長岡技術科学大学

Nagaoka University of Technology
PLASMA LABORATORY

High Energy Density Experiments based on Extream Power Devices at NUT

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Extreme Energy-Density Research Institute
NUT

12th US-Japan Workshop on
Heavy Ion Fusion and High Energy Density Physics

Outline

- Introduction to Extreme Power Devices in NUT

- Generation and Evaluation for High Energy Density Matter based on Pulsed-power and Intense Charged Particle Beams
  - Pulsed-power Device
  - e-Beam
  - Ion beam

- Concluding Remarks

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Pulsed-power Generator "ETIGO-II"

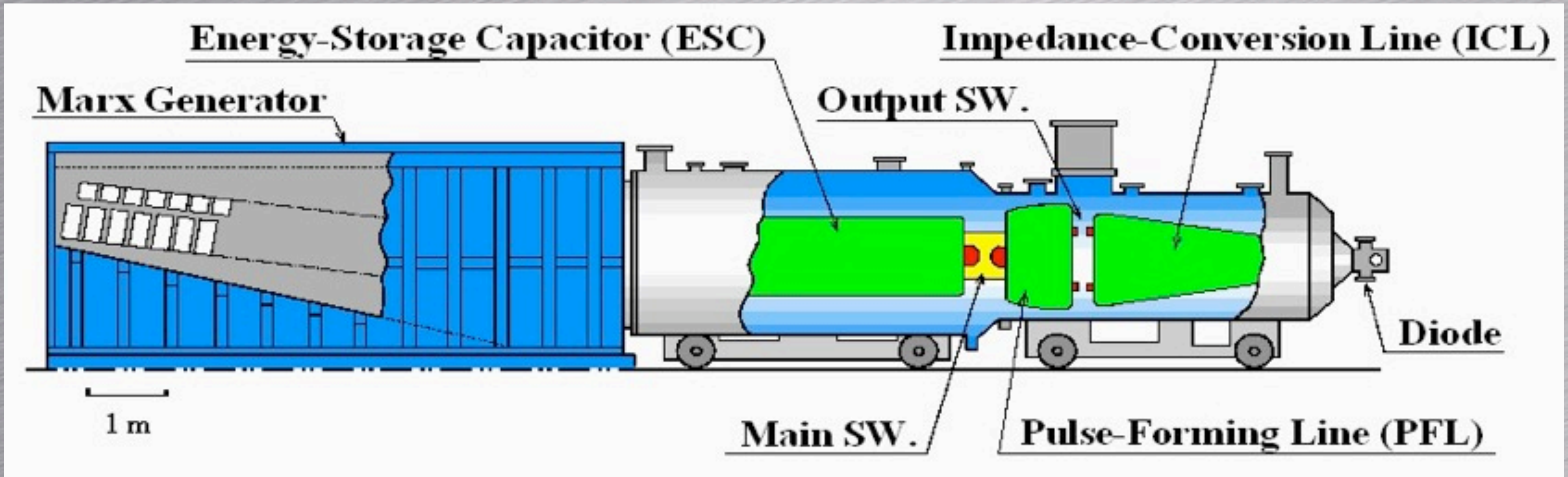
➢ 3MV, 460kA, 50ns H+

-> 1.4 TW, 160 KJ

➢ ETIGO-II is used for

1) Studies on pulsed ion beam generated ablation plasma.

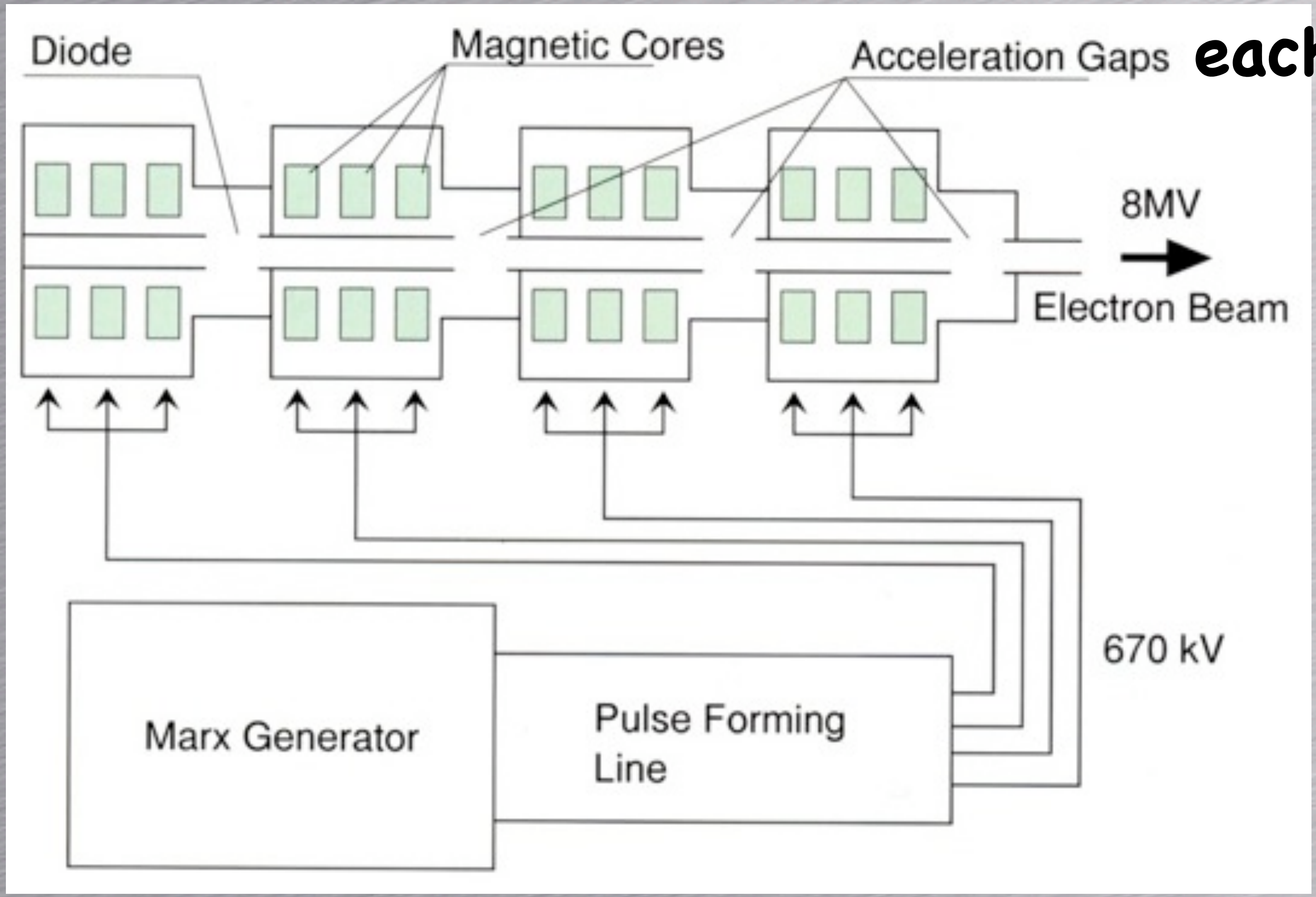
2) Tin film deposition.



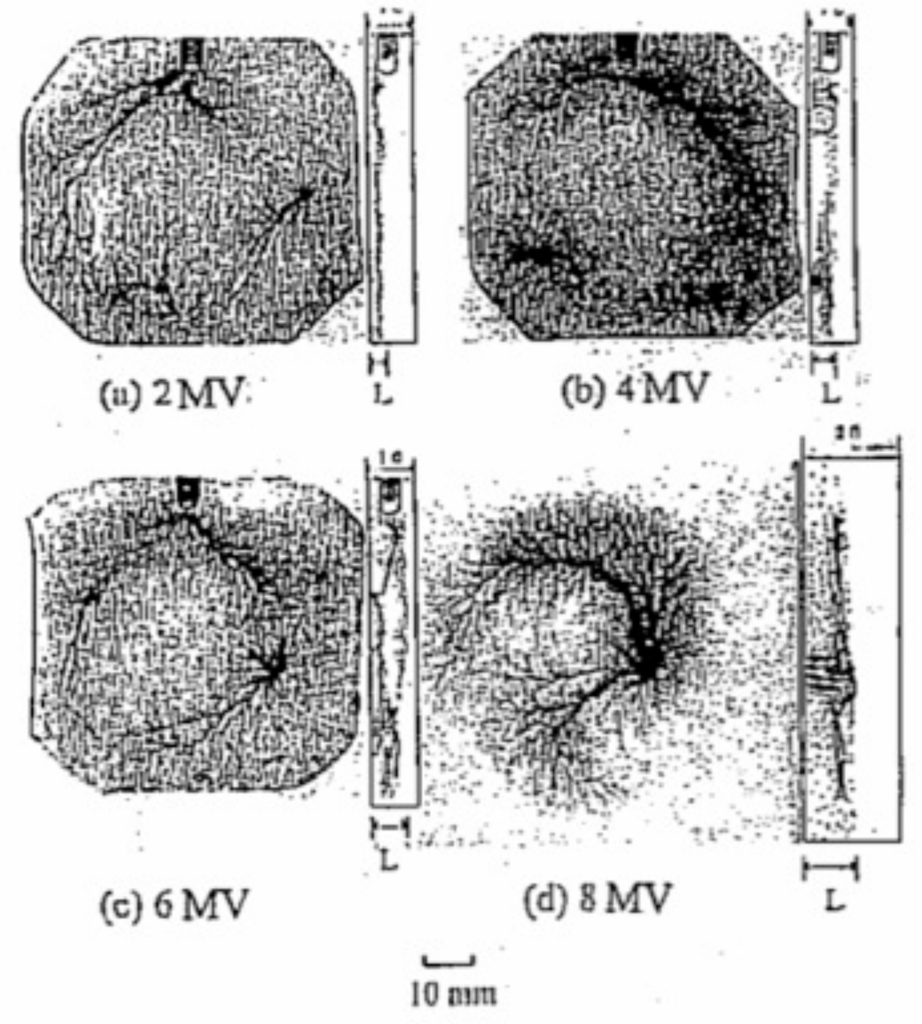
Linear Induction Accelerator "ETIGO-III"

- 8 MV, 5 kA, 30 ns, e-beam
  -> 40 GW, 1.2 KJ
- ETIGO-III is used for

1) Flue gas treatment.
2) Strong microwave device.

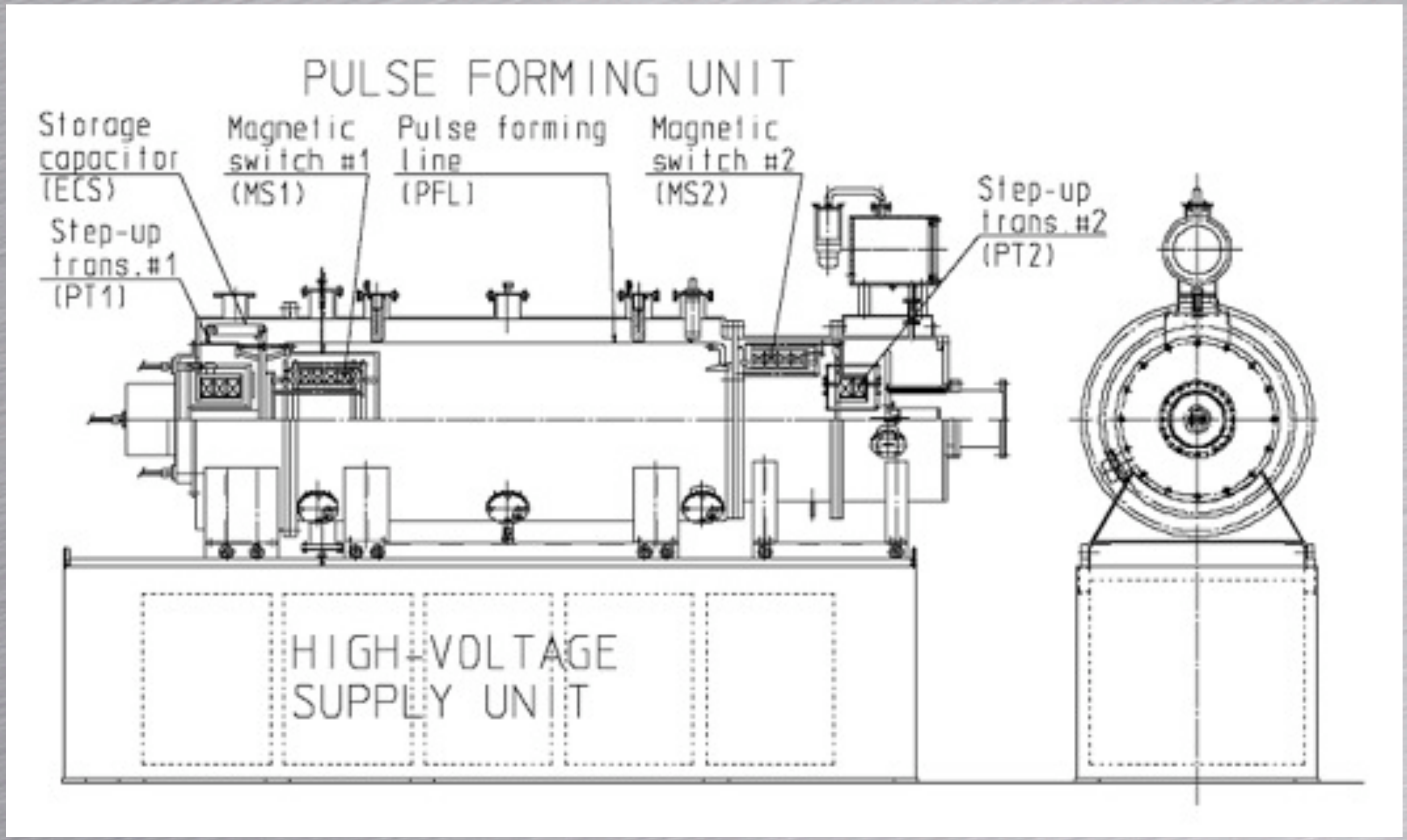


each 2MV

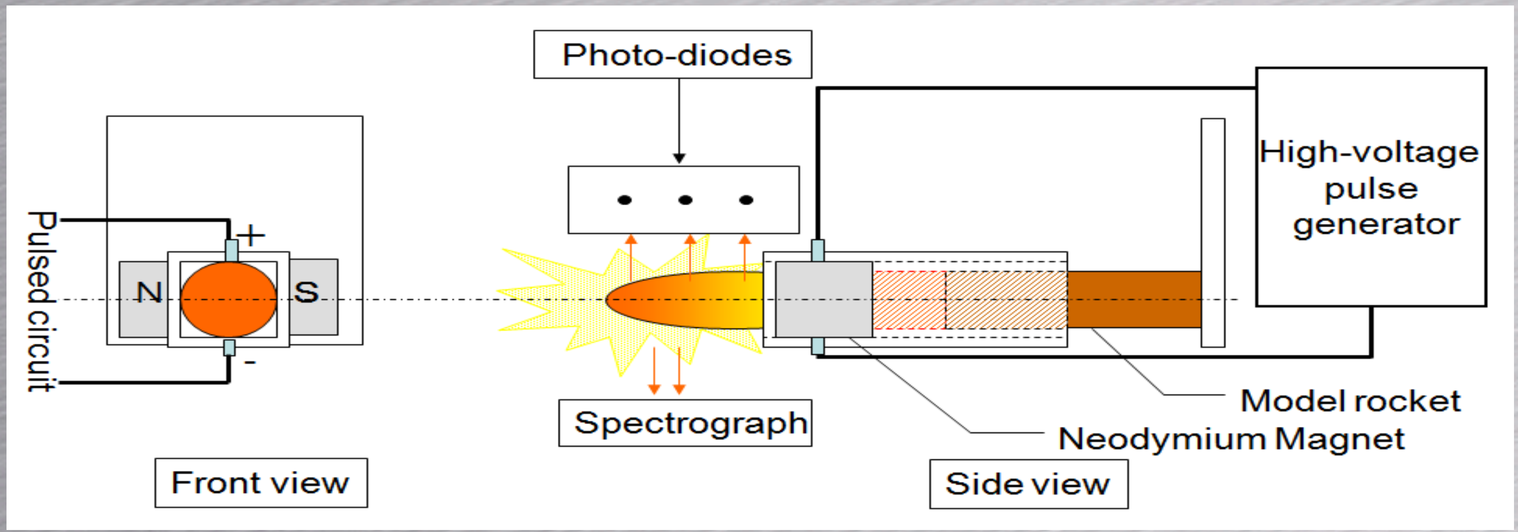


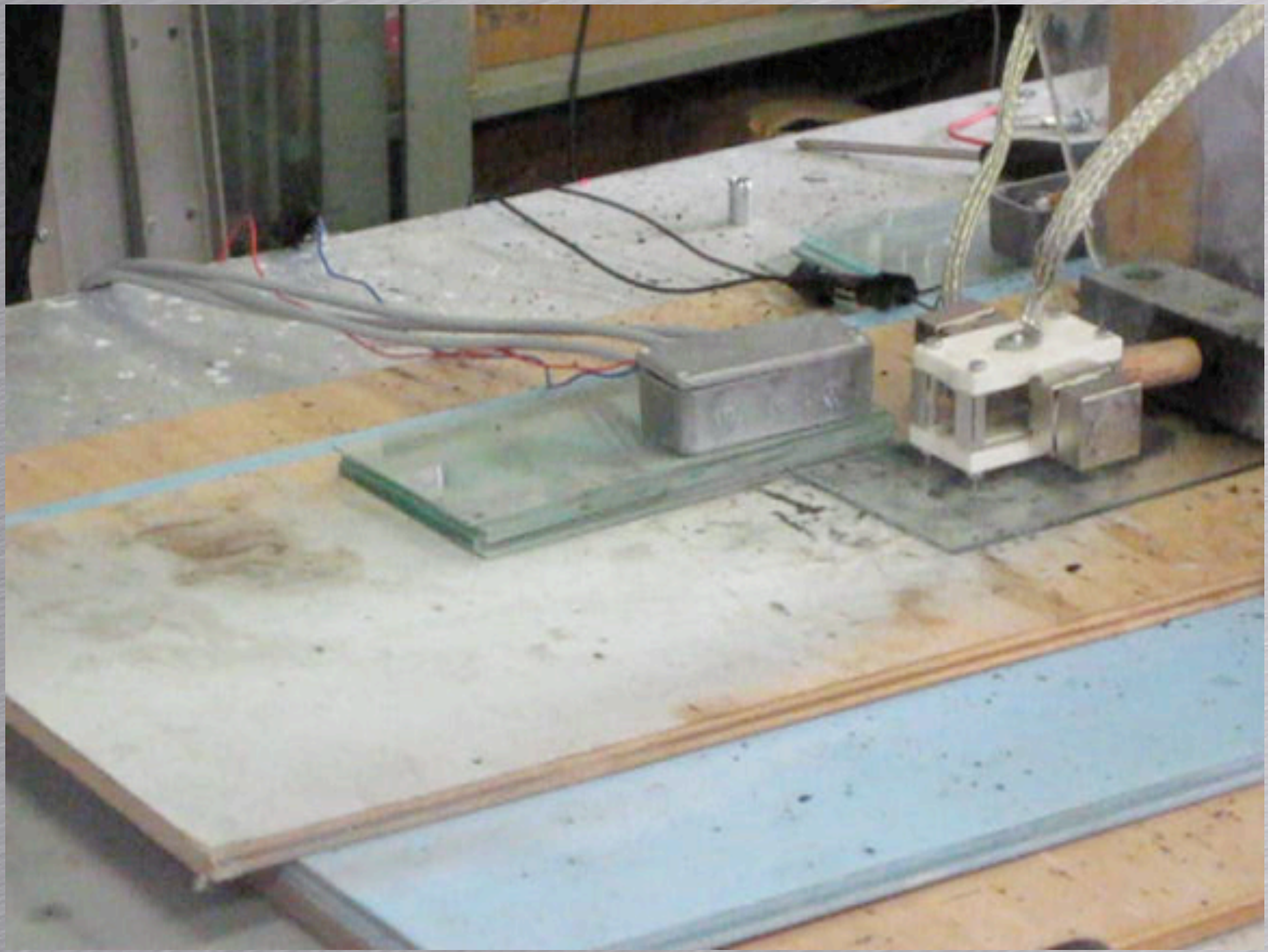
Repetitive Pulsed-power Generator "ETIGO-IV"

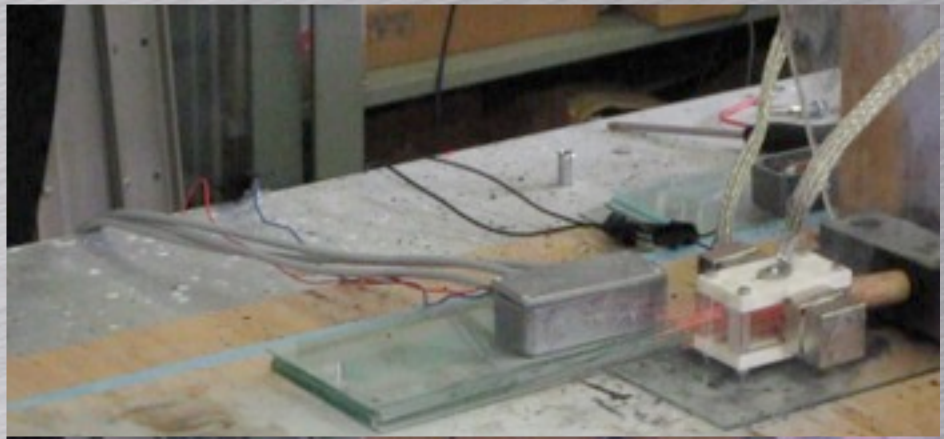
- 400~500 kV, 13 kA, 200 ns e-beam
  -> 40 GW, 1.2 KJ
- ETIGO-IV is used for
  1) Flue gas treatment.
  2) Large Orbit Gyrotron.

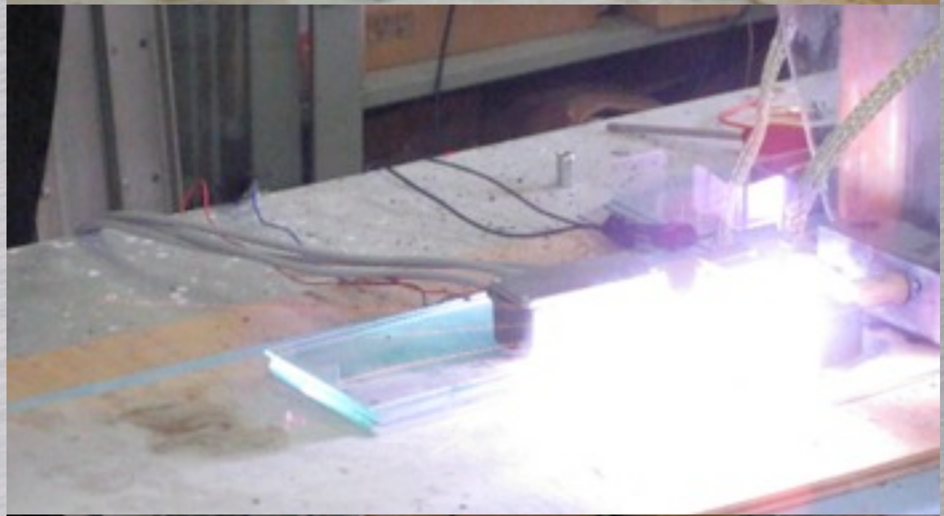


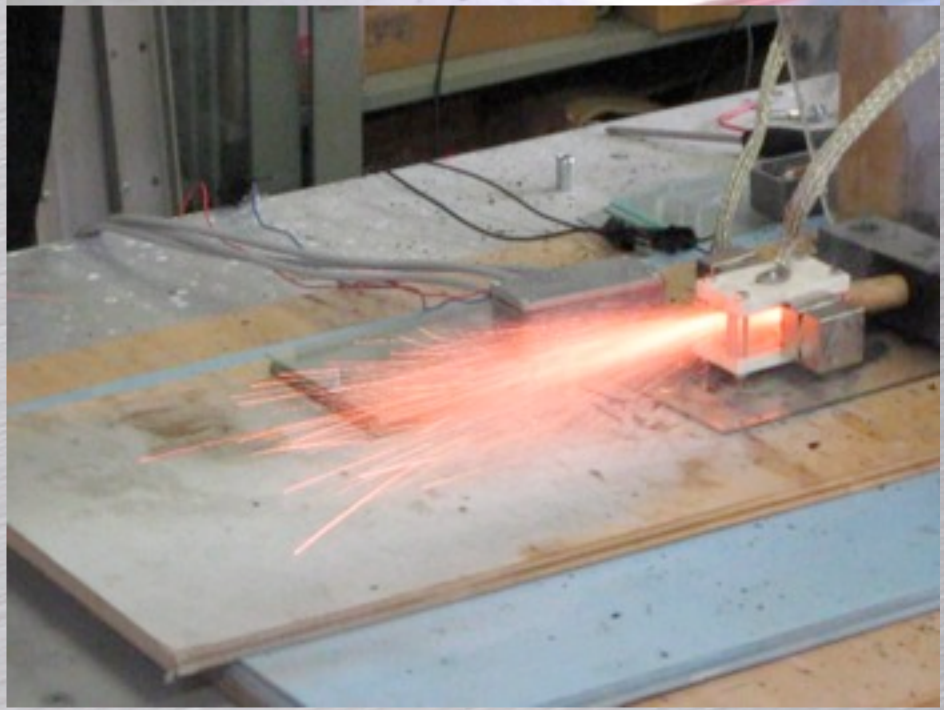
Pulsed-MHD Accelerator or Generator is Demonstrated











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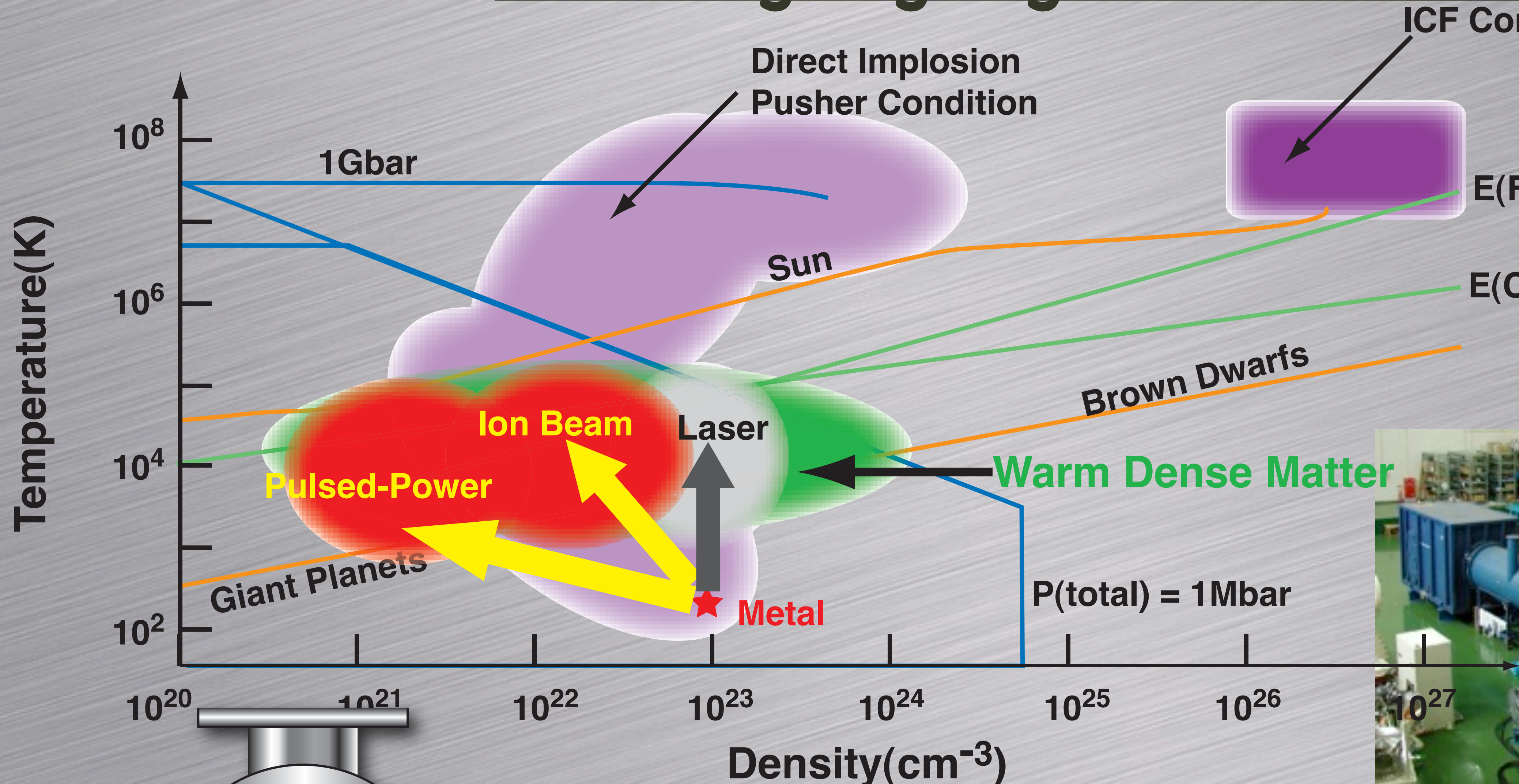
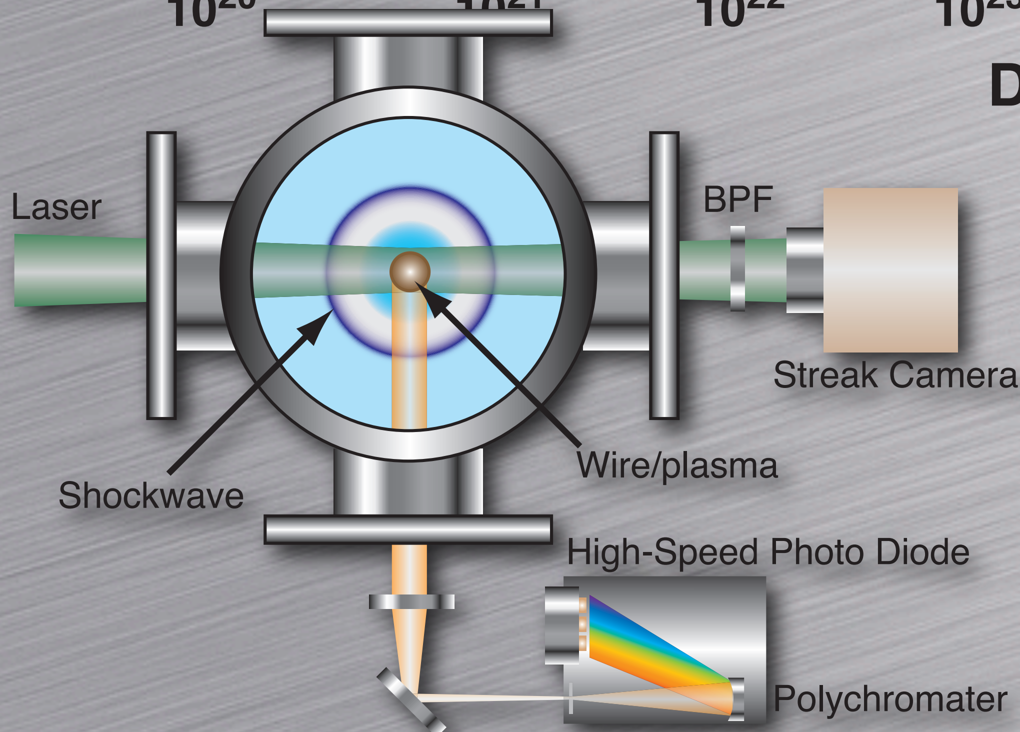
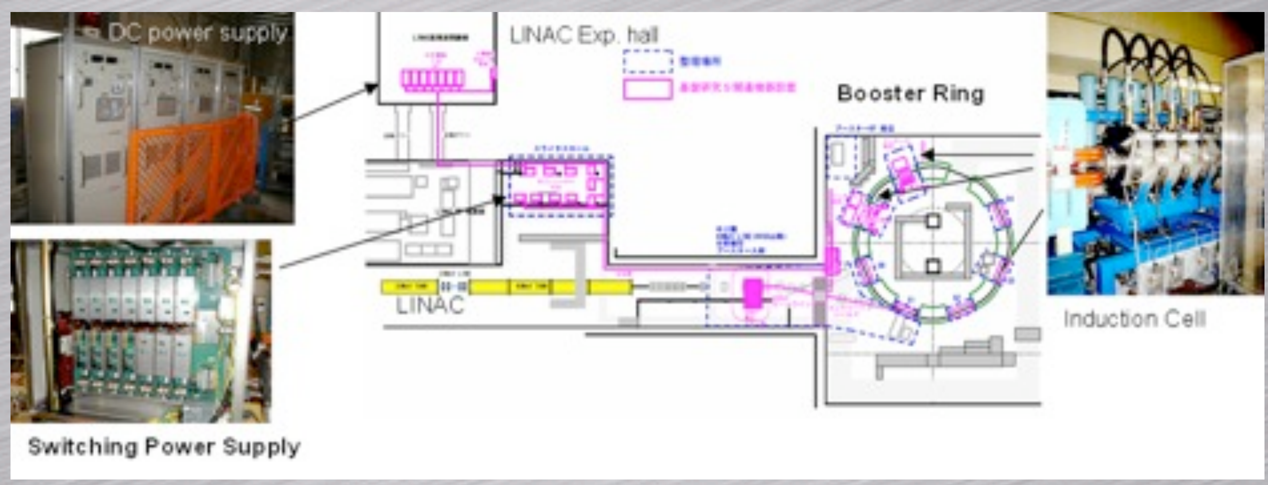
HED matters are evaluated

for designing High Yield Fusion Pellet







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Warm Dense State

Features of Warm Dense State

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

- ➢ Electrons are in partially degenerate regime

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

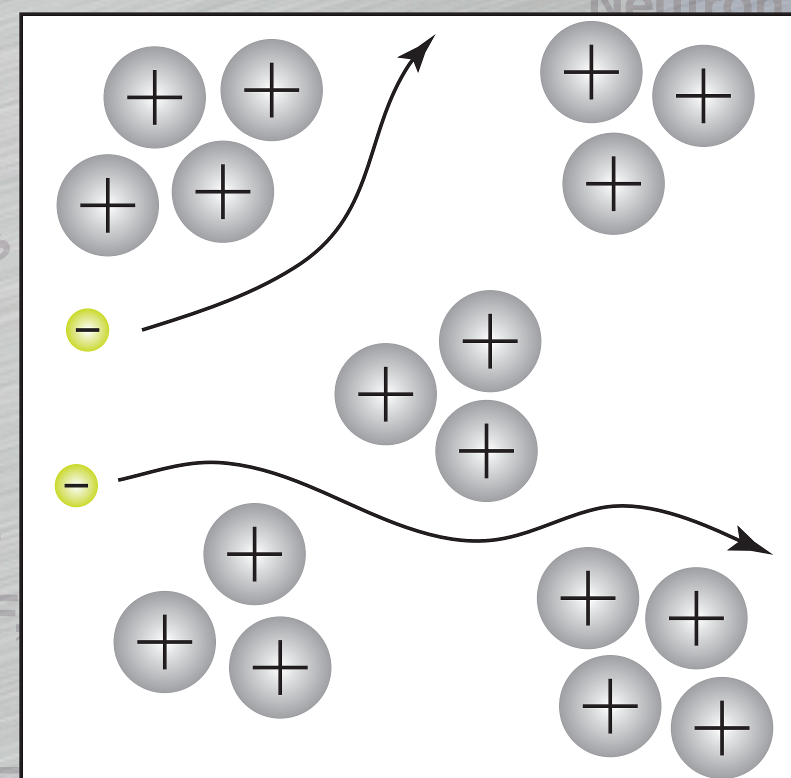
- ➢ Coupled Plasma State

--- $\Gamma > 1$

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

- ➢ Phase Transition

(Liquid-Vapor, Critical Point)



Evaluate Physical Parameter in Warm Dense State

- How to diagnose the target state?

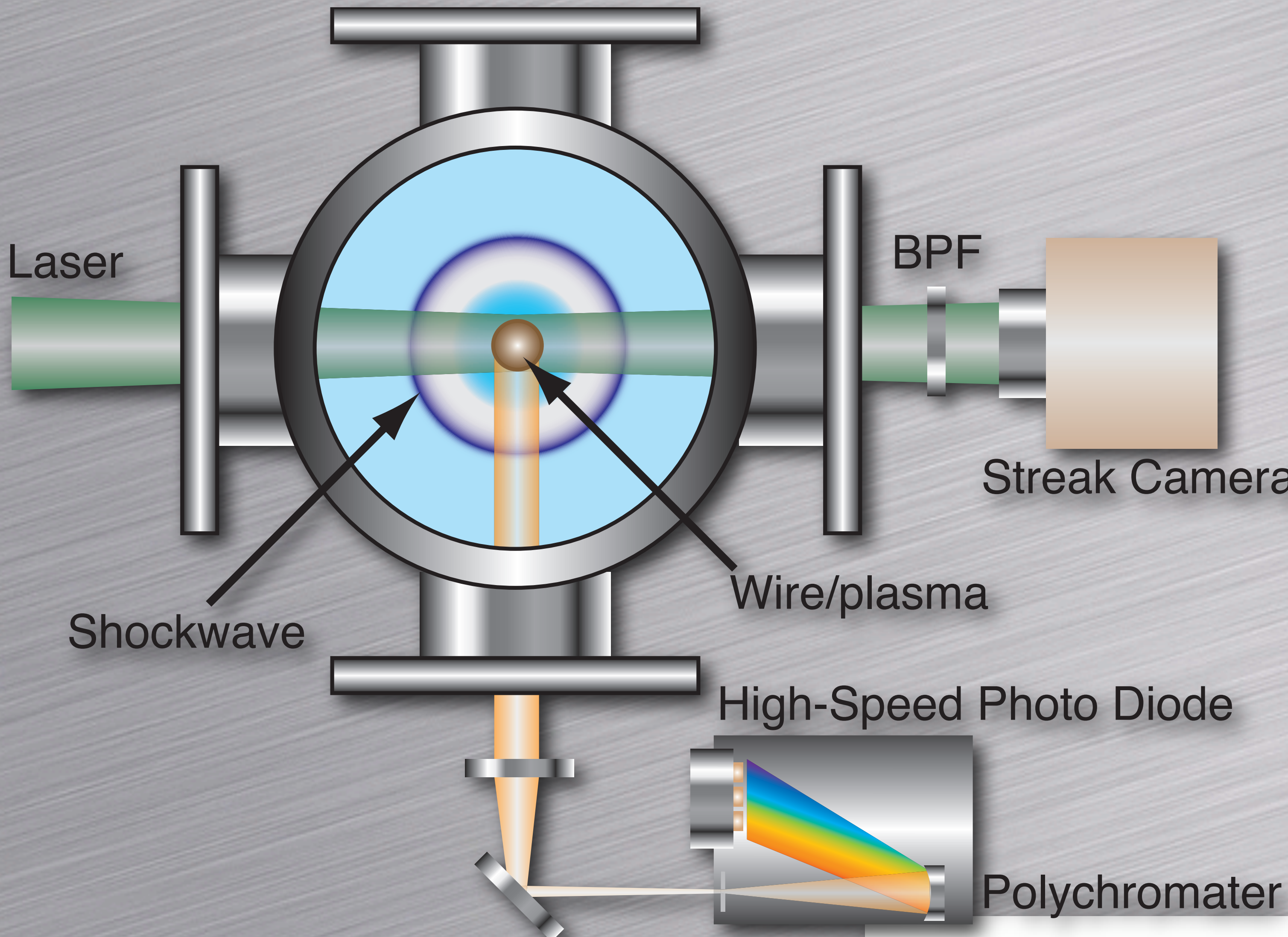
Optically thick
Homogeneity
→ Making well-defined state
i.e. quasi-uniform,
coaxial symmetric, etc.

- Achievable parameter region of warm dense matter?

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

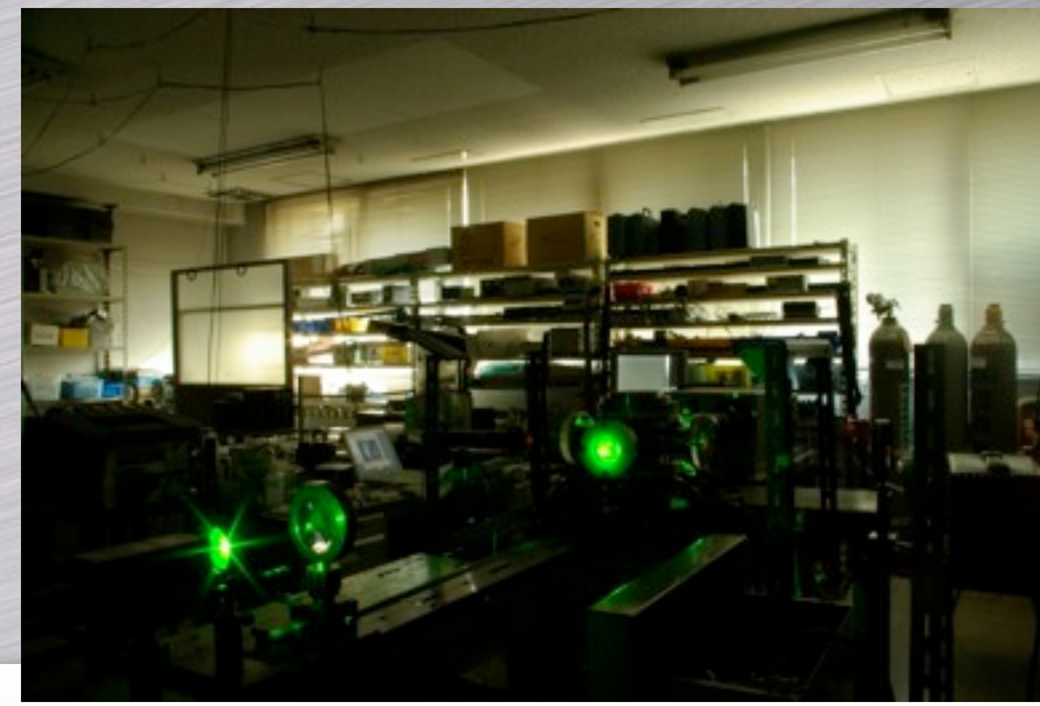
→ Complementary approach for warm dense matter study using pulsed-power devices and intense ion beams

Advantages of Discharge Produced Plasma in Water



Charge Voltage: 10kV

Circuit Inductance: 105nH

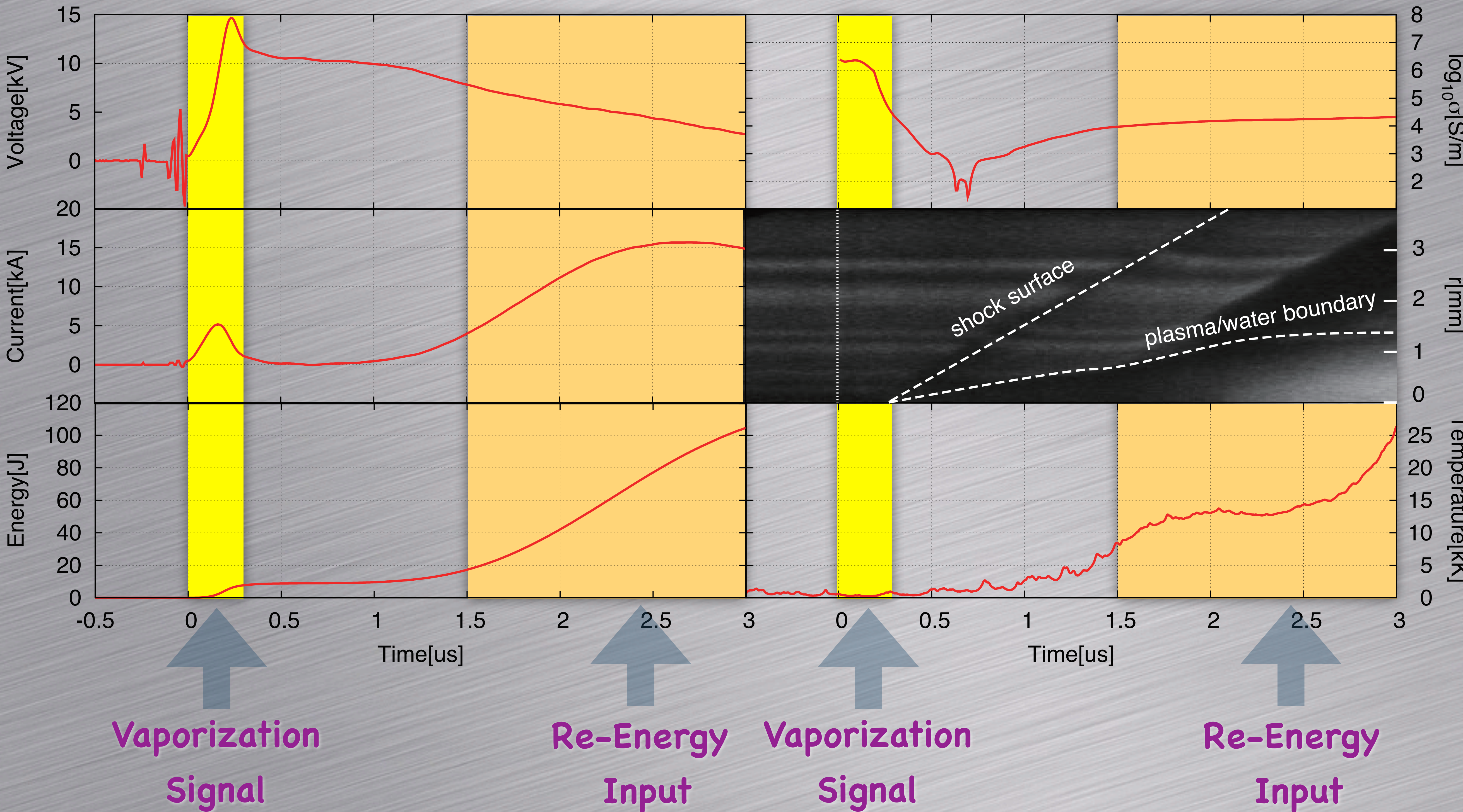


Advantages

- Easy to Generate
- Axial Symmetry
- Ease of Evaluation of Conductivity and Input Energy History by Voltage and Current.
- Tamper Effect
- Transparent

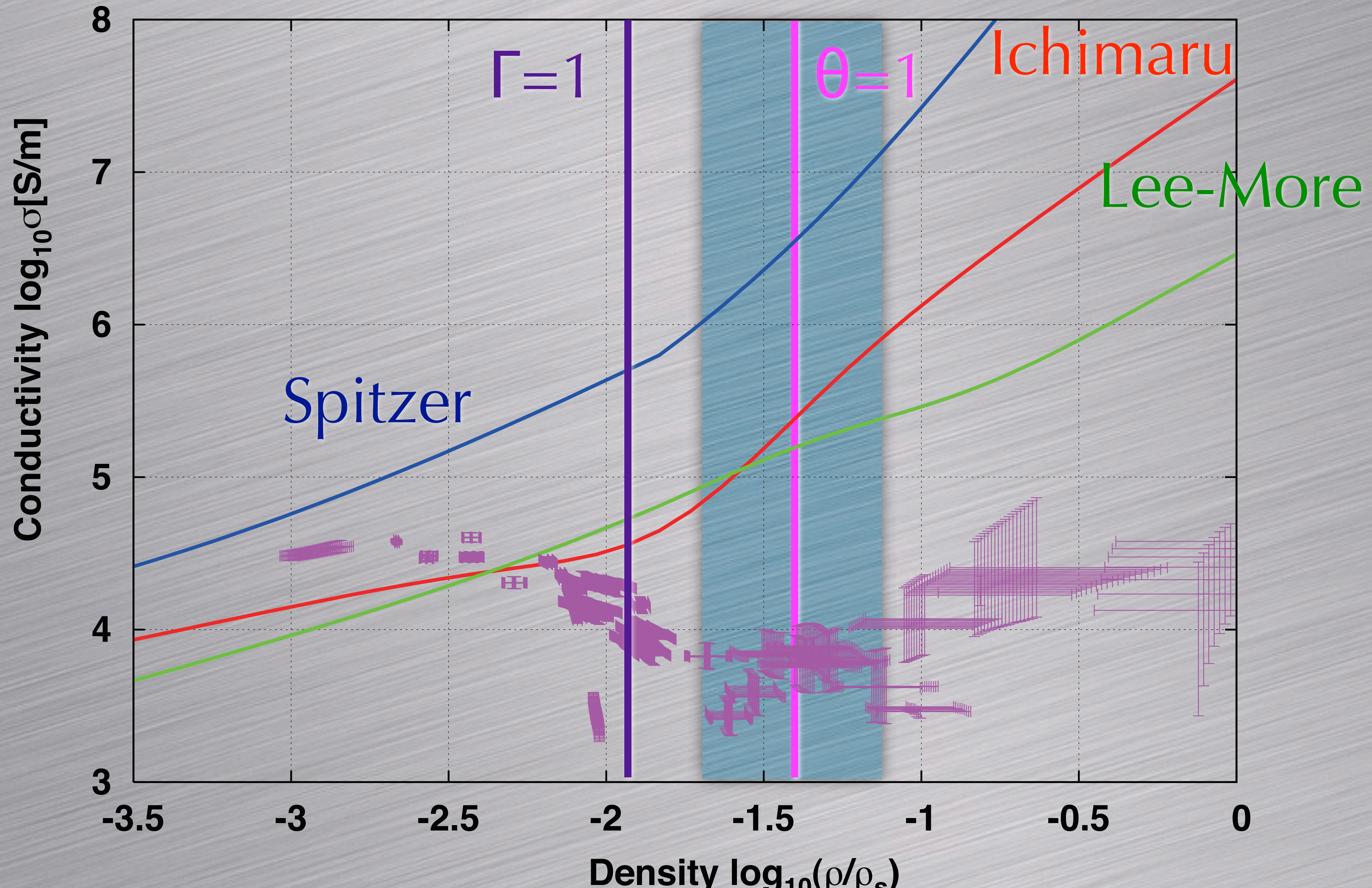
Typical Evolution of Aluminum-Wire Explosion

(φ=100um, l=18mm)



➢ **Hydrodynamic behavior depends on the input energy history.**

Comparison of conductivity measurements with theoretical estimations for aluminum at 5000K

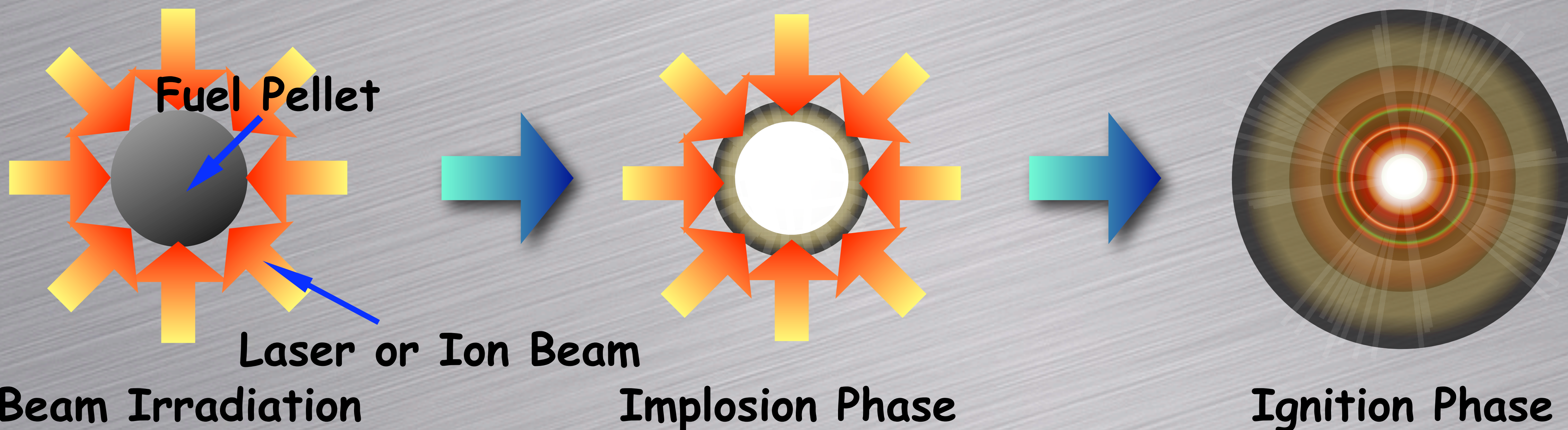


➢ The Lee-More and the Ichimaru theories are in agreement for density at $\log_{10}(\rho/\rho_s) < -2$.

➢ Conventional theoretical models does not predict the conductivity dependency at dense region.

Low-density foam layers is expected to suppress the non-uniformity of target

In the case of direct drive ignition scheme, deposition energy profiles strongly affect the implosion dynamics.



Setting low-density foam layer between the fuel and the pusher, the target uniformity is derived by the theta-direction radiation transport.

Assumed uniform foam layer... → Evaluating consistency of this assumption!!

Estimated homogeneity time of foam plasma

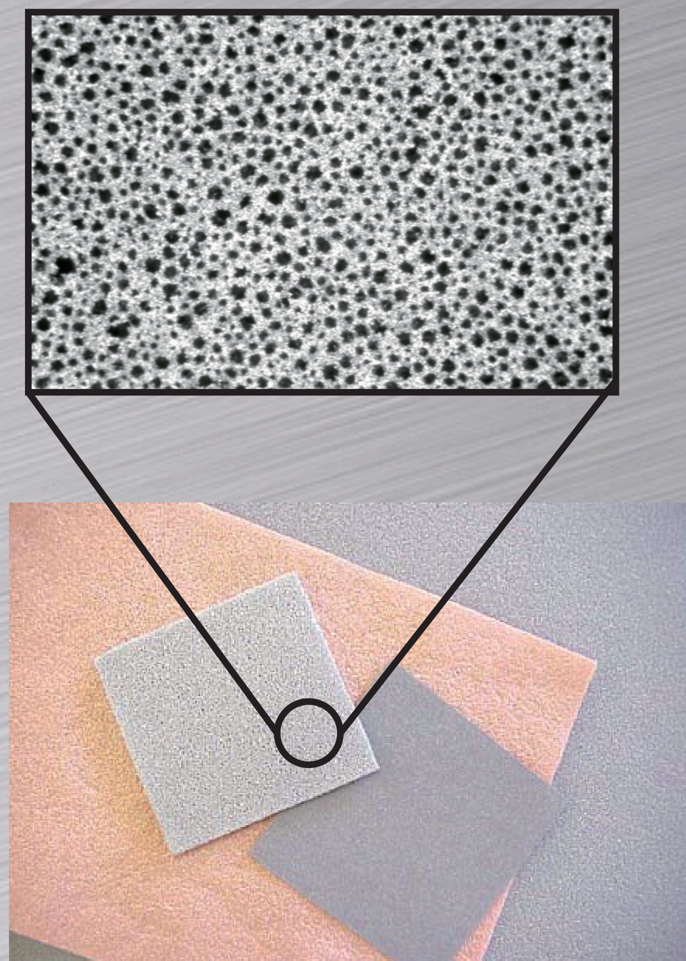
Porous size -> order of 1~100um in radius

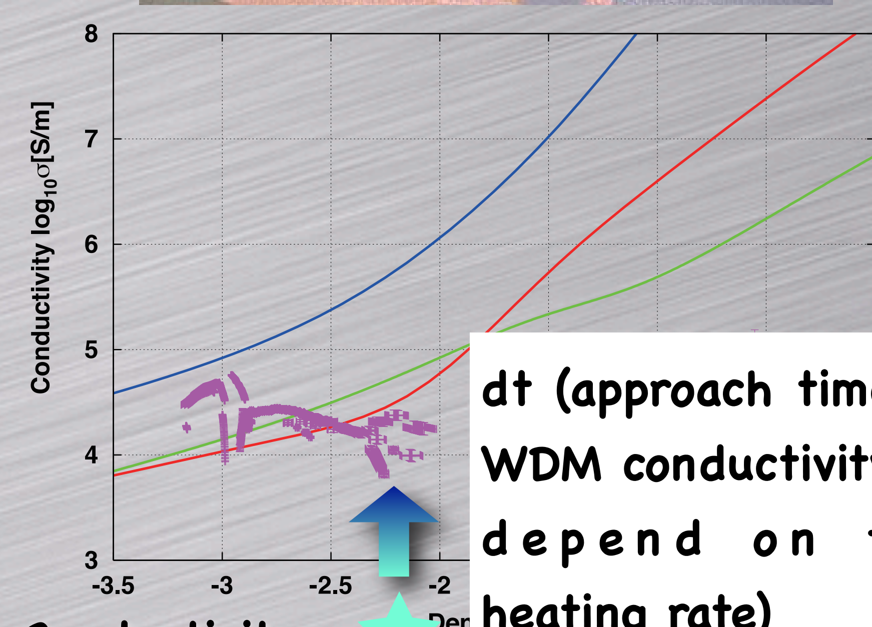
Sound velocity -> a few thousand m/s

in solid state

Homogeneity time of foam plasma is estimated to be order of 1~100ns.

Conductivity of WDM state can be used for the homogeneity time of foam plasma as a function of heating rate.

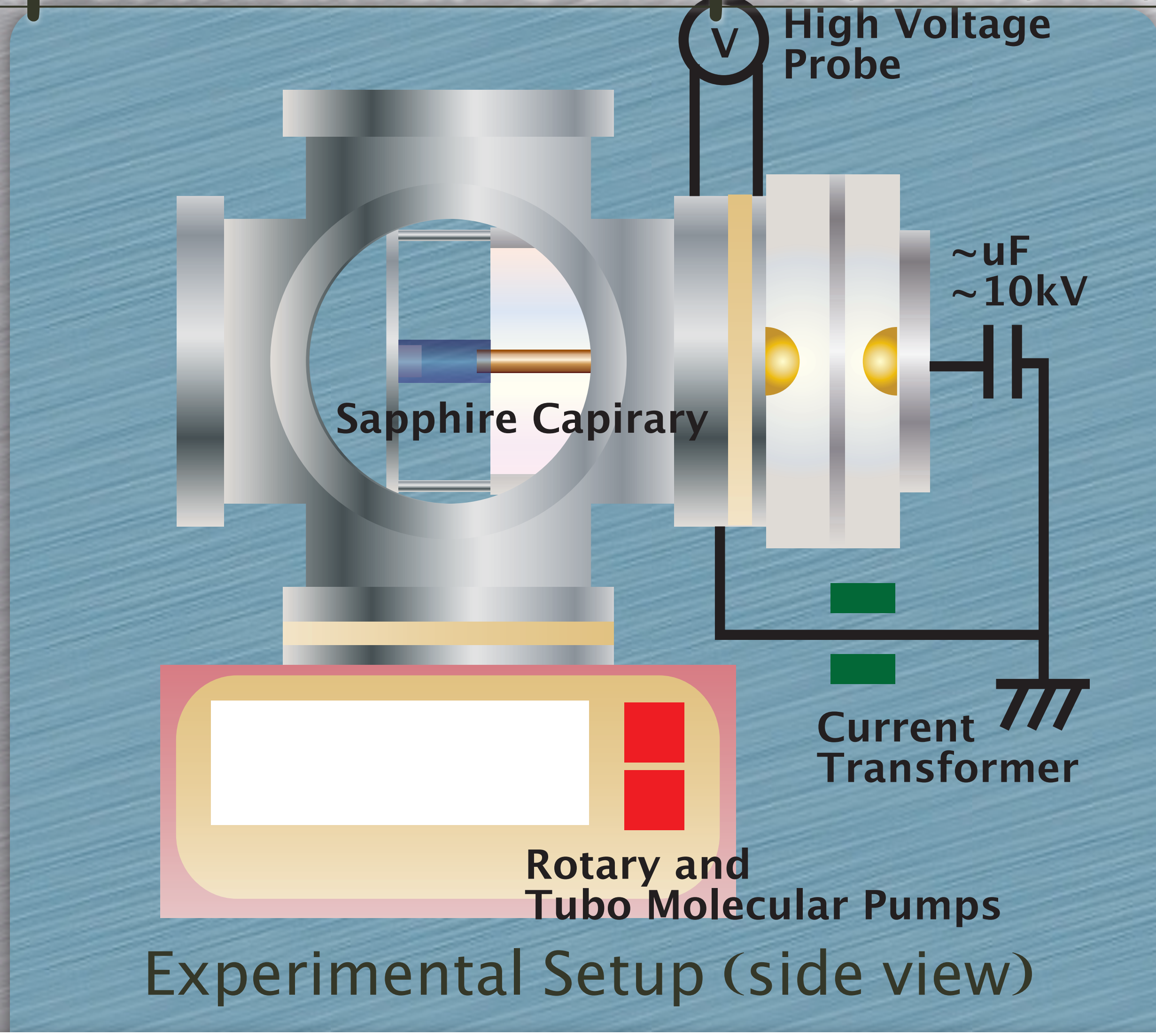


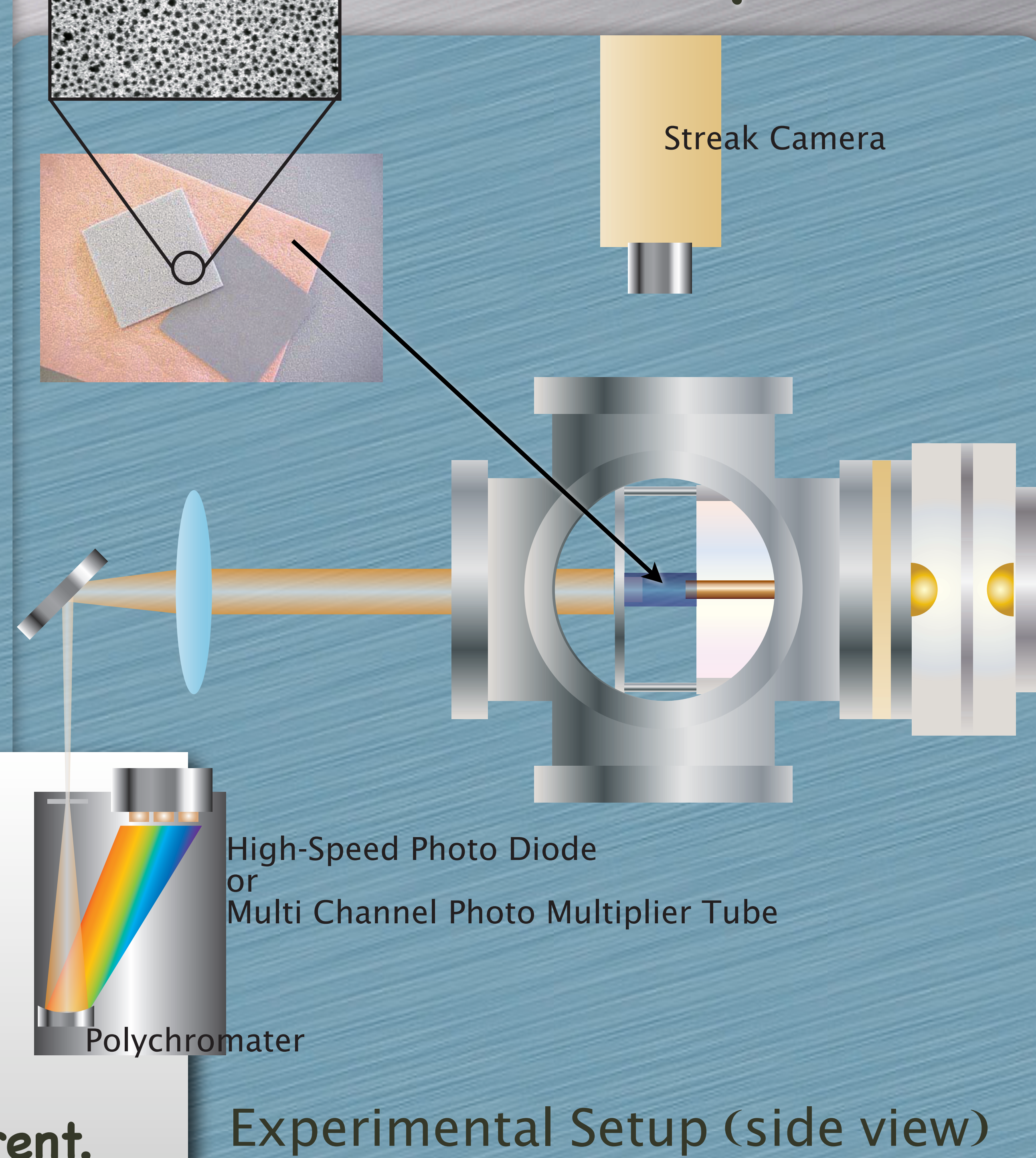


dt (approach time o
WDM conductivity:
depend on th
heating rate)

Initial Foam Conductivity

Experimental Setup for homogeneity time of foam/plasma





Advantages

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

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Current Requirement by e-Beam Irradiation

By Energy Balance Equation,

Beam Current [A]

$$I_b = \frac{\pi\, r_f^2\, R_s\, e(T)}{(1 - Y_r) E_k\, \tau_b}$$

Parameters for Estimation

* M. Murakami, et al., J. X-Ray Sci. Tech. 2 (1990) 127.

Coefficients of Specific Internal Energy *

$$e(T) = e_0 \left(\frac{T\ [\mathrm{K}]}{1.14 \times 10^4} \right)^{\mu}$$

$$e_0 = 3.6 \times 10^7$$

$$\mu = 1.2$$

for Aluminum Target

Beam Spot Radius:

r_f=1 [mm]

Y_r R_s

Radiation Yield & Stopping Range

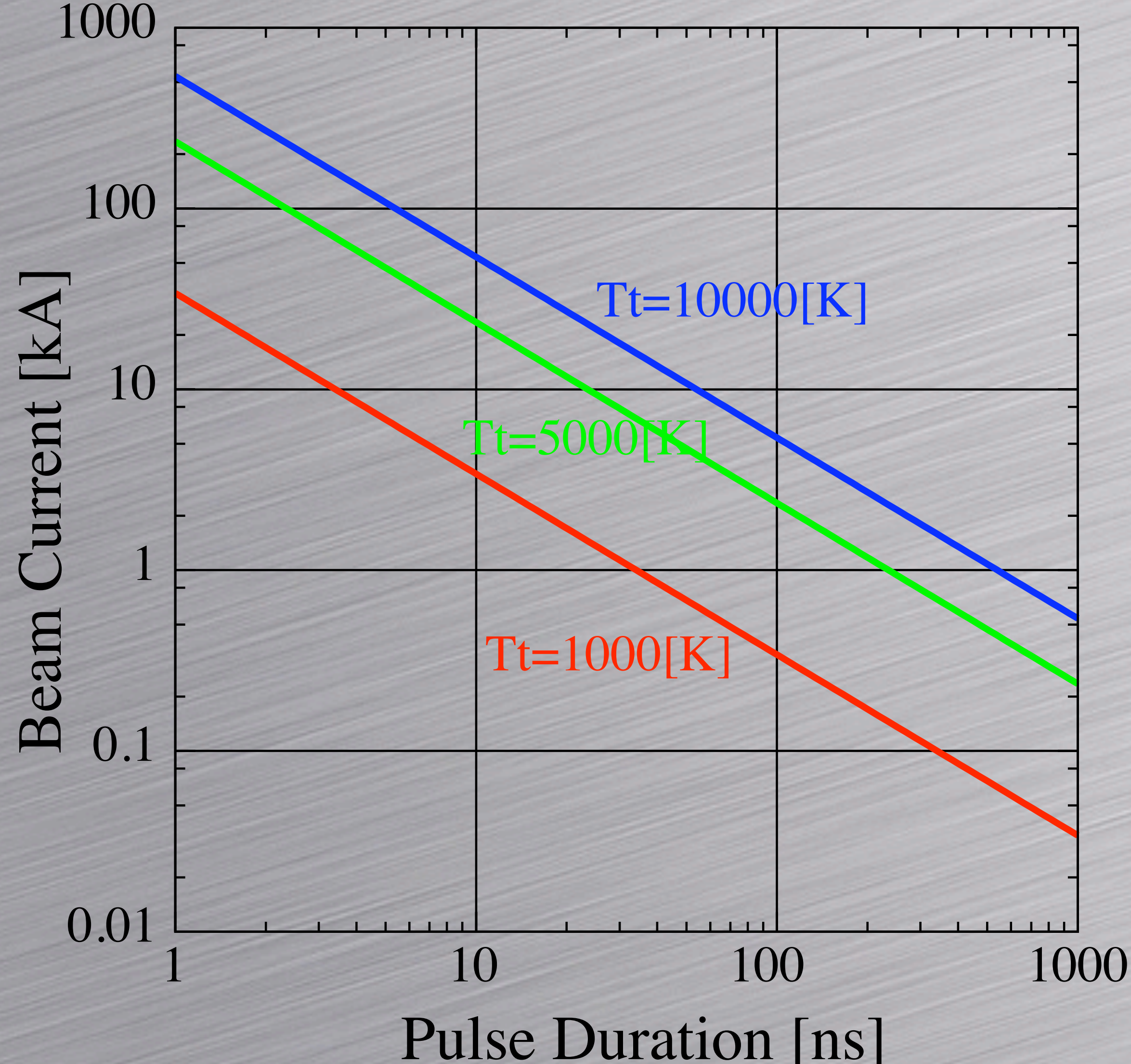
Courtesy for NIST ESTAR Data

T. Kikuchi, T. Sasaki, K. Horioka, Nob. Harada, Plasma Fusion Res. 4 (2009) 026.

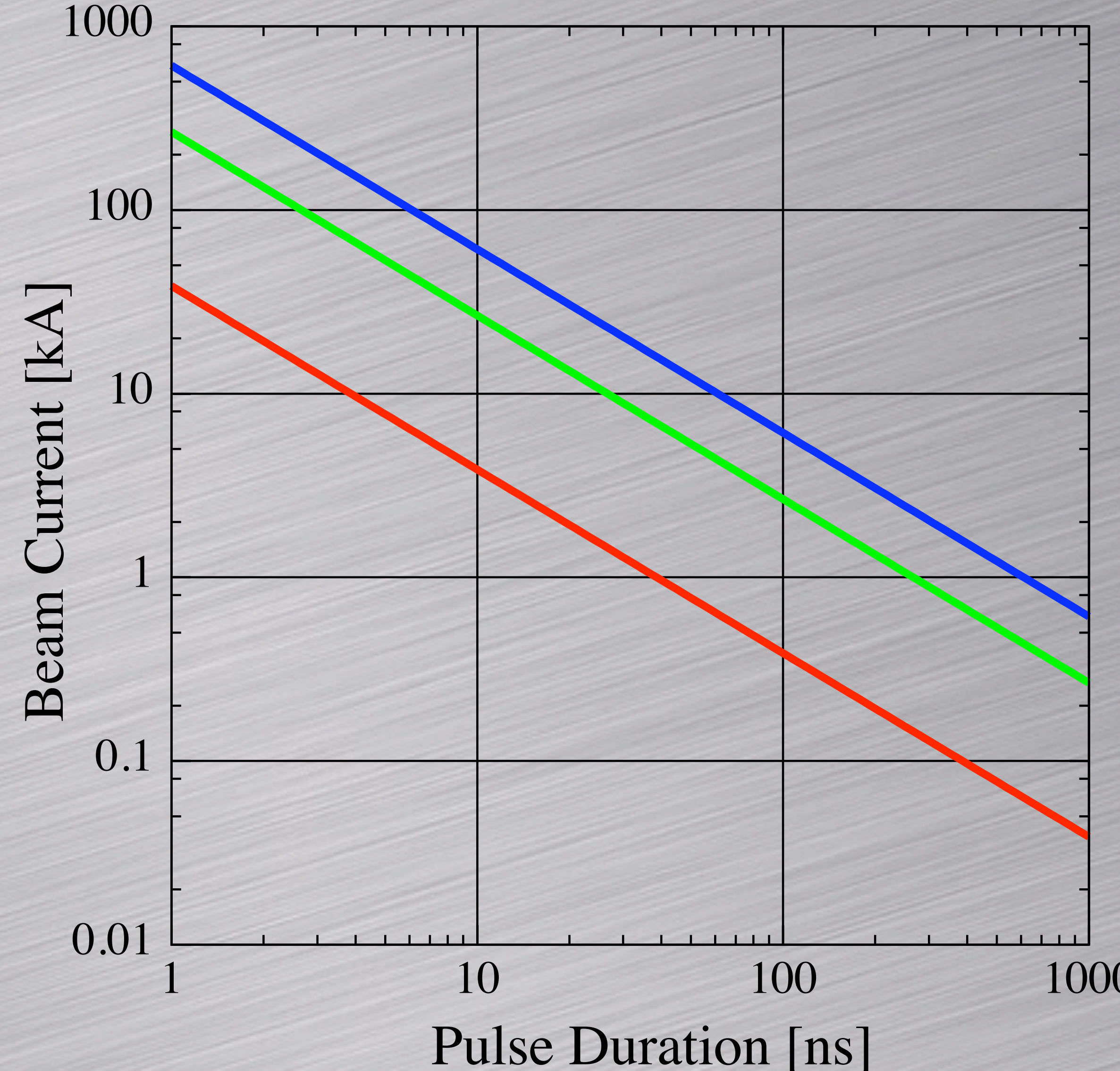
Evaluated by Dr. T. Kikuchi

Beam Current for WDM driven by e-Beam

E_k=1MeV Y_r=0.76% L_d=2mm



E_k=10MeV



for 5000-10000K Target Temperature
Pulse Duration=100ns
Beam Current=2.3-5.4kA

Y_r=7.45%
L_d=2cm

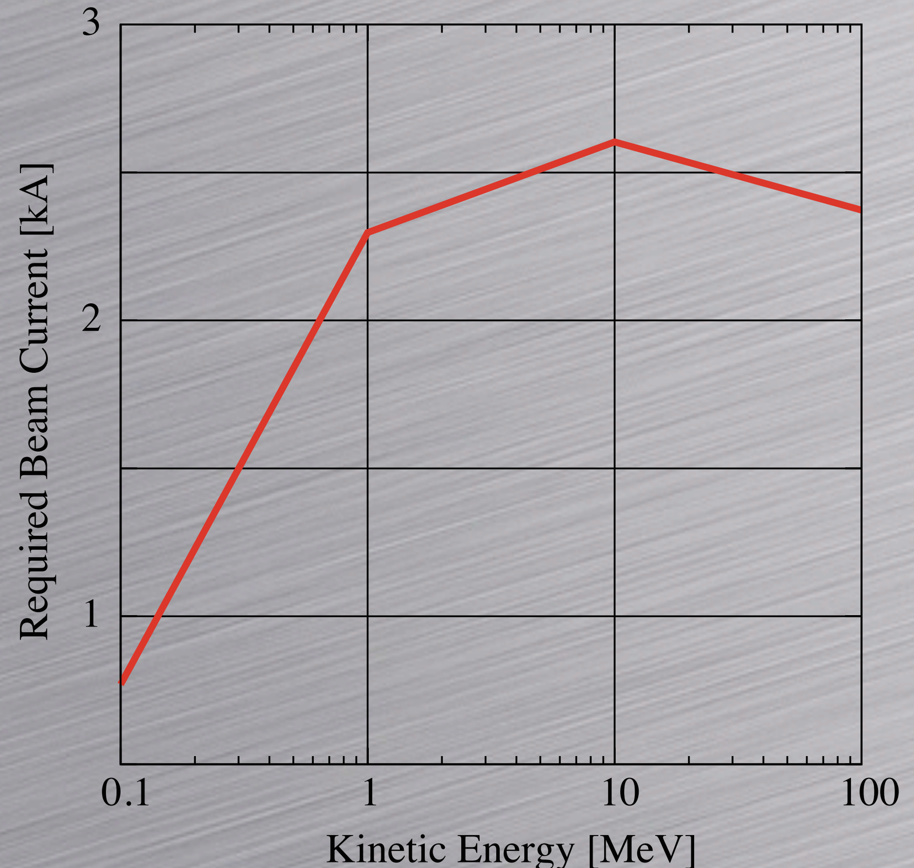
T. Kikuchi, T. Sasaki, K. Horioka, Nob. Harada, Plasma Fusion Res. 4 (2009) 026.

Evaluated by Dr. T. Kikuchi

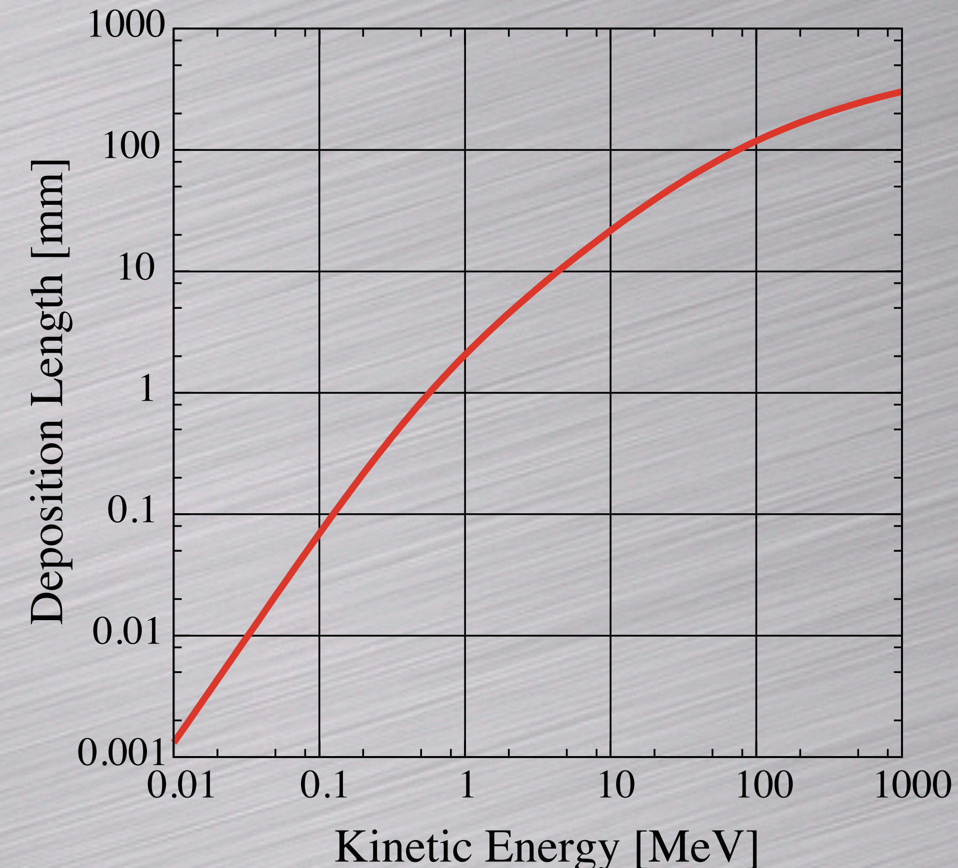
2009年9月11日金曜日

Beam Current Requirement & Deposition Length

for 5000K WDM
Pulse Duration=100ns



in solid Al



Low kinetic energy is better than high kinetic energy from viewpoint of requirement for beam current.

$$L_d = \frac{R_s(E_k)}{\rho_t}$$

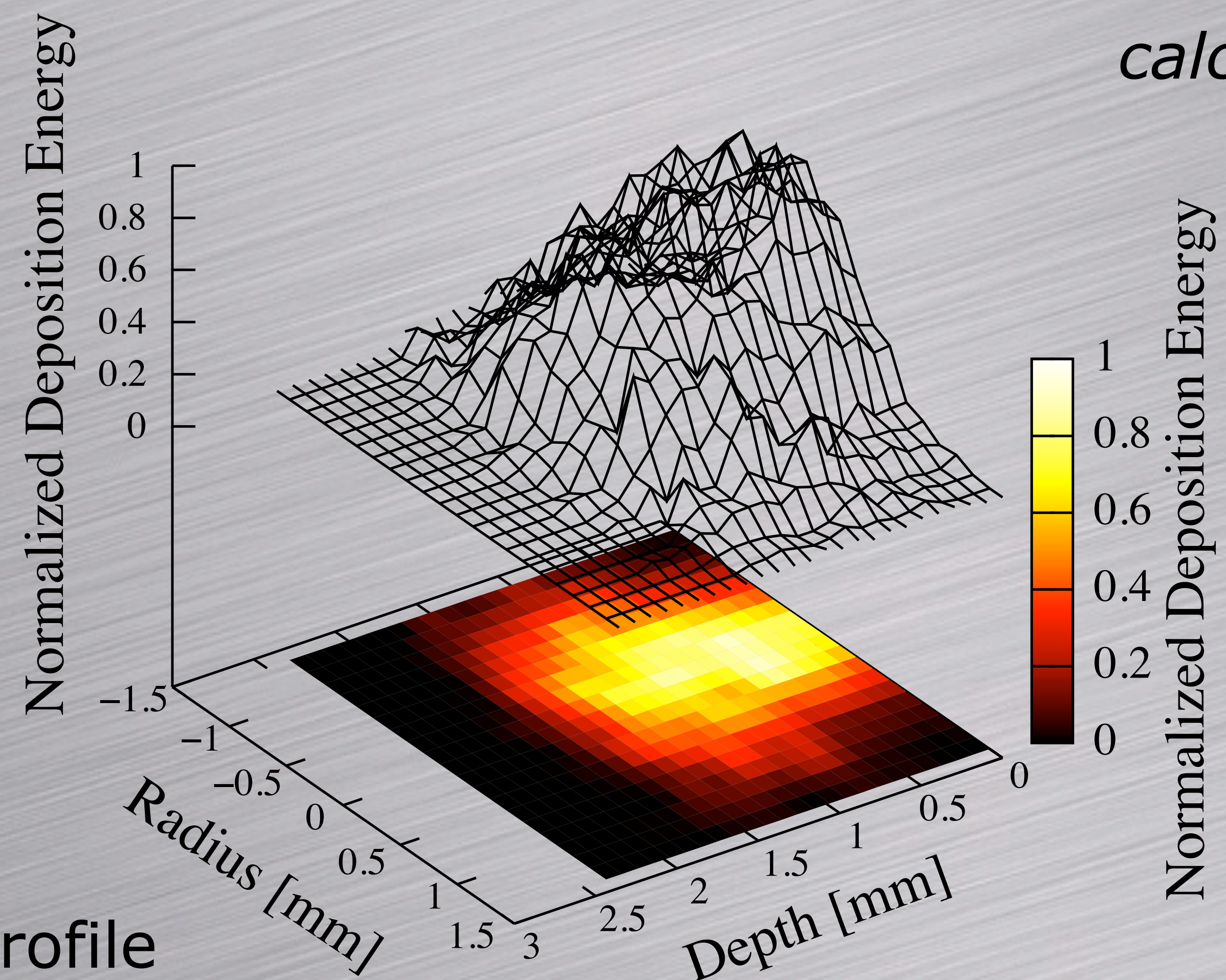
T. Kikuchi, T. Sasaki, K. Horioka, Nob. Harada, Plasma Fusion Res. 4 (2009) 026.

Evaluated by Dr. T. Kikuchi

Deposition Energy Distribution

Deposition energy distribution of 1 MeV electron beam in solid Al

*calculated by CASINO**



Deposition energy profile confirms that >50% of input beam energy is distributed to a depth of 1.5 [mm].

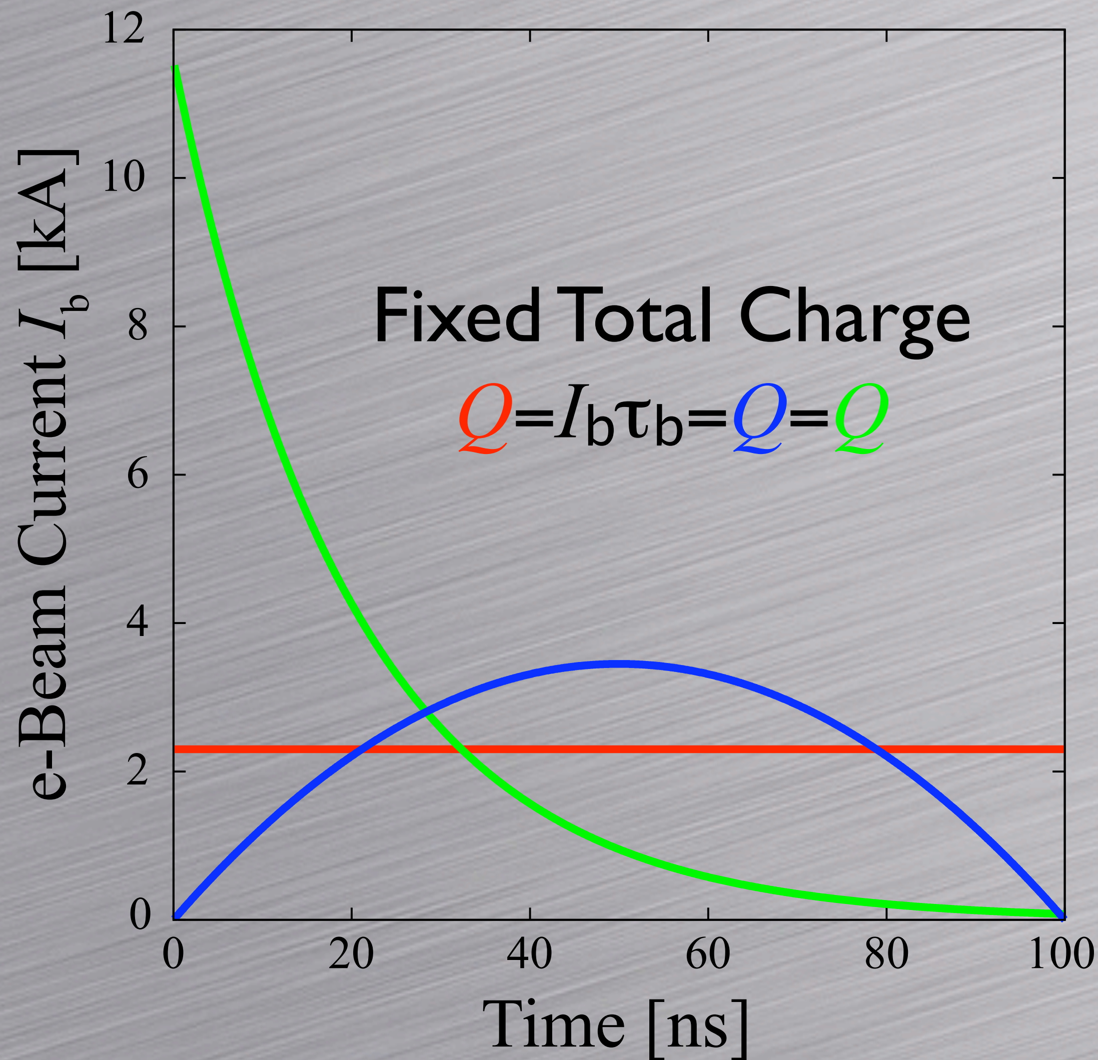
**D. Drouin, et al., "CASINO V2.42—A Fast and Easy-to-use Modeling Tool for Scanning Electron Microscopy and Microanalysis Users", Scanning 29, 92 (2007).*

T. Kikuchi, T. Sasaki, K. Horioka, Nob. Harada, Plasma Fusion Res. 4 (2009) 026.

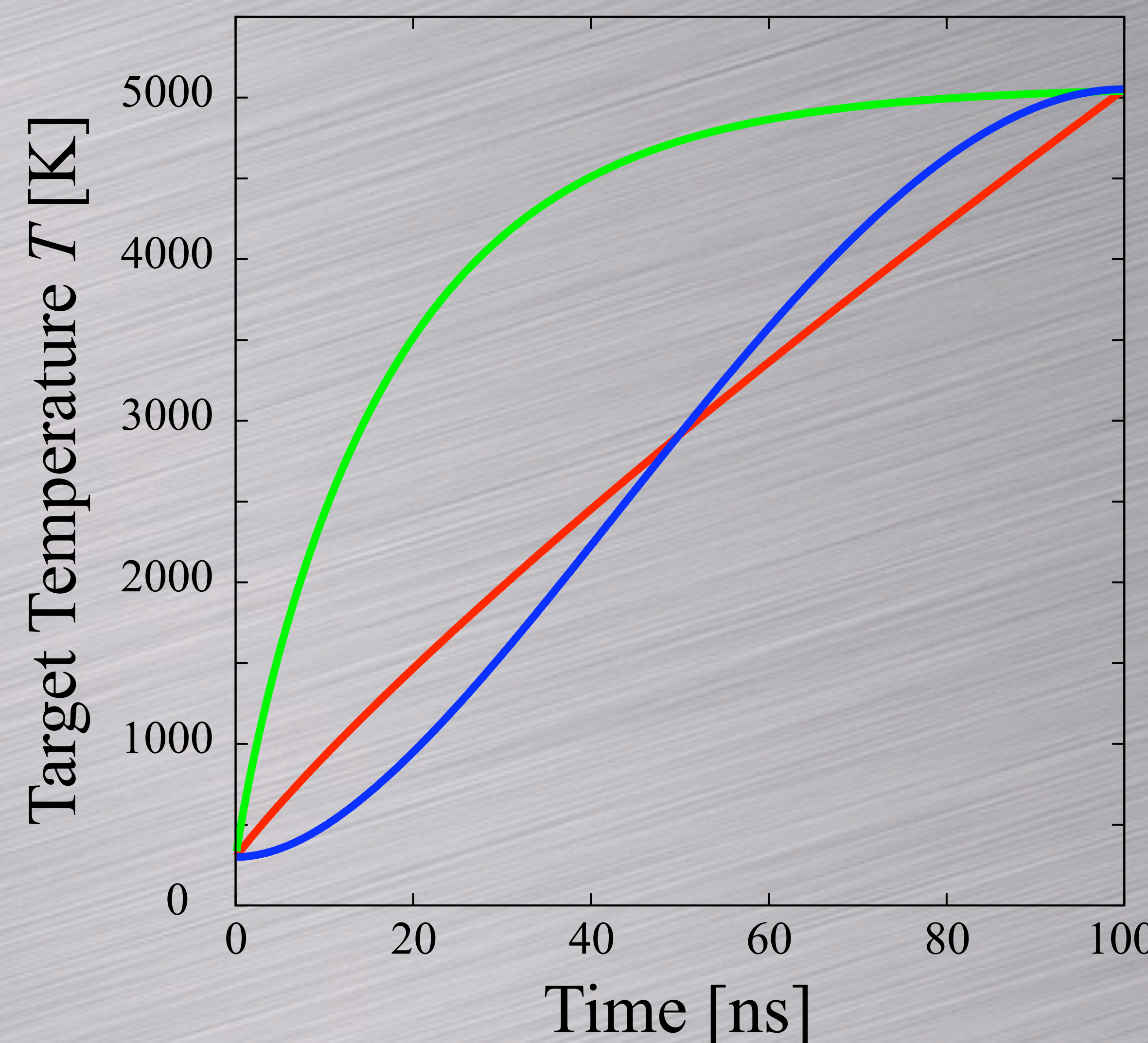
Evaluated by Dr. T. Kikuchi

Temperature History during e-Beam Irradiation

e-Beam Current Profile



Target Temperature History



High e-Beam Current in early stage of pulse is favorable for long time maintain of suitable target temperature, if total input current is fixed.

Evaluated by Dr. T. Kikuchi

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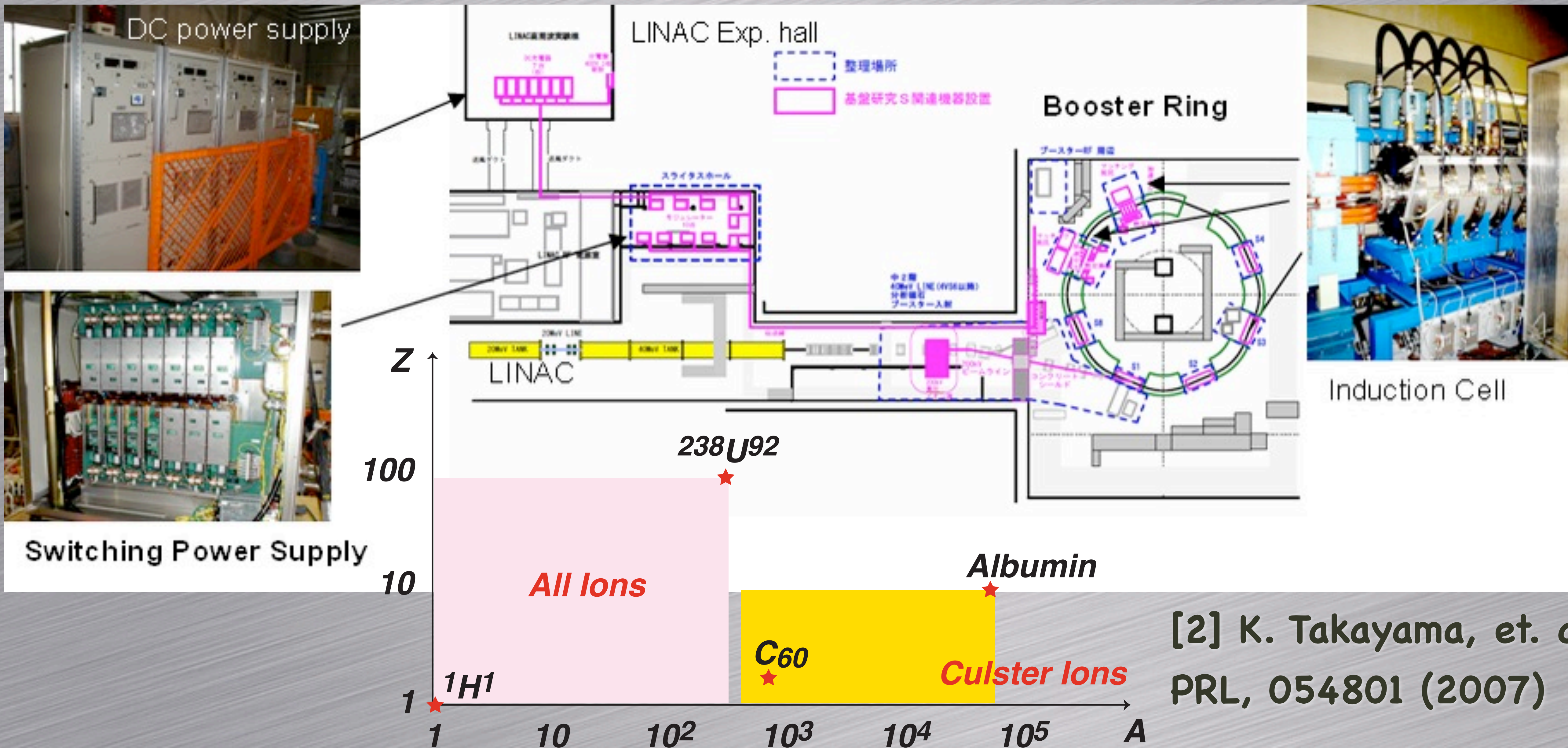
KEK digital accelerator (DA) is a multi-purposes facility for science, engineering, and medical therapy

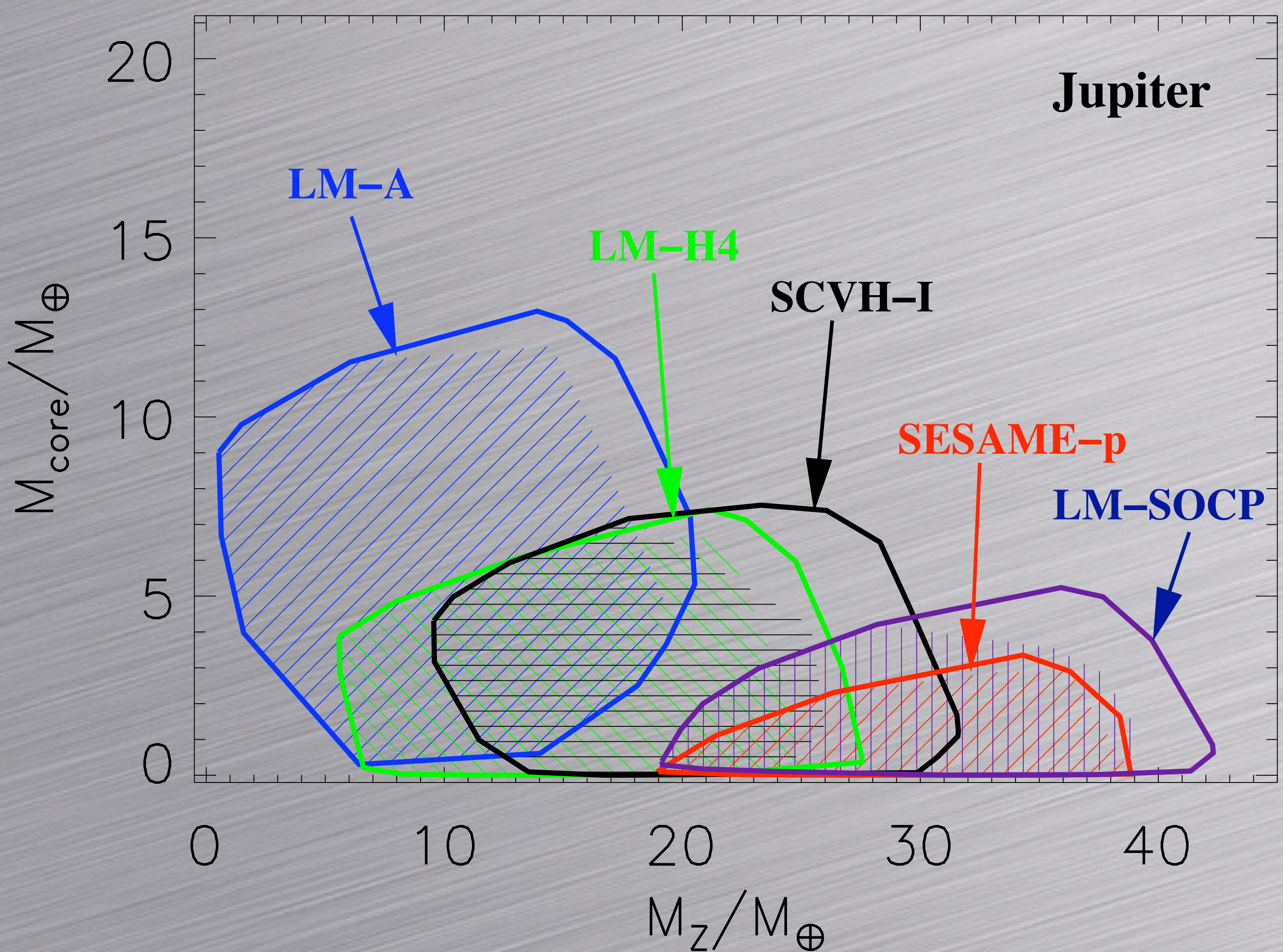


[2] K. Takayama, et. al., PRL, 054801 (2007)

KEK DA is proposed

- ➢ High energy density physics (HEDP) study
- ➢ Hybrid cancer therapy using proton and carbon
- ➢ Material science
- ➢ Selective mutation breeding

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

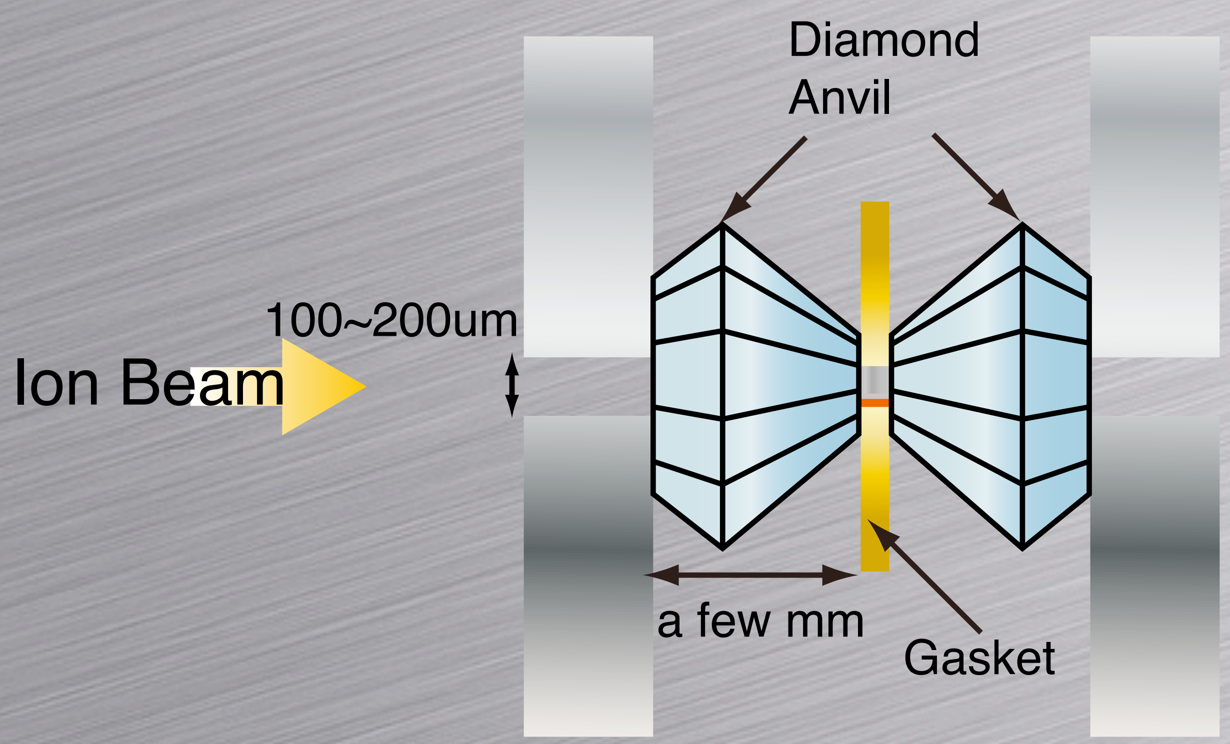
➢ Entropy Condition

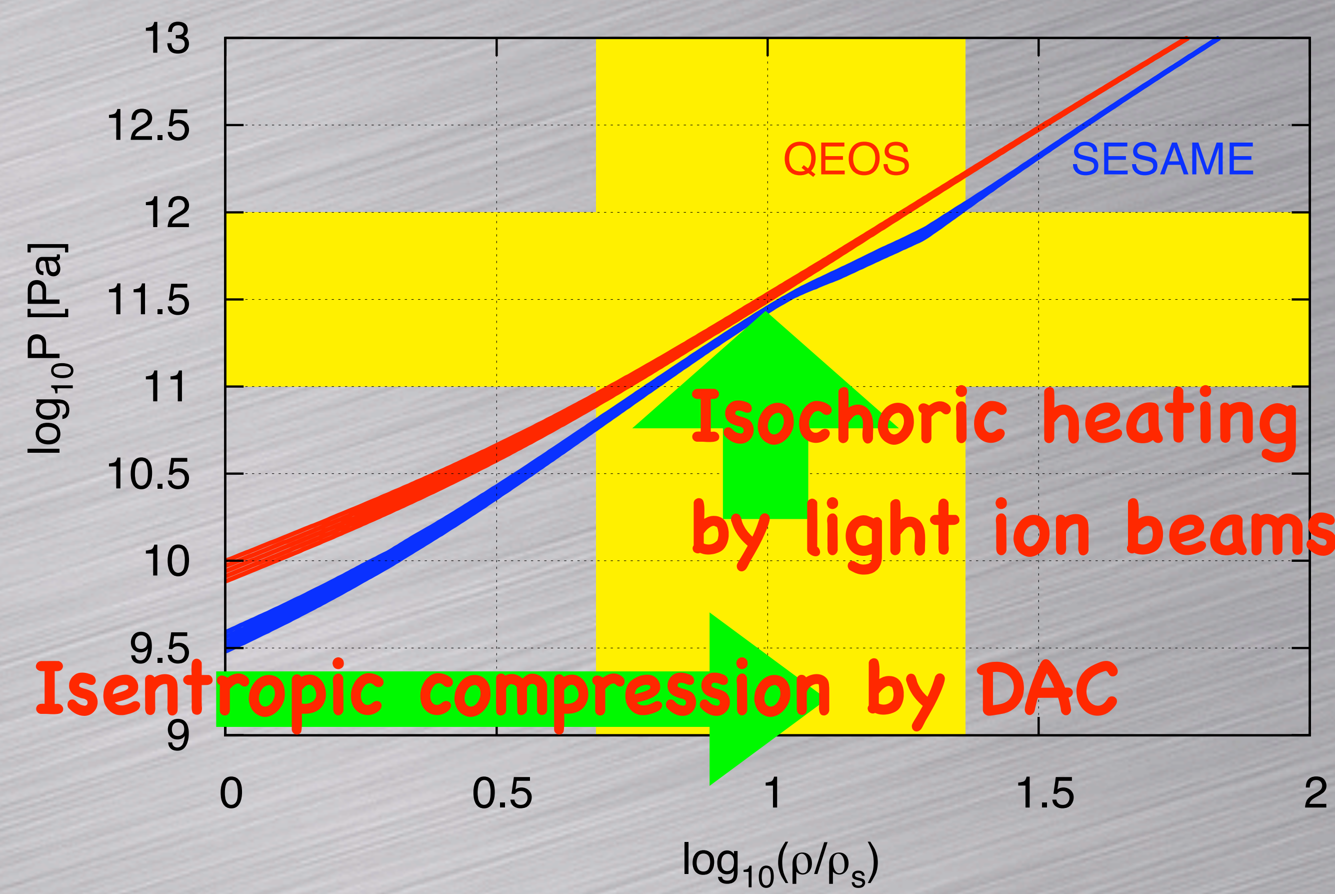
If we use the shock compression,

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

Strongly depend the initial target condition

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





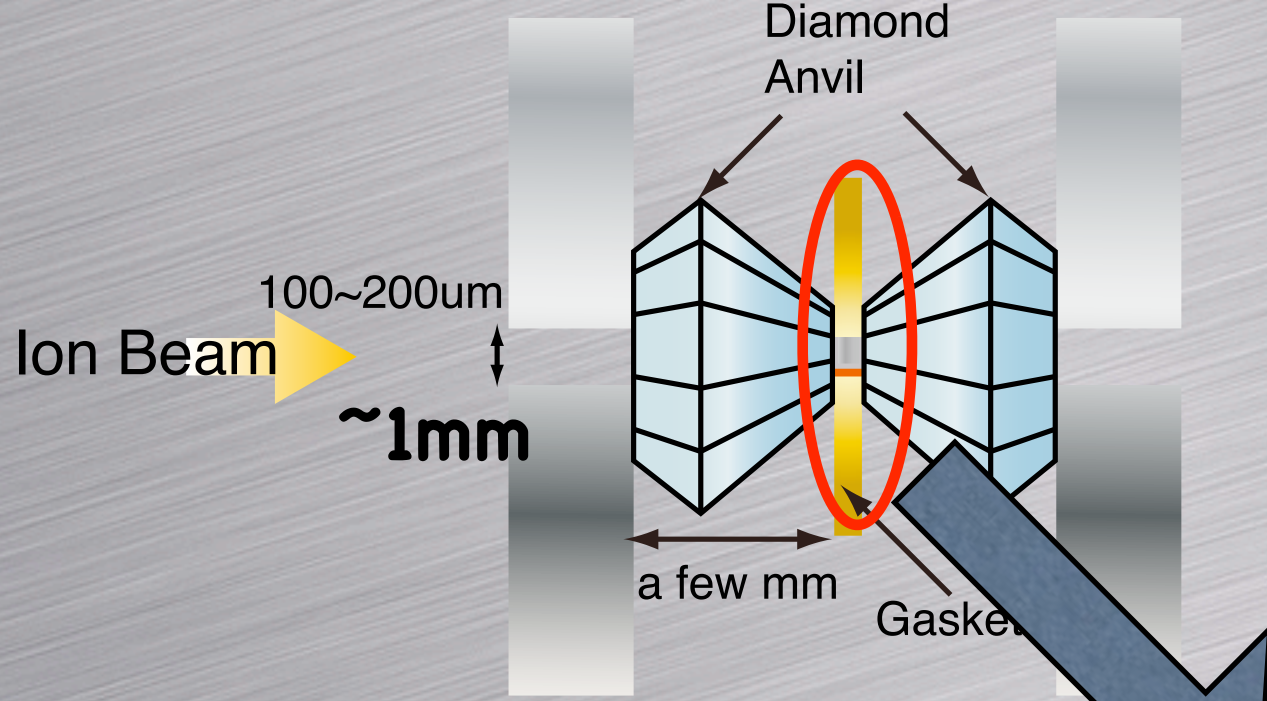
Merits of DAC with intense ion beam

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

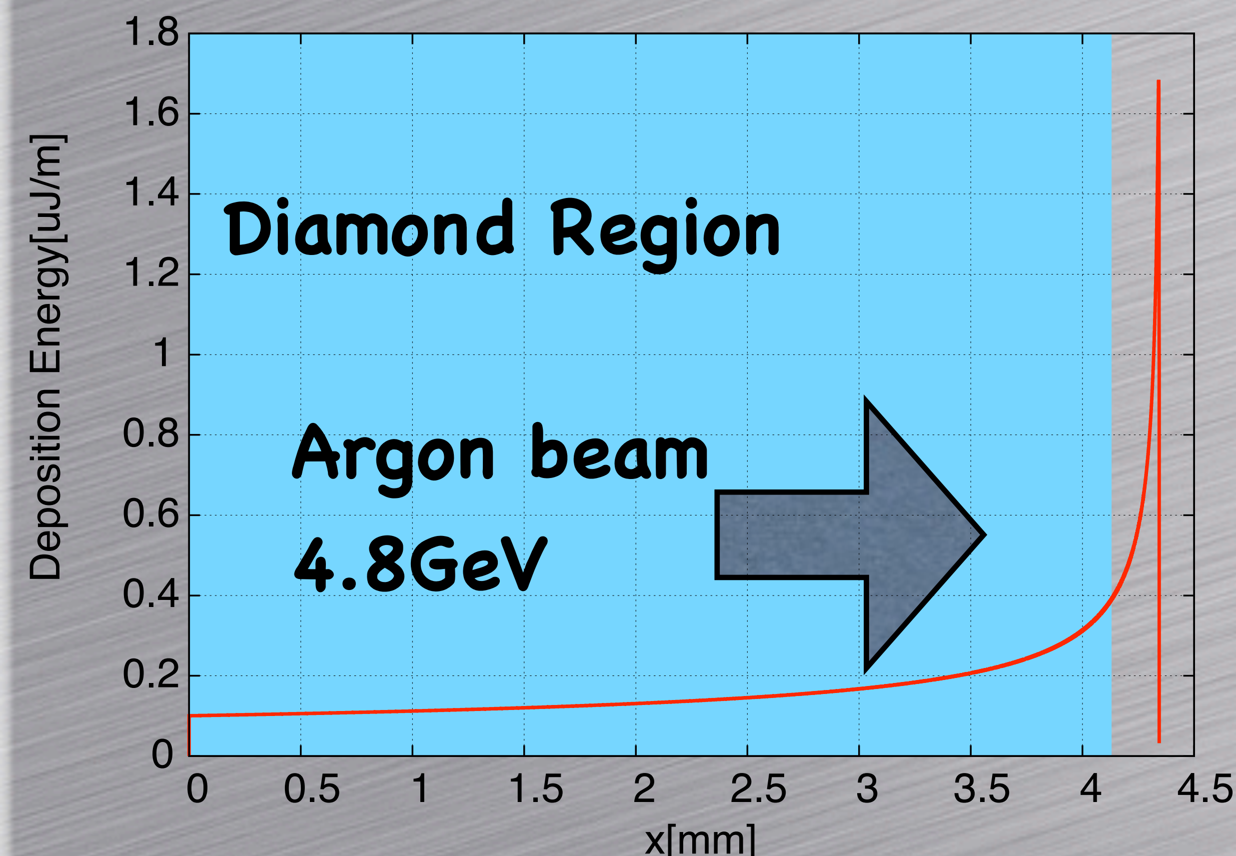
Demerits of DAC with intense ion beam

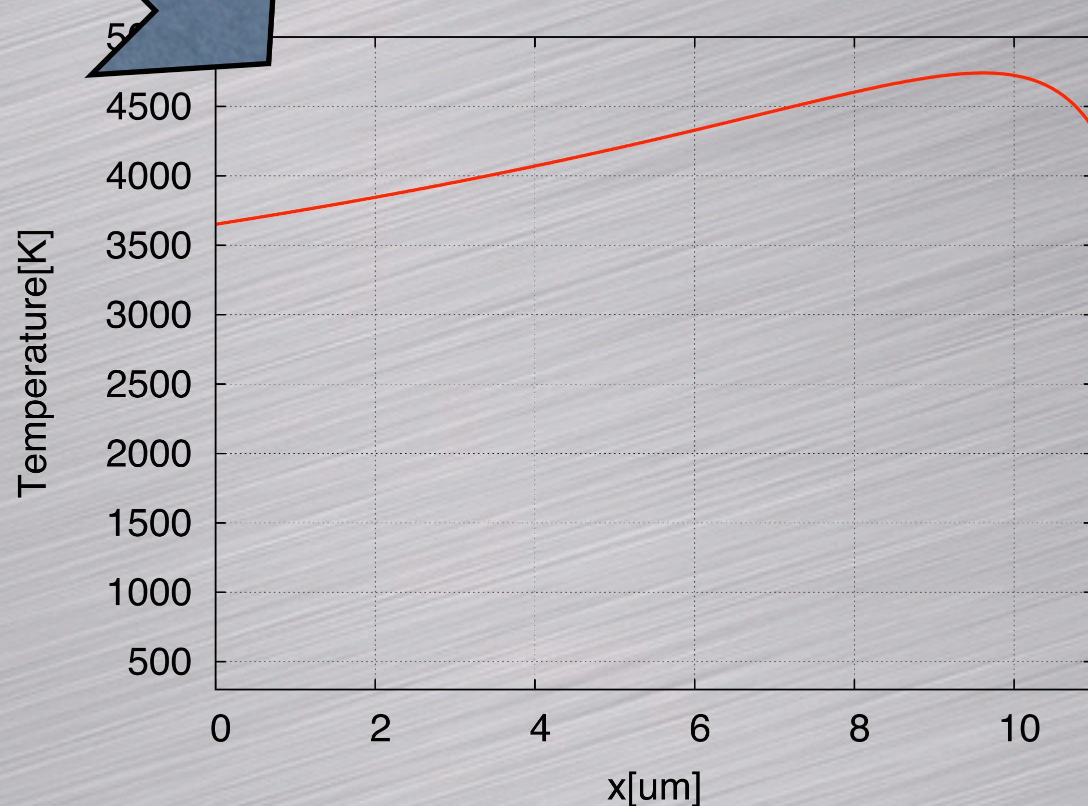
- ➢ Small sample size

Possible parameter region based on DAC with intense ion beams



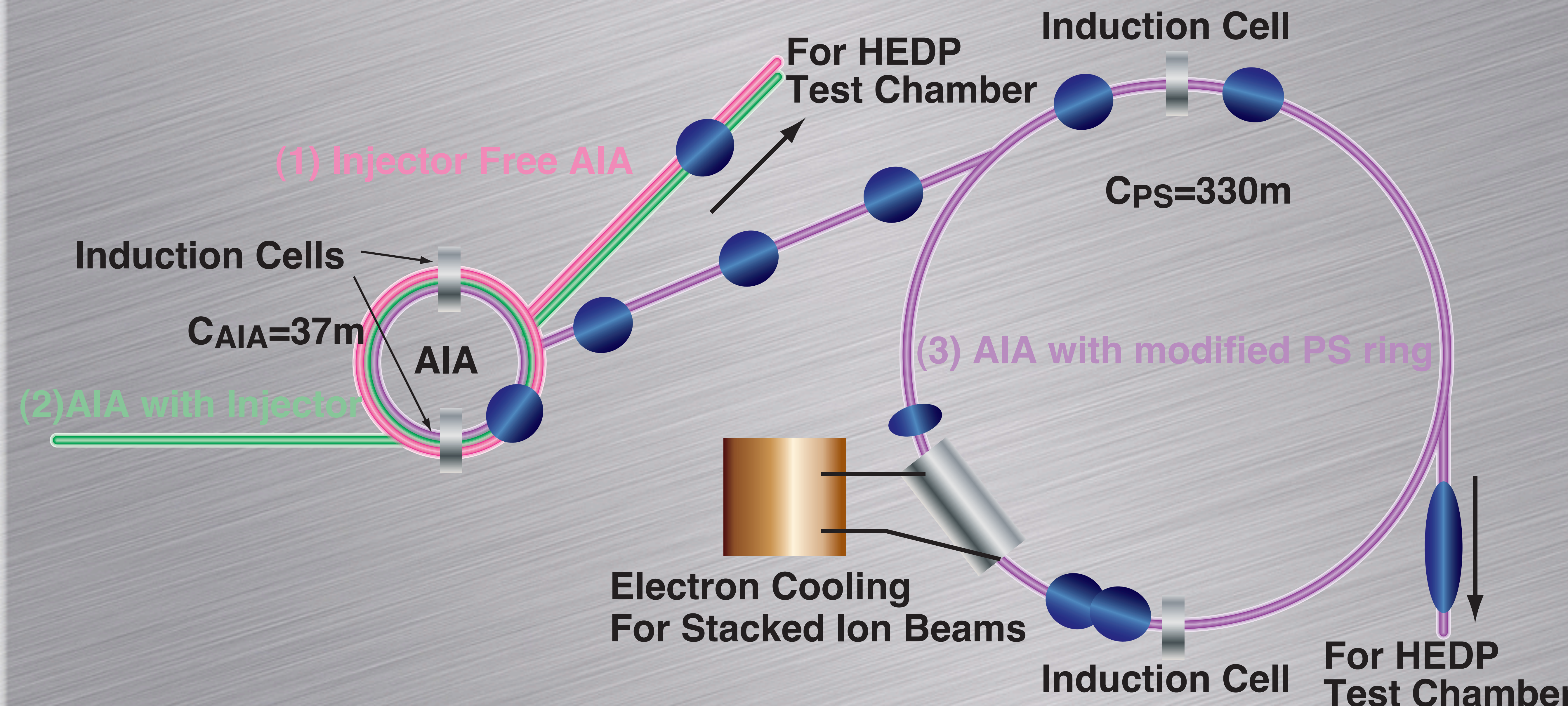
10x compressed hydrogen irradiated by argon ion beams with 1.9×10^{10} per bunch





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

KEK DA Schemes



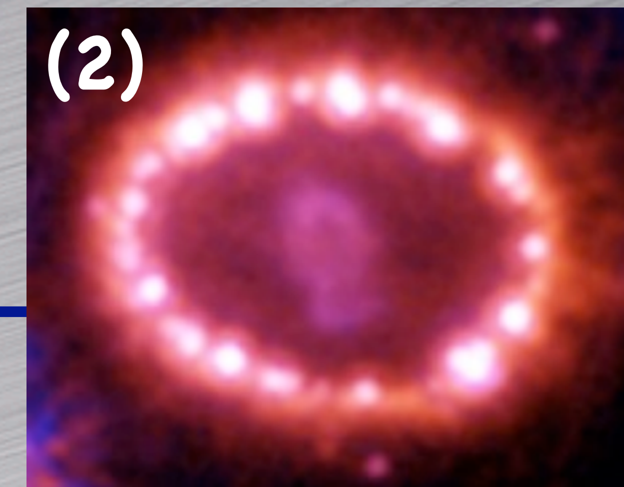
- ➢ Providing ion beam with 10Hz repetition in AIA
- ➢ Arbitrary synchrotron timing and waveform for induction cell.

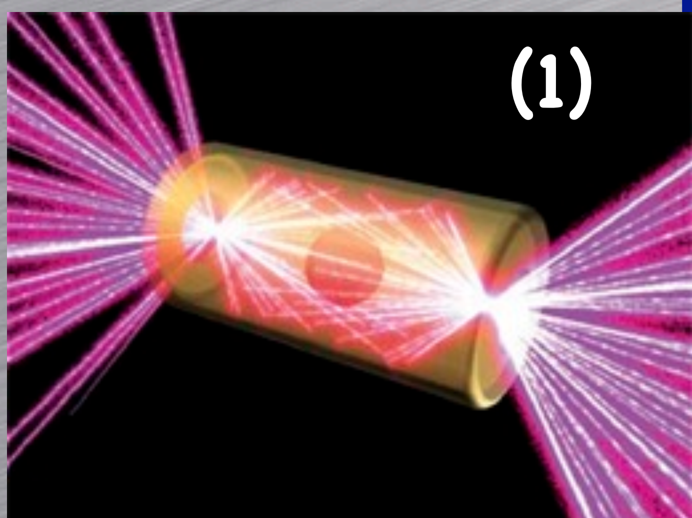
Arbitrary Beam Controlling Systems are Promised

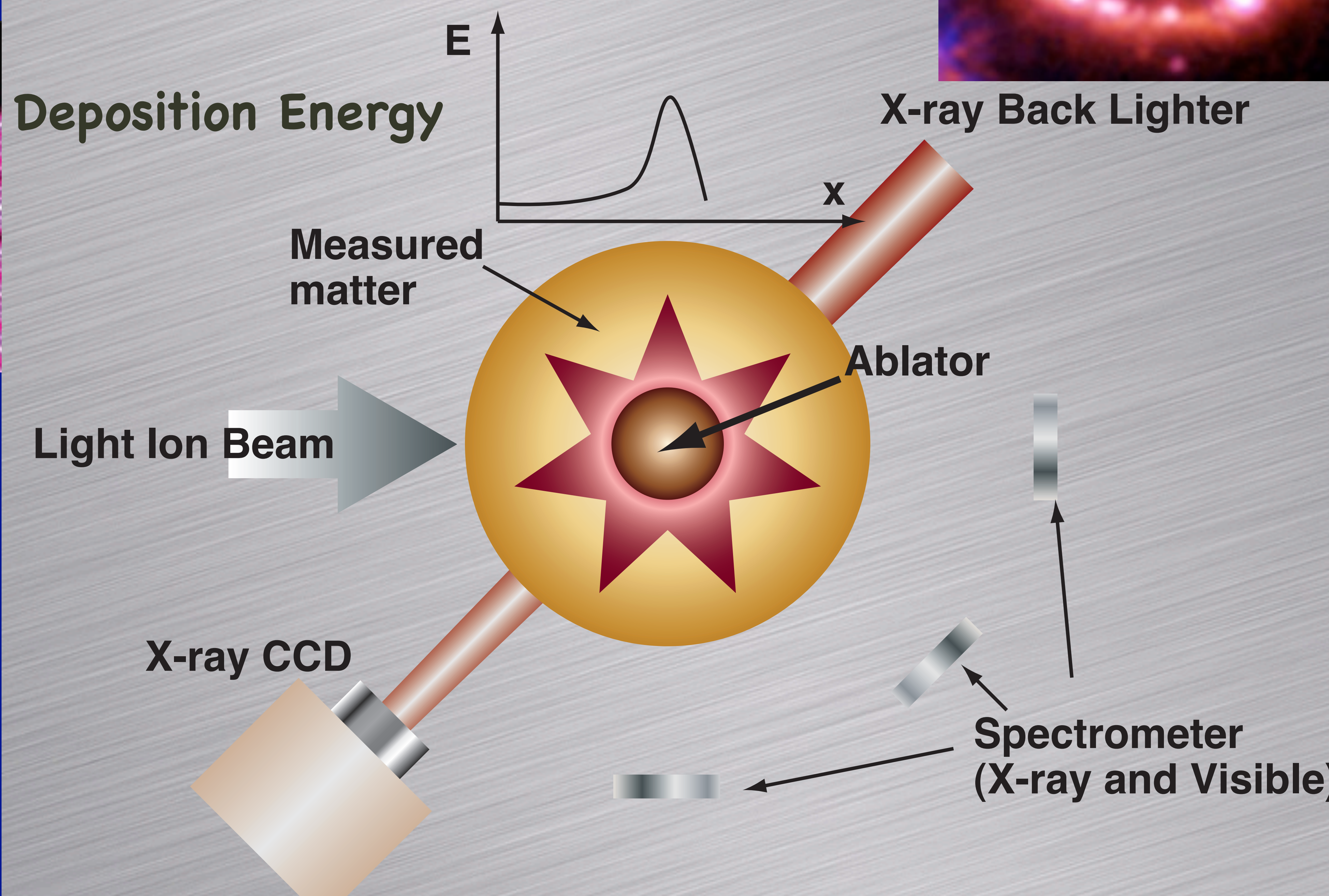
Radiation dominant matter is created for exploring astrophysical Phenomena and efficient indirect ICF

$$R = \frac{F_{rad}}{F_m} = \frac{\sigma T^4}{\rho \epsilon C_s} > 1$$

Radiation dominant matter (RDM) condition







(1)https://lasers.llnl.gov/programs/nic/icf/plasma_physics.php

(2) NASA, P. Challis, R. Kirshner (Harvard-Smithsonian Center for Astrophysics) and B. Sugerman (STScI)

Preliminary results of point-spot radiation source simulation

Ar Ion Beam:

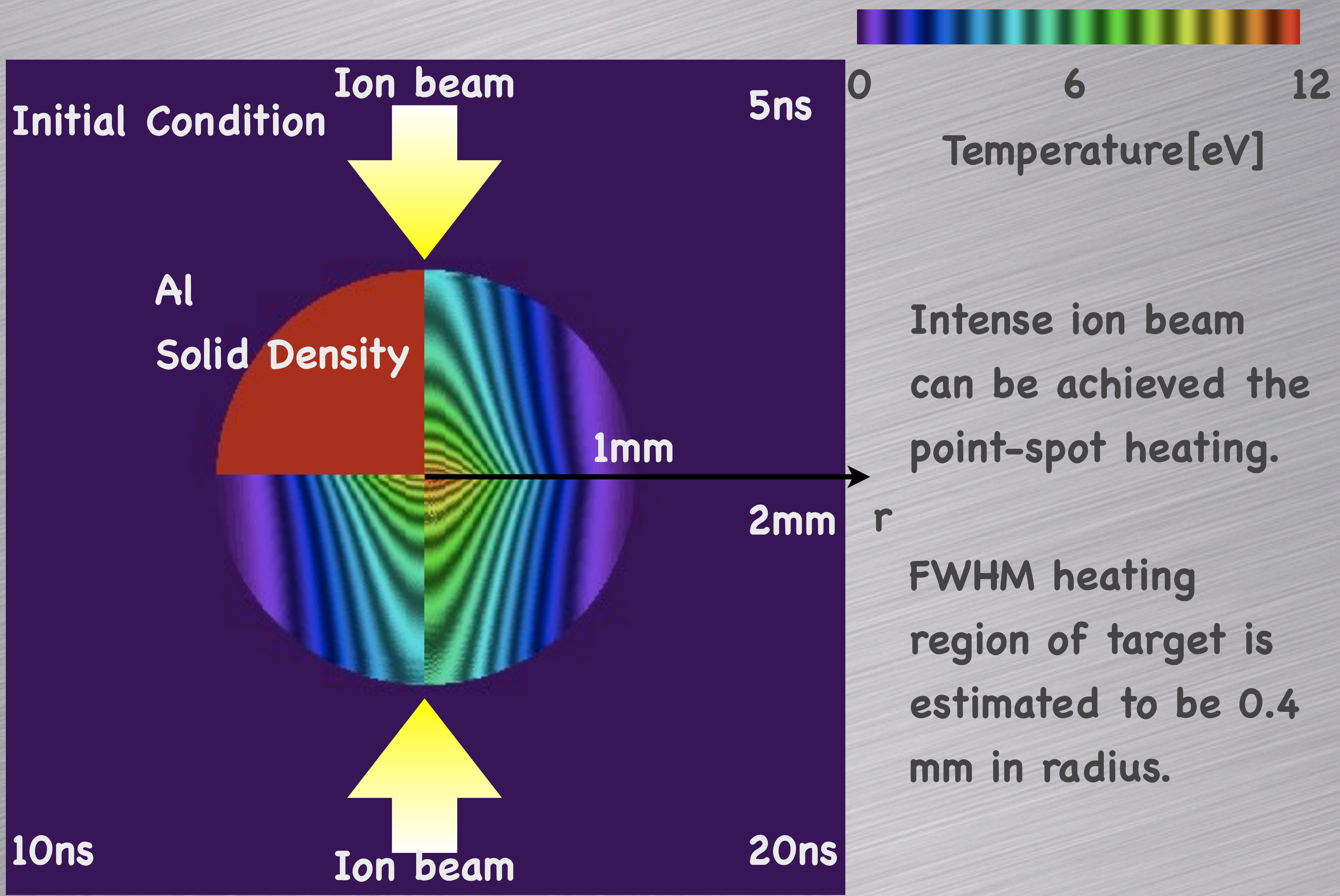
1.67GeV,

2×10^{13} /bunch,

duration: 100ns

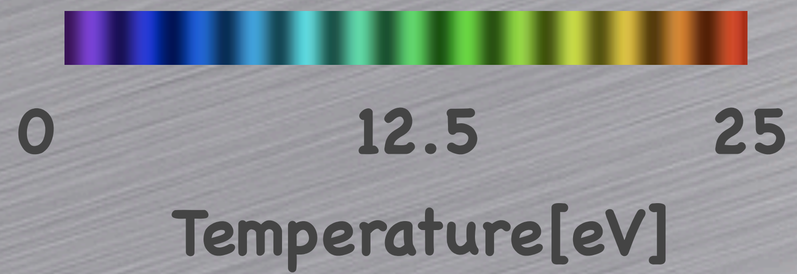
r_b = 1mm,

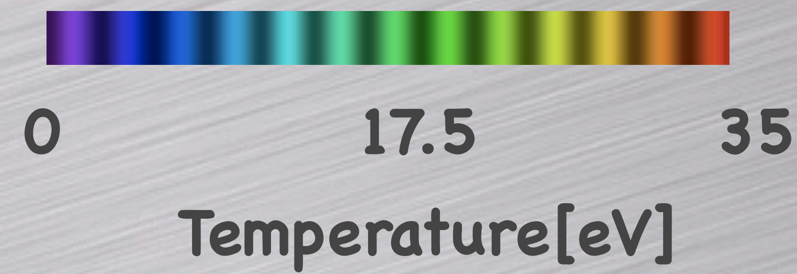
Gaussian Dist.



Intense ion beam can be achieved the point-spot heating.

FWHM heating region of target is estimated to be 0.4 mm in radius.





Concluding Remarks

➢ NUT has many experimental opportunities as a tool of the charged particle beam and the pulsed-power systems for understanding HEDP phenomena.

➢ Intense charged particle beams and pulsed-power devices can be generated the HEDP state. Tuning of the target system, we can evaluate the interesting phenomena with well-defined condition.