Progress in Laser-Plasma Sources – 13.5 nm & Beyond.

Padraig Dunne, Takeshi Higashiguchi, Takamitsu Otsuka, Noboru Yugami, Weihua Jiang, Akira Endo, Bowen Li, Colm Harte, Colm O'Gorman, Emma Sokell, Thomas Cummings, Fergal O'Reilly, Frank McQuillan, Imam Kambali and Gerry O'Sullivan.

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2013.06.07 13:15

Looking back.

- Early EUVL with LPPs:

Nagel, Brown, Peckerar, Ginter, Robinson, McIlrath and Carroll PK,
Appl. Opt. ***23*** *(9) 1428, 1984*

4 – 8 nm, steel spectrum,
20 min exposure at 10 Hz.

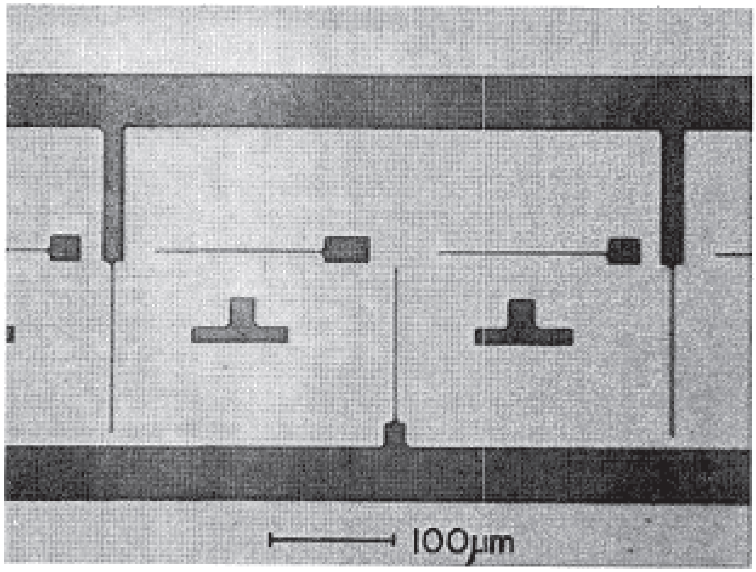

Fig. 10. Photomicrograph of a replica in photoresist of the gate level mask for a large-scale dynamic shift register made using soft x rays from the source operating at 10 Hz.

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Contents

- 13.5 nm – recent progress
- 6.X nm – Gd & Tb, Ge & Ga.
- Water Window (2.4 – 4.4 nm) – Zr.

Contents

- 13.5 nm – recent progress
  - Understanding Sn sources
  - Developing new applications
  - Novel source ideas

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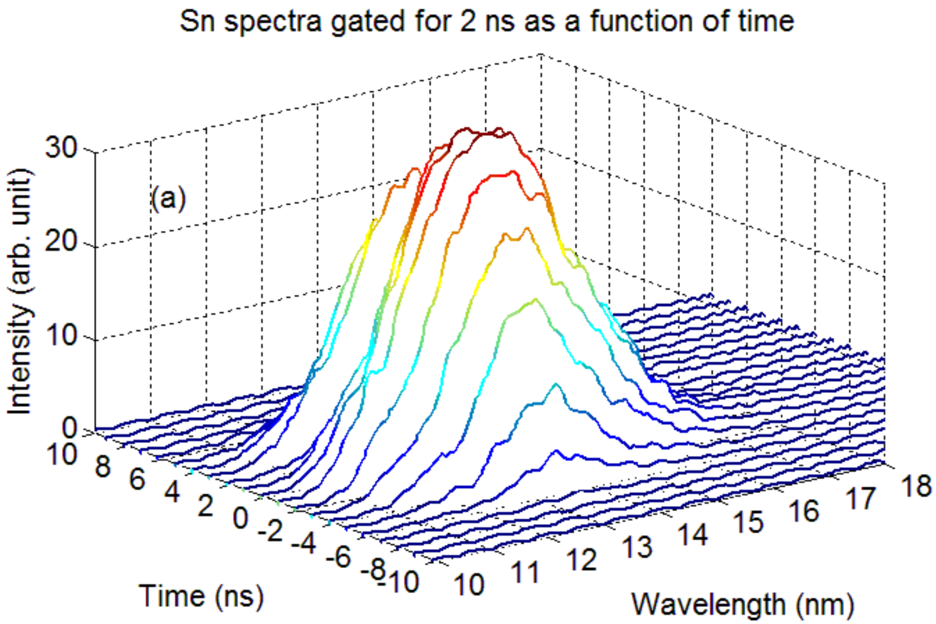
13.5 nm

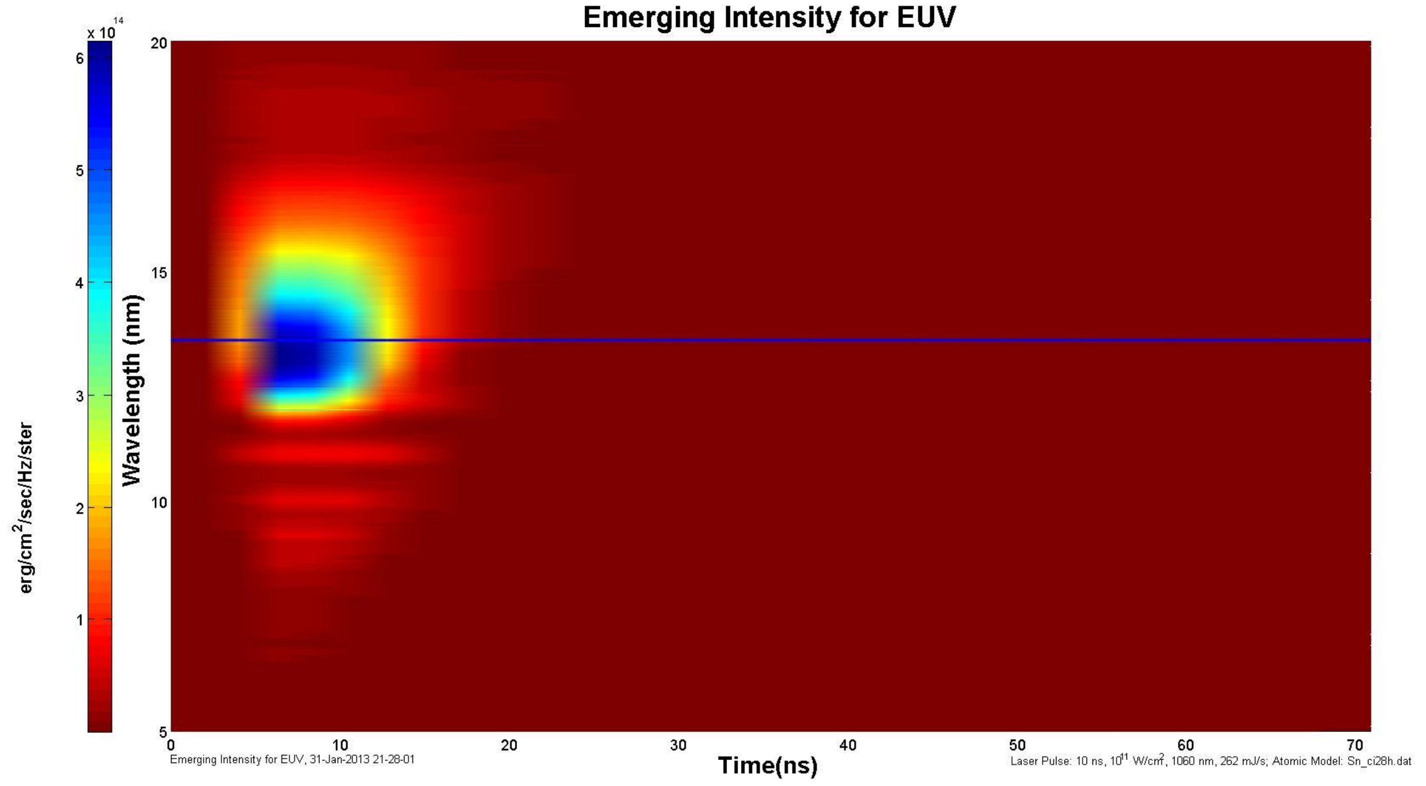
- Time-resolved Sn Emission:



Φ = 4.4x10^{12} W/cm^2
Pulse duration = 7 ns (fwhm)

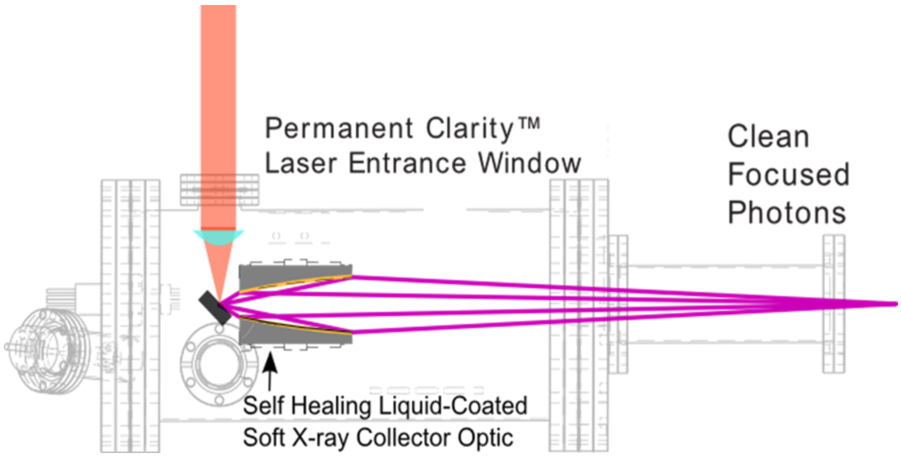
13.5 nm

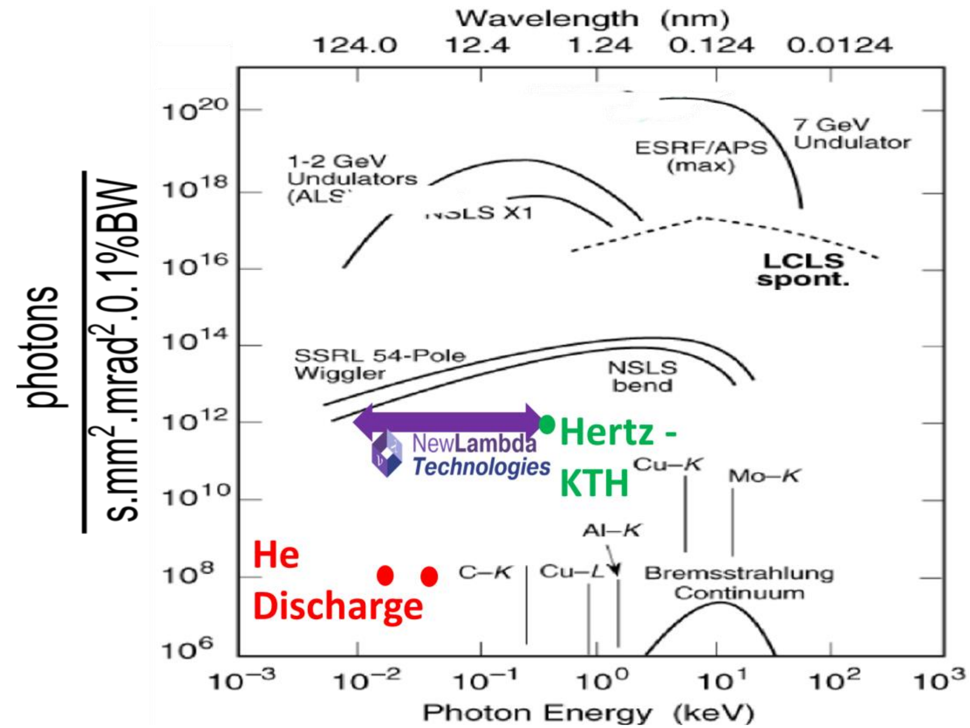
- Simulation of Sn LPP using CRETIN (with Howard Scott, LLNL)



13.5 nm

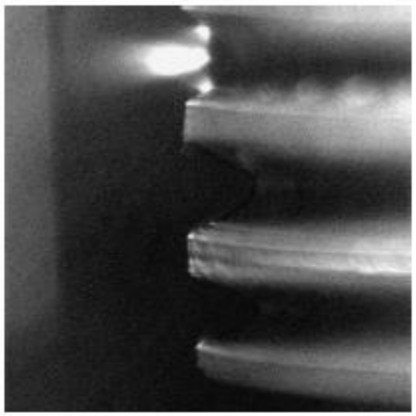
- Small Source development – high brightness (NLT)

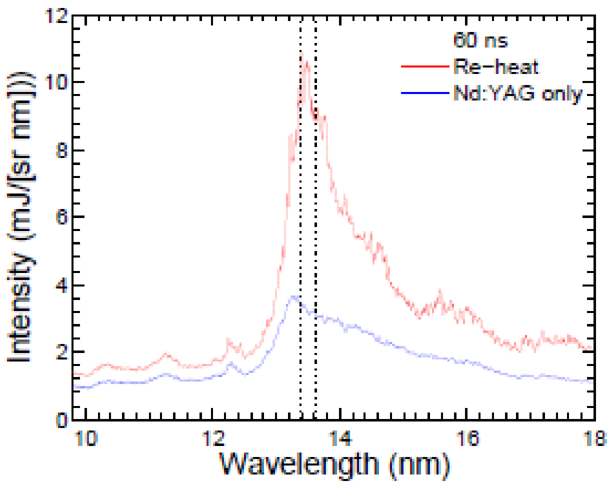


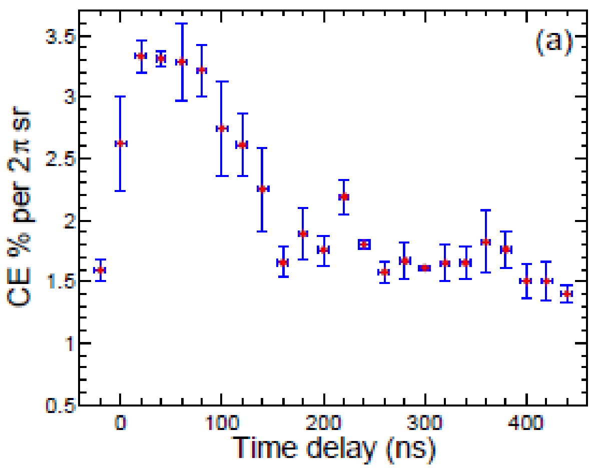


13.5 nm

- Novel Colliding-Plasma Substrate for HVM Source







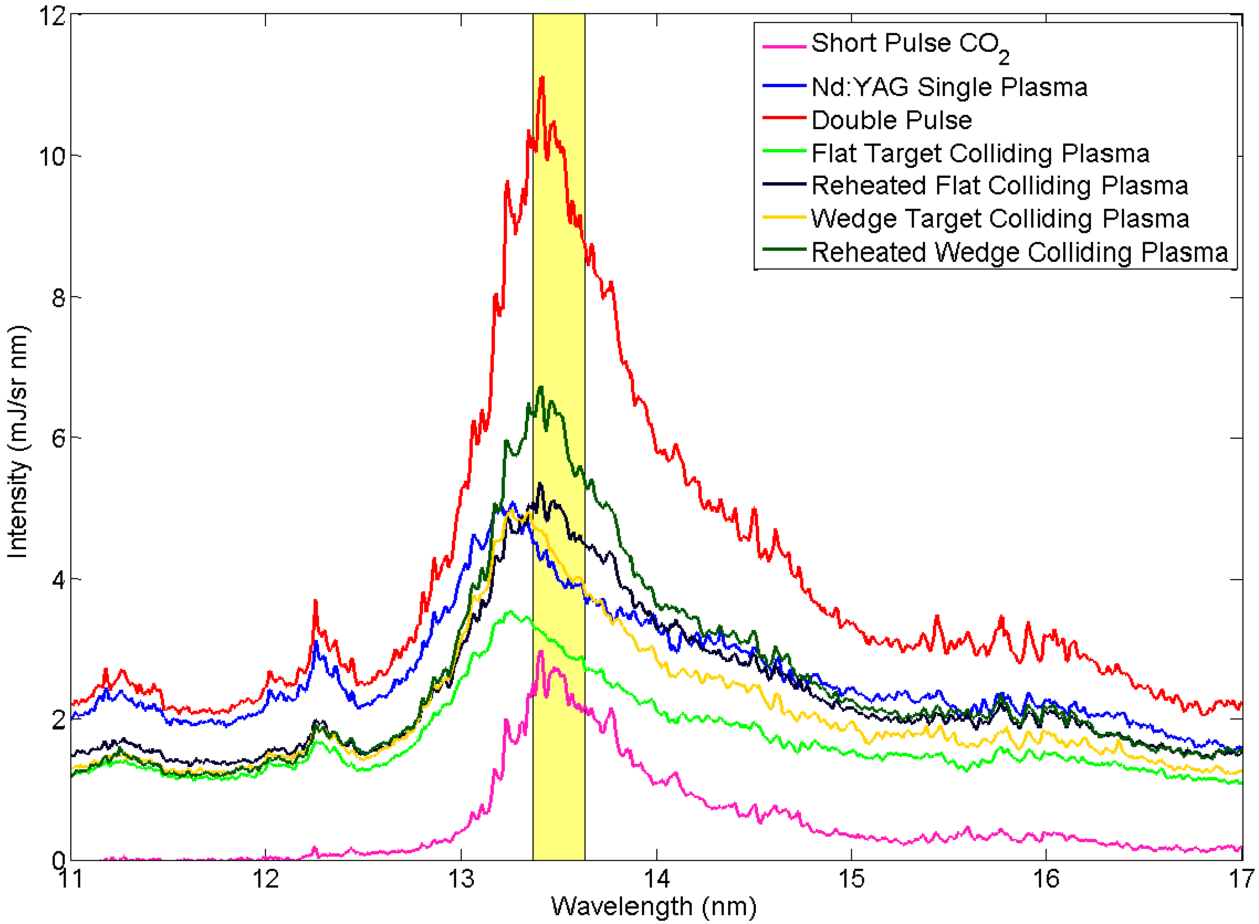
Collisionality Parameter:

$$\xi = \frac{D}{\lambda_{ii}}$$

Plasma - Plasma Separation

Ion - Ion Mean Free Path (mfp)

13.5 nm – comparison of spectra



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- 13.5 nm – recent progress
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  - Looking for targets that work at lower ϕ
  - Looking for targets potentially suitable for liquid drop targets
- Water Window (2.4 – 4.4 nm) – Zr.

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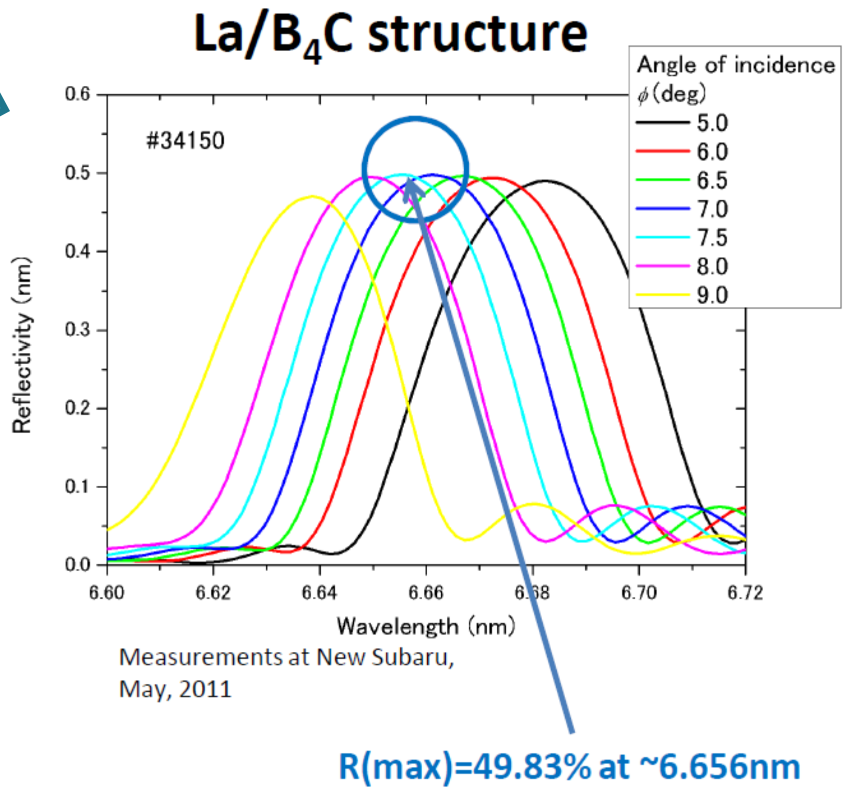
6.x nm

- Motivation:
- Materials: Tb & Gd
- Potentially Ge & Ga

Y. Platinov et al., “Status of multilayer coatings for EUV Lithography” 2011 Int. Workshop on EUV Lithography, Hawaii



6.x nm – Tb

The most important transitions occur in Ag-like, Pd-like and Rh- like

Gd XVIII-XX, Tb XIX - XXI

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

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

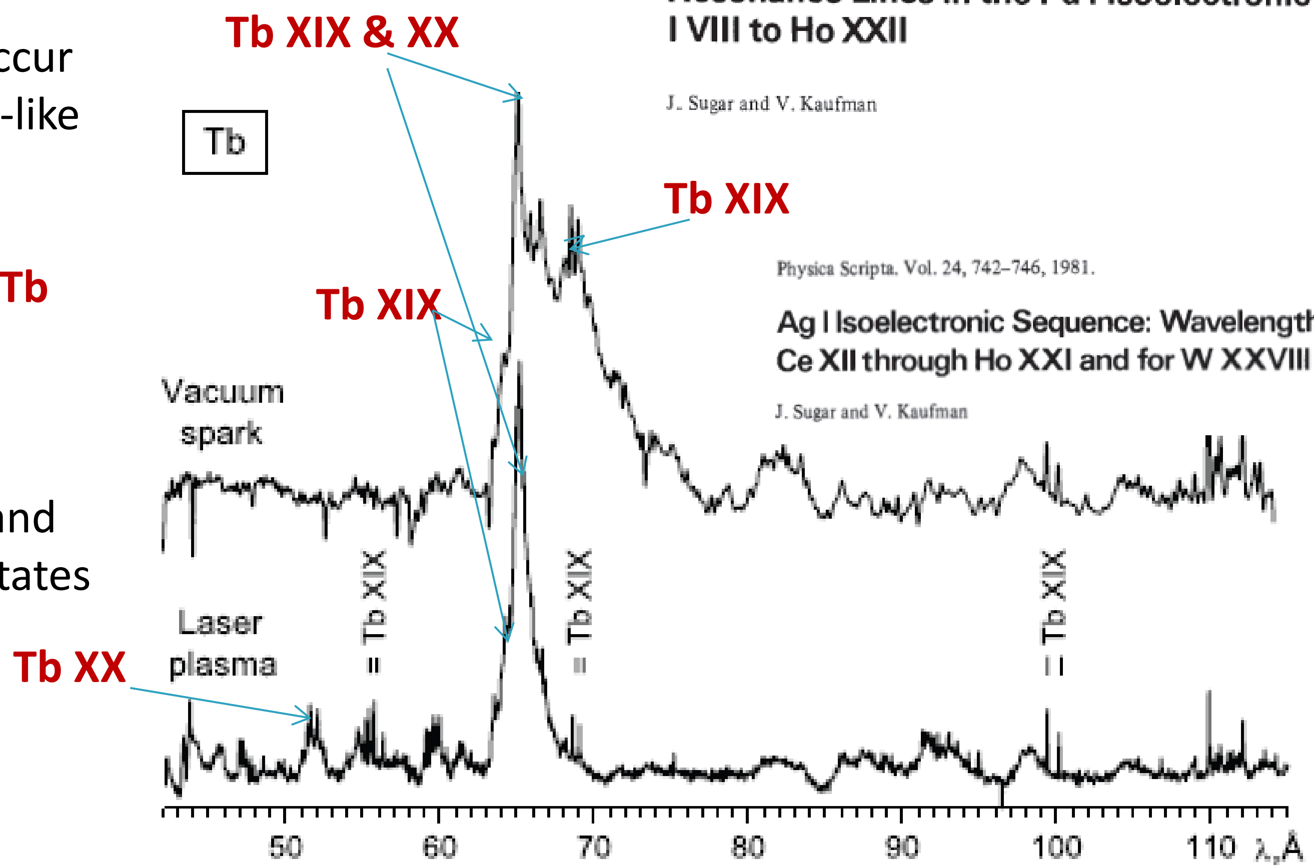


Figure 2. Spectra of terbium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace). ∗, $4f^2$–$4f5d$ transition array in Tb XVIII classified in the present work.

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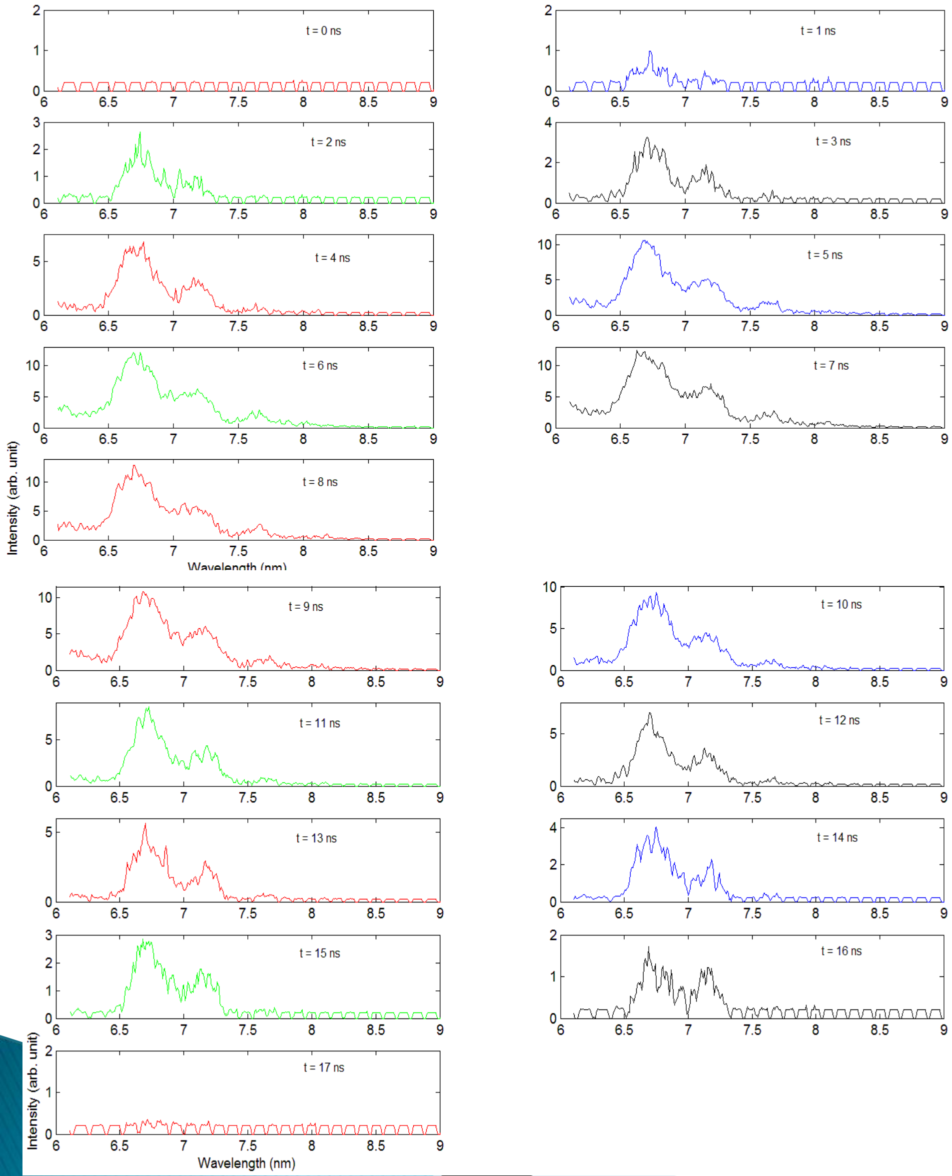
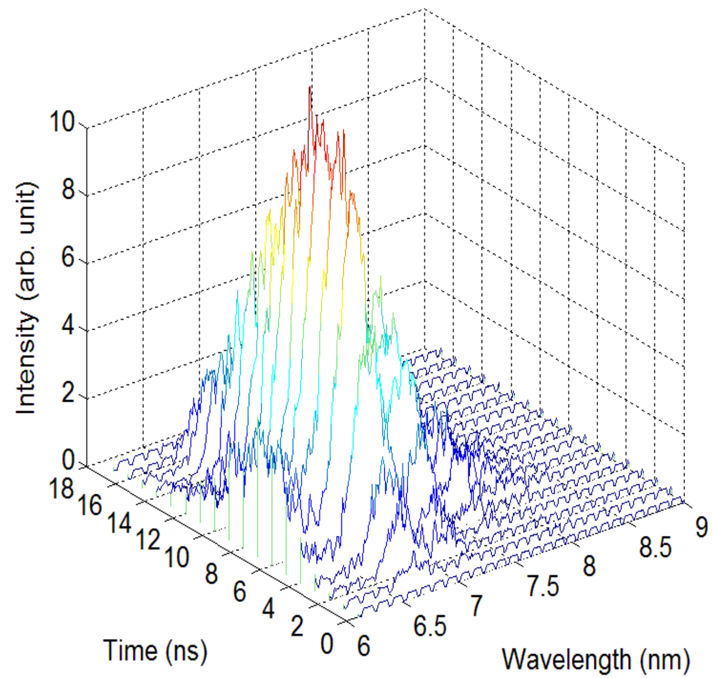
6.x nm – Gd

Temporal evolution of Gd spectra at $\Phi = 5.5\times10^{12}$ W/cm^2





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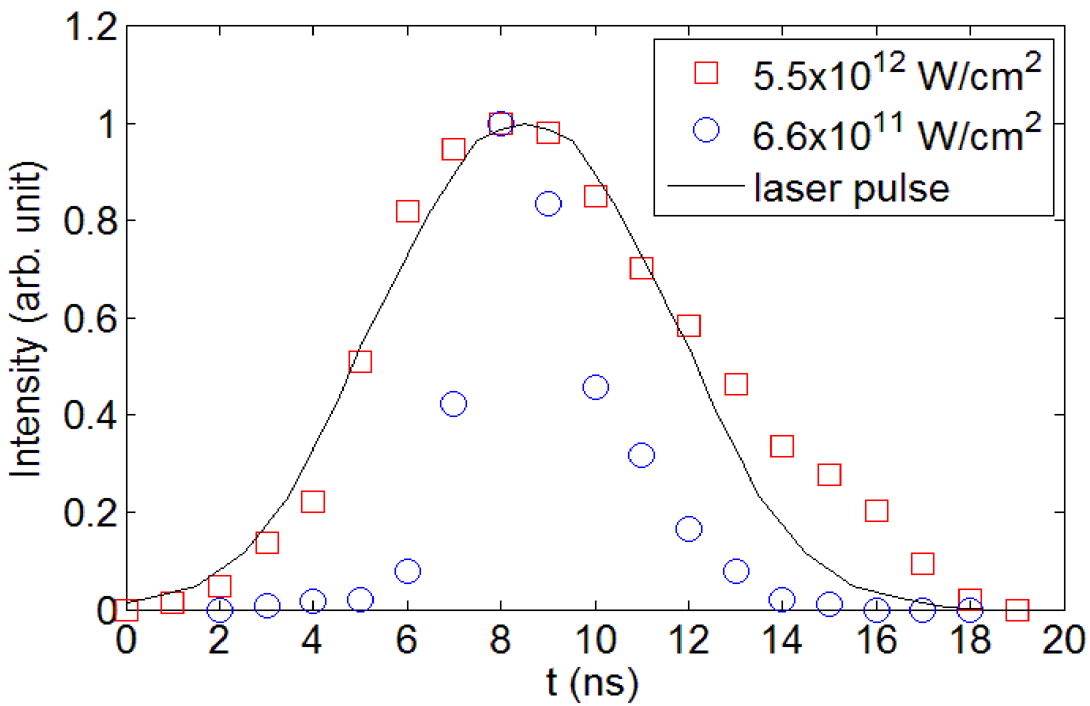
6.x nm – Gd

- 6.x nm temporal width reduced at lower power density:



6.x-nm emission duration.
2.5 ns for Φ = 6.6x10^{11} W/cm^2
7.5 ns for Φ = 6.6x10^{11} W/cm^2

Nd:YAG λ = 1064 nm, 7 ns (FWHM) @50 Hz.

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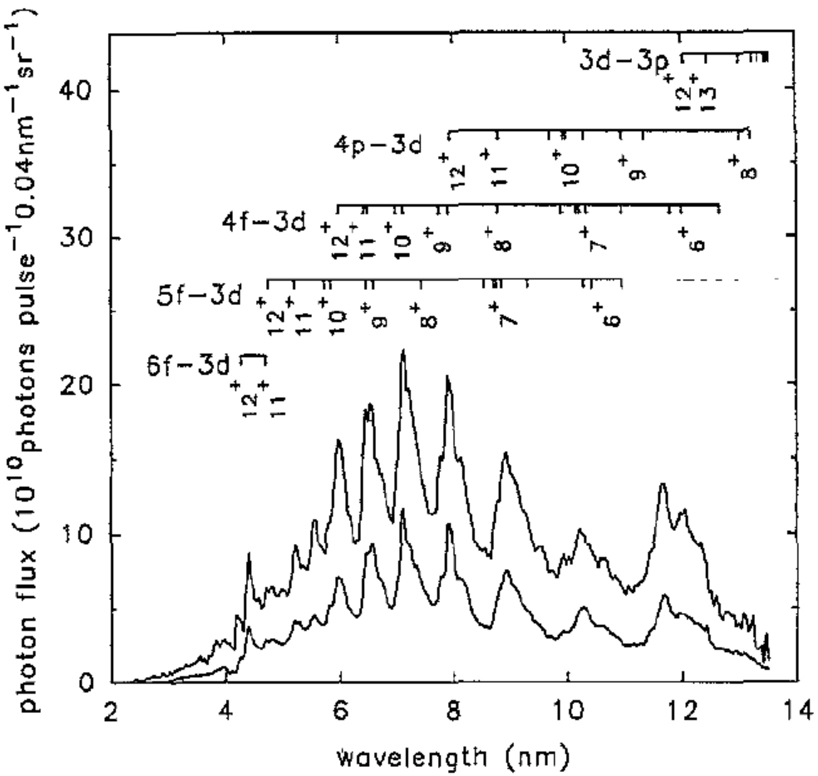
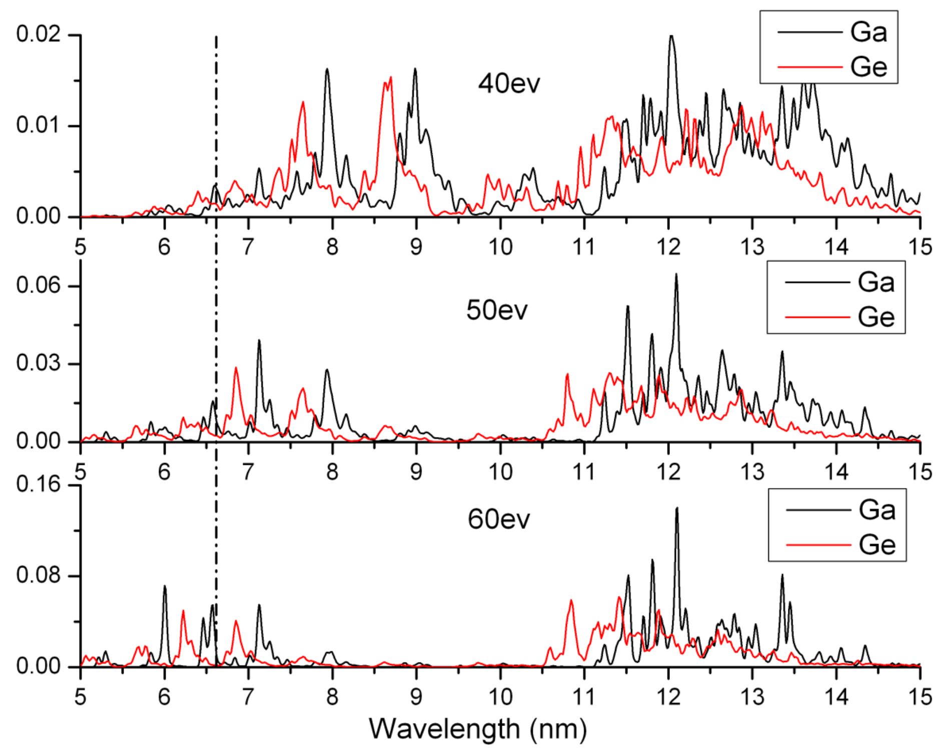
6.x nm – Ga & Ge



Dohring *et al* JPB **27**, L663 (1994)

Calculation of 3d-4f emission in Ga and Ge for an optically thin plasma



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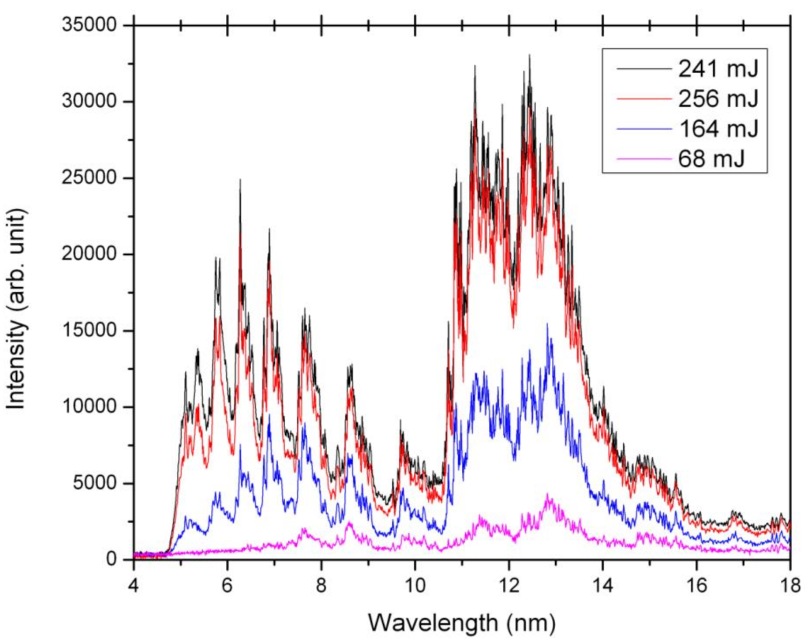
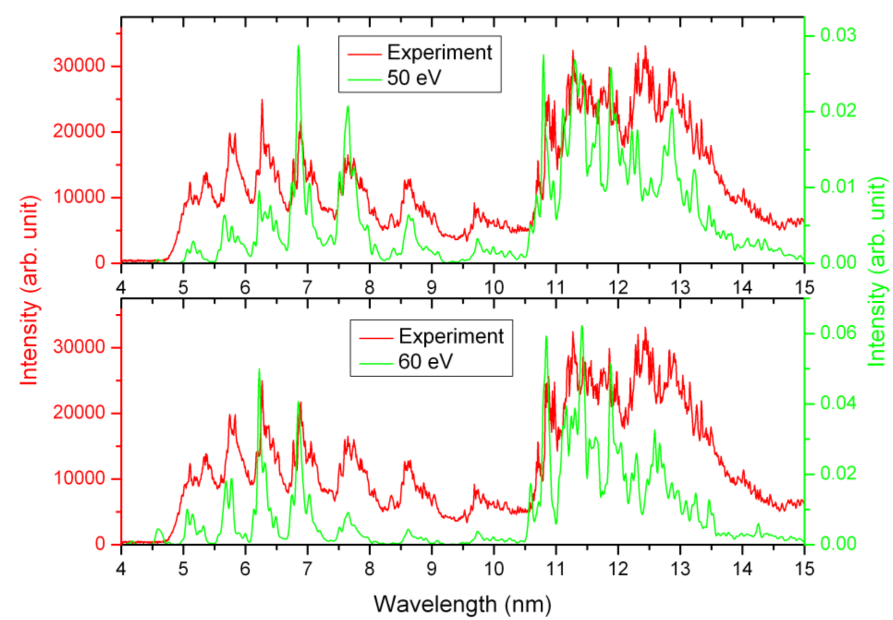
6.x nm – Ge

- Ga is liquid at 30 ºC
- T_e of 50–60 eV required compared to 110 eV for Gd....
- Spectra below are of Ge, similar to Ga.





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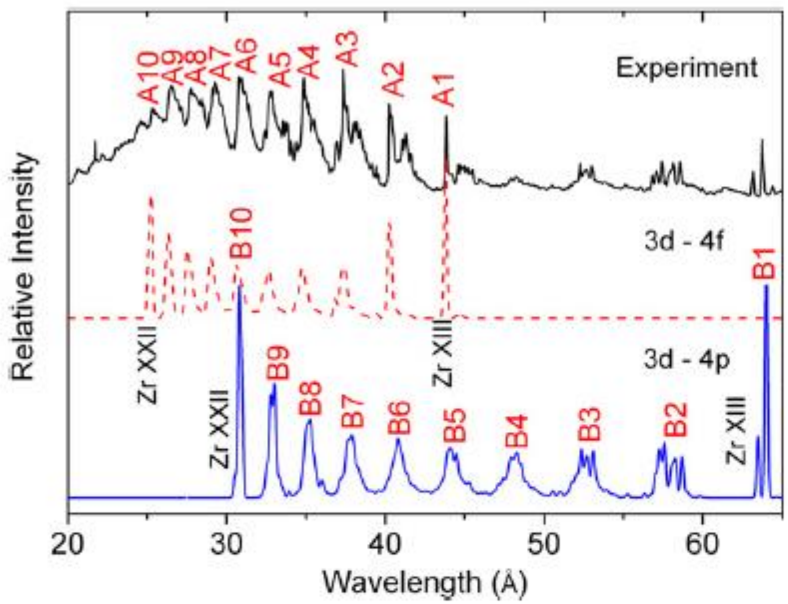
2.4 – 4.4 nm – “The Water Window”

IOP PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. **45** (2012) 245004 (6pp) doi:10.1088/0953-4075/45/24/245004

XUV spectra of laser-produced zirconium plasmas

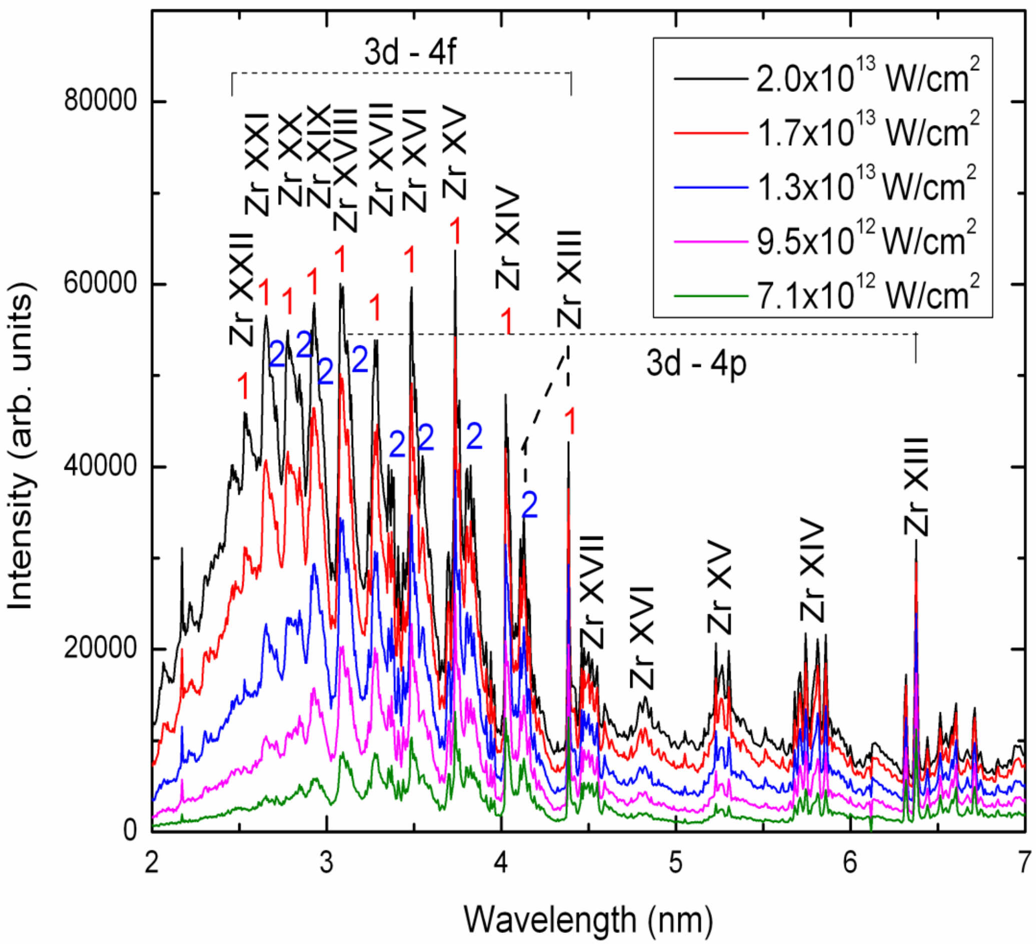
Bowen Li[1], Takeshi Higashiguchi[2], Takamitsu Otsuka[2], Weihua Jiang[3], Akira Endo[4], Padraig Dunne[1] and Gerry O’Sullivan[1]



Comparison of experimental Zr spectrum with theoretical 3d-4f (A) & 3d-4p (B) resonance transitions.

Laser power density = 2 x 10^{13} W/cm^2
Pulse duration = 150 ps
Pulse energy = 240 mJ

2.4 – 4.4 nm – Zr



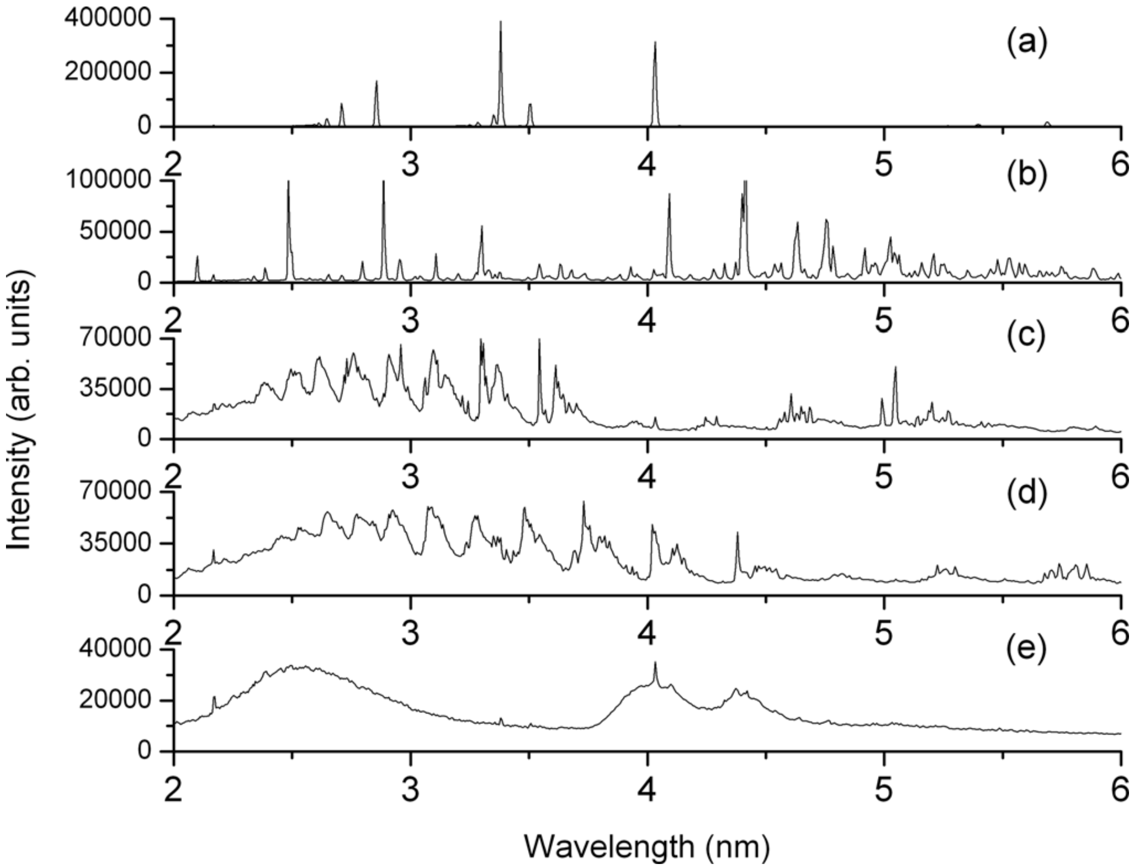
Spectral behavior of Zr plasmas as a function of laser intensity.

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 with other targets:

Spectra from 150-ps LPP formed on:

a) C
b) Si_3N_4
c) Mo
d) Zr
e) Bi



APPLIED PHYSICS LETTERS 102, 041117 (2013)

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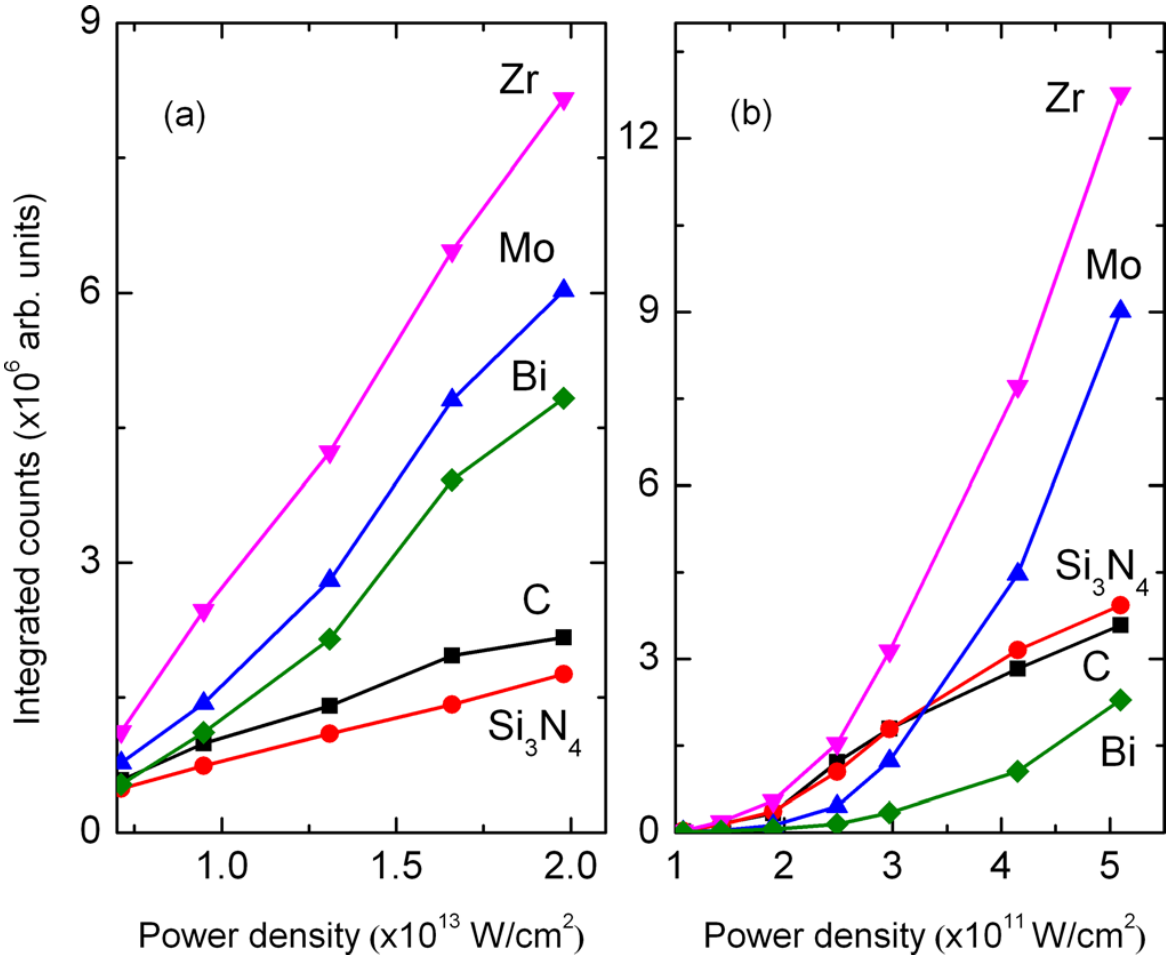
Comparison with other targets:



Water window emission (total counts) as a function of power density for 150-ps (a) and 7-ns (b) lasers

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- Utsunomiya University: Hao Tan

- Collaborators: DCU: Prof. John Costello, Colm Fallon, TCD: Prof. James Lunney and Issac Tobin

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Thank You

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Colliding-plasma data

Experiment	Distance mm	Delay ns	Laser Energy mJ		EUV Energy mJ/2πsr		CE %		SP %
			Nd:YAG	CO_2	IB	BB	IB	BB	
CO_2	-	-	-	119	4.2	19.8	**3.5**	16.6	**21.3**
Nd:YAG	-	-	496	-	6.9	99.7	1.4	20.11	7
DP	0	100	496	119	**16.7**	**149.1**	3.4	**24.2**	11.2
FCP	-	-	496	-	5.1	64.9	1.04	13.1	7.9
FCP - RH	0.2	200	496	119	8.3	88.7	1.6	14.4	9.3
WCP	-	-	496	-	7.3	72.8	1.47	16.1	9.1
WCP - RH	0	100	496	119	10.3	94.9	2.1	15.4	10.8

Table 1.1: A table of the optimum results recorded for the first experimental setup. The results in bold (key: DP = Double Pulse, FCP = Flat Target Colliding Plasma, FCP - RH = Reheated Flat Target Colliding Plasma, WCP = Wedge Target Colliding Plasma, WCP - RH = Reheated Wedge Target Colliding Plasma, IB = In band, BB = Broad band, CE = Conversion Efficiency, SP = Spectral Purity)

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