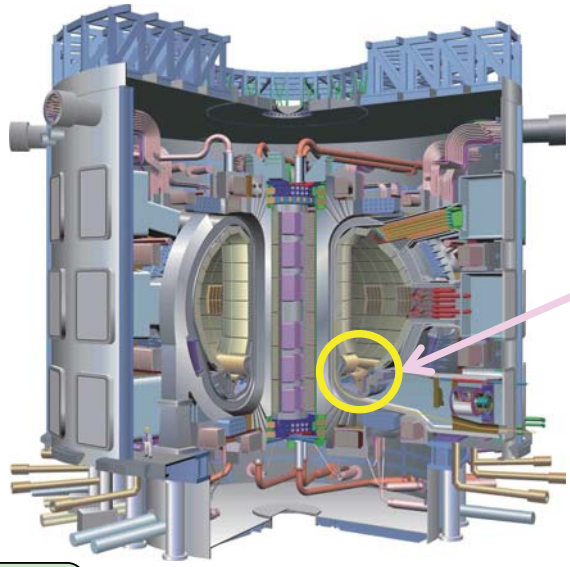
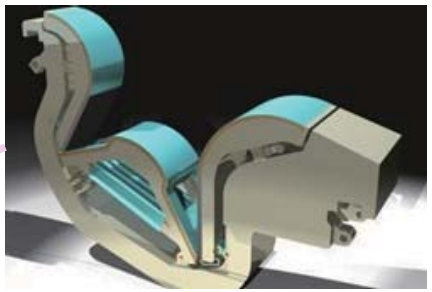
LHDにおけるタングステンの分光計測
Spectroscopy of tungsten in LHD

C. Suzuki[1], T. Kato[1], H. A. Sakaue[1], D. Kato[1], I. Murakami[1], K. Sato[1],
N. Tamura[1], S. Sudo[1], R. D'Arcy[2], C. Harte[2], G. O'Sullivan[2]

[1]National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[2]University College Dublin, Belfield, Dublin 4, Ireland

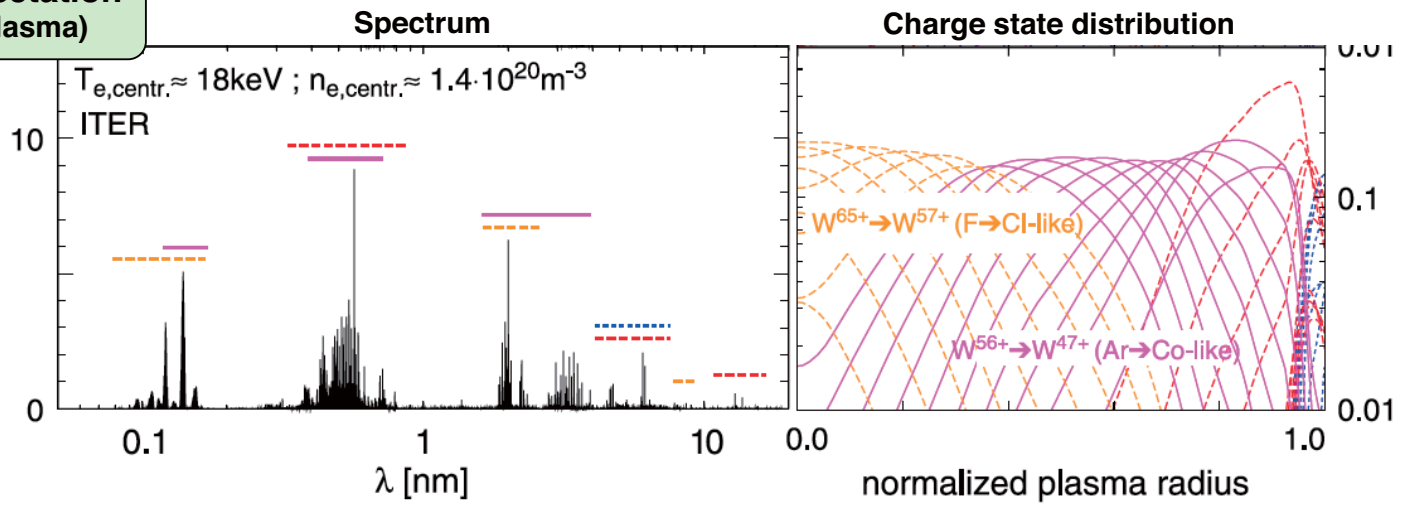
Importance of tungsten in ITER





Tungsten is used as a plasma facing component in ITER divertor.

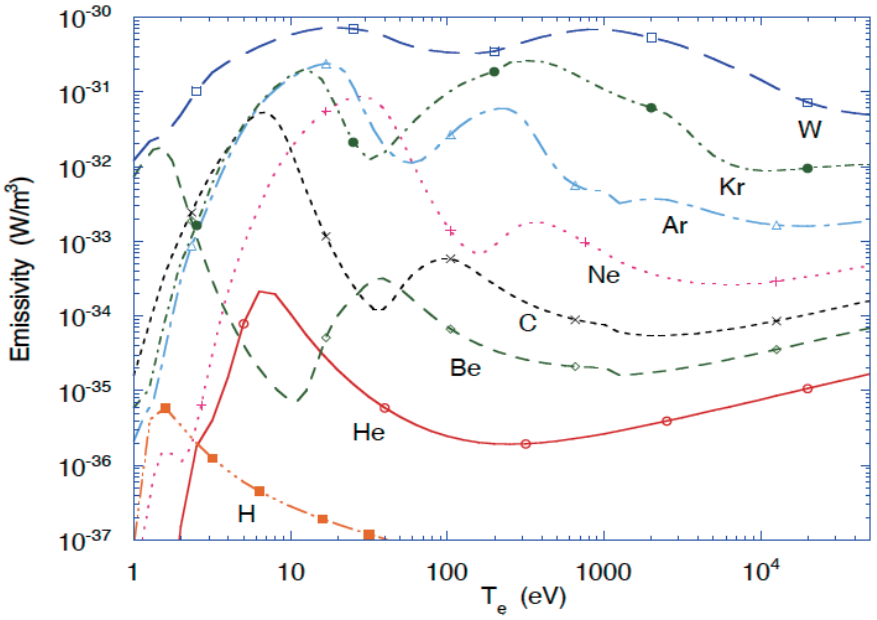
ADAS expectation
(in main plasma)



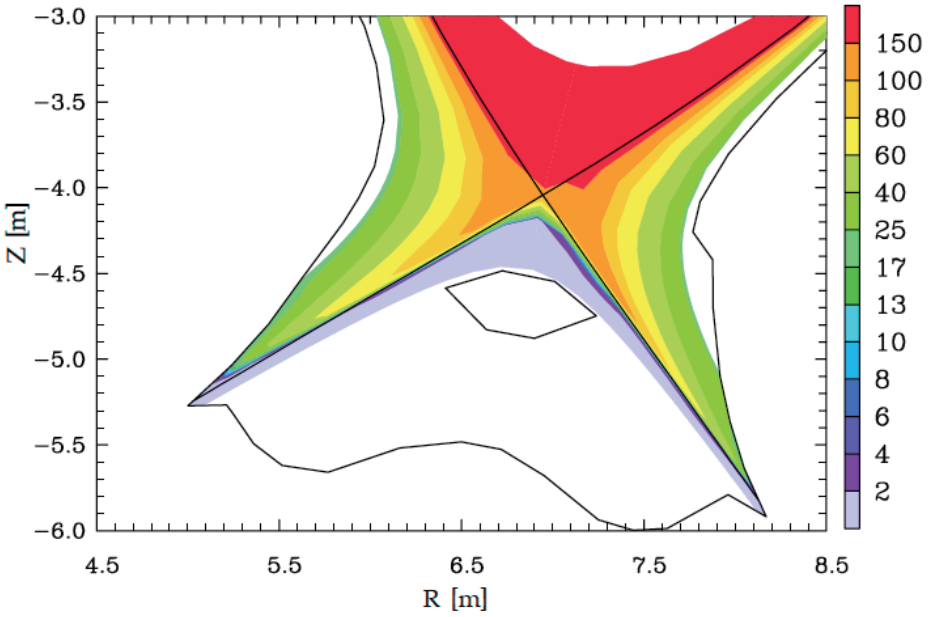
T. Pütterich *et al.*, Plasma Phys. Control. Fusion **50**, 085016 (2008).

ITER divertor plasma

Radiation loss rate



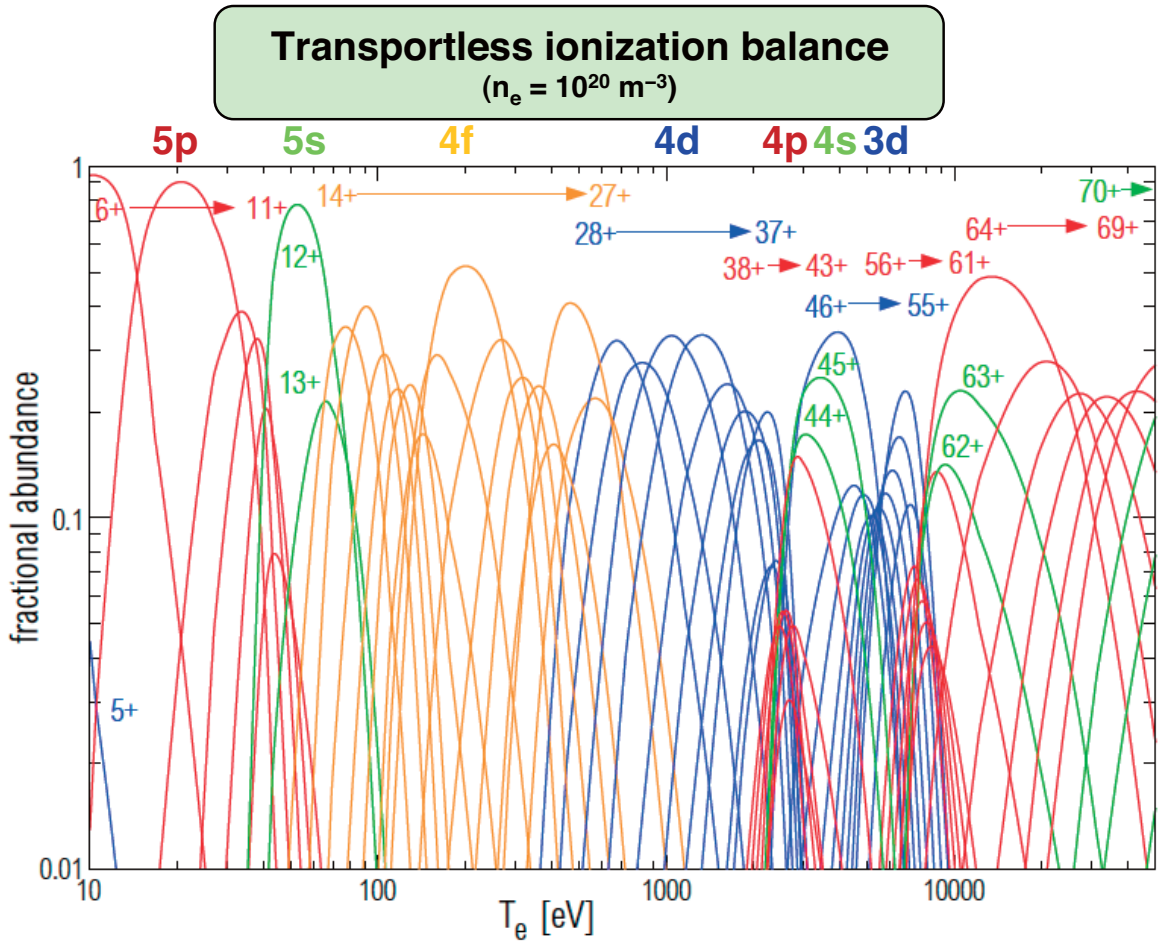
2D profile of T_e (eV) in the divertor region



ITER Physics Expert Group on Divertor *et al.*, Nucl. Fusion **39**, 2391 (1999).

- **Large radiation loss rates from low charged tungsten ions are expected in the ITER divertor region ($10 < T_e < 150$ eV).**

Open 4f ions are important in edge/divertor plasma

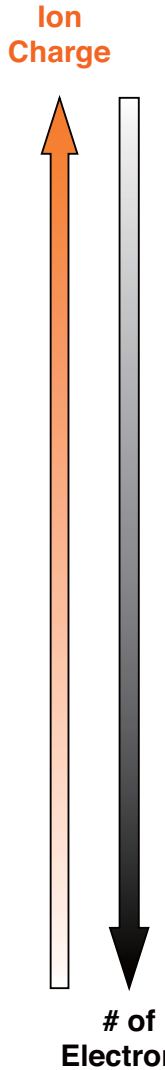


modeled by
'modified CADW+408'

T. Pütterich, Ph.D. Thesis, University of Augsburg (2005)

- **Open 4f (W^{14+} ~ W^{27+}) and 5s/5p (W^{6+} ~ W^{13+}) subshell ions may possibly be dominant emitters in ITER edge/divertor plasma (< 500 eV).**

General spectral feature of open N shell ions



# of electrons	Ion charge	Iso. sequence	Ground State Configuration								
			M	N				O			P
			3d	4s	4p	4d	4f	5s	5p	5d	6s
28	46	Ni	10								
29	45	Cu	10	1							
30	44	Zn	10	2							
31	43	Ga	10	2	1						
32	42	Ge	10	2	2						
33	41	As	10	2	3						
34	40	Se	10	2	4						
35	39	Br	10	2	5						
36	38	Kr	10	2	6						
37	37	Rb	10	2	6	1					
38	36	Sr	10	2	6	2					
39	35	Y	10	2	6	3					
40	34	Zr	10	2	6	4					
41	33	Nb	10	2	6	5					
42	32	Mo	10	2	6	6					
43	31	Tc	10	2	6	7					
44	30	Ru	10	2	6	8					
45	29	Rh	10	2	6	9					
46	28	Pd	10	2	6	10					
47	27	Ag	10	2	6	10	1				
48	26	Cd	10	2	6	10	2				
49	25	In	10	2	6	10	3				
50	24	Sn	10	2	6	10	4				
51	23	Sb	10	2	6	10	5				
52	22	Te	10	2	6	10	6				
53	21	I	10	2	6	10	7				
54	20	Xe	10	2	6	10	8				
55	19	Cs	10	2	6	10	9				
56	18	Ba	10	2	6	10	10				
57	17	La	10	2	6	10	11				
58	16	Ce	10	2	6	10	11	1			
59	15	Pr	10	2	6	10	11	2			
60	14	Nd	10	2	6	10	12	2			
61	13	Pm	10	2	6	10	13	2			
62	12	Sm	10	2	6	10	14	2			
63	11	Eu	10	2	6	10	13	2	2		

Open 4s/4p ions

Smaller number of energy levels in subshells

Discrete line spectral feature

Open 4d ions

4d-4f (+ 4p-4d) UTA appears around

Sn: 13.5 nm

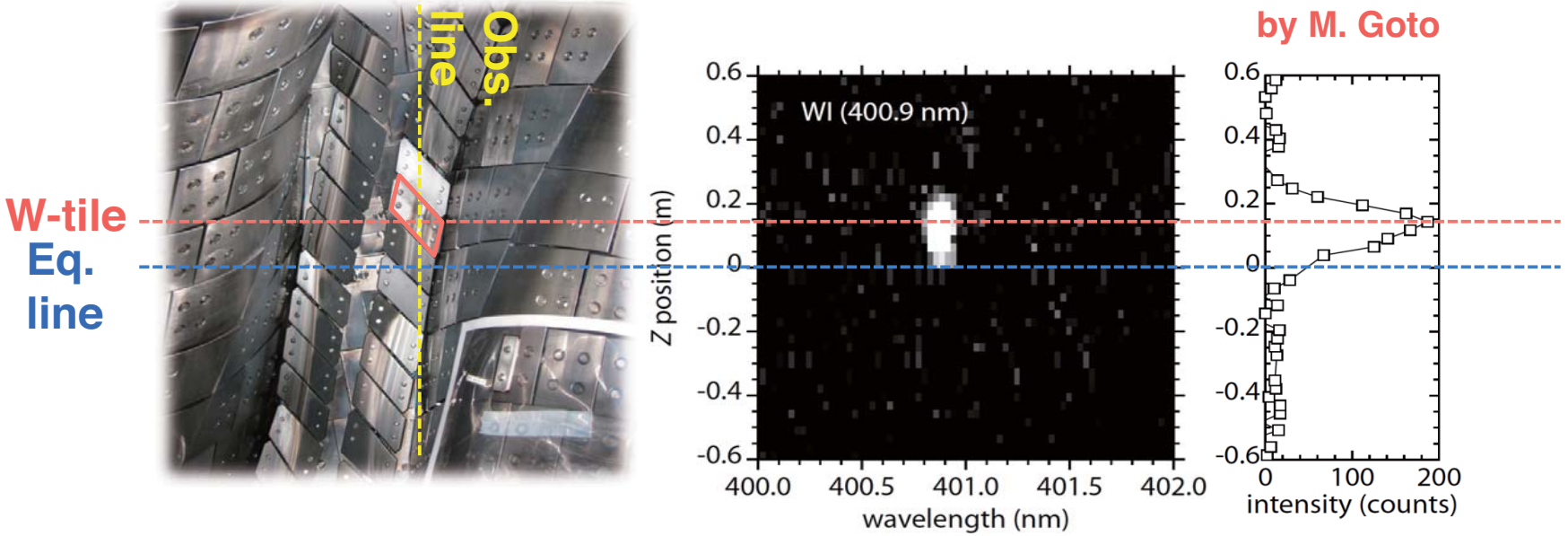
Xe: 11 nm

W: 5 nm

Open 4f ions

Huge number of energy levels and more complex quasicontinuous feature

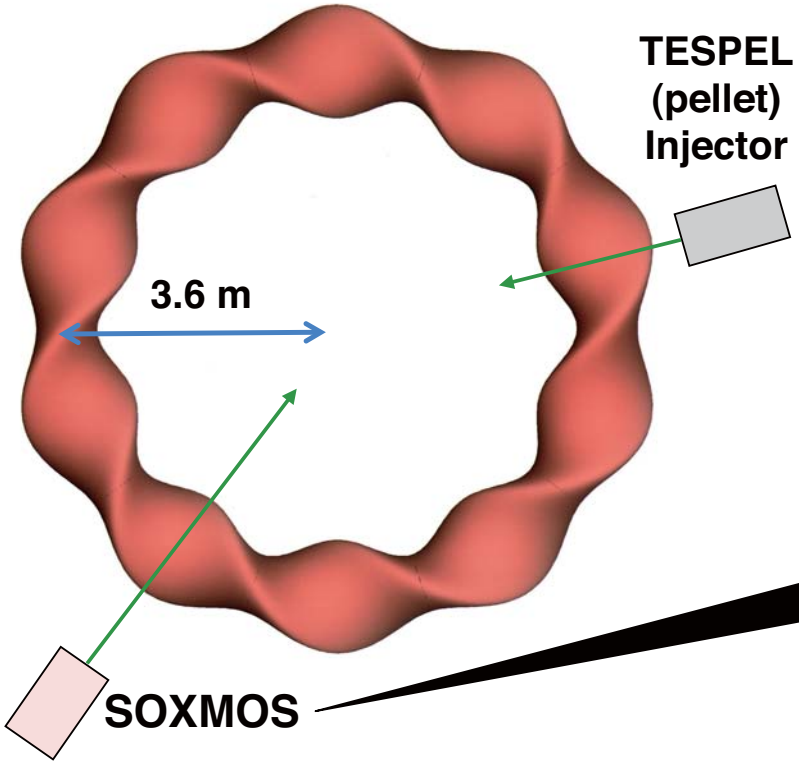
Tungsten tile and W I emission in LHD

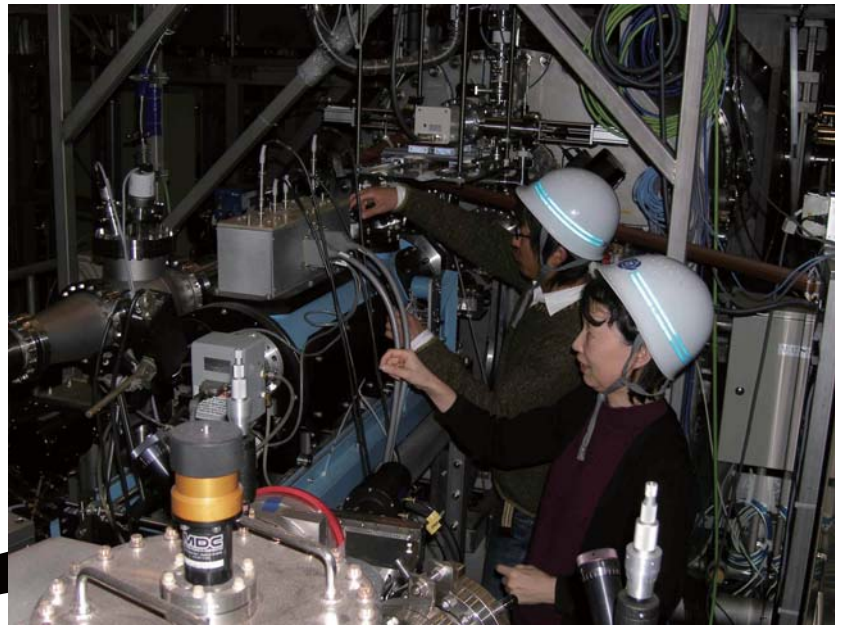


#102241, T_i ~ 6 keV, 3.9 ~ 4.8 s (Time integration)
(with C pellet injection)

- **Visible W I line (400.9 nm) was clearly observed from the W-tile.**
- **Spatial distribution of the W I emission is not broad. This means that emitted W atoms are not so deeply injected into the bulk plasma.**

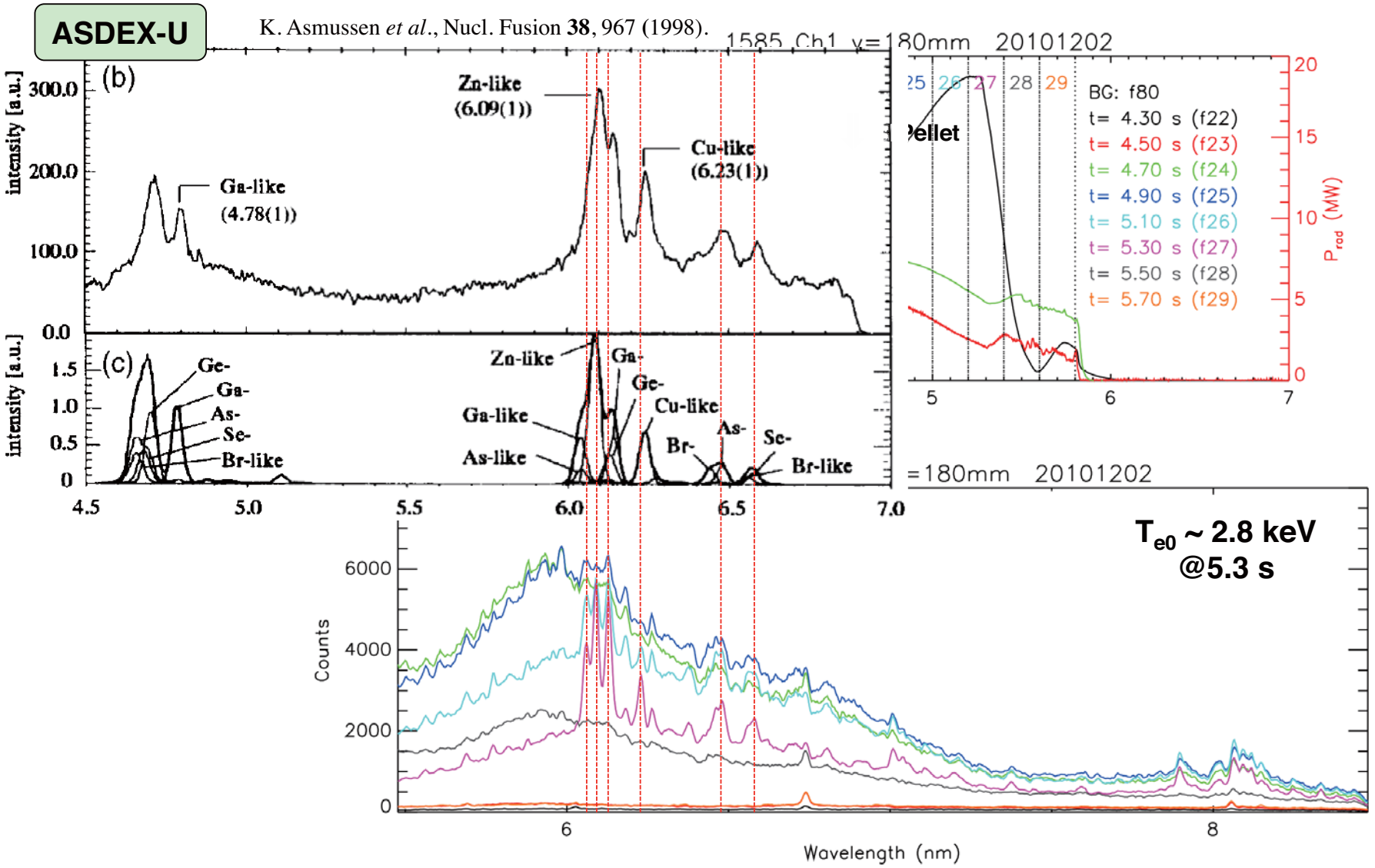
VUV spectrometer "SOXMOS"



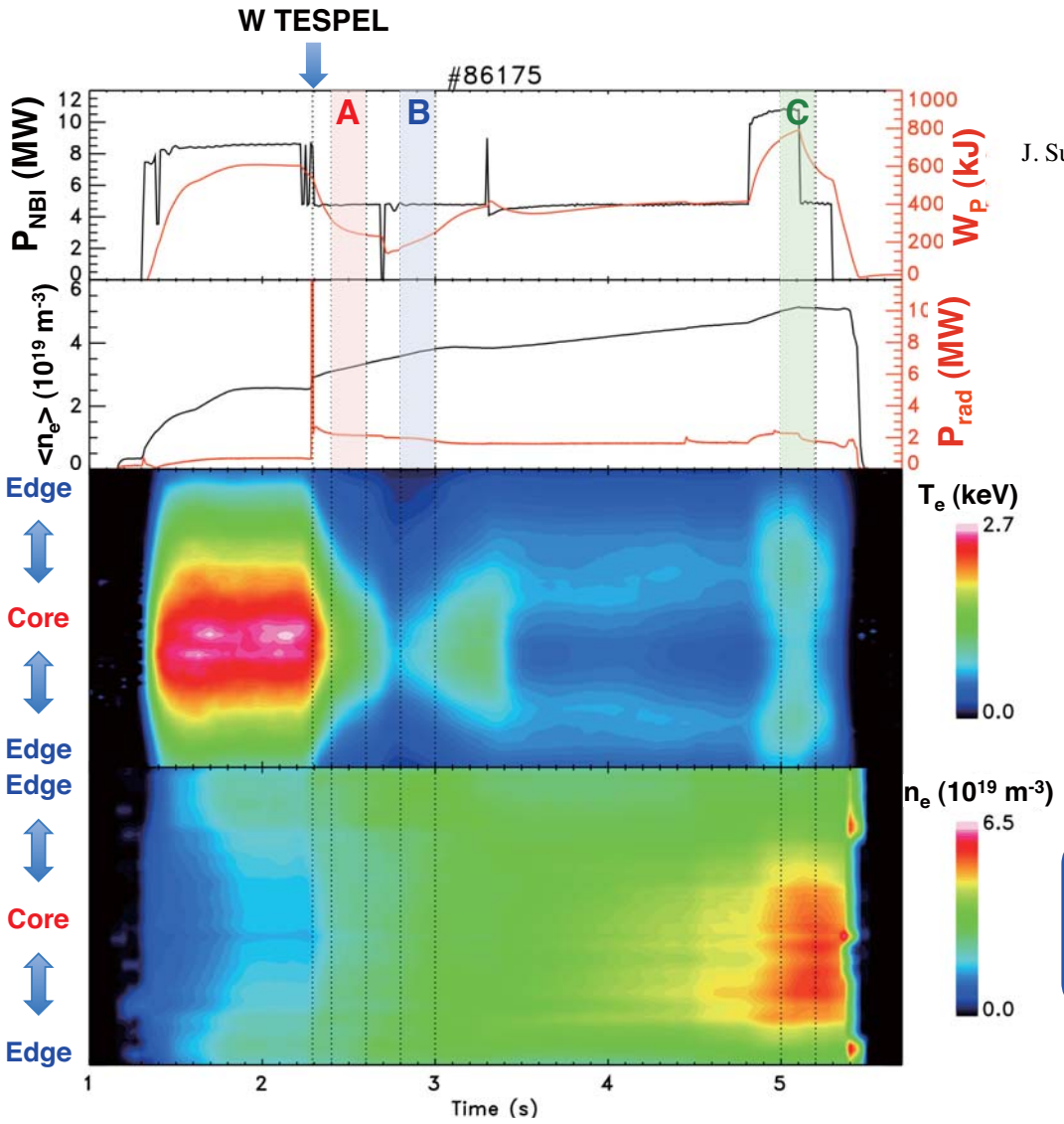


Type	Schwob-Fraenkel 2 m grazing incidence spectrometer
Grooves	600 grooves/mm
Wavelength	1 ~ 35 nm
Detector	2 MCPs + Phosphor + Photodiode Array
Resolution	~ 0.01 nm

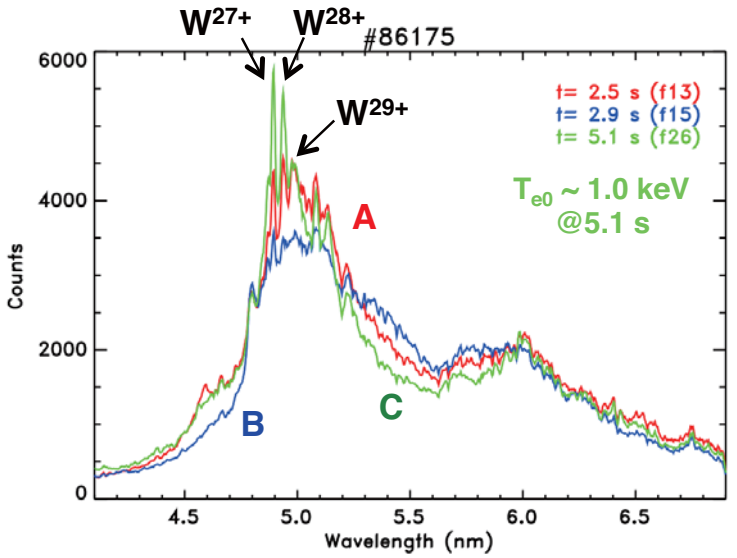
Cu-like W XLVI line observed in LHD with pellet



T_e dependence of structure around 5 nm in LHD



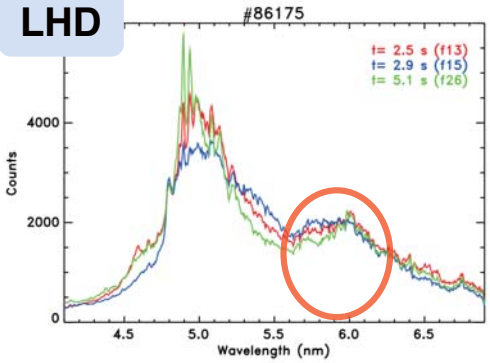
J. Sugar, V. Kaufman, W. Rowan, J. Opt. Soc. Am. B **10**, 799, 1321, 1977 (1993).

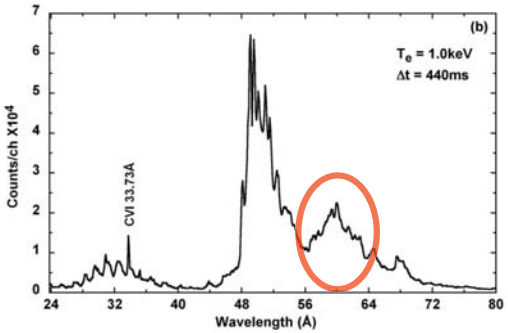


Quasicontinuum structure observed for T_e < 500 eV is from charge states below W^{27+} (open 4f subshell).

Contribution of open 4f subshell W ions?

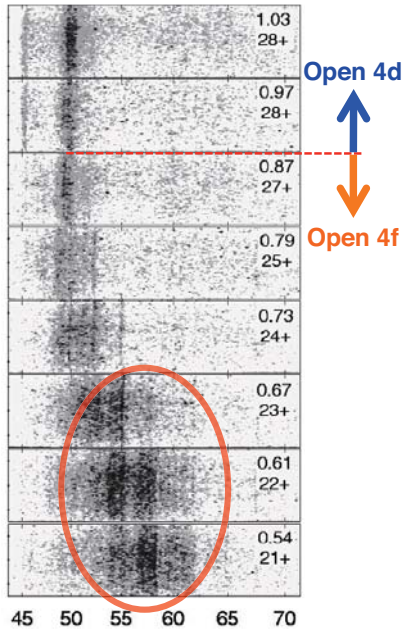
LHD





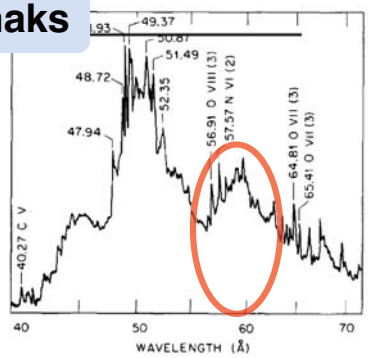
M. B. Chowdhuri *et al*., Plasma and Fusion Research **2** (2007) S1060

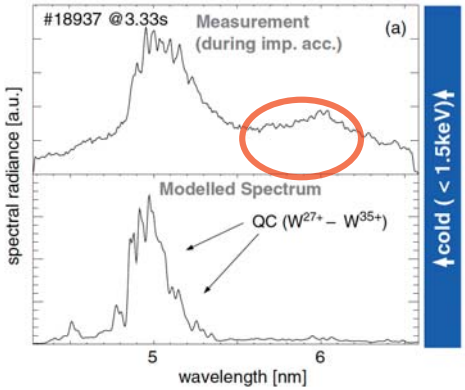
Berlin EBIT



R. Radtke *et al*., Phys. Rev. A **64**, 012720 (2001).

Tokamaks





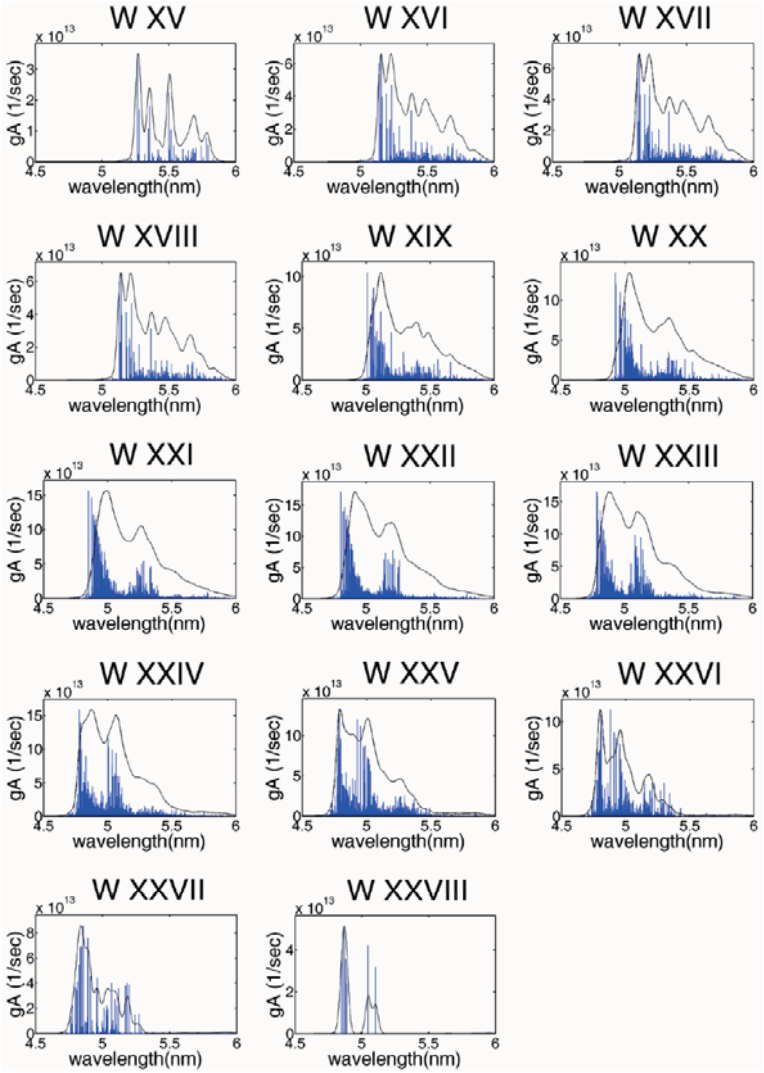
R. C. Isler, R.V. Nerdigh, R. D. Cowan, Phys. Lett. **63**, 295 (1977).
T. Pütterich *et al*., Plasma Phys. Control. Fusion **50**, 085016 (2008).

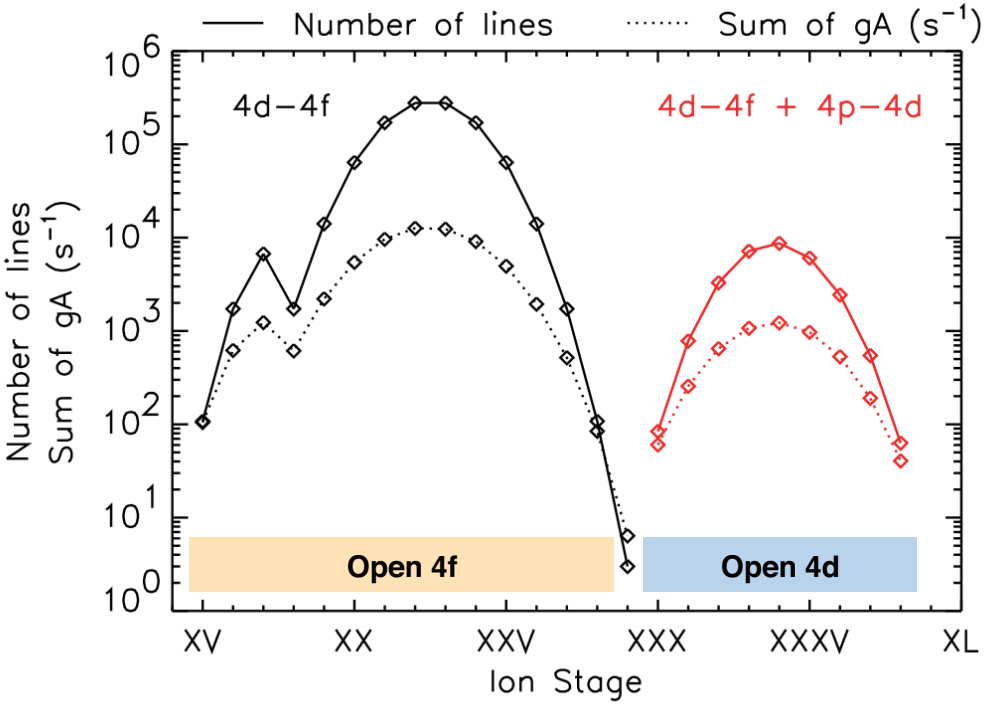
- **Smaller broad peak around 6 nm are commonly observed.**
  - **Contributions of open 4f subshell ions?**

Data of open 4f tungsten ions are still insufficient

- Open 4s and 4p tungsten ions have been well investigated in tokamaks such as ASDEX-U and JT-60U and EBITs.
- Quasicontinuous feature from open 4d tungsten ions have been measured in tokamaks and EBITs, and compared with model calculations.
- However, data for open 4f tungsten ions are still missing in recent compilation of tungsten spectral lines by Kramida and Shirai.
- Experimental identifications and theoretical calculations of open 4f tungsten ions are challenging because of more complex energy level structure and spectral feature.

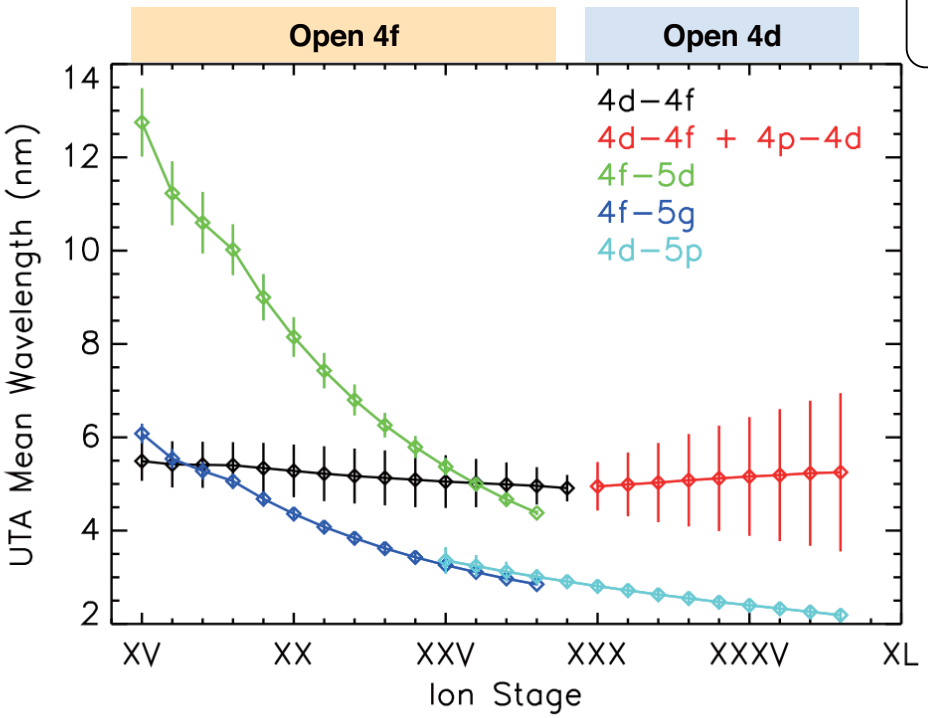
Huge number of lines calculated for open 4f ions





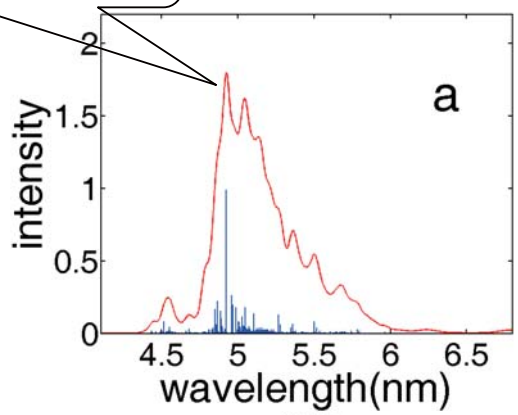
The number of calculated lines and contribution to emissivity drastically increases for open 4f ions far from the closed shell.

UTA calculations for open 4f/4d tungsten ions

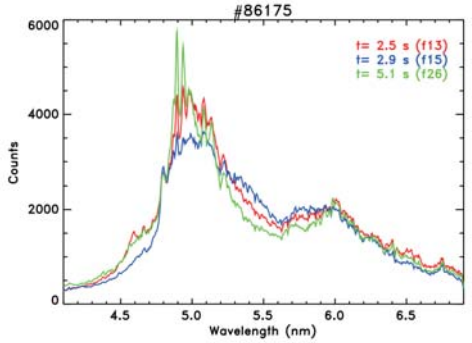


Superimposed
W XV-XXXIII 4d-4f (+ 4p-4d)

calc.

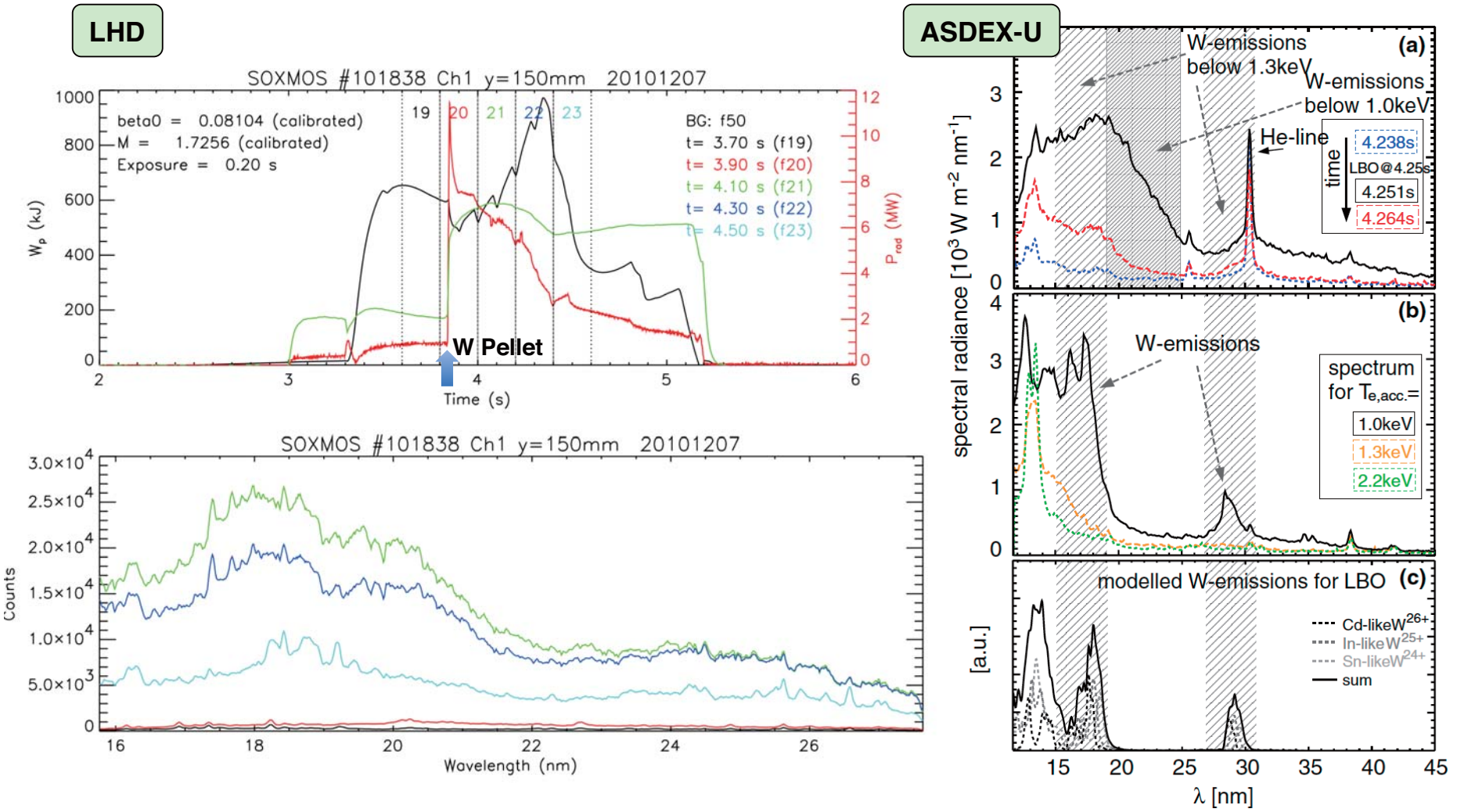


LHD



- **The smaller broad peak around 6 nm in the experiments cannot be reproduced only by 4d-4f transition.**
  - **possibly 4f-5d transitions of W XXIII-XXIV?**

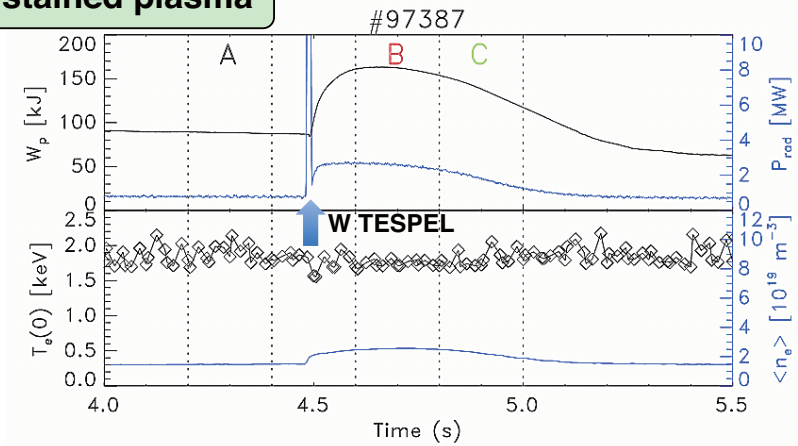
Quasicontinuous feature around 18 nm

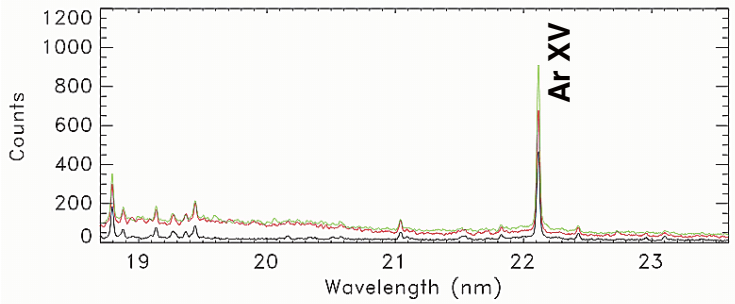


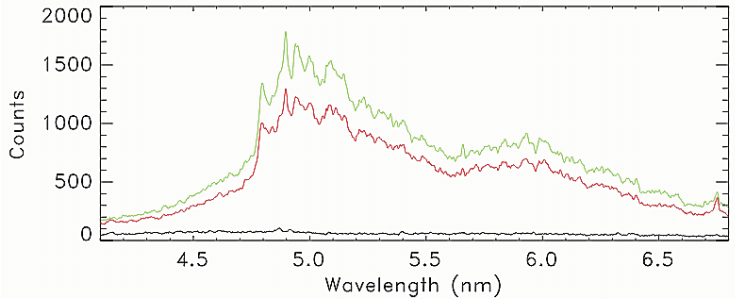
Pütterich et al., Plasma Phys. Control. Fusion **50**, 085016 (2008).

Quasicontinuous feature for lower T_e

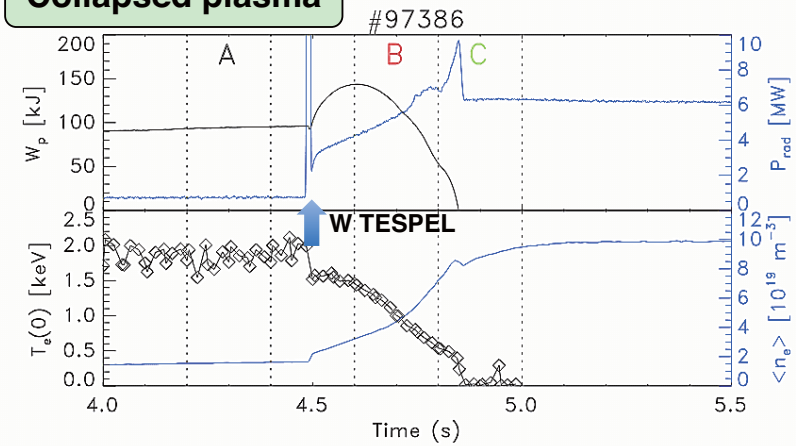
Sustained plasma

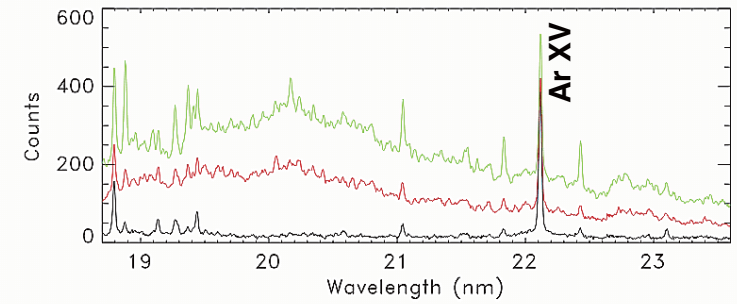


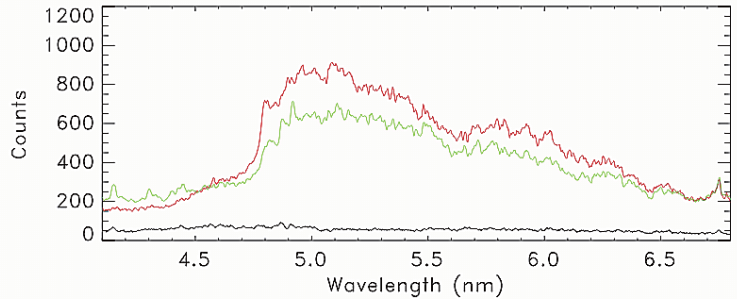




Collapsed plasma

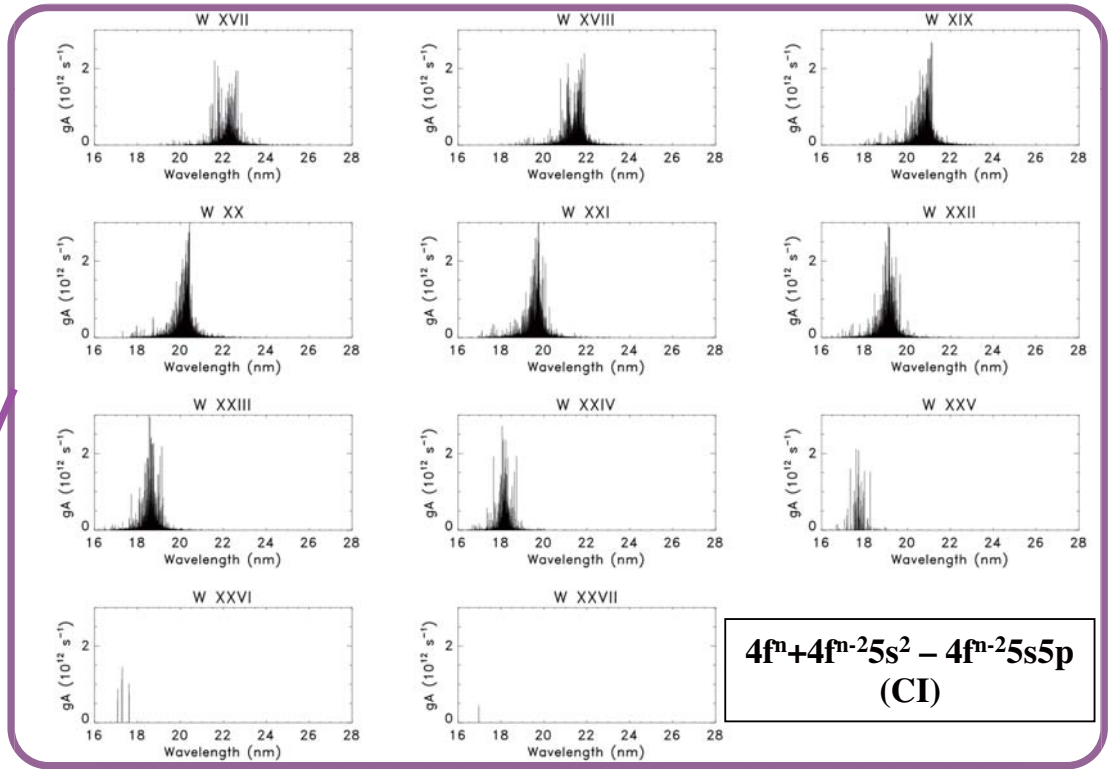


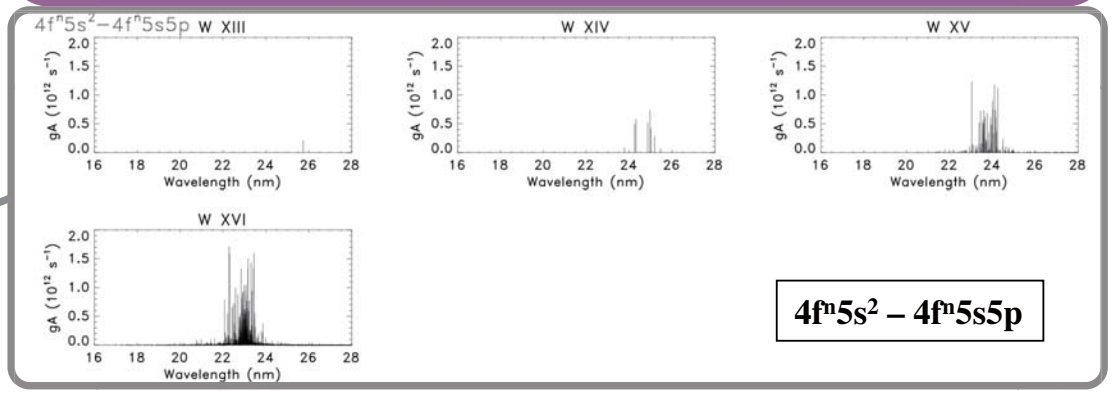




Example of calculation for n = 5 - 5 transitions

# of electrons	Ion charge	Iso. sequence	Ground State Configuration								
			M	N				O			P
			3d	4s	4p	4d	4f	5s	5p	5d	6s
28	46	Ni	10								
29	45	Cu	10	1							
30	44	Zn	10	2							
31	43	Ga	10	2	1						
32	42	Ge	10	2	2						
33	41	As	10	2	3						
34	40	Se	10	2	4						
35	39	Br	10	2	5						
36	38	Kr	10	2	6						
37	37	Rb	10	2	6	1					
38	36	Sr	10	2	6	2					
39	35	Y	10	2	6	3					
40	34	Zr	10	2	6	4					
41	33	Nb	10	2	6	5					
42	32	Mo	10	2	6	6					
43	31	Tc	10	2	6	7					
44	30	Ru	10	2	6	8					
45	29	Rh	10	2	6	9					
46	28	Pd	10	2	6	10					
47	27	Ag	10	2	6	10	1				
48	26	Cd	10	2	6	10	2				
49	25	In	10	2	6	10	3				
50	24	Sn	10	2	6	10	4				
51	23	Sb	10	2	6	10	5				
52	22	Te	10	2	6	10	6				
53	21	I	10	2	6	10	7				
54	20	Xe	10	2	6	10	8				
55	19	Cs	10	2	6	10	9				
56	18	Ba	10	2	6	10	10				
57	17	La	10	2	6	10	11				
58	16	Ce	10	2	6	10	11	1			
59	15	Pr	10	2	6	10	11	2			
60	14	Nd	10	2	6	10	12	2			
61	13	Pm	10	2	6	10	13	2			
62	12	Sm	10	2	6	10	14	2			
63	11	Eu	10	2	6	10	13	2	2		





Summary

- In terms of the importance of tungsten in ITER, we have observed EUV spectra from tungsten ions in LHD plasmas with pellet injection by a grazing incidence spectrometer.

- The measured quasicontinuous spectral feature around 5 nm region suggests large contributions from open 4f subshell ions as well as open 4d subshell ions in low temperature conditions. However, available data for open 4f subshell tungsten ions are still insufficient.

- The observed spectra around 5 nm were compared with theoretical calculations for open 4d/4f subshell tungsten ions by Cowan code. The results indicate the contribution of open 4f subshell ions to the measured spectral feature.

- Another quasicontinuous feature around 18 nm has been observed in LHD under lower temperature conditions below 500 eV. The calculation shows that it could be interpreted as n = 5 – 5 transitions of open 4f subshell ions.