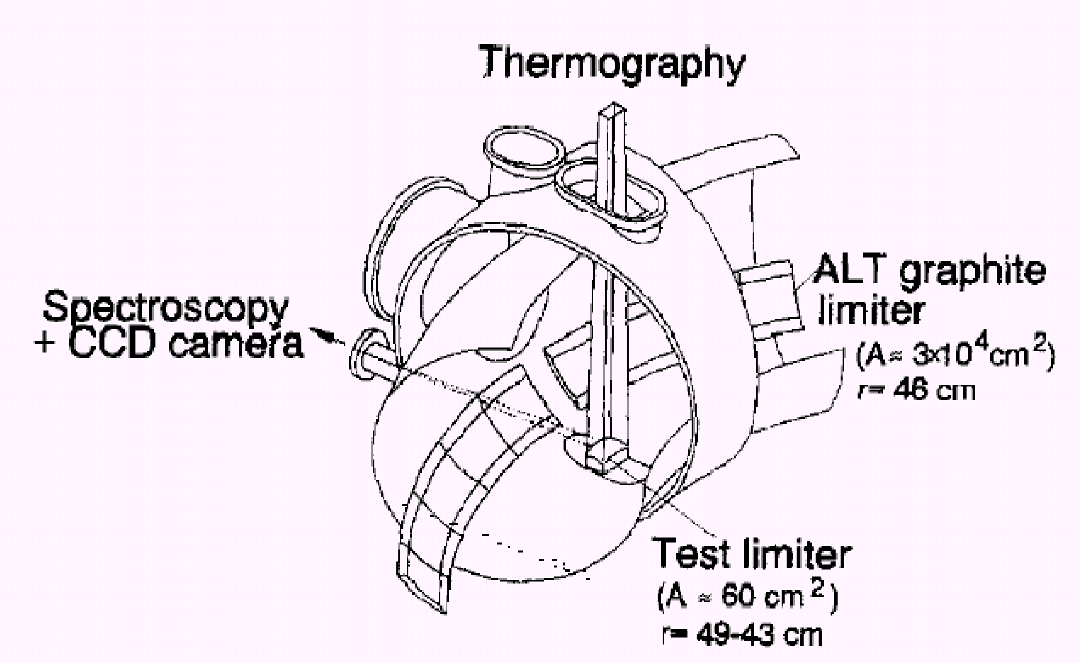
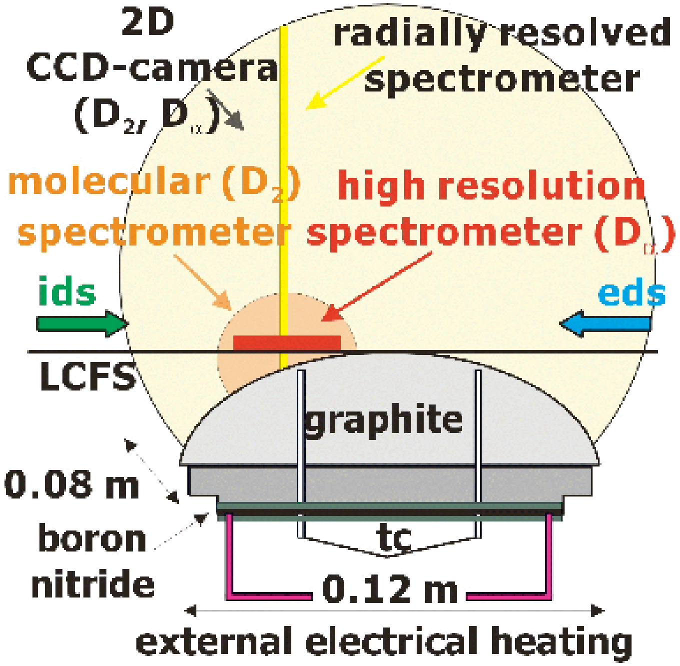
W-spectroscopy in the visible and UV
Set-up for spectroscopy on a TEXTOR limiter lock



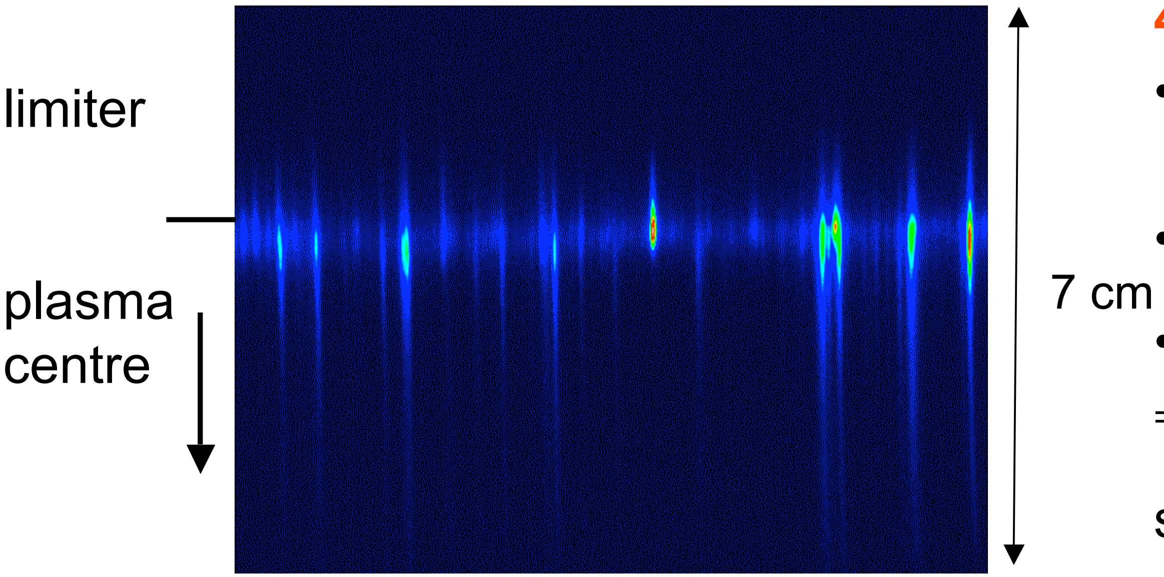


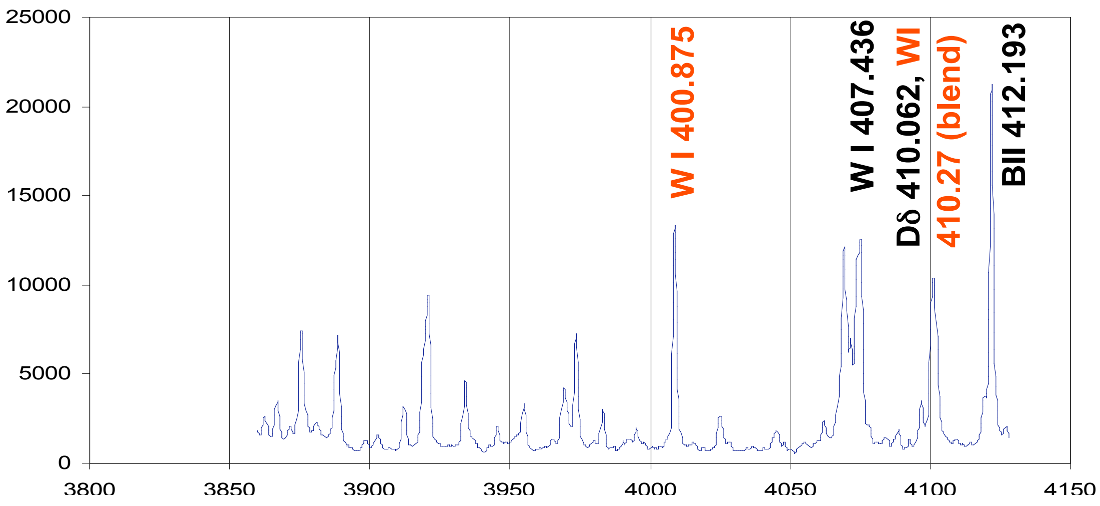
Spectrometers:	**overview 200 - 464 nm**	**R** : 1500
Spatially resolving	**medium 200 - 750 nm**	**R** : 5500
Broad band	**Echelle (220) 375 - 750 nm**	**R** :20000

observation of several distant W-lines necessary

W-spectroscopy in the visible and UV

Search for suitable W lines





400.9 nm ^{7}S – ^{7}P

- well separated, very intense line
- S/XB is known
- but: far blue

⇒ fiber transmission low

search for other W-lines with

- longer wavelengths:

⇒ may be affected during extreme heating

- UV lines

⇒ direct LOS necessary

⇒ both extensions are useful

W-spectroscopy in the visible and UV
Useful wavelength ranges

From new NIST tables (version 3.0)
Yu. Ralchenko et al. "New Generation of the NIST Atomic Spectroscopic Databases," in *Atomic and Molecular Data and Their Applications*, AIP Conference Proc., Vol. 771 Ed. by E.T. Kato et al. (AIP Press, Melville, NY,2005), p. 276-285.

A.E.Kramida, T.Shirai, J.Chem.Phys. (in press):
W I: 7049 lines, W II: 2838 linesterm designations not complete

wavelengths ranges for intense W-lines:

W I	(8 eV)	UV- visible: up to 5600 Å
W II	(15 eV)	UV - visible: up to 4200 Å
W III	(25 eV)	UV: up to 2700 Å
W IV	(39 eV)	UV: up to 2700 Å
W V	(53 eV)	UV: up to 2300 Å
W VI		VUV: up to 1500 Å

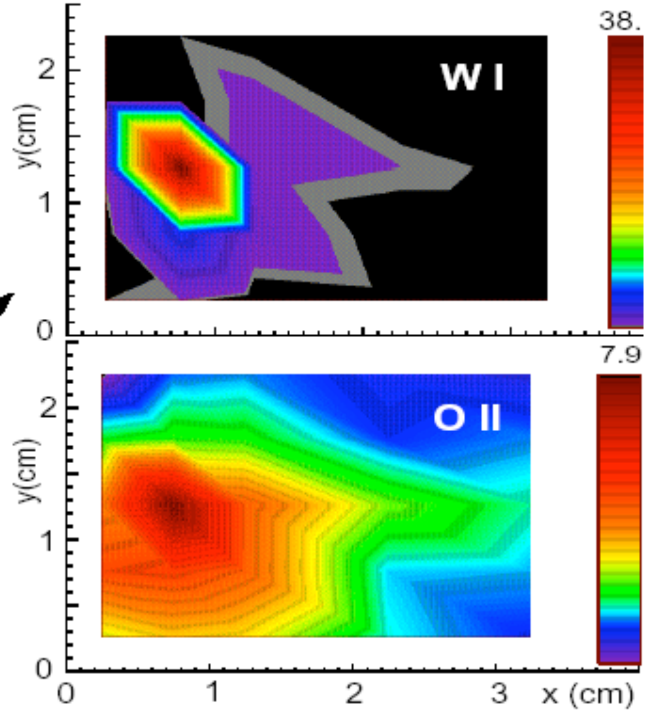
W I and W II lines often very close to each other
⇒ spectrometers with good resolutions are needed or
⇒ regions with sufficient separation

W-spectroscopy in the visible and UV
In-situ determination of S/XB (400.9nm)

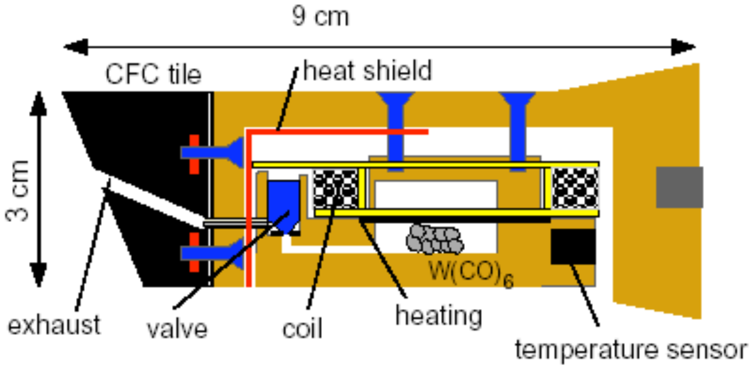
Influx measurements using photon efficiency:

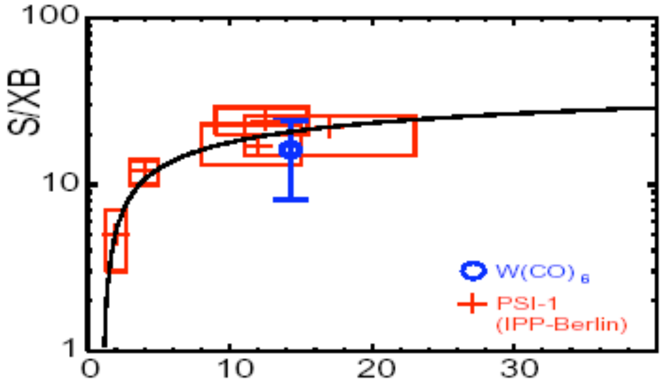
$$\Gamma_W = S/XB\ \Gamma_{ph}$$

Determination of S/XB (WI)
- PSI (IPP-Berlin, Steinbrink EPS97)
- ’insitu’ by injection of $W(CO)_6$ in the divertor of ASDEX Upgrade (Geier, PPCF 2002): simultaneous observation of WI and OII plumes



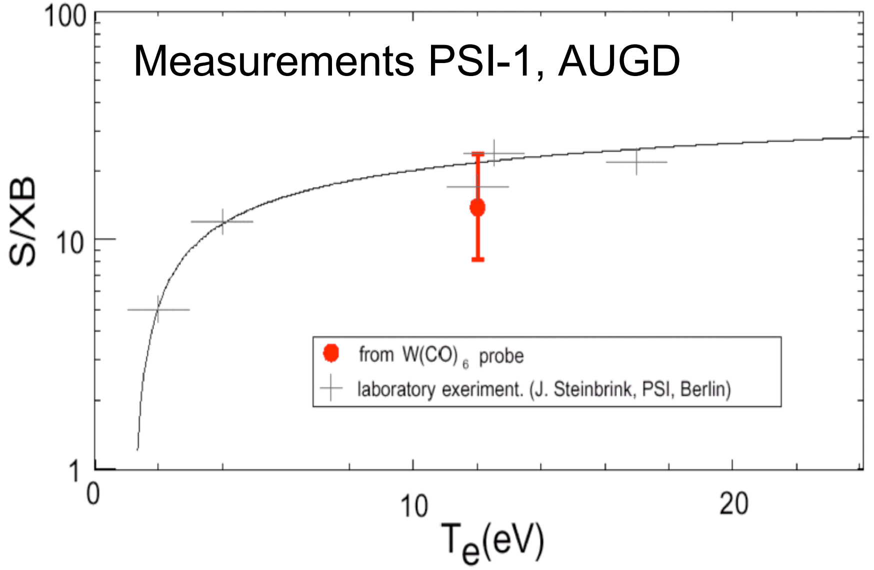
$W(CO)_6$-probe for ASDEX Upgrade Div II

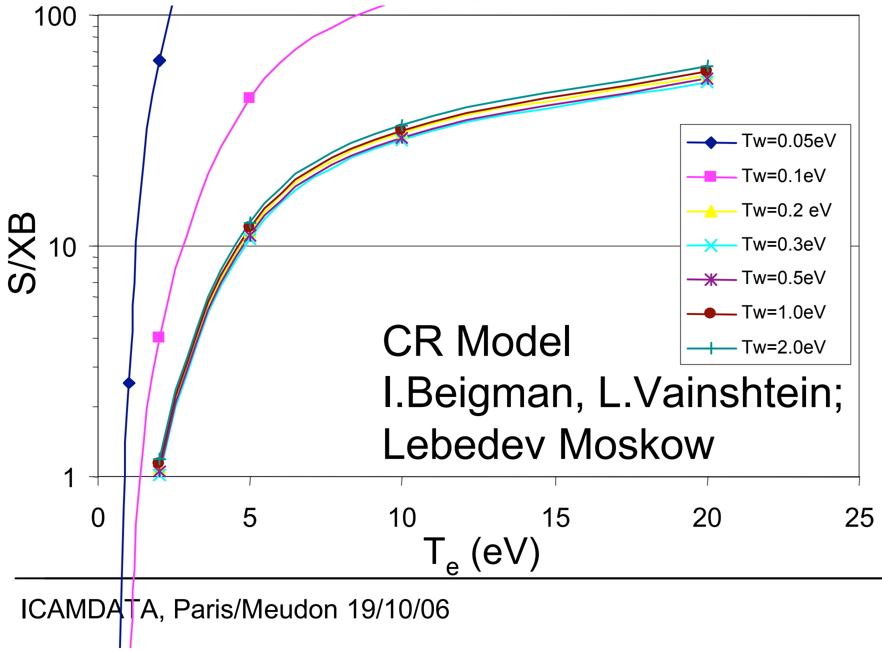




W-spectroscopy in the visible and UV

Calculation of S/XB (400.9nm)





- ionisation rate

  ATOM code calculations
  (lowest configurations)

- excitation rate:

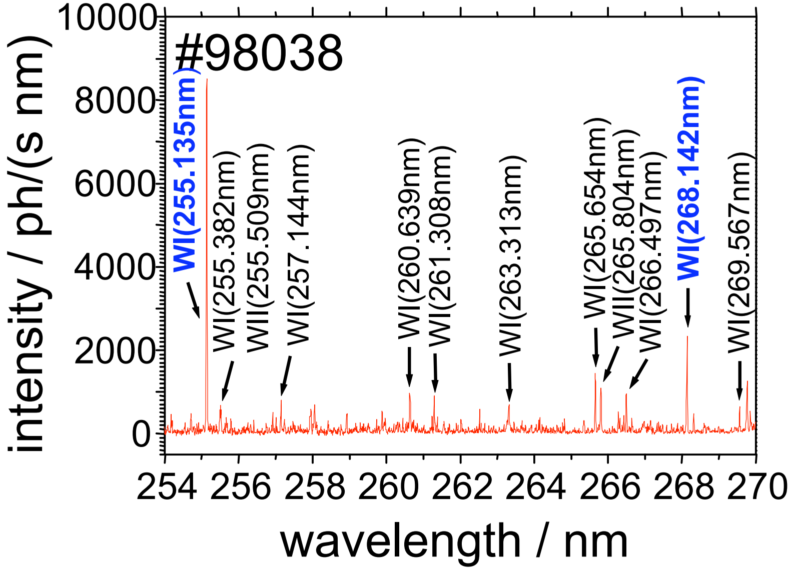
  - semi-empirical v. Regemorter formula (complicated coupling scheme + configuration mixing)
  - corona approximation: only excitation from 'ground' state

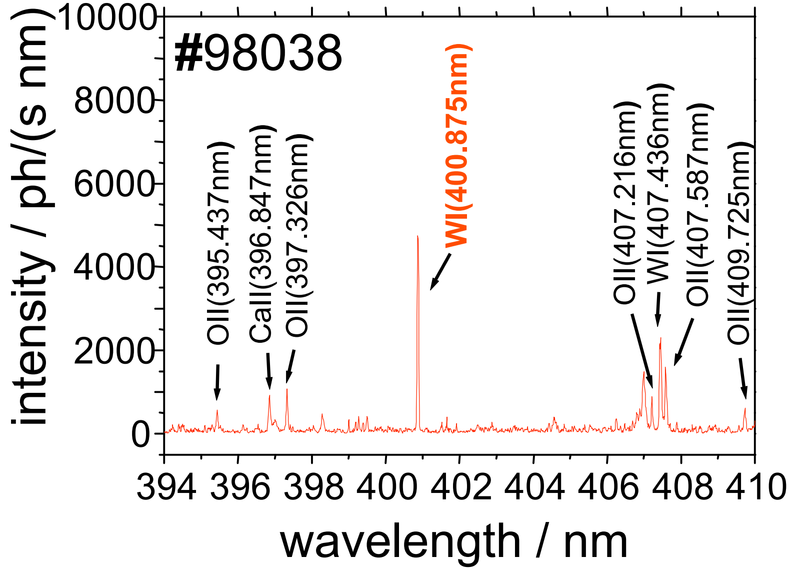
for $T_W \geq 0.2$ eV:

- reasonable agreement with experiment
- small T_W dependence

W-spectroscopy in the visible and UV

Alternative WI lines





Measurement of W spectra in TEXTOR (240 – 780nm)

- UV: low background from thermal radiation
- suitable WI lines for influx measurements:
  255.135nm, 268.142nm,
  498.259nm ,505.328nm
  400.8753nm (probably blended by WII (400.8751nm))

A. Pospieszczyk, G. Sergienko et al.

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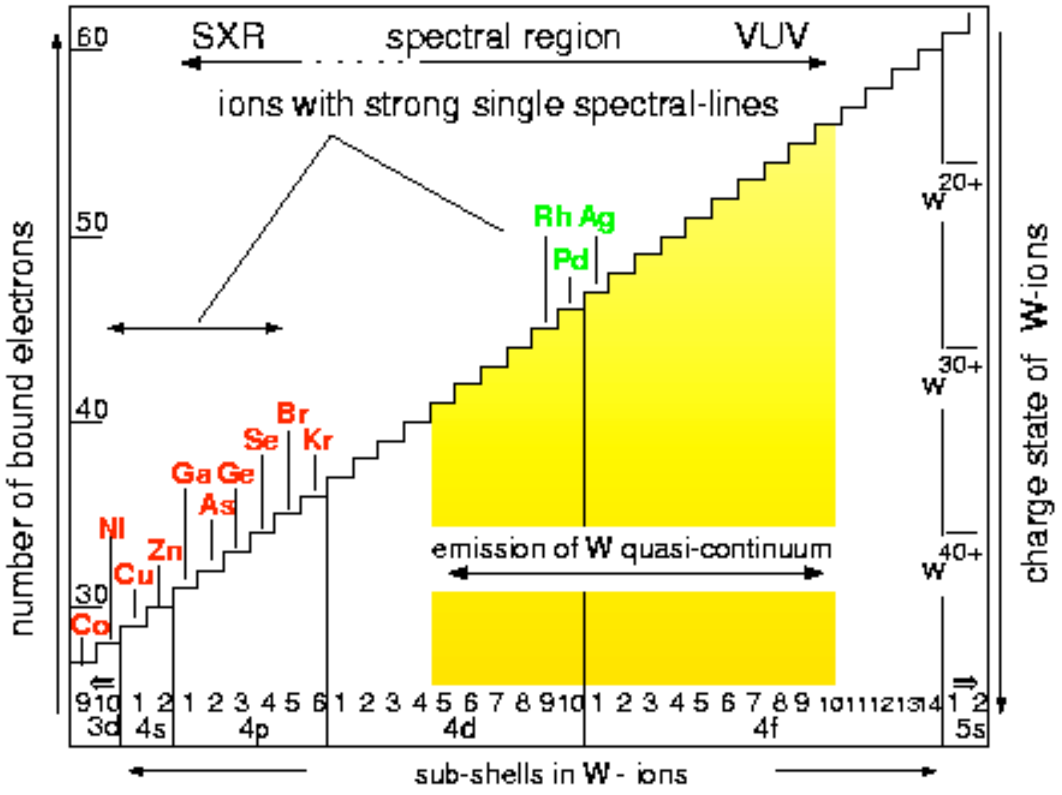
W Spectroscopy in the VUV and SXR

Investigated transitions

Accessible ionisations states in ASDEX Upgrade

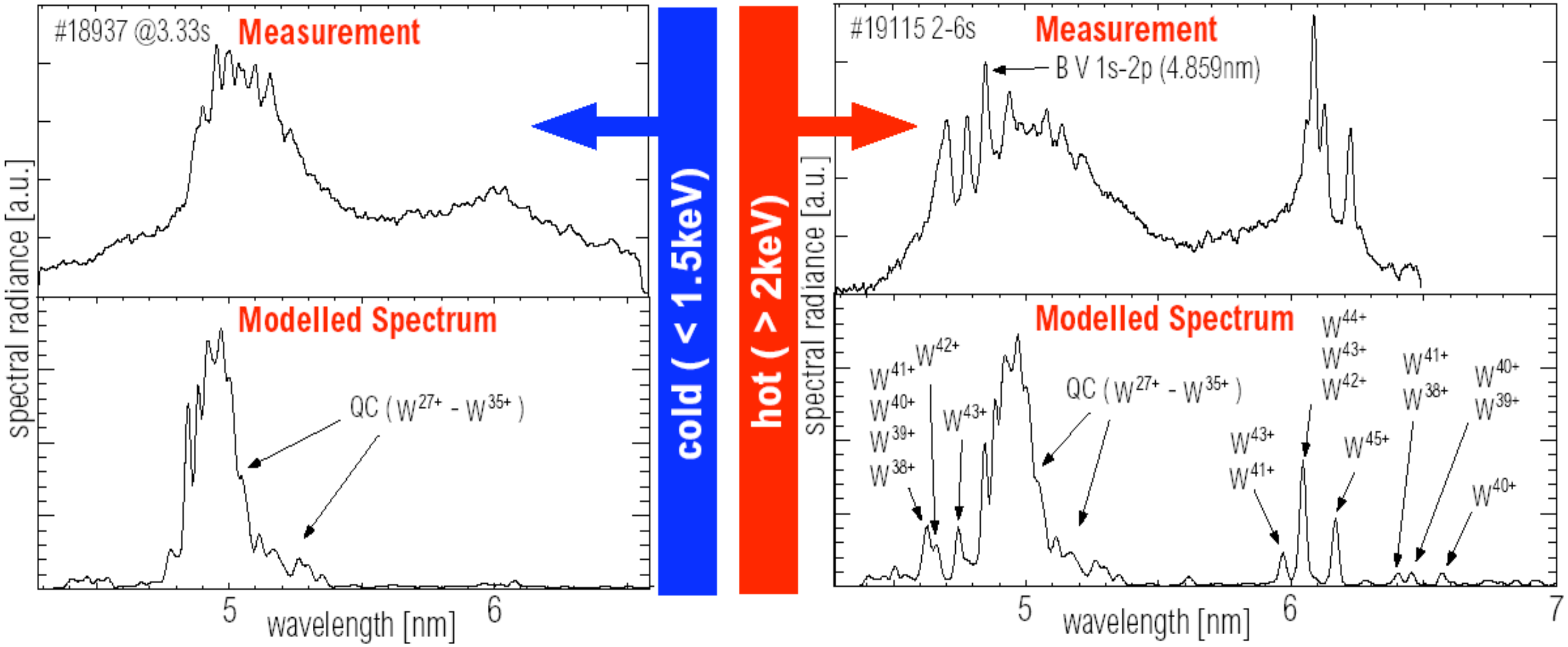
- $\Delta n=0$ transition observable in the VUV
- $\Delta n=1$ transition observable in the SXR
- quasi continuum emission from states around W^{30+}
- strong single line transitions observed for ionisation states around Ni-like W (W^{46+}, $3d^{10}$)



W Spectroscopy in the VUV and SXR
Detailed investigations in the VUV

- Around 5 nm: Features emitted at $T_e \approx 0.8 - 1.5$ keV and at $1.8 - 4.5$ keV
- Detailed EBIT measurements (Berlin, LLNL) available
- Disagreement in many details
- Rough structure of predictions is found in the spectrum

Th. Pütterich (PhD thesis)

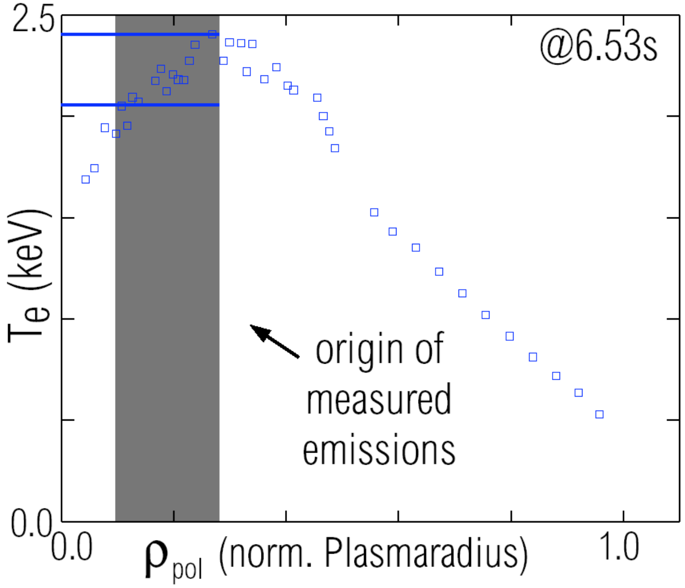


W Spectroscopy in the VUV and SXR

Reduction of ambient ionisation states by accumulation

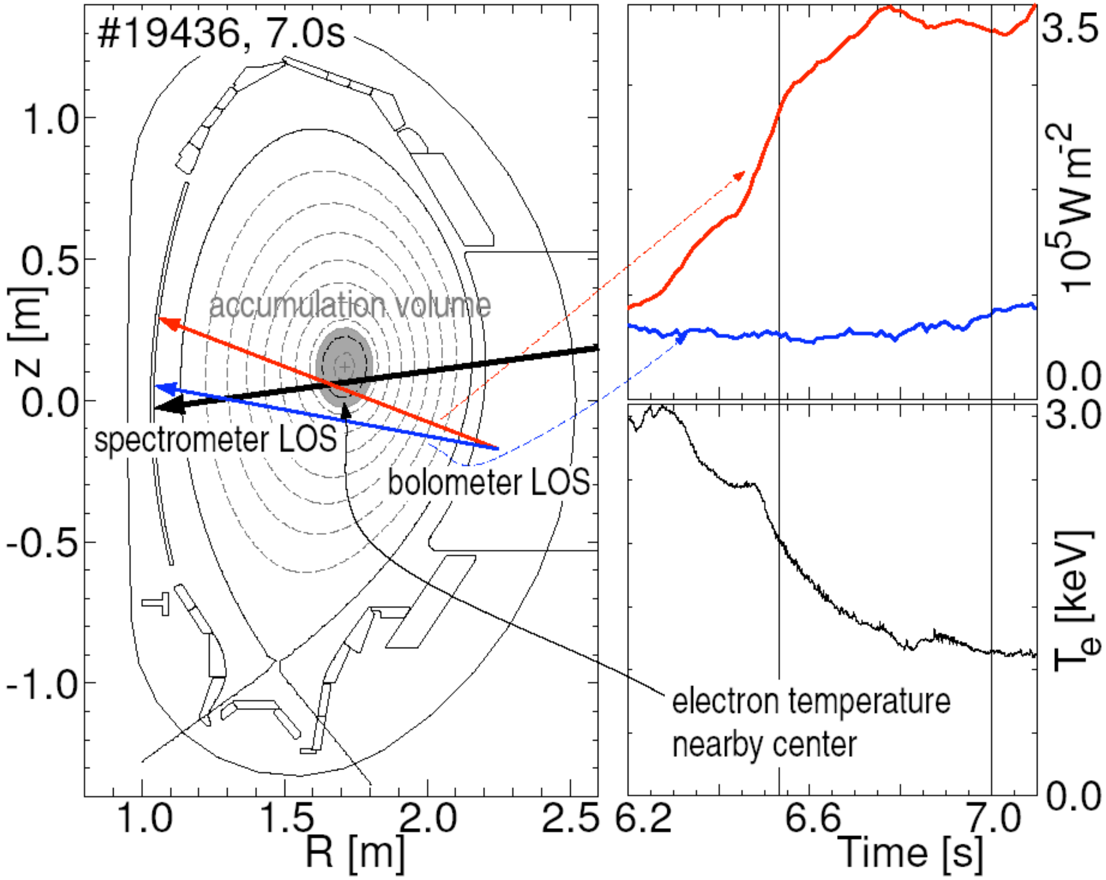
- W can accumulate in plasma centre due to ‚neoclassical‘ transport
- central concentration can be increased by up 50 times
- radiation originates from very small volume / radial range

⇒ dominated by very few ionisation states



@6.53s

origin of measured emissions



#19436, 7.0s

accumulation volume

spectrometer LOS

bolometer LOS

electron temperature nearby center

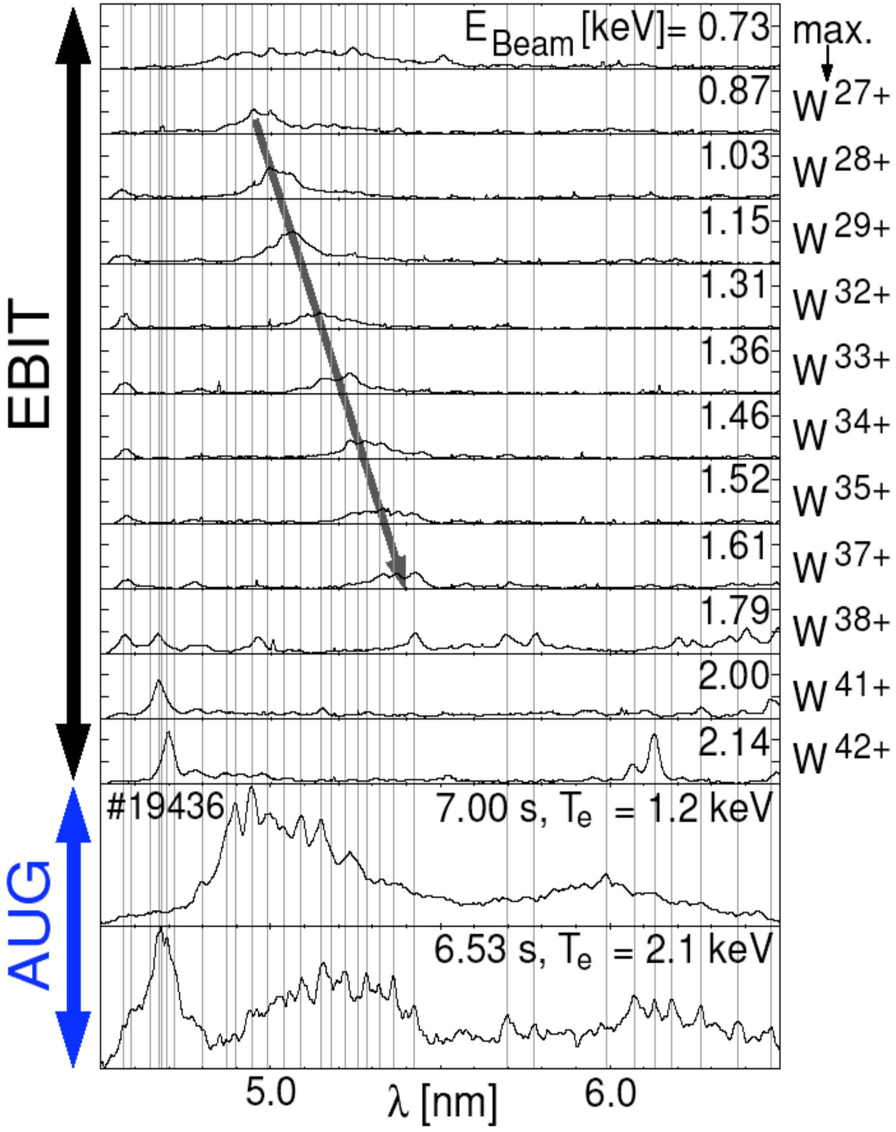
W Spectroscopy in the VUV and SXR

Disentangling W quasi-continuum

Comparison with EBIT investigations

central accumulation facilitates resolving spectral features

→ locally higher W-density
→ emission mostly from a few ionisation states
⇒ situation resembling to EBIT
⇒ similar single line spectra



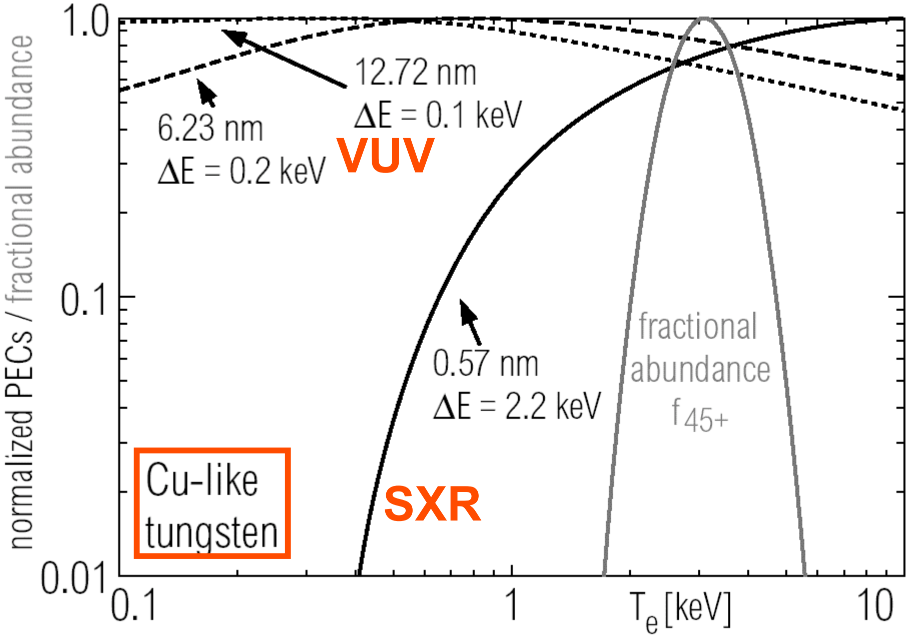
Th. Pütterich et al., J. Phys. B 38 (2005) 3071

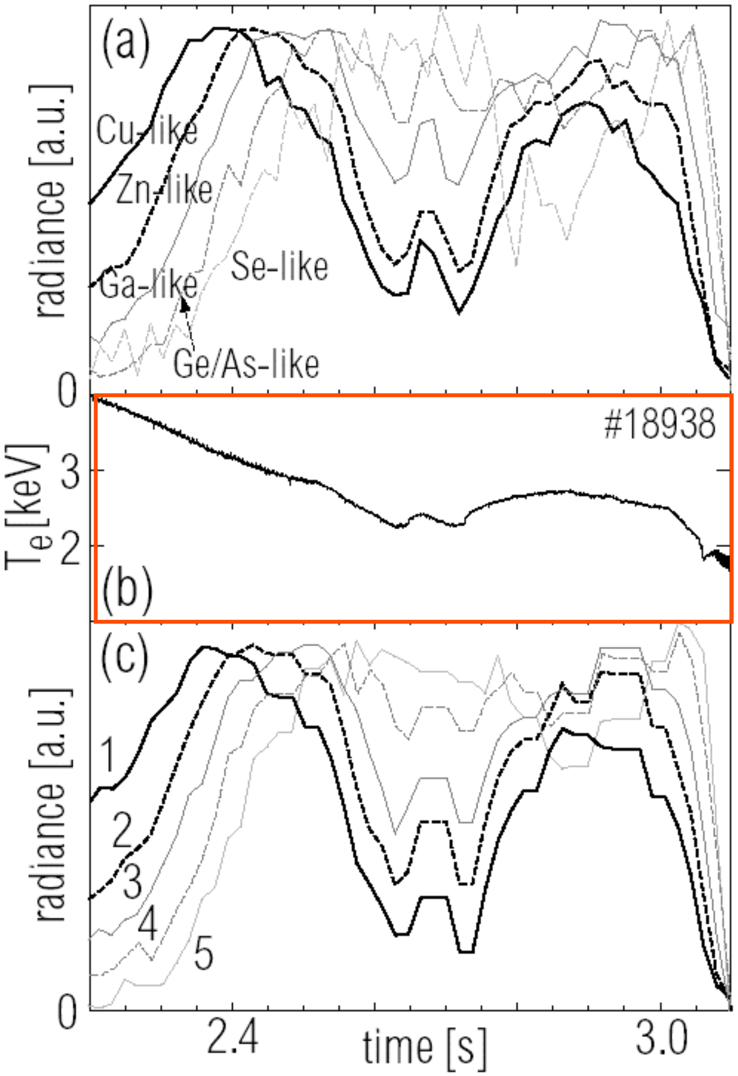
W Spectroscopy in the VUV and SXR

Line intensities dominated by abundance of ionisation state

Temperature dependence of fractional abundance much stronger than of PECs (especially for Δn=0 VUV transitions)

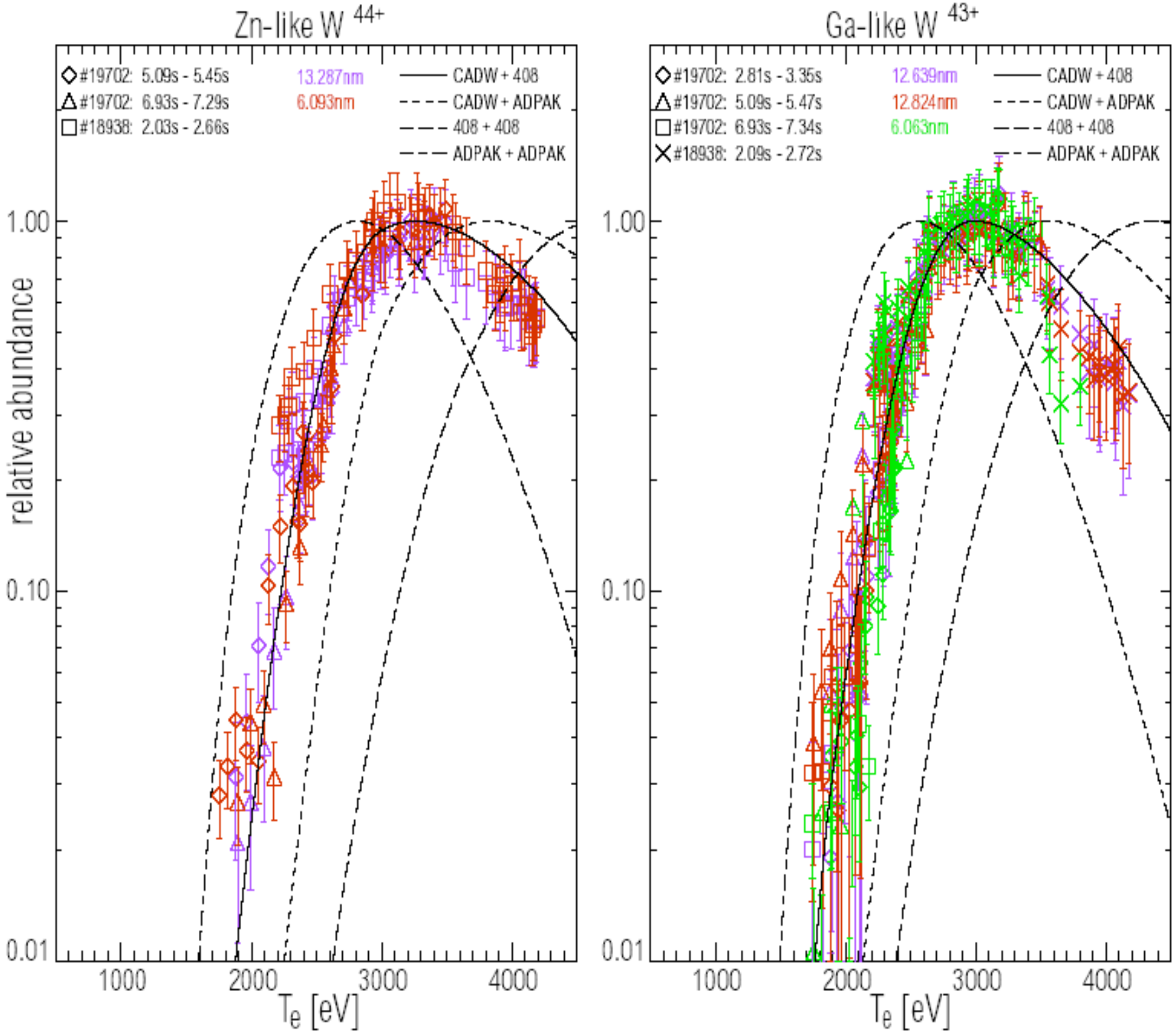
⇒ **intensity variations can be used for deduction ionisation equilibrium**





W Spectroscopy in the VUV and SXR

Revision of ionization equilibrium

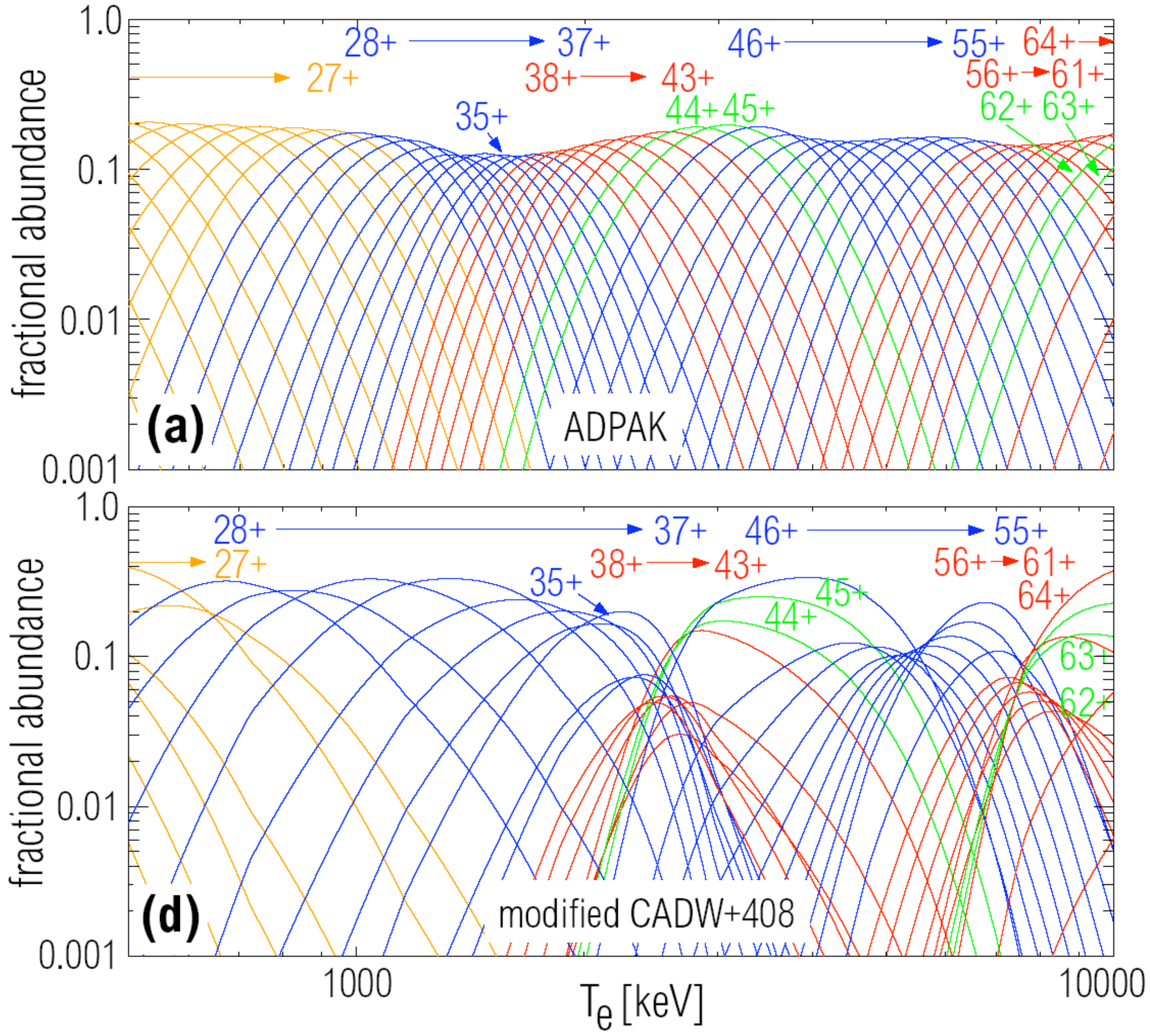


- Benchmark for atomic data
- Baseline ADAS (408+408) not good enough
- Good agreement for ion states Se-like W^{40+} to Ni-like W^{46+}

Th. Pütterich (PhD thesis)

W Spectroscopy in the VUV and SXR

Revision of ionization equilibrium



standard
‚ADPAK‘

ionisation/
recombination
rates

CADW
ionisation rates

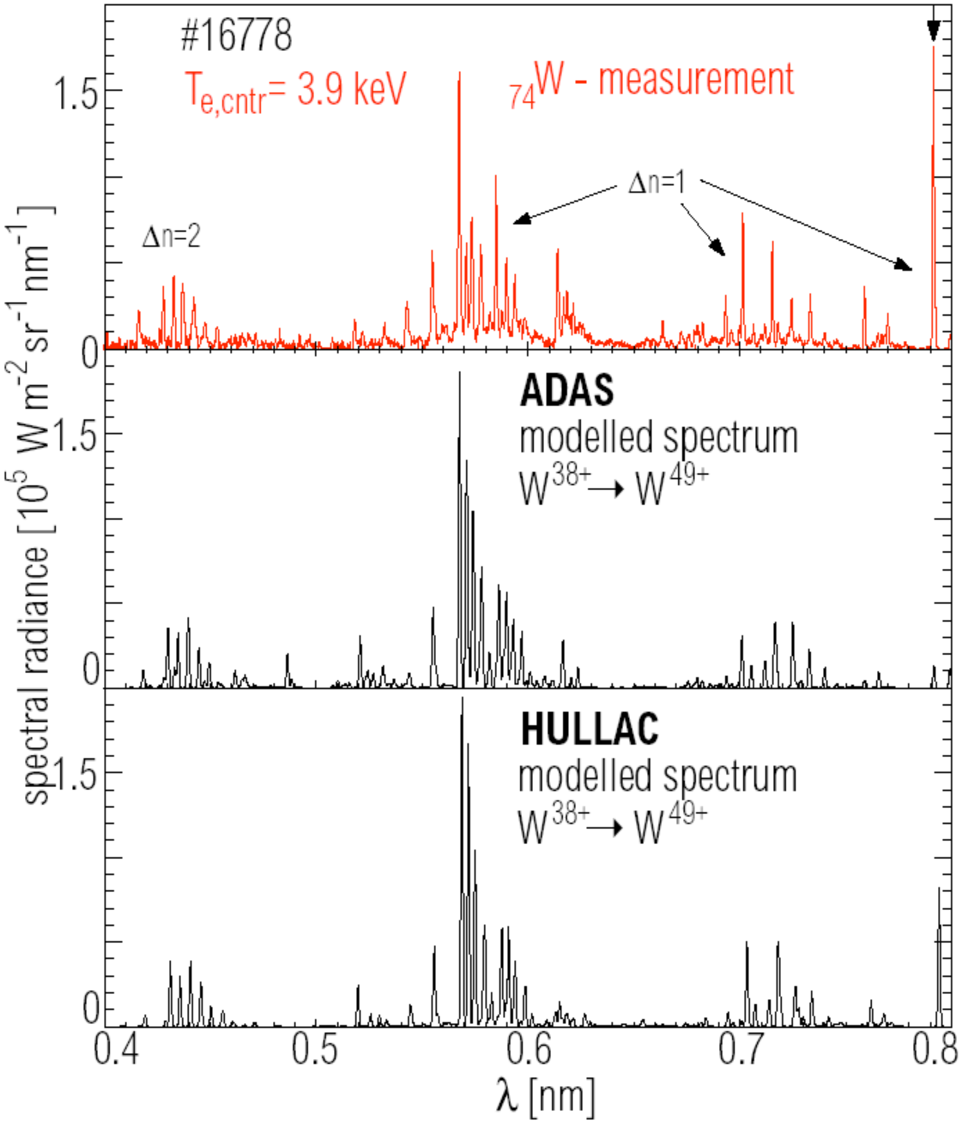
ADAS
recombination
rates
(adjusted to
experiment)

W Spectroscopy in the VUV and SXR

Detailed investigations in SXR region

- Spectral lines of Kr-like W^{38+} to about Mn-like W^{49+}
- Ni-like W^{46+} exhibits most intense spectral lines
- At ASDEX Upgrade the electric quadrupole line at 0.793 nm is monitored

Th. Pütterich (PhD thesis)

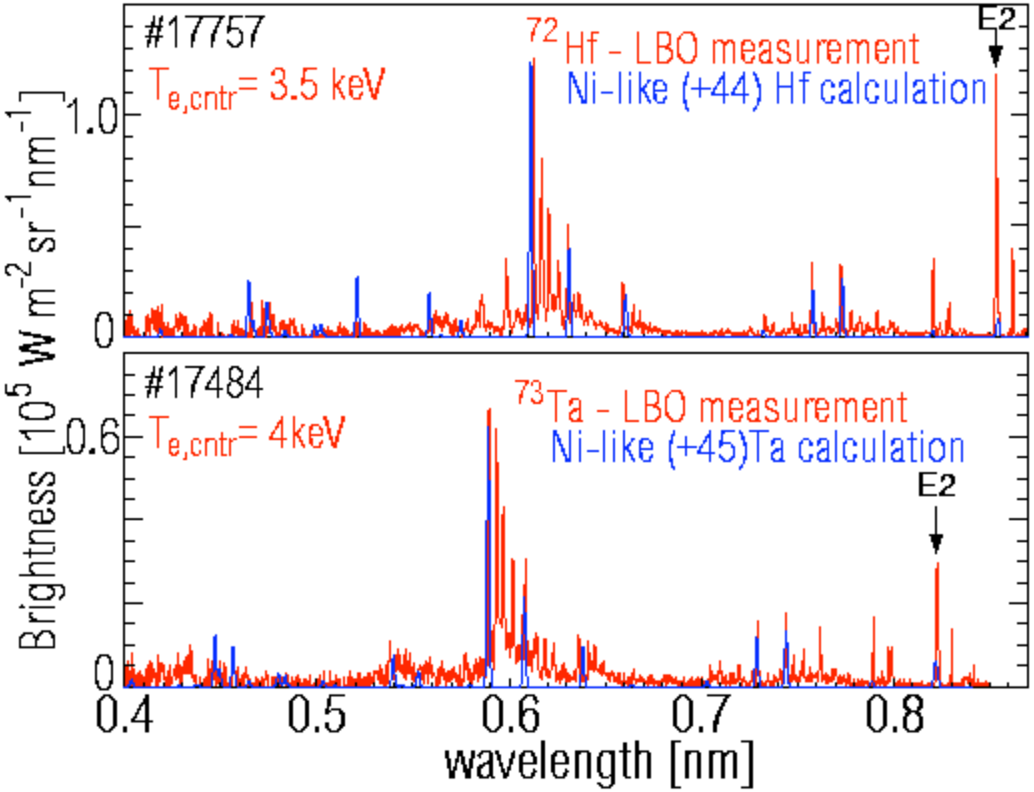


W Spectroscopy in the VUV and SXR

Investigation of Iso-electronic sequences (SXR)

Investigation of Hf, Ta, Re, Au, Pb, Bi emission and SXR

- spectra show similar features as W
- ADAS calculations reproduce overall features, but strongly underestimate E2 transitions in Ni-like ions
  (strong M3 contribution! Ralshenko et al.)
- HULLAC calculations just started

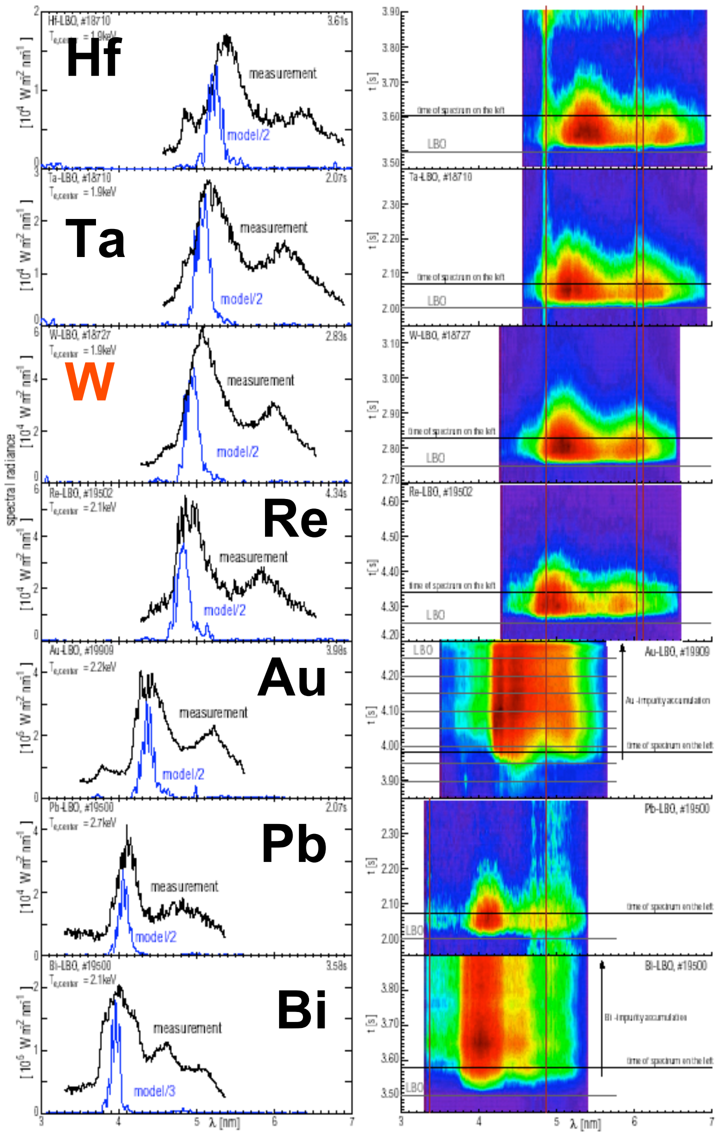


W Spectroscopy in the VUV and SXR

Investigation of Iso-electronic sequences (VUV)

Investigation of
Hf, Ta, Re, Au, Pb, Bi
emission in VUV and SXR

- spectra show similar features as W
- ADAS calculations reproduce overall features, but width of quasicontinua is always too small



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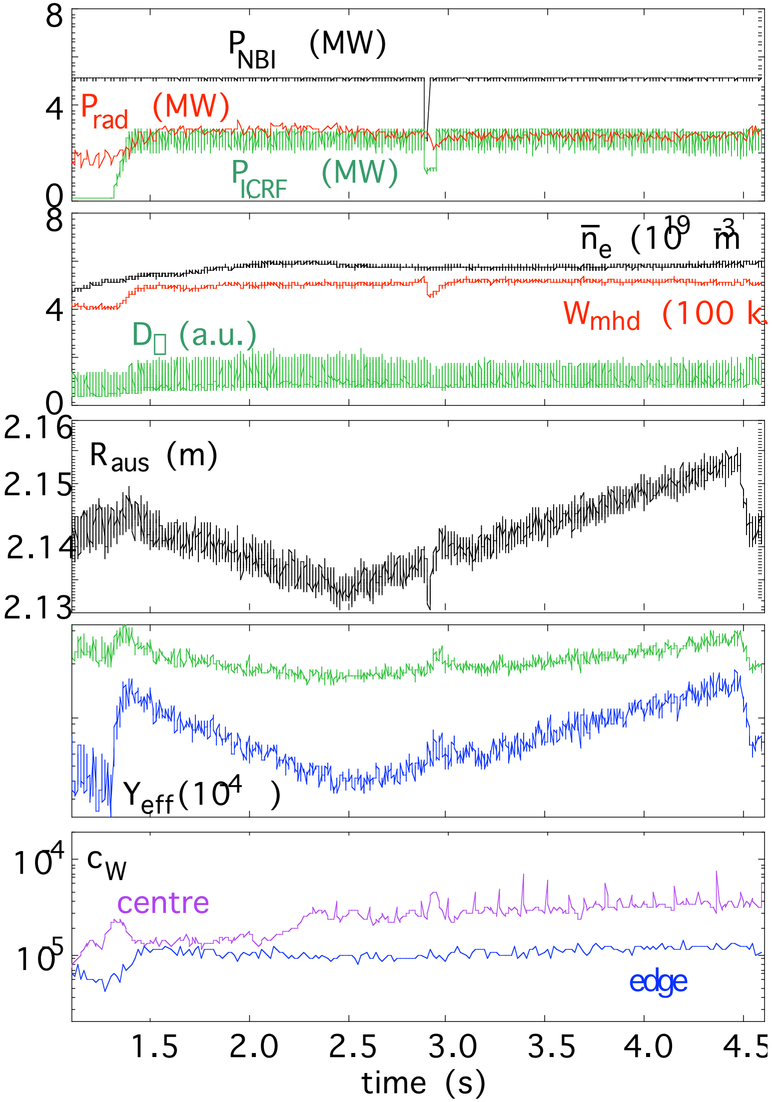
Conclusions and outlook

Spectroscopic measurements as standard diagnostic tool

Time dependent measurement of W erosion and W concentration

W influx / sputtering →

W concentration → centre / edge



Conclusions and outlook

Spectroscopic measurements as standard diagnostic tool

spectroscopy:

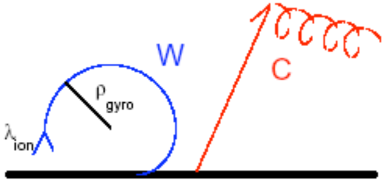
- sputtering yields much larger than expected from pure H/D sputtering
- no difference visible for H,D
- light impurities dominate yield
- C-deposition and re-erosion (Schmid PSI 2002) have to be taken into account

probe erosion:

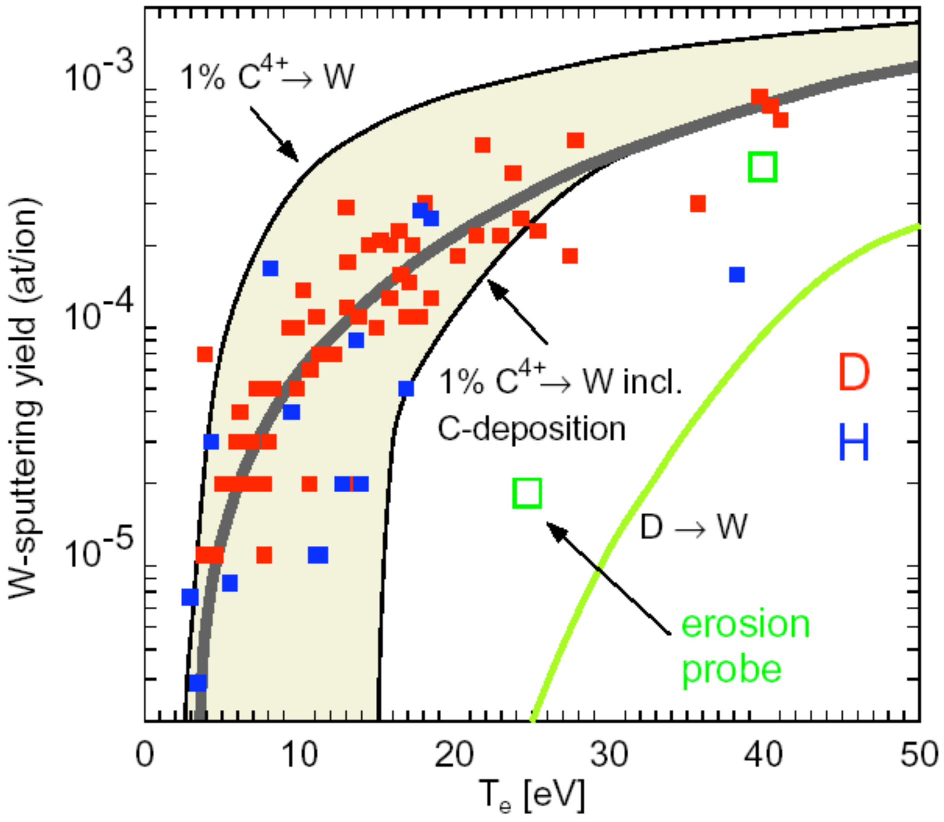
- net erosion factor 10 lower than gross erosion

⇒ prompt redeposition has to be taken into account

C : $f_r \leq 0.2$
W: $f_r \geq 0.9$



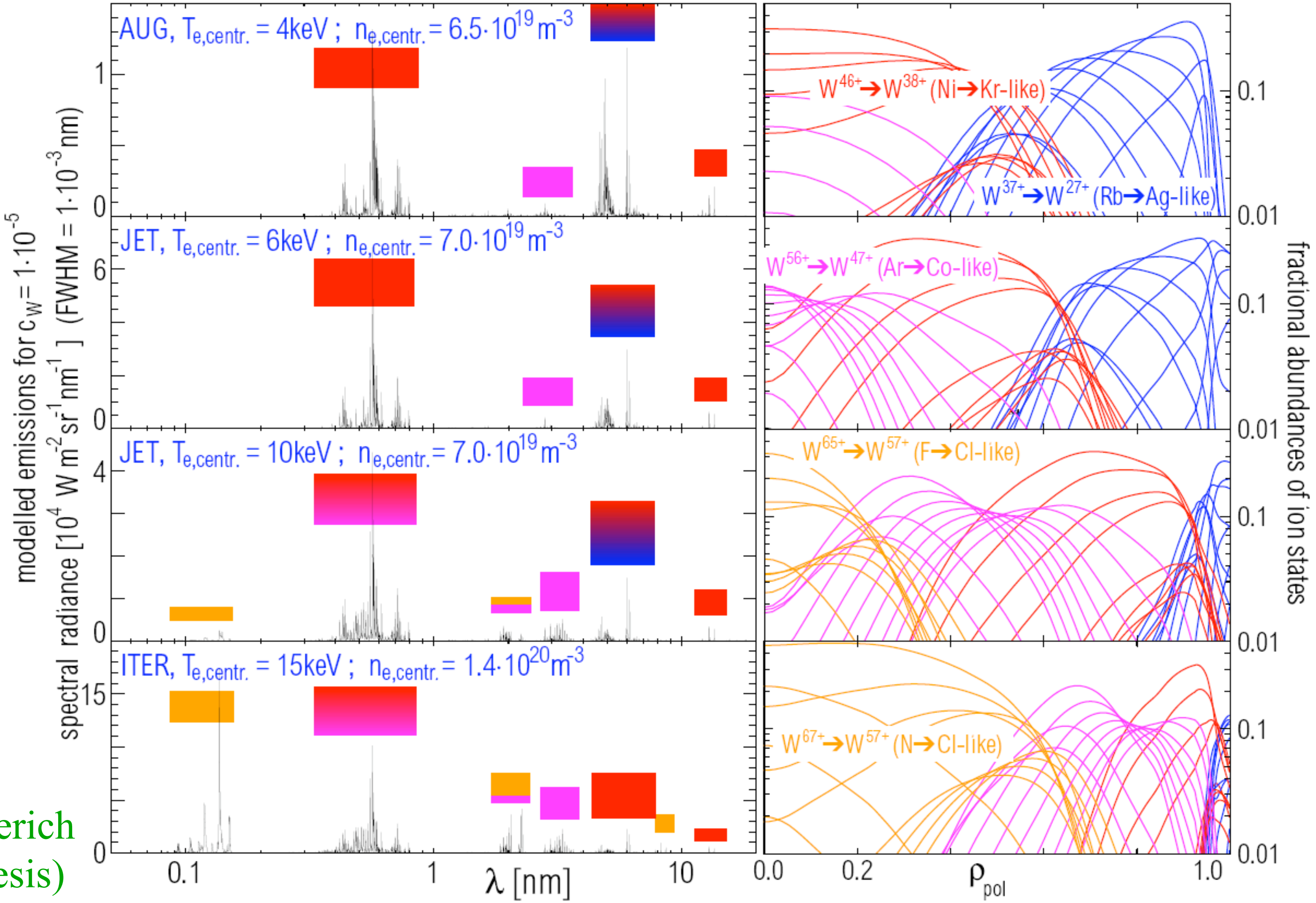
effective W-sputtering yield in the ASDEX Upgrade W divertor



Conclusions and outlook

Extrapolation to JET and ITER

Modelled W emission (ADAS) @ different temperatures



Th. Pütterich
(PhD thesis)

Conclusions and outlook

- W is a serious candidate for the plasma facing material in a fusion reactor
- JET and ITER will use W in the divertor region
- ASDEX Upgrade and TEXTOR have set-up a basis for spectroscopic W diagnostic in fusion plasma
- EBIT measurements are an excellent tool facilitating the interpretation of complex W spectra
- Broader dataset for W influx measurements highly desirable (WI, WII lines, WX-WXX for plasma edge)
- Revision of ionisation/recombination rates necessary
- Extrapolation to higher plasma temperature/ionisation states
- Close collaboration to theoretical data production