長岡技術科学大学
Nagaoka University of Technology

# Activities for Heavy Ion Inertial Fusion & High Energy Density Science on Nagaoka University of Technology

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13th Japan-US Workshop on Heavy Ion Fusion and High Energy Density Physics
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Nagaoka University of Technology
PLASMA LABORATORY

# Changes of implosion dynamics derived by difference of equation-of-state

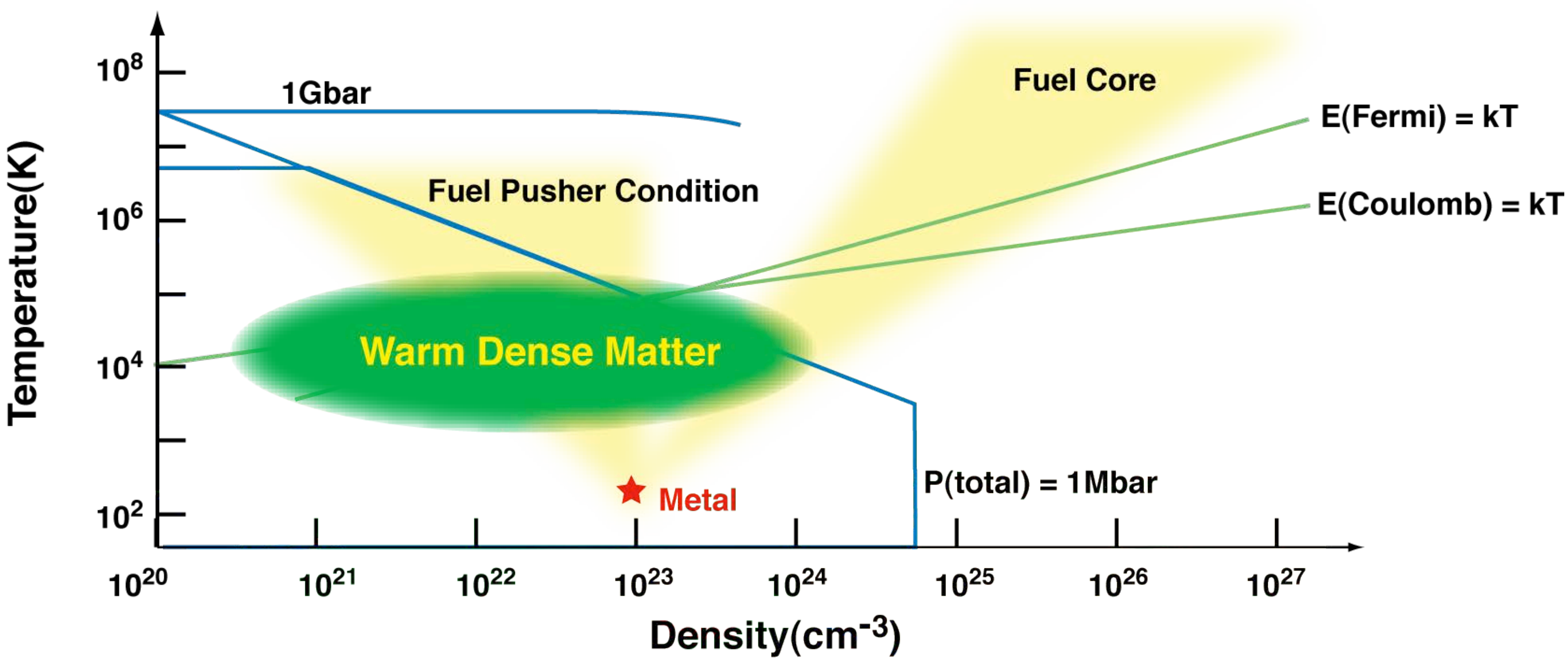
**Yu Komatsu, Toru Sasaki, Takashi Kikuchi, Nob. Harada, and Hideo Nagatomo***

**Nagaoka University of Technology**

***ILE, Osaka University**

# Introduction

- During the implosion process, the target material passes through a transition from solid to plasma
- Equation of state (EOS) should cover all these range



# Equation-Of-State models in ICF

- QEOS [1)]
  - Thomas-Fermi model for electrons
  - Cowan model for ions

  ⇒Easy to use of derivatives as Cvi, Cve, Cs, etc

- SESAME [2)]
  - Based on table of data ($\rho, T \Rightarrow P, E$)
  - Including theoretical models and fitting experimental data
  - Reliable EOS

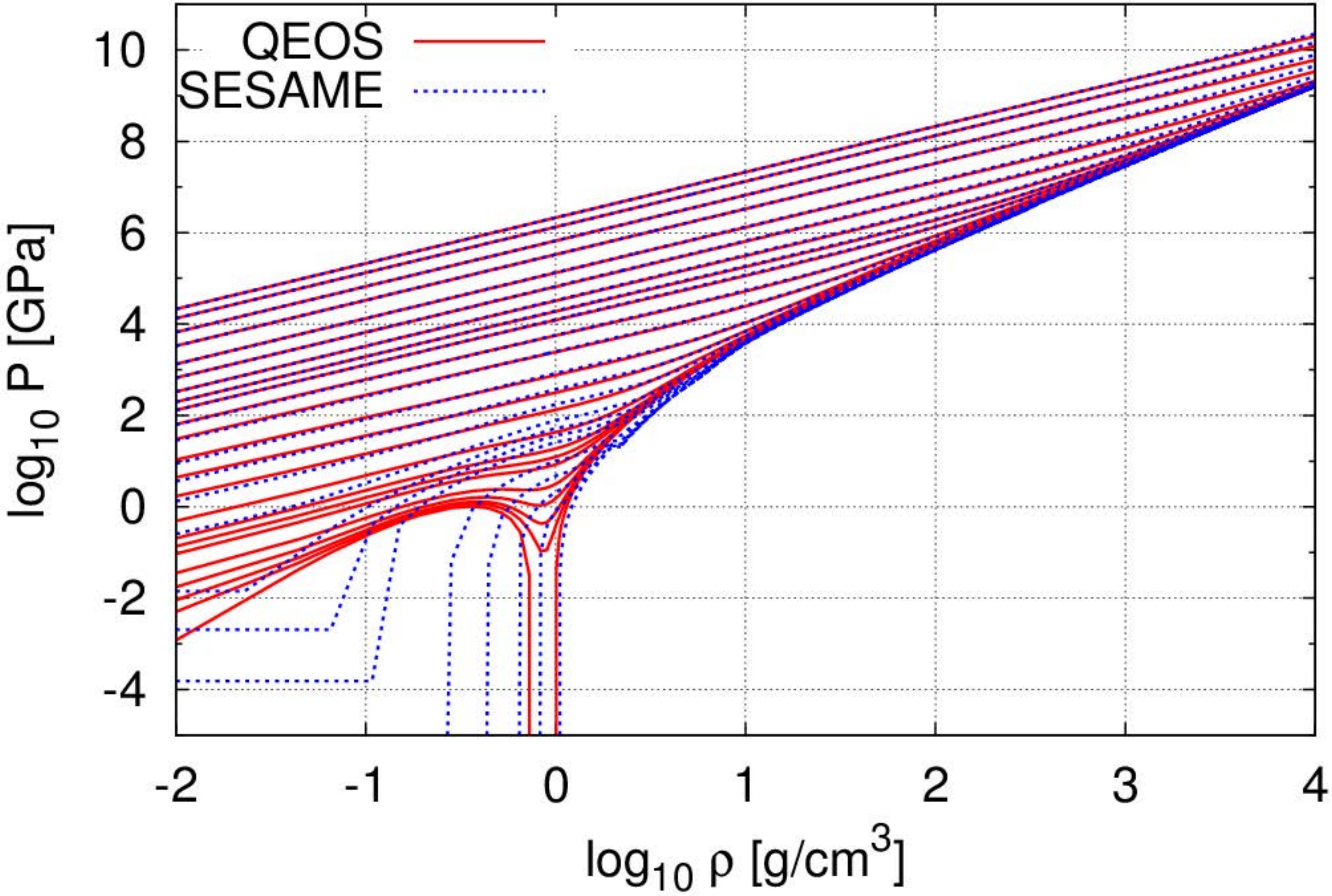
  However

  ⇒ Considering interpolation scheme

  ⇒ Inaccurate derivatives

1) R. M. More, et. al., Phys. Fluids 31, 3059 (1988)
2) S. P. Lyon, J. D. Johnson, Group T-1, LA-CP-98-100 (1988)

# Comparison between SESAME and QEOS pressure curves at constant temperature(CH)




Pressure difference near the solid density ⇒ Important for ICF?

# Purpose

- Difference of EOS models should be evaluated to affect the implosion dynamics of ICF

⇒ We compare the implosion dynamics for QEOS, SESAME, and ideal gas EOS by numerical simulations

# Computational code

## 2-D Radiation hydrodynamic code "PINOCO" 3)

3) H. Nagatomo, et al., Phys. Plasmas 14, 056303 (2007)

- 2 temperature model
  - Hydro ALE-CIP method
  - Thermal transport

    flux limited type, Spitzer-Härm
  - Radiation transport

    multi-group diffusion approximation

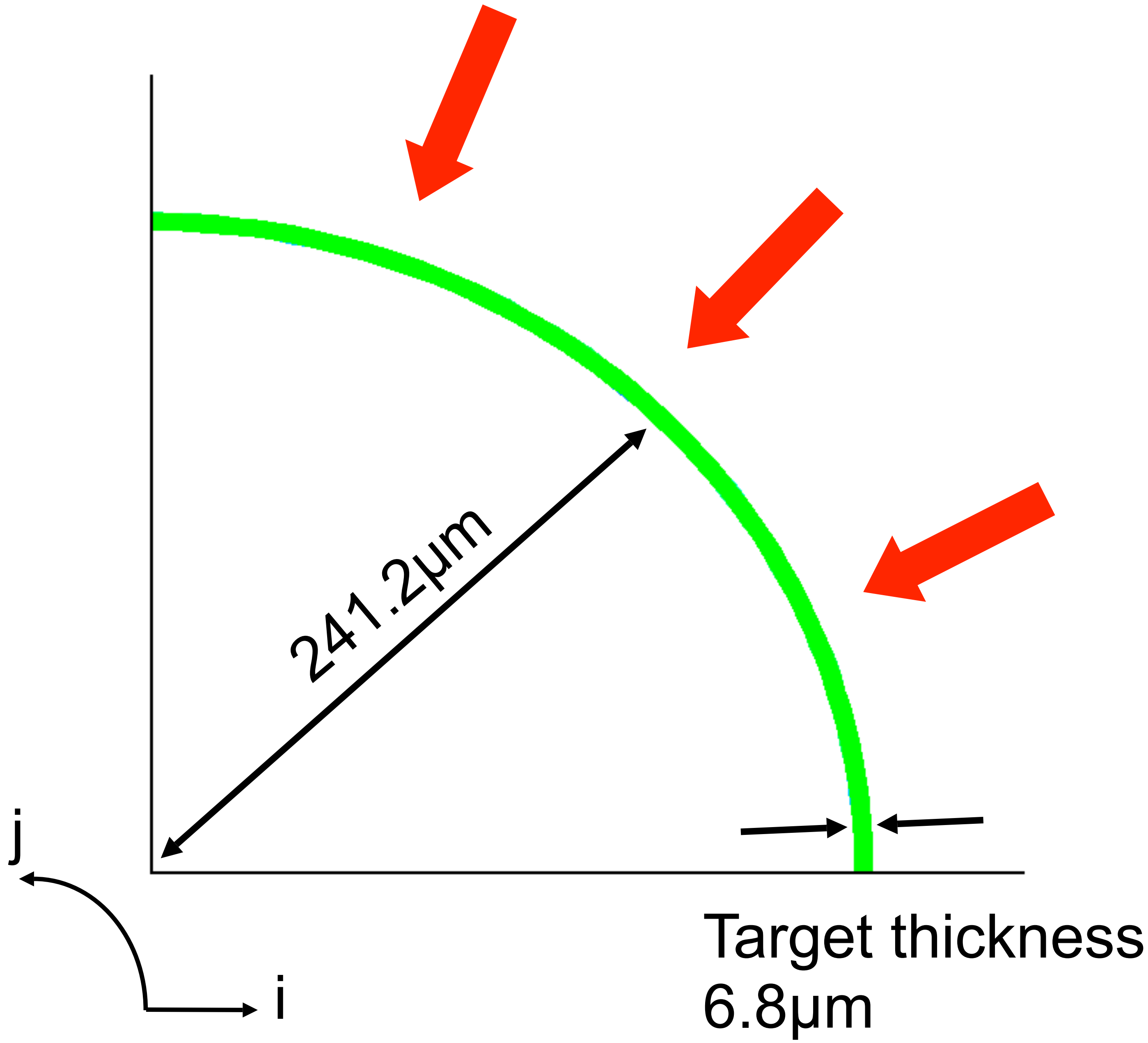
    Opacity, Emissivity (LTE, CRE)
  - Laser energy deposition

    1-D ray-trace
  - Equation of state

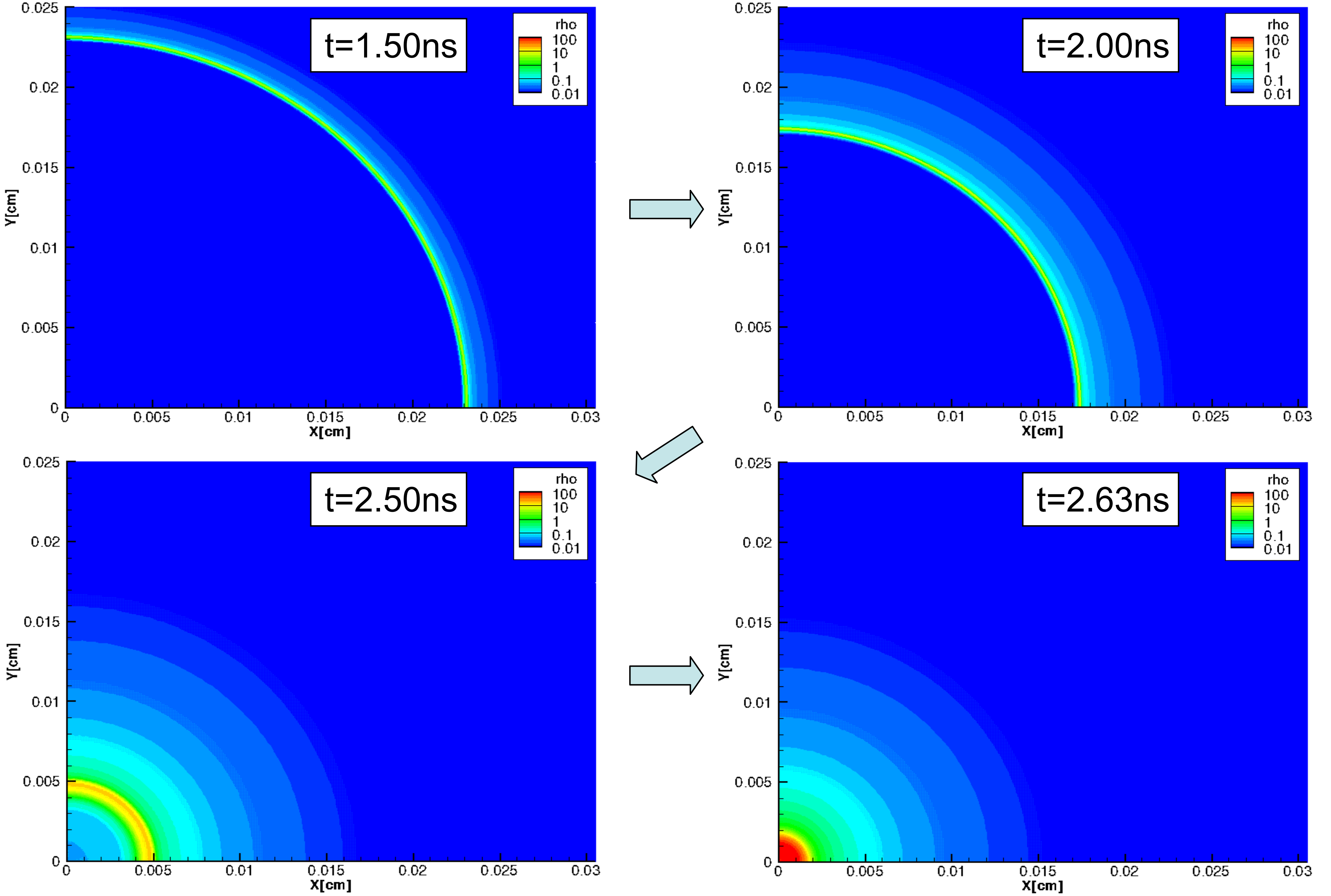
    QEOS, ideal gas, + SESAME

# Initial condition

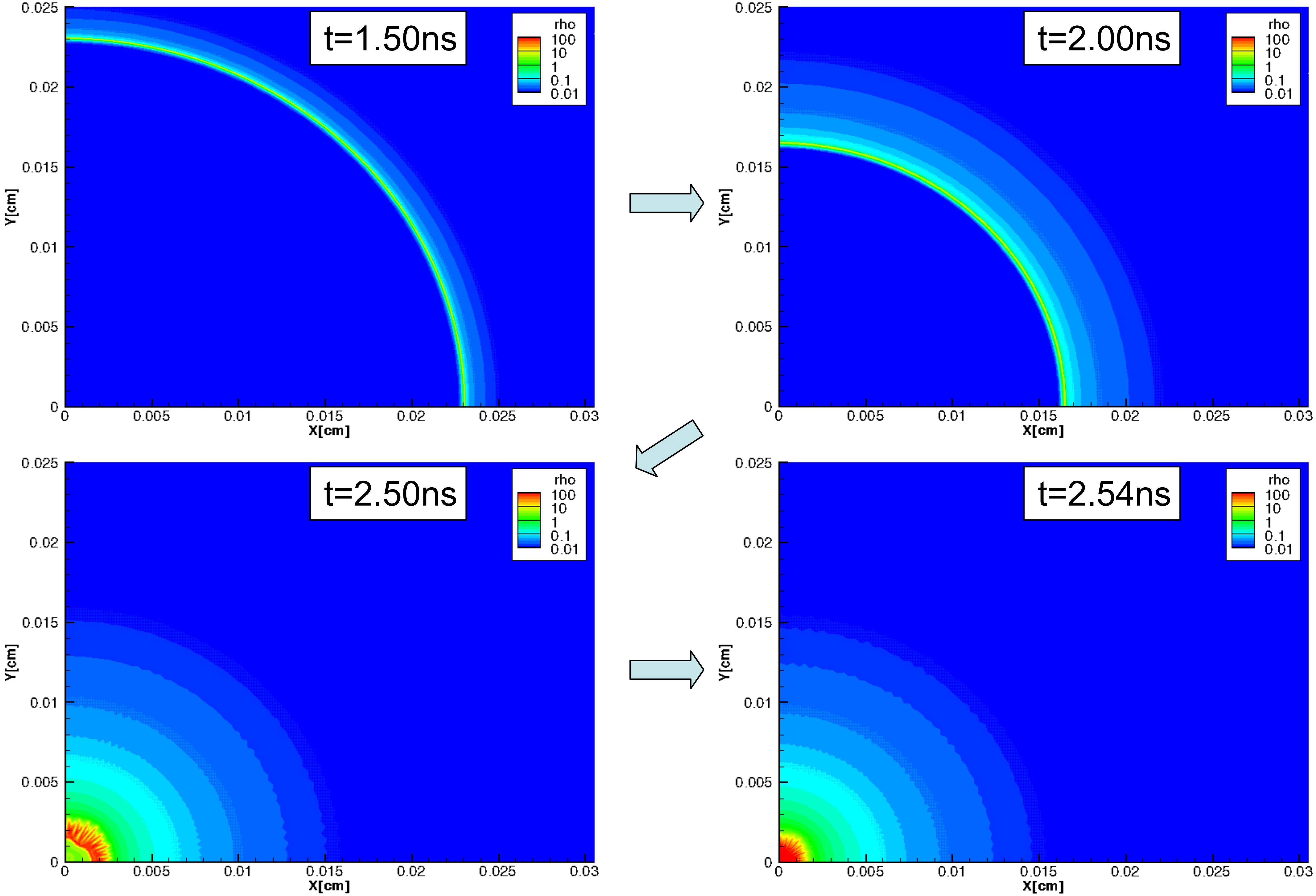
- Spherical target (CH)
- Radiation : off
- Initial density
  Background :$1x10^{-6}$g/cm$^3$
  Target :1g/cm$^3$
- Laser condition
  Energy : 2.0kJ
  Gaussian (0.5+0.5ns)
  Spatially-uniform irradiation
- Computational grids
  300 (i) x 61 (j)



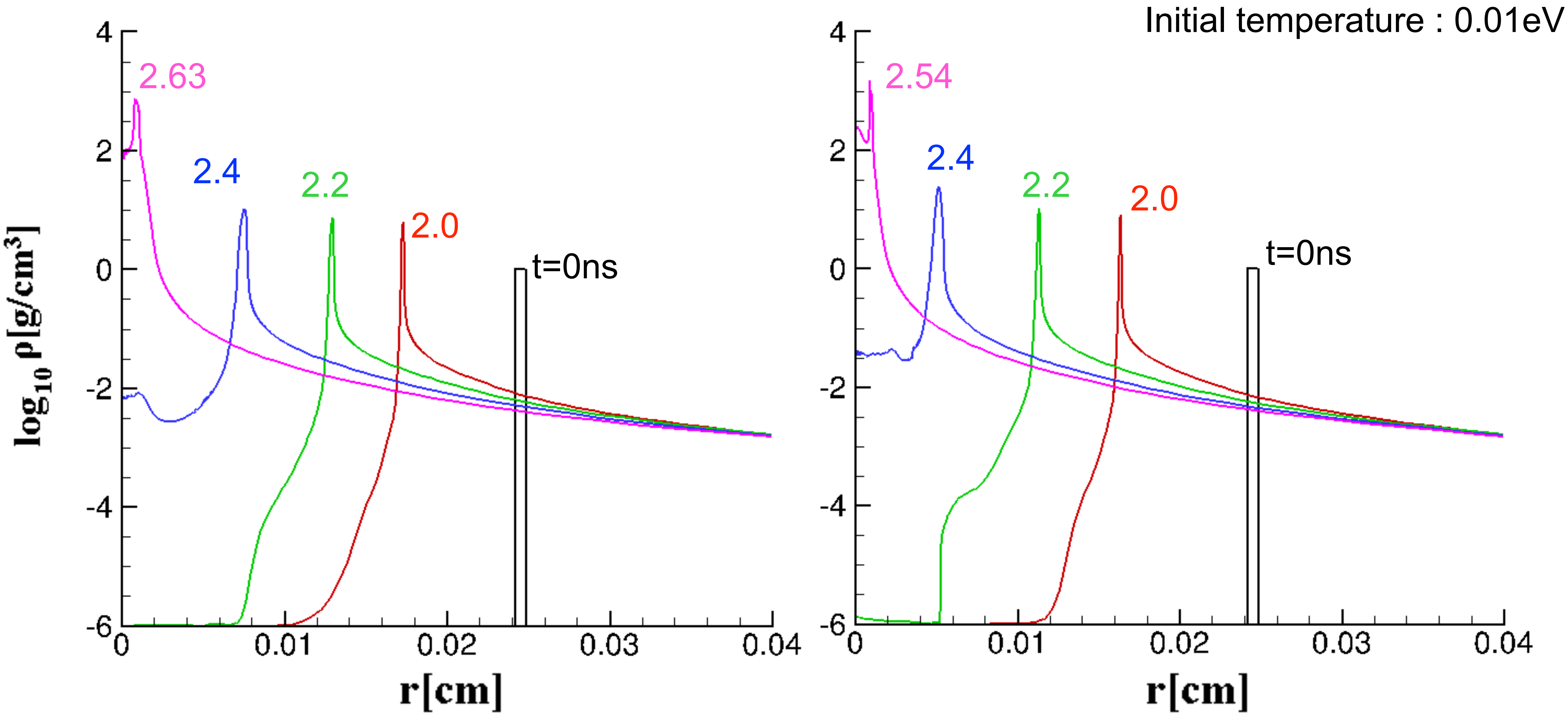
# Density profiles during implosion process (QEOS)



# Density profiles during implosion process (ideal gas EOS)



# Density profiles during implosion process (QEOS vs ideal gas EOS)




QEOS

Ideal gas EOS

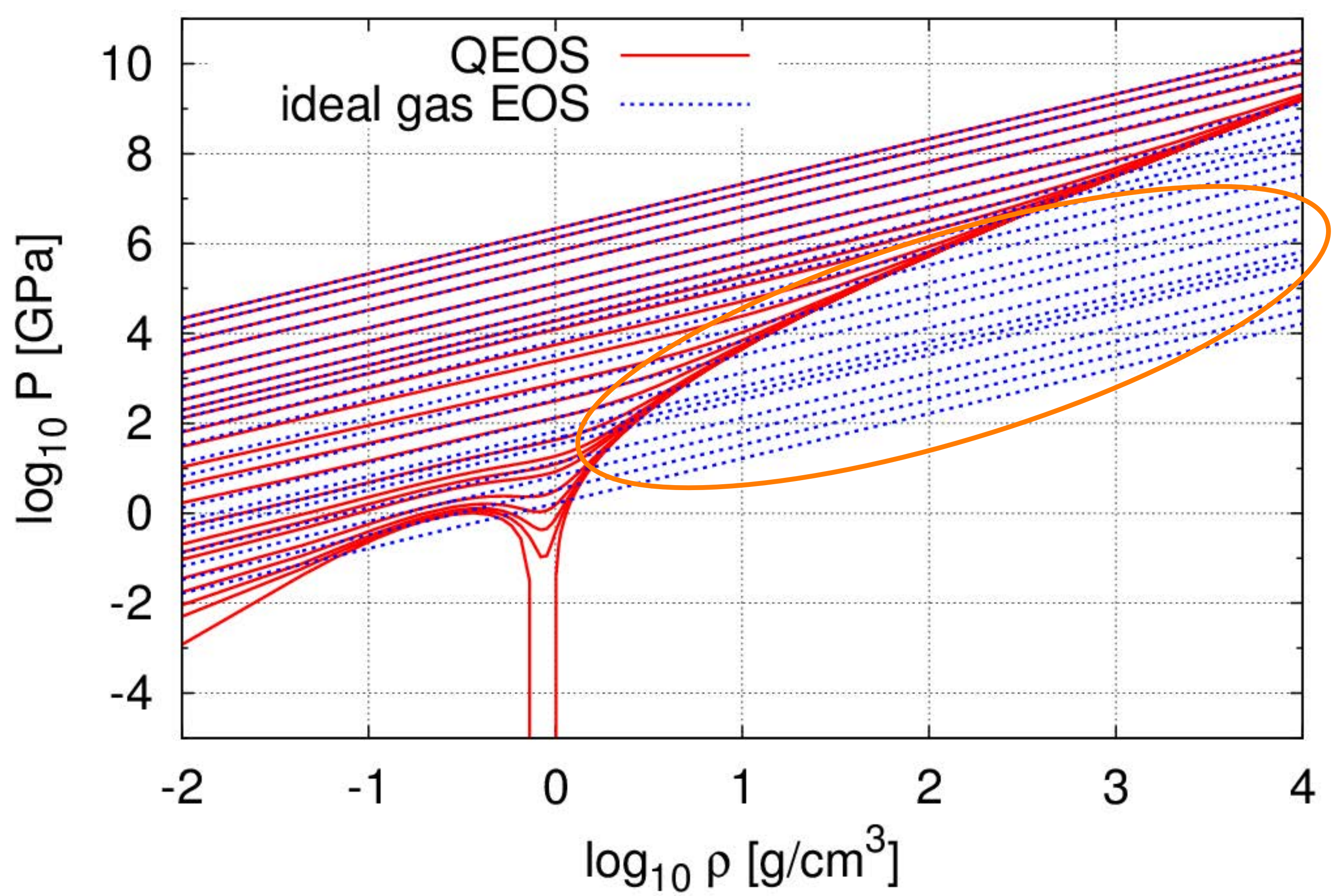
The maximum density for the ideal gas EOS is higher than that for the QEOS

# Comparison of implosion dynamics at the different EOS models

| | QEOS | Ideal gas EOS |
|---|---|---|
| Maximum density [g/cm$^3$] | 730 | 2140 |
| Time of maximum compression [ns] | 2.63 | 2.54 |

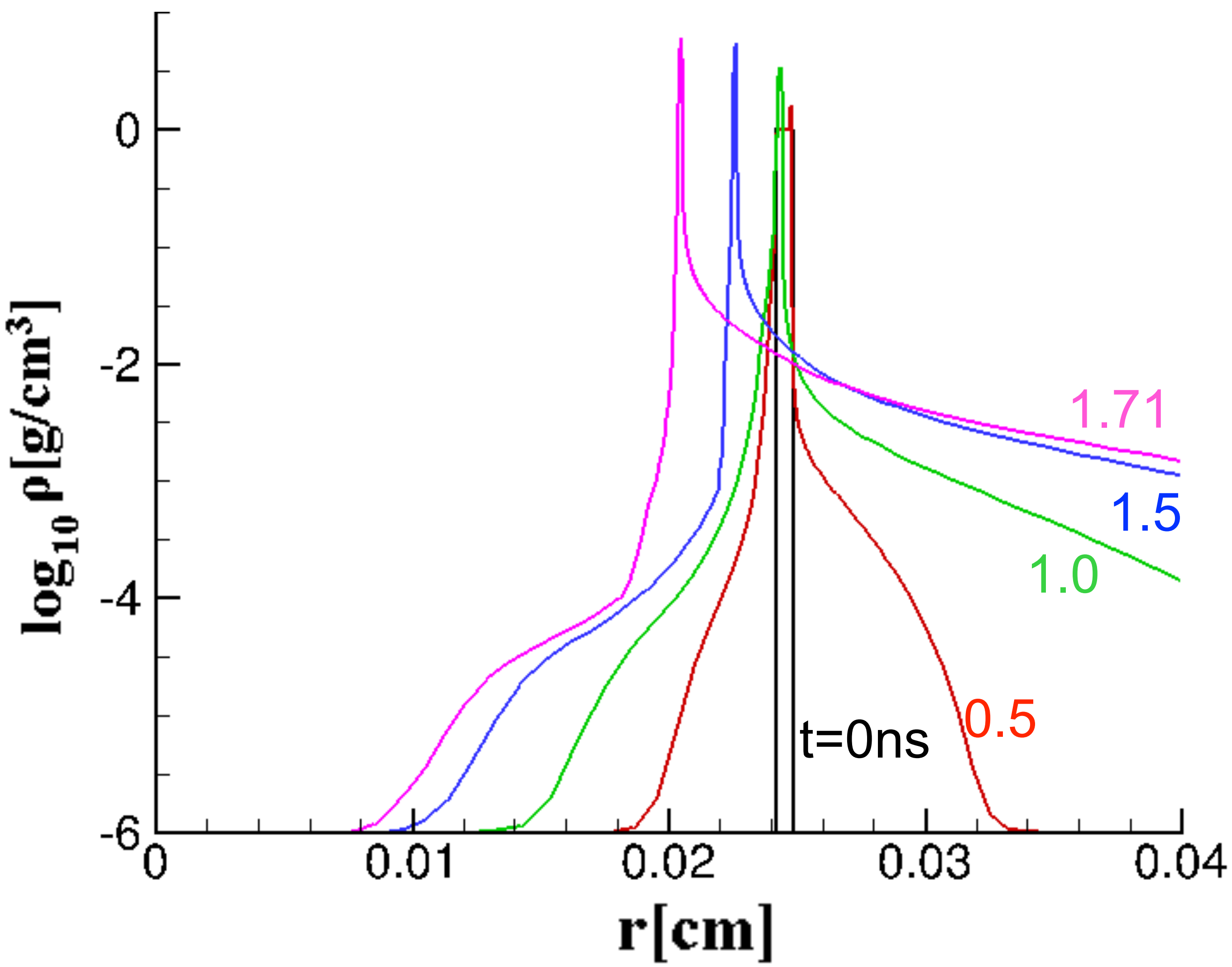
In high density, low temperature regime, $P_{QEOS} > P_{ideal}$

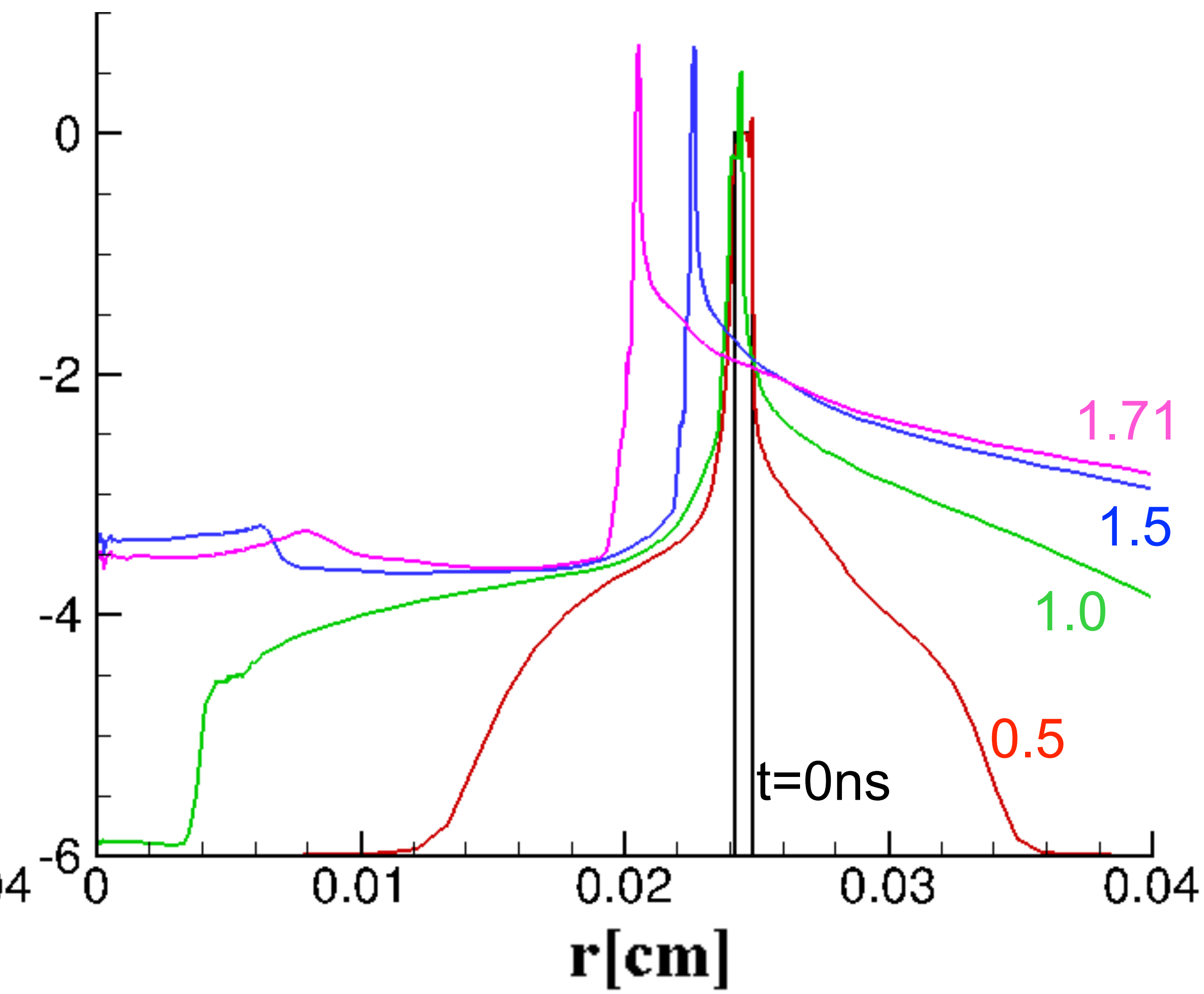
⇒The maximum density for the ideal gas EOS is higher than that for the QEOS



# Density profiles during implosion process (QEOS vs SESAME)

Initial temperature : 0.1eV



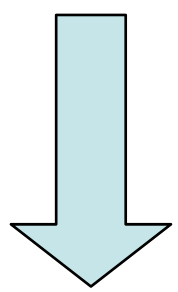

QEOS

SESAME

The difference of sound velocity affect to the implosion dynamics of interior of shell

# Conclusions

- Using numerical simulation by PINOCO, we investigated the implosion dynamics with the QEOS, ideal EOS , and SESAME
  - The maximum density for the ideal gas EOS is higher than that for the QEOS
  - The sound velocity of the SESAME is faster than that for the QEOS



Consider
・ion-ion coupling
・degenerated electrons
・phase transition etc…

Essential and easy to use EOS model

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- ☐ Bunch Compression Study by Compact Simulator
  *with K. Horioka @ TIT*
- ☐ Ion Beam Driven WDM/HEDP Experiment Project in KEK-DA
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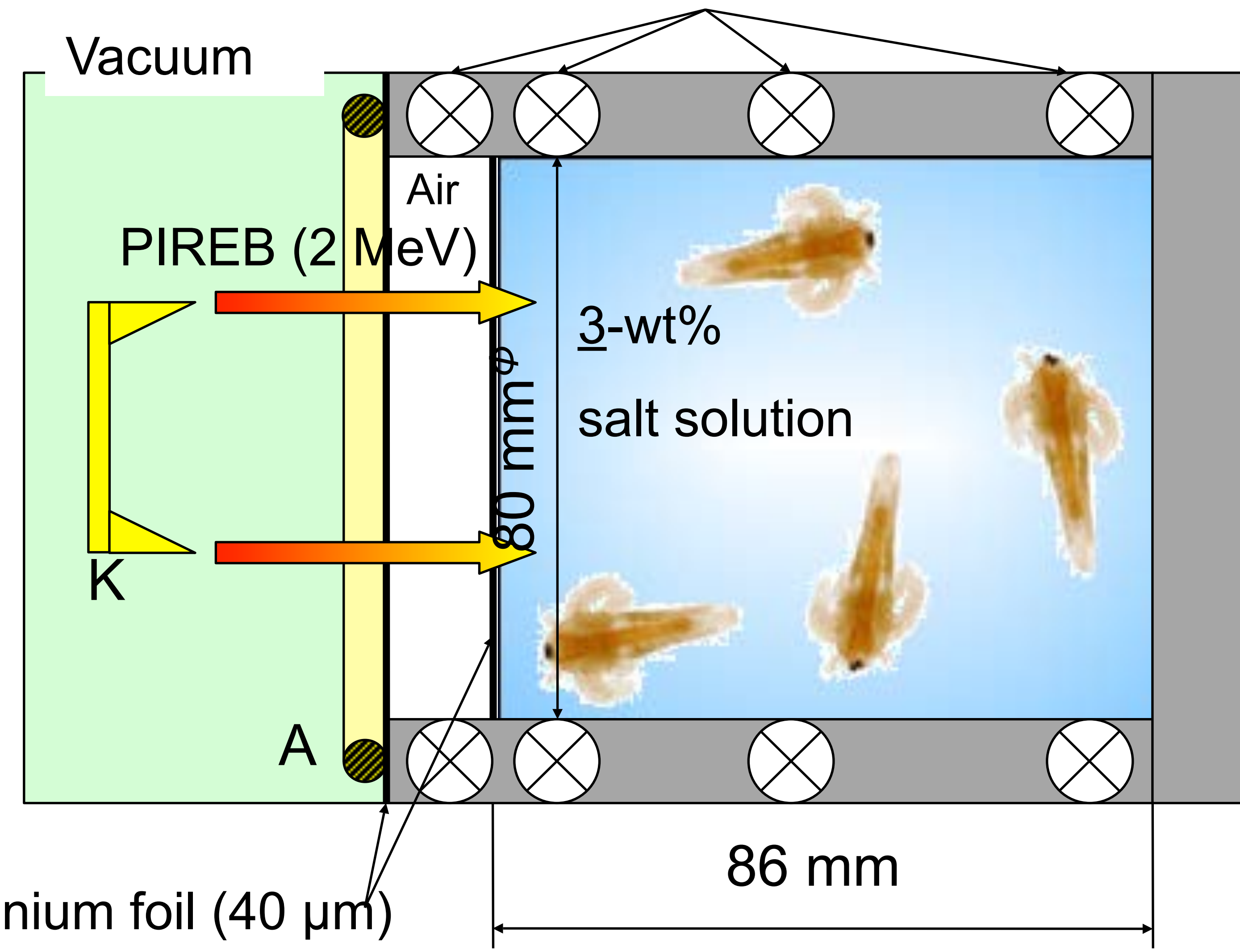
  *in NUT*

# Experimental apparatus


PIREB generator “ETIGO-Ⅲ”

in EDI@NUT

Induction Accelerator

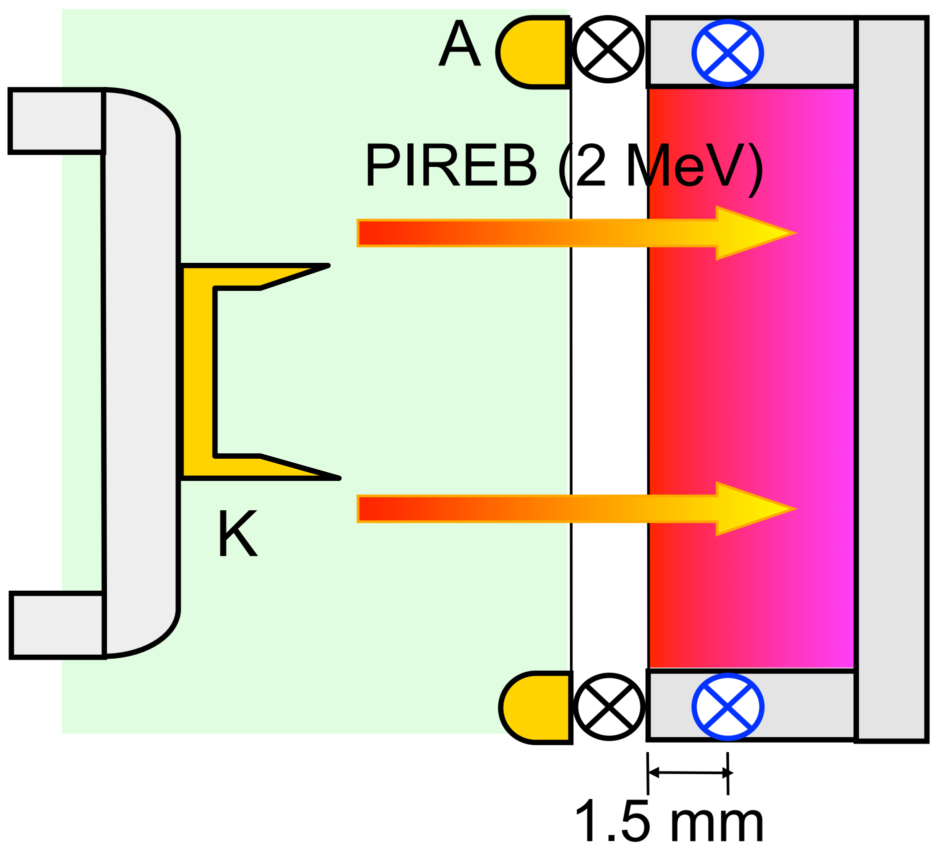



- Artemia larvae as zooplankton and 3-wt% salt solution are contained in the chamber, and 2 MeV of PIREB generated by “ETIGO-III” are irradiated. Artemia larvae are inactivated.
- → Ballast Water Problem for Maritime Environment Preservation

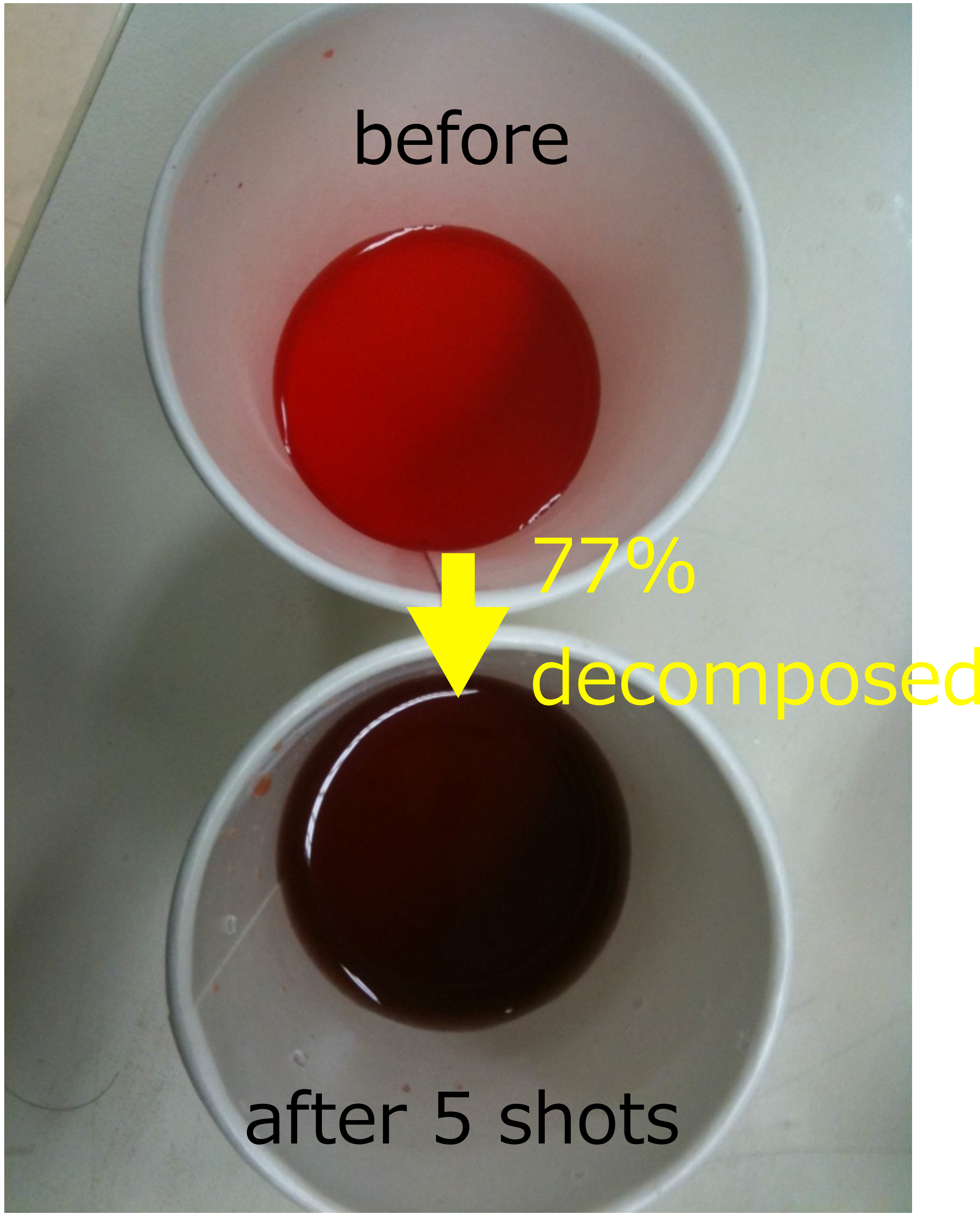
H. Kondo, H. Takehara, T. Kikuchi, T. Sasaki, G. Imada, Nob. Harada, Plasma Fusion Res. 5, 036 (2010).

# PIREB Irradiation to Congo Red Solution

The reaction of congo red, a well-known toxic azo dye, occurred after irradiation by a pulsed intense relativistic electron beam (PIREB).




An aquation of congo red was irradiated by PIREB (2MeV, 0.36kA, 140ns).




T. Kikuchi, H. Moriwaki, H. Nakanishi, H. Kondo, T. Sasaki, G. Imada, Nob. Harada, Plasma Fusion Res. 6, 1206021 (2011).

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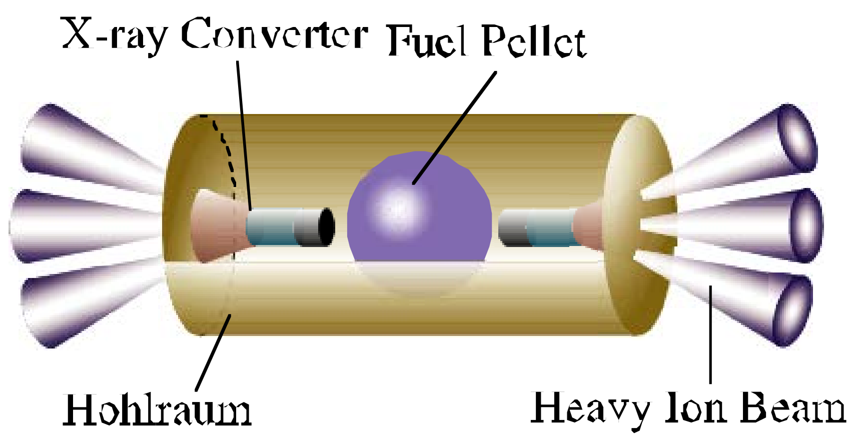
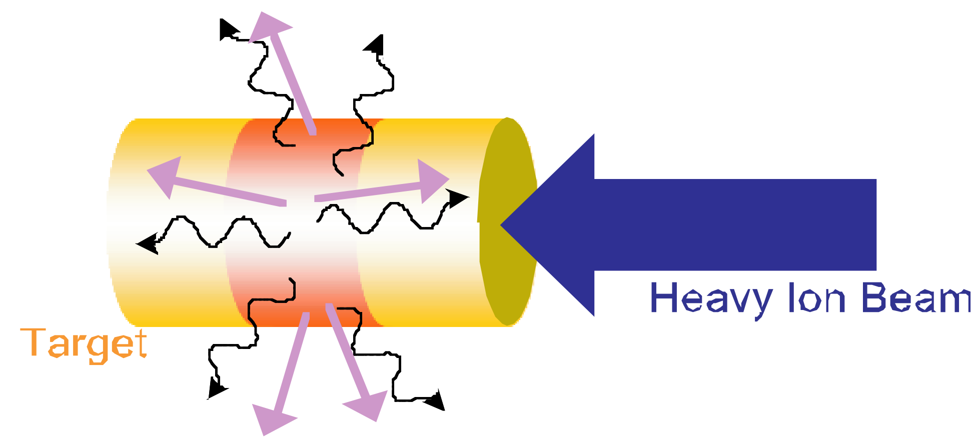
  *in NUT*

# Particle Beam for HIF & HEDP, WDM Applications

For HIF & Ion Beam Driven HEDP, WDM researches




→ HED Plasma Generation by High Power Beam Illumination

Power = Kinetic Energy x Beam Current

High Energy Particle → Broad Energy Deposition

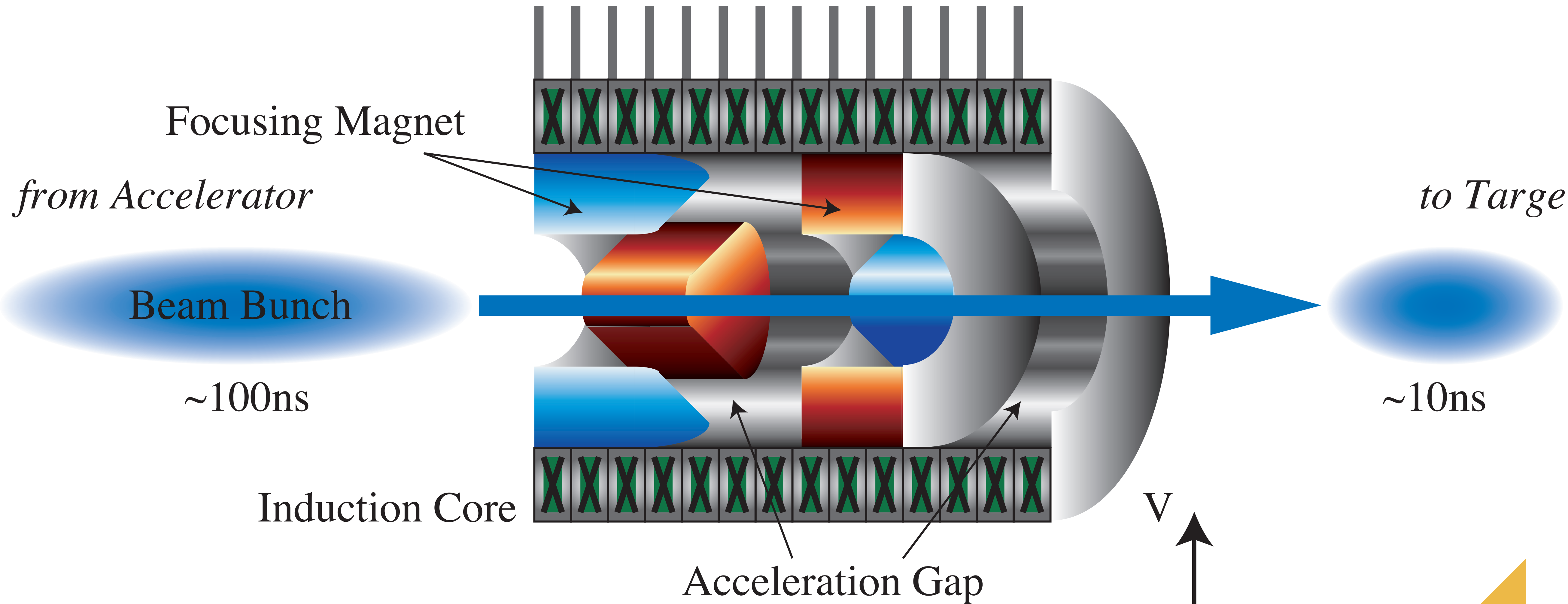
→ High Current Beam

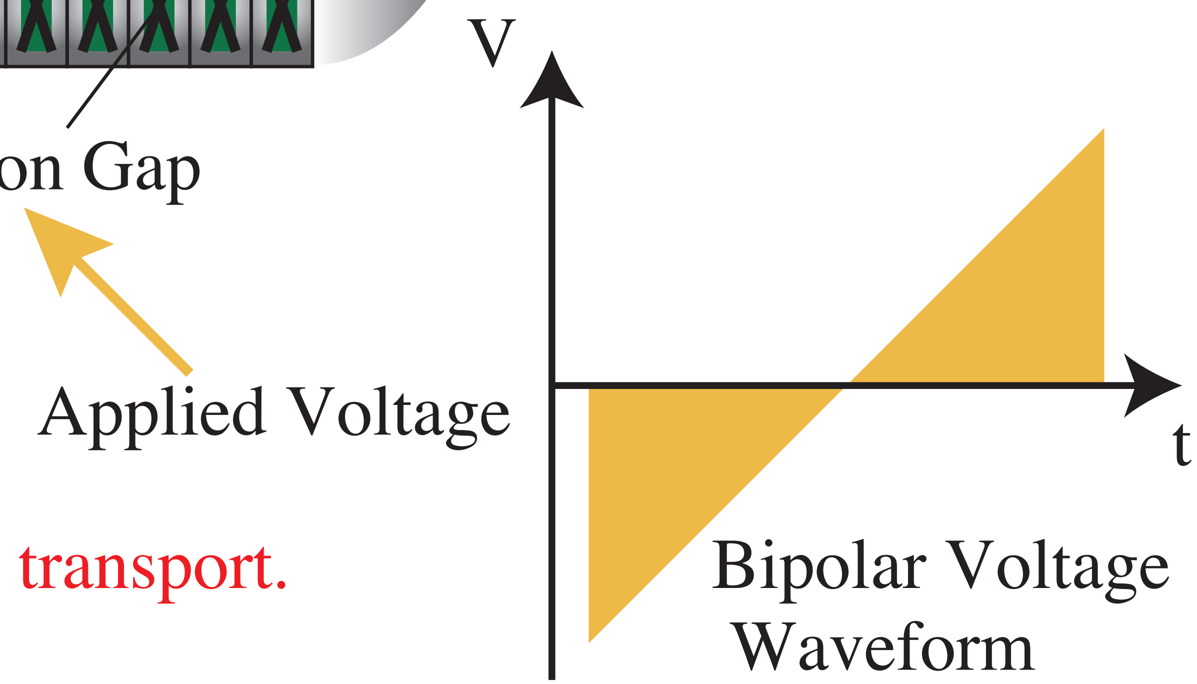
↓

Space-Charge-Dominated Beam Physics

# Bunch Compression using Induction Modulator

Induction buncher consists of periodic lattice




- Head & Tail Velocity Tilt is applied in Induction Buncher.

Beam Bunch becomes Short Pulse during transport.

# Purpose

Bunch Compression is key issue for effective heavy ion inertial fusion energy

- final compression ratio
- beam quality (emittance)
- pulse shape control

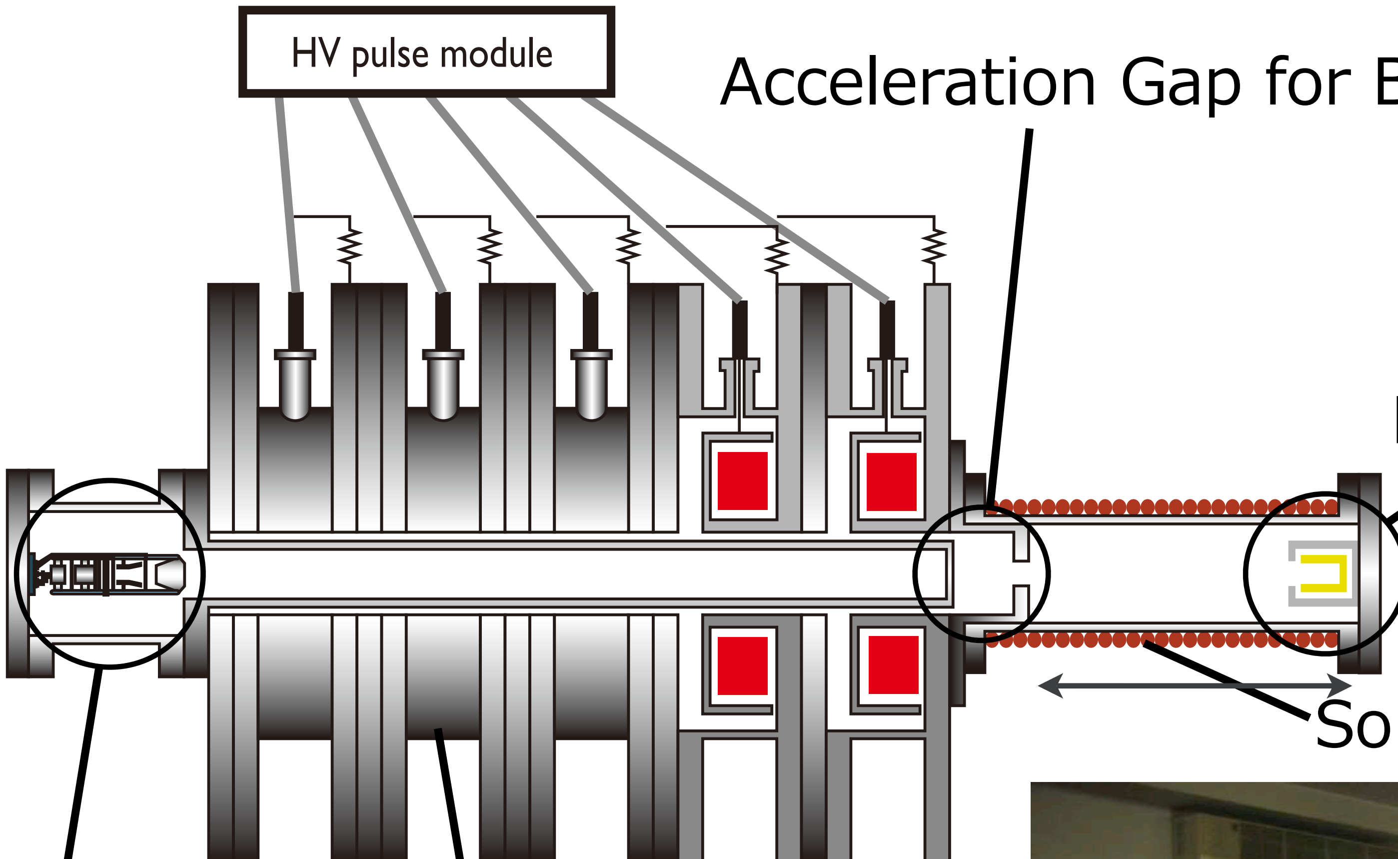
<u>Using Compact Simulator by Electron Beam</u>

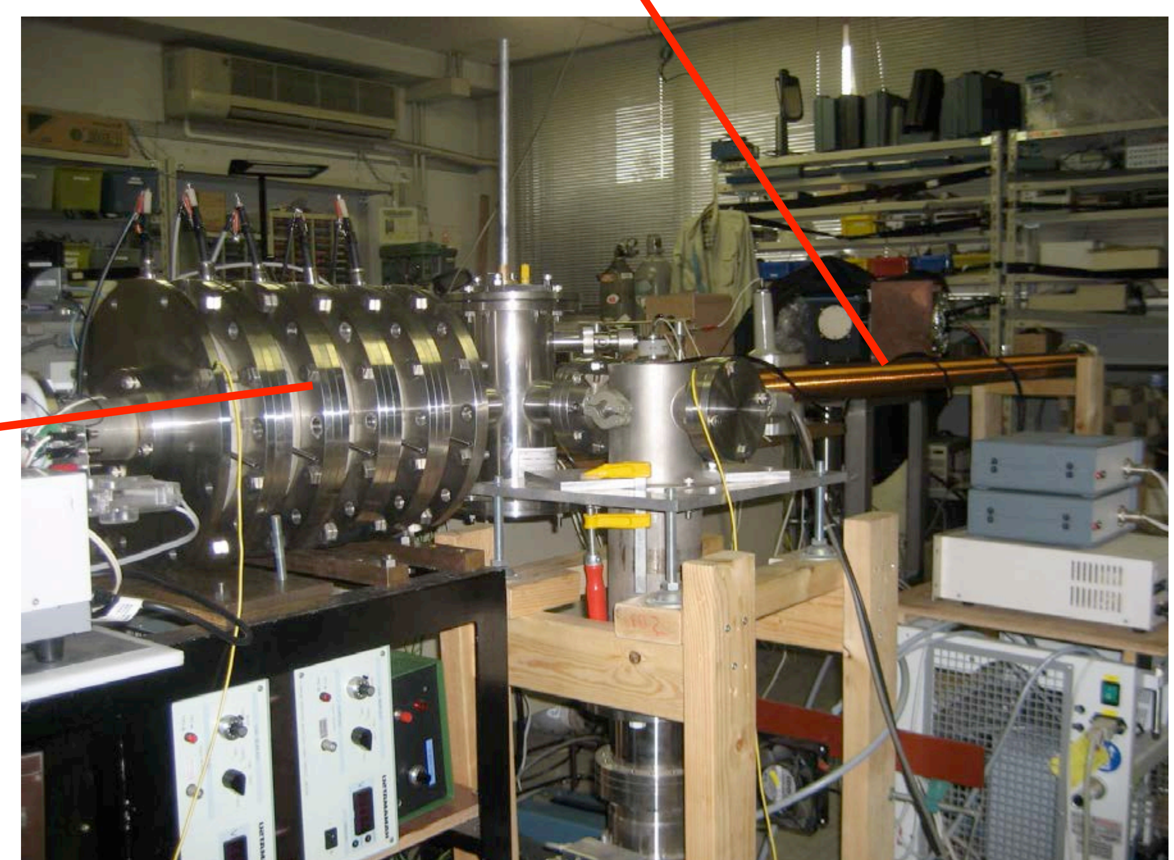
## Beam Dynamics Analysis in Extreme Pulse Compression using Electron Beam Compact Simulator

Research Topics: Key violation issues for extreme pulse compression

- applied voltage errors
- space charge effect
- thermal effect
- mismatch transport
- finite gap length

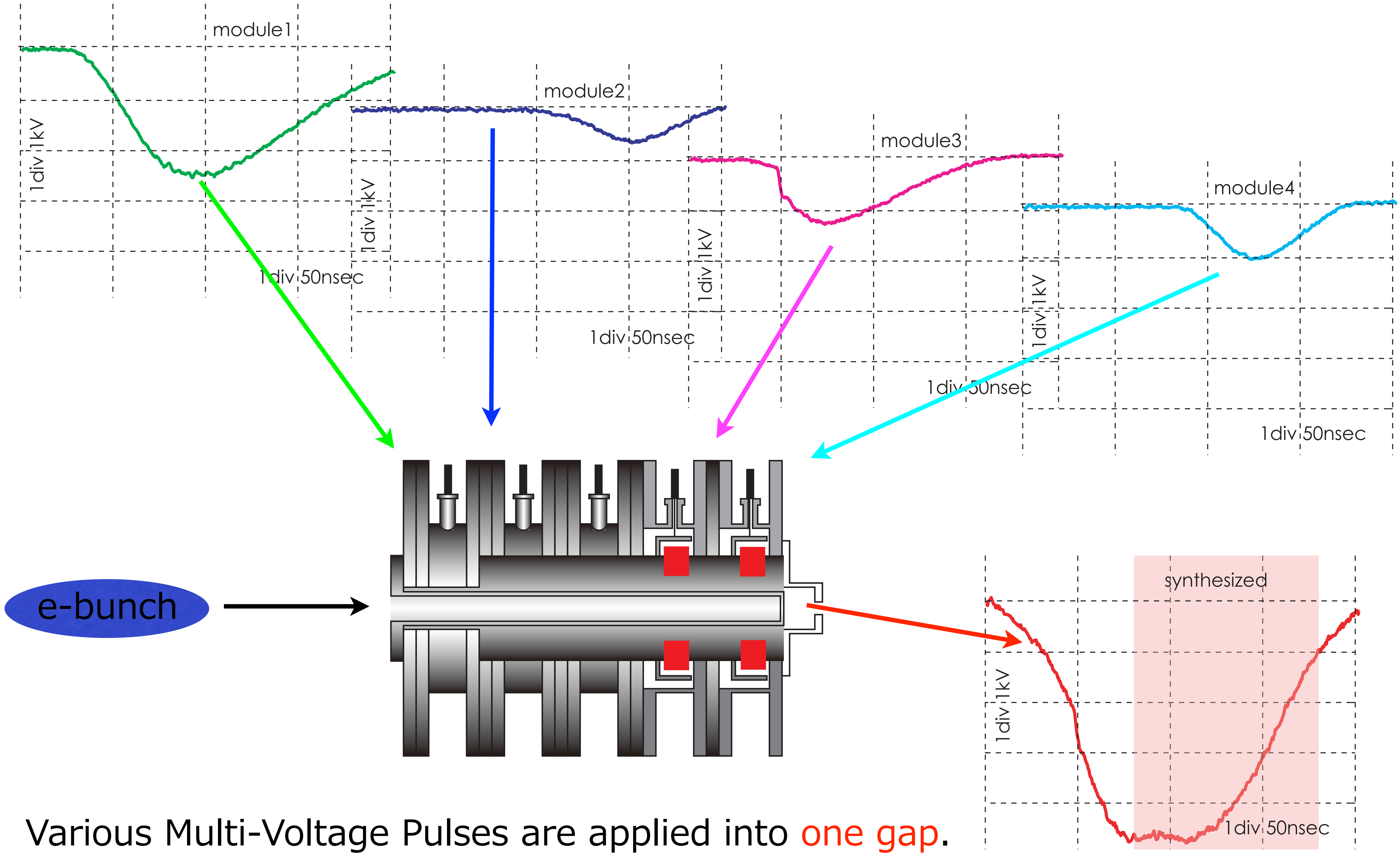
# Experimental Arrangement in Tokyo Tech.



*courtesy of K. Horioka@Tokyo Tech.*

# Multi-Pulse -> 1 Gap

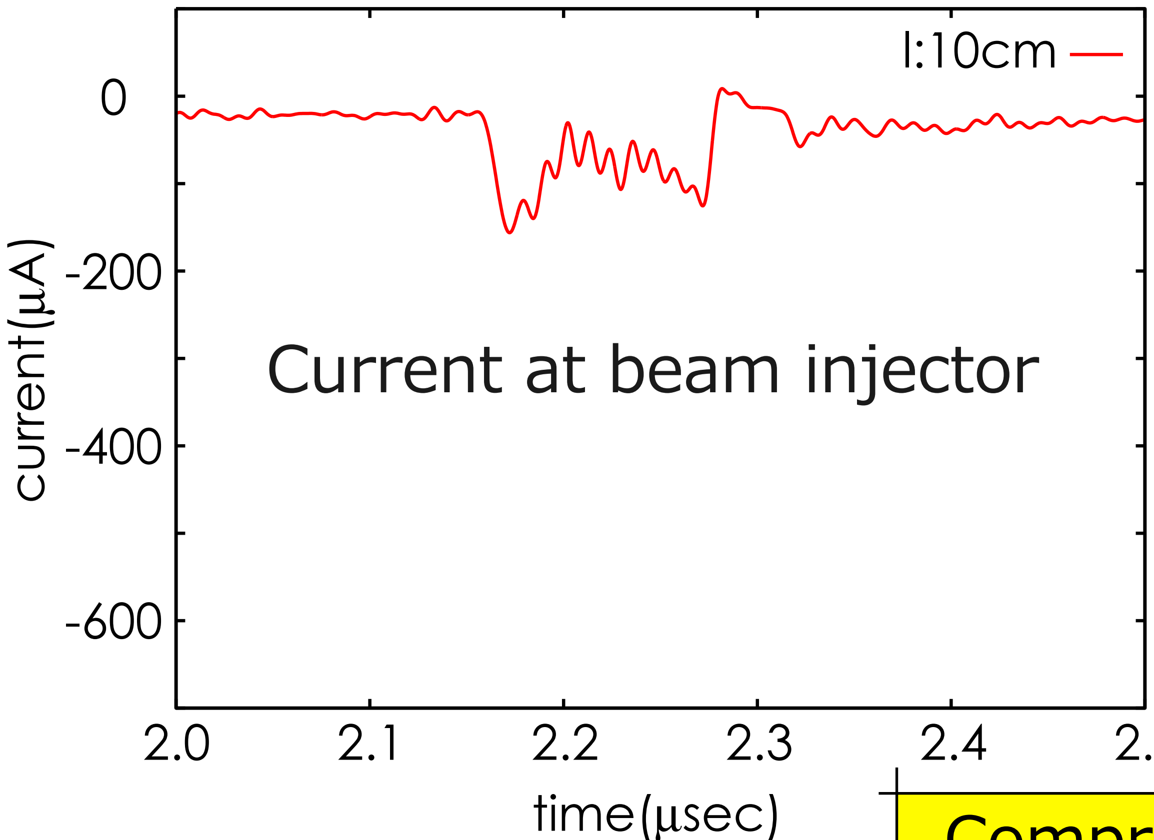


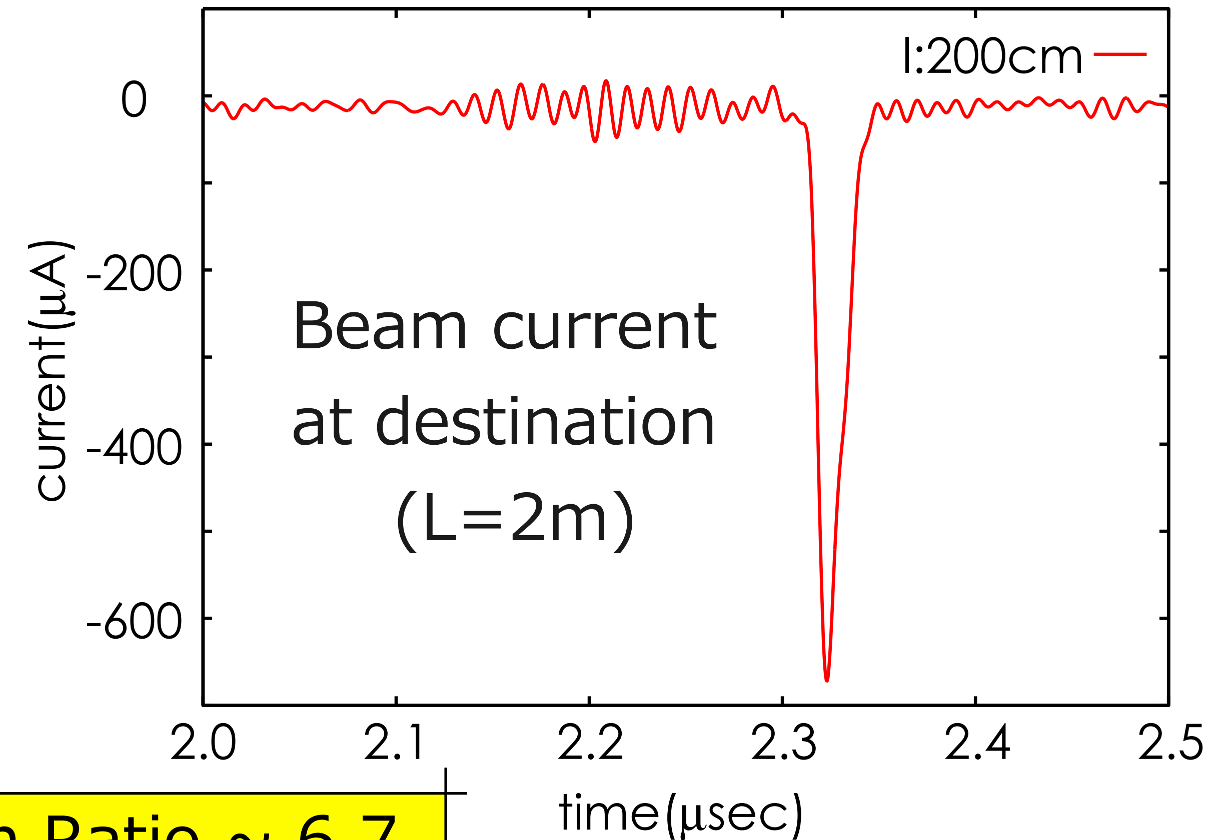

Various Multi-Voltage Pulses are applied into one gap.

-> Synthesized voltage pulse can compress electron beam bunch.

# Waveforms of beam current at injection & at the destination

Injection 2.8keV, Pulsed Beam T=100ns, L=2m




Compression Ratio ~ 6.7

$I_{peak} \approx 100\mu A$

$\Delta t \approx 100nsec$

$J \approx 3.2mA/cm^2$

→

$I_{peak} \approx 670\mu A$

$\Delta t \approx 15nsec$

$J \approx 21mA/cm^2$

$\boldsymbol{B} \simeq 0.03T$

*courtesy of K. Horioka@Tokyo Tech.*

# Numerical Simulation

Assumptions for Numerical Simulation:

- 1D electrostatic particle-in-cell method
- long wave approximation for electric field

$$E_z = -\frac{g}{4\pi\varepsilon_0}\frac{d\lambda}{dz}$$

$g$: geometry factor = 2

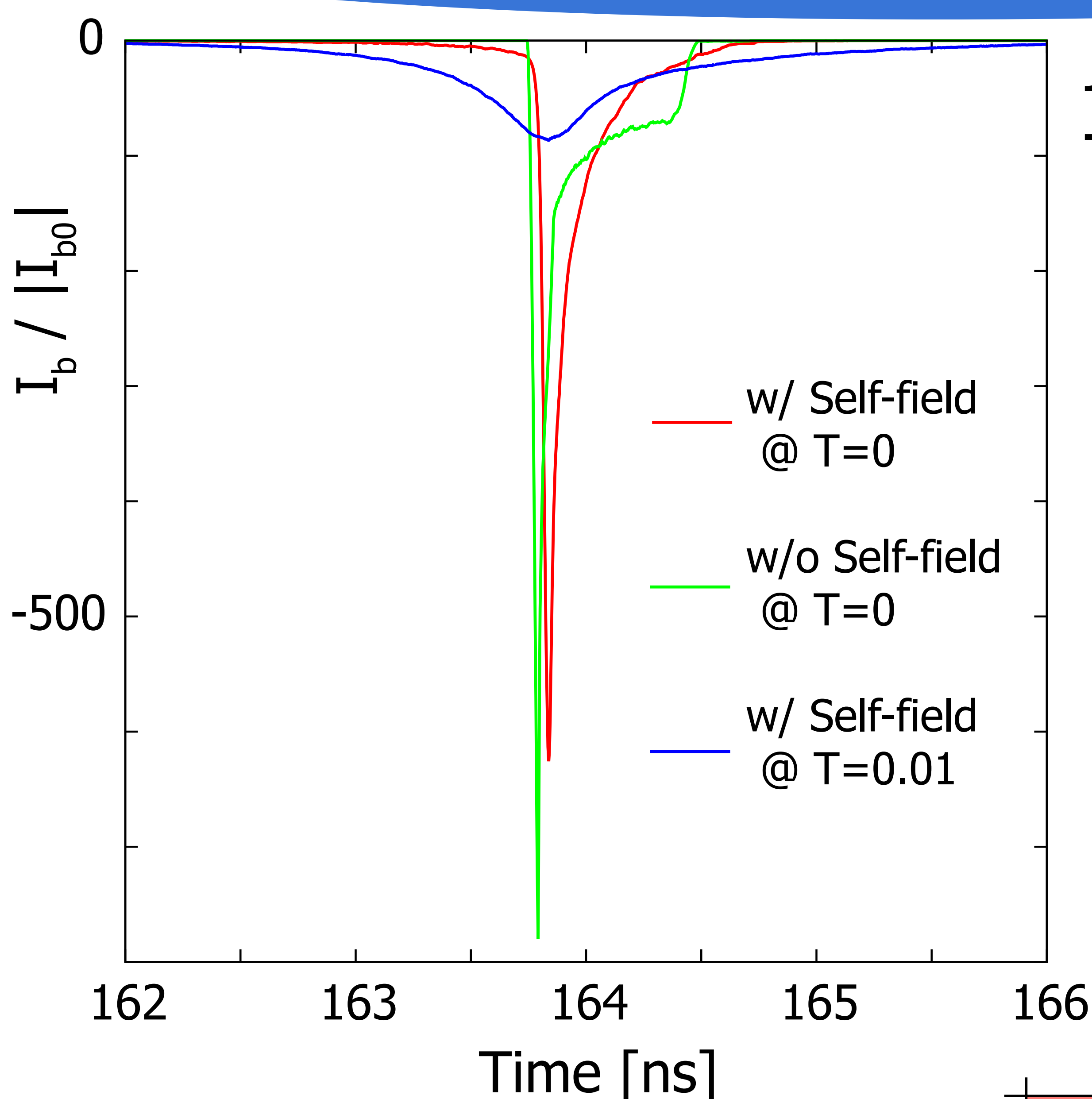
$\lambda$: line-charge density

- Initial thermal velocity is applied by $v_{th} = \sqrt{\frac{k_B T_e}{m_e}}$
- Bunch compression voltage at gap is applied by

$$V_{dec}(t) = \frac{m_e}{2q}\frac{1}{\left(\sqrt{\frac{m_e}{2qV_0}} + \frac{T-t}{L}\right)^2} - V_0$$

$V_0$=2.8kV @ L=2m, T=100ns

# Limitation for Pulse Compression




1D PIC result

Applied voltage for the pulse compression is good enough for the operation.

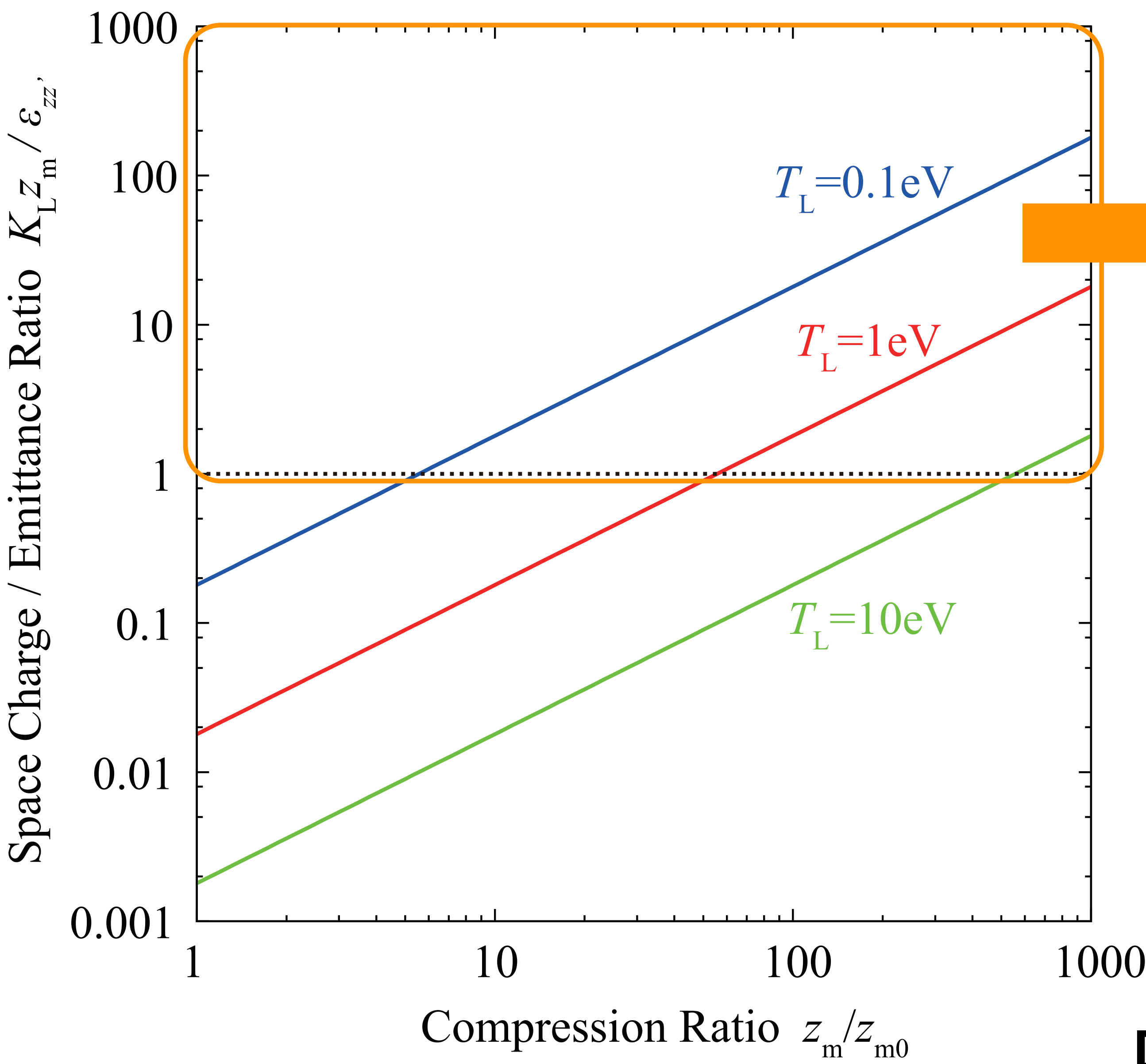
Space charge effect & initial temperature of electron bunch can interfere extreme pulse compression.

In this experimental condition, initial temperature of electron bunch is main issue of interference for extreme pulse compression.

# Estimation for Space Charge Dominated Condition

$$z_m'' + k_z z_m - \frac{K_L}{z_m^2} - \frac{\varepsilon_{zz'}^2}{z_m^3} = 0$$

$$\frac{K_L z_m}{\varepsilon_{zz'}^2} = \frac{3egI_{b0}\tau_{b0}}{40\pi\varepsilon_0 z_m k_B T_L} \geq 1$$




Space Charge Dominated

for experimental condition

$I_{b0}$ =100 μA, $\tau_{b0}$ =100 ns, g= 2, $k_B T_L$ =1 eV

Pulse compression of x57.8 (1.73ns pulse duration)

# Summary

Numerical Study for Electron Beam Dynamics in Compact Simulator for Heavy Ion Inertial Fusion

Research Topics: Key violation issues for extreme pulse compression

- applied voltage errors
- space charge effect
- thermal effect
- mismatch transport
- finite gap length

<u>from comparison with experimental and numerical simulation results:</u>

- Applied voltage for the pulse compression is good enough for the operation.
- Space charge effect & initial temperature of electron bunch can interfere extreme pulse compression.
- In this experimental condition, initial temperature of electron bunch is main issue of interference for extreme pulse compression.

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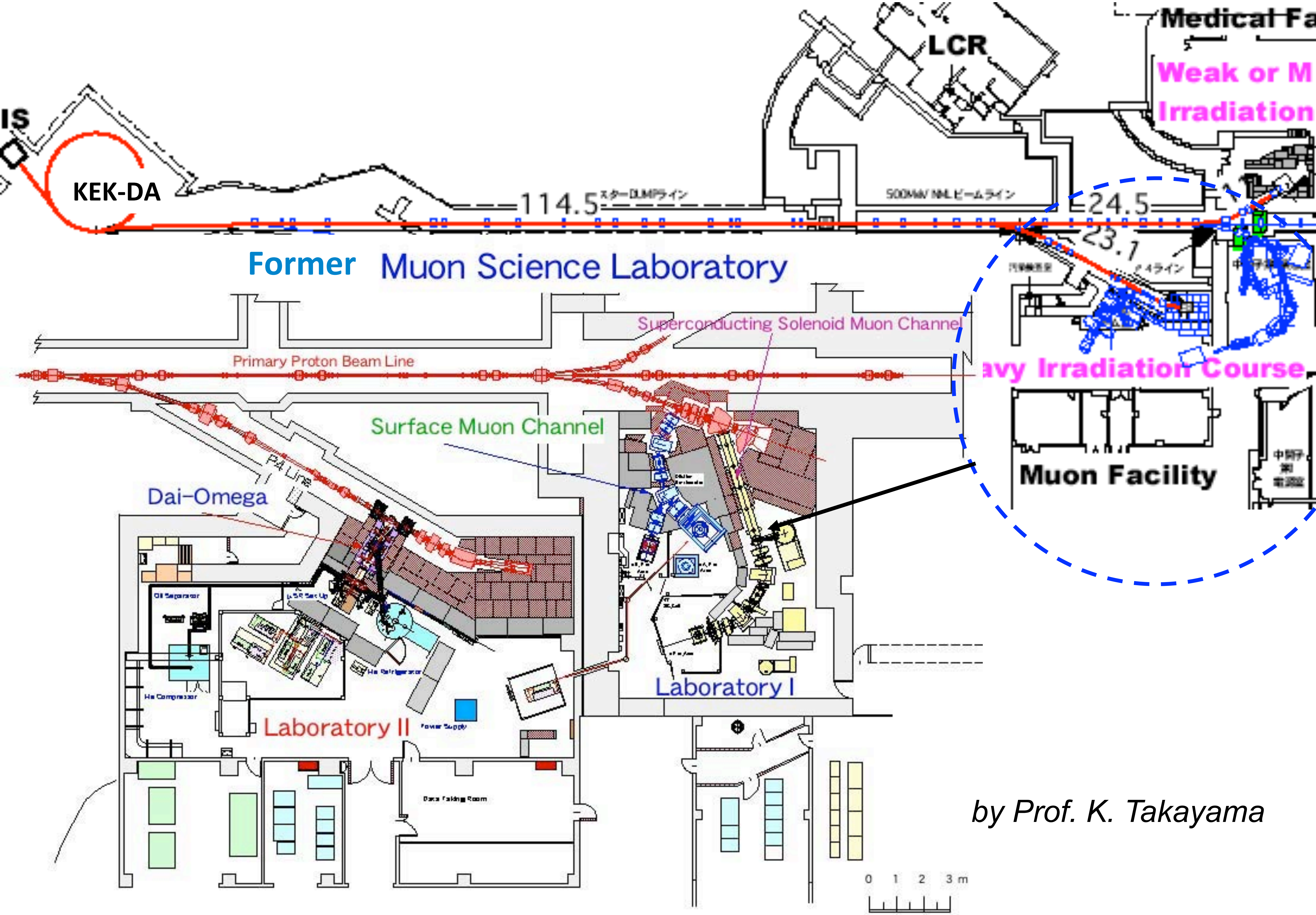
# KEK-DA & Existing Beam Lines




by Prof. K. Takayama

# How to minimize a beam size and compress the bunch length

| in DA-Ring | on Beam Line | in Target |
|---|---|---|

**transverse**

- Mini-beta focusing
- Plasma lens

*by Prof. K. Takayama*

**longitudinal**

in DA-Ring:

- Barrier squeezing

on Beam Line:

- Bunch rotation using induction acceleration cells with acceleration gradient of MeV/m x 3 (available) driven newly developed pulse power supply, pulse shaping is required.
- Commpression through plasma ?

**undesired features caused by coupling and its counter measure**

in DA-Ring:

Limitation due to momentum aperture $x_{eq}=D(s)(\Delta p/p)_{max} < 2$ cm

on Beam Line:

- Limitation due to chromatic effects caused by large Δp/p
- Compensation by sextupole magnets is possible or not?

$$\frac{d^2x}{ds^2} + \frac{K(s)}{1+\Delta p/p} \times x + \frac{K'(s)}{1+\Delta p/p} \times x^2 = 0$$

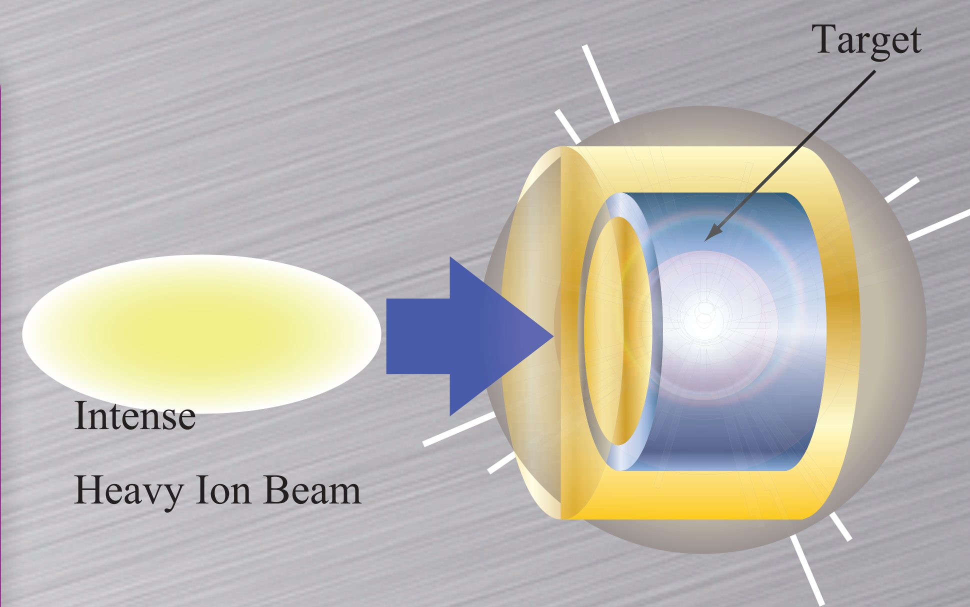
$$\text{introducing } x = \chi(s) + D(s)\frac{\Delta p}{p}$$

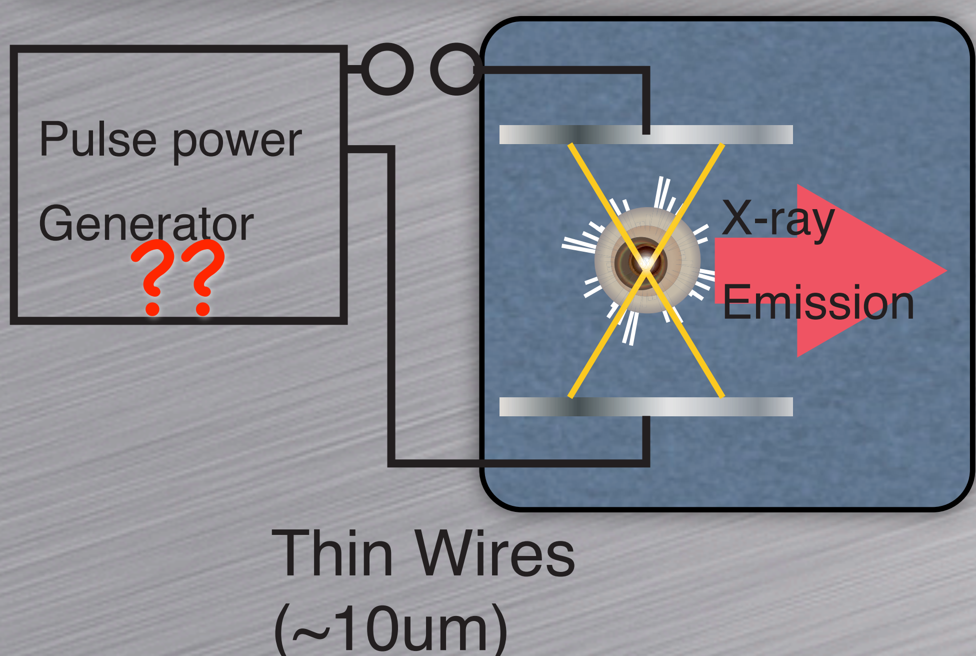
$$\chi''(s) + K(s)\cdot\chi + K'(s)\cdot\chi^2 + \boxed{\left[-K(s) + 2K'(s)\cdot D(s)\right]\cdot\frac{\Delta p}{p}\cdot\chi} = -K(s)\cdot D(s)\frac{\Delta p}{p}$$

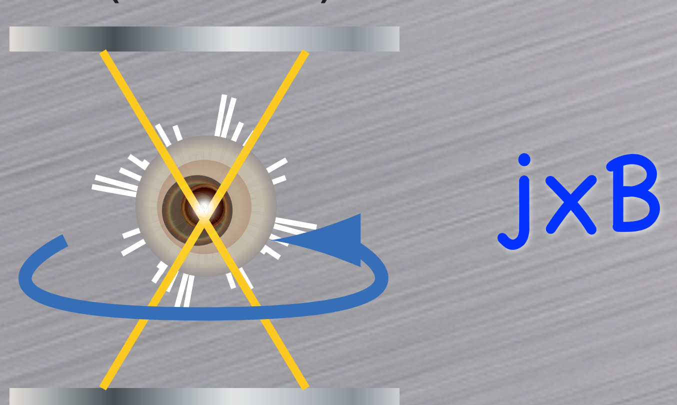
# Requirement parameters for X-ray sources

**Observing plasma parameters**

- Density range -> 0.1ρs - ρs
- Temperature range -> 0.3-10 eV
- Plasma size -> um-mm
- Typical time scale size -> 0.1 ns-10 ns



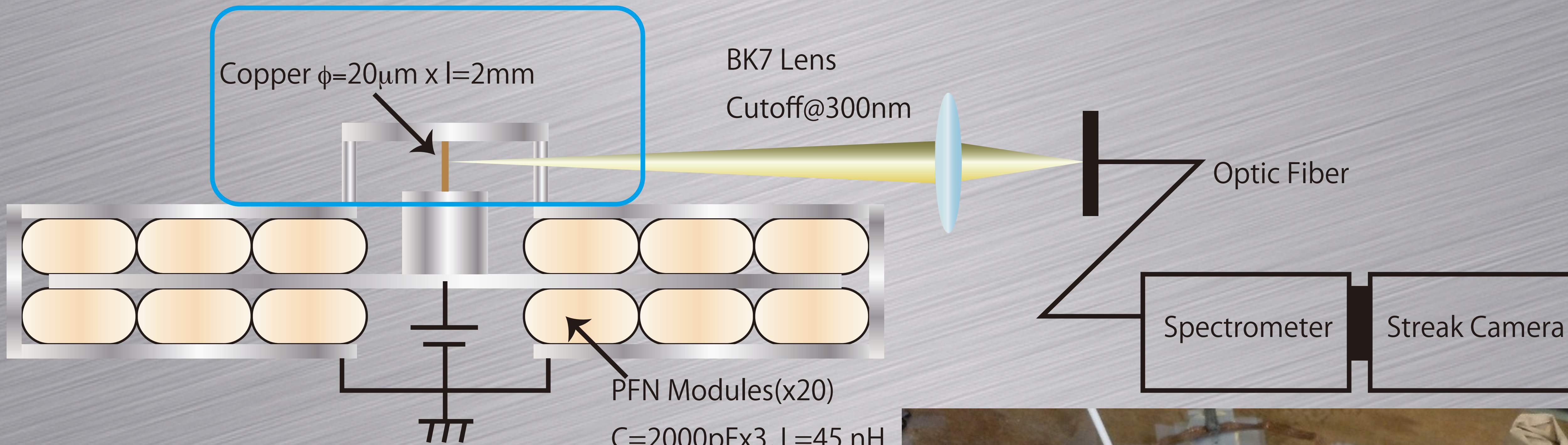



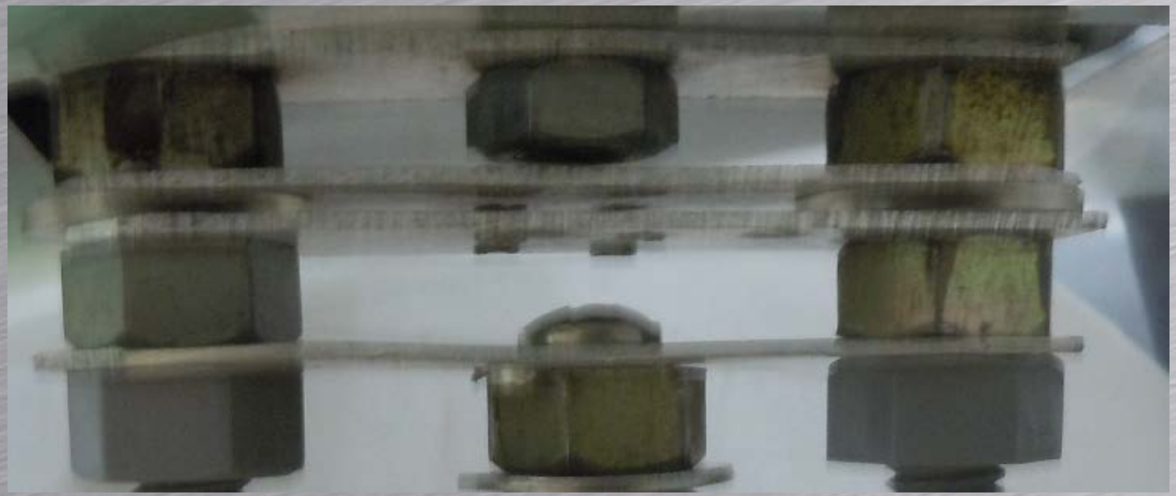




**X-ray source parameters**

- Less than 100 um (as small as possible)
- Sub-ns duration
- Intense x-ray with short wavelength
- ~ns time jitter

# Demonstrating PFN system



Stored Voltage: 20kV
Load: Copper wire
(φ=20μm, l=2mm)
Circuit Inductance: 100nH

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  *in NUT*

# Evaluate Physical Parameter in Warm Dense State

- How to diagnose the target state?

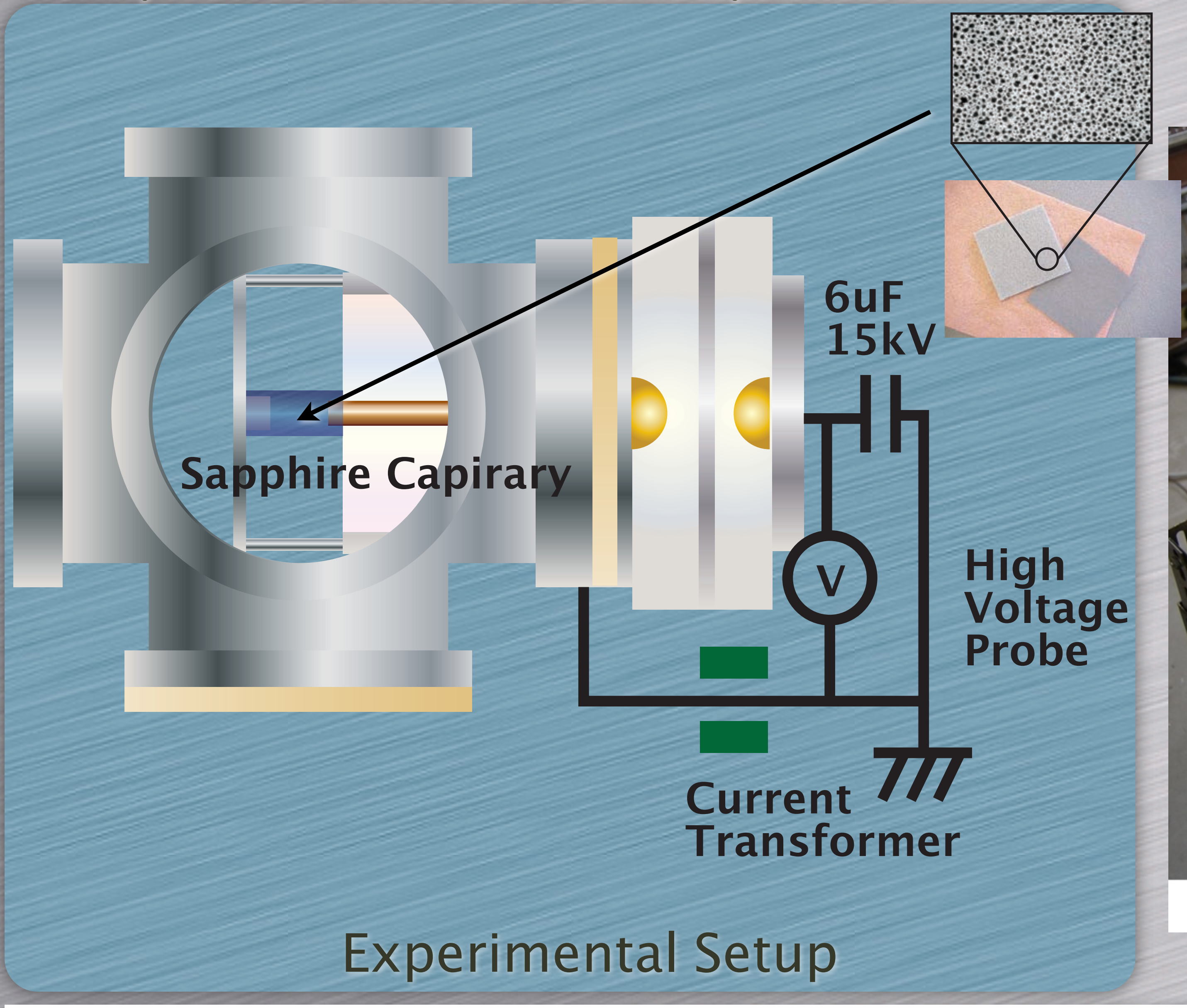
Optically thick
Homogeneity → Making well-defined state
i.e. quasi-uniform,
coaxial symmetric, etc.

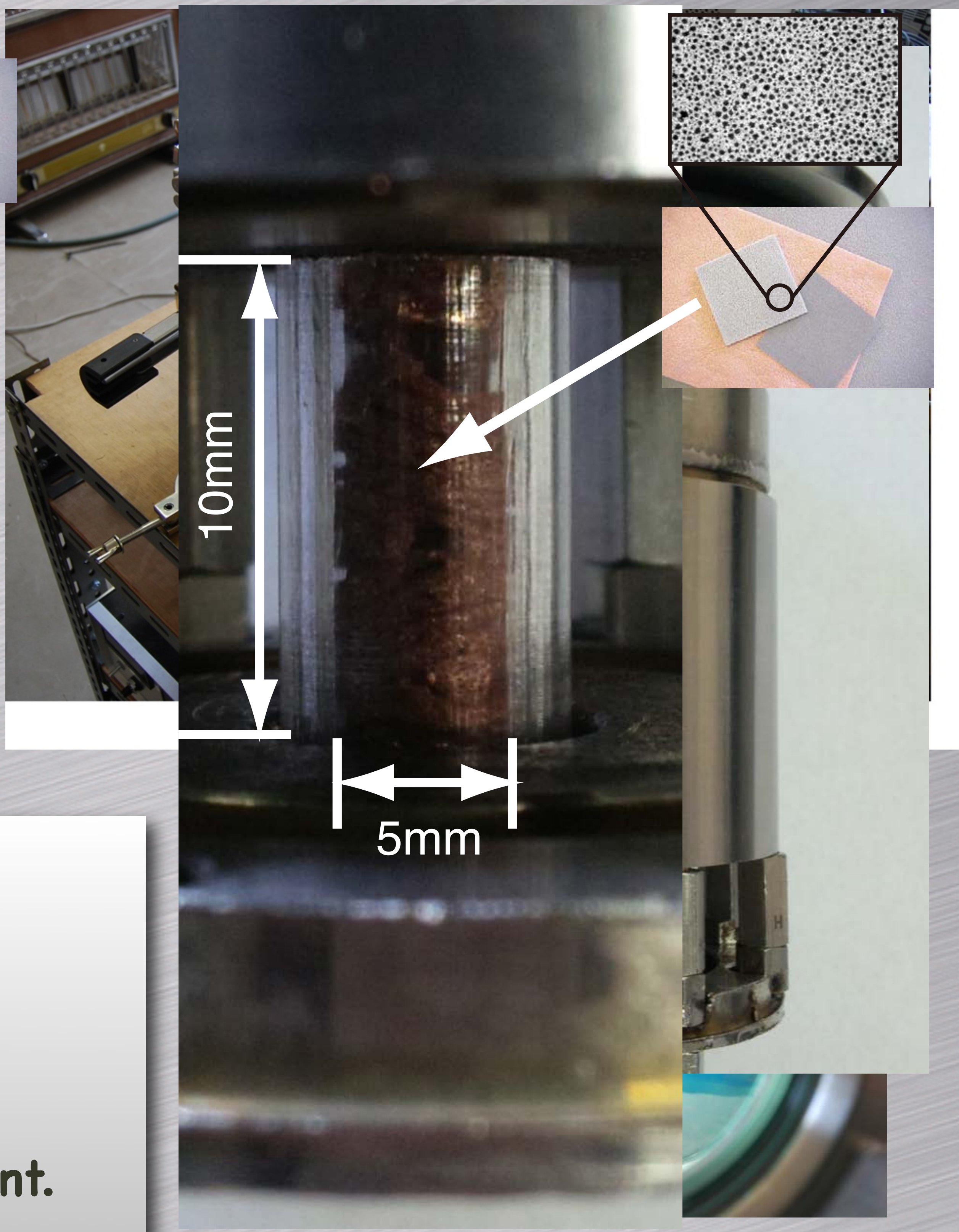
- Achievable parameter region of warm dense matter?

Depending pulsed-power devices → Compared to the expansion time and pulse duration.

→ Complementary approach for warm dense matter study using pulsed-power devices and intense ion beams

# Experimental setup for evaluating foam/plasma conductivities

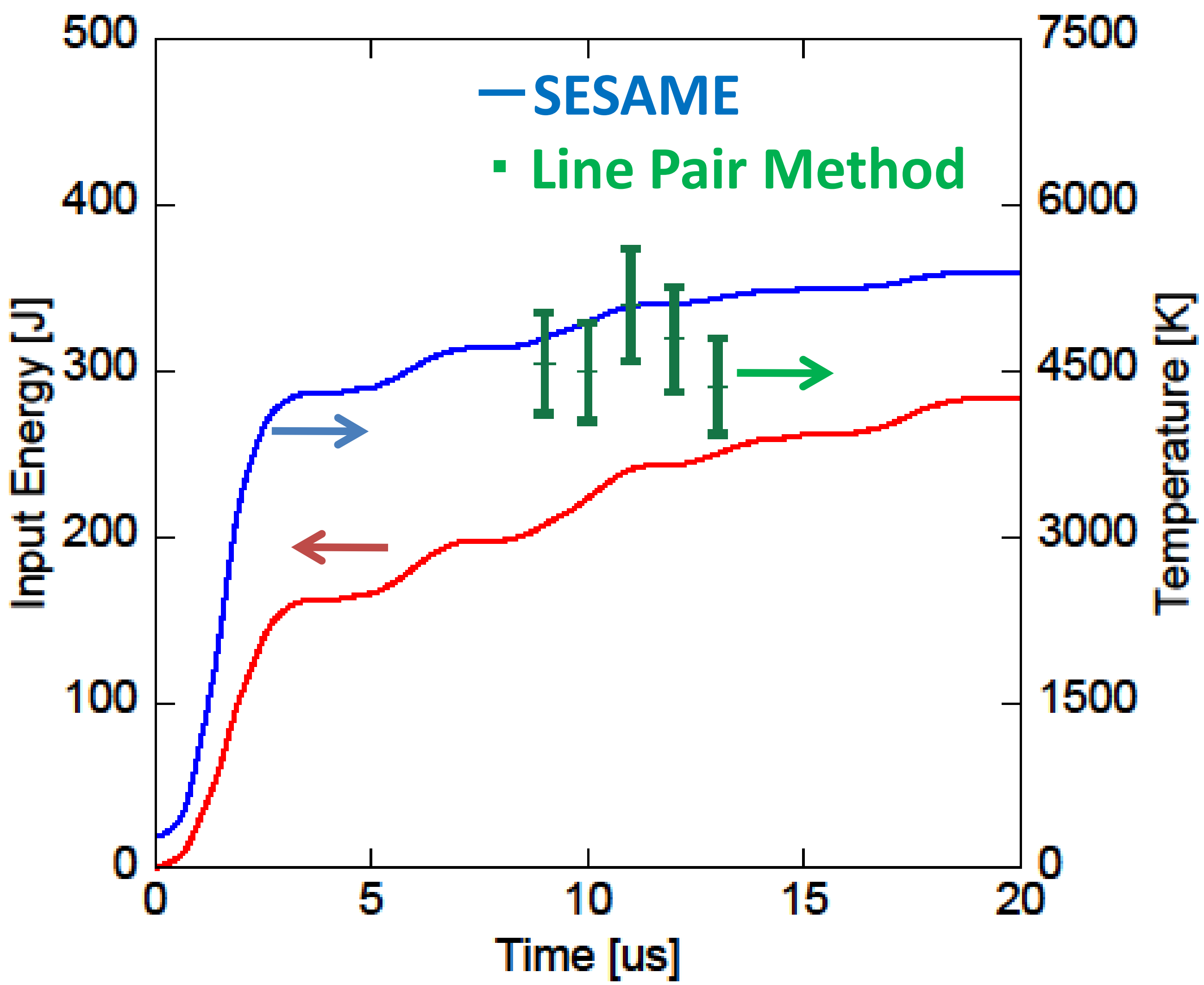



## Advantages

- ➢ Compact Pulsed-power Device
- ➢ Axial Symmetry
- ➢ Ease of Evaluation of Conductivity and Input Energy History by Voltage and Current.
- ➢ Tamper Effect by Sapphire

# Comparison of Foam/plasma Temperature estimated by the Line Pair Method or SESAME




**Input Energy**

⇓

$$E = \int V_{Foam} \cdot I dt$$

**Foam/Plasma Temperature**

⇓

**Line Pair Method using CuI spectrum at 477nm and 610 nm**

$$\ln\left(\frac{\varepsilon_{21}\lambda_{21}}{A_{21}g_2}\right) = \frac{E_2}{k_B T} + \ln K$$

**or**

**SESAME Equation of State Table[2]**

[2]S.P.Lyon, J.D.Johnson, T-1 Handbook of the SESAME Equation of State Library

**Plasma temperature is estimated to be about 5000K**

⇒ **WDM state can be generated**

# Calculation Condition for Thermal Diffusion in Sapphire Capillary

**Copper Region:**

Initial Temperature $T_0$=300 [K]

Thermal Conductivity $\kappa=\kappa(T)$ [W/m K]

Specific Heat $C_v=C_v(T)$ [J/kg K]

Solid Density $\rho_s$=8920 [kg/m$^3$]

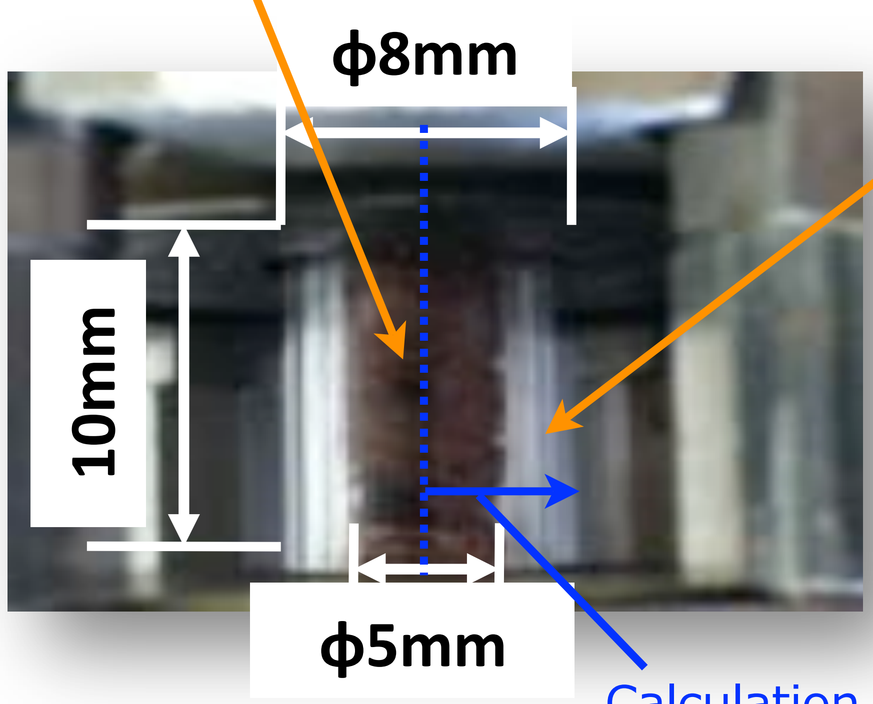
**Sapphire Region:**

Initial Temperature $T_0$=300 [K]

Thermal Conductivity $\kappa$=42 [W/m K]

Specific Heat $C_v$=750 [J/kg K]

Solid Density $\rho_s$=3970 [kg/m$^3$]




Exp. Data & Interpolation Model

*Fitting & Experimental Data*

$\kappa(T)$ = Ref.[1-2]

$C_v(T)$ = Ref.[3-4]

Time-dependent One-dimensional Thermal Diffusion Equation with Cylindrical Symmetry Configuration

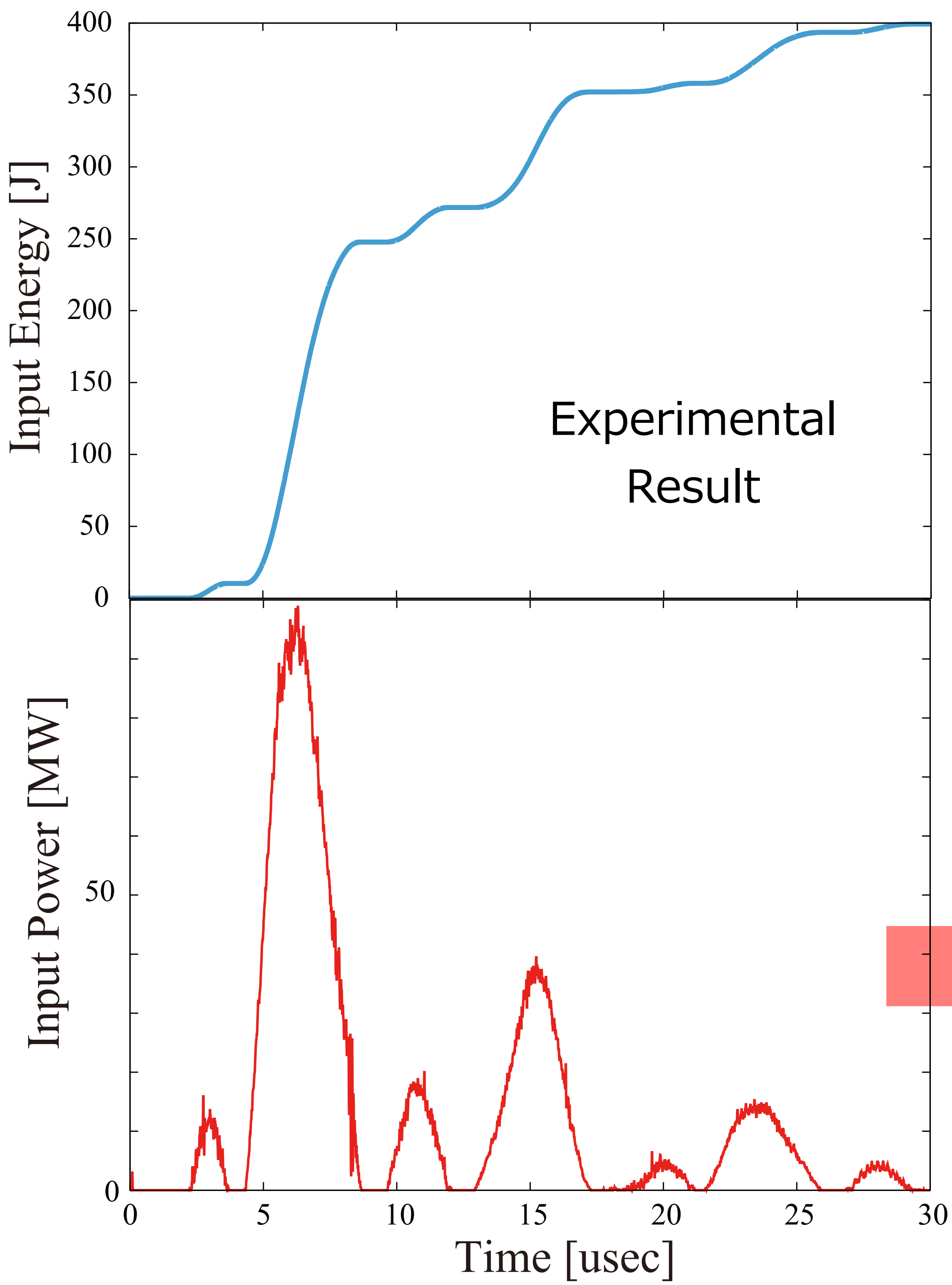

[1] C.Y. Ho, R.W. Powell, P.E. Liley, Thermal Conductivity of the Elements, JPCRD 1(2) pp.279-422 (1972) (See p.54 for Cu)

[2] C.Y. Ho, R.W. Powell, P.E. Liley, Thermal Conductivity of the Elements: A Comprehensive Review, JPCRD 3(Supplement 1) pp.1-796 (1974)

[3] NIST Standard Reference Database Number 69

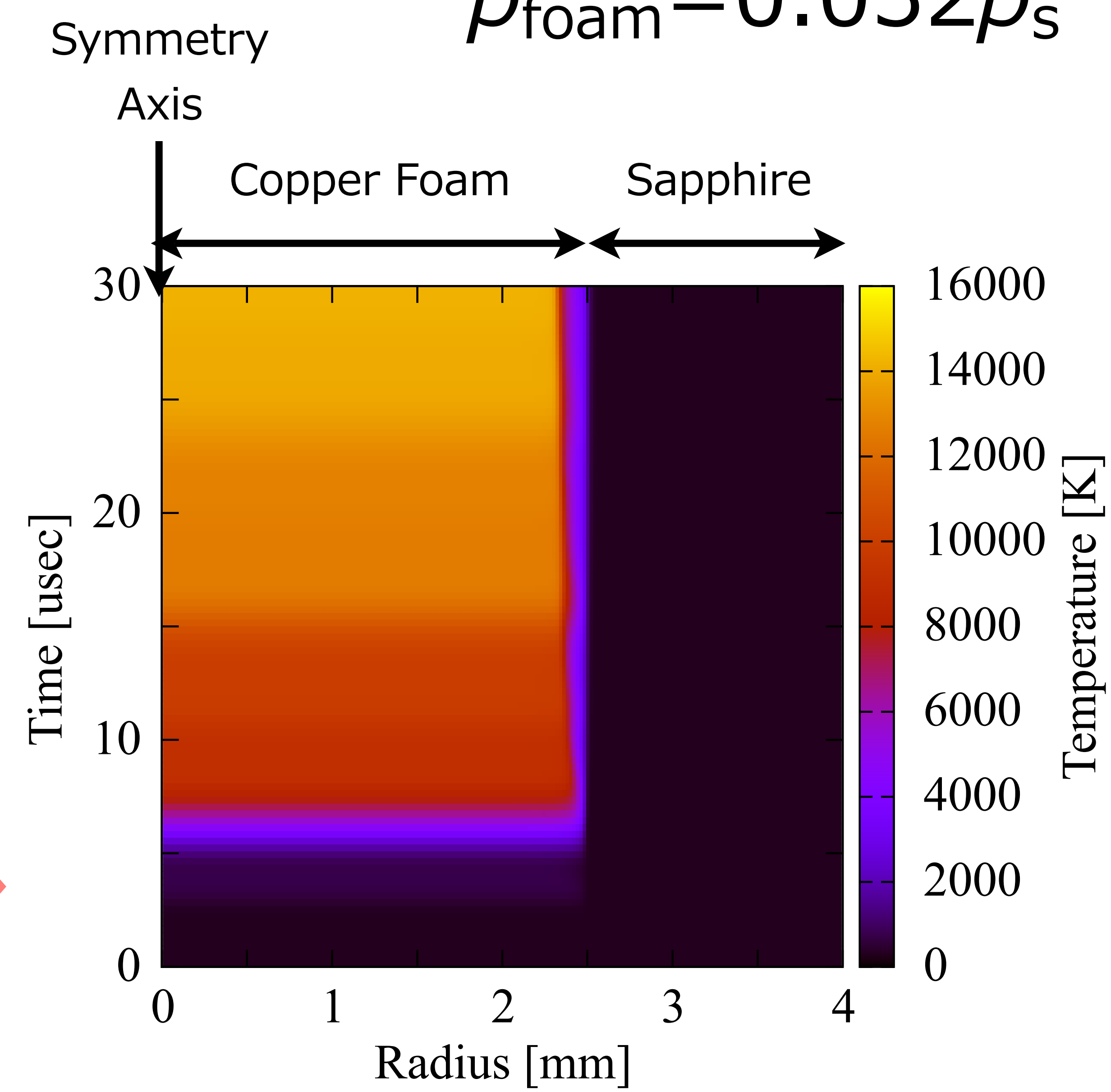
[4] M.W. Chase, NIST-JANAF Themochemical Tables, Fourth Edition, J. Phys. Chem. Ref. Data, Monograph 9, 1998, 1-1951.

# Calculation Results of Thermal Diffusion in Sapphire Capillary



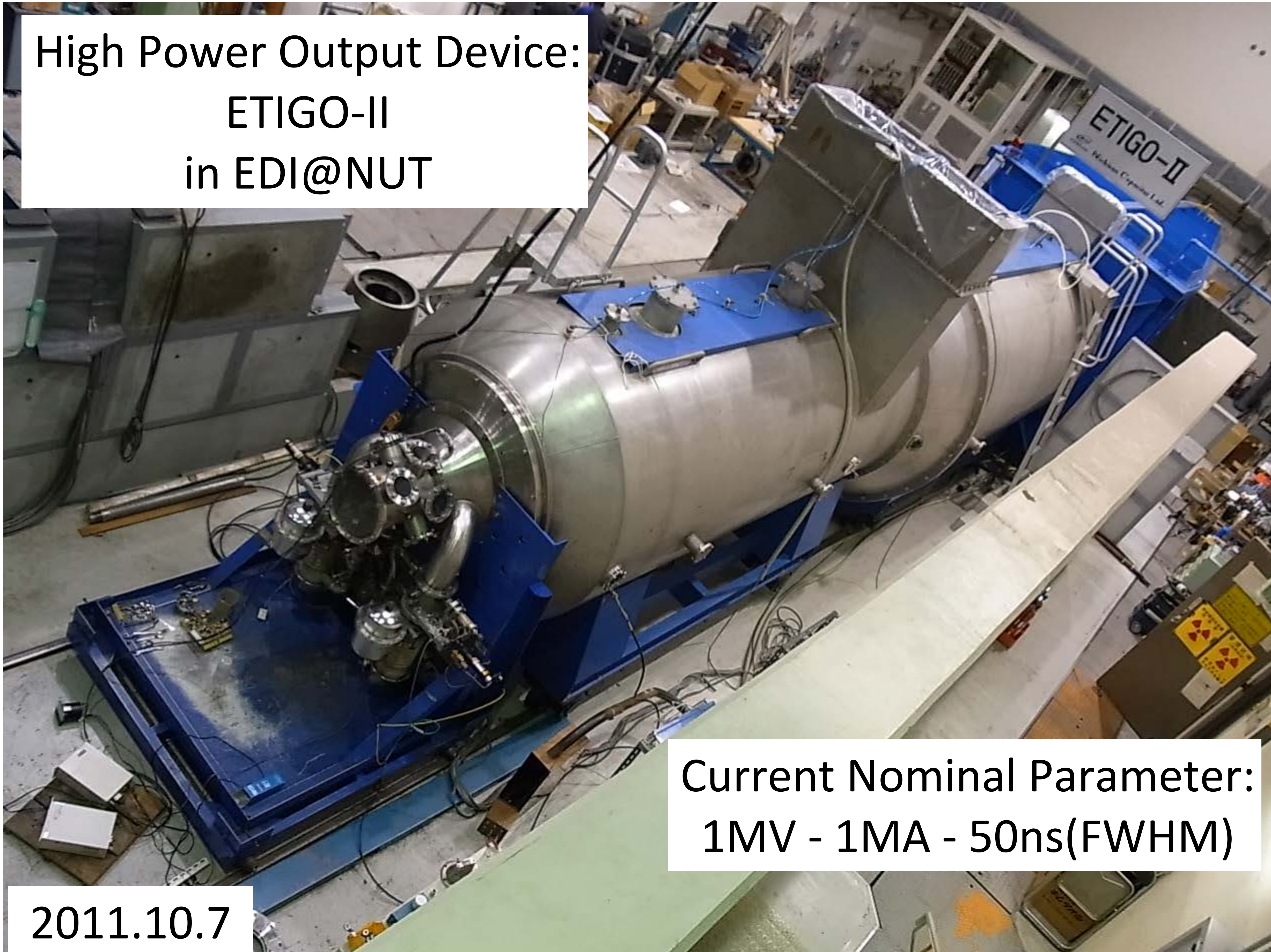

Uniform Heating in Radius

$\rho_{foam}=0.032\rho_s$



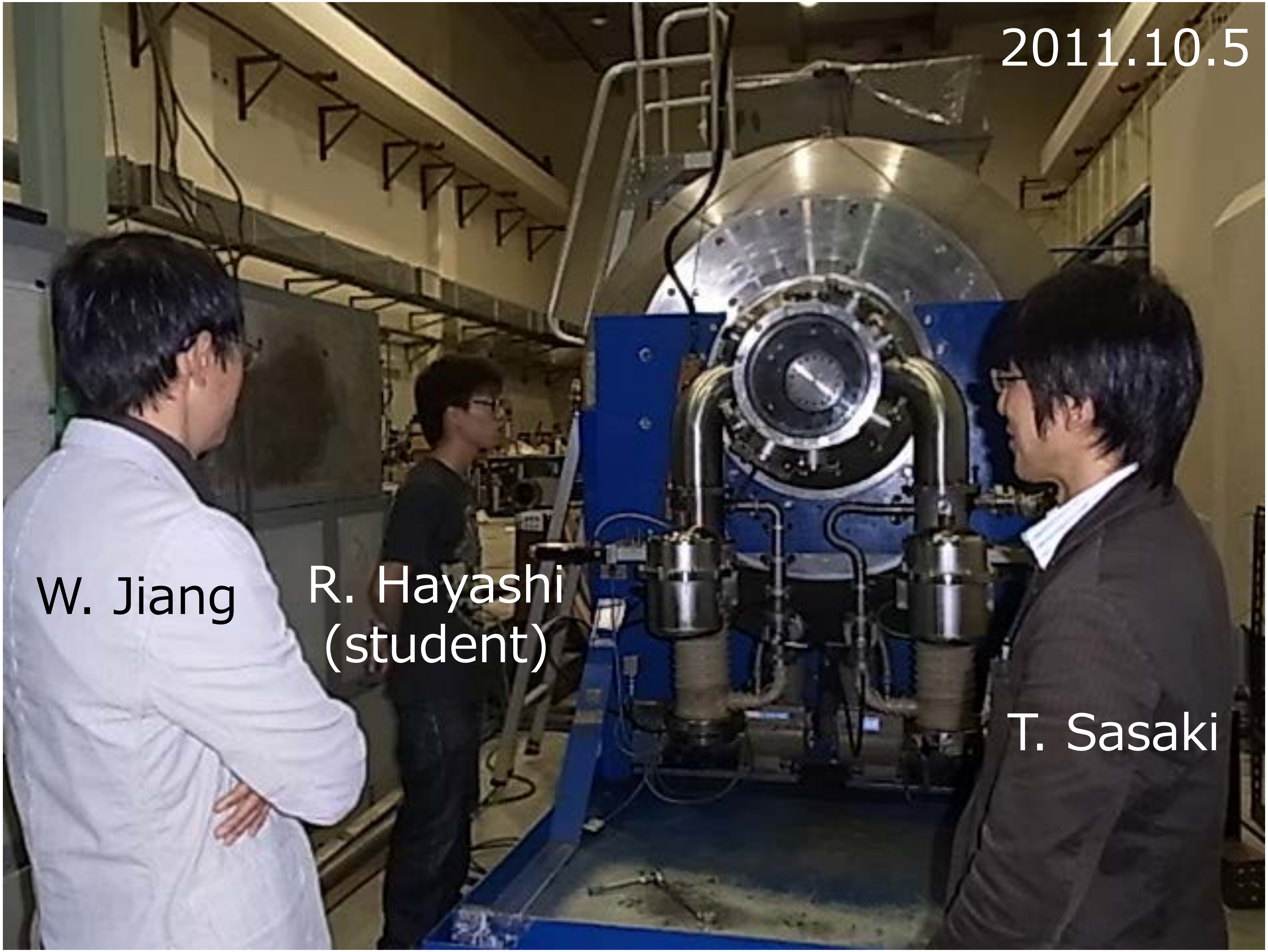

Exp. Data & Interpolation Model

High Power Output Device:
ETIGO-II
in EDI@NUT




Current Nominal Parameter:
1MV - 1MA - 50ns(FWHM)

2011.10.7


2011.10.5
W. Jiang
R. Hayashi
(student)
T. Sasaki

# Summary

- Implosion Dynamics and Equation-Of-State
  *with H. Nagatomo @ ILE*
- Intense Beam Applications by Induction Accelerator ETIGO-III
  *with G. Imada @ NIIT*
- Bunch Compression Study by Compact Simulator
  *with K. Horioka @ TIT*
- Ion Beam Driven WDM/HEDP Experiment Project in KEK-DA
  *with K. Takayama @ KEK*
- WDM/HEDP Studies Driven by Pulsed Power Devices
  *in NUT*

# Related Talks

more detail of

☑ Bunch Compression Study by Compact Simulator

by K. Horioka @ TIT
*Beam Physics Study at Tokyo Tech*, Oct.13

Another Topic of NUT Activity
by W. Jiang @ NUT
*Power Devices for Induction Accelerators*, Oct.13

more detail of

☑ Ion Beam Driven WDM/HEDP Experiment Project in KEK-DA
☑ WDM/HEDP Studies Driven by Pulsed Power Devices

by T. Sasaki @ NUT
*Warm Dense Matter Experiments and Diagnostics by using Pulsed-Power Devices and Intense Ion Beams*, Oct.13

# Collaborators

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Thank you !!