Radiative Hydrodynamic Simulation of Laser-produced Tin Plasma for Extreme Ultraviolet Lithography

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We have simulated EUV emission from the laser-produced tin plasmas for EUVL.

Atomic physics

Brief theory of EUV conversion efficiency

Appropriate density and temperature for EUV emission

LPP

Laser-produced Plasma

Radiation Hydrodynamic simulation for EUV emission

Two wavelength double laser irradiation for tin droplet

We found that we can get more than 5% EUV conversion efficiency with the optimized droplet diameter, the delay time between pre-pulse and main CO_2 pulse and the laser spot diameters.

Theory

EUV conversion efficiency consists of three factors.

EUV[1)] Conversion efficiency (CE)

[1)] 13.5nm wavelength with 2% bandwidth

= **laser absorption fraction** × **X-ray conversion fraction** × **EUV spectral efficiency**

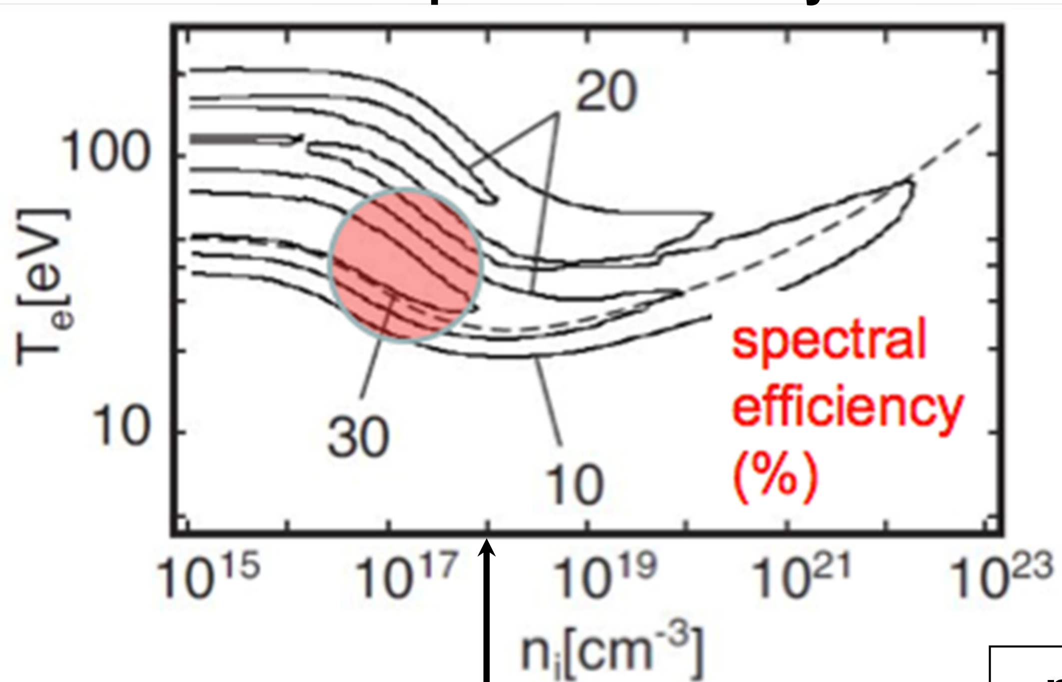
$$\frac{\text{absorbed laser energy}}{\text{input laser energy}} \qquad \frac{\text{x-ray emission energy}}{\text{inputed energy into plasma}} \qquad \frac{\text{EUV emission energy}}{\text{x-ray emission energy}}$$

In order to get high EUV CE, we have to maximize the product of three factors.

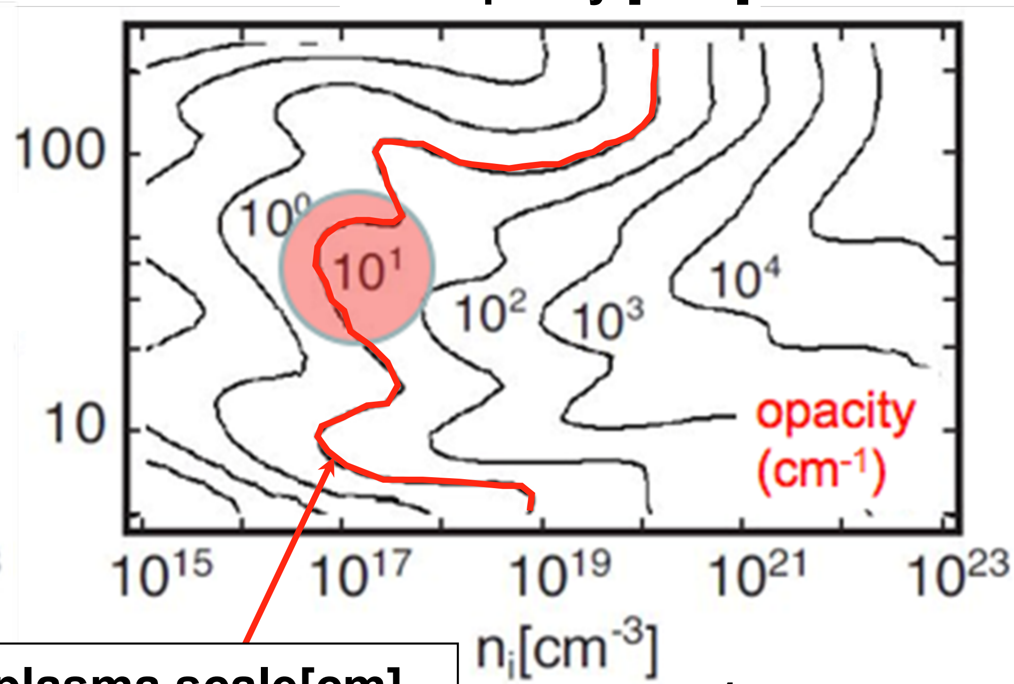
Theory

Appropriate density and temperature can be found by the atomic physics.

EUV spectral efficiency[1)]



EUV opacity [cm^{-1}]



$n_i = 10^{18}$cm^{-3} with Z=10

LPP

CO_2 laser can generate plasma with the density of $n_e = 10^{19}$cm^{-3}

plasma scale[cm] with optical thickness =1 $= \dfrac{1}{\text{EUV opacity[cm}^{-1}]}$

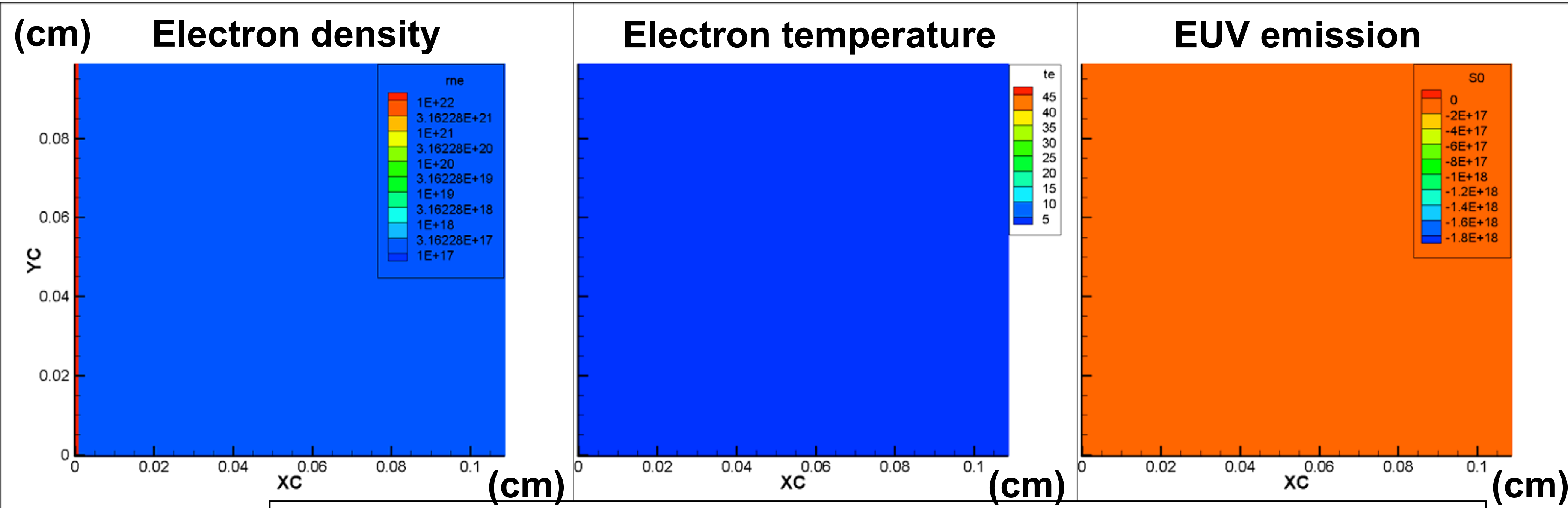
$\vee$

Etendue criterion(~0.1cm)

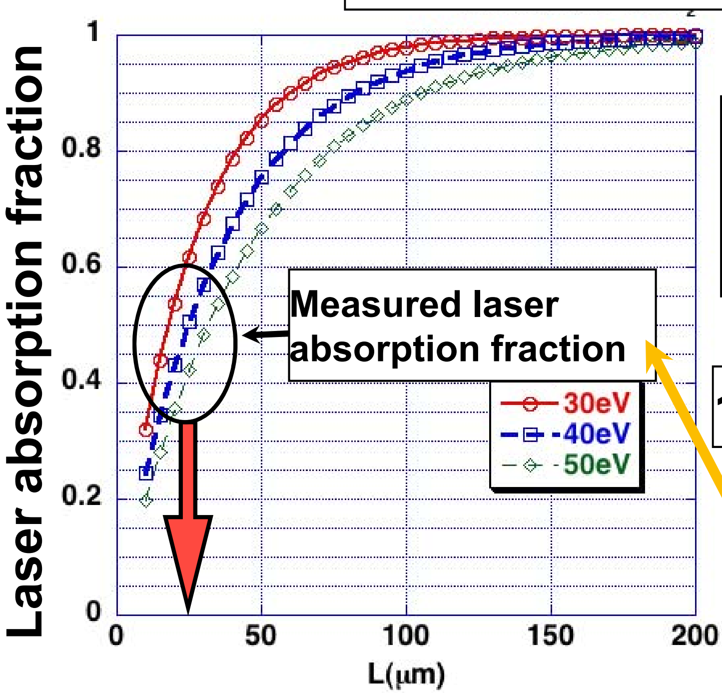
After A. Sasaki et al., JAP(2010)

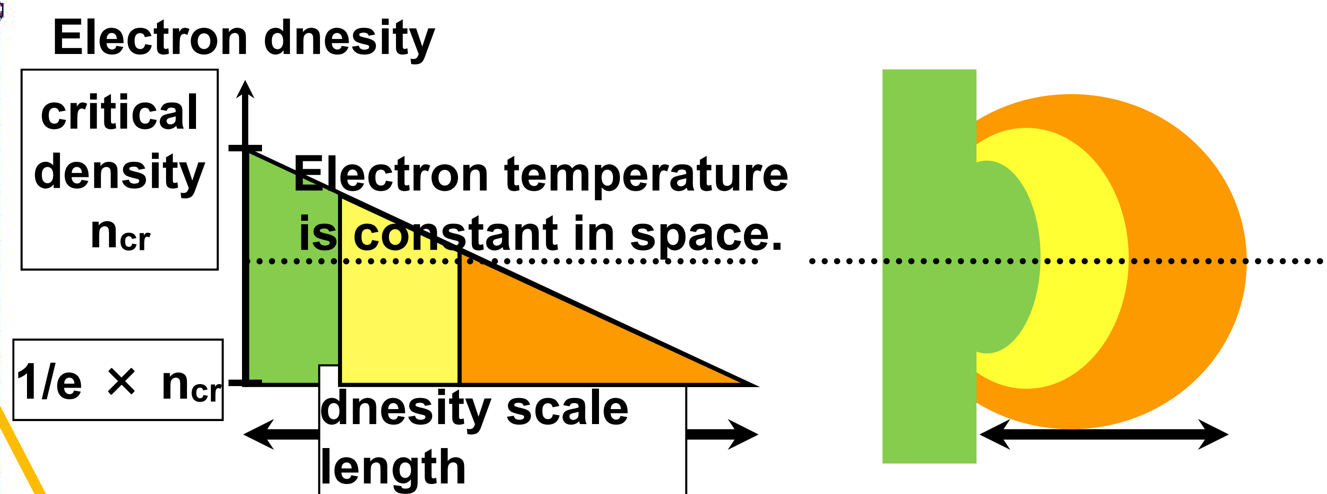
[1)] At optical thickness = 1, effective EUV spectral efficiency should be multiplied by 0.37.

We have simulated CO_2 laser irradiation on tin plate.



CO_2 Laser intensity: 10^{10} W/cm^2, duration: 110ns, spot radius: 200μm$^{\Phi}$

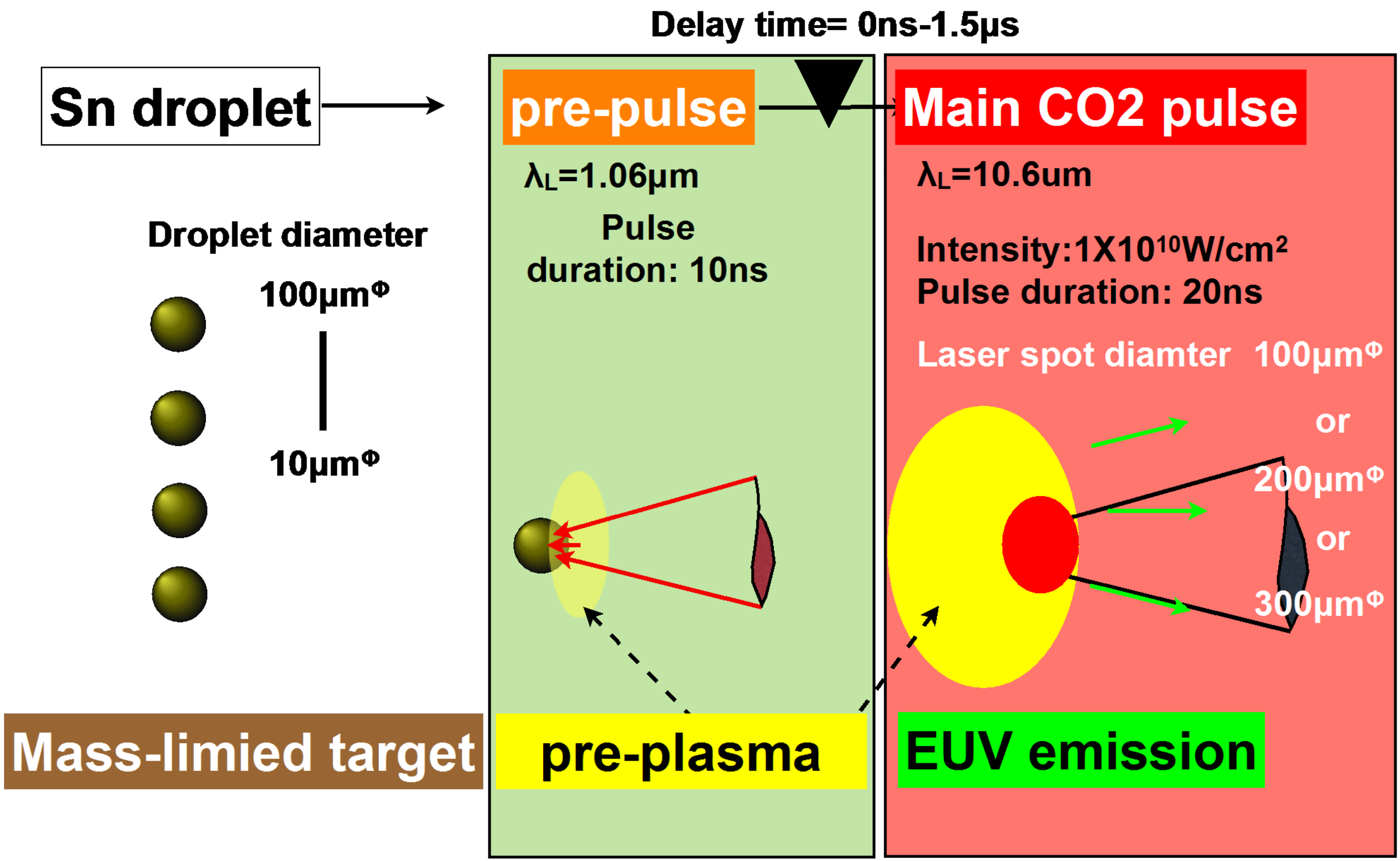




With single pulse irradiation, the density scale length keeps 25μm with time due to lateral flow.

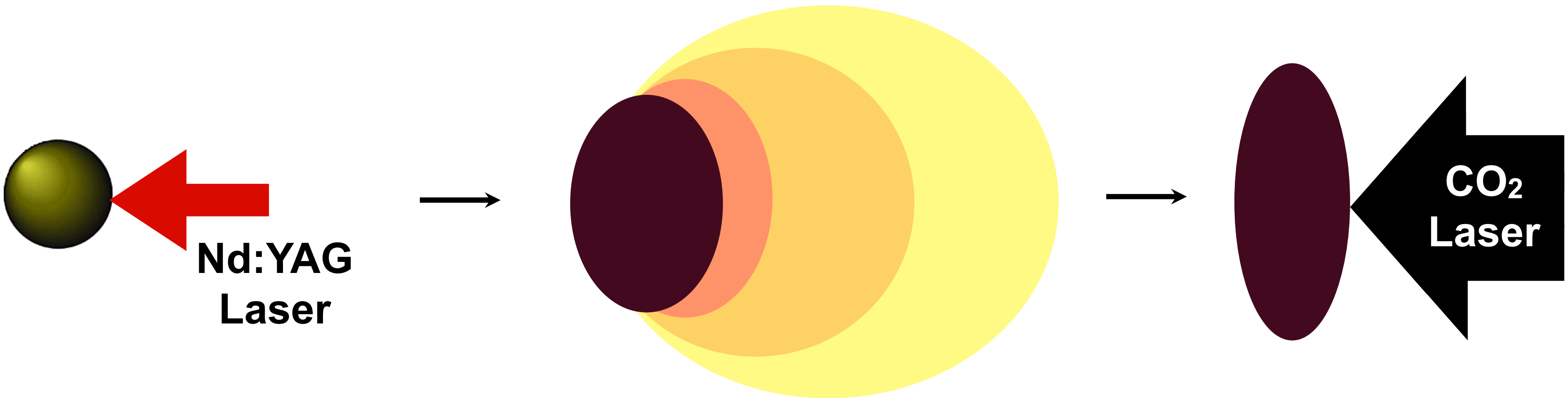
LPP

We have simulated the double pulse irradiation on tin droplet.

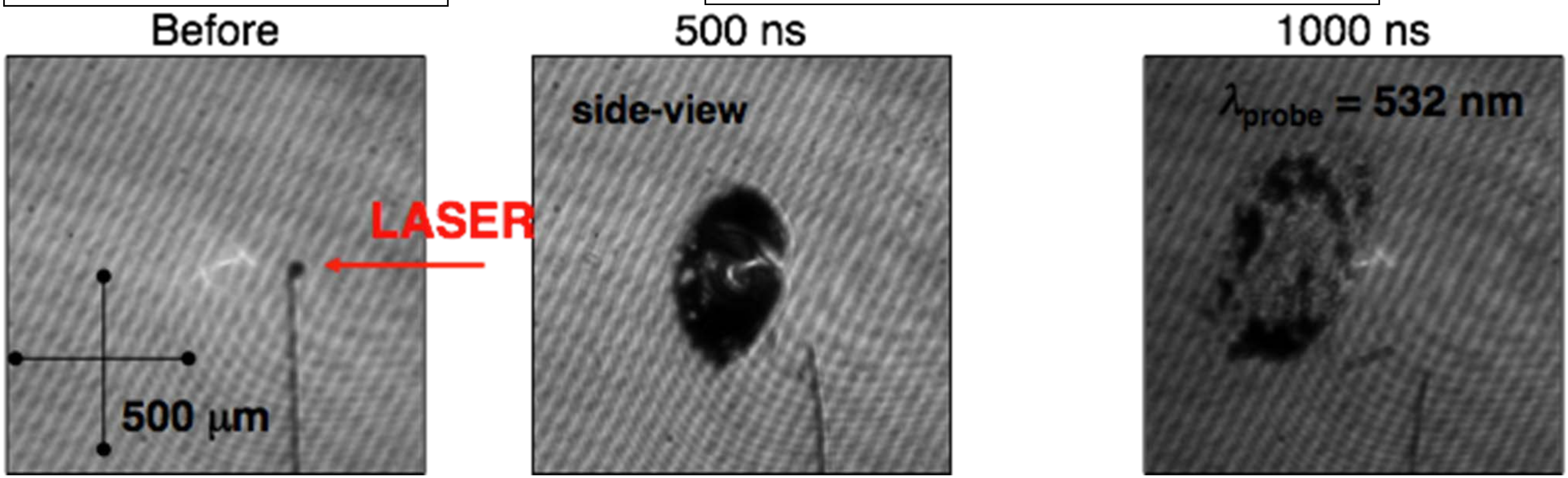


LPP

Nd:YAG irradiation on tin droplet can change the shape of the droplet and expand it.



Irradiation of pre-pulse — Change of shape and moving → Time



After irradiation of Nd:YAG laser on tin droplet, the change of shape, expansion and moving are observed.

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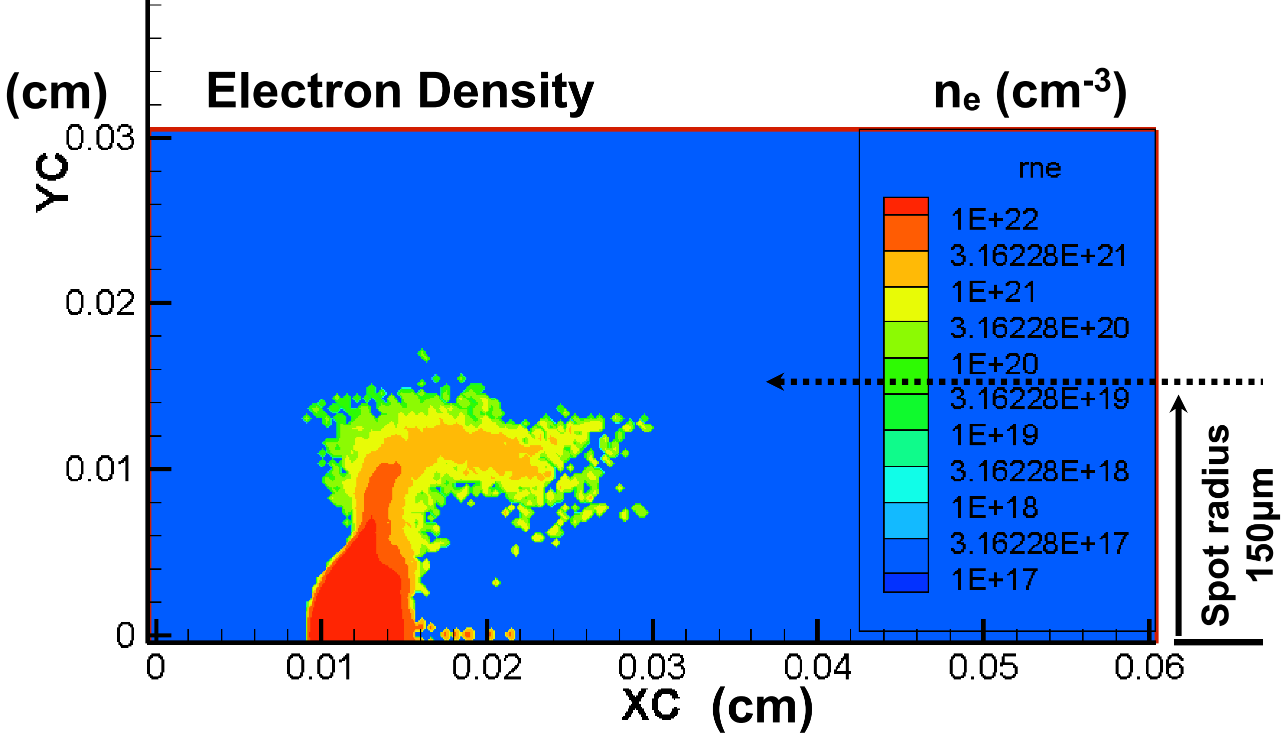
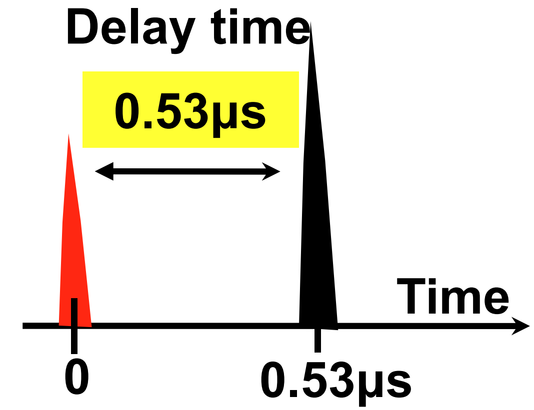
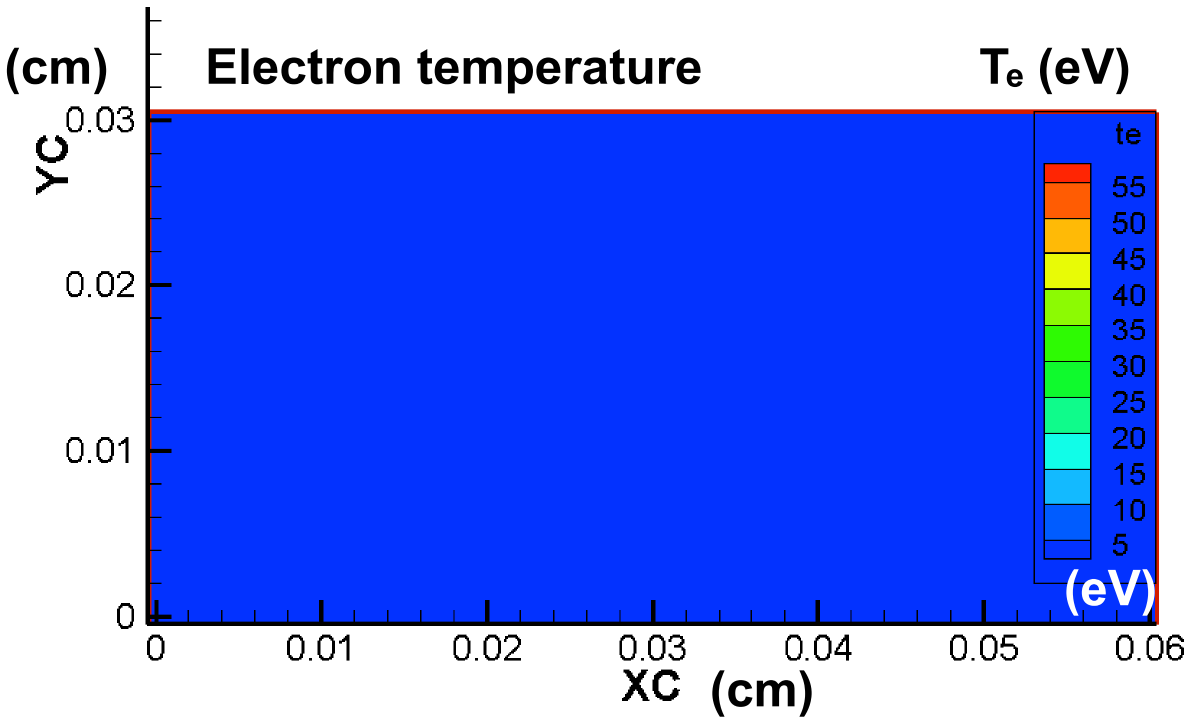


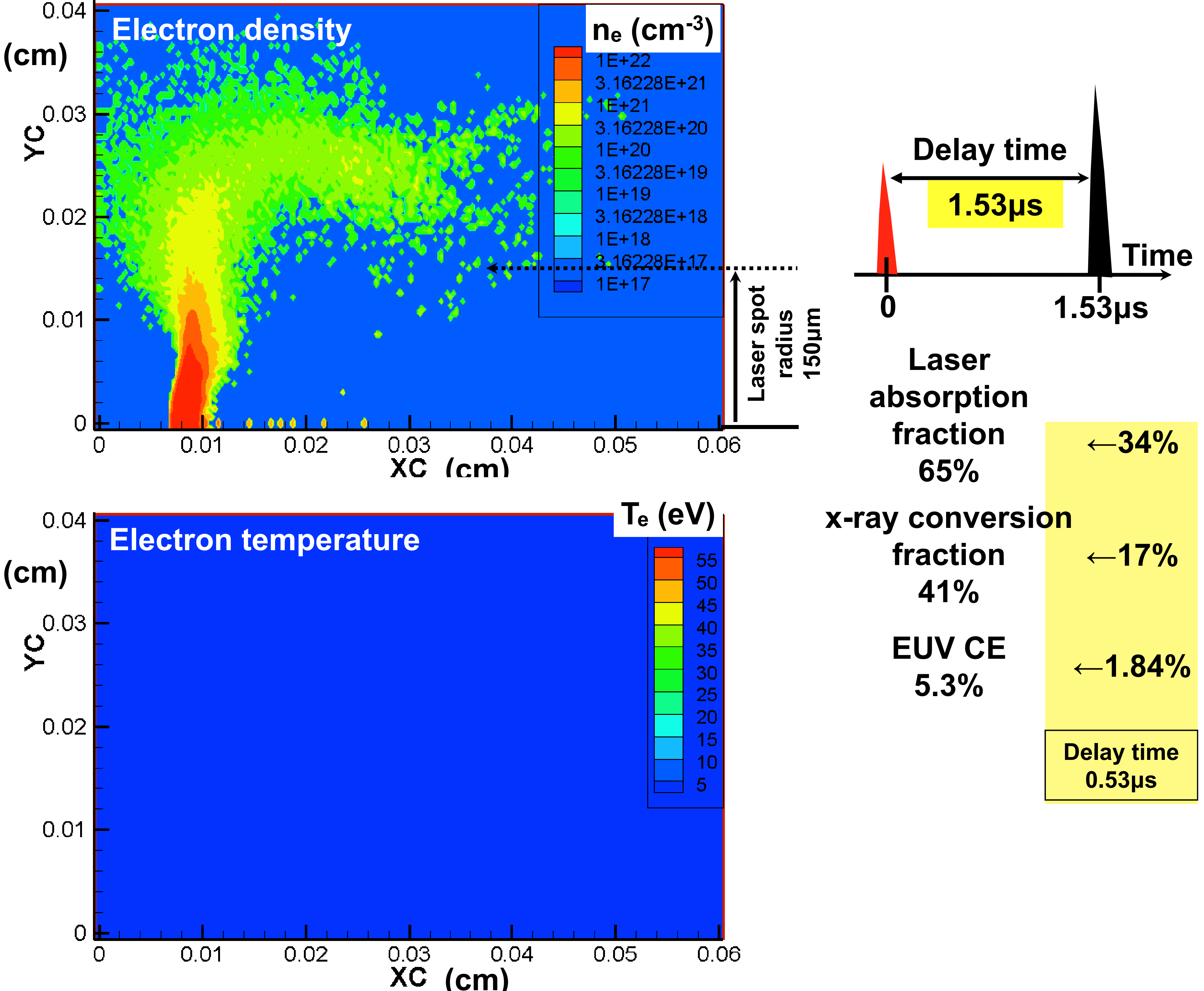


Laser absorption fraction
34%

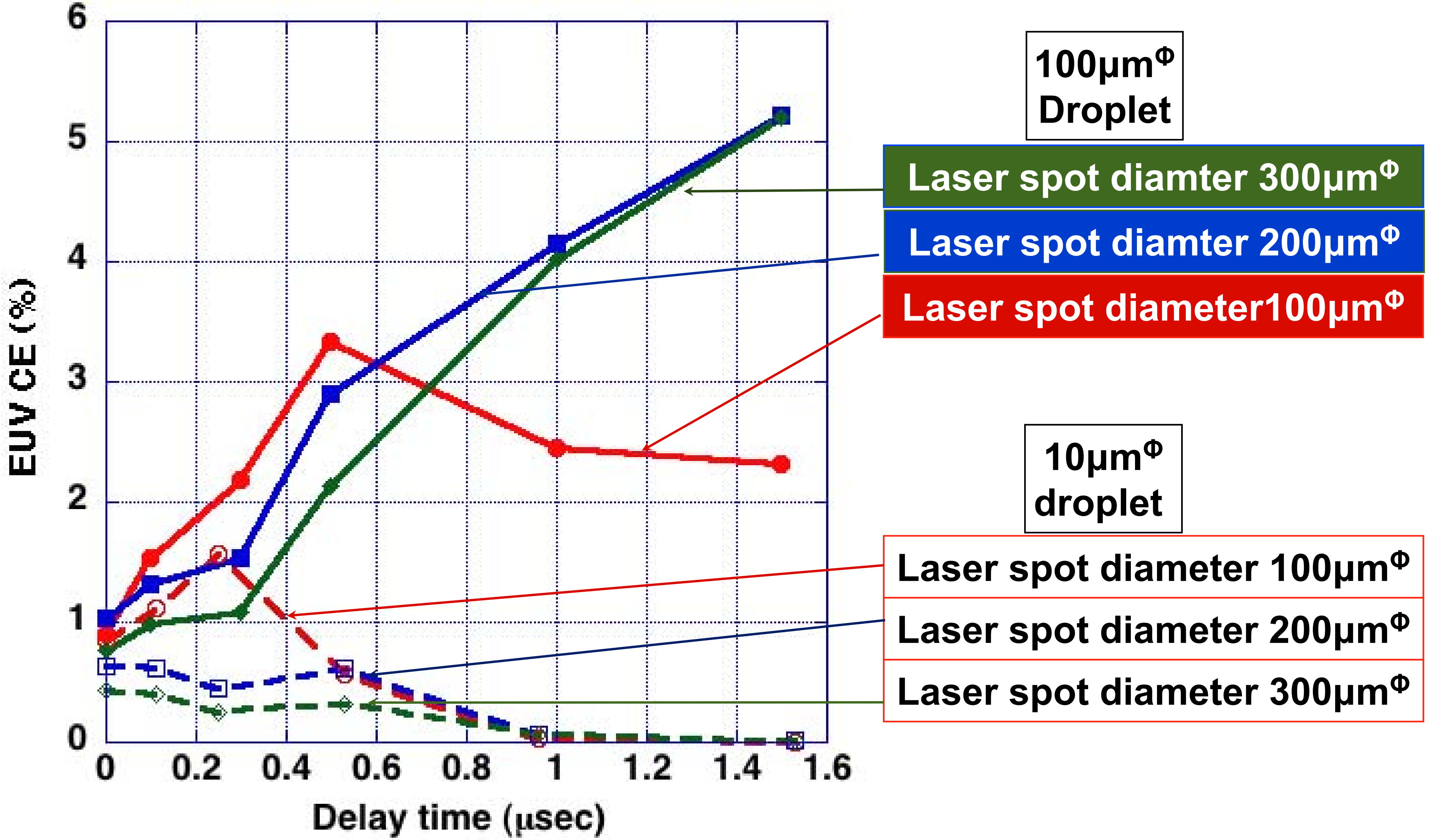
x-ray conversion fraction
17%

EUV CE
1.84%




Electron density
n_e (cm^{-3})
1E+22
3.16228E+21
1E+21
3.16228E+20
1E+20
3.16228E+19
1E+19
3.16228E+18
1E+18
3.16228E+17
1E+17
YC (cm)
XC (cm)
0.04
0.03
0.02
0.01
0
0.01
0.02
0.03
0.04
0.05
0.06
Laser spot radius 150µm
Delay time
1.53µs
Time
0
1.53µs
Laser absorption fraction 65%
←34%
x-ray conversion fraction 41%
←17%
EUV CE 5.3%
←1.84%
Delay time 0.53µs
Electron temperature
T_e (eV)
55
50
45
40
35
30
25
20
15
10
5

We can get relatively high EUV CE with the double pulse irradiation.



After optimization of the delay time, the laser spot diameter, and droplet diameter, we can get the high EUV conversion efficiency.

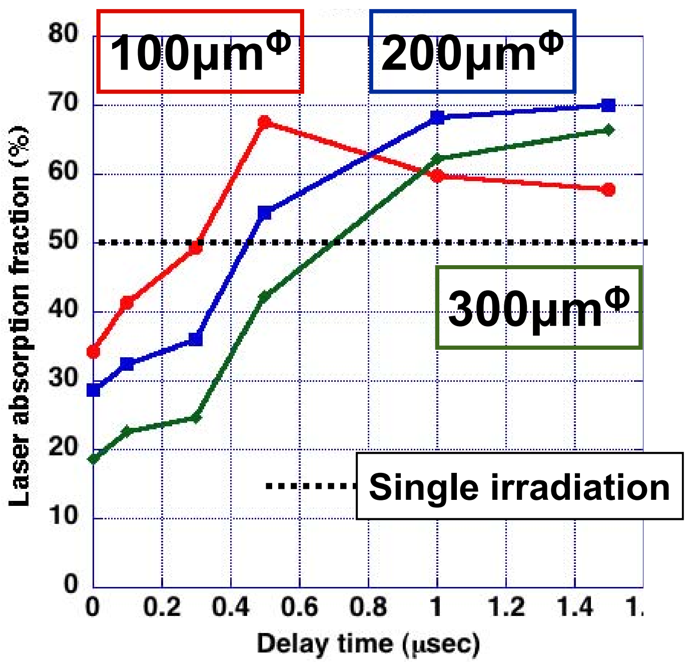
Conversion efficiency (CE)

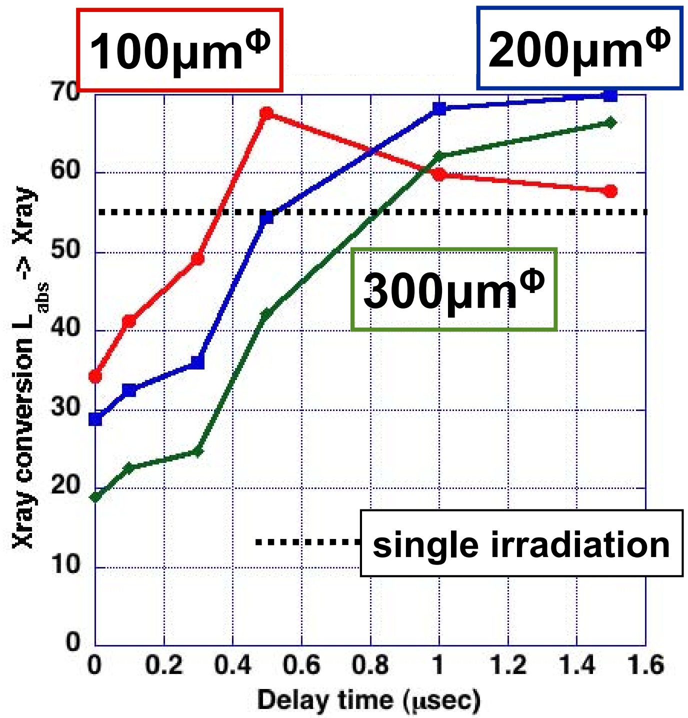
Droplet diameter 100μm

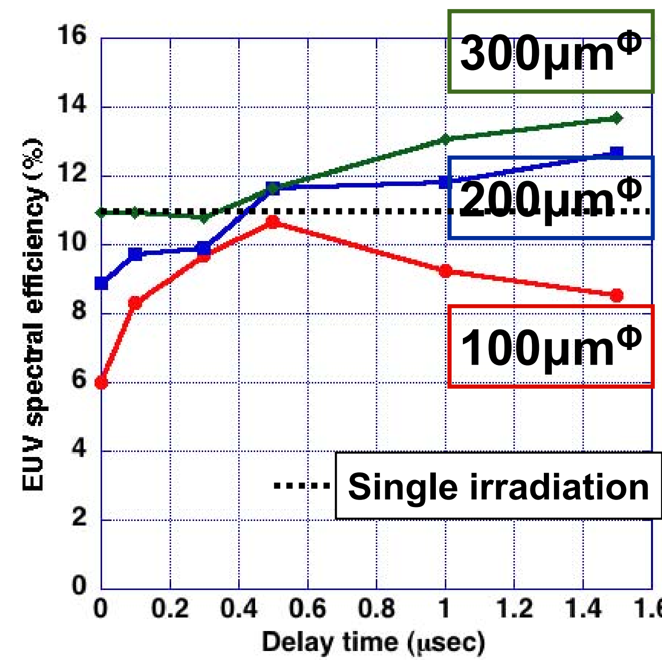
Laser spot diameter **100μm$^{\Phi}$** **200μm$^{\Phi}$** **300μm$^{\Phi}$**

Delay time 0~1.5μs

= Laser absorption fraction × x-ray conversion fraction × EUV spectral efficiency







With large laser spot, the appropriate delay time is increased.

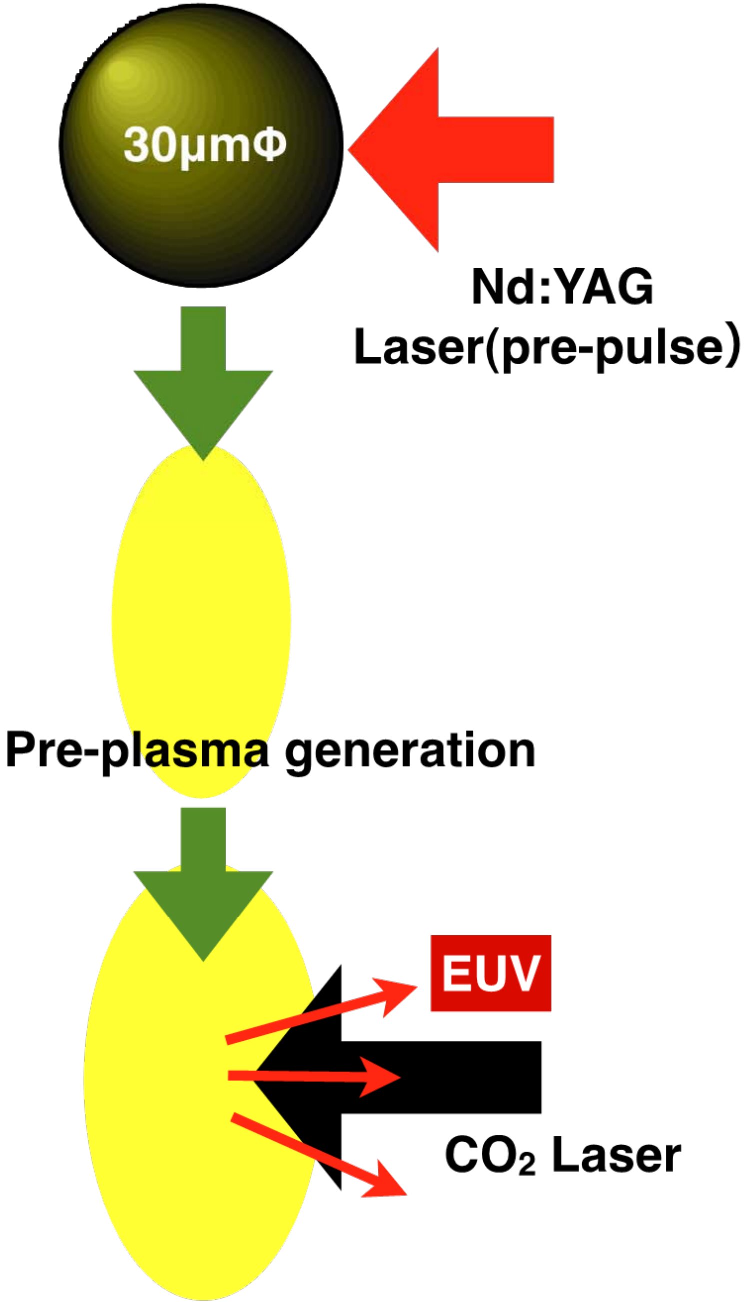
After optimization of the delay time, x-ray conversion increases compared to that with single irradiation.

With large laser spot, the EUV spectral efficiency increases.

With the appropriate delay time, and large spot > 200μm double pulse irradiation, the three important factors can be maximized compared to that with single irradiation.

LPP

After optimization of laser and target conditions, we can get 5% EUV CE.



With 30μm$^{\Phi}$ droplet diameter

Simulation condition	EUV CE (%)
Condition A	4.6
Condition B	5.9
Condition C	5.1

Osaka Univ.(Leading Project)
36μm$^{\Phi}$ droplet exp. showed 4%CE.

EUVA Hiratuska
20μm$^{\Phi}$ droplet exp. showed 3% CE.

Both simulation and experiments have showed the higher EUV CE.

Summary and conclusion

- In order to get the high EUV CE from the CO_2 laser-produced plasmas, the laser absorption fraction should be increased, and more than 100μm density scale length is required.

- Two wavelength double pulse irradiation scheme is effective for obtaining the longer density scale length.

- With the appropriate delay time, the large laser spot > 200 μm of CO_2 laser, and the droplet size, the three important factors [laser absorption fraction, x-ray conversion fraction and EUV spectral efficiency] can be maximized respectively, compared to that with single irradiation.

- After optimization of droplet size, laser spot, delay time, laser intensity and pulse duration, we found that we can get more than 5% EUV CE with the double pulse irradiation scheme.

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