# Critical issues of KOYO-F
# -Aerosols and droplets -

*T. Norimatsu[1], A. Yamaji[1], Y. Shimada[2], H. Furukawa[2], T. Kunugi[3], H. Nakajima[4], Y. Kajimura[4], and K. Mima[1]*

1) *Institute of Laser Engineering, Osaka University, Suita, Osaka, Japan*
2) *Institute for Laser Technology, Osaka, Japan*
3) *Department of Nuclear Engineering, Kyoto University*
4) *Department of Engineering Science, Kyushu University*

***Presented at US/Japan workshop on Fusion Power Reactor Design and Related Advanced Technologies with participation of EU and China***

***University of Tokyo in Kashiwa, March 16-18, 2009***

# Purpose



- In a future laser fusion reactor with liquid wall, about 10 kg of liquid metal will be ablated after every laser shot.

- It is expected that the ablated vapor condenses on the opposite wall by cryogenic effect. However, stagnation of evaporated vapor and formation of aerosols are not clear.

- The goal of this study is to make reliable scenario on the chamber clearance through simulation and elemental experiments.

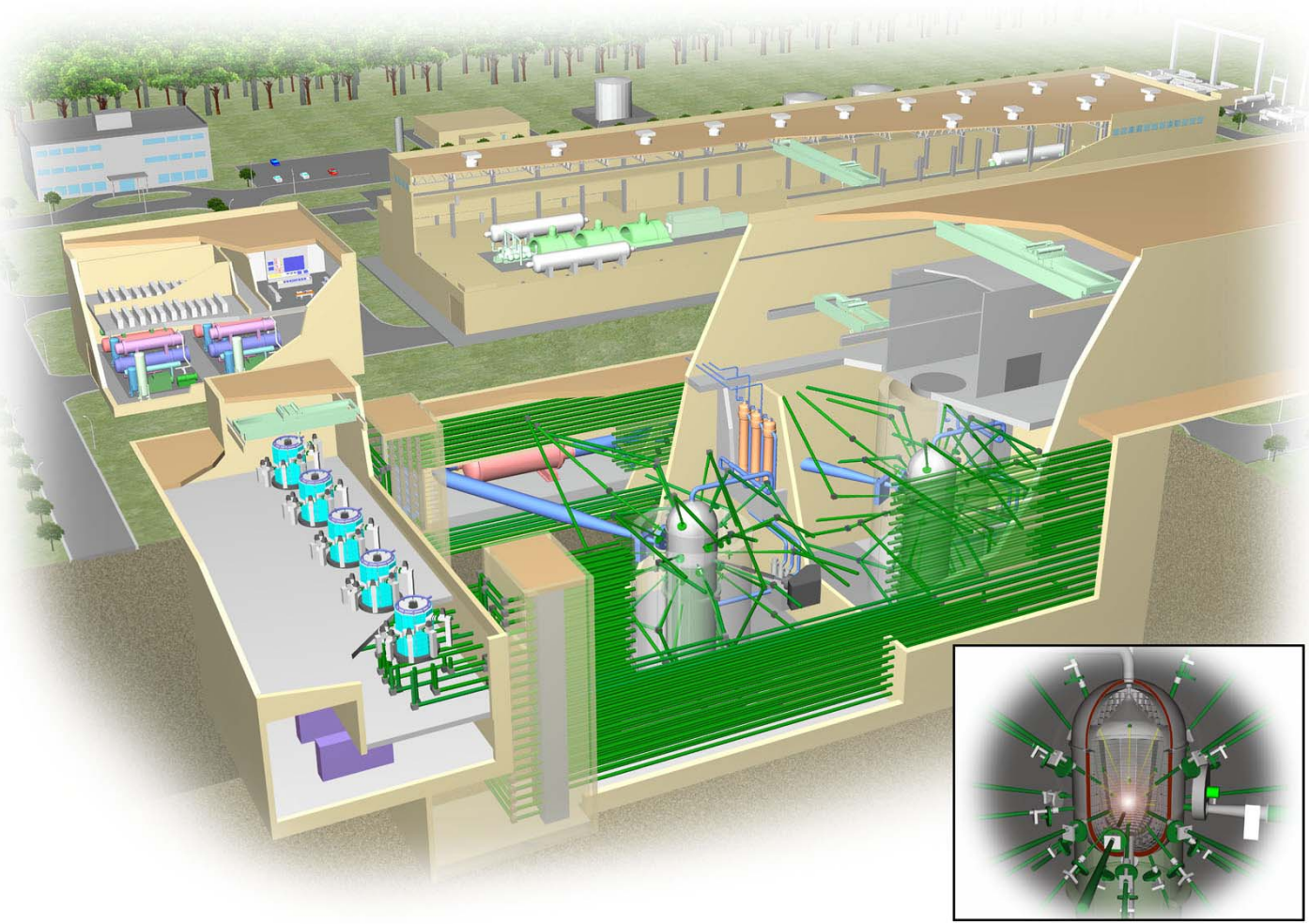
# Outline



- **Introduction of KOYO-F**
  - **Critical issues of KOYO-F chamber and past achievements**
- **Aerosol formation**
- **Hydrodynamic view of ablation**
- **Summary**

# KOYO-F is a commercial or very “close to” commercial power plant.

ILE, Osaka



**System specification**

| | |
|---|---|
| Thermal out put | 3664 MW |
| Electric power | 1280 MW |
| System efficiency | 33 % |

**Laser**

Cooled Yb:YAG Ceramic
1.2MJ/16Hz
(1.1MJ+100kJ)

Efficiency 13.1% for Main
5.4% for heating
11.8% in total

**Plasma**

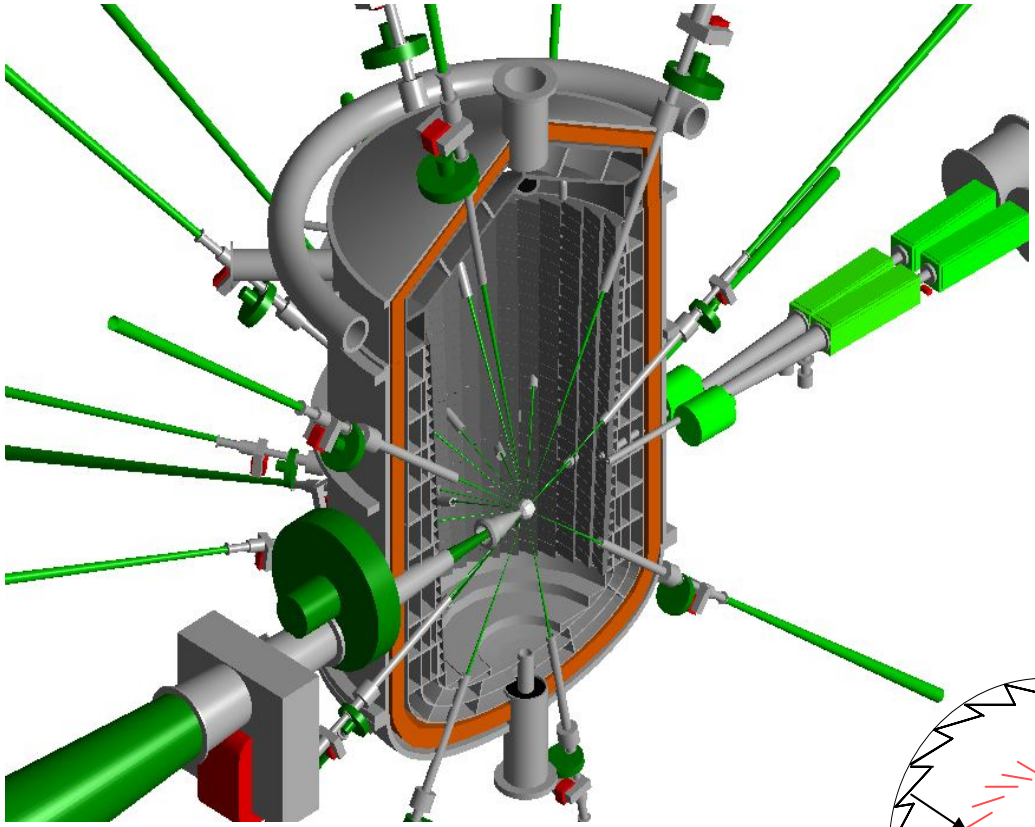
| | |
|---|---|
| Gain | 160 |
| Fusion Yield | 200MJ |

**Reactor**

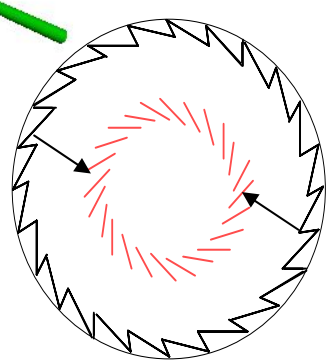
4 modular reactors

First wall Liquid LiPb
Cascade flow

# KOYO-F with 32 beams for compression and one heating beam



| Parameter of KOYO-F | |
|---|---|
| Number of beams | 32 (compression)<br>1 (heating) |
| Inner size of chamber | 3 m in radius<br>12 m in height |
| Thermal load on the first wall | 1.8 MJ/m$^2$ |



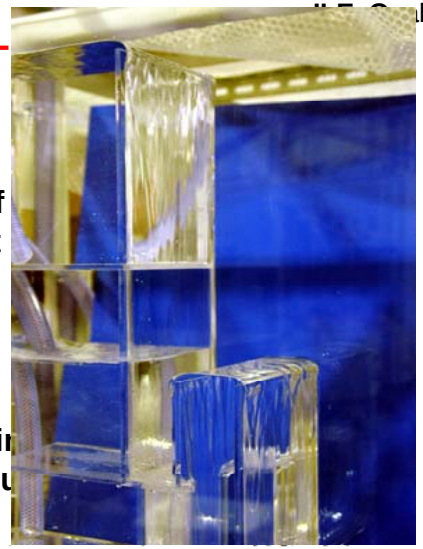
**Tilted first panels to make no stagnation point of ablated vapor**

# Critical issues in chamber 1
## (from J-US WS on reactor 2007)

- **Probability for direct exposure of the same place <1/10$^3$ –**

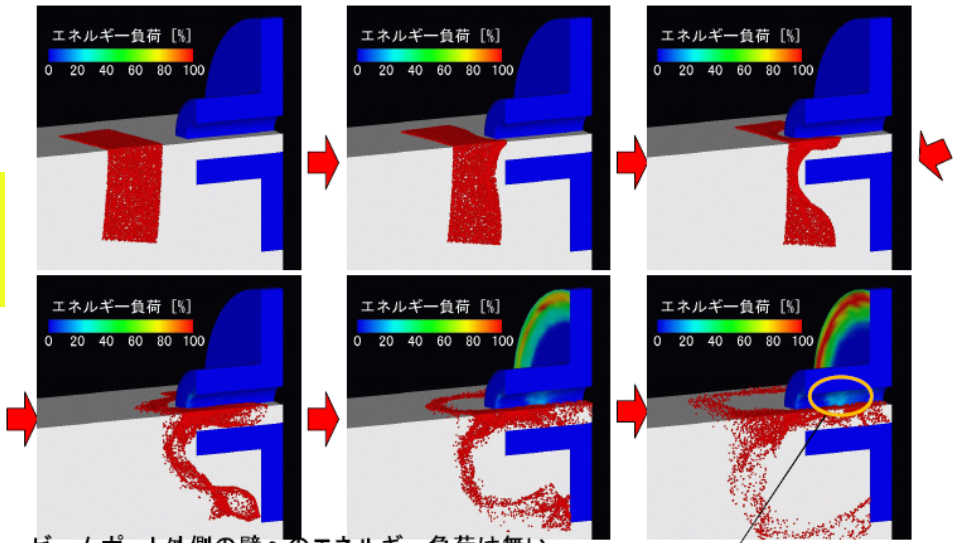
  - **If we assume maintenanc ears and acceptable erosion of**

**Dr Kunugi demonstrated a stable flow >3 mm using water**



- **Protection of beam ports**
  - **Our first plan was to keep the surface temperature less than surroundi condensation. But this would not work because of the small temperatu condensation.**
  - **Porous metal saturated with liquid LiPb**
  - **Magnetic field**

**Dr. Kajimura showed protection of the beam port by a 1T magnetic field.**

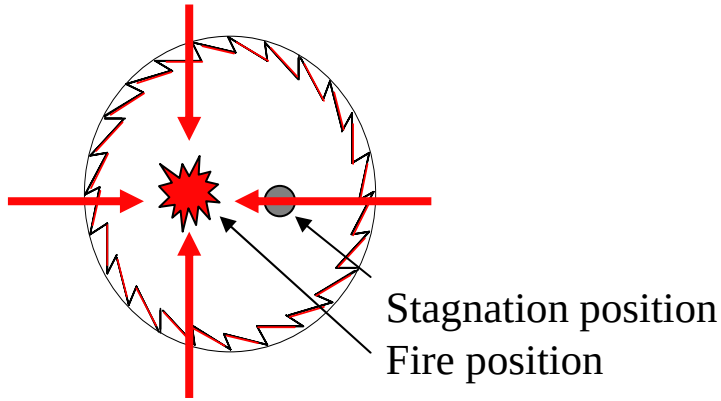


# Critical issues in chamber 2

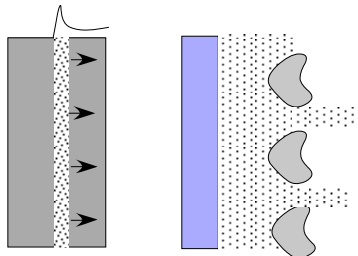
**(from J-US WS on reactor 2007)**



- Although tilted front panels will reduce the stagnation to $1/10^3$, few gram of LiPb vapor will stagnate at the center.
  - Off set irradiation,




  - Large ( ~3 μm) particles due to RT instabilities and related secondary particles



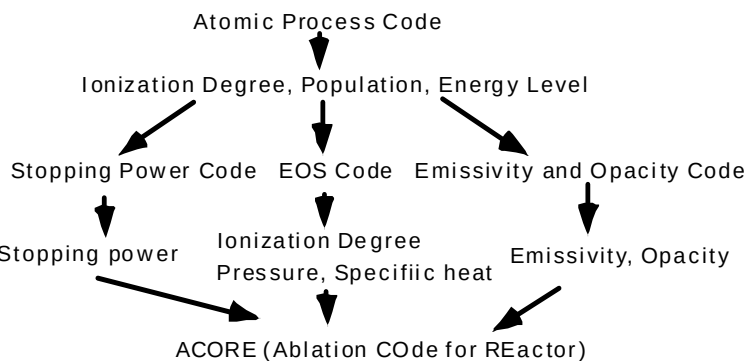
# Outline

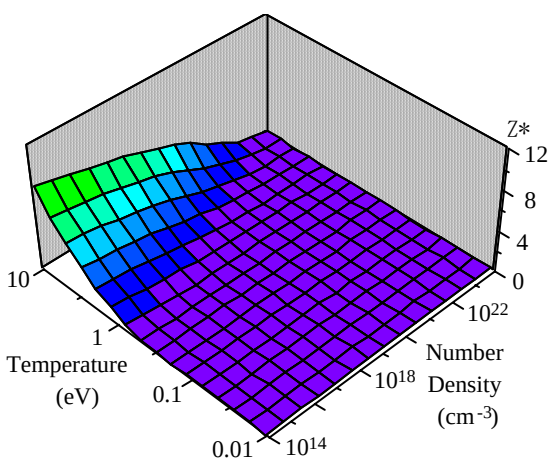


- Introduction of KOYO-F
  - Critical issues of KOYO-F chamber and past achievements
- Aerosol formation
  - Simulation code
  - Experiment to check code
  - Aerosols
  - Influence on target injection
- Hydrodynamic view of ablation
- Summary

# We estimated the ablation process using ACORE. Stopping power in ionized vapor was calculated.

ILE, Osaka



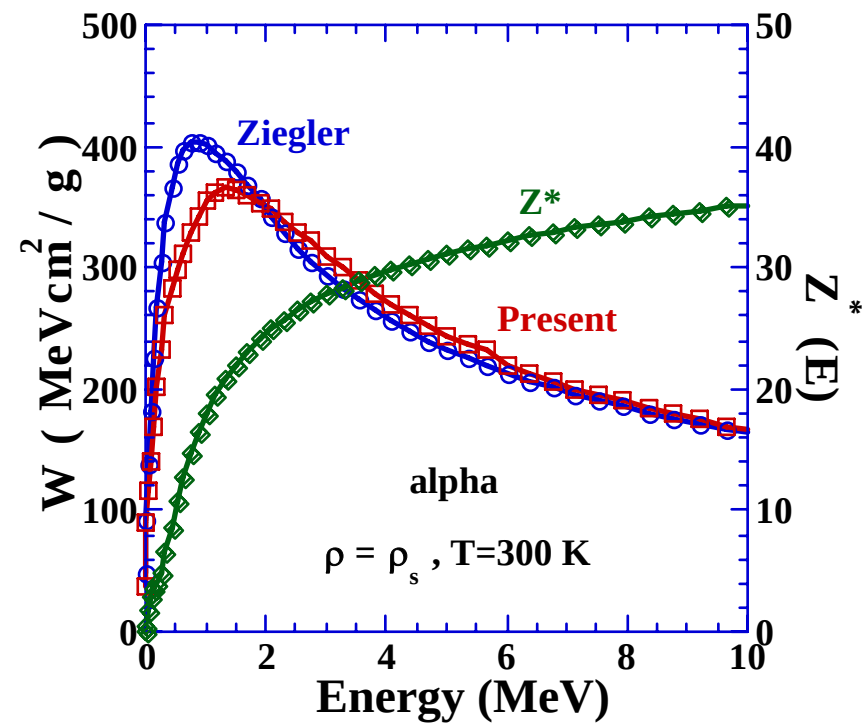

Ionization rate of Pb

Ziegler's model

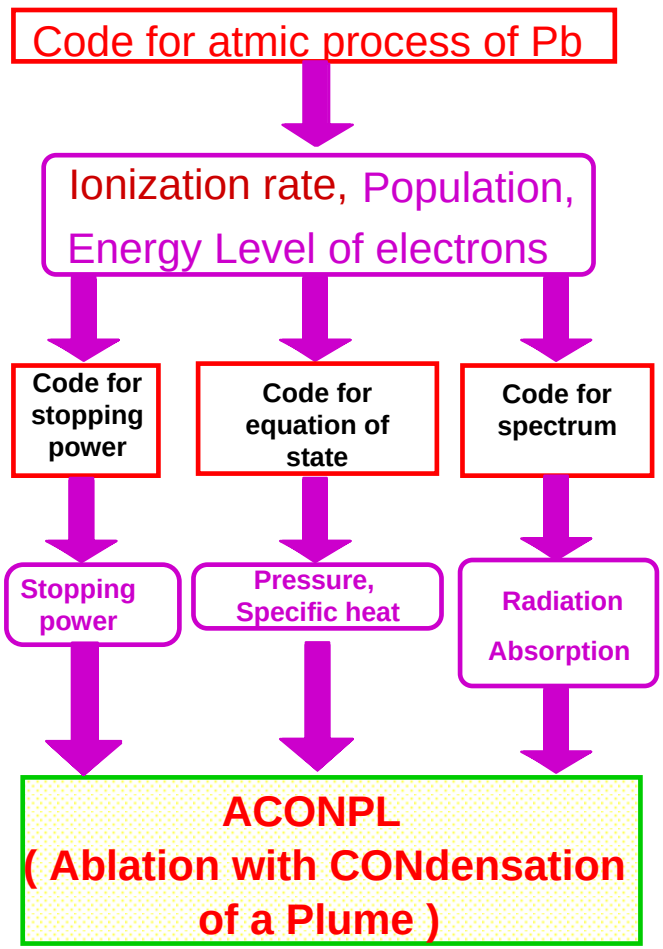
$$-\frac{dE}{dx} = \frac{4\pi e^4 Z_0^2 n_e}{m_e v^2} K_0\left(\frac{h}{n_e v^2}\sqrt{\frac{4\pi n_e e^2}{m_e}}\right)$$

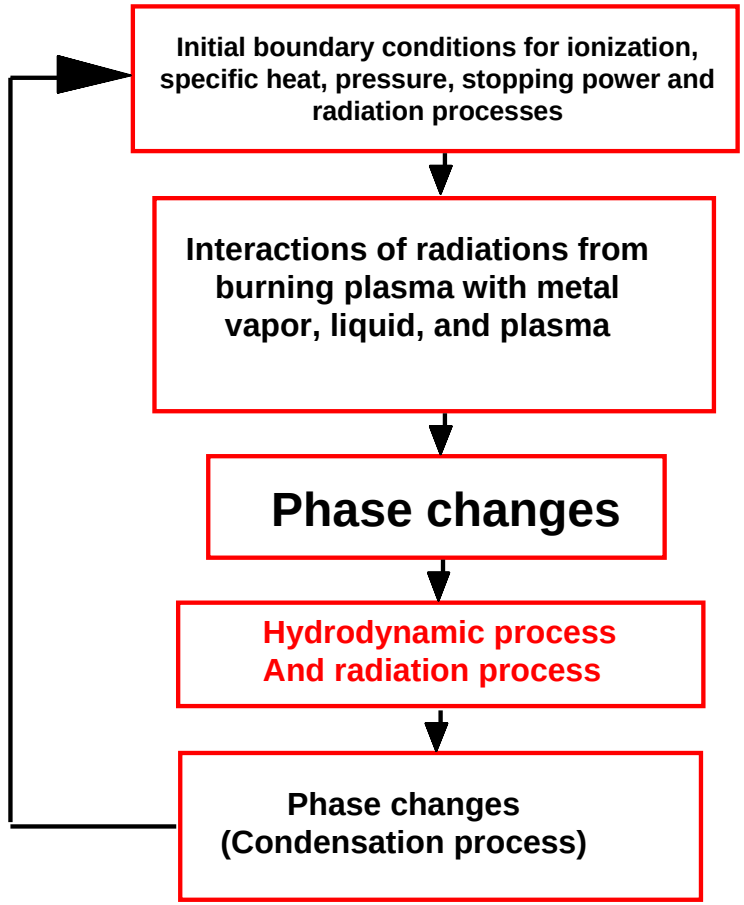
Present model

$$-\frac{dE}{dx} = n_i \sum_n \sum_l I_{nl} P_{nl} \pi \left(\frac{Z_0 e^2}{I_{nl}}\right)^2 G\left(\frac{v}{v_{nl}}\right) \quad G(V) = \frac{\alpha^{3/2}}{V^2}\left[\alpha + \frac{2}{3}(1+\beta)\ln(2.7+V)\right]$$



# Integrated codes for aerosol formation




**ACONPL**
**(Ablation with CONdensation of a Plume)**

**Atomic process code was New Screened Hydrogen Model with l-splitting that was originally developed by Nishikawa of Okayama University**

# Condensation of plume (Vapor to liquid)

○The boiling point is given as a function of the density.

$$T_c(\rho) = q\,\Phi(\rho) \qquad \frac{1}{\Phi(\rho)^3}\exp\left[-\frac{1}{\Phi(\rho)}\right] = B\,\rho\left(\frac{q^2}{T_s T_\ell}\right)^{3/2}$$

q : Latent heat of evaporation (Kelvin)

○Condensation of plume based on improved Luk'yanchuk Model

Condensation rate (y=0, vapor, y=1, liquid droplet) $y(x,t) = \nu(x,t)\cdot g(x,t)$

Ratio of clusters to the ablated materials

$$\frac{d\nu(x,t)}{dt} = \kappa_{\nu 0}\left[1-y(x,t)\right]\frac{\rho(x,t)}{\rho_0}\exp\left[-\frac{T_{nuc}}{T(x,t)}\frac{1}{\theta(x,t)^2}\right]$$

The size of cluster

$$\frac{d\,g(x,t)}{dt} = \kappa_{g0}\,g^{2/3}\sqrt{T}\left[1-y(x,t)\right]\frac{\rho(x,t)}{\rho_0}\left\{1-\exp\left[-\frac{q}{T}\left(\theta-\alpha g^{-1/3}\right)\right]\right\}$$

The temperature of cluster

$$\left[1+y(x,t)\right]\frac{dT(x,t)}{dt} + \left[1-y(x,t)\right]\frac{2T(x,t)}{3}\left[-\frac{1}{\rho(x,t)}\frac{d\rho(x,t)}{dt}\right] = \left[\frac{2}{3}q - T(x,t)\right]\frac{d\,y(x,t)}{dt}$$

Super Cooling Parameter

$$\theta(x,t) = \left[T_i(x,t) - T(x,t)\right]/T_i(x,t)$$

Reference

B. S. Luk'yanchuk, S. I. Anisimov et. al., SPIE **3618** (1999) 434-452.

# ACONPL (Ablation with CONdensation of a PLume )

○ 1-fluide, 2-temperature-model

$$\frac{d\rho(x,t)}{dt} = -\rho(x,t)\nabla\cdot v(x,t) \qquad \rho(x,t)\frac{dv(x,t)}{dt} = -\nabla\left[P_e(x,t)+P_i(x,t)+P_{nv}(x,t)\right]$$

$$\rho(x,t)c_v^{(e)}\frac{dT_e(x,t)}{dt} = -\nabla\cdot q_e(x,t) - \gamma\left[T_e(x,t)-T_i(x,t)\right] - P_{th}^{(e)}(x,t)\nabla\cdot v(x,t)$$

$$+Q_p(x,t)+Q_X(x,t)+Q_{rad}(x,t)$$

$$\rho(x,t)c_v^{(i)}\frac{dT_i(x,t)}{dt} = -\nabla\cdot q_i(x,t) + \gamma\left[T_e(x,t)-T_i(x,t)\right]$$

$$-\left[P_{th}^{(i)}(x,t)+P_{nv}(x,t)\right]\nabla\cdot v(x,t) + \rho(x,t)c_v^{(i)}\left[\frac{2}{3}q - T(x,t)\right]\frac{dy(x,t)}{dt}$$

$P_{nv}$ : viscosity q : Latent heat of evaporation （Kelvin)

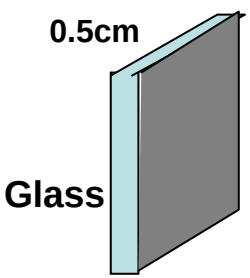
The 4th term comes from heat release by condensation.

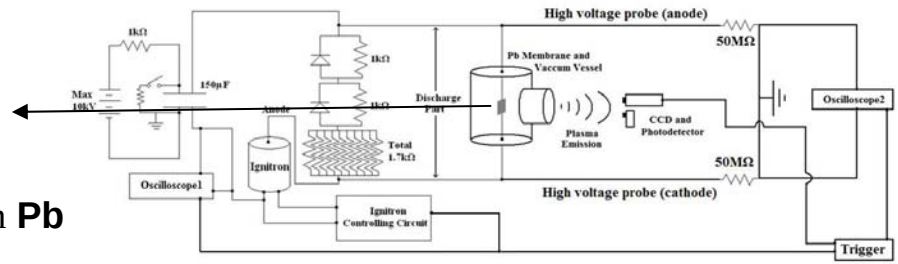
**It was assumed that; 1) two clusters became one after the collision.**
**2) Clusters move with surrounding gas.**

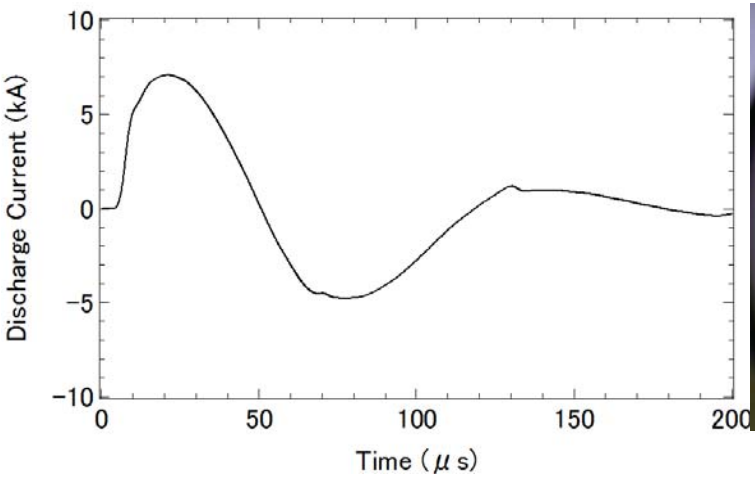
# To check the code, 10mm thick Pb membrane was heated and aerosols were captured on a witness plate.

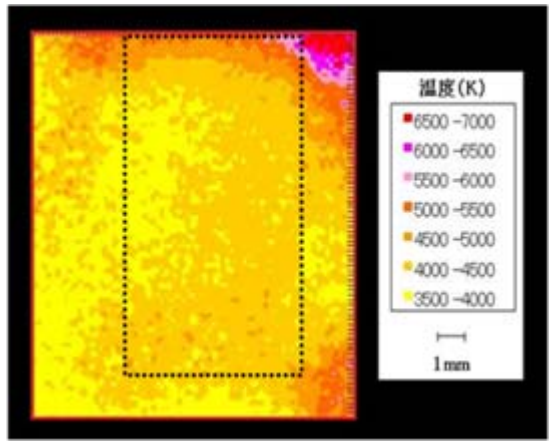
ILE, Osaka

| | Depth of ablation ($\mu$m) | Heating time ($\mu$s) | Areal thermal load (MJ/m$^2$) | Temperater (K) |
|---|---|---|---|---|
| This experiment | 10 | 23.0 | 1.6 | 4000-6000 |
| KOYO-F | 12.3 | 0.1 | 0.4 | 15000 |

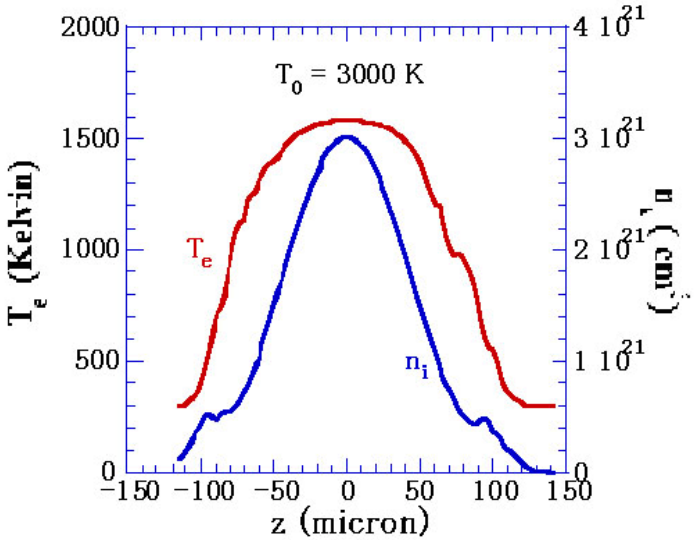


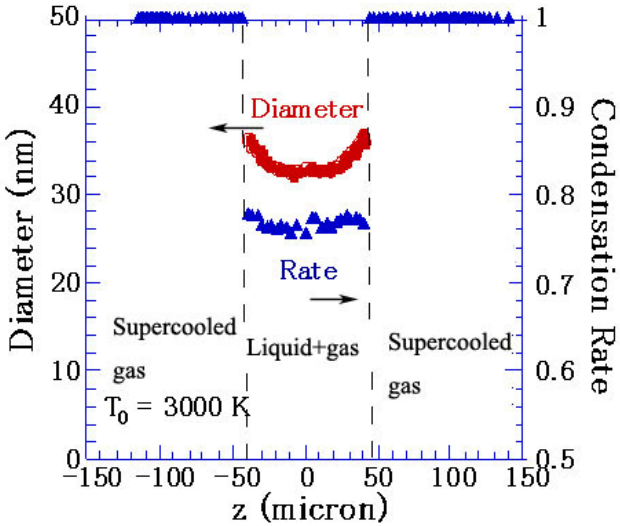



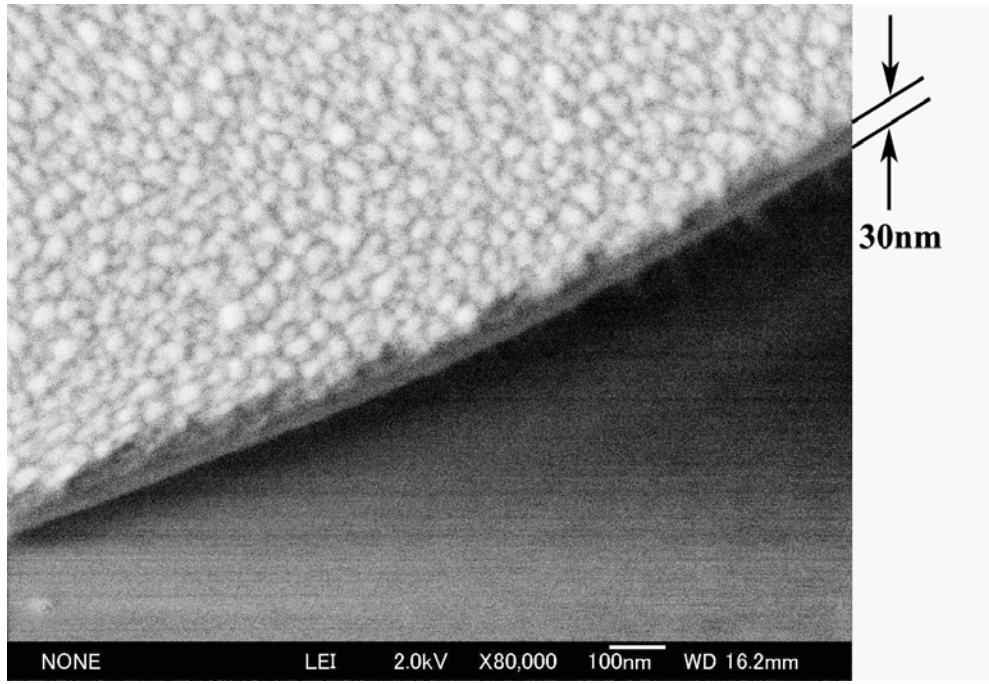


# Diameter of particles agreed with simulation result.




ILE, Osaka

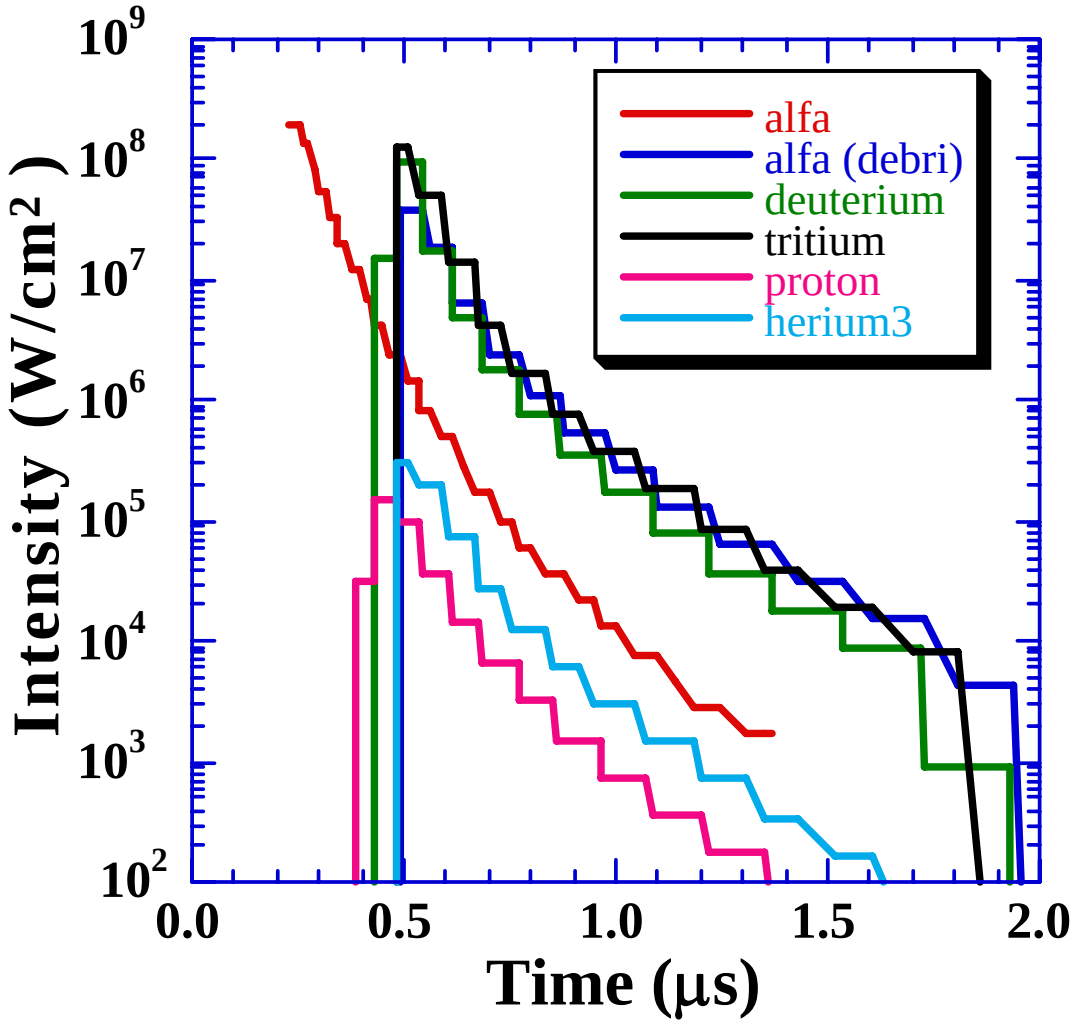



**Particles on continuous membrane**

**The continuous membrane was formed with leading, super-cooled plume.**

# Thermal load on the first wall of KOYO-F (@r=3m)

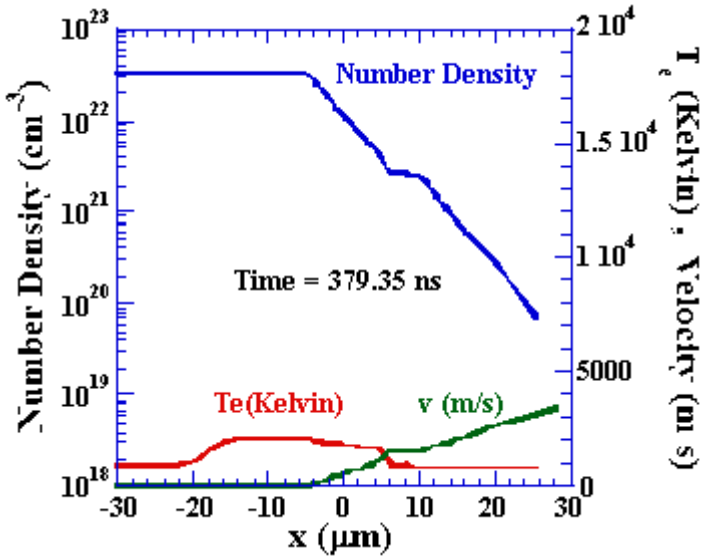


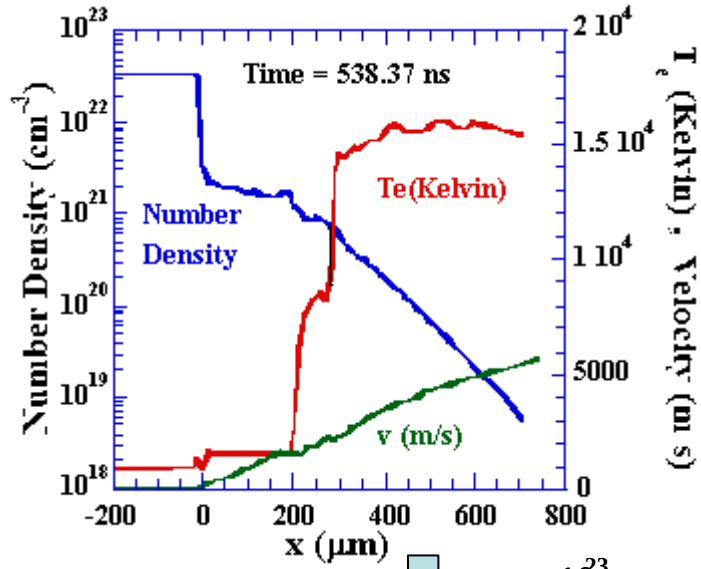


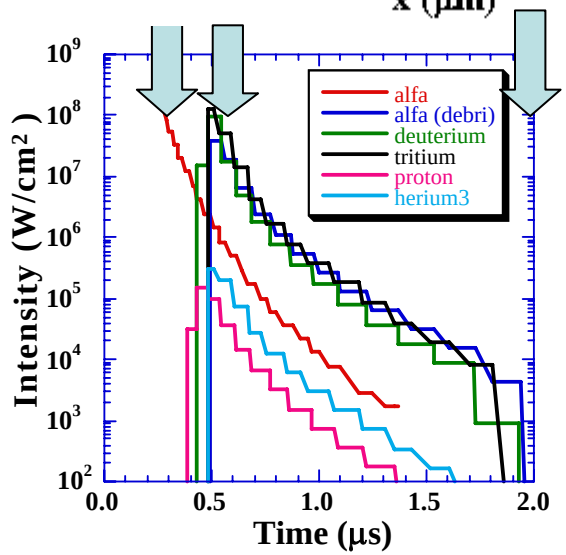

$\Phi\alpha$=0.4MJ/m$^2$

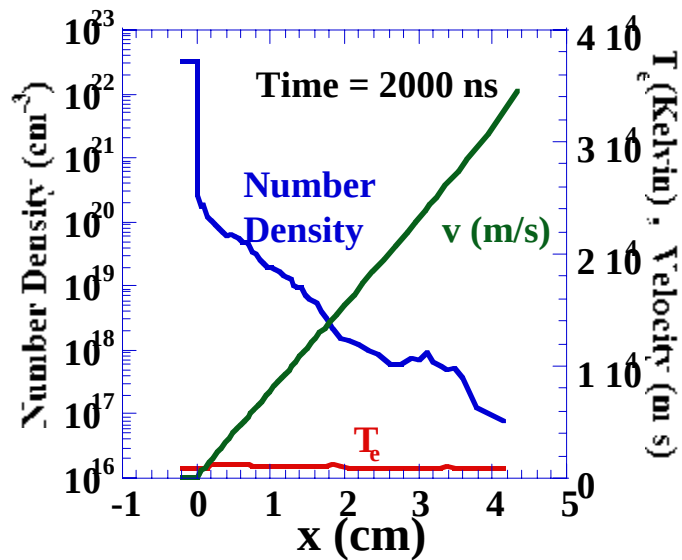
# Density, Temperature and velocity profile of ablated material.

ILE, Osaka



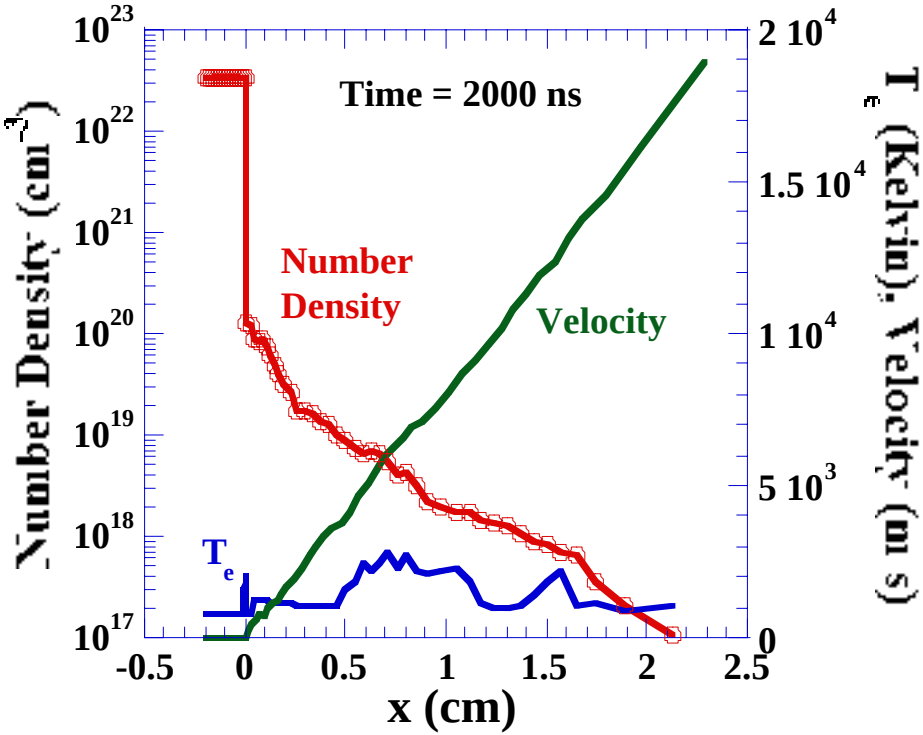



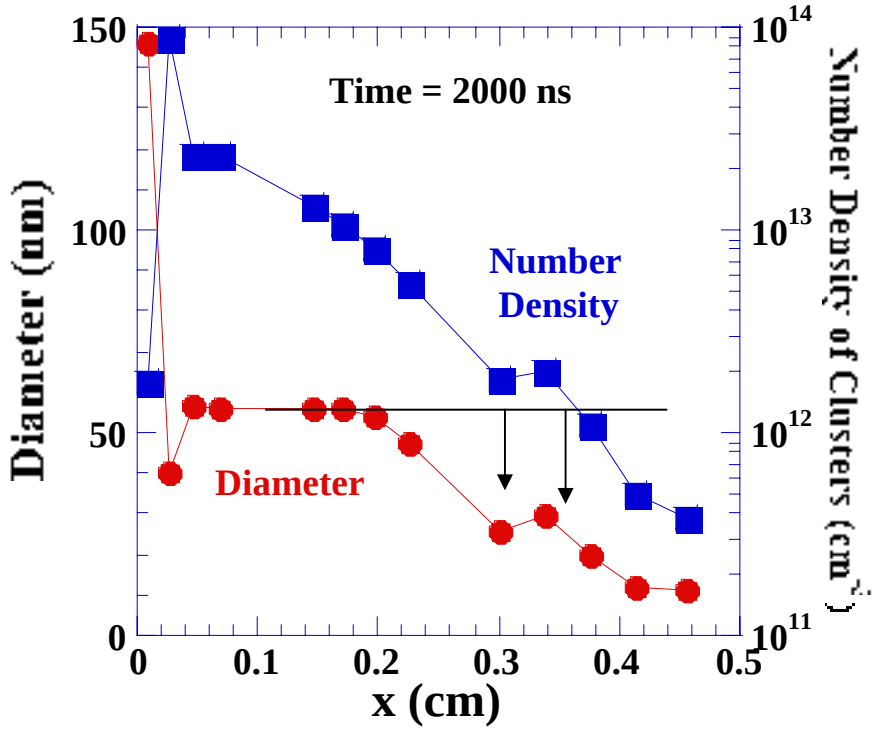



# Due to after glow heating, clusters in leading plume evaporate and become smaller.

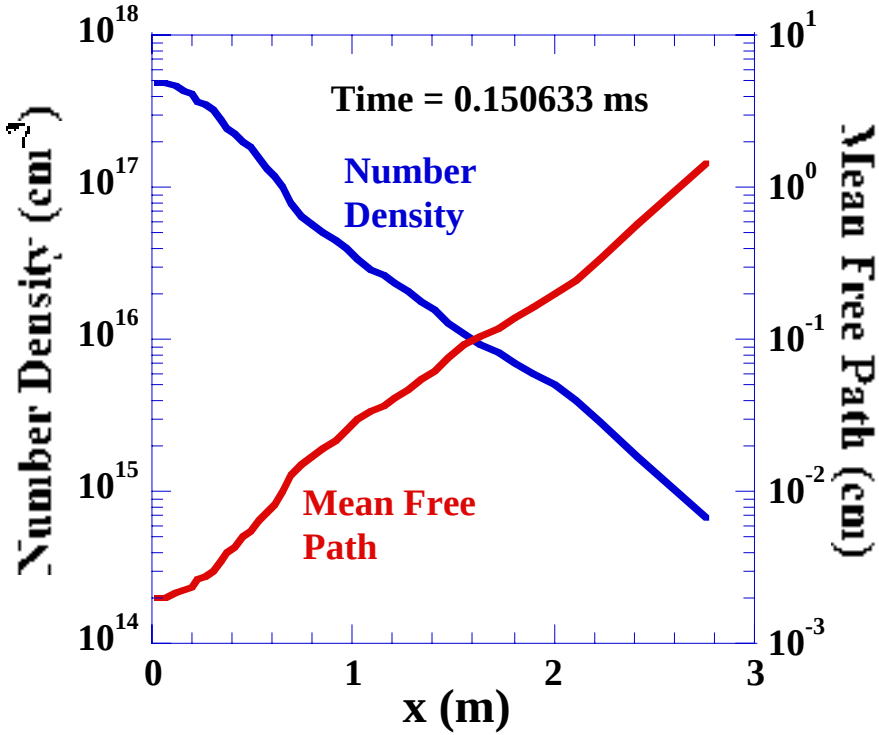
ILE, Osaka

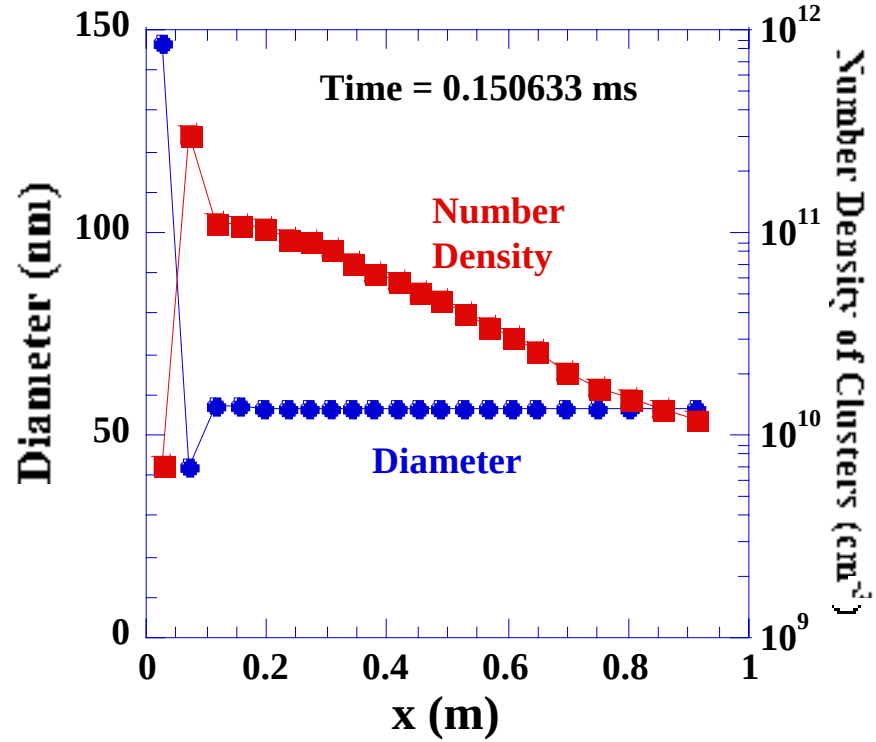


# When the leading edge of plume reached the chamber center, the number density and the average diameter were $10^{10}/cm^3$ and 60 nm, respectively.

ILE, Osaka

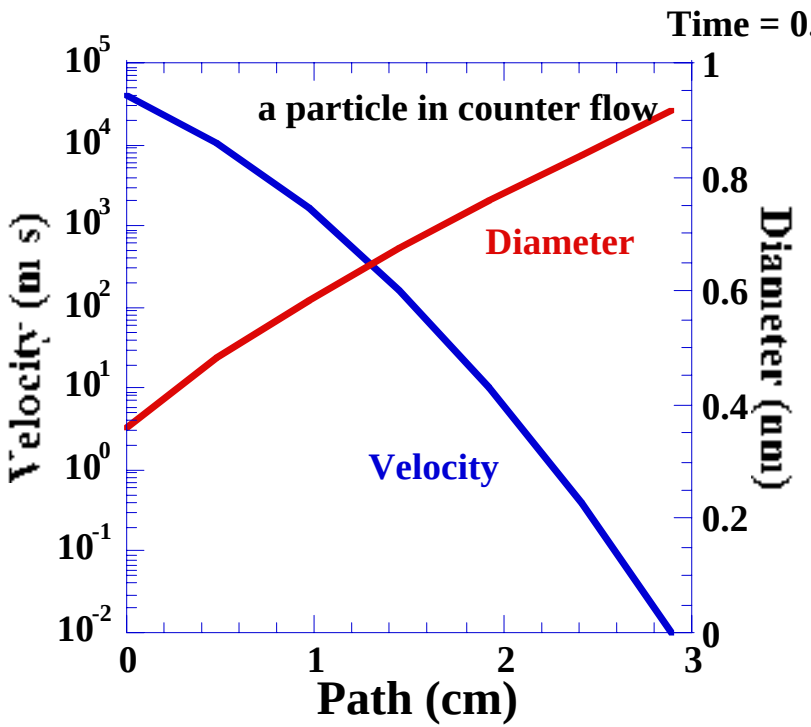


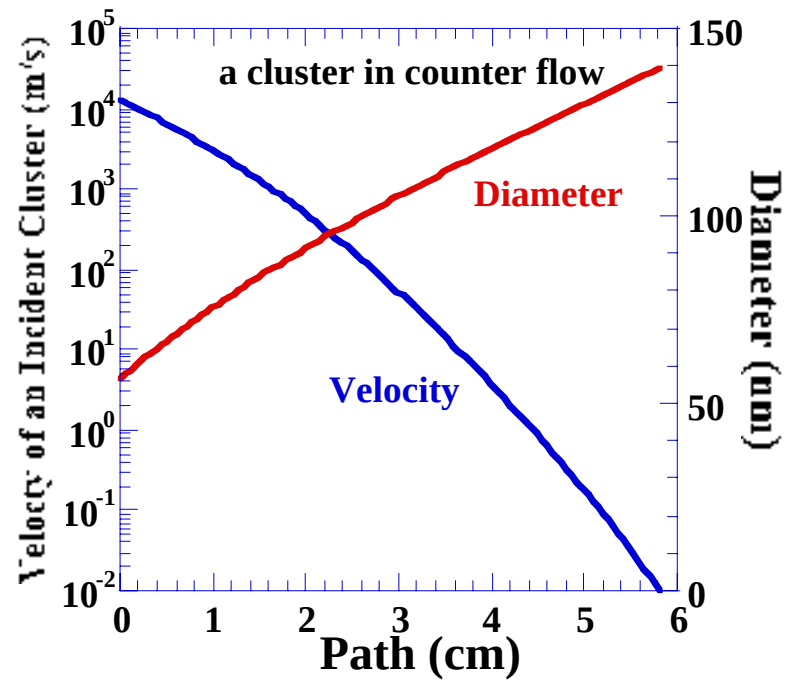



# Growth of particles after collision of plumes (The scale length for stagnation at the center is about 3 cm)

ILE, Osaka

$$\frac{d\,v_{incident}}{d\,s} = -\nu = -n\sigma v_{incident} = n\pi\left(r_{incident} + r_{field}\right)^2 v_{incident} \quad , \quad \frac{d\,g_{incident}}{d\,s} = \frac{g_{field}}{mfp}$$



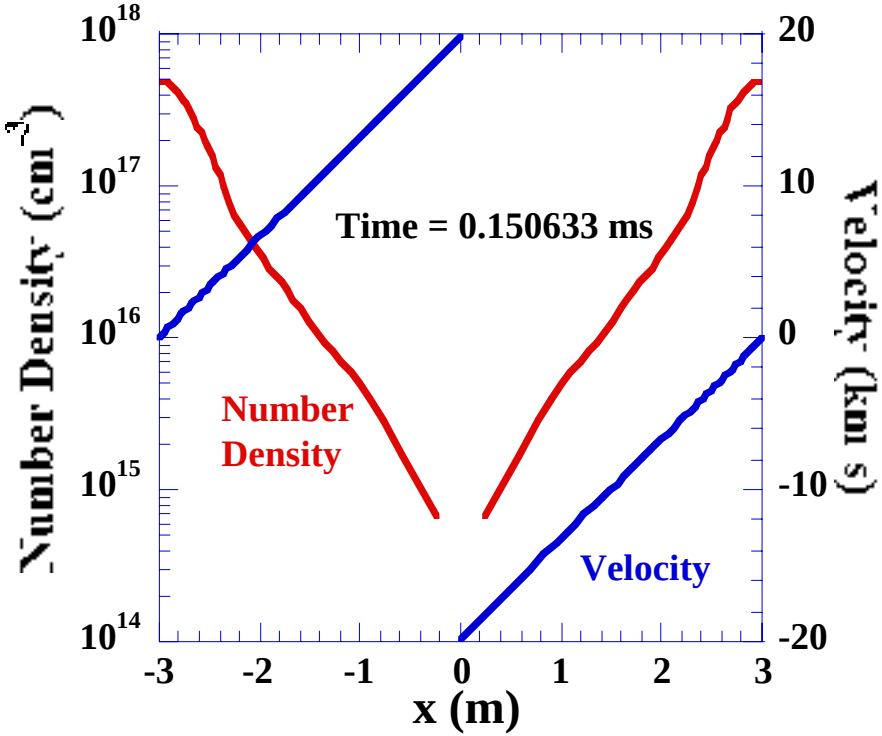



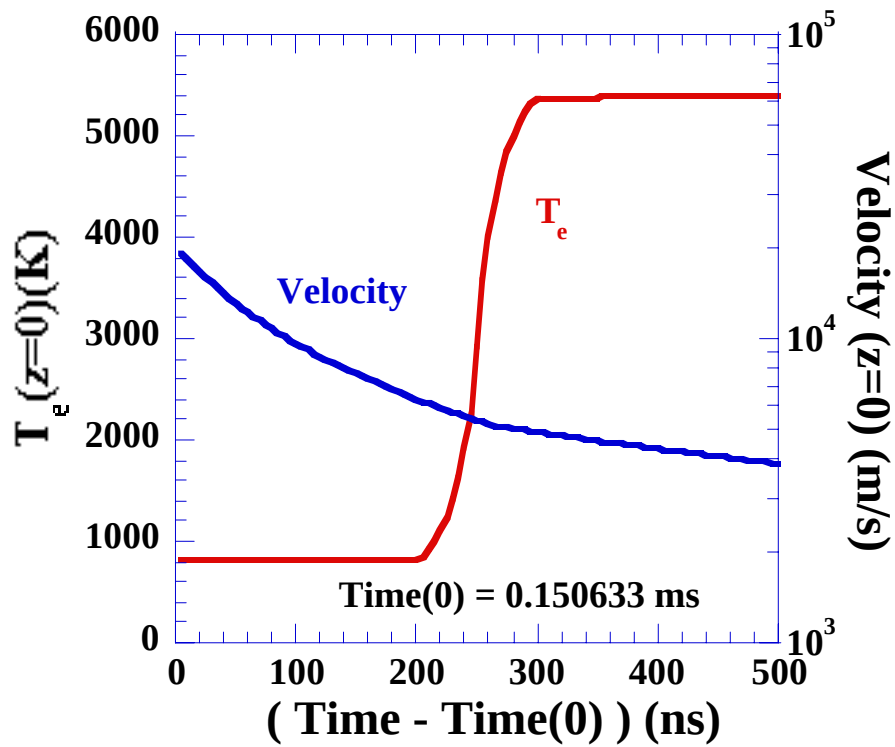

Growth of particles in the counter plume < 150 nm

Range of cluster in the counter plume < 6 cm

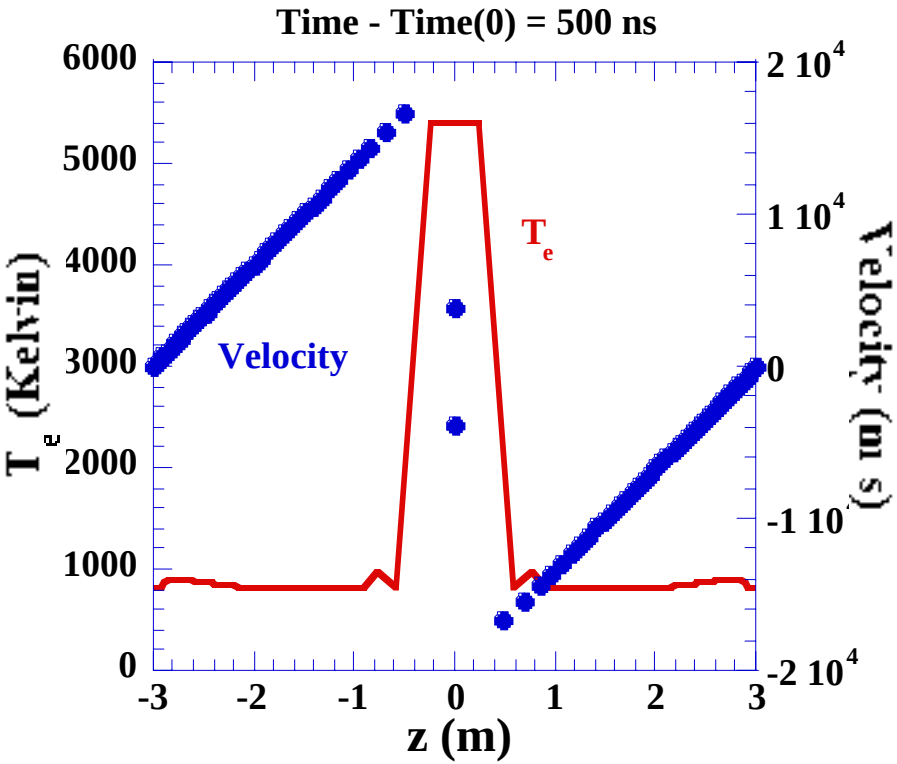
# When counter plumes collide at the center, the temperature becomes 5000K.

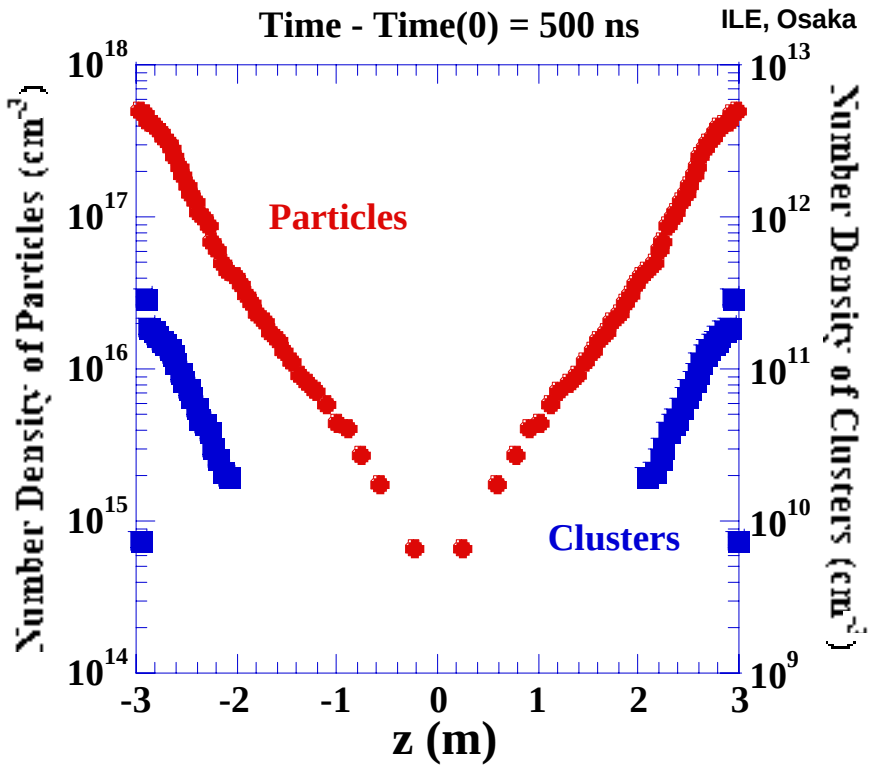




# After collision, clusters disappear due to heating by PdV work.

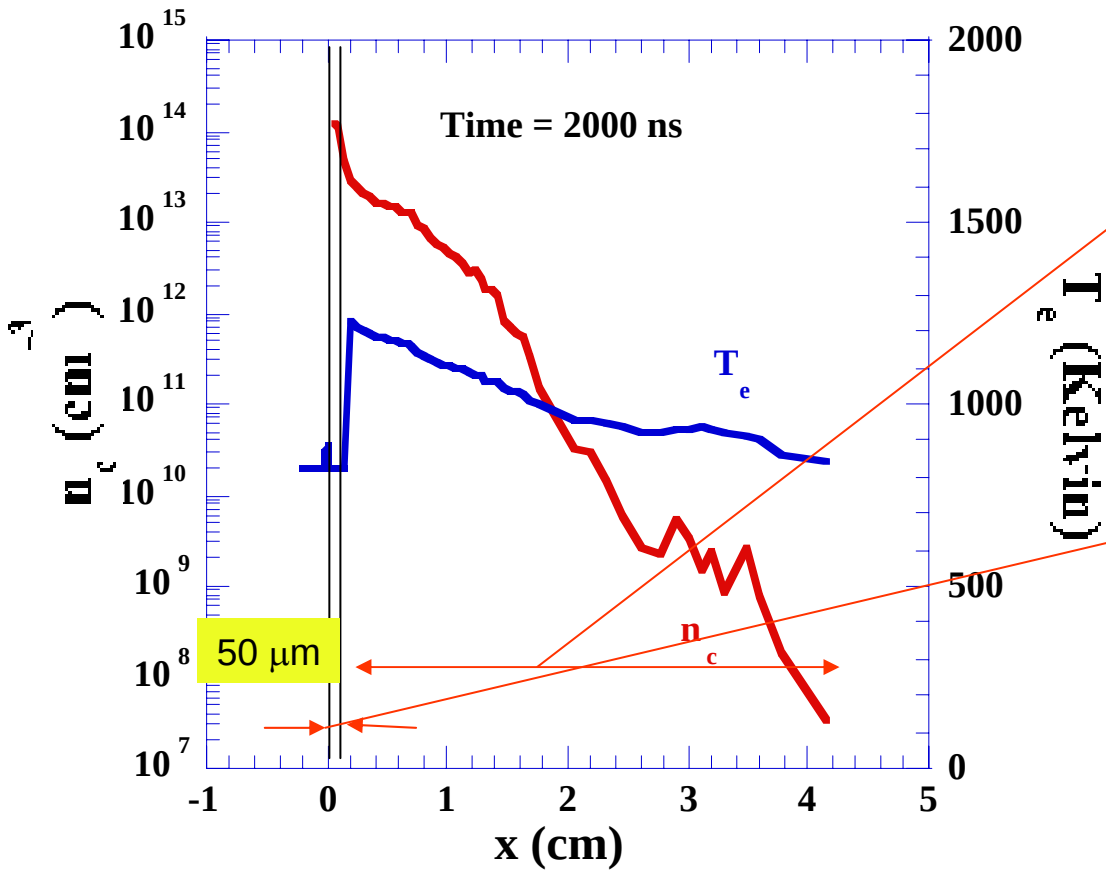



**Collision at the center makes hot, low density zone and clusters in the zone disappear due to evaporation.**
**We need not worry about condensation.**

# Number density at the next target injection is estimated to be $10^7/cm^3$.






If there is no interaction with counter plume, clusters in this region will disappear after collisions with the opposite wall.

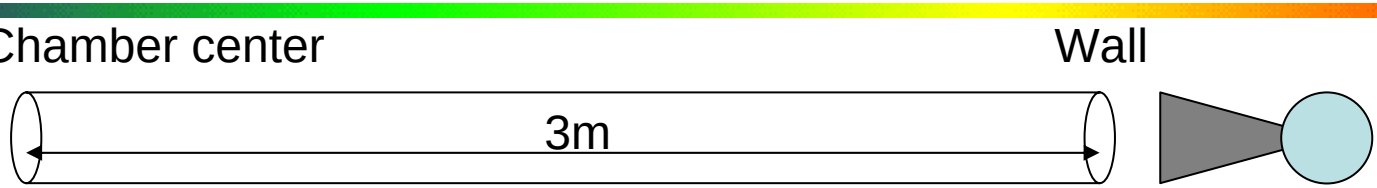
Clusters in this region expand to chamber volume before next target injection.

The resulting $n_c$ at the next target injection is;

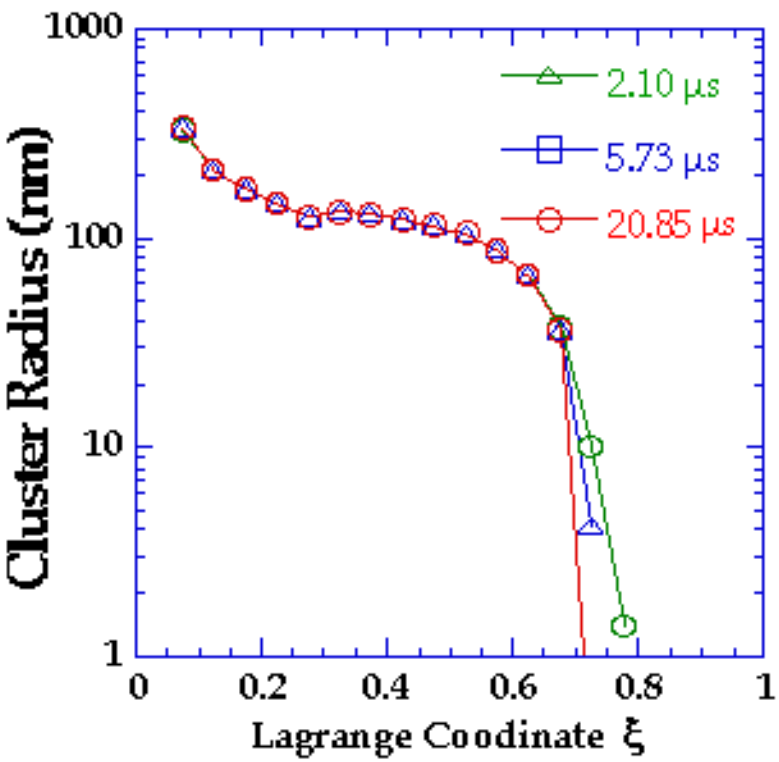
$8 \times 10^6 /cm^3$

# Influence of aerosols on target injection can be ignored.

ILE, Osaka




$N_c = 10^7$ /cm$^3$




**Total mass of aerosols in the column**

**$1.06 \times 10^{-4}$ g**

**(0.4 μm in the thickness of deposition layer)**

$$\frac{\text{Aerosol mass}}{\text{Target mass}} = 2 \times 10^{-4}$$

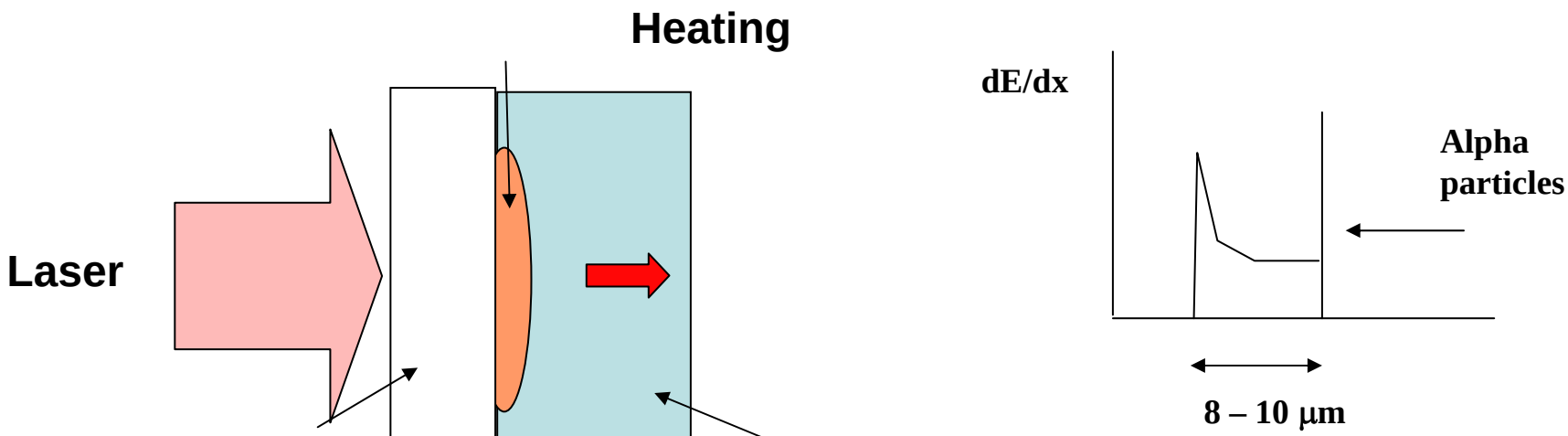
**We can ignore the influence on target trajectory.**

# Outline

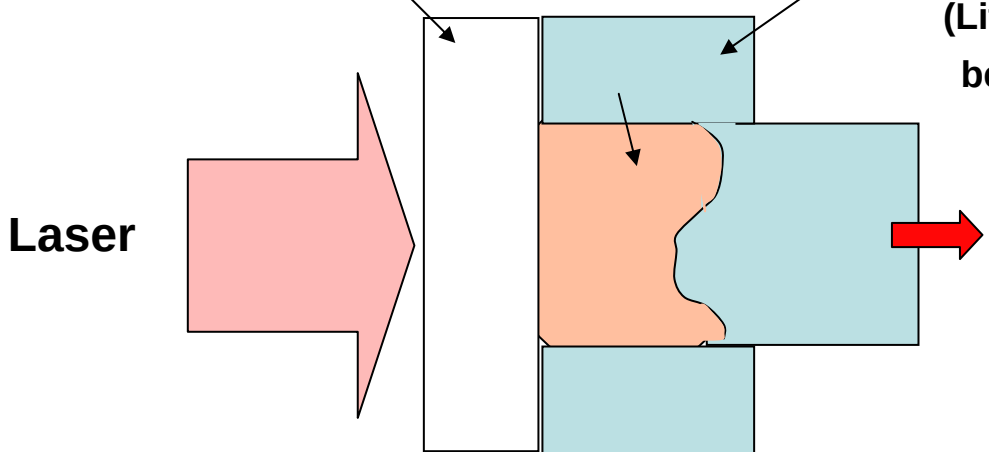


- Introduction of KOYO-F
- Critical issues of KOYO-F chamber and past achievements
- Aerosol formation
- Hydrodynamic view of ablation
- Summary

# Laser irradiation simulates for $\alpha$-particles heating from backside of metal layer

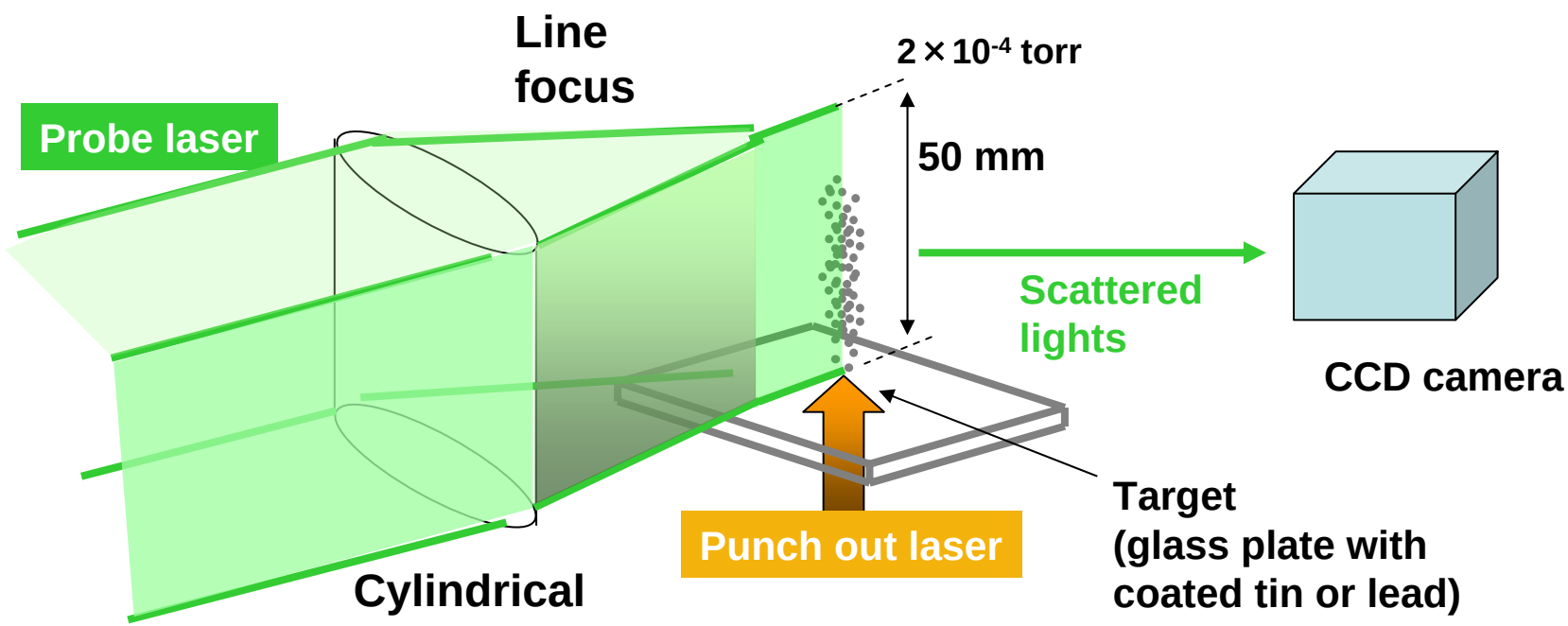



(Lithium was ignored because of light weight)

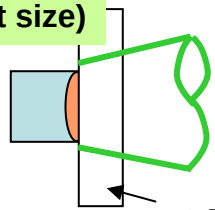



| | This experiment | KOYO-F |
|---|---|---|
| Energy density | 5 MJ/m$^2$ | 0.35 MJ/m$^2$ |
| Pulse width | 15 ns | 50 ns |

# Experimental setup. Laser-scattering measurement was used to observe flying situation of metal




Dot target
Diameter : $\phi$500 $\mu$m
(smaller than laser spot size)

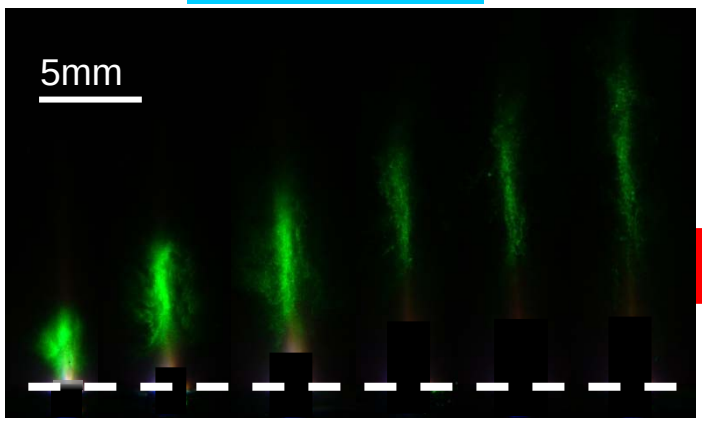



Intensity: 0.5 – 1 GW/cm$^2$
Spot size : 700 - 800 $\mu$m$^{\phi}$
Pulse duration : 15 ns

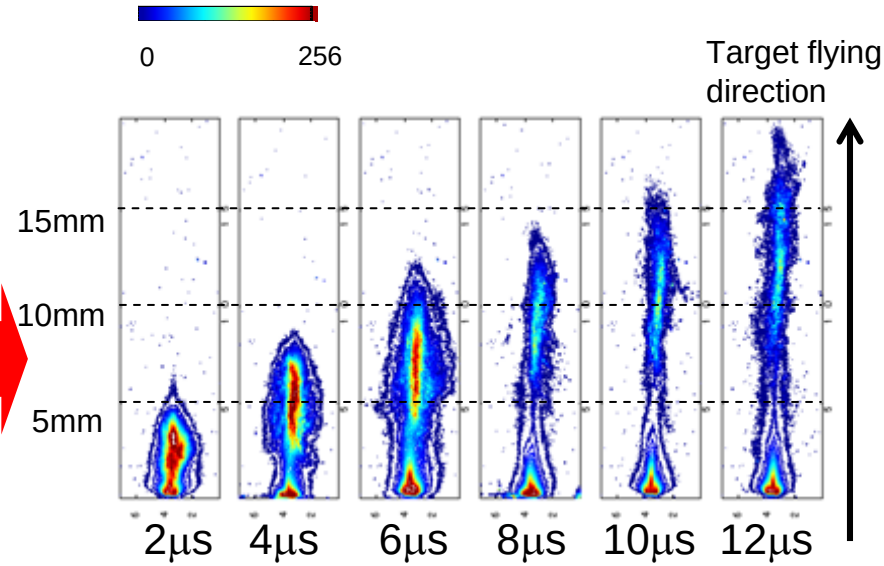
# Dot target propelled forward without large divergence angle

ILE, Osaka

**Dot tin 9μm**

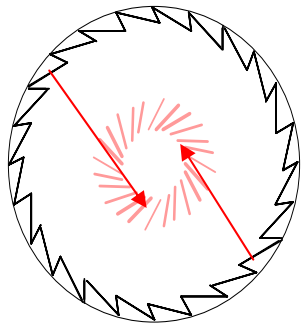



2μs 4μs 6μs 8μs 10μs 12μs




**Time resolution : 7.5 ns**

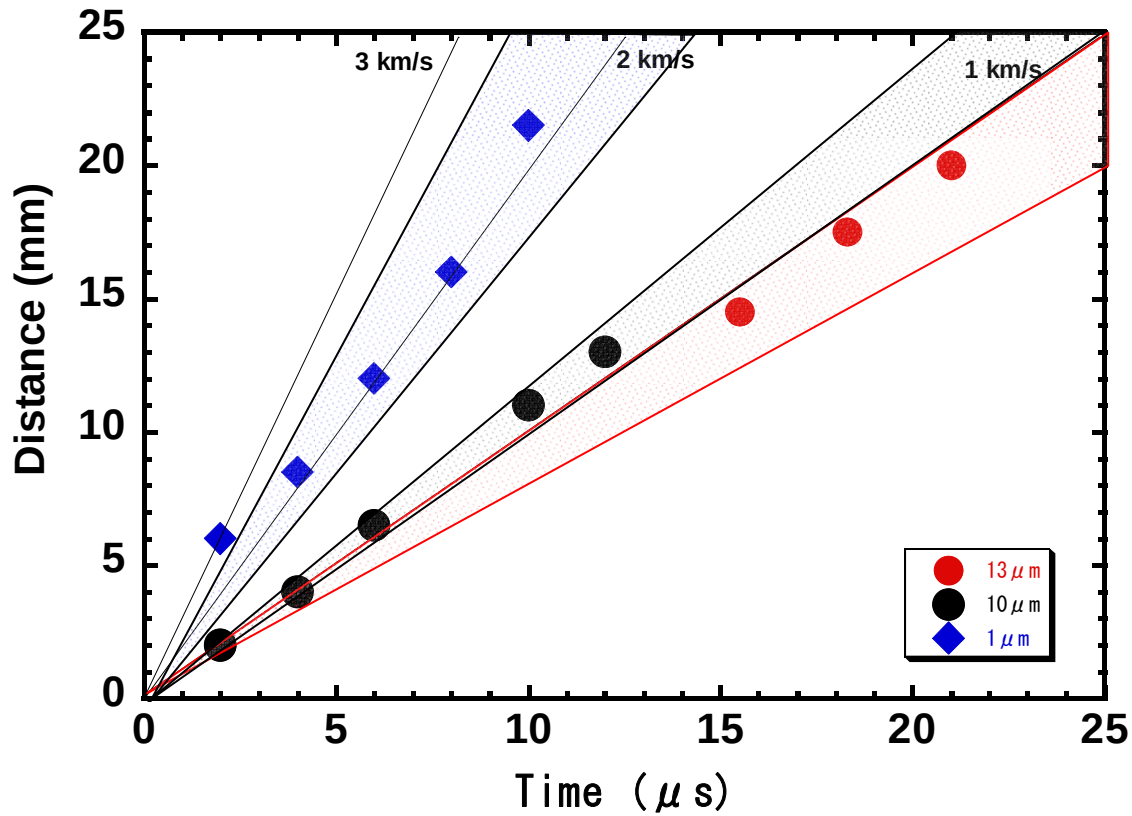
**Targets were propelled forward without large divergence angle**



This result indicates the tilted-front-panel concept works well.

# Velocities of mass center of tin particles were 1.0 ~ 1.5 km/s

ILE, Osaka




$$\frac{dP}{dt} = m\frac{dv}{dt}$$

**p ~ 0.8 kbar**

**@ 1km/s**

**(Similar to simulation)**

**1.0 ~ 1.5 km/s @ 10 μm thickness**

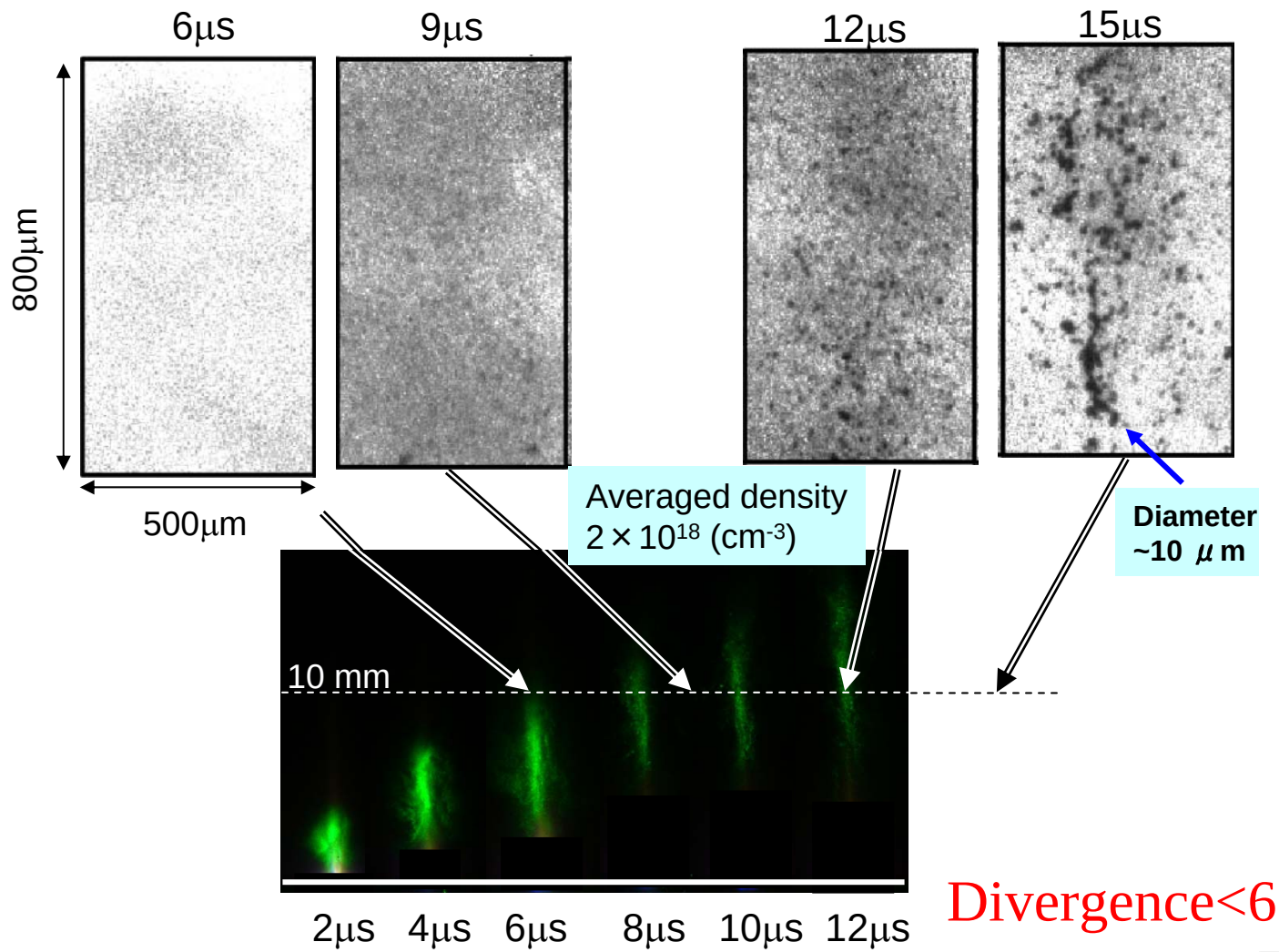
5MJ/m$^2$

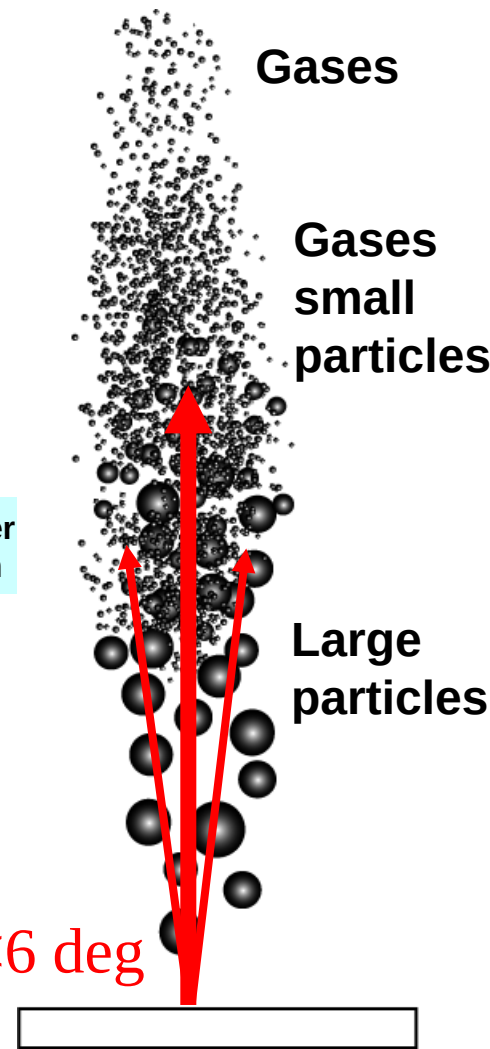
**250 ~400 m/s @ KOYO-F**

0.35 MJ/m$^2$

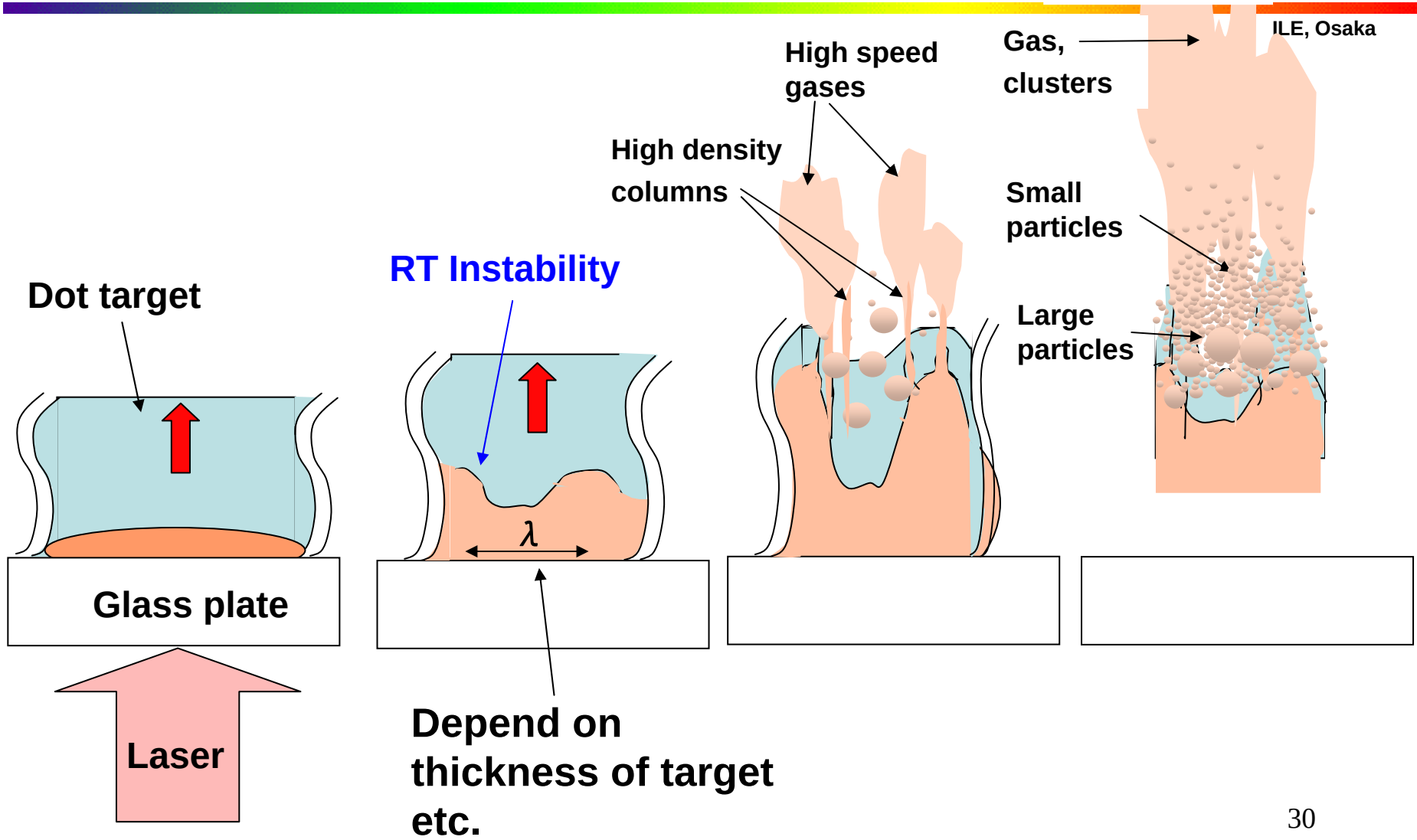
# Spouted gas and small particles, and large particles were detected at 10-mm away from glass plate

ILE, Osaka



# Laser irradiation induces RT instability and break up solid thin surface, generates gas clusters and large particles



# Summary

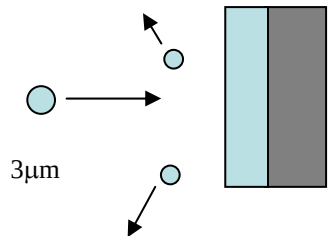


- The growth of clusters are calculated until the collisions of plumes at the center. The expected diameter is less than 150 nm.

- After collisions of plumes, the temperature becomes 5000K keeping the same density. Clusters vanish in this hot region. We need not worry about condensation of ablated materials at the stagnation point.

- Large diameter ( 3 μm) particles would be formed during ablation process.

- Remaining issue
  - Discussion on the secondary particles are necessary.



# Future works:
# What happens when small, high speed droplet collide with the surface?



1. Structure of stagnation point at the next laser shot.

2 Secondary particles

In research on milk crown, the height of crown depends on the depth of pool. (from H. Guji of Kyoto Univ.)

1mm 2mm 3mm 5mm 7mm 9mm

Collisions of droplets ( 3 μm) with a shallow liquid metal layer (10 μm) would happen on the ceiling of KOYO-F.

- *Thank you for your attention!*