Optimization of laser-produced plasma light sources for EUV lithography

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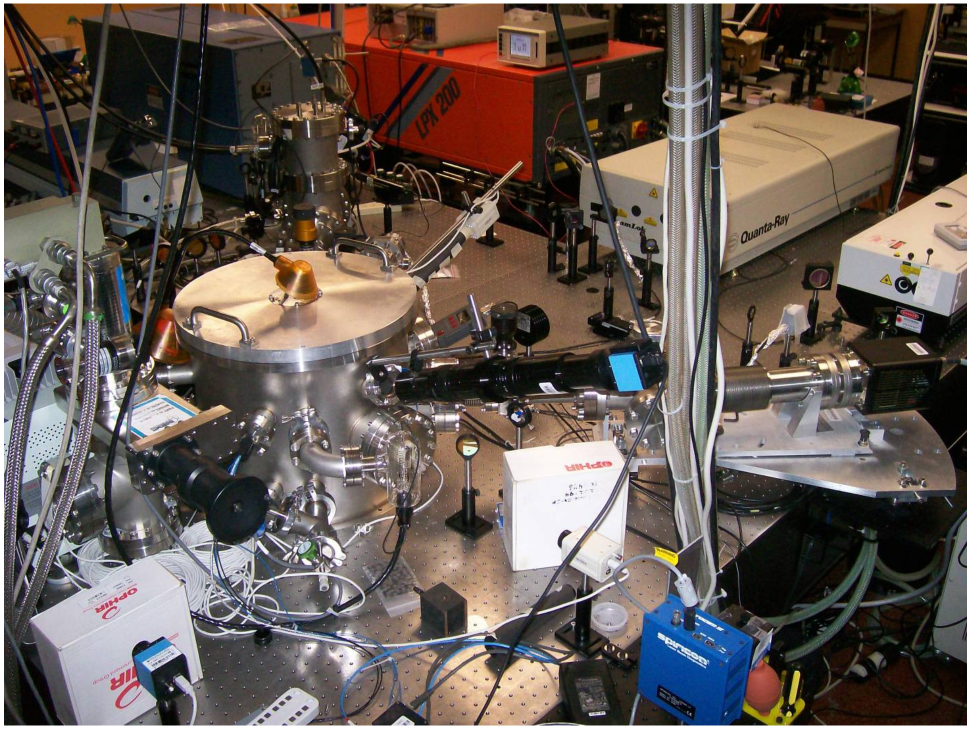
Introduction

- Our recent research explores both HVM and actinic metrology issues
- We perform university-scale single-shot experiments, focused on fundamental understanding of laser-produced plasmas
- **Comprehensive diagnostics**
- CO_2 laser-produced plasma
  1) Confinement effects
  2) Non-isothermal expansion
  3) Charged particle emissions
- Nd:YAG laser-produced plasma
  - Long-pulse (>10 ns) studies



Facilities for EUV source studies at UCSD

Lasers: 4 Nd:YAG and 3 CO_2

Nd:YAG: Pulse duration: 0.1 ~ 40 ns

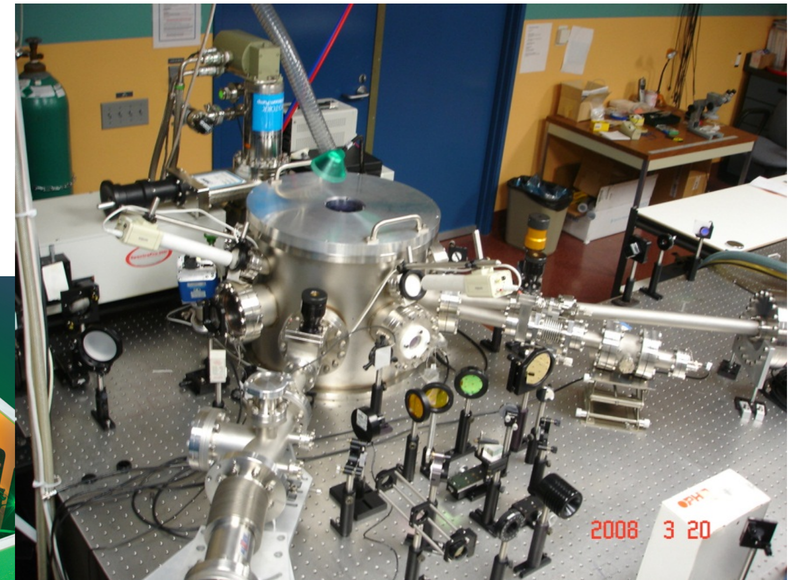
Intensity: up to 10^{14} W/cm^2

Sync. jitter: < 0.5 ns

CO_2 : Pulse duration: 10 ~ 200 ns

Intensity: up to 8×10^{10} W/cm^2

Sync. jitter: < 5 ns



Targets:

Aqueous droplet: ~ 30 µm

Sn droplet: >50 µm

Sn sphere: 30-250 µm

Sn coatings: 10 nm ~ 100 nm

Diagnostics

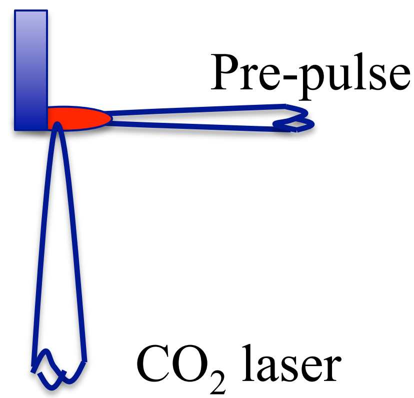
<u>Soft x-ray emission</u>: Energy monitor
- TGS spectrometer
- In-band soft x-ray waveform

<u>Ions</u>: Electrostatic Energy Analyzer
- space & time resolved visible spectroscopy
- Faraday cups

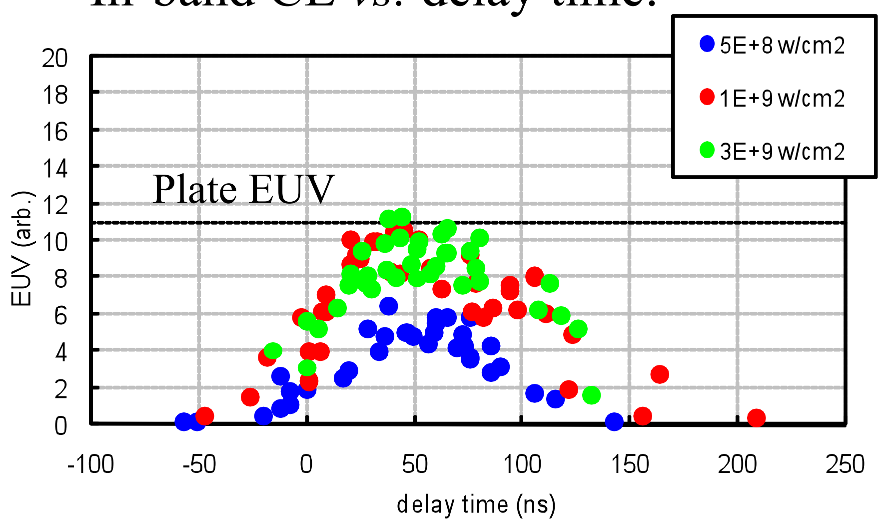
<u>Plasma</u>: Green and IR interferometers
- In-band soft x-ray imaging
- Fast (2 ns) visible imaging

Confinement by a crater results in higher CE in a CO_2 LPP

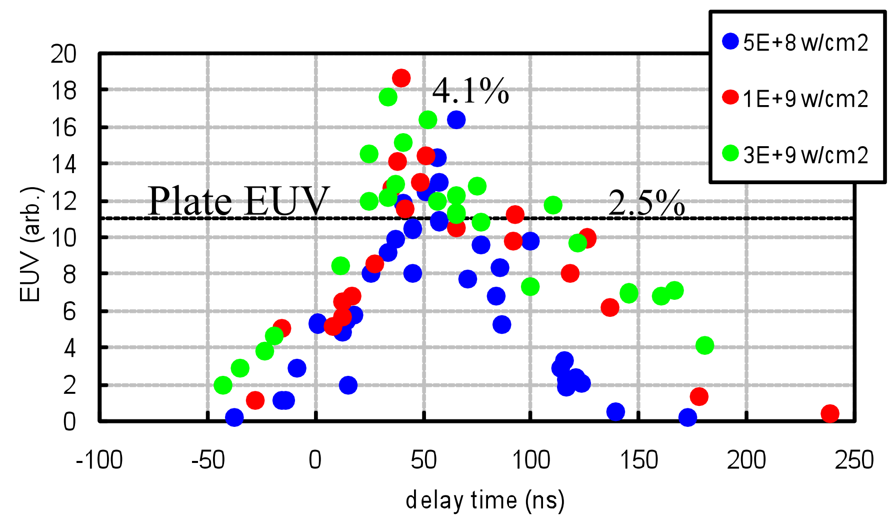
- 1 µm wavelength is too short; opacity is too high.
- 10.6 µm wavelength is too long; plasma density is sub-optimal.



In-band CE *vs.* delay time:

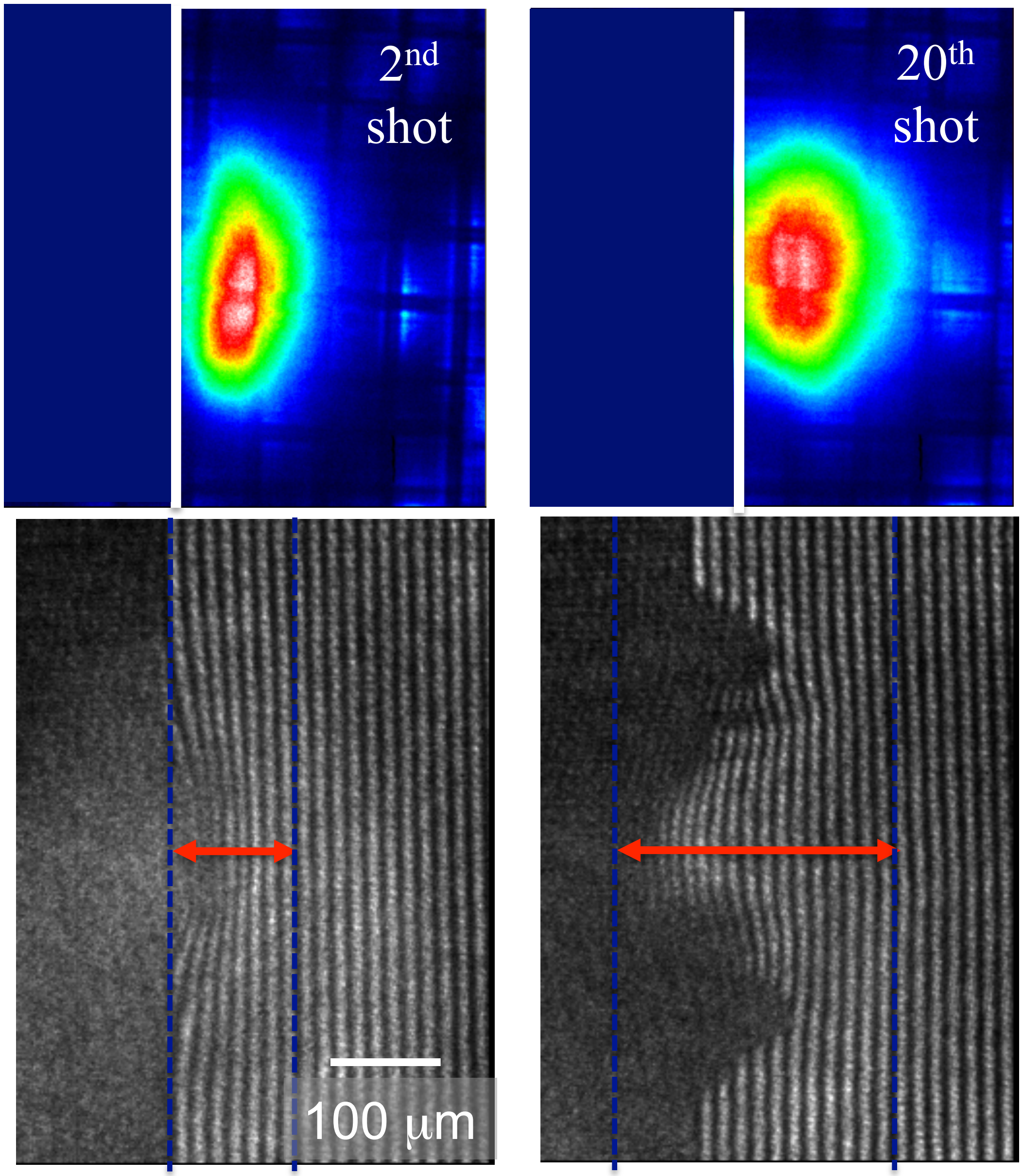


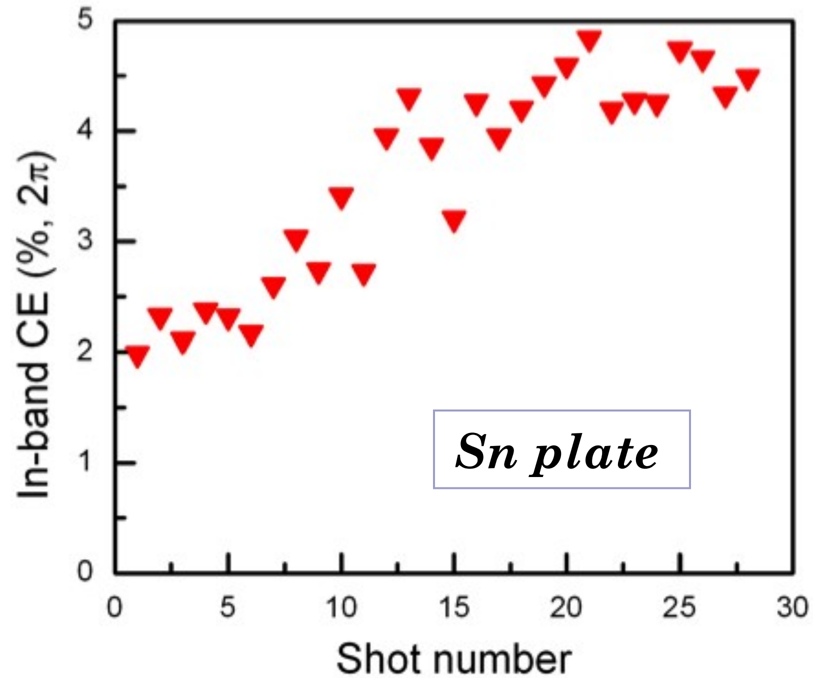
Planar (one pre-pulse)



Crater (100 accumulated pre-pulses)

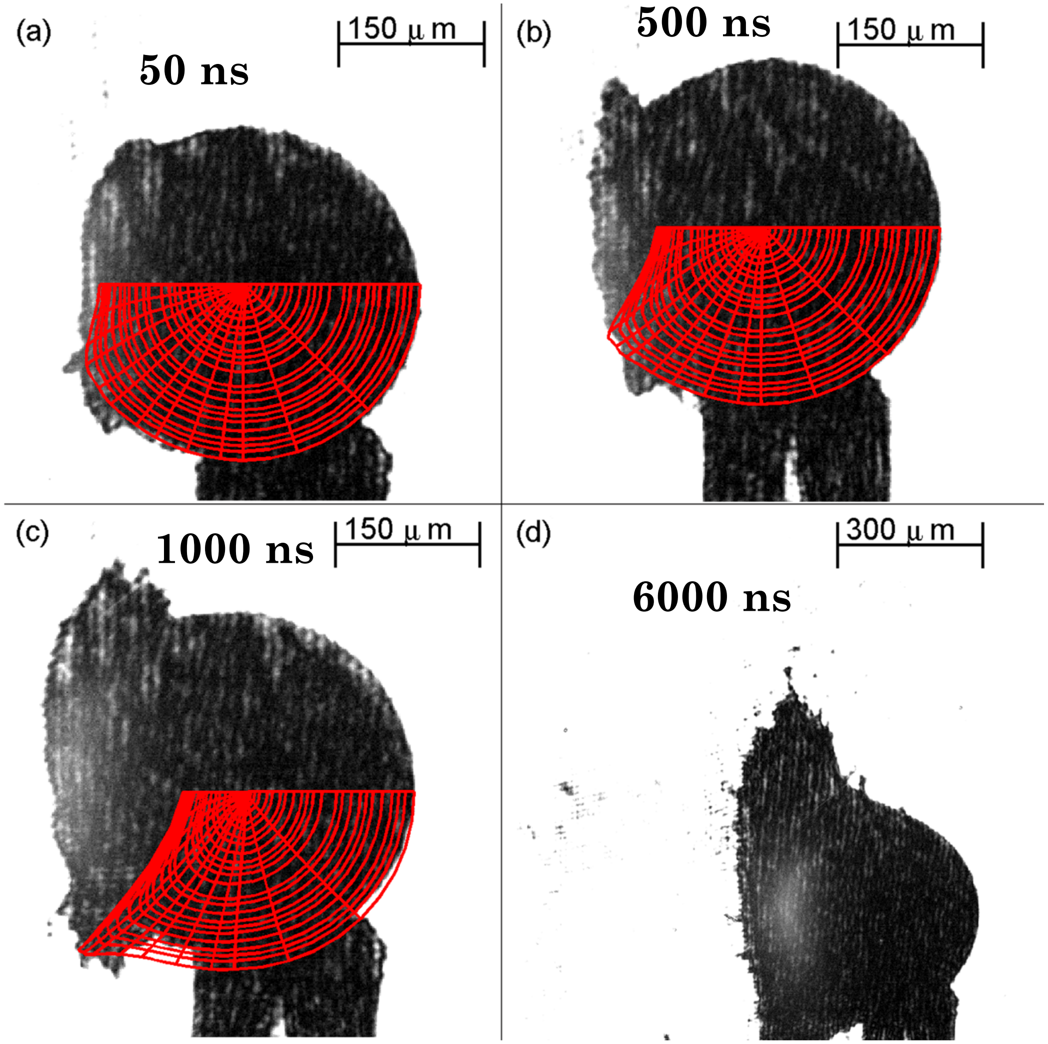
Larger corona and emitting volume enhance CE





150-μm Sn wire used for interferometry

Laser pre-pulses can create well-formed craters



- Black images are experimental shadowgraphs
- Red grids represent 2-D hydrodynamic simulation using h2d.
- The expansion at later times results in a disk-like shape.
- A crater may also appear in smaller droplets under proper conditions. The time scale will change.

S. Yuspeh, Y. Ueno, M. S. Tillack, R. Burdt, Y. Tao, and F. Najmabadi, "Cavity formation in a liquid Sn droplet driven by laser ablation pressure for an extreme ultraviolet light source target," *J. Applied Physics* **109**, 076102 (2011).

Non-isothermal expansion occurs with CO_2 LPP

Plasma electron density

$$n_e \propto \exp[-x/l_s]$$

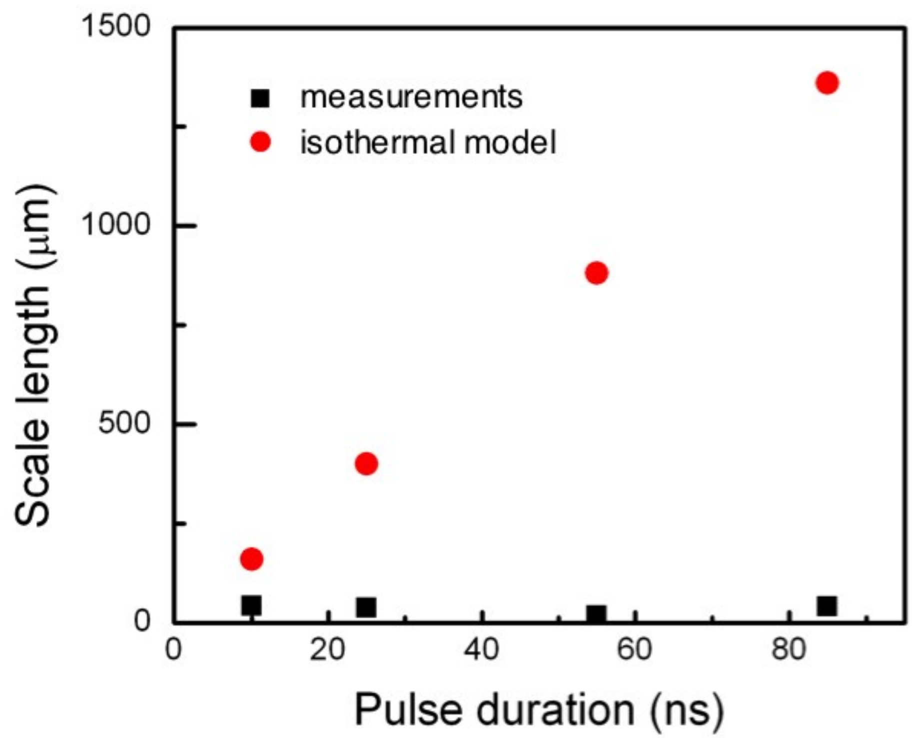
Scale length

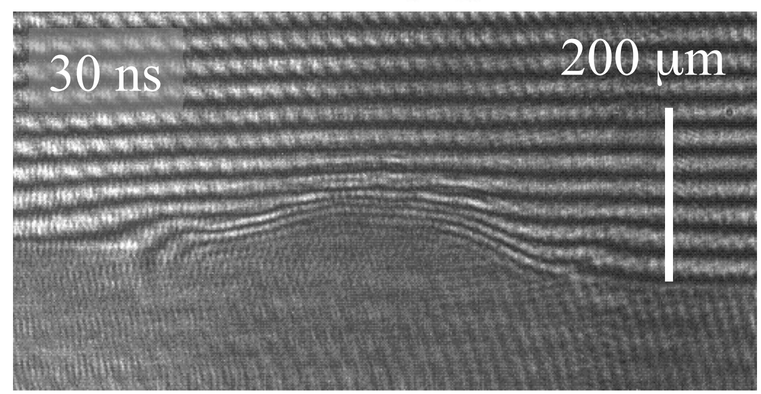
$$l_s = c_s t$$

Ion sound speed

$$c_s = \sqrt{(ZT_e/M_i)}$$

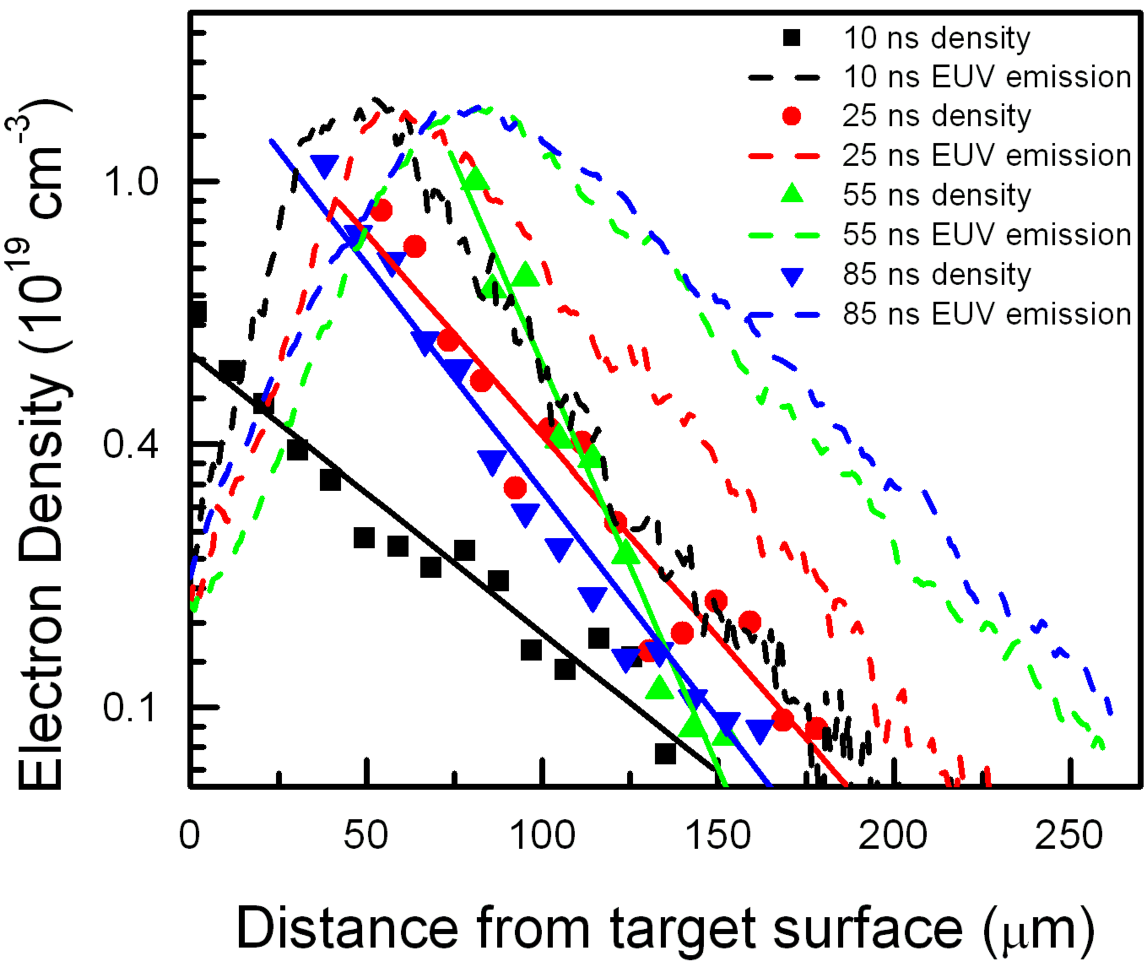
Assumptions: T_e=30 eV, Z=10





Y. Tao, M. S. Tillack, S. Yuseph, R. Burdt, and F. Najmabadi, "Non-classical hydrodynamic behavior of Sn plasma irradiated with a long CO_2 laser pulse," *Applied Physics B 99 (2010) 397-400.*

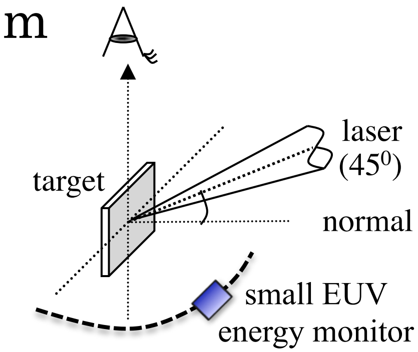
The coronal density profile collapses after ~30 ns

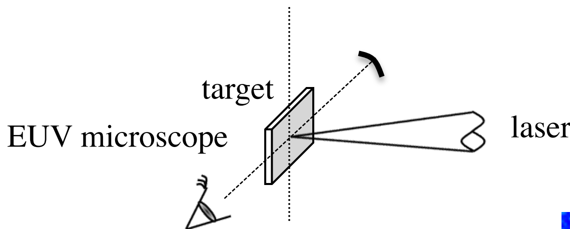


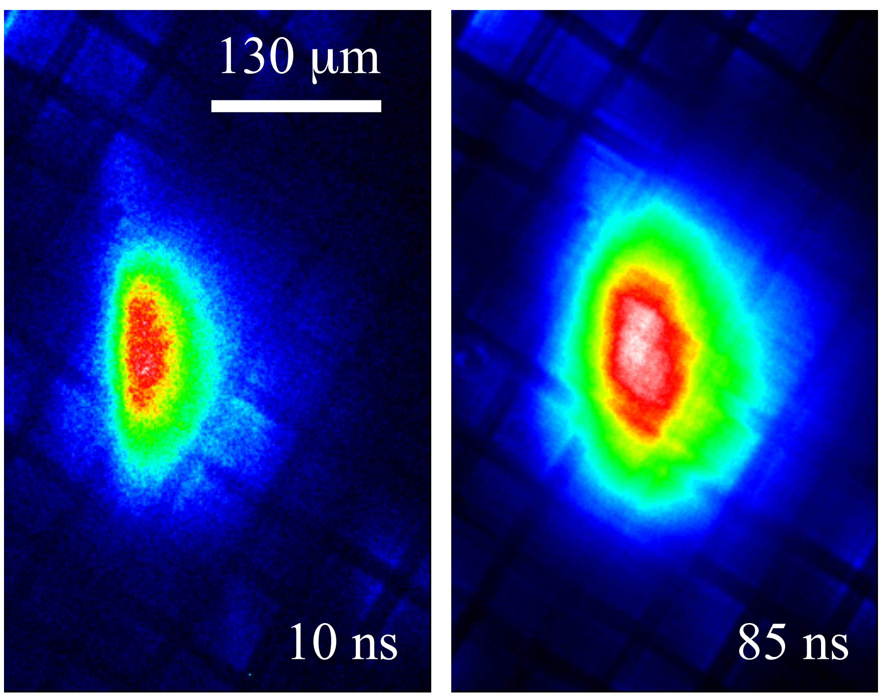
- Small plasma scale length
- Burn-through occurs
- EUV DER remains localized near n_c

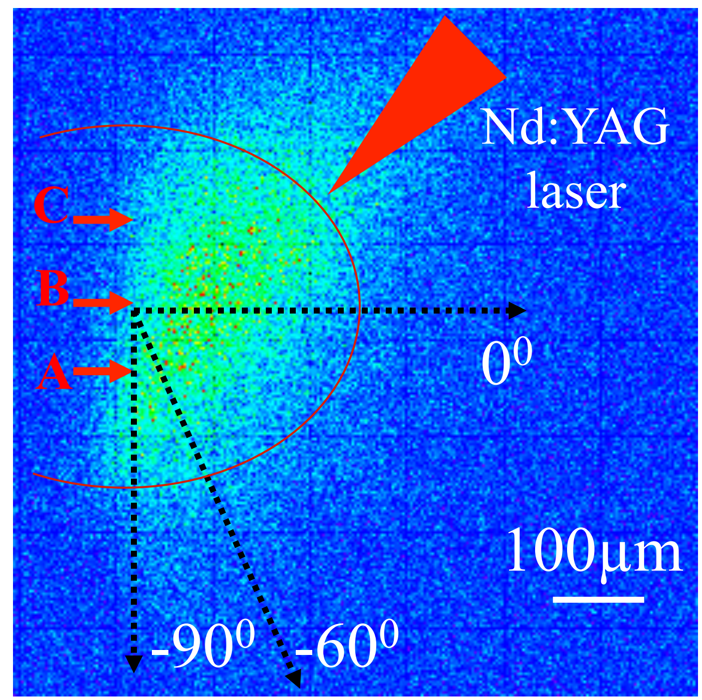
The emitting region moves very slowly

- Ablation is limited, implying a small flux limiter @10 μm
- Poor conductivity between n_c and ablation surface

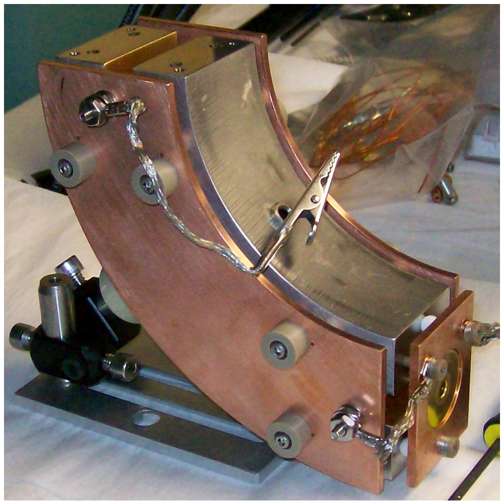


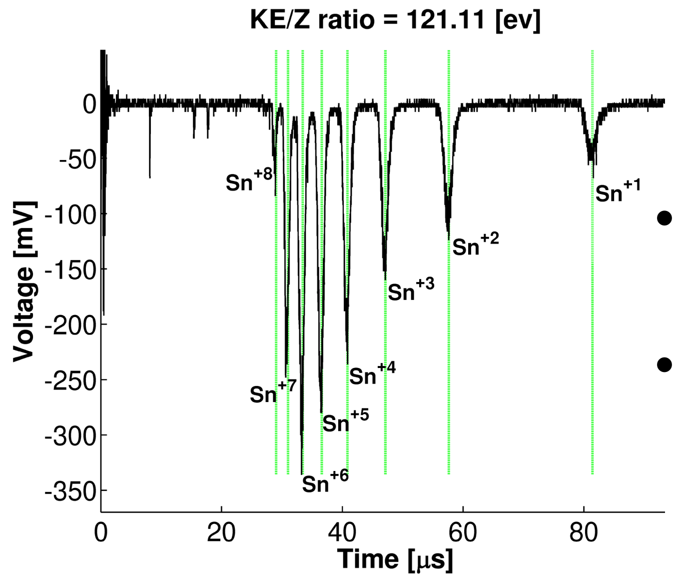




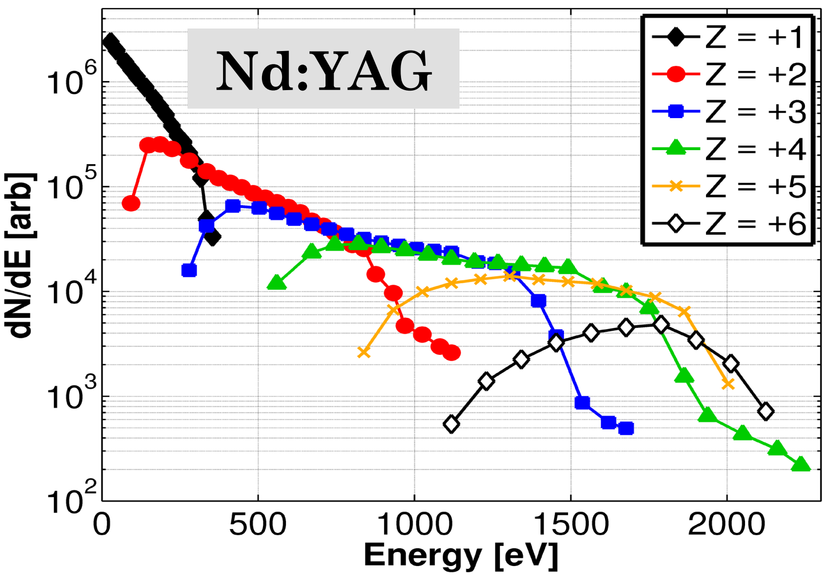


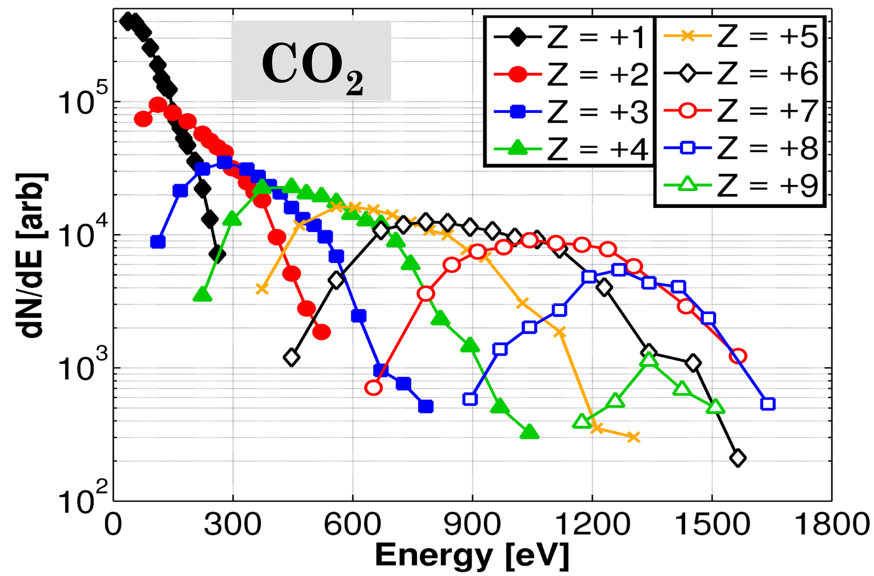
Ion energy spectra *vs.* charge state were measured for both CO_2 and Nd:YAG LPP





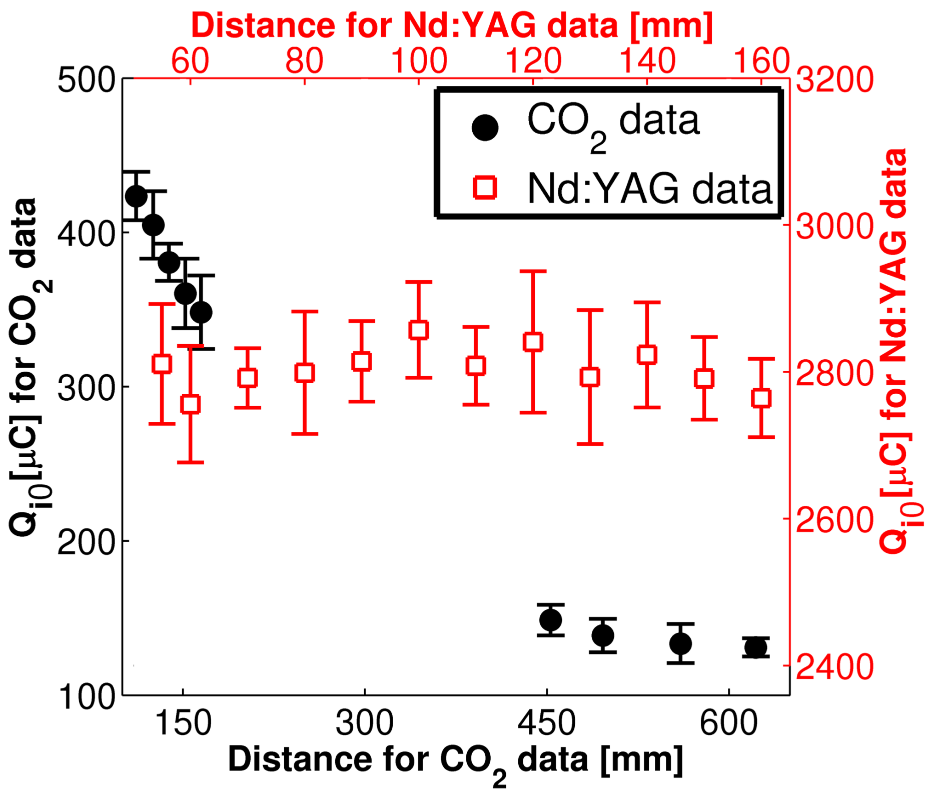
- Example spectrum from CO_2 LPP with Sn target
- Lower energy, fewer ions, higher charge state with CO_2 laser



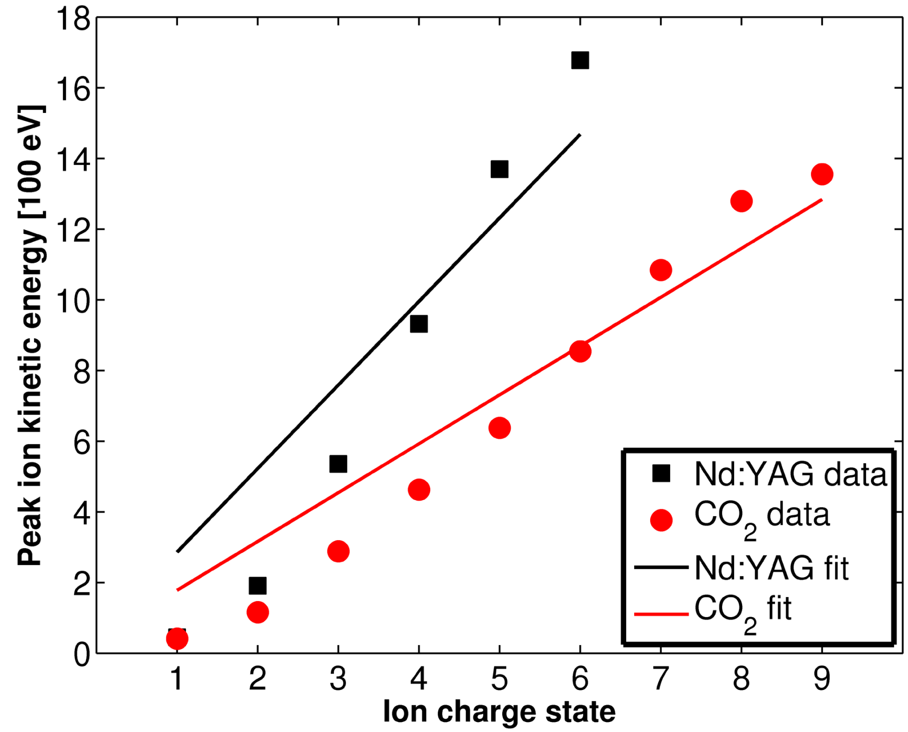


Higher charge state and longer critical length are observed in CO_2 laser-produced Sn plasma

Ion charge *vs*. distance from target



Kinetic energy *vs*. charge state



Goals for actinic metrology and mask inspection

High average brightness to obtain higher resolution

- Small EUV source, 10-30 μm
- Stable and stationary emitting region
- Nd:YAG laser appears better suited to these very small plasmas

Lower peak intensity to avoid mask damage under high EUV flux

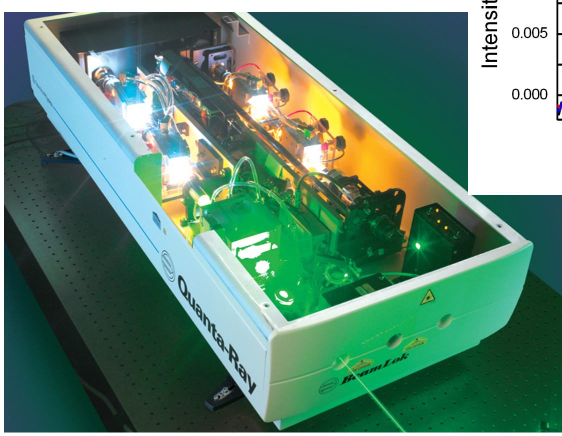
- Long duration (> 10 ns) laser pulse may be better than short pulse
- The longer the pulse duration the better
- However, the following issues have to addressed in order to apply long duration laser pulse to an EUV source,

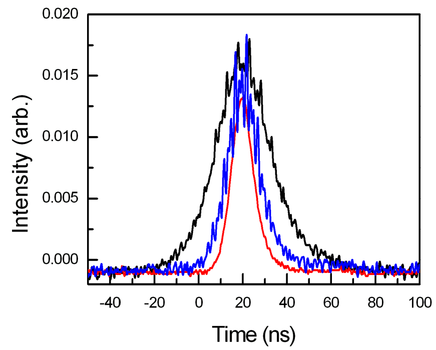
    1. *Is high CE possible with longer pulses? – Opacity*
    2. *Is it possible to obtain small source size? – Plasma expansion*
    3. *What are ion energies with a longer pulse?*

Efficient and small in-band EUV source driven with long pulse Nd:YAG laser

The pulse length was varied by manipulating the oscillator voltage and the Q-switch delay on our QuantaRay laser

Even longer pulses are possible, but require laser modifications



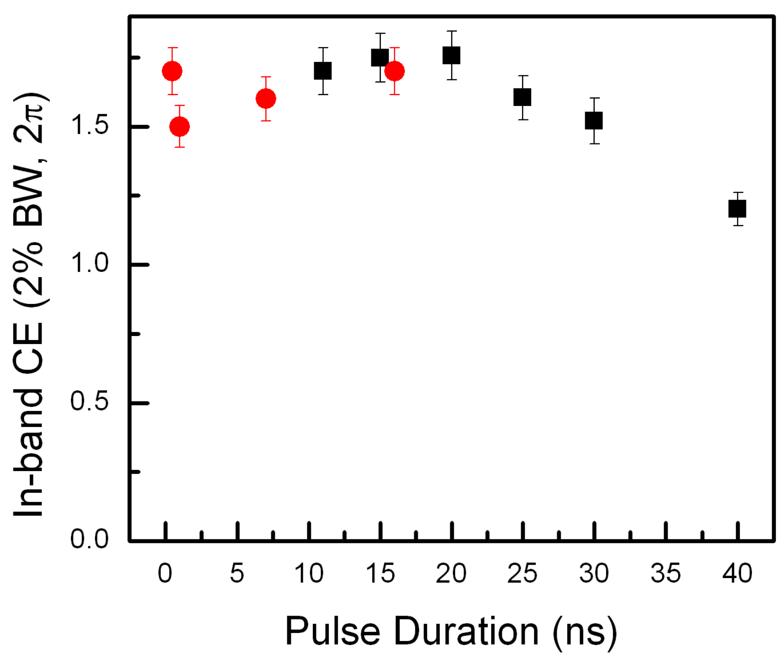


Focal spot diameter: 40 μm

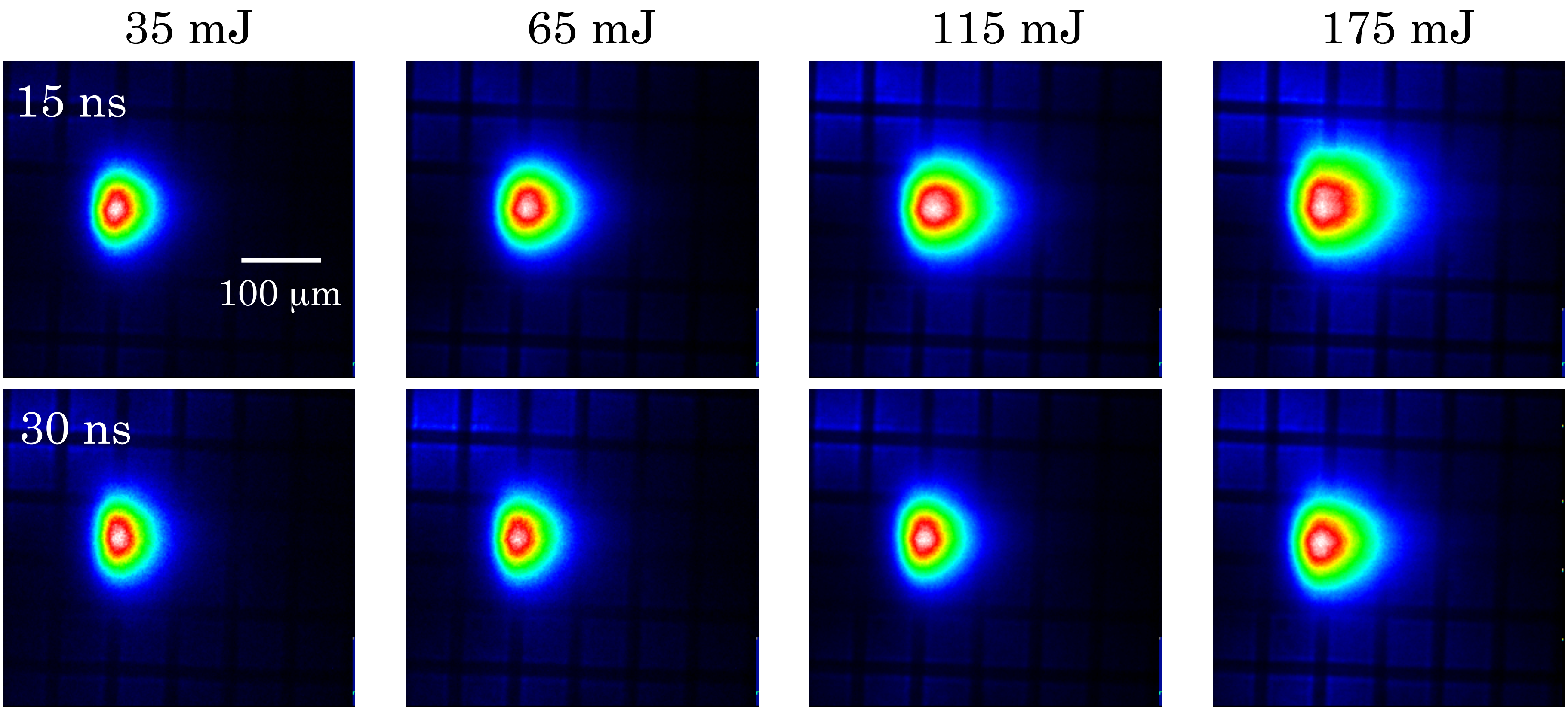
Laser pulse duration: 0.13 – 40 ns

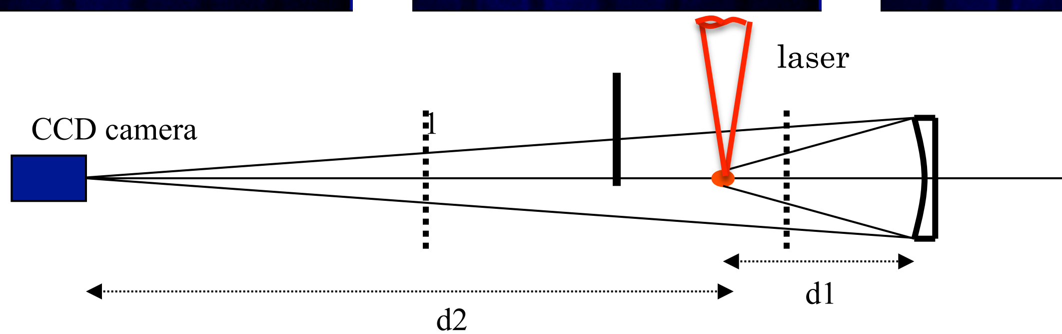
Laser intensity: 2×10^{10} - 2×10^{11} W/cm^2

In-band CE *vs.* laser pulse duration



The EUV source size depends more strongly on intensity than pulse length

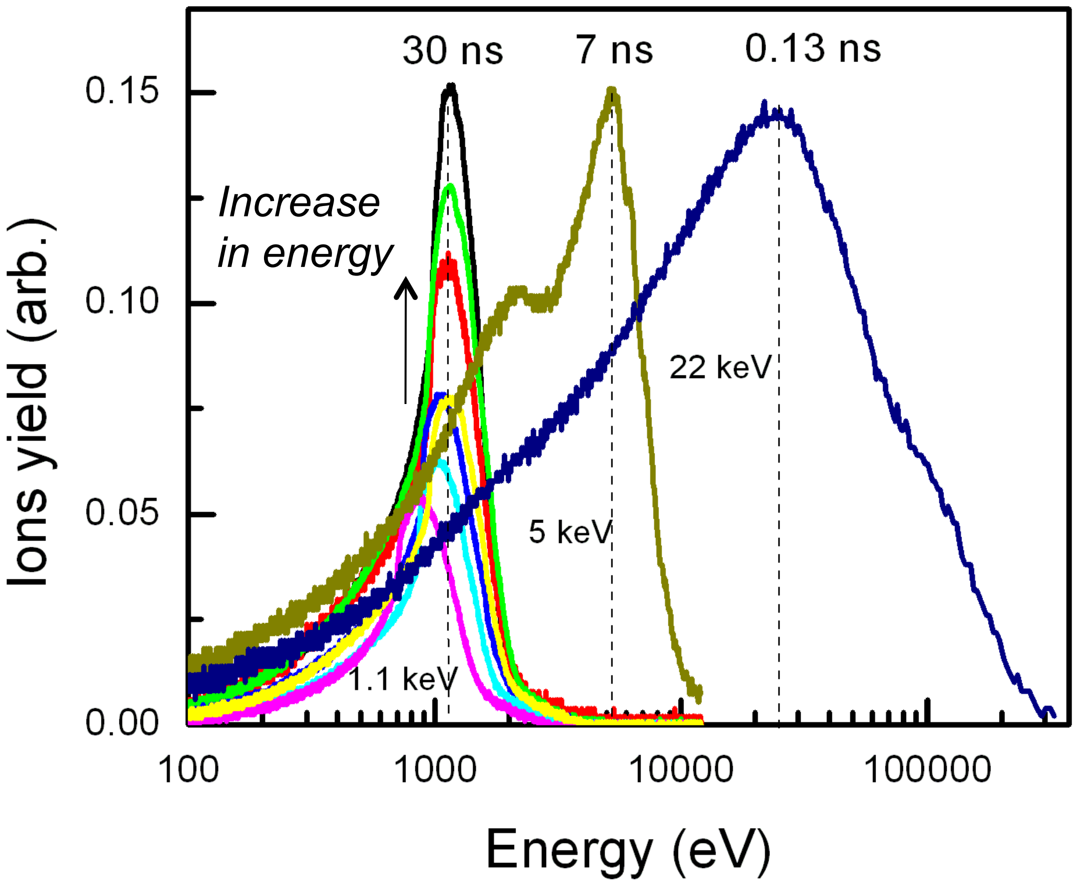




High resolution narrowband EUV imaging

Sn plasma driven by a long laser pulse produces much slower ions compared with shorter pulses

Kinetic energy of Sn ions driven by 0.13, 7 and 30 ns pulses

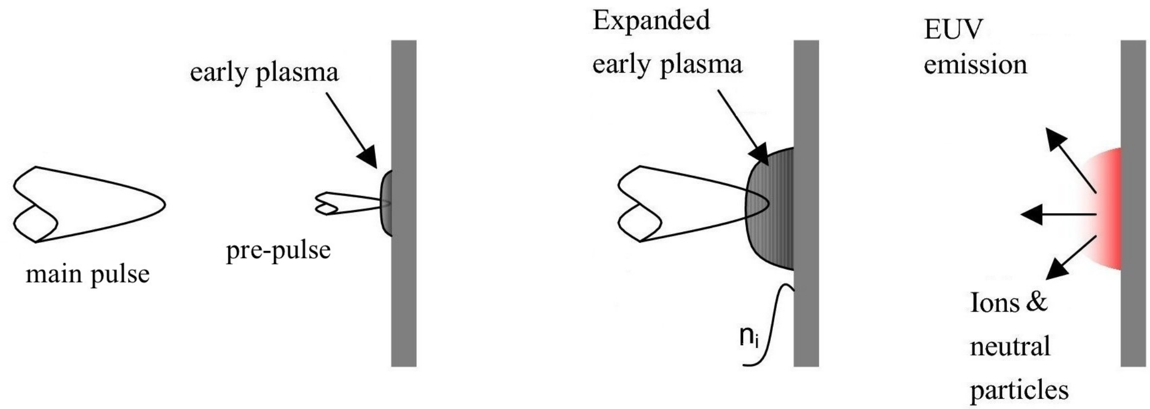


Laser intensities (W/cm^2):

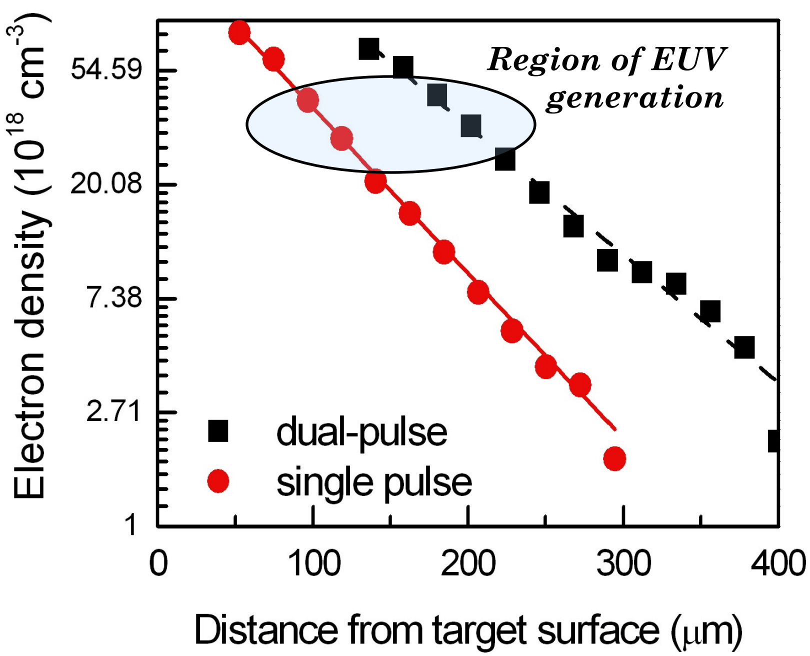
0.13 ns	1×10^{12}
7 ns	2×10^{11}
30 ns	$1\times10^{10} – 2\times10^{11}$

For 0.13 and 7 ns pulse durations, the laser intensities are optimized to obtain the highest CE.

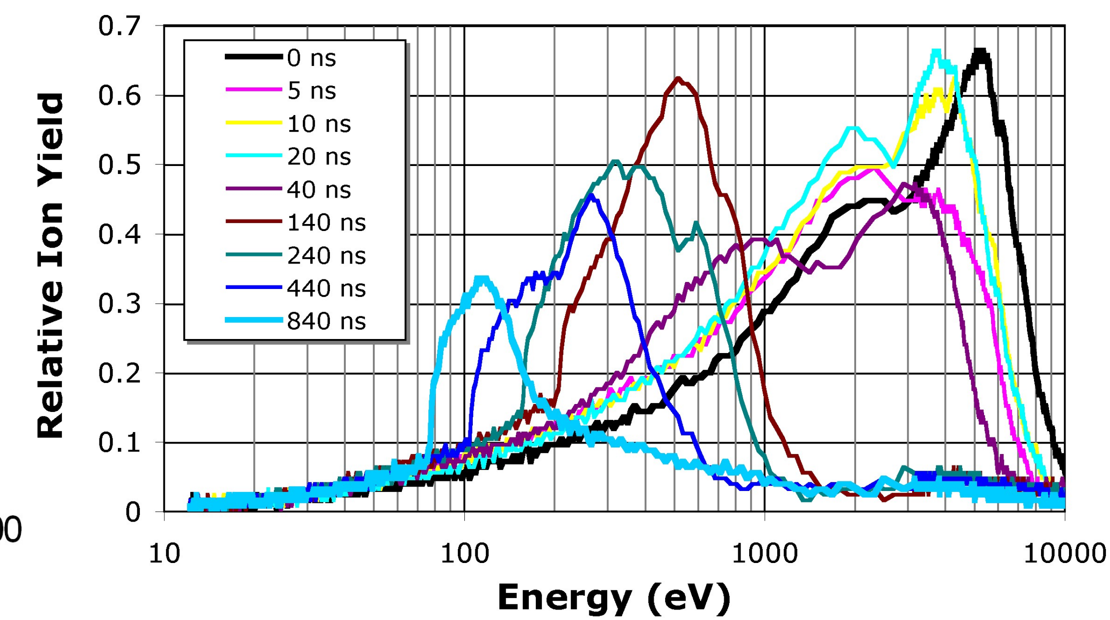
Our earlier pre-pulse results showed the importance of a "gentle" density gradient



Density profiles from interferometry



Energy spectra of ions *vs*. time delay



Acknowledgements

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