Beam and/or Pulse Power driven WDM Science in TIT

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Research Group

- Tokyo Institute of Technology
  - Kazuhiko Horioka（High Energy Density Science）
  - Yoshiyuki Oguri（Accelerator Science）
  - Jun Hasegawa（Plasma Physics）
  - Tohru Kawamura（Atomic Physics）
  - Mitsuo Nakajima (Accelerator Technology)
  - Masahiro Ikoma (Planetary Science)
- Utsunomiya University
  - Shigeo Kawata（Plasma Physics）
- Nagaoka University of Technology
  - Takashi Kikuchi（Beam Physics）
- Nihon University
  - Toru Sasaki（MHD Simulation）
- KEK
  - Ken Takayama (Accelerator Science)

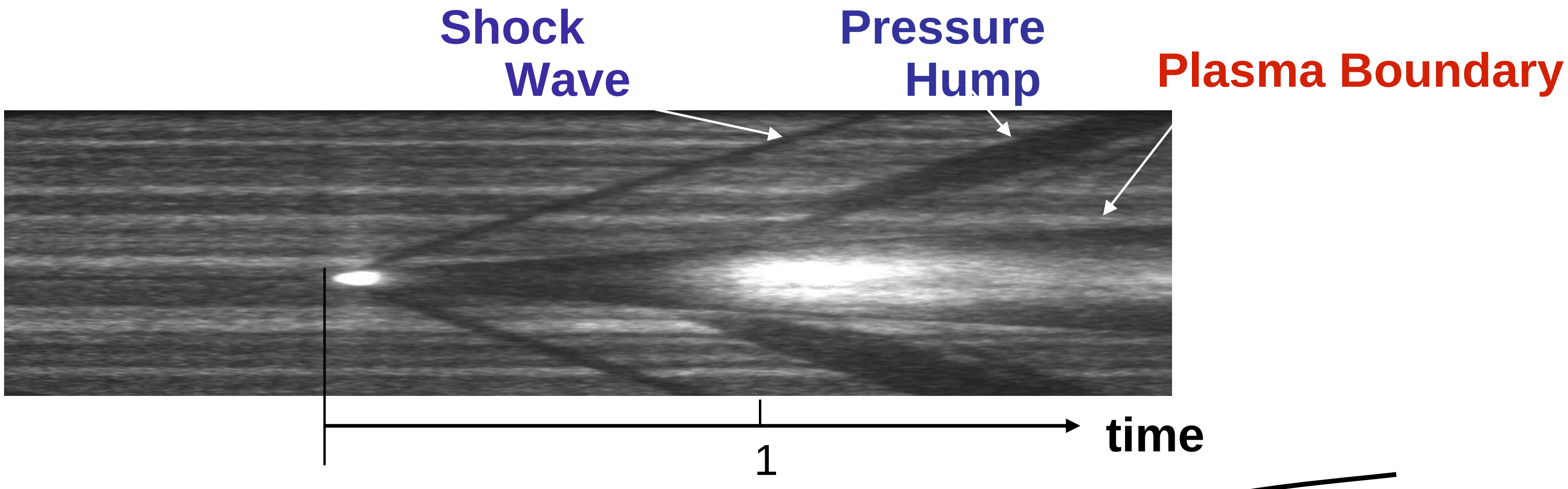
Goals and Strategies

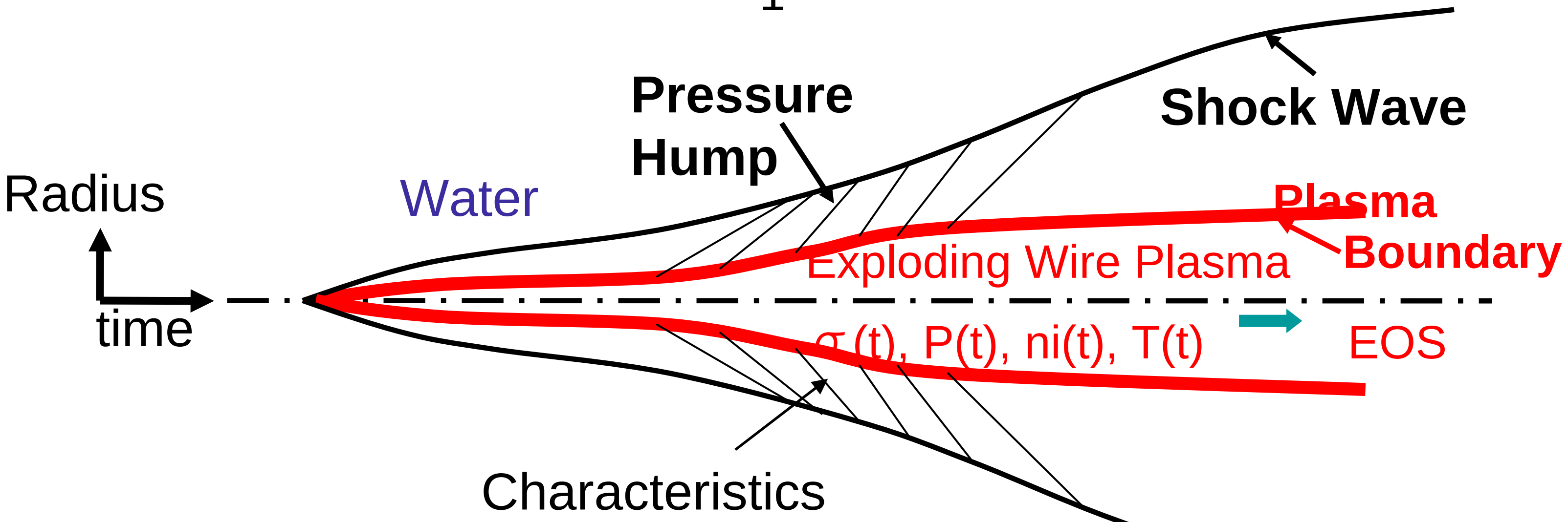
- To get
- Self-consistent combination of EOS and transport coefficients of matter in WD state
  - Conductivity scaling
  - Hydrodynamics of WDM with well-defined condition
  - Measure the relaxation time

- EOS of Hydrogen at 6000K and 200Gpa
  - Pulse-power assisted beam drive
  - Behavior of statically tamped target

Wire-explosion in water

Semi-empirical fitting of hydrodynamic behavior brings us EOS modeling

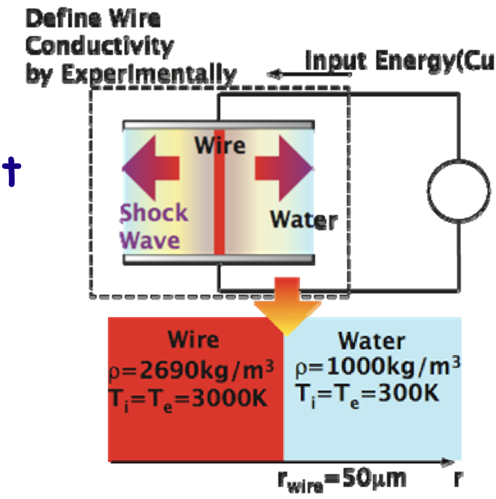


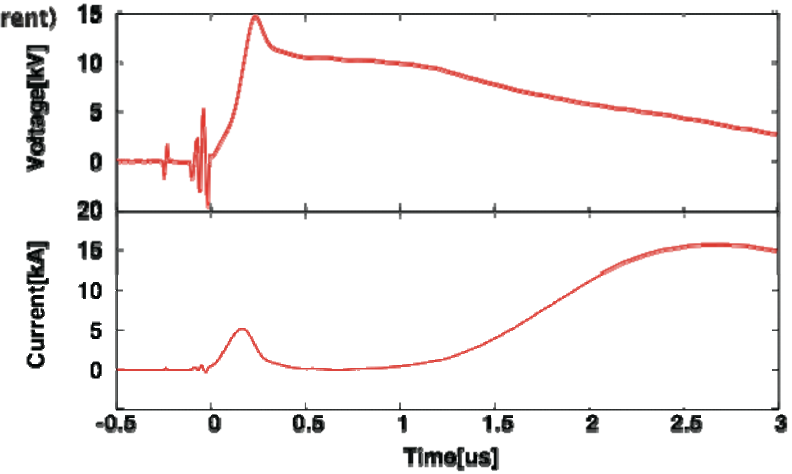


Streak Image and Schematic of the Wire Explosion in Water

Magneto-Hydrodynamic Simulation

Initial Condition and Energy Input





Hydrodynamics ↔ $p = p(\rho, T)$

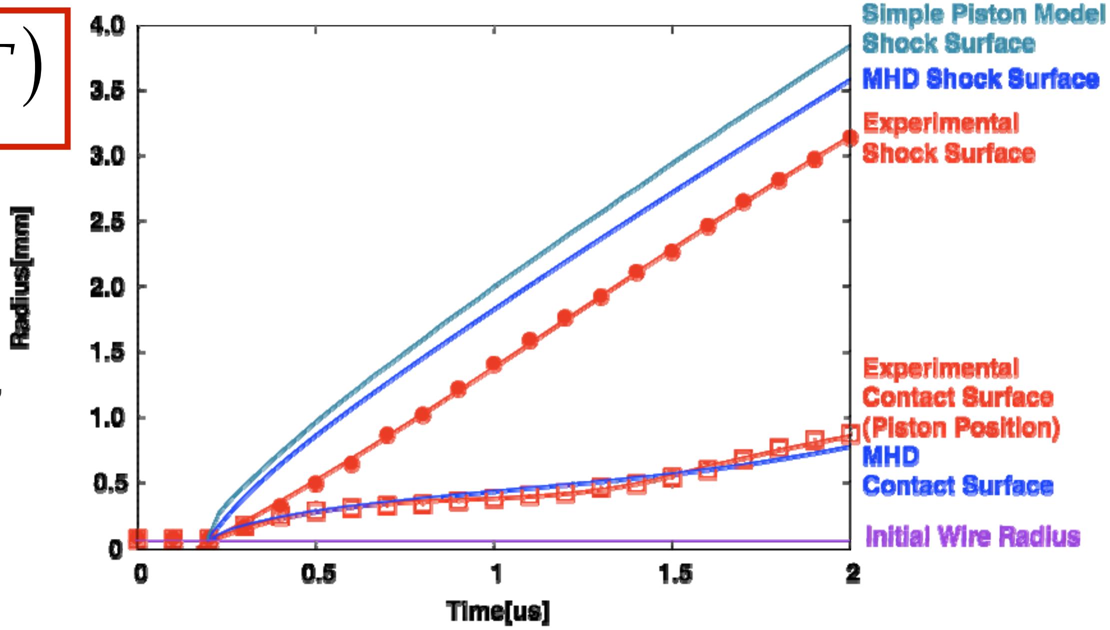
Equation of State (EOS)

-> for Water: IAPWS95[2]

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

[2] IAPWS Released on the IAPWS Formulation 1995, IAPWS Secretariat(1996)

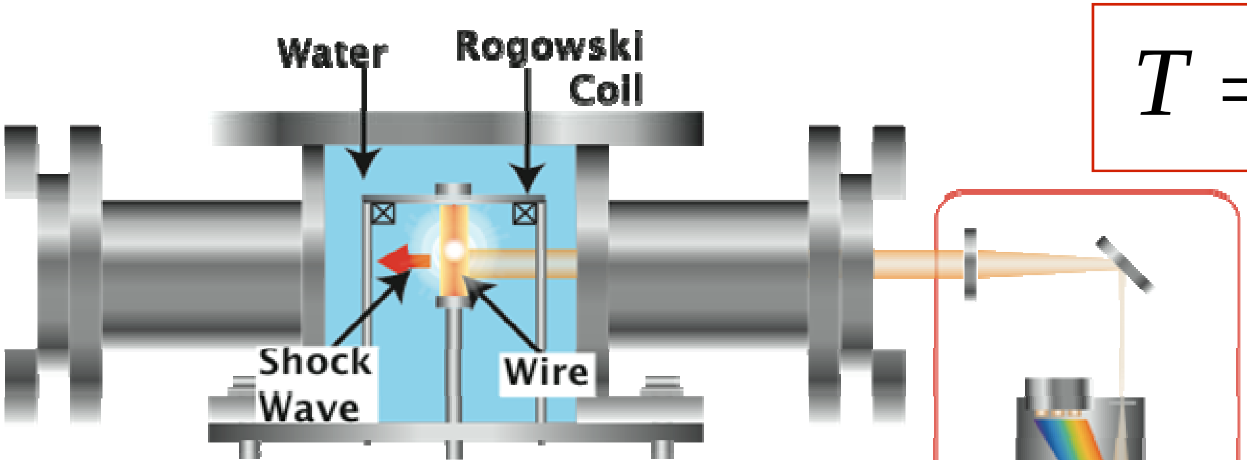
[3] R. M. More, et. al., Phys. Fluids 31, 3075 (1988)

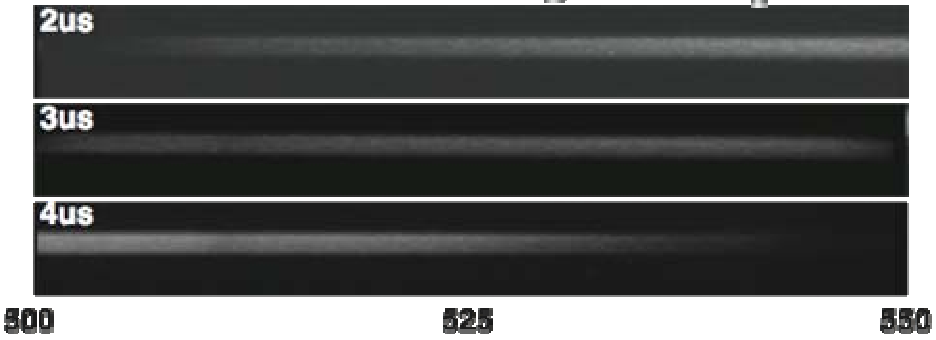


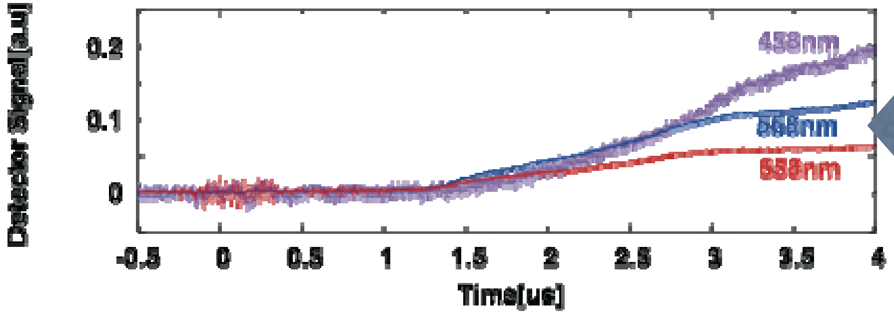
Comparison of numerical results with experimental observation

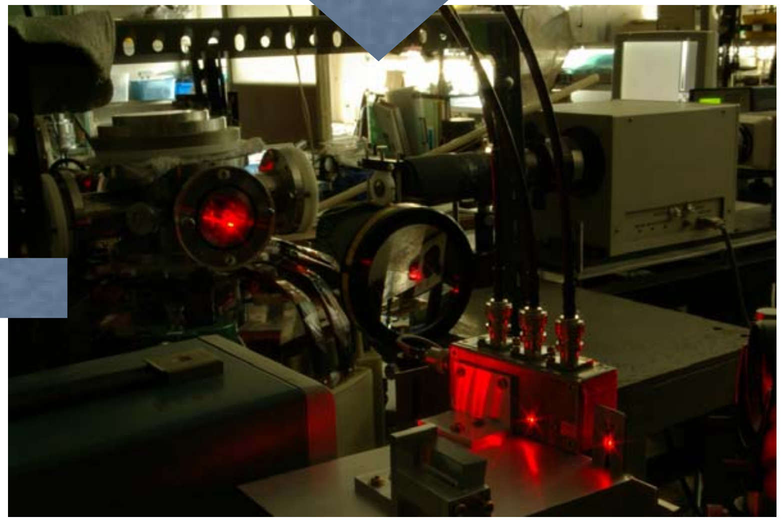
Temperature measurements by radiation pyrometer

$$T = T(t)$$



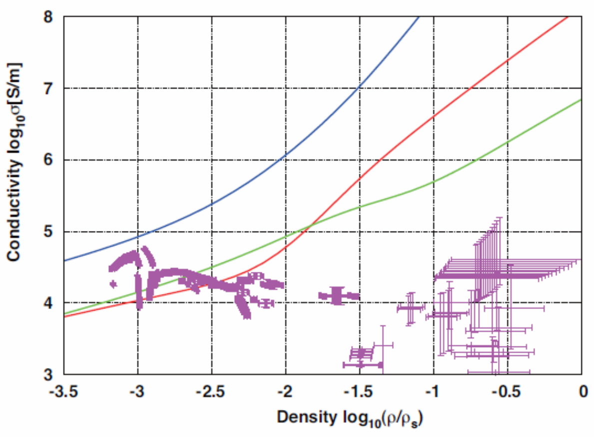




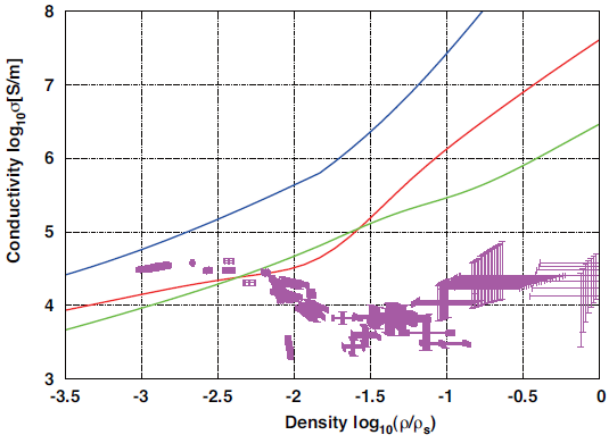


Re-plotted conductivity has a minimum around $(\rho/\rho_s) \sim 1/30$

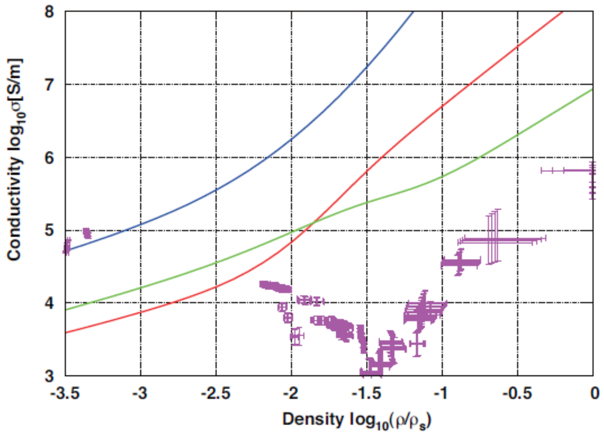
$$\begin{aligned} \sigma &= \sigma(t) \\ \rho &= \rho(t) \\ T &= T(t) \end{aligned} \quad \Longrightarrow \quad \sigma = \sigma(\rho, T)$$



(a) Copper



(b) Aluminum



(c) Tungsten

T=5000K ± 10%

We can draw Zeff· τ vs ρ based on a classical conductivity model

$$\sigma = \sigma(\rho, T)$$

$$\sigma = \sigma_T(\rho) = \frac{e^2 n_e \tau}{m_e} = \frac{e^2 \rho}{A m_p m_e}(Z_{eff}\tau)$$

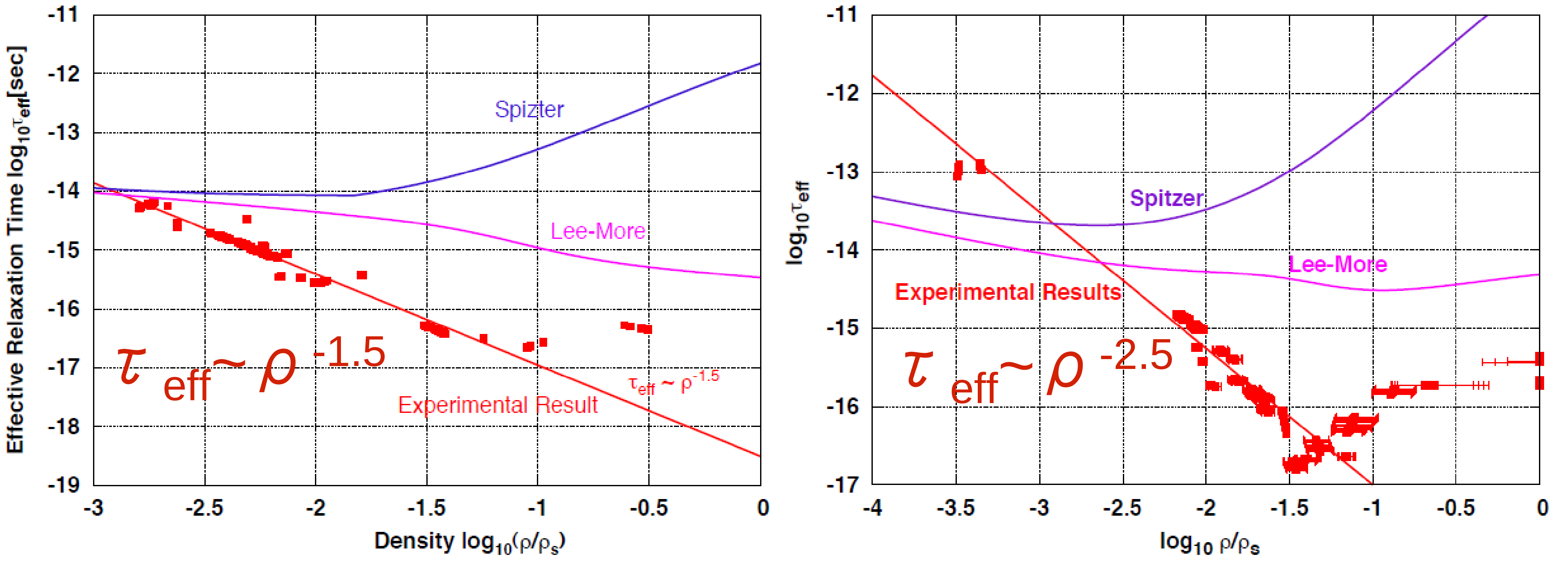
$$\left(\because n_e = Z_{eff} n_i\right)$$

τ : Relaxation time

$$\left(Z_{eff}\tau\right) = f(\rho, \sigma)$$

Zeff･τ decreases almost linearly down to the minimum in log-log plane

$$\tau_{eff} = Z_{eff}\,\tau$$



(a) Aluminum

(b) Tungsten

T=5000K(±10%)

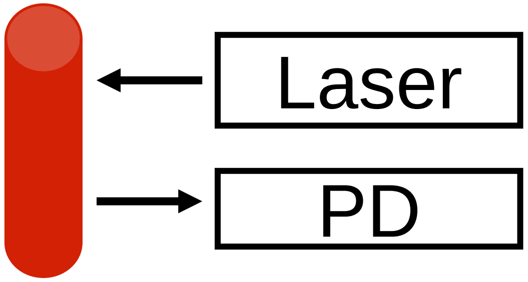
Conductivity scaling and estimation of relaxation time are expected to allow us to estimate a self-consistent combination of transport coefficient and EOS

$$\sigma = \sigma(\rho, T)$$

$$\sigma_T(\rho) = \frac{e^2 n_e \tau}{m_e} = \frac{e^2 \rho}{A m_p m_e}(Z_{eff}\tau)$$

$$(\because n_e = Z_{eff} n_i)$$

$$\sigma(\omega) = \frac{\sigma}{1+\omega^2\tau^2}$$



$$\rho = \rho(T, Z_{eff})$$

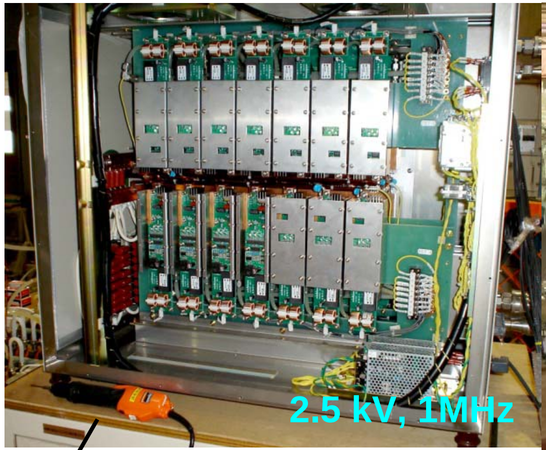
$$\sigma(\rho)$$

Beam driven target

Layout of the KEK Digital Accelerator

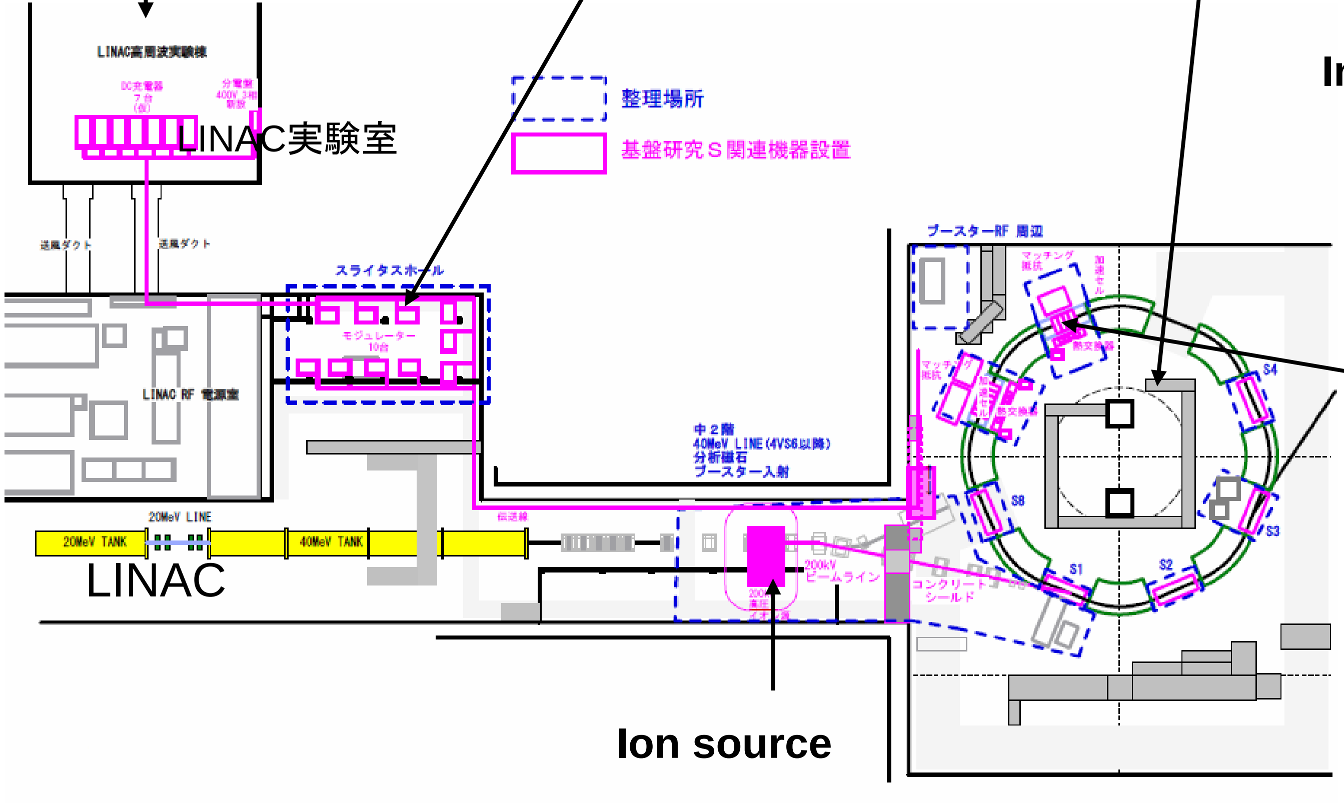
DC power supply

Switching power supply

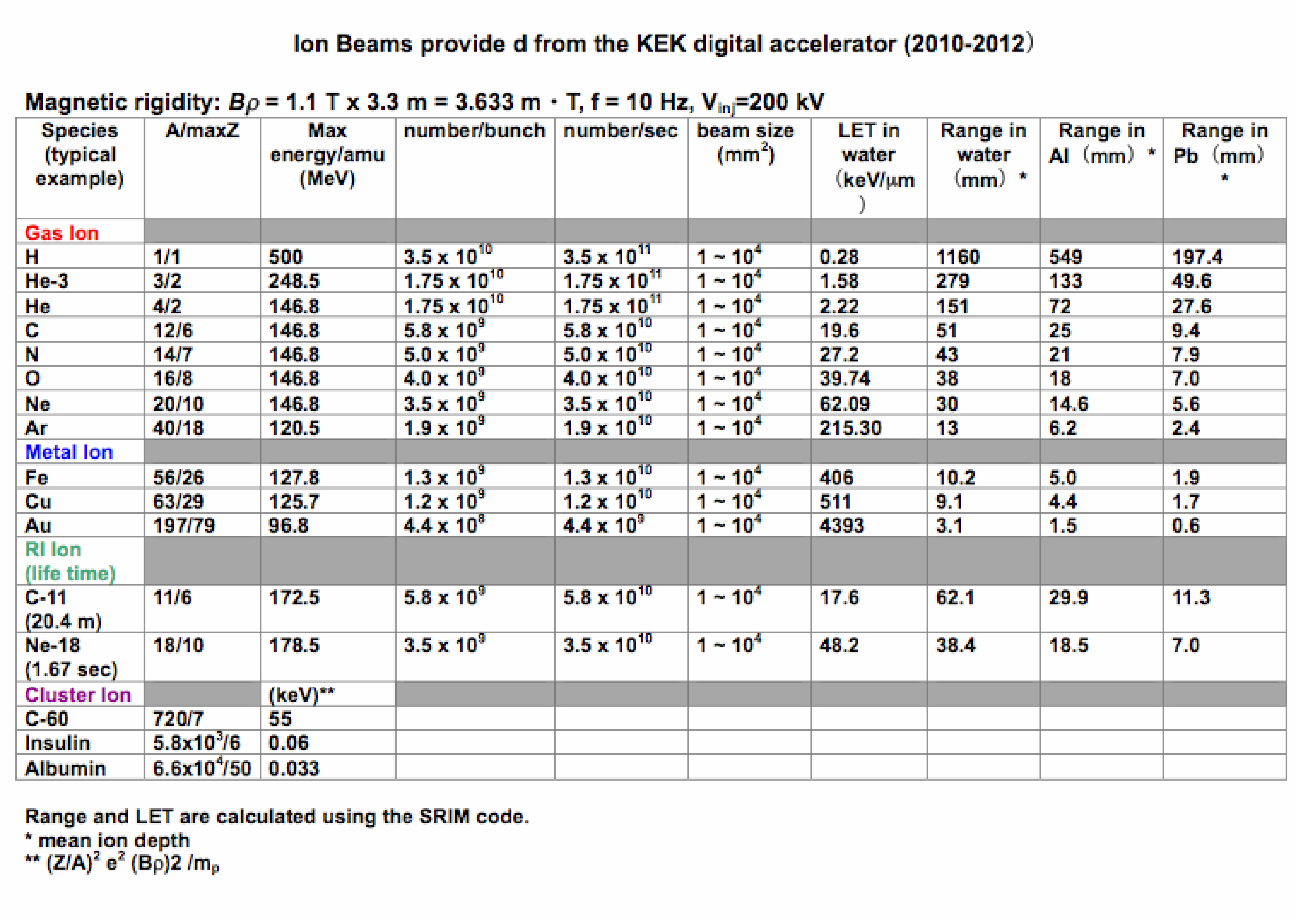


KEK digital accelerator
former 500 MeV Booster PS

Induction acceleration cell



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	$5.8 \times 10^3/6$	0.06							
Albumin	$6.6 \times 10^4/50$	0.033							

Range and LET are calculated using the SRIM code.

* mean ion depth

** $(Z/A)^2 e^2 (B\rho)2 / m_p$

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

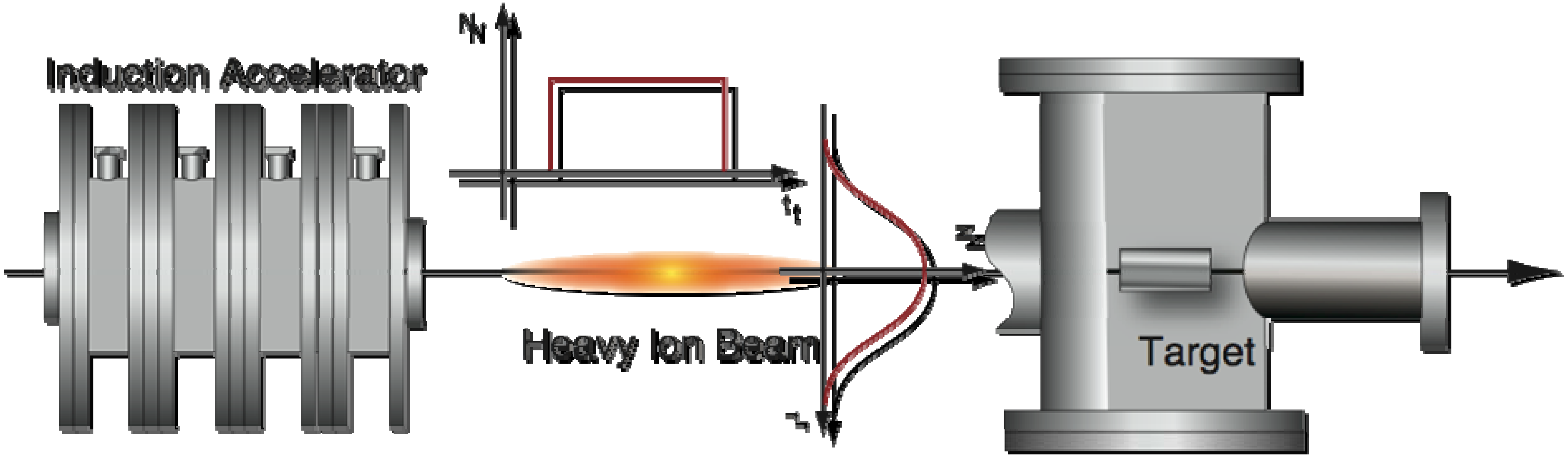
- Our Strategy

- 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

Beam Parameters for Target Irradiation



Beam Condition

-1×10^{10} particles/bunch

-14GeV, uranium projectile

-100ns pulse duration

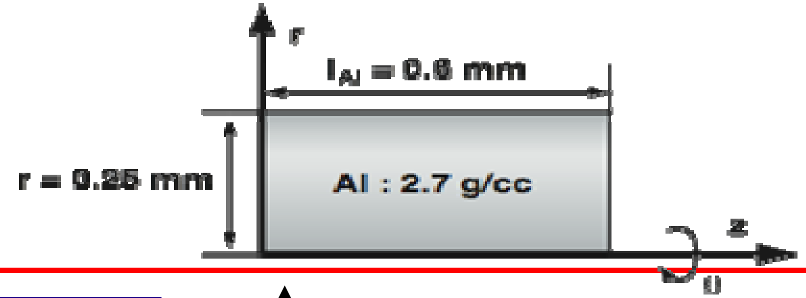
-Gaussian distribution in radial direction

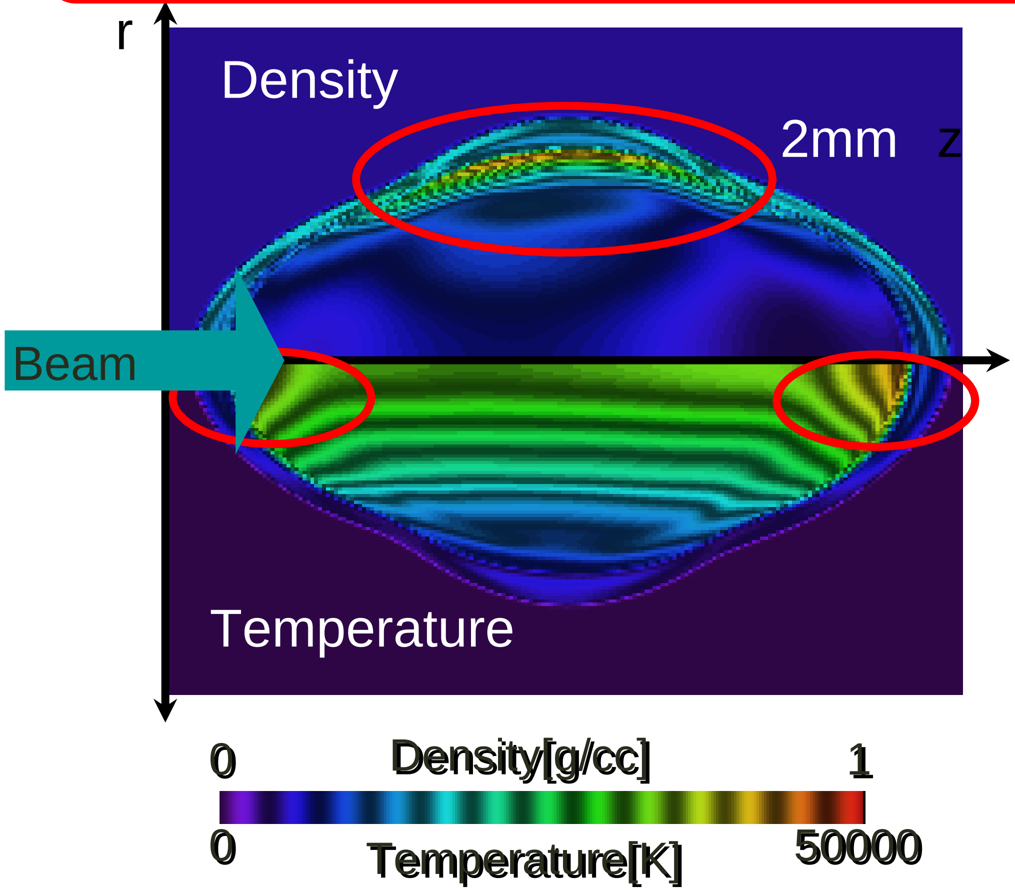
-no beam emittance

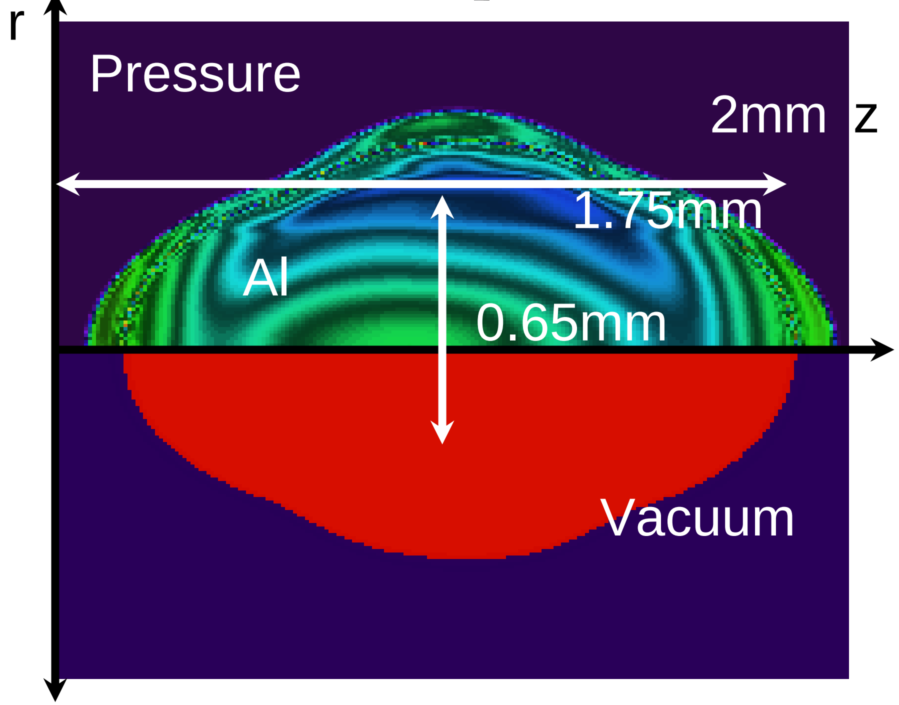
Free Expansion makes a Complex Structure

Target Structure and
Beam Parameter

Beam Radius: 0.35mm





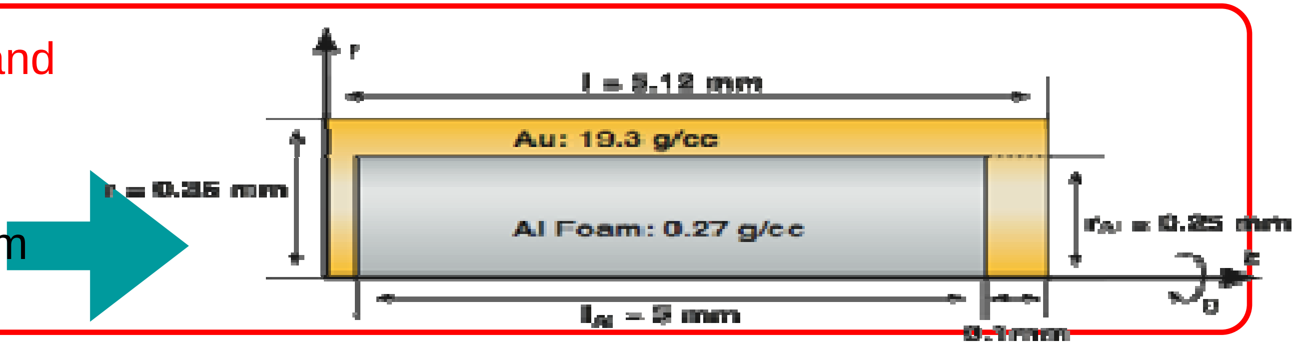


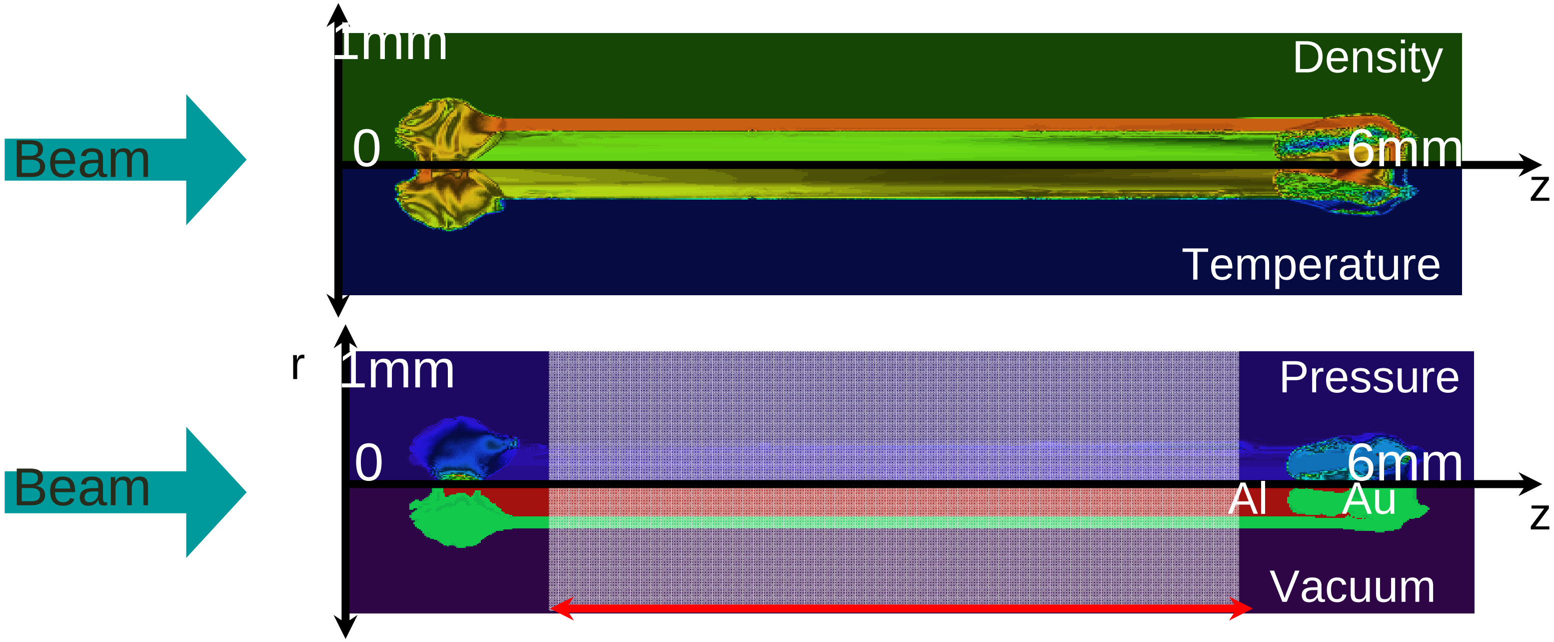
Strongly Nonuniform Target Structure (at 100ns)

Tamper provides a Quasi-uniform State up to 75ns

Target Structure and Beam Parameter

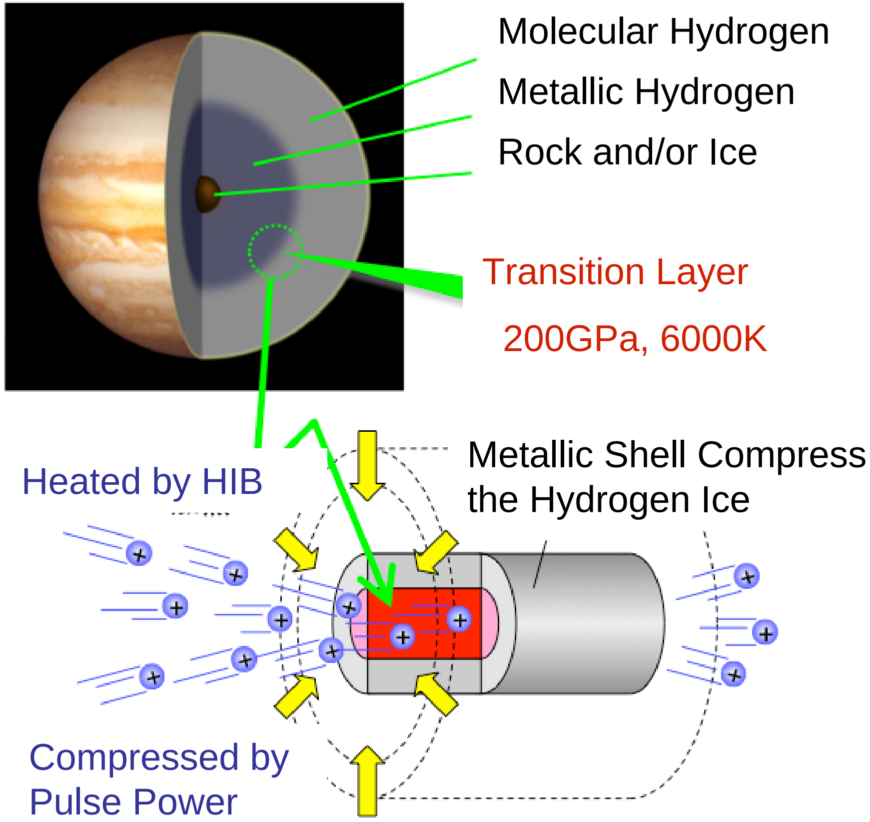
Beam Radius: 0.5mm





~4mm **Quasi Uniform region**

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



Molecular Hydrogen

Metallic Hydrogen

Rock and/or Ice

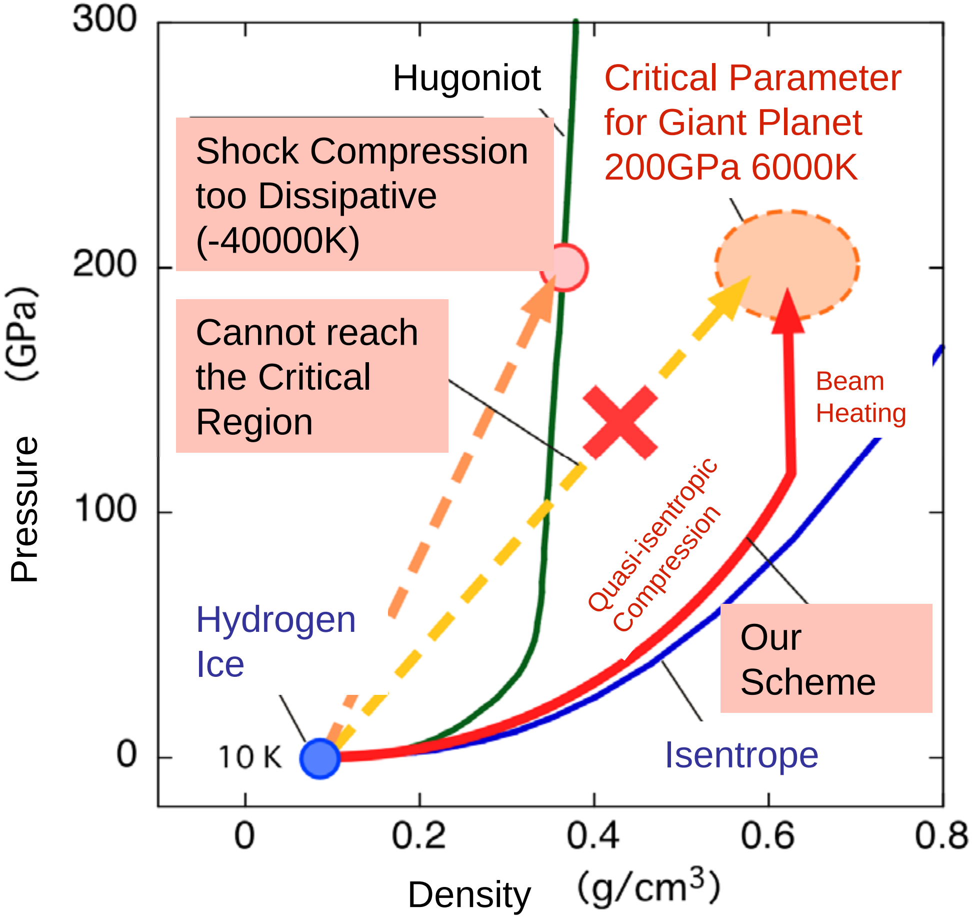
Transition Layer

200GPa, 6000K

Heated by HIB

Metallic Shell Compress the Hydrogen Ice

Compressed by Pulse Power



Shock Compression too Dissipative (-40000K)

Cannot reach the Critical Region

Critical Parameter for Giant Planet 200GPa 6000K

Our Scheme

Self-consistent combination of transport coefficient and EOS

Wire explosion

$$\sigma_{DC}, \rho, T, \sigma(\omega)$$

$$\rho = \rho(T, Z_{eff})$$

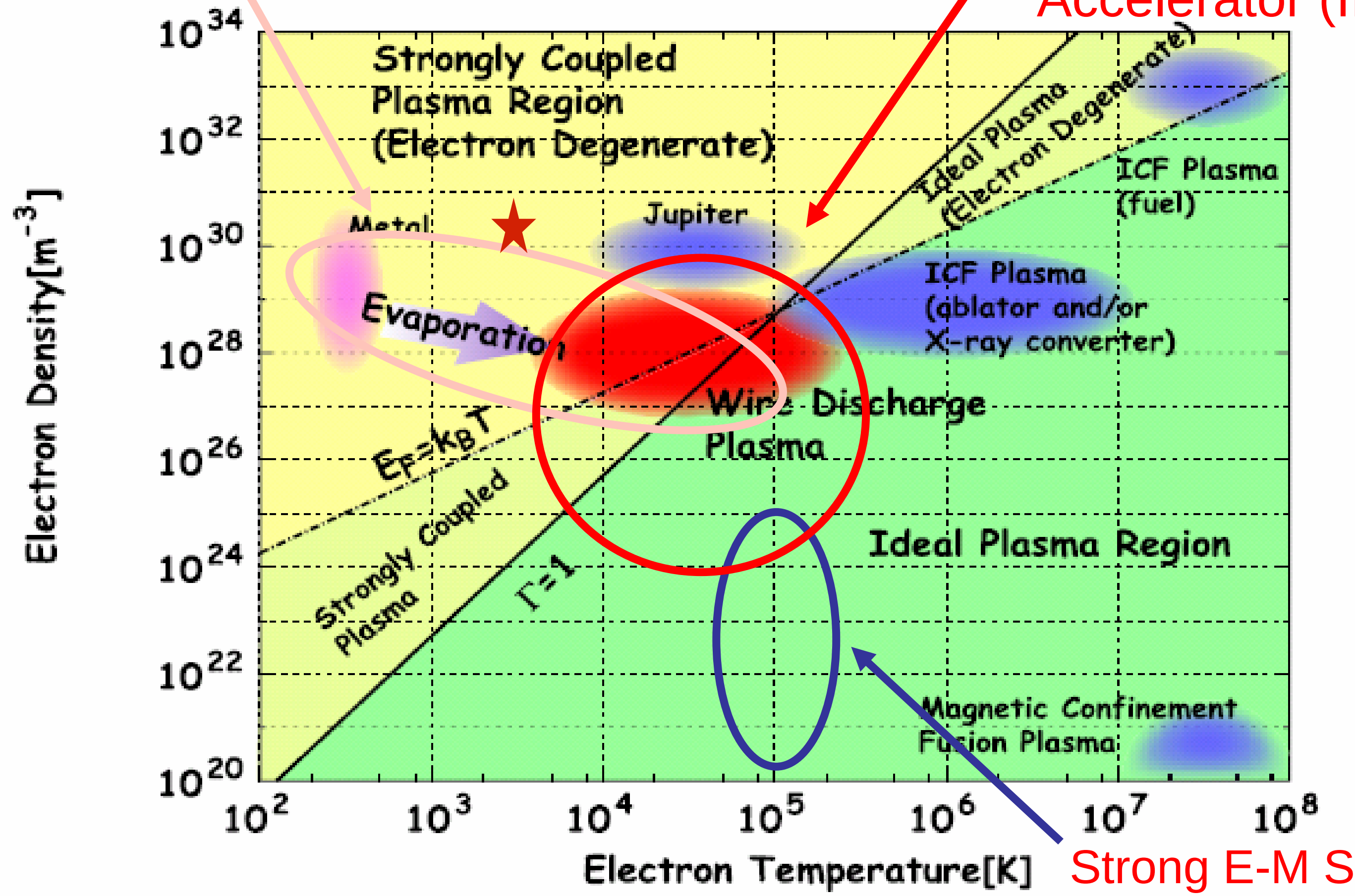
Beam target

$$\rho, E_{in}, Hydro, \sigma(\omega)$$

$$P = P(\rho, E_{in})$$

Hydrogen at 6000K, 200GPa

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

Concluding Remarks

- Strategy to derive self-consistent combination of EOS and transport coefficient of WDM
- Pulse-Power-assisted HIB target is proposed for Hydrogen EOS study in critical WD parameter region.