Sources for Water Window Imaging

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Outline

Overview of

- Water window sources,
- laser produced plasmas,
- unresolved transition arrays (UTA)

$\Delta n = 0$ UTA

n= 4 – n=4 emission

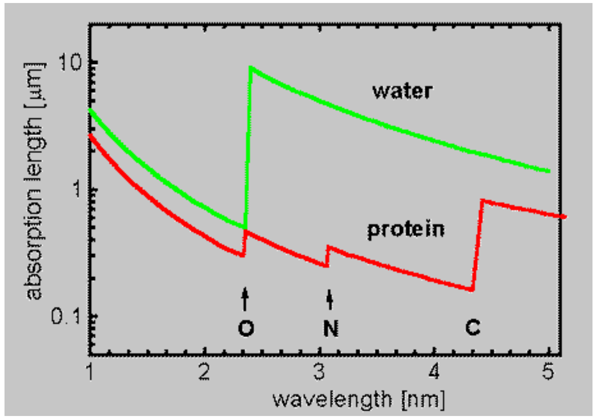
$\Delta n = 1$ UTA

2nd Transition row (n= 3- n=4)

3rd transition row (n=4-n=5)

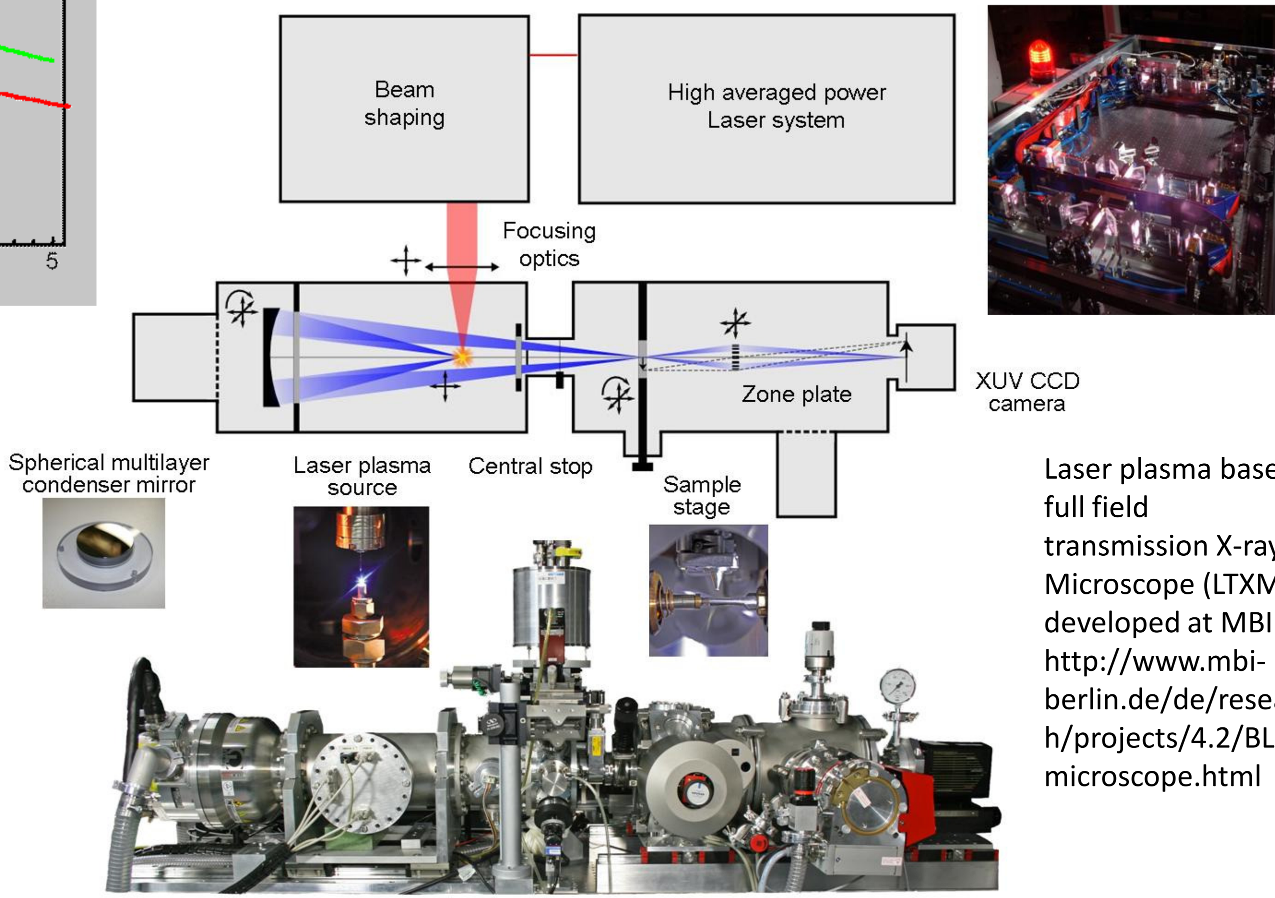
Conclusions

Water window source development



Water window : 2.34-4.38 nm.

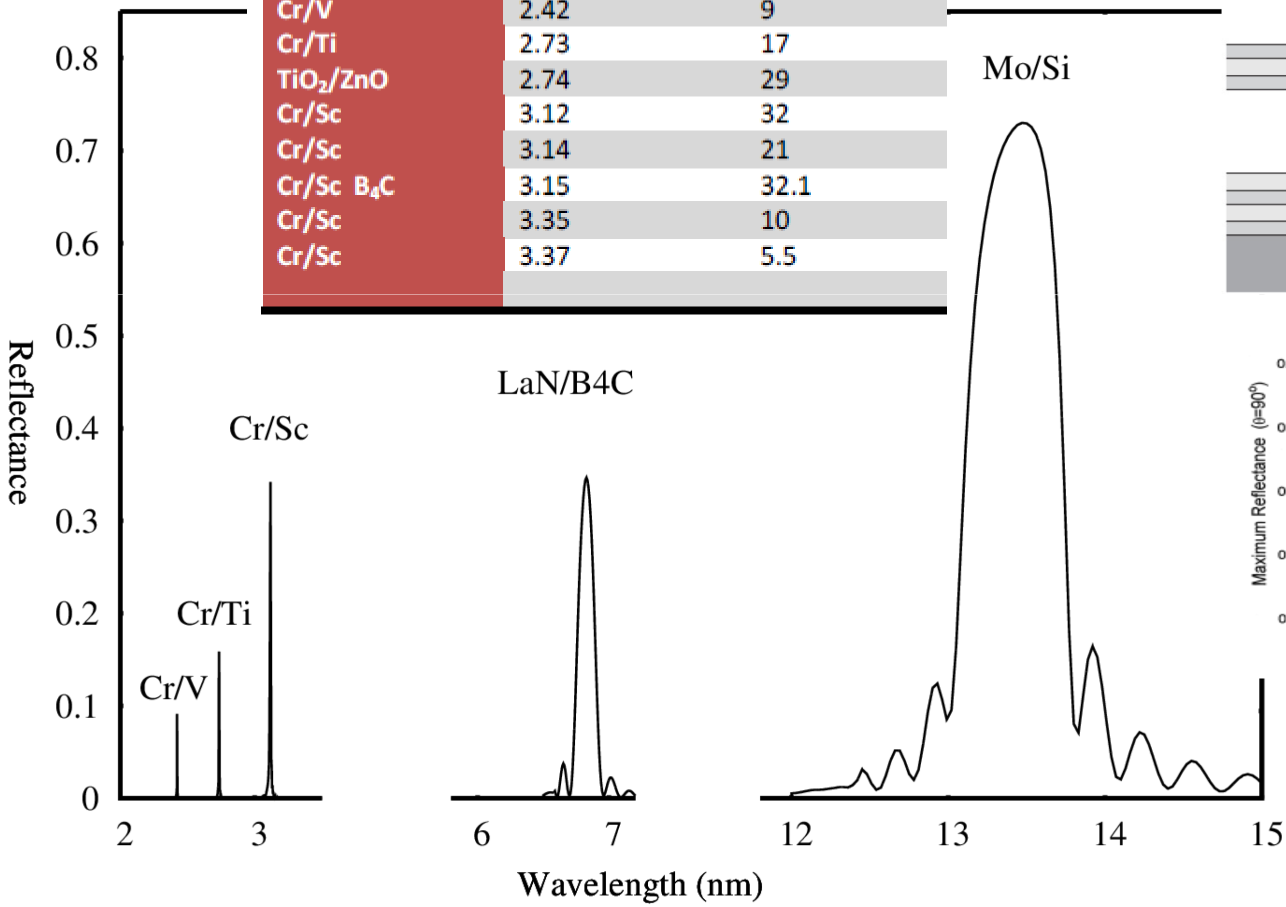
Relative transparency of water allows investigation of biomolecules, cells and proteins in their natural aqueous environment by x-ray transmission microscopy or tomography

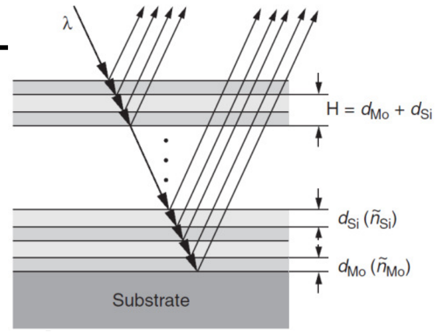


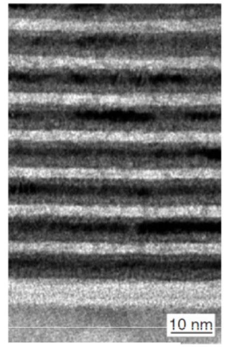
Laser plasma based full field transmission X-ray Microscope (LTXM) developed at MBI. http://www.mbi-berlin.de/de/research/projects/4.2/BLIX/microscope.html

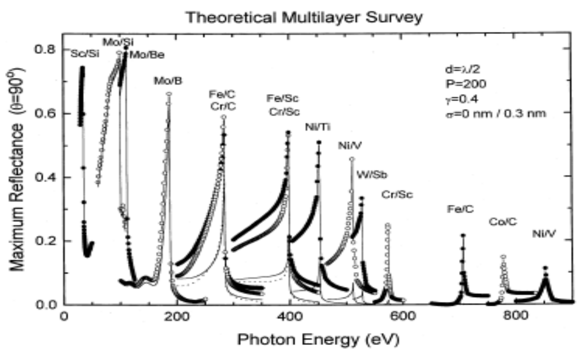
Multilayer Mirrors at different SXR wavelengths

Material	Wavelength (nm)	Reflectivity (%)
Cr/V	2.42	9
Cr/Ti	2.73	17
TiO_2/ZnO	2.74	29
Cr/Sc	3.12	32
Cr/Sc	3.14	21
Cr/Sc B_4C	3.15	32.1
Cr/Sc	3.35	10
Cr/Sc	3.37	5.5



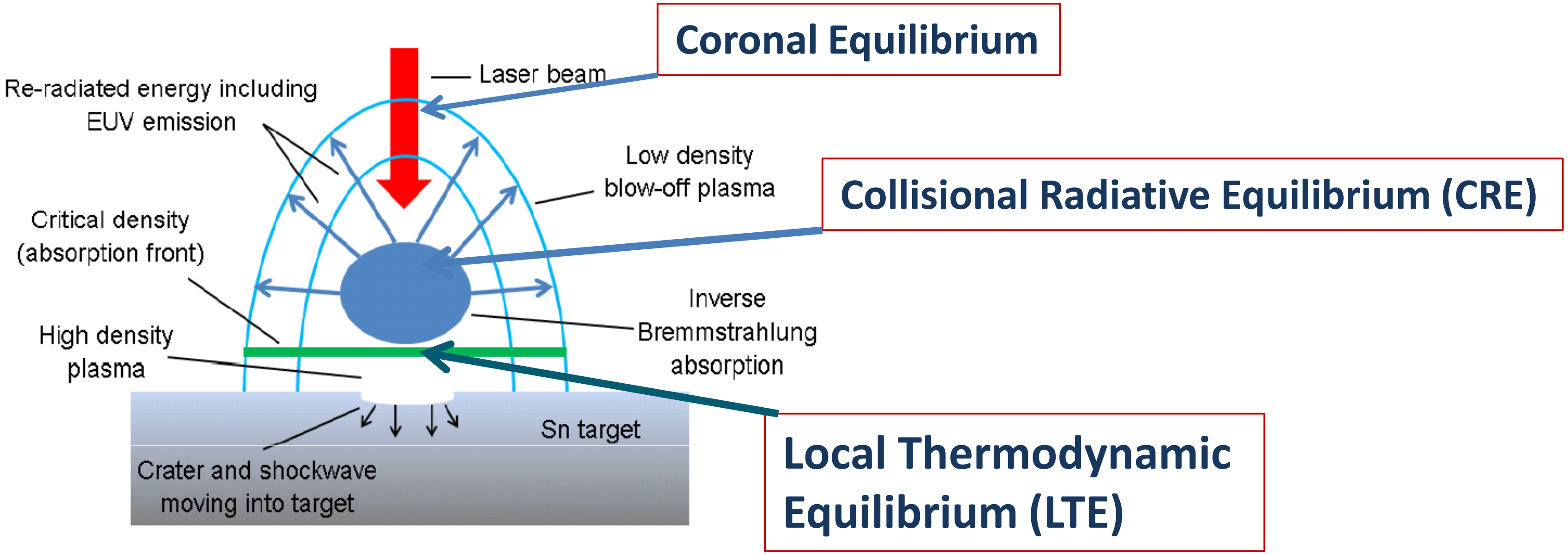






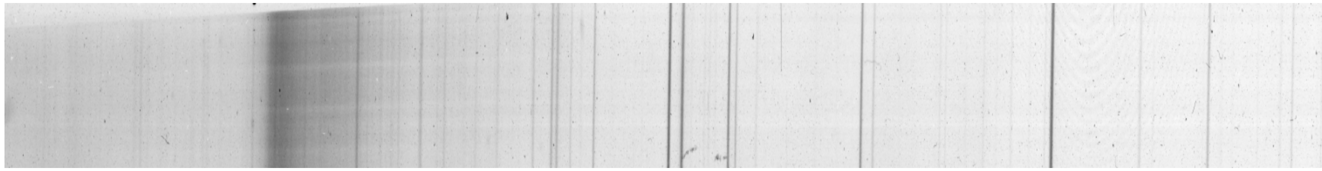
F. Schäfers / Physica B 283 (2000) 119–124

Laser Produced Plasmas (LPPs)



- Critical electron density, $\mathbf{n_{ec}}$ $=10^{19} – 10^{21}$ cm^{-3} depends on laser wavelength **(n_{ec}~$10^{21}/\lambda(\mu m)^2$ cm^{-3})**
- Temperature depends on laser power density (Φ), **$T_e(eV) \approx (\lambda^2\Phi)^{3/5}$**
- **Average charge ≈ 0.67 $(AT_e)^{1/3}$**
- Hottest at centre, cooler margins- **opacity issues**
- Expansion velocity ≈ 10^6 - 10^7 cms^{-1}

‘Typical’ EUV LPP Spectrum



Spectrum consists of:

- lines (bound-bound transitions), because of high density, lines from high n states are usually not seen
- recombination radiation (bound-free transitions) which scales as $\langle\zeta\rangle^4$ where $\langle\zeta\rangle$ is the average ionic charge
- bremsstrahlung (free-free)

For an optically thin plasma: $P_{lines}:P_{recomb}:P_{brem} = 100:10:1$

In some cases lines cluster together to form a UTA (unresolved transition array)

What is a UTA?

- A UTA generally has too many lines to identify individual transitions.
- Ideally linewidth > line separation
- Both the energy levels and spectra can be parameterised statistically in terms of moments of the array *(Bauche, and Bauche-Arnoult Phys Scr* ***T40****, 58, 1992)*
- UTA described by:
  - Position - μ_1
  - Width - $\sigma = [\mu_2 - \mu_1^2]^{1/2}$

$$\mu_n = \sum_{a,b} \frac{[\langle a|H|a\rangle - \langle b|H|b\rangle]^n w_{ab}}{W}$$

$$w_{ab} = |\langle a|\mathbf{D}|b\rangle|^2, \qquad \mathbf{D} = -\Sigma_i e\mathbf{r}_i$$

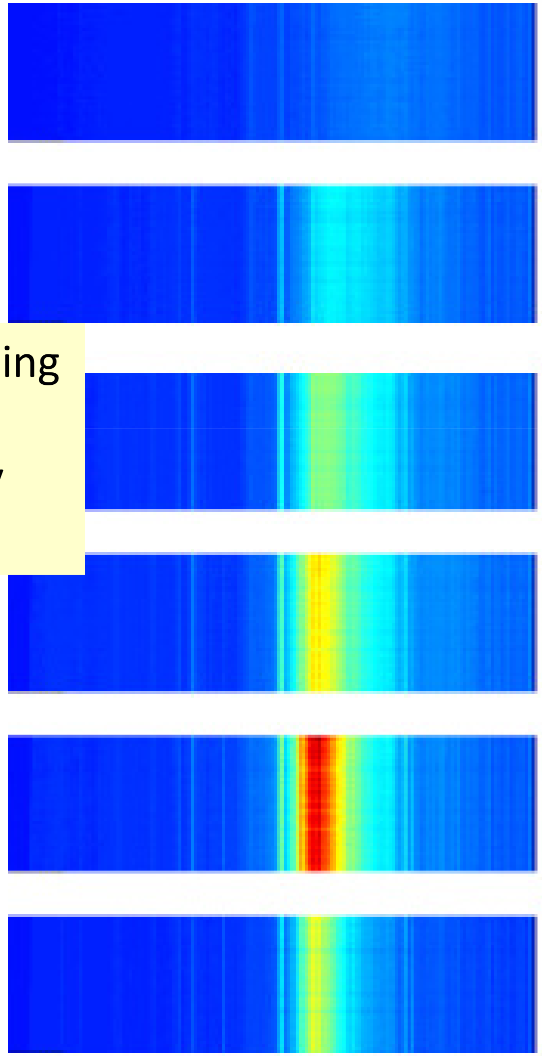
$$W = \sum\nolimits_{a,b} w_{ab}$$

For nl^{N+1} - $nl^N n'l'$ transitions, the shift from the average position, $\delta\mathbf{E}$, rather than μ_1 is the quantity of most interest:

$$\delta E = N\frac{(2l+1)(2l'+1)}{4l+1}\left(\sum_{k\neq 0} f_k F^k(l\,l') + \sum_k g_k G^k(l\,l')\right)$$

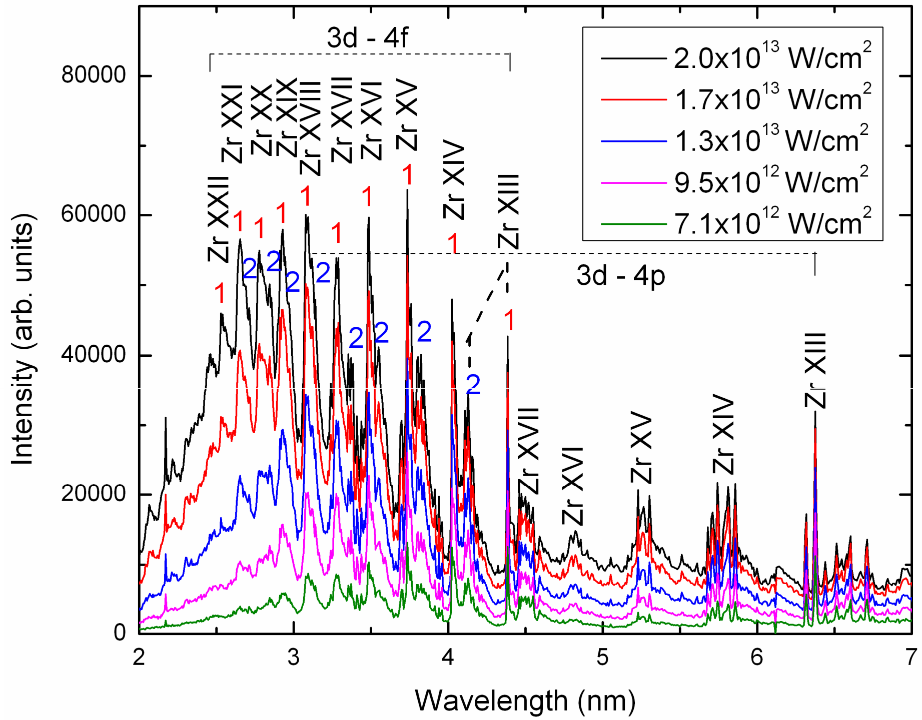
Two types of UTA in XUV spectra

Δn = 0



Increasing power density ↓

Δn > 0



Δn = 0 transitions overlap in adjacent ion stages.

Δn = 0 transitions do not overlap in adjacent ion stages and move to shorter wavelengths with increasing ionization.

Outline

- Water window sources, Laser Produced plasmas, Unresolved Transition Arrays

$\Delta n = 0$ UTA

n= 4 – n=4 emission

- $\Delta n = 1$UTA

2nd Transition row (n= 3- n=4)

3rd transition row (n=4-n=5)

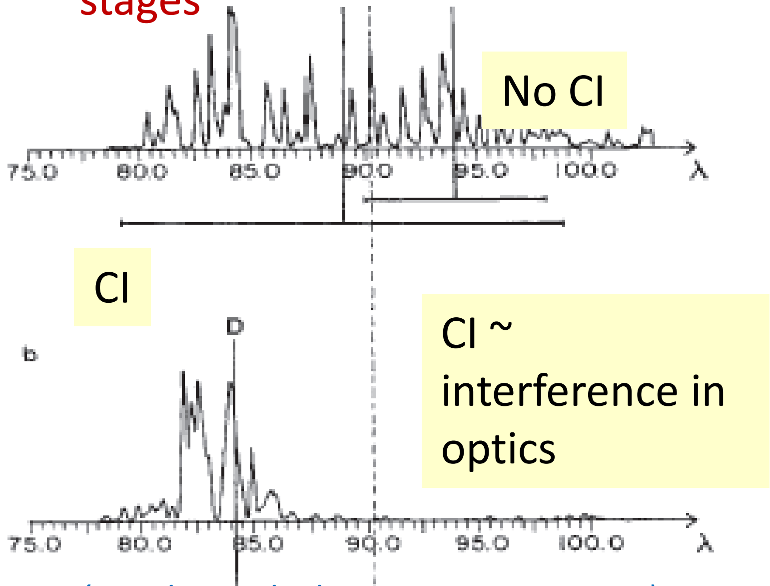
- Conclusions

Narrowing in mixed arrays

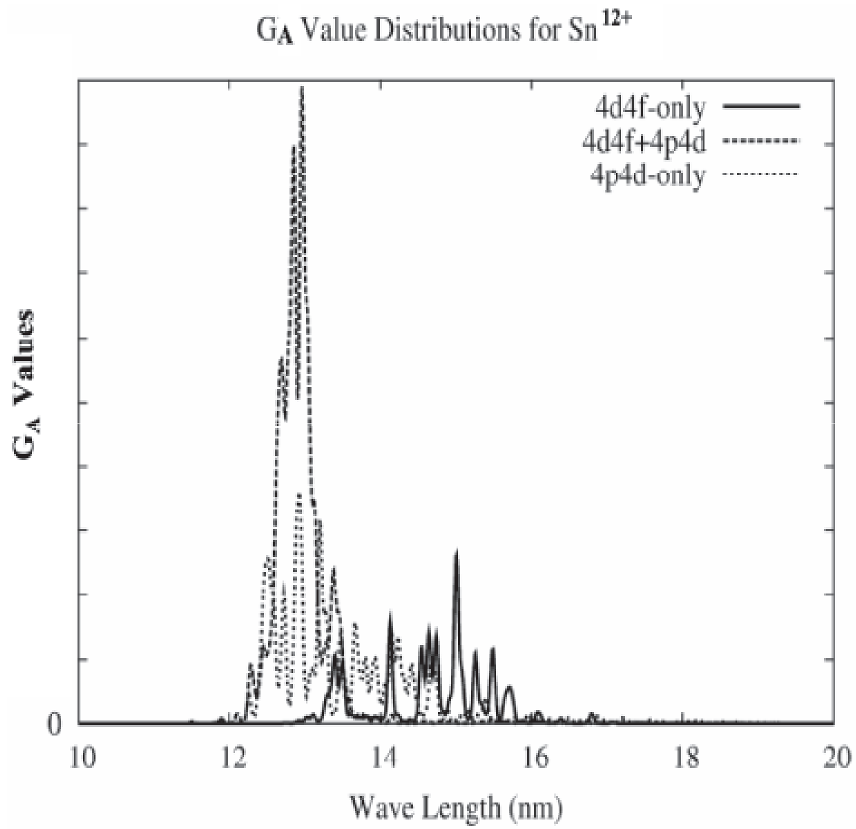
In spectra due to $4p^6 4d^{N+1}$- $4p^6 4d^N 4f$ + $4p^5 4d^{N+2}$ transitions

Configuration interaction causes

- Spectral narrowing.
- Strong peaking of oscillator strength.
- Increased localisation of transitions at ~ the same position in successive ion stages

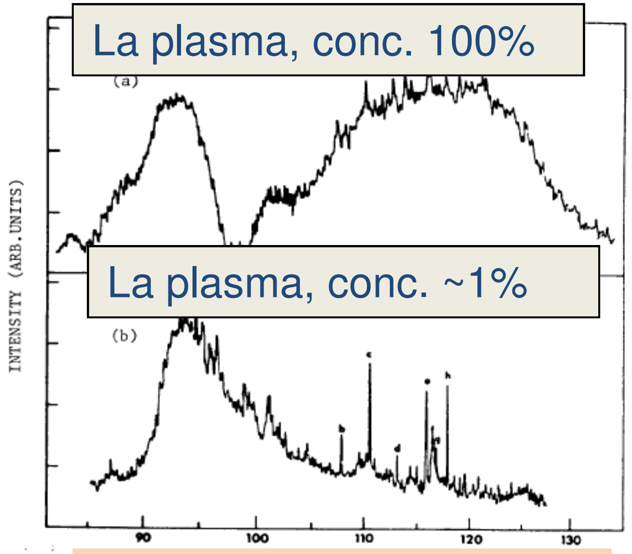


(Bauche et al. Phys. Scr. 37, 359, 1988)

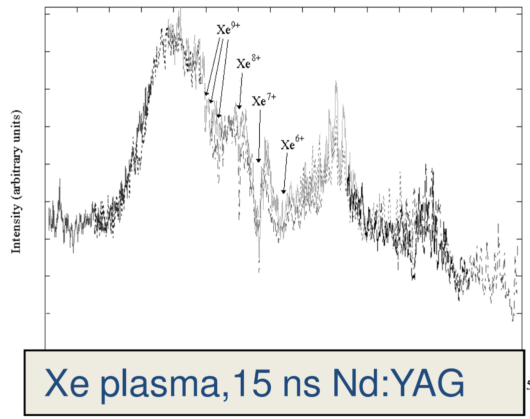


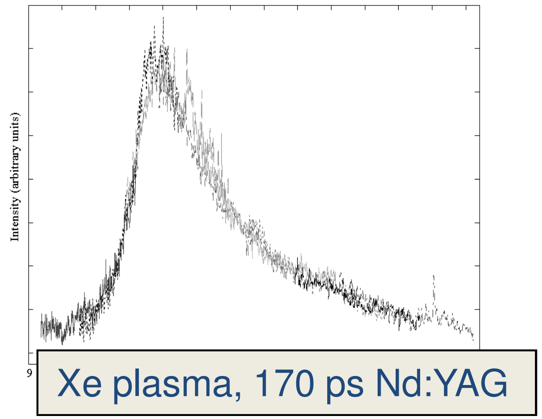
(F. Koike et al. J. Plasma Fusion Res. SERIES 7,253 2006)
F. Koike and S. Fritzsche Rad. Phys. And Chem. 76, 404, 2007)

Opacity in Δn=0 Arrays

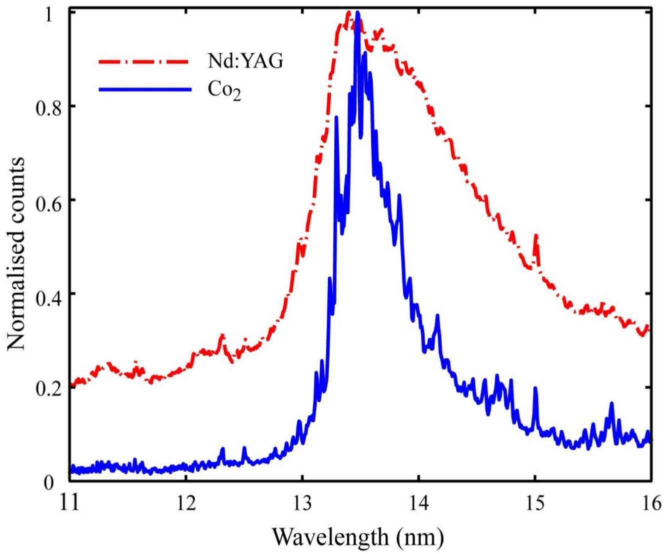


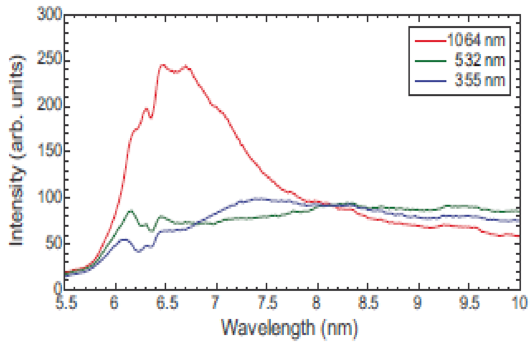
Target Concentration



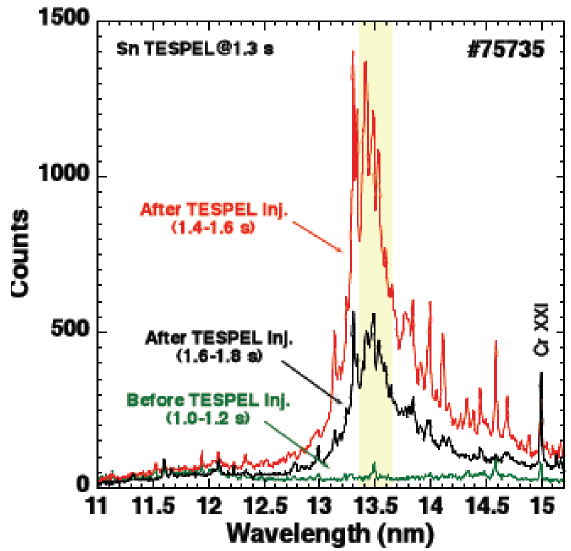


Laser Pulse Duration



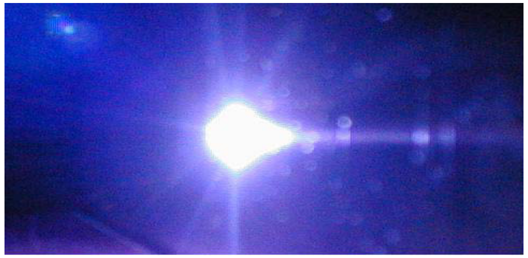


Laser Wavelength



Plasma Density

Effect of laser Wavelength on Ion Expansion

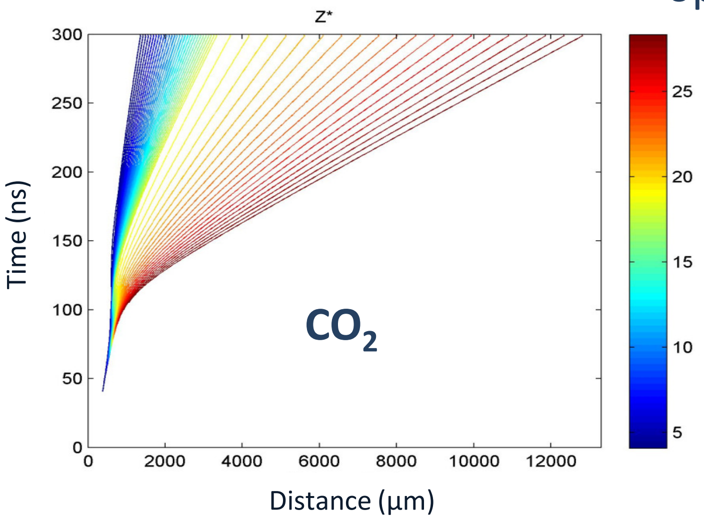


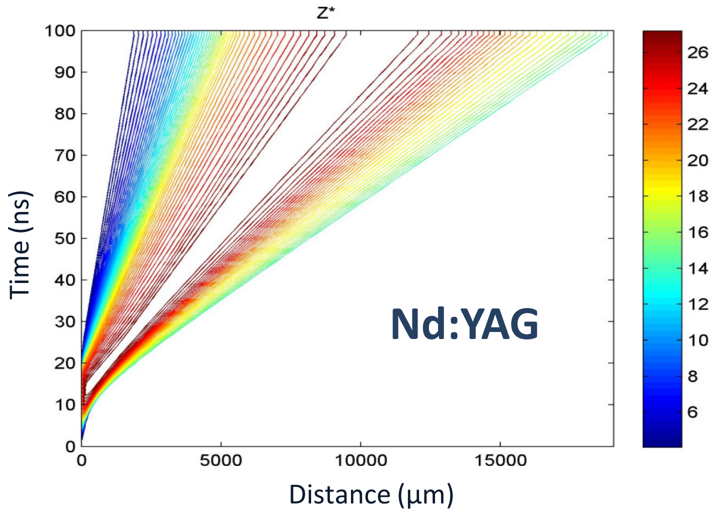
$n_e = n_{ec} \approx 10^{21} \lambda^{-2}$
$T_e \propto Z^{1/5}(\lambda^2\varphi)^{3/5}$

Laser-plasma interaction code Med 101 *(J.P. Christiansen, D. E. T. F. Ashby, and K.V. Roberts, Comp. Phys Commun* ***7****, (271-287, P.A. Rodgers, A.M. Rogoyski, and S. J. Rose, MED101: a laser-plasma simulation code. User guide 1974)*

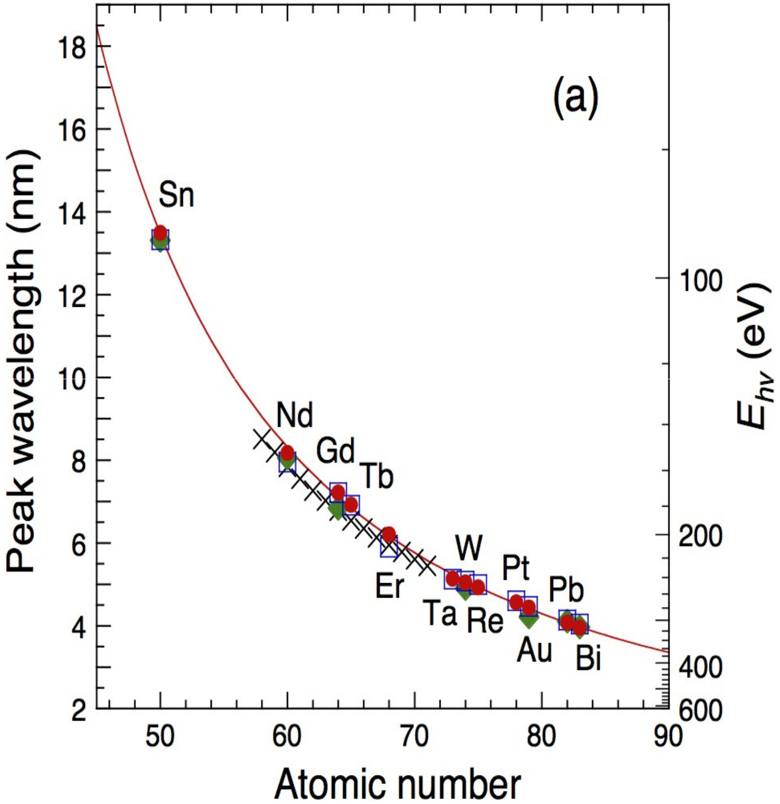
Nd:YAG highest Z ions behind plasma expansion front.

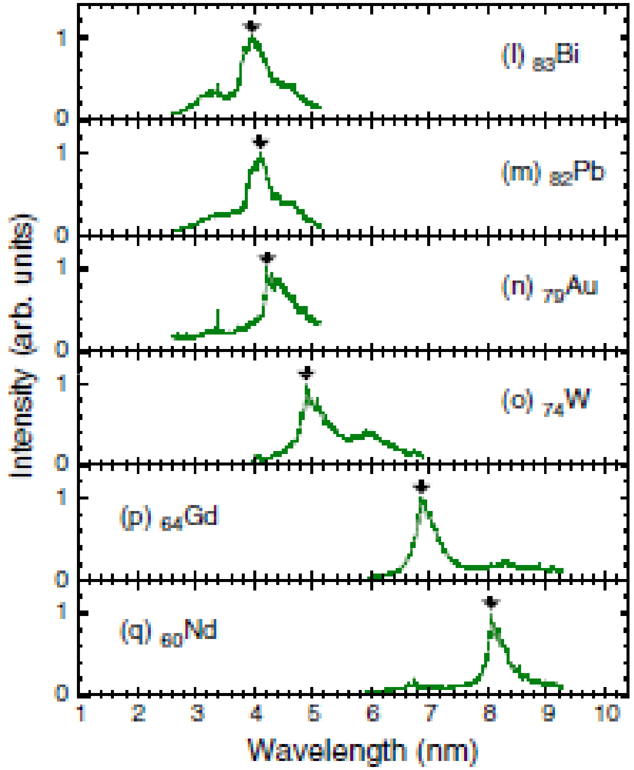
CO_2 Highest Z ions in plasma expansion front, less opacity





Evolution with Z of $\Delta n=0$, $n=4 - n=4$ Arrays





Ohashi *et al* APL 104, 234107 (2014)

Outline

- Water window sources, Laser Produced plasmas, Unresolved Transition Arrays

- $\Delta n = 0$ UTA

  n= 4 – n=4 emission

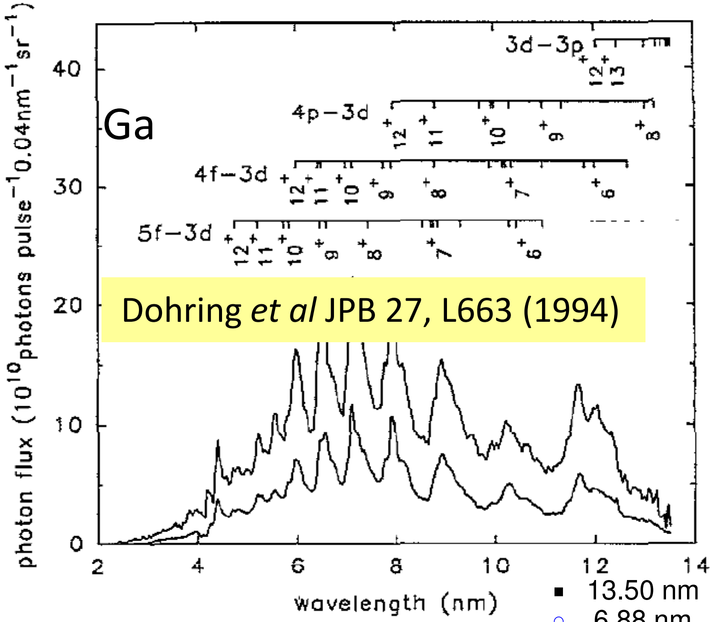
Δn= 1 UTA

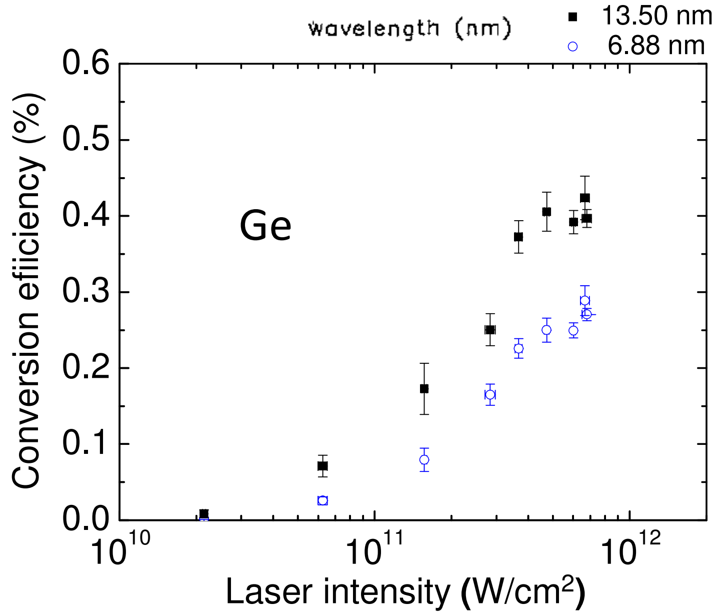
2nd Transition row (n= 3- n=4)

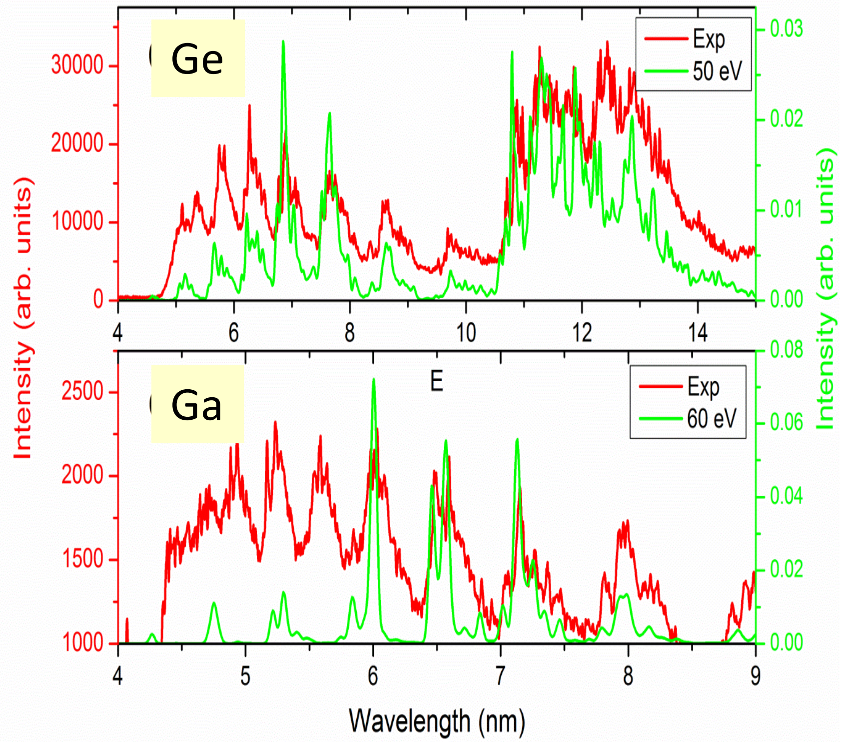
3rd transition row (n=4-n=5)

- Conclusions

Δn = 1 UTA: Ge and Ga LPPs



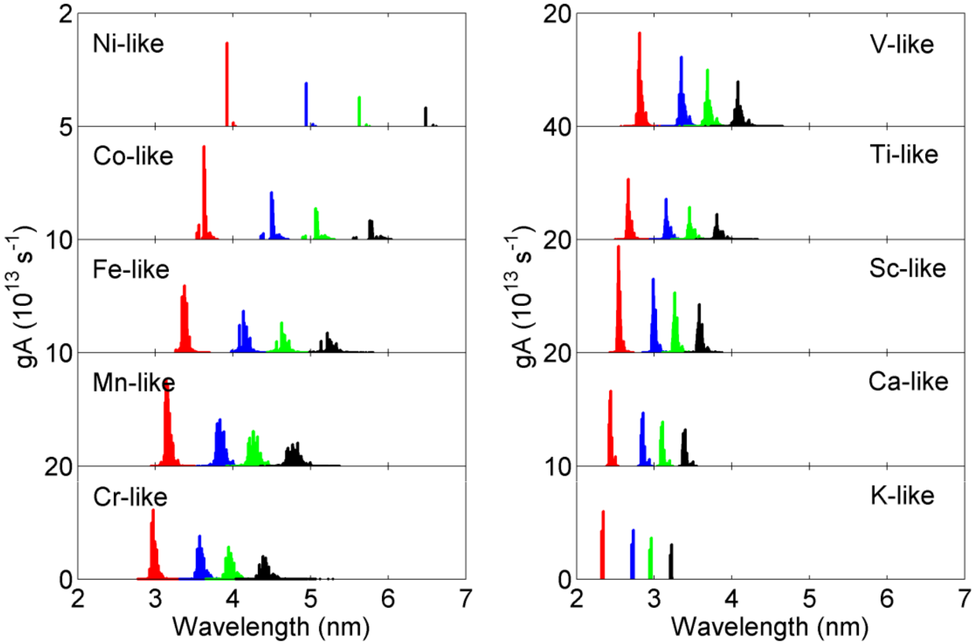




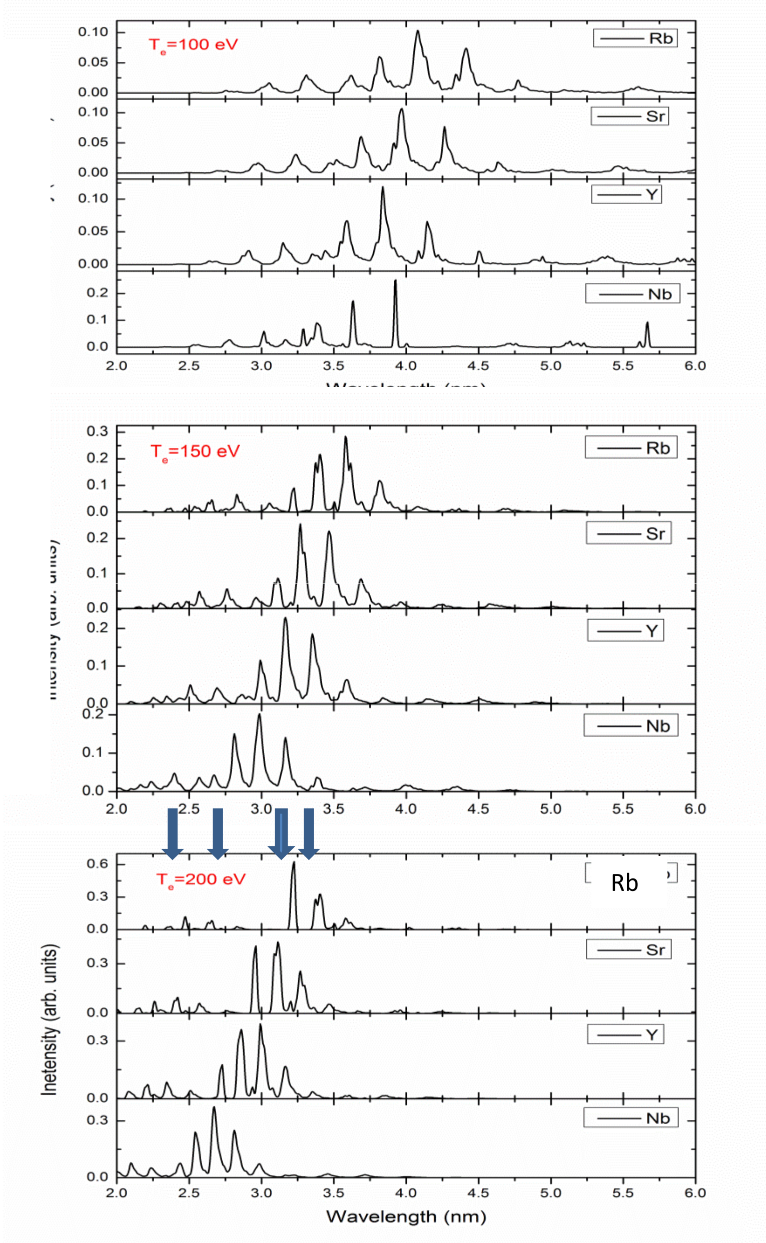
T_e of 50-60 eV required.

CE~0.28% @ 6.88 nm in Ge

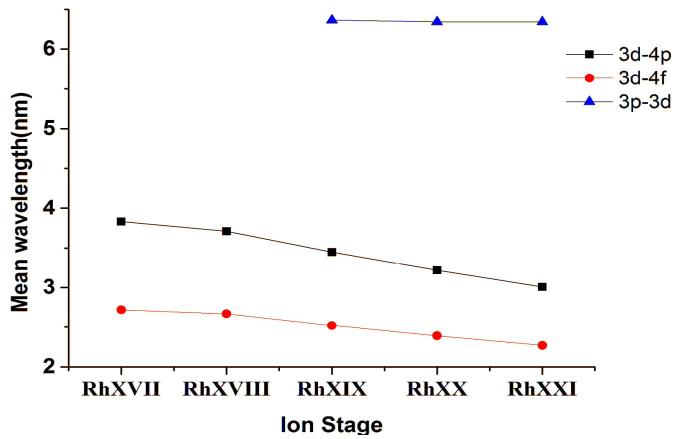
Calculations for 3rd Row Transition Elements

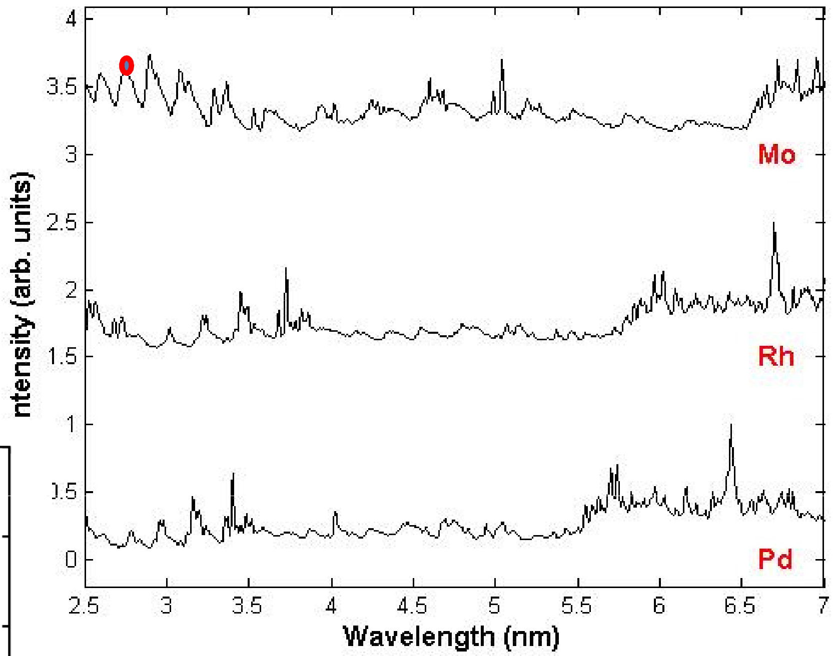


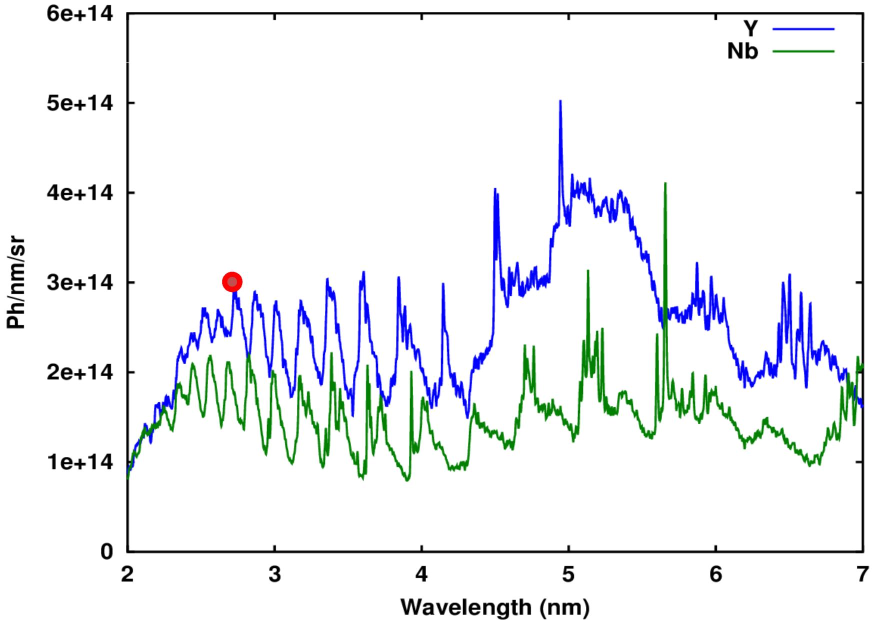
Calculated 3d-4f transitions of Rb (black), Sr (green), Y (blue) and Nb (red).

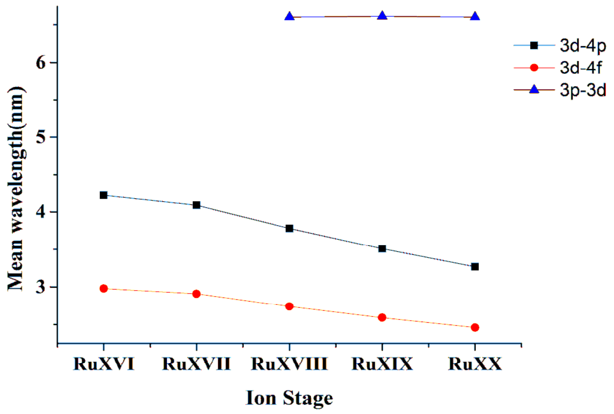


Observations for 3rd Row Transition Elements

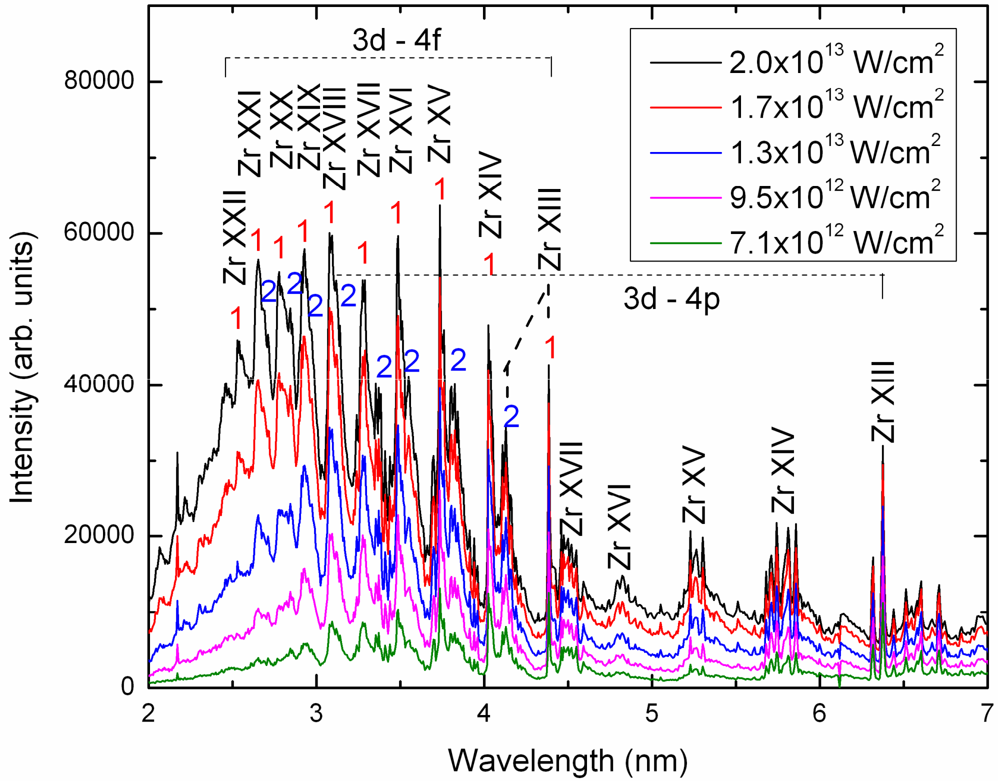








Variation of emission with laser Intensity

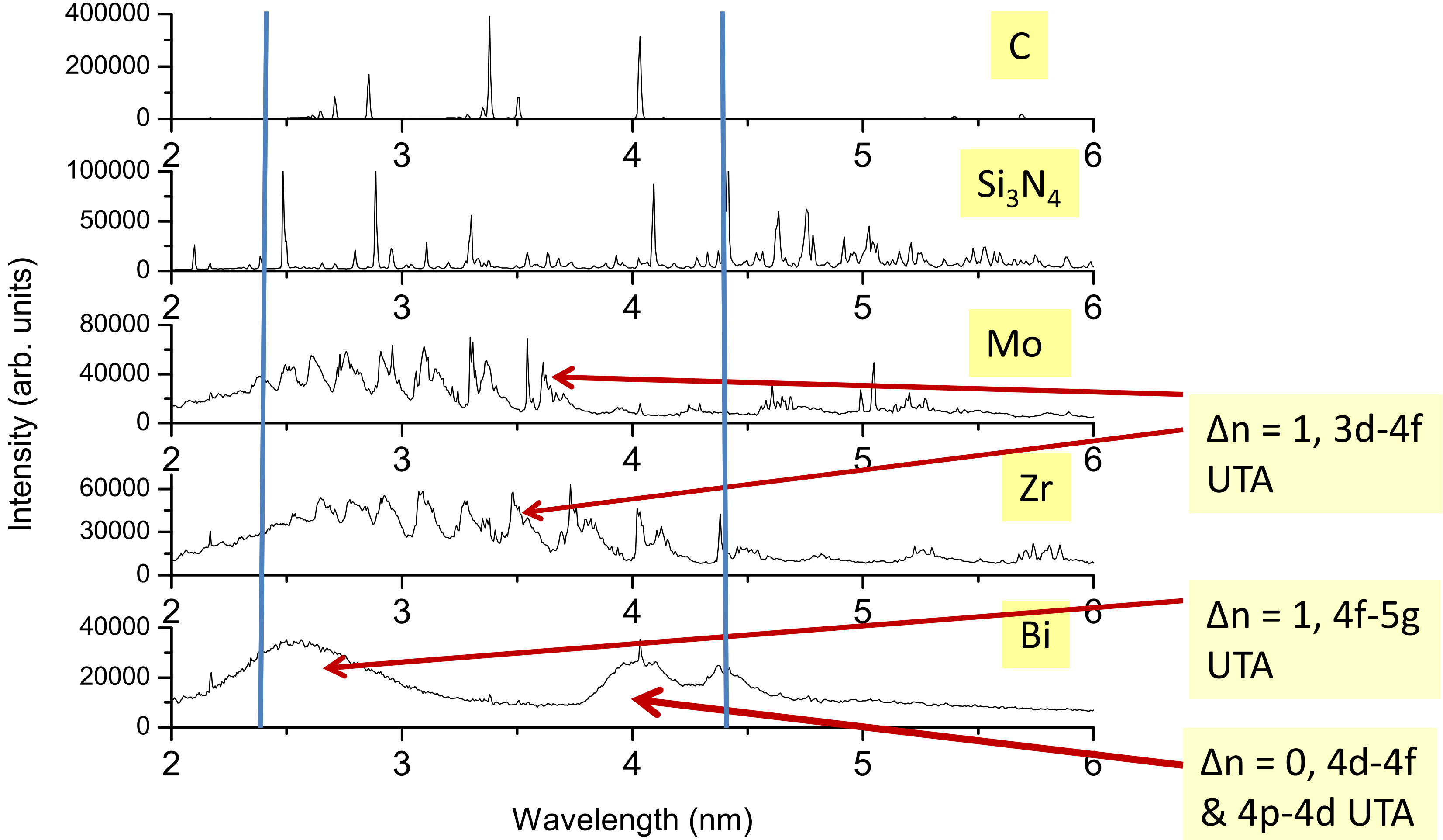


Δn = 1 3d-4f and 3d-4p UTA emission from Zr

Spectral behavior of Zr plasmas as a function of laser laser intensity

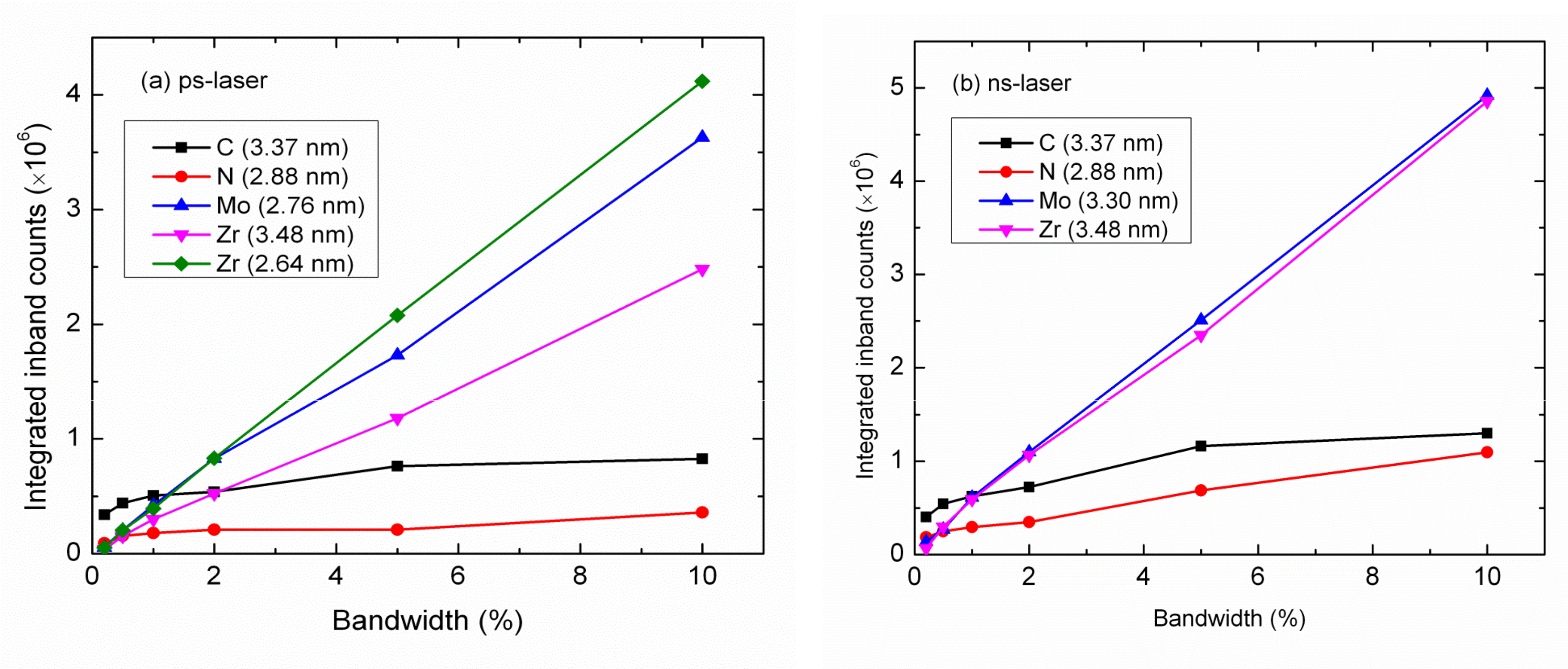
Resonant 3*d*–4*f* (1) and 3*d*–4*p* transitions as well as satellite lines from $3d^{n-1}4s4f$–$3d^{n-2}4s4f$ (2)

Comparison of Water Window Emission Spectra



Time-integrated spectra from picosecond-laser-produced plasmas

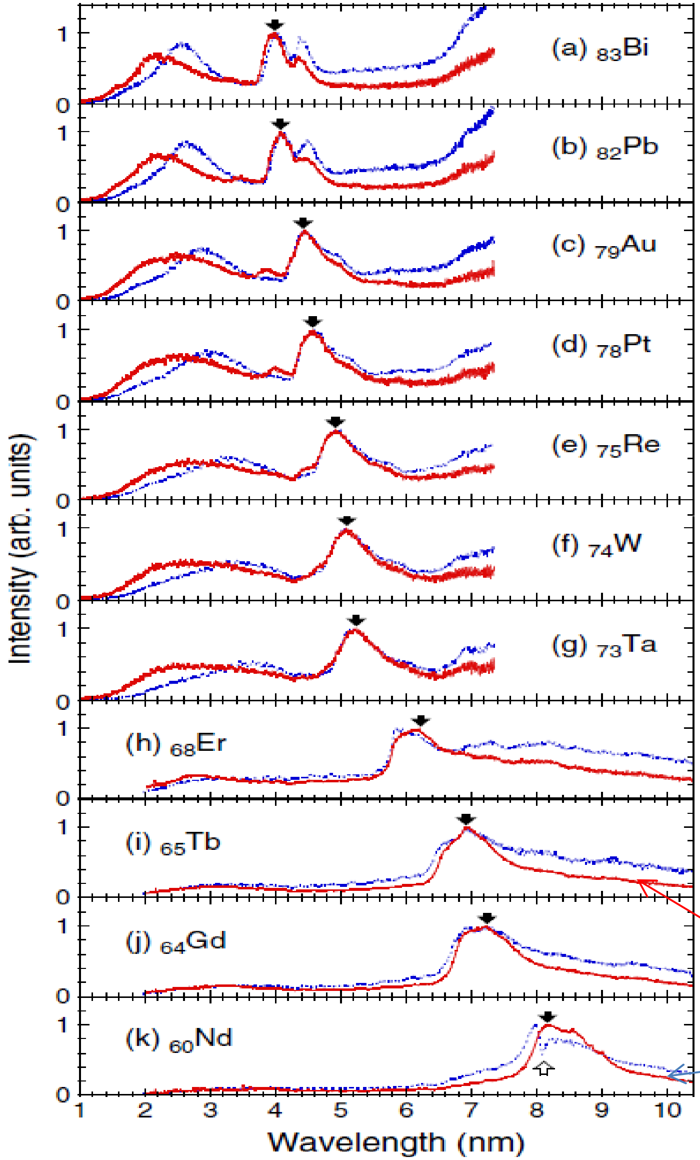
Effect of mirror bandwidth

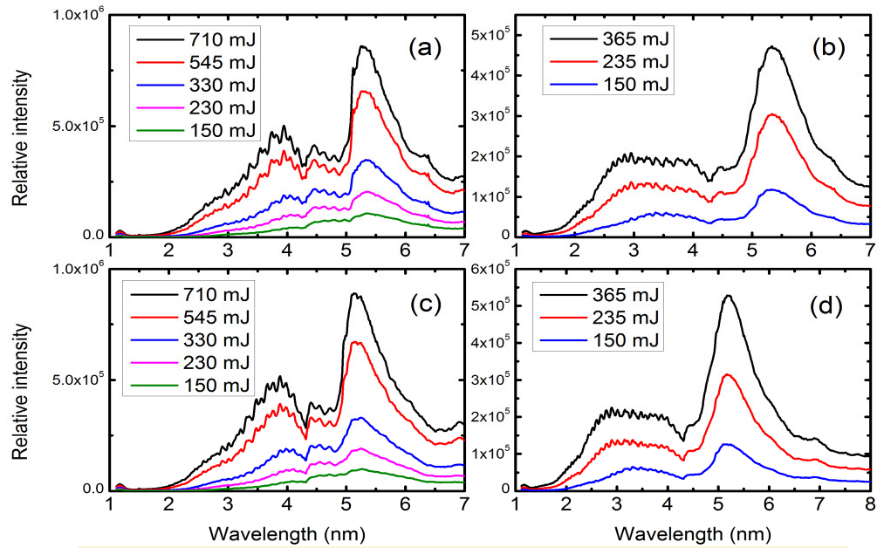


Integrated in-band counts against bandwidth (0.5%, 1%, 2%, 5% and 10%) for ps (a) and ns (b) laser.

Line sources win at bandwidths < 1%

4th Transition Row Elements





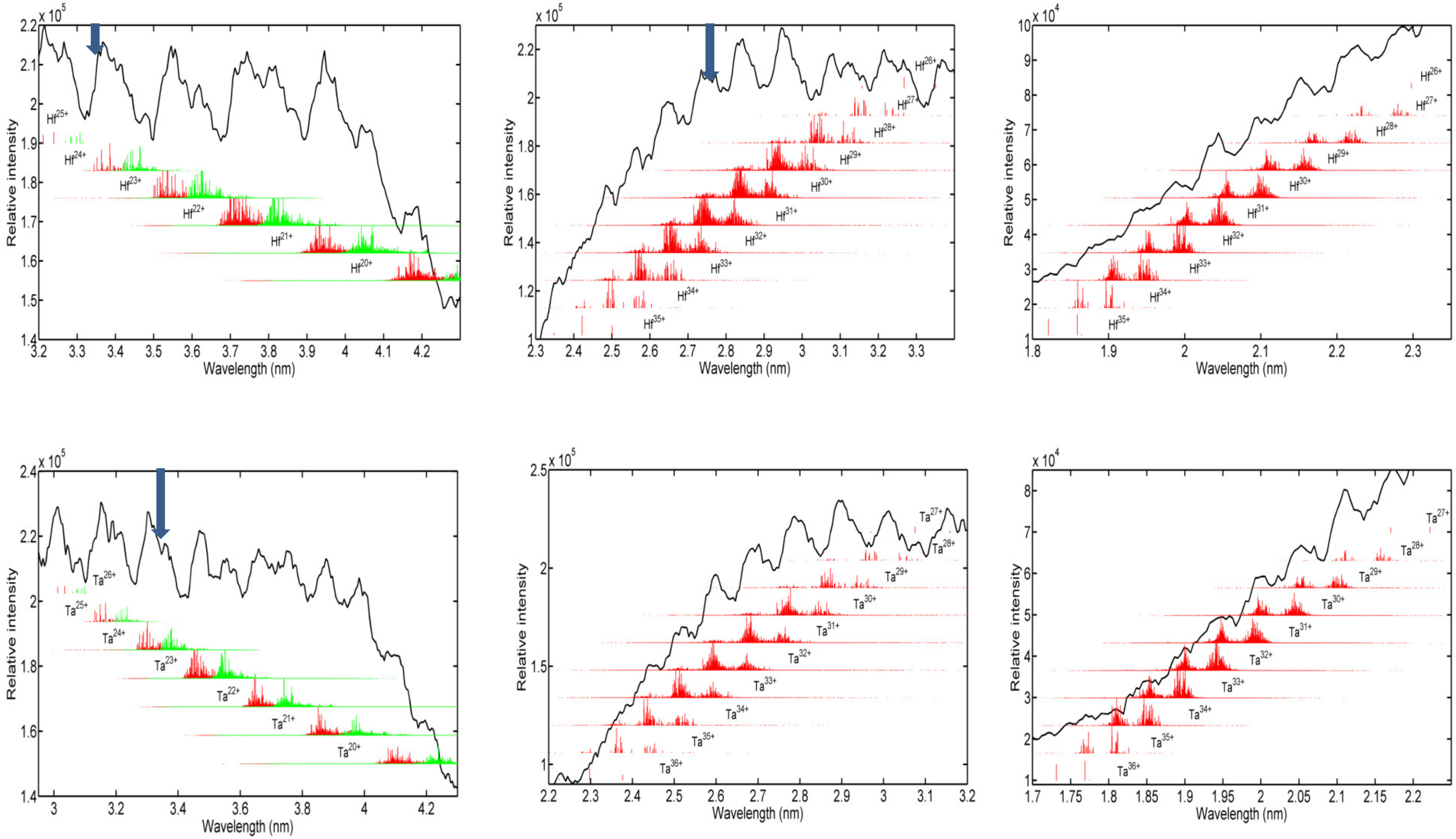
Spectra of HF and Ta for Nd:YAG LPPs with 10 ns (a) and 170 ps (b) laser pulse durations
Focal spot diameter ~50 µm.

ps Spectra

ns Spectra

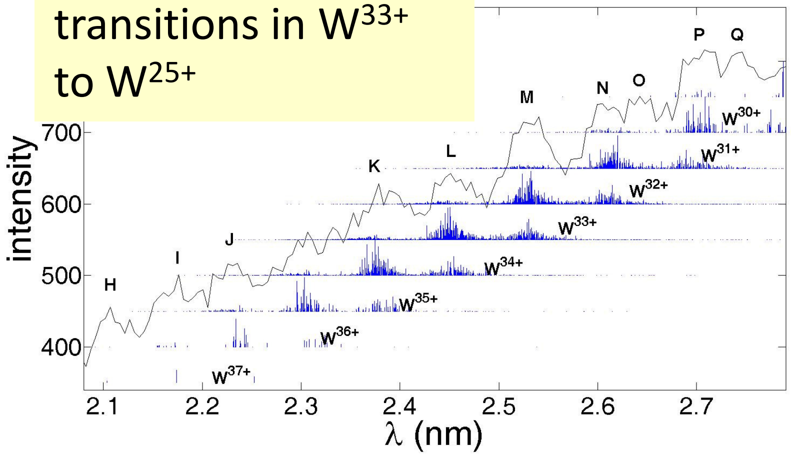
Ohashi *et al* APL 104, 234107 (2014)

4f-5g, 4d-5p and 4d-5f UTAs in Hf and Ta

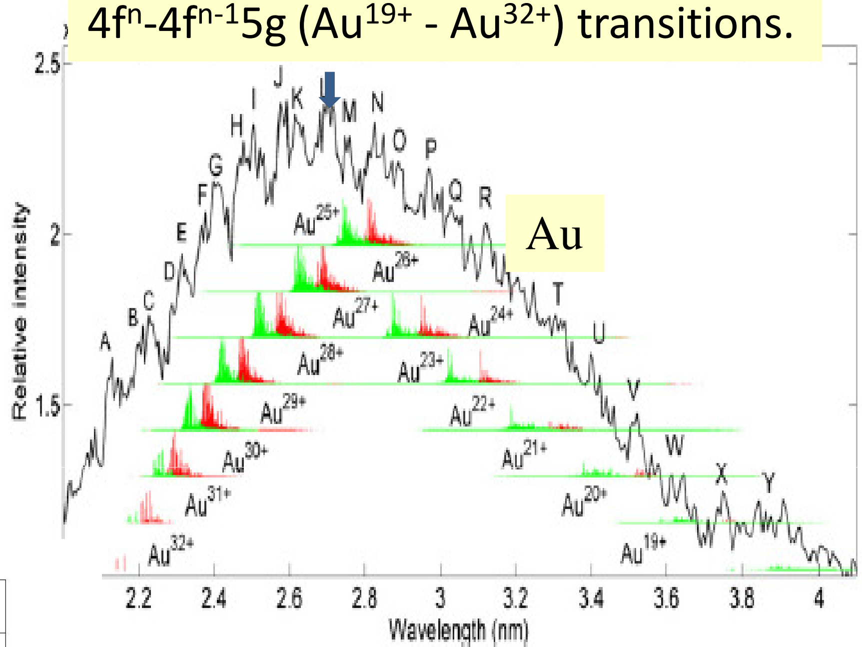


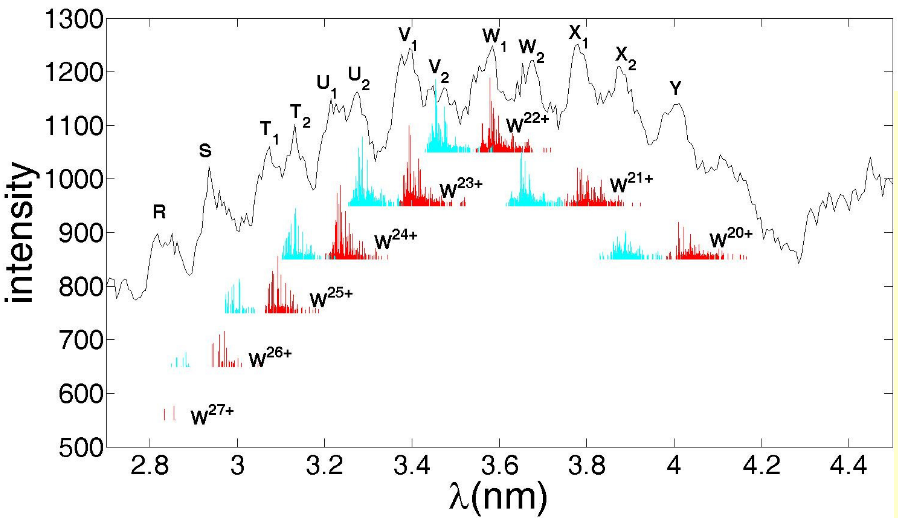
Δn=1 UTA in W and Au

4d^{n} - 4d^{n-1}5p transitions in W^{33+} to W^{25+}



4f^{n}-4f^{n-1}5g (Au^{19+} - Au^{32+}) transitions.





4f^{n} - 4f^{n-1}5g transitions for W^{20+} - W^{27+} ions (red). Also included are the satellite 4f^{n-1}5s - 4f^{n-2}5s5g transitions for W^{20+} - W^{26+} (cyan).

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- $\Delta n= 1$UTA
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  - 3rd transition row (n=4-n=5)
- Conclusions

Conclusions

Optimum sources for the water window at specific wavelengths matching MLM reflectivity remain to be identified.

Atomic data are essential for source identification.

Need for spectral wavelength and **intensity** data for a large range of elements

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