Development and Optimization of EUV Emission from Laser Produced Plasmas

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Main Issues

- Plasma opacity (optimum ion density)
- Choice of target geometry (plasma scale length)
- Optimum pulse power density on target (plasma conditions, ion population, electron temperature)...
- Optimum laser wavelength (plasma density)
- Optimum laser pulse length
- Optimum laser pulse shape

Outline

- Historical Background

  Properties of Laser Produced Plasmas relevant to EUVL

- Results from studies of Xe and Sn Nd:YAG LPP

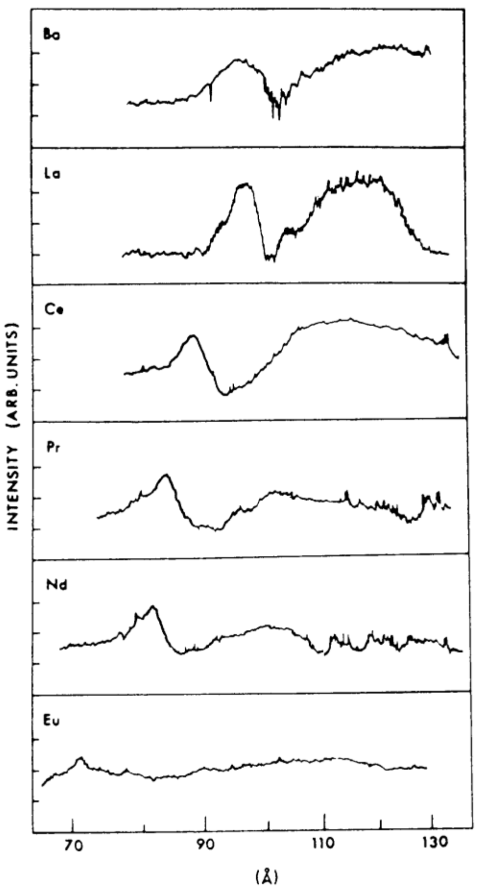
- Results from studies of Xe and Sn CO_2 LPP

- Recent work on Gd and Tb sources for 6.7 nm

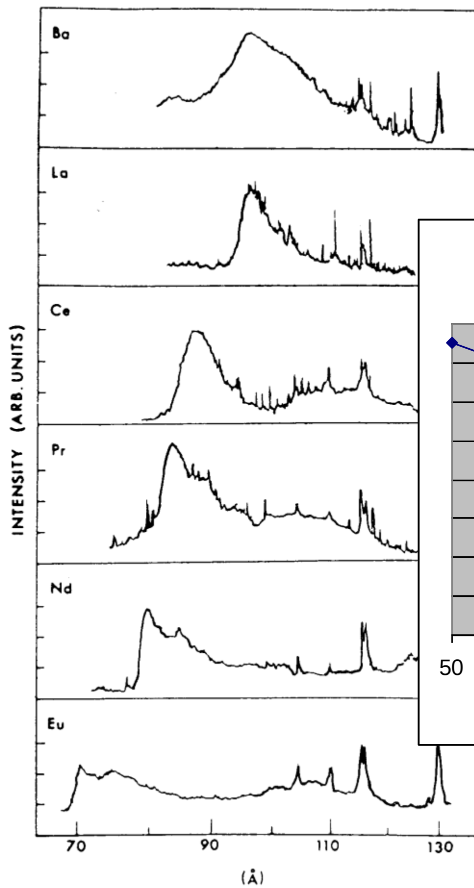
Spectra from plasmas of elements with Z > 50

Spectra from elements with Z > 50 contain lines and an intense UTA due to $4p^6 4d^n$ - $4p^5 4d^{n+1} + 4d^{n-1} 4f$ ($0 \le n \le 9$) 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.

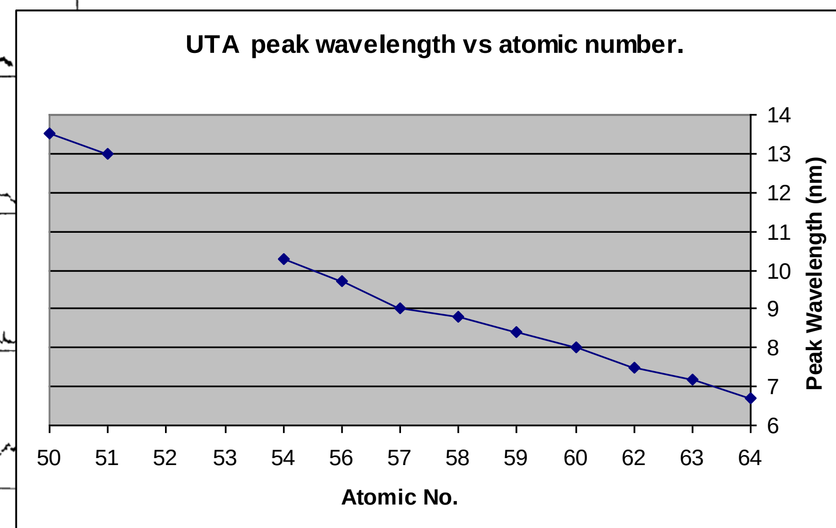


Metal Targets



Salt Targets

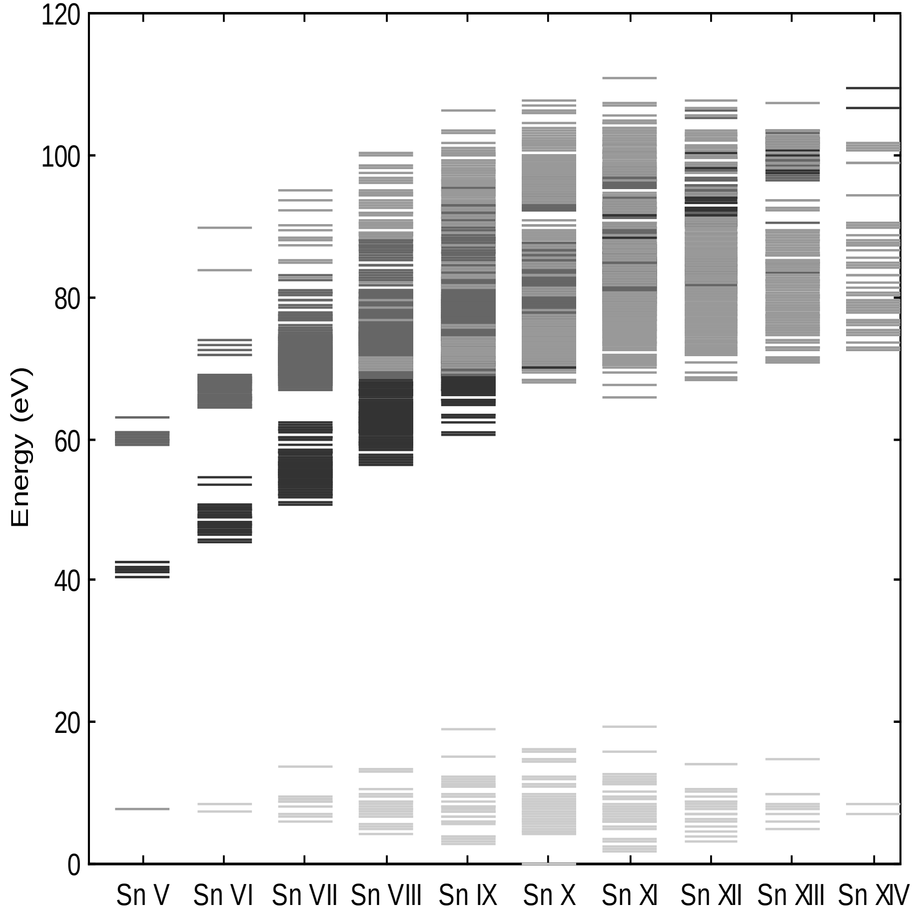
(Carroll and O'Sullivan PRA25, 275 1982)



Differences are due to opacity

Origin of the UTA

Levels of $4p^64d^n$ & ($4p^54d^{n+1}+4d^{n-1}4f + 4d^{n-1}5p$)
Calculated with Cowan suite of codes

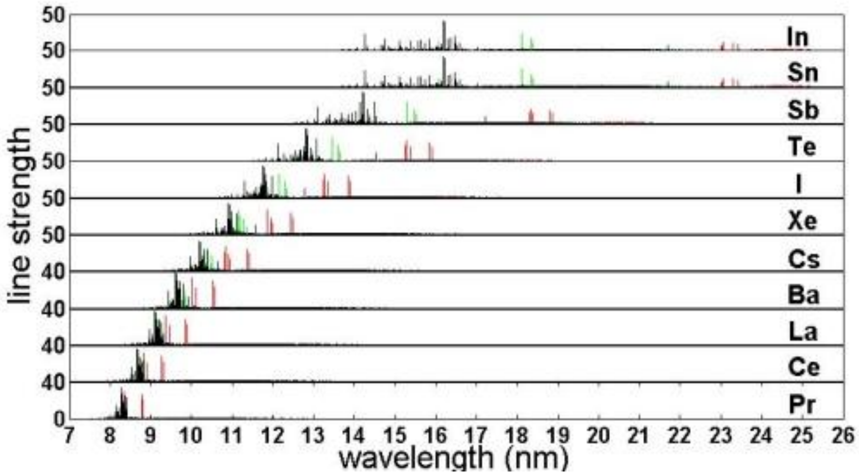


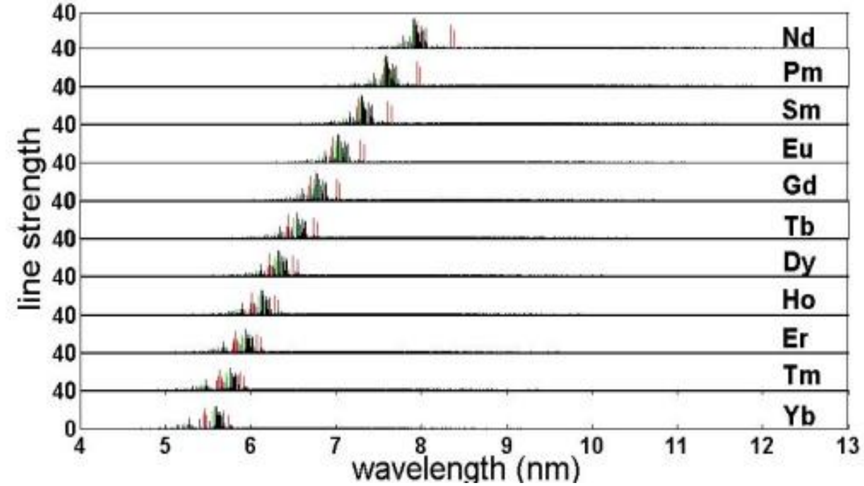
The Sn UTA is due to $4p^64d^n \rightarrow$ ($4p^54d^{n+1}+4d^{n-1}4f + 4d^{n-1}5p$) ($0 \le n \le 9$) transitions. CI (configuration interaction) causes transitions in successive ion stages to partially overlap in energy.

CI effects also cause a spectral narrowing.

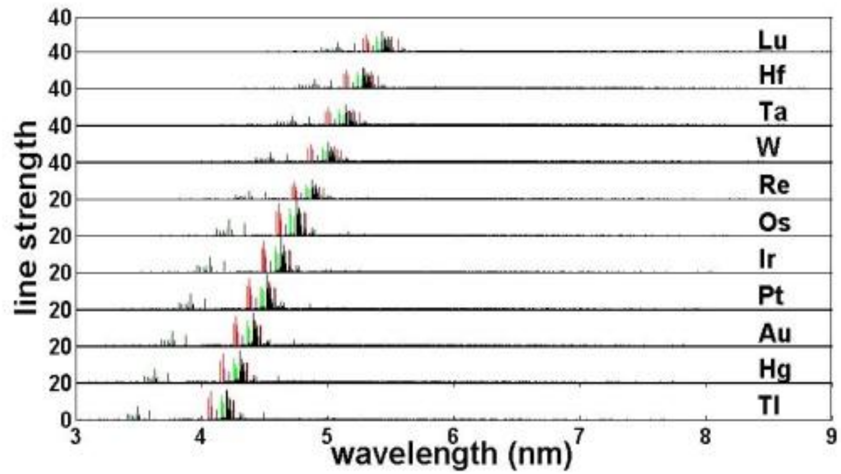
Satellite emission important at high densities

Variation of UTA position with Z





Width of UTA is a minimum in heavier rare earths, due to complete contraction of 4f wavefunction and almost constant value of <4d|4f> . Broadens in very high Z due to 4d and 4p spin orbit splitting.



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Ruby vs CO_2, VUV Intensities

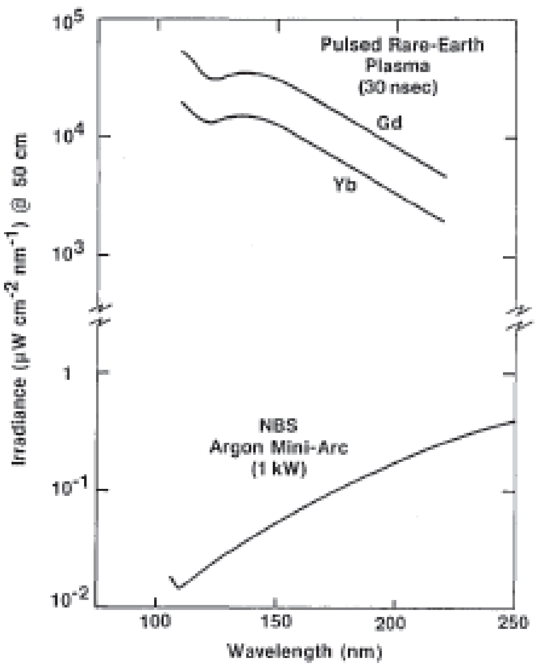


Fig. 2. Spectral irradiances of gadolinium and ytterbium targets in the 110–220-nm region compared with a National Bureau of Standards standard mini-arc.

(O'Sullivan, Roberts, Ott, Bridges, Pittman and Ginter Opt. Lett. 7, 31, 1982)

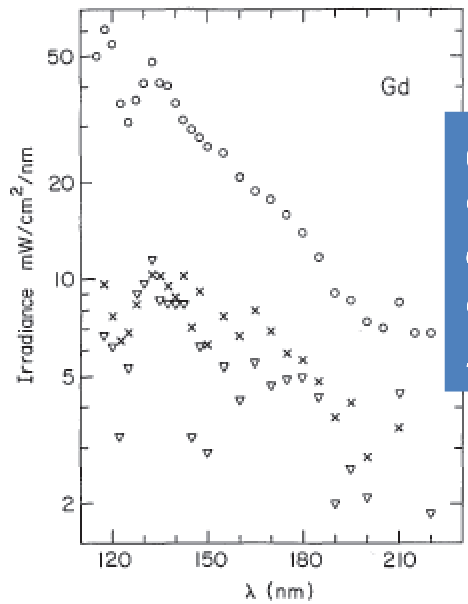


Fig. 4. Spectral irradiance values from Gd plasmas (plane target irradiated at 45° to normal) for the following: ○, ruby laser (2.0 J); ×, first CO_2 pulse (1.6 J); and ▽ second CO_2 pulse (3.4 J).

(O'Sullivan, Carroll, McIlrath and Ginter Appl. Opt. 20, 3043 1981)

It appears possible, therefore, that much greater conversion efficiencies of incident laser energy into VUV radiation can be attained if a prepulse is used to generate an absorbing plasma.

ytterbium. We feel that the differences in the irradiance distribution evident in Figs. 4 and 5 can be attributed to an increase in the intensity of line emissions in the CO_2-produced plasmas. Furthermore, where

Prepulses

Enhanced line emission with CO_2

Early LPP based EUVL

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

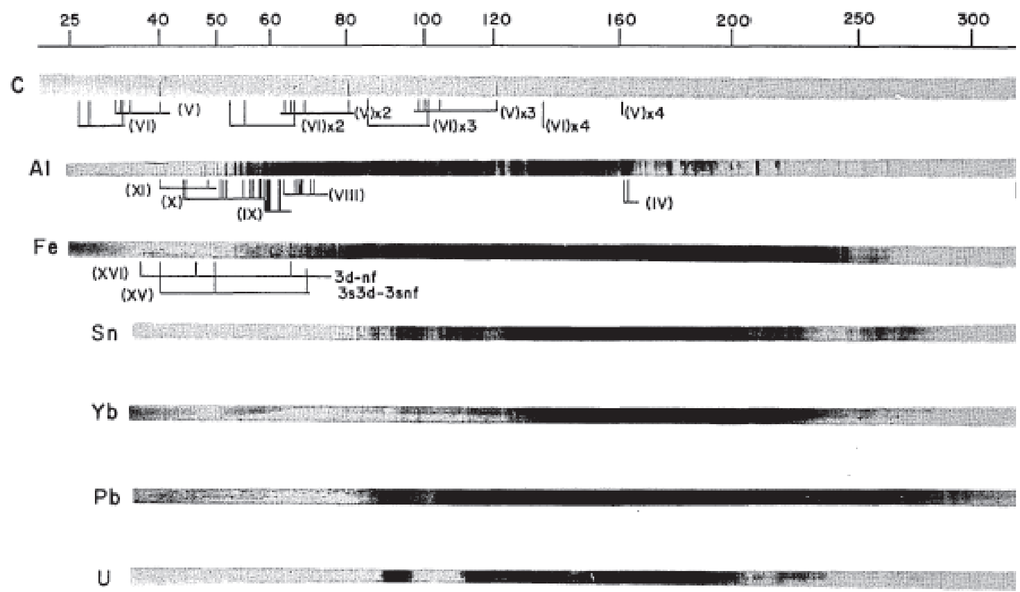


Fig. 5. Typical spectra obtained from the plasma source using a 1-m grazing incidence spectrograph. The target elements app left of each spectrum and the higher orders (x order number) of several ion stages (Roman numerals) are indicated below the spe... Al, and Fe (from steel).

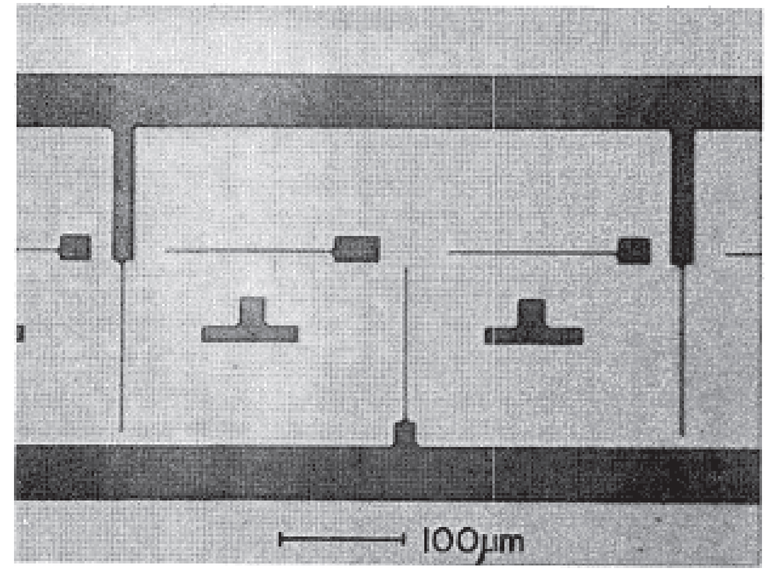


Fig. 10. Photomicrograph of a replica in photoresist of the gate level mask for a large-scale dynamic shift register made using soft x rays from the source operating at 10 Hz.

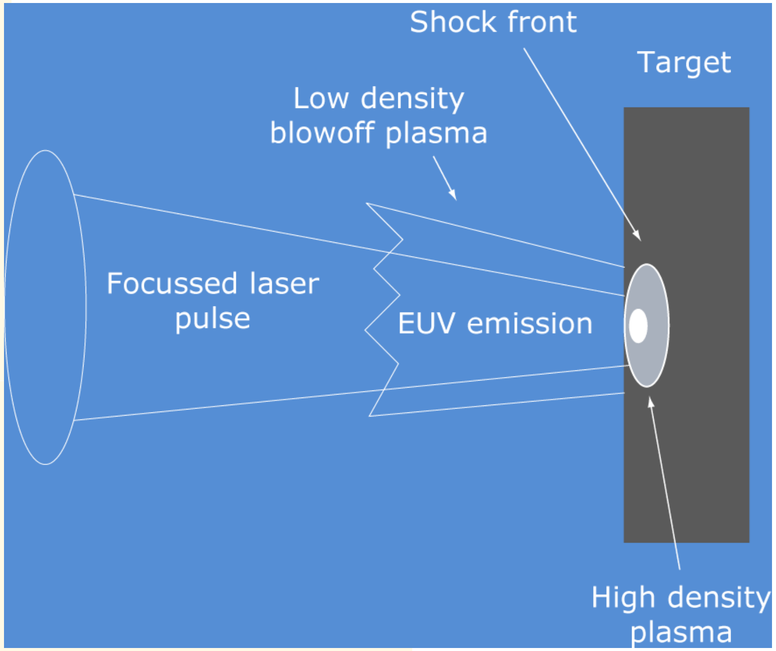
4.5 nm<λ<8 nm,
limited by reflectivity
of mask, steel target.

Laser produced plasma properties

Temperature depends on laser power density (Φ).

$T_e(\text{eV}) \approx (\lambda^2\Phi)^{3/5}$

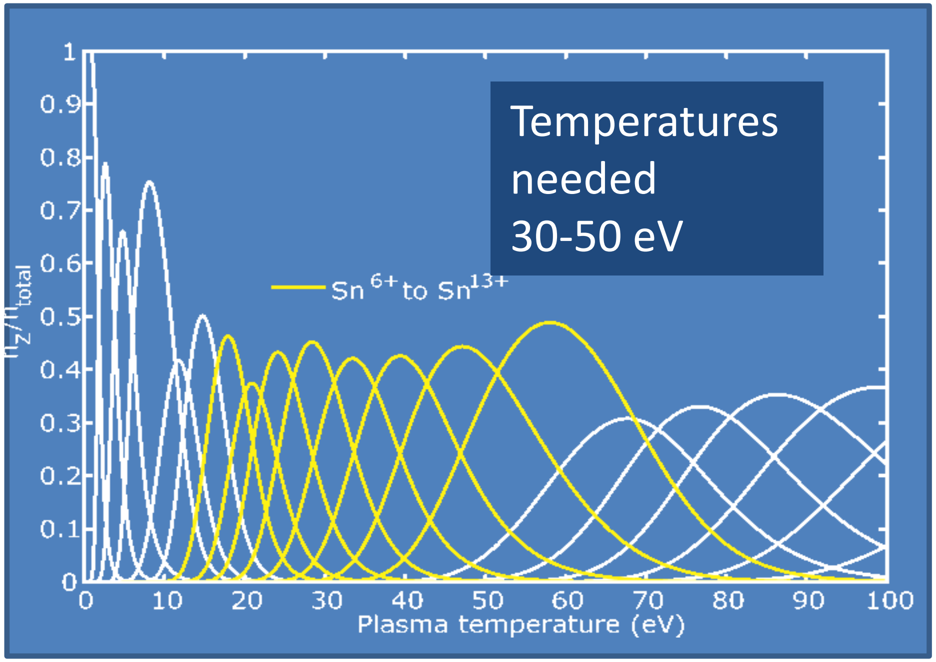
Average charge ≈ 0.67 $(AT_e)^{1/3}$



- Electron density $10^{19} - 10^{21}$ cm^{-3} depending on laser wavelength ($n_{ec} \sim 10^{21}/\lambda^2$ cm^{-3})
- Hottest at centre, cooler margins- opacity issues
- ≈ 100 μm size
- Expansion velocity ≈ 10^6 - 10^7 cms^{-1} Fast ions and neutrals are a problem *(studied by e.g. Harilai et al JAP **98**, 013306, 2005, Mathew et al JPD **40**, 447, 2007, Fujioka et al JAP 2008)*

Sn ion fractions from a collisional-radiative model

(D. Colombant and G. F. Tonon, (1973) J. Appl. Phys. 44 3524)



$$f_z = \frac{n_{z+1}}{n_z} = \frac{S(z)}{\alpha_r(z+1) + n_e\alpha_{3b}(z+1)}$$

n_z = density of ion z,
n_e = electron density,
S = collisional ionisation rate coefficient,
α_r = radiative recombination rate coefficient,
$n_e\alpha_{3b}$ = three-body recombination rate coefficients and T_e = electron temperature

Theoretical investigation of dielectronic recombination of Sn^{12+} ions

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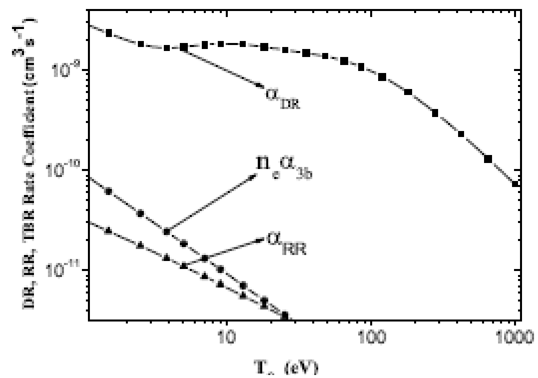

$$\alpha_{DR}(kT_e) = kT_e^{-3/2}\sum_i c_i exp(-\frac{E_i}{kT_e})$$

FIG. 5: DR, RR, and TBR rate coefficients of Sn^{12+} ions α_{DR}, α_{RR}, $n_e\alpha_{3b}$, where n_e is the number density of free electrons which are assumed as $10^{21} cm^{-3}$. α_{DR} $(n = 4-100)$ is the sum of DR rate coefficients over $n = 4$ to 100.

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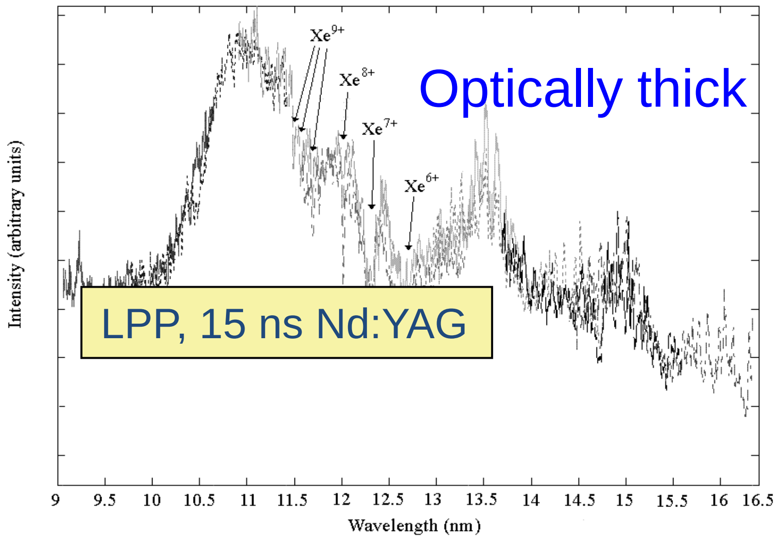
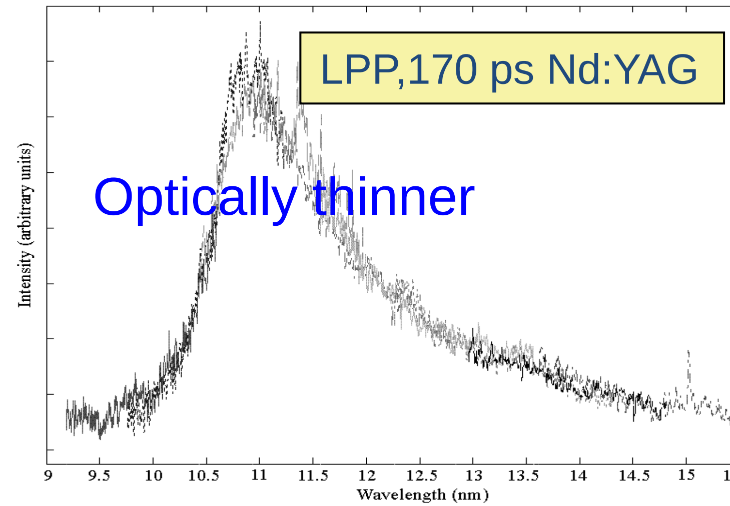
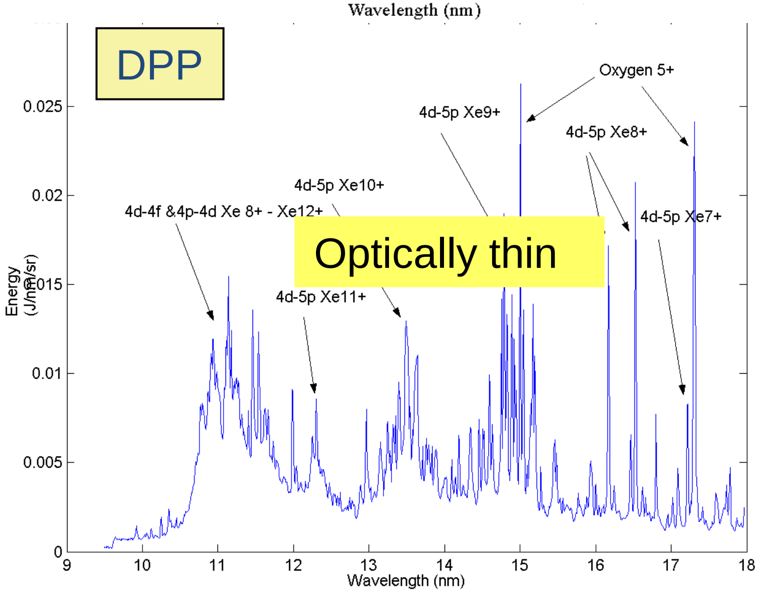
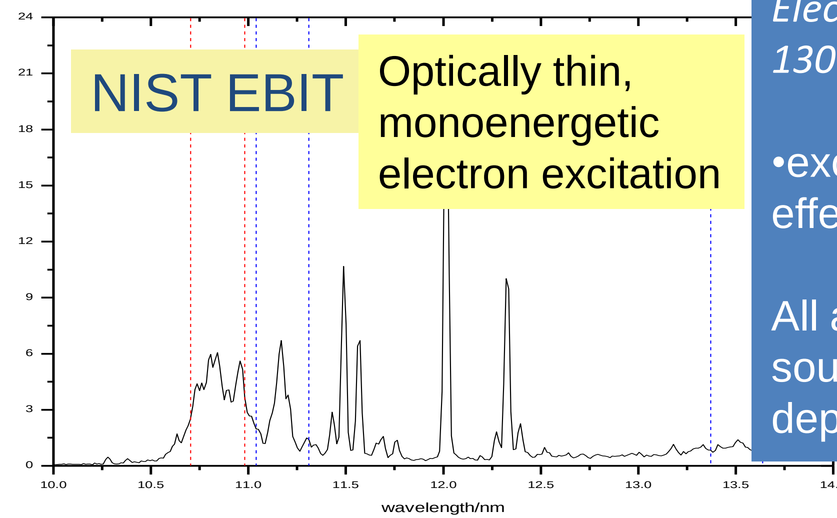
Experimental Spectra of Xenon; Source Dependence









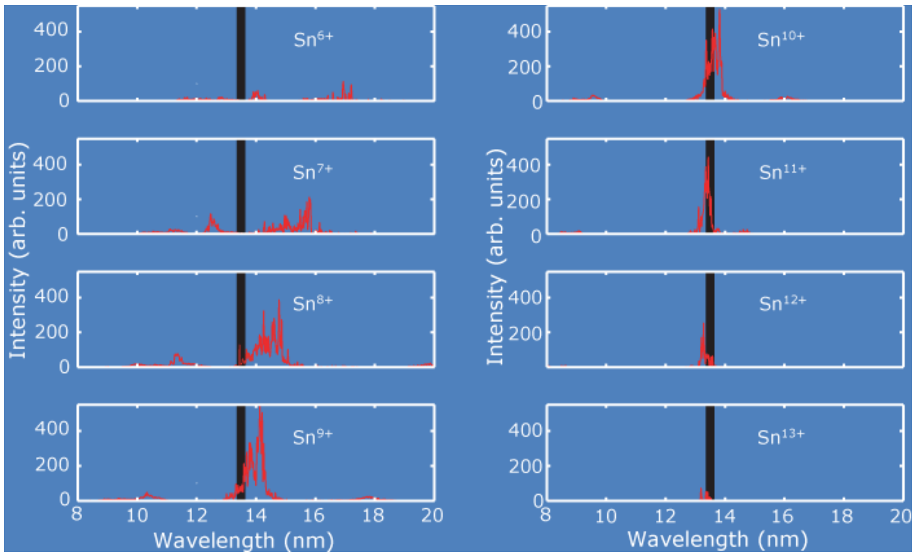
Spectral shape modified by
- density effects: opacity, satellite lines *(Sasaki et al. IEEE Journal of Quant. Electron.10, 1307 2004)*
- excitation effects

All are source dependent

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

Max. CE ~1% with solid Xe LPP

Sn^{5+}–Sn^{13+} emit $4p^64d^n \rightarrow 4d^{n-1}4f + 4p^54d^{n+1}$UTA, Sn^{10+}–Sn^{13+} emit near 13.5 nm



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

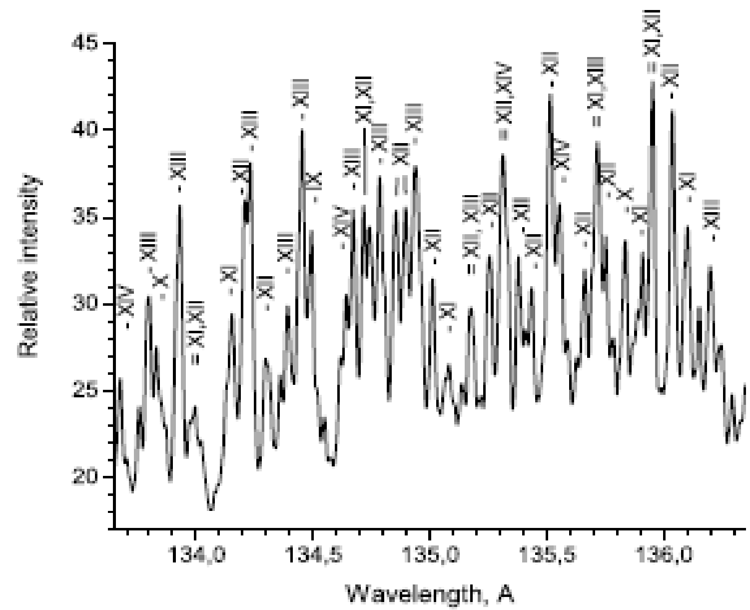


Figure 3. The classification of the most intense lines in the 2% interval near 135 Å.

Analysis by Churilov and Ryabtsev *Phys. Scr. 73 614-619, 2006*

Charge exchange (CX) spectra of Sn and Xe

(Tanuma et al. J. Phys Conf . Series 58, 231, 2007)

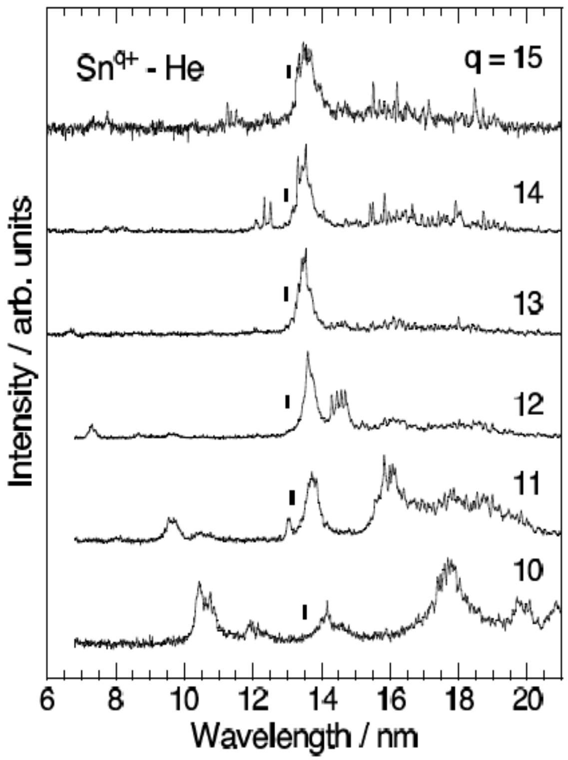


Figure 1. EUV emission spectra resulting from the collisions of Sn^{q+} (q = 10–15) ions with He gas at the energies of 20q keV. The short bars beside peaks indicate the averaged wavelengths of 4d-4f transitions of $Sn^{(q-1)+}$ ions calculated with the HULLAC code.

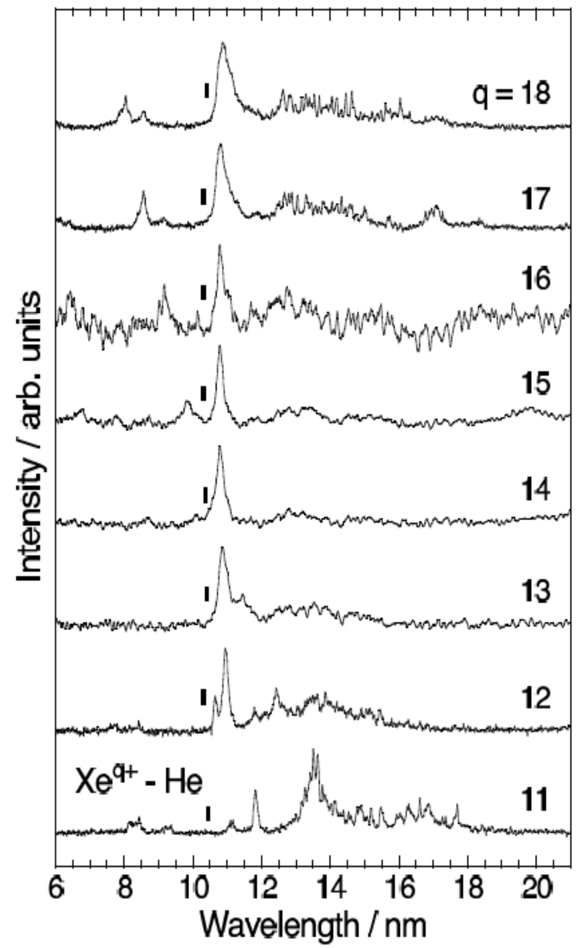
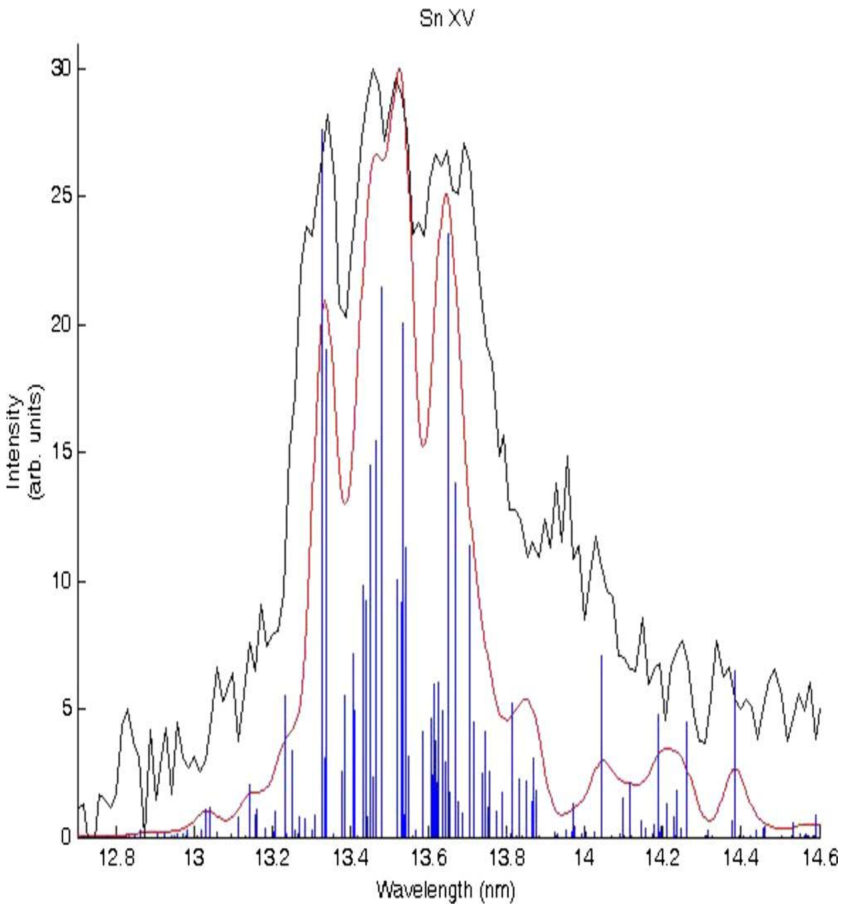
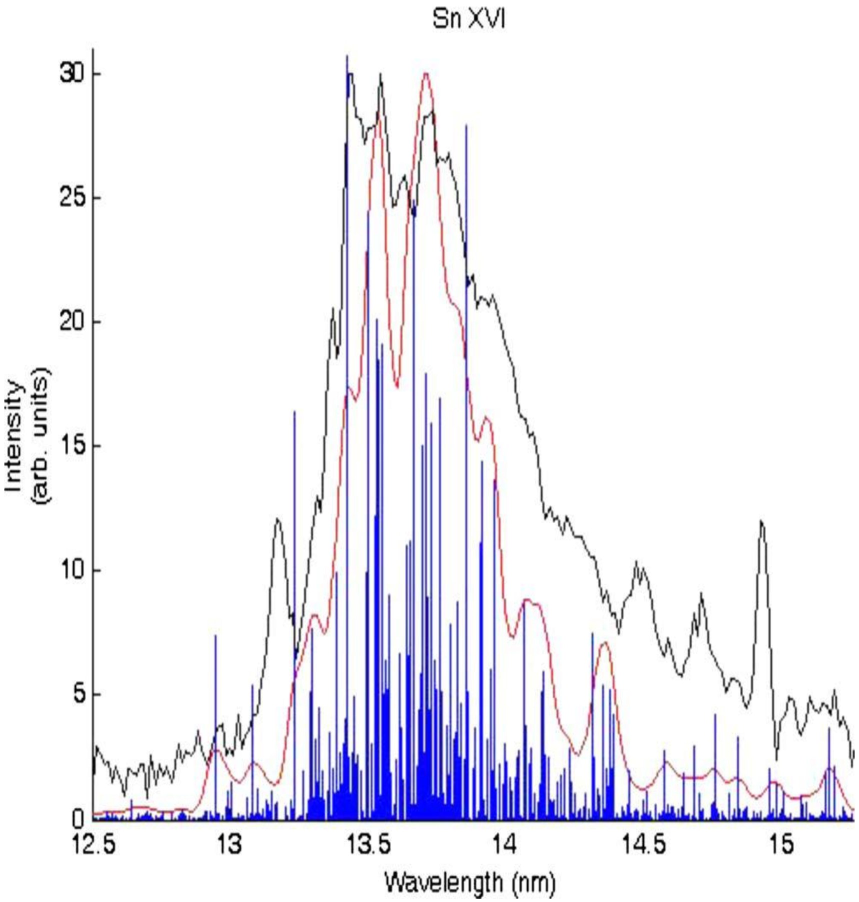


Figure 2. EUV emission resulting from the collisions of Xe^{q+} (q = 11–18) ions with He gas at the energies of 20q keV; same as Figure 1.

Charge Exchange Spectra

D'Arcy et al PRA 79, 042509 (2009)





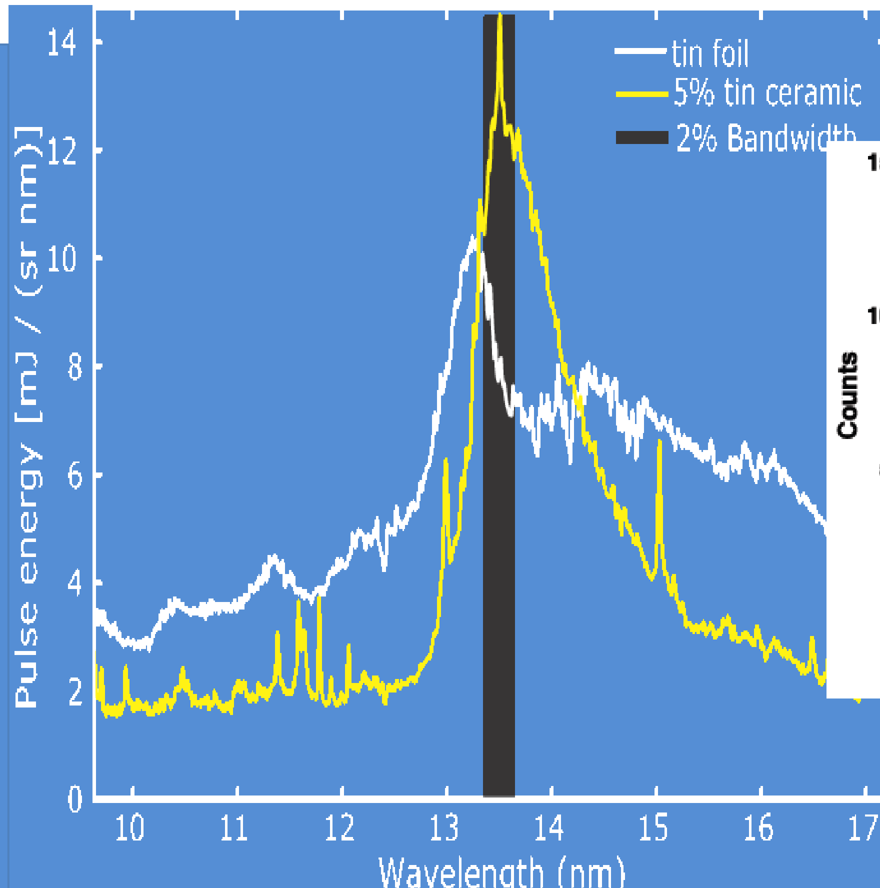
Expect to see:
4p^6 $^1S_0$ – 4p^{5}4d $^1P_1$ of Sn XV,
instead observed 4p^{5}4d – 4p^{4}4d^2+4p^{5}4f satellite lines.
Satellites lie on long wavelength side.

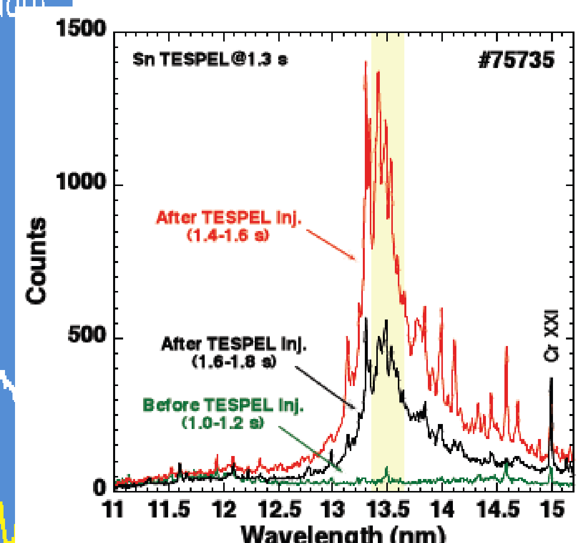
Comparison between the emission of high and low density Sn targets

The UTA narrows with decreasing tin concentration

As concentration decreases off-band emission decreases.

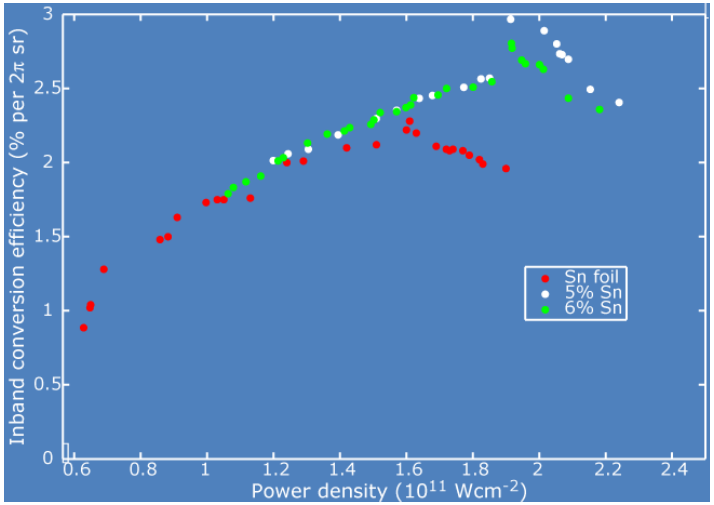
UTA intensity grows with slab targets and reaches a maximum at concentrations (by number) of ~2% - 5%. *(Hayden et al Microelectron Eng. 83, 699 2006)*

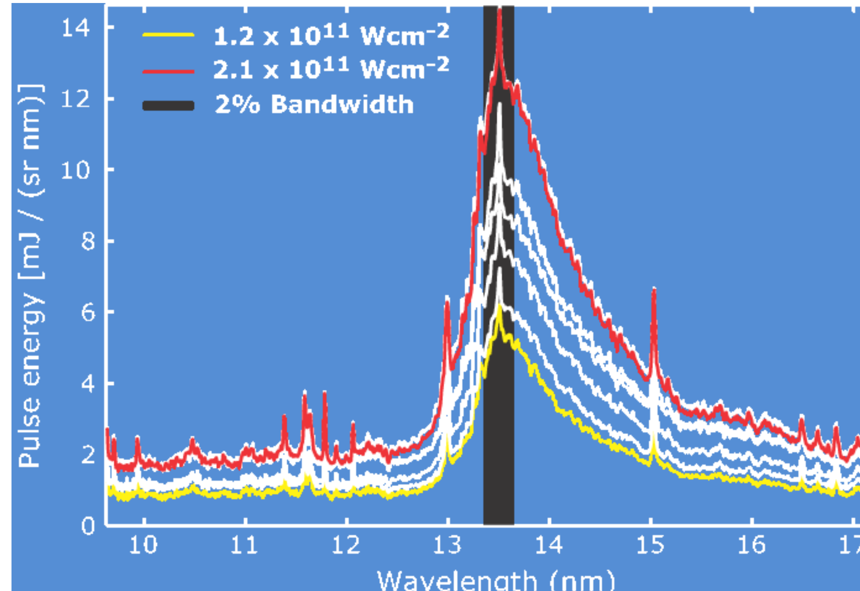


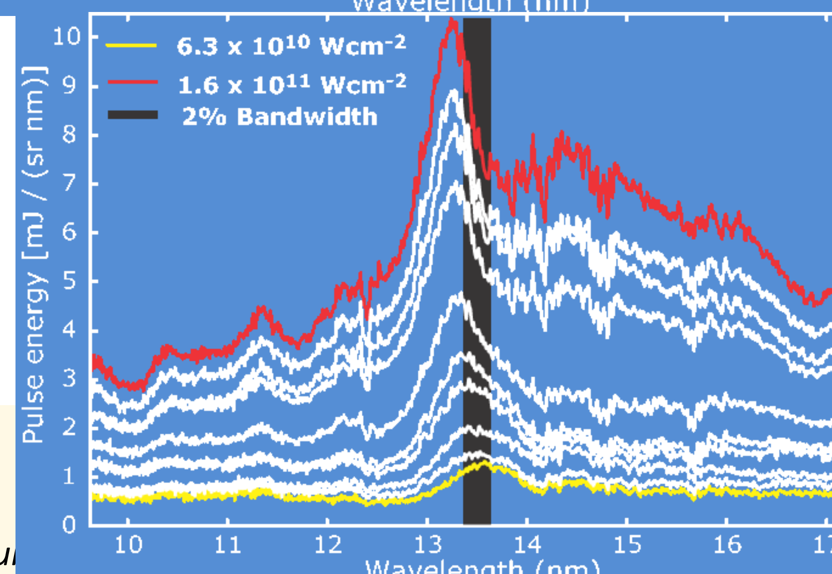


Optically thin spectrum -NIFS *(Suzuki et al JPB 4 , 074027, 2010)*

Sn is the brightest emitter at 13.5 nm







Max inband conversion efficiency *(Hayden et al JAP **99**, 9 ,2006)*

~ 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

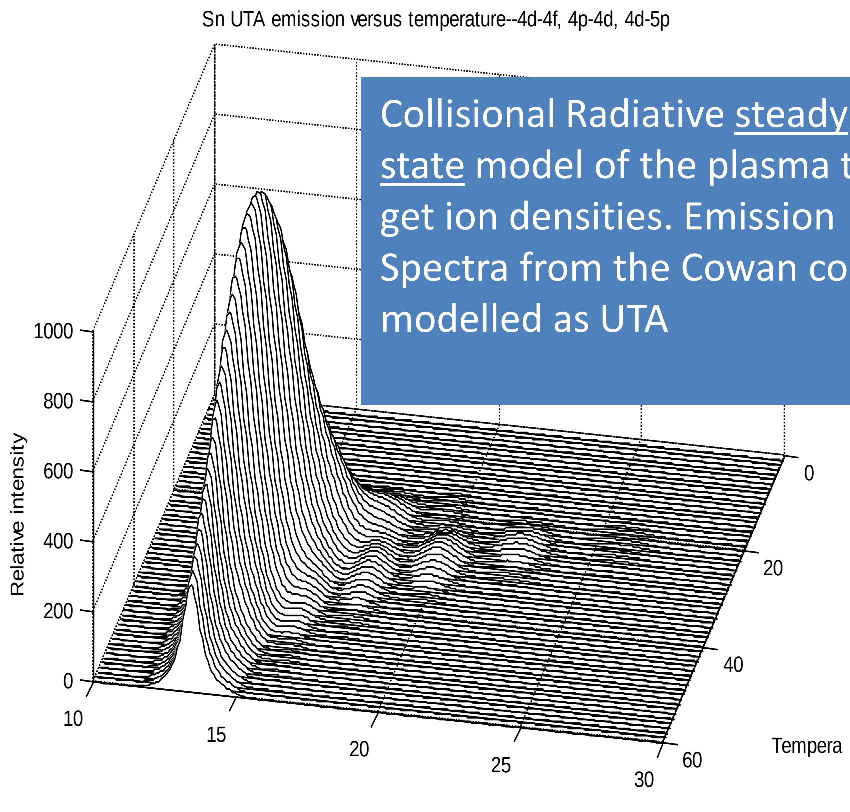
at $\phi \approx 2 \times 10^{11}$ Wcm^{-2}

CE $_{max}$@ 0.5 – 1.0×10^{11} Wcm^{-2} for spherical targets *(Nakai et al. 2004 Proc SPIE Vol. 5196, 289, Nishihara et al. 3rd EUVL Symposiu ... yazaki)*

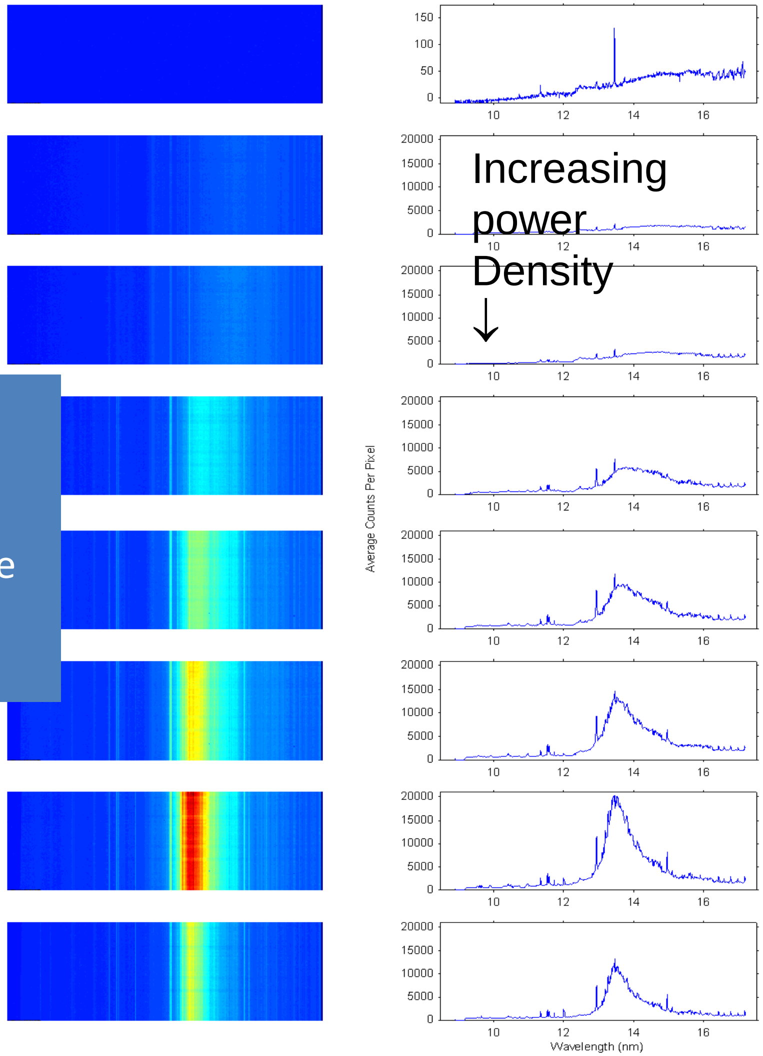
Experimental and theoretical observation of effect of increasing Φ (Optically Thin plasma)

UTA emission increases up to a critical point (Φ ~2×10^{11} Wcm^{-2}).

Maximise contribution from Sn^{9+} - Sn^{12+}



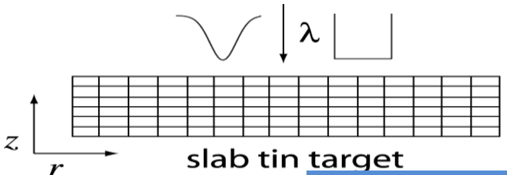
Collisional Radiative steady state model of the plasma to get ion densities. Emission Spectra from the Cowan code modelled as UTA



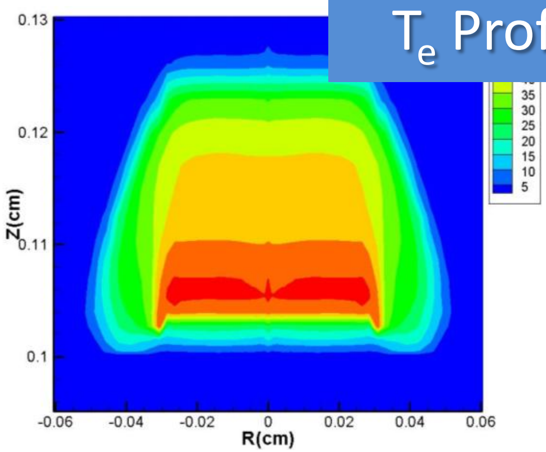
Optimum 30 < T_e< 40 eV

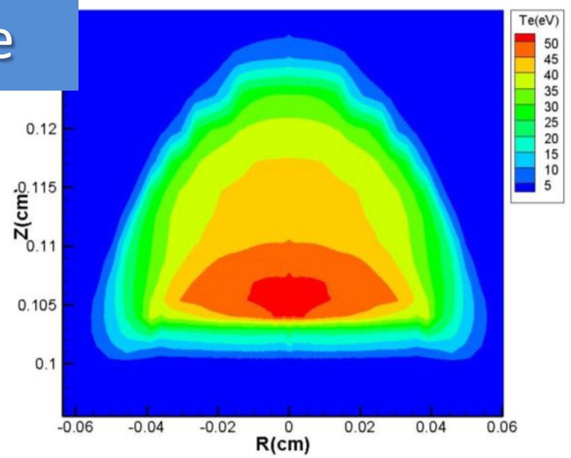
Effect of Pulse Shape

Z* code developed by EPPRA sas *(Zakharov et al 4th EUVL Symposium San Diego 2005).*

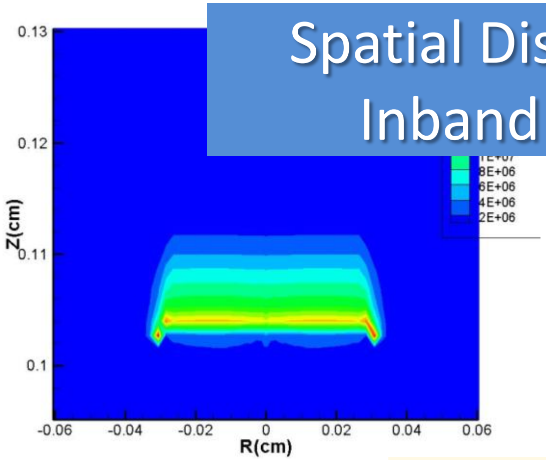


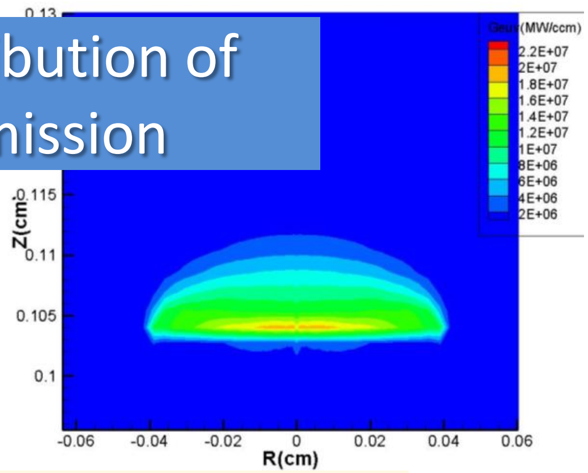
T_e Profile

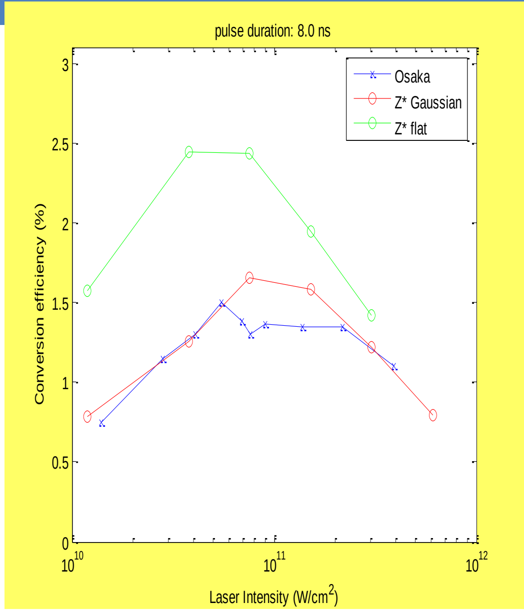




Spatial Distribution of Inband Emission







Comparison with ILE data (Nd:YAG Gaussian profile)

Top-Hat profile always gives higher CE than Gaussian.

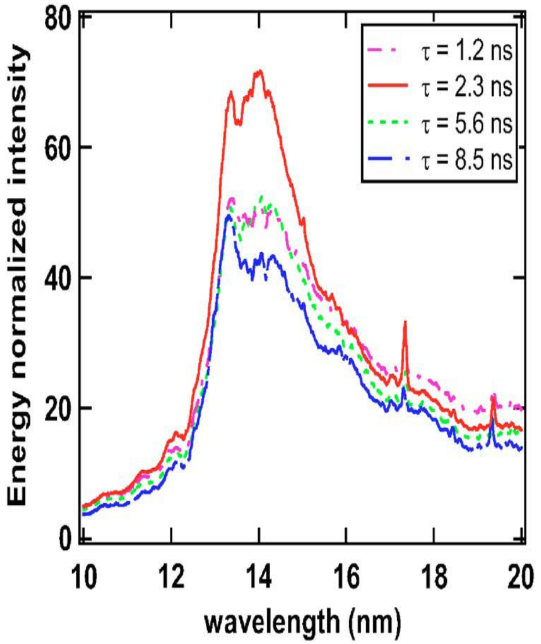
CE lower for longer pulse.

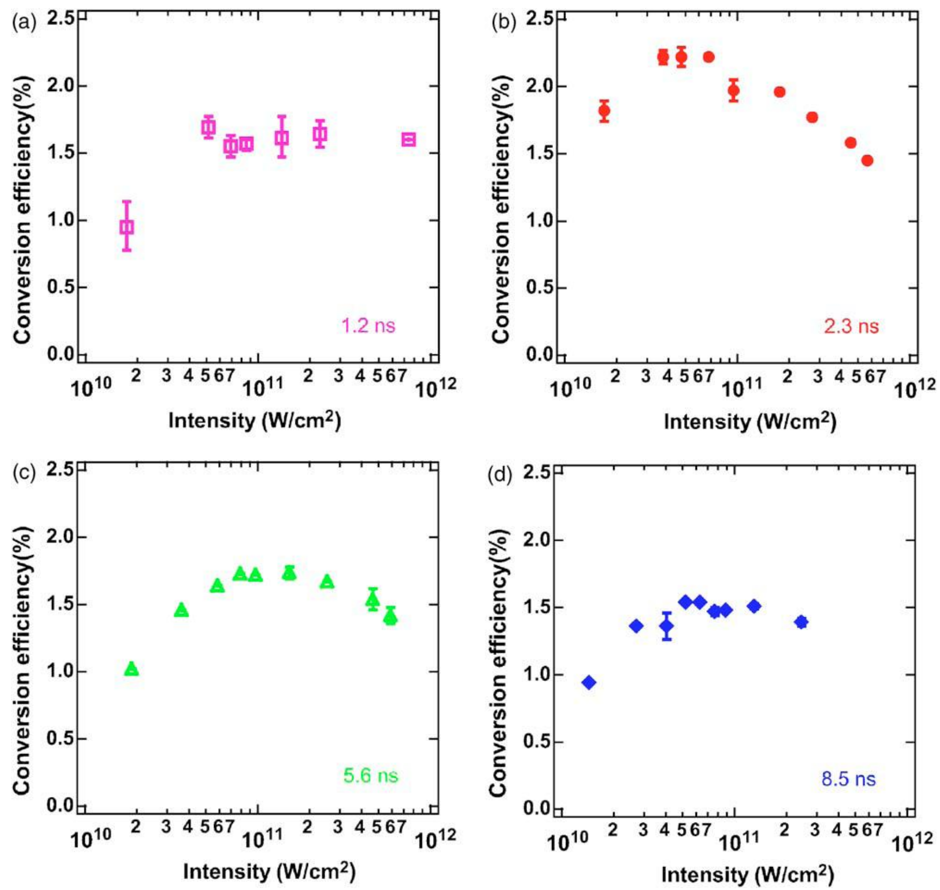
White et al APL ***92****, 151501 (2008)*

Effect of Pulse Duration

Ando et al. *(2006 APL **89**, 151501) studied* CE for a number of pulse lengths varying from 1.2 to 8.5 ns.

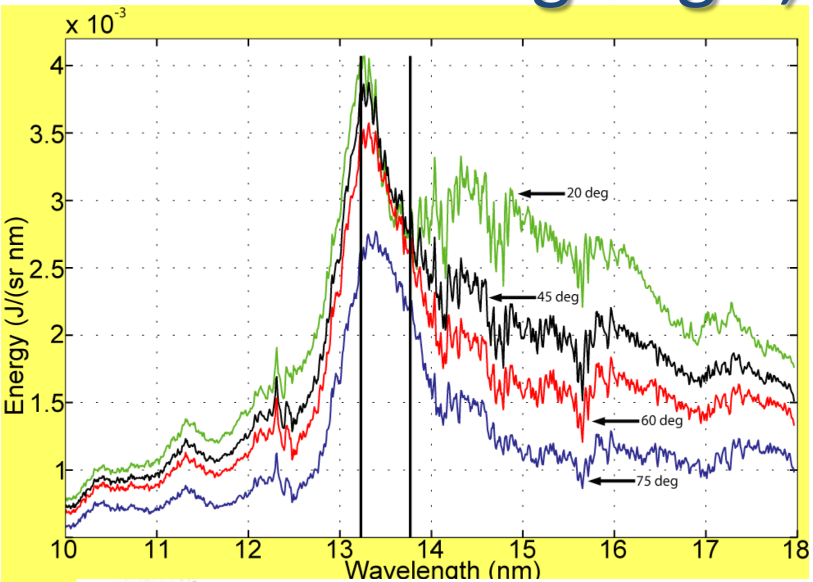
optical depth α pulse duration×(Intensity)$^{5/9}$ ×(λ)$^{-4/3}$

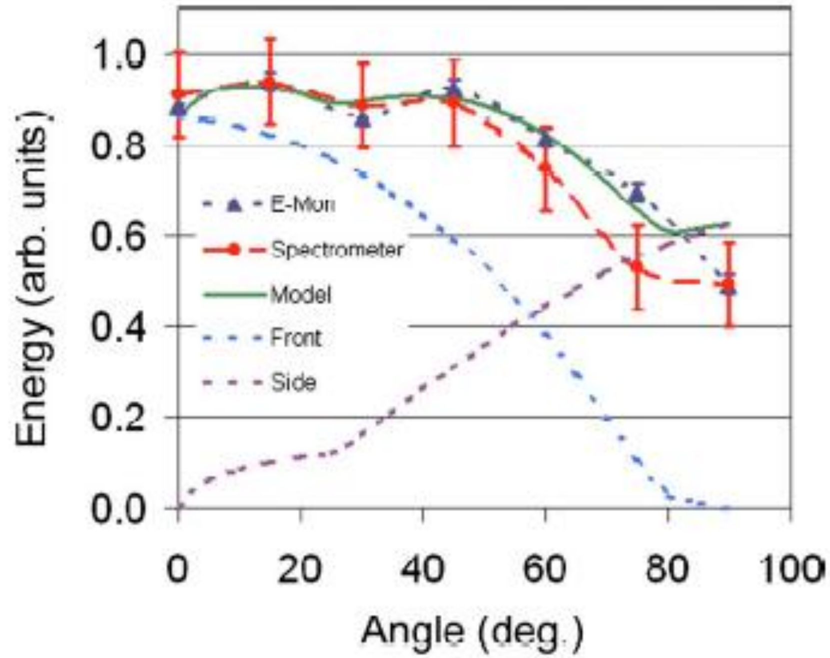




Intensities at different pulse lengths and corresponding EUV CE for Nd: YAG irradiation of solid Sn

Effect of viewing angle, anisotropy of emission





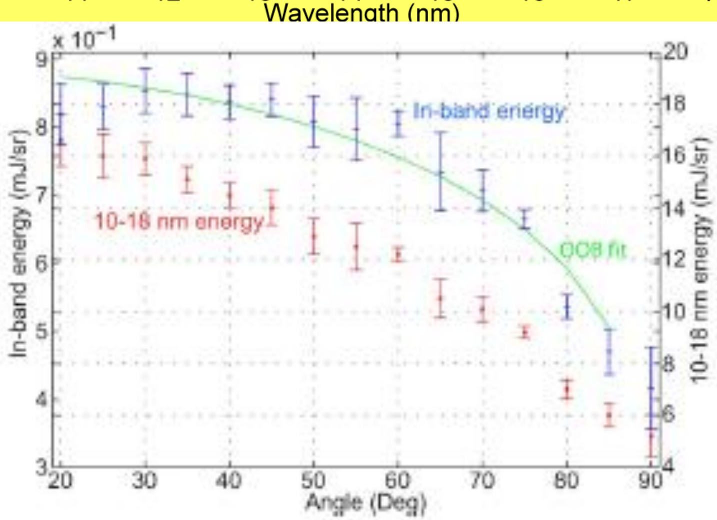


FIG. 4. (Color online) Angular distributions of intensities emitted in the 2% band centered on 13.5 nm [including the (OOB) fit (Ref. 9)] and between 10 and 18 nm.

Angular variation of emission from a laser produced Sn plasma, as a function of viewing angle from normal incidence. *(Sequoia et al APL **92**, 221505 2008, Morris et al. JAP **92** 231503 (2008)*

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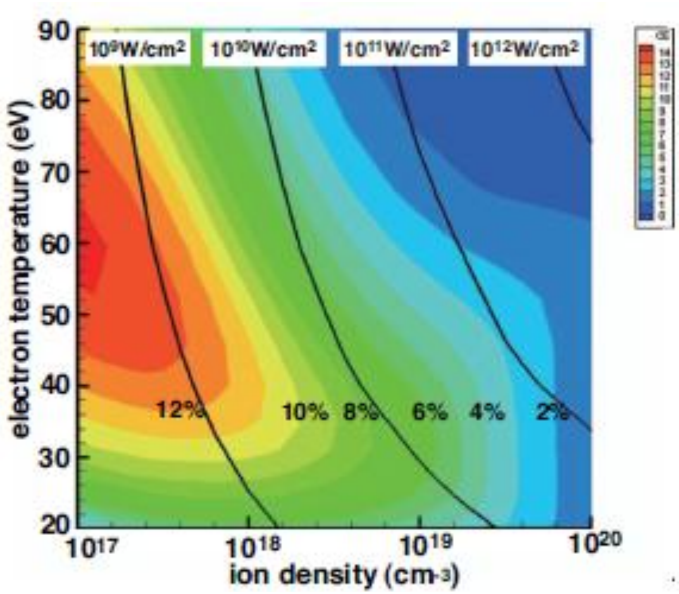
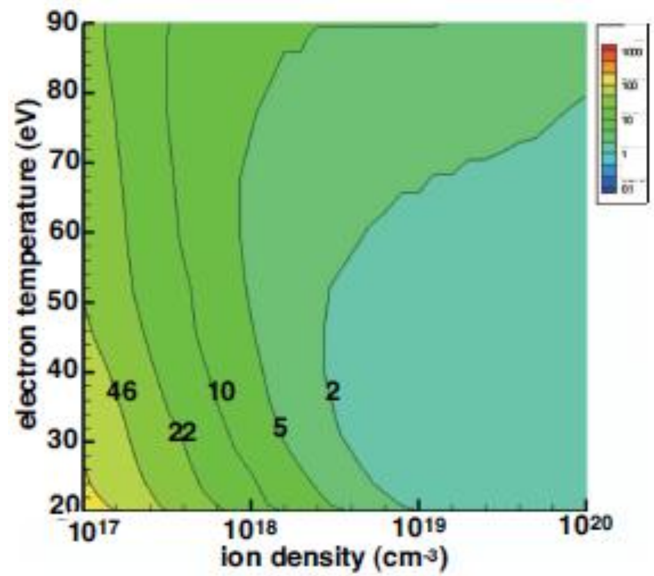
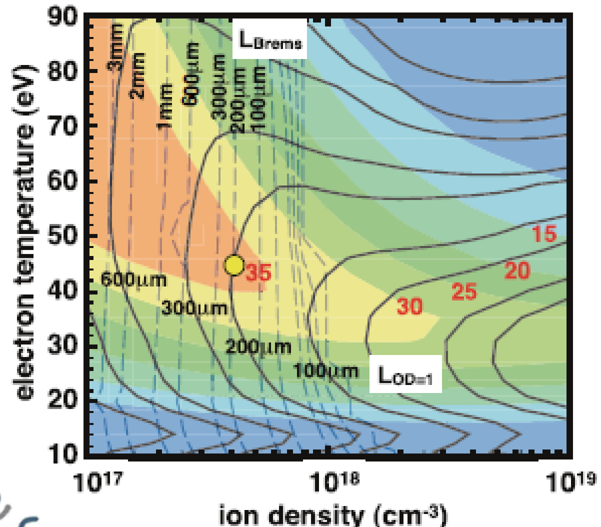
Theoretical Predictions for Optimum conditions

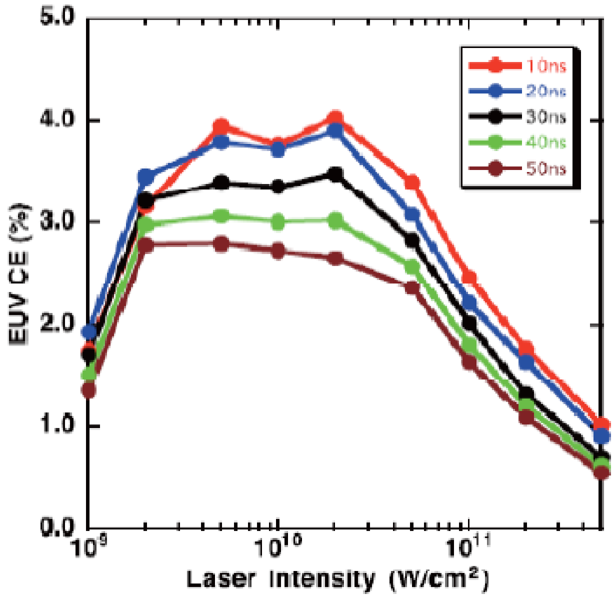






Optimum conversion efficiency, optimum pulse durations and spectral efficiencies for maximum conversion as a function of ion density and plasma electron temperature. *(Nishihara et al Phys Plasmas 15, 056708 2008)*

Effect of pulse duration and target shape



Effects of CO_2 pulse duration on EUV conversion efficiency from slab Sn targets *(Sunahara et al Plasma and Fusion Res.3,43 2008)*

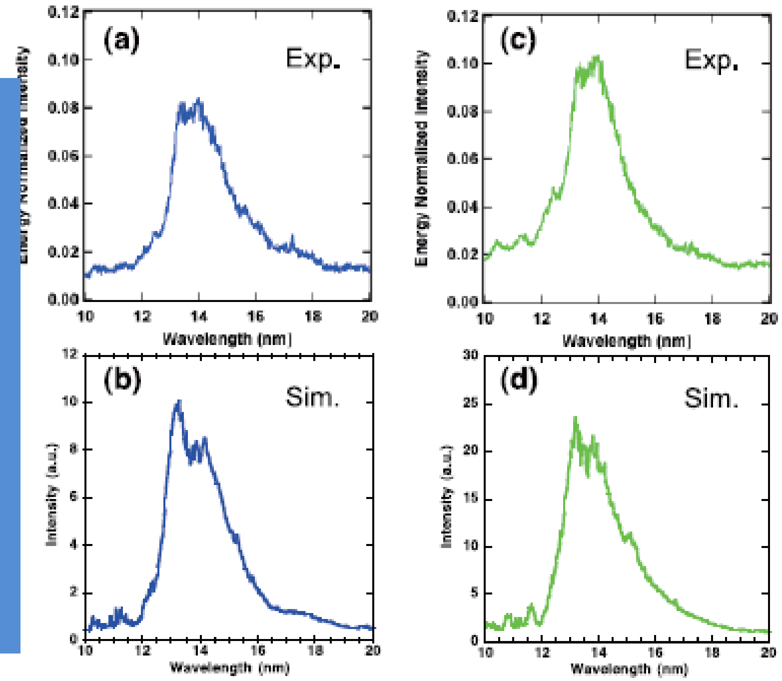
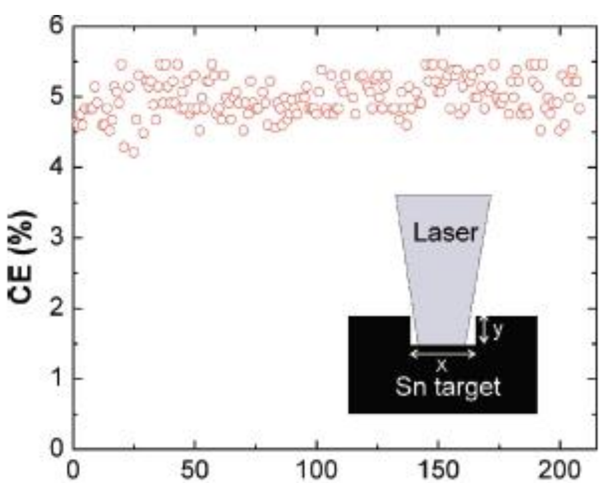


Fig. 3 Comparison of EUV spectra. (a) Experiment with 4×10^{10} W/cm^2. (b) Calculated with 4×10^{10} W/cm^2. (c) Experiment with 1×10^{11} W/cm^2. (d) Calculated with 1×10^{11} W/cm^2.



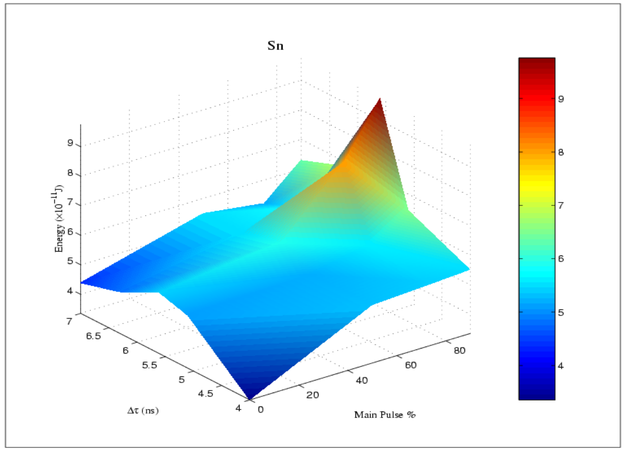
The CE obtained from a 400 µm wide, 200 µm deep grooved target. The spot size used in the measurement was 325 µm. *(Harilal APL* 96, 111503 *2010)*

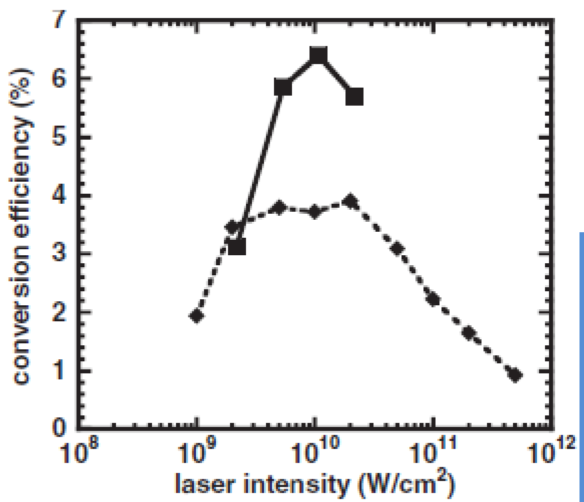
Effect of Prepulses

The use of prepulses greatly enhances intensity in X-ray and EUV regimes

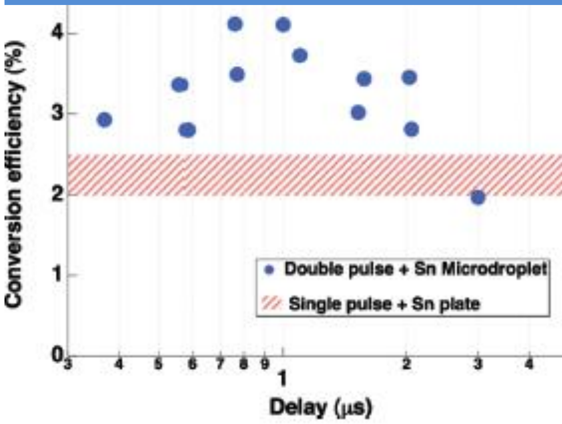
e. g. Mochizuki et al. 1986 PRA33, 525
Kodama et al. 1987 Appl. Phys. Lett. 50, 720
Tanaka et al. 1988 J. Appl. Phys. 63, 1767
Teubner et al. 1991, Appl. Phys. Lett. 59,2672
Wulker et al. PRE 1994, 4920

Efficiency increases because of increased emitting volume with lower density and opacity





CE as a function of interpulse delay for a 40 ns pulse *(Fujioka Plasma and Fusion Research 4, 048, 2009)*



Conversion efficiency dependence on CO_2 laser intensity for single (dashed) and double (solid) irradiation by a 10 ns pulses. The interpulse delay was 180 ns *(Nishihara et al Phys Plasmas 15, 056708 2008)*

Outline

- Historical Background

  Properties of Laser Produced Plasmas relevant to EUVL

- Results from studies of Xe and Sn Nd:YAG LPP

- Results from studies Sn CO_2 LPP

- Recent work on Gd and Tb sources for 6.7 nm

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

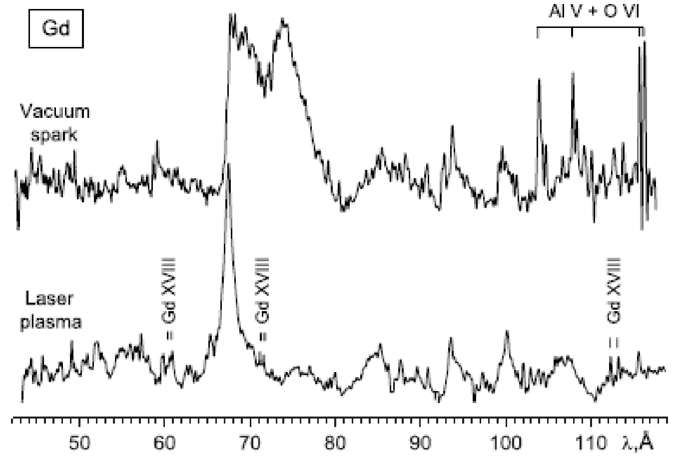


Figure 1. Spectra of gadolinium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace).

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*
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[4]*Forschungszentrum Dresden, Bautzner Landstrs. 400, D-01328 Dresden, Germany*

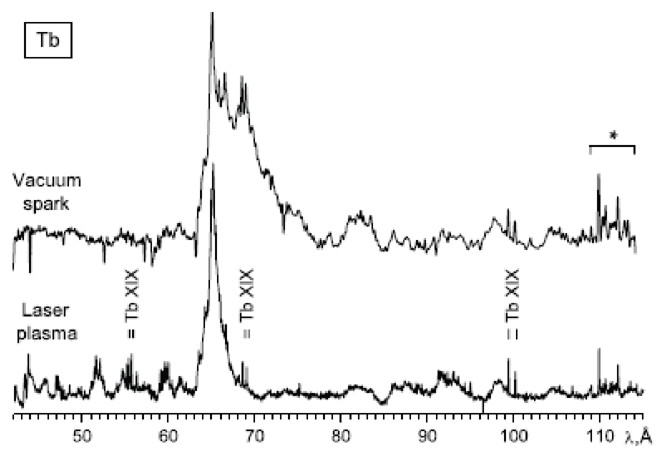


Figure 2. Spectra of terbium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace). ∗, $4f^2$–$4f5d$ transition array in Tb XVIII classified in the present work.

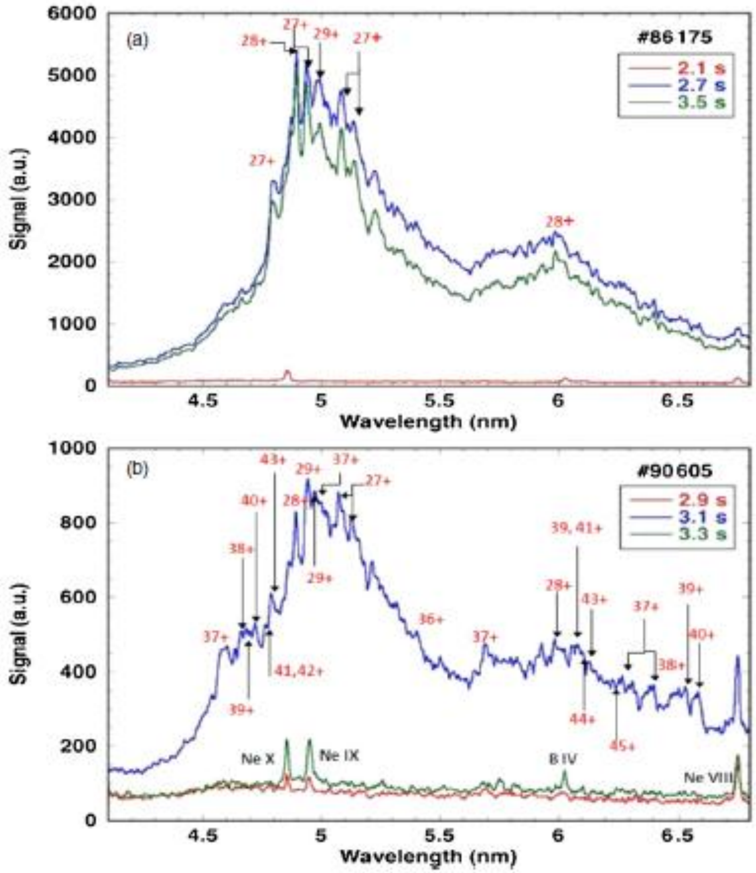
Most Important Stages?

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

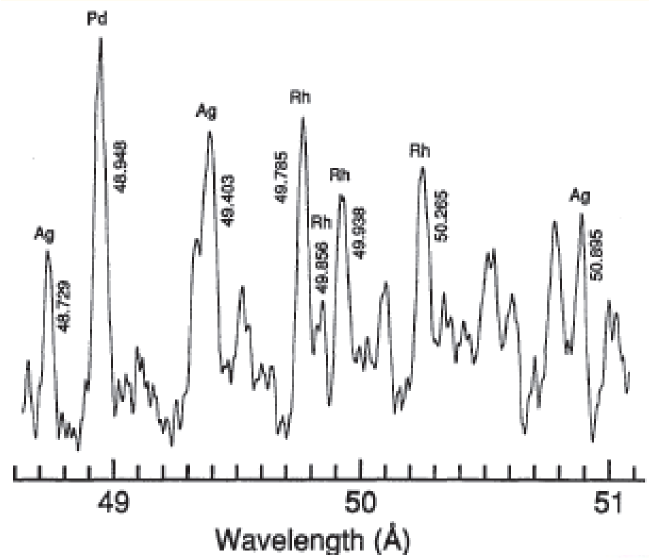


The most important transitions can be inferred from studies of W spectra.

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
$\lambda = 1.06\ \mu m$
$\Phi = (5\text{–}8)\times10^{11}\ Wcm^{-2}$

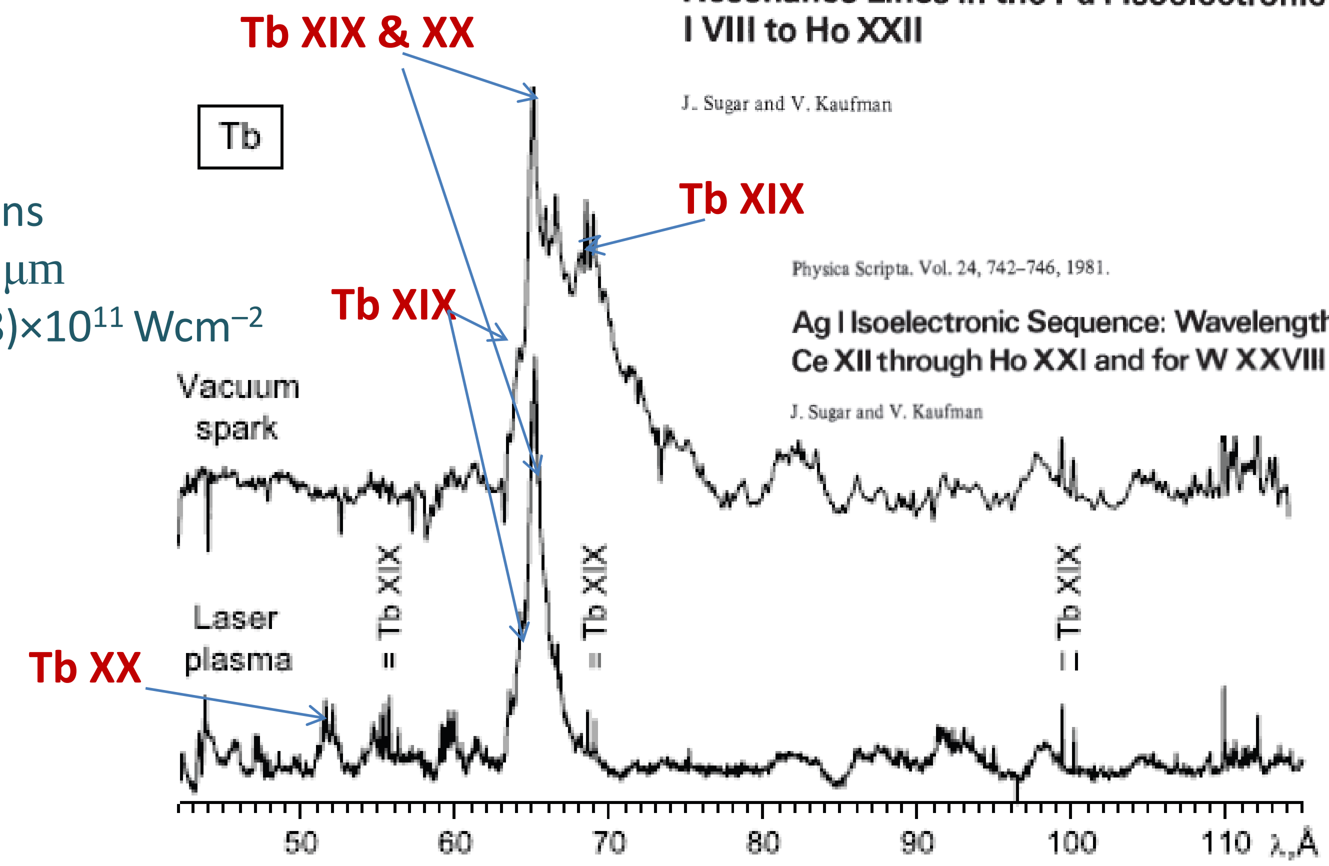
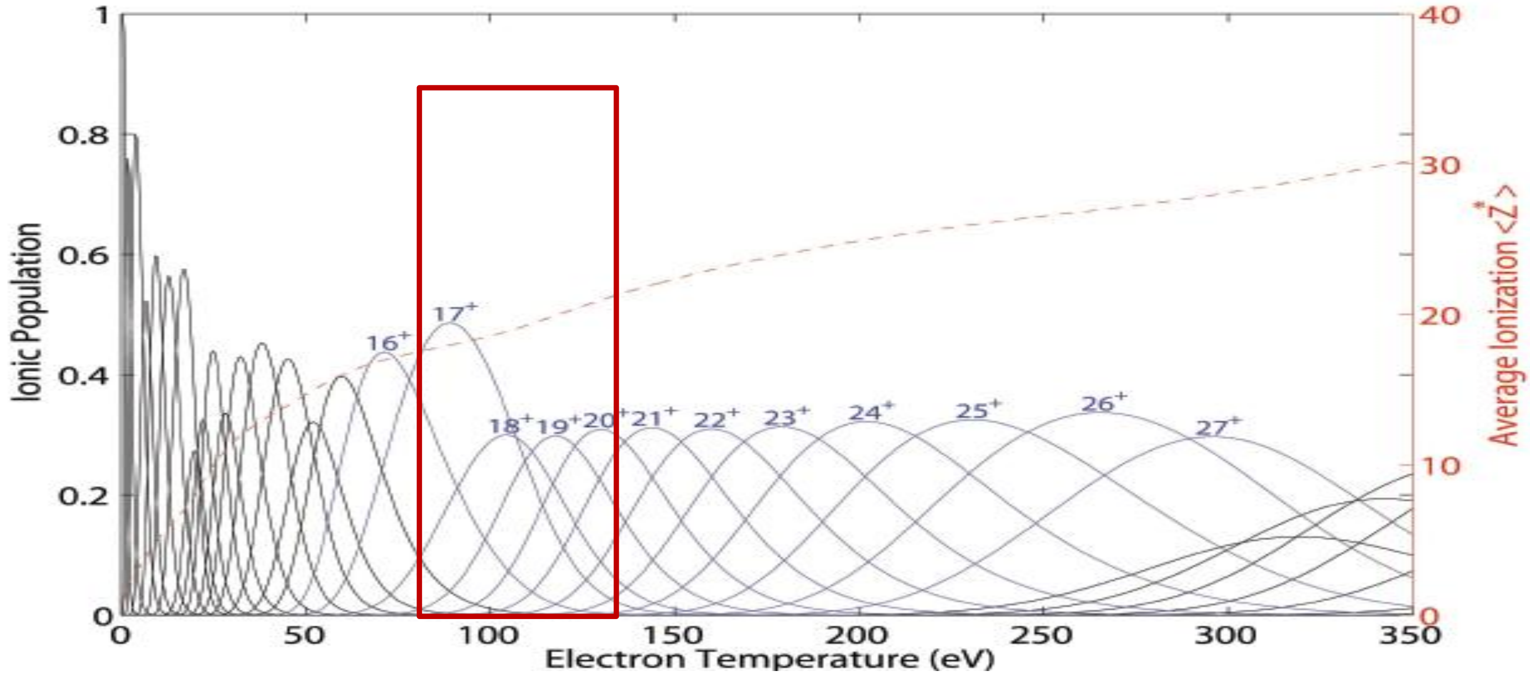


Figure 2. Spectra of terbium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace). ∗, $4f^2$–$4f5d$ transition array in Tb XVIII classified in the present work.

Power Density Requirements

Ion populations and average ionization of a Gd plasma as a function of T_e computed with the CR model. Most important stages are Ag-, Pd- and Rh- like (17+ - 19+)

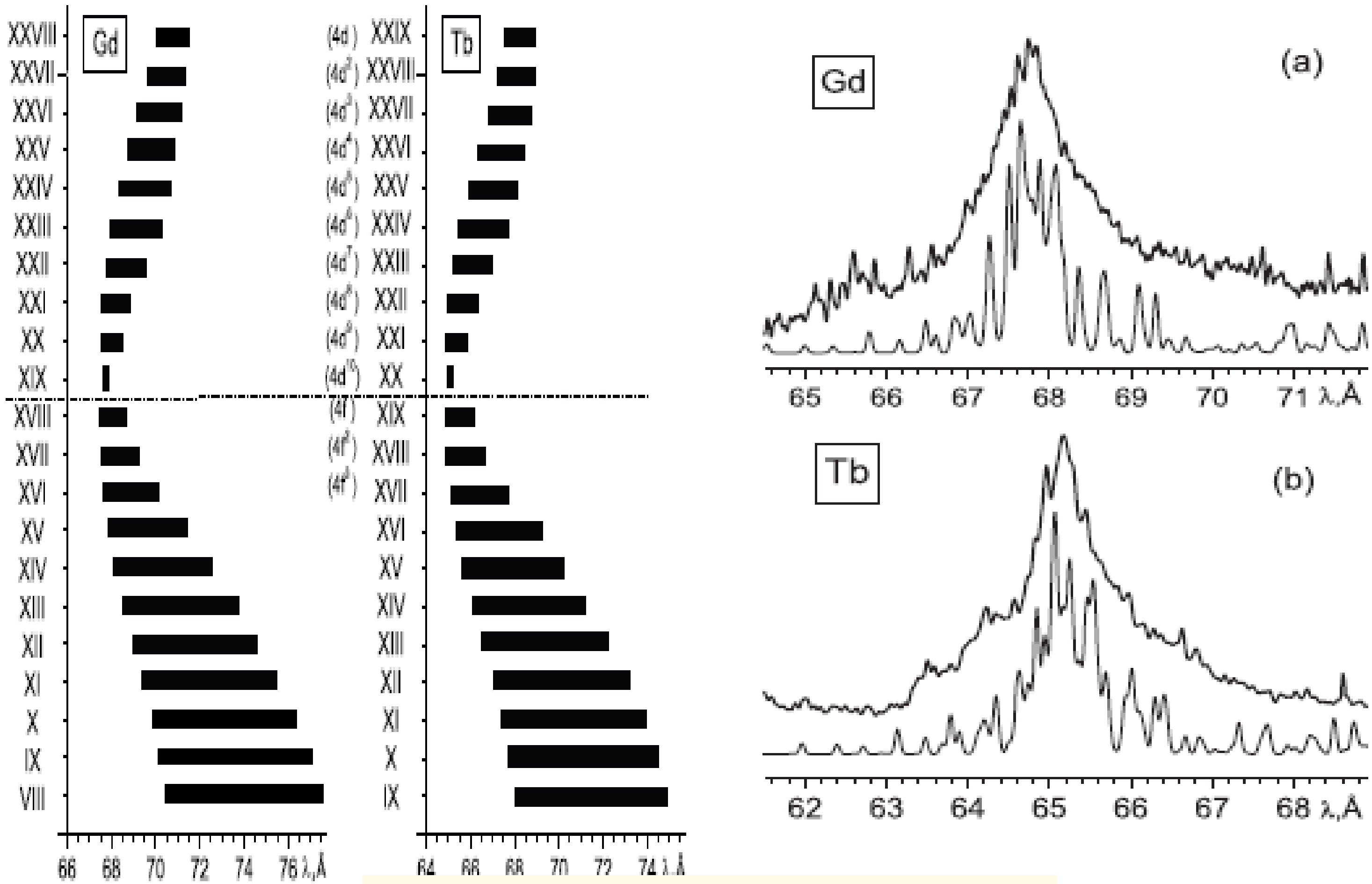


The laser power density required lies in the range

$2x10^{12} – 10^{13}$ Wcm^{-2} @λ =1.06 µm

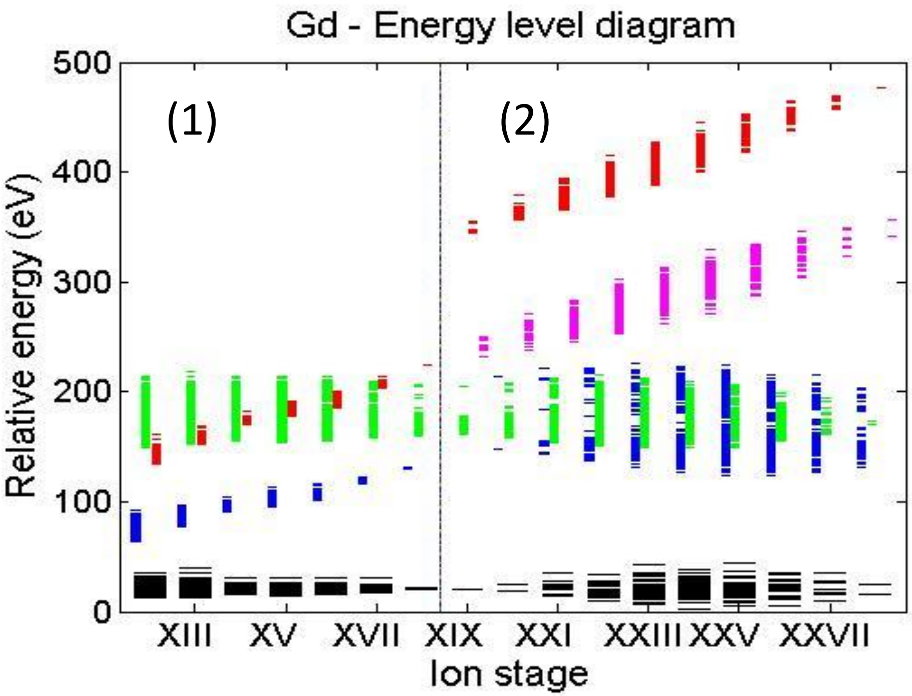
$2x10^{11} – 10^{12}$ Wcm^{-2} @λ =10.6 µm

First Calculation of Spectral Emission

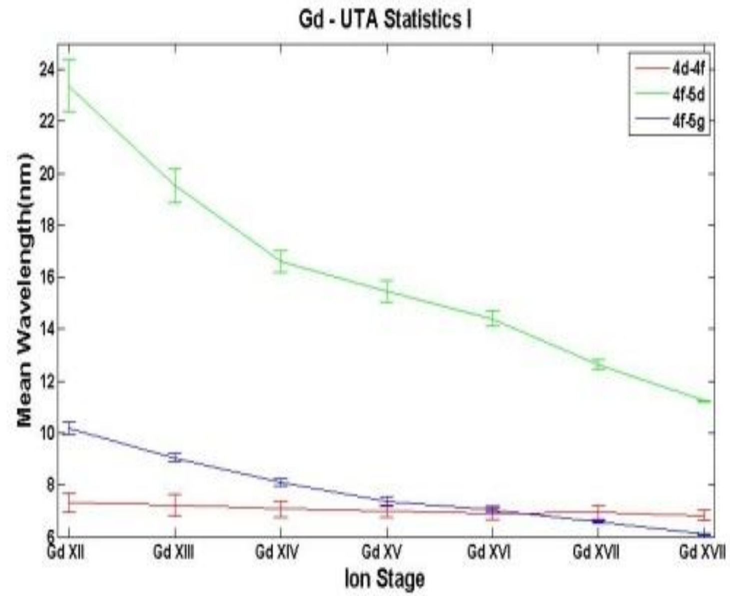


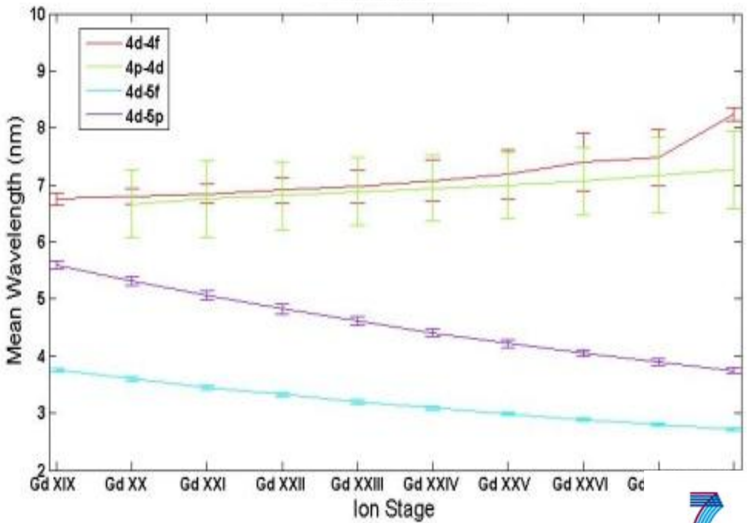
Churilov et al Phys Scr. 80, 045303, 2009

Levels and Transitions in Gd



Energy-level diagram. (1) Gd XII – Gd XVIII: 5d (blue), $4d^{-1}$ (green), 5g (red) and 4f (black).
(2) Gd XIX – Gd XXVIII: 4p (blue), 4f (green), 5f (red) , 5p (magenta) and 4d (black).





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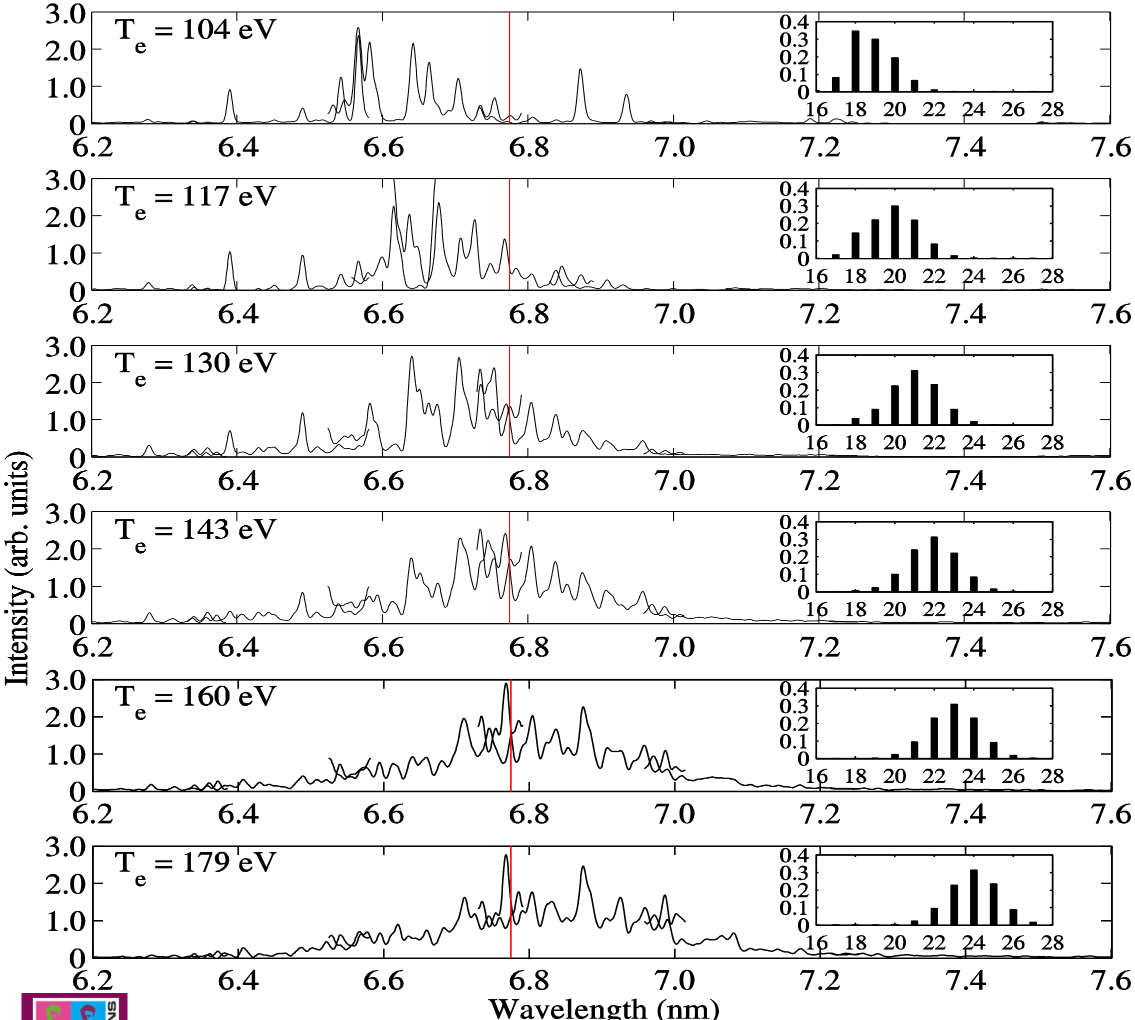
FAC Code Calculations for Gd

JOURNAL OF APPLIED PHYSICS 108, 104905 (2010)

Extreme ultraviolet emission spectra of Gd and Tb ions

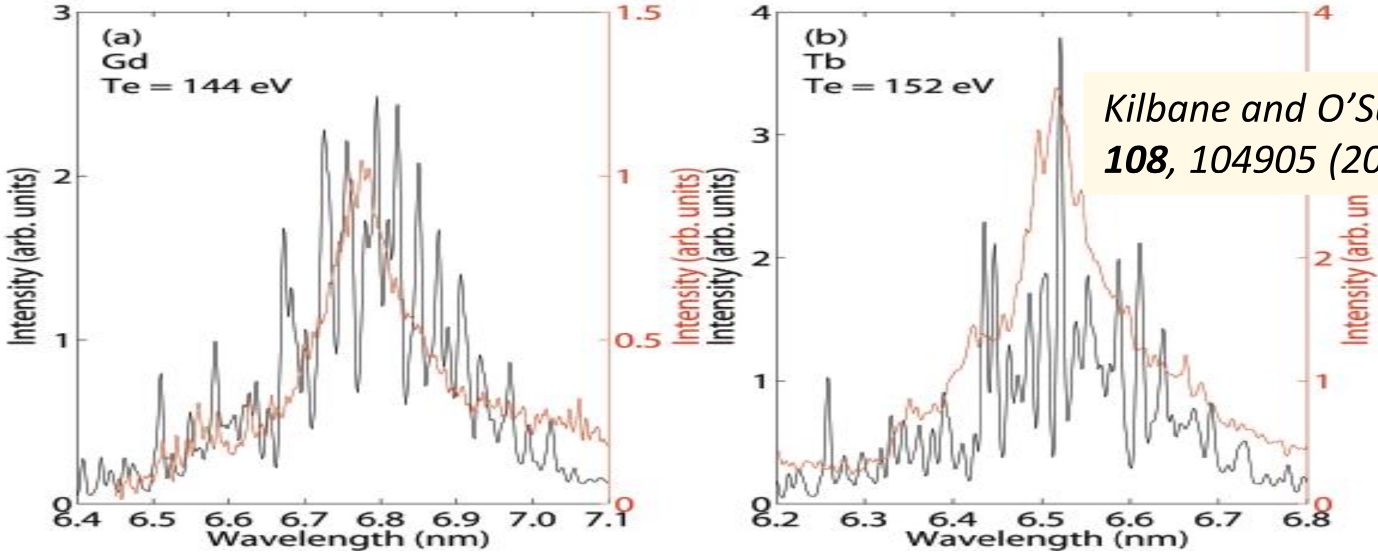
D. Kilbane[a] and G. O'Sullivan
School of Physics, University College Dublin, Belfield, Dublin 4, Ireland



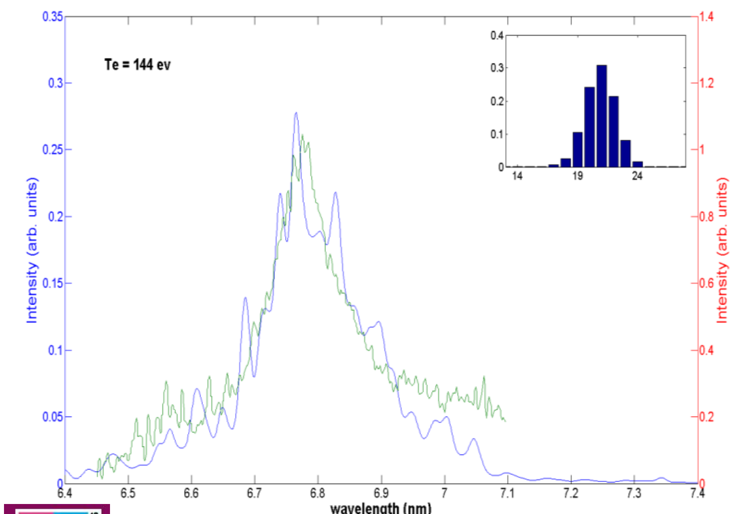
Calculations more complex than for Sn because of open 4f subshell in ions lower than 18+

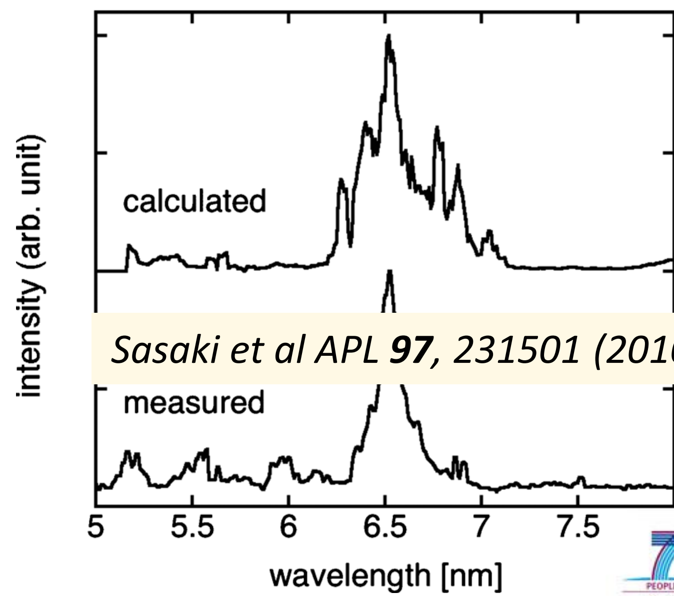
In low stages, 4f, 5p and 4f, 5s level crossings give rise to very complex interacting configurations

Calculations for Gd and Tb spectra



*Kilbane and O'Sulivan JAP **108**, 104905 (2010);*





*Sasaki et al APL **97**, 231501 (2010);*

Experimental Investigations on Gd

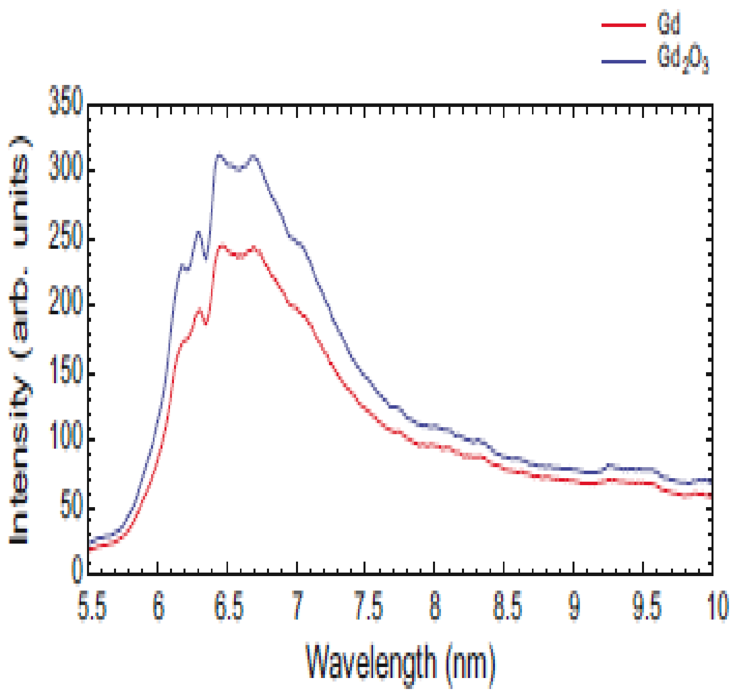


FIG. 3. (Color online) Spectral comparison for the low- (blue) and the solid-density target (red) at different laser intensities of 1.6×10^{12} W/cm^2.

Opacity an issue, CE improves as concentration decreases

CEs up to 1.8% (in 2% bandwidth measured)

CO_2 should be more effective than Nd:YAG

Otsuka et al. APL 97 111503 2010
Otsuka et al. APL 97 231503 2010

Conclusions

13.5 nm:

•Highest conversion efficiencies in Sn plasmas.

•Ideally need short ~ 10 ns, flat-top CO_2 pulse irradiated droplet targets

•$\Phi \sim 5\times10^9 - 1\times10^{10}$ Wcm^{-2}

•T_e ~ 40 eV

•CE (optimum) ~ 6%

6.X nm:

•Broadly same physics as Sn sources, ion stages with 4d subshell greater than half full now more important (opposite to Sn case)

•Strongest lines expected from Ag-like and Pd-like ions.

•Opacity an issue…low density targets or CO_2 plasmas

•Ideally need short ~ 10 ns, flat-top CO_2 pulse

•$\Phi \sim 2\text{x}10^{11} – 10^{12}$ Wcm^{-2} @λ =10.6 μm

•T_e < 140 eV (~100 eV optimises 17+ - 19+)

•CE will be lower because of higher plasma temperature

Thanks to

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- *Akiro Endo, Forschungszentrum Dresden*
- *Takako Kato, Daiji Kato & Chihiro Suzuki NIFS*
- *Hajime Tanuma, Tokyo Metropolitan University*
- *Dong Chenzhong & Su Maogen, Lanzhou*
- *K. Nishihara, H. Nishimura & S. Fujioka ILE Osaka*
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