Warm Dense Matter Experiments and Diagnostics by using Pulsed-power Devices and Intense Ion Beams

Toru Sasaki, Takashi Kikuchi, Weihua Jiang[1], and Nob. Harada

Department of Electrical Engineering, Nagaoka University of Technology

[1]Extreme Energy-Density Research Insutitute , Nagaoka University of Technology

Outline

- Introduction to Warm Dense Matter Exp.

- Generation and Evaluation for High Energy Density Matter based on Pulsed-power and Intense Charged Particle Beams
  - Pulsed-power Device
  - Intense Ion Beams
  - X-ray Diagnostic Source

- Concluding Remarks

Warm Dense State

Features of Warm Dense State

- High Density($10^{-3}\rho_s \sim \rho_s$) and Low Temperature(0.1~10eV)

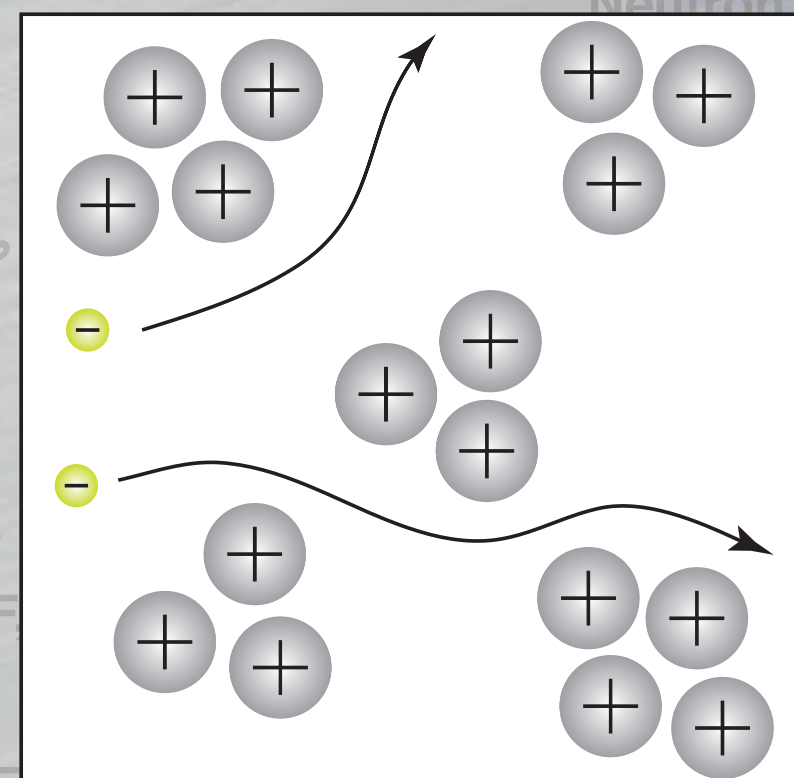
- Electrons are in partially degenerate regime

$$\theta = \frac{E_{kin}}{E_F} = \frac{k_B T}{\frac{\hbar^2}{2m_e}(3\pi^2 n)^{2/3}}$$

- Coupled Plasma State

--- $\Gamma > 1$

$$\Gamma = \frac{E_{pot}}{E_{kin}} = \frac{\frac{(Z^* e)^2}{4\pi\epsilon_0 a}}{k_B T}$$



- Phase Transition

(Liquid-Vapor, Critical Point)

Evaluate Physical Parameter in Warm Dense State

- How to diagnose the target state?

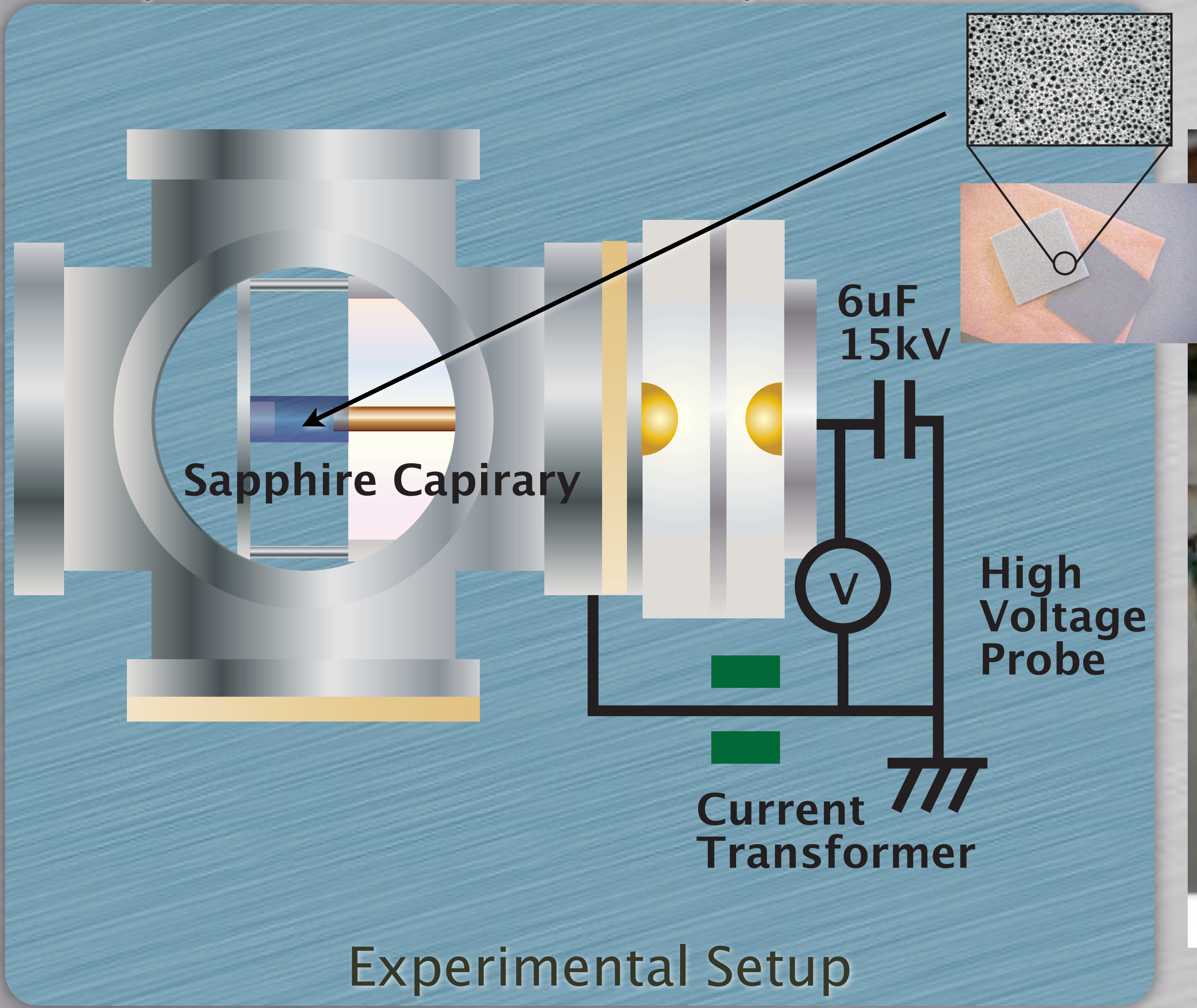
Optically thick
Homogeneity
→
Making well-defined state
i.e. quasi-uniform,
coaxial symmetric, etc.

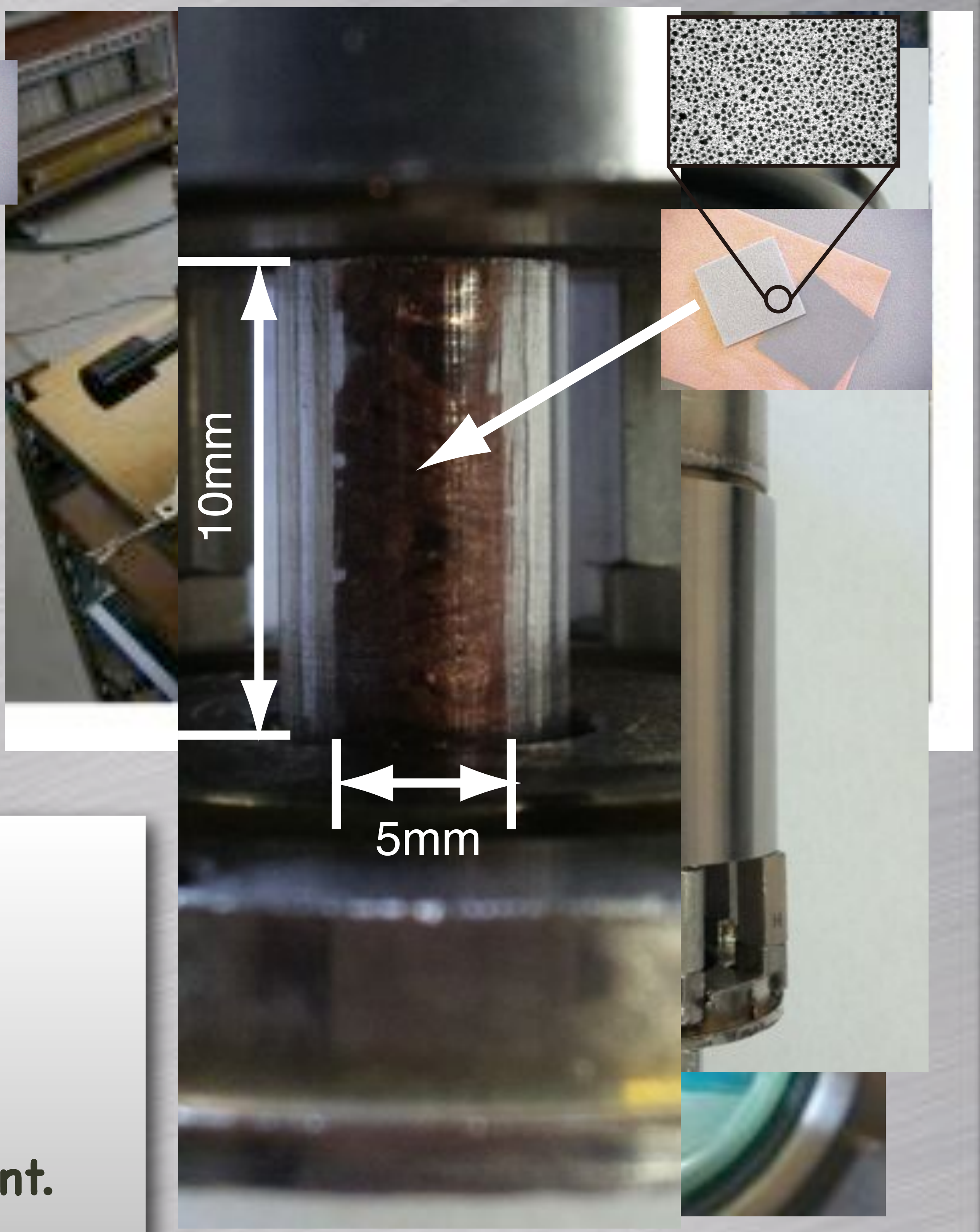
- Achievable parameter region of warm dense matter?

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

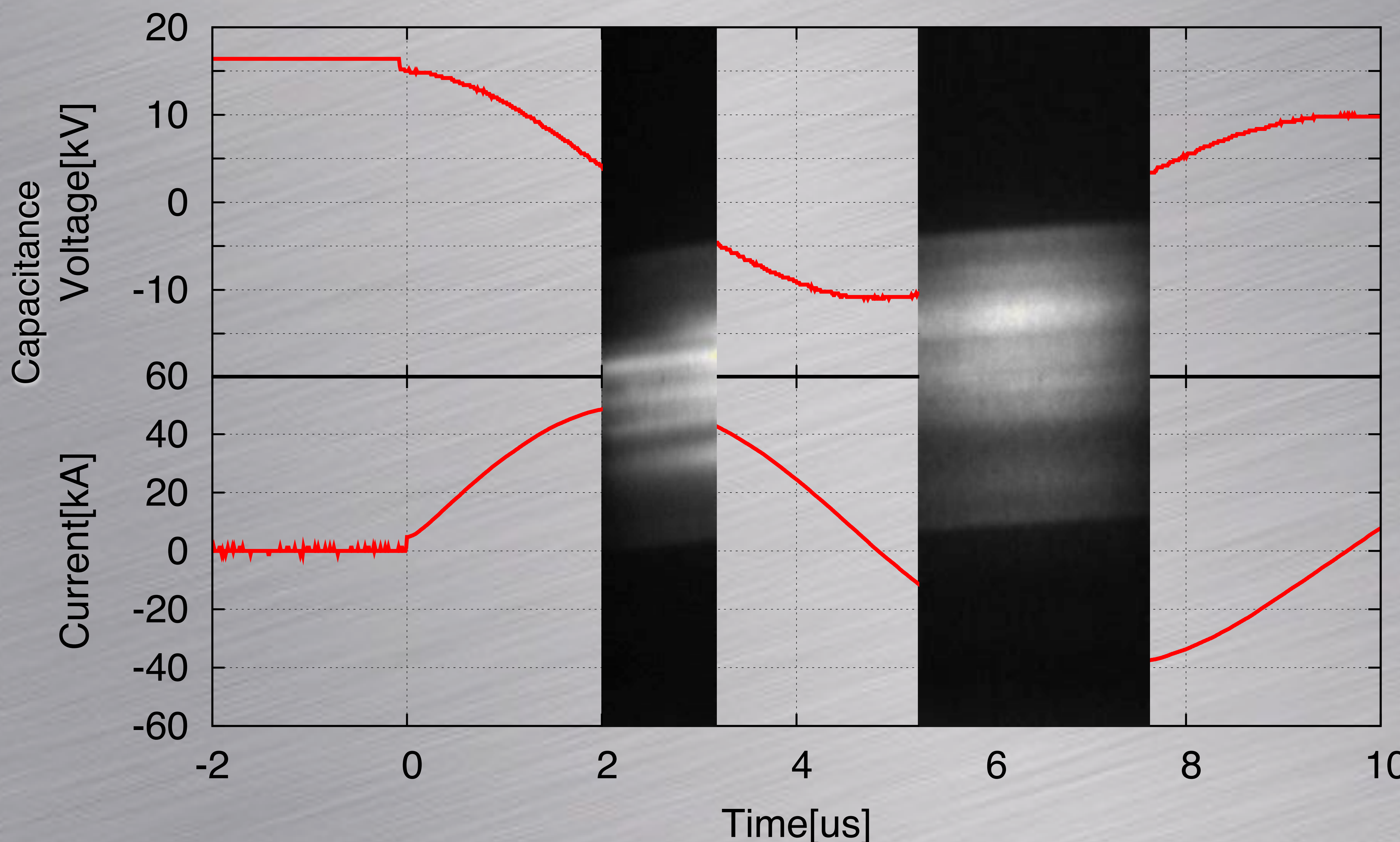




Advantages

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

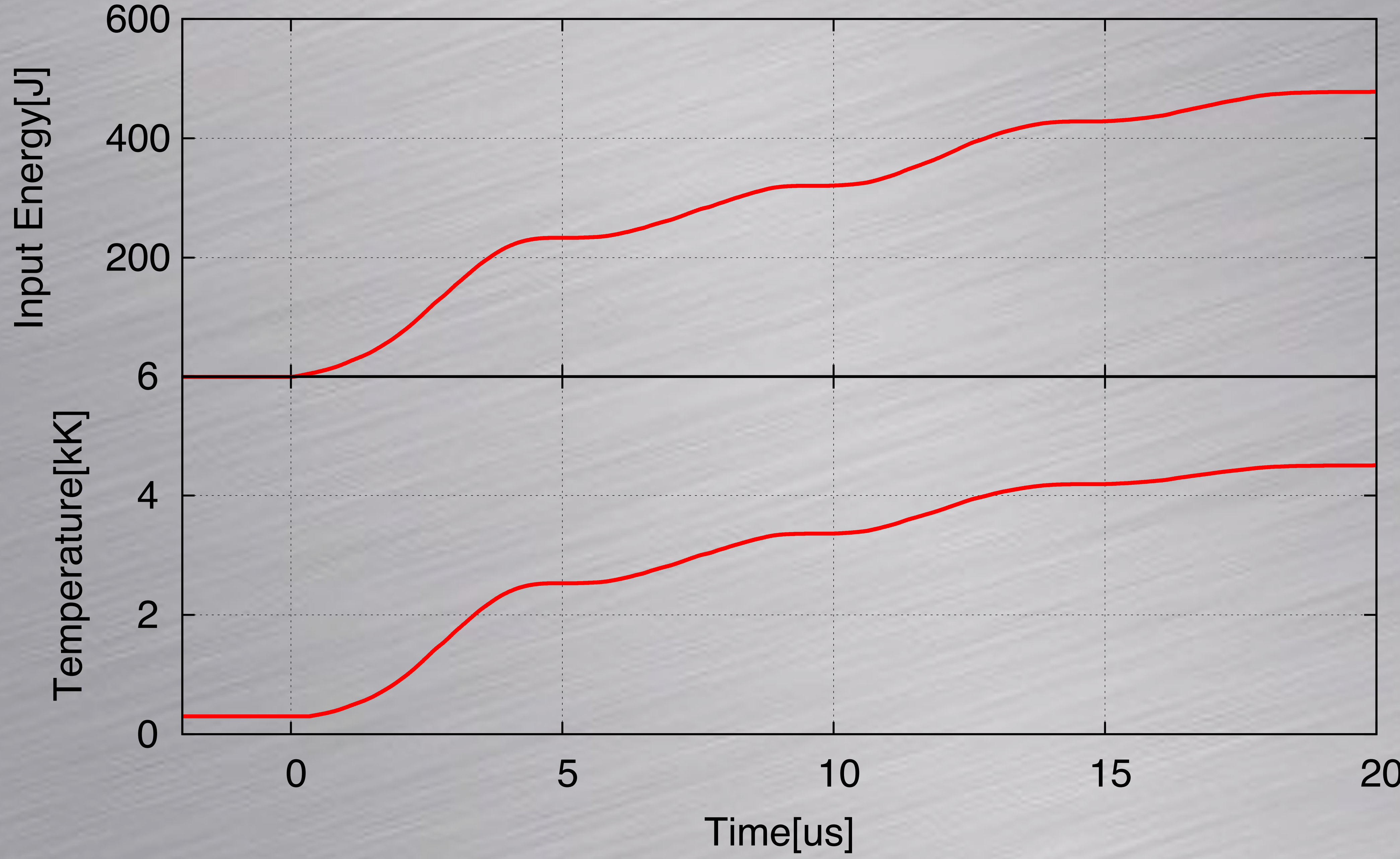
Typical evolutions of dense foam/plasma using isochoric-pulsed discharges



Foam/plasma was confined by sapphire capillary.

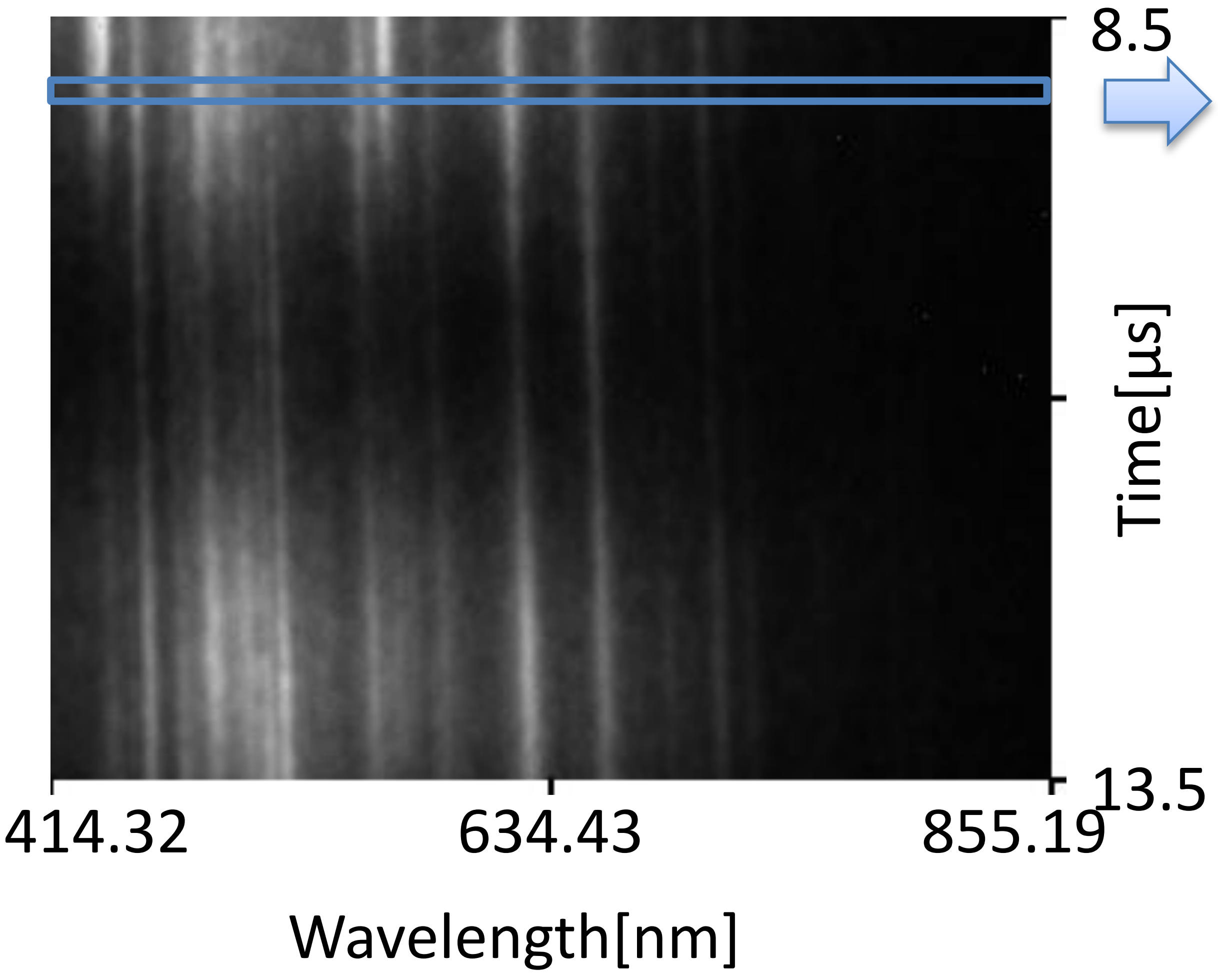
=> Foam/plasma density is determined.

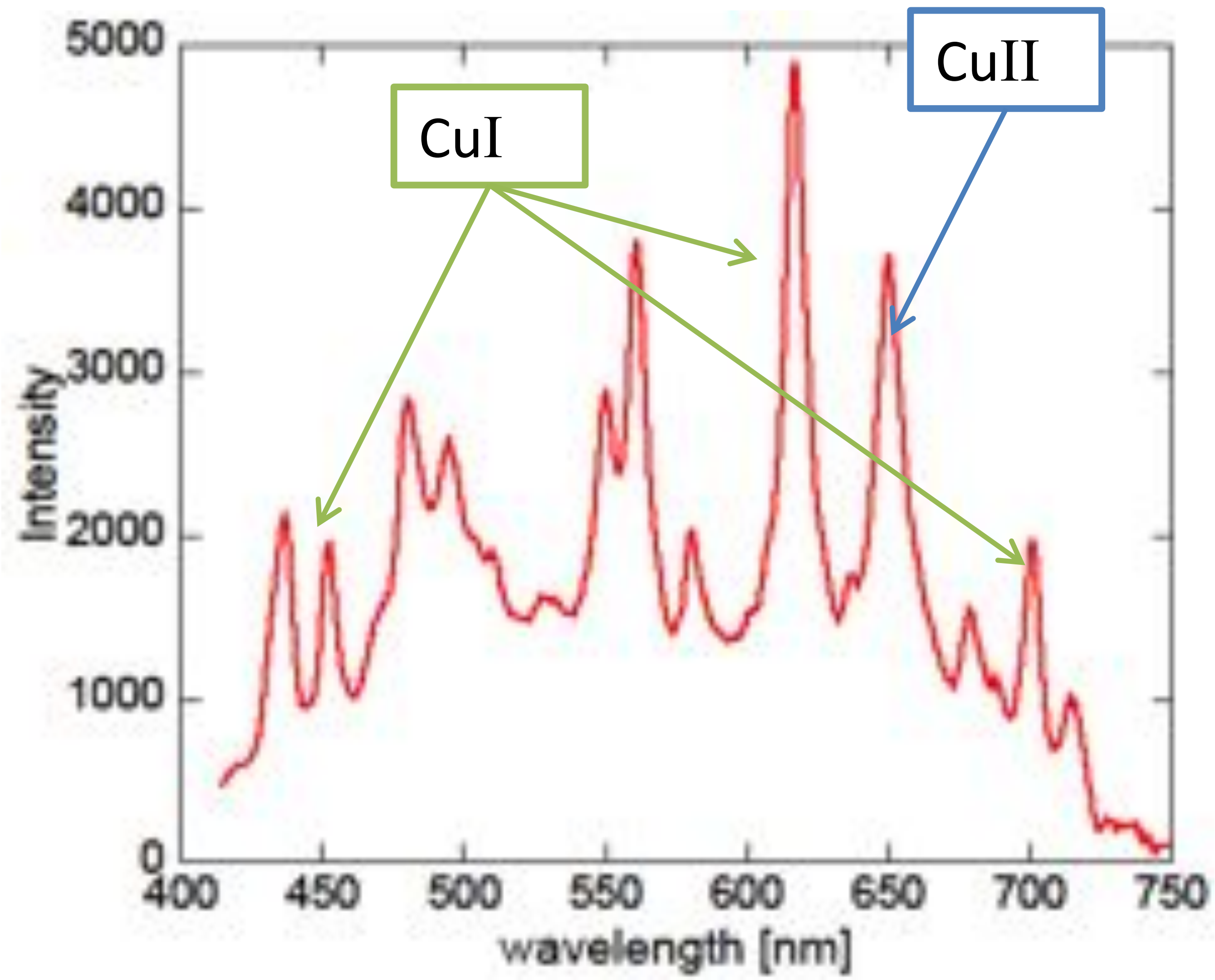
Dense foam/plasma temperature achieves about 4000K estimated by SESAME(Cu:3333)



Foam/plasma temperature is estimated by SESAME EOS assuming homogenous condition.

Typical Spectrum (@0.032ρs) of Copper Foam/plasma





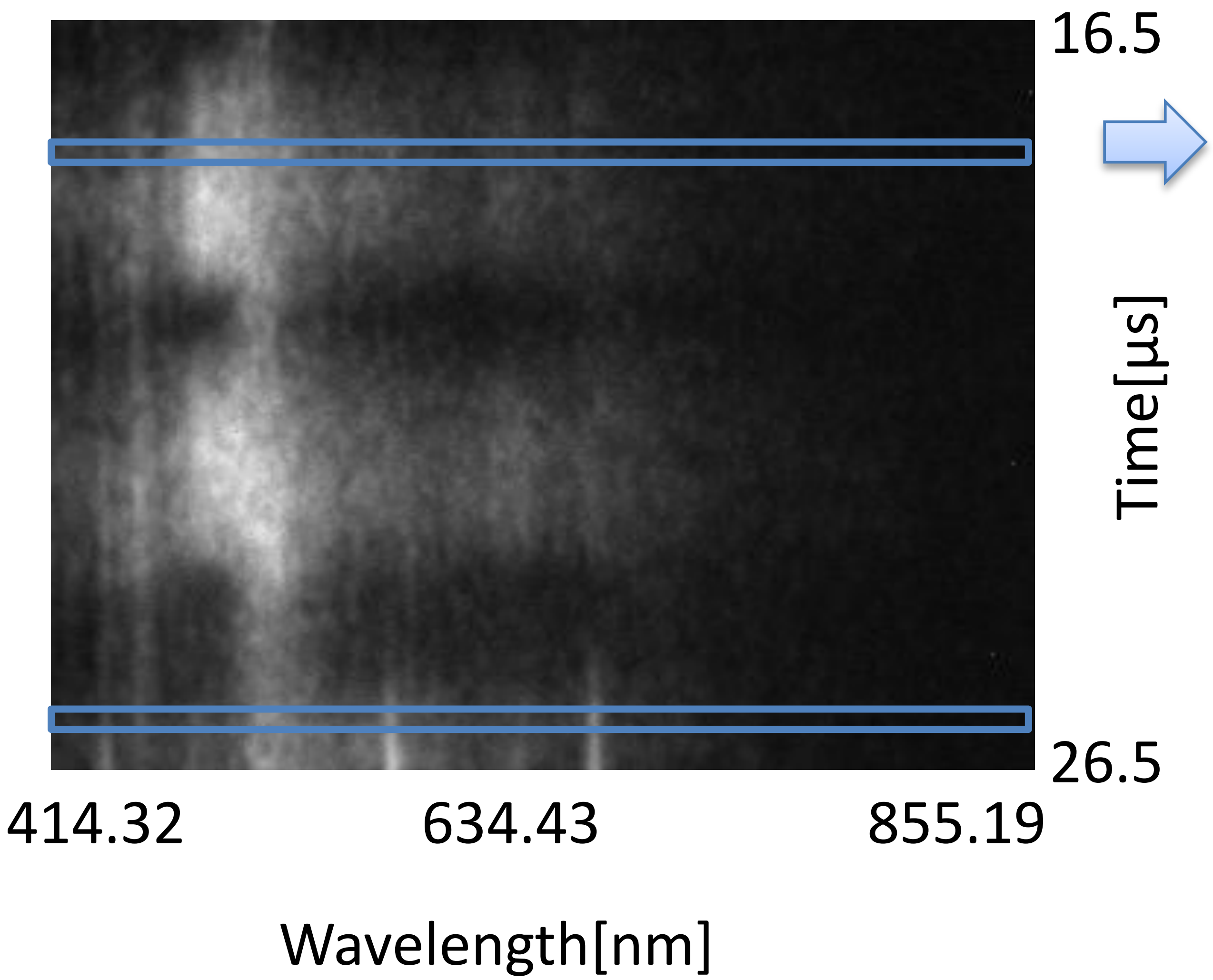
9 μs from the beginning of discharge

Emission spectrum of CuII can be confirmed at 651 nm

⇩

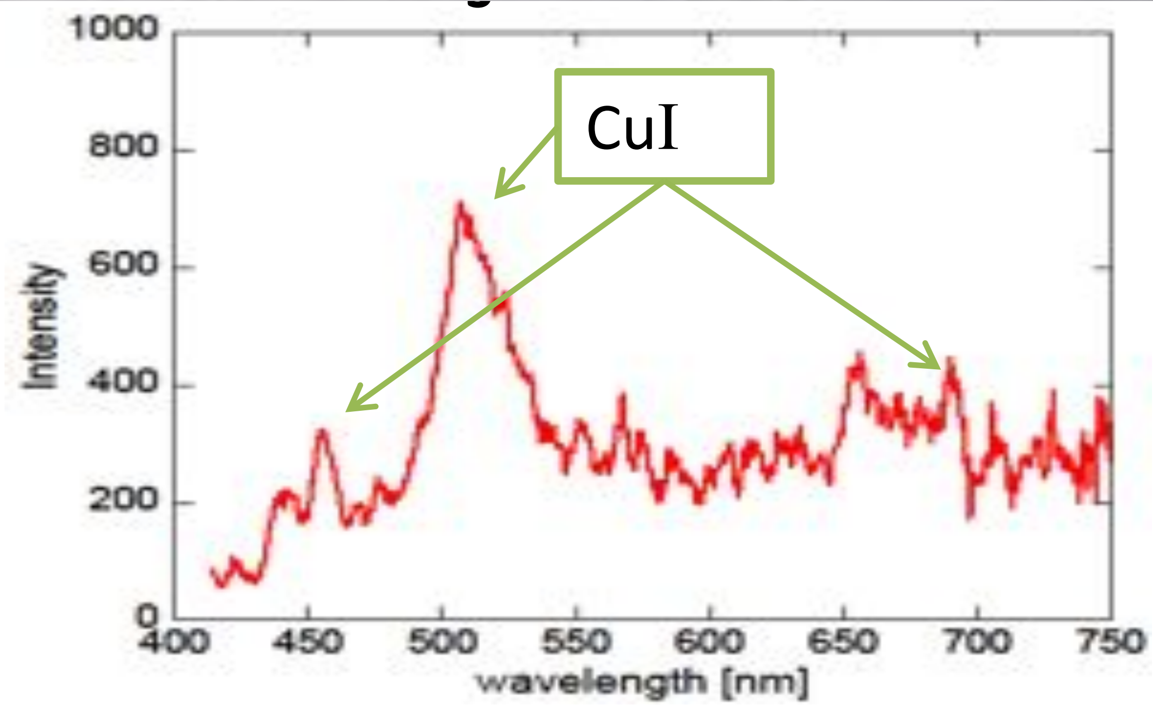
Emission of Copper Plasma ⇒ Estimating Plasma Temperature

Typical Spectrum (@0.17ρ$_s$) of Copper Foam/plasmas

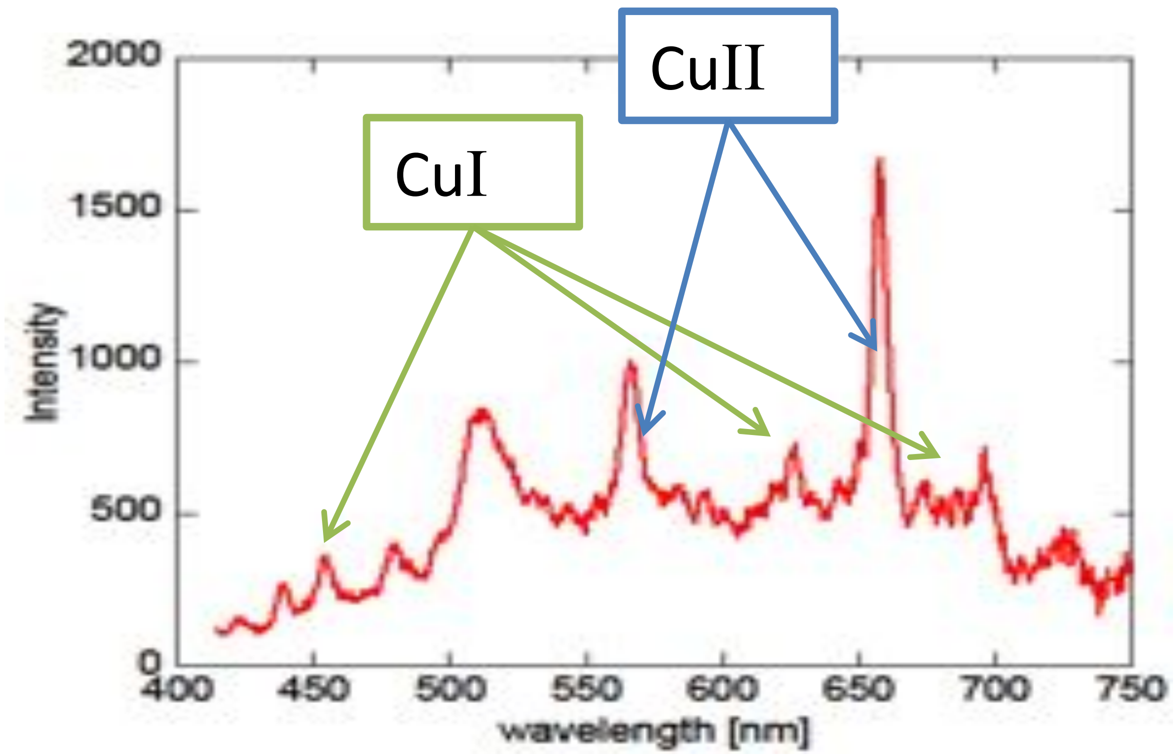


Spectrum changes in final phase of the electric discharge

Foam ⇒ Plasma

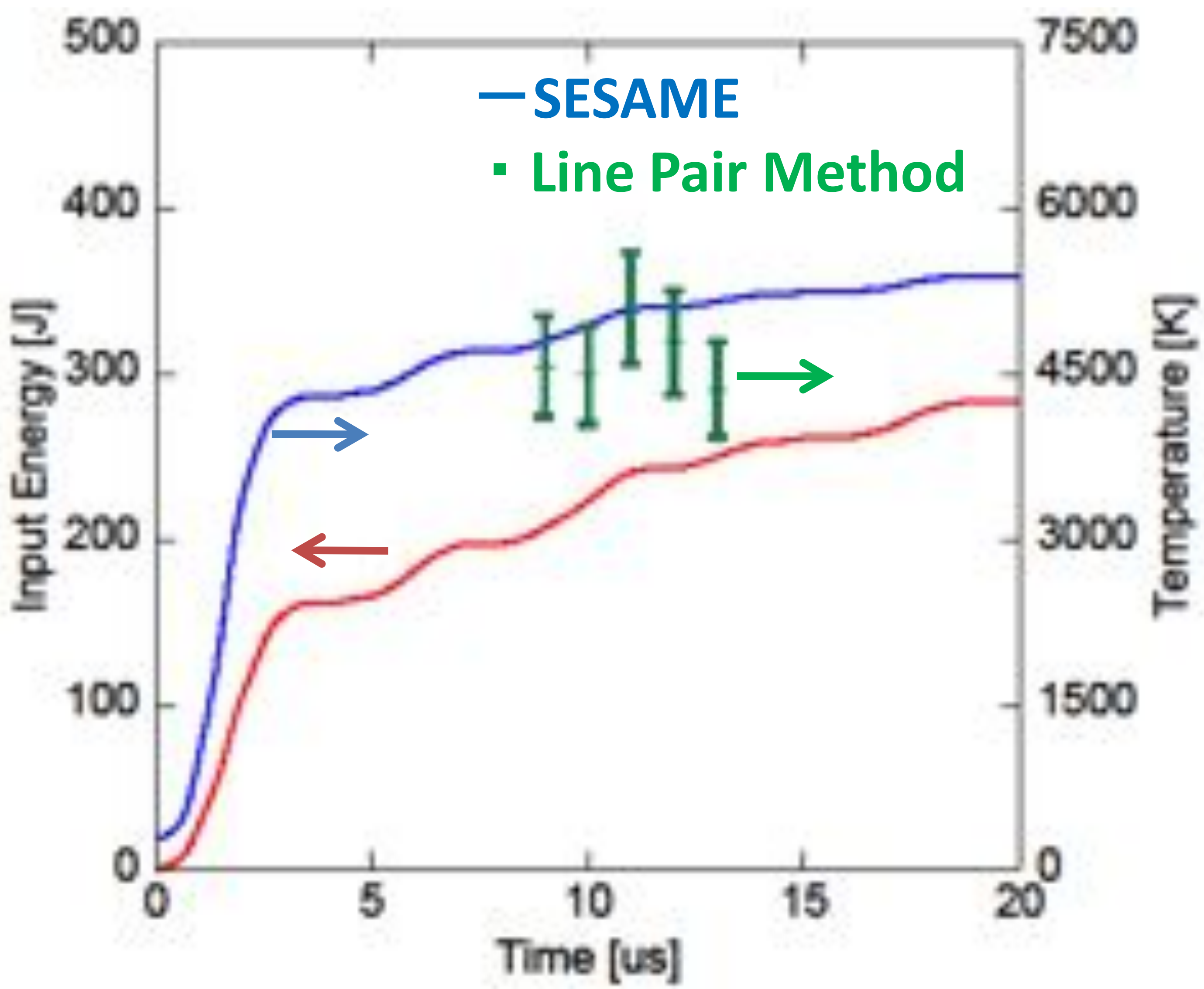


16 µs from the beginning of discharge



26 µs from the beginning of discharge

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

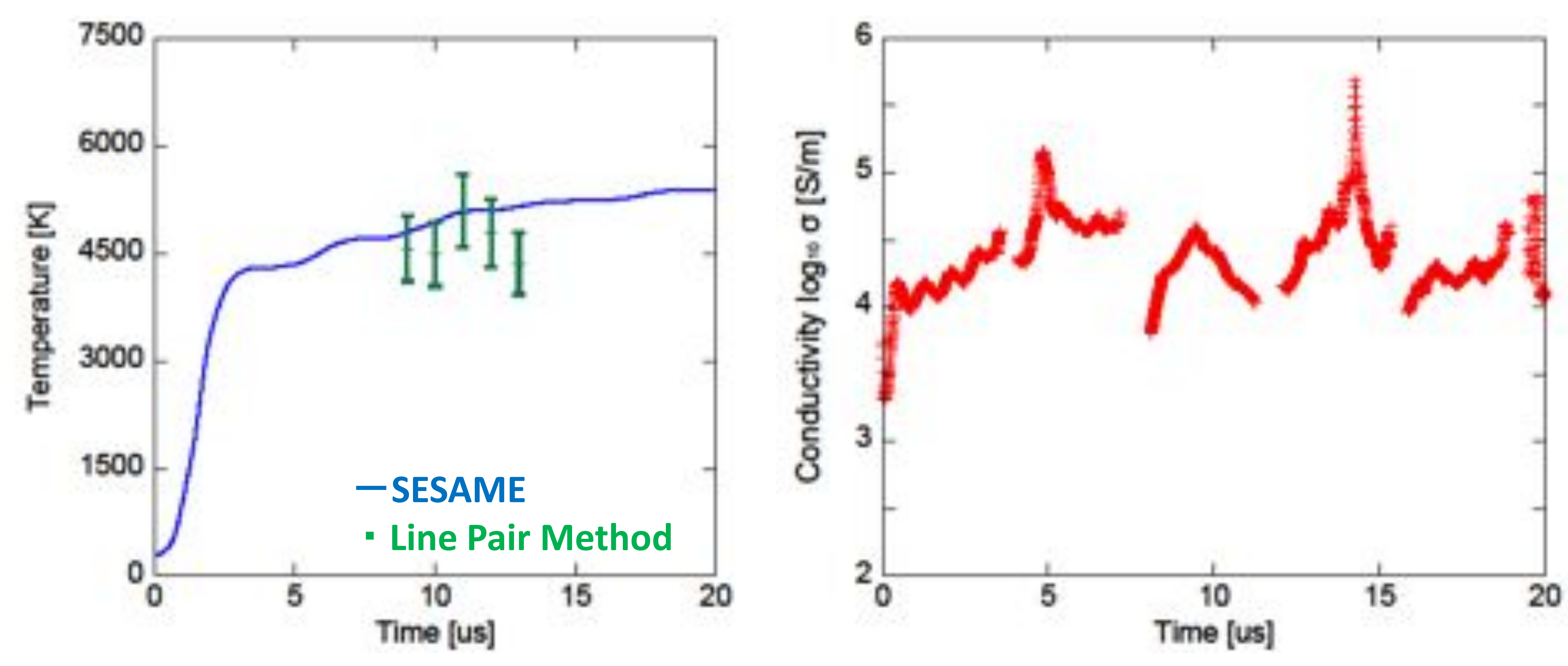
SESAME Equation of State Table[2]

[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

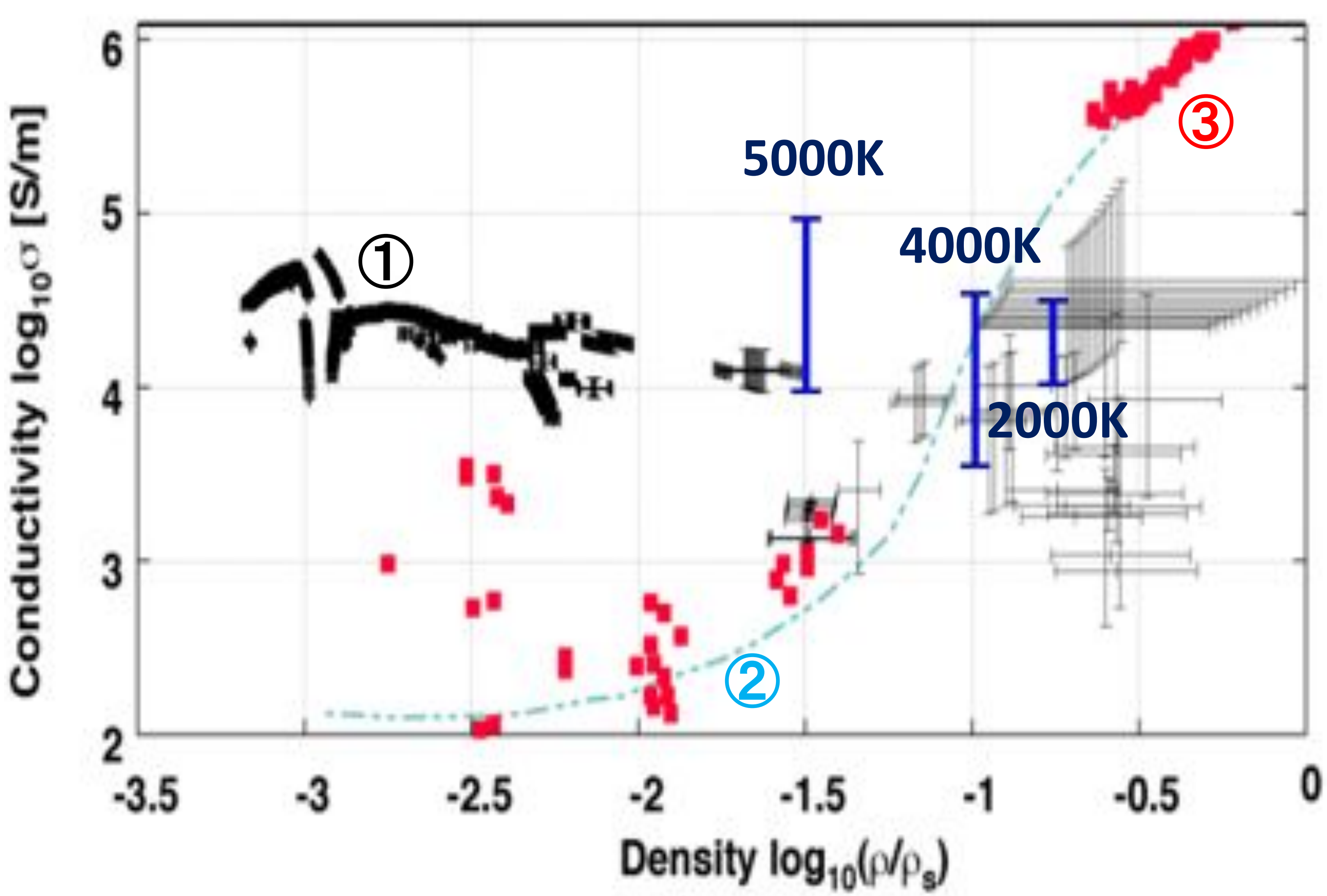
⇒ WDM state can be generated

Typical Evolution of Foam/plasma Temperature and Electrical Conductivity (@0.032ρ_s)



The electrical conductivity of foam/plasma is estimated to be 10^4~10^5S/m.

Comparison of Electrical Conductivity



① The experimental result using thin wire (5000K), T.Sasaki, et. al., Phys. Plasmas, 17, 084501(2010)

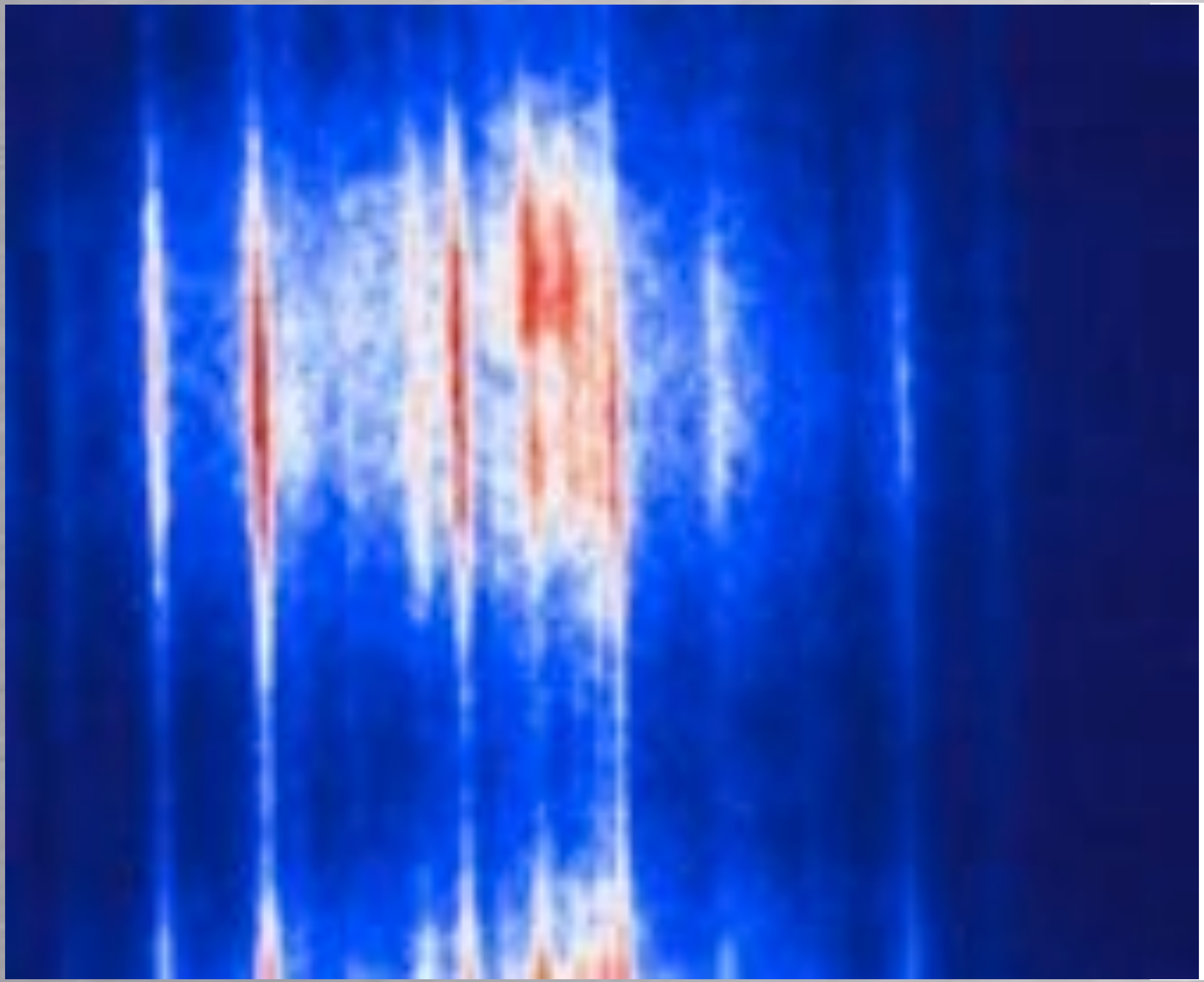
② The theory value by Lee-More-Desjalaius (6000K), M.P.Desjarlais, J.D.Kress, and L.A. Colins, Phys. Rev. E 66, 025401(2002)

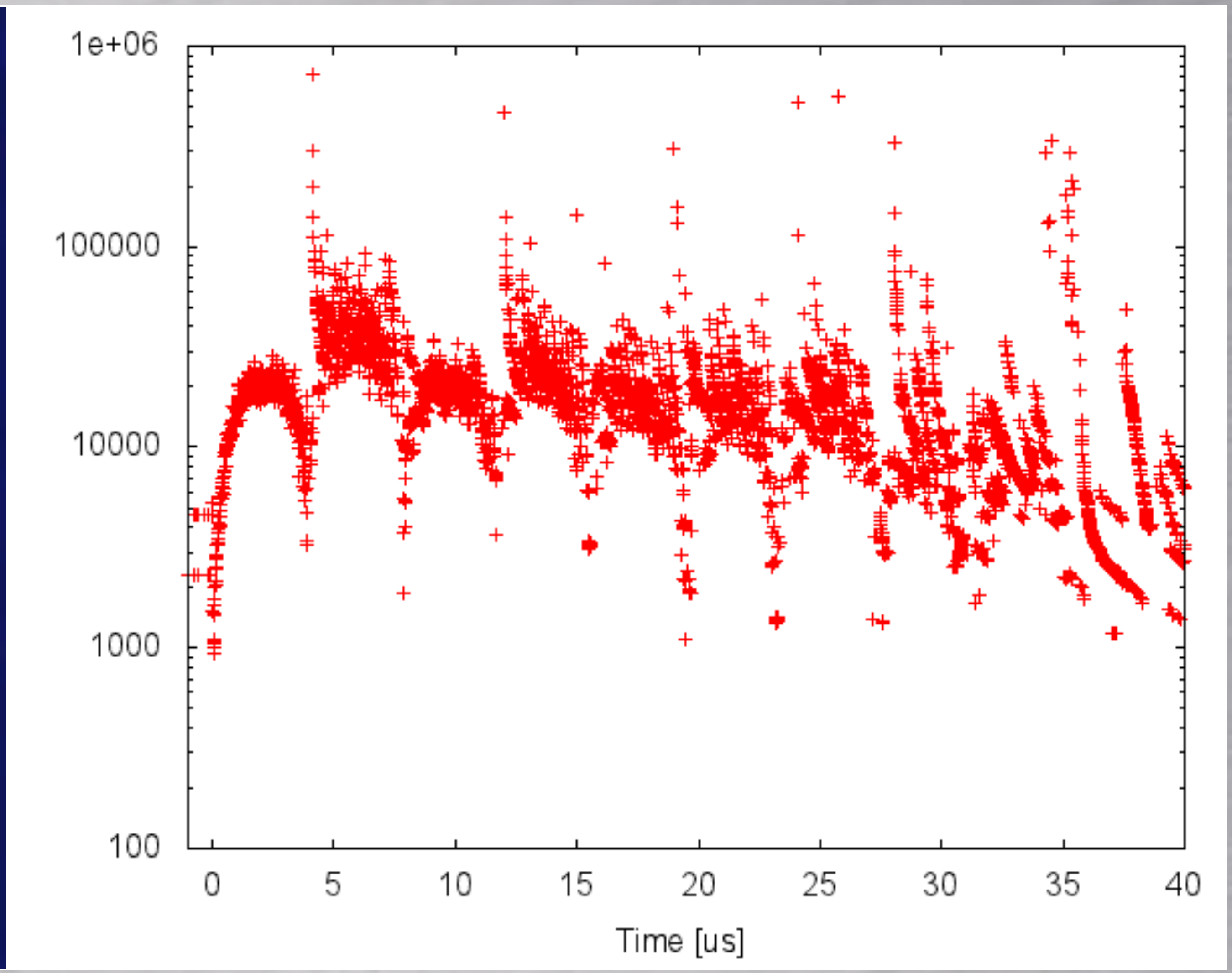
③ The experimental result by DeSilva (6000K), A.W.DeSilva and J.D.Katsouros, Phys. Rev.E 57, 5945 (1998)

The results indicate that the electrical conductivity by using isochoric heating method is comparable to the previous experiments.

We will evaluate the temperature dependence of electrical conductivity.

Gold foam/plasma is also evaluated





The results indicate that the electrical conductivity by using isochoric heating method is comparable to the previous experiments.

Remarks on KEK DA's study

Evaluate Physical Parameters of Matters in High Energy Density State based on Intense Charged-particle Beams

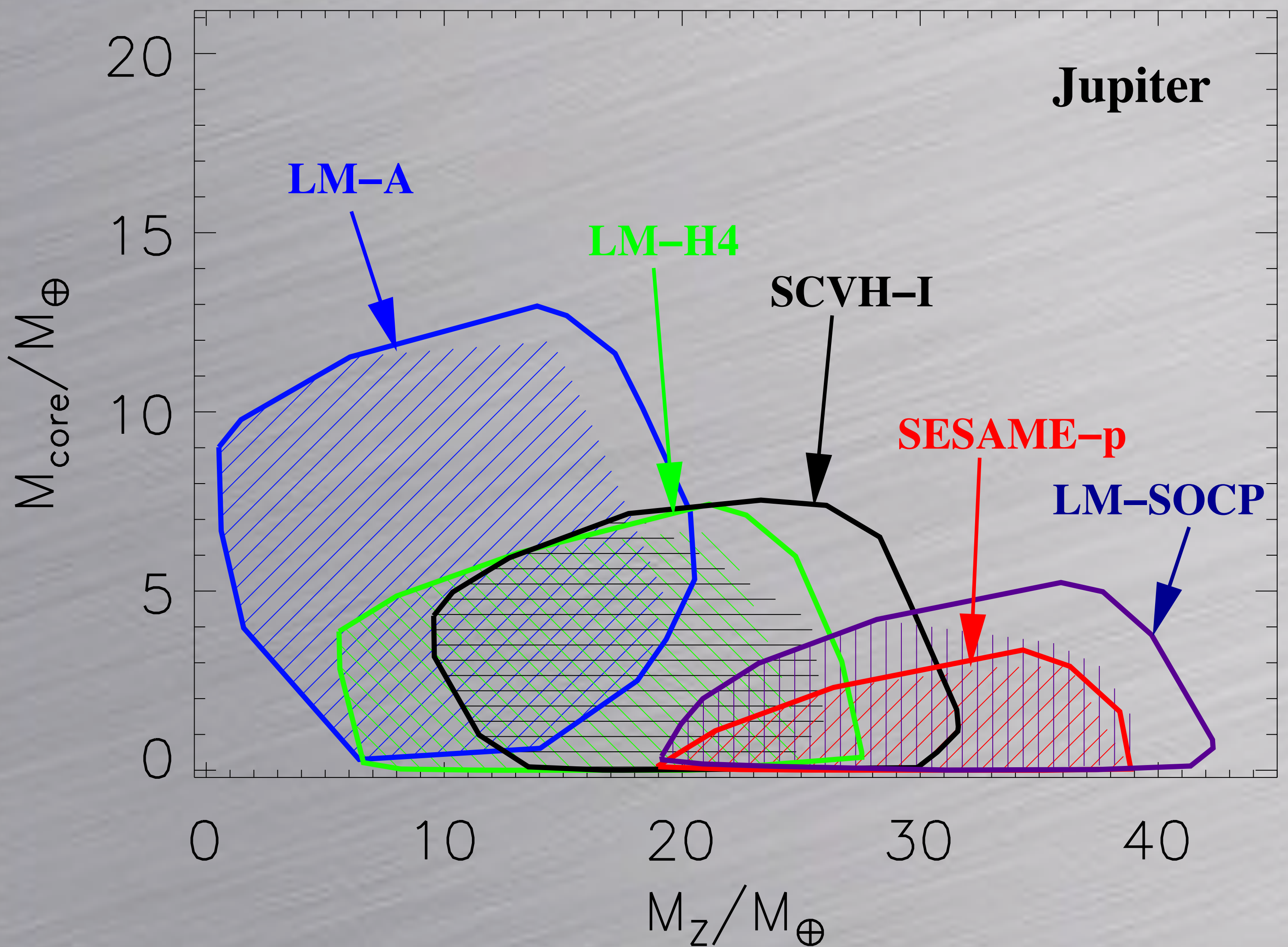
For DA and Beamline

- ➢ Achievable beam parameter from KEK DA to HEDP experiment section?
  - Provable Beam Number
  - Extending Accelerator with beam controlling technique (accumulation, cooling, bunching)

For HED Target

- ➢ Achievable parameter region of matters in HED state?
- ➢ How to make quasi-uniform target?
- ➢ What are research opportunities?

Exploration of the origin of the solar system from the internal structure of the giant planets



➢ To evaluate the interior of giant planet as the Jupiter, we make the same condition (P~200GPa, T~6000K)*

*D. Saumon, et. al., Astrophys. J., 609, 1170(2004)

➢ Energy Density

➢ Achievable Density

➢ Entropy Condition

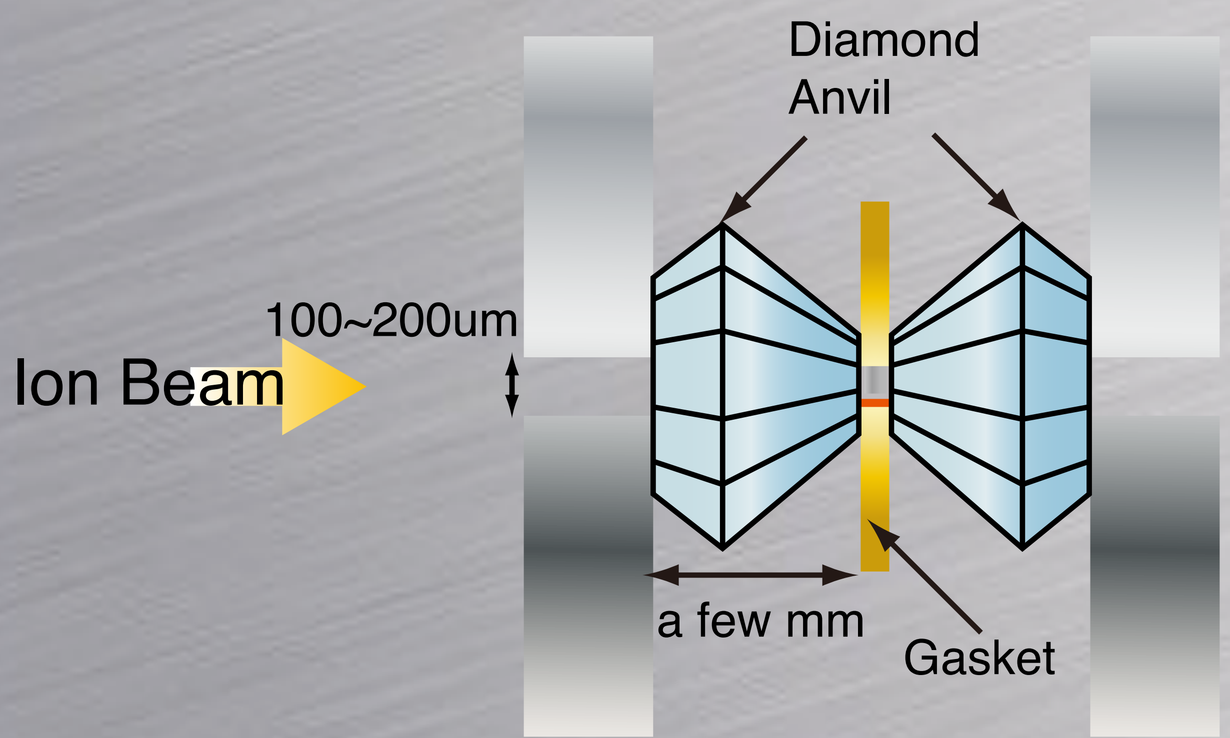
If we use the shock compression,

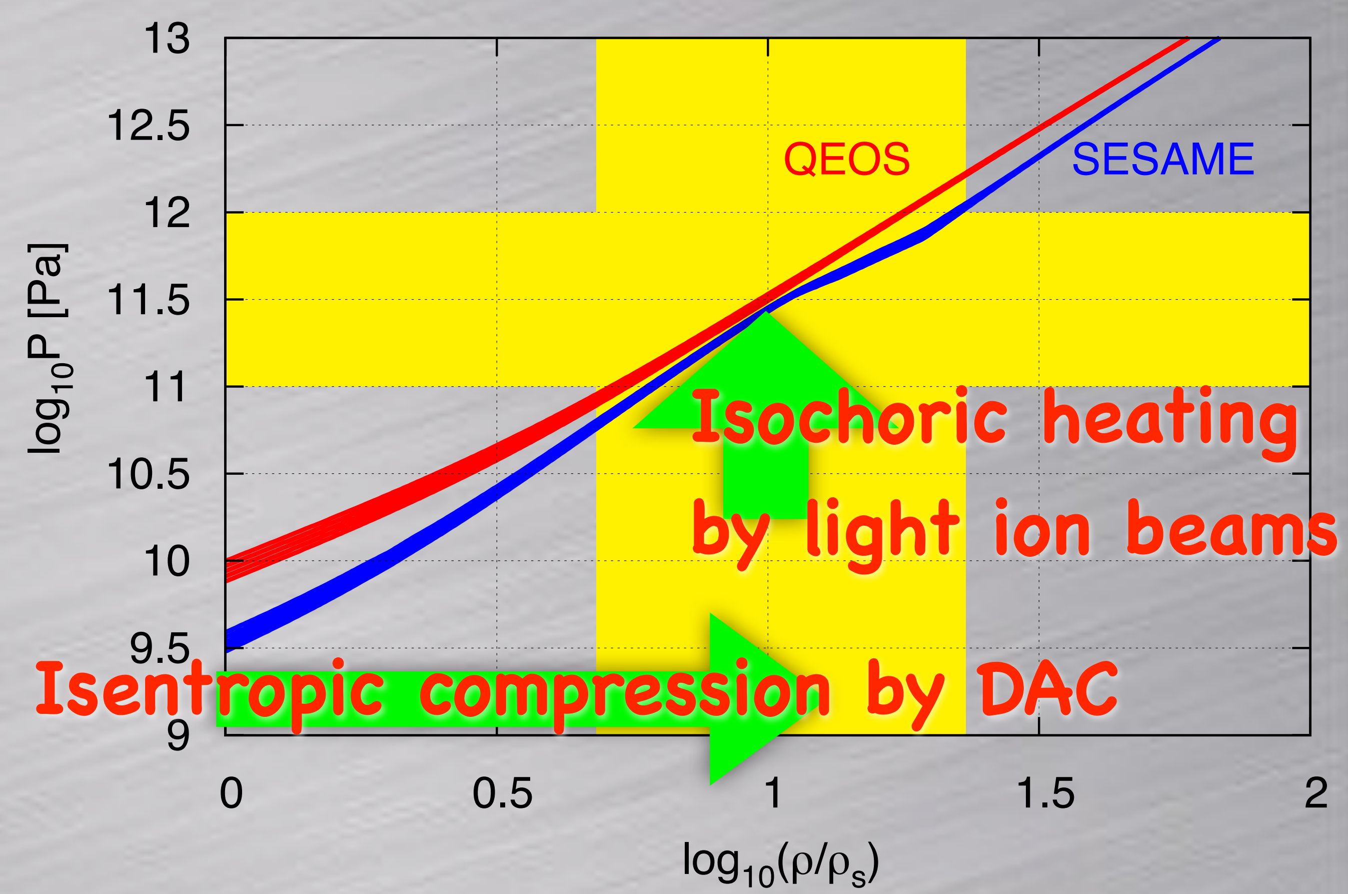
$$S_1 - S_0 = C_v \ln\left(\frac{p_1\rho_0^\gamma}{p_0\rho_1^\gamma}\right) = C_v\left\{(\gamma-1)\ln\left(\frac{p_0}{p_1}\right) + \gamma\ln\left(\frac{T_1}{T_0}\right)\right\} > 0.$$

Strongly depend the initial target condition

11年10月25日火曜日

The information of Jovian interior will be provided by diamond anvil cell (DAC) with intense ion beams





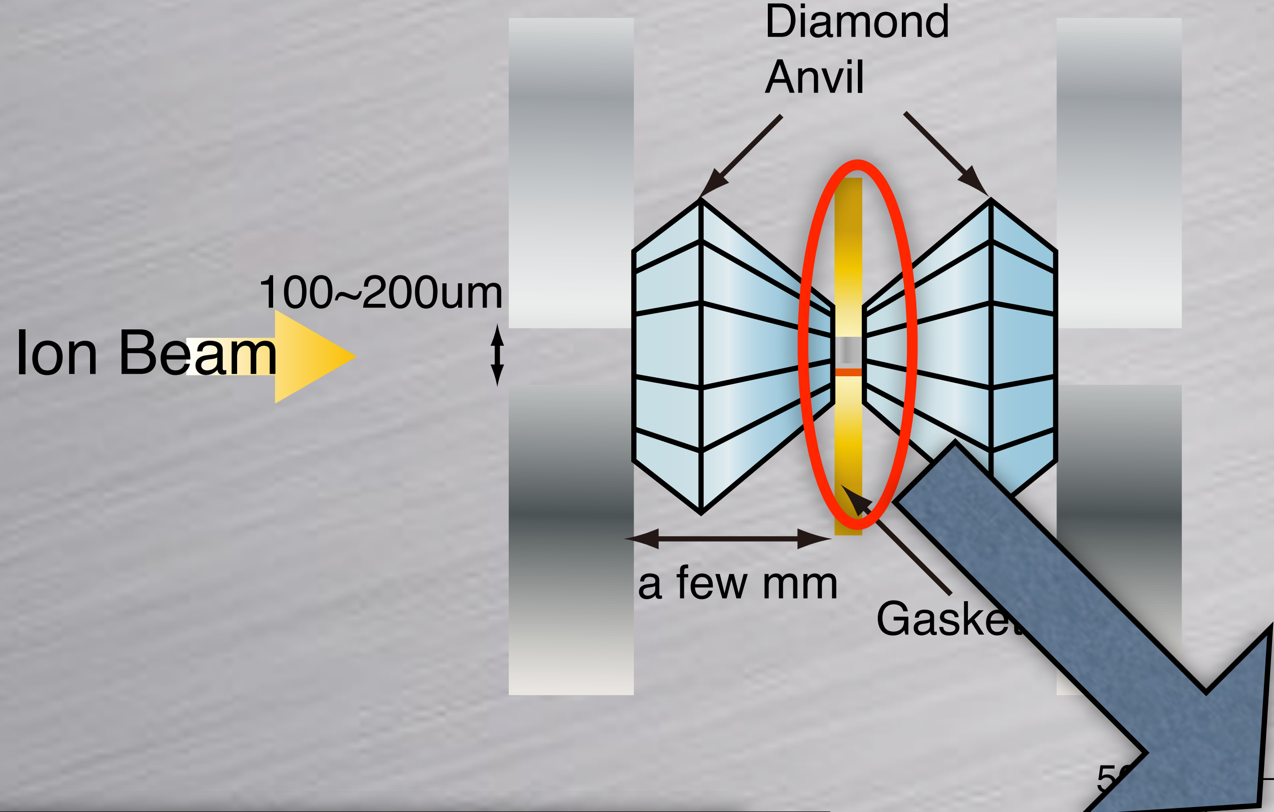
Merits of DAC with intense ion beam

- Direct heating by Bragg peak -> efficient heating
- Well-known deposition profile at diamond anvil
- Low costs, and simple structure

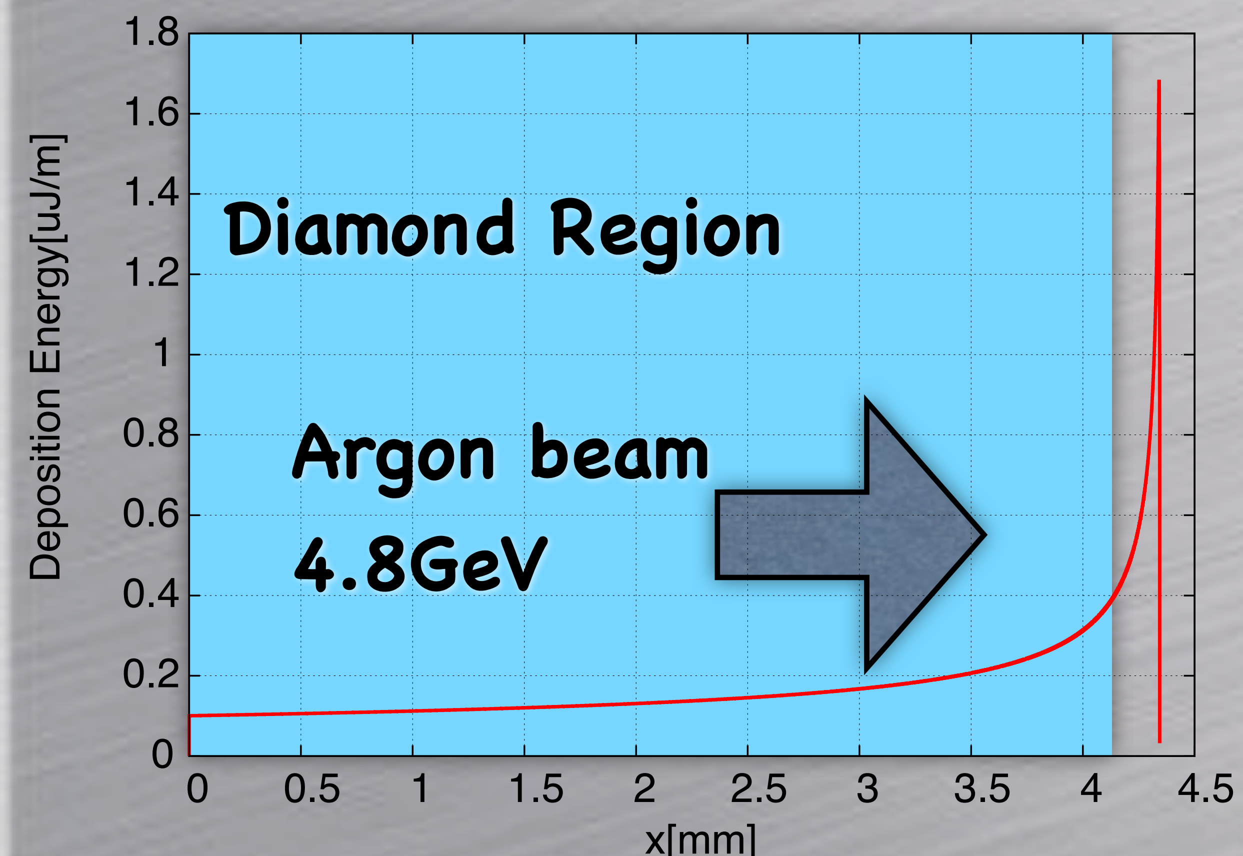
Demerits of DAC with intense ion beam

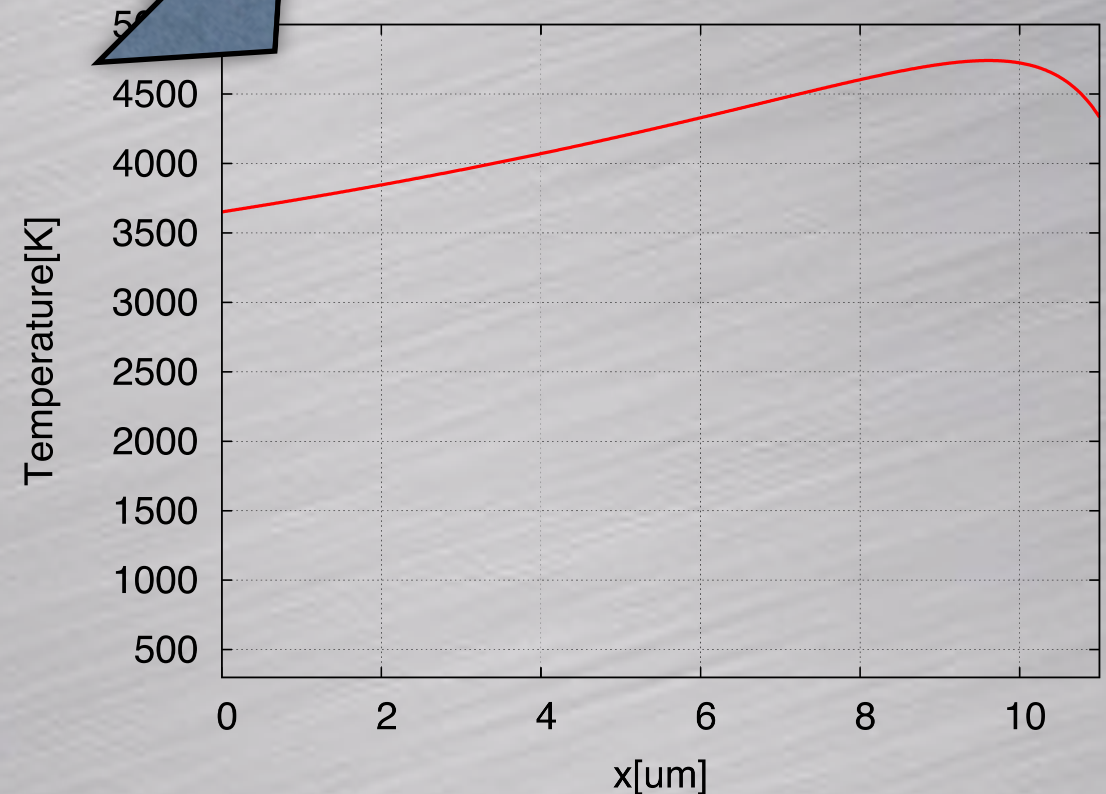
- Small sample size

Possible parameter region based on DAC with intense ion beams



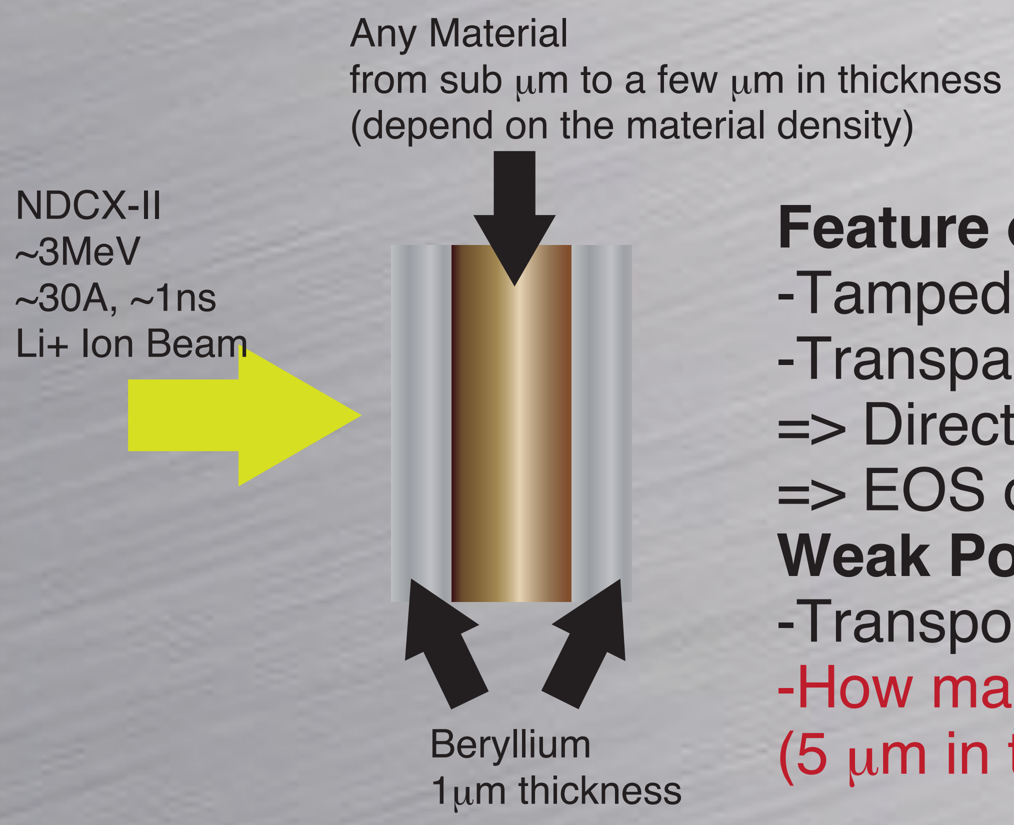
10x compressed hydrogen irradiated by argon ion beams with 1.9×10^{10} per bunch





Achievable target temperature is 4300K with 10 um in length.

WDM experiment with NDCX-II (sandwiched target)



Feature of the target

-Tamped observation material by Beryllium.

-Transparent for X-ray Regime.

=> Directly observe the hydrodynamic motion of any material.

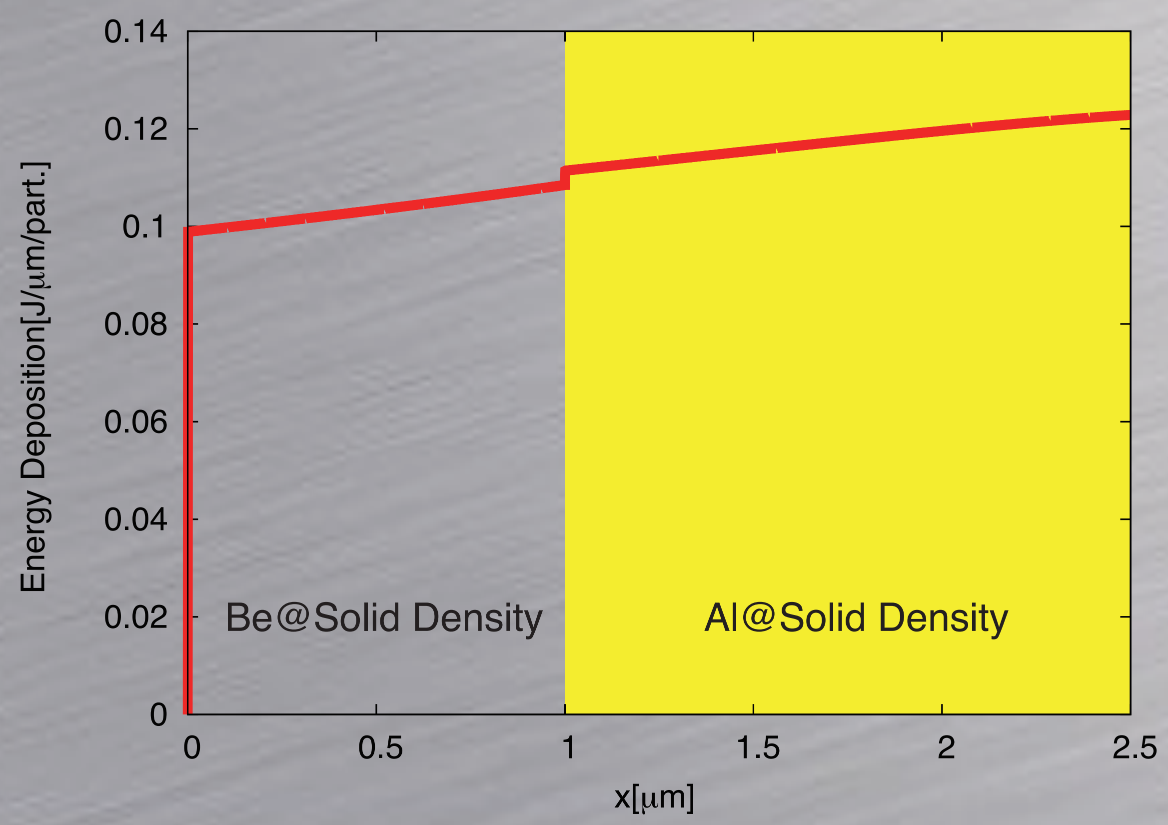
=> EOS comparative study both Ex. and Sim. results.

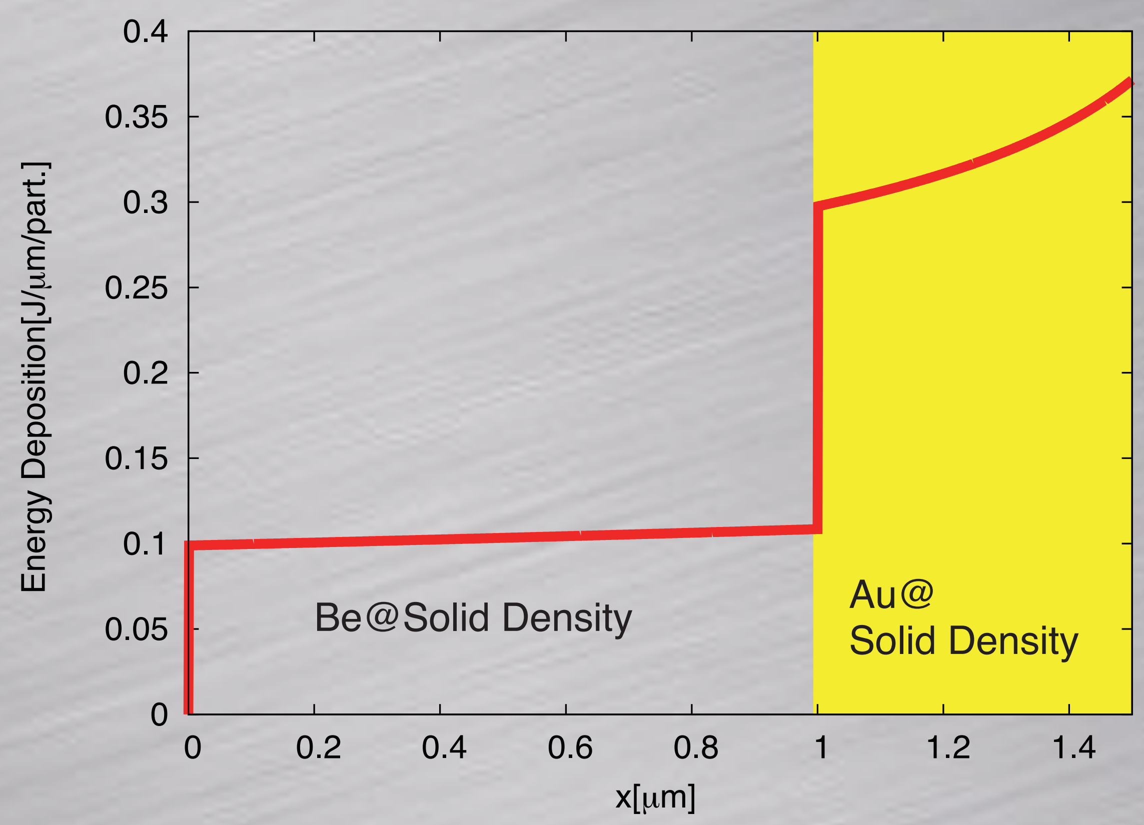
Weak Point

-Transport properties as an electrical conductivity is difficult to evaluate.

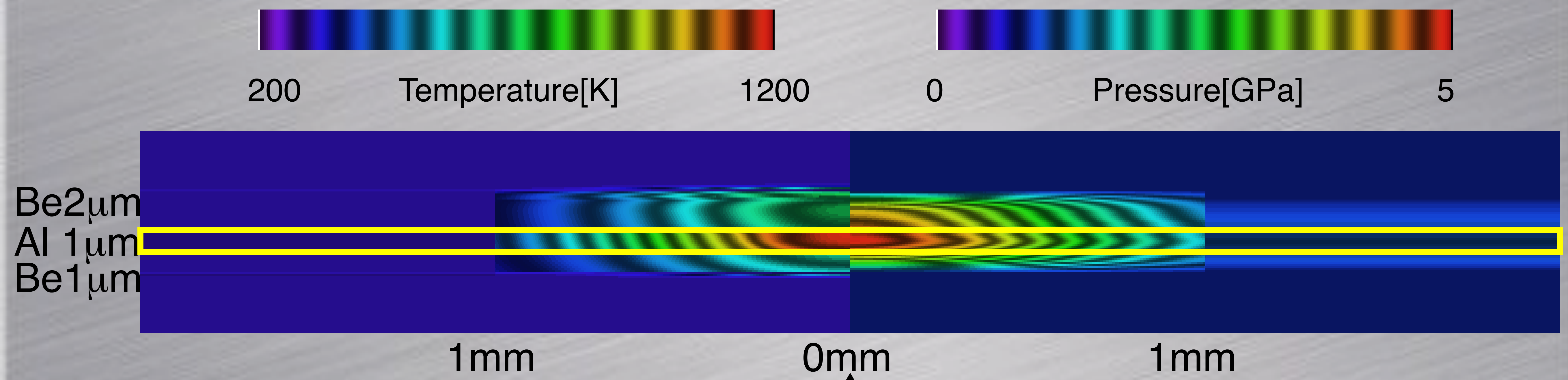
-How mach is the possible thickness of Be?(vapor deposition?)

(5 μm in thickness of Be is produced, industrially.)

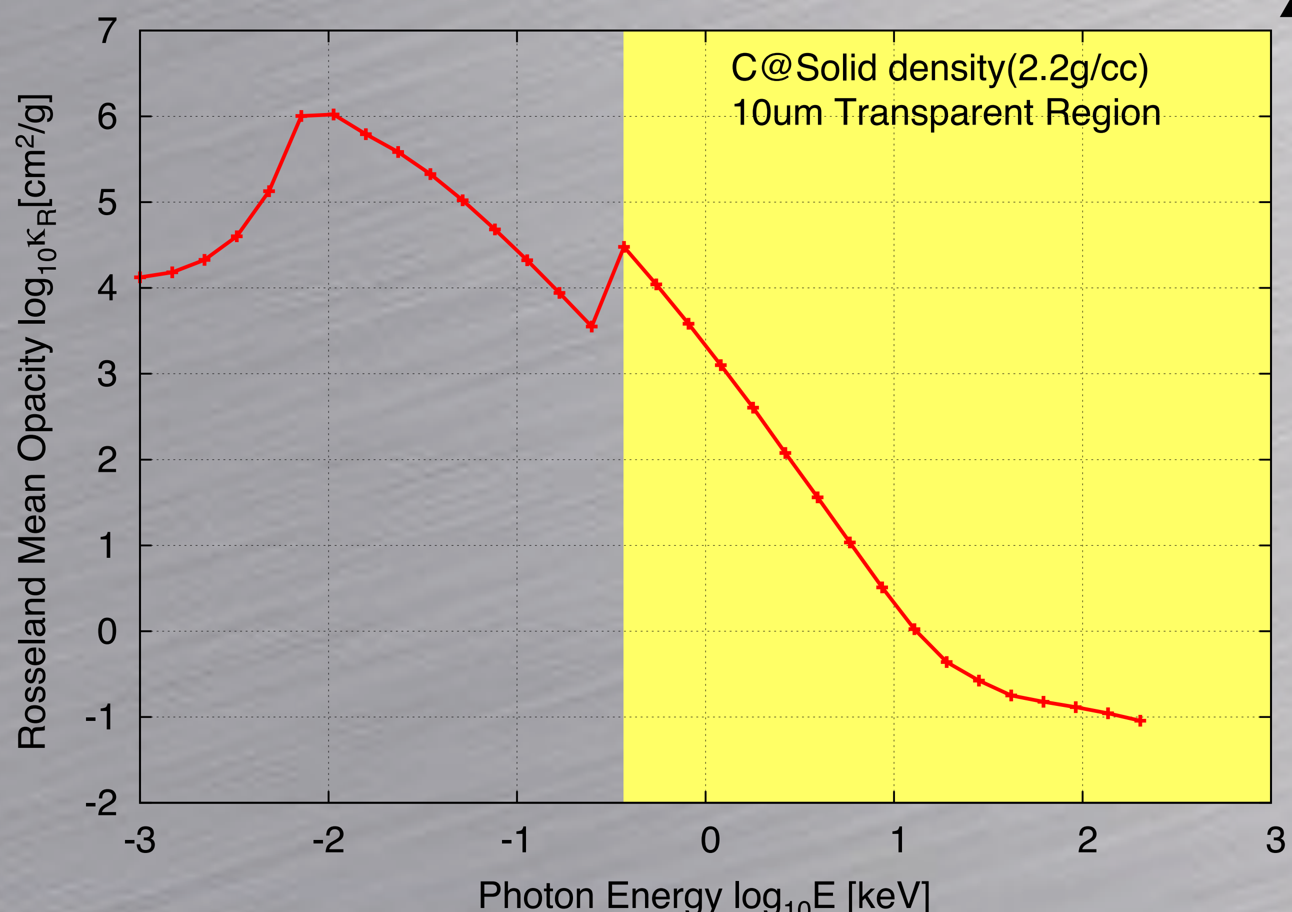




Preliminary results for sandwiched target(@0.1ns)



Li+ Ion Beam
3MeV ~30A r_b=1mm
R-direction: Gauss Dist.
L-direction: Flat



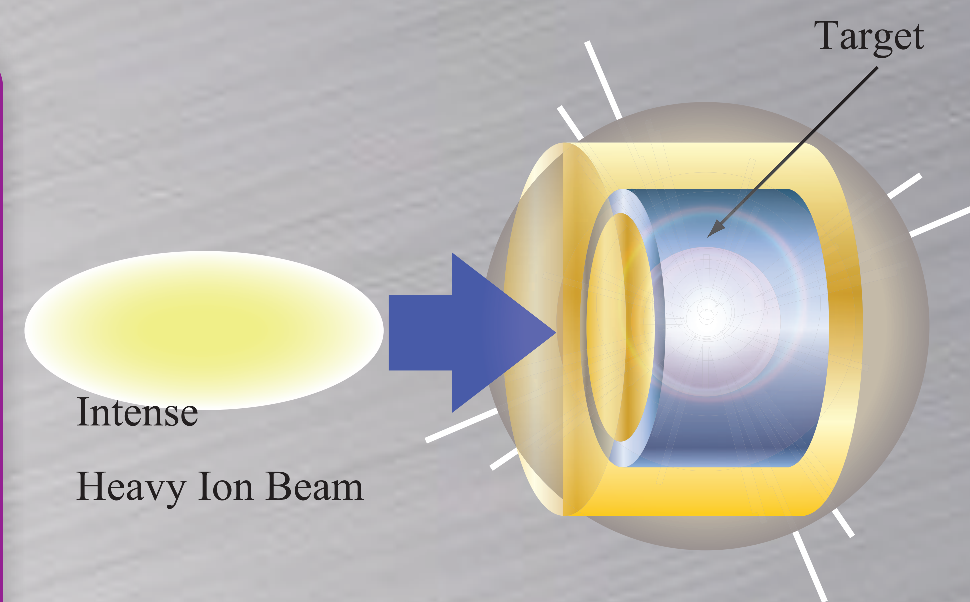
Homogeneous regime is about 0.1mm.

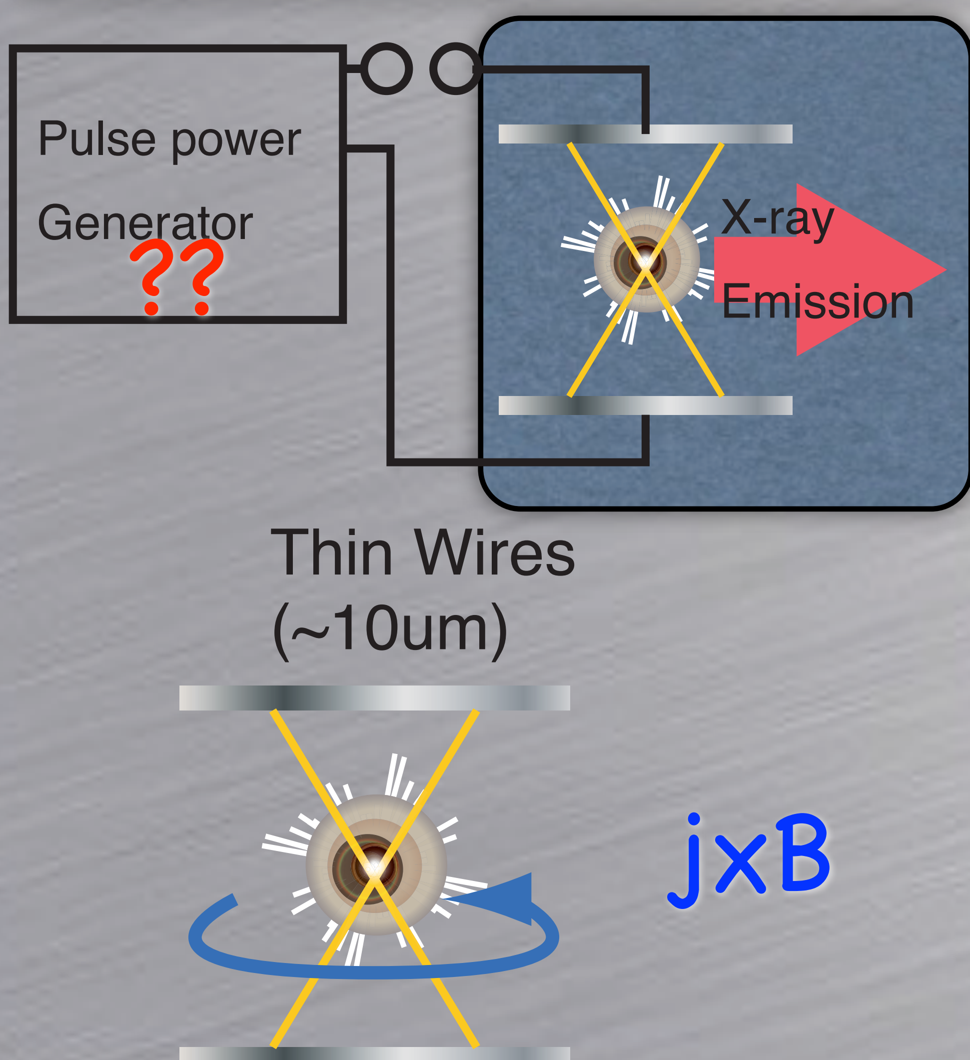
=> required point spot X-ray sources

Requirement parameters for X-ray sources

Observing plasma parameters

- Density range -> $0.1\rho_s - \rho_s$
- 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

Estimation of required pulse generator

$$\frac{1}{2}\Delta m v^2 = \frac{3}{2} nkT\Delta V$$

$$\Rightarrow \quad v = \sqrt{\frac{3\left(1+Z_{eff}\right)kT}{Am_p}}$$

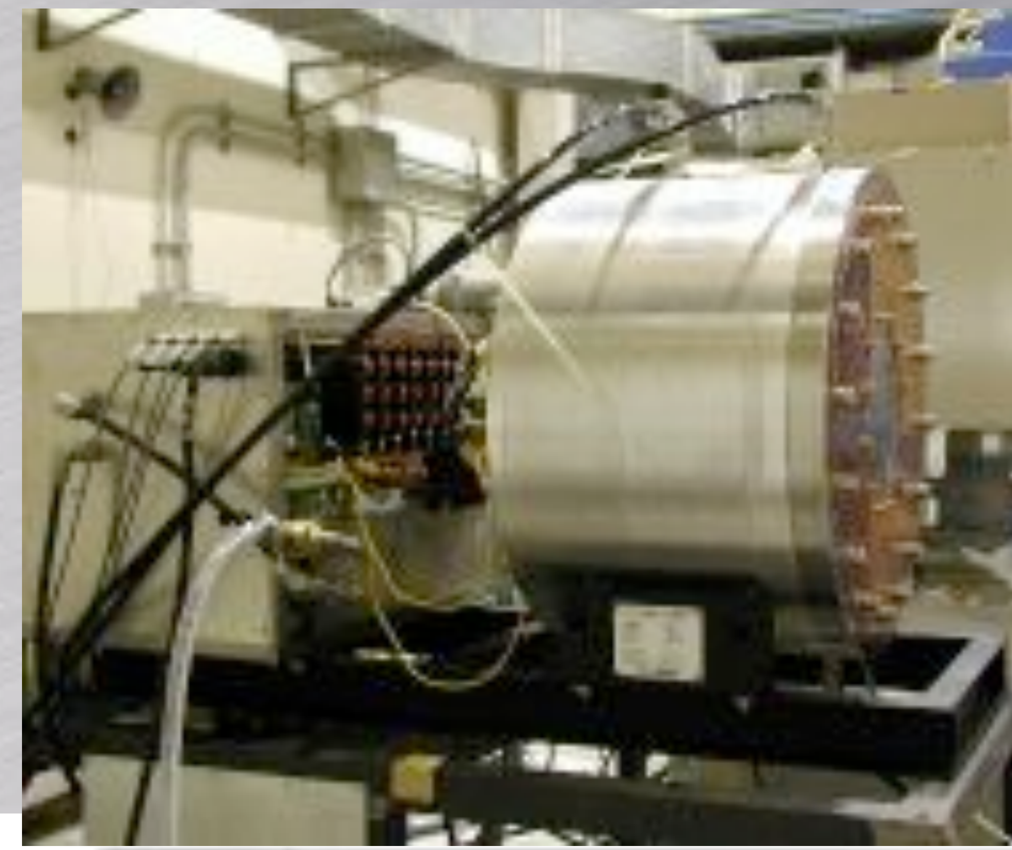
T=2keV and Fully ionized aluminum: v ~ 10^6 m/s

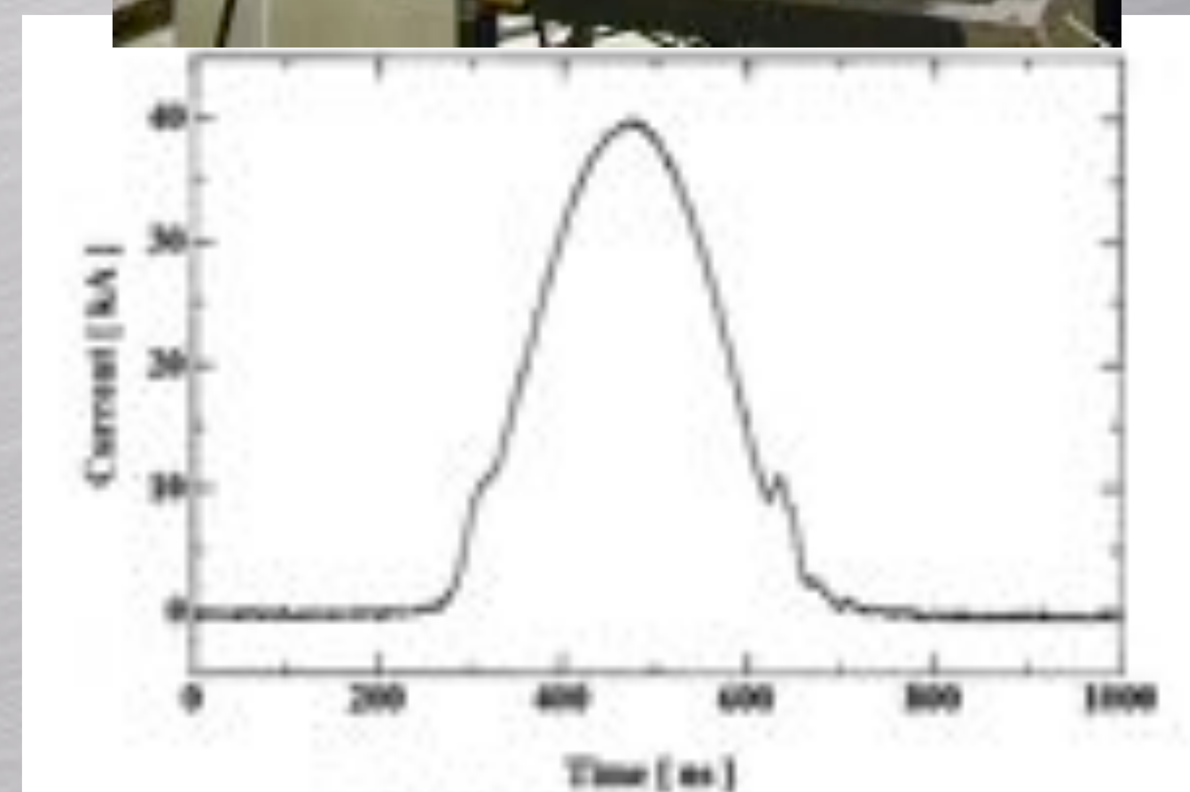
$$W = \frac{d}{dt}\left(\frac{1}{2}LI^2 + RI^2\right) = \frac{d}{dt}\left(\frac{1}{2}mv^2\right)$$

$$\frac{1}{2}\dot{L}I^2 + LI\dot{I} = mv\dot{v}$$

I=100kA, r=1um, L~100nH, and dv/dt~10^{18}m/s^2

$\Rightarrow$ dI/dt=10^{12}~10^{13}A/s =>100kA-100ns

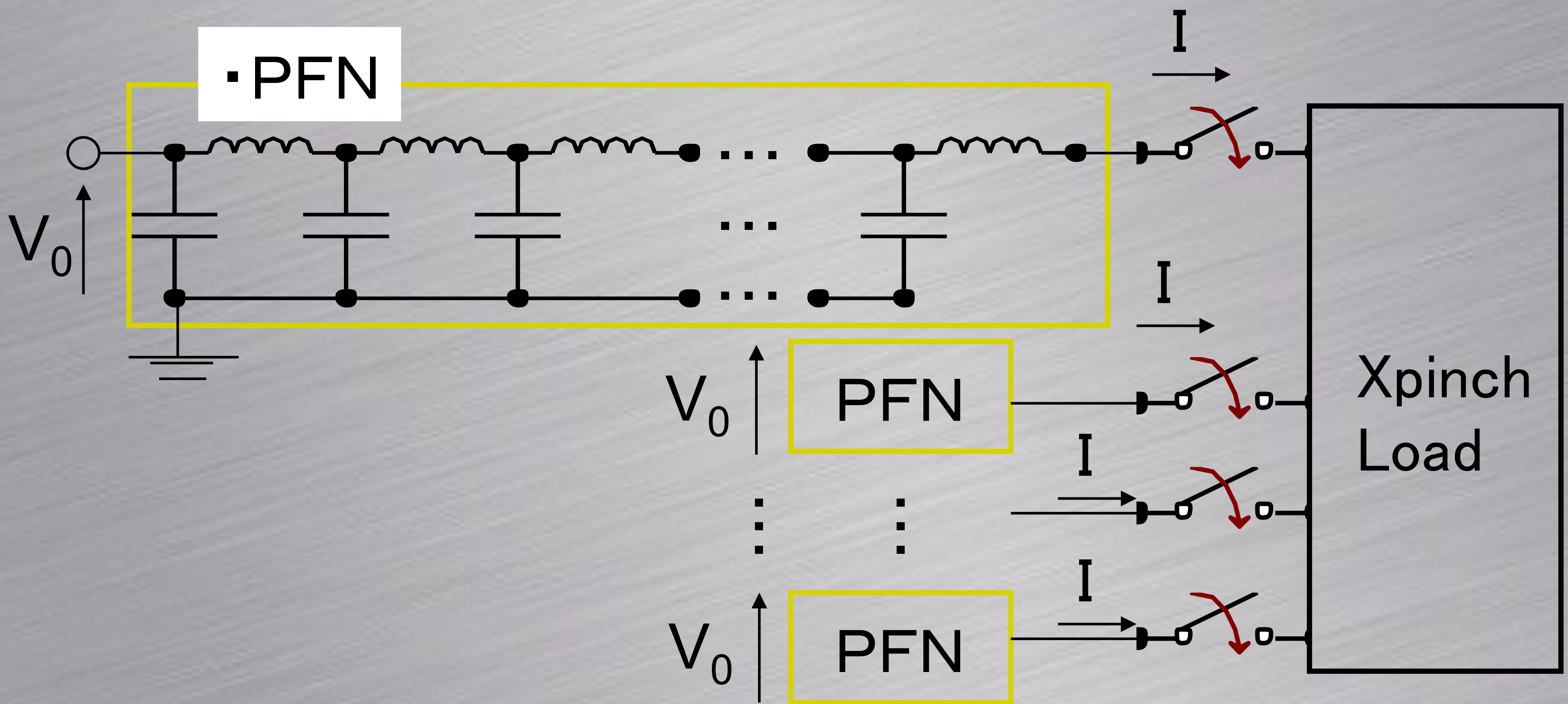




Magnetic pulse-compression system

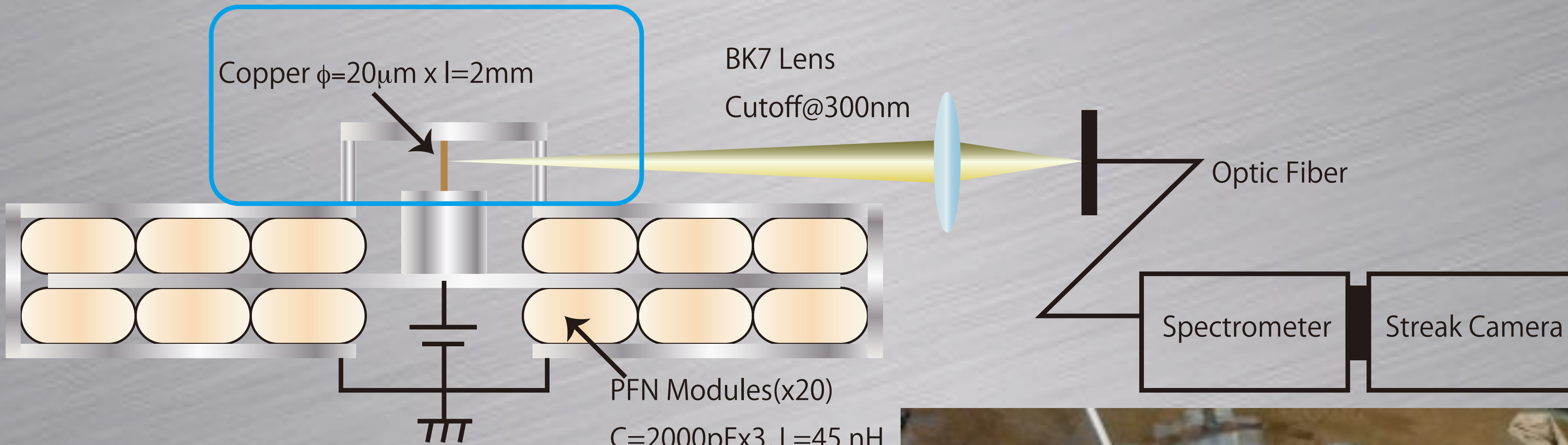
N. Ohshima et.,al, IEEJ FM Vol. 125 (2005) pp.25-29

Pulse Forming Network (PFN) Modules



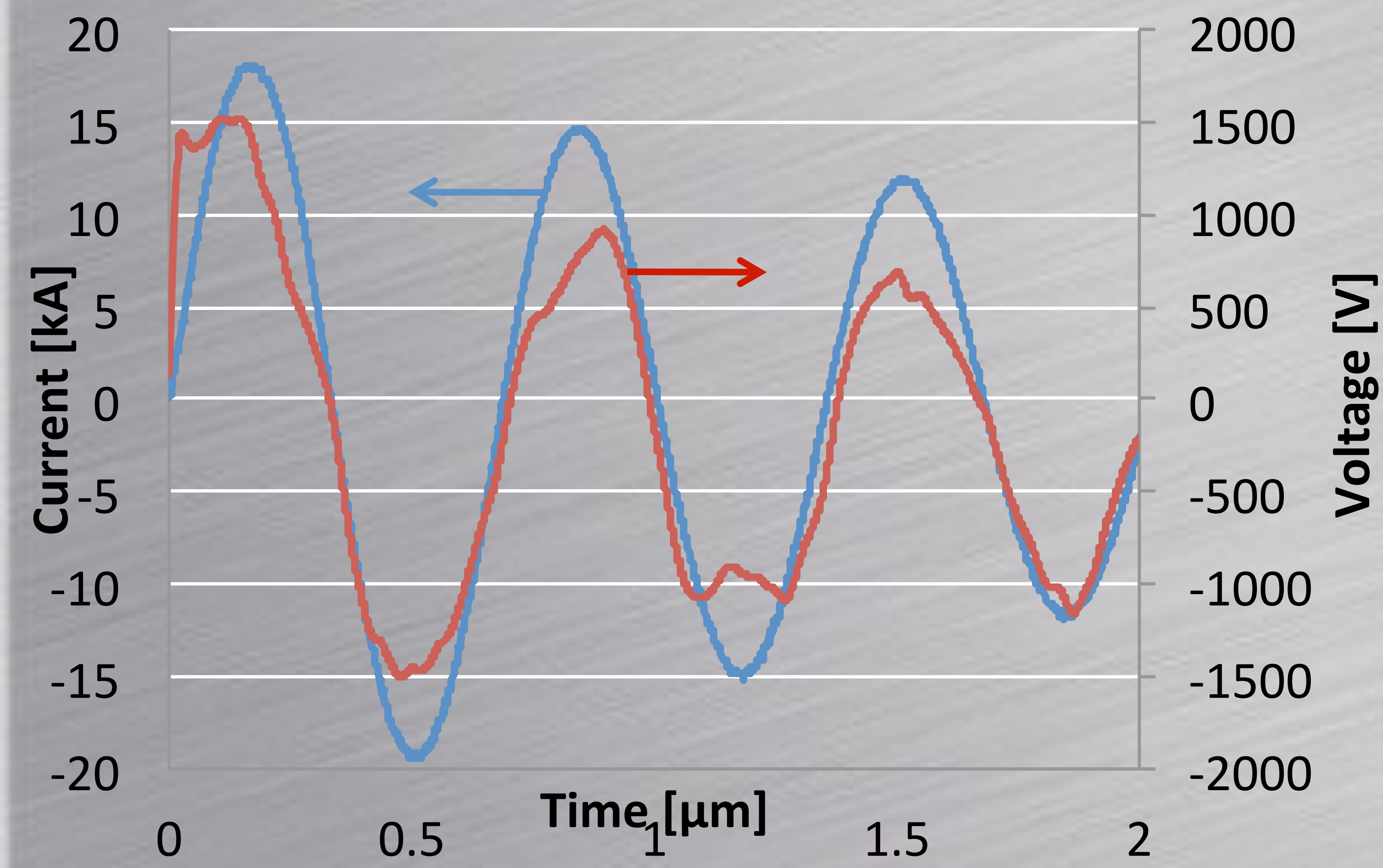
➢ **Lowering output impedance, PFN modules are parallel configuration.**

Demonstrating PFN system



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

Demonstrating PFN system



$$V_{Load} = V - L\frac{dI}{dt}$$

Applied Voltage at load → 1.5kV

Peak Current → 18 kA

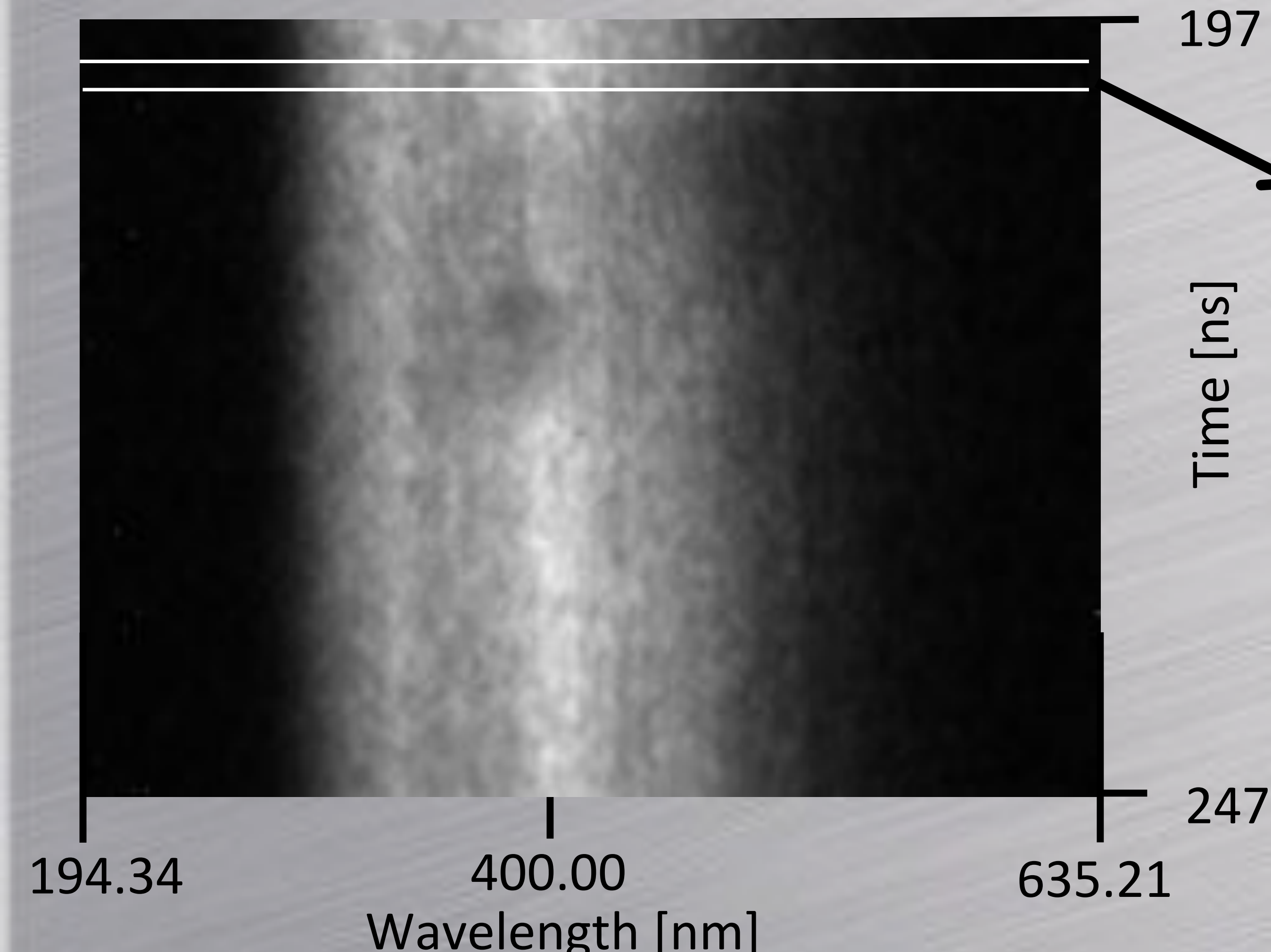
Discharge Cycle → 0.6 us

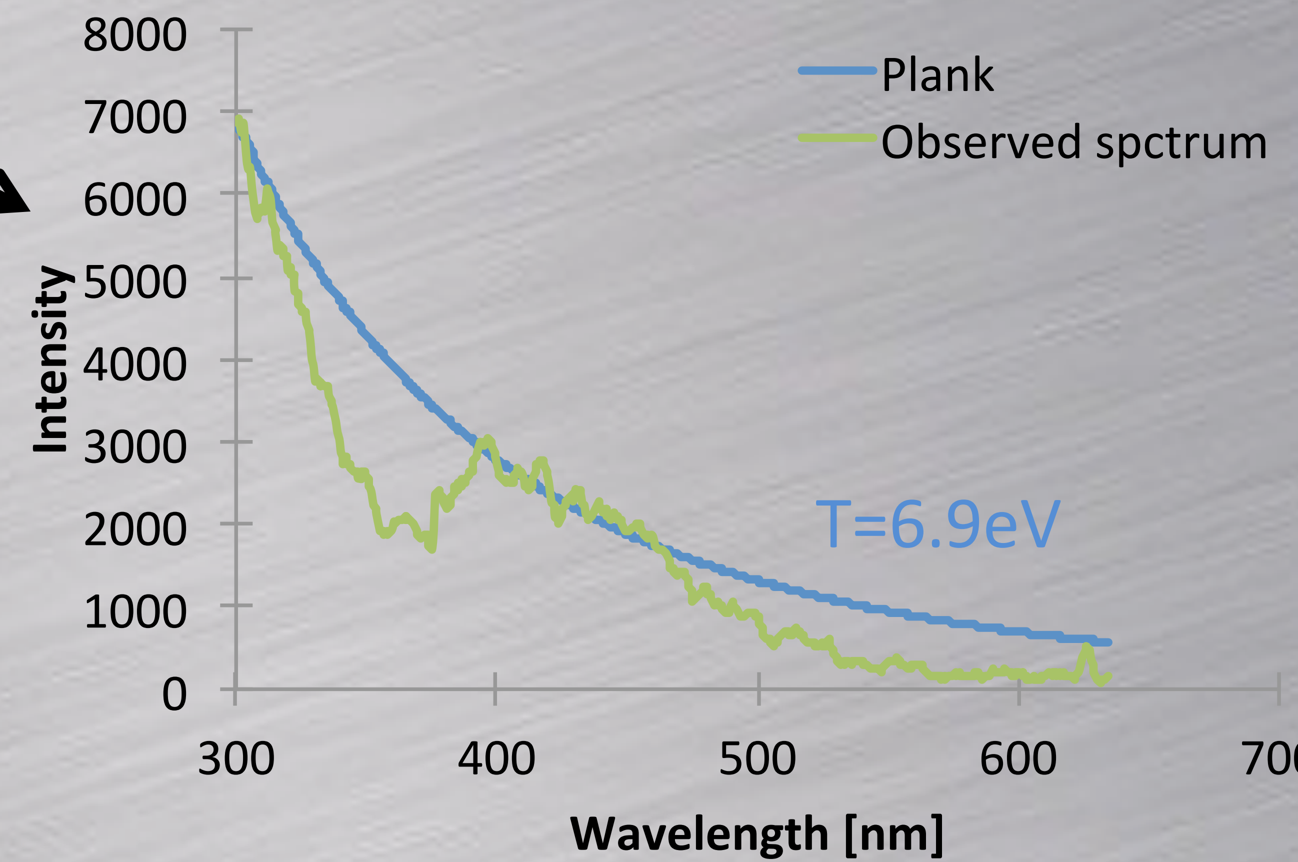
Rising Time → 107 ns

Current rising rate is estimated to be 1.8×10^{11} A/s.

⇒Current rising rate can be increased PFN voltage.

Typical Emission Spectrum and Temperature





202ns from the beginning of discharge

- Emission spectrum can be assumed blackbody radiation.
- Radiation temperature estimated to be 6.9eV.

$$I(\lambda,T)d\lambda = \frac{2hc^2}{\lambda^5}\frac{d\lambda}{\exp\left(\frac{hc}{\lambda kT}\right)-1}$$

Planck's Formula

Concluding Remarks

- ➢ WDM experiment by using pulsed-power devices with isochoric heating is demonstrated. The results indicate that the observed electrical conductivity is comparative to the previous experiments.

- ➢ WDM experiment by using intense ion beam target is calculated. The target structure of intense ion beam have a potential as flexible geometry, and huge approach of scientific abundances.

- ➢ Point spot X-ray generator is demonstrated for single wire explosion. The current rising time is estimated to be order of 10^{11} A/s.