Towards Shorter Wavelength EUV and Soft X-ray Sources

Gerry O'Sullivan, Deirdre Kilbane, Thomas Cummins, Rebekah D'Arcy, Tony Donnelly, Akira Endo*, Colm Harte, Takeshi Higashiguchi**, Imam Kambali, Mahmoad Mahmoad, Colm O'Gorman, Fergal O'Reilly, Takamitsu Osuka**, Enda Scally, Emma Sokell , John White and Padraig Dunne .

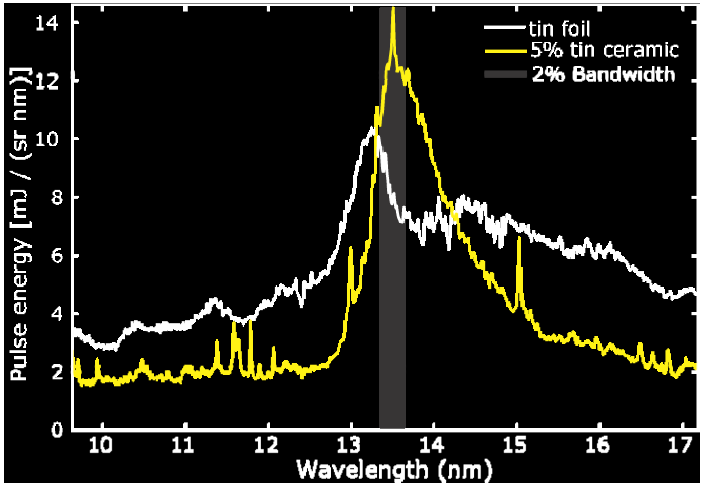
School of Physics, University College Dublin, Belfield, Dublin 4, Ireland.
*Forschungszentrum Dresden, Bautzner Landstrs. 400, D-01328, Dresden, Germany.
**Centre for Optical Research and Education, Utsunomiya University, Yato 7-1-2, Utsunomiya, Tochigi 321-8585, Japan.

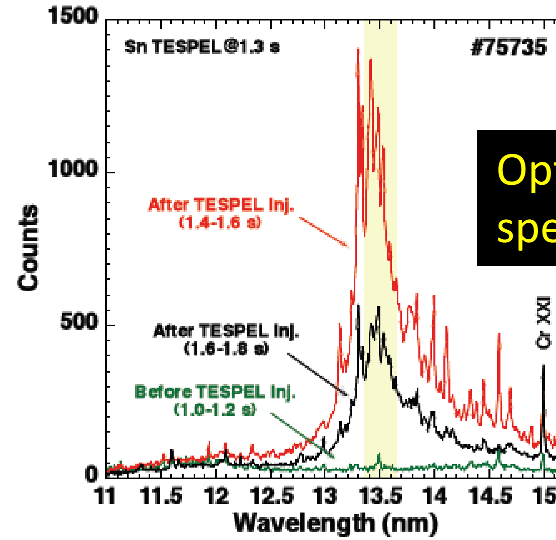
2010 International Workshop on EUV Sources, UCD, Nov. 14th 2010

Outline

- Background (Sn and Xe)
- Results at high Z (W) and implications for other elements
- Recent work on Gd and Tb sources for 6.7 nm
- Other potential sources

Sn is the brightest source at 13.5 nm



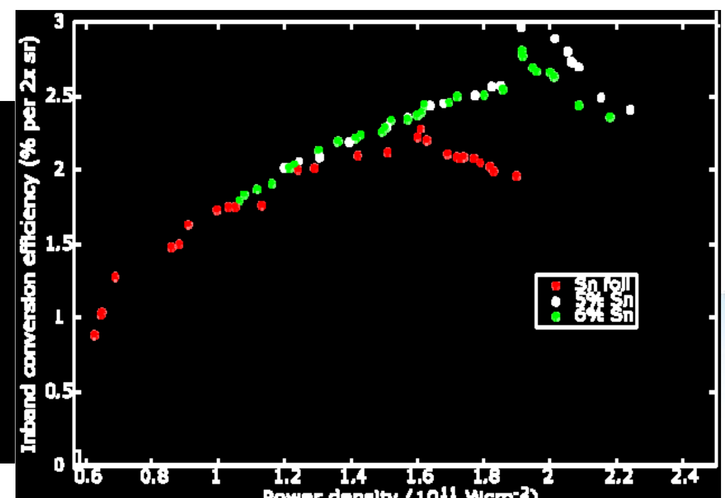


Optically thin spectrum (NIFS)

Because of opacity, the UTA narrows and increases in intensity with decreasing tin concentration (up to ~2%).

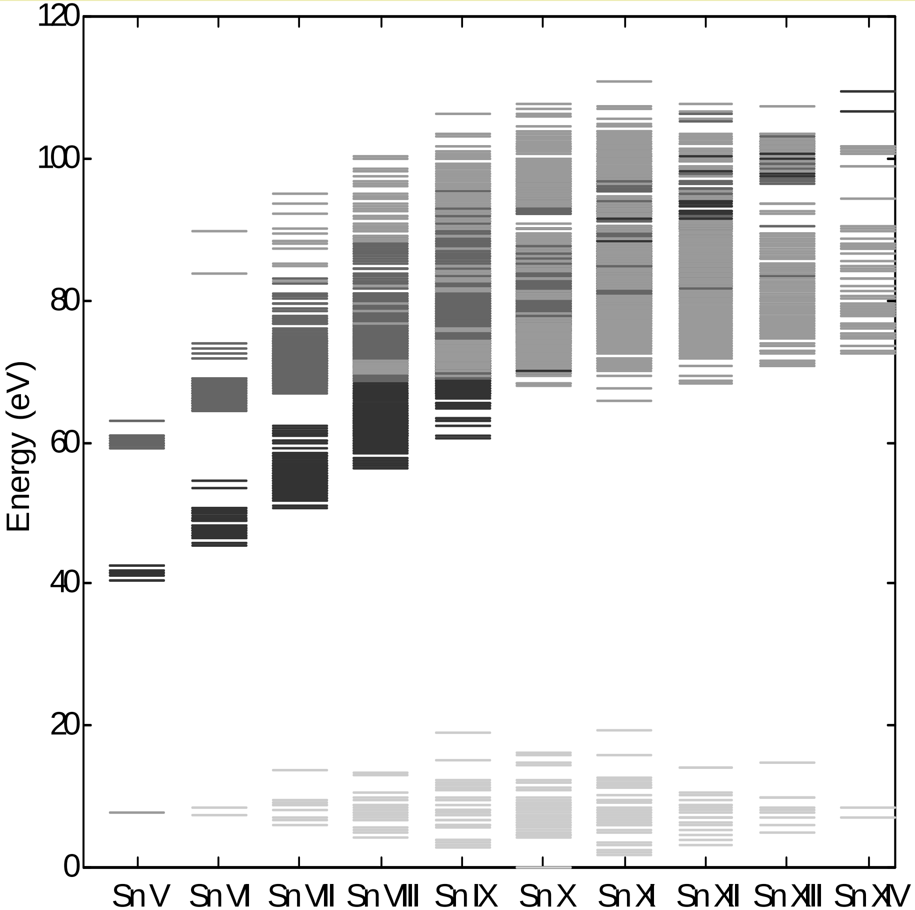
As concentration decreases out-of-band emission decreases.

Max inband conversion efficiency
~ 2.3% per 2π sr for 100% Sn
at $\phi \approx 1.6 \times 10^{11}$ Wcm^{-2}
~ 2.9% per 2π sr for 5% tin
at $\phi \approx 2 \times 10^{11}$ Wcm^{-2}



Origin of the Sn UTA

Levels of $4p^6 4d^n$ & $(4p^5 4d^{n+1} + 4d^{n-1} 4f + 4d^{n-1} 5p)$
Calculated with Cowan suite of codes

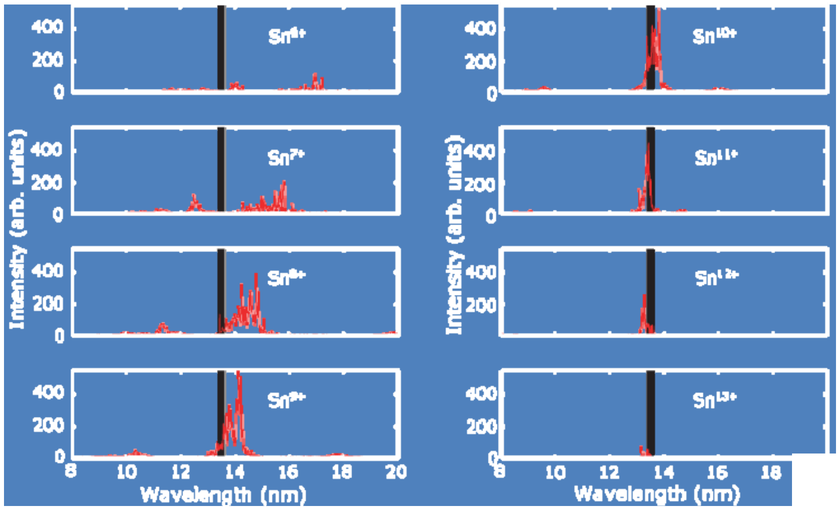


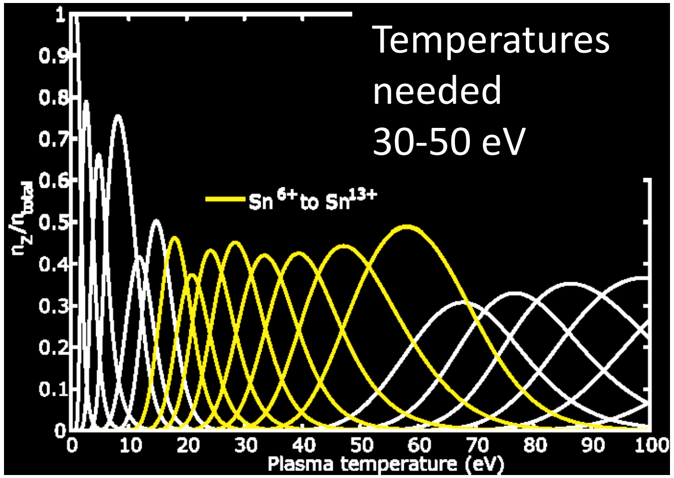
The Sn UTA is due to $4p^6 4d^n \rightarrow (4p^5 4d^{n+1} + 4d^{n-1} 4f + 4d^{n-1} 5p)$ $(0 \leq n \leq 9)$ transitions. CI (configuration interaction) causes transitions in successive ion stages to partially overlap in energy.

(O'Sullivan and Faulkner Opt. Eng. 33, 3978-3983 (1994), Koike et al J. Elec. Spec. Relat. Phen. 144, 1227 (2005))

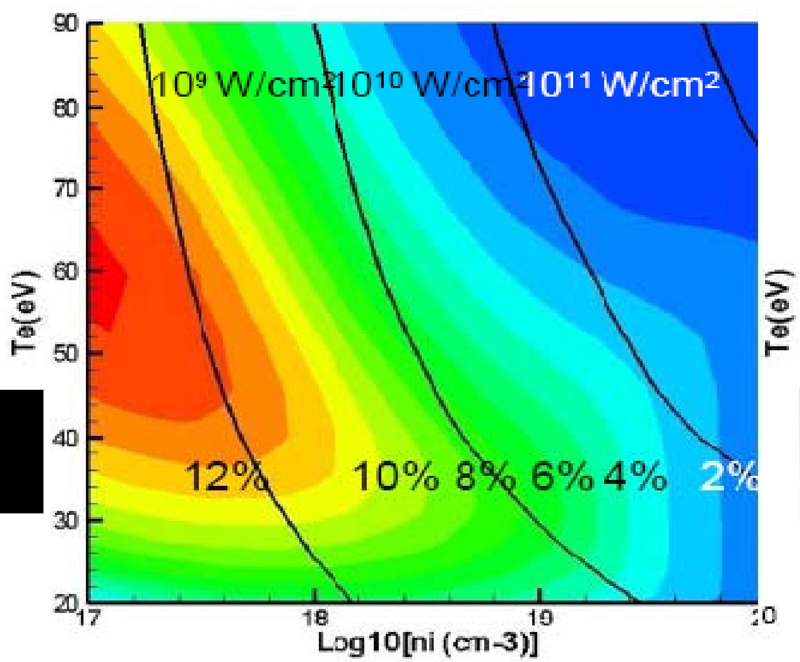
CI effects also cause a spectral narrowing, so the individual arrays have widths of ~ 5eV.

Sn^{5+}–Sn^{13+} emit $4p^6 4d^n \rightarrow 4d^{n-1}4f + 4p^5 4d^{n+1}$ UTA, Sn^{10+}–Sn^{13+} near 13.5 nm



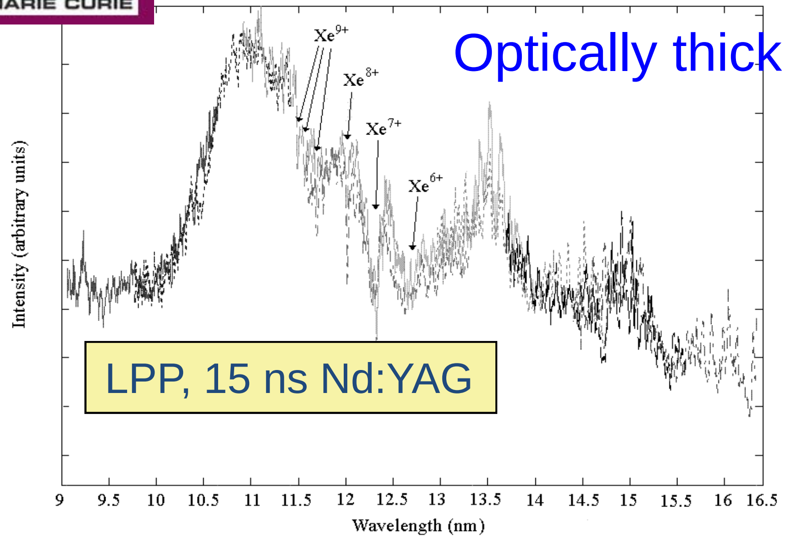


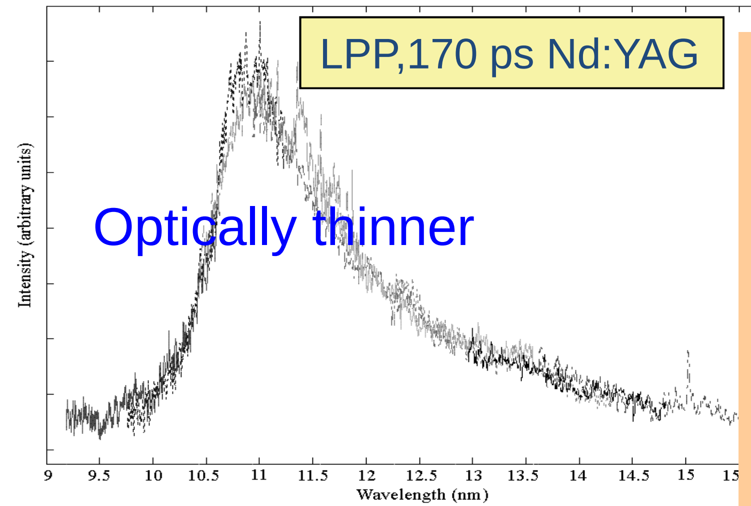
Configuration Interaction effects are very important *(Koike et al 2005 J. Elec. Spe. Relat. Phen. 144, 1227, O'Sullivan and Faulkner 1994 Opt. Eng. 33, 3978)*

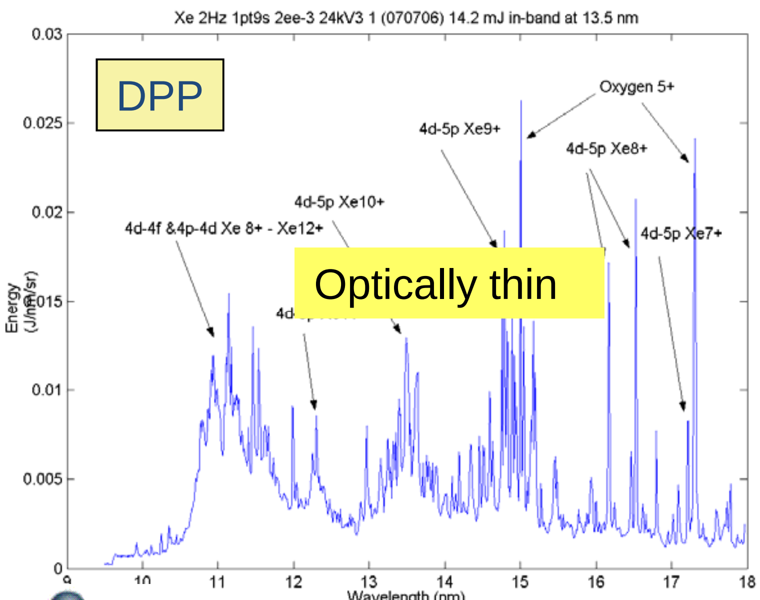


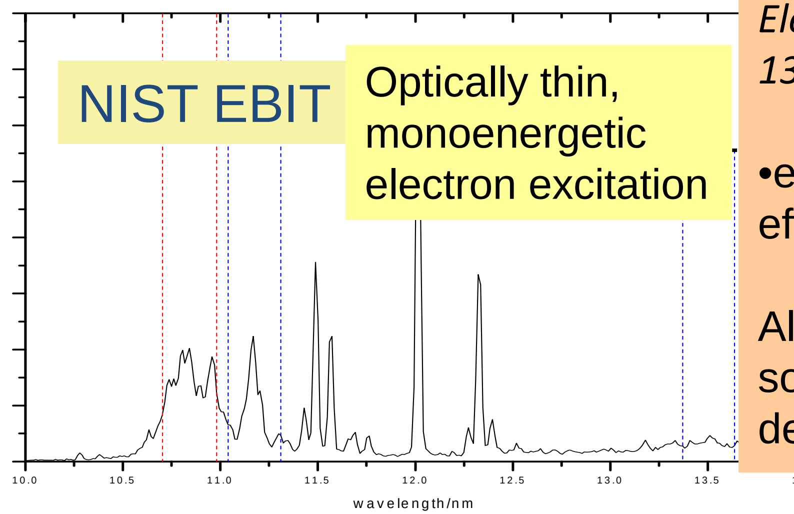
Optimum plasma conditions
(Nishihara et al 2008)

Experimental Spectra of Xenon; Source Dependence:









Spectral shape modified by
•density effects: opacity, satellite lines *(Sasaki et al. IEEE Journal of Quant. Electron.10, 1307 2004)*

•excitation effects

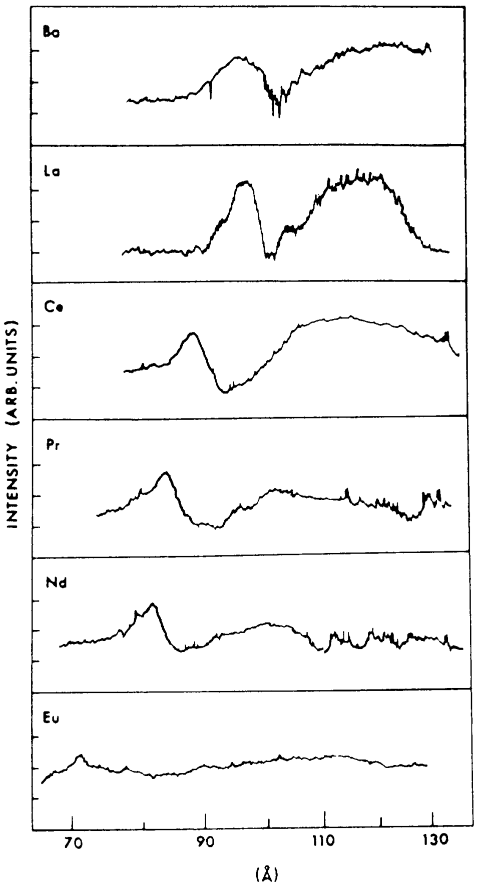
All are source dependent

K. Fahy et al. J. Phys. D **37** 3225-3232 (2004)

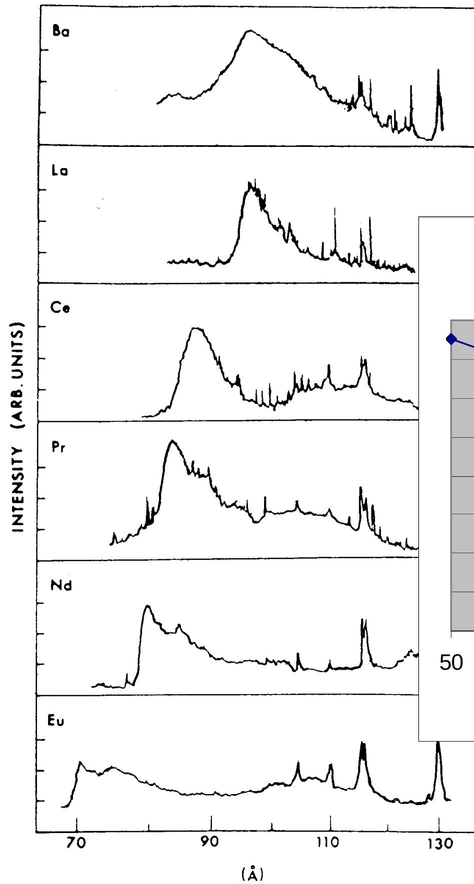
Spectra from plasmas of elements with Z > 50

Spectra from elements with Z > 50 contain lines and an intense UTA due to $4p^64d^n$ - $4p^54d^{n+1}$+$4d^{n-1}4f$ ($0 \le n \le 9$) transitions. The effects of CI are to cause a transitions in successive ion stages to overlap in energy.

The degree of overlap improves with Z up to Z = 62.

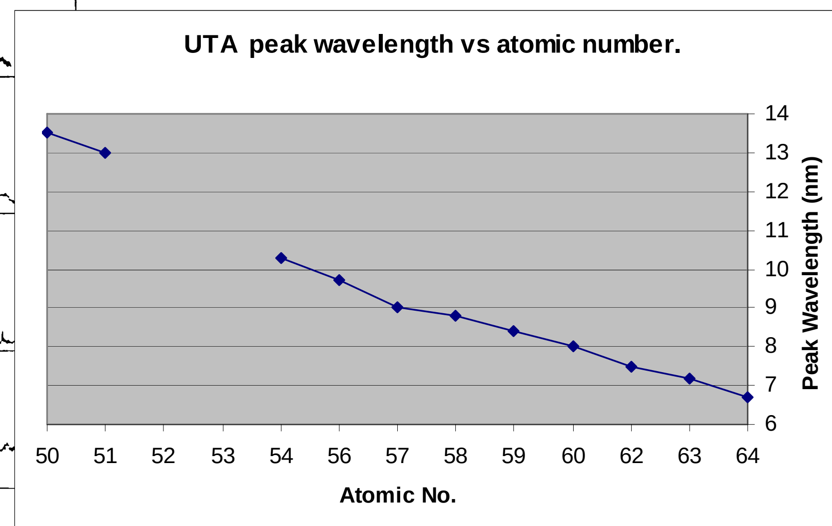


Metal Targets



Salt Targets

(Carroll and O'Sullivan PRA25, 275 1982)



Shorter wavelength sources

IOP Publishing — Physica Scripta
Phys. Scr. **80** (2009) 045303 (6pp) — doi:10.1088/0031-8949/80/04/045303

EUV spectra of Gd and Tb ions excited in laser-produced and vacuum spark plasmas

S S Churilov[1], R R Kildiyarova, A N Ryabtsev and S V Sadovsky

Establishment of the Russian Academy of Sciences Institute of Spectroscopy RAS, Troitsk, Moscow region 142190, Russia

E-mail: ryabtsev@isan.troitsk.ru

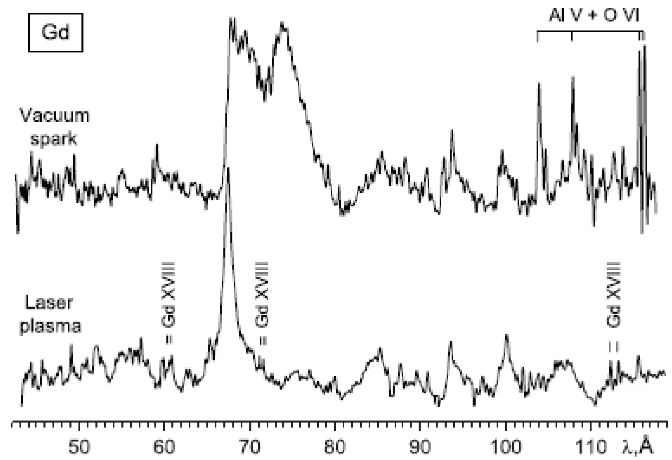


Figure 1. Spectra of gadolinium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace).

Interest in sources at 6.7 nm due to availability of Mo/B4C multilayer mirrors with a reflectivity of 40%

APPLIED PHYSICS LETTERS 97, 111503 (2010)

Rare-earth plasma extreme ultraviolet sources at 6.5–6.7 nm

Takamitsu Otsuka,[1,a)] Deirdre Kilbane,[2] John White,[2] Takeshi Higashiguchi,[1,b)] Noboru Yugami,[1] Toyohiko Yatagai,[1] Weihua Jiang,[3] Akira Endo,[4] Padraig Dunne,[2] and Gerry O'Sullivan[2]

[1]*Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585, Japan*
[2]*School of Physics, University College Dublin, Belfield, Dublin 4, Ireland*
[3]*Department of Electrical Engineering, Nagaoka University of Technology, Kami-tomiokamachi 1603-1, Nagaoka, Niigata 940-2188, Japan*
[4]*Forschungszentrum Dresden, Bautzner Landstrs. 400, D-01328 Dresden, Germany*

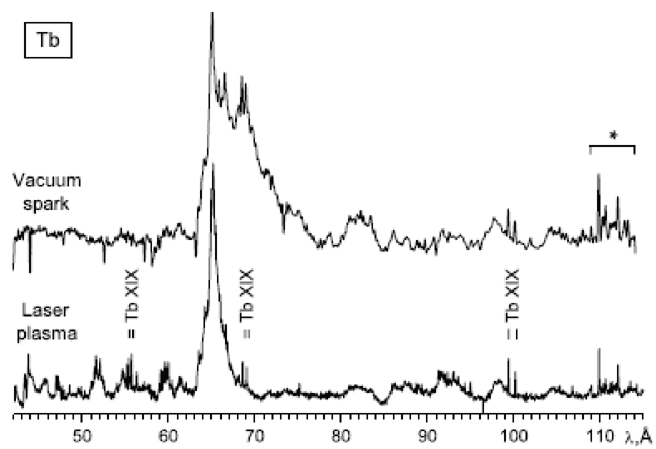


Figure 2. Spectra of terbium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace). ∗, $4f^2$–$4f5d$ transition array in Tb XVIII classified in the present work.

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Most Important Stages?

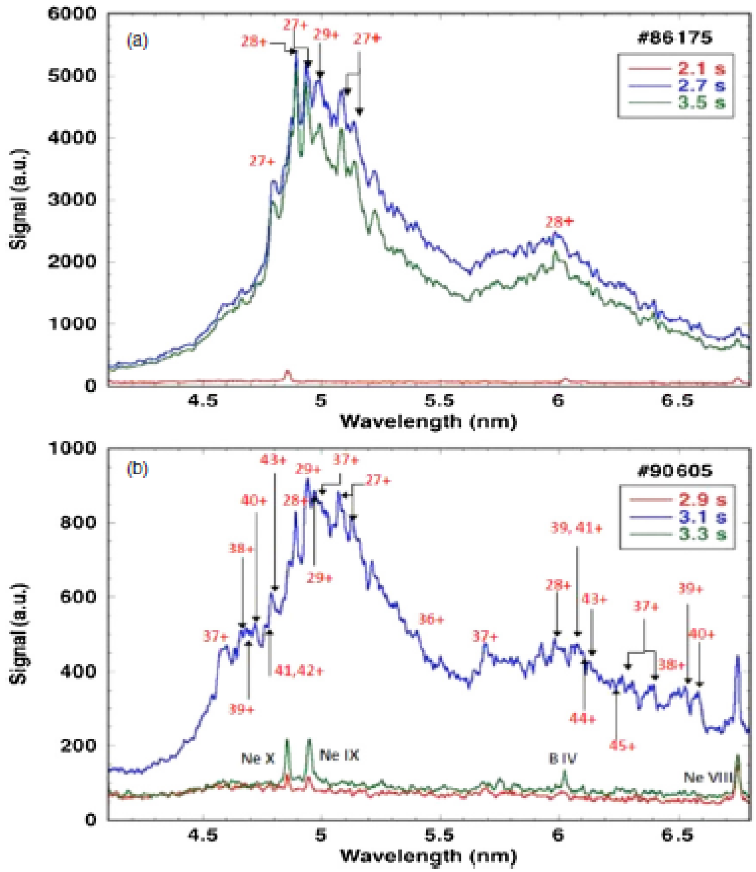
IOP Publishing — Journal of Physics B: Atomic, Molecular and Optical Physics
J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 205004 (14pp) doi:10.1088/0953-4075/43/20/205004

Tungsten spectra recorded at the LHD and comparison with calculations

C S Harte[1], C Suzuki[2], T Kato[2], H A Sakaue[2], D Kato[2], K Sato[2], N Tamura[2], S Sudo[2], R D'Arcy[1], E Sokell[1], J White[1] and G O'Sullivan[1]

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

E-mail: colm.s.harte@ucd.ie

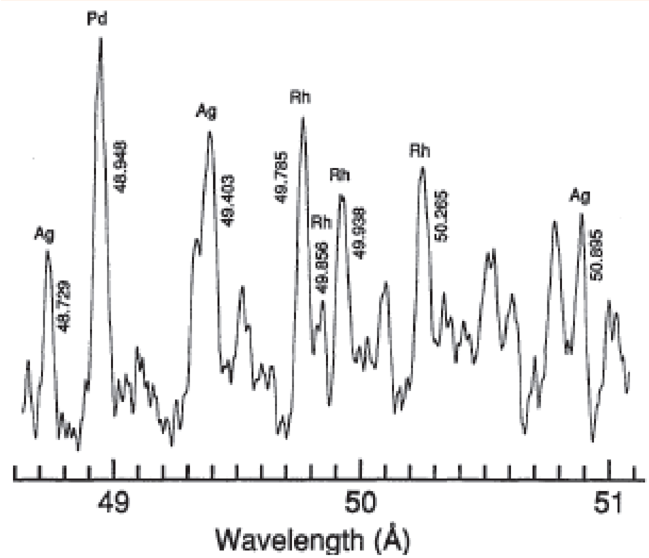


The most important transitions can be inferred from studies of W spectra.

They occur in Ag-like, Pd-like and Rh- like W^{27+}- W^{30+}. *Sugar et al JOSA 10, 1321 (1993)*

Gd XVIII-XX, Tb XIX - XXI

i.e. Ions with $4d^{10}4f$, $4d^{10}$ and $4d^{9}$ ground states



Ag–like and Pd–like lines

Physica Scripta. Vol 26, 419–421, 1982

Resonance Lines in the Pd I Isoelectronic Sequence: I VIII to Ho XXII

J. Sugar and V. Kaufman

Physica Scripta. Vol. 24, 742–746, 1981.

Ag I Isoelectronic Sequence: Wavelengths and Energy Levels for Ce XII through Ho XXI and for W XXVIII

J. Sugar and V. Kaufman

Laser:
3 J in 20 ns
$\lambda = 1.06\ \mu m$
$\Phi = (5\text{–}8)\times10^{11}\ Wcm^{-2}$

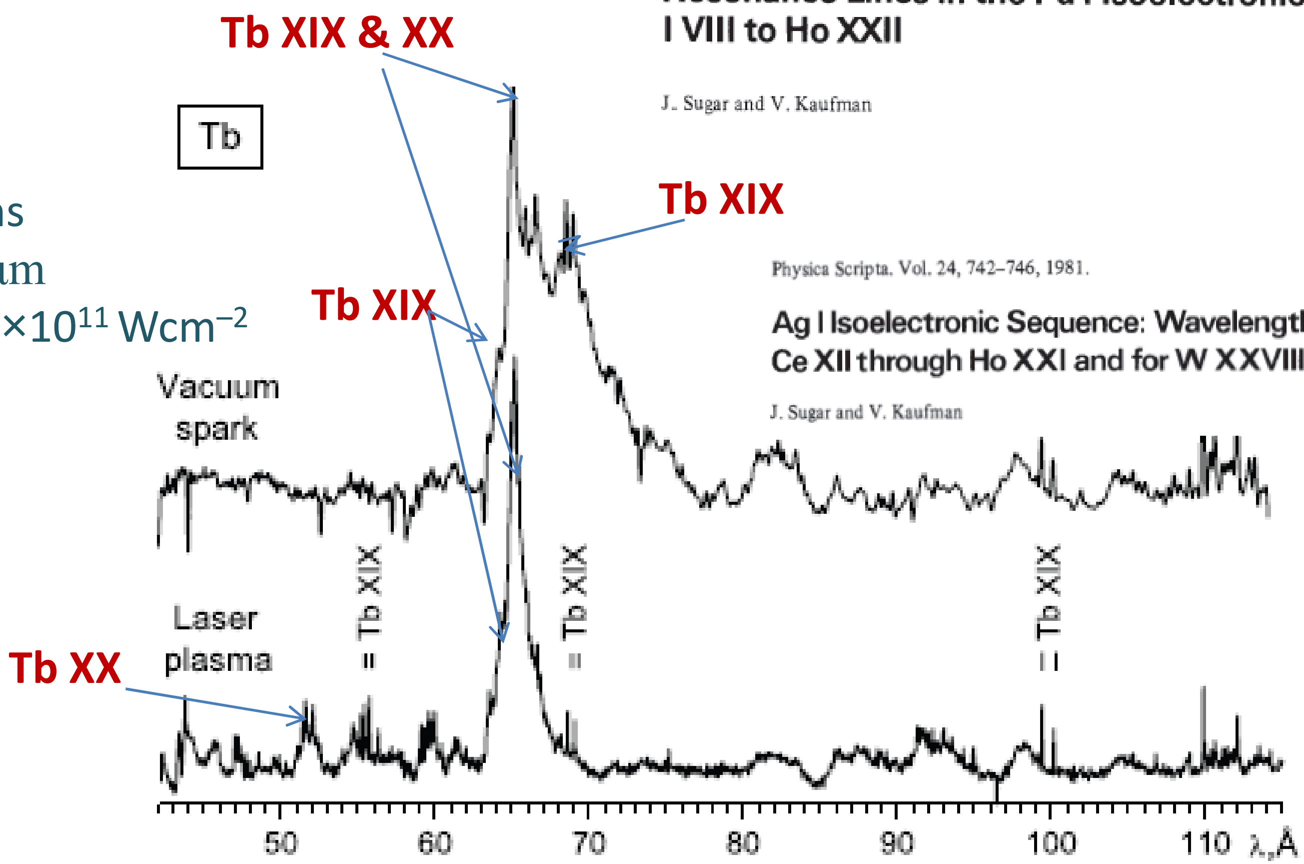
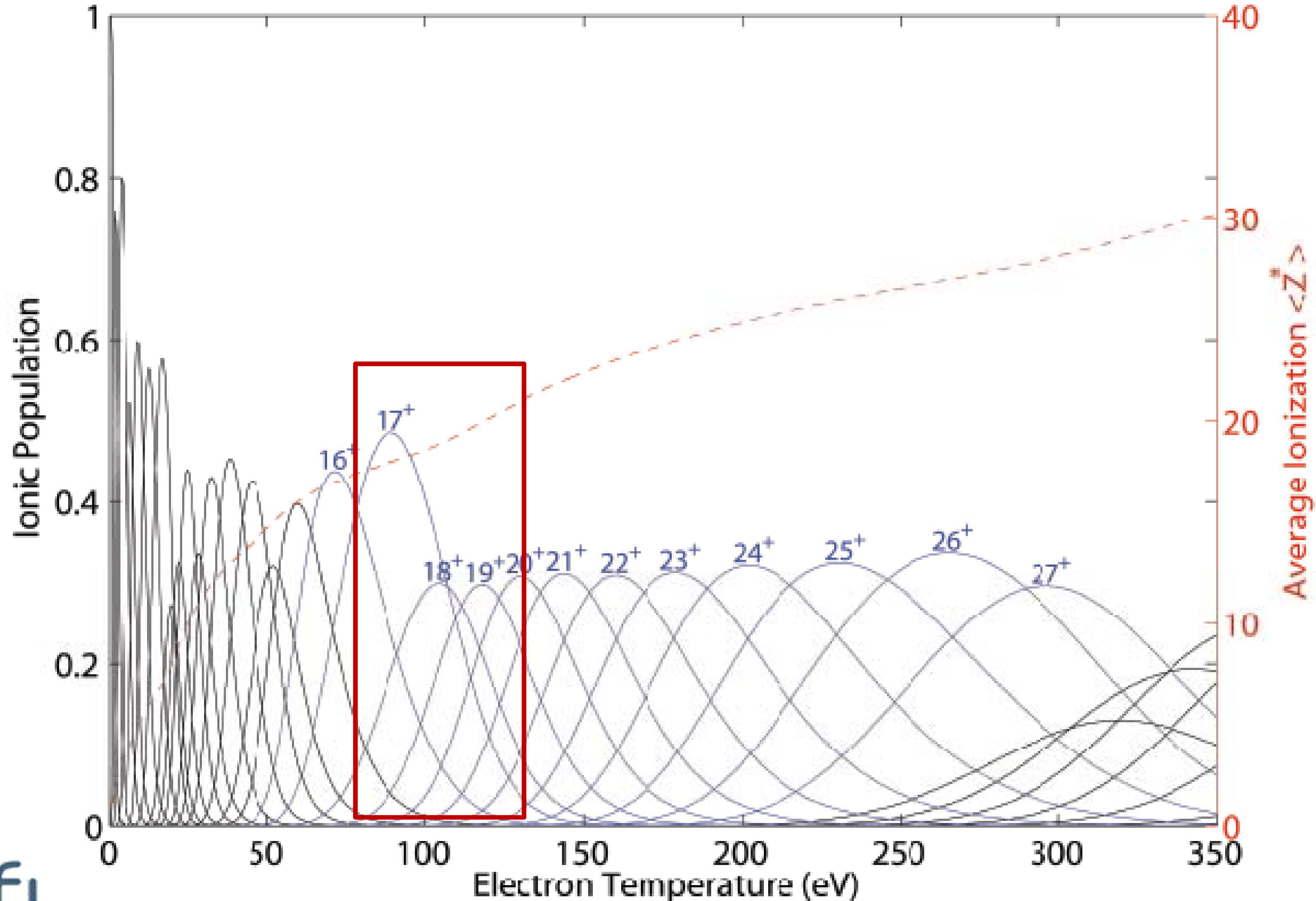


Figure 2. Spectra of terbium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace). ∗, $4f^2$–$4f5d$ transition array in Tb XVIII classified in the present work.

Ion populations and average ionization of a Gd plasma as a function of T_e computed with the CR model.



Power Density Requirements

The laser power density required lies in the range

$2\times10^{12} - 10^{13}$ Wcm^{-2} @λ =1.06 μm

$10^{11} - 10^{12}$ Wcm^{-2} @λ =10.6 μm

Next Step: Calculations for emission from different ions

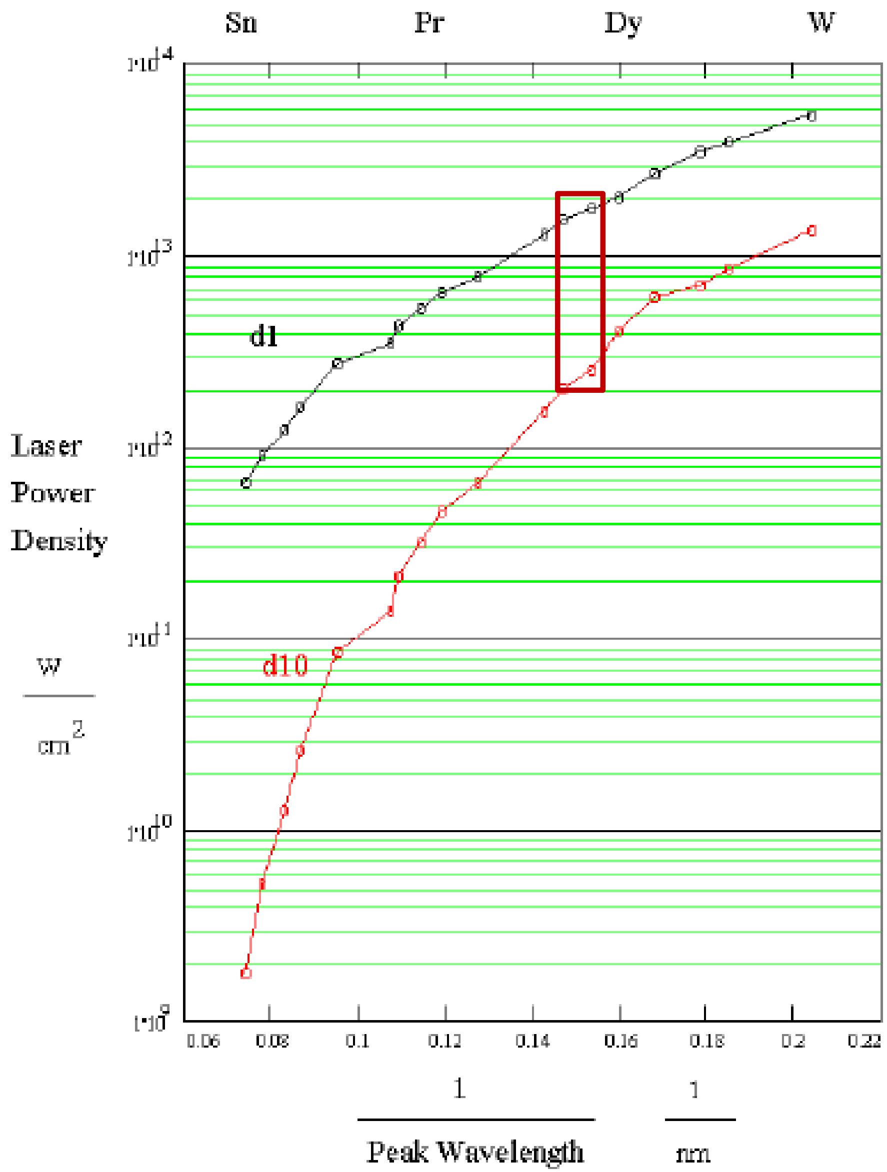


Fig. 5a: Approx. laser power density required for the RbI and PdI like isoelectronic sequences

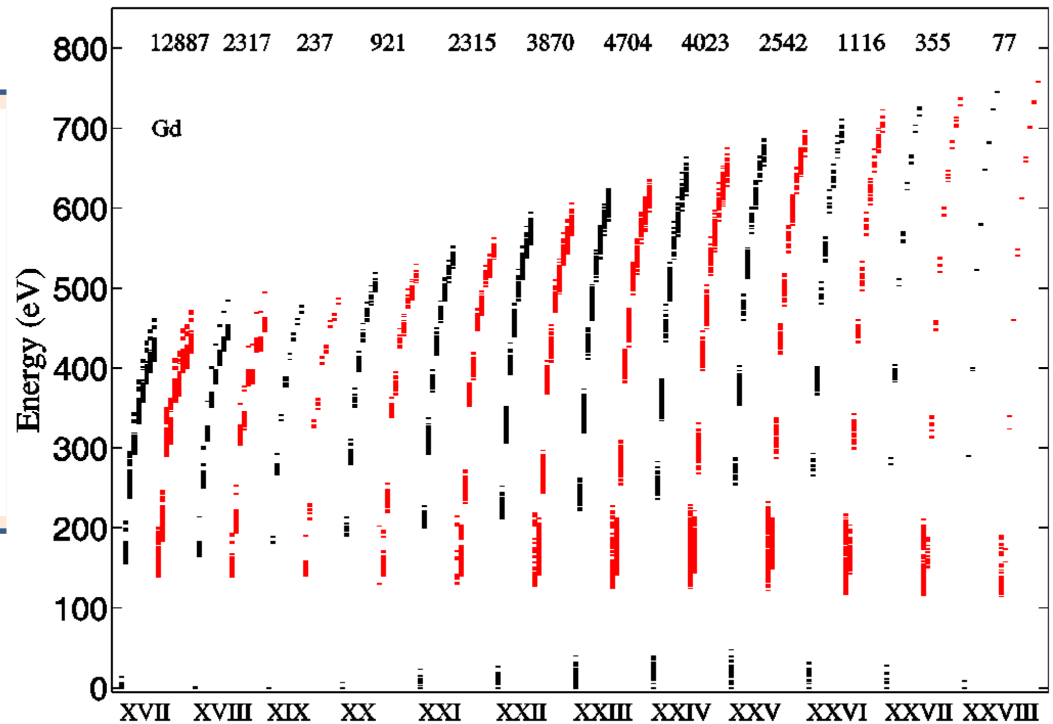
Calculations for Gd and Tb

Singly excited configurations of Gd and Tb ions included in the calculations

Gd XVII - Gd XVIII	Gd XIX	Gd XX - Gd XXVIII
Tb XVIII - Tb XIX	Tb XX	Tb XXI - Tb XXIX
$4p^6 4d^{10} 4f^M$	$4p^6 4d^{10}$	$4p^6 4d^N$
$4p^6 4d^9 4f^{M+1}$	$4p^6 4d^9 nl$	$4p^6 4d^{N-1} nl$
$4p^6 4d^9 4f^M nl$		$4p^5 4d^{N+1}$
$(n \leq 8, l \leq 3, M \leq 2)$	$(1 \leq N \leq 10)$	

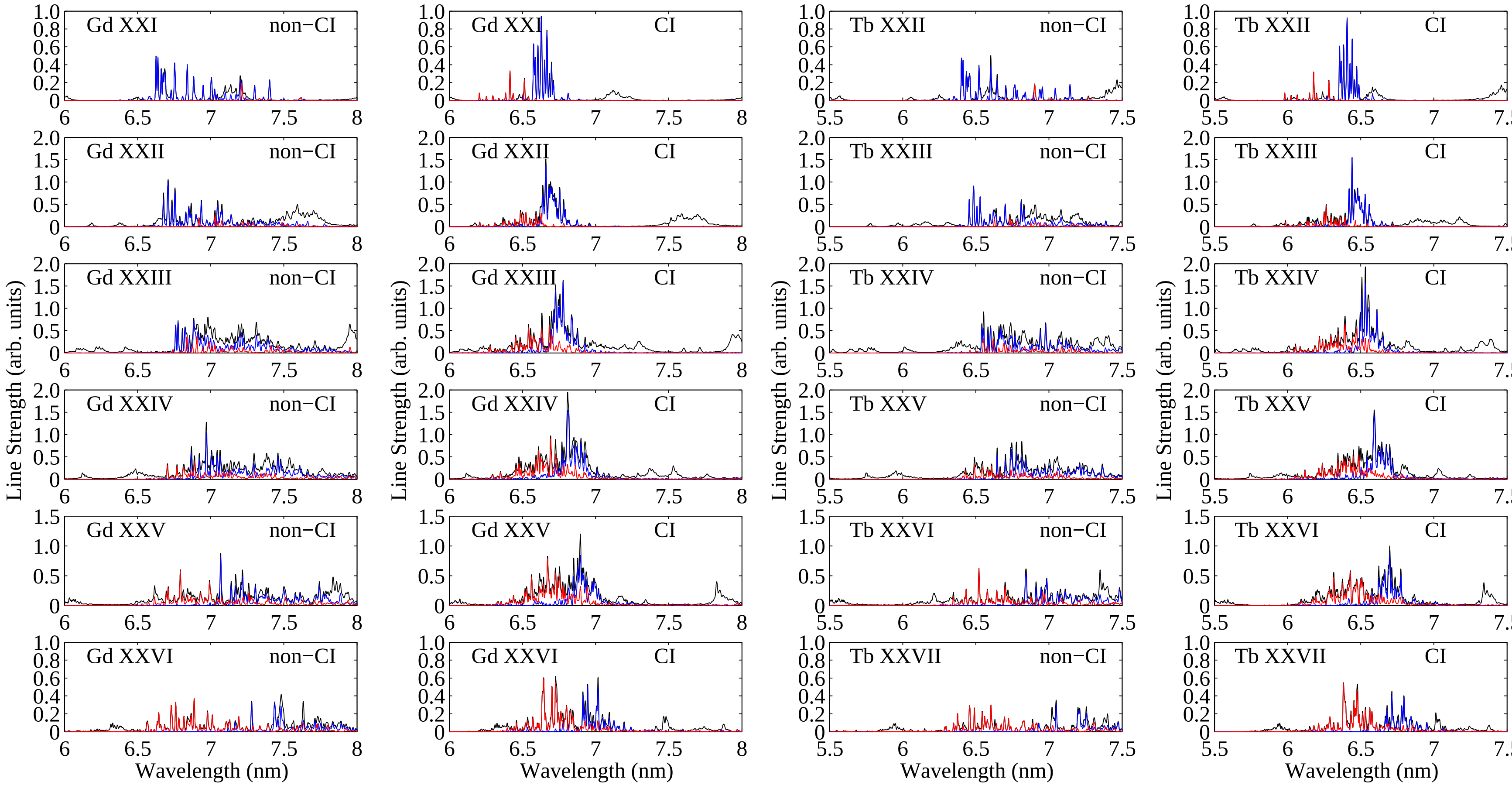
Problem, low ion stages contain open 4f (and 5p) subshells, difficult to calculate.

(Kilbane and O'Sullivan JAP in press)



Energy levels of Gd^{16+} - Gd^{27+} computed with the FAC code including CI. The number of states of each ion is shown at the top.

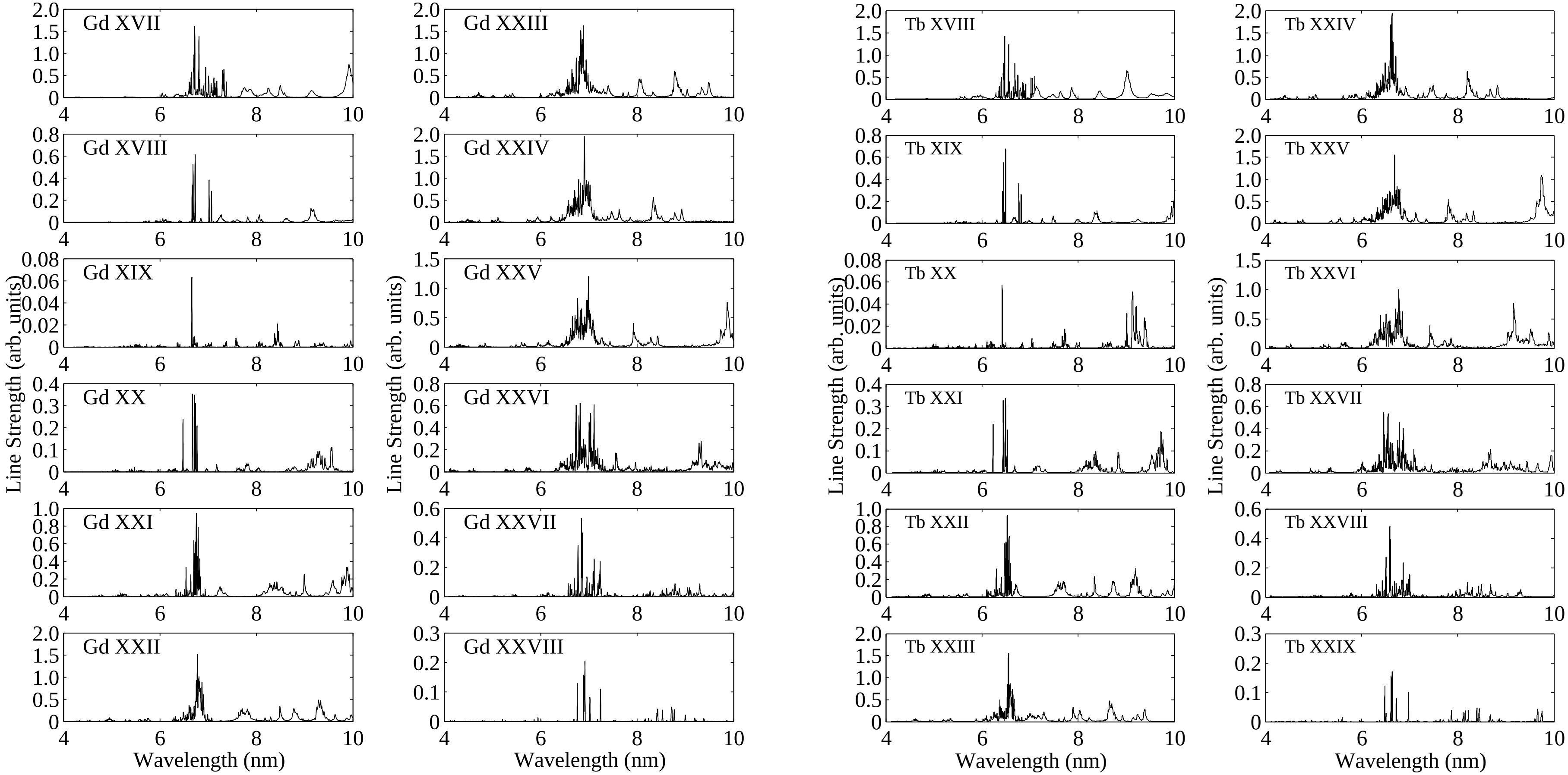
Effects of CI in Gd and Tb Spectra



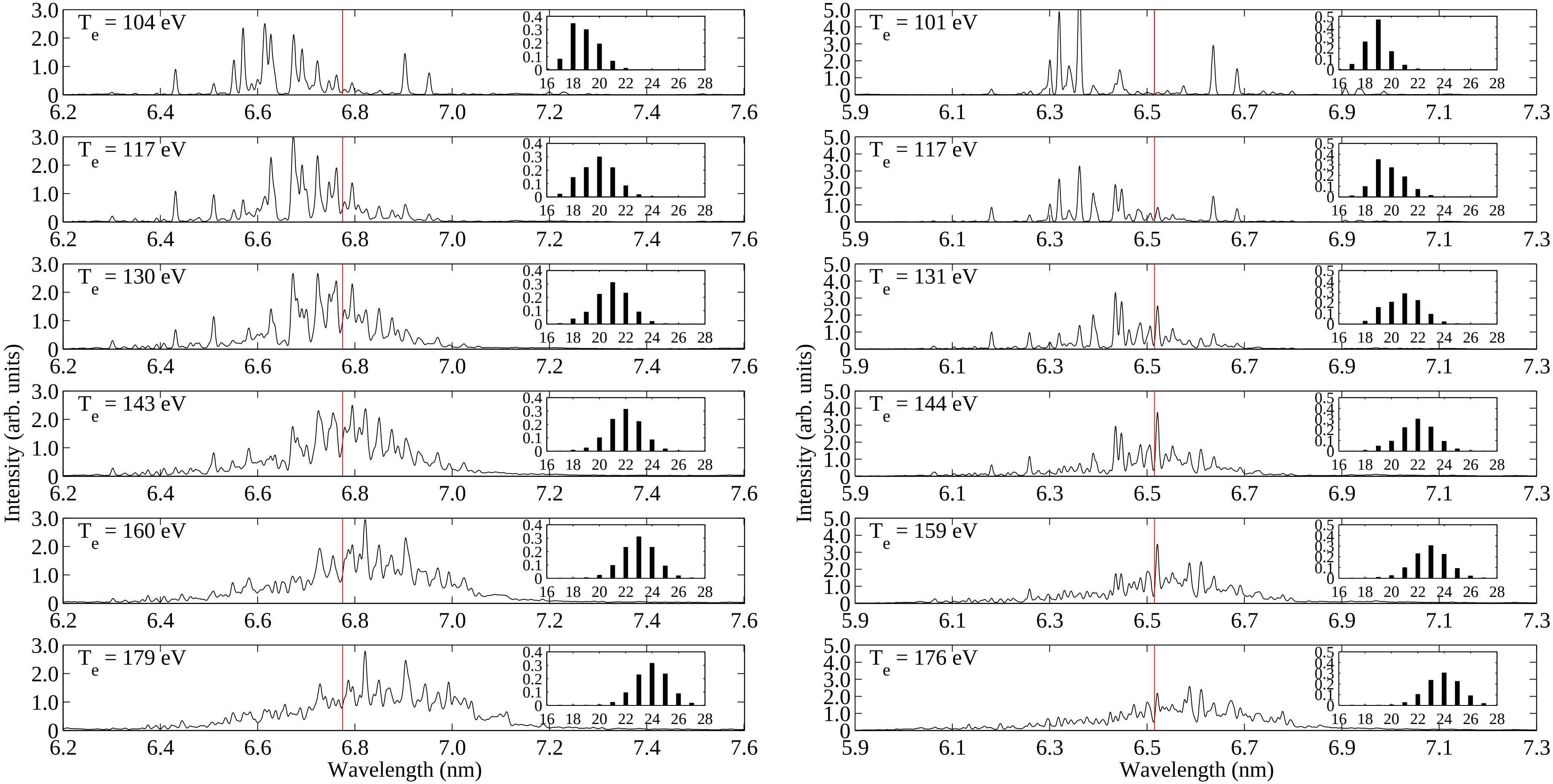
Gd^{20+} - Gd^{25+}, and Tb^{21+} - Tb^{26+}, spectra excluding CI (left) and including (right). 4d -4f (blue), 4p -4d (red) and all transitions (black)

CI not as effective at spectral narrowing in highest stages

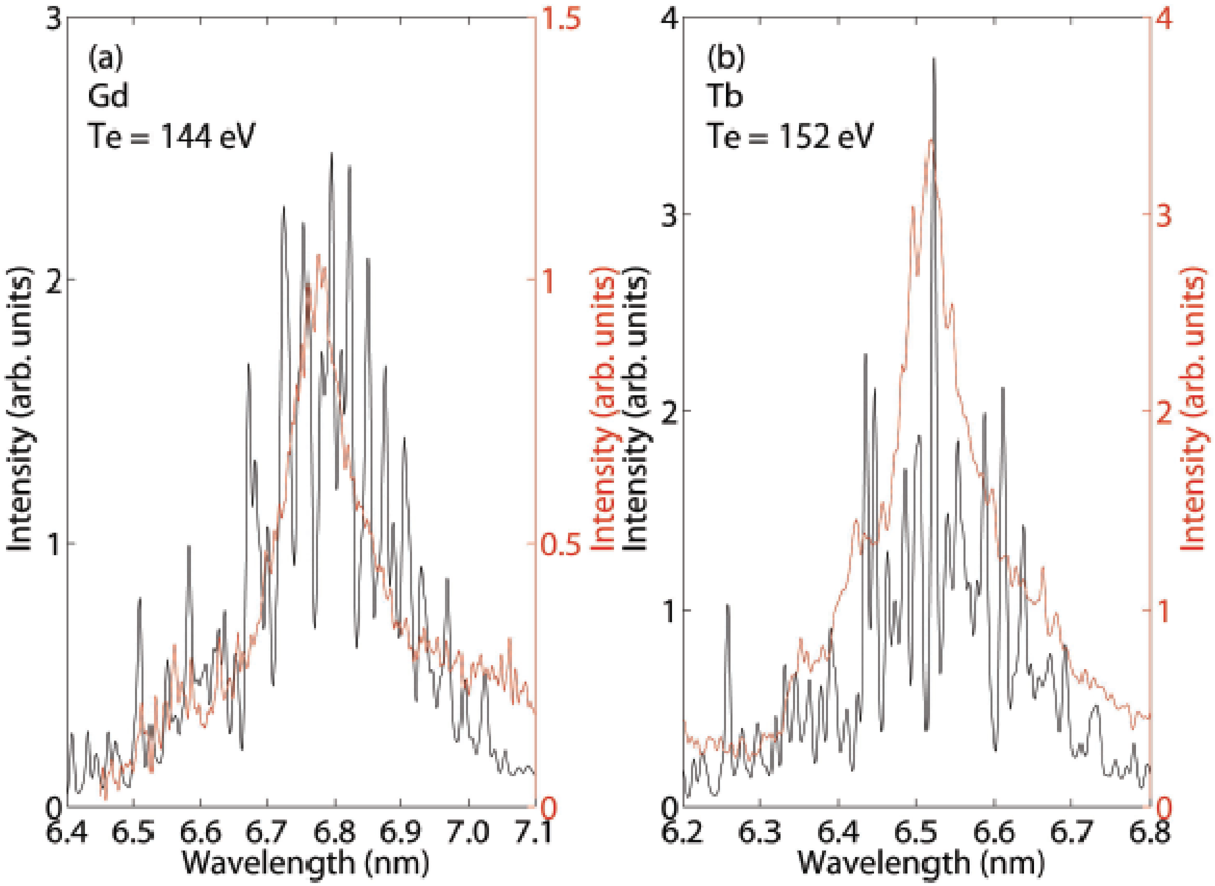
Line Strengths of Gd^{16+} - Gd^{27+} and Tb^{17+} - Tb^{28+} including CI



Emission of Gd and Tb at various electron temperatures T_e



Theoretical and experimental (Churilov et al) Gd and Tb spectra



Other results will be discussed in:

Rare-earth Plasma Extreme Ultraviolet Sources at 6.5-6.7 nm for Next Generation Semiconductor Lithography (P6)

Takeshi Higashiguchi, Utsunomiya University

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Δn = 0, n= 4 UTA in other elements

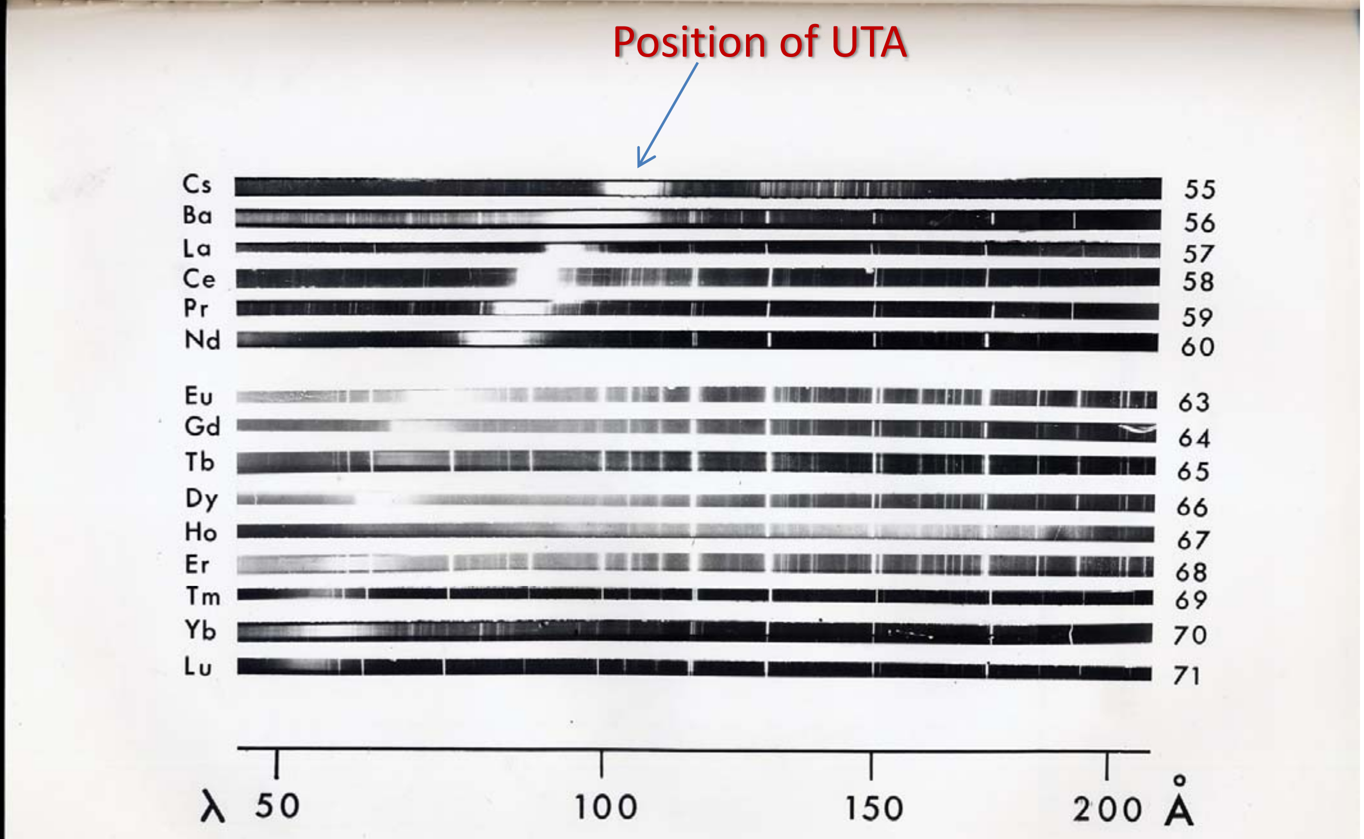


Fig. 5.2 Emission Spectra from Targets of Salts of the Elements from Cesium to Lutetium.

Impurity lines are O V, O VI

At low concentration get high spectral purity and low opacity

a: Metal Target
b: Salt Target

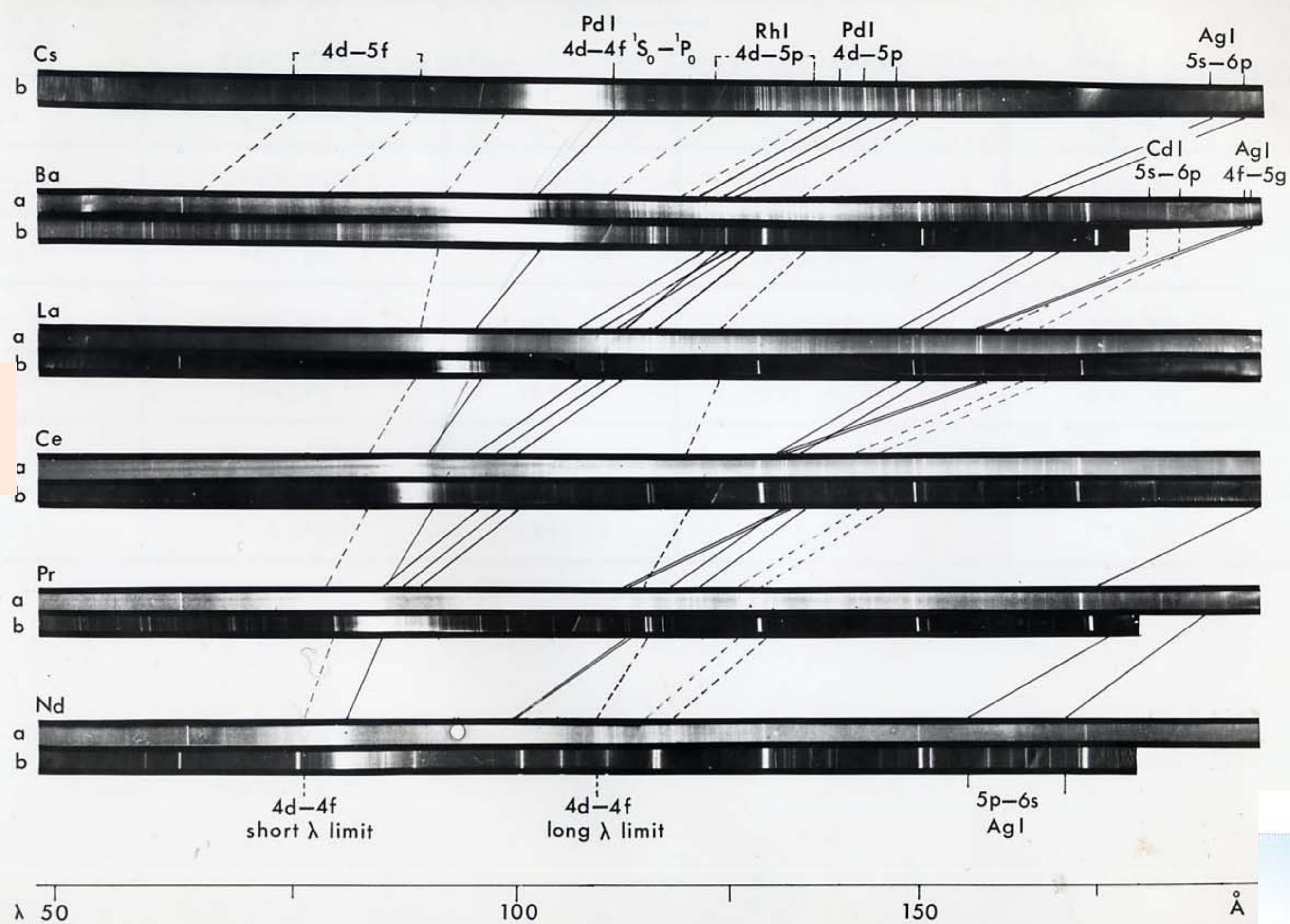


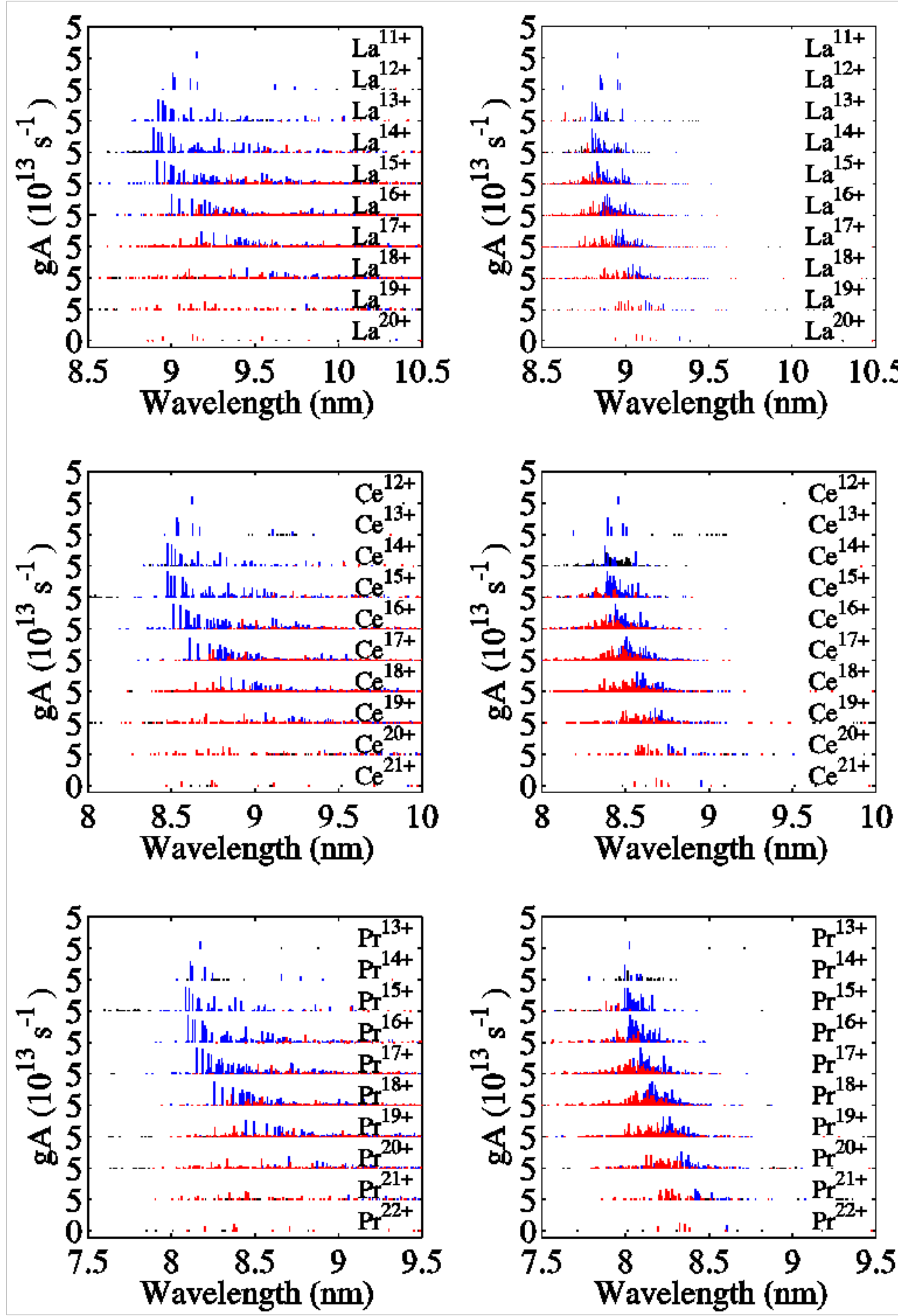
Fig. 5.4 Emission Spectra of the elements from Cs to Nd. (a) refers to Metallic
(b) refers to Salt Spe

Ground configurations of ions in stages V – XVII for elements lanthanum through hafnium.

	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII
La	$5s^25p^5$	$5s^25p^4$	$5s^25p^3$	$5s^25p^2$	$5s^25p$	$5s^2$	$5s$	$4d^{10}$	$4d^9$	$4d^8$	$4d^7$	$4d^6$	$4d^5$
Ce	$5s^25p^6$	$5s^25p^5$	$5s^25p^4$	$5s^25p^3$	$5s^25p^2$	$5s^25p$	$5s^2$	$5s$	$4d^{10}$	$4d^9$	$4d^8$	$4d^7$	$4d^6$
Pr	$5p^64f$	$5s^25p^6$	$5s^25p^5$	$5s^25p^4$	$5s^25p^3$	$5s^25p^2$	$5s^24f$	$5s^2$	$5s$	$4d^{10}$	$4d^9$	$4d^8$	$4d^7$
Nd	$5p^64f^2$	$5p^64f$	$5s^25p^6$	$5s^25p^5$	$5p^34f$	$5p^24f$	$5s^24f^2$	$5s^24f$	$5s^2$	$5s$	$4d^{10}$	$4d^9$	$4d^8$
Pm	$5p^64f^3$	$5p^64f^2$	$5p^64f$	$5p^54f$	$5p^34f^2$	$5p^24f^2$	$5s^24f^3$	$5s^24f^2$	$5s^24f$	$5s^2$	$4f$	$4d^{10}$	$4d^9$
Sm	$5p^64f^4$	$5p^64f^3$	$5p^64f^2$	$5p^54f^2$	$5p^34f^3$	$5p^24f^3$	$5s^24f^4$	$5s^24f^3$	$5s^24f^2$	$5s^24f$	$5s4f$	$4f$	$4d^{10}$
Eu	$5p^64f^5$	$5p^64f^4$	$5p^64f^3$	$5p^54f^3$	$5p^34f^4$	$5p^24f^4$	$5s^24f^5$	$5s^24f^4$	$5s^24f^3$	$5s^24f^2$	$5s4f^2$	$4f^2$	4f
Gd	$5p^64f^6$	$5p^64f^5$	$5p^64f^4$	$5p^54f^4$	$5p^44f^4$	$5p^24f^5$	$5s^24f^6$	$5s^24f^5$	$5s^24f^4$	$5s^24f^3$	$5s4f^3$	$4f^3$	$4f^2$
Tb	$5p^64f^7$	$5p^64f^6$	$5p^64f^5$	$5p^54f^5$	$5p^44f^5$	$5p^24f^6$	$5s^24f^7$	$5s^24f^6$	$5s^24f^5$	$5s^24f^4$	$5s4f^4$	$4f^4$	$4f^3$
Dy	$5p^64f^8$	$5p^64f^7$	$5p^64f^6$	$5p^54f^6$	$5p^44f^6$	$5p^24f^7$	$5p4f^7$	$5s^24f^7$	$5s^24f^6$	$5s^24f^5$	$5s^24f^4$	$4f^5$	$4f^4$
Ho	$5p^64f^9$	$5p^64f^8$	$5p^64f^7$	$5p^54f^7$	$5p^44f^7$	$5p^24f^8$	$5p4f^8$	$5s^24f^8$	$5s^24f^7$	$5s^24f^6$	$5s^24f^5$	$4f^6$	$4f^5$
Er	$5p^64f^{10}$	$5p^64f^9$	$5p^64f^8$	$5p^54f^8$	$5p^44f^8$	$5p^24f^9$	$5p4f^9$	$5s^24f^9$	$5s^24f^8$	$5s^24f^7$	$5s^24f^6$	$5s4f^6$	$4f^6$
Tm	$5p^64f^{11}$	$5p^64f^{10}$	$5p^64f^9$	$5p^64f^8$	$5p^44f^9$	$5p^24f^{10}$	$5p4f^{10}$	$5s^24f^{10}$	$5s^24f^9$	$5s^24f^8$	$5s^24f^7$	$5s4f^7$	$4f^7$
Yb	$5p^64f^{12}$	$5p^64f^{11}$	$5p^64f^{10}$	$5p^64f^9$	$5p^44f^{10}$	$5p^34f^{10}$	$5p4f^{11}$	$5s^24f^{11}$	$5s^24f^{10}$	$5s^24f^9$	$5s^24f^8$	$5s4f^8$	$4f^8$
Lu	$5p^64f^{13}$	$5p^64f^{12}$	$5p^64f^{11}$	$5p^64f^{10}$	$5p^44f^{11}$	$5p^34f^{11}$	$5p4f^{12}$	$5s^24f^{12}$	$5s^24f^{11}$	$5s^24f^{10}$	$5s^24f^9$	$5s4f^9$	$4f^9$

Discrepancies between the current table and Carroll and O'Sullivan (1982) are highlighted in red.

Pd-like through Rb-like spectra of La, Ce and Pr

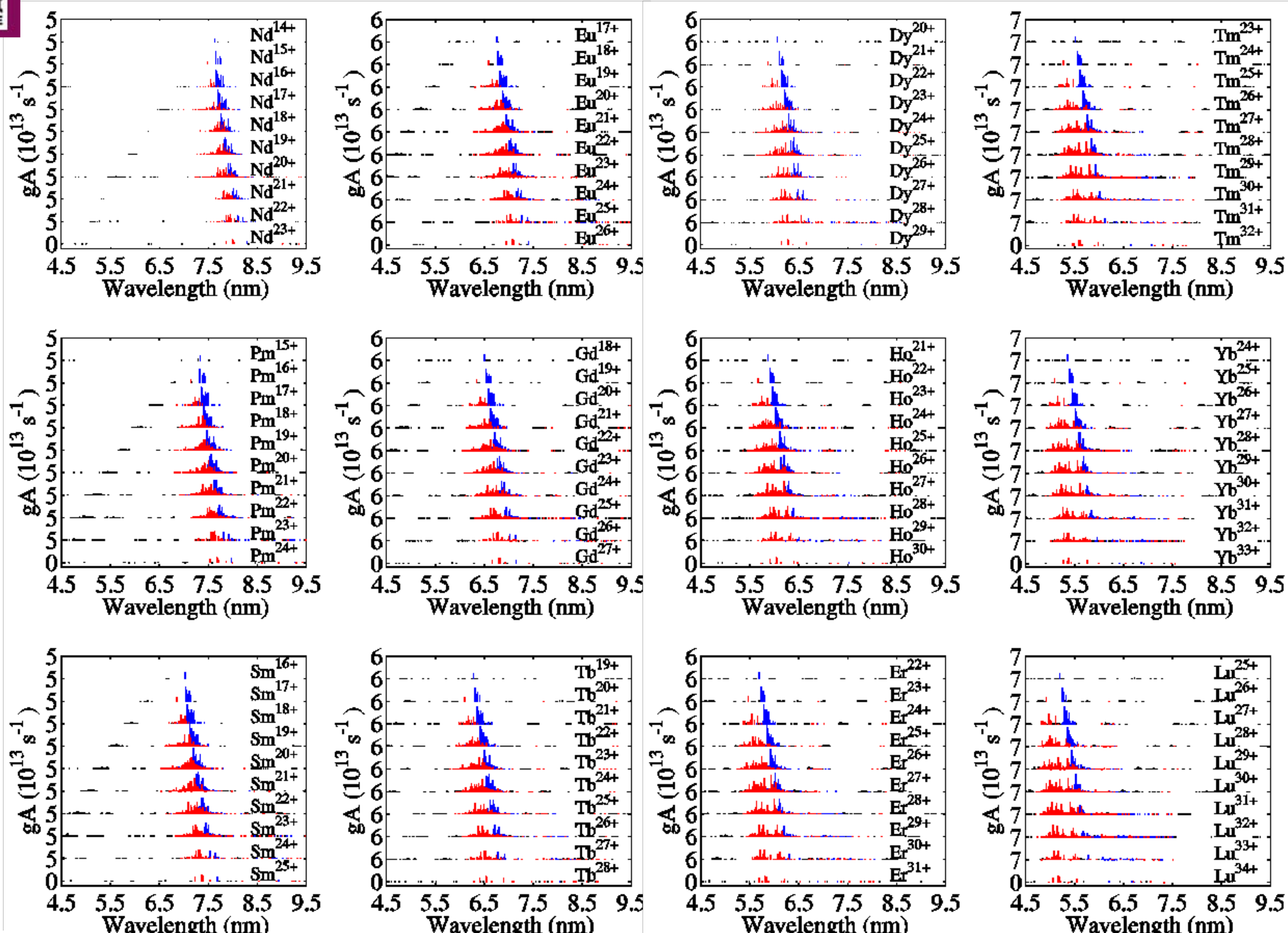


Excluding CI (left)
Including CI (right).

4d - 4f (blue),
4p – 4d (red) and
all transitions (black)

(Kilbane and O'Sullivan PRA in press)

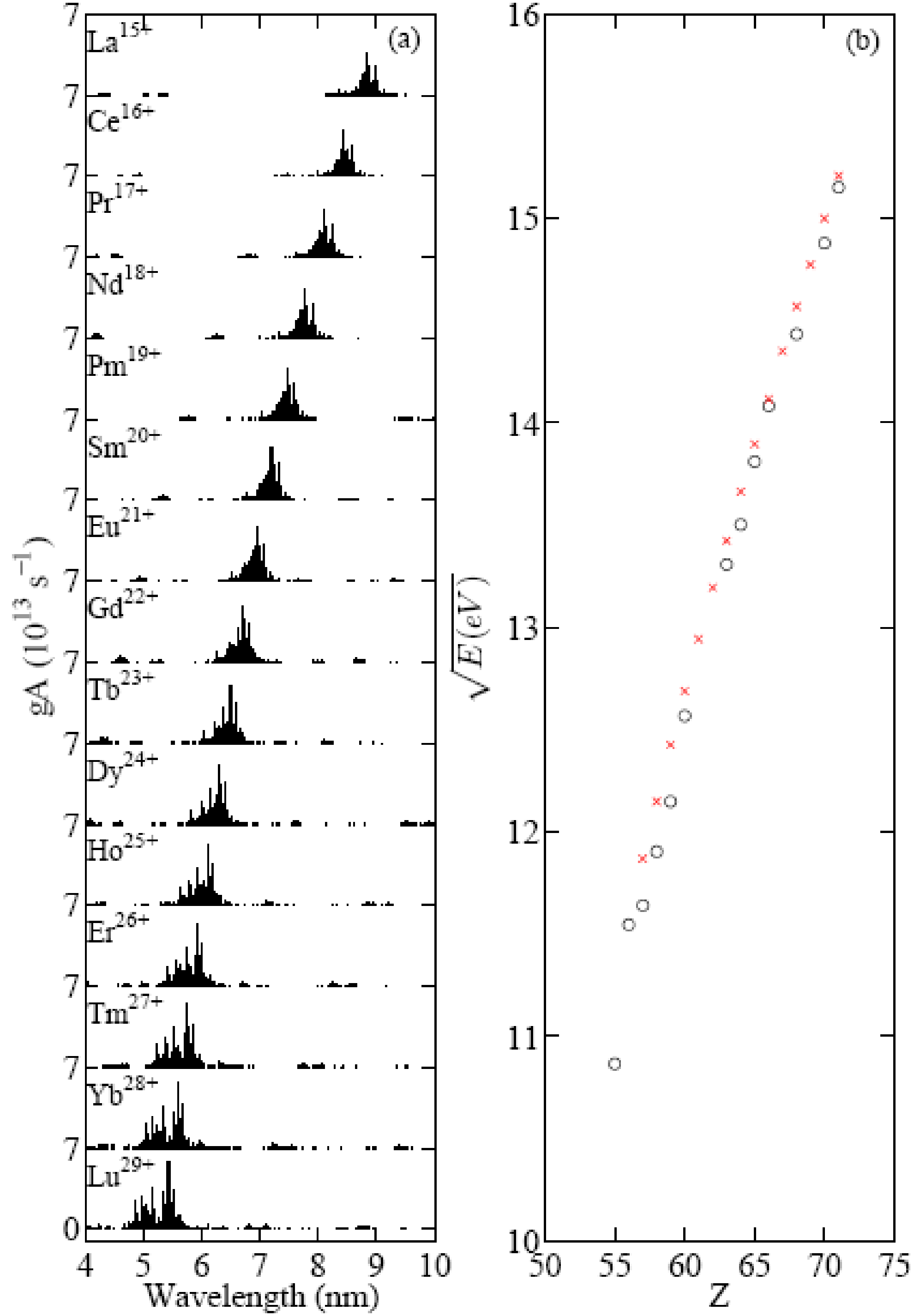
Pd-like through Rb-like spectra of Nd through Lu



4d - 4f (blue), 4p – 4d (red) and all transitions (black)

Maximum peak emission from $\Delta n = 0$, 4 - 4 UTAs in the lanthanides.

Dependence of UTA transition energies on Z. O'Sullivan and Carroll 1982(o), current work (x)



Conclusion

- $\Delta n = 0$, n = 4 – 4 UTA provide bright EUV sources in the 5 - 13.5 nm range
- Broadly same physics as Sn sources, but ion stages with 4d subshell greater than half full now more important (opposite to Sn case)
- Opacity an issue…low density targets or CO_2 plasmas
- Strongest lines expected from Ag-like and Pd-like ions.
- Emission bandwidth less than Sn and narrowest around Ce/Nd.

Thank You!

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