Atomic and radiative processes in shorter wavelength extreme ultra-violet (EUV) light sources

Quantum Beam Science Directorate
Japan Atomic Energy Agency
Akira Sasaki

Subjects of basic research of EUV sources

High power EUV source has been developed and installed in the scanner; being tested for production.

☞ Studies of future EUV sources.

- Atomic processes for shorter wavelength EUV sources.

☞ Improvement of the model of EUV sources for further optimization.

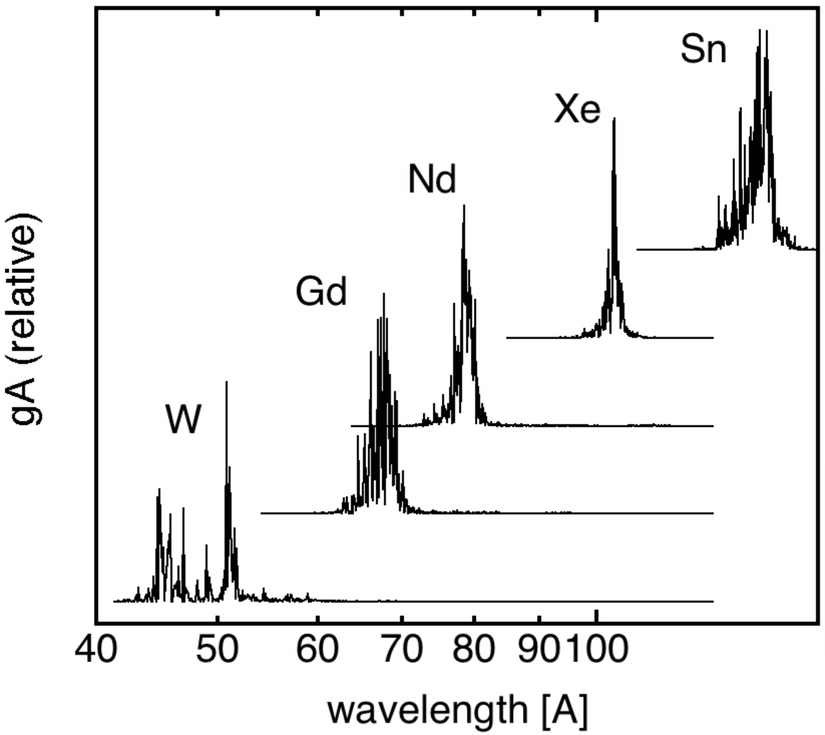
- Radiation hydrodynamics of plasmas, ablation of solid target and emission of debris particles.

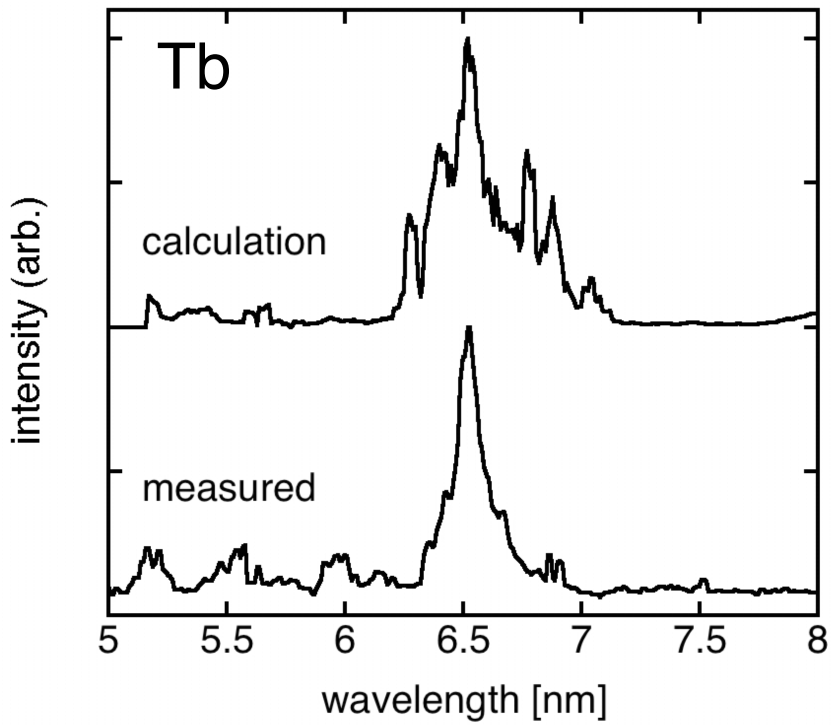
Topics

- Atomic process of λ=6nm sources using 4d-4f transition of Gd/Tb and other atomic transitions.
- New hydrodynamics model to investigate particle emission from source plasmas during ablation.

λ=6nm source using Gd/Tb plasmas

- Emission of 4d-4f transition is scalable to short wavelength by increasing the atomic number.
- Calculation is confirmed by experiment.

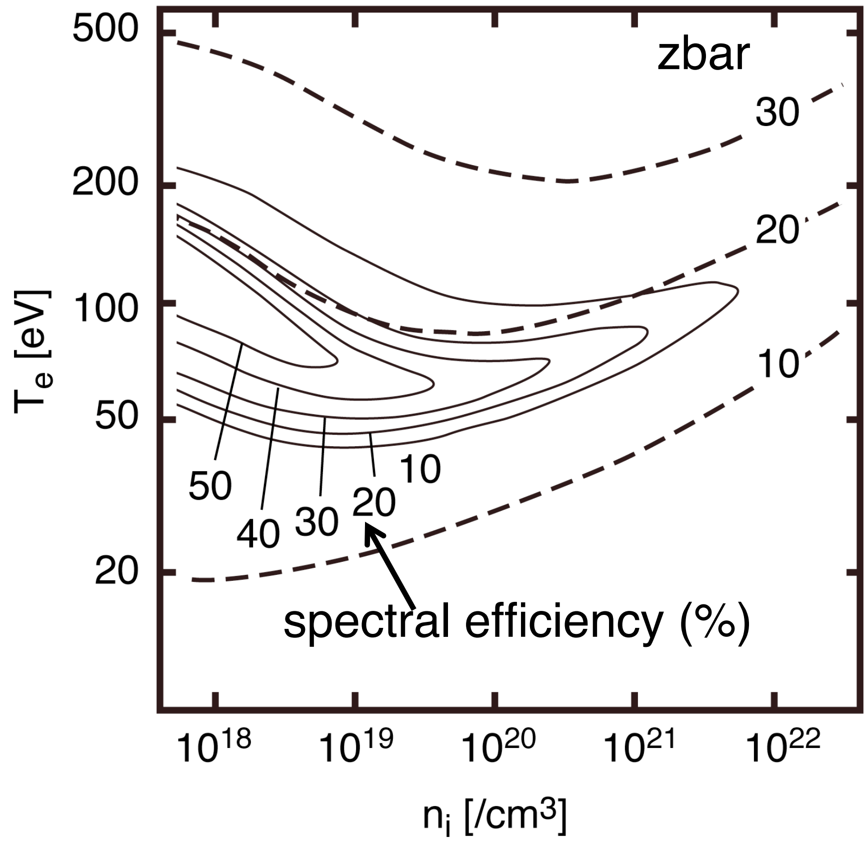


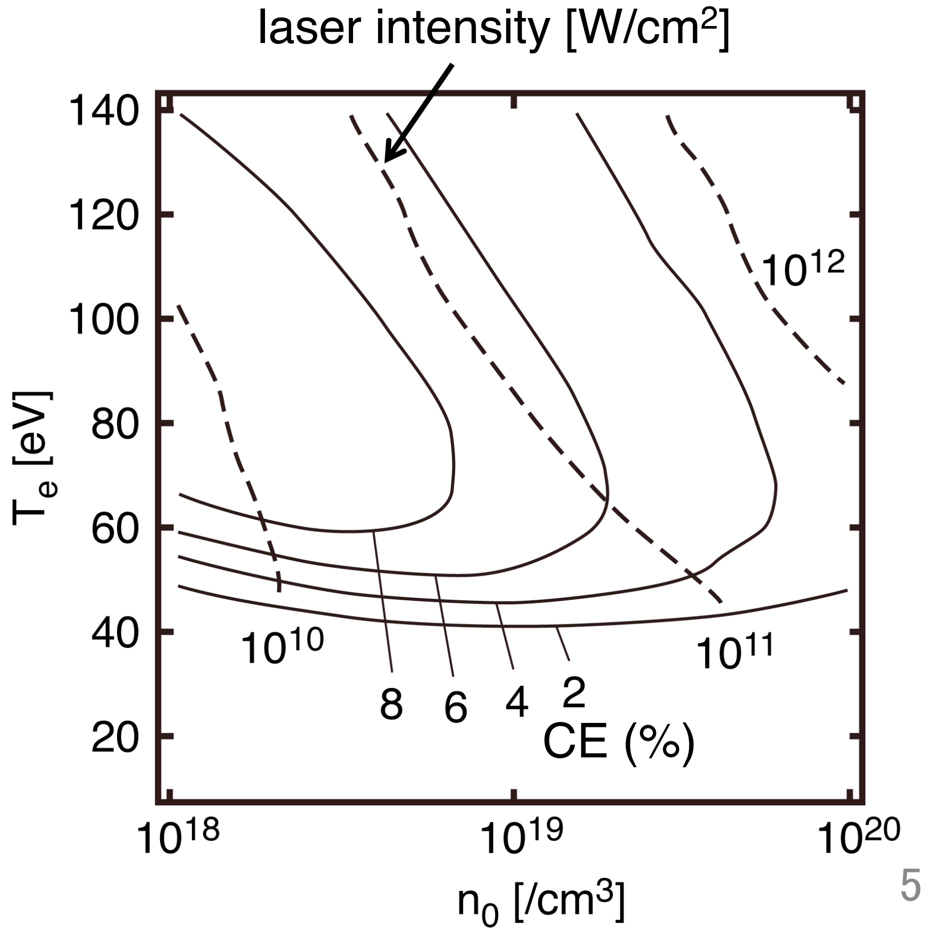


T_e=80eV, n_0=10^{19}/cm^3, l= 50μm, $\Delta\lambda$=-0.15nm
S. S. Churilov, Phys. Scr. 80, 045303 (2009).

Expected efficiency of Gd/Tb sources

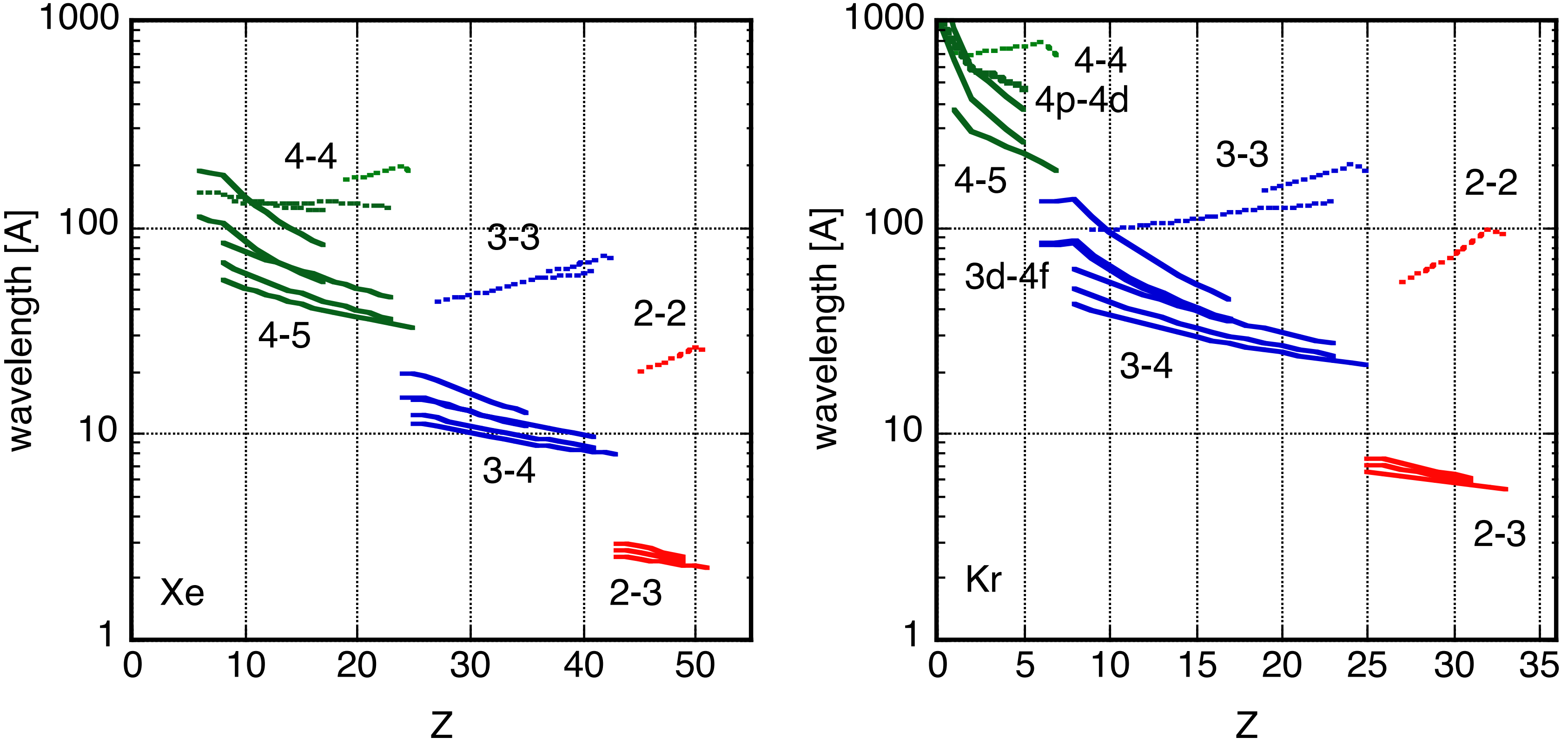
- Model shows optimum efficiency is comparable to Sn.
- Higher temperature (≈100eV) requires pumping power 10 times larger than Sn sources.





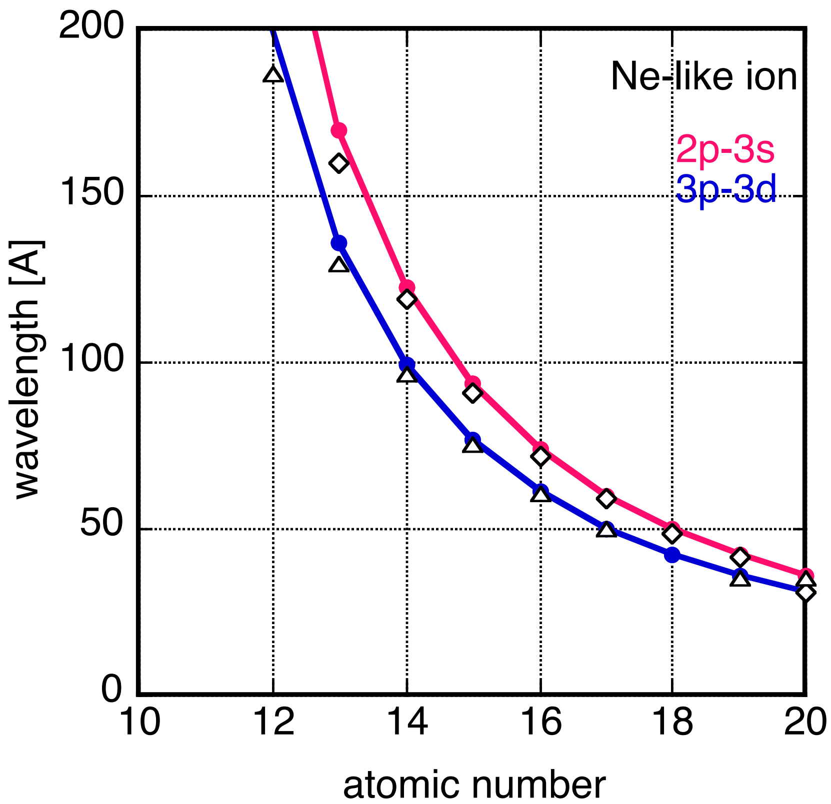
Possibility of using other atomic transitions

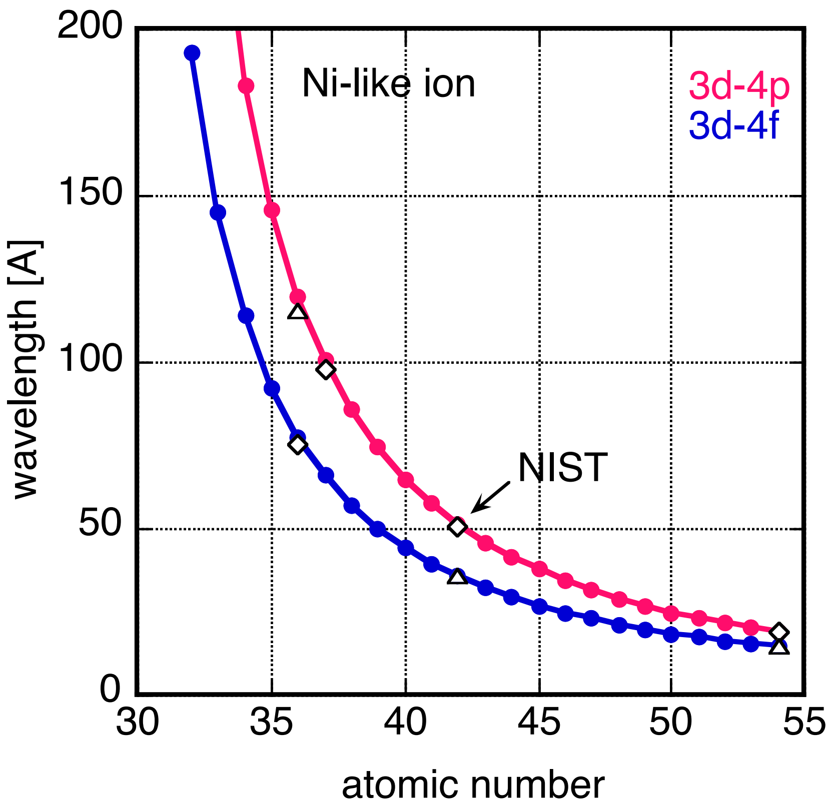
- High-z atoms can be used as the light source at several different wavelength regions as ionization proceeds.



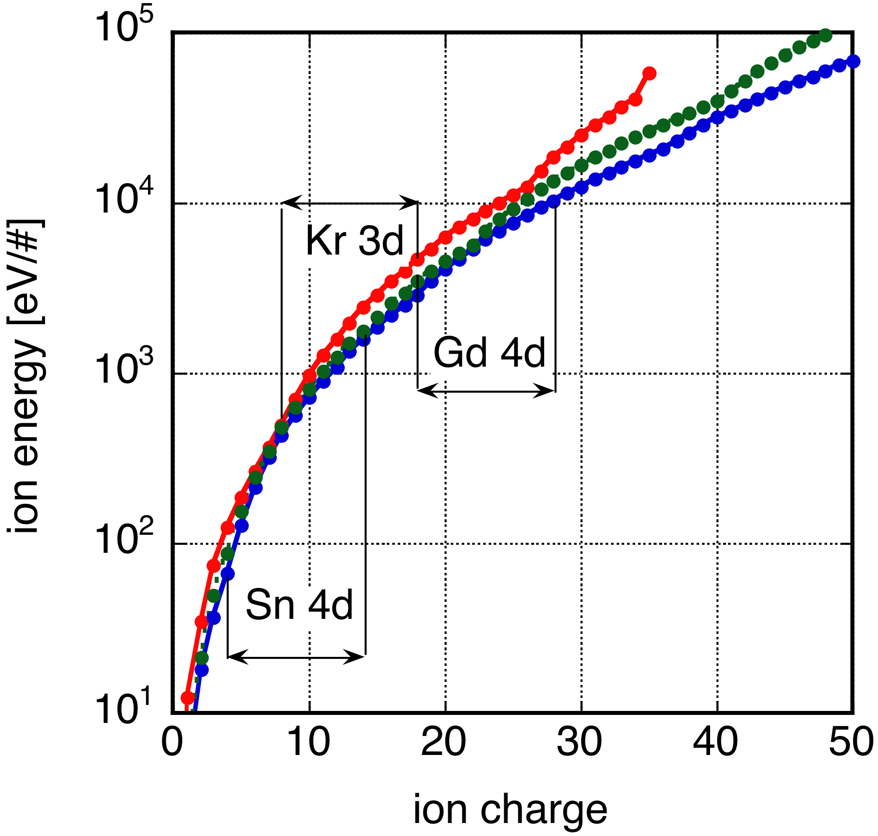
Properties of Ne-like 2-3 & Ni-like 3-4 transitions

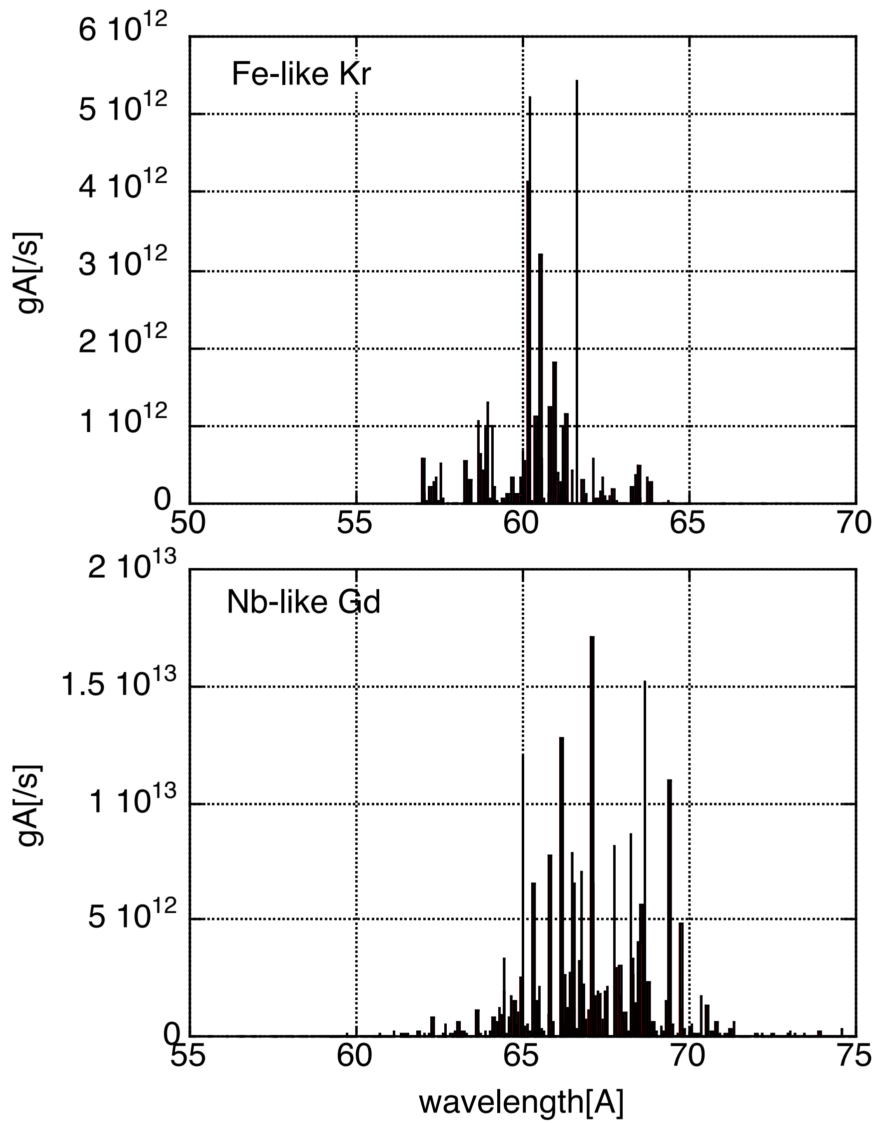
- Emission at 6nm is likely to be obtained using 2-3 transitions of S and 3-4 transitions of Kr.
- Not enough spectral data for Ne- and Ni-like ions.





Advantages of using other atomic transitions





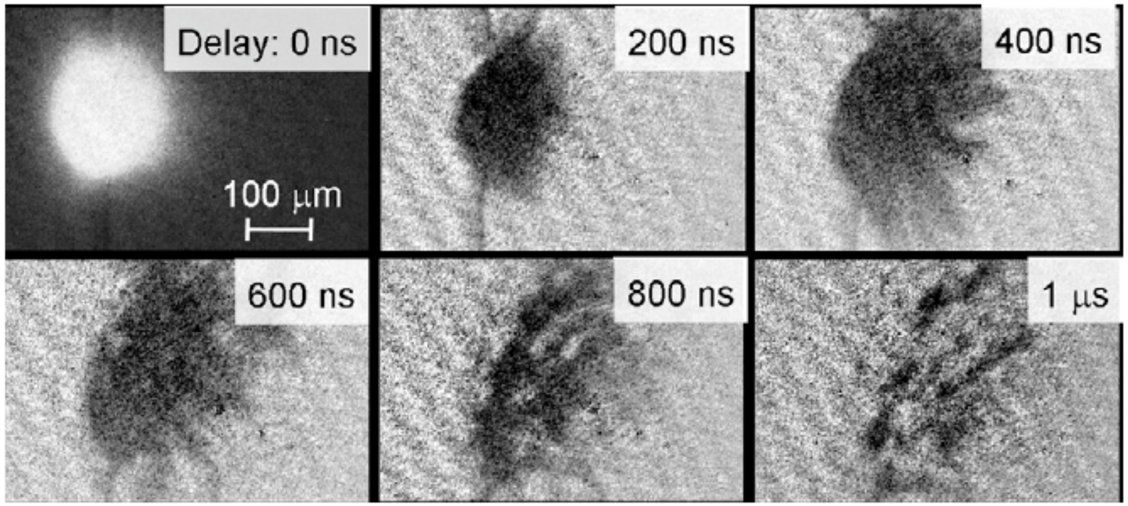
- Smaller energy required for producing emitting ions.
- Narrower emission spectrum.

Summary of studies of atomic processes

- Extending the analysis methods used for Sn plasmas, Gd/Tb plasmas are shown to be useful for 6nm EUV sources.
- However, even for Sn plasmas, significant difference of spectrum and efficiency is seen between simulation and experiment. Atomic data and radiation hydrodynamics model may need improvement.
- 6nm emission can also be obtained through 2-3 and 3-4 transitions from lighter elements. Investigation of spectral properties of a wide variety of ions has not been done yet and may be useful for future applications.

Modeling of debris emission

- During the laser irradiation ablation of the solid target shows non-uniform structure and emission of debris.
- Debris emission is difficult to calculate using radiation-hydrodynamics models.



D. Nakamura, et al., J. Phys. D: Appl. Phys. **41** (2008) 245210.

Modeling of phase transition

- Structure formation occurs during phase transition; evaporation of solid fuel.
- Hydrodynamics simulation based on particle model is developed to calculate large-scale deformation due to structure formation.

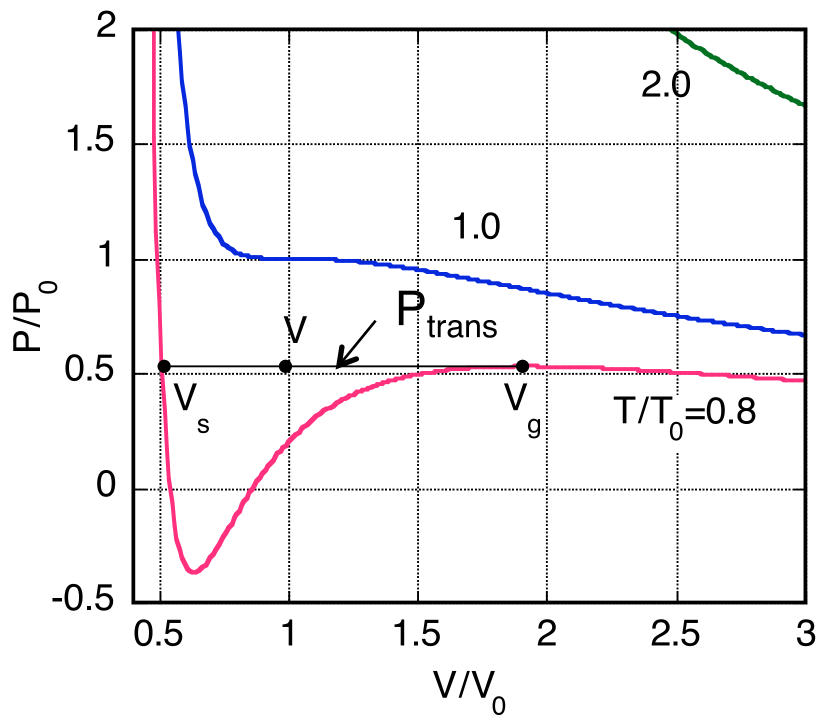
Isothermal expansion model

- For the preliminary calculation, Van-der-waals equation of state is used to simulate a typical condition of phase transition.
- Calculation is carried out assuming isothermal expansion.

$$\frac{D\mathbf{r}}{Dt} = \mathbf{u}(\mathbf{r},t)$$

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla P$$

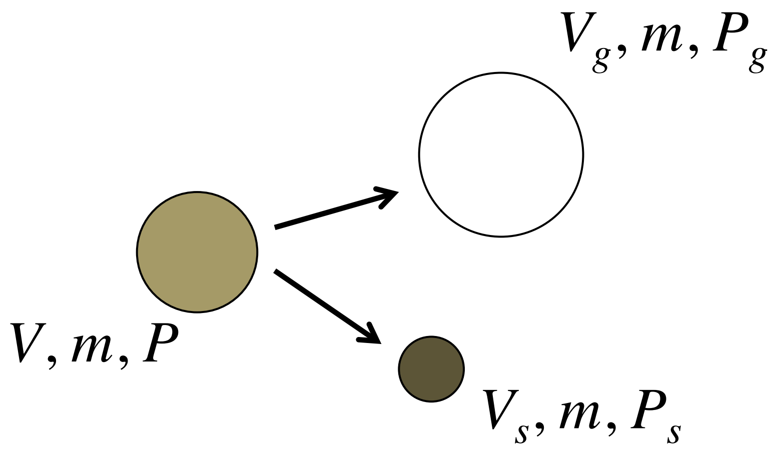
+ EOS



In the analysis of LPP, the spatial-temporal profile of the plasma is approximated by those of isothermal expansion.

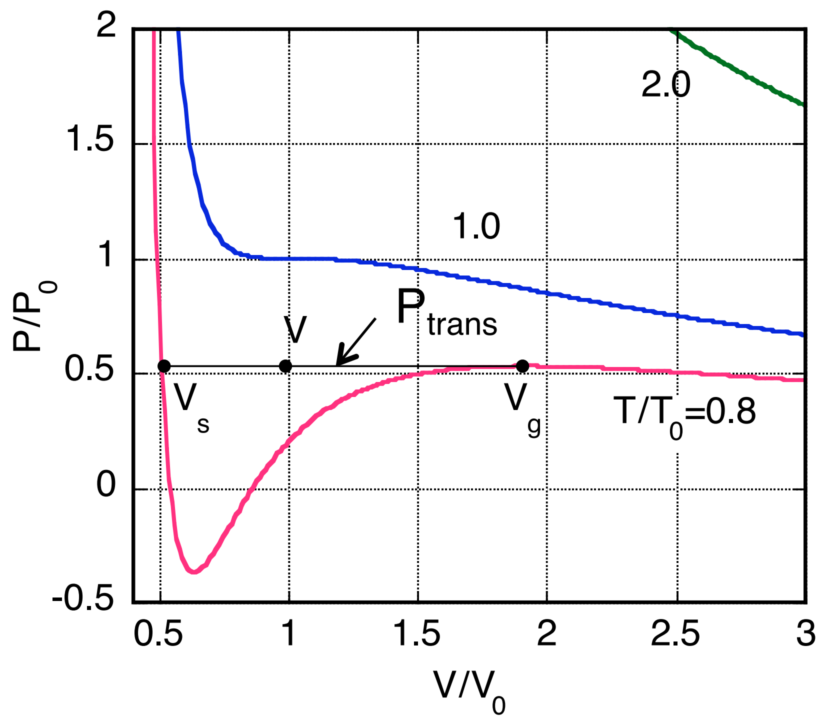
Particle model of phase transition

- A hydro cell is divided into 2 gas and liquid phase cells, when the condition for phase transition is occurred ($V_s < V < V_g$), maintaining total mass, volume and pressure.

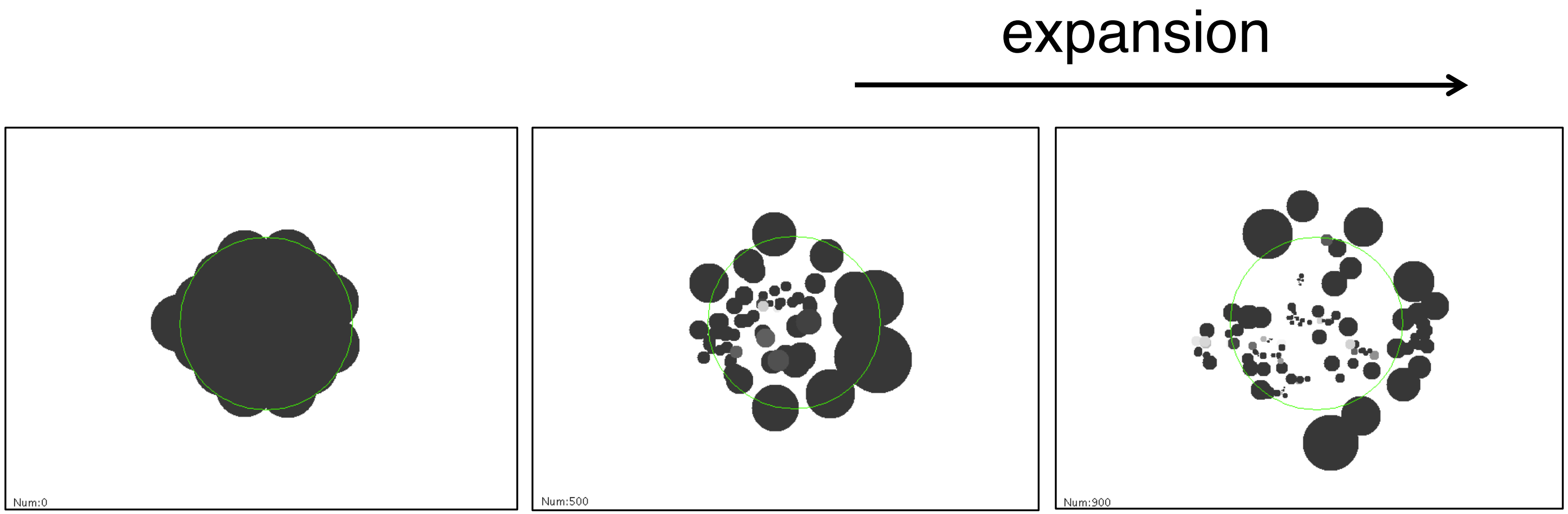


$$m_s V_s + m_g V_g = mV$$

$$m_s + m_g = m, \quad P_s = P_g = P_{trans}$$



- Calculation corresponds to evaporating laser heated liquid droplet is carried out.
- During expansion droplet divides into fragments; evaporation shows bubbling like behavior.
- Background gaseous region follows the profile of isothermal expansion, while fragments exist for a long time.



Preliminary

Summary of modeling of debris

- Preliminary model of evaporation of liquid droplet shows interesting behavior, suggesting modeling phase transition is useful for the simulation of laser ablation.
- Code is being developed and tested before performing simulations of realistic fuel droplet taking material properties and heating conditions into account.