Recent Activities on Beam Dynamics and Warm Dense Matter Science in TIT-DES

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In acknowledgement of their collaboration and discussions;

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OUTLINE

- Studies on Beam Dynamics for Intense HIB
  - Beam dynamics in final bunching stage (DES-TIT,NUT)
  - Laser Ion Source (DES-TIT, BHL)
- Warm Dense Matter Study with Wire-explosions in Water and in Semi-rigid Vessel (DES-TIT, NUT)
- MD Simulation Studies (DES-TIT)
  - Equation of State and Conductivity of WDM
  - Transient Effects on the Ablation
- HED/WDM Physics (DES-TIT, RLNR-TIT, UU, KEK)
  - WDM study with HIB and/or PP
  - Quasi-statically tamped/ slightly expanding target
- Summary

BEHAVIOR during LONGITUDINAL MANIPULATION of CHARGED PARTICLE BEAMS

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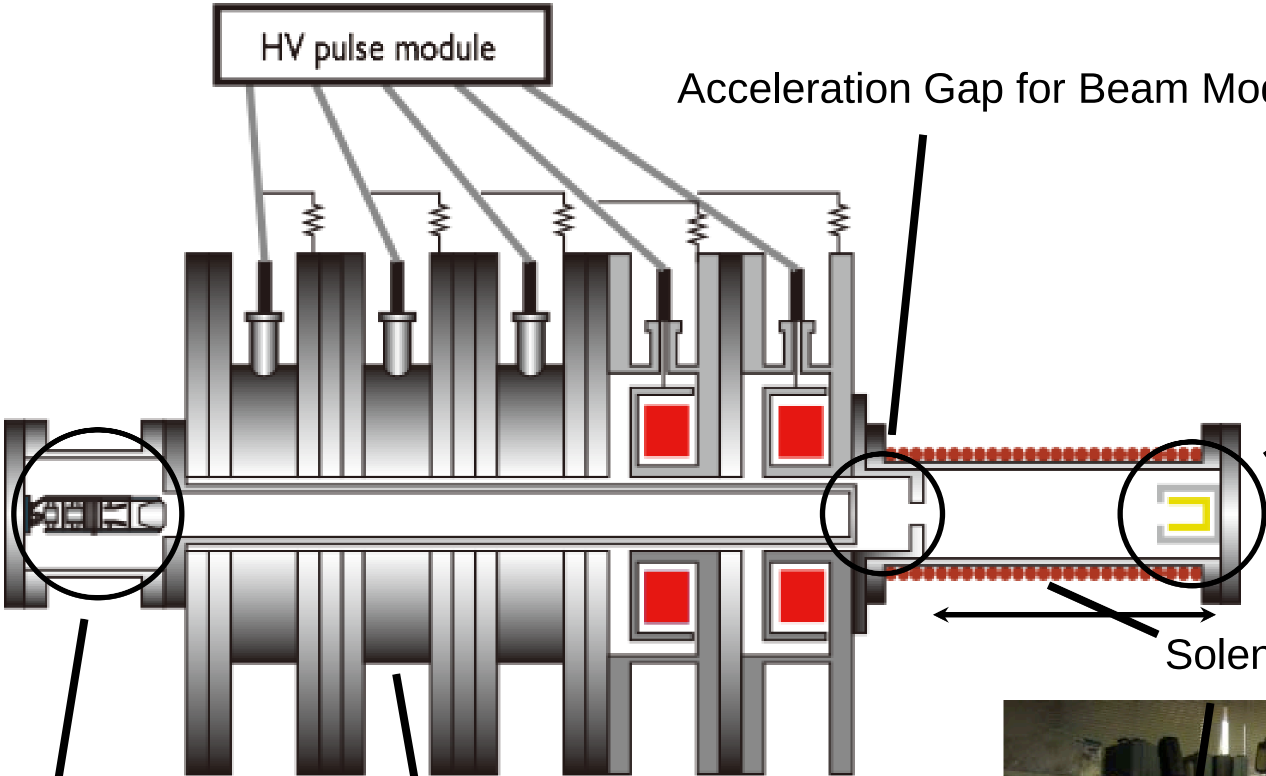
Issues

- Bunch Compression Experiments using Induction Voltage Modulator
- Emittance Growth accompanied by the Beam Manipulation
- Coupling Effects between Longitudinal and Transverse Modes
- Collective Effects during the Bunch Compression

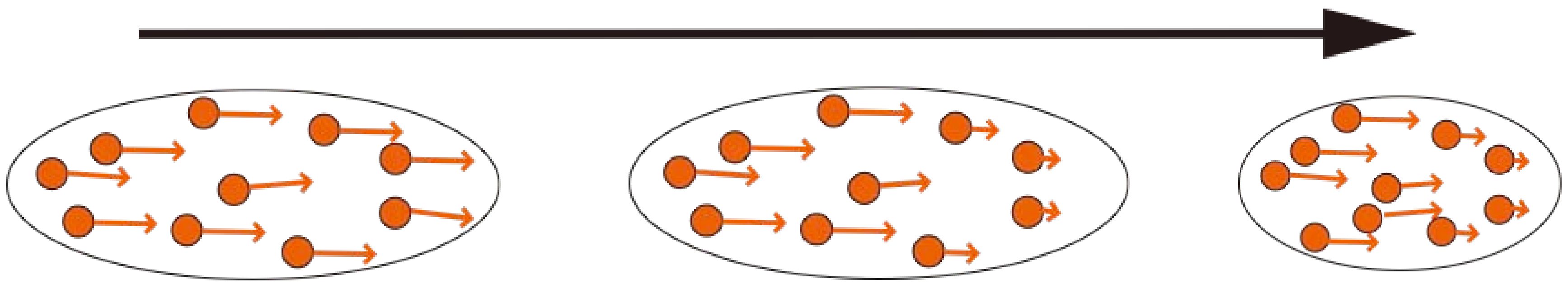
Experimental Arrangement



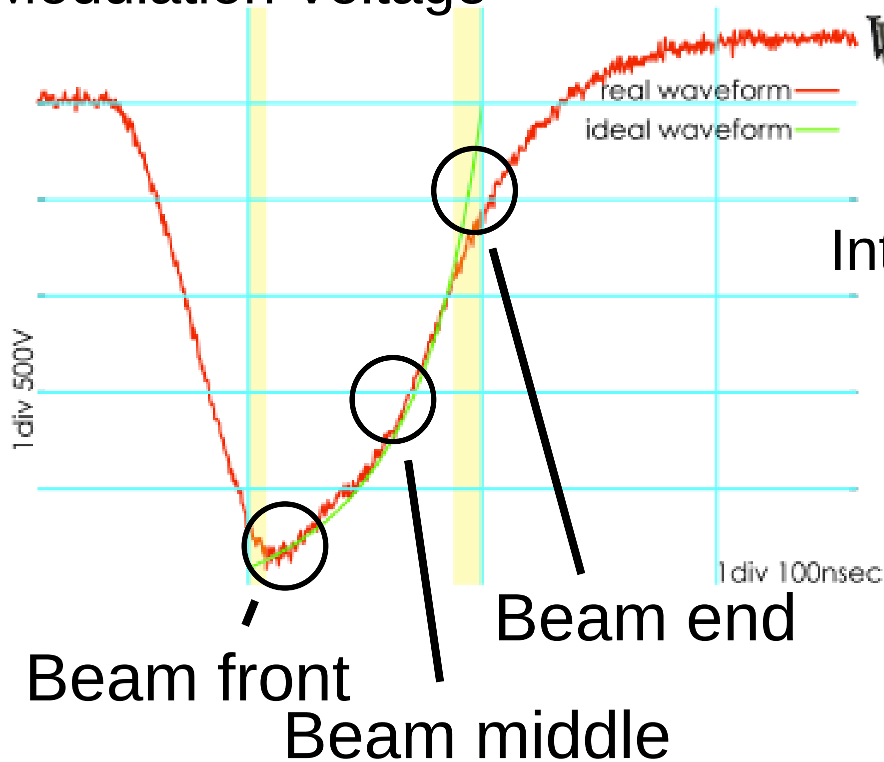
Strategy

- FET-based voltage driver for Induction Adder
- Grid-controlled e-gun
- Solenoidal transport line

Voltage for Longitudinal Compression



Modulation Voltage

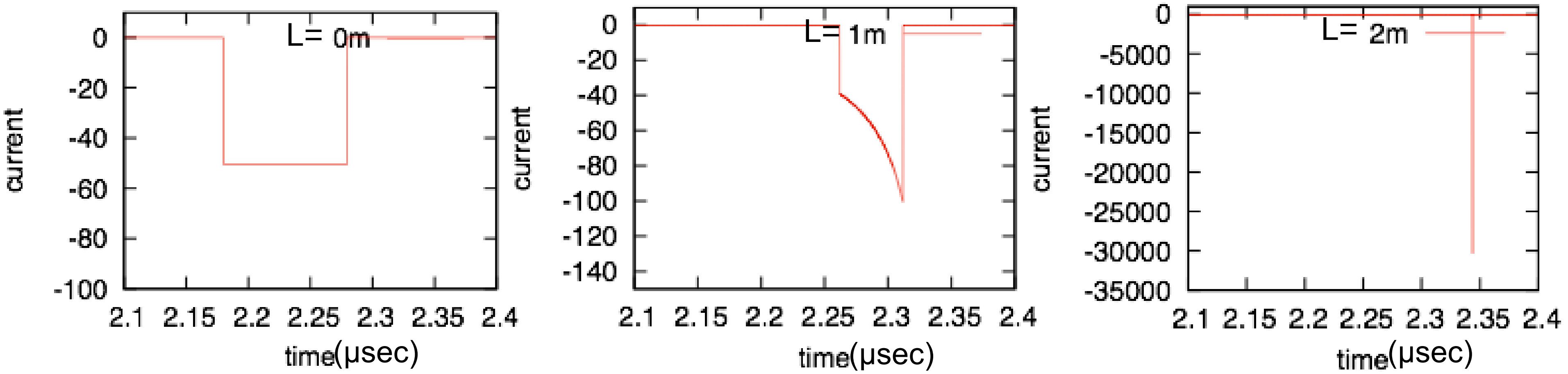


$$V_{dec}(t) = \frac{m_e}{2q_e} \cdot \frac{1}{\left(\sqrt{\frac{m_e}{2q_e V_0}} + \frac{T-t}{L}\right)^2} - V_0$$

Intended Voltage at Beam buncher

- V_0 : Injector Voltage
- T : Pulse Width
- L : Transport Distance

Time-Of-Flight Simulation



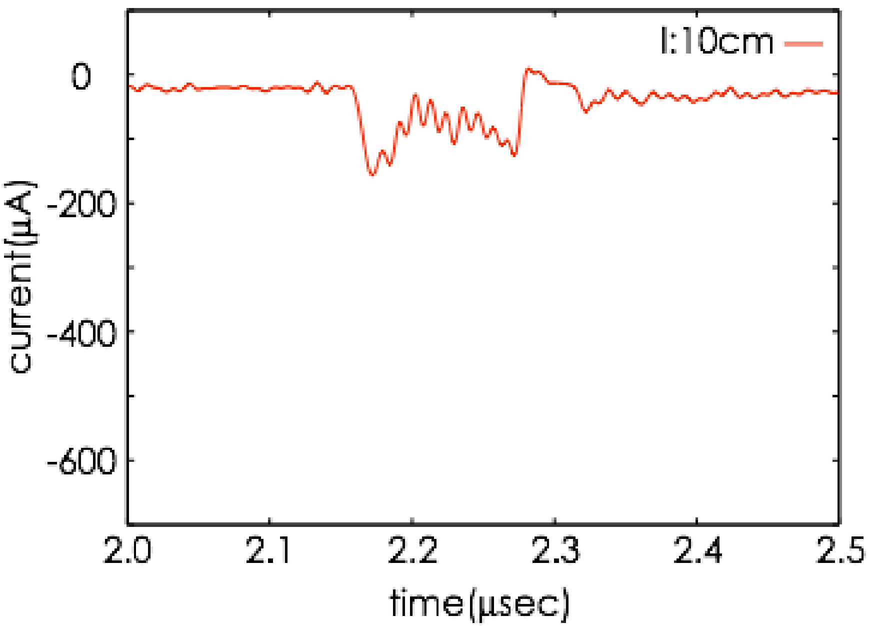
Calculation method

- Charge flux of test particles (N=1000) are estimated as a function of transport distance
- $1/2mv^2=q_e(V_0-V_i)$

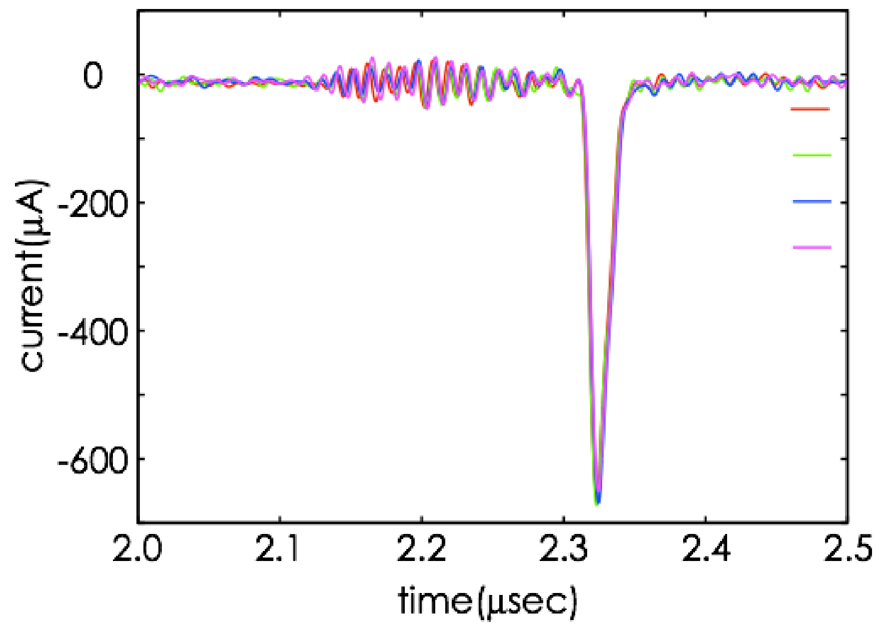
V_0 : Injection voltage V_i : Modulation voltage

Waveforms of beam current at injection and at the destination

Injection 2.8keV, Pulsed Beam T=100ns, $\boldsymbol{B} \simeq 0.03T$



Current at beam injector



Beam current at destination (L=2m)
Successive 4-shots were over lapped

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

$$\Delta t \approx 100nsec$$

$$J \approx 3.2mA/cm^2$$

→

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

$$\Delta t \approx 15nsec$$

$$J \approx 21mA/cm^2$$

Summary

- We developed ;
  - FET-driven voltage adder for longitudinal beam modulation
  - Grid-controlled quasi-static electron gun
  - 2m solenoidal transport line

- Beam bunch was compressed with factor 6-7 and good reproducibility

Influence Factors of Compression Ratio (Emittance Growth)

- Accuracy of Modulation Voltage
- Longitudinal Emittance at Injector
- Space Charge Effect
- Collective Effect

Future Plans

- Faster semiconductor switch for more precise modulation waveform
- Stronger magnetic field for stronger control of transverse beam motion
- Discuss transverse-longitudinal coupling and/or collective effects on the emittance growth

↓

Scaling the emittance evolution during the longitudinal bunching of intense particle beams

WDM Studies using Wire Explosion in Semi-rigid Vessel

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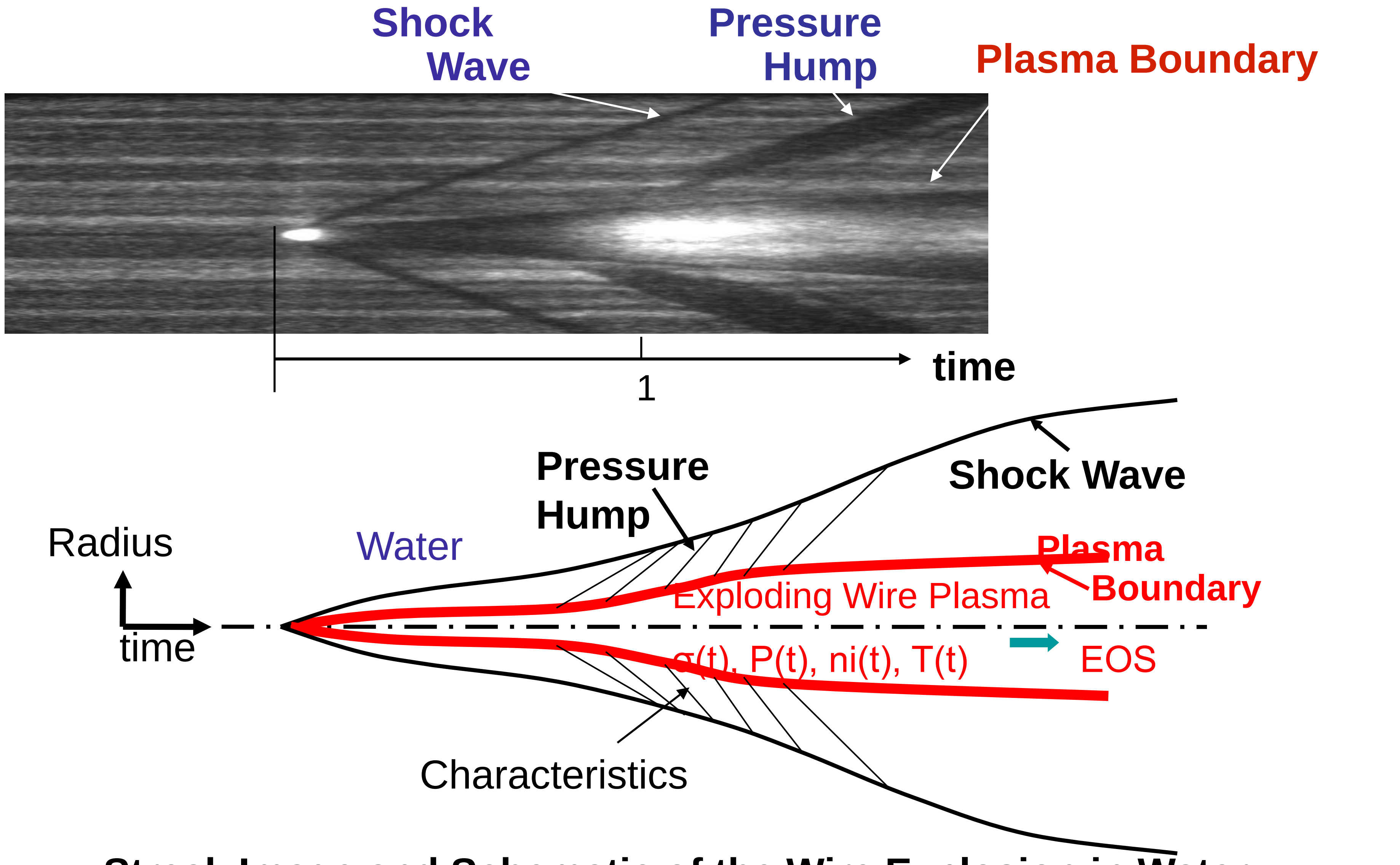
Issues

- Conductivity Scaling
- Minimum Value of the Conductivity
- Metal-Insulator Transition

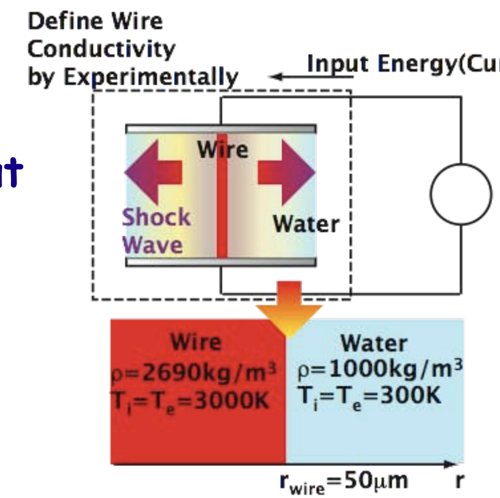
Semi-empirical fitting of hydrodynamic behavior brings us EOS modeling

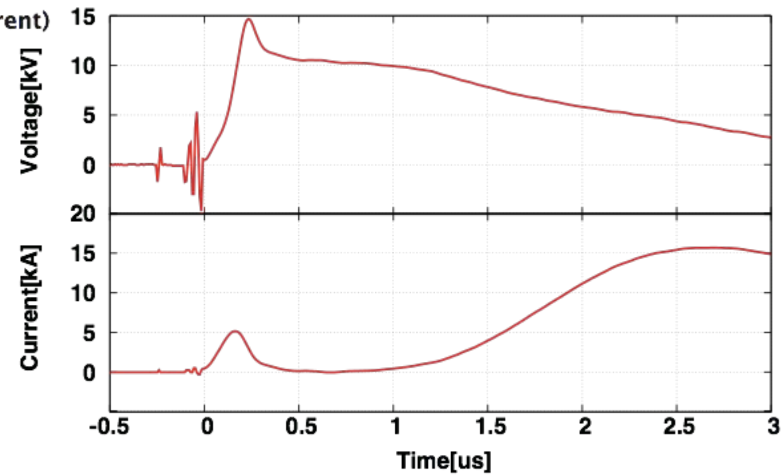


Streak Image and Schematic of the Wire Explosion in Water

Magneto-Hydrodynamic Simulation

Initial Condition and Energy Input



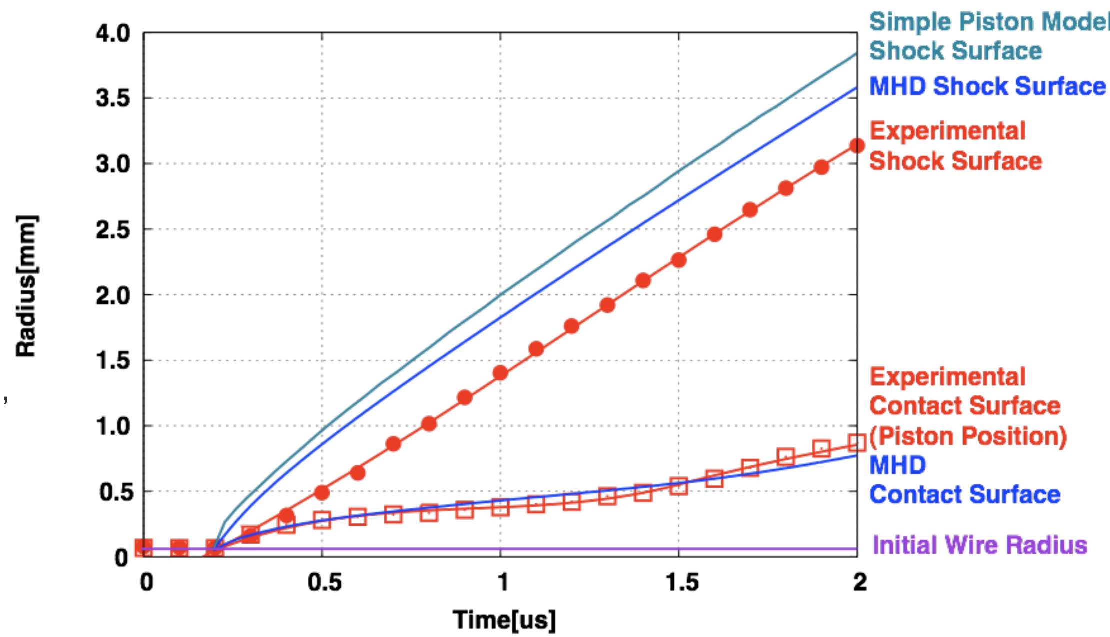


Equation of State (EOS)

-> for Water: IAPWS95[2]

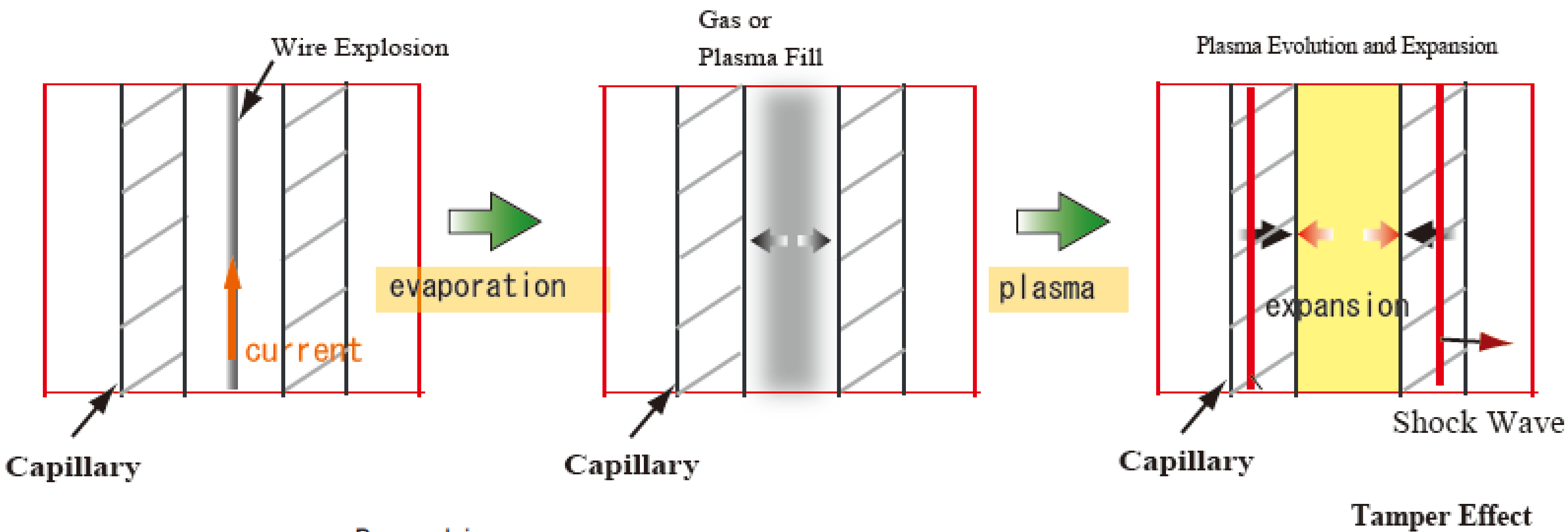
-> for Wire: QEOS[3] or Ideal EOS

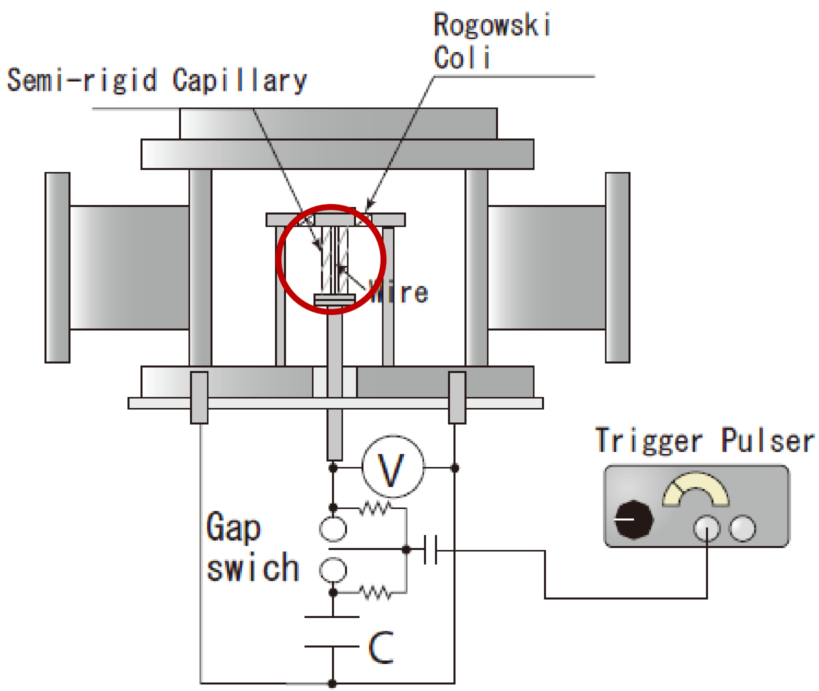
[2] IAPWS Released on the IAPWS Formulation 1995, IAPWS Secretariat(1996)
[3] R. M. More, et. al., Phys. Fluids 31, 3075 (1988)



Comparison of numerical results with experimental observation

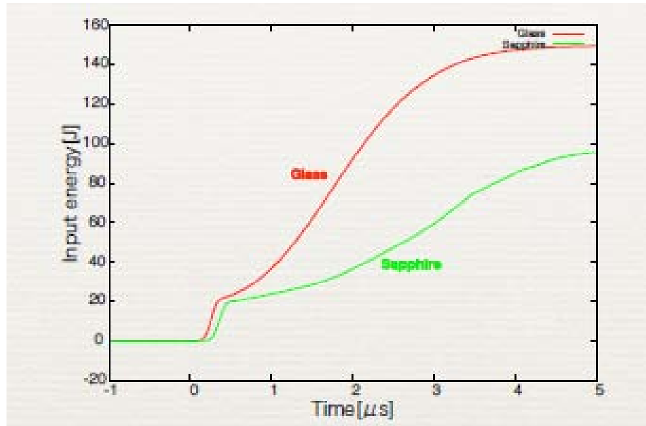
Wire Explosion in Semi-rigid Vessel

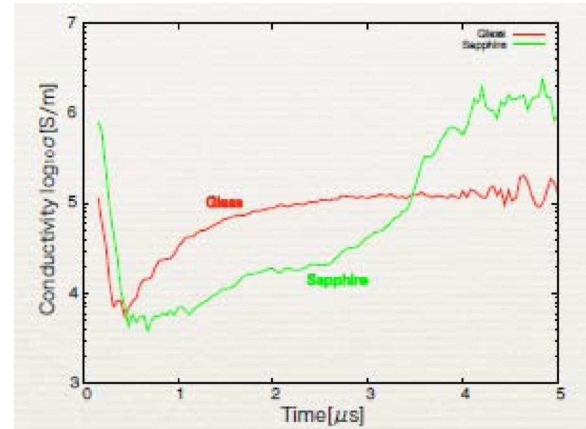




- WDM in slightly expanding vessel
- Conductivity measurements as a function of density
- Cylindrical symmetry up-to the fracture of vessel
- Expansion depends on elasticity of the vessel

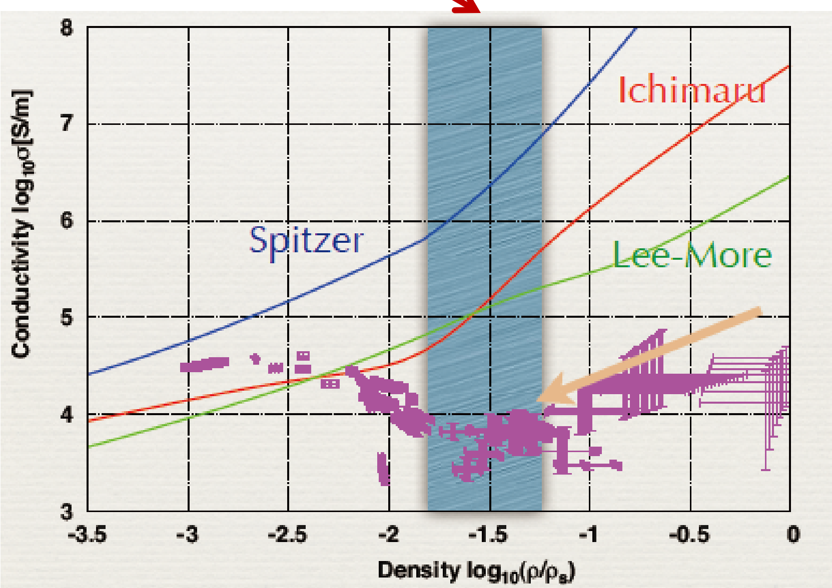
Exploding wire experiments indicate conductivity decreases less than 10000 S/m at 1/30ρ_s



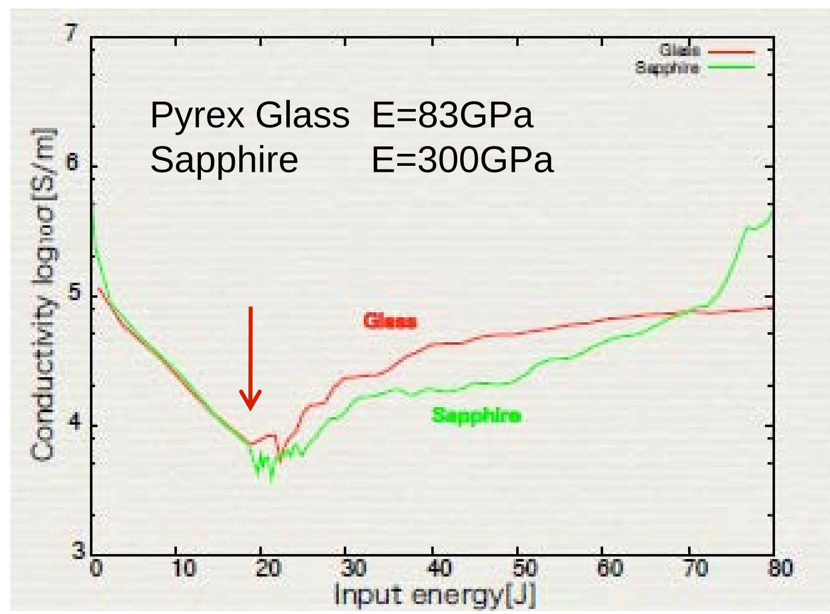


Conductivity minimum at

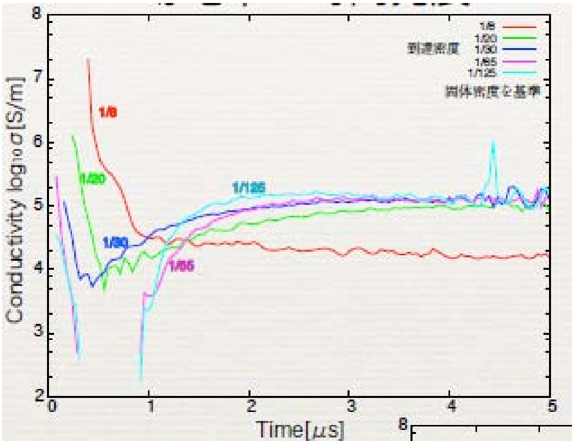
1/30ρ_s($\log_{10}(\rho/\rho_s)$=-1.5)



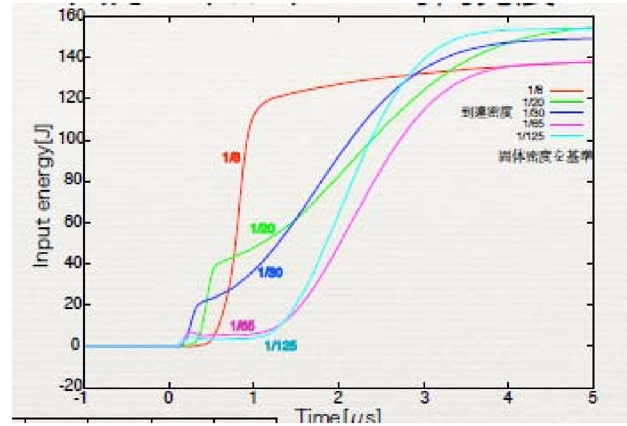
Conductivity versus density at 5000K (T.Sasaki et. al.,)



We can measure the conductivity as a function of input energy

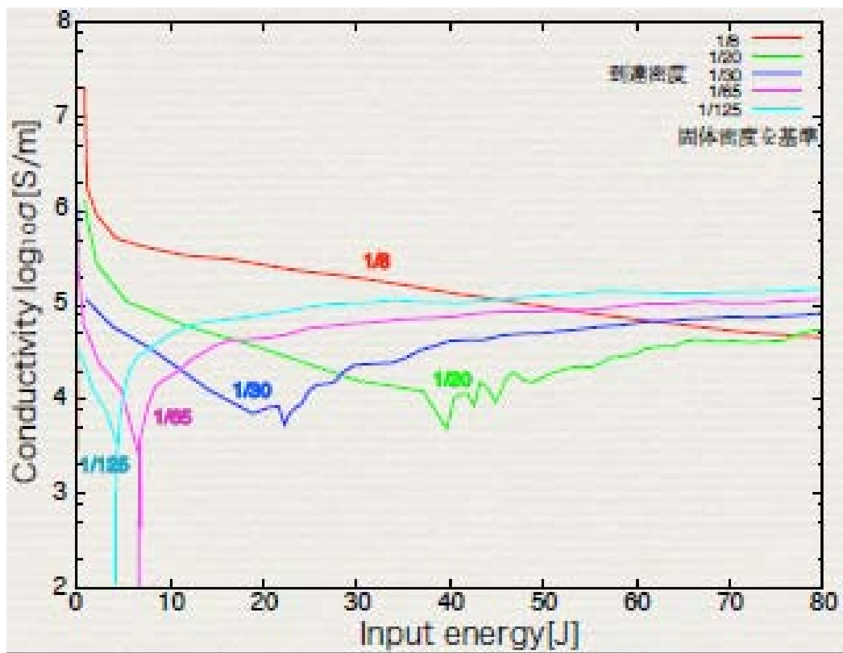


Conductivity versus discharge time



Input energy versus discharge time

Density:
can be controlled
by the initial
loading of wire



Conductivity versus Input energy

Molecular Dynamical Simulation Studies of WDM

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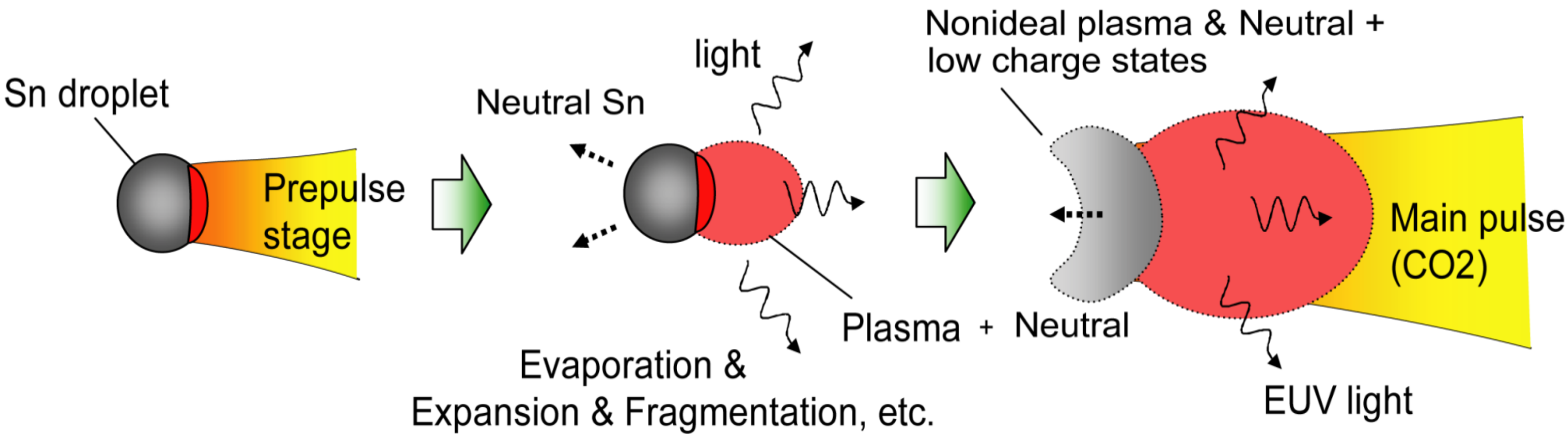
Issues

- Conductivity and/or EOS Scaling
- Transient Effect on the Phase Transition
- Study on WDM with Microscopic View

Background & Motivation

LPP extreme ultraviolet (EUV) source for EUV lithography



Nakamura, J. Phys. D (2008) & Shimomura, Appl. Phys. Express (2008).

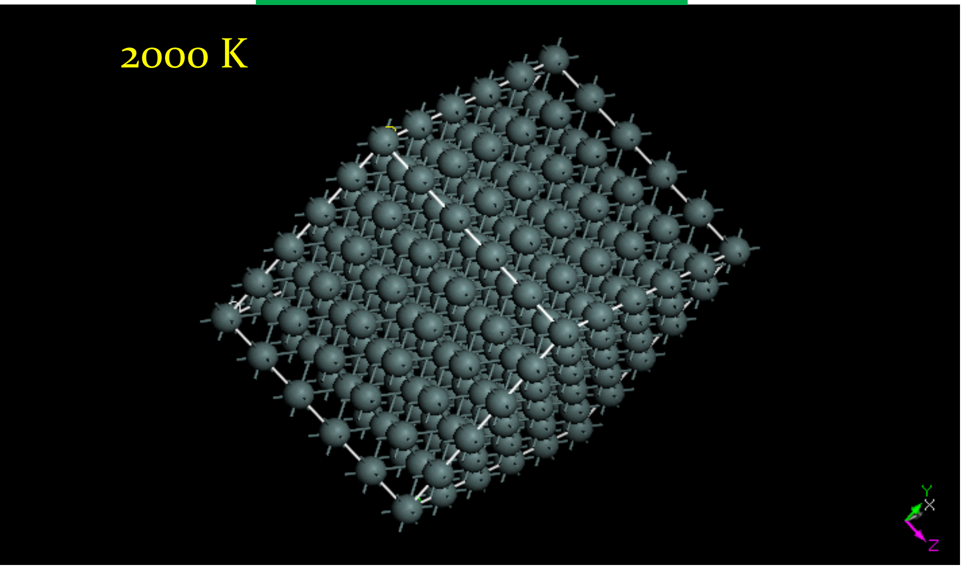
LPP experiments (high heating /cooling rate):

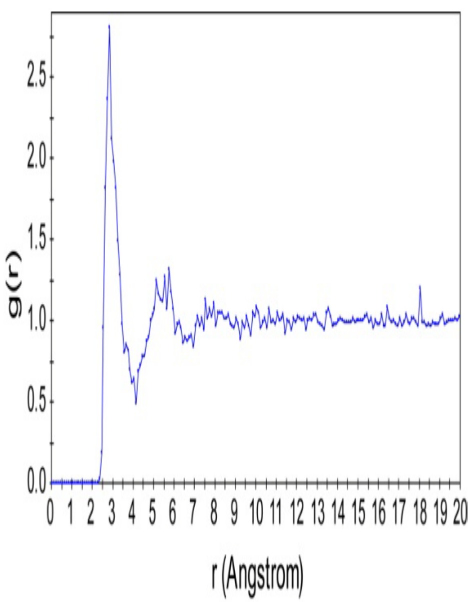
1. **Is really possible to control particle trajectory?**
2. **What is thermodynamic pathway?**
3. **What is equation of state (EOS)?**
4. **Time is not a thermodynamic coordinate. Is kinetic phase transition important?**

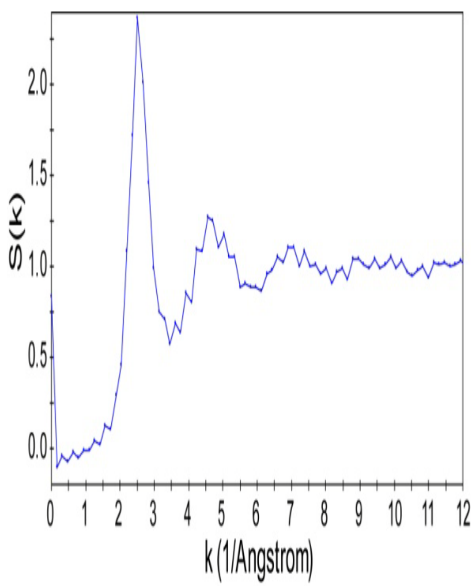
1. **Debris-mitigation including neutral Sn**
2. **Physics of laser ablation including condensation**
3. **EUV mirror contamination**
4. **Improving plasma radiation**

MS: BCT Sn at high temperature

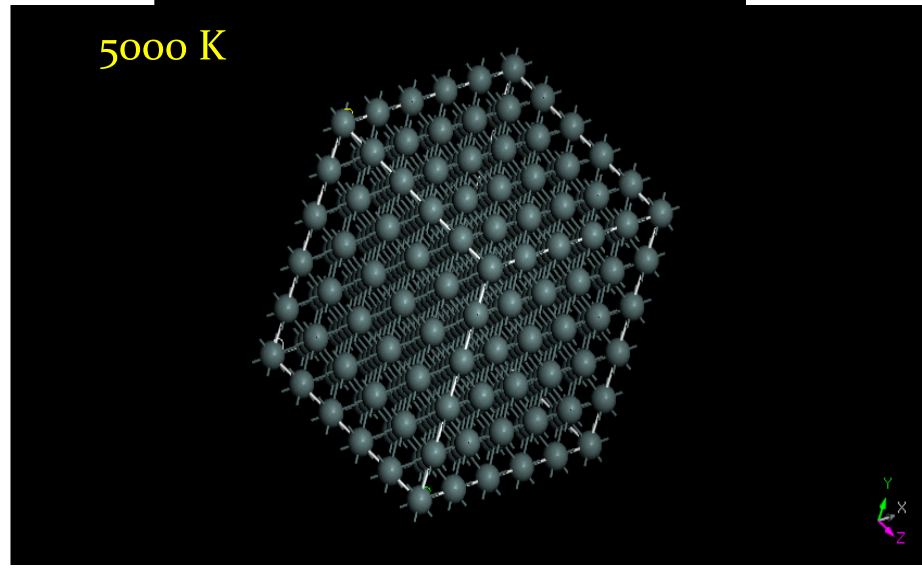
Atmospheric pressure

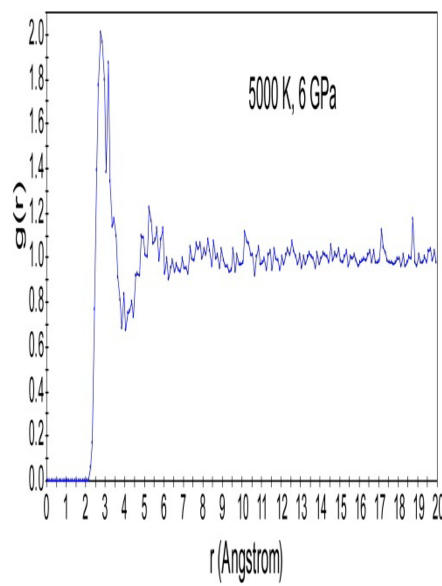


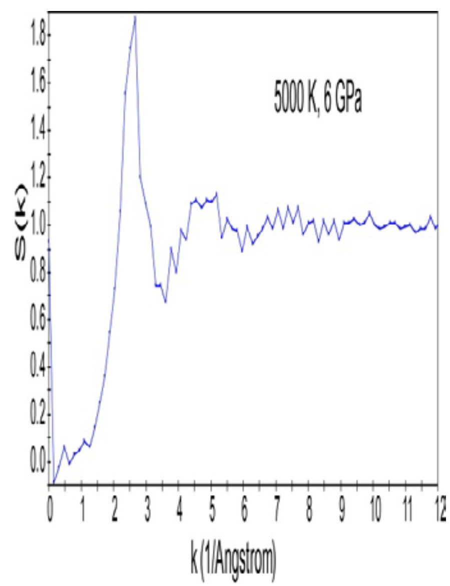




Under 6 GPa external pressure







T-V isobar diagram & Temperature hysteresis

Liquid Sn is cooled down to becomes solid and then solid is heated until it melts.

Luo, J. Chem. Phys. (2004) & Phys. Rev. B (2003).

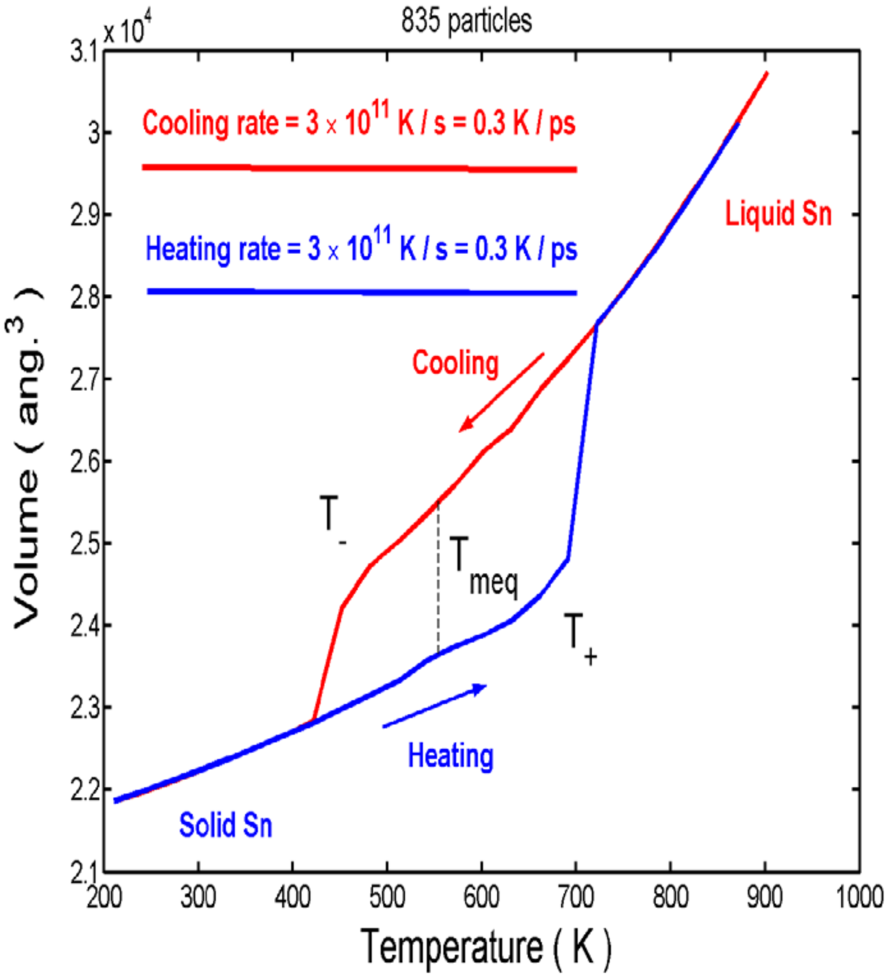
Equilibrium melting temperature, superheating (cooling) degree for this heating rate:

$T_{meq} = T_+ - (T_+ T_-)^{0.5} + T_- \approx 560$ K

Superheating $(T_+ - T_{meq})/T_{meq} \approx 0.2$

Supercooling $(T_{meq} - T_-)/T_{meq} \approx 0.2$

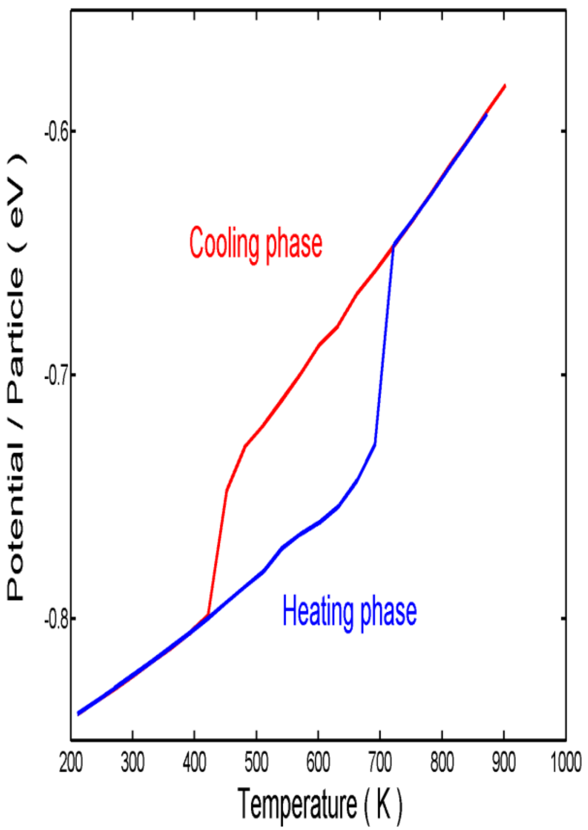
1. In fast experiment [high heating (cooling) rate] kinetic effects become important.
2. Faster heating: solid melts at higher temperature.
3. Faster cooling: liquid may becomes glass or amorphous.

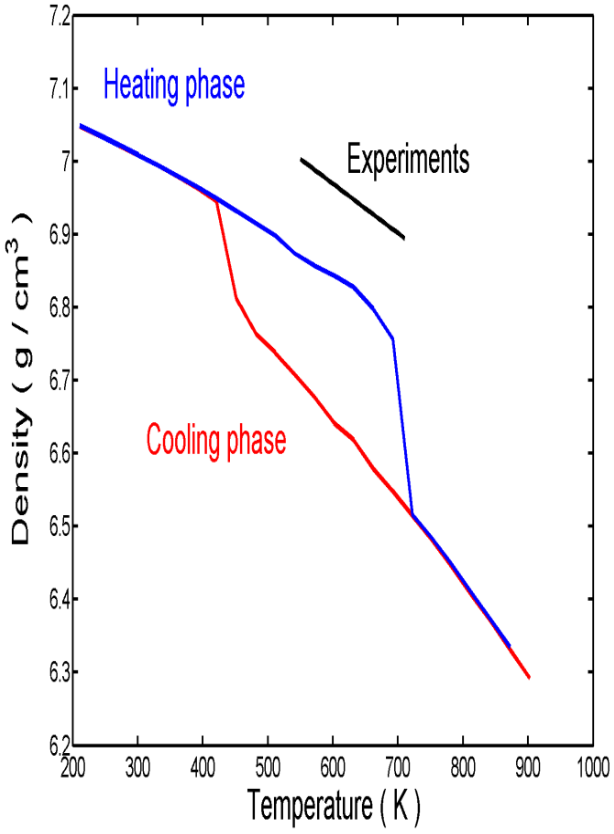


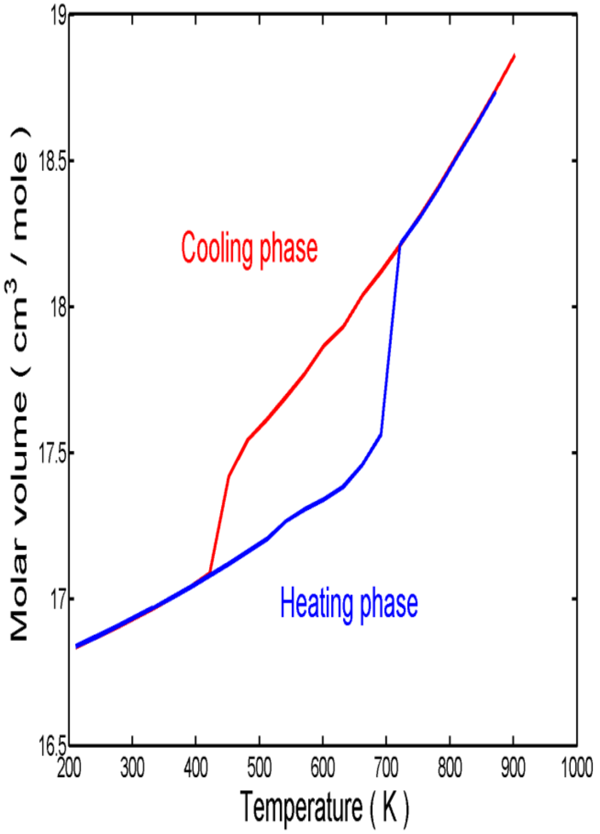
Volume versus temperature.

T-V isobar diagram & Temperature hysteresis

Melting and solidification can also be judged by other parameters like potential, density and molar volume.







Results are in agreement to previous experimental and theoretical reports, for example, density against temperature of liquid Sn as reported by Alchagirov, High Tem. (2000).

Beam driven WDM Studies

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Issues

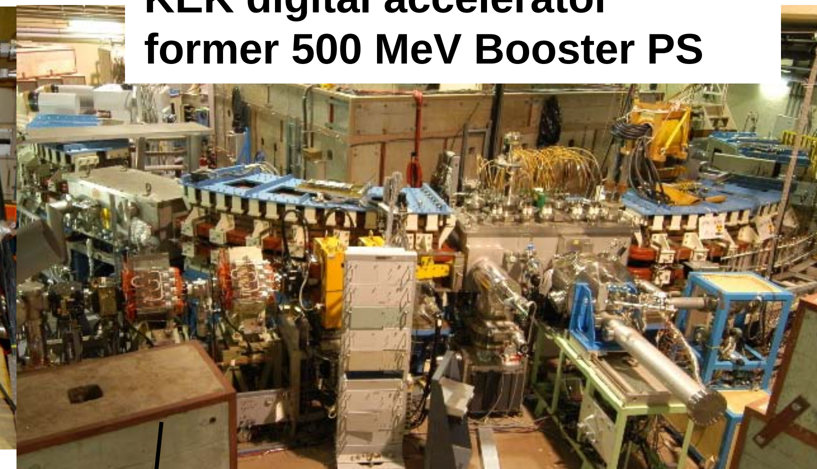
- Accelerator Physics including Laser Ion Source
- EOS of Hydrogen, Form, and others..
- Planetary Science and Heavy Ion Fusion

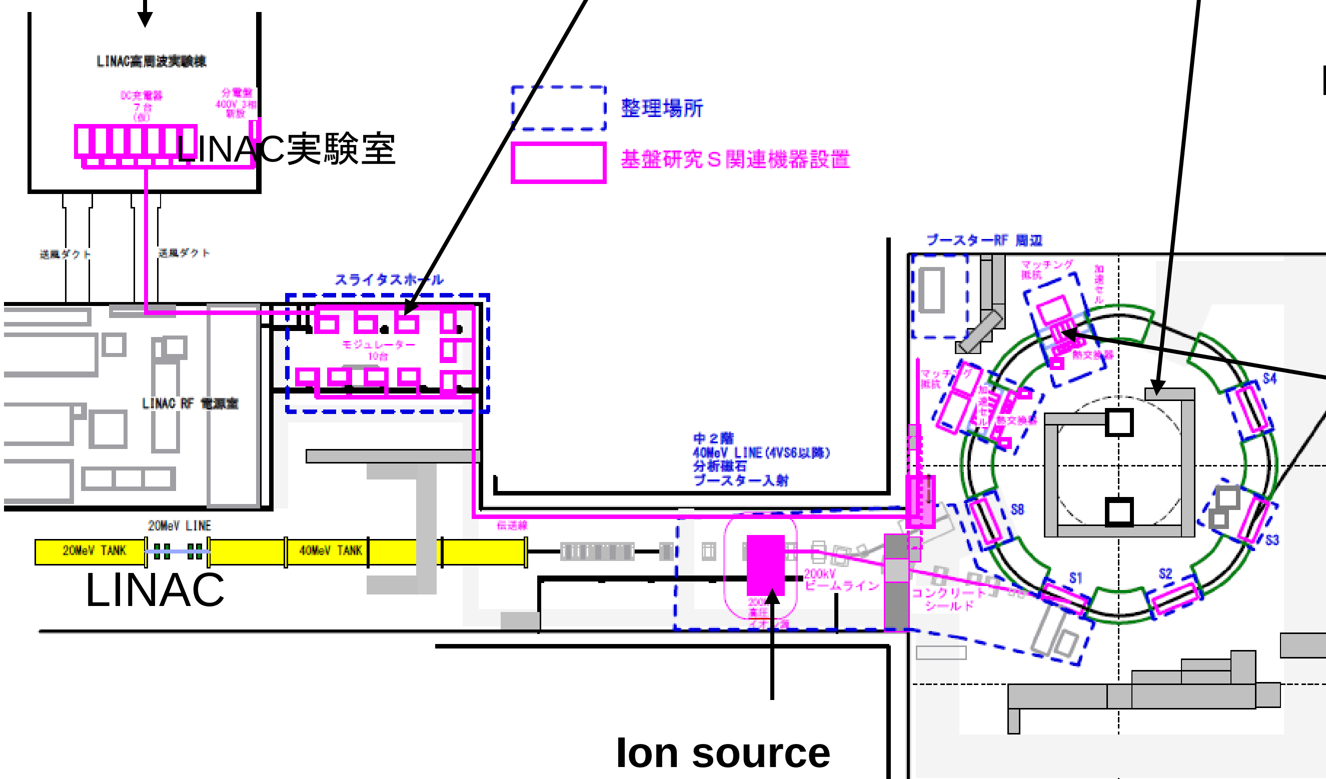
Layout of the KEK Digital Accelerator

DC power supply

Switching power supply

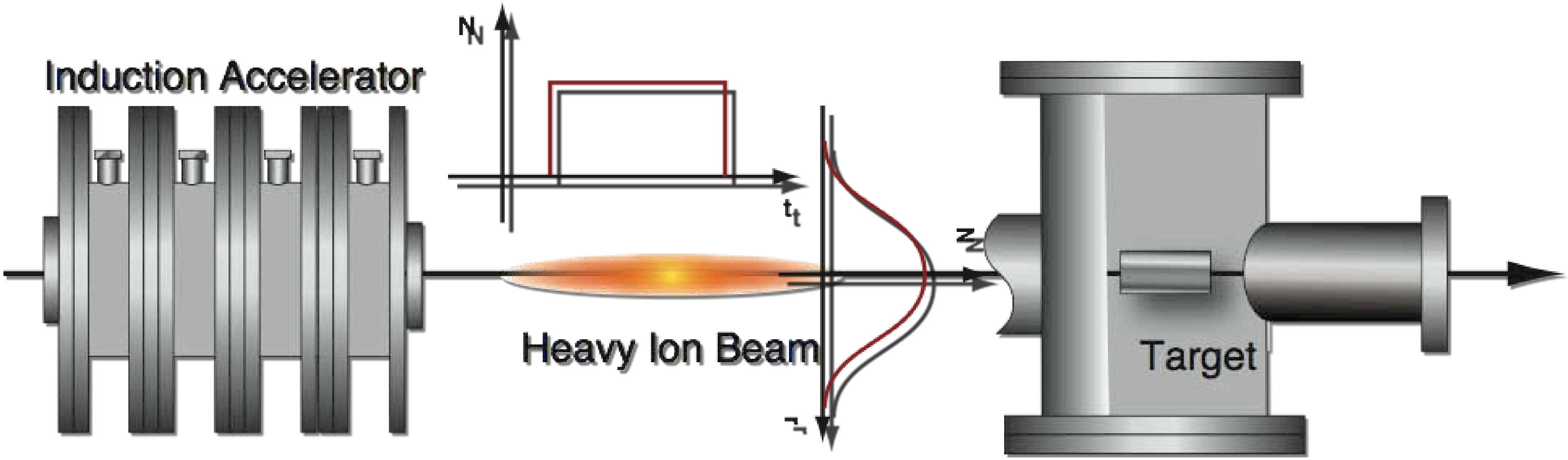
KEK digital accelerator former 500 MeV Booster PS





Induction acceleration cell

Beam Parameters for Target Irradiation

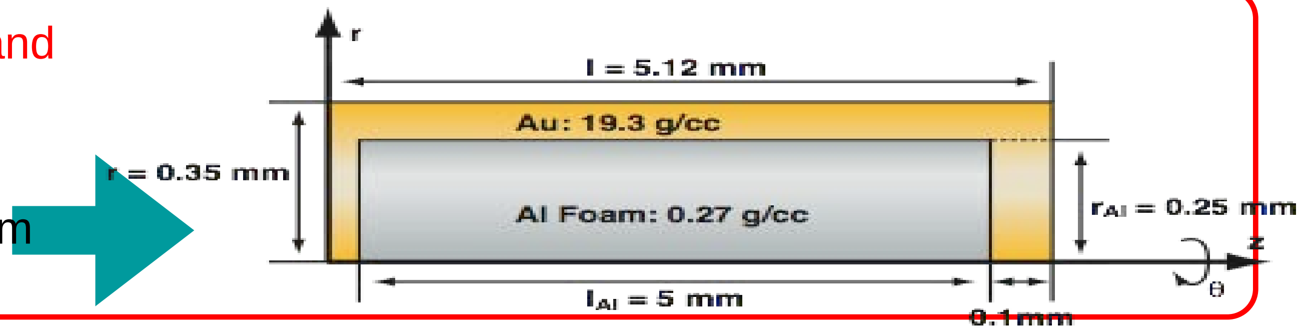


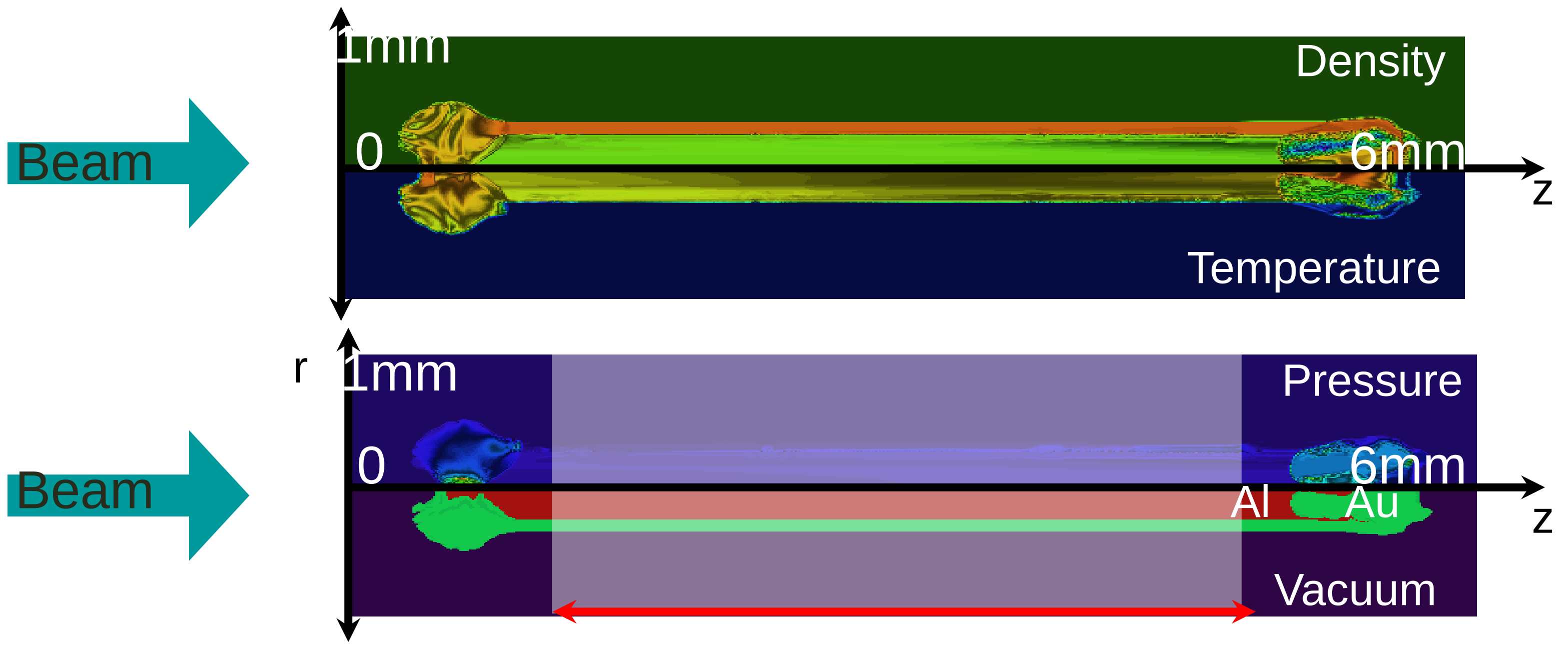
Beam Condition
-1×10^{10} particles/bunch
-14GeV, uranium projectile
-100ns pulse duration
-Gaussian distribution in radial direction
-no beam emittance

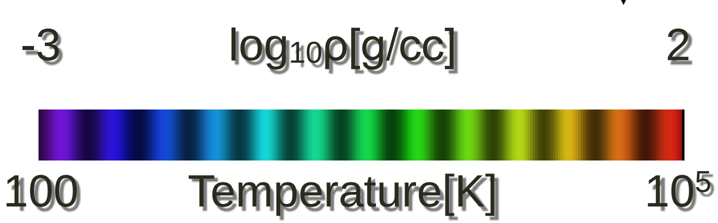
Tamper provides a Quasi-uniform State up to 75ns

Target Structure and Beam Parameter

Beam Radius: 0.5mm

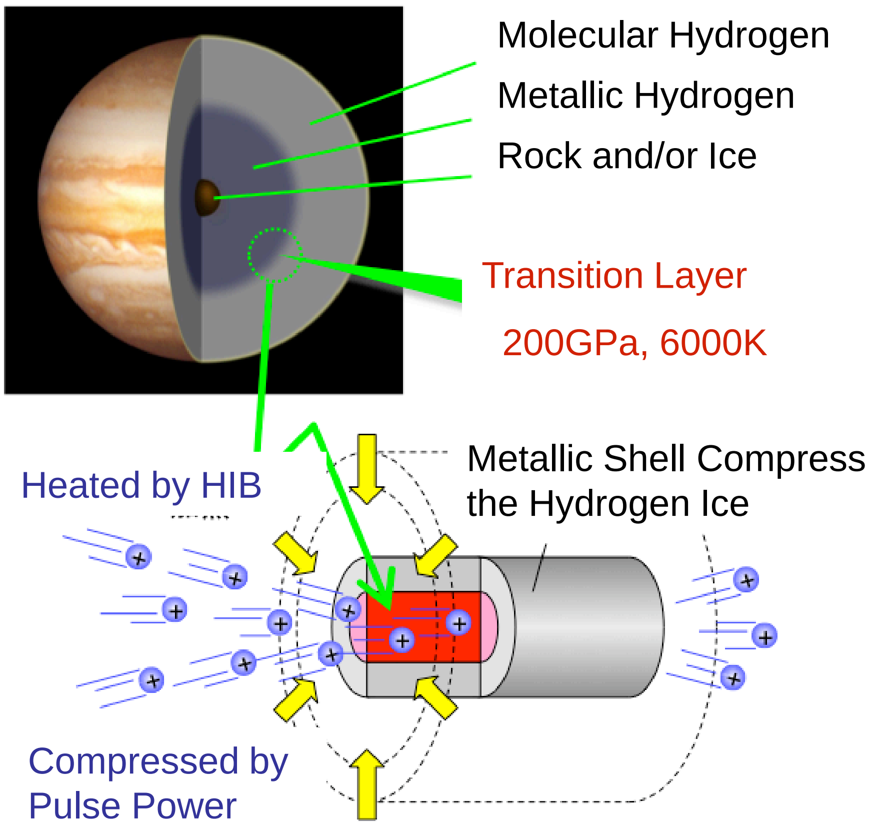


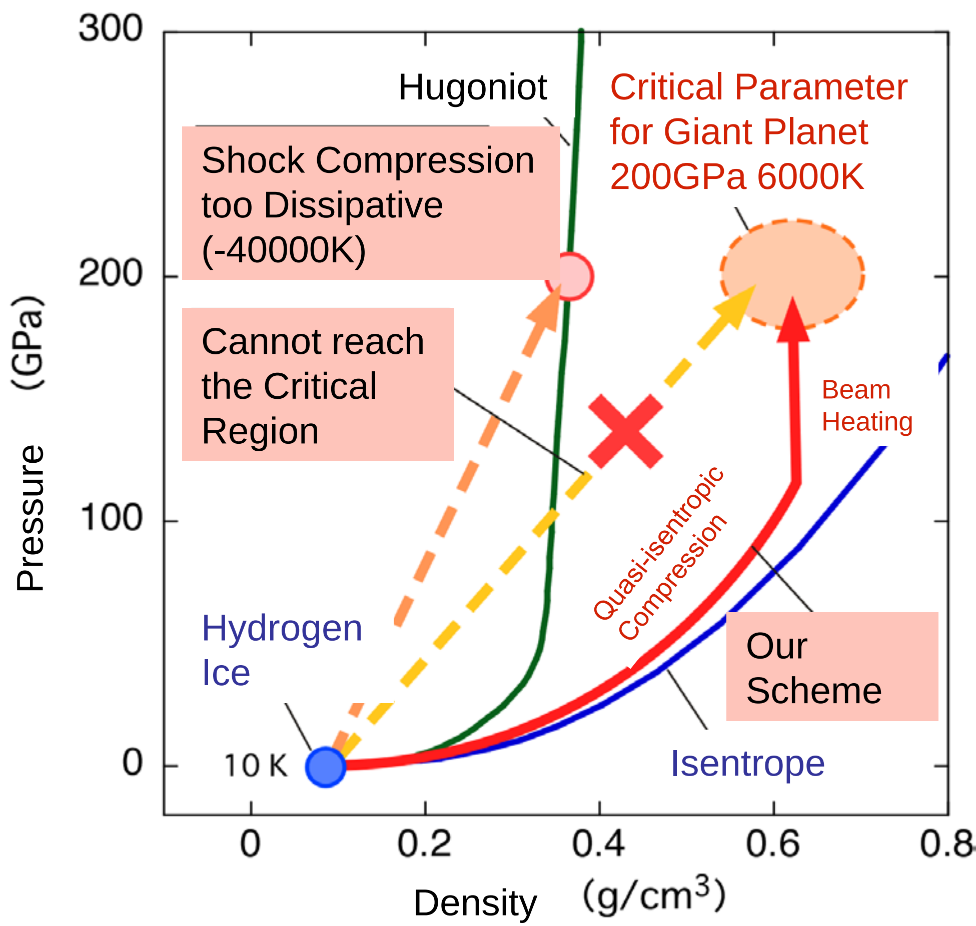




~4mm Quasi Uniform region

HIB Target assisted by PP-compression Scheme can contribute Planetary Science





Concluding Remarks

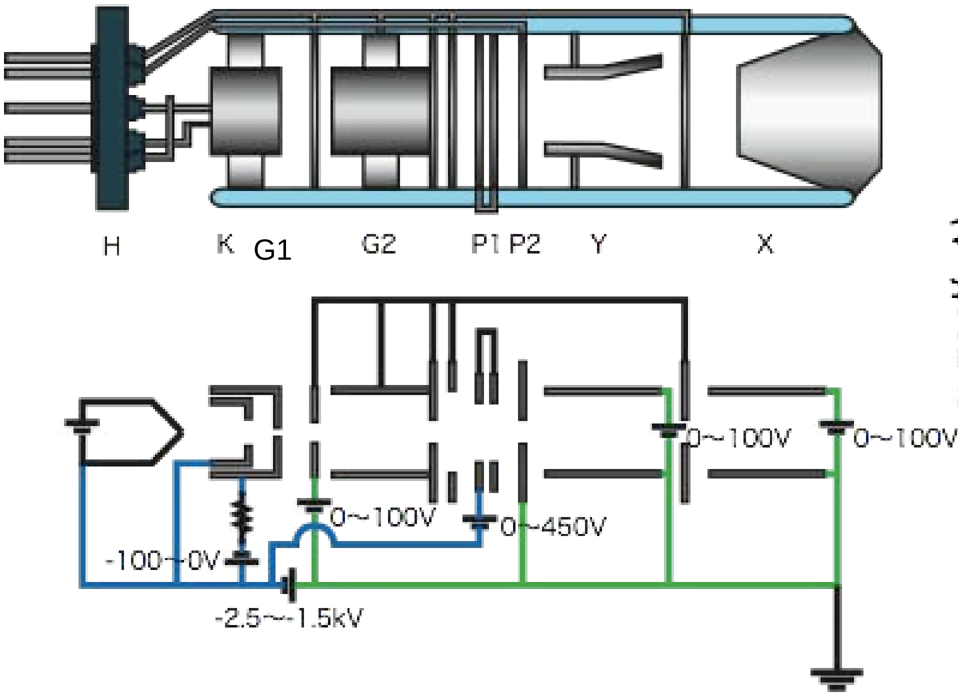
- Scaled experiments on beam dynamics during final bunching
- Conductivity measurements at dense (1/30ρ_s), moderate temperature (～5000K) regime
- MD approach to WDM science
- Accelerator physics
- HI-beam driven target for WDM science and HIF in much more wider parameter region

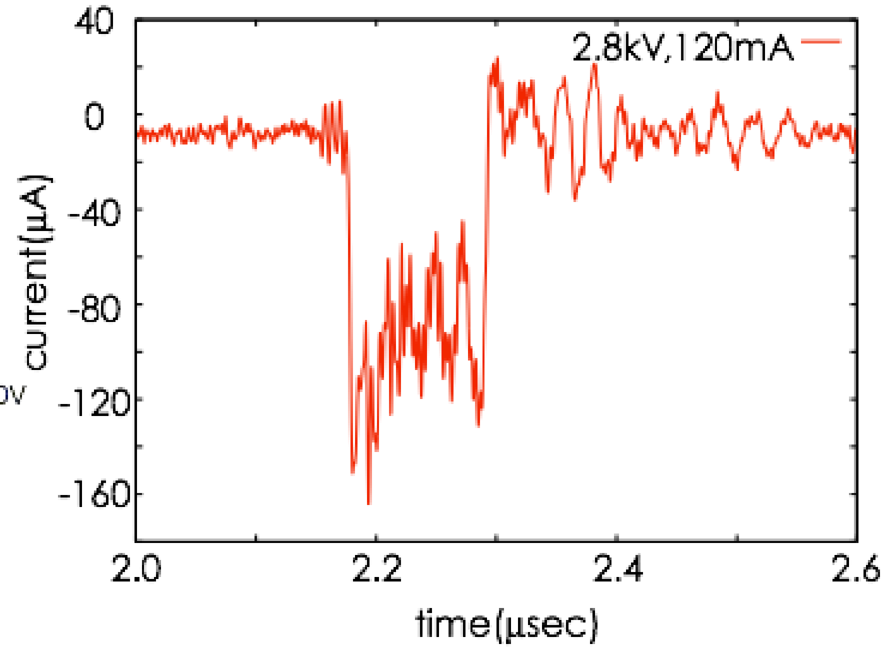
Thank you for your kind attention

Concluding Remarks

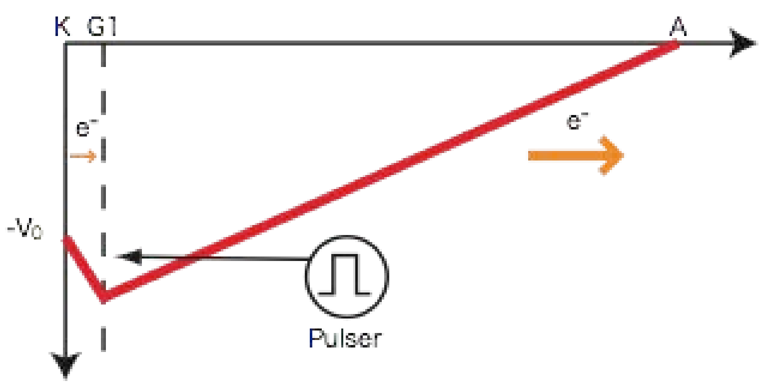
- HIF scenario has been sophisticated
- R&D on ID Synchrotron was upgraded to the second phase
- HIB is expected to contribute not only to inertial fusion but to WDM physics as well.
  - Especially to planetary science; to explore the origin of our solar system and/or the beginning of our life

Grid-controlled Electron Gun





Typical Waveform of e-Injector Current



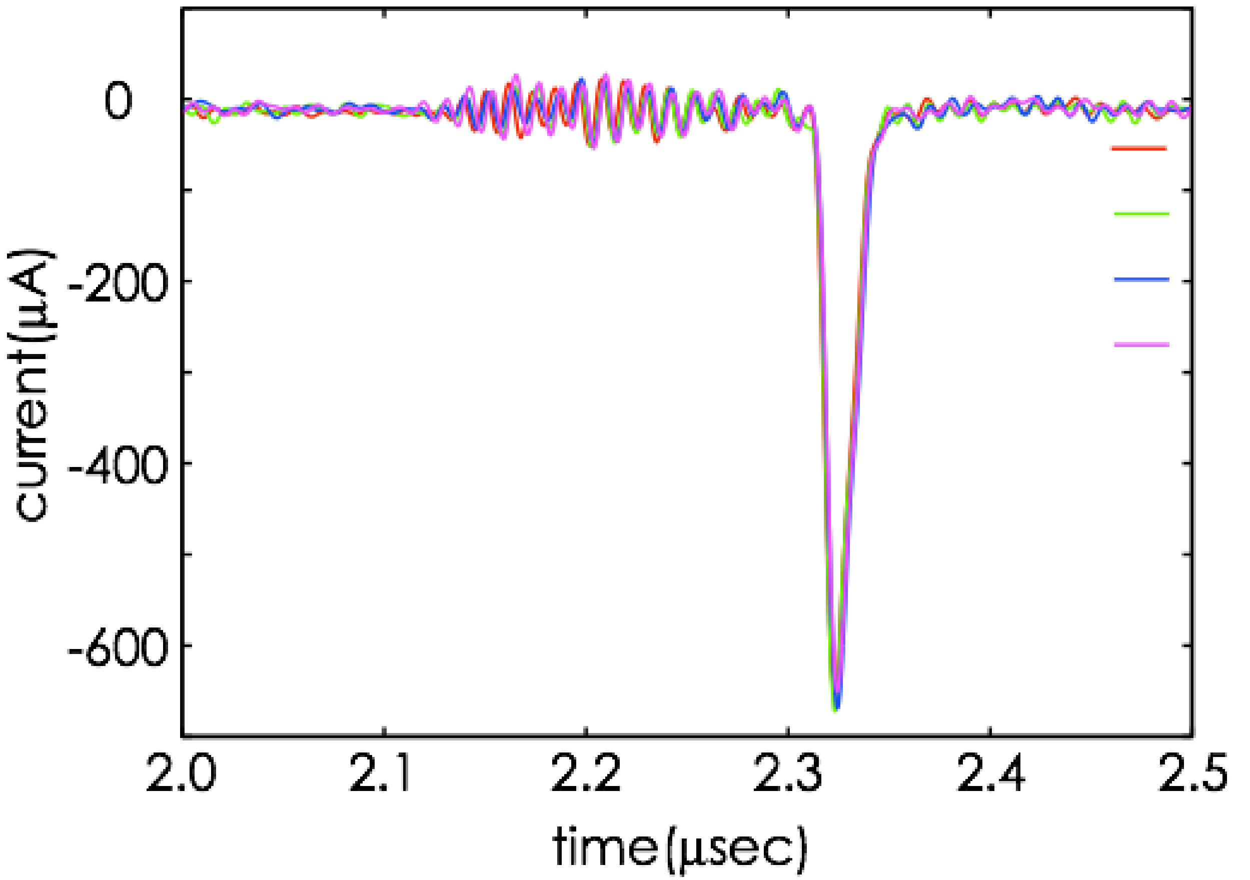
Electron Gun

- Thermo-electric Emission
- Statically Biased

Electrodes

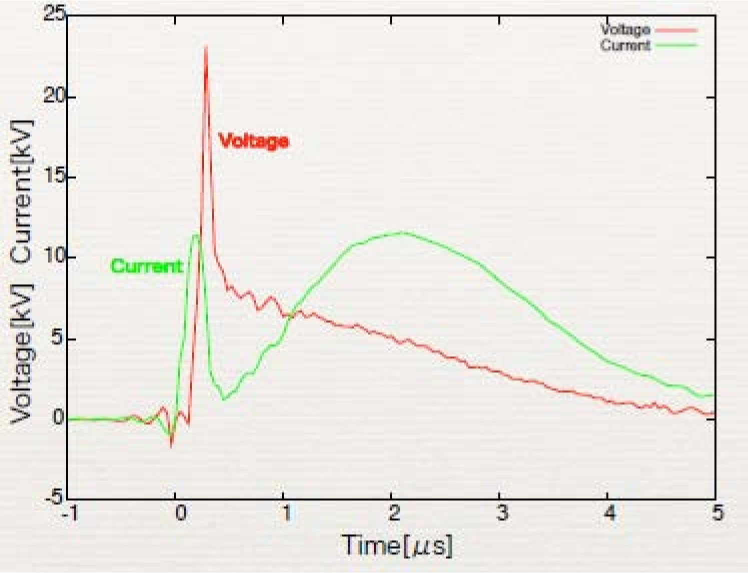
- Grid-controlled

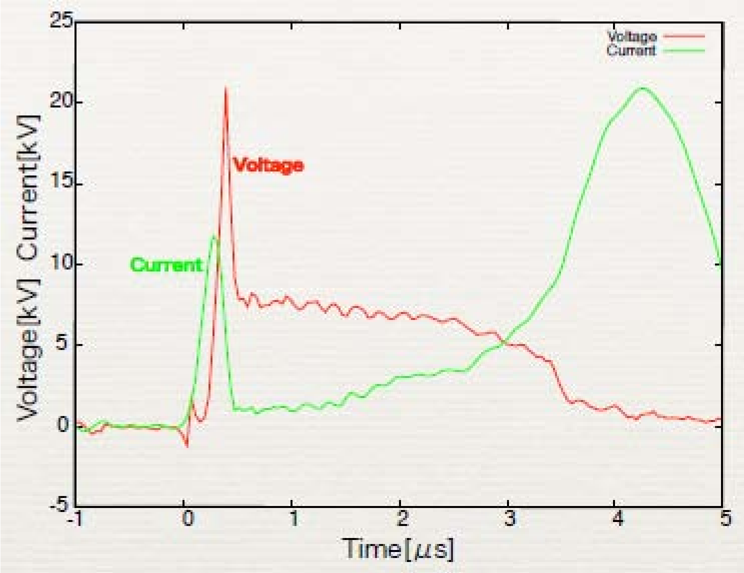
Reproducibility of the Compressed Waveform



Successive 4-shots traces were overlapped

Reproducibility was vastly improved by the Grid-controlled electron gun and FET voltage modulator





ヤング率　ガラス：83[GPa]
サファイア：300[GPa]

Expected Specifications of Digital Accelerator

Ion Beams provide d from the KEK digital accelerator (2010-2012)

Magnetic rigidity: $B\rho$ = 1.1 T x 3.3 m = 3.633 m・T, f = 10 Hz, V_{inj}=200 kV

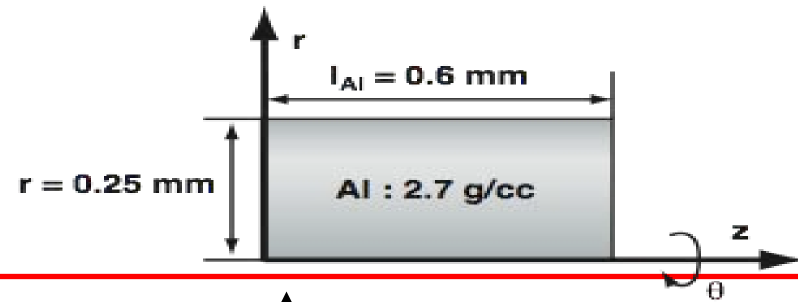
Species (typical example)	A/maxZ	Max energy/amu (MeV)	number/bunch	number/sec	beam size (mm^2)	LET in water (keV/µm)	Range in water (mm) *	Range in Al (mm) *	Range in Pb (mm) *
Gas Ion									
H	1/1	500	3.5×10^{10}	3.5×10^{11}	$1 \sim 10^4$	0.28	1160	549	197.4
He-3	3/2	248.5	1.75×10^{10}	1.75×10^{11}	$1 \sim 10^4$	1.58	279	133	49.6
He	4/2	146.8	1.75×10^{10}	1.75×10^{11}	$1 \sim 10^4$	2.22	151	72	27.6
C	12/6	146.8	5.8×10^{9}	5.8×10^{10}	$1 \sim 10^4$	19.6	51	25	9.4
N	14/7	146.8	5.0×10^{9}	5.0×10^{10}	$1 \sim 10^4$	27.2	43	21	7.9
O	16/8	146.8	4.0×10^{9}	4.0×10^{10}	$1 \sim 10^4$	39.74	38	18	7.0
Ne	20/10	146.8	3.5×10^{9}	3.5×10^{10}	$1 \sim 10^4$	62.09	30	14.6	5.6
Ar	40/18	120.5	1.9×10^{9}	1.9×10^{10}	$1 \sim 10^4$	215.30	13	6.2	2.4
Metal Ion									
Fe	56/26	127.8	1.3×10^{9}	1.3×10^{10}	$1 \sim 10^4$	406	10.2	5.0	1.9
Cu	63/29	125.7	1.2×10^{9}	1.2×10^{10}	$1 \sim 10^4$	511	9.1	4.4	1.7
Au	197/79	96.8	4.4×10^{8}	4.4×10^{9}	$1 \sim 10^4$	4393	3.1	1.5	0.6
RI Ion (life time)									
C-11 (20.4 m)	11/6	172.5	5.8×10^{9}	5.8×10^{10}	$1 \sim 10^4$	17.6	62.1	29.9	11.3
Ne-18 (1.67 sec)	18/10	178.5	3.5×10^{9}	3.5×10^{10}	$1 \sim 10^4$	48.2	38.4	18.5	7.0
Cluster Ion		(keV)**							
C-60	720/7	55							
Insulin	$5.8\times10^3/6$	0.06							
Albumin	$6.6\times10^4/50$	0.033							

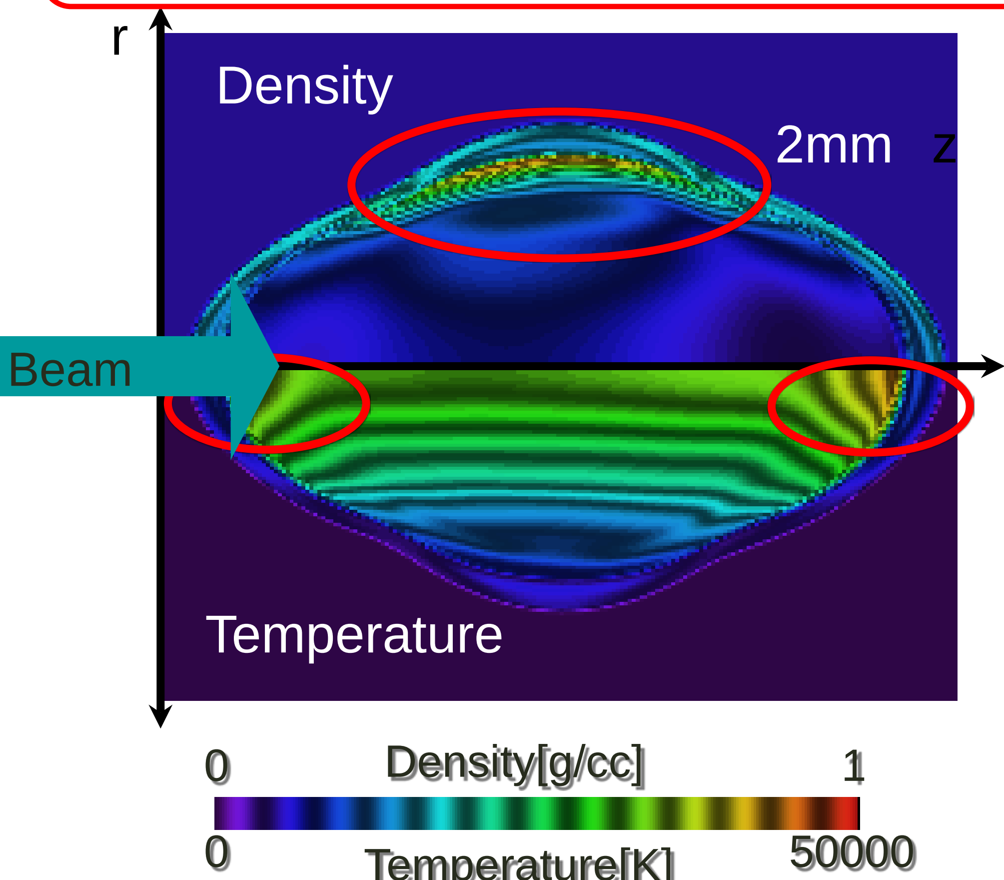
Range and LET are calculated using the SRIM code.
* mean ion depth
** $(Z/A)^2 e^2 (B\rho)2 / m_p$

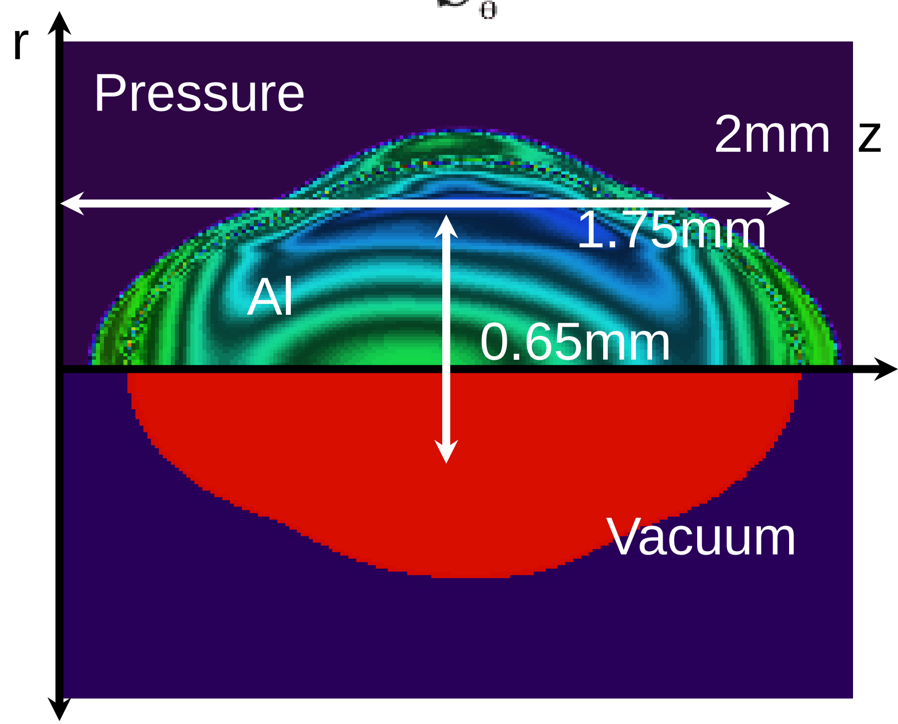
Free Expansion makes a Complex Structure

Target Structure and
Beam Parameter

Beam Radius: 0.35mm







Strongly Nonuniform Target Structure (at 100ns)

Advantages and strategy of Beam-driven WDM/HED physics

- Accelerator based drivers bring us a well defined, large scale length, and long-life sample for WDM/HED science

- Hydrodynamic behaviors driven by the well defined energy deposition profile are useful test problem for EOS models and transport coefficients of materials in a WD state

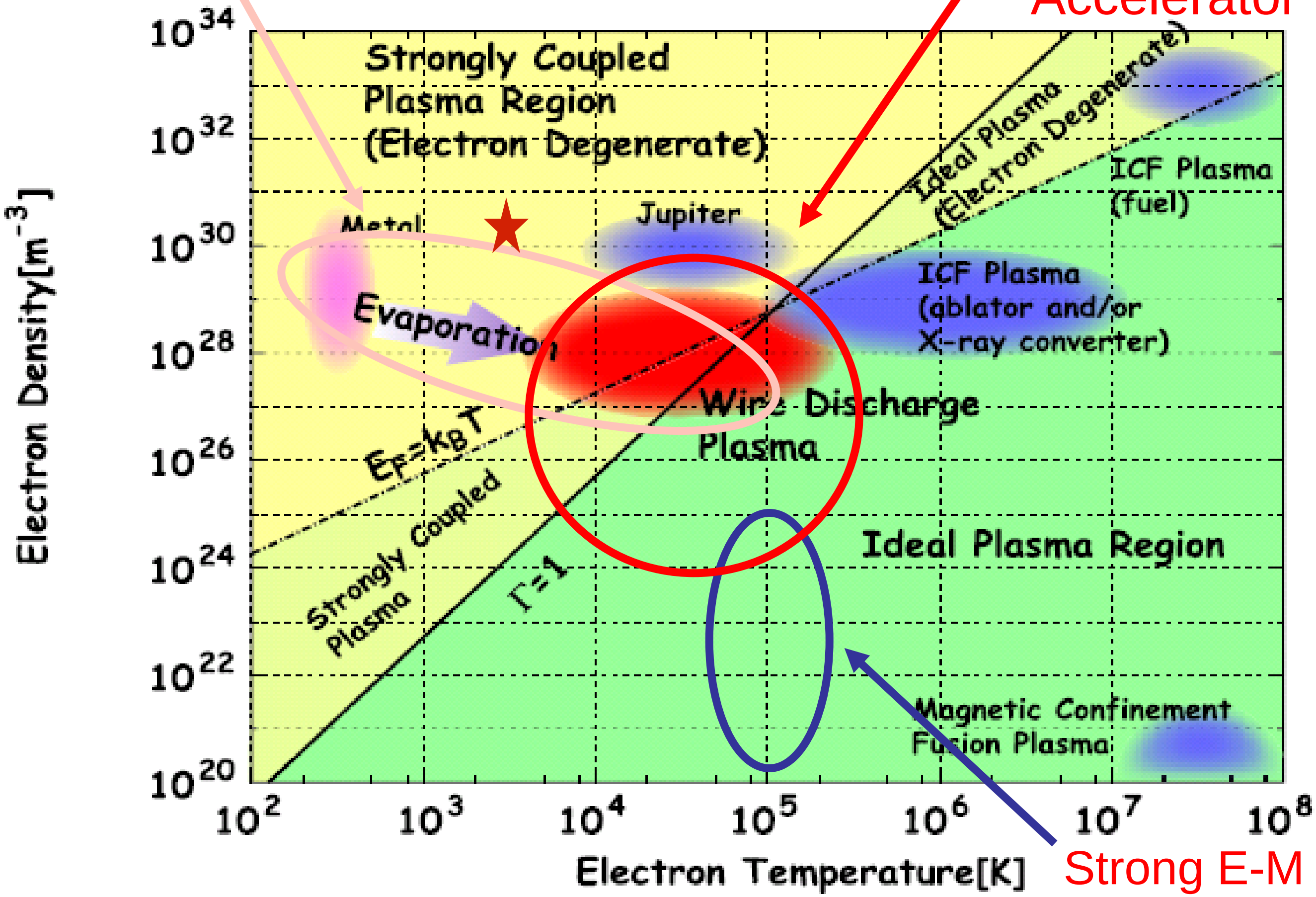
- Our Strategy

- Comparative study of experiments in a well-defined condition* and corresponding numerical simulations
  - *The geometry should be as simple as possible
  - *The time scale should be larger than
    - the hydro-time and
    - the equilibration time

Expected range of pulse power and accelerator driven HED materials

Wire Discharged Plasma in Water

Plasma Target driven by Accelerator (ID-S)



Strong E-M Shock Waves

•Induction synchrotron has a possibility to cover extremely wide

•parameter region in density-temperature plane