# A laser-produced plasma extreme ultraviolet (EUV) source by use of liquid microjet target

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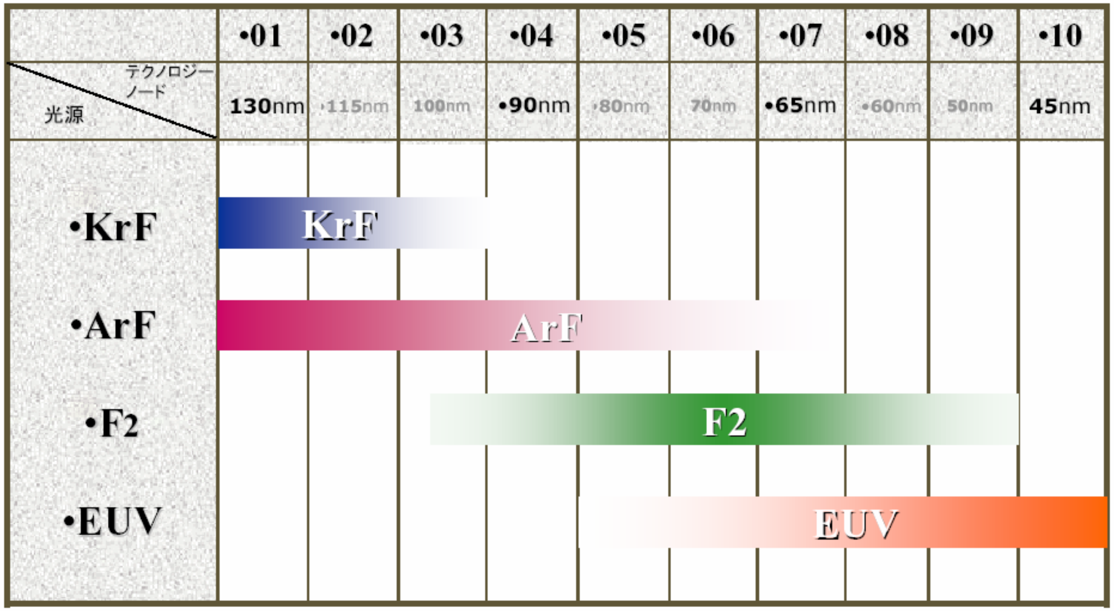
# Background: EUV light source for the next generation lithography



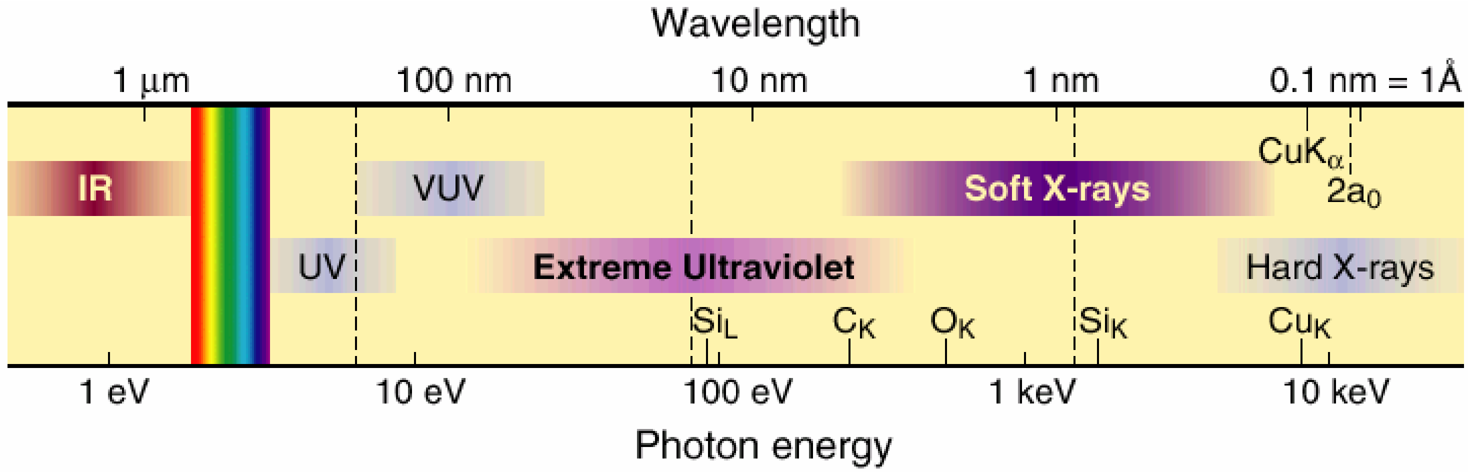
| テクノロジーノード / 光源 | •01 | •02 | •03 | •04 | •05 | •06 | •07 | •08 | •09 | •10 |
|---|---|---|---|---|---|---|---|---|---|---|
| | 130nm | ·115nm | 100nm | •90nm | ·80nm | 70nm | •65nm | •60nm | 50nm | 45nm |
| •KrF | | KrF | | | | | | | | |
| •ArF | | | | ArF | | | | | | |
| •F2 | | | | | | F2 | | | | |
| •EUV | | | | | | | | EUV | | |

International Technology Roadmap for Semiconductors (ITRS)

Engineering Test Stand

Bill Replogle, Sandia National Laboratories

Proc. SPIE **4688**, 310 (2002)



D. Attwood, “Soft X-Rays and Extreme Ultraviolet Radiation” (Cambridge University Press, 2000).

# Joint requirements for EUV source: 13.5 nm (2%BW), 115 W, 7-10 kHz

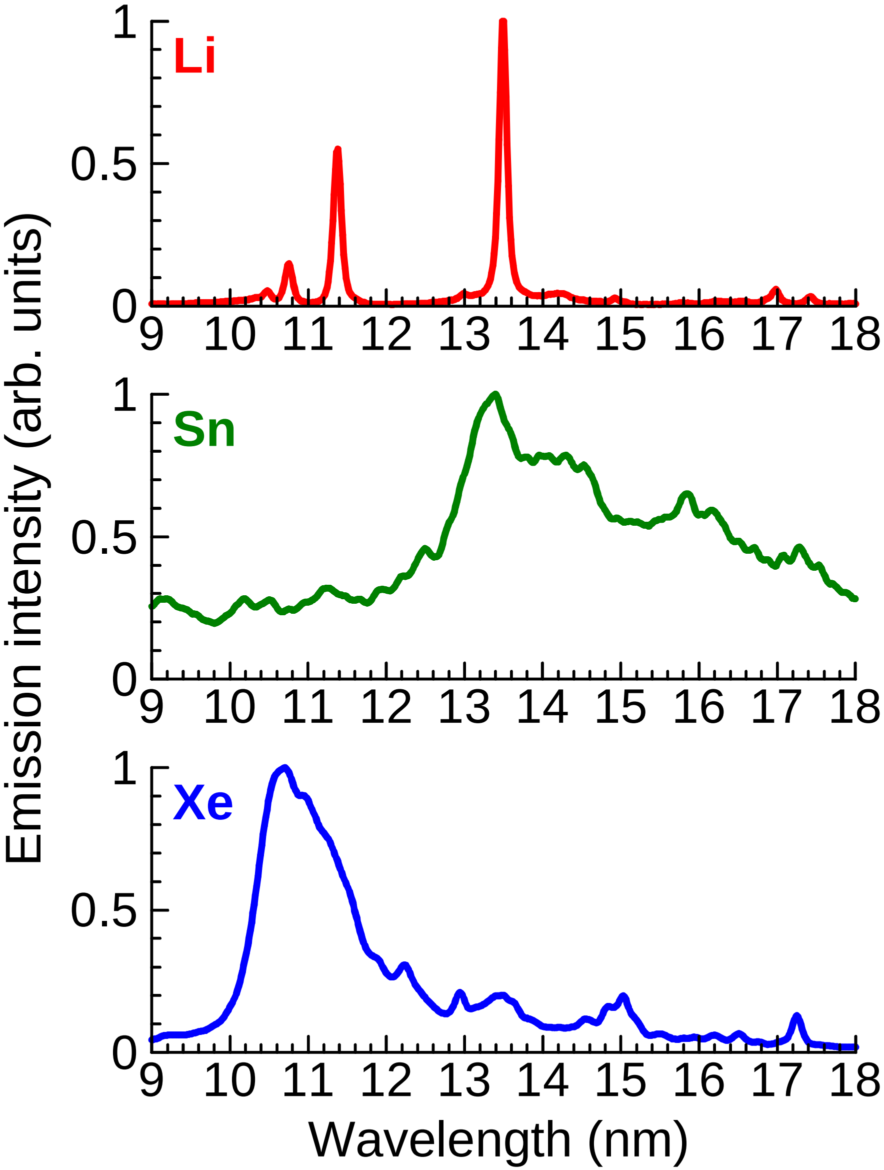
## Joint Requirements for EUV Source

| SOURCE CHARACTERISTICS | REQUIREMENTS |
|---|---|
| ▪Wavelength | 13.5 (nm) |
| ▪EUV Power (in-band) | 115 (W) (after intermediate focus) |
| ▪Repetition Frequency | > 7 - 10 kHz * |
| ▪Integrated Energy Stability | ± 0.3% (3σ over 50 pulses) |
| ▪Source Cleanliness | ≥ 30,000 hours (after intermediate focus) |
| ▪Etendue of Source Output | 1 – 3.3 mm²sr (max)* |
| ▪Maximum Solid Angle to Illuminator | 0.03 – 0.2 (sr)<br>(depending on particular optical scheme)* |
| ▪Spectral Purity | |
| 130 - 400 nm (DUV/VUV) | ≤ TBD – 7% (design dependent)* |
| > 400 nm (Vis/IR) | TBD |

* Not agreed among participants

Kazuya Ota, Source Workshop, Santa Clara, CA, USA (2003).

# EUV emission spectra from possible plasma materials



**3rd International EUVL Symposium**

Date : **November 1 - 4, 2004**
Venue : **Sheraton Grande Ocean Resort**
**Miyazaki, JAPAN**

Committee : Conference chairperson : Prof. Y. Horiike
Program committee chairperson : Dr. S. Okazaki

Deadline of abstract submission : **July 1st, 2004**

URL : www.euva.or.jp
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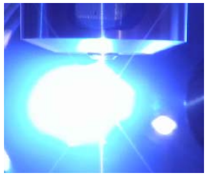
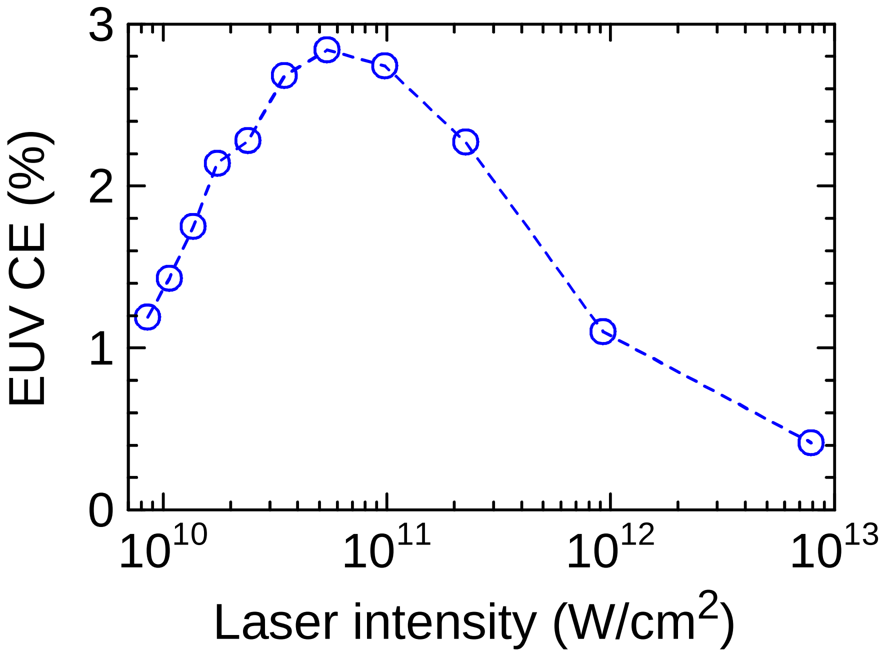
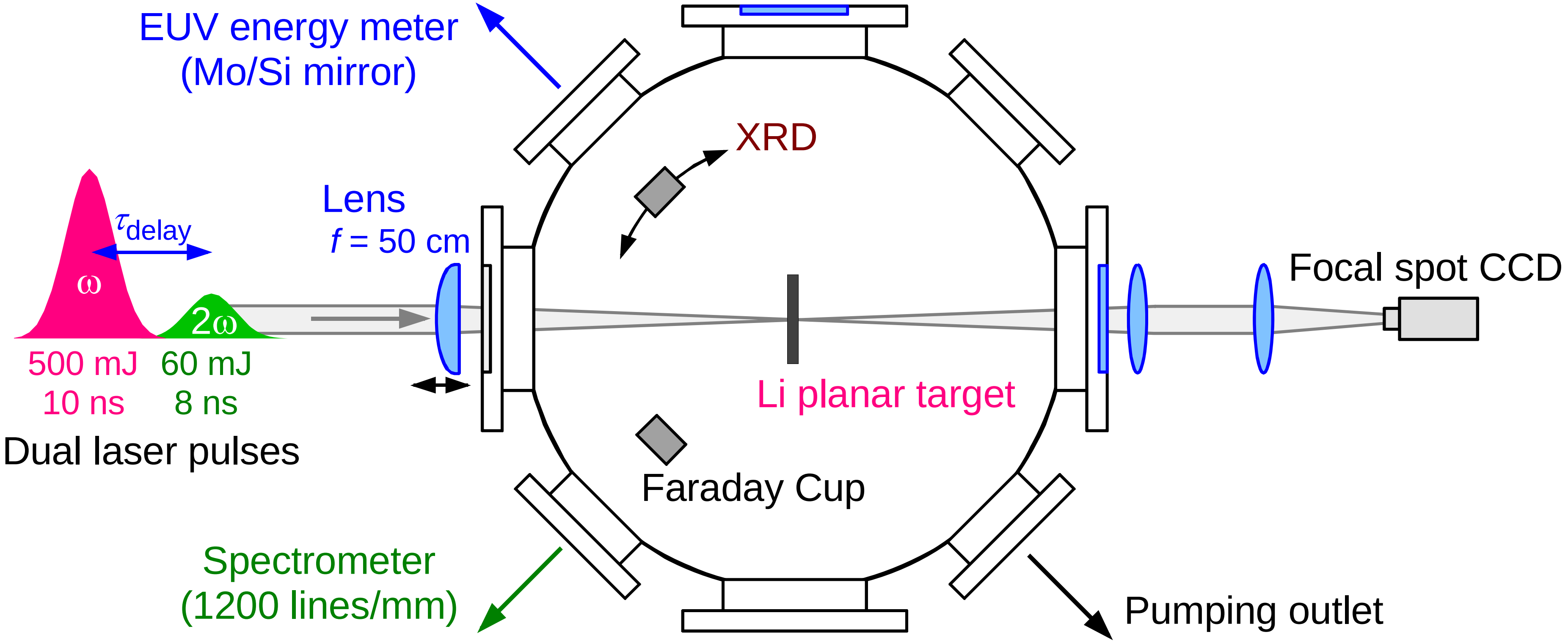




**"The Optimal Source Path to HVM"**
D. Myers, B. Llene, I. Fomenkov,
B. Hansson, and B. Bolliger (CYMER)

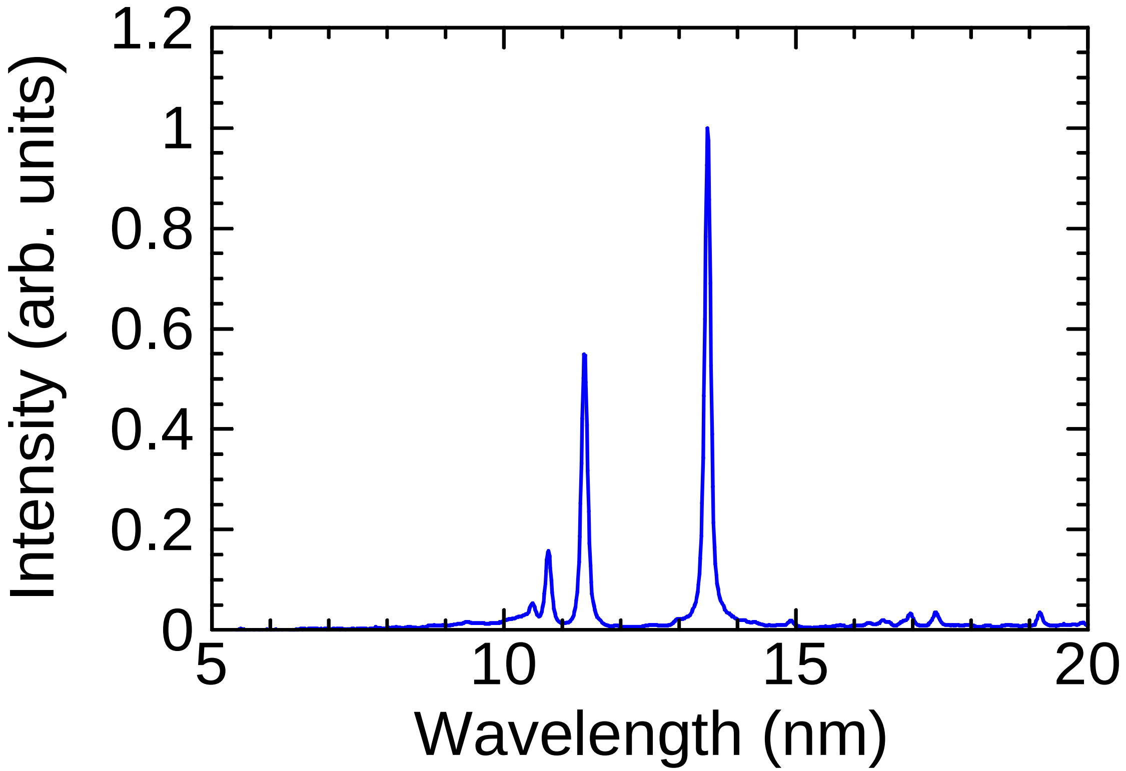
# Schematic diagram of experimental setup using planar Li target

Wavelength: 1064 nm
Laser energy : < 1.4 J
Pulse width: 10 ns (FWHM)
Spot size: 300 μmϕ

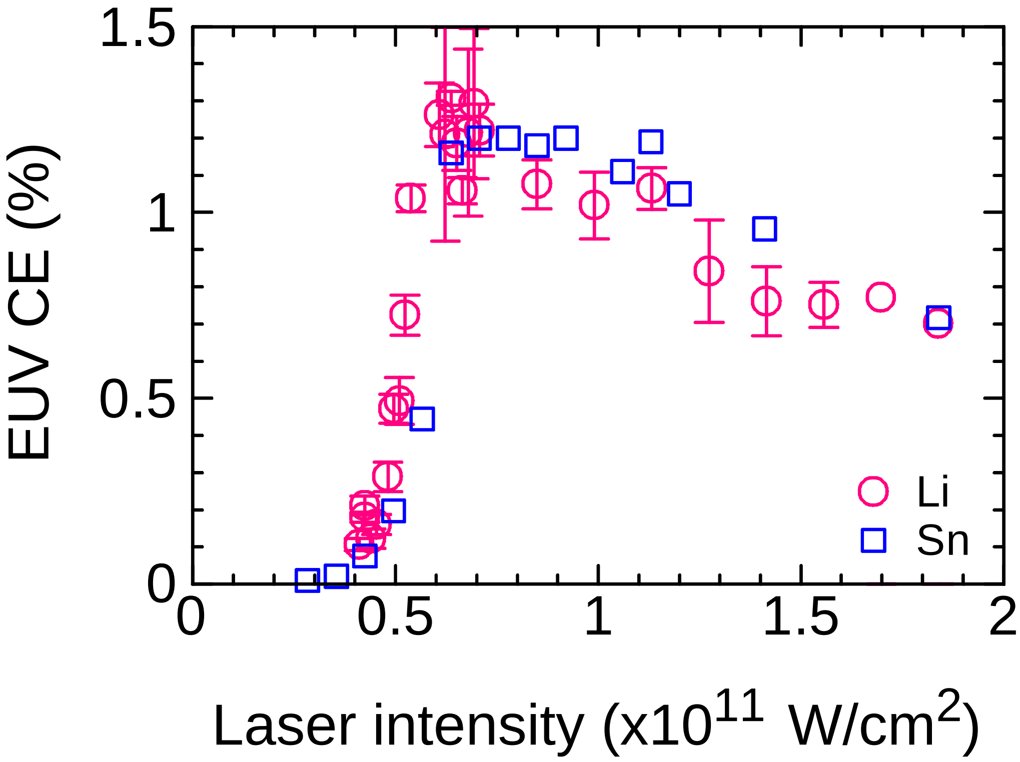


# EUV spectrum of a laser-produced lithium plasma

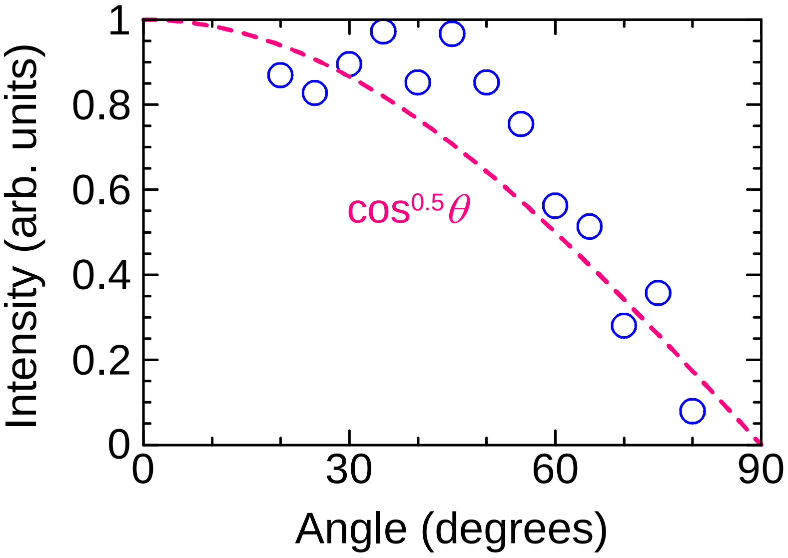
Laser intensity: 7 x $10^{10}$ W/$cm^2$
Laser energy : 500 mJ
Pulse width: 10 ns (FWHM)
Spot size: 300 μmϕ



# Laser intensity dependence of EUV CE using a single laser pulse

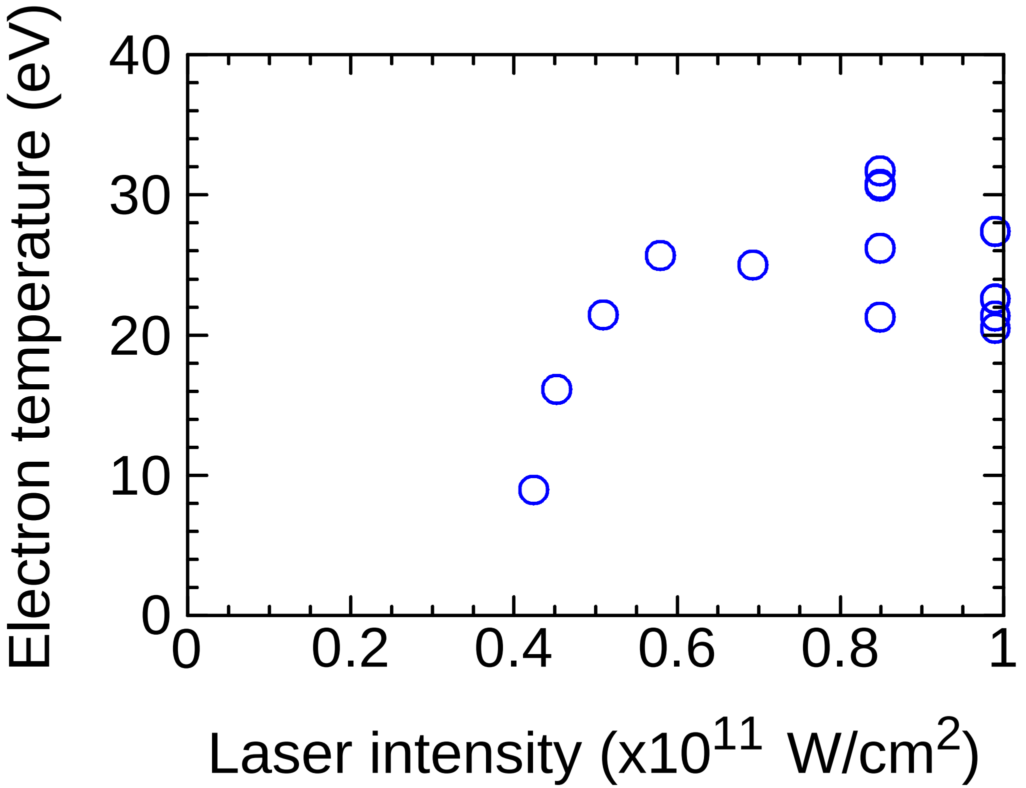


Angular distribution

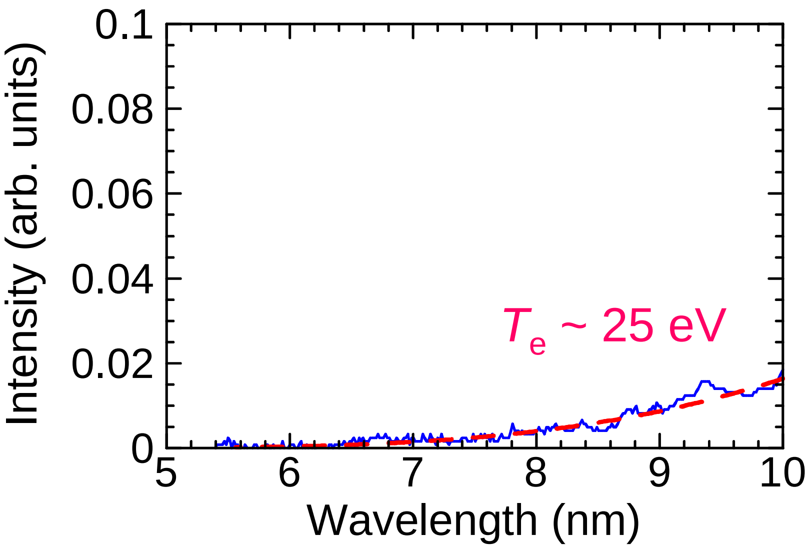


T. Higashiguchi *et al*., (submitted).

# Estimation of an electron temperature using bound-free transitions in $Li^{2+}$ ions



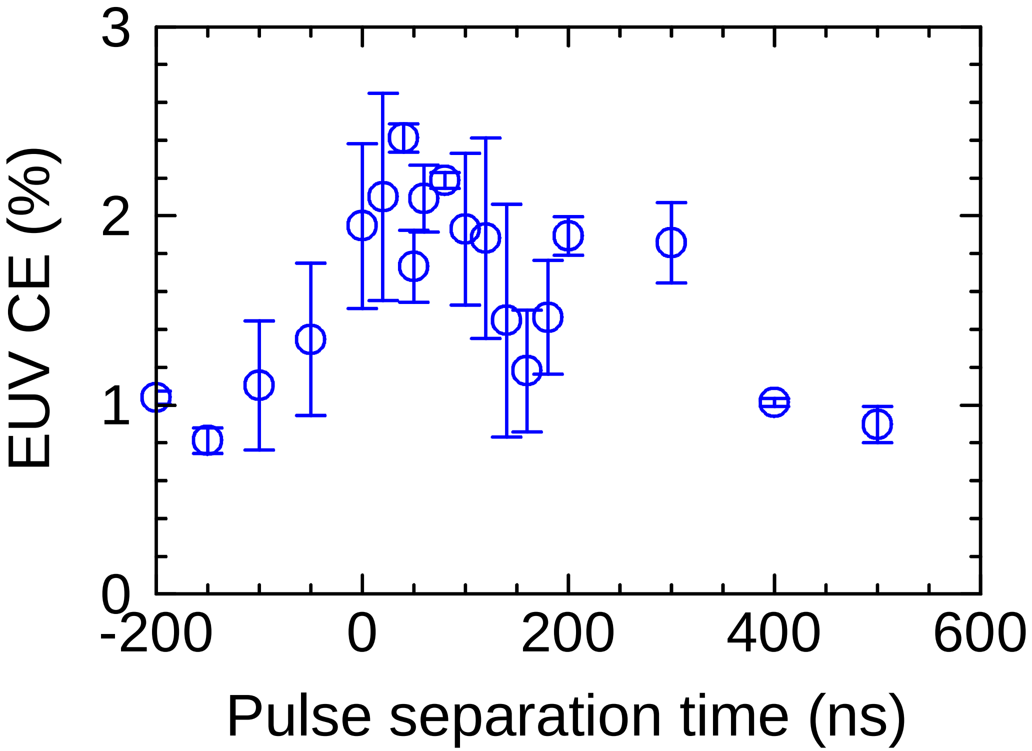
Emission due to bound-free transitions



Y. B. Zel'dovich and Y. P. Raizer, *"Physics of shock waves and high-temperature hydrodynamic phenomena"* (Dover Publication, Inc., New York, Mineola, 1966).

# Pulse separation time dependence of EUV CE utilizing dual laser pulses

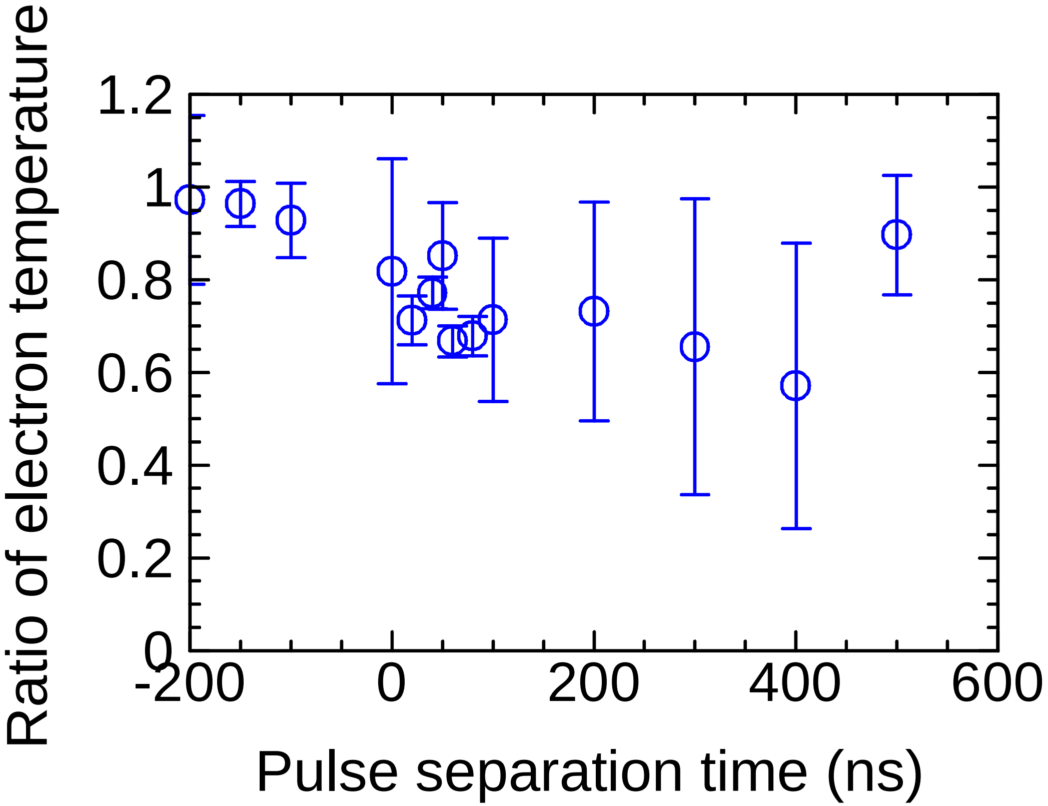
Pre-pulse: 532 nm, 60 mJ, 8 ns (< 2 x $10^{10}$ W/cm$^2$)
Main pulse: 1064 nm, 500 mJ, 10 ns, 300 μm (7 x $10^{10}$ W/cm$^2$)
Optimum delay separation time: 20-50 ns



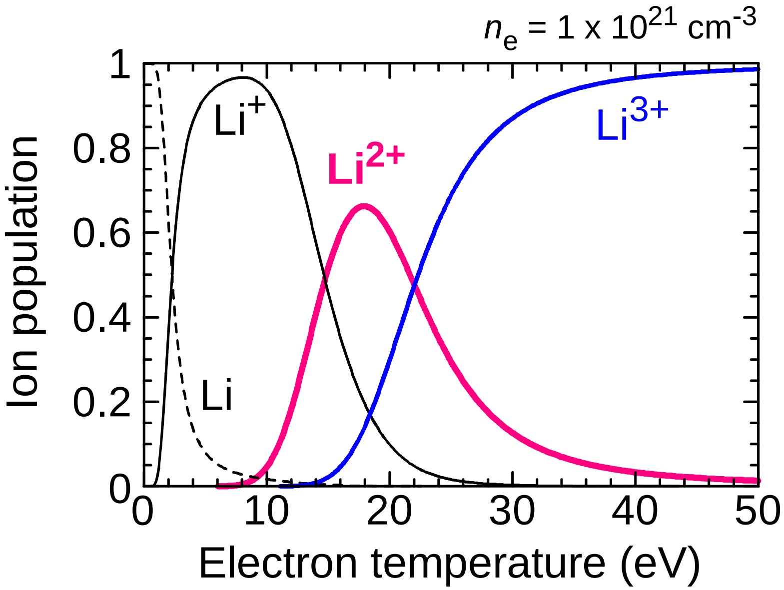
T. Higashiguchi *et al*., (submitted).

# Ratio of electron temperature as a function of pulse separation time

Pre-pulse: 532 nm, 60 mJ, 8 ns (< 2 x $10^{10}$ W/cm$^2$)
Main pulse: 1064 nm, 500 mJ, 10 ns, 300 $\mu$m (7 x $10^{10}$ W/cm$^2$)



CR model



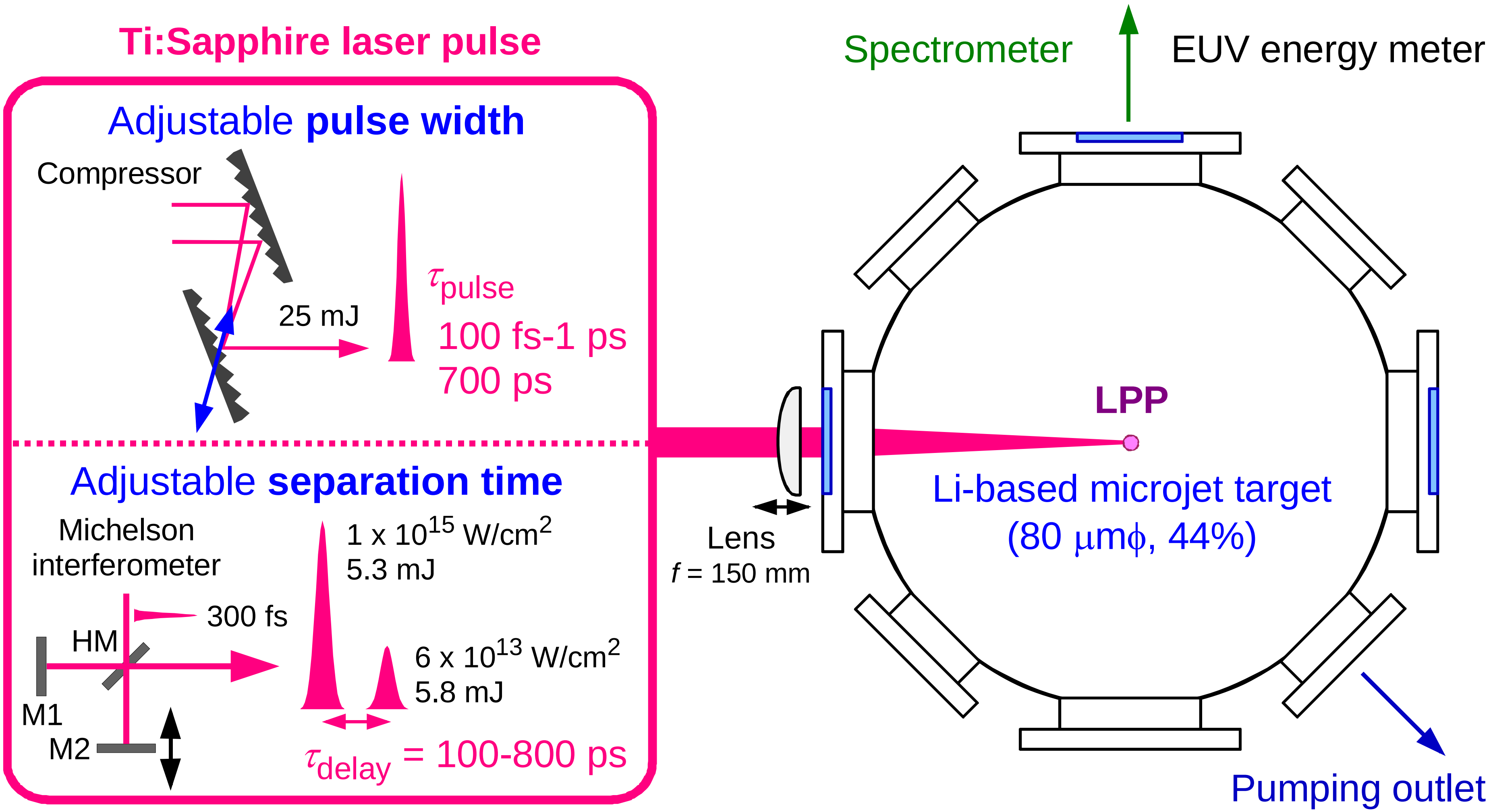
T. Higashiguchi *et al*., (submitted).

[1] D. Colomband and G. F. Tonon, J. Appl. Phys. **44**, pp. 3524 (1973).
[2] M. J. Bernstein and G. G. Comisar, J. Appl. Phys. **41**, pp. 729 (1970).

# Objective:
# Enhancement of the EUV CE

- Enhancement of the EUV CE by use of ***dual*** laser pulses
    - Plasma hydrodynamics of a Li plasma should be regulated.
    - Optimum Li plasma parameters could thus be realized.

# Experimental setup using ultrashort, high-intensity laser pulses



**Ti:Sapphire laser pulse**

Adjustable **pulse width**

Compressor

25 mJ

$\tau_{\text{pulse}}$

100 fs-1 ps

700 ps

Adjustable **separation time**

Michelson interferometer

HM

M1

M2

300 fs

$1 \times 10^{15}$ W/cm$^2$

5.3 mJ

$6 \times 10^{13}$ W/cm$^2$

5.8 mJ

$\tau_{\text{delay}}$ = 100-800 ps

Lens

*f* = 150 mm

Spectrometer

EUV energy meter

**LPP**

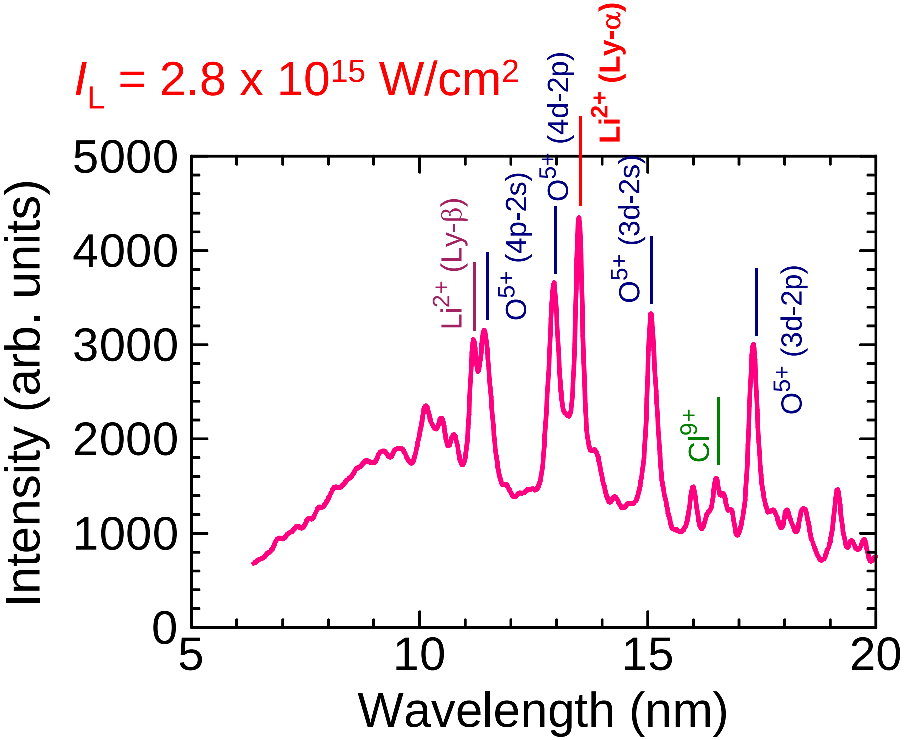
Li-based microjet target

(80 μmφ, 44%)

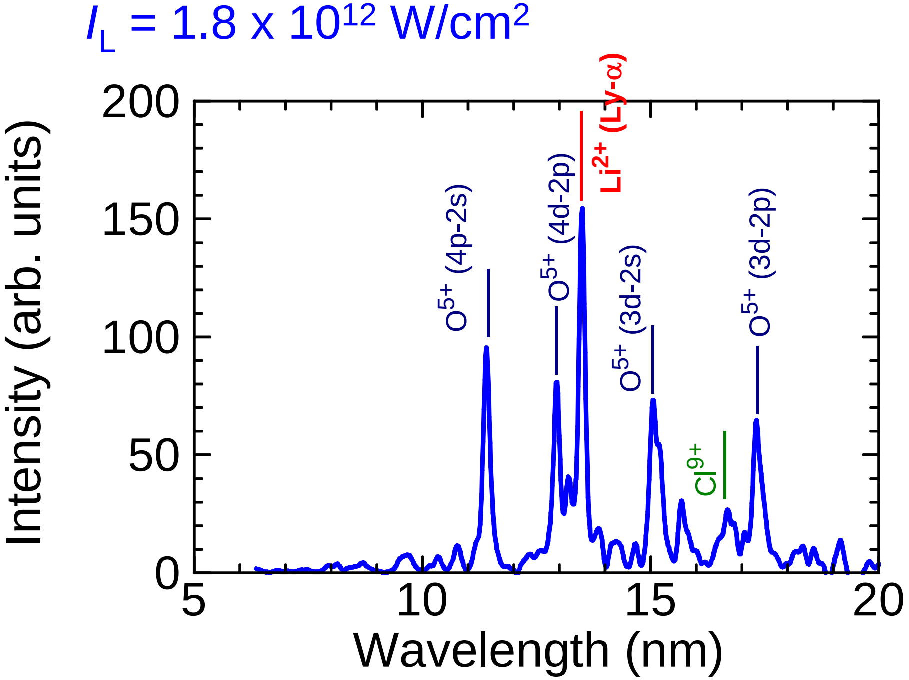
Pumping outlet

# EUV spectra from a Li-contained plasma at different laser intensities

Li concentration (by mass): 44.4%
Jet diameter: 80 μmϕ
Laser energy: 25 mJ



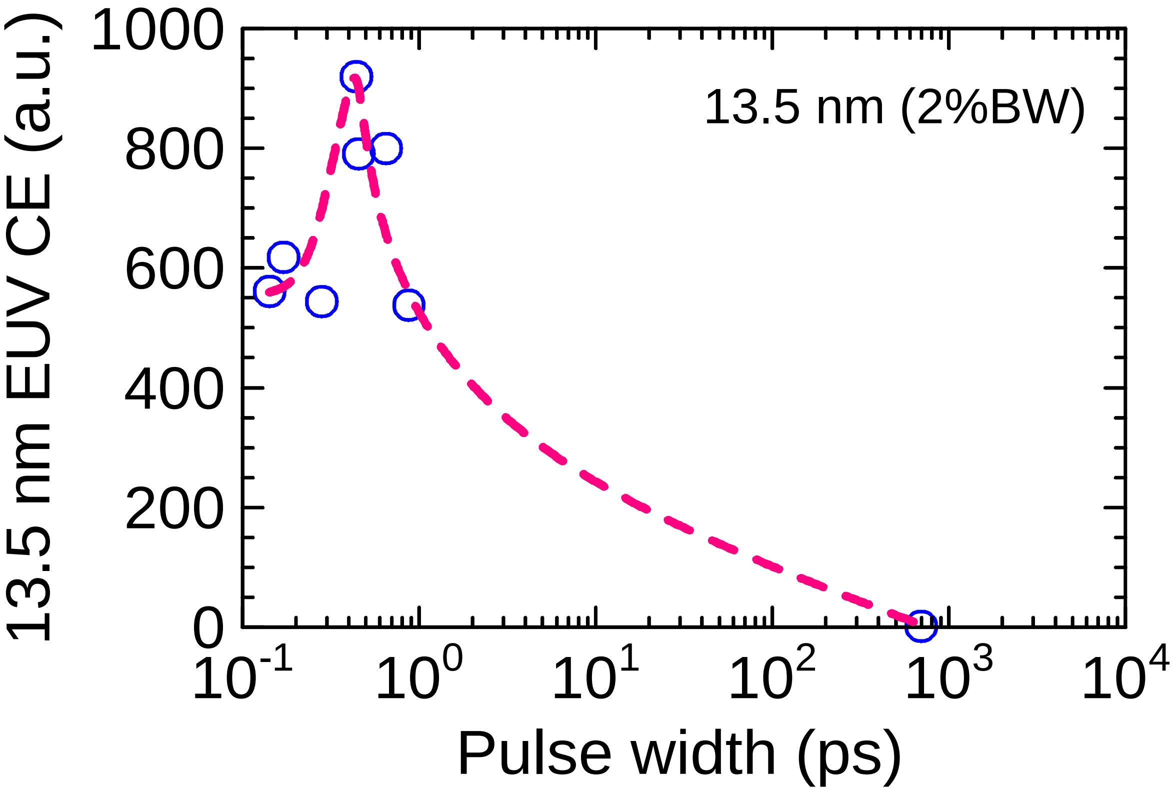
$I_L$ = 2.8 x $10^{15}$ W/cm$^2$



$I_L$ = 1.8 x $10^{12}$ W/cm$^2$

# Subpicosecond pulse width dependence of the EUV CE

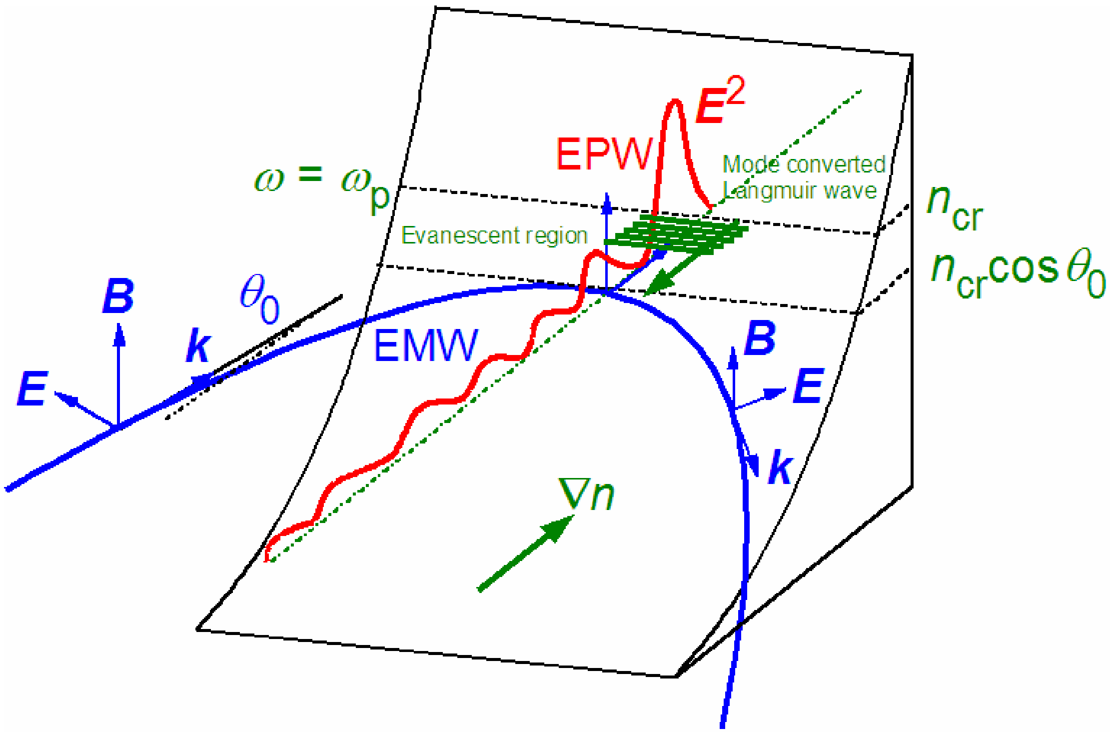
Li concentration (by mass): 44.4%
Jet diameter: 80 μmϕ
Laser energy: 25 mJ



APL **86**, 231502 (2005)

# Optimum pulse width explained by the resonant absorption process

Resonant absorption is dominant in a steepened density profile.



## Absorption thickness

$$L_{cr} = L_{opt} \approx \frac{3\sqrt{3}}{8k\cos^3\theta}$$

$$L_{opt} \approx c_S \tau_{pulse}$$

$c_S \approx 2 \times 10^7$ cm/s,
$\lambda = 2\pi/k = 0.8\ \mu$m,
$L_{opt} \approx 82$ nm for $\theta = 0$

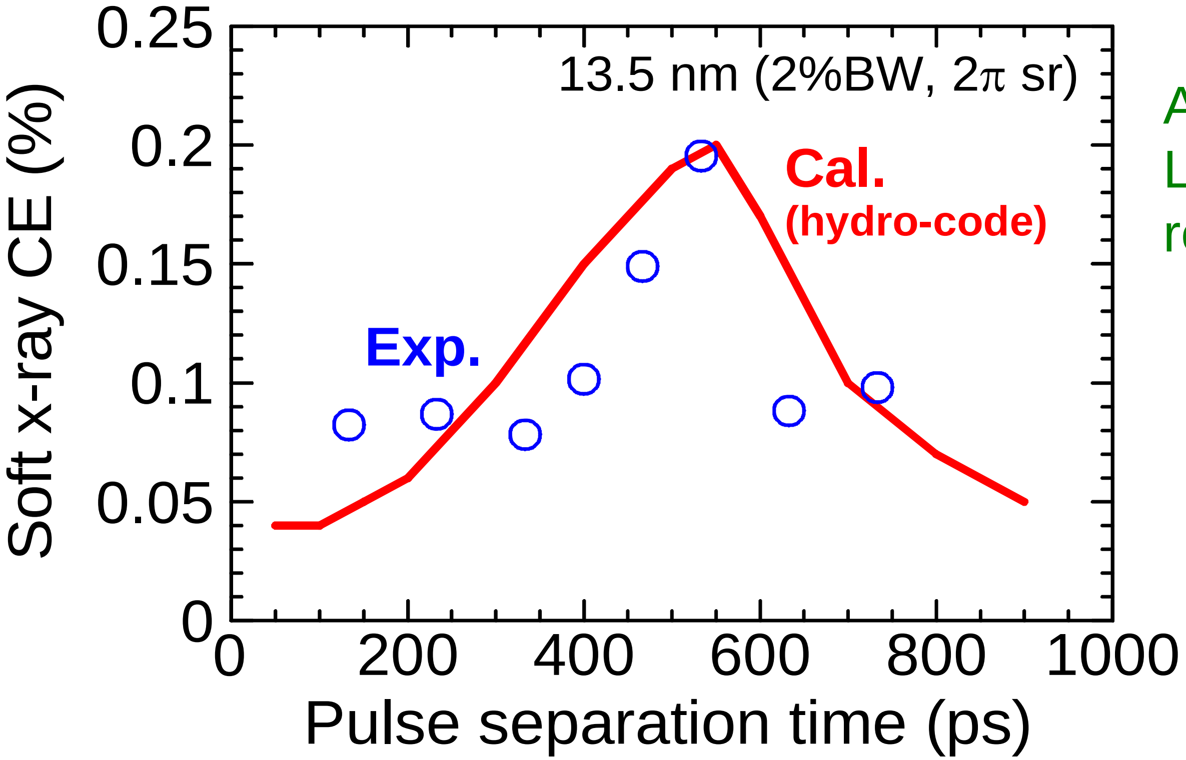
$$\tau_{pulse} \approx 400 \text{ fs}$$

[1] C. Garban-Labaune, E. Fabre, C. E. Max, R. Fabbro, F. Amiranoff, J. Virmont, M. Weinfeld, A. Michard, Phys. Rev. Lett. **48**, 1018 (1982).

[2] V. L. Ginzburg, “Propagation of Electromagnetic Waves in Plasmas” (Pergamon, New York, 1970).

[3] E. Parra, I. Alexeev, J. Fan, K. Y. Kim, S. J. McNaught, and H. M. Milchberg, Phys. Rev. E **62**, R5931 (2000).

# Enhancement of the EUV CE by use of dual subpicosecond laser pulses



A one-fluid two-temperature Lagrangian code well reproduced the experiments.

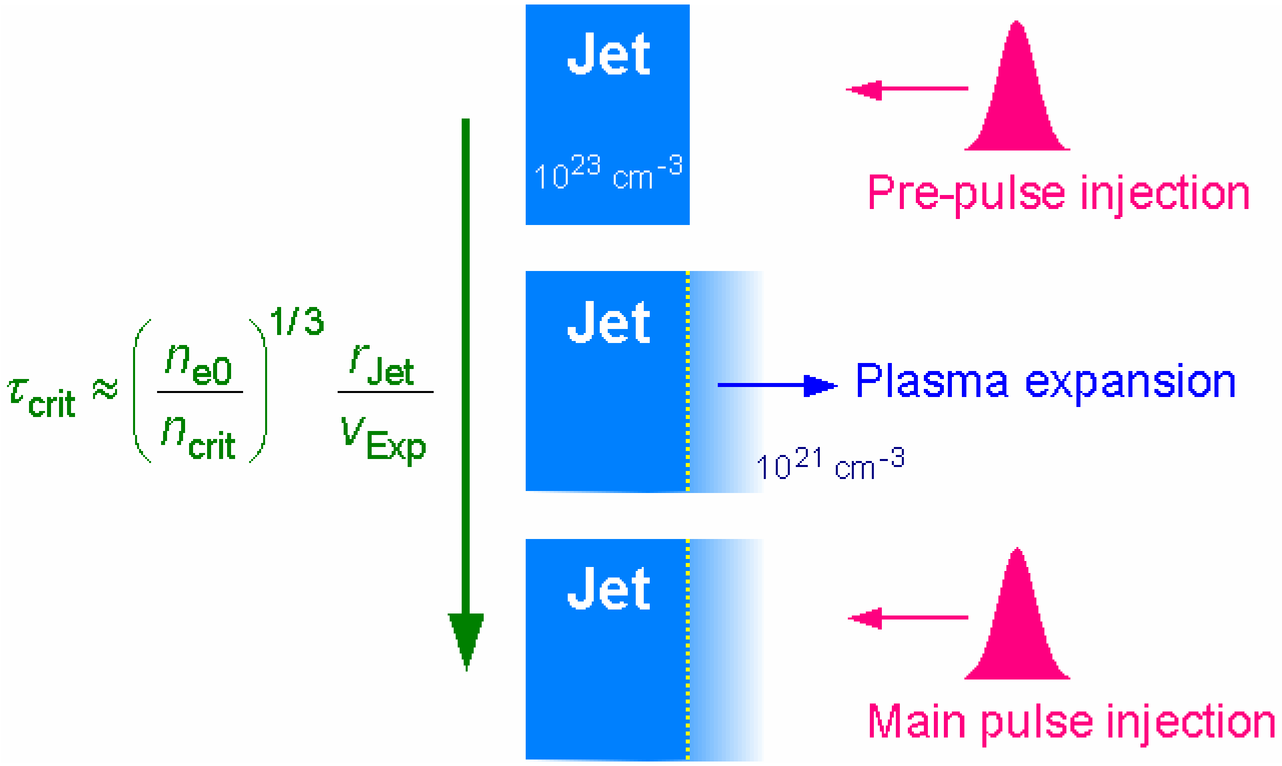
**- Plasma hydrodynamic**

**- Atomic code**

**- Plasma emission**

APL **86**, 231502 (2005)

# Optimum delay time explained by the plasma expansion (simpler estimate)

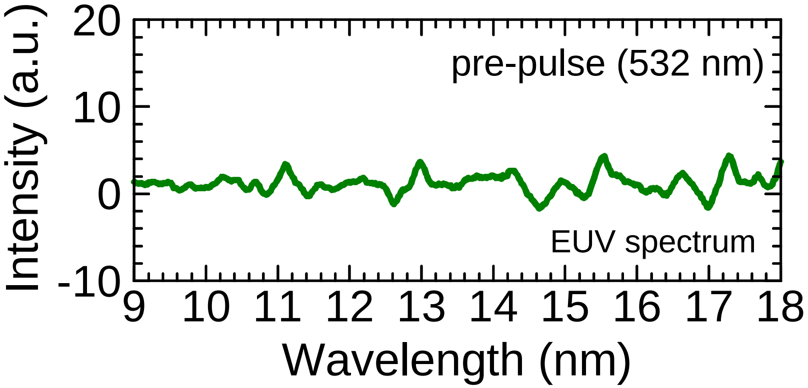


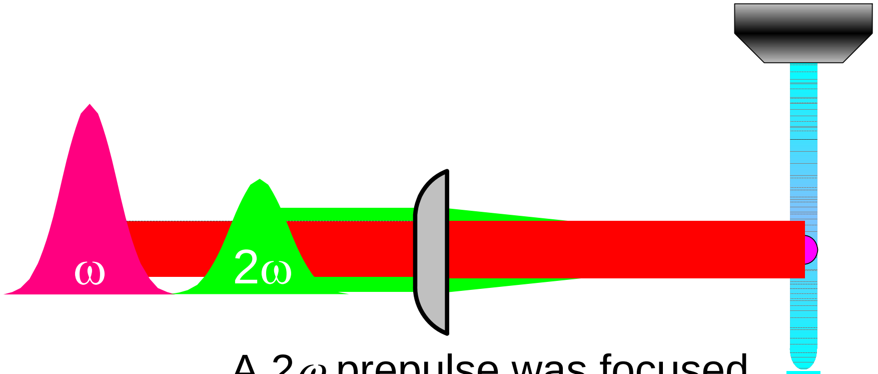
$$\tau_{crit} \approx \left(\frac{n_{e0}}{n_{crit}}\right)^{1/3} \frac{r_{Jet}}{v_{Exp}}$$

$n_{e0}$ = $10^{22}$-$10^{23}$ cm$^{-3}$
$n_{crit}$ = 1.7 x $10^{21}$ cm$^{-3}$
$r_{Jet}$ = 40 μm ($2r_{Jet}$ = 80 μm)
$v_{exp} \approx c_s \approx 2 \times 10^7$ cm/s

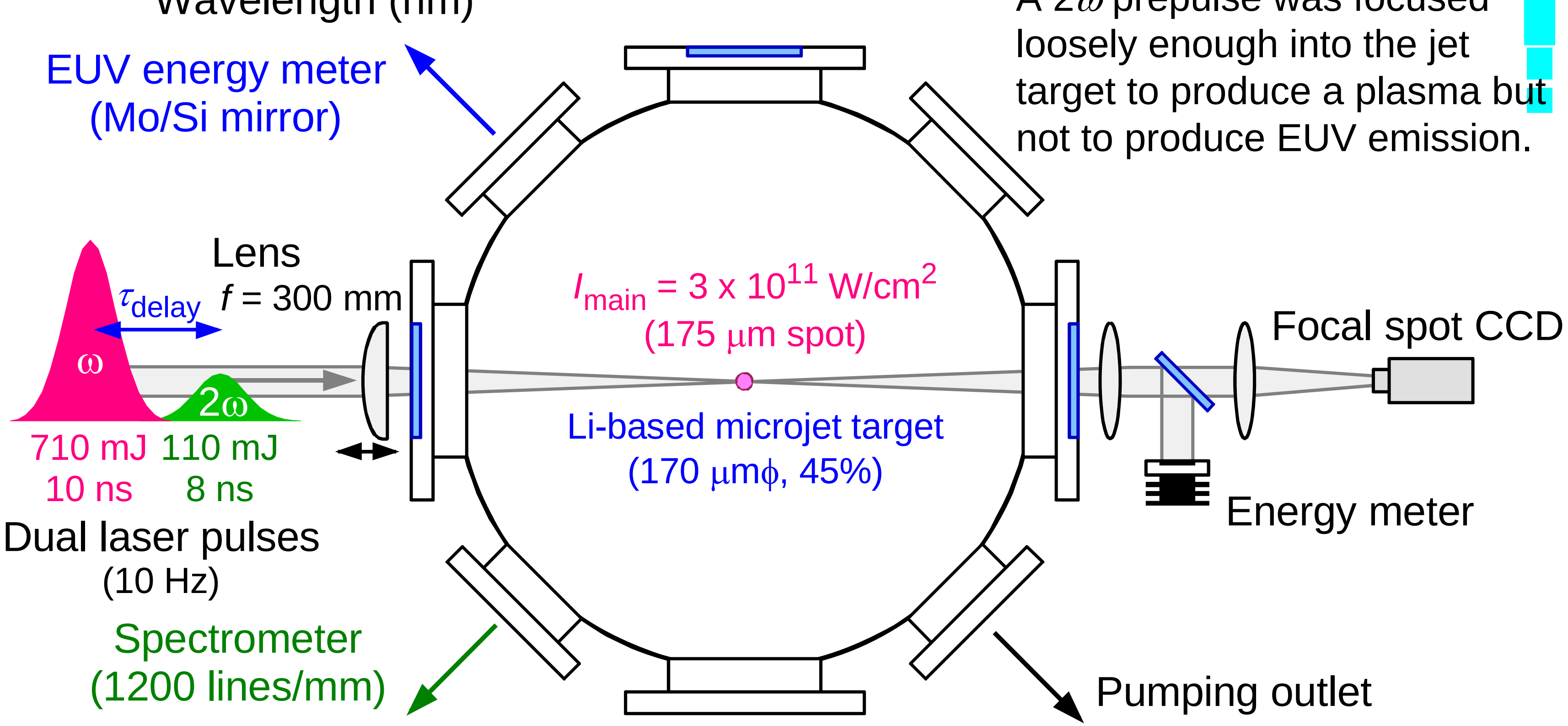
$\tau_{exp} \approx 400$ ps

# Experimental setup using dual nanosecond laser pulses





A 2$\omega$ prepulse was focused loosely enough into the jet target to produce a plasma but not to produce EUV emission.



EUV energy meter
(Mo/Si mirror)

Lens
$f$ = 300 mm

$\tau_{delay}$

710 mJ
10 ns

110 mJ
8 ns

Dual laser pulses
(10 Hz)

$I_{main}$ = 3 x $10^{11}$ W/cm$^2$
(175 μm spot)

Li-based microjet target
(170 μmϕ, 45%)

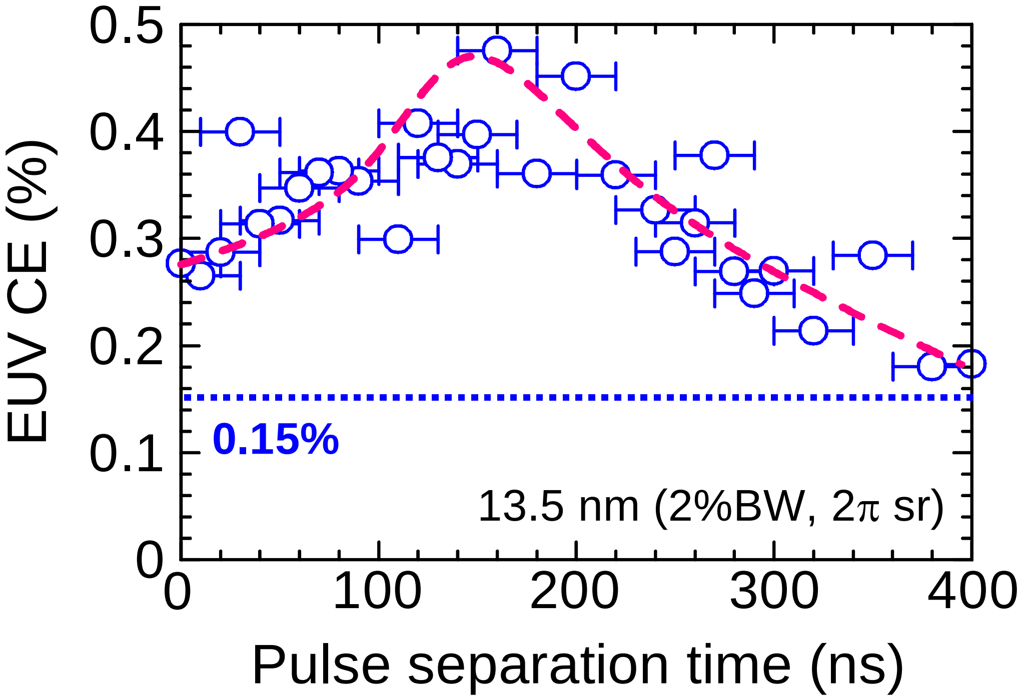
Focal spot CCD

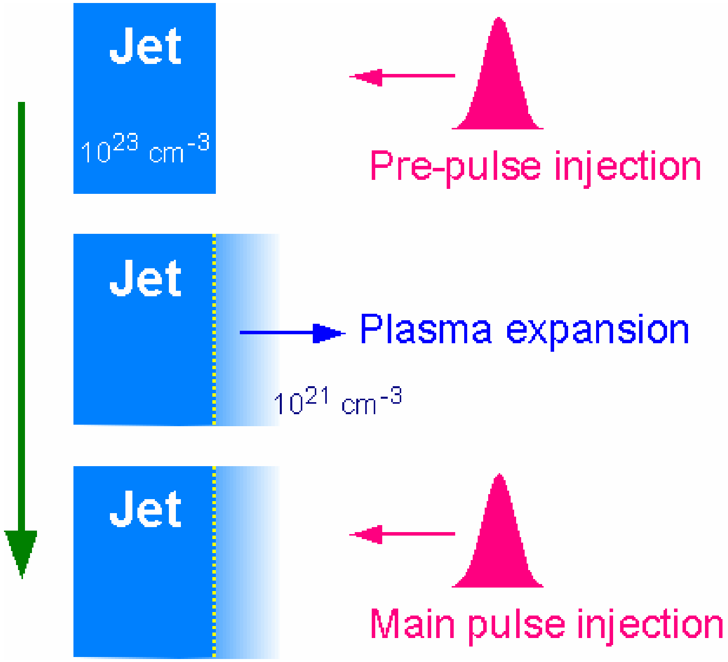
Energy meter

Spectrometer
(1200 lines/mm)

Pumping outlet

# Enhancement of the EUV CE by use of dual nanosecond laser pulses





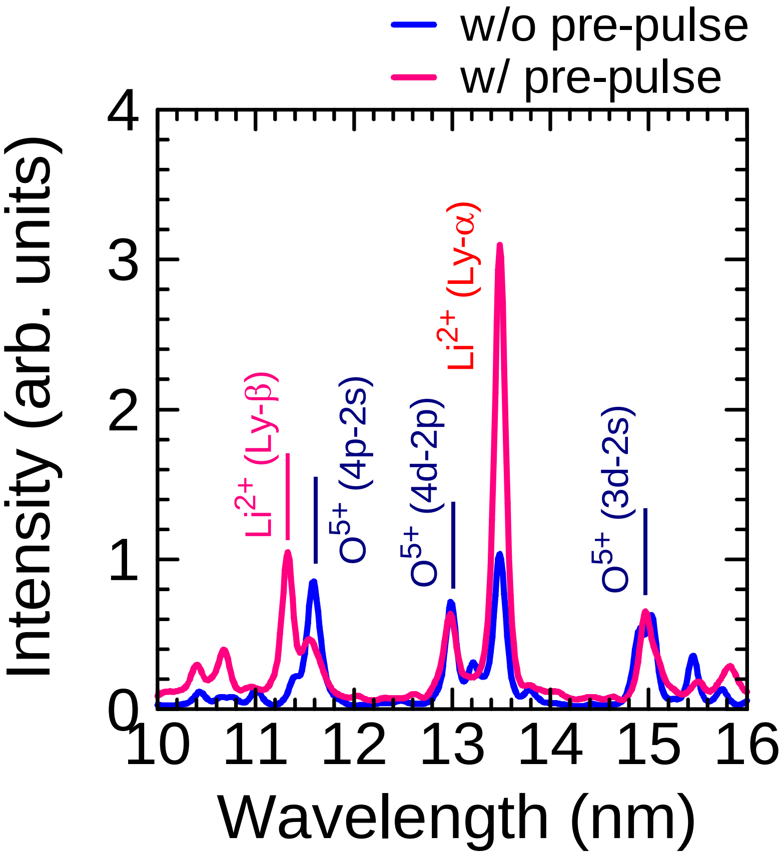
$$\tau_{crit} \approx \left(\frac{n_{e0}}{n_{crit}}\right)^{1/3} \frac{r_{Jet}}{v_{Exp}} \approx 80\text{ ns}$$

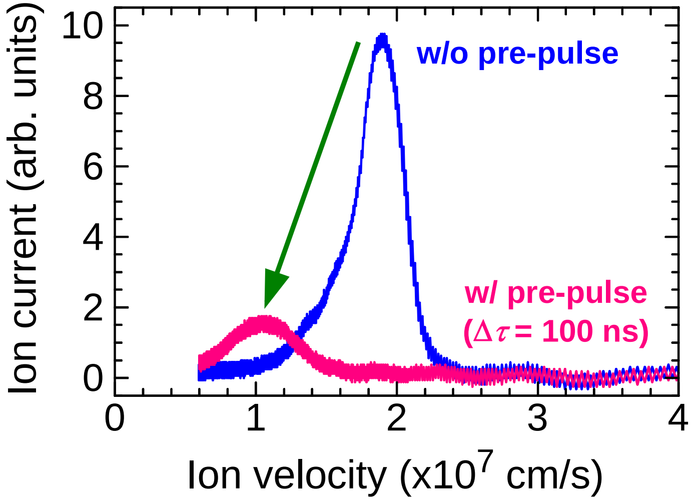
$n_{e0}$ = $10^{23}$ cm$^{-3}$
$n_{cric}$ = $10^{21}$ cm$^{-3}$@$\lambda_L$ = 1 μm
$2r_{Jet}$ = 170 μm
$v_{Exp}$ = 5 x $10^5$ cm/s@$10^{21}$ cm$^{-3}$

A plasma expansion time to its critical density was responsible for the optimal pulse separation time.

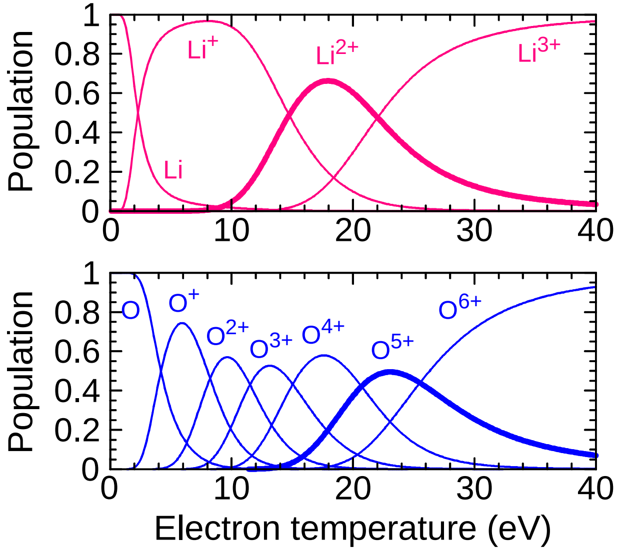
APB **80**, 409 (2005).

# Optimum plasma conditions obtained for the Lyman-α emission at 13.5 nm





CR model



🟥 $Li^{2+}$ (13.5 nm) population: $T_e \approx 18$ eV

🟦 $O^{5+}$ (13.0 nm) population: $T_e \approx 25$ eV

Optimum dual laser parameters produced a plasma where Li 13.5 nm emission became dominant.

APB **80**, 409 (2005).

# Summary

- Optimum dual laser parameters for the EUV CE enhancement
    - Subpicosecond pulse width dependence revealed the optimal prepulse width of 400 fs, which corresponded to resonance absorption time of a short scale-length plasma.
    - Dual laser pulse irradiation increased the in-band EUV CE from 0.08% to 0.2% for subpicosecond laser pulses, and from 0.15% to 0.5% for nanosecond laser pulses.
    - Pulse separation time dependence indicated the optimum time separation of 500 ps and 100 ns for subpicosecond and nanosecond laser pulses, respectively, corresponding to the plasma density decrease to its critical density due to the plasma expansion. The difference of the optimum delay time is mainly due to the difference of the plasma expansion velocities determined by different laser intensities.