Determination of Tungsten Fluxes from W I- and W II-lines

A.Pospieszczyk, G.Sergienko, S.Brezinsek, I.Beigman*, L.Vainshtein*

R.Doerner, D.Nishijima**, W.Bohmeyer*****

Institut für Energieforschung - Plasmaphysik, Forschungszentrum Jülich GmbH, *Lebedev Physical Institute, Moscow, **UCSD-Center for Energy Research, San Diego, ***MPIPP-Berlin-HUB

Present status

- Results from TEXTOR **(published in 2007, PPCF 49, 1833)**
modelling of the corresponding S/XB

Latest S/XB experimental data for W I
- measurements on PISCES-B (weight loss)
- measurements on TEXTOR (injection)

Measurements on W II - (transport studies)
- comparison of experimental and theoretical data

Conclusions

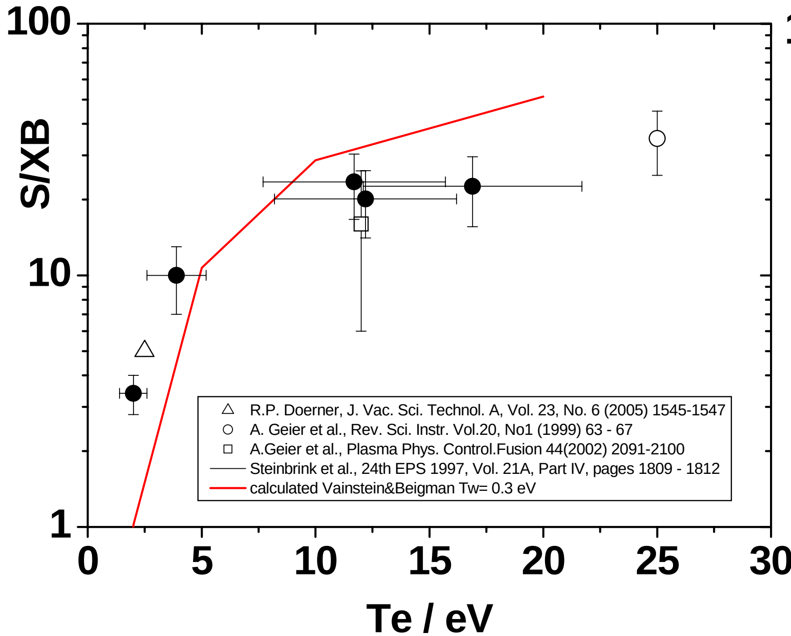
S/XB for 4008 Å

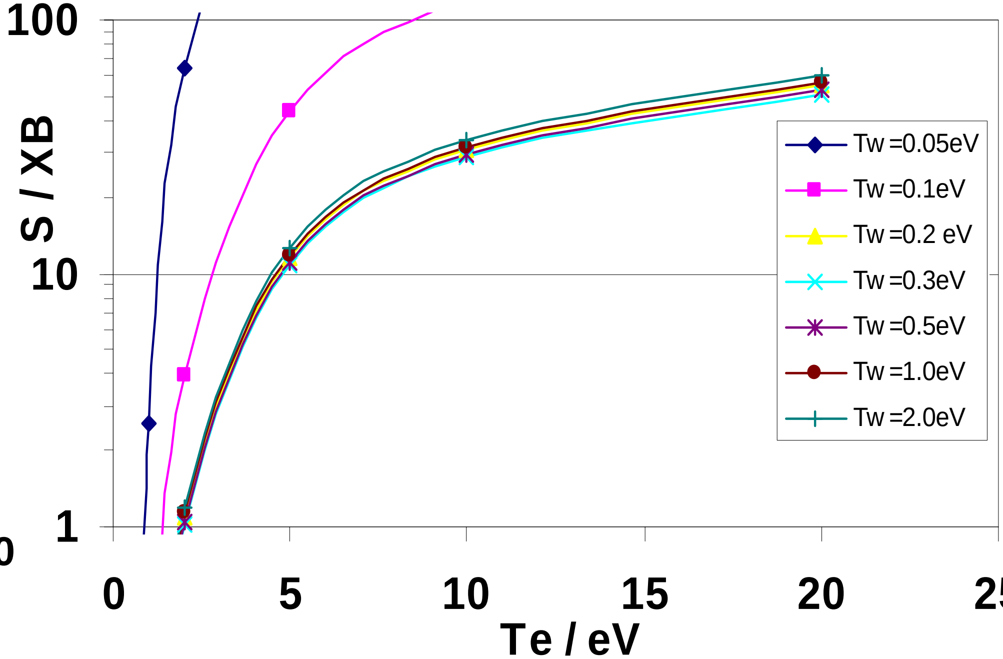
from PSI-1 (Berlin, Germany)

ASDEX-U, PISCES

from Model (Beigman & Vainshtein)

„ATOM“, v.Regemorter, cor. approx.





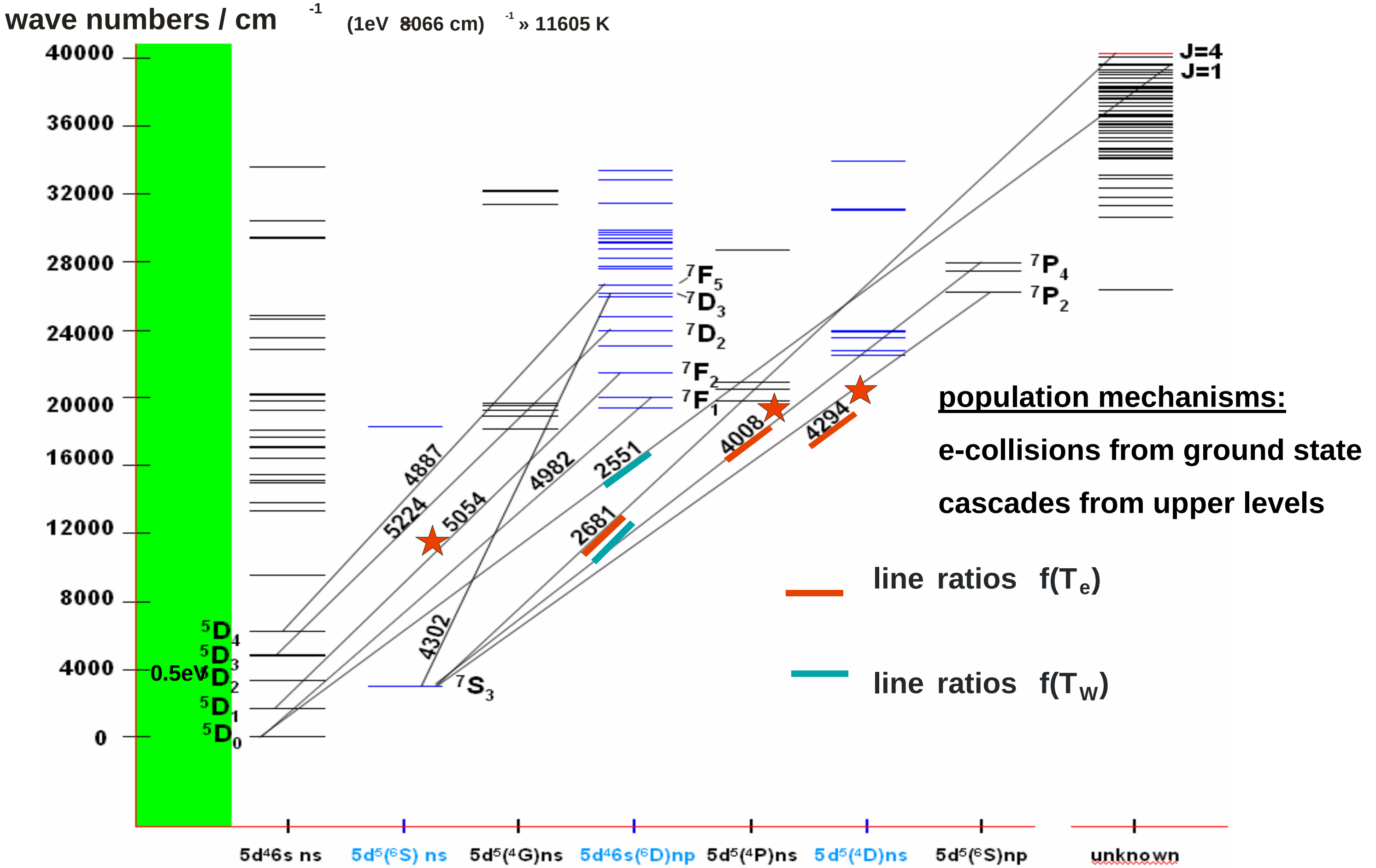
Test other lines for quantitative measurements

Longer wavelengths: **better for fiber transmission**

Shorter wavelengths: **better for hot surfaces**

$$\Phi_A = \frac{4\pi}{\Gamma}\frac{I_{tot}}{h\nu}\frac{<\sigma_I v_e>}{<\sigma_{Exg} v_e>} = 4\pi\frac{I_{tot}}{h\nu}\frac{S}{XB}$$

Grotrian diagram for W I - NIST tables version 3



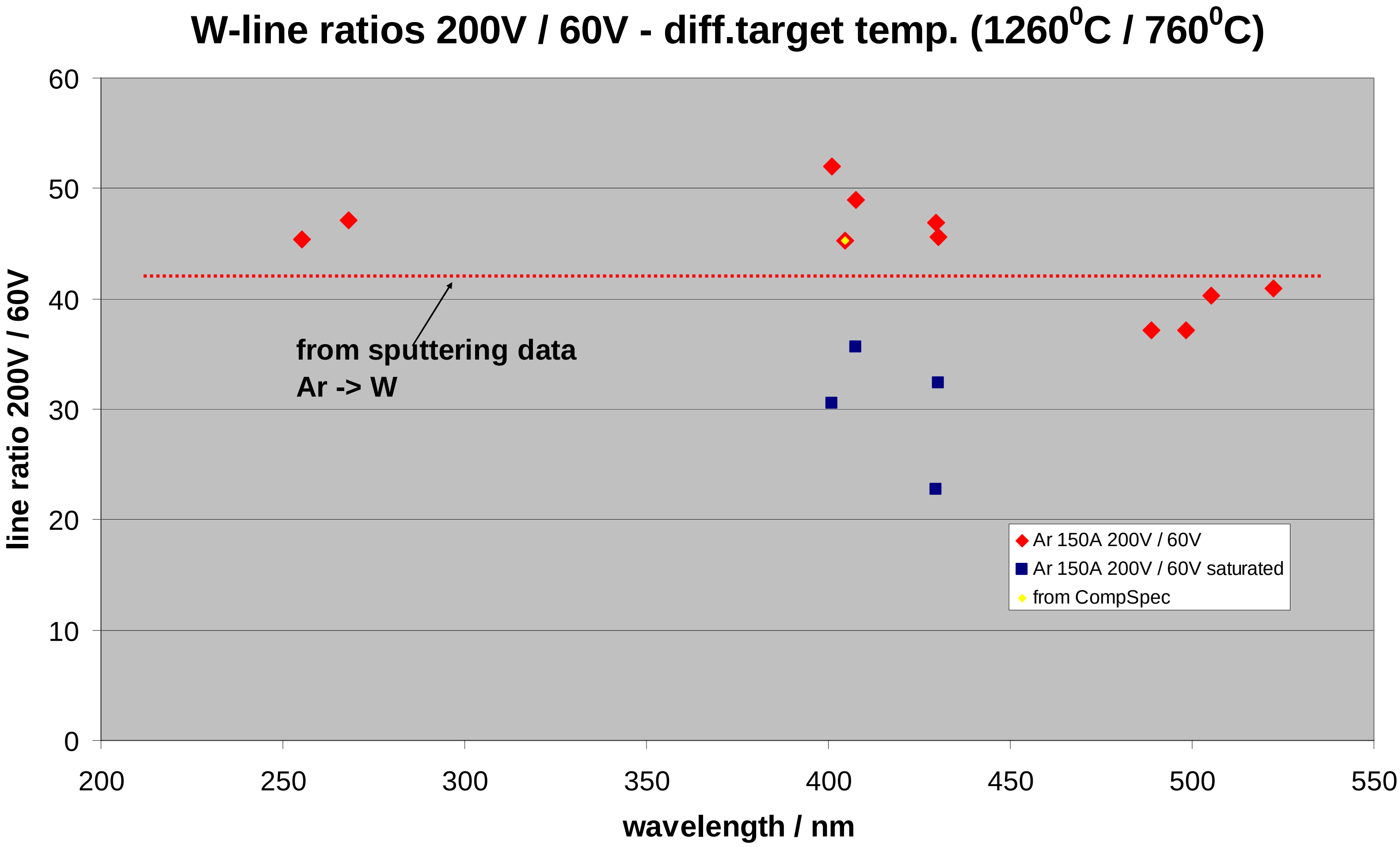
A.E.Kramida, T.Shirai **W I: 7049 lines, W II: 2838 lines**
(J. Phys. Chem. Ref. Data, Vol. 35, No. 1, 2006)
522 lines with A_{ik} , term designations not complete

R. Kling, M. Kock JQSRT 62 (1999) 129 - **263 lines**
C.H.Corliss, W.R.Bozman NBS 53 (1962) 499 - **261 lines**

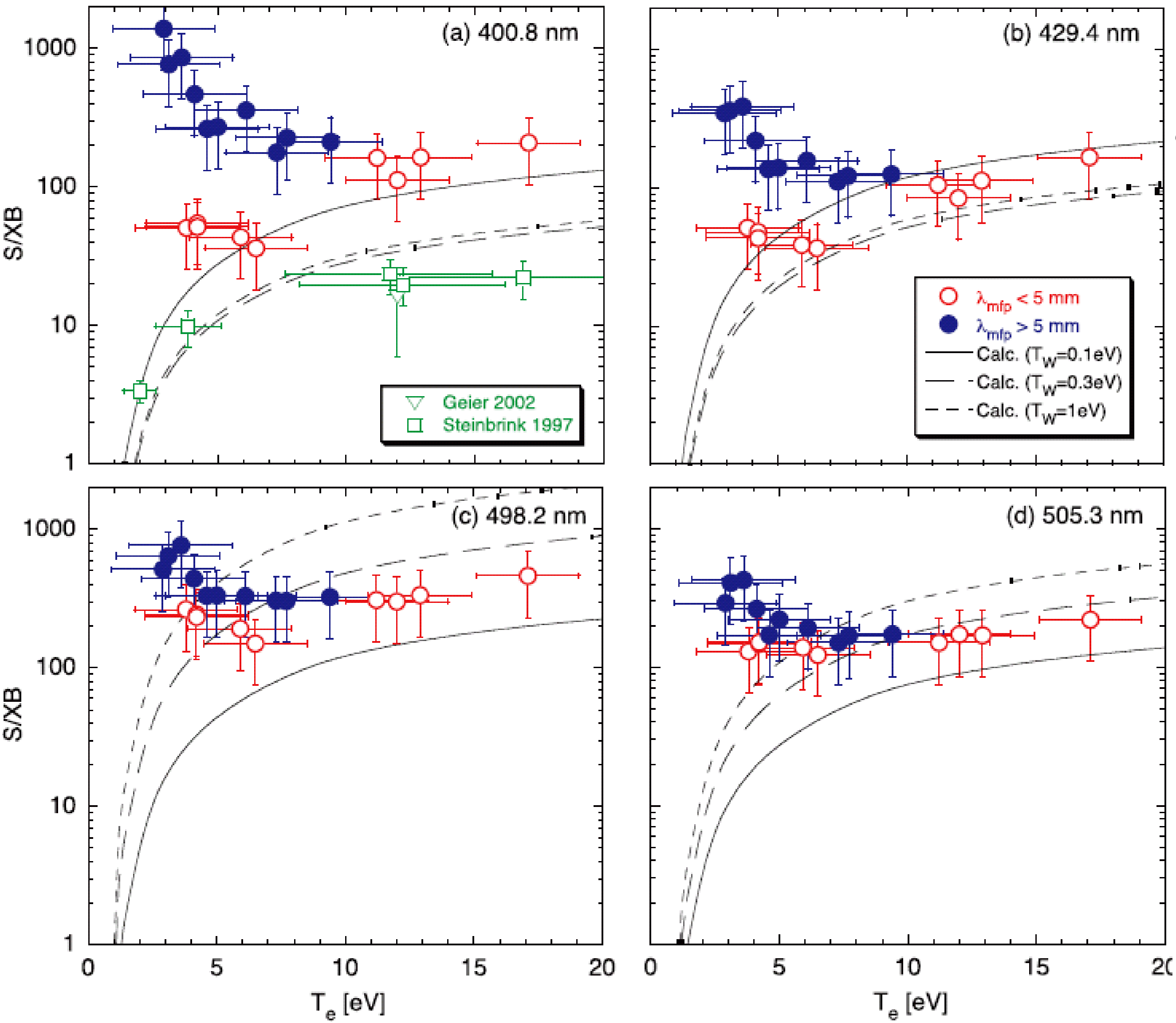
note: the large number of W I lines is a strong help for absolute calibrations (via br -> UV)

one useful example found: 426.022 / 261.308 – A_{ik} in $10^8 s^{-1}$ 0.174 / 0.54

W I lines - dependence on target temperature



Tungsten S/XB from sputtering experiments (Ar) - PISCES-B



$$\Phi_A = \frac{4\pi}{\Gamma}\frac{I_{tot}}{h\nu}\frac{<\sigma_I v_e>}{<\sigma_{Exg} v_e>} = 4\pi\frac{I_{tot}}{h\nu}\frac{S}{XB}$$

↓

S / XB =

$$\frac{<\sigma_I v_e>}{\Gamma<\sigma_{Exg} v_e>} = \frac{\Phi_A}{4\pi\left(I_{tot}/h\nu\right)}$$

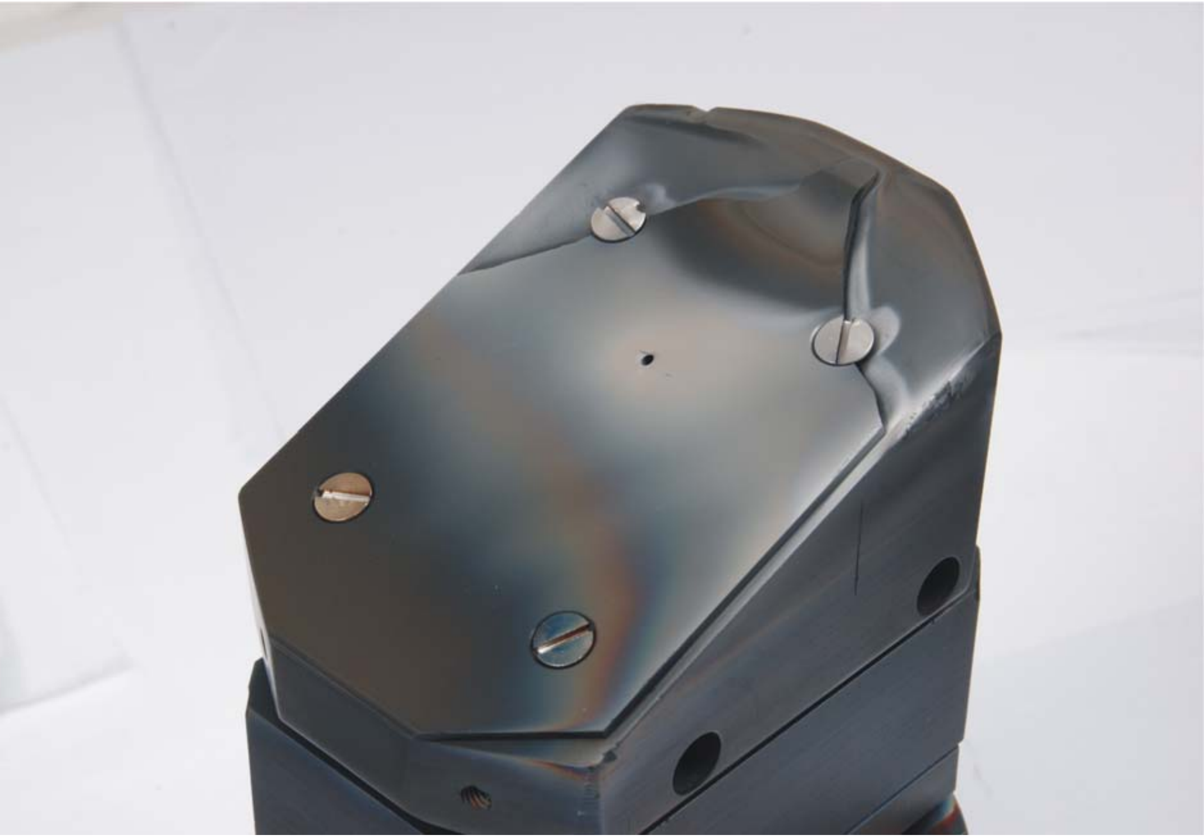
Measure

flux & line intensity

(weight loss & photons)

WF_6-blow through a hole in a graphite plate in Limiter Lock 1 (TEXTOR)

During 107368-107378 7 discharges with WF_6 blow – 1 (0.5) s

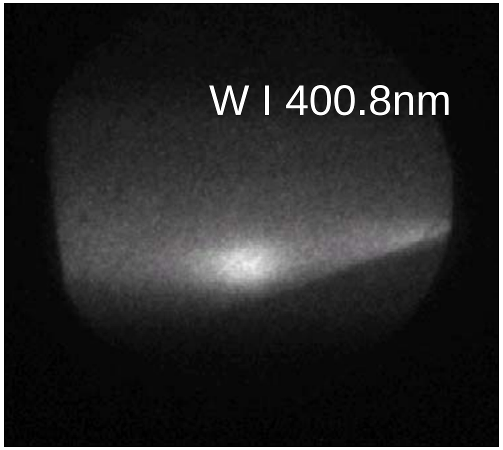


Tungsten transport in SOL

- defined conditions

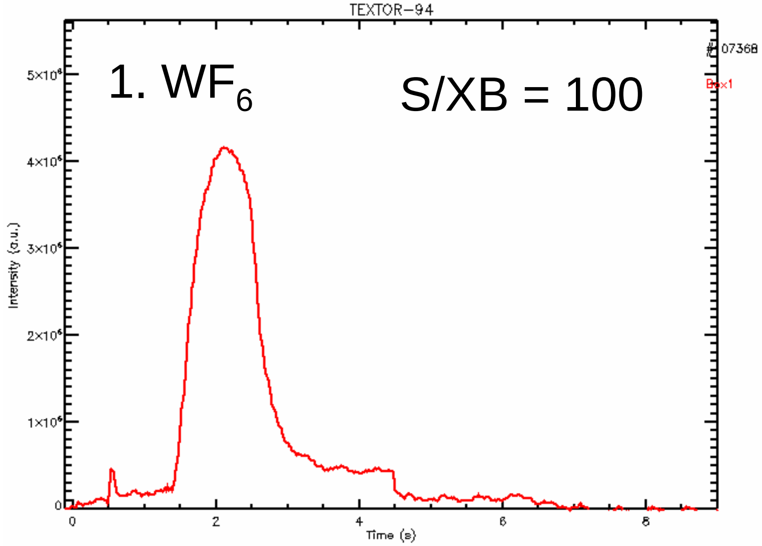
- controlled amount (about 4% of the D-content)

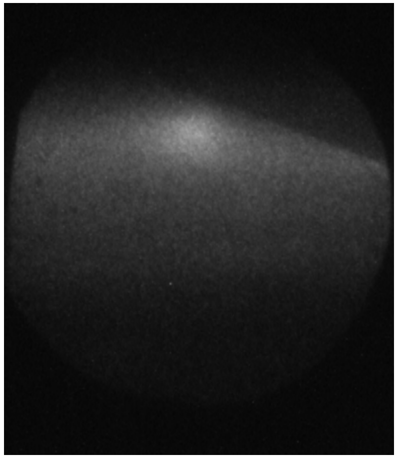
Safety measures had been taken



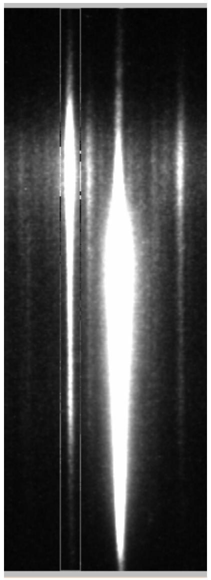
S/XB (400.8nm) from flux calibration

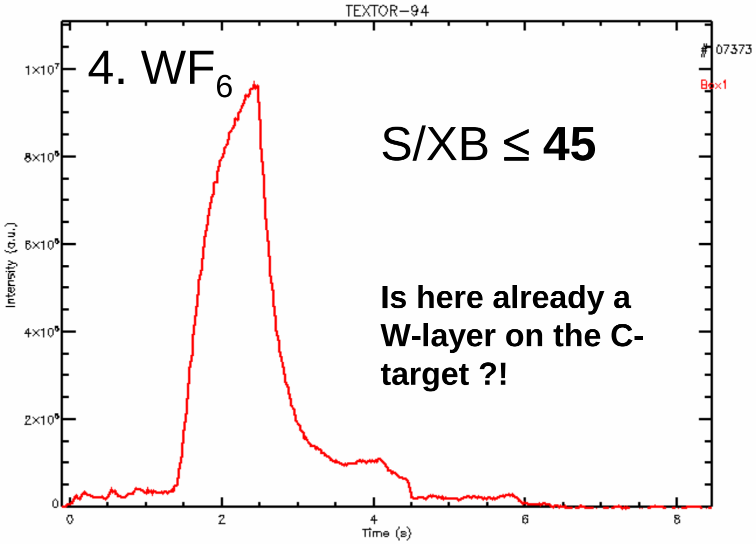
Nominally identical WF_6- flux – but factor of 2 in intensity

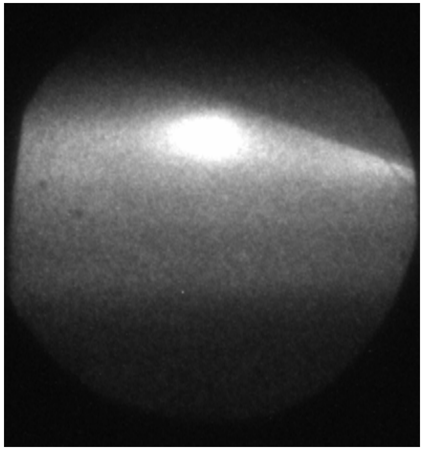




WI 400.8







Measure

flux & line intensity

2350 Å – 2750 Å range

(hot) W-target plate

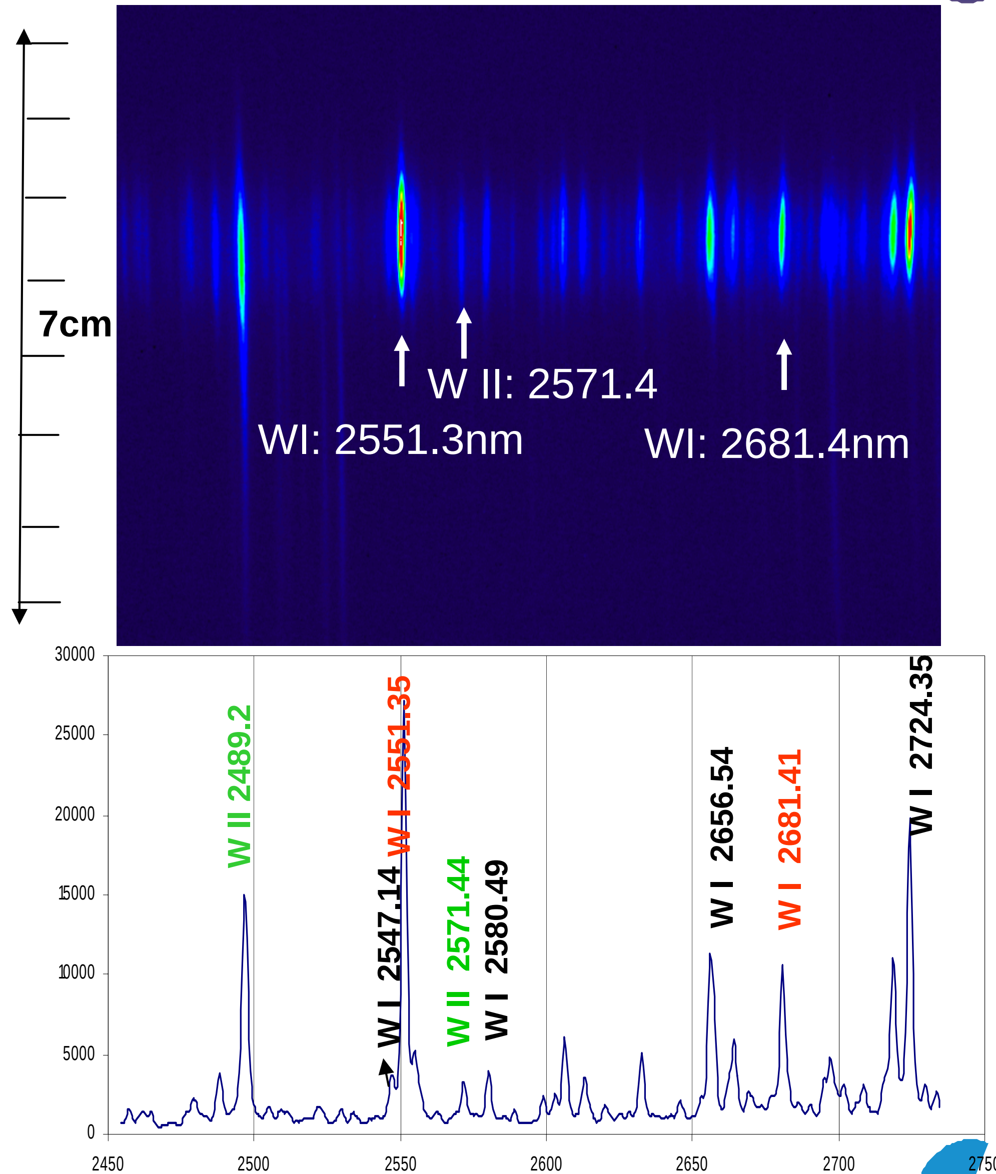
- **strong isolated W I lines exist in the UV range**
- **well separated**
- **not influenced by continuum radiation of T= 3500 ^{0}C**

- **also W II lines can be seen**
- **radial penetratration depth helps**
- **S/XB ?**

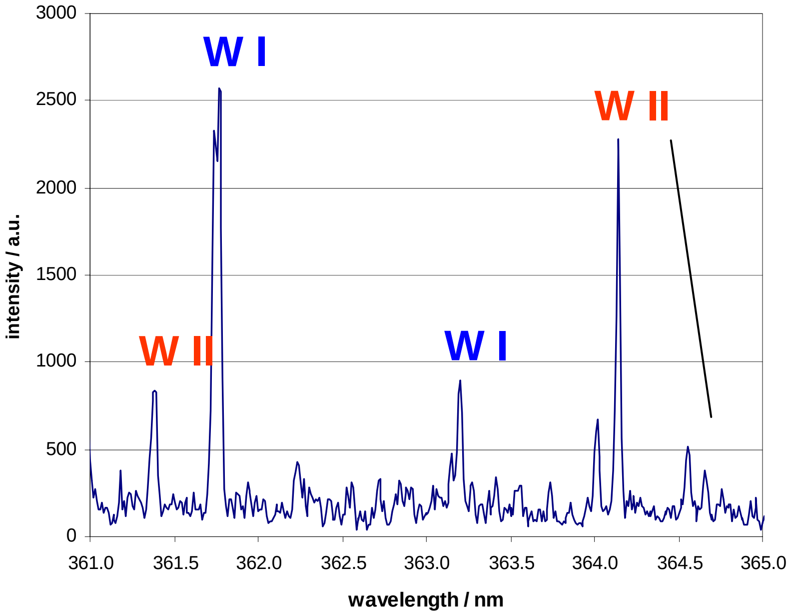
recently calculated by

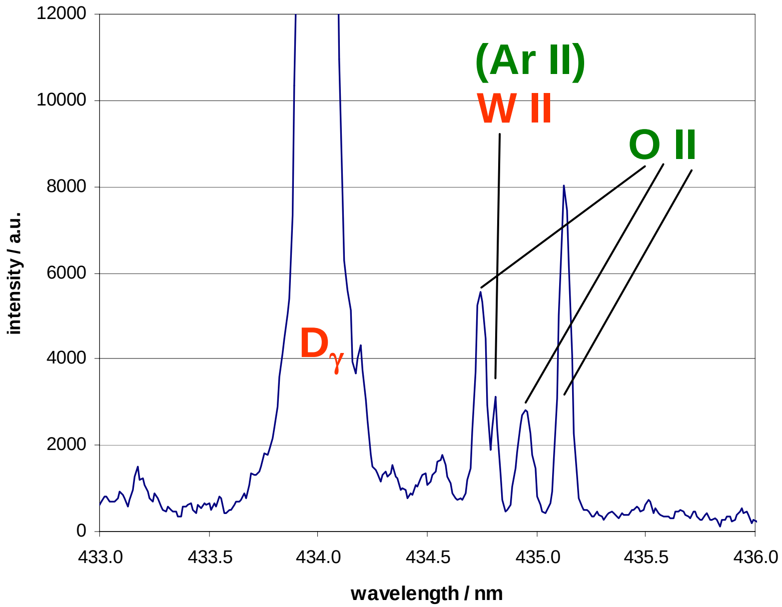
Beigman & Vainshtein

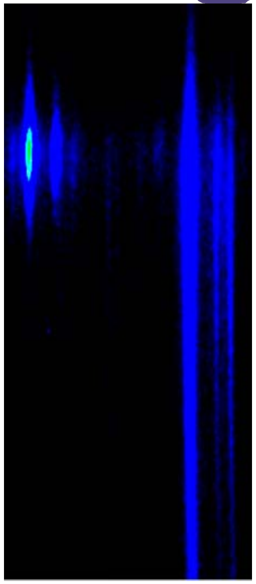
W II in the visible ?



W II – lines from HR-spectroscopy at TEXTOR

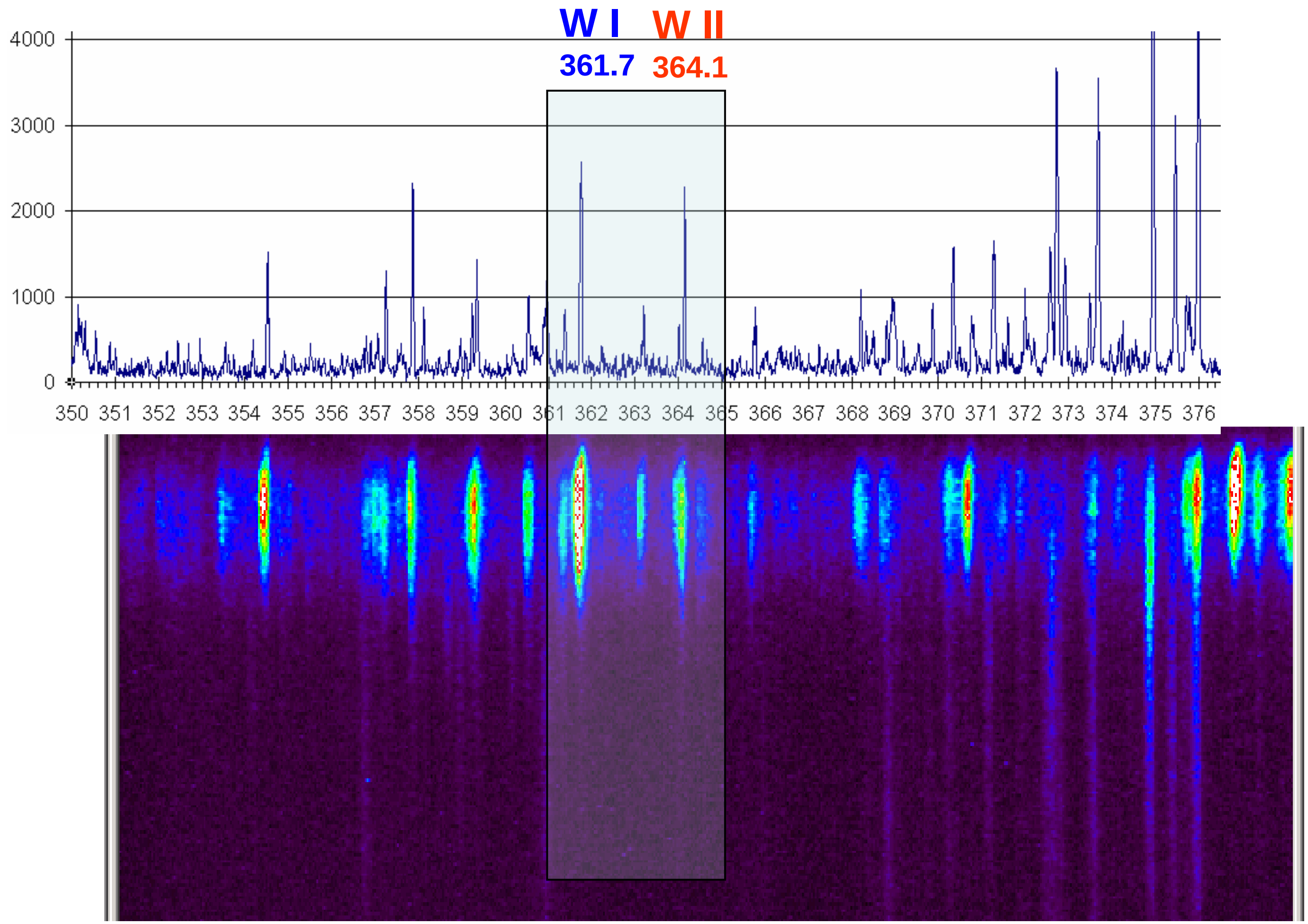






Ion	Wavelength (nm)	Rel. Int.	A_{ki}(s^{-1})	Configurations			Terms		
W II	**361.379036**	**133**	**1.15e+07**	**5*d*⁴(⁵D)6*s***	**-**		**⁴D**	**-**	
W I	361.7522	500	1.1e+07	5*d*⁵(⁶S)6*s*	-	5*d*⁴6*s*(⁶D)6*p*	⁷S	-	⁵P°
W I	363.1953	200	1.3e+06	5*d*⁴6*s*²	-	5*d*⁴6*s*(⁶D)6*p*	⁵D	-	⁵D°
W II	**364.14078**	**113**	**9.91e+06**	**5*d*³6*s*²**	**-**		**⁴F**	**-**	
W II	**364.559609**	**134**	**1.46e+06**		**-**	**5*d*³(⁴F)6*s*(⁵F)6*p***		**-**	**⁶G°**
W II	**400.87075**	**999m**	**?????**						
W I	400.8749	1000	1.63e+07	5*d*⁵(⁶S)6*s*	-	5*d*⁵(⁶S)6*p*	⁷S	-	⁷P°
W II	**434.81130**	**109**	**5.06e+06**	**5*d*⁴(⁵D)6*s***	**-**		**⁴D**	**-**	

Comparison W II – lines from HR-spectroscopy and 2-D spectroscopy at TEXTOR



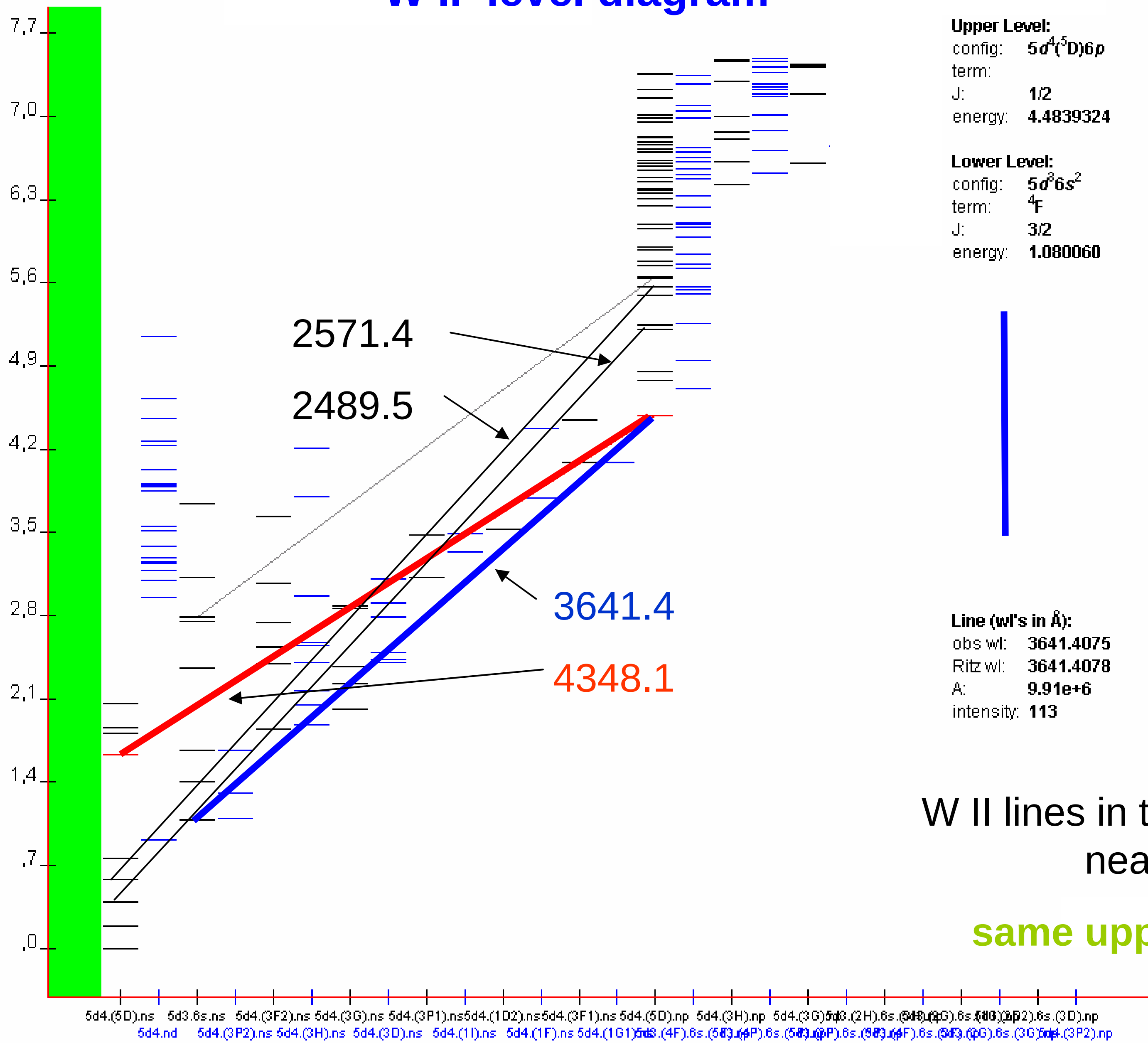
HR spectrometer

good resolution is needed

LimLock1 spectrometer with radial resolution

108216

W II level diagram



Upper Level:	
config:	$5d^4(^5D)6p$
term:	
J:	1/2
energy:	4.4839324

Lower Level:	
config:	$5d^36s^2$
term:	^4F
J:	3/2
energy:	1.080060

Line (wl's in Å):	
obs wl:	3641.4075
Ritz wl:	3641.4078
A:	9.91e+6
intensity:	113

Upper Level:	
config:	$5d^4(^5D)6p$
term:	
J:	1/2
energy:	4.4839324

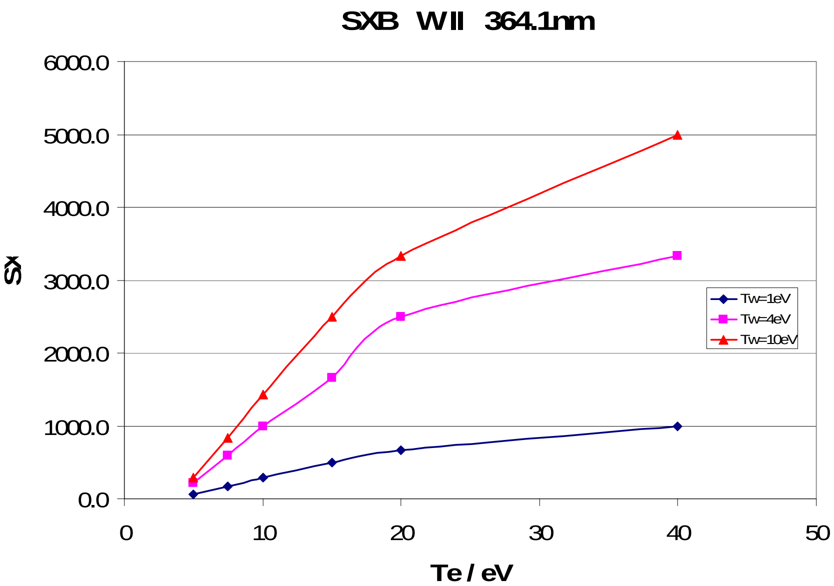
Lower Level:	
config:	$5d^4(^5D)6s$
term:	^4D
J:	1/2
energy:	1.6332855

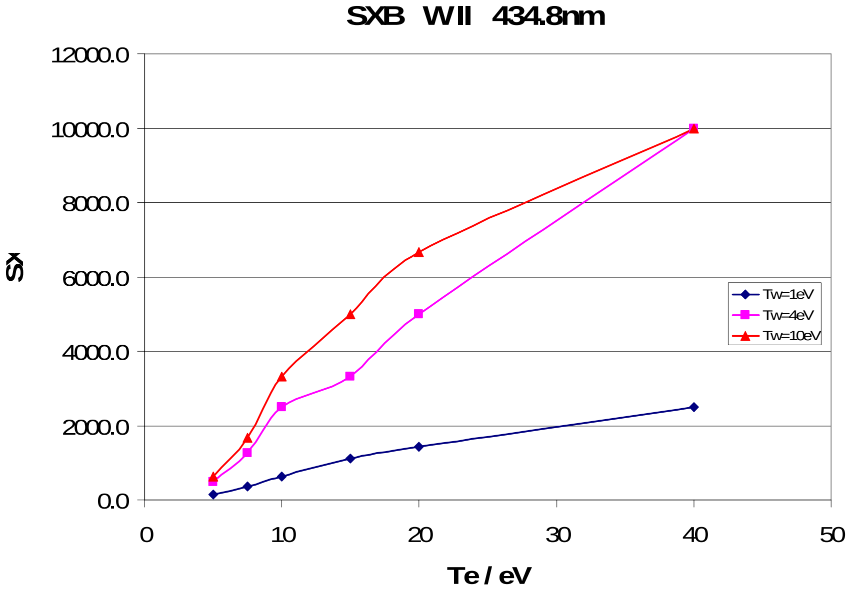
Line (wl's in Å):	
obs wl:	4348.1130
Ritz wl:	4348.1130
A:	5.06e+6
intensity:	109

W II lines in the visible and near UV

same upper level !!

some S/XBs for W II - flux comparison with W I





	W I		W II	
λ / nm	400.9	429.5	434.8	364.1
Intensity / au	2.22 ×10⁴	1.72 ×10⁴	1.92 ×10³	4.25 ×10³
S/XB @ 20eV $T_{W= 4eV}$	60	112	6000	2500
S/XB @ 20eV $T_{W= 1eV}$	57	106	1423	666
$Flux_{4eV}$	1.33×10^6	1.93×10^6	1.15×10^7	1.06×10^7
$Flux_{1eV}$	1.27×10^6	1.82×10^6	2.73×10^6	2.83×10^6

Calculations similar as for the W I case

conclusions

Recent injection experiments confirm the known S/XB values for the W I 400.8nm line

Additional experimental data for 3 other W I lines – in the blue and green – are now available (better transmission characteristics)

For different W-target temperatures (in our cases between 700^{0}C and 1300^{0}C) the level population of the W-lines investigated remains unchanged

“branching” method for spectrometer calibrations seems to be possible with W-atoms

S/XB values have now also been calculated for several W II lines in the UV and visible

To fit to the W I fluxes a ground state population with extremely low “T_W” has to be assumed

Always advisable

refine level populations (cascading, transfer, ground state) – experimental input

The End

Model Calculations

ionization rate coefficients: from the **Code "ATOM" (B & BO appr.)** for the lowest configurations $5d^4$ (^6S) $6s^2$ and $5d^5$ (^6S) $6s$ using

$$\langle v\sigma_{iz}\rangle = 10^{-8} A \frac{\sqrt{\beta}\,(\beta+1+D)}{(\beta+\chi)(\beta+1)\sqrt{\beta_{iz}+1}} e^{-\beta_{iz}} \left[cm^3 s^{-1}\right],$$

$$\beta = Ry/T_e;\ \beta_{iz} = E_{iz}/T_e,$$

E_{iz}=7.864 *eV* ionization energy, T_e is the electron temperature; *A*=84.9, χ=0.22, *D*= -0.4 from the code

excitation rates: complicated coupling scheme and configuration mixing. For many levels the identification is unknown: =>semi-empirical **van Regemorter formula:**

$$\langle v\sigma_{k_0,k}\rangle = 0.11\cdot 10^{-16}\cdot \frac{g_k}{g_{k_0}} A_{k,k_0} \left(\frac{Ry}{\Delta E}\right)^3 u(T_e) e^{-\beta_{ex}} [cm^3 s^{-1}],$$

$$u(T_e) = \beta^{0.5} l\,og(2+1/(1.78\beta_{ex})),\ \beta_{ex} = \Delta E/T_e,\ \beta = Ry/T_e,$$

where $A_{k,k0}$ is the radiative transition probability. Non-dipole collisional transitions were not considered.

Model: ***Coronal approximation*** with excitation only from the group of "ground" levels
$5d^4$ (^5D) $6s^2$ ^5D_J and $5d^5$(^6S) $6s$ $^7S_3$

$$Q_{k,k'} = \frac{A_{k,k'}}{A_k}\sum_{k_0} N_{k_0}\langle v\sigma_{k_0,k}\rangle, \qquad S/XB = \langle v\sigma_{iz}\rangle / Q_{k,k'}$$

$A_k = \sum_{k''} A_{k,k''}$. is the total radiative decay probability:

Lines with transition probabilities A(k,k') and A(k,k_0) used if provided in the NIST tables (522 lines)
Assumption: level population (k_0) -> Boltzmann distribution with T_W (free parameter)

W-I lines considered

λ / A	E / cm^{-1} E / eV		g_L		Transition		A / s^{-1}	br
	low	Up	low	up	Low	Up		%
2551.35	0.00 0.000	39183.20 4.858	0.0	1.00	a $^5D_0$	x J=1	1.8e+8	79
2681.42	2951.29 0.366	40233.97 4.988	1.98	1.50	b $^7S_3$	x J=4	7.4e+7	86
4008.75	2951.29 0.366	27889.68 3.458	1.98	1.70	b $^7S_3$	d $^7P_4$	1.6e+7	99
4294.61	2951.29 0.366	26229.77 3.252	1.98	1.84	b $^7S_3$	d $^7P_2$	1.2e+7	94
4886.90	6219.33 0.771	26676.48 3.307	1.50	1.46	a $^5D_4$	c $^7F_5$	8.1e+5	100
4982.59	0.00 0.000	20064.30 2.488	0.0	1.54	a $^5D_0$	c $^7F_1$	4.2e+5	79
5053.28	1670.29 0.297	21453.90 2.660	1.51	2.51	a $^5D_1$	c $^7D_1$	1.9e+6	52
5224.66	4830.00 0.859	23 964.67 4.261			a $^5D_3$	b $^7D_2$	$1.2 \cdot 10^6$	

Designations: a=$5d^4(^5D)6s^2$, b=$5d^5(^6S)6s$, c=$5d^4(^5D)6s6p$, d= $5d^5(^6S)6p$,
x means unidentified.

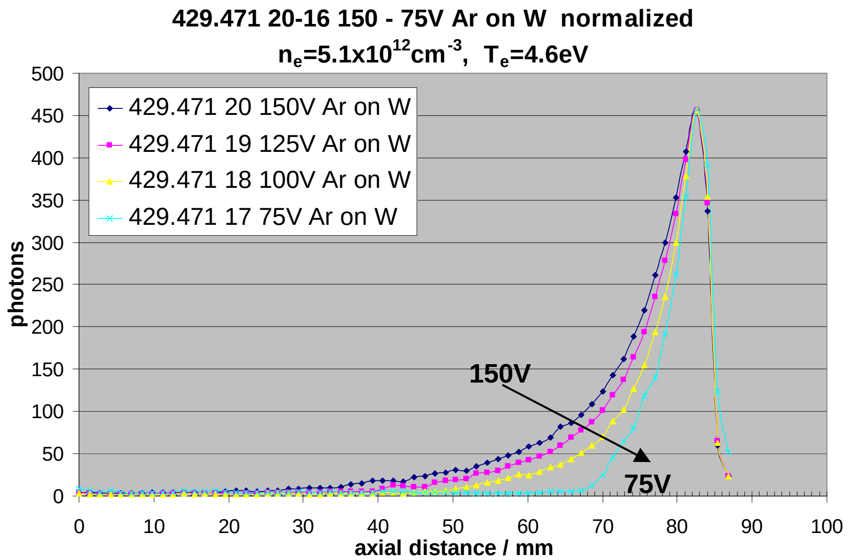
from NIST; other sources: R. Kling, M. Kock JQSRT 62 (1999) 129 - **263 lines**

C.H.Corliss, W.R.Bozman NBS 53 (1962) 499 - **261 lines**

note: the large number of W I lines is a strong help for absolute calibrations (via br -> UV)

one useful example found: 426.022 / 261.308 – A_{ik} in $10^8 s^{-1}$ 0.174 / 0.54

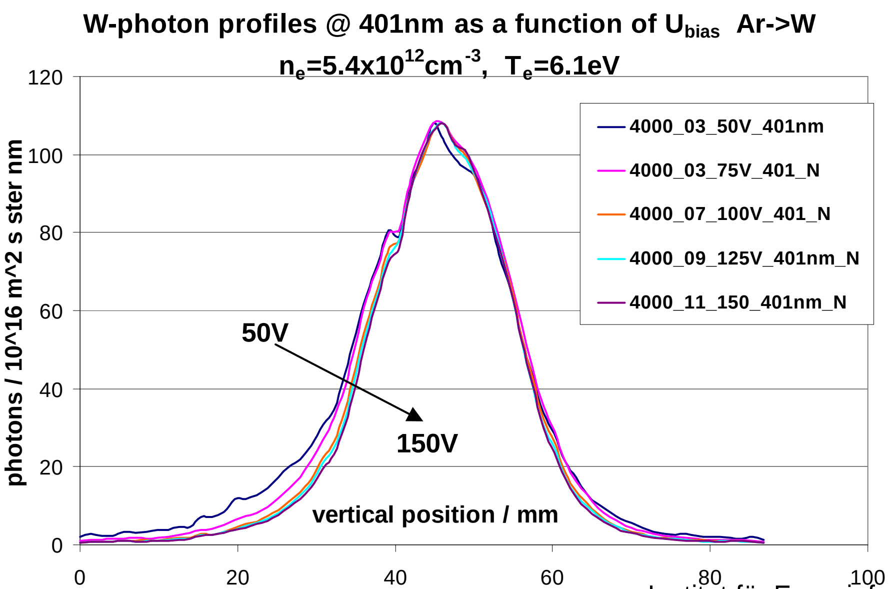
Tungsten distribution with sputtering energy (Ar) - PISCES-B



Increase of W-penetration depth with sputtering energy

Reason : Cooling of plasma by radiating W particles ?

concentration in forward direction



Concentration (narrowing) of the emission cone into the forward direction with increasing sputtering energy