

Density measurement of extreme ultraviolet emission region in laser-produced Sn plasmas

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Presentation on 3rd EUVL symposium,
Miyazaki, Japan. Nov. 1-4,2004



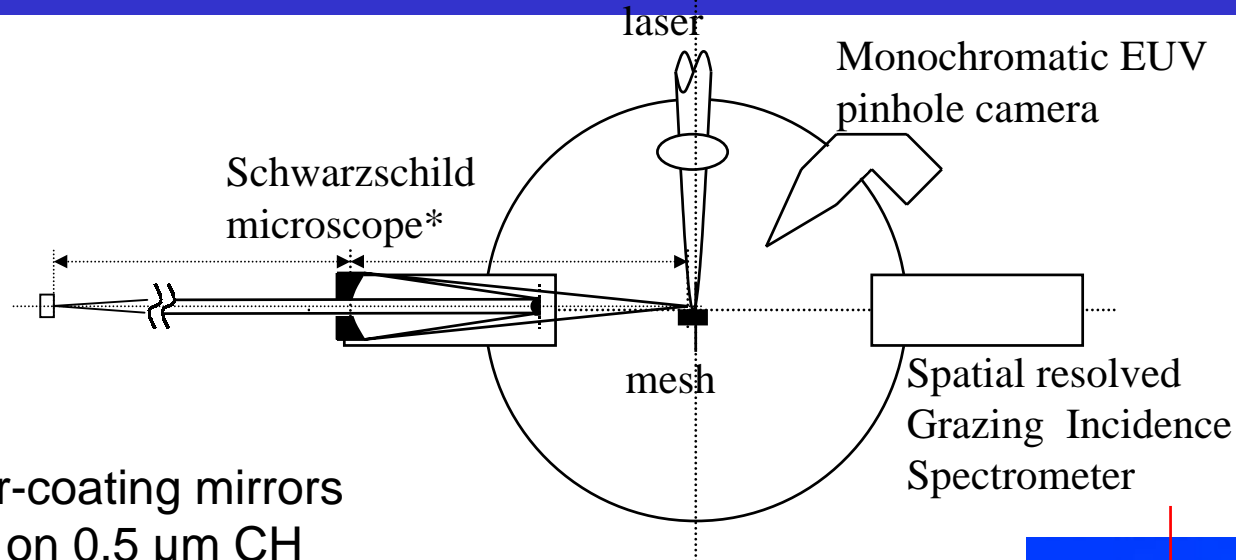
Contents

- The purpose is **to identify** and **characterize** the dominant emitting region of **monochromatic** 13.5nm EUV emission in laser-produced Sn plasma, **to** clarify the physics of EUV generation and transportation, and **to** provide experimental data to benchmark simulation code for EUVL development.
- Measurement on temporally resolved 13.5nm monochromatic EUV emission profile.
- Measurement of electron density profile in the region favorable 13.5nm EUV emission.
- Discussions



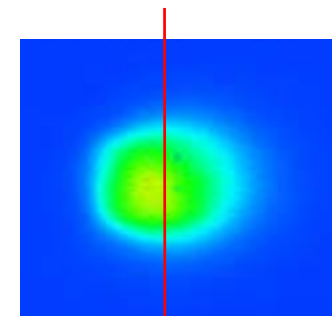
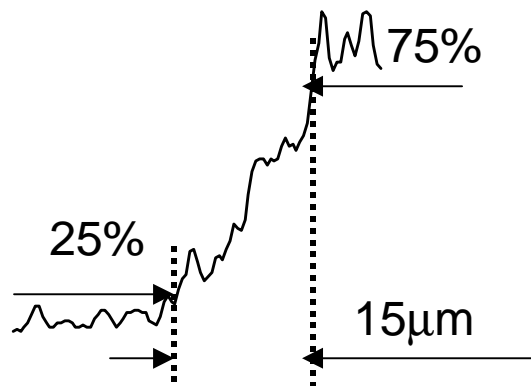
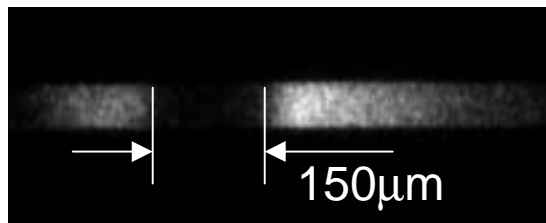
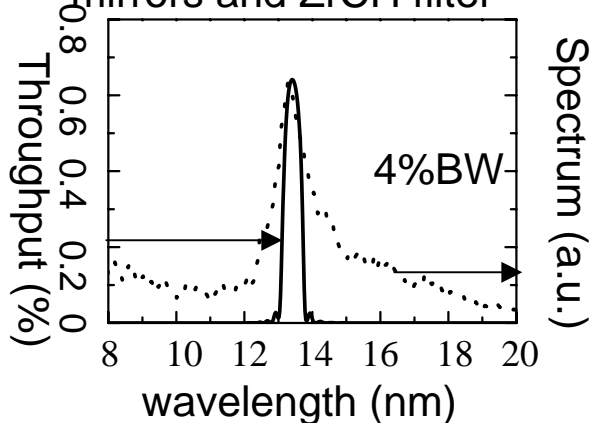
2. Measurement of temporally resolved EUV emission profile

X-ray streak camera
HamamatsuC7700-31

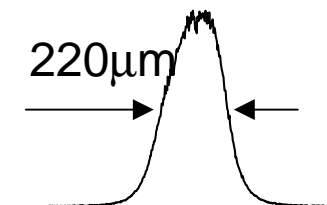


- Mo/Si multilayer-coating mirrors
- filter: 0.4 μm Zr on 0.5 μm CH

Calculated throughput of two mirrors and ZrCH filter



EUV image of focal spot



* Y.Tao et al. Rev.Sci.Instrum., (accepted for publication)

Typical temporal resolved EUV emission profile from LP Sn Plasma

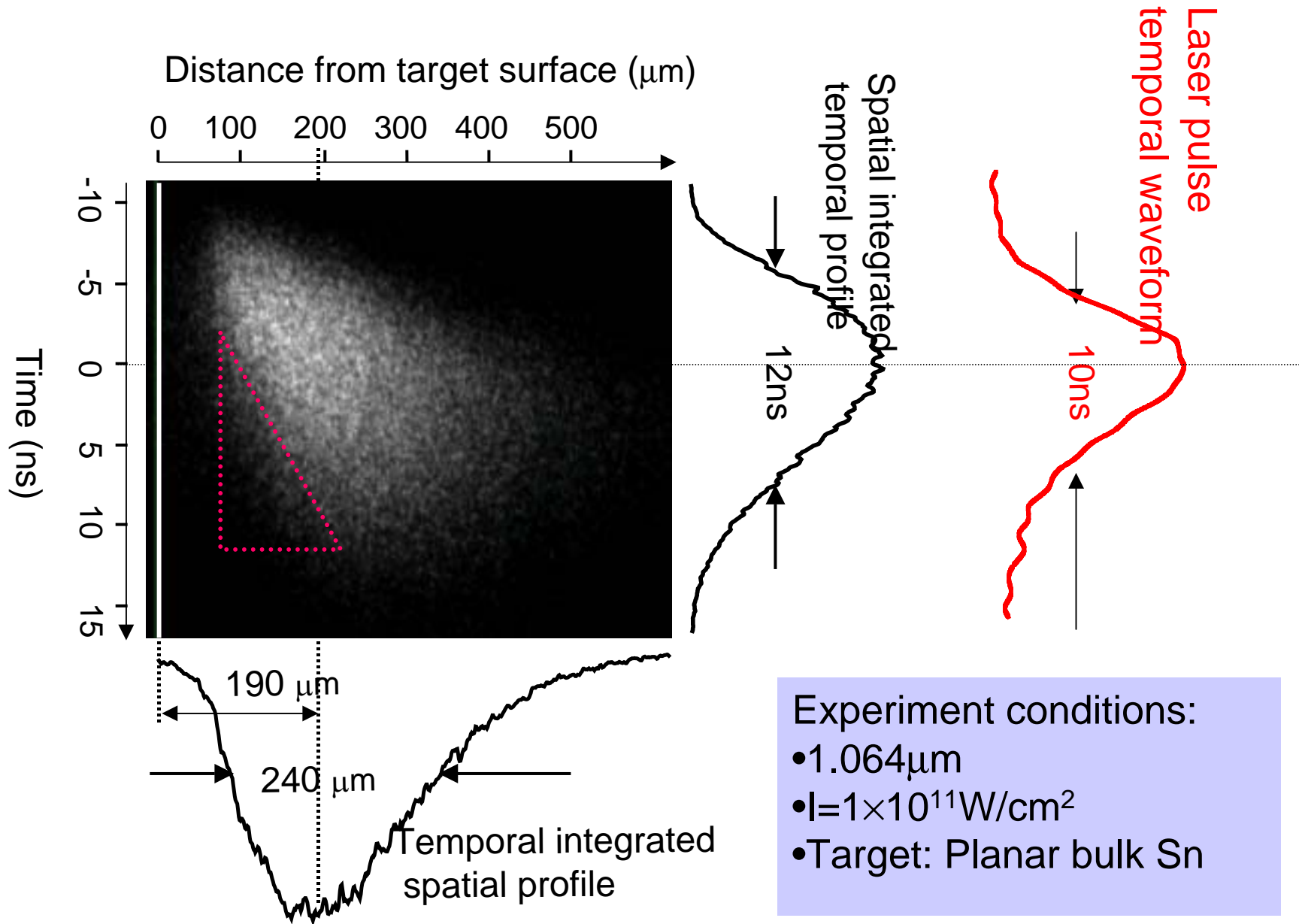
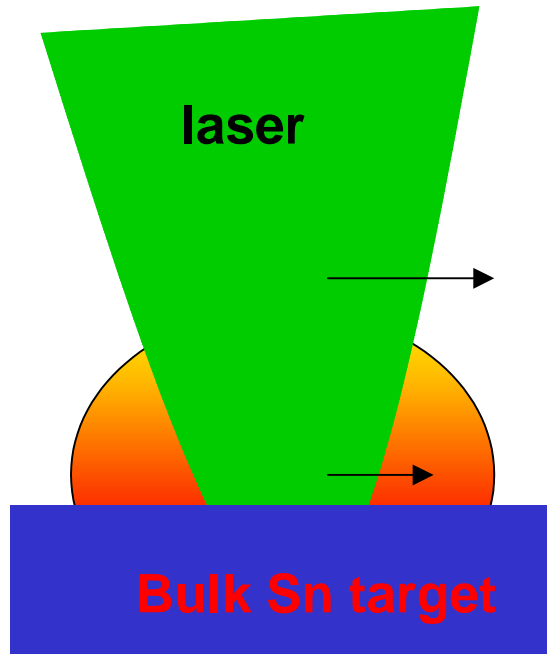
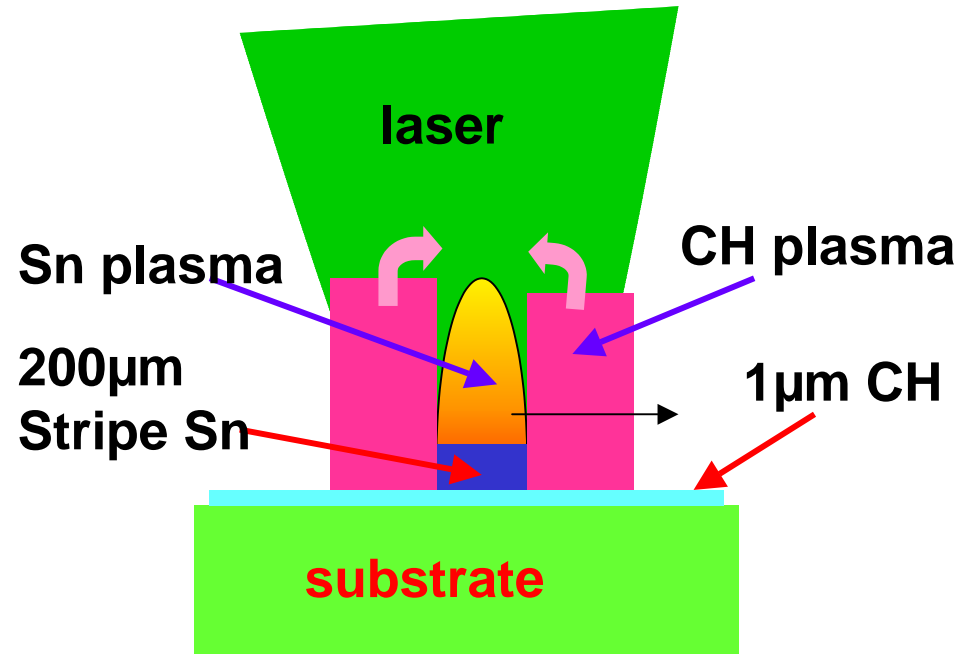


Illustration of absorption by surrounding cold plasma and mitigating it by adopting stripe target



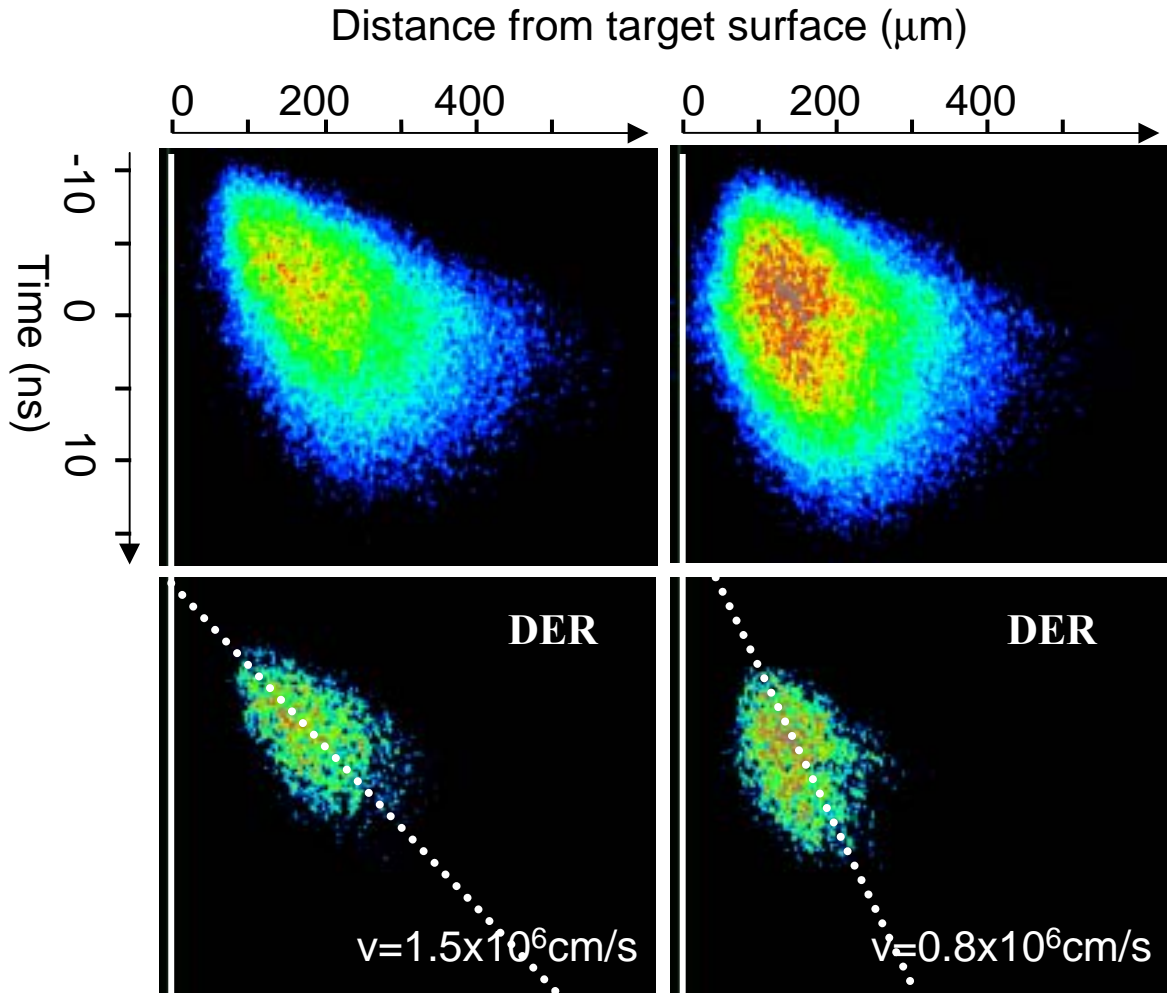
Bulk Sn target



Stripe Sn target



EUV emission profile from bulk and stripe targets



Bulk planar Sn target

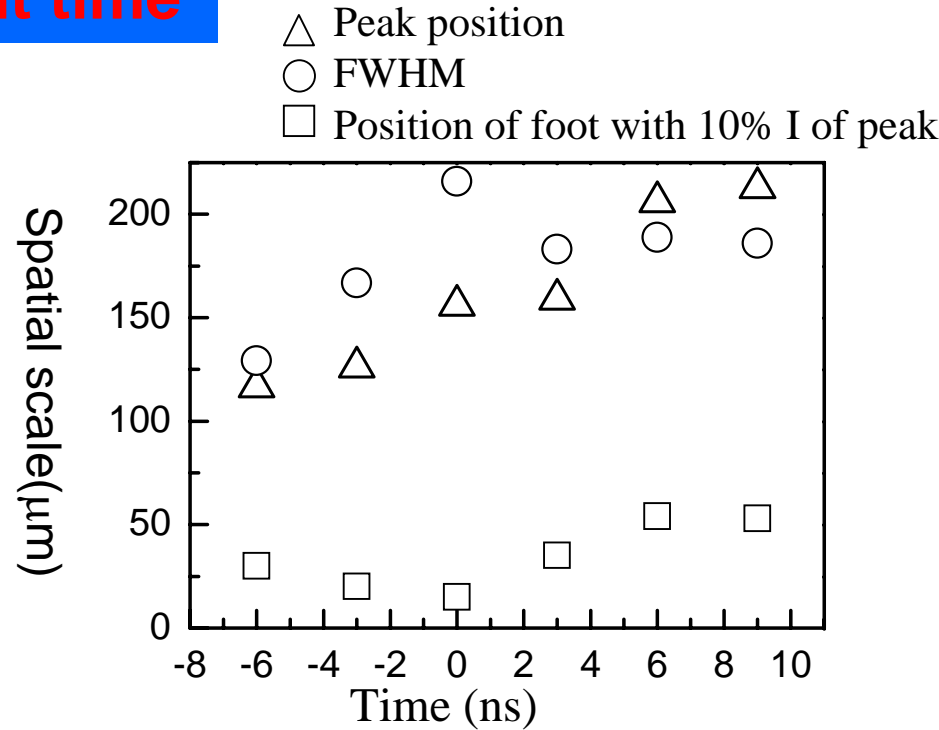
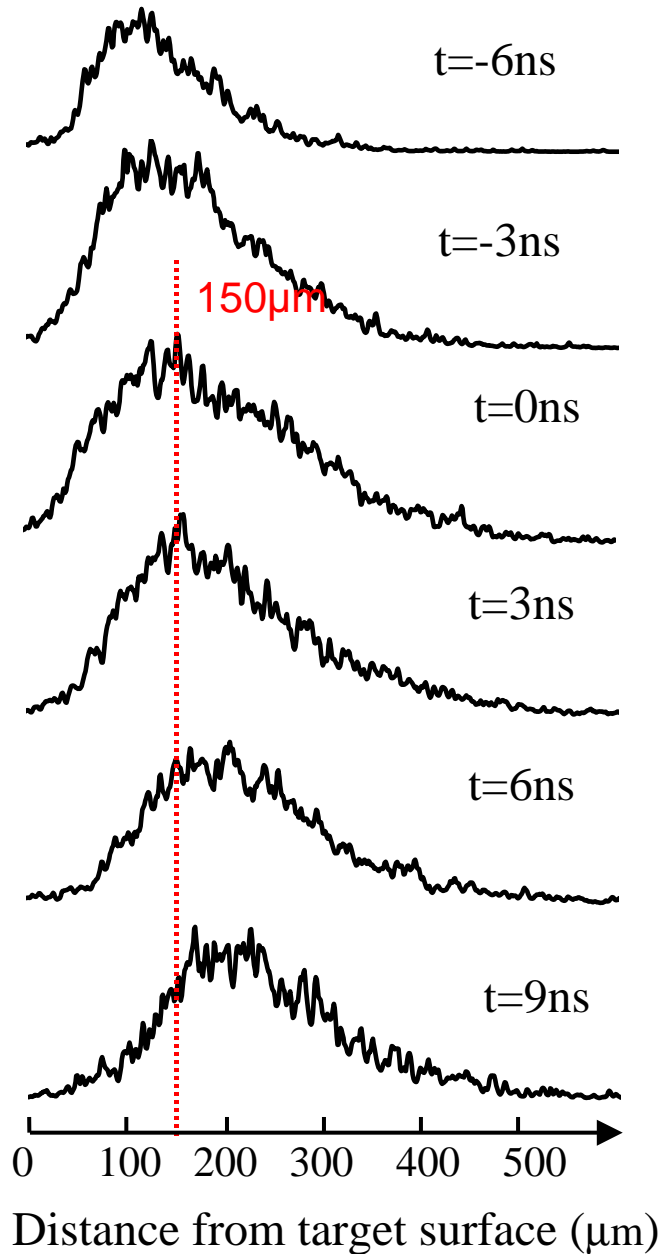
Stripe Sn target

DER: Dominant Emission Region
contains >75% total EUV

- The expansion of EUV DER in these two cases are nearly same.
- The faster shift of EUV DER in the case of bulk target arises from the self-absorption of the expanding cold plasma.

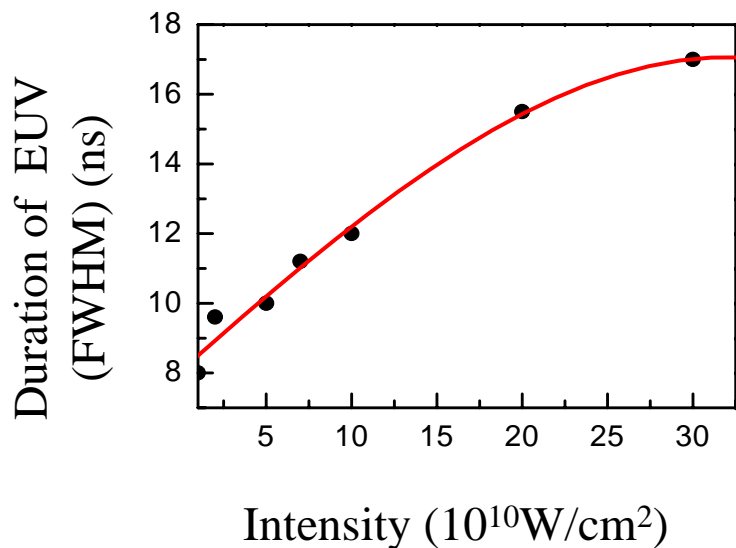
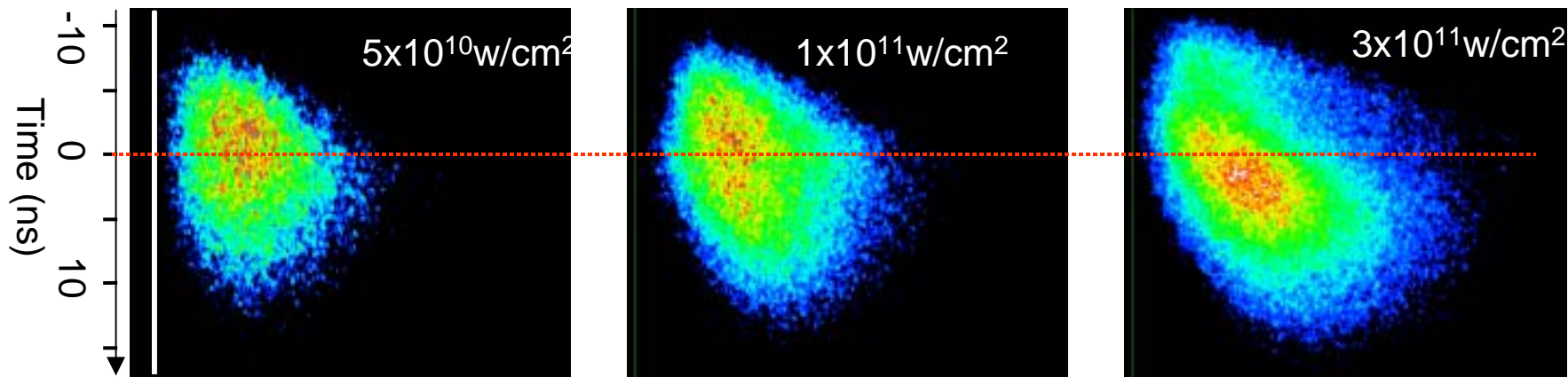


Spatial distribution at different time

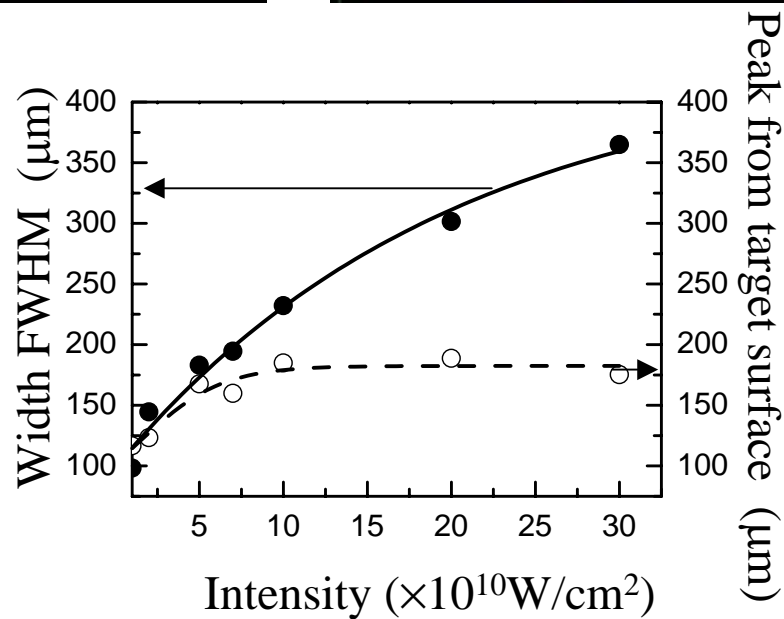


- EUV DER expands into vacuum with time, the widest DER appears around the peak of laser pulse.
- The peak of emission shifts away from target surface.
- The start position of the emission shows a minimum value at the peak of laser pulse.

EUV emission profiles at various intensities



Duration of EUV emission vs. intensity



Spatial profile of EUV emission vs. intensity

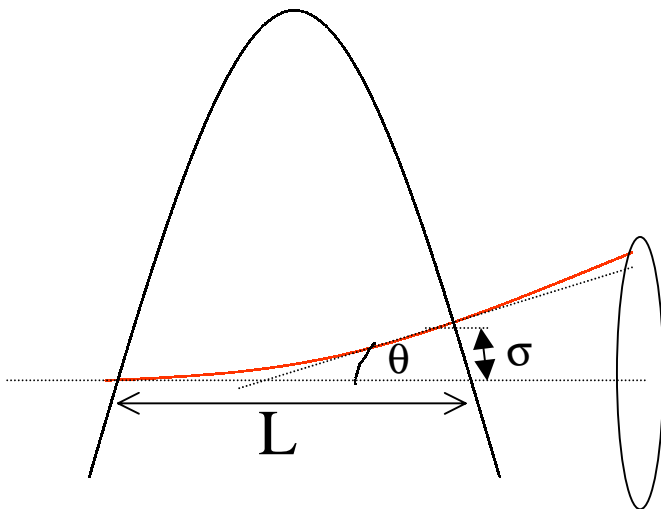


3. Electron density profile measured by both green and UV interferometer

$$\Delta \varphi(\mathbf{x}) = \frac{2\pi}{\lambda} \int_{-l/2}^{l/2} (n - 1) dy$$

$$n = \sqrt{1 - \frac{n_e}{n_c}} \approx 1 - \frac{n_e}{2n_c} \quad (n_e \ll n_c)$$

Error induced by refraction is reduced by using a large F number imaging lens



Error $\sigma = \theta \cdot L \leq 15\mu\text{m}$

Probing length $L = 300\mu\text{m}$

Deflection angle $\theta \leq 0.04$

$$\theta \approx 1/F\# \Rightarrow F\# = 25$$

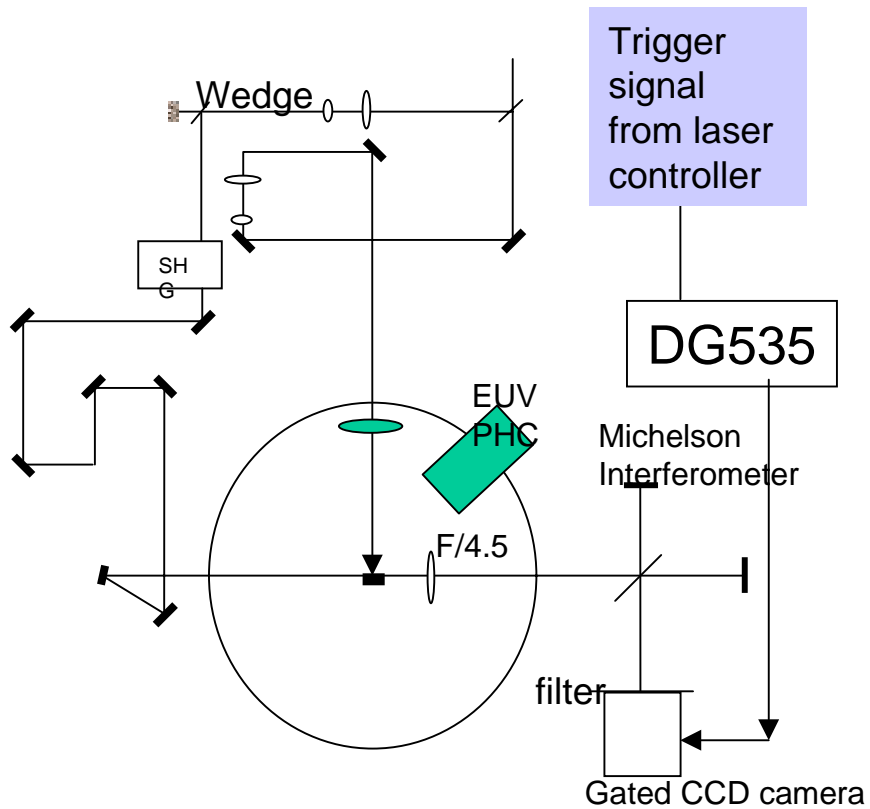
$$\theta \approx L \left(\frac{n_e(z)}{2n_c l_{\text{scale}}} \right) \Rightarrow$$

$$n_{e\text{max}} = \frac{2n_c l_{\text{scale}} \theta}{L} = 1.5 \times 10^{21} \text{ cm}^{-3} (266\text{nm})$$

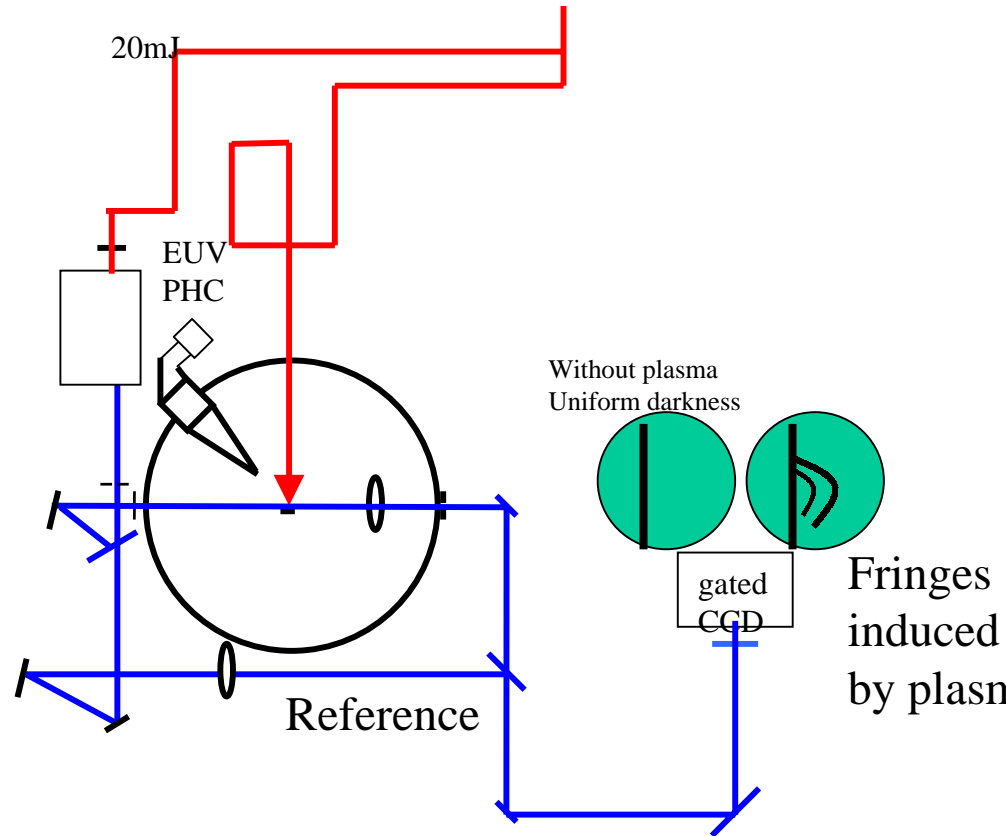
$$l_{\text{scale}} = 300\mu\text{m}$$

Plasma scale length

Arrangements for green and UV interferometers

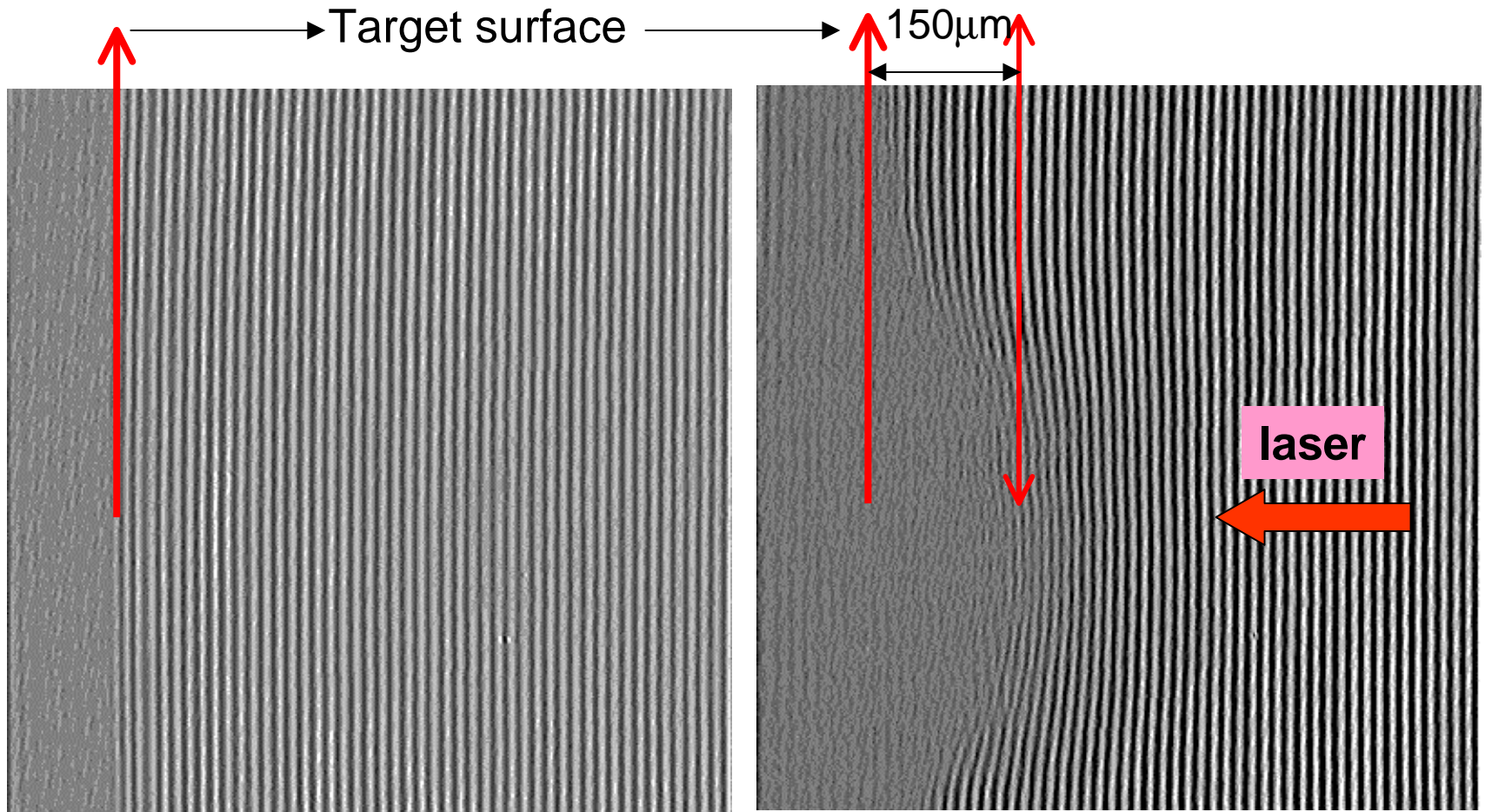


532nm Michelson interferometer



266nm Mach-Zehnder interferometer

Typical inteferograms without plasma and with plasma taken by green interferometer



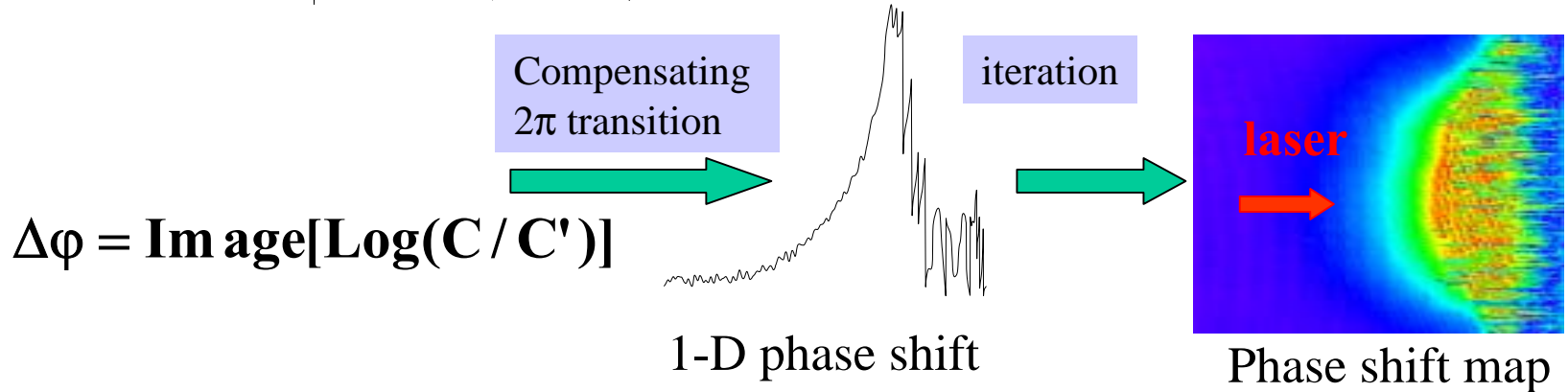
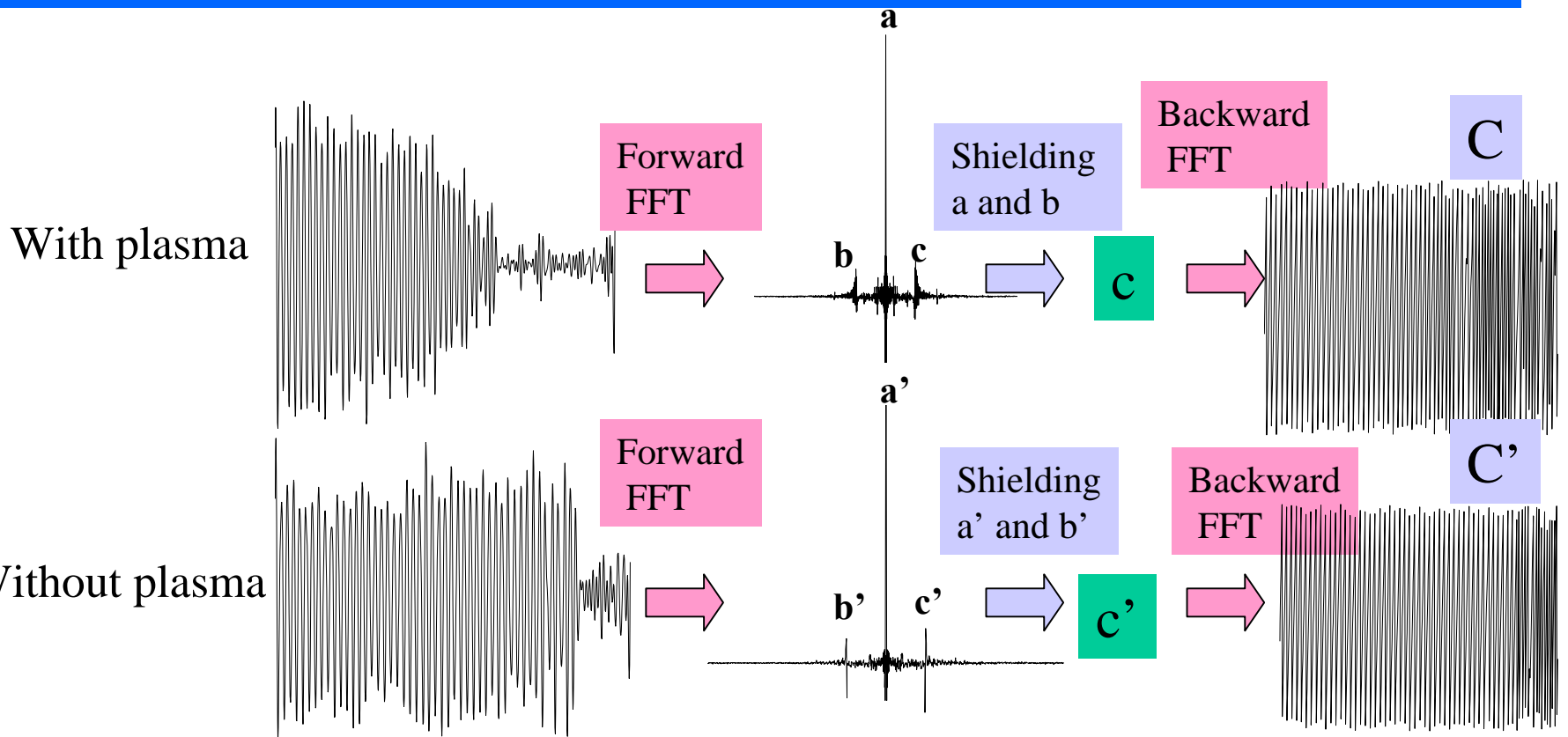
Without plasma

With plasma

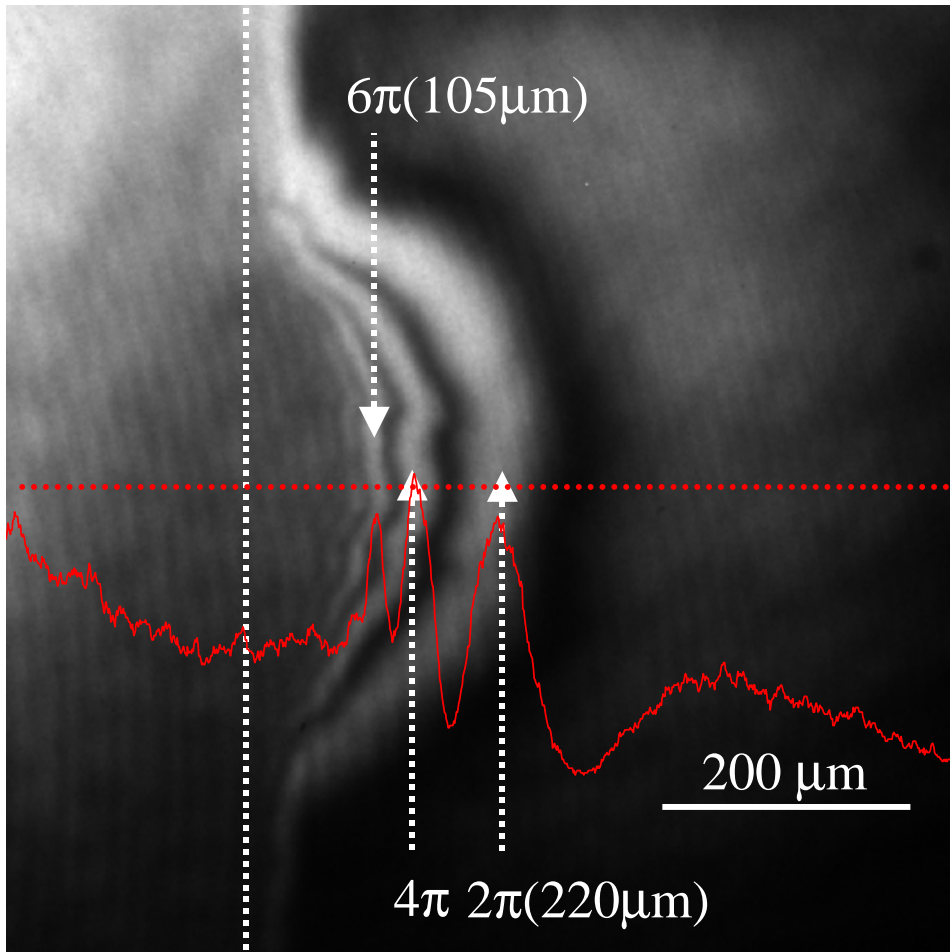
Scale 300 μ m



Phase shift extraction using 1-D Fast Fourier Transform



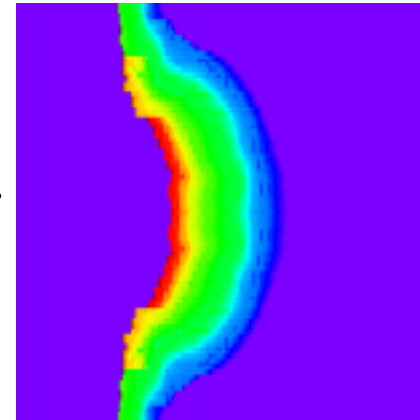
Typical interferogram of laser-produced Sn plasma taken by 4 ω interferometer at peak of laser pulse



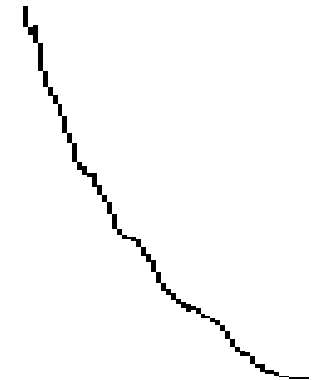
Target surface

$$n_e = \frac{\Delta\phi \cdot \lambda}{\pi \cdot L} n_c \quad (L=300\mu\text{m}, 6\pi=0.7 \times 10^{20} \text{cm}^{-3})$$

Dense region has a steeper gradient.



Phase shift map



profile

$$\Delta\phi(x) = \frac{2\pi}{\lambda} \int_{-1/2}^{1/2} (n-1) dy,$$

$$n = \sqrt{1 - \frac{n_e}{n_c}} \approx 1 - \frac{n_e}{2n_c} \quad (n_e \ll n_c)$$

$$n_c = 1.6 \times 10^{22} \text{cm}^{-3}$$

Extracting density profile from phase shift using Abel inversion

$$\Delta\varphi(\mathbf{x}) = \frac{2\pi}{\lambda} \int_{-1/2}^{1/2} (\mathbf{n} - 1) dy, \quad \mathbf{n} = \sqrt{1 - \frac{\mathbf{n}_e}{\mathbf{n}_c}} \approx 1 - \frac{\mathbf{n}_e}{2\mathbf{n}_c} \quad (\mathbf{n}_e \ll \mathbf{n}_c)$$

$$\mathbf{n}_c = \frac{\pi m_e c^2}{e^2 \lambda_0^2} = 1.1 \times 10^{21} \left(\frac{1}{\lambda[\mu\text{m}]} \right)^2 \text{cm}^{-3} = 1.6 \times 10^{21} \text{cm}^{-3} \quad (\lambda = 0.266 \mu\text{m})$$

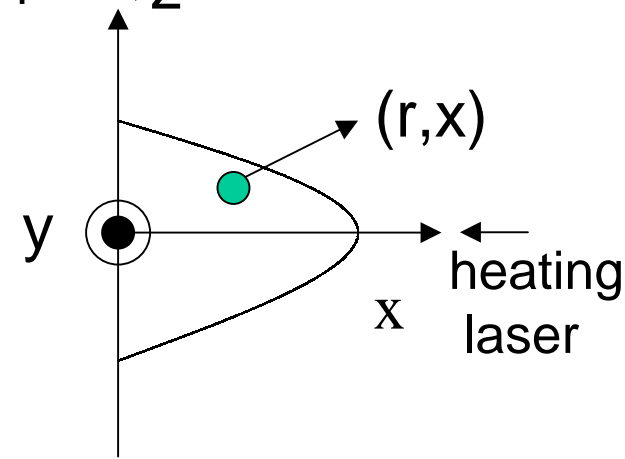
For cylindrical symmetry, Abel inversion can be applied, z

$$\mathbf{k}_0(\mathbf{n}(\mathbf{r}, \mathbf{x}) - 1) = -\frac{1}{\pi} \int_r^{r_0} \left[\frac{d\varphi(\mathbf{x}, z)}{dz} \right] \frac{dz}{\sqrt{z^2 - r^2}} = \mathbf{A}$$

$$\mathbf{n}_e(\mathbf{r}, \mathbf{x}) = \frac{\lambda}{\pi} \mathbf{n}_c \mathbf{A} \frac{1}{\text{scale}(\text{pixel})}$$

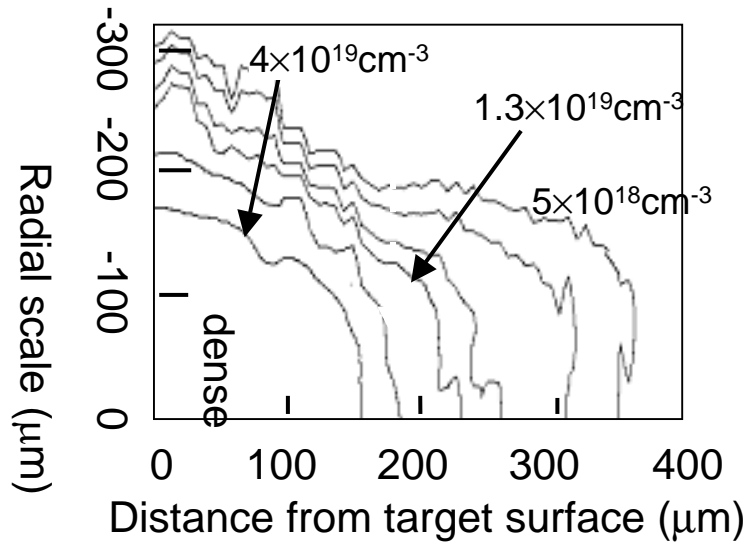
Abel inversion by IDEA software

Optimized input parameter (number of cubic polynomials) is chosen when both f-interpolation and FFT methods lead to the same result.

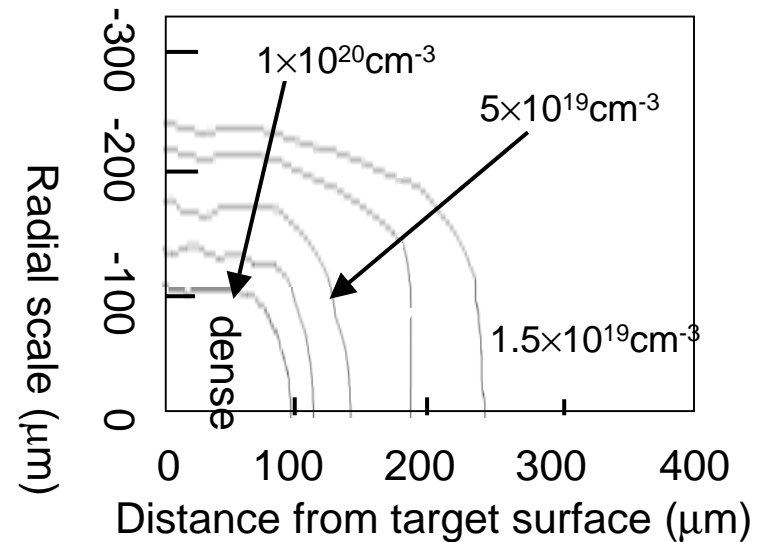


Probe laser propagation axis, y
Cylindrical symmetry axis, x

Density map of Sn plasma at the conditions of $I=1\times 10^{11}\text{W/cm}^2$, pulse width 10ns (FWHM), focal spot diameter $220\mu\text{m}$ (FWHM).



Density map from 2ω interferometer

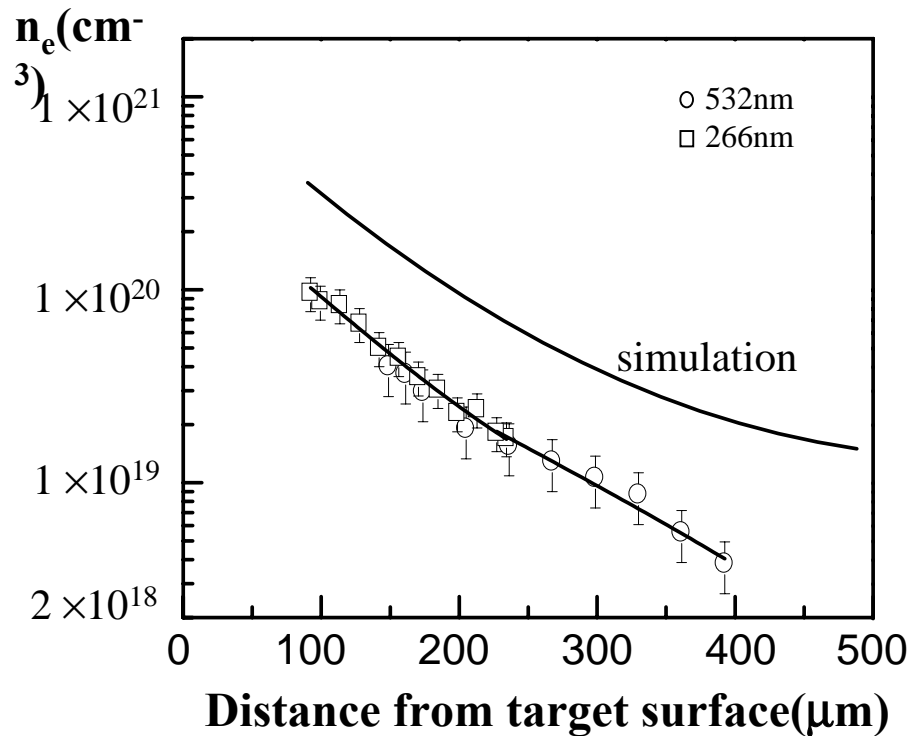


Density map from 4ω Interferometer

- The density map taken by UV interferometer extends to relatively dense region and the green interferometer shows detail in low density region.
- The basic information, including the scale length and lateral size, from 4×10^{19} to $1\times 10^{19}\text{cm}^{-3}$ is coincident in the two density maps.

Combined density profile from 2ω and 4ω interferometers

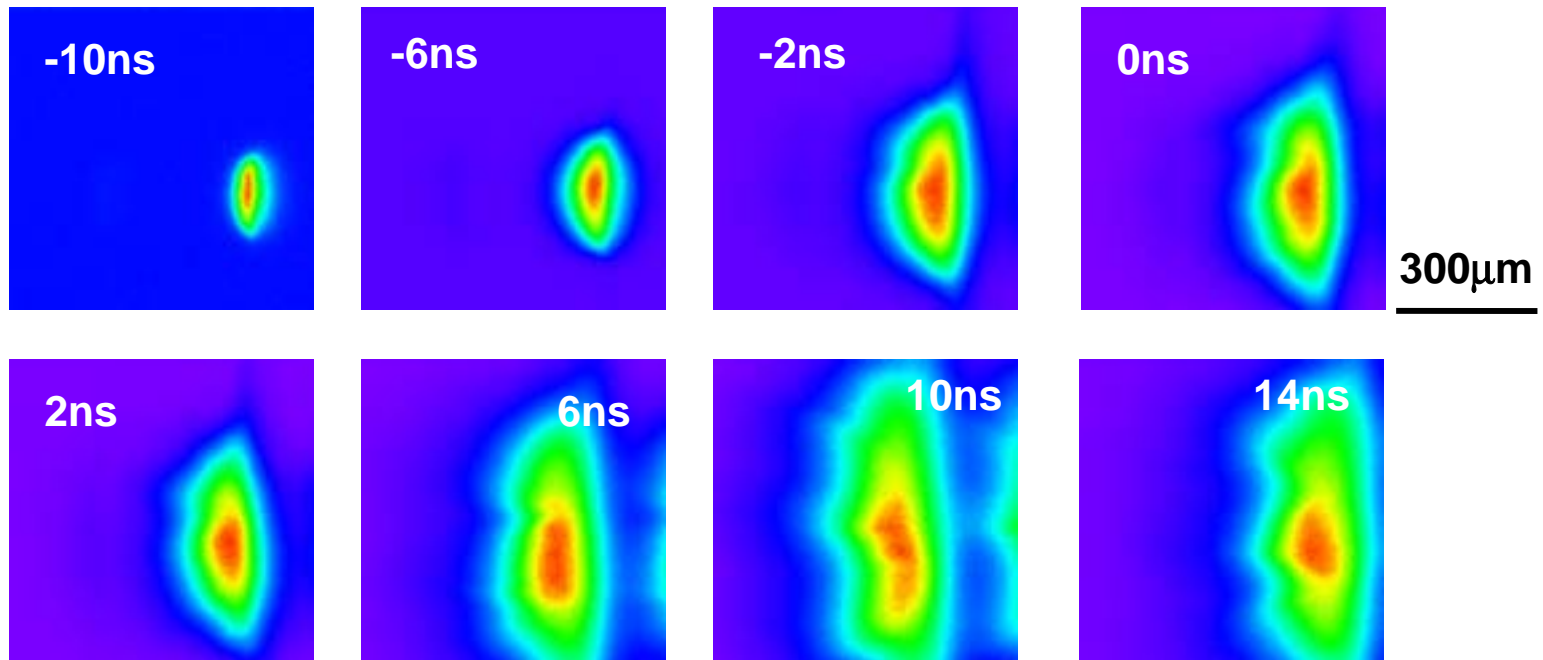
Laser conditions: $1064\mu\text{m}$, 10ns , $220\mu\text{m}$, $1 \times 10^{11}\text{W}/\text{cm}^2$.



Reliable : (1) data can be fitted by exponential function, (2) the coincidence between the two interferometers, (3) be close to estimated value.

- The possible reasons for the discrepancy,
- 2-D effect, lateral expansion,
 - Low intensity region both in time and space

Temporal resolved self emission from LPPs Sn plasma taken at side view using interferometer setup



- Lateral expansion with time is confirmed.
- Longitude expansion becomes saturated in later time.

Acknowledgement

This work was performed under the auspices of Ministry of Education, Culture, Science, and Technology, Japan (MEXT) under contract subject “Leading Project for EUV lithography sources development”.

