Development of EUV Lithographic Sources at UCD

Deirdre Kilbane

School of Physics, University College Dublin

Deirdre.Kilbane@ucd.ie

14th ADAS WORKSHOP, Ringberg Castle, Germany, October 5th 2009

Outline

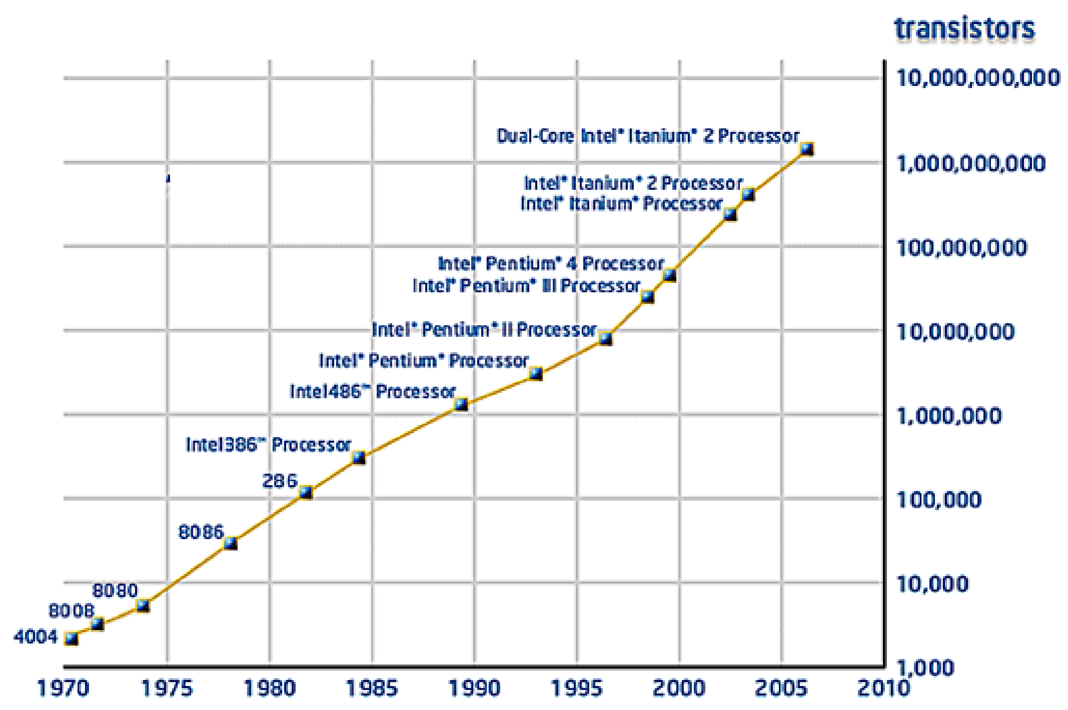
- Motivation
- LPPs as a source
    - Target material
- Experimental Sn emission spectra
    - Variable laser power density
    - Variable target composition
- Theoretical comparison
    - Time dependent 1-D model
    - Z* calculations
- Summary

Moore's law

Number of transistors doubles every two years

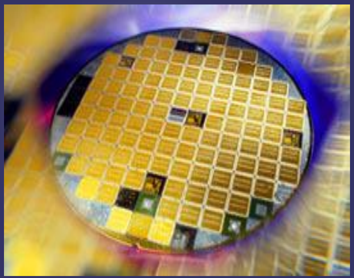
Currently @ 45 nm node

Source λ=193 nm
ArF excimer
    @ 65 nm (dry)
    @ 45 nm (immersion)



Recent chip manufacturing timetable

Year	**2004**	**2005**	**2007**	**2009**	**2011**
Node	90	65	45	32	22
Source	193 nm ArF	193 nm ArF (with immersion)		13.5 nm LPP/DP	



Mo / Si mirrors require high intensity flux in 13.5 nm ±1%

Laser produced plasmas as a source

$T_e(\mathrm{eV}) \approx bA^{1/5}(\lambda^2\Phi)^{3/5}$

$\langle Z \rangle \approx 0.67\,(AT_e)^{1/3}$

laser power density, Φ, controls:

plasma temperature, T_e, 10 – 100 eV

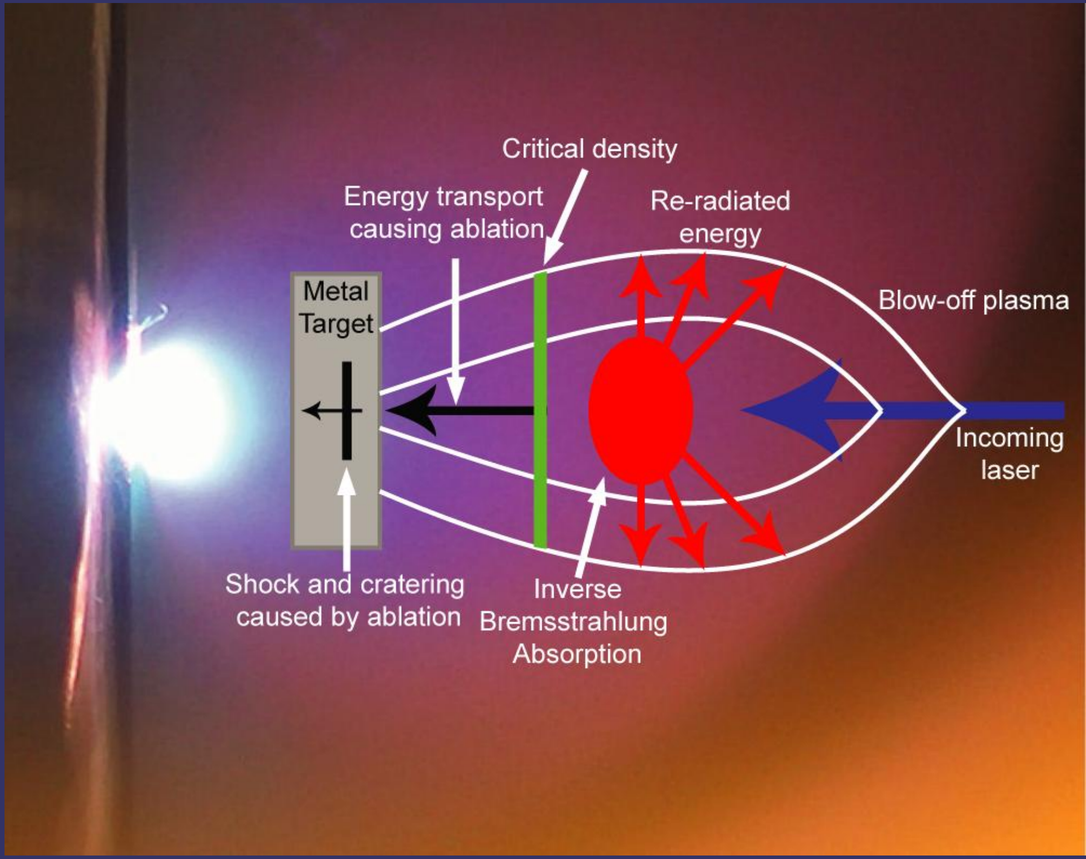
ion distribution ~ 20 times ionised

$n_{ec} \approx 10^{21}/\lambda^2\ \mathrm{cm}^{-3}$

Laser wavelength, λ, controls:

Electron density, n_{ec}, 10^{19} – 10^{21} cm^{-3}

Hottest at centre, cooler margins - opacity issues



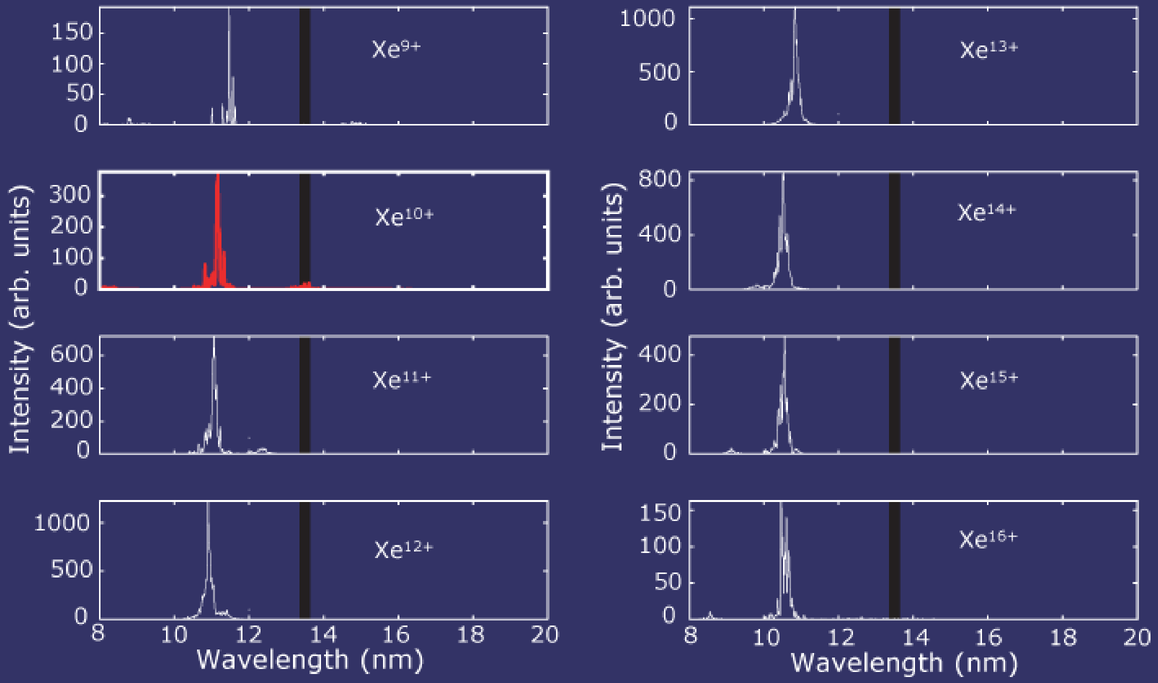
Conversion Efficiency

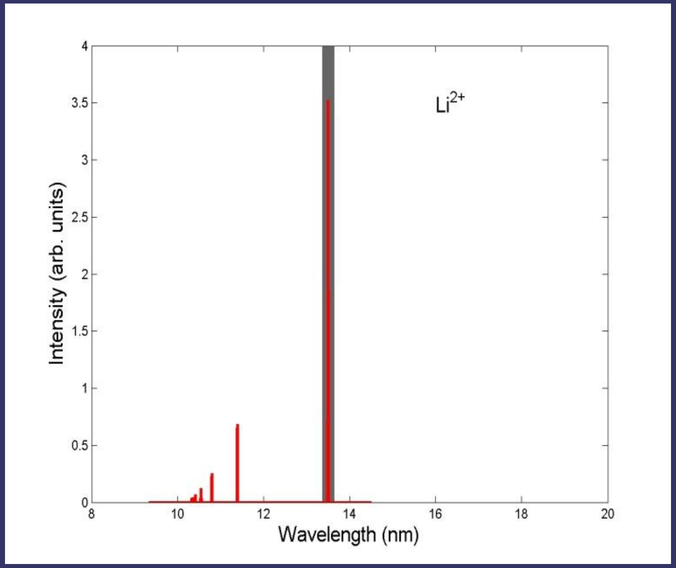
$$CE(\%) = \frac{E_{13.5nm\pm1\%}}{E_{laser}} \times 100$$

Target material

Xenon: 13.5 nm emission originates from 4d - 5p lines only from Xe^{10+}

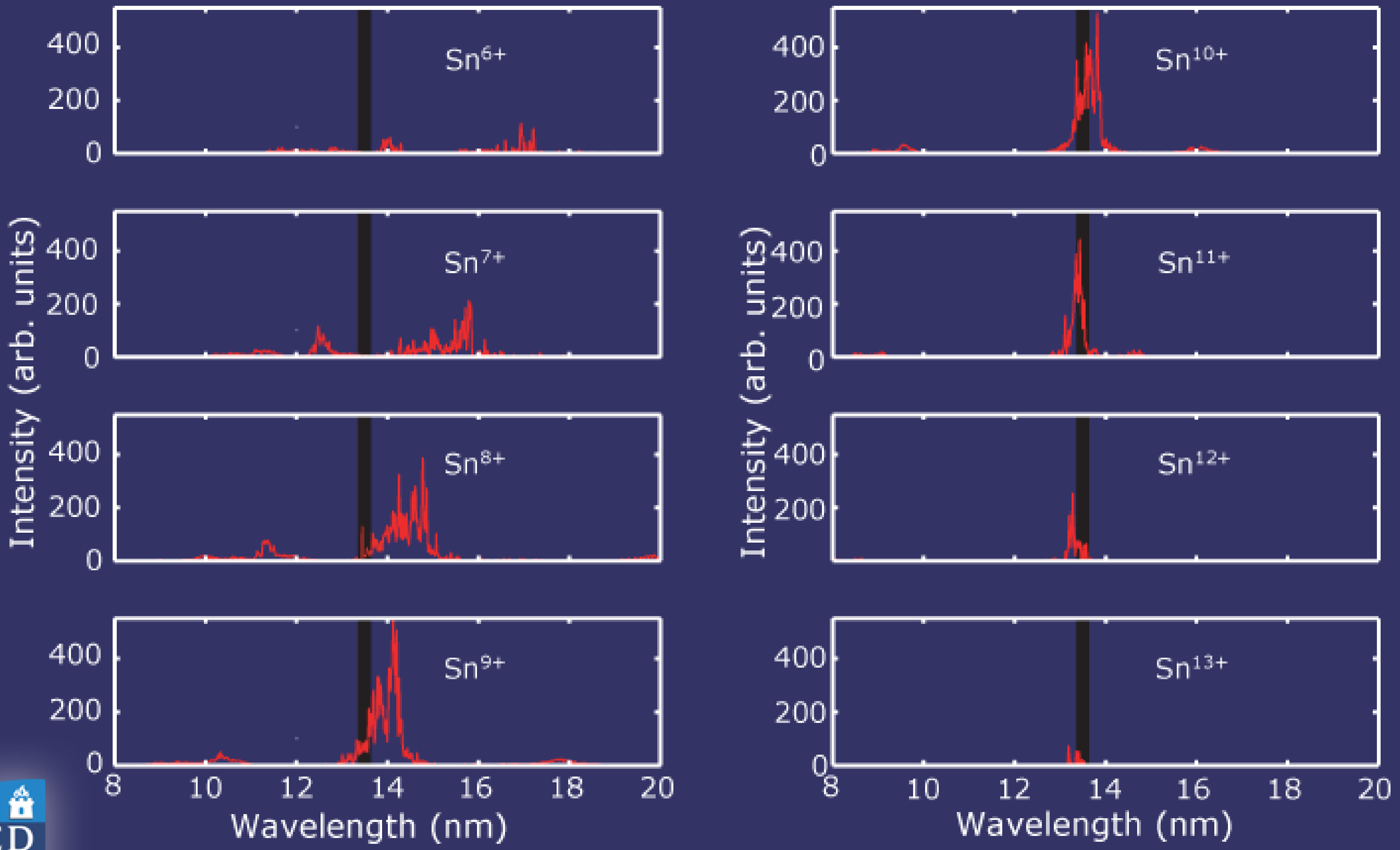
Lithium: Li^{2+} has only one line 1s – 2p at 13.5 nm





Tin: Strong 4d - 4f and 5p - 4d transitions near 13.5 nm from many different ions results in an Unresolved Transition Array (UTA)

Many ion species (Sn^{6+}–Sn^{13+}) contribute to $4p^64d^n$ - $4d^{n-1}4f$ + $4p^54d^{n+1}$ UTA, centred at 13.5 nm

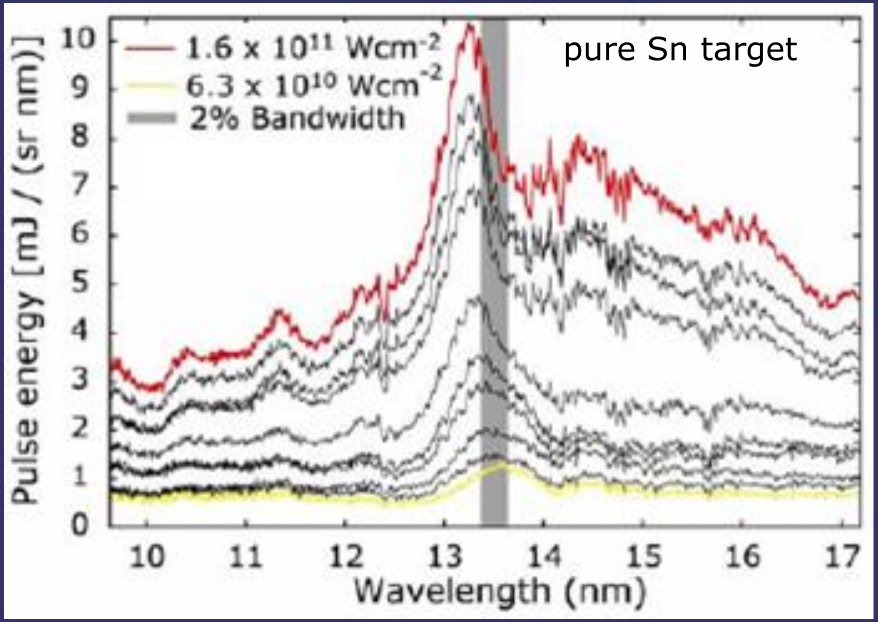


Configuration Interaction effects are very important

Koike et al, *J. Elec. Spec. Relat. Phen.* **144** 1227 (2005)

G. O'Sullivan, and R. Faulkner, *Opt. Eng.* **33** 3978 (1994)

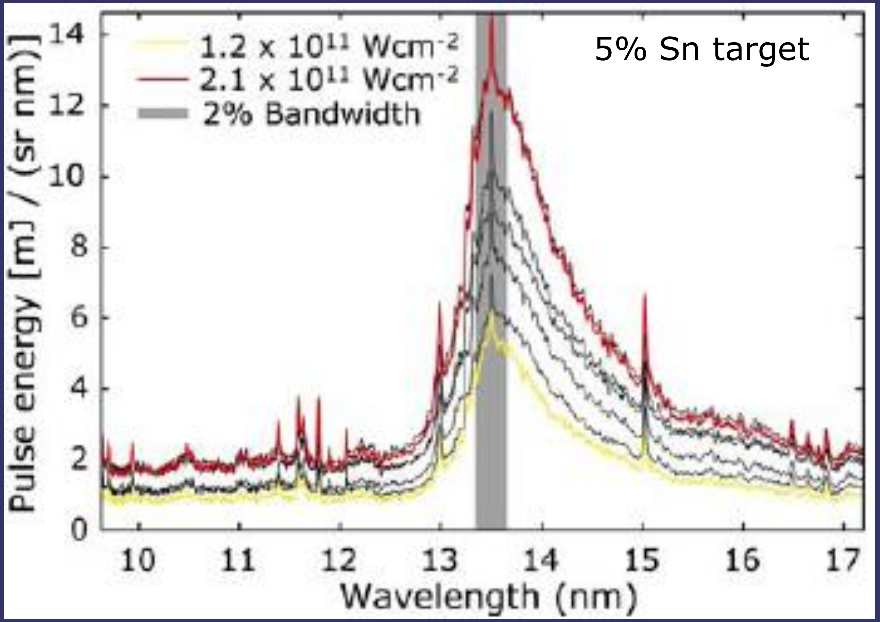
Experimental Sn spectra – Effect of increasing Φ



As Φ increases UTA peak shifts from 13.57 nm – 13.25 nm

Max CE = 2.3% @

$\Phi = 1.6\times10^{11}$ Wcm^{-2}



Max CE = 2.9% @

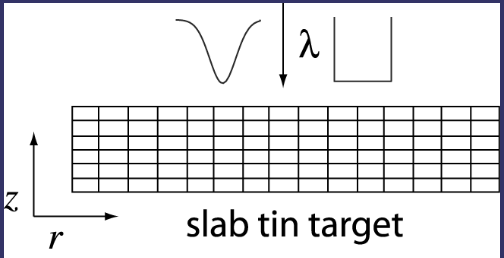
$\Phi = 2\times10^{11}$ Wcm^{-2}

Time-dependent CR and 1-D hydro code (MEDUSA), CE = 3%

A. Cummings et al, *J. Phys. D:* **38** (4) 604-616 (2005)

G. O'Sullivan, A. Cummings, C. Z. Dong, P. Dunne, P. Hayden, O. Morris, E. Sokell, F. O'Reilly, M. G. Su, and J. White, *Journal of Physics: Conference Series* **163** 012003 (2009)

Z* Calculations for Electron Temperature

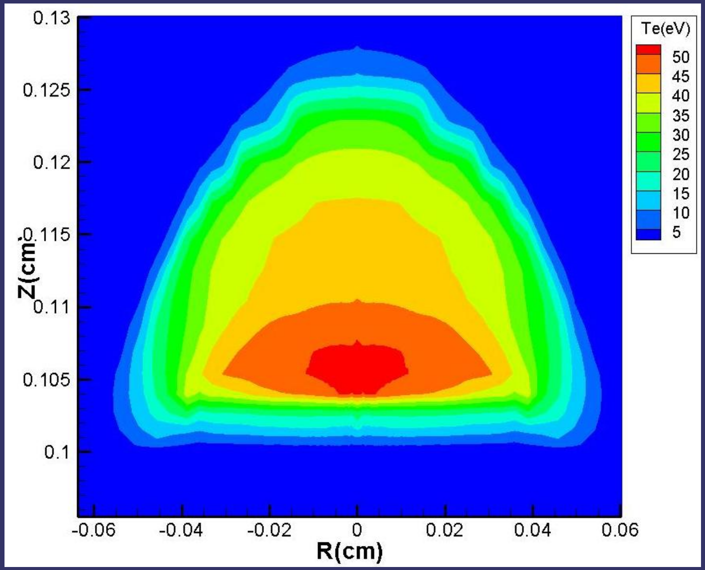


Z* Radiative 2-D hydrodynamic code using average atom model developed by EPPRA

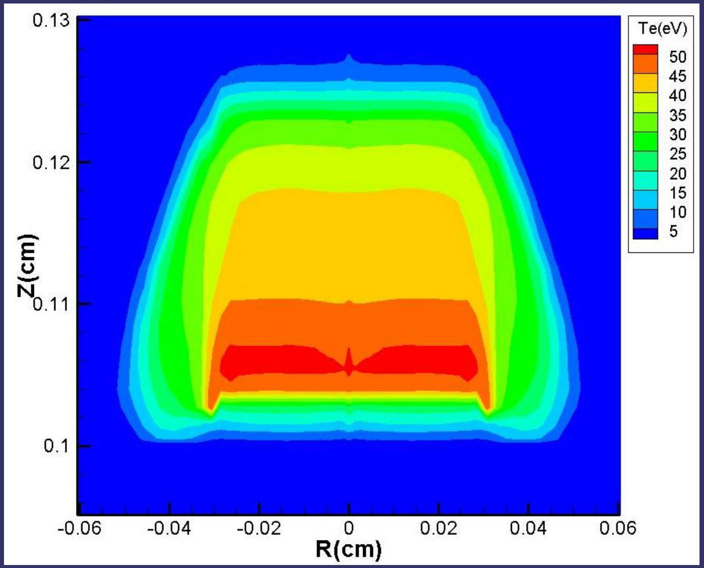
Zakharov et al, *4th EUVL Symposium San Diego* (2005)

T_e at peak emission for 2.2-ns FWHM laser pulse

Gaussian



Flat-top

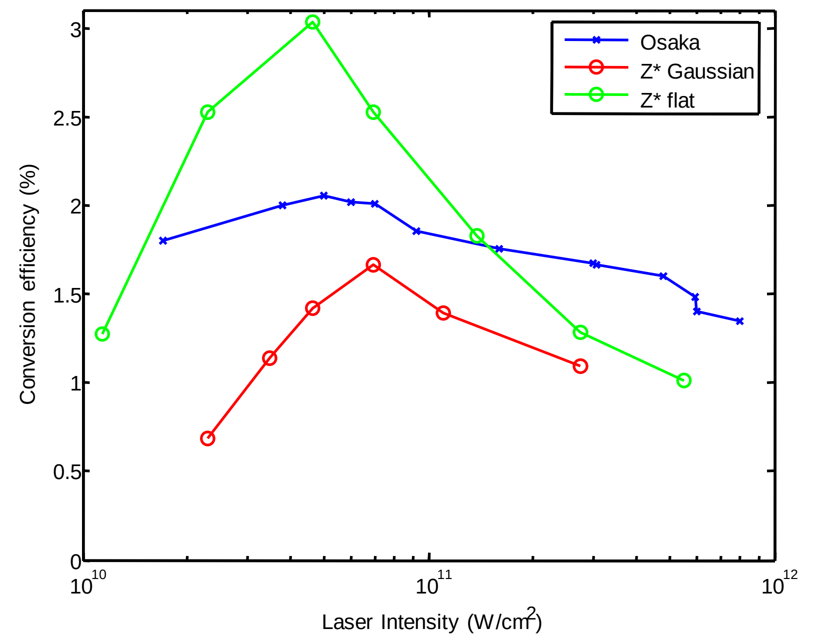


Larger hot core region, higher emission for the flat-top pulse

J. White, S. Zakharov, V. Zakharov, S. Fujioka, K. Nishhara, H. Nishimura, P. Choi and G. O’Sullivan, *Appl. Phys. Lett.* **92** 151501 (2008)

CE: Effect of increasing Φ

2.2 ns pulse

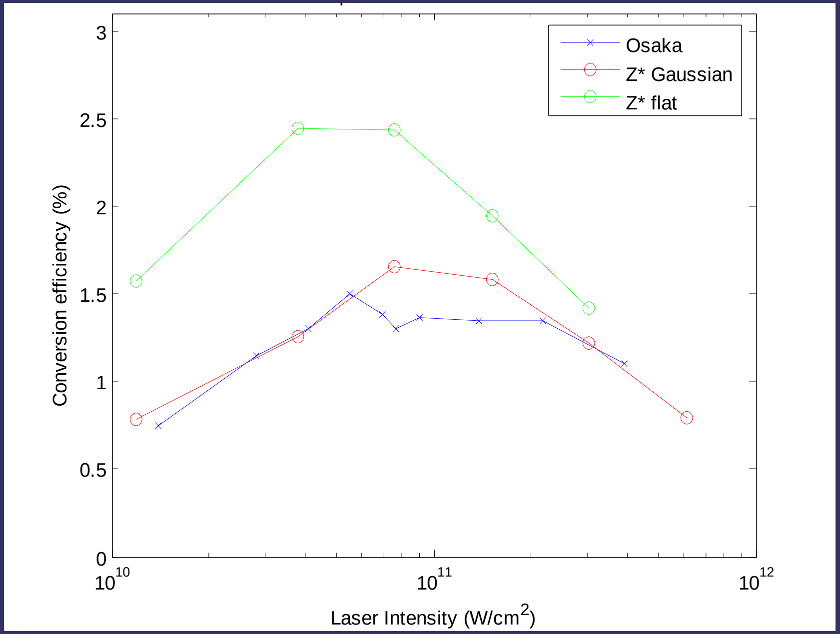


ILE experiment: Nd:YAG laser with Gaussian pulse profile

Max CE = 3.04%, 2.2 ns flat-top pulse @ Φ = 4.6×10^{10} W cm^{-2}

$$CE = \frac{\int\limits_{2\pi}\ \int\limits_{13.5-1\%}^{13.5+1\%}\ \int\limits_{0}^{t\max} I_{out}(\lambda,t,\vec{\Omega})\lambda^{-2}\,dt\,d\lambda\,d\vec{\Omega}}{E_{laser}}$$

8.0 ns pulse



J. White, G. O’Sullivan, S. Zakharov, P. Choi, V. Zakharov, H. Nishimura, S. Fujioka, and K. Nishara, *Appl. Phys. Lett.* **92** 151501 (2008)

Summary

Nd:YAG lasers $n_e \sim 10^{21}$ cm^{-3}

Particle-cluster	CE ~ 3 - 5%	T. Aota, and T. Tomie, *Phys. Rev. Lett.* **94** 015004 (2005)
Spherical	CE = 3%	Y. Shimada et al, *Appl. Phys. Lett.* **86** 051501 (2005)
5% Planar	CE = 2.9%	P. Hayden et al, *J. Appl. Phys.* **99** 093302 (2006)

Low density required to avoid self-absorption

CO_2 laser $n_e \sim 10^{19}$ cm^{-3}

Planar	CE ~ 2.6%	Y. Tao et al, *Appl. Phys. Lett.* **92** 251501 (2008)
Cavities	CE ~ 4%	Y. Ueno et al, *Appl. Phys. Lett.* **91** 231501 (2007)

Nd:YAG prepulse + CO_2 main pulse

$\text{Droplet}_{\text{sim}}$	CE ~ 6 - 7%	K. Nishihara et al, *Phys. Plasmas* **15** 056708 (2008)
$\text{Droplet}_{\text{exp}}$	CE = 4%	S. Fujioka et al, *Appl. Phys. Lett.* **92** 241502 (2008)

Acknowledgements

- **Dong Chenzhong & Su Maogen, Lanzhou**
- **Takako Kato, Daiji Kato & Chihiro Suzuki NIFS**
- **Hajime Tanuma, Tokyo Metropolitan University**
- **K. Nishihara, H. Nishimura and S. Fujioka ILE Osaka**
- **Fumihiro Koike, Kitsato University**
- **David Attwood, CXRO**
- **Martin Richardson, UCF**
- **John Costello and Paddy Hayden, DCU**
- **Bob McCullough, QUB**
- **David Ruzic, UIUC**
- **Chang Kuang-Po, ITRI, Taiwan**
- **Vivek Bakshi, International Sematech**
- **Sergei Zakharov, Gráinne Duffy and Peter Choi, EPPRA**
- **Leonard Hobbs, Intel Ireland**
- **Samir Ellwi, Powerlase UK**
- **Robert Bristol, Intel Oregon**