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

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“Development of a shock-produced plasma target for nonlinear beam-plasma interaction experiments”

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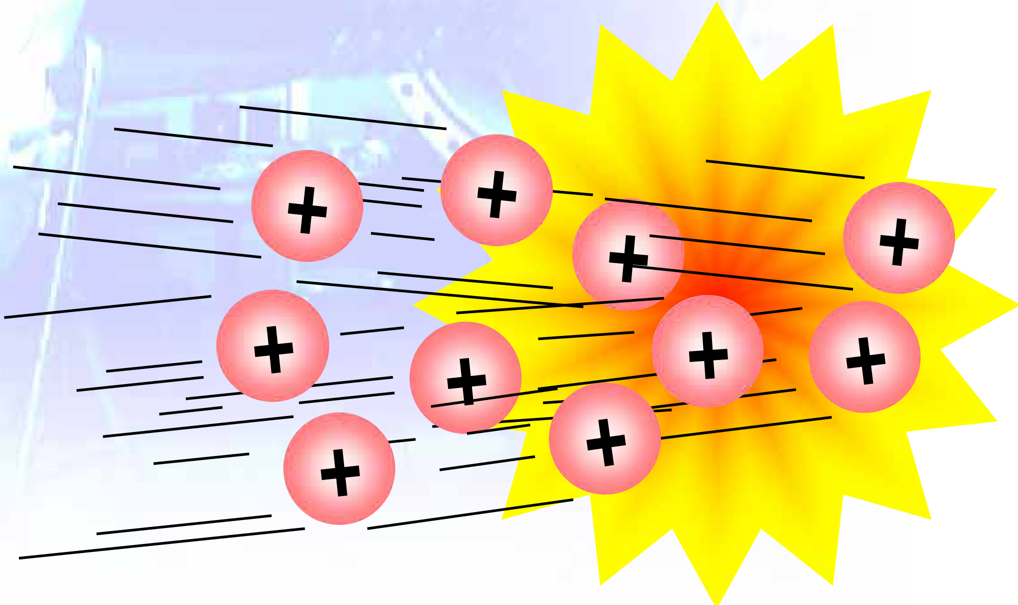
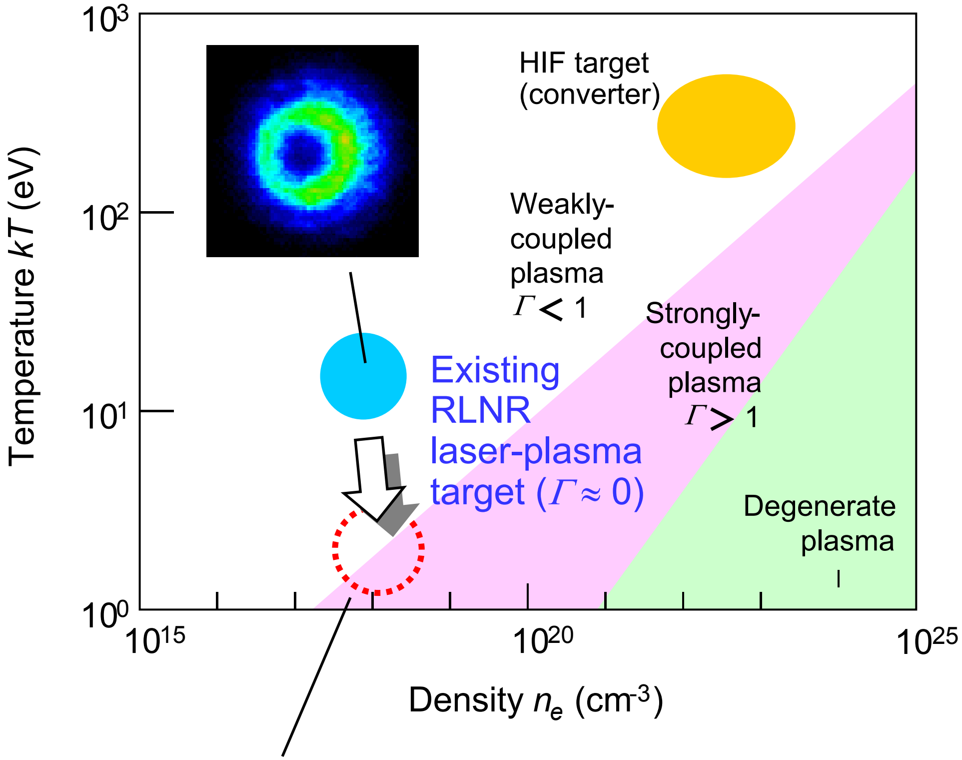


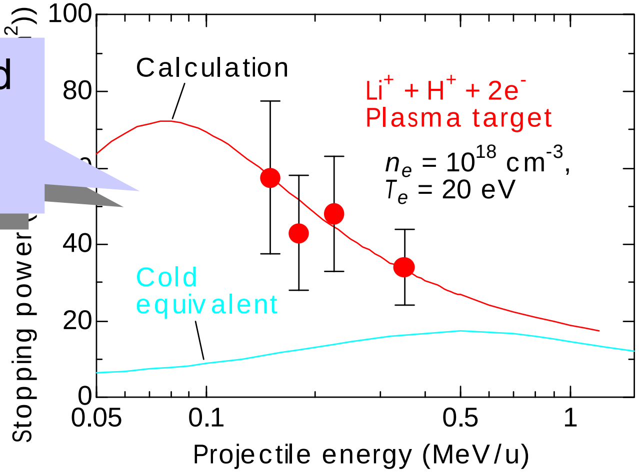
Beam-plasma interaction experiments with non-ideal plasma targets are being planned at RLNR/Tokyo-Tech.

- Experiments performed so far using Tokyo-Tech 1.7 MV tandem accelerator:

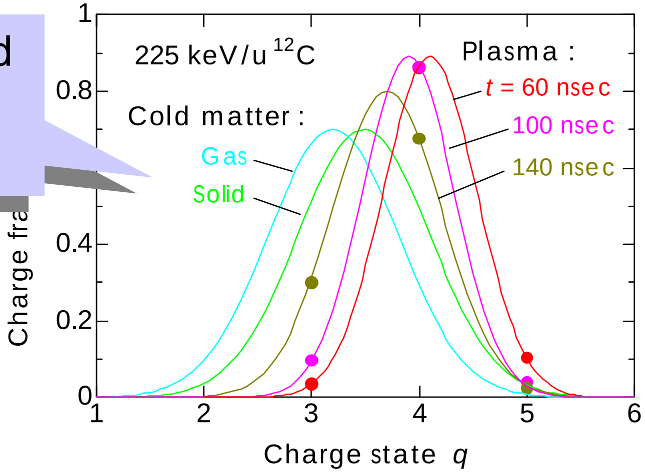


Weakly non-ideal plasma target being developed ($\Gamma \approx 0.1 \neq 0$)

Enhanced *-dE/dx* in plasmas

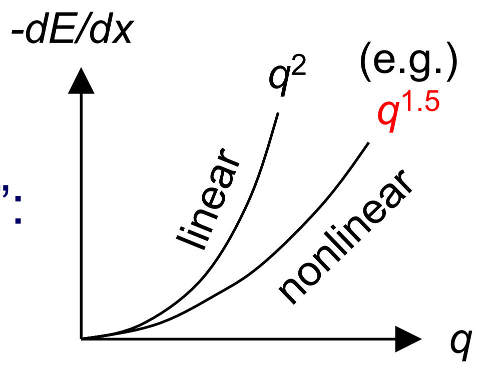


Enhanced charge in plasmas

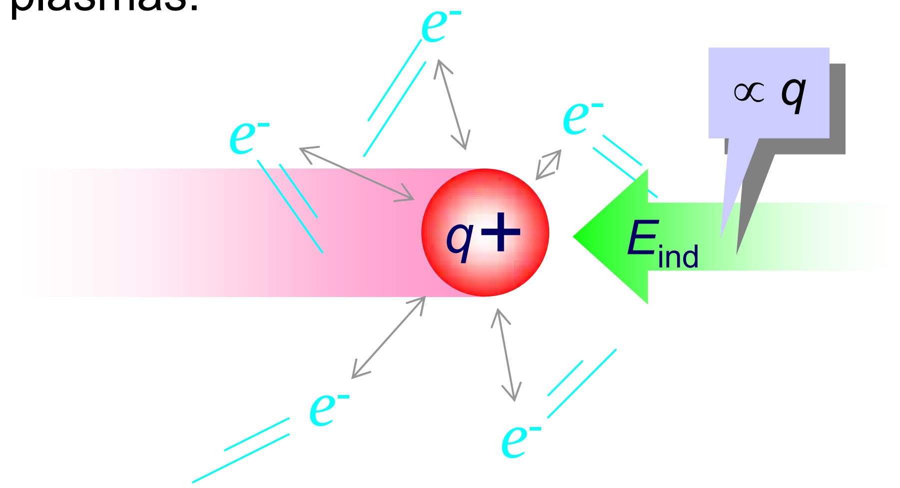


Nonlinear effects are expected for projectile stopping in dense ($n_e \approx 10^{22}$ cm^{-3}) plasmas in fusion targets.

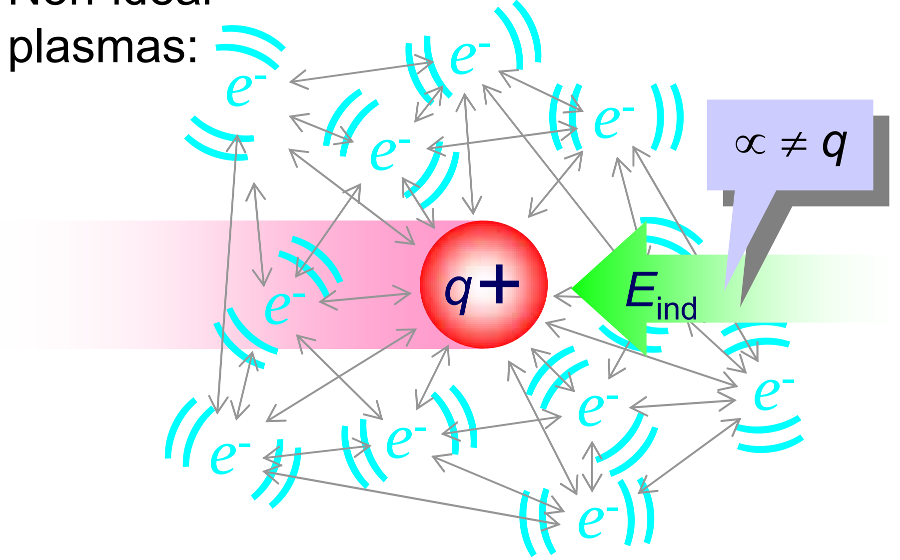
- Ideal (dilute hot) plasmas → "Linear stopping":
  - Induced decelerating field $E_{ind} \propto q$
  - $-dE/dx = q \times E_{ind} \propto q \times q = q^2$ (q: projectile charge)
- Non-ideal (dense cold) plasmas → "Nonlinear stopping":
  - Induced decelerating field $E_{ind} \propto q^m$ ($m < 1$)
  - $-dE/dx = q \times E_{ind} \propto q \times q^m = q^{1+m} = q^n$ ($1 < n < 2$)



Ideal plasmas:



Non-ideal plasmas:

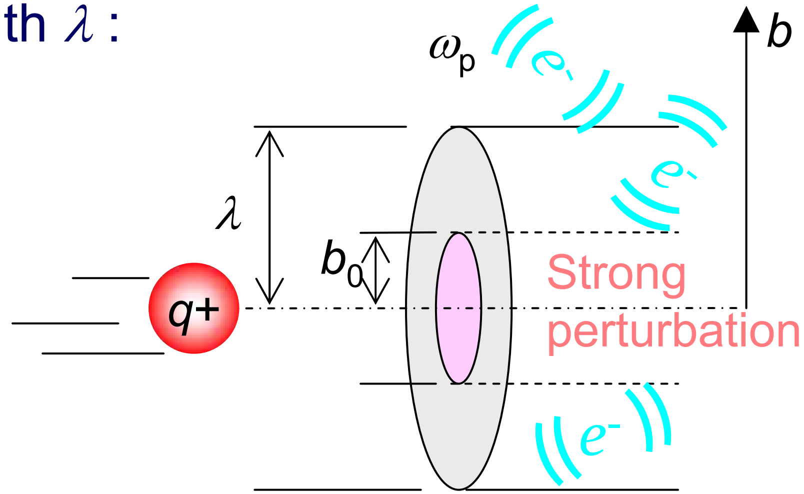


Projectile-plasma coupling constant γ is defined for projectiles moving in the plasma.

- Perturbations to the plasma electrons are possible only for the collision parameters *b* smaller than screening length λ :

$$b < \lambda = \frac{\langle v_\mathrm{r} \rangle}{\omega_\mathrm{p}}, \quad \langle v_\mathrm{r} \rangle = v_\mathrm{th}\sqrt{1+\left(\frac{v_\mathrm{proj}}{v_\mathrm{th}}\right)^2}$$

  - $\langle v_\mathrm{r} \rangle$: averaged relative velocity



- If *b* is smaller than the classical collision diameter b_0, the perturbation is strong enough to induce nonlinear effects:

$$\frac{qe^2}{4\pi\varepsilon_0 b_0} = m\langle v_\mathrm{r} \rangle^2, \quad \text{or} \quad b_0 = \frac{qe^2}{4\pi\varepsilon_0 m\langle v_\mathrm{r} \rangle^2}.$$

- The projectile-plasma coupling strength is estimated by the critical ratio $\gamma \equiv b_0/\lambda$:

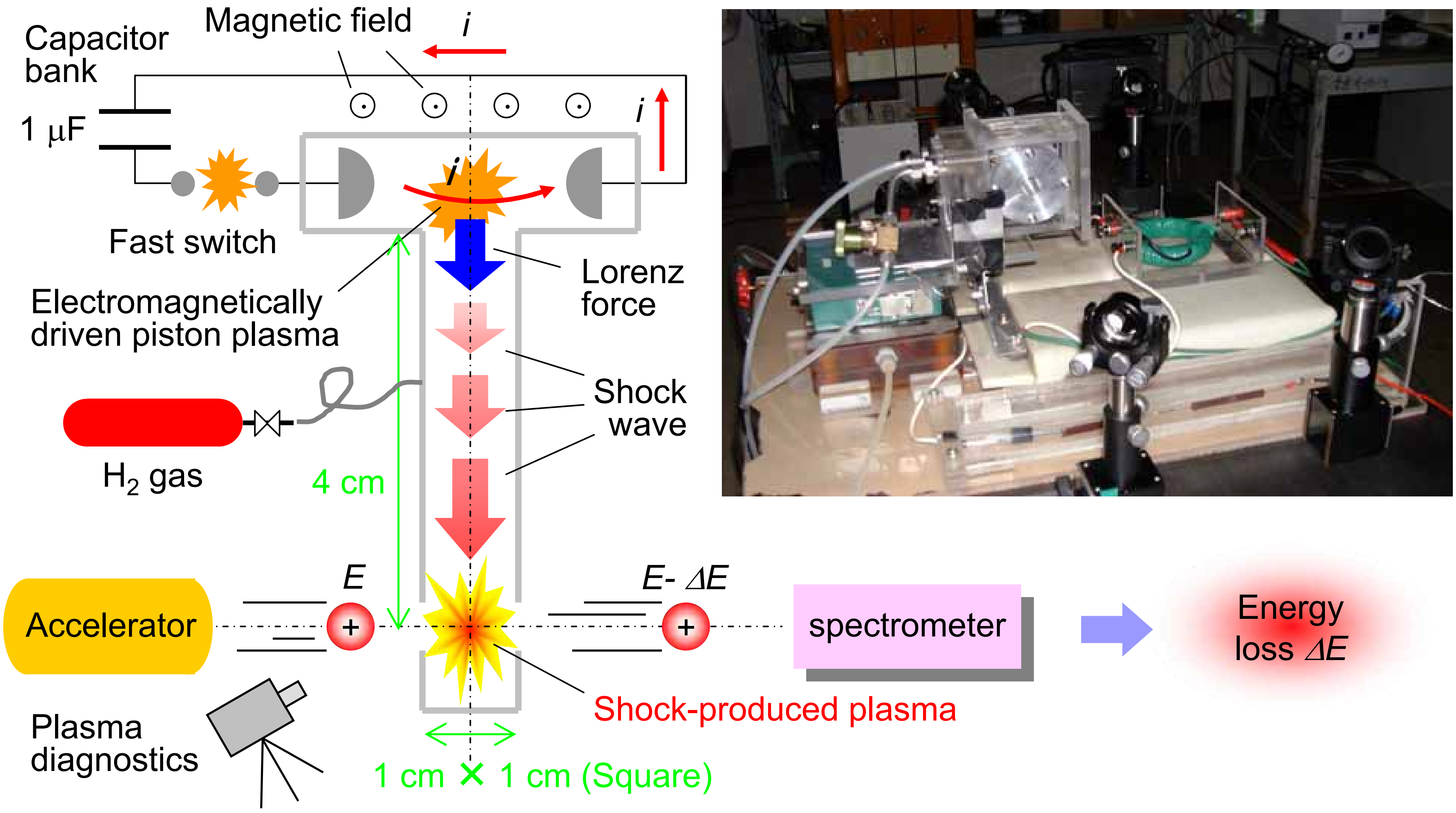
Plasma coupling constant

$$\gamma \equiv \frac{b_0}{\lambda} = \frac{qe^2\omega_\mathrm{p}}{4\pi\varepsilon_0 m\langle v_\mathrm{r} \rangle^3} = \frac{\sqrt{3}q\Gamma^{3/2}}{\left\{1+\left(v_\mathrm{proj}/v_\mathrm{th}\right)^2\right\}^{3/2}}$$

  - Numerical calculation by a particle code
    → Nonlinear effects are clearly observable for $\gamma > \approx 0.1$

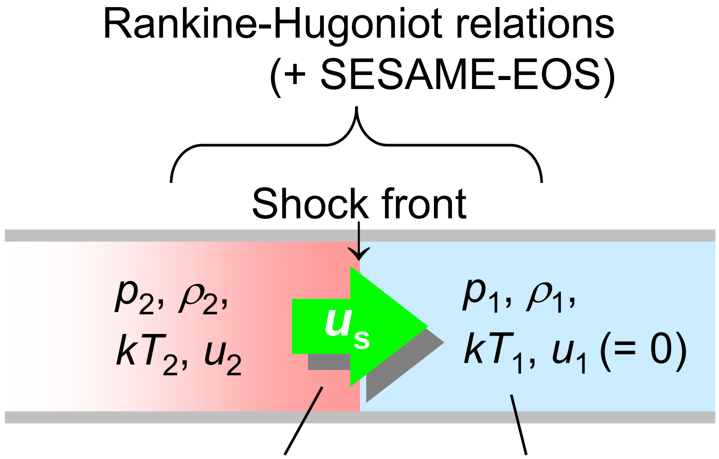
An electromagnetically-driven shock tube is being developed to produce weakly-non-ideal plasma targets.

- Discharge energy ≈ 0.1 kJ during ≈ 1 μs:



Conditions to realize $\gamma > 0.1$ have been searched by adjusting different projectile-target parameters.

- Projectile:
  - Projectile (tentative): 12.5 keV/u ^{91}Nb
  - Effective charge $q \approx 4$
    cf. averaged charge in cold H_2 gas ≈ 3
- Plasma target:
  - Beam-plasma coupling constant $\gamma > 0.1$
    to observe nonlinear effects
  - High ionization degree $\alpha >> 0.5$
    to clearly observe plasma effects
  - Target thickness > 5 mm
    to eliminate tube wall effects
  - Energy loss $\Delta E/E < \approx 0.2$
    to define interaction energy
  - Compact size and low discharge energy
    for installation in the beam line



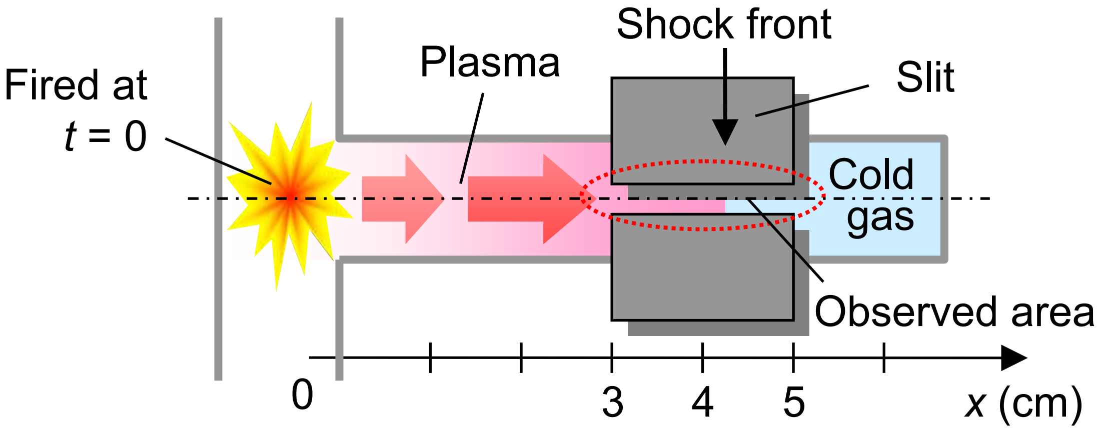
Behind the shock:
$n_e = 2.8\times10^{18}$ cm^{-3},
$kT = 1.6$ eV,
$\alpha = 0.7$, $\Gamma = 0.22$
$\rightarrow \gamma = 0.1$!

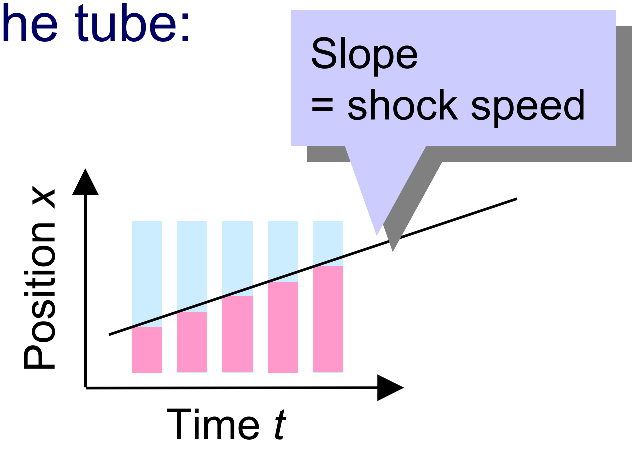
Initial condition:
$p_1 = 5$ Torr,
$T = 300$ K

Goal of the R&D:
Shock speed $u_s = 48$ km/s
(Mach number $M \equiv u_s/c = 36$)

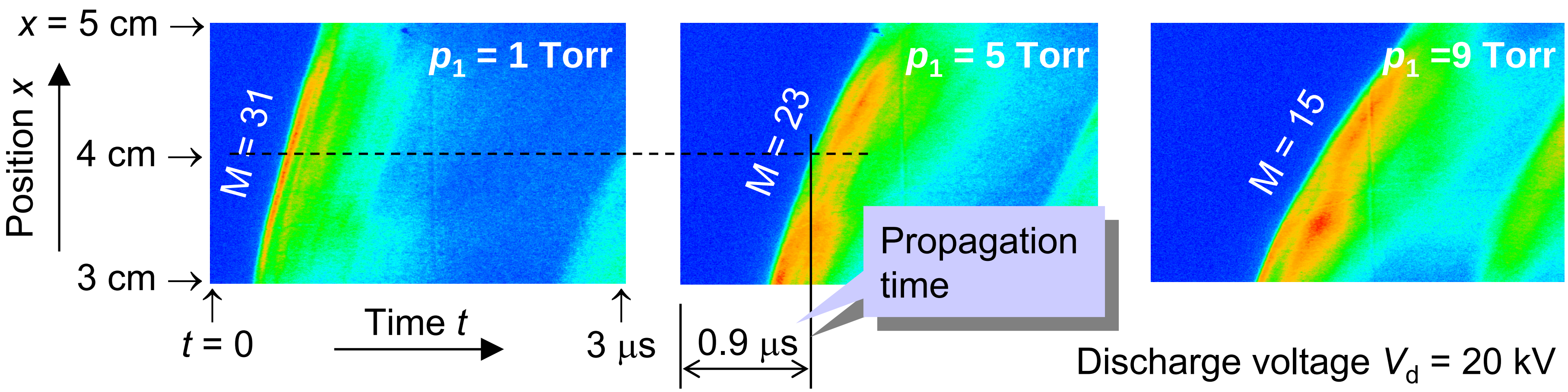
The shock velocity was measured by a fast photography with a streak camera.

- Streak imaging of the shock front propagating in the tube:




Slope = shock speed

- The shock front was clearly observed on the streak images:

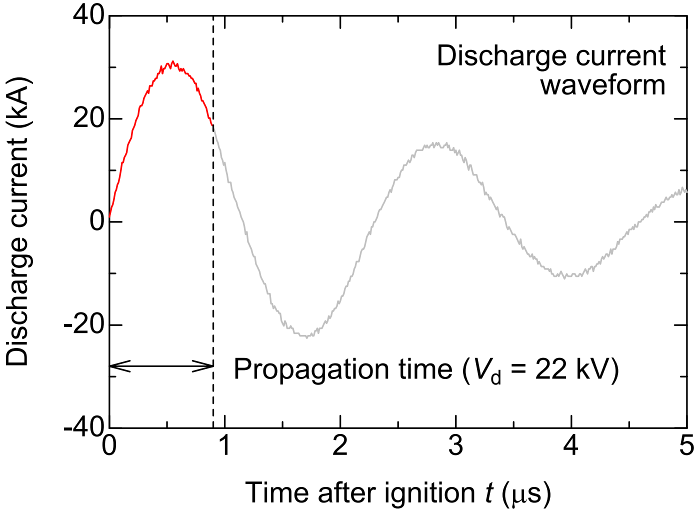


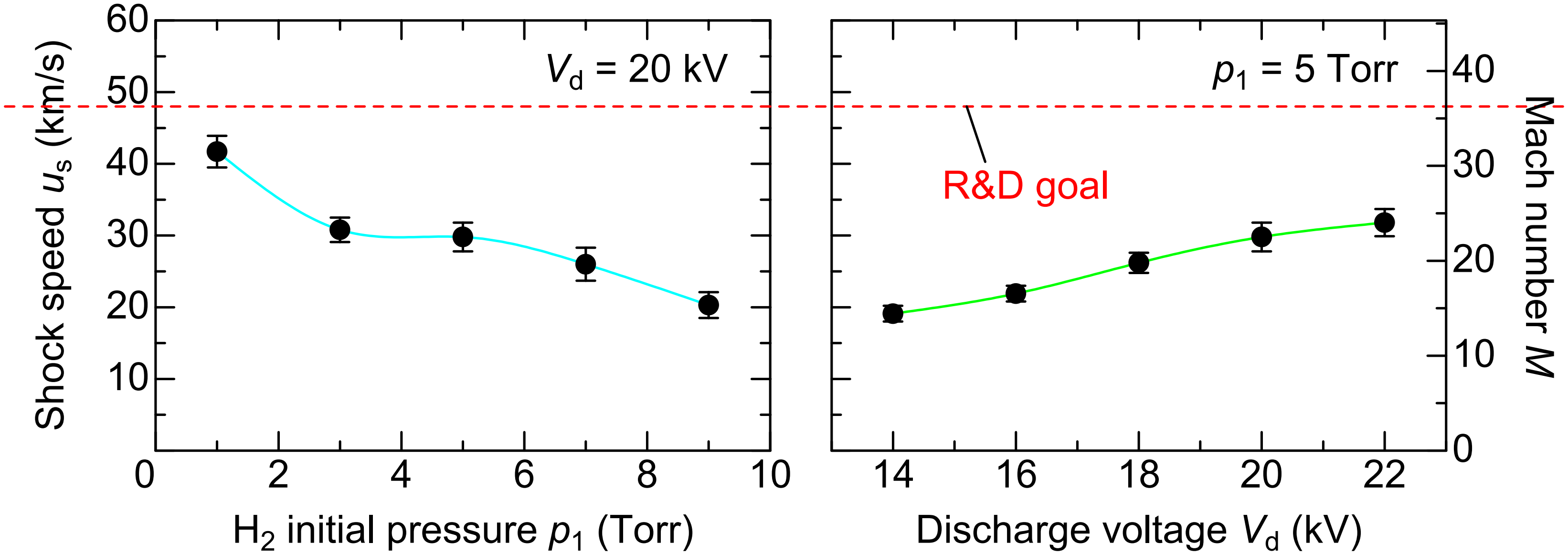
Propagation time

Discharge voltage V_d = 20 kV

So far $M = 24$ ($u_s = 32$ km/s) has been obtained for $p_1 = 5$ Torr at the interaction point.

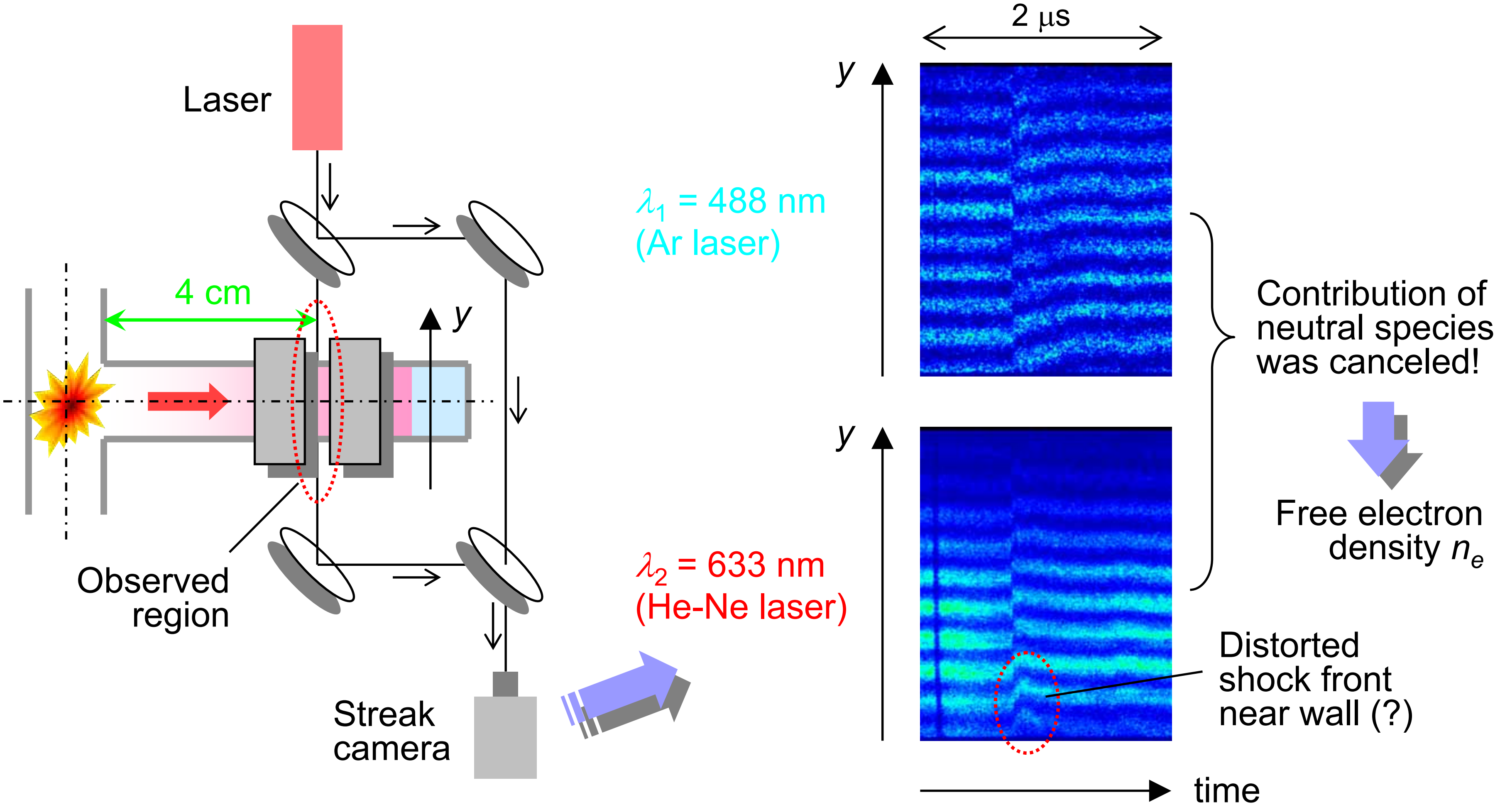
- Measured shock speed at the interaction point ($x = 4$ cm):
  - Low initial pressure is favorable to reach higher shock speed
  - $u_s = 48$ km/s (goal) is expected for discharge voltages of $V_d \approx 40\text{-}50$ kV.





Electron density of the plasma was determined by laser interferometry with two different wavelengths.

- A Mach-Zehnder interferometer was integrated on the shock-tube base:



λ_1 = 488 nm (Ar laser)

λ_2 = 633 nm (He-Ne laser)

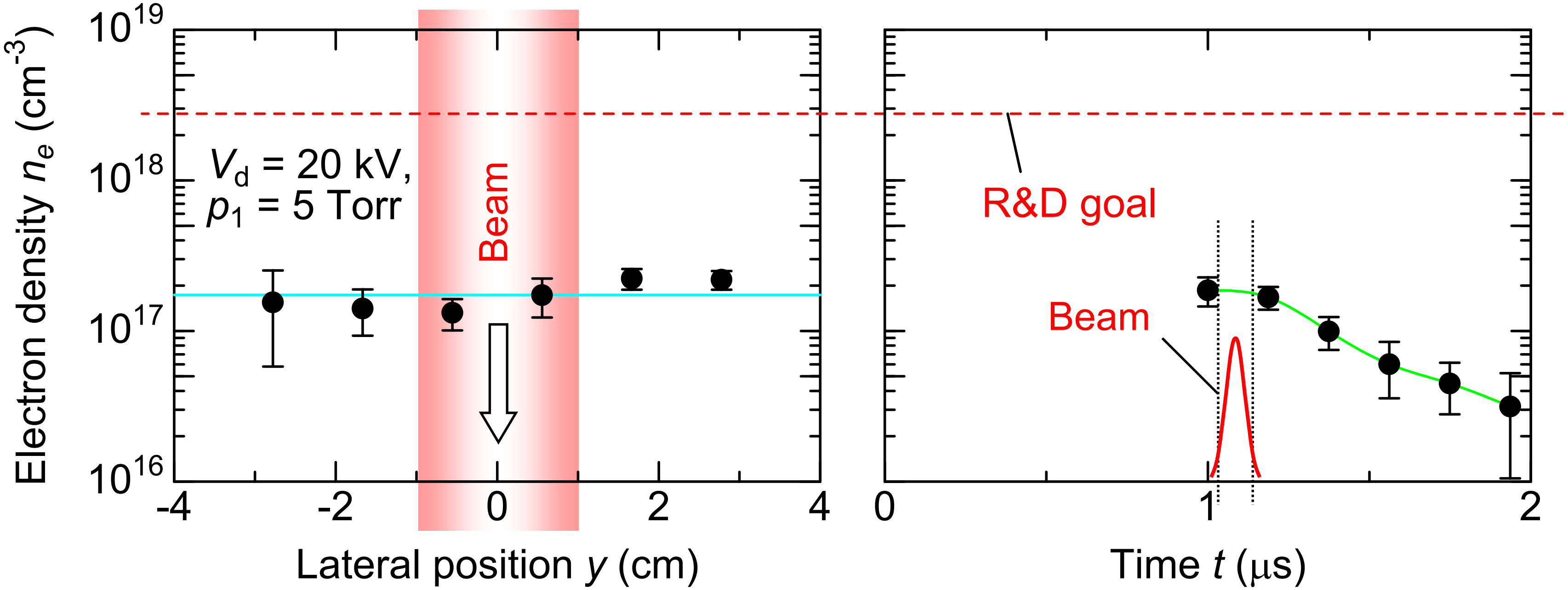
Contribution of neutral species was canceled!

Free electron density n_e

Distorted shock front near wall (?)

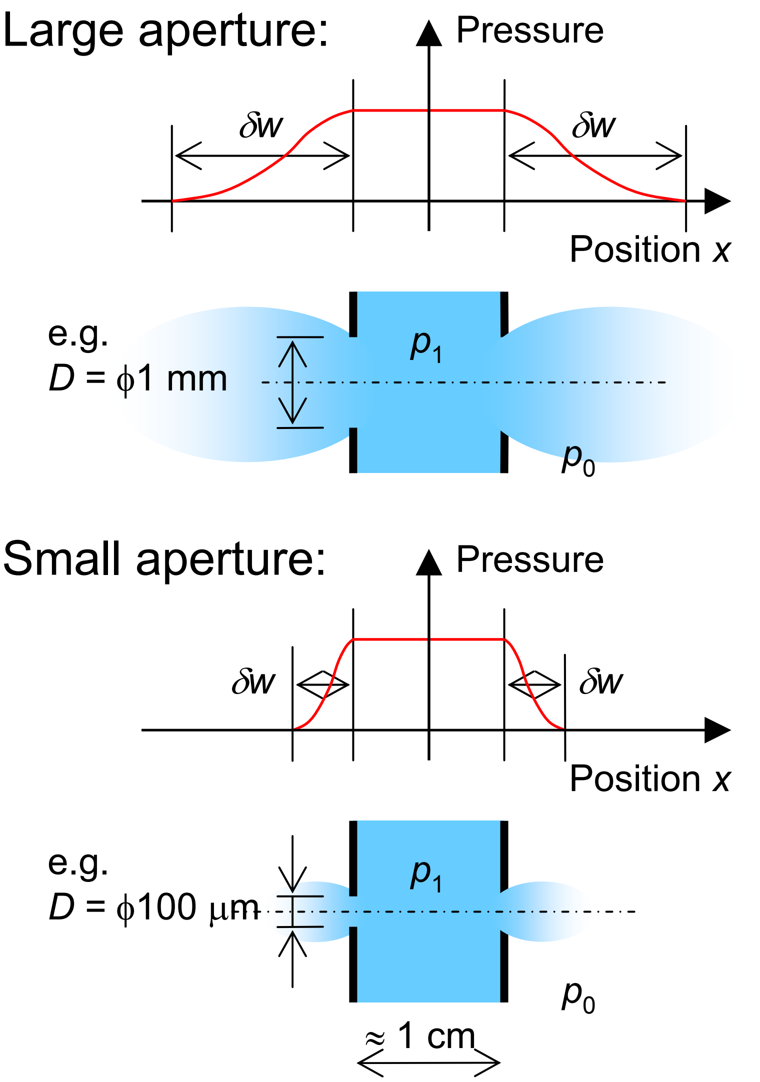
Spatial and temporal homogeneity was enough to perform the planned beam experiments.

- n_e behind (0.2 μs) the shock front (lateral spatial distribution):
  - So far ≈ 10^{17} cm^{-3} ($\alpha \approx 0.2$)
  - Much better homogeneity than laser plasmas
  - ϕ1 mm-beam can be used.
- n_e at the interaction point (temporal evolution at $y = 0$):
  - decreases due to recombination after passage of the shock.
  - ≈ constant (?) for ≈100 ns
  - Pulsed beams with duration ≈ 100 ns can be used.



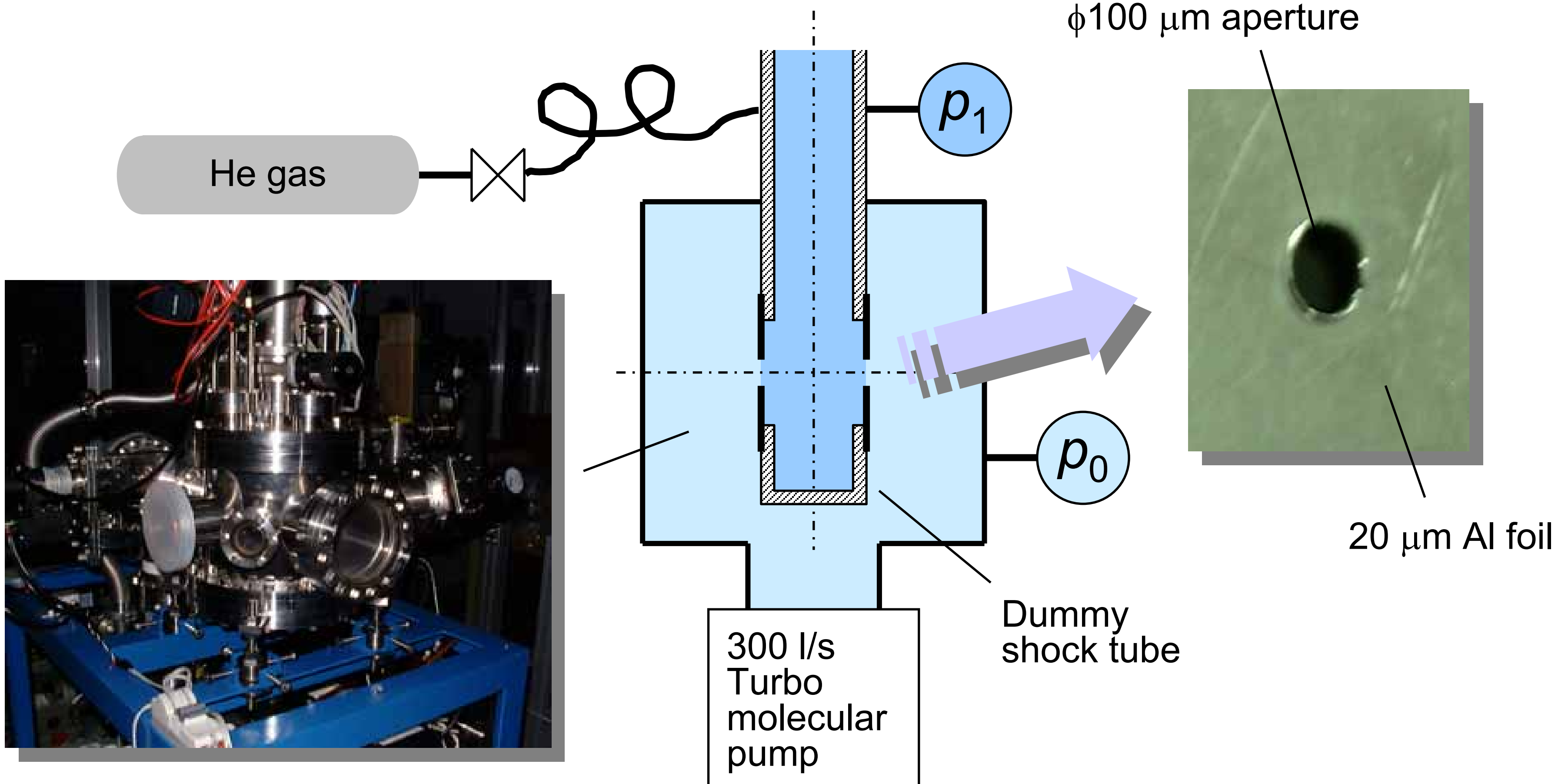
To establish a well-defined target thickness, very small beam apertures are needed.

- Pressure requirements:
  - Initial pressure $p_1 = 5$ Torr
  - Beam line pressure $p_0 < 10^{-5}$ Torr
- Low energy (keV/u) heavy projectiles:
  - can stop even by 1 μm plastic film
    ∴ Windowless target
- Fast valve does not work!
- Differential pumping system with very small apertures:
  - Target thickness (≈ 1 cm)
    must be >> relaxation length *δw*.
  - *δw* ≈ aperture diameter *D* (?)
    ∴ *D* must be < ≈ ϕ100 μm!



A differentially-pumped gas cell with ϕ100 μm-apertures was employed for the test experiment with He.

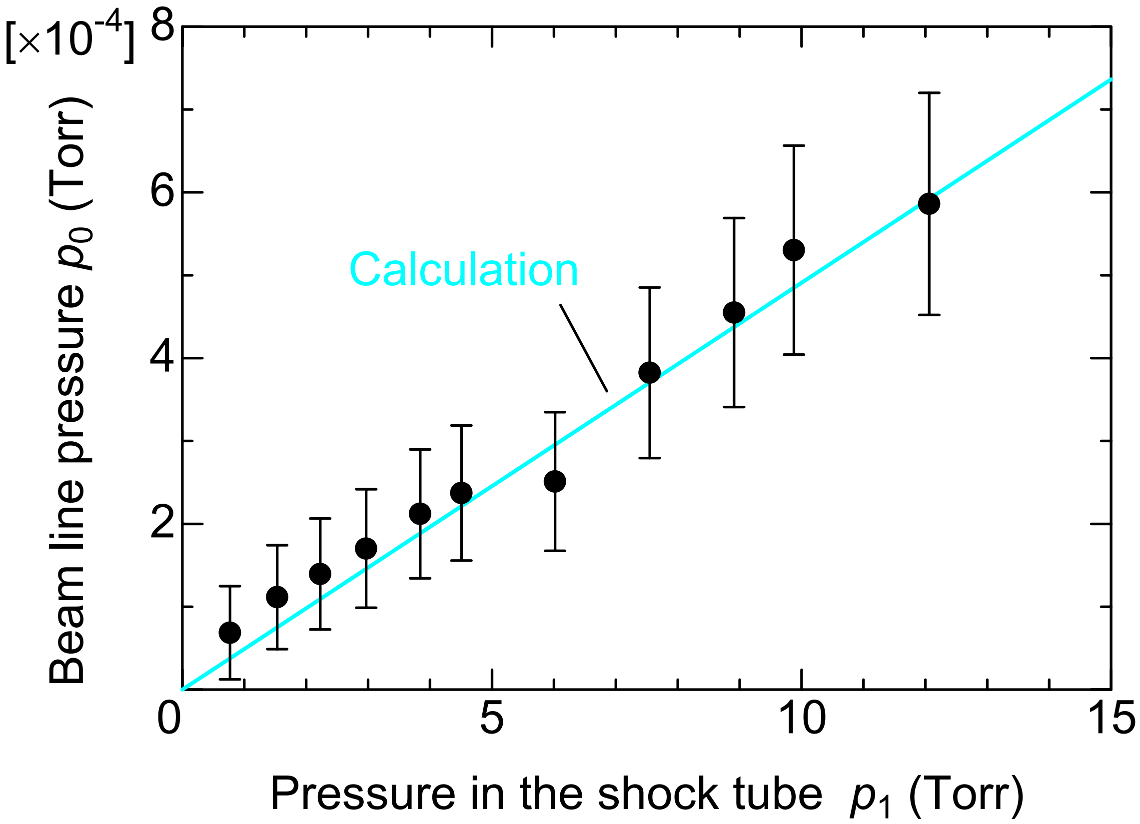
- Relationship between the tube pressure p_1 and the chamber pressure p_0 was investigated for different gas-flow rates.



Test chamber

Measured results were fairly-well reproduced by a simple calculation assuming molecular flow.

- Experimental result using He gas:
  - ϕ100 μm aperture < ≈ mean free path of He gas molecules (≈ 150 μm)
  - Solid line: calculation using molecular-flow conductance of a “thin” small aperture



$$F = C(p_1 - p_0)$$

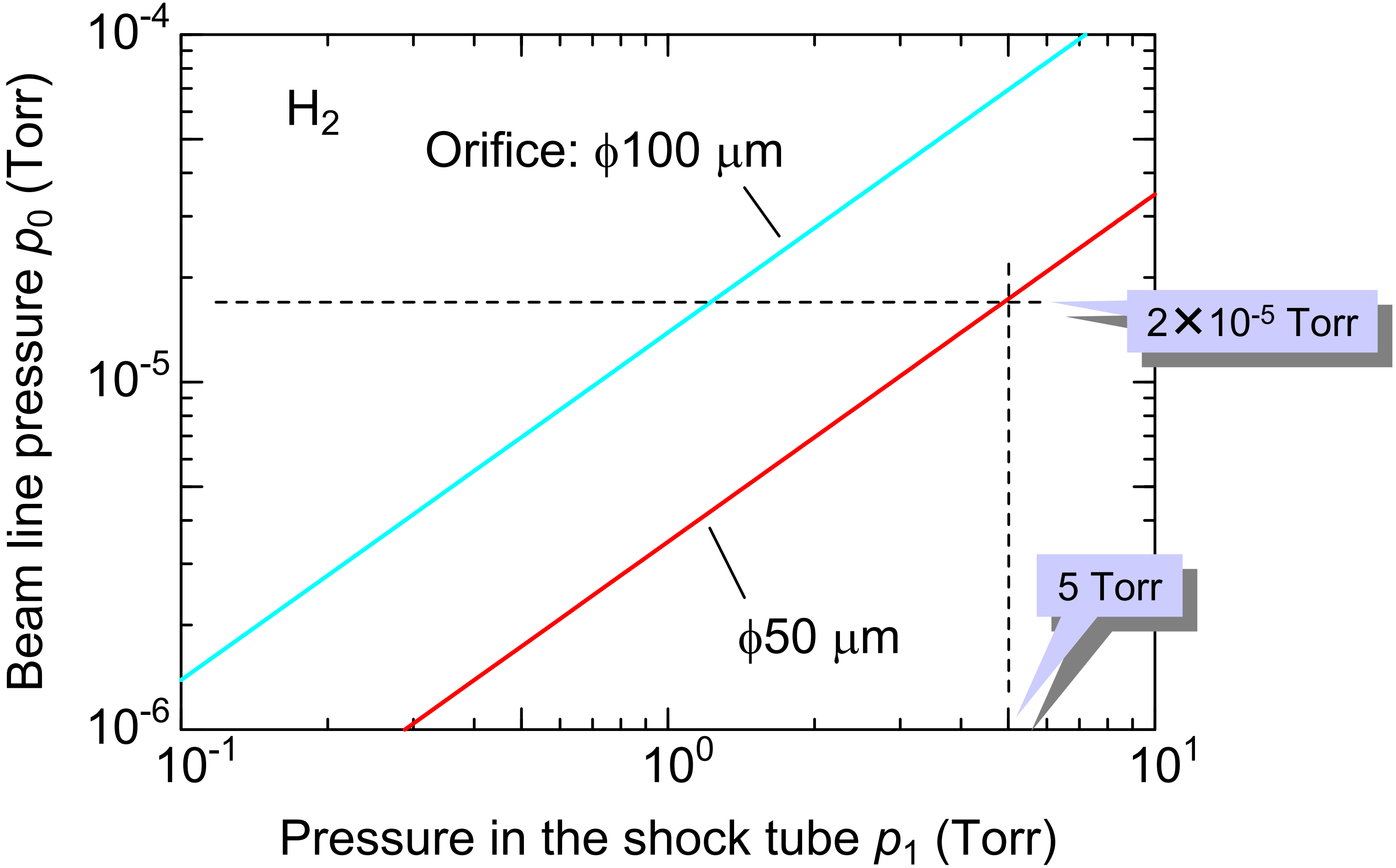
$$C = \frac{62.5}{\sqrt{M}} A$$

$$p_0 = \frac{F}{S}$$

F : flow rate
C : conductance (l/s)
A : aperture area (cm^2)
M : gas molecular weight
S : pumping speed of TMP

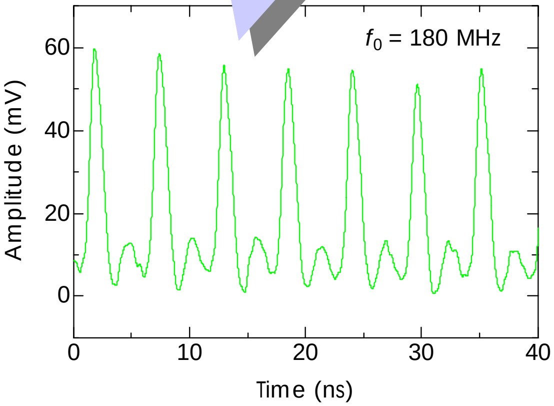
If the orifice diameter is further reduced, the beam line pressure can be as low as ≈ 10^{-5} Torr.

- Beam line pressure p_0 expected for operations with H_2 gas:



Si surface-barrier detector (SSD) was used to measure very low intensity beams through very small apertures.

- MCPs for TOF measurements:
  - High time resolution (< ns)
  - Sensitive to “beam current”, not to particle energy
  - Single-particle detection efficiency < 100%
  - Very sensitive to surface conditions
  - Expensive

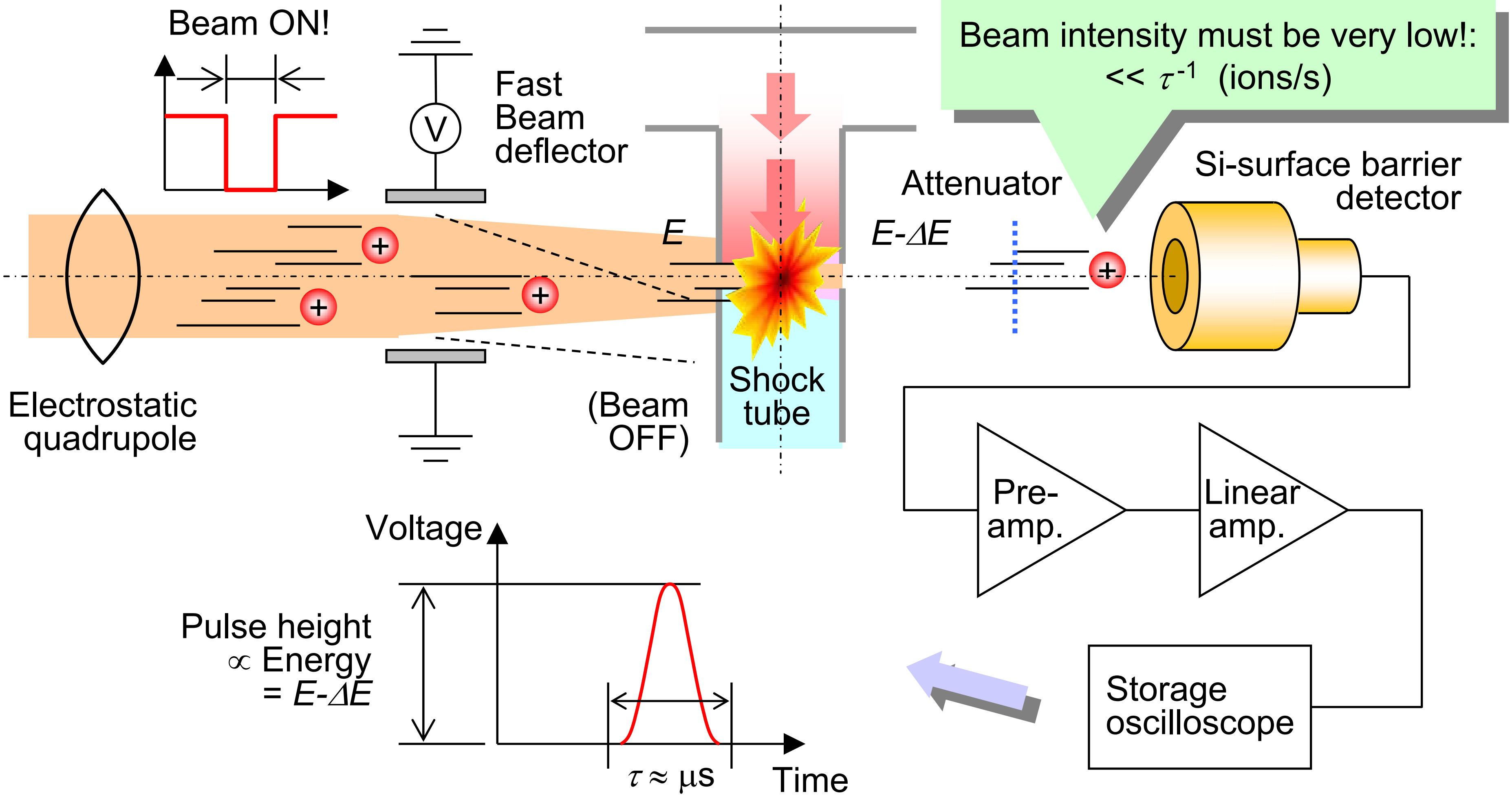


Typical time signal of a bunched beam measured by an MCP

- Direct energy measurement by SSDs:
  - Energy-sensitive, single-particle detection
  - 100% detection efficiency
  - Much more robust than MCPs
  - Low time resolution (≈ μs)
  - Unable to use for high intensity beam

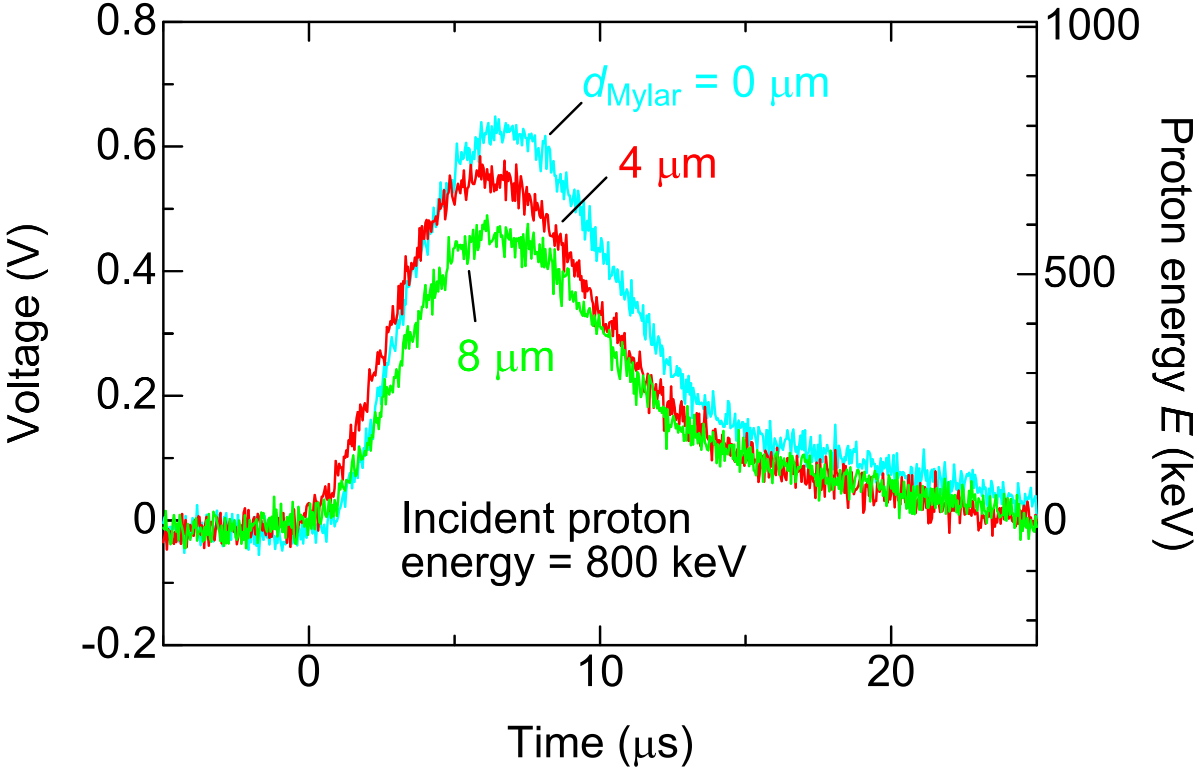
For time-resolved measurements, the SSD has to be used in combination with a fast beam deflector.

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



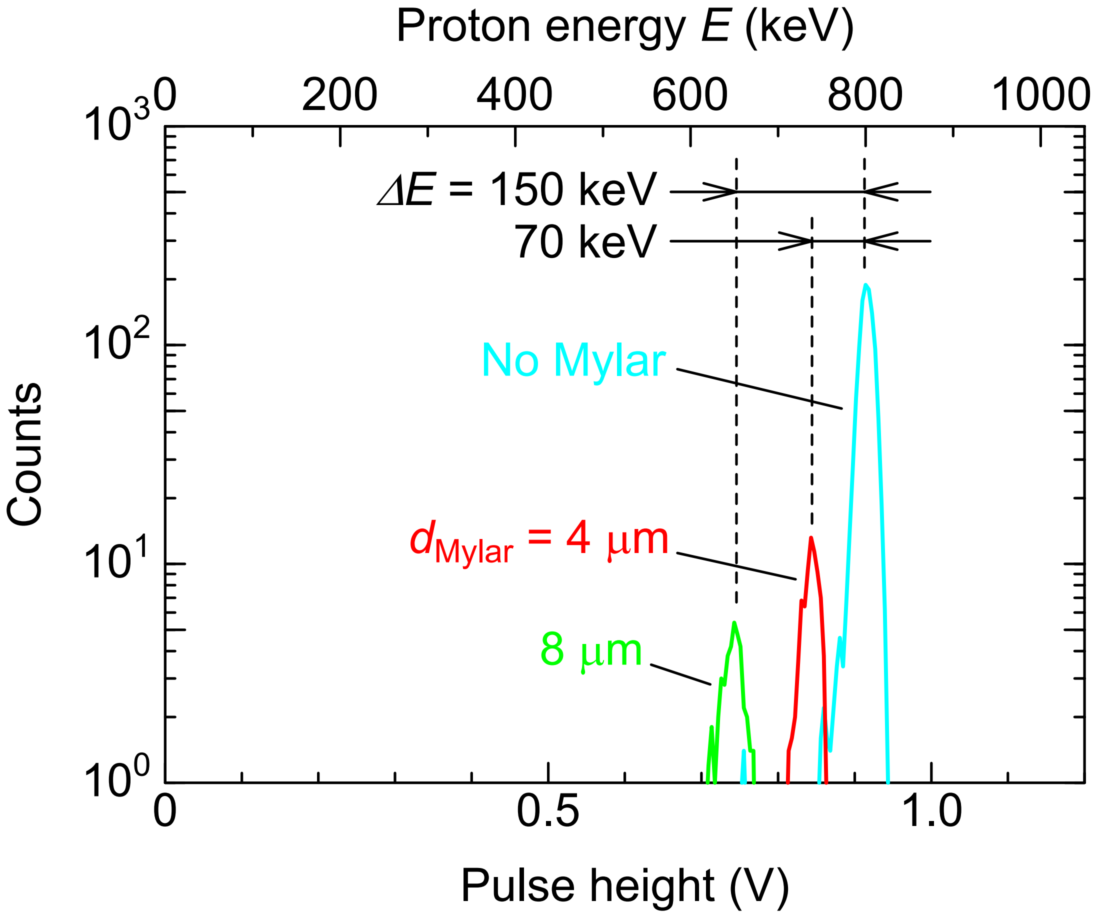
Energy loss of each single projectile can be evaluated by measuring the height of each pulse from the detector.

- SSD output waveforms for measurements with Mylar^{TM} foil targets:
  - Projectile: 800 keV-protons through two apertures
  - Very low intensity (≈ 10^3 ions/s) beam through the apertures
  - Fast beam deflector not yet in operation



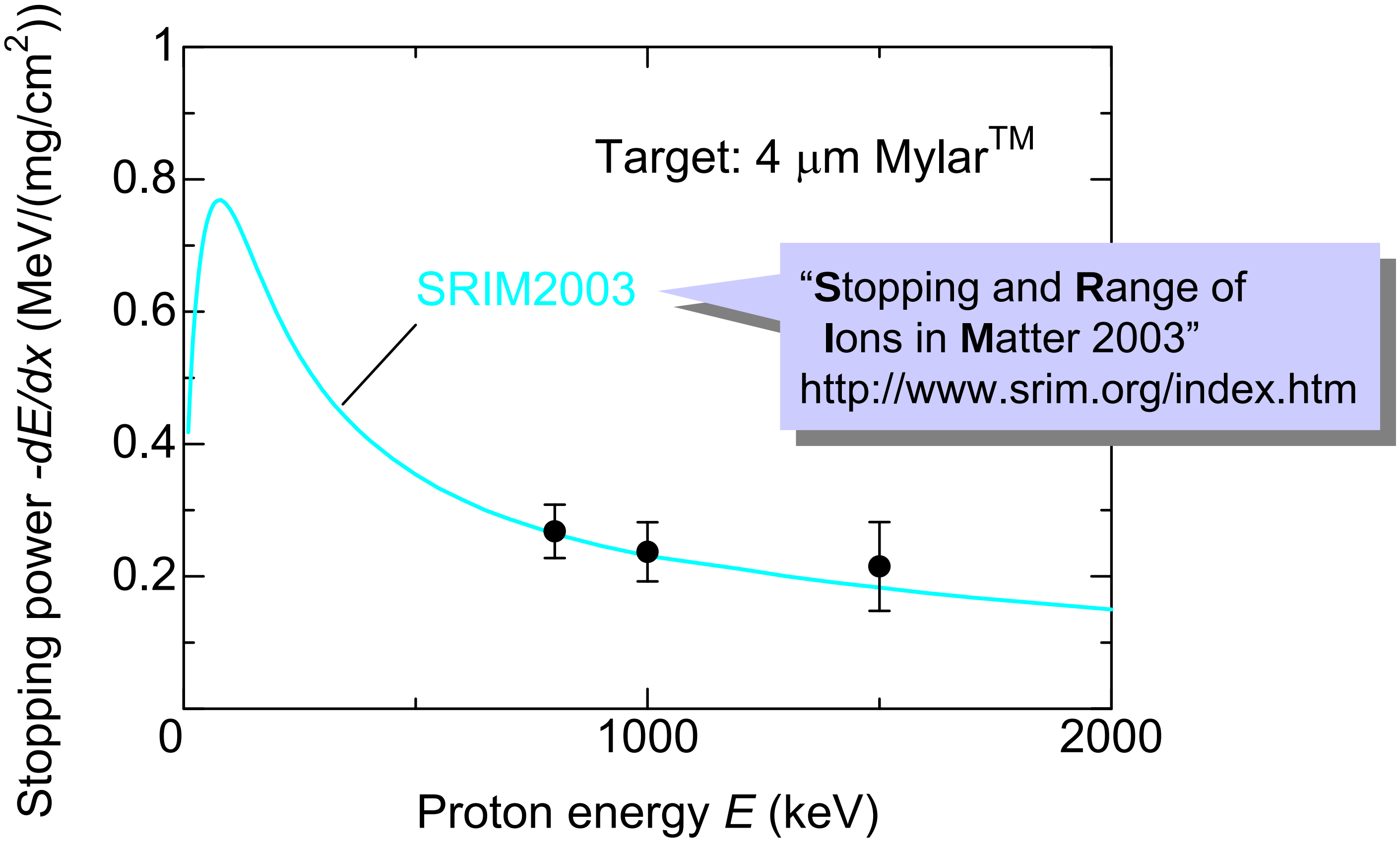
The statistical energy resolution is enough to evaluate the projectile energy loss.

- Pulse height distribution for many shots (= energy spectrum):
  - Beam current was kept as low as possible to prevent “pile up” of pulses.



The measured energy loss was in a good agreement with calculations using a Monte-Carlo code.

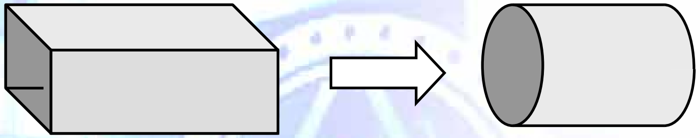
- Comparison between the experimental and calculated results:
  - Circles : measurement with SSD
  - Solid line : Monte-Carlo calculation using “SRIM2003”



“**S**topping and **R**ange of **I**ons in **M**atter 2003”
http://www.srim.org/index.htm

Summary and outlook

- Shock speed must be increased further by +50% ($M = 24 \rightarrow 36$):
  - Higher discharge energy
  - High-voltage switch with lower impedance
  - Square tube → cylindrical tube to reduce friction losses (?)



- Differentially-pumped gas cell works well:
  - Aperture should be further reduced from ϕ100 μm to ϕ50 μm.
  - Alignment of two apertures will be tough!
- Projectile energy loss was successfully measured by an SSD:
  - Low-intensity beams through small apertures can be measured.
  - Fast deflector is necessary for time resolved measurement. (R&D under way.)
  - Noise due to plasma emission (?)
- Atomic physics issues:
  - Projectile charge q (effective charge) ≈ averaged charge?
  - Charge-changing reactions of slow ions in partially-ionized plasmas