Overview of High Energy Density Physics Research in Japan

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Laser related topics will be given in this meeting by

- Implosion and Ignition Physics
  H.Azechi, M.Murakami, K.A.Tanaka (ILE)
- WDM Physics with Ultra-short pulse Laser
  H.Yoneda (UEC)
- Laser-Plasma Acceleration toward High Energy Physics
  K.Nakajima (KEK)
- Monoenergetic Acceleration of Electrons by Laser Driven Plasma
  K.Koyama (AIST)

ILE : Institute of Laser Engineering
UEC : The University of Electro-Communications
KEK : High Energy Accelerator Research Organization
AIST : National Institute of Advanced Industrial Science and Technology

Activities on Accelerator and/or Pulse-power based High-Energy-Density Physics Researches in Japan

- Pulse Power driven WDM and Strong Shock Studies (TIT)
- Ion Source Development (TIT, RIKEN)
- Repetitive induction Modulator (TIT, KEK, JAERI)
- kHz Induction Voltage Modulator (TIT, KEK)
- Beam Physics in Final Transport (TIT, RIKEN, UU)
- Beam Plasma Interaction Experiments (TIT, RIKEN)
- Target Physics (ILE, UU)
- New Concept (ILE, UU, TIT,..)

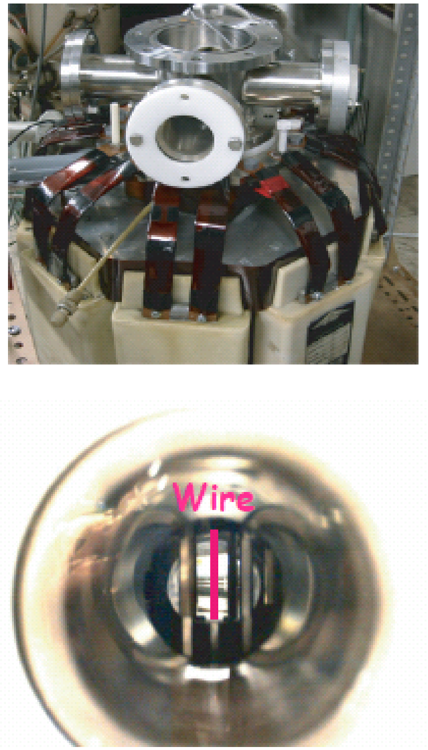
  - ***TIT: Tokyo Institute of Technology***
  - ***RIKEN: The Institute of Physical and Chemical Research***
  - ***KEK: High Energy Accelerator Organization***
  - ***JAERI: Japan Atomic Energy Research Institute***
  - ***UU: Utsunomiya University***
  - ***ILE: Institute of Laser Engineering, Osaka University***

Outline of Presentation

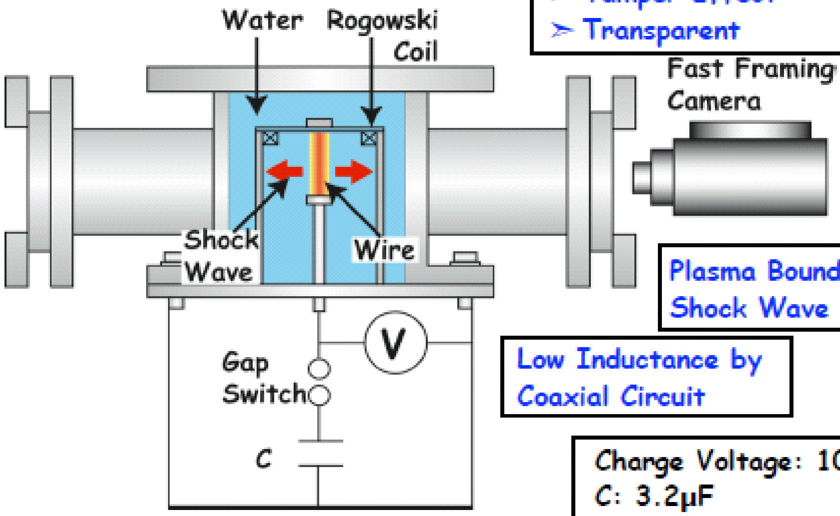
- Pulse-power-driven HED Physics
  - EOS and transport coefficient
  - Electromagnetically driven strong shock waves
- Accelerator based HED Physics
  - Beam dynamics
  - Ion beam interaction with HED plasma

Warm-dense matter studies using pulse-powered wire plasma in water

Experimental Setup



Picture of Load Section



Experimental Arrangement

Load Section Filled with Water
- ➢ Tamper Effect
- ➢ Transparent

Plasma Boundary
Shock Wave Behavior

Low Inductance by
Coaxial Circuit

Charge Voltage: 10kV
C: 3.2μF
Circuit Inductance: 112nH
Load: Al, Cu and W Wire

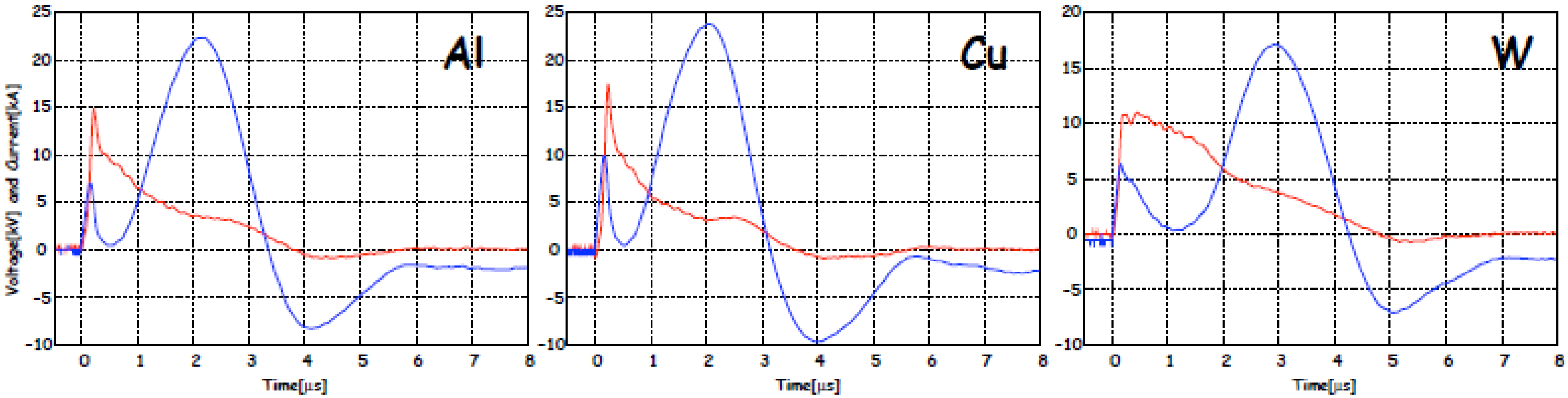
Advantages of This Scheme

(1) Electrical conductivity is directly measured by wire voltage and current.

(2) Density is measured by evolution of wire radius.

(3) Pressure history can be measured by shock wave trajecties in water.

Typical waveforms (voltage and current) of wire explosion in water

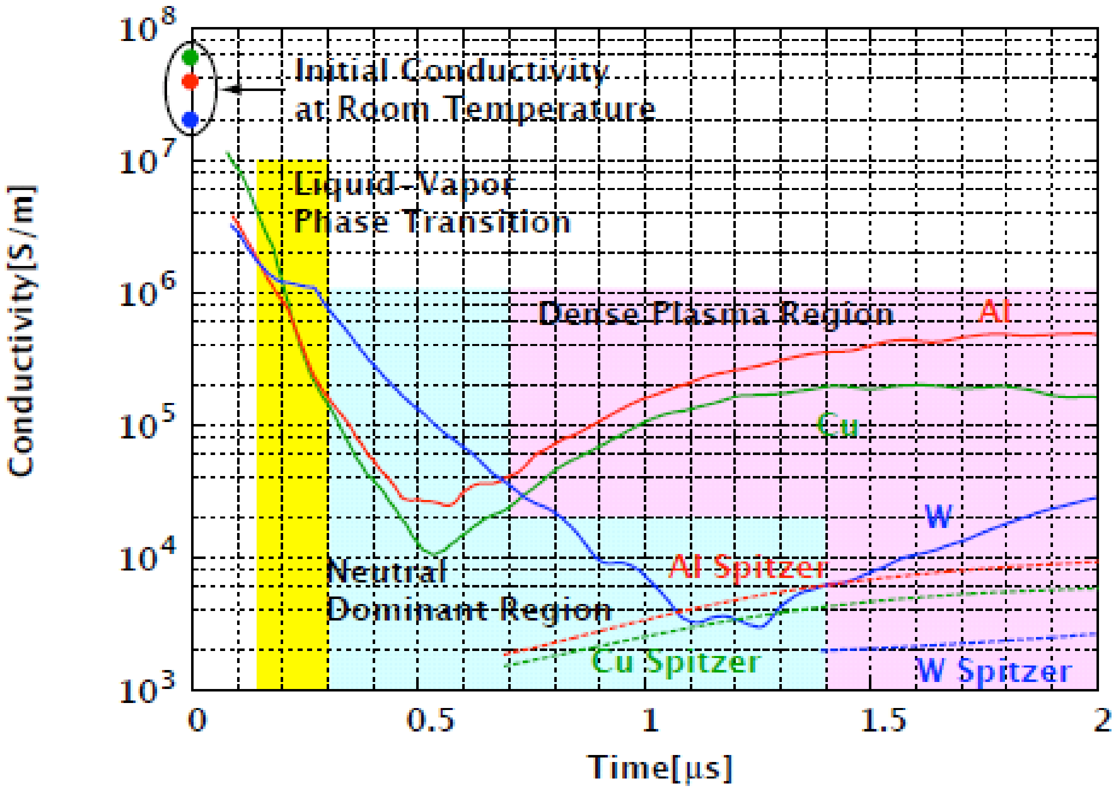


🟥 Voltage

🟦 Discharge current

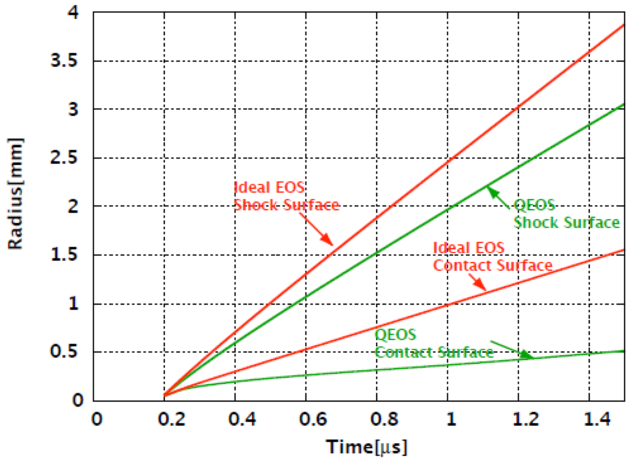
- ➢ **The voltage waveform depends on the wire materials.**
- ➢ **Waveforms are reproducible.**

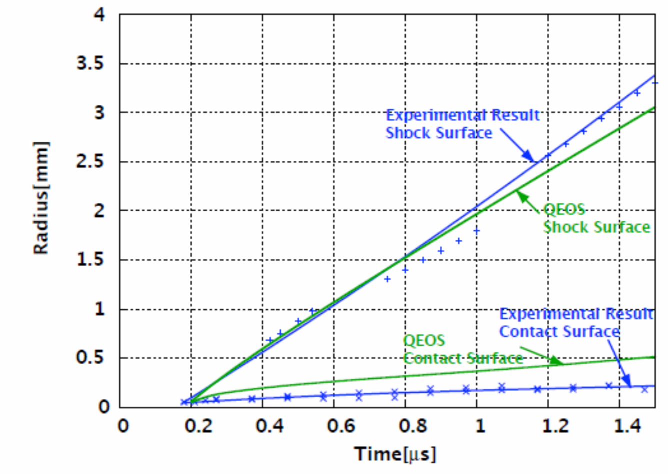
Evolutions of wire/plasma conductivity

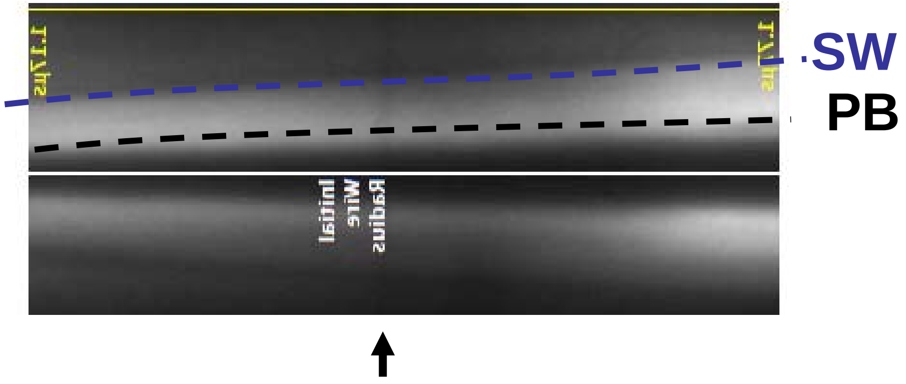


- Conductivity curve has a bottom at ~500ns for Al and Cu-Wire, at ~1.2us for W-Wire.
- About 10 times compared with Spitzer's conductivity.

Numerical Hydrodynamic Behaviors depend strongly on EOS Model







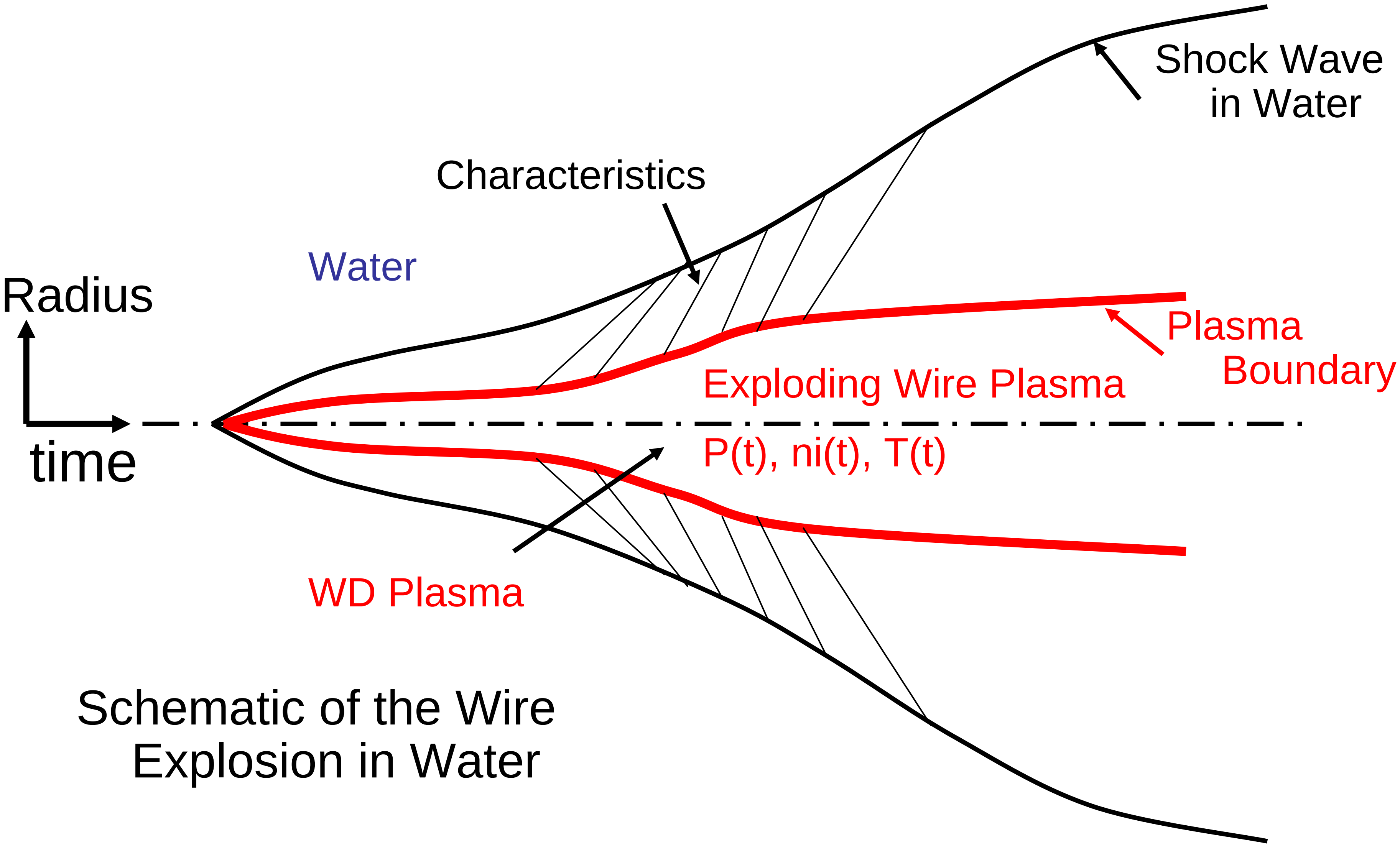
A Streak-shadow image of wire explosion in water

SW: Shock Wave

PB: Plasma Boundary

Comparison with numerical simulation

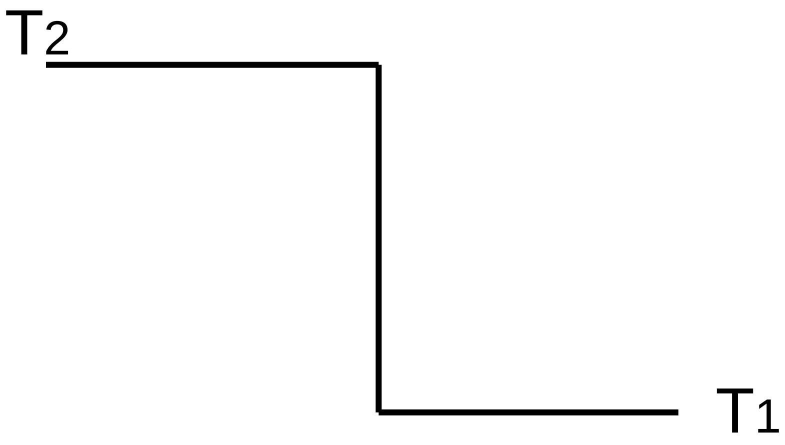
Semi-empirical fitting of hydrodynamic behavior brings us EOS modeling



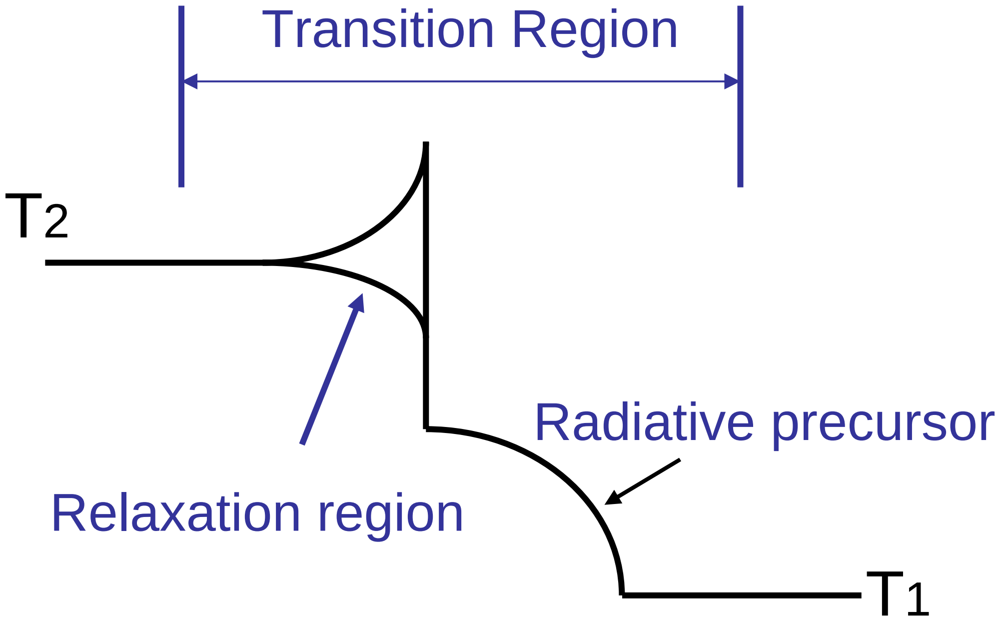
Schematic of the Wire Explosion in Water

Formation of 1-D strong shock wave

- 1-D assumption enables us to use simplified analytical estimation



Hydrodynamic Shock Wave

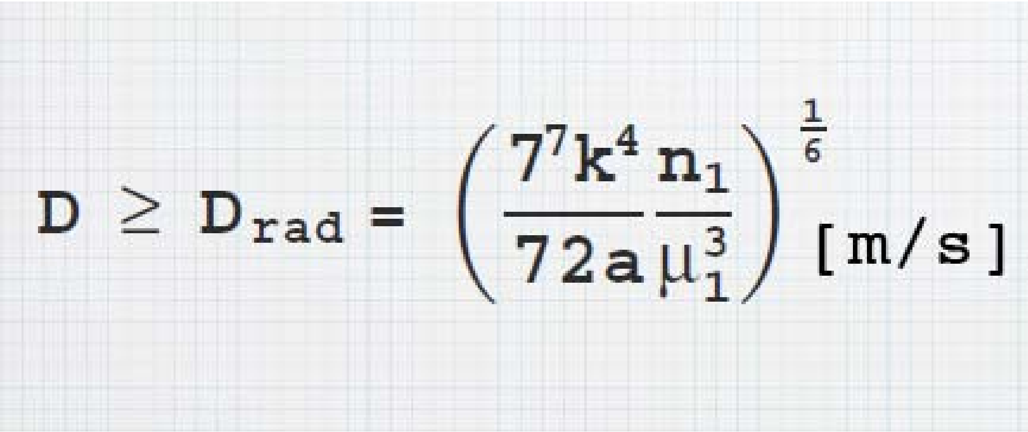


Strong Shock Wave

Criterion for radiative shock wave

- 1-D simplified analytical estimation yields a criterion* of shock speed for radiative regime,

From the requirement of Prad/Pthe > 1



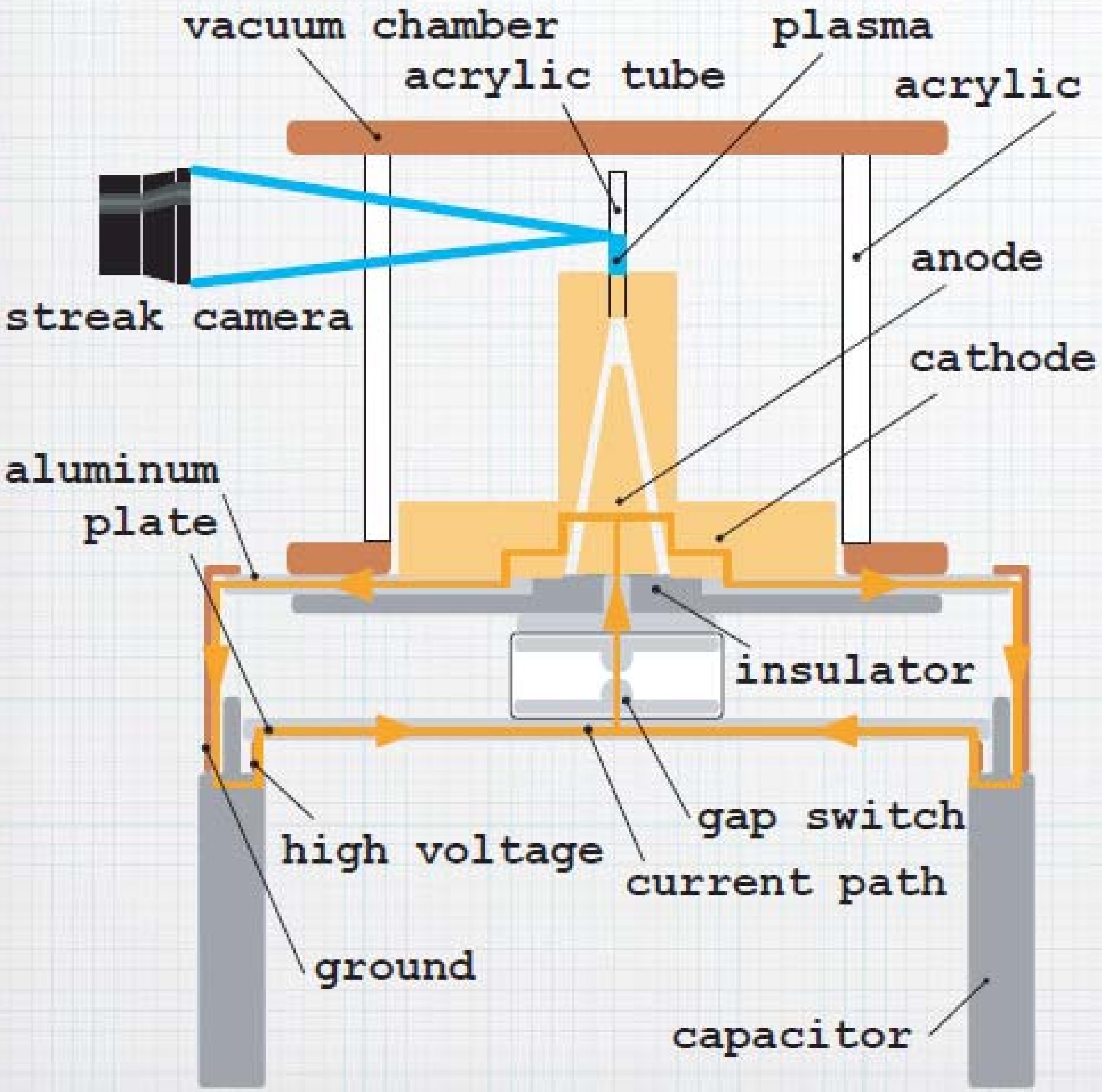
$$D \geq D_{rad} = \left(\frac{7^7 k^4}{72a} \frac{n_1}{\mu_1^3} \right)^{\frac{1}{6}} [m/s]$$

K : Bolzmann’s Constant, a: Radiative constant

n1: Particle Density, μ 1: Particle mass

* S.Bouquet, et.al., Astrophysical J. Supp. 127, 245 (2000)

Experimental arrangement for E-M driven 1-D strong shock wave formation



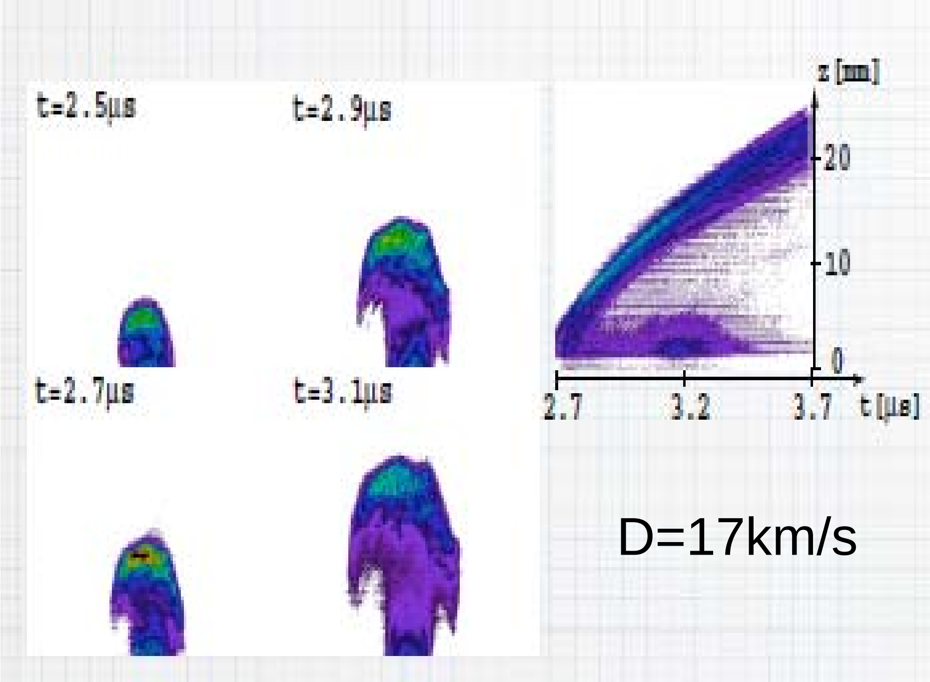
Gases : Xe, Ar

Initial pressure

: 50 ~ 8000 mtorr

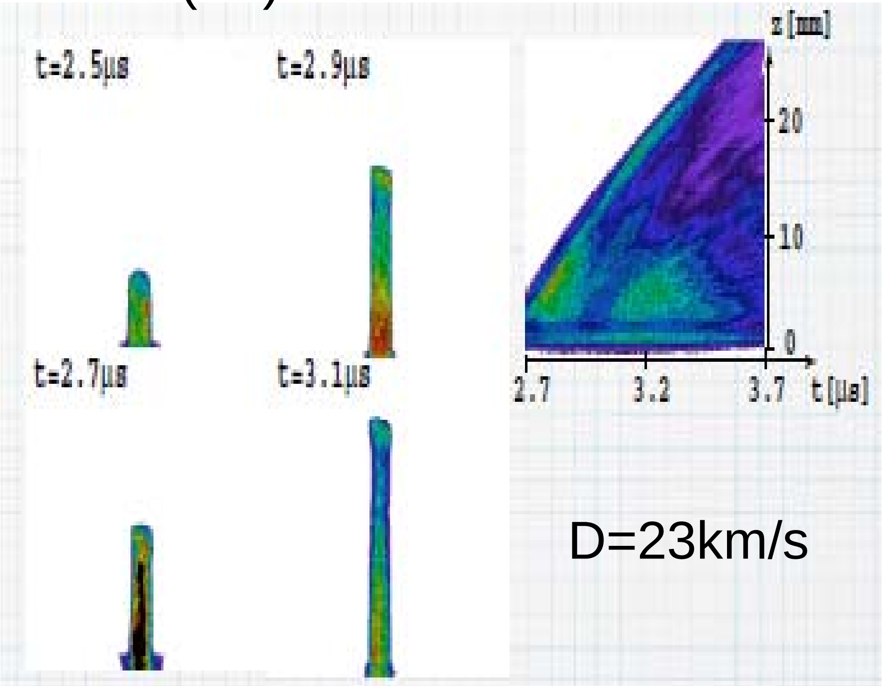
Quasi-one dimensional shock wave was formed by tapered electrodes and a guiding tube

Initial condition 300mtorr (Xe)



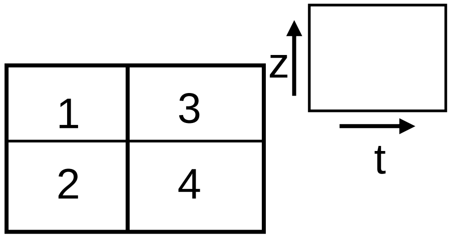
D=17km/s

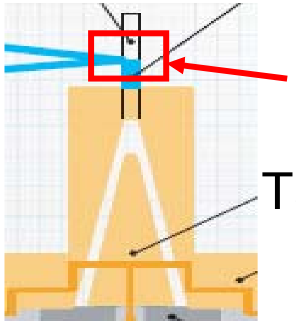
Without guiding tube



D=23km/s

With guiding tube



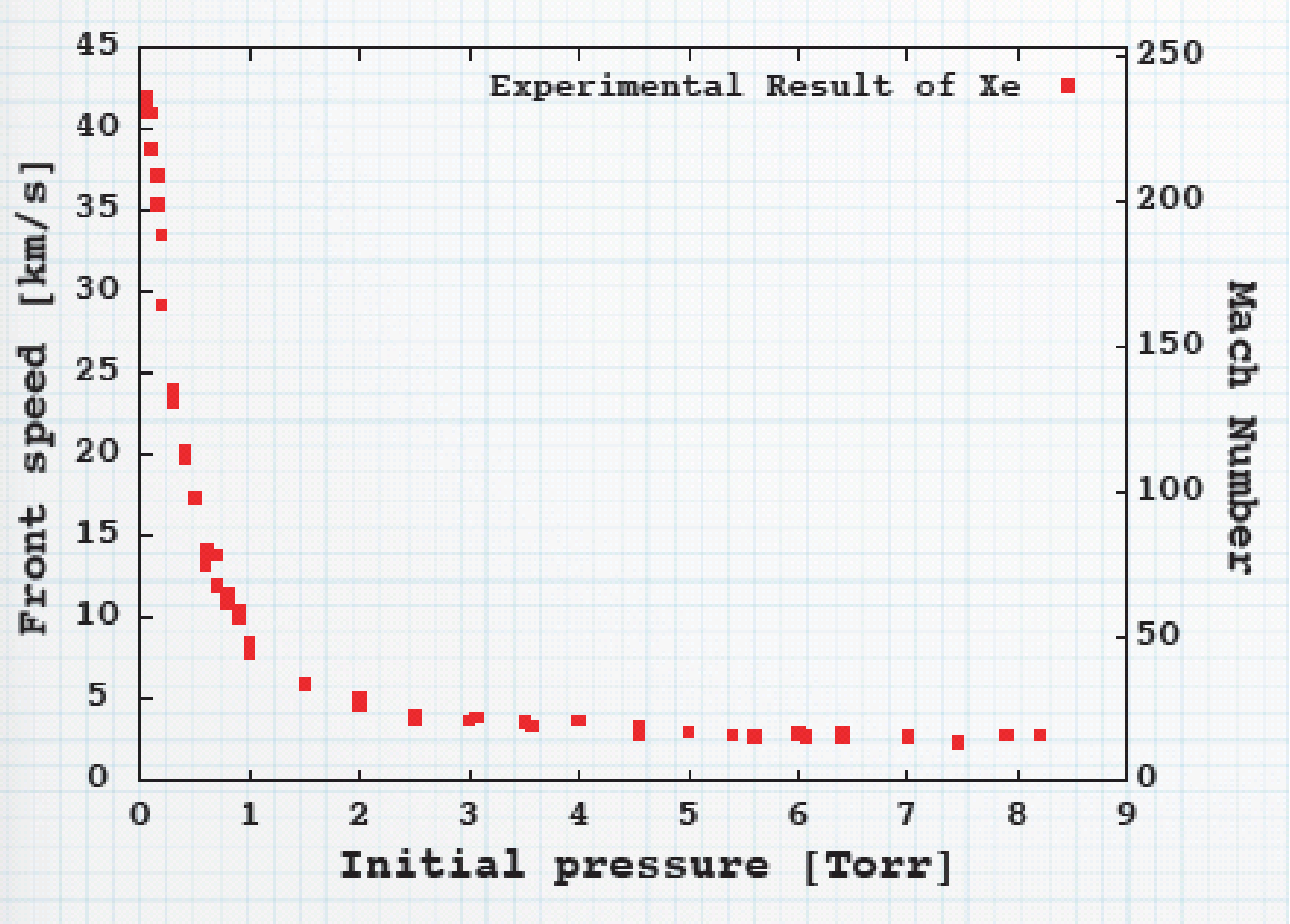


Guiding tube

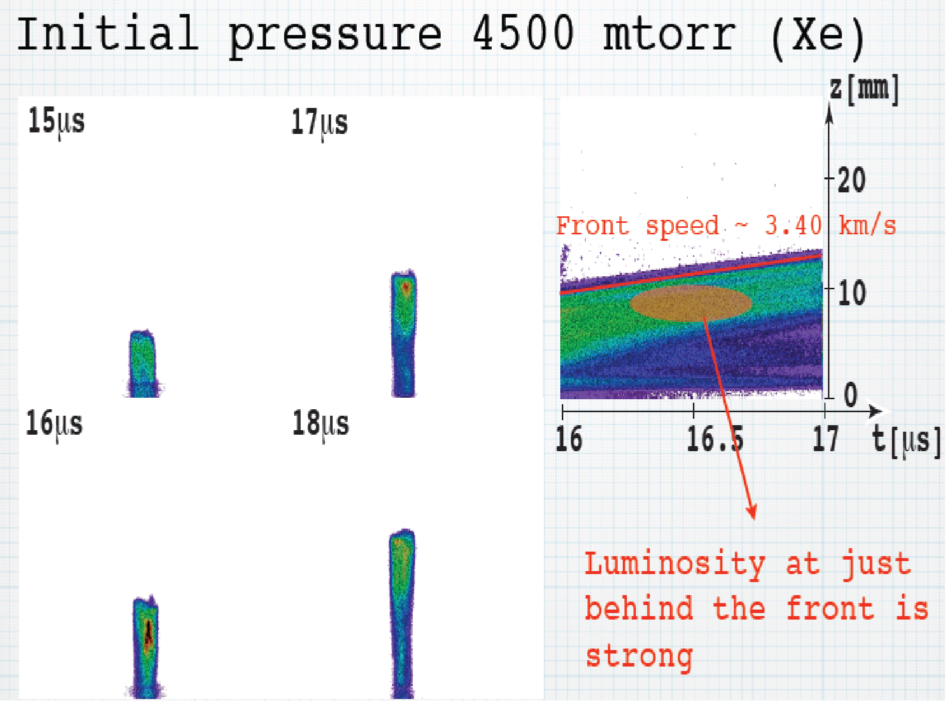
Observing region

Tapered electrodes

Shock Mach Number exceeds 200 at low filling pressure



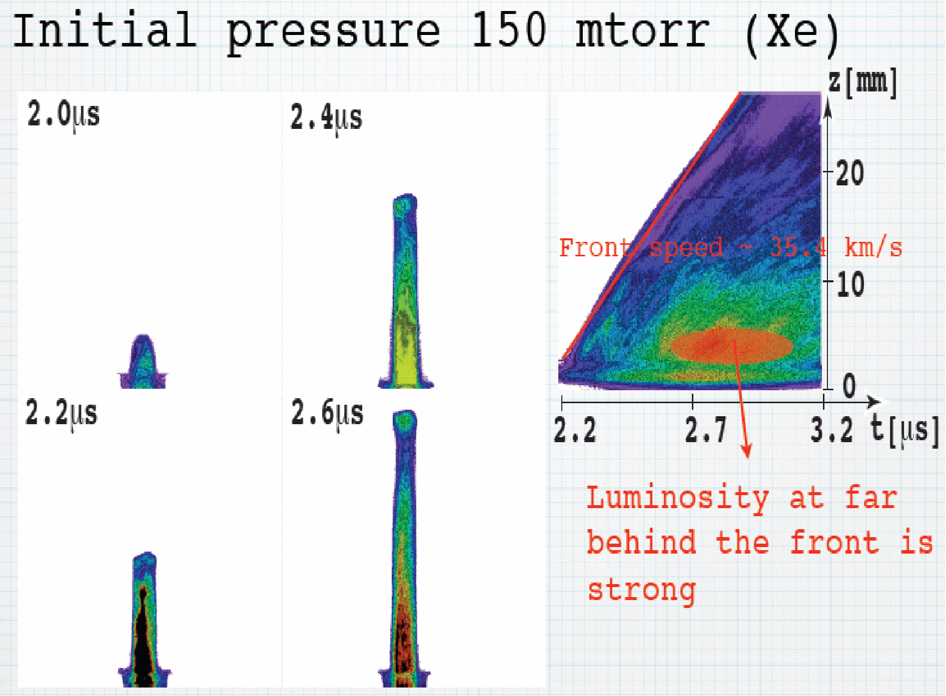
Typical Images of fast framing/streak camera


Initial pressure 4500 mtorr (Xe)

Front speed ~ 3.40 km/s

Luminosity at just behind the front is strong

M～20


Initial pressure 150 mtorr (Xe)

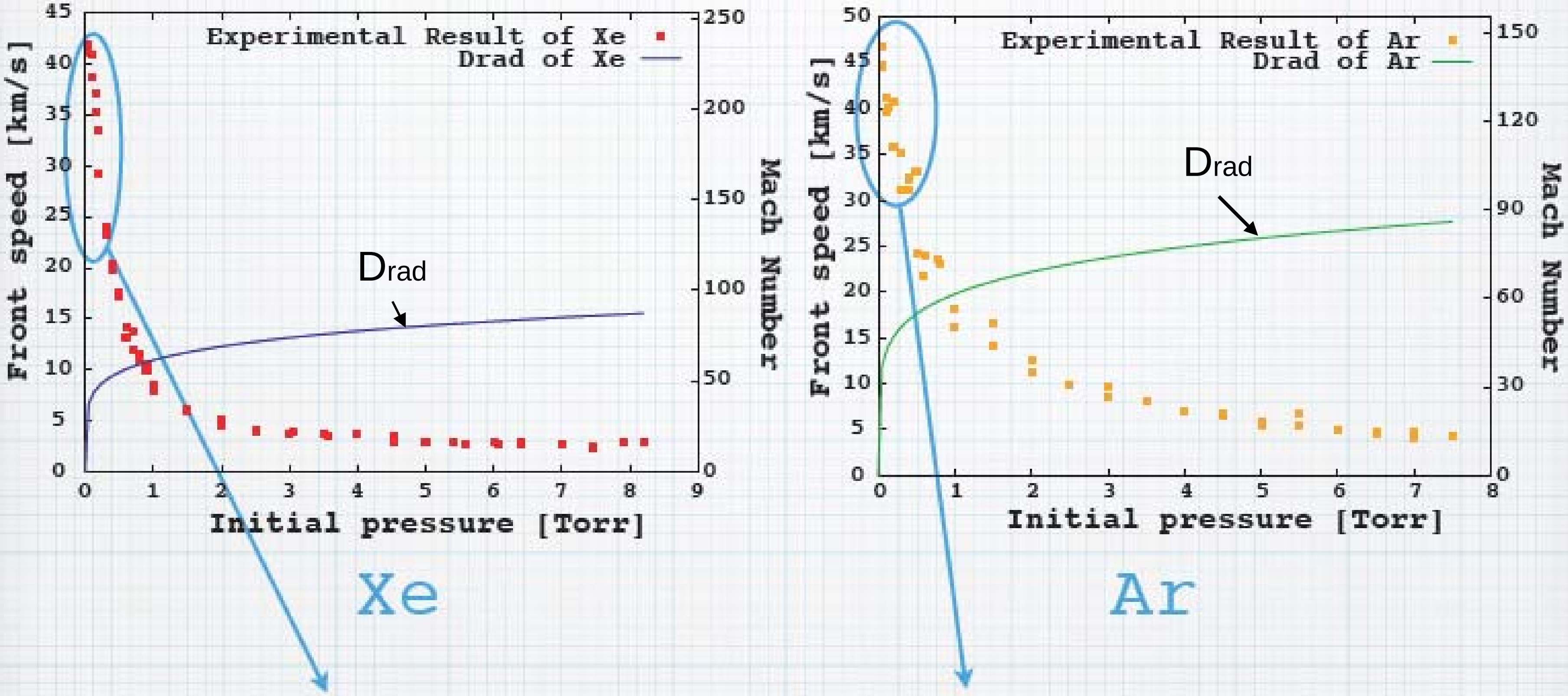
Front speed ~ 35.4 km/s

Luminosity at far behind the front is strong

M～200

Visible image changed with shock strength

At low filling pressure shock speed exceeds Drad



The luminosity changed both in Xe and Ar.

Indicating the existence of radiative front in Strong shock waves (M>100)

Summary of pulse-power-driven shock experiments

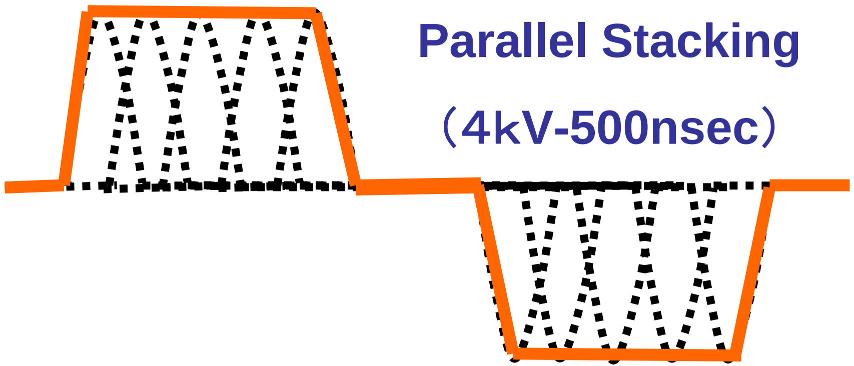
- Quasi-1D strong shock waves can be formed
- Shock Mach number exceeded 200 under low pressure condition of Xe
- When the front speed exceeded a critical value D_{rad}, the image structure changed
- Results indicates formation of a radiative shock wave

Accelerator based HED Physics

Possible Research Topics

- High Power Beam Dynamics
  - Induction synchrotron, Beam Compression,
  - Plasma Lens, Integrated simulation code
- Beam-(HED) Plasma Interaction
  - Energy deposition profile
- HED Physics using Ion Beam Produced Plasma
  - With well-defined and large scale-length plasma

Concept for Waveform Control

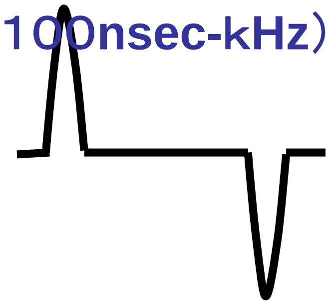


Parallel Stacking

（4kV-500nsec）

Typical Waveform of Module

（4kV-100nsec-kHz）



Module Structure

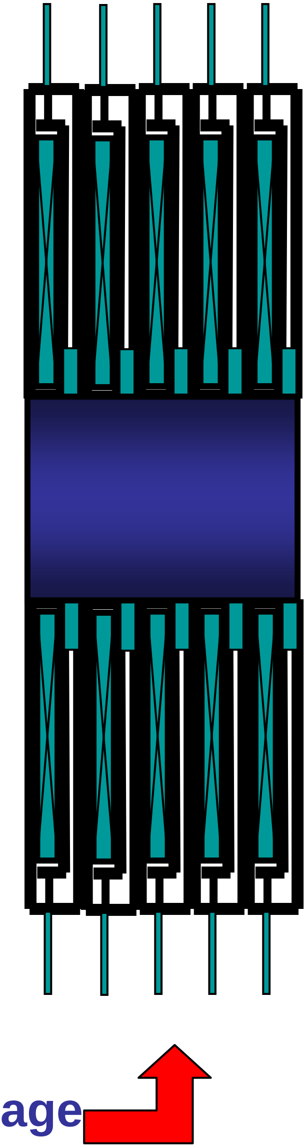
FET-Driver

Waveform Stacking

Robust against Load Condition

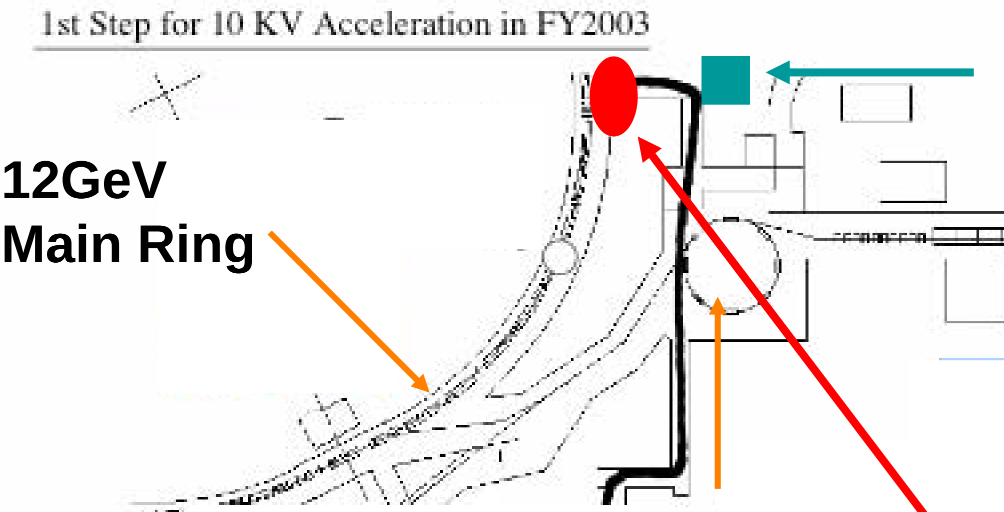
Series Stacking

（20kV-100nsec）



Voltage Driver

Arrangement of Devices/Cables

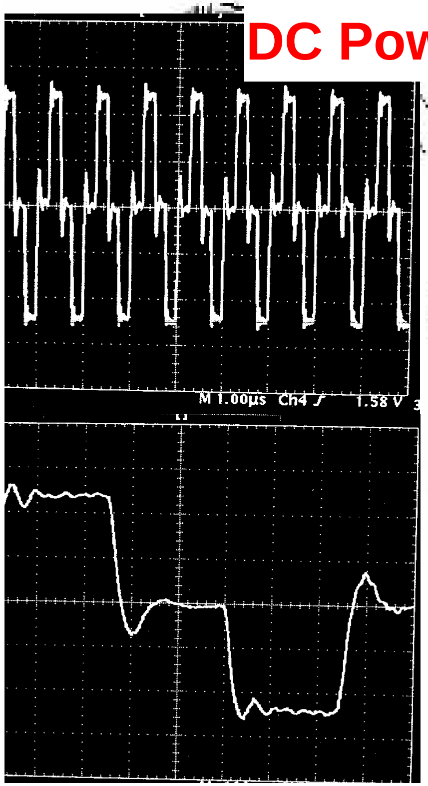


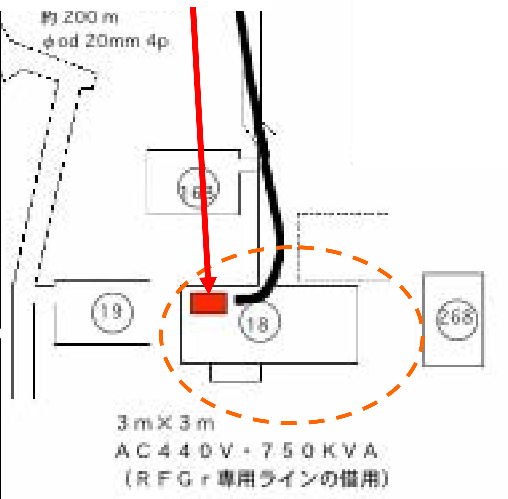
12GeV
Main Ring

Induction Accelerating Cavity

DC Power Supply

Booster

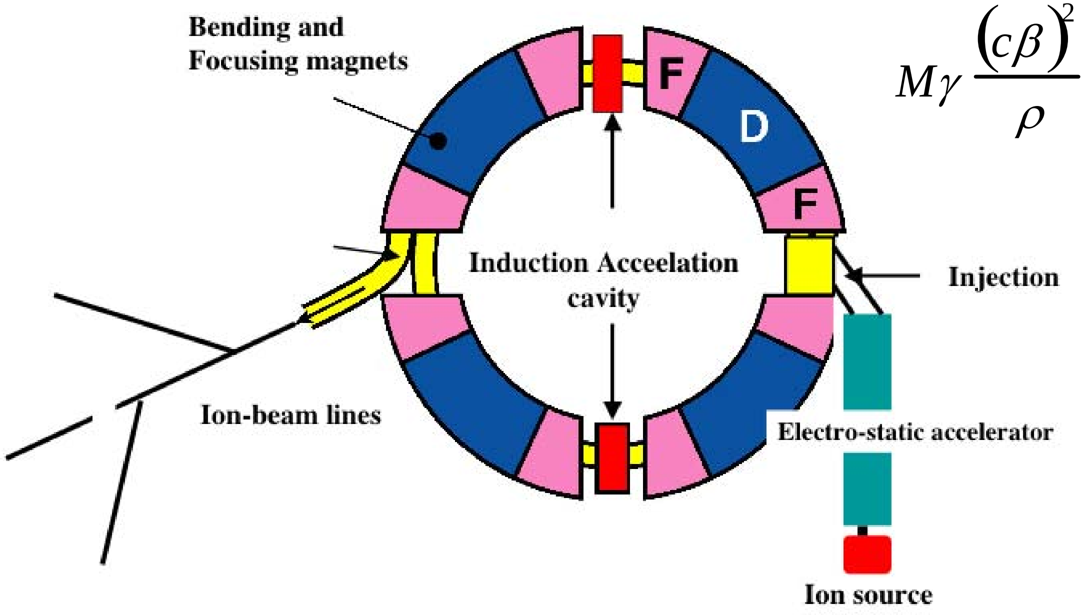




CW 1MHz
2kV/unit, 250nsec FT
operation

All Ion Accelerator (more by K.Takayama)

- Driven by controllable induction modulator
- Induction modulator works both for acceleration and confinement
- Can accelerate ions with arbitrary masses and charges
- Modification of KEK500MeV Booster is planning



Typical Arrangement of All Ion Accelerator (K.Takayama et al.,)

Balance Eq.

$$M\gamma \frac{(c\beta)^2}{\rho} = Q\cdot(c\beta)\cdot B \Rightarrow A\cdot m\cdot\gamma\frac{c\beta}{\rho} = Z\cdot e\cdot B$$

Acceleration

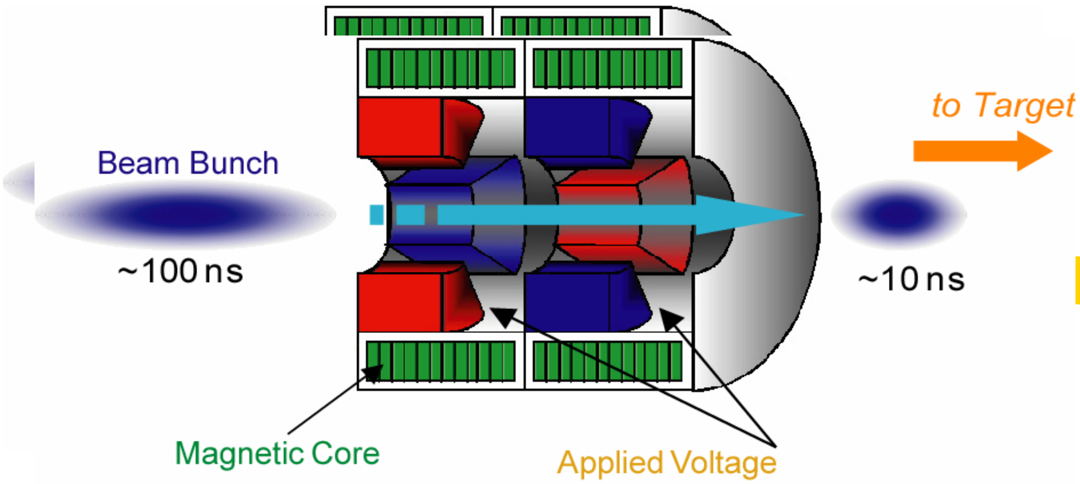
$$A\cdot mc^2\cdot\dot{\gamma} = \frac{Z\cdot ec\beta}{C_0}\cdot V_{acc}(t)$$

Acceleration Voltage

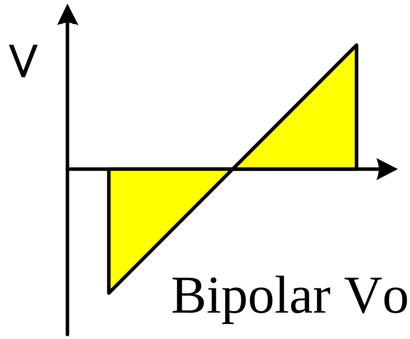
$$V_{acc}(t) = \rho\cdot C_0\cdot\frac{dB}{dt}$$

Heavy Ion Beam Bunching by Induction LINAC

Apply Bunching Voltage at each Gap

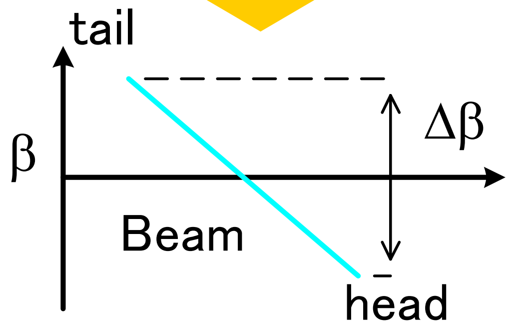


● for beam bunching



Bipolar Voltage Waveform

apply to beam



Induction buncher consists of periodic lattice, acceleration gaps & FODO quadrupole.

Beam head is decelerated
Beam tail is accelerated

by

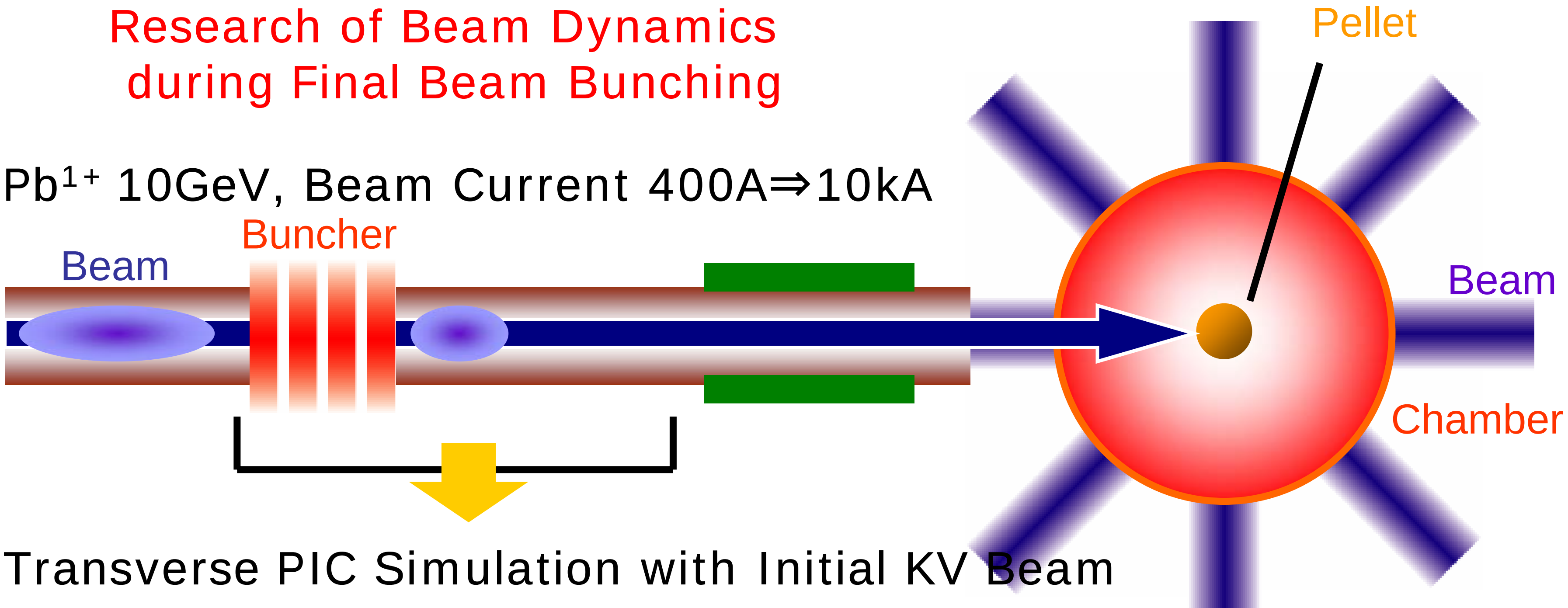
Head & tail velocities are modulated.

Δβ/β indicates Velocity Tilt.

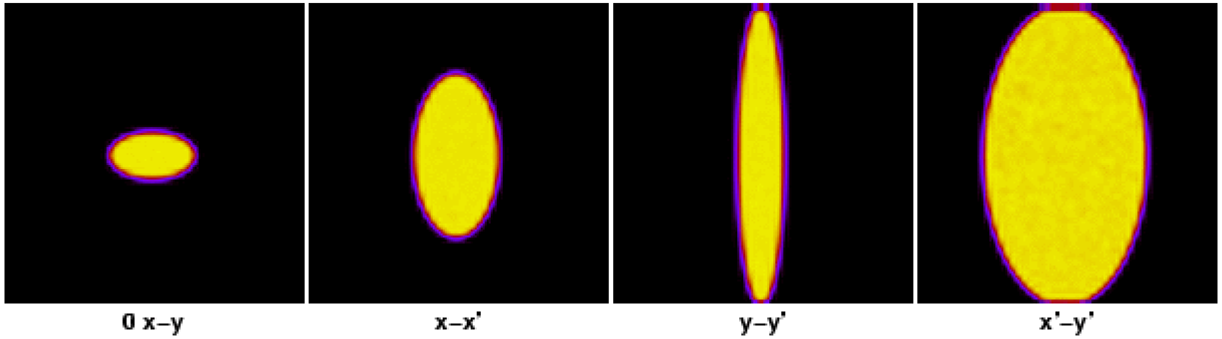
Final Beam Bunching

Research of Beam Dynamics during Final Beam Bunching

Pb^{1+} 10GeV, Beam Current 400A⇒10kA



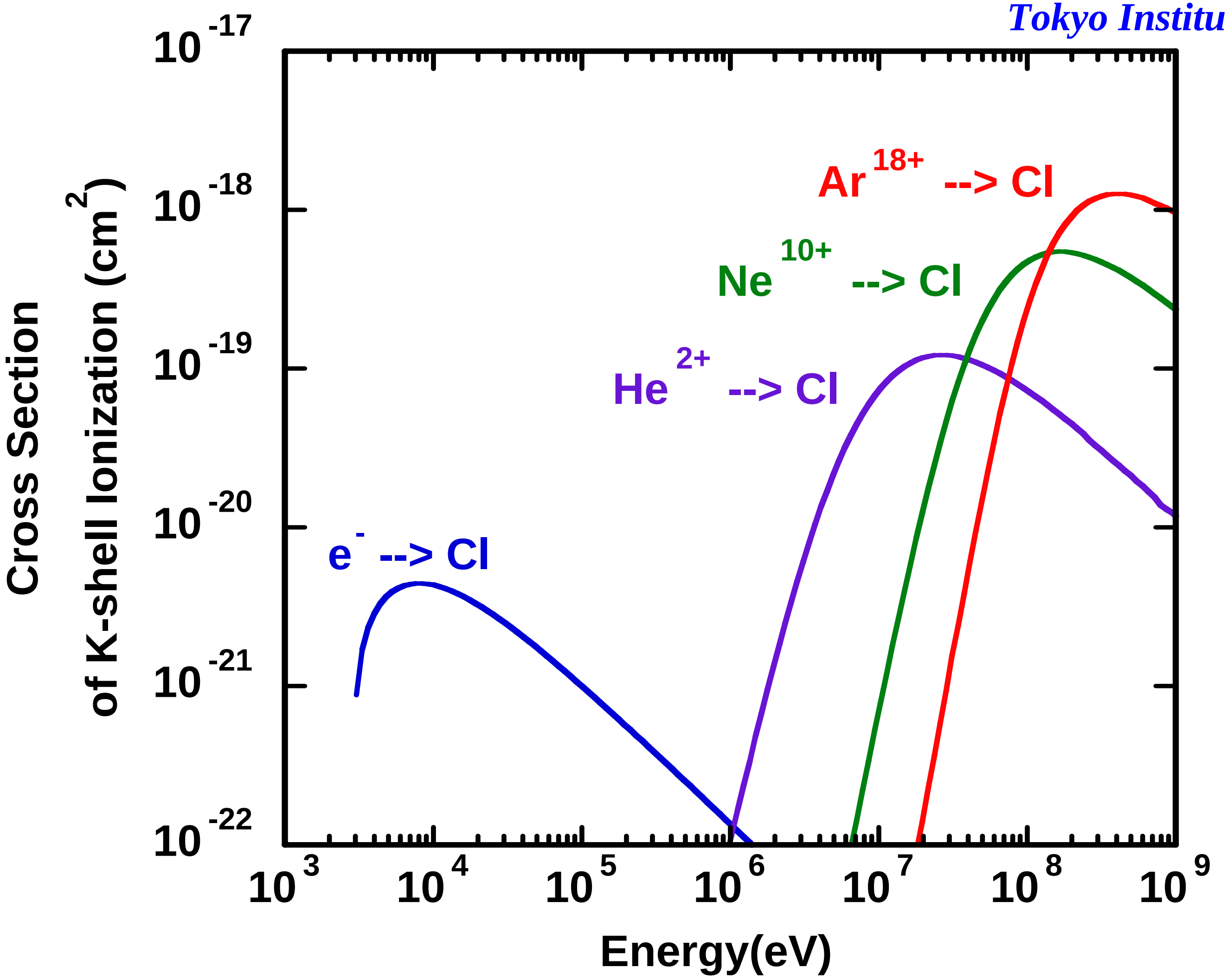
Transverse PIC Simulation with Initial KV Beam



T. Kikuchi, K.Horioka, et.al., Phys. Rev. ST-AB 7 (2004) 034201.
T. Kikuchi, K.Horioka, et.al., J. Plasma Fusion Res. 80 (2004) 87.

For chlorine plasmas, ion energy of more than few tens MeV is necessary to occur the K-shell ionization.

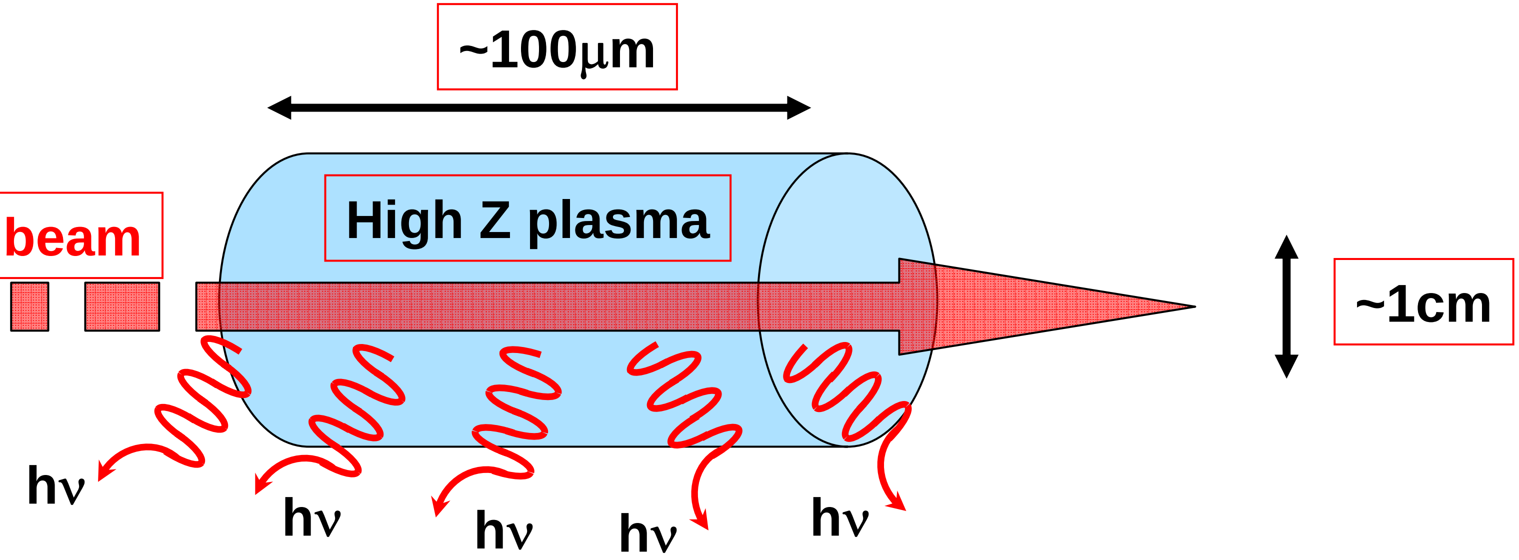
Tokyo Institute of Technology



T.Kawamura, Numerical Study on K-alpha Radiation from High Density Plasma by Energetic Particles, (This meeting)

Consideration of Kα-radiation by ion beams for plasma diagnosis. With spatial resolved observation of Kα-radiation, plasma heating process can be understood clearer than the traditional way of "TOF".

Tokyo Institute of Technology



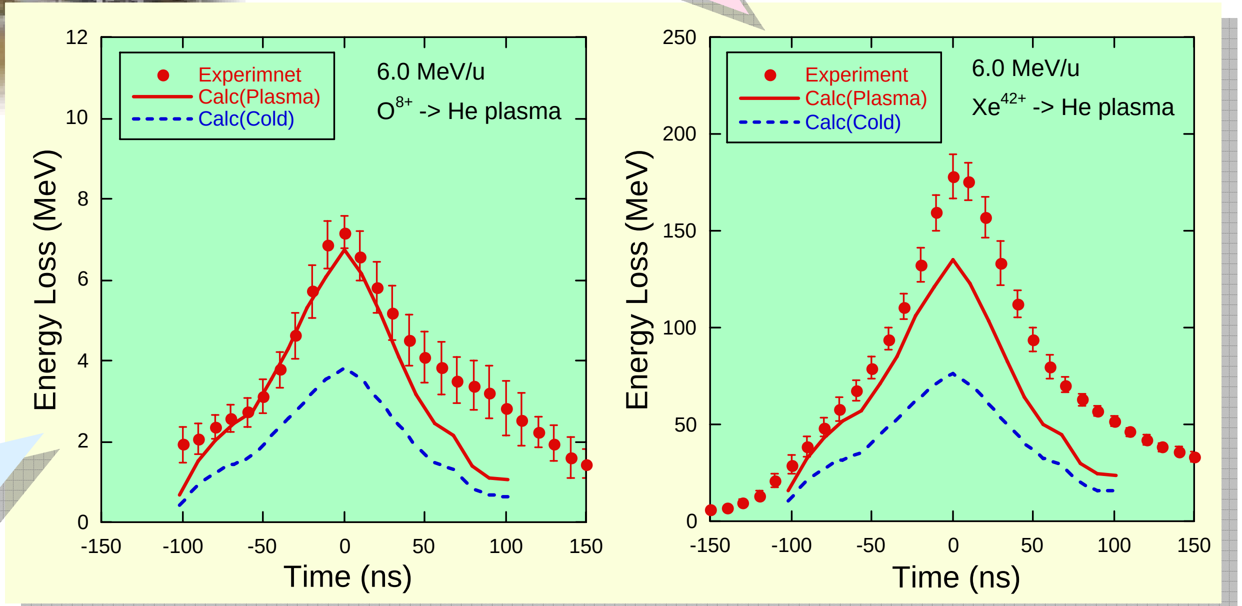
Kα from low charge state

Kα from high charge state

Spatial resolved diagnosis of heating process is possible.

Beam-plasma interaction experiments using a dense z-pinch plasma at Tokyo Tech.

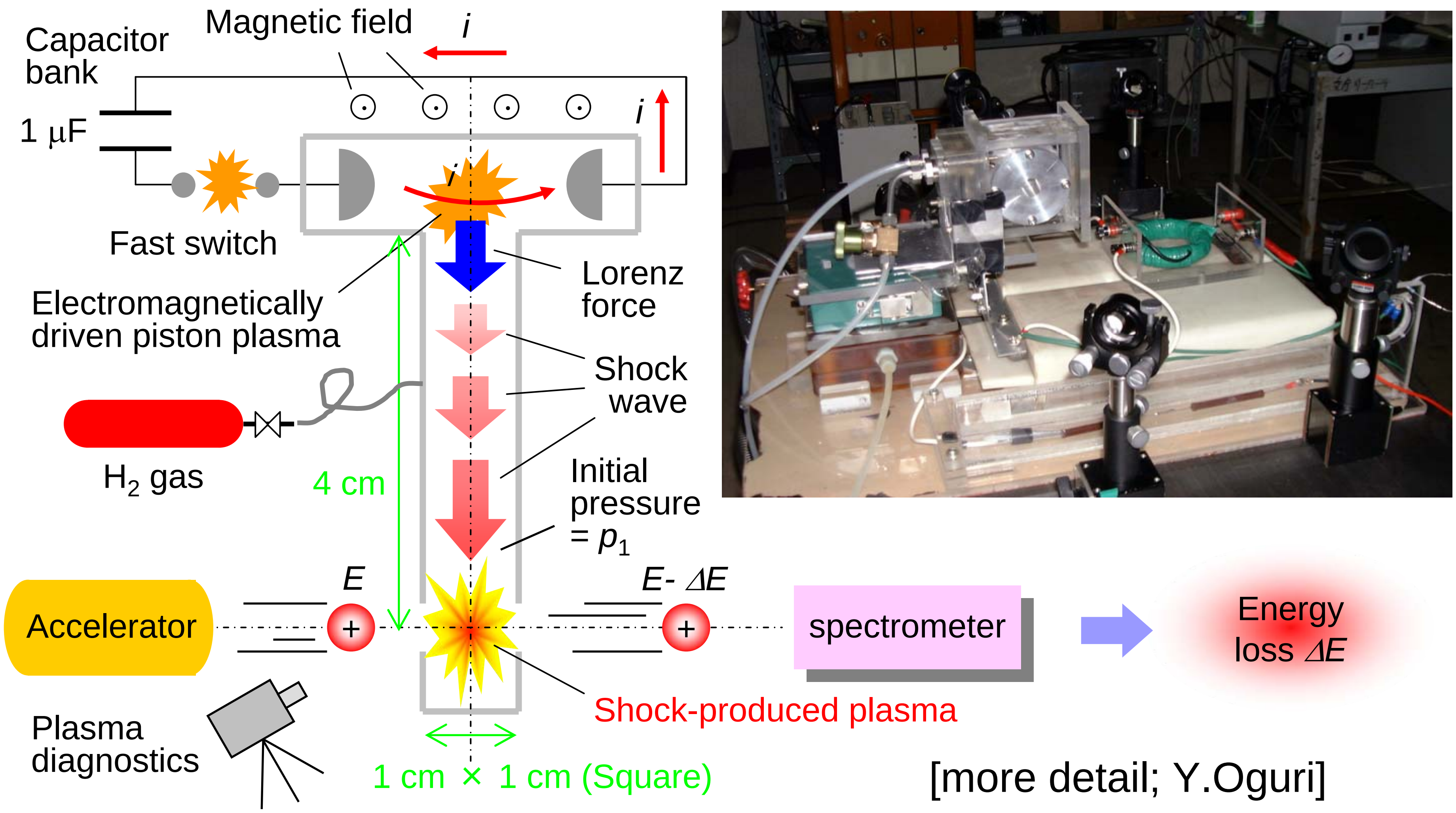
Large enhancement of energy losses of xenon ions was observed under target plasma densities above 10^{19} cm^{-3}, which was caused by an increase in projectile effective charge due to some density effects.



Energy loss of fully-stripped oxygen ions showed good agreement with theoretical predictions.

An electromagnetically-driven shock tube is being developed to produce weakly-non-ideal plasma targets.

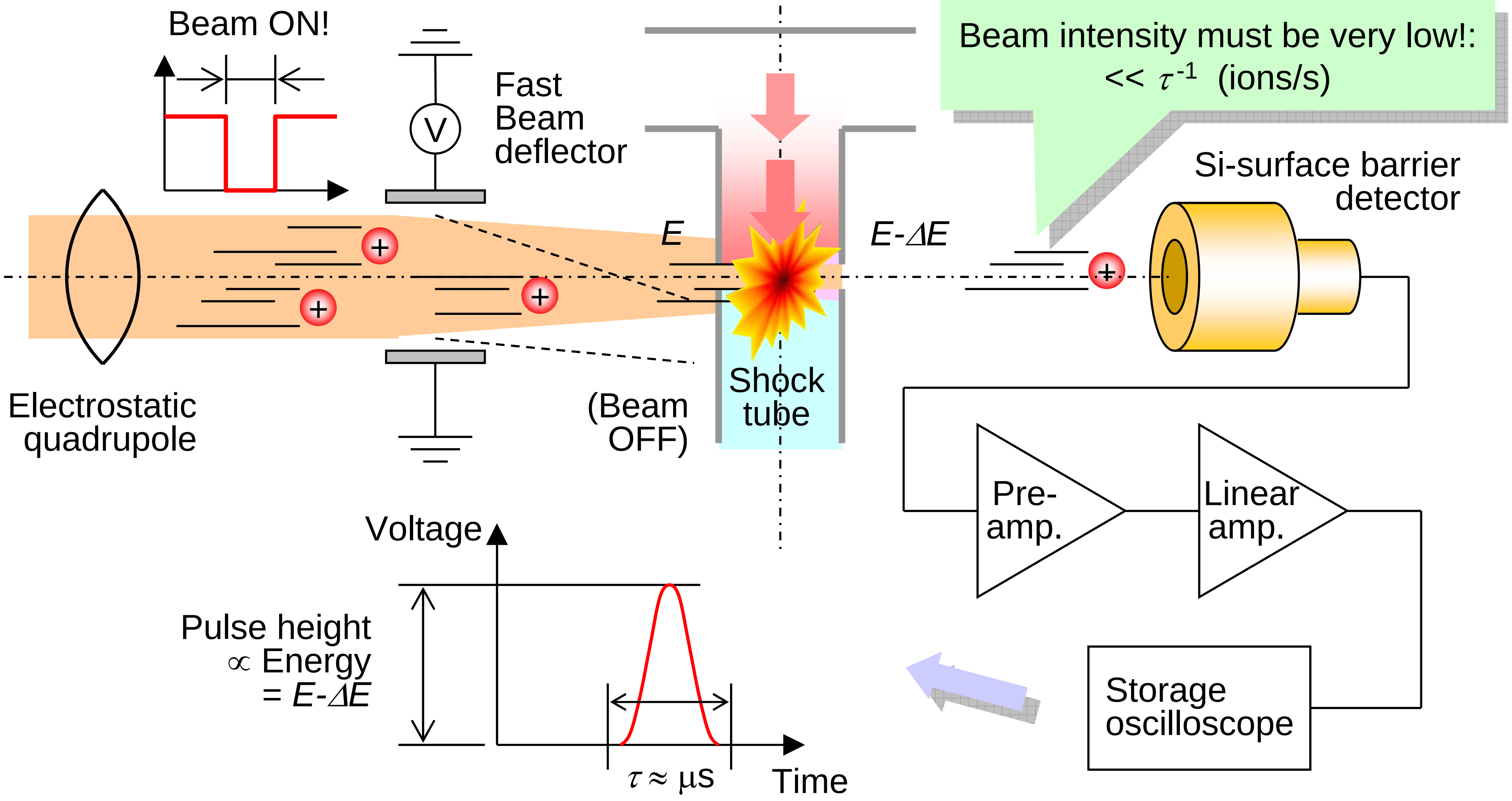
- Discharge energy ≈ 0.1 kJ during ≈ 1 μs:



[more detail; Y.Oguri]

For time-resolved measurement, the SSD has to be used in combination with a fast beam deflector.

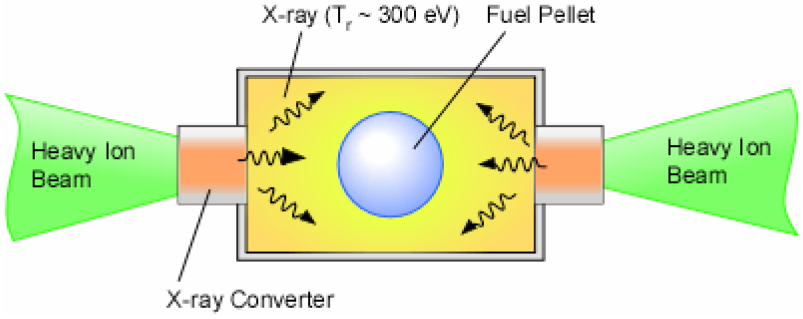
- The fast beam deflector has to be synchronized to the shock wave:



Beam intensity must be very low!:
<< τ^{-1} (ions/s)

Driver beams interact with converter plasmas having Γ values of 0.1~1.

Target Heating in HIF



X-ray converter（T~300 eV）is highly ionized ⇒ stopping power enhancement, range shortening

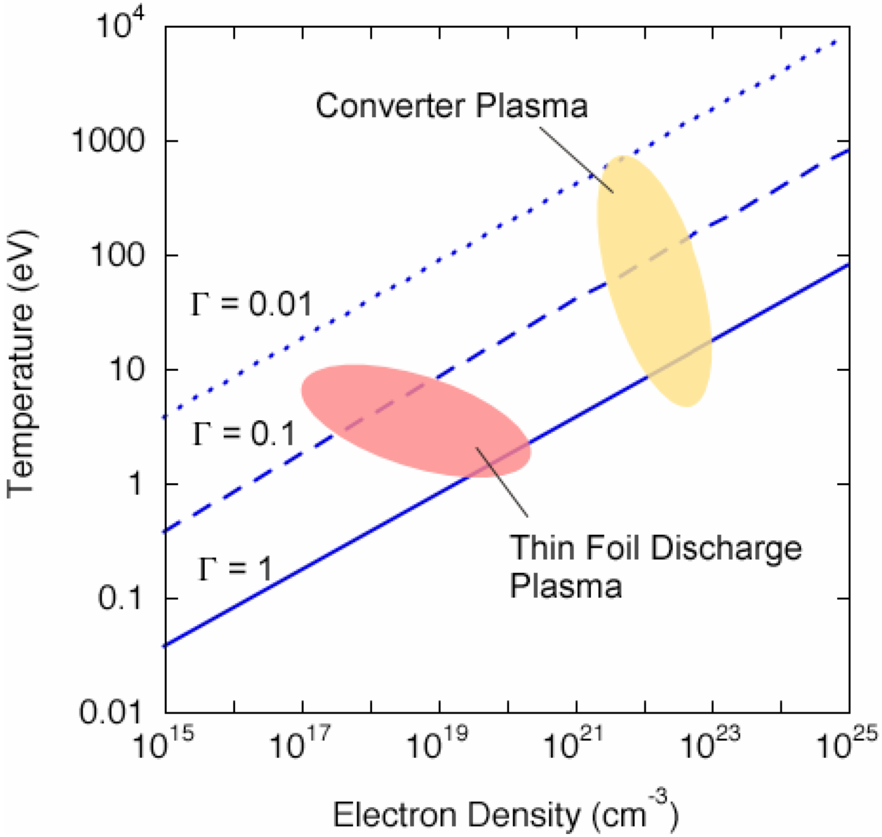
Plasma targets for interaction exp.

⇒ Z-pinch plasma, Laser-produced plasma

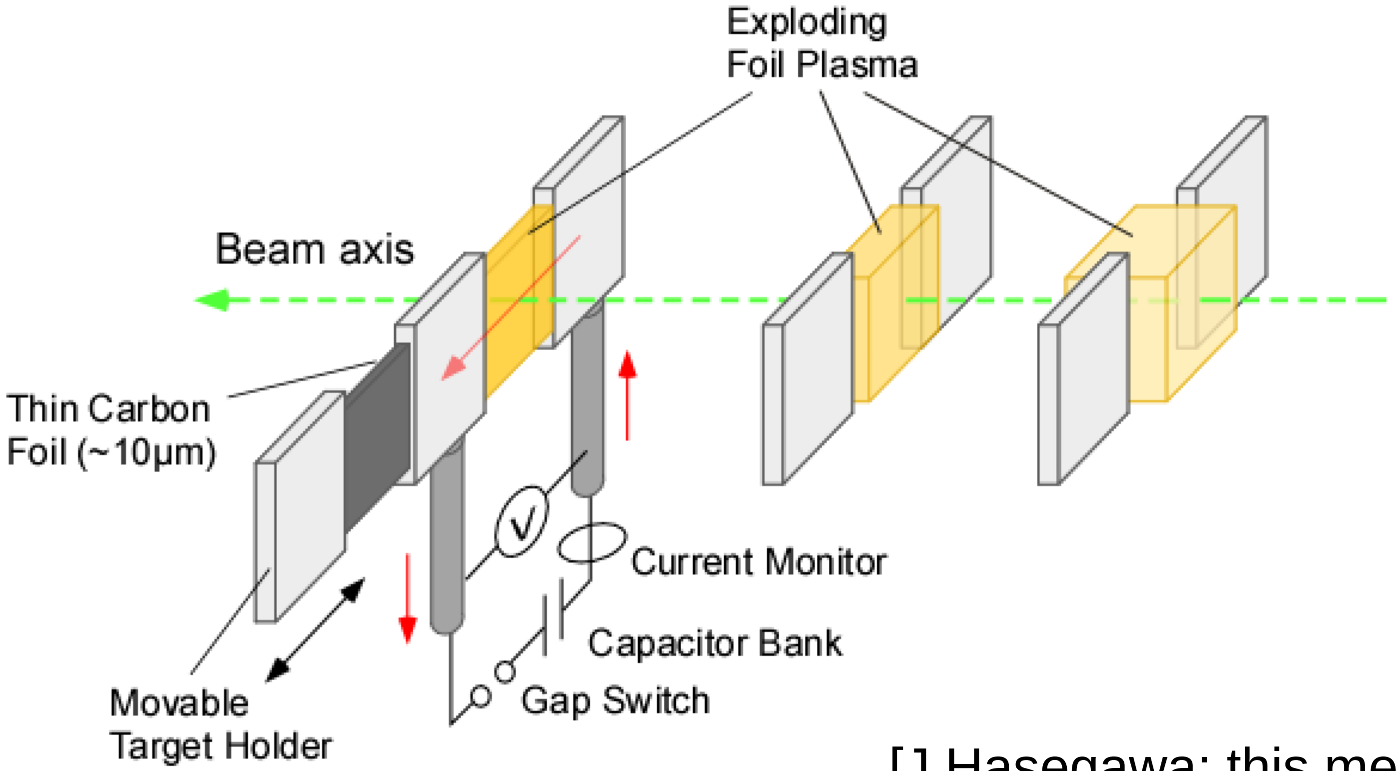
↓（higer density and Γ value）

Thin-foil-discharge (TFD) plasma

Plasma parameter $\Gamma_{ee} = \dfrac{e^2}{4\pi\varepsilon_0 akT}$



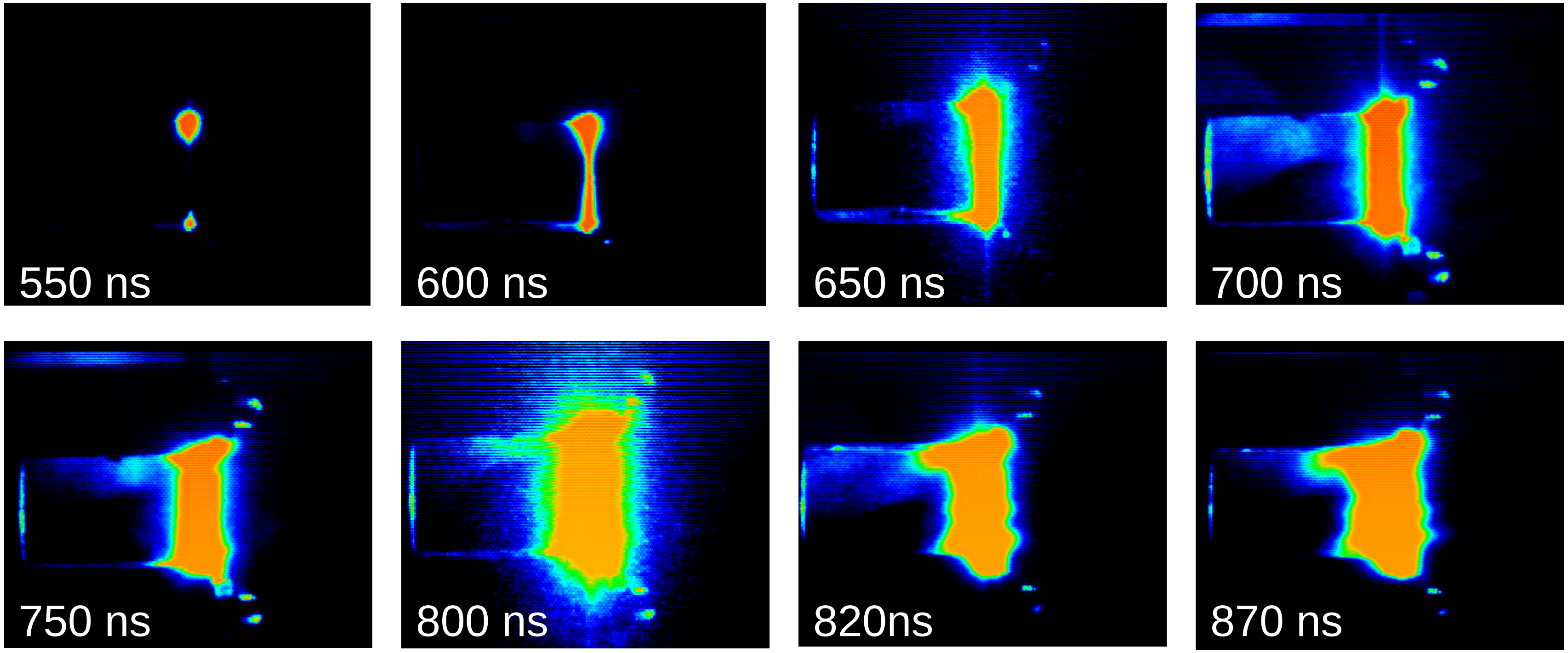
The Principle of Thin-Foil-Discharge (TFD) plasma generation



[J.Hasegawa; this meeting]

- Areal density keeps constant in the early stage of discharge.
- Dense plasma is easily available. (~0.01 n_{solid})
- Plasma effects on stopping power can be easily extracted.

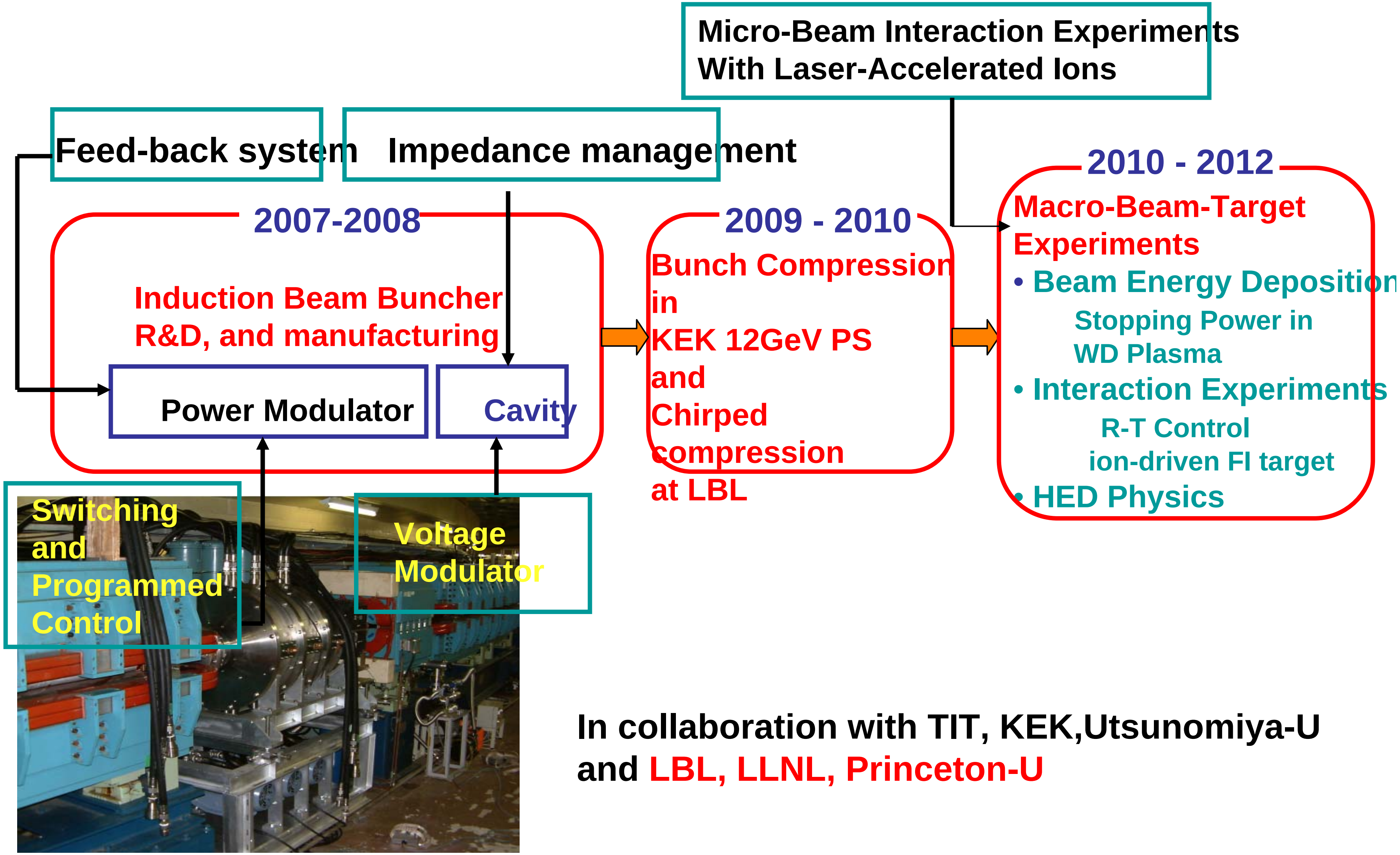
Time evolution of TFD plasma
（Aluminum, 12 μm）



- TFD plasma expands freely into vacuum with time.
- Until 750 ns, the plasma boundary looks stable.
- At 820 ns or later, the surface became jaggy.

Proposed Research Project (2007-2012)

Ion-Bunch Compression and Beam-Target Interaction Experiments



Micro-Beam Interaction Experiments
With Laser-Accelerated Ions

Feed-back system

Impedance management

2007-2008

Induction Beam Buncher
R&D, and manufacturing

Power Modulator

Cavity

Switching
and
Programmed
Control

Voltage
Modulator

2009 - 2010

Bunch Compression
in
KEK 12GeV PS
and
Chirped
compression
at LBL

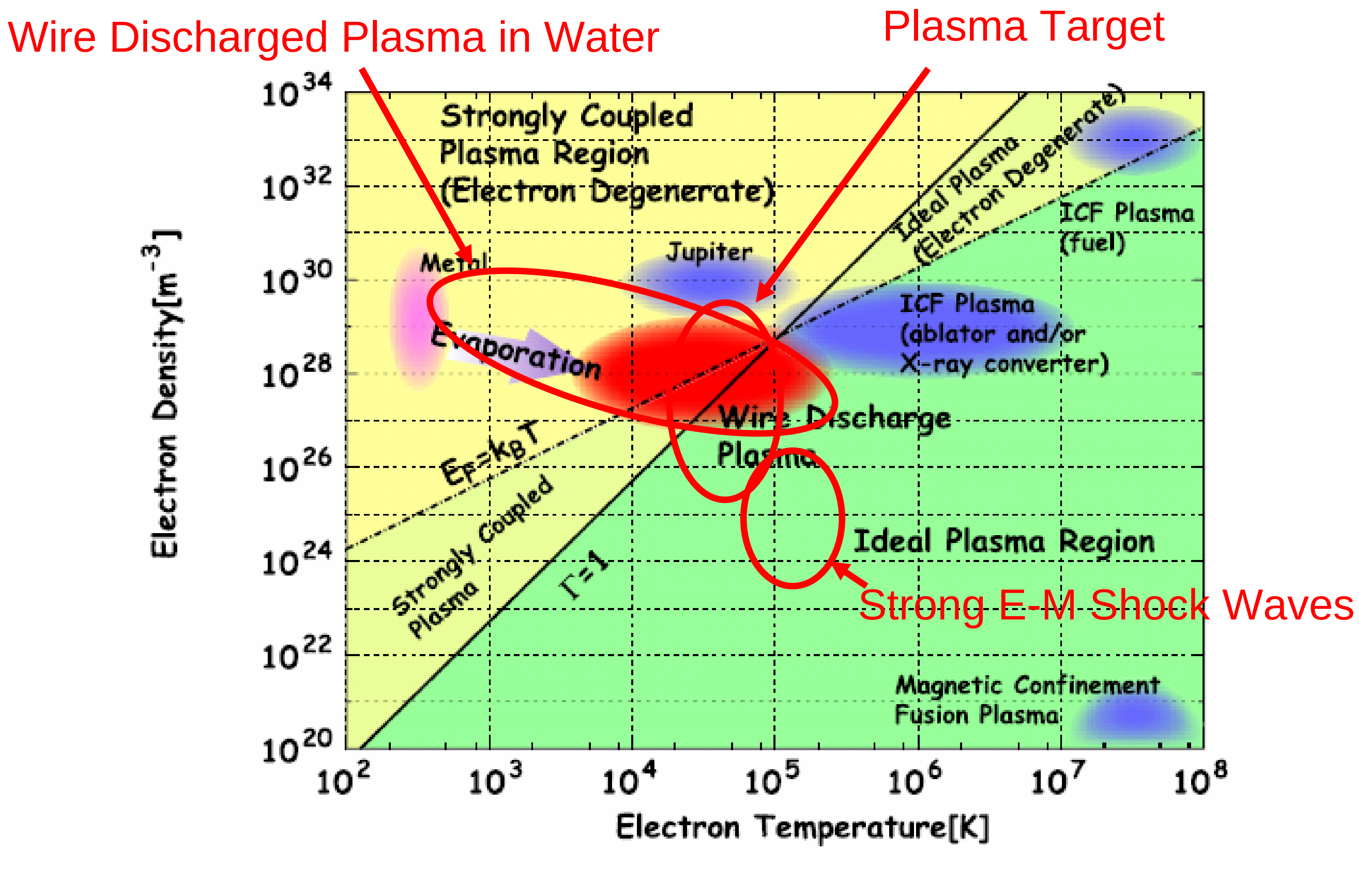
2010 - 2012

Macro-Beam-Target
Experiments

- Beam Energy Deposition
  - Stopping Power in
  - WD Plasma
- Interaction Experiments
  - R-T Control
  - ion-driven FI target
- HED Physics

In collaboration with TIT, KEK,Utsunomiya-U
and LBL, LLNL, Princeton-U

Expected experimental range of pulse power and accelerator driven HED physics research in Japan



Concluding remarks

- Compared with laser driven HED researches, we have just begun to study pulse-power and/or accelerator based HED physics

- There have been some advances in WDM physics, strong shock wave researches and beam-plasma interaction experiments

- Design works for a modification of the KEK facility are in the making stage and a 5-years US-J collaboration project in the HED (fast ignition) physics has been proposed