Properties of ions emitted from Sn plasma produced by Nd:YAG and CO_2 lasers for extreme ultraviolet lithography

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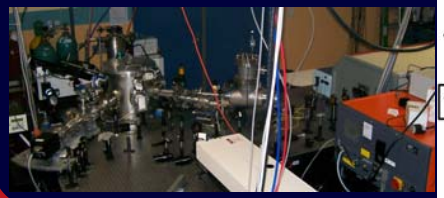
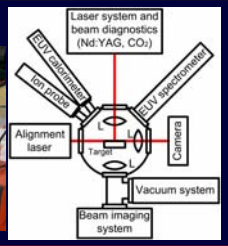
Objectives

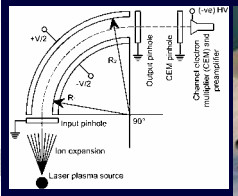
- How does laser wavelength affect the charge states and energies of ions in the far expansion zone?
- How does laser wavelength affect the spatial evolution of the charge state distribution during plasma expansion into vacuum?
- How can the experimental measurements, recorded at distances very far from the target surface as compared the initial spot size, be used to infer plasma properties near the target surface, at the scale of the spot size?
- How does this work influence the EUV x-ray source application?

Experimental arrangement





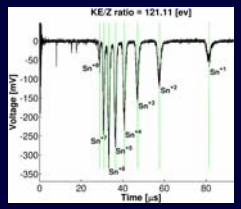
Electrostatic ion energy analyzer



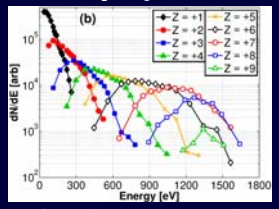
Laser wavelength effects on the charge state resolved ion energy distributions[a]

Wavelength [μm]	Pulse duration [ns]	Pulse energy [mJ]	Focal diameter [μm]	Resultant laser intensity [W/cm²]
1.064	7	120	80	3.4×10^{11}
10.6	85	120	100	1.8×10^{10}

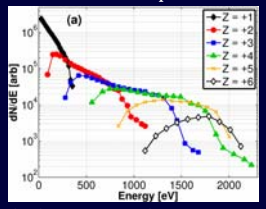
Sample time-of-flight data from the electrostatic ion energy analyzer



CO_2 ion spectrum



Nd:YAG ion spectrum



Significant absorption occurs at the critical density, which controls the initial density of hot plasma:

$$n_{cr} \approx \begin{cases} 10^{21}\ \text{cm}^{-3},\ \lambda = 1.064\ \mu\text{m} \\ 10^{19}\ \text{cm}^{-3},\ \lambda = 10.6\ \mu\text{m} \end{cases}$$

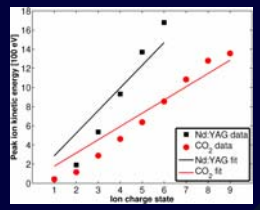
The dominant recombination mechanism in the expanding plasma is three-body recombination:

$$\left(\frac{dn_e}{dt}\right)_C \propto T_e^{-9/2} n_e^2 n_i$$

The data fits approximately with an electrostatic model of ion acceleration[b]

$$E_{ion} = nZT + T$$

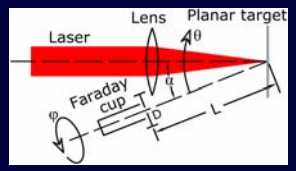
- **for Nd:YAG, T ≈ 50 eV**
- **for CO_2, T ≈ 40 eV**



Laser wavelength effects on the spatial evolution of the charge state distribution[c]

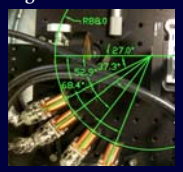
Wavelength [μm]	FWHM pulse duration [ns]	Pulse energy [mJ]	($1/e^2$) focal diameter [μm]	Resultant laser intensity [W/cm²]
1.064	7	165	60	8.3×10^{11}
10.6	35	50	85	2.5×10^{10}

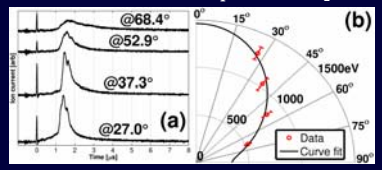
Experimental technique to measure spatial variations in the charge state distribution



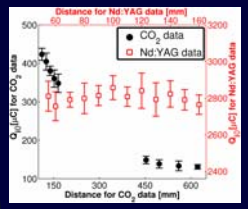
$$Q_{i0} = Q_i\left(\Omega_{eff}/2\pi\right) \qquad \Omega_{eff} = \int_0^{2\pi}\int_0^{\Theta} \cos^p(\theta+\alpha)\sin\theta\, d\theta\, d\phi$$

Angular distribution measurements to determine 'p' for the CO_2 LPP





Results and explanation of experiments to determine critical length



- **L_{CR} is derived by balancing energy lost in hydrodynamic expansion with energy released in three-body recombination[d]**

$$L_{CR} \propto \left(T_e^{13/2} v_i^{14/6} \tau_L^{13/6}\right) \Big/ \left(n_c^{8/8} d_S^{8/6}\right)$$

- **More energy is released in three-body recombination at the shorter laser wavelength**
- **L_{CR} < 6 cm for the Nd:YAG LPP**
- **L_{CR} > 60 cm for the CO_2 LPP**

Numerical simulation of plasma expansion into vacuum

Zero dimensional model illustrates the importance of the decay of T_e

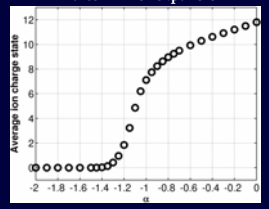
$$\frac{dN_m}{dt} = \underbrace{\left(\frac{dN_m}{dt}\right)_i}_{\text{Electron impact ionization}^e} + \underbrace{\left(\frac{dN_m}{dt}\right)_c}_{\text{Three-body recombination}^f} + \underbrace{\left(\frac{dN_m}{dt}\right)_r}_{\text{Radiative recombination}^g}$$

- $N_m(t=0)$ determined by CRSS model[h]

$$\frac{dT_e}{dt} = \alpha\frac{T_e}{t},\ -2 < \alpha < 0$$

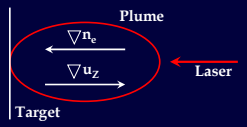
- $n_{e0} = 10^{20}$ cm^{-3}, $t_{e0} = 50$ eV, $R_0 = 100$ μm, $u_0 = 3\times10^6$ cm/s
- Expansion must be non-adiabatic (α>-2) to preserve high charge states in the far expansion zone

<Z> after 1 m of expansion



One dimensional lagrangian hydrodynamics and atomic physics simulation of plasma expansion into vacuum

'Recombination model' geometry



Initial spatial distributions ($0<r<r_0$)

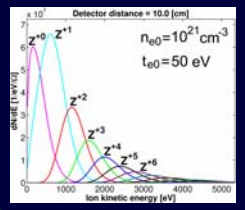
$$n_e(r) = n_{e0} \times \exp(-r/L)$$
$$u(r) = 3 \times c_S \times (r/r_0)$$
$$T_e(r) = T_i(r) = T_{e0}$$

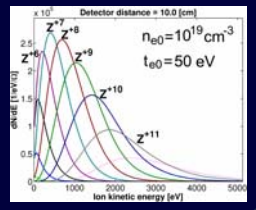
Simplified algorithm

i) Initialize r, u, T_e, N_e, $N_{i,z}$, <Z>, p, ρ
ii) Calculate du/dt and dt for stability
iii) Update r and u by leapfrog method
iv) Calculate N_e, $N_{i,z}$, T_e from t to (t+dt) using rate equations
v) Update p, ρ, <Z>; repeat (ii) thru (v)

Electron energy balance

$$\frac{dT_e}{dt} = \underbrace{-2T_e\frac{\dot{r}}{r}}_{\text{Expansion}} + \underbrace{\frac{T_i - T_e}{\tau_{ei}}}_{\text{Temperature relaxation}} + \underbrace{\frac{2}{3}\frac{Q}{1+\bar{Z}}}_{\text{Excess energy of three-body recombination}}$$





Conclusions

- A longer laser wavelength leads to:
  - Higher charge state ions in the far expansion zone
  - Longer distance over which the charge state distribution evolves
- Ion acceleration can be interpreted by an electrostatic model
  - T_e is lower at the longer laser wavelength
- Ion acceleration can be interpreted by a recombination model
  - Presence of high charge state ions in the far expansion zone is a result of non-adiabtic decay

Acknowledgements

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References

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