

# Numerical Analysis of Extreme Ultra-Violet Emission from Laser-Produced Tin Plasmas

Institute for Laser Technology

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EUVL draft

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## Summary

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We simulated EUV emission from laser-produced Tin plasma.

Calculated X-ray emission spectrum are in good agreement with the experimental ones.

With 10ns 0.26 $\mu\text{m}$  and 0.53 $\mu\text{m}$  laser pulse, both simulations and the experiments give the dip spectrum at 13.5nm wavelength.

Due to less self-absorption, the longer wavelength laser gives higher conversion efficiency with 1-10ns pulse.

The optimum laser intensity is shifted to the lower intensity as the laser pulse duration increases.

**A one fluid two temperature model is adopted for the hydrodynamic part of our radiation hydro simulation code.**

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## Basic equations

### Hydro part

$$\frac{d\nu}{dt} = -\frac{1}{\rho} \frac{\partial(p_i + p_e + q)}{\partial x}$$

$$\rho c_{vi} \frac{dT_i}{dt} = -p_{THi} \frac{\partial\nu}{\partial x} + \frac{\partial}{\partial x} \left( \kappa_i \frac{\partial T_i}{\partial x} \right) + \alpha(T_e - T_i) + Q_i$$

$$\rho c_{ve} \frac{dT_e}{dt} = -p_{THE} \frac{\partial\nu}{\partial x} + \frac{\partial}{\partial x} \left( \kappa_e \frac{\partial T_e}{\partial x} \right) - \alpha(T_e - T_i) + Q_e$$

### Radiation transport part

$$\rho \frac{d}{dt} \left( \frac{E^\nu}{\rho} \right) - \frac{\partial}{\partial x} \left( D^\nu \frac{\partial E^\nu}{\partial x} \right) = 4\pi\eta^\nu - c\chi^\nu E^\nu$$

$\rho$  : density

$\nu$  : velocity

$p_i$  : ion pressure

$p_e$  : electron pressure

$p_{THi} = T_i (\partial p_i / \partial T_i)_\rho$

$p_{THE} = T_e (\partial p_e / \partial T_e)_\rho$

$q$  : numerical viscosity

$T_i$  : ion temperature

$T_e$  : electron temperature

$c_{vi}$  : ion specific heat

$c_{ve}$  : electron specific heat

$\kappa_i$  : ion conductivity

$\kappa_e$  : electron conductivity



## Laser intensity dependence

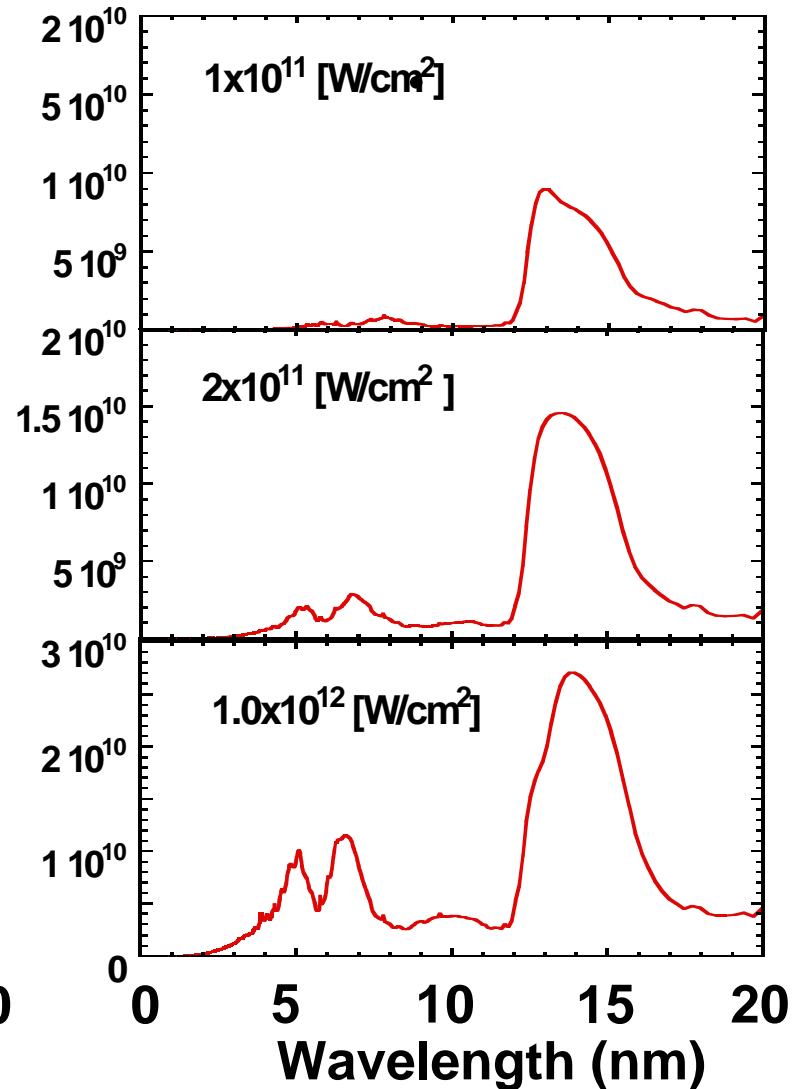
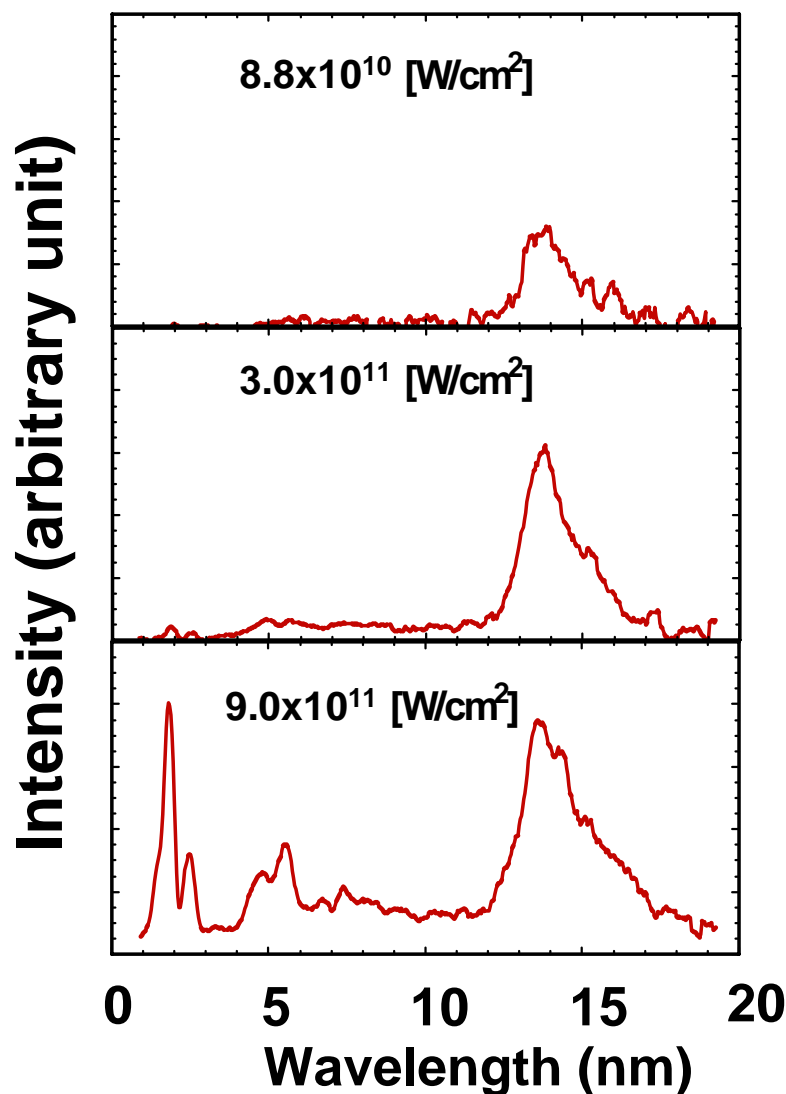
- **1.06 $\mu\text{m}$  (partially 10.6) laser wavelength**
- **1.2ns pulse duration**

Calculated X-ray emission spectrum using Hullac and AA model are in good agreement with the experimental observations.

By K. Gamada

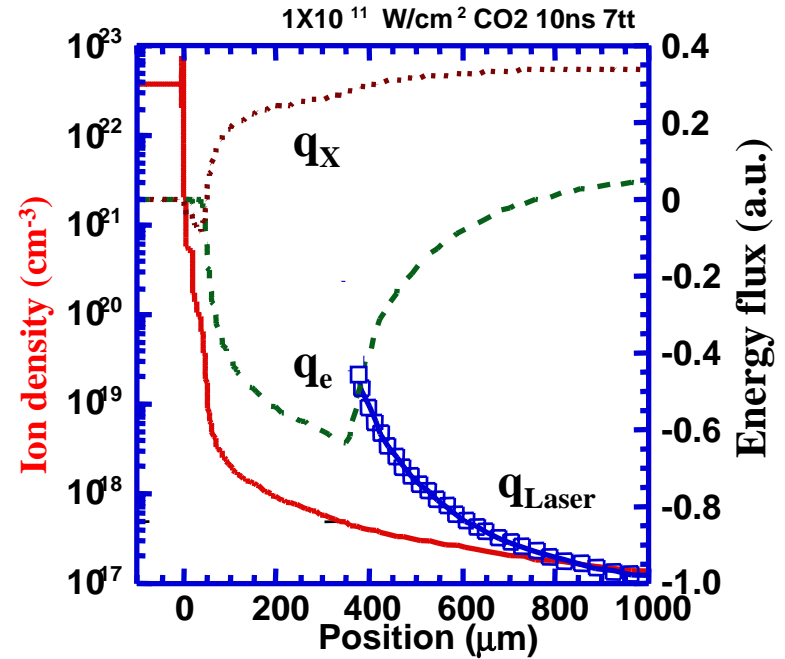
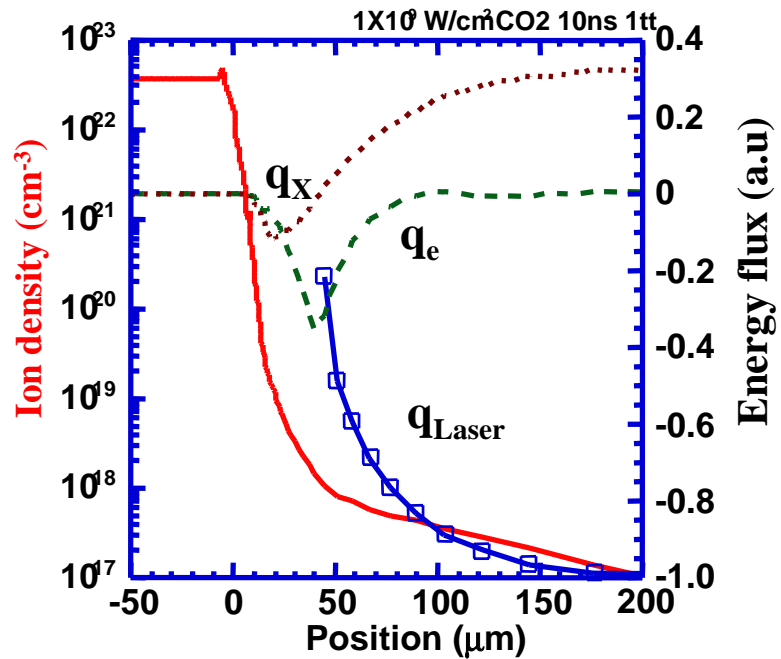
**Exp.**

**Sim**



## Laser intensity dependence

For CO<sub>2</sub> laser produced plasma, the electron thermal conduction plays an important role on energy transfer beyond the critical density.

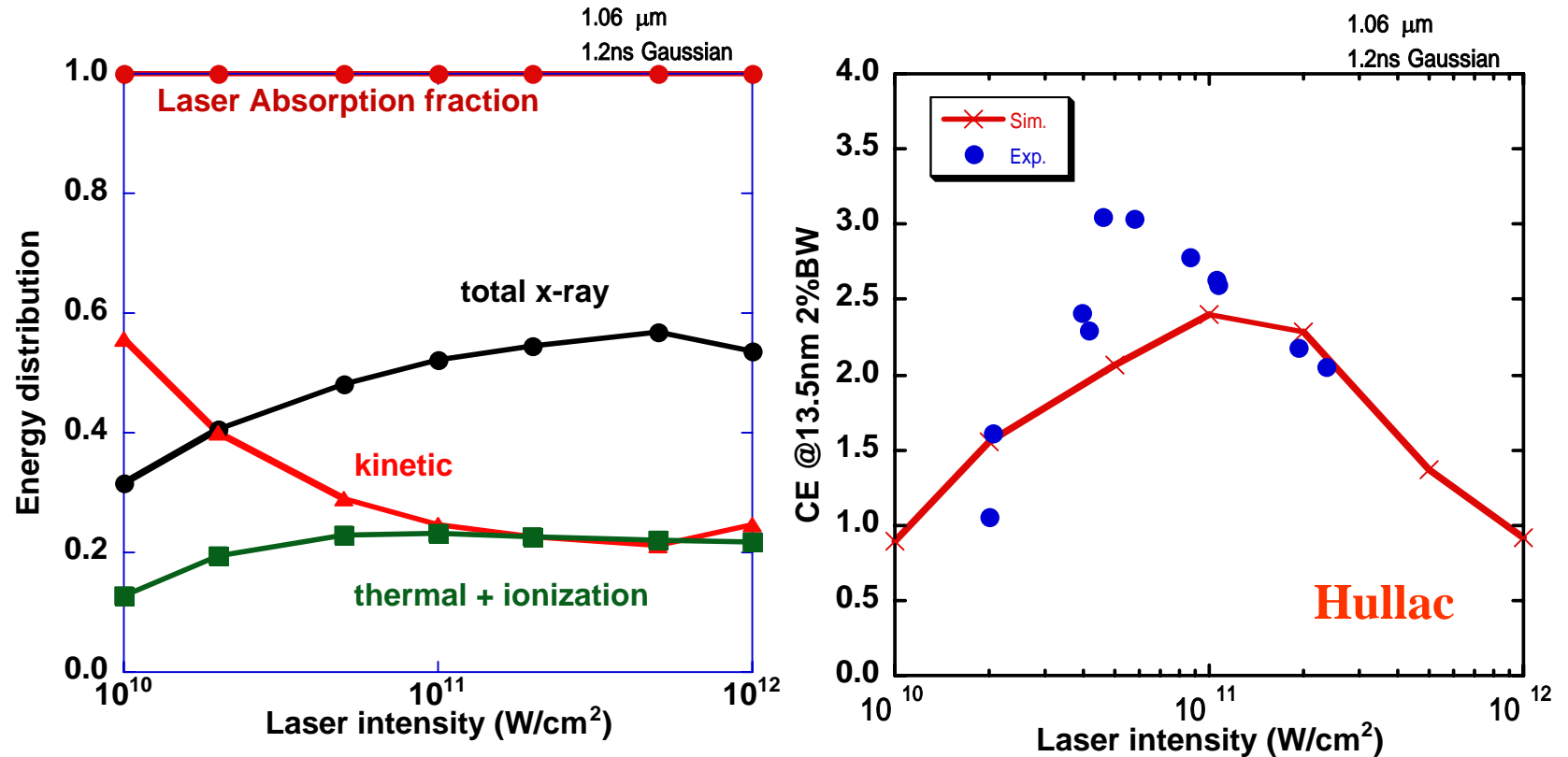


CO<sub>2</sub> laser :  $n_{ec}=10^{19}\text{cm}^{-3}$

CO<sub>2</sub> laser-produced Tin plasma can yield an efficient EUV emission due to the heated dense region by the electron conduction.

## Laser intensity dependence

Calculated EUV conversion efficiency using Hullac table is in good agreement with the GXII 1.06 $\mu\text{m}$  1.2ns pulse experimental results.



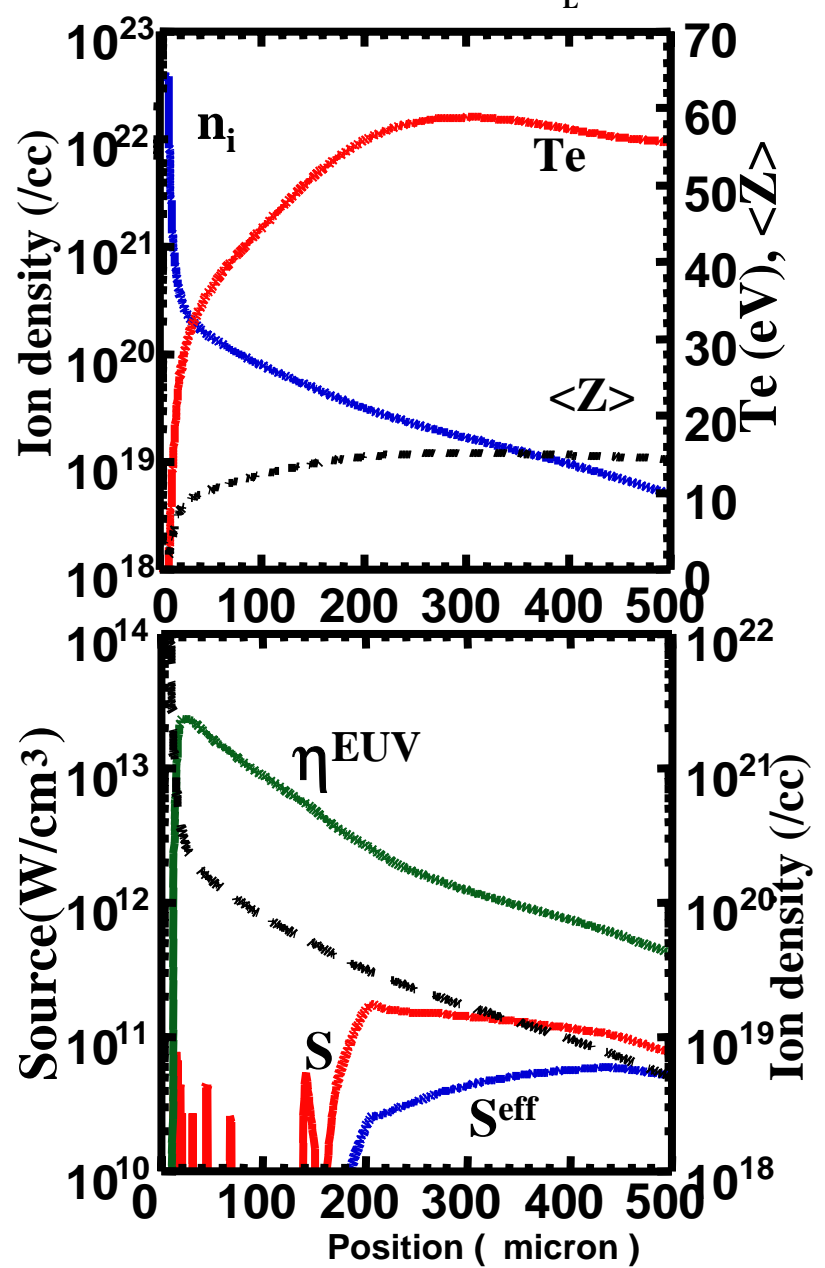
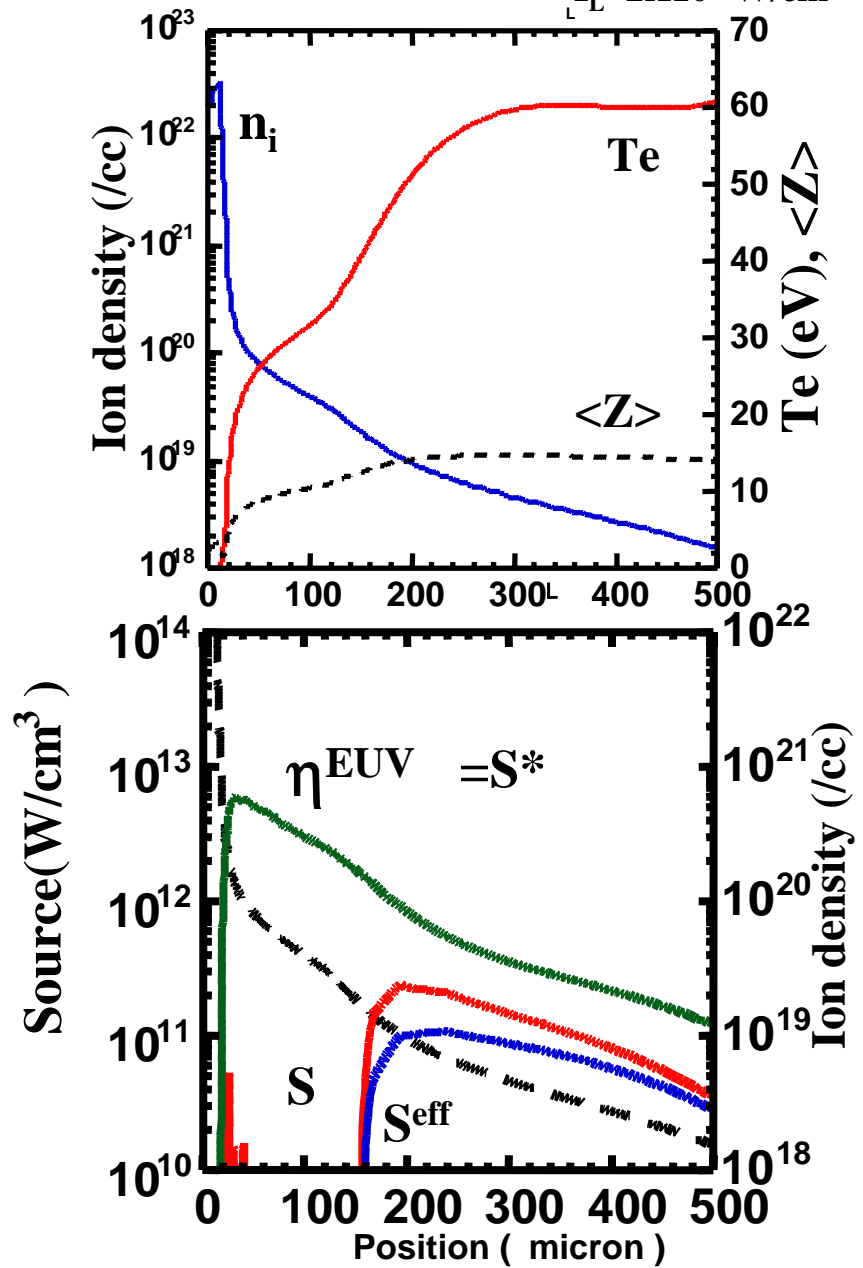
## Laser wavelength dependence

- **0.26 $\mu\text{m}$  laser wavelength**
- **1.06 $\mu\text{m}$  laser wavelength**
- **10.6 $\mu\text{m}$  laser wavelength**
  
- **10ns pulse duration**

**Laser wavelength dependence**

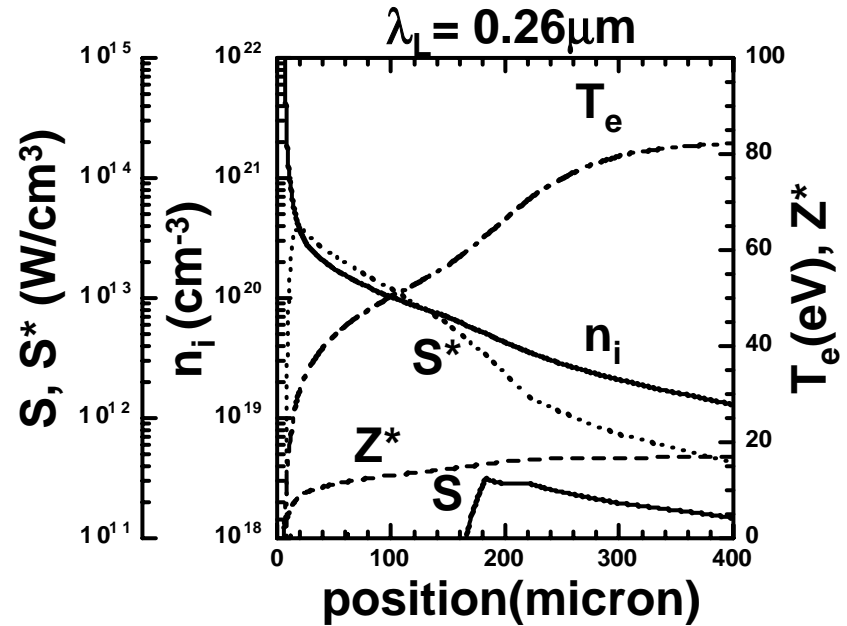
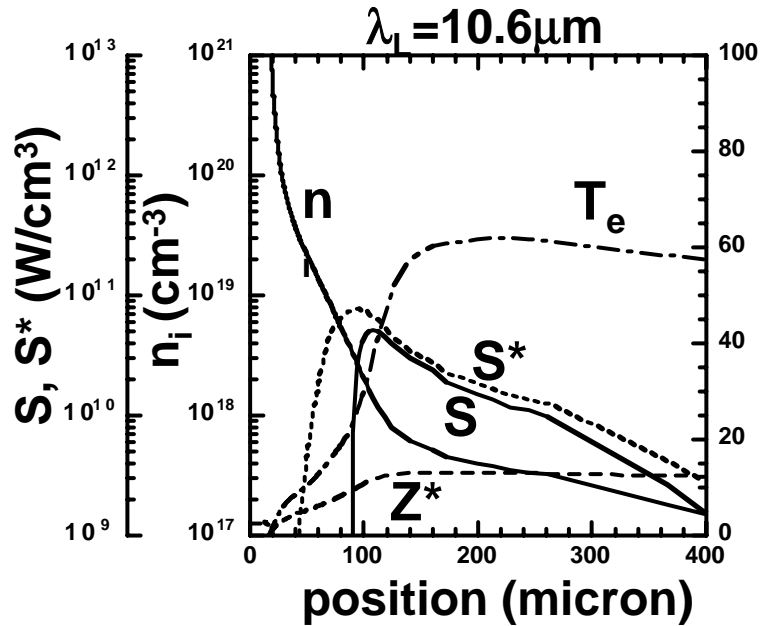
$\lambda_L = 1.06 \mu\text{m}$   
 $I_L = 2 \times 10^{11} \text{W/cm}^2$

$\lambda_L = 0.26 \mu\text{m}$   
 $I_L = 1 \times 10^{12} \text{W/cm}^2$



## Laser wavelength dependence

With short wavelength laser, the heated region is denser, and EUV emission is highly absorbed. The resulted EUV CE becomes lower.

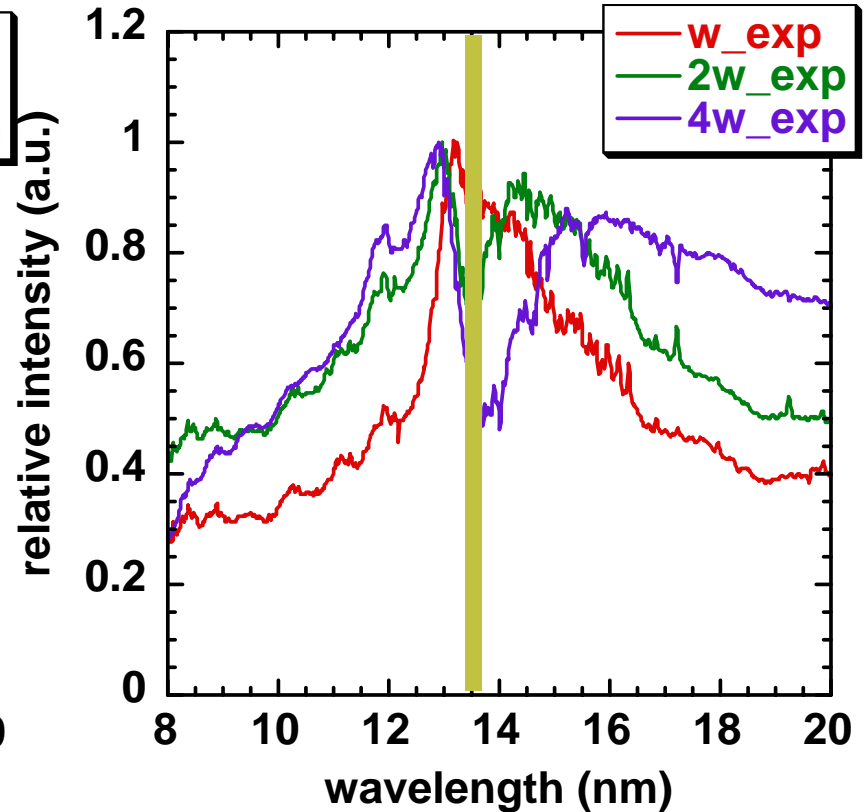
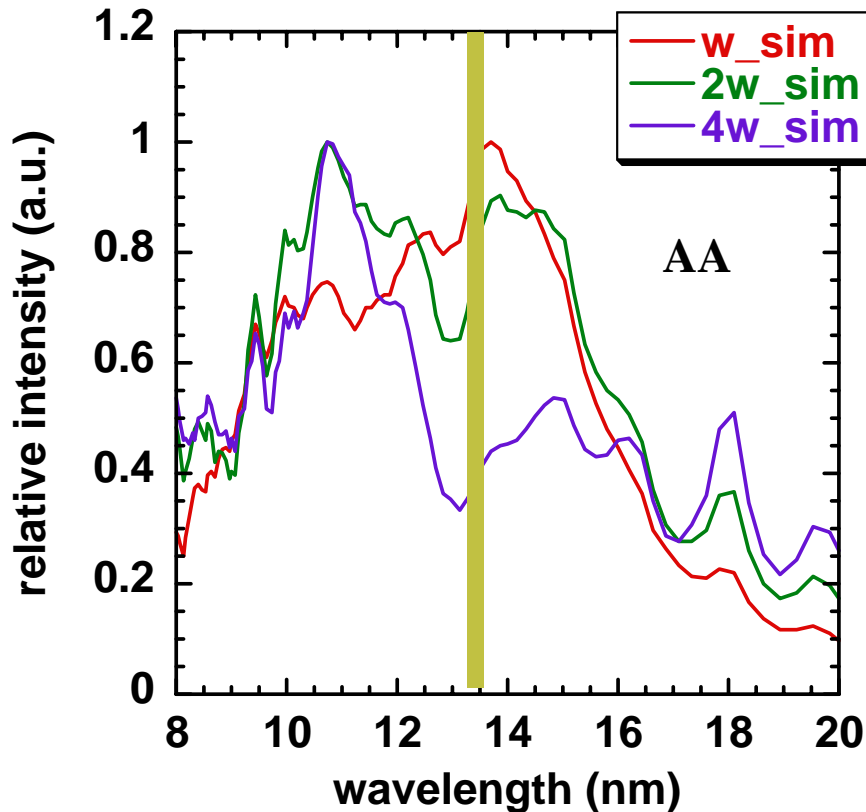


$\lambda_L$ ( $\mu\text{m}$ )	$\tau_L$ (ns)	$I_L$ (W/cm <sup>2</sup> )	$x_s$ ( $\mu\text{m}$ )		$L_s$ ( $\mu\text{m}$ )
10.6	10	$1 \times 10^{10}$	101		50
1.06	10	$2 \times 10^{11}$	172		153
0.26	10	$1 \times 10^{12}$	183		245

EUV emission point is shifted to the denser region and scale length is longer as the laser wavelength becomes shorter.

## Laser wavelength dependence

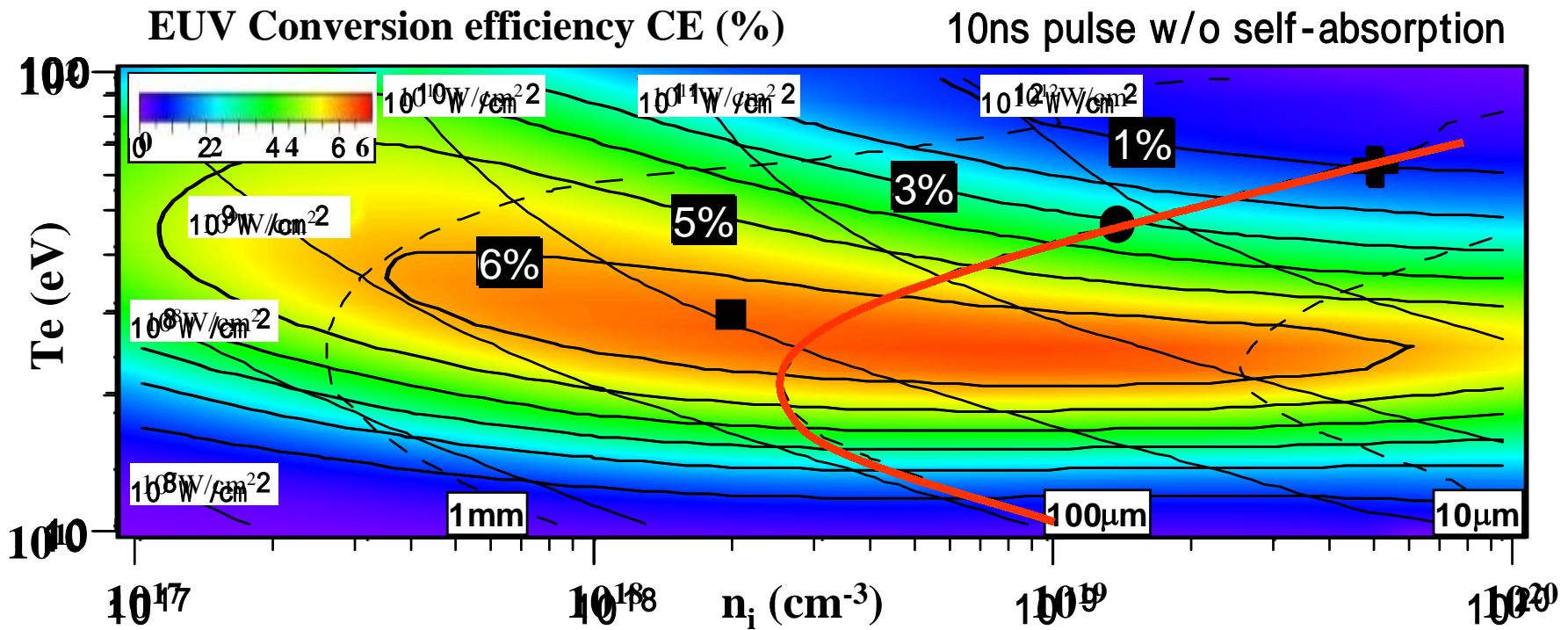
With 10ns 0.26 $\mu\text{m}$  and 0.53 $\mu\text{m}$  laser pulses, both simulations and the experiments give a dip spectrum at 13.5nm wavelength.



This result represents self-absorption effect of EUV light due to the large opacity for the cases of shorter wavelength lasers.

1) given by Dr. Yamaura

# Comparison of simulation results with the power-balance model <sup>1)</sup>



<sup>1)</sup> This model is derived by Prof. Nishihara

## Simulation results

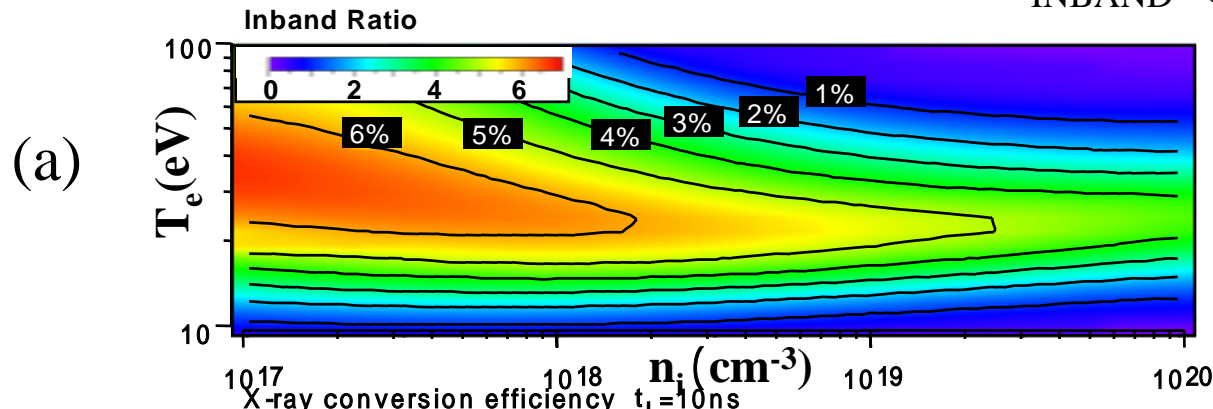
$\lambda_L$ ( $\mu\text{m}$ )	$\tau_L$ (ns)	$I_L$ ( $\text{W}/\text{cm}^2$ )	$x_S$ ( $\mu\text{m}$ )	$L_S$ ( $\mu\text{m}$ )
10.6	10	$1 \times 10^{10}$	101	50
1.06	10	$2 \times 10^{11}$	172	153
+ 0.26	10	$1 \times 10^{12}$	183	245

This comparison also shows the dip in spectrum as shorter wavelength

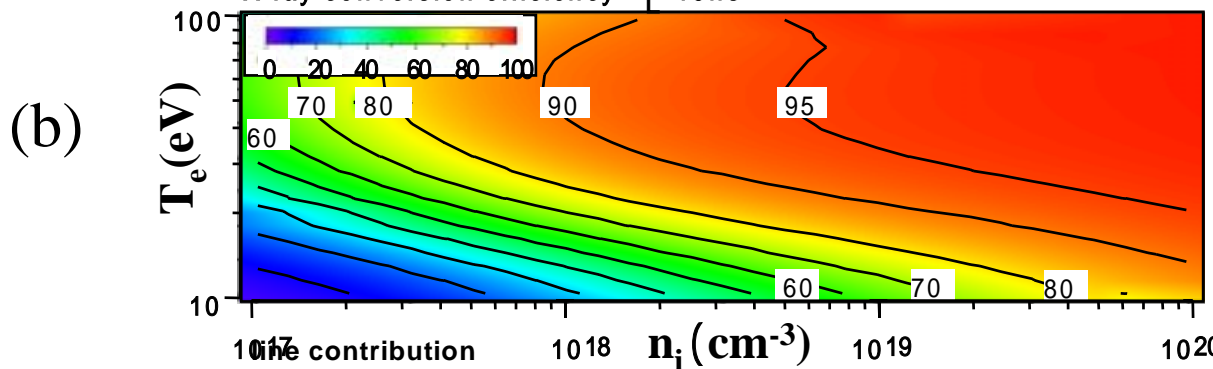
The longer wavelength laser may give larger CE.

**EUV CE is mainly determined by the power fraction of EUV in band (13.5nm 2%BW) and the total x-ray conversion efficiency.**

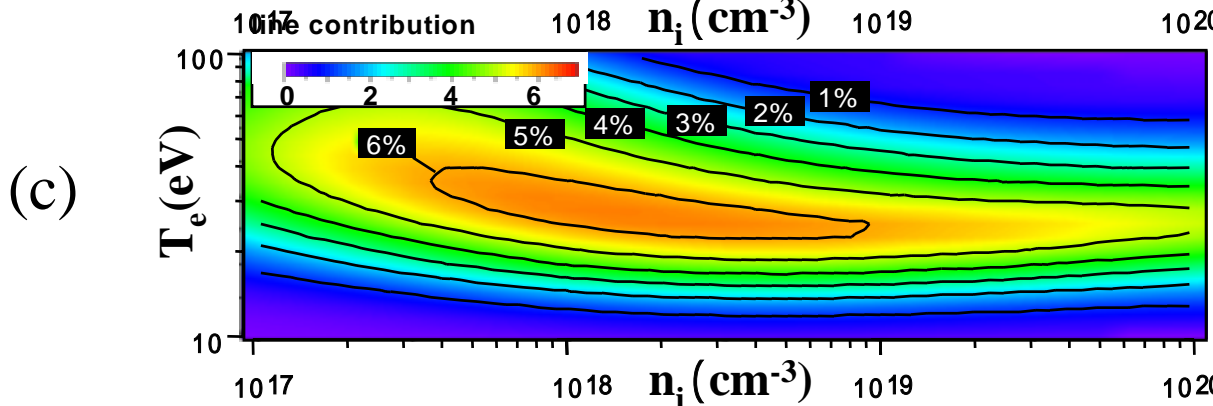
$$\text{EUV CE} = R_{\text{INBAND}}(n_i, T_e) \times \eta_X(n_i, T_e, V)$$



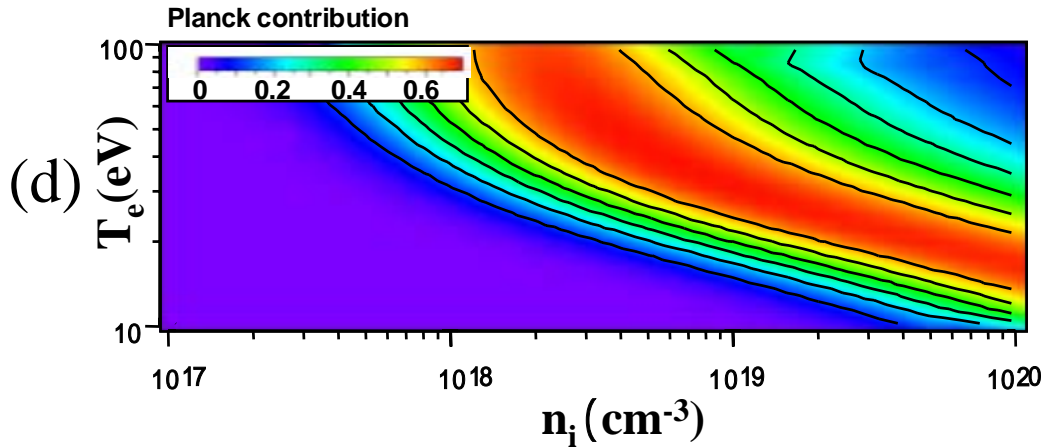
As the plasma density decreases, the EUV power fraction increases.



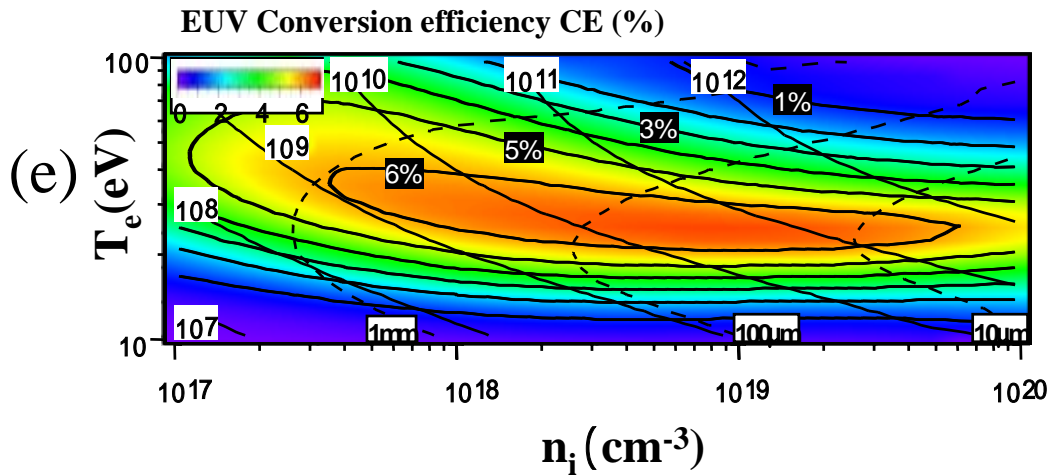
X-ray conversion efficiency increases with plasma volume.



(c) = (a) \* (b)



The contribution of Planck emission To EUV CE is estimated to be less than 0.6%.



$$(e) = (c) + (d)$$

The power balance model shows that the optimum density has a relatively wide range. However, it should be noted that this estimation assumes no self-absorption. With self-absorption of EUV, the optimum range becomes narrow in the high density limit ( $n_i \sim 10^{19}$ ).

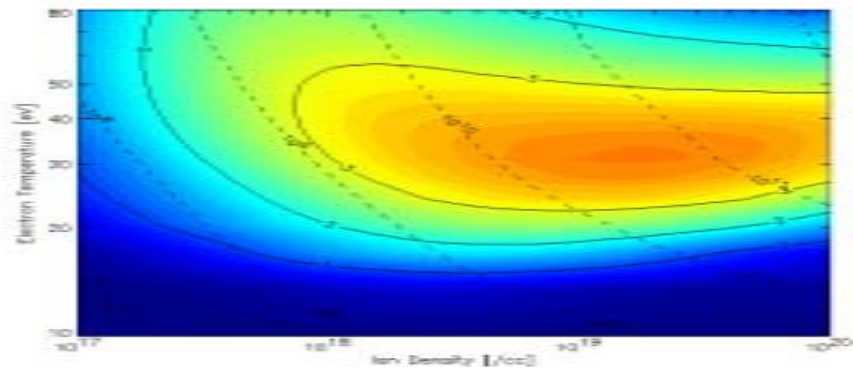
# Conversion Efficiency

By K. Gamada

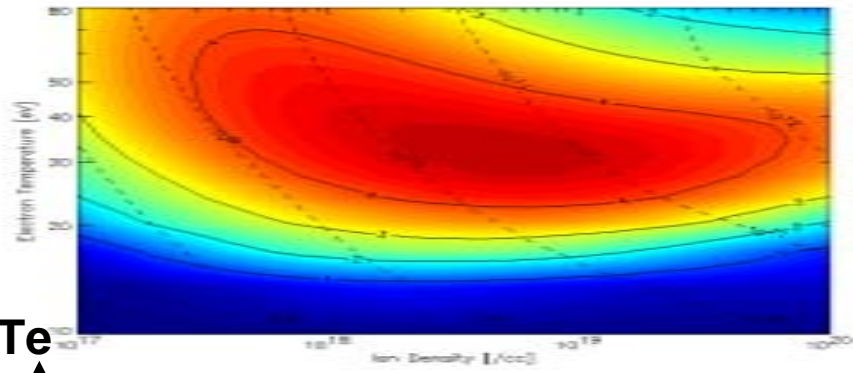
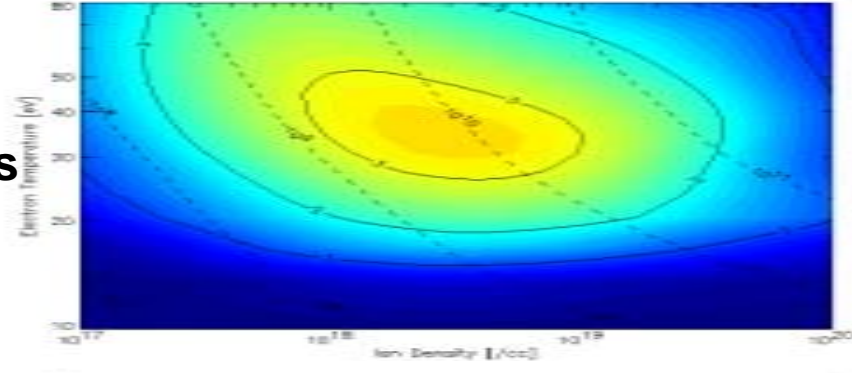
no self-absorption

pulse duration

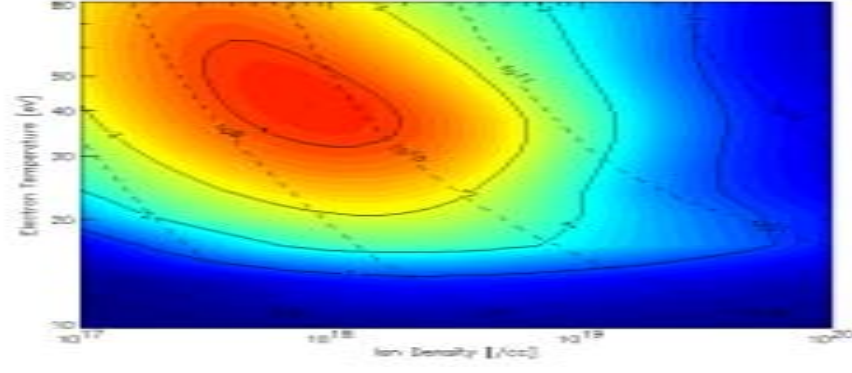
with self-absorption



1.2ns



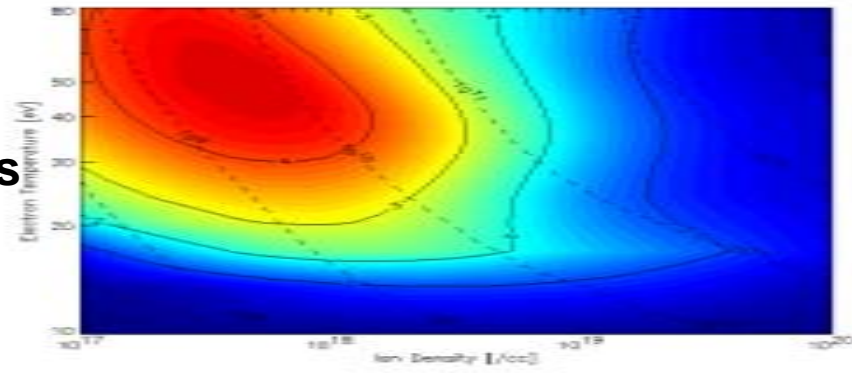
5ns



$T_e$

50  
30  
20  
10

10ns



10<sup>17</sup>

10<sup>18</sup>

10<sup>19</sup>

10<sup>20</sup>

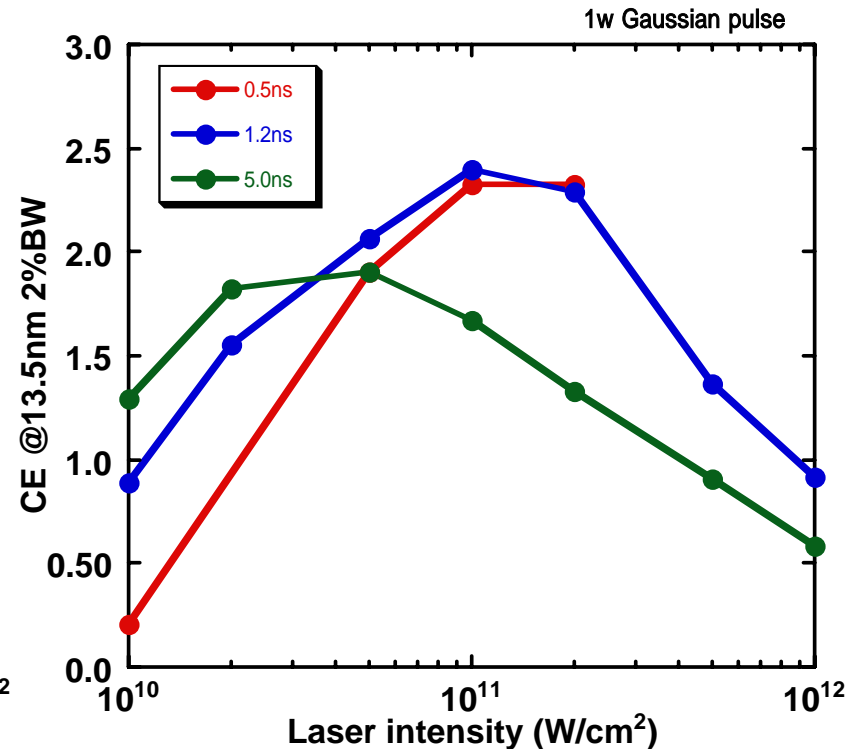
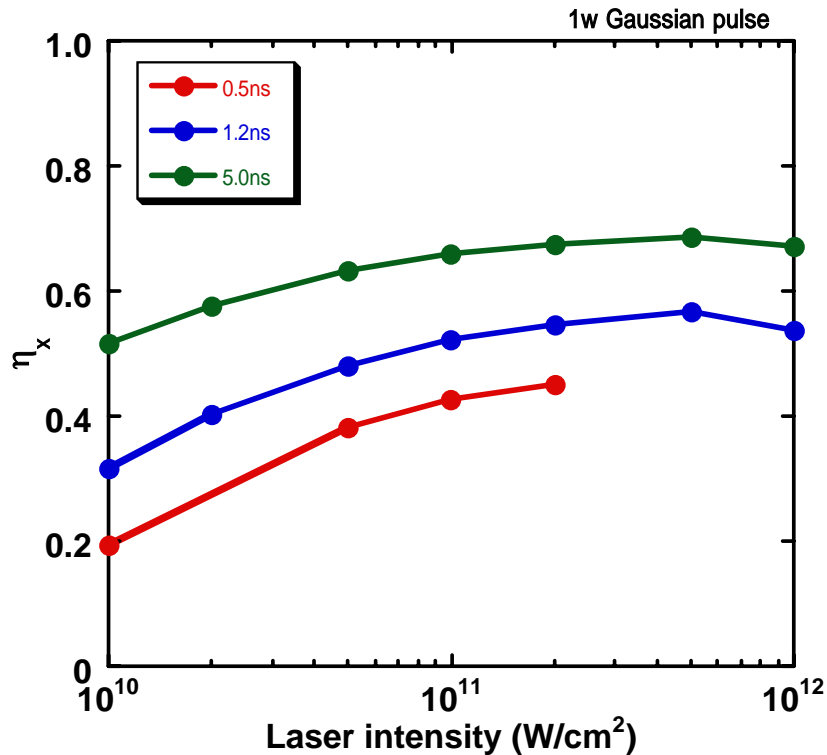
$n_0$

## Pulse duration dependence

- 0.26 $\mu\text{m}$  laser wavelength
- 1.06 $\mu\text{m}$  laser wavelength
- 10.6 $\mu\text{m}$  laser wavelength
  
- 0.5ns
- 1.2ns      Pulse duration with Gaussian profile.
- 5.0ns
- 10.0ns

## Pulse duration dependence

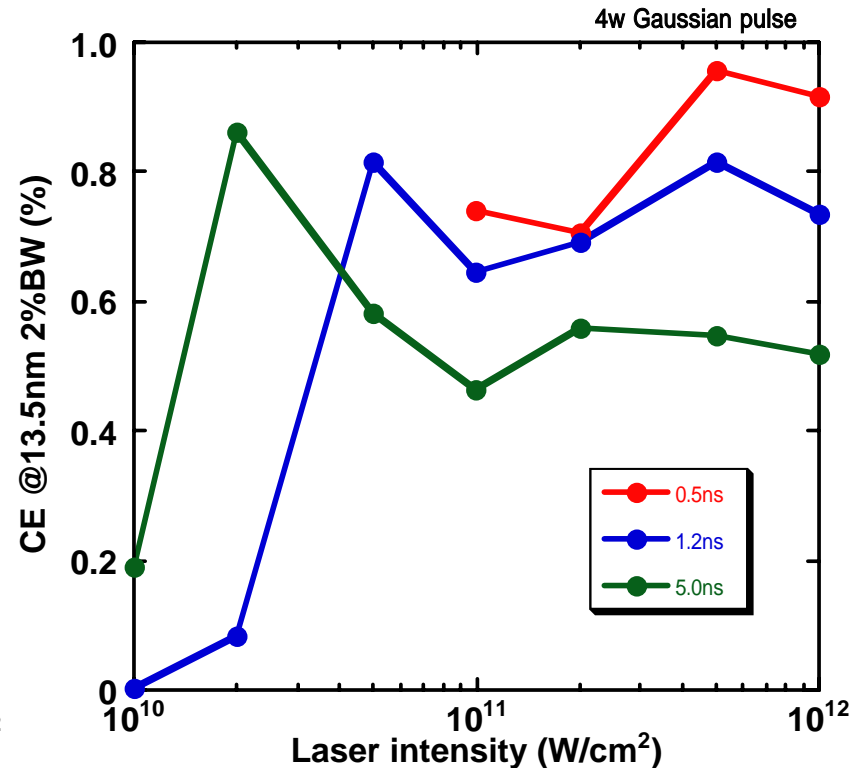
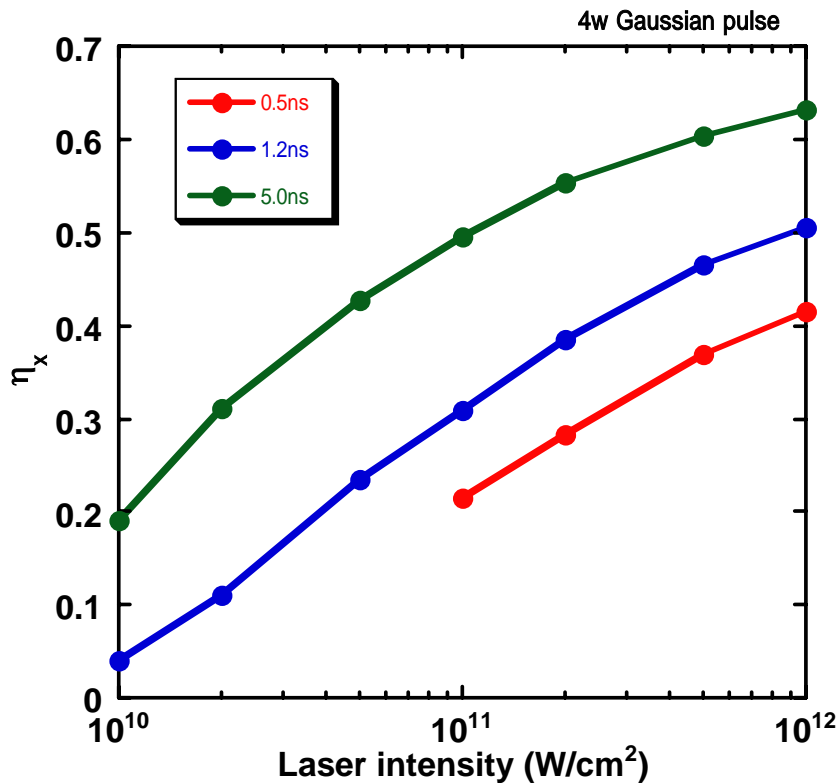
With 1.06 $\mu\text{m}$  laser, EUV CE has a peak around 1.2ns duration. The intensity corresponding to peak CE shifts towards lower values with longer pulse.



Max CE ~2.5% @ 1X10<sup>11</sup>W/cm<sup>2</sup> 1.2ns

## Pulse duration dependence

When the pulse duration increases, the laser intensity giving CE peak moves towards lower values because the self-absorption decreases.



Max CE ~1% @ 5X10<sup>11</sup>W/cm<sup>2</sup> 0.5ns  
~0.9% @ 2X10<sup>10</sup>W/cm<sup>2</sup> 5.0ns

## Summary/Conclusion

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We simulated EUV emission from laser-produced Tin plasma.

Calculated X-ray emission spectra are in good agreement with the experimental ones.

With 10ns 0.26 $\mu\text{m}$  and 0.53 $\mu\text{m}$  laser pulse, both simulations and the experiments give the spectrum with a dip at 13.5nm wavelength.

Due to decreased self-absorption, the longer wavelength laser gives higher conversion efficiency.

The optimum laser intensity shifts towards the lower side as the laser pulse duration increases.

With the Tin plasma, self-absorption effect plays an important role on optimization of the laser conditions. The longer wavelength laser may give larger EUV CE due to large in-band power and total x-rays.