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

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Bldg. 47 Conference Room
Lawrence Berkeley National Laboratory
Berkeley, CA USA

WDM experiments at Tokyo Tech (II):

“Time-resolved single-ion spectrometry for beam-plasma interaction experiments”

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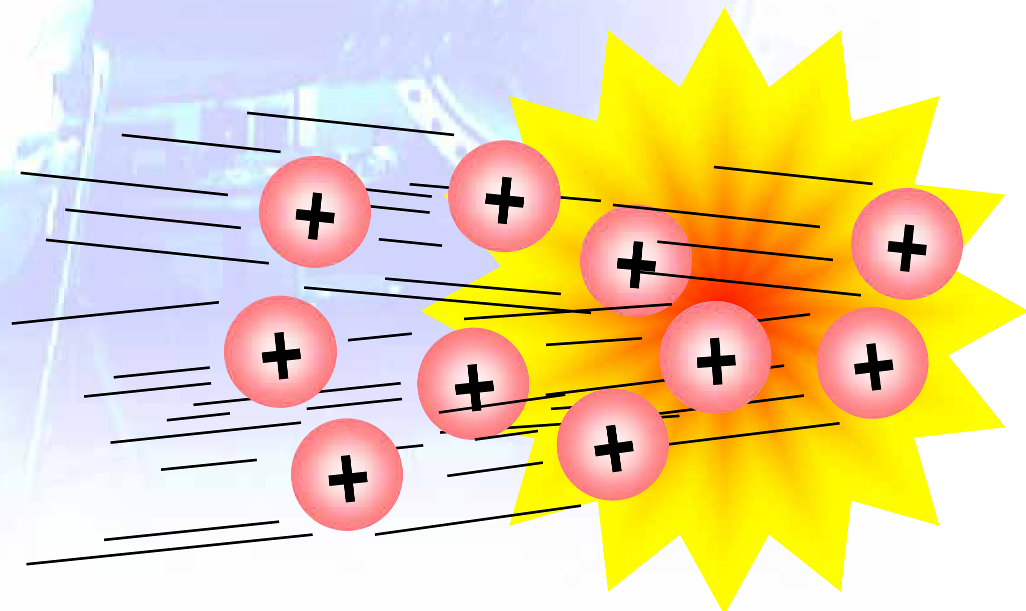


Differential pumping system is needed to introduce heavy projectiles into the shock-driven plasma target.

- Requirements for the target:
  - High target density (~10^{18} cm^{-3}) } for non-linear stopping regime
  - Low projectile velocity (~ 10 keV/u) } for non-linear stopping regime
  - $\Delta E/E$ ~ 10% for well-defined interaction energy

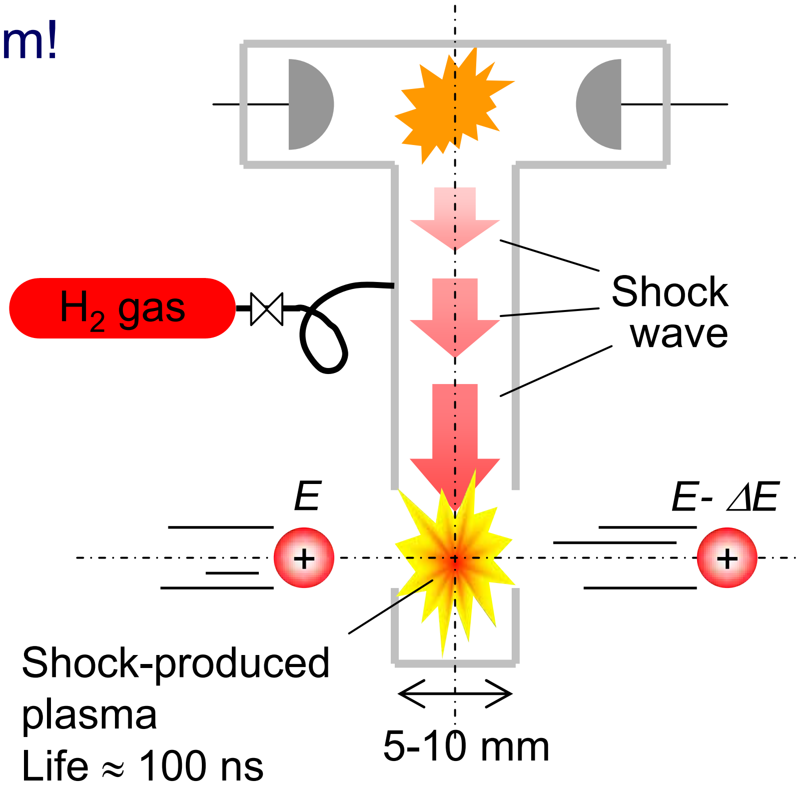
  → Target must be as thin as $\Delta x \approx$ 5-10 mm!
- The tube has to be filled with the material gas (H_2) before ignition.
  - cf. Laser-produced plasma target
- Confinement of target material by:
  - Thin foil window ?

    → Low energy (~ 10 keV/u) projectiles can stop even by a 1-μm plastic film!
  - Fast valves ?

    → Requirement:
    ~~Valve speed > sound speed~~
    ~~Valve thickness << target thickness~~

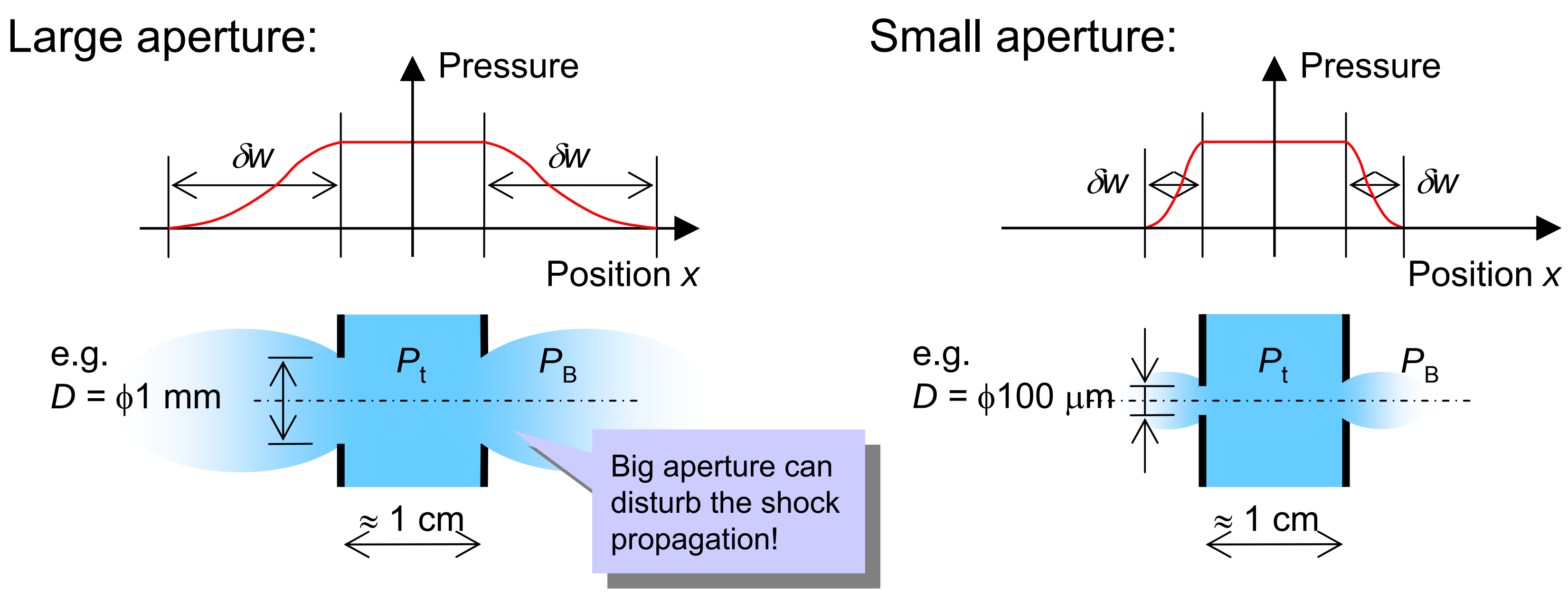
∝ Nonlinearity

$$\gamma \equiv \frac{\sqrt{3q}\,\Gamma^{3/2}}{\left\{1+\left(v_{proj}/v_{th}\right)^2\right\}^{3/2}}$$



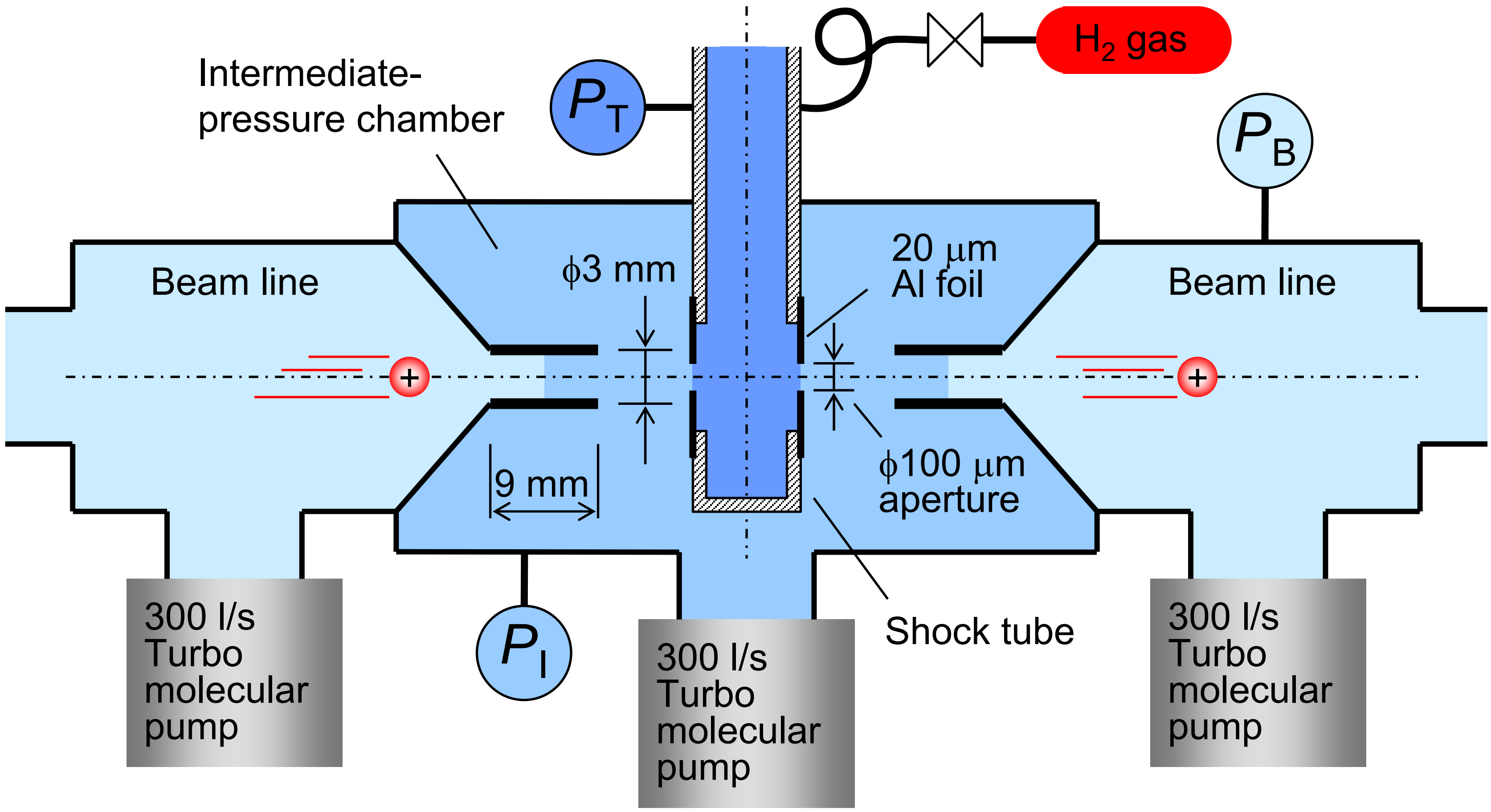
To establish a well-defined target thickness, very small beam apertures are needed.

- Pressure requirements:
  - Shock tube initial pressure $P_t \approx 5$ Torr
  - Beam line pressure $P_B < 10^{-7}$-10^{-6} Torr (to avoid charge exchange)
- Differential pumping system with very small apertures:
  - Target thickness ($\approx$ 1 cm) must be >> relaxation length δw.
  - $\delta w \approx$ aperture diameter D $\therefore$ D must be $< \approx \phi 100\ \mu$m!



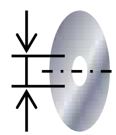
A multi-stage differentially-pumped target was developed for the interaction experiment.

- Relationship between the tube pressure P_T, intermediate pressure P_I and beam line pressure P_B was investigated for different gas-flow rates.



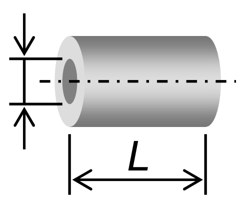
The differential pumping system successfully confined the hydrogen gas in the shock tube as expected.

- Experimental result using H_2 gas:
  - ϕ100 μm aperture < ≈ mean free path of H_2 gas molecules (≈ 20 μm)
- Measured results were fairly-well reproduced by a simple calculation using molecular-flow conductance C (l/s):
  - Thin aperture: ϕD



$$C = 2.86\sqrt{\frac{T}{M}}D^2$$

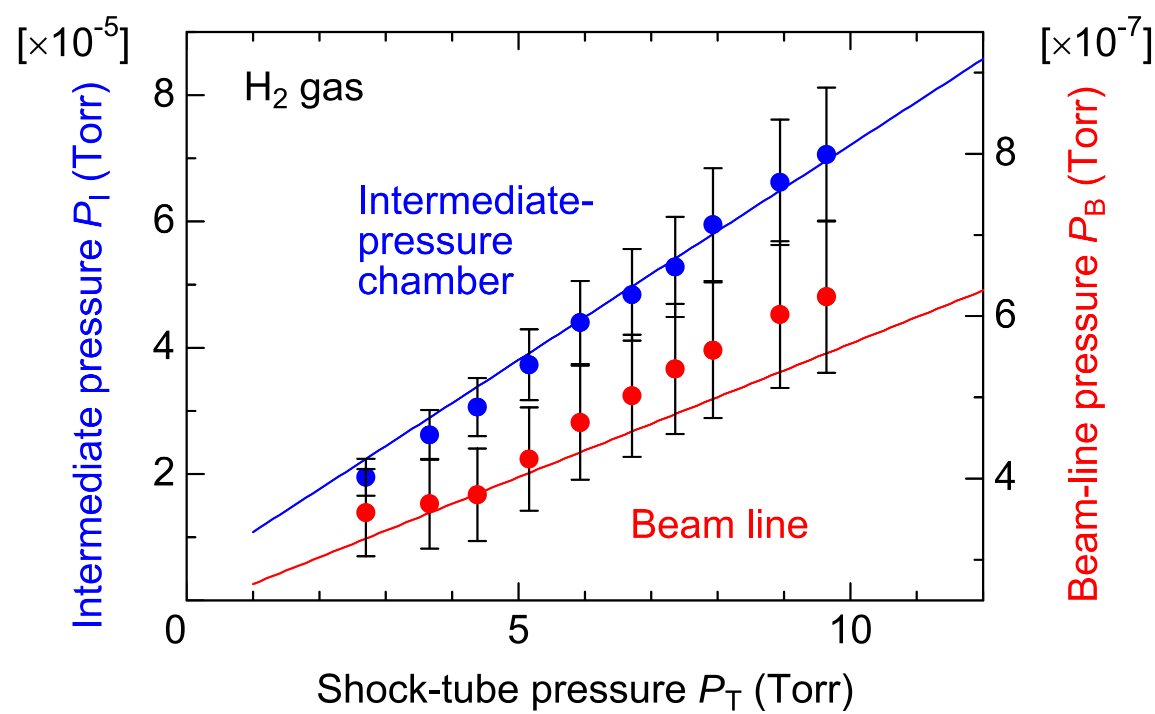
  - Tube:



$$C = 3.81\sqrt{\frac{T}{M}}\frac{D^3}{L + \frac{4}{3}D}$$

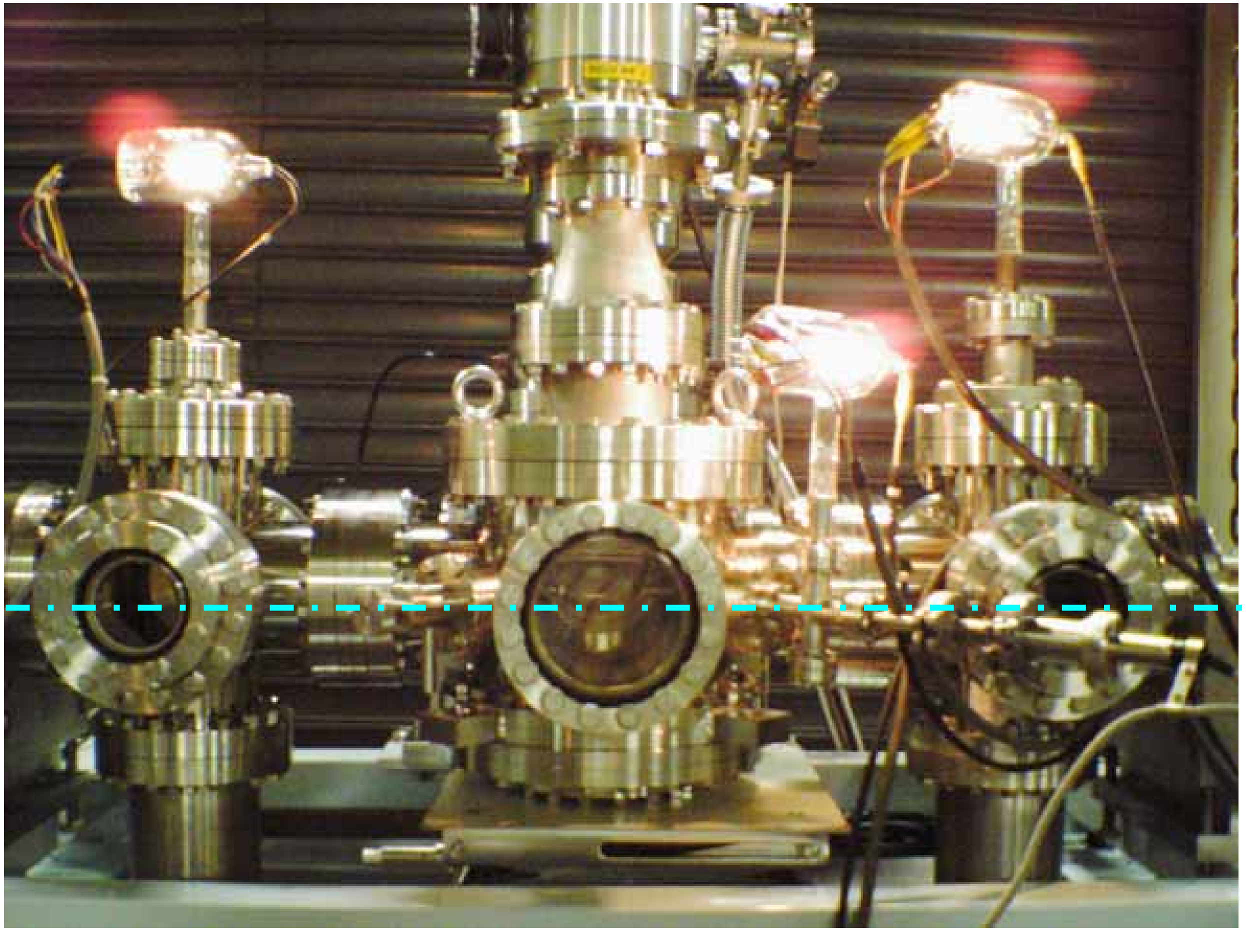
T : temperature (K)

M : gas molecular weight



The target system is being installed in the beam line of the Tokyo-Tech tandem accelerator.

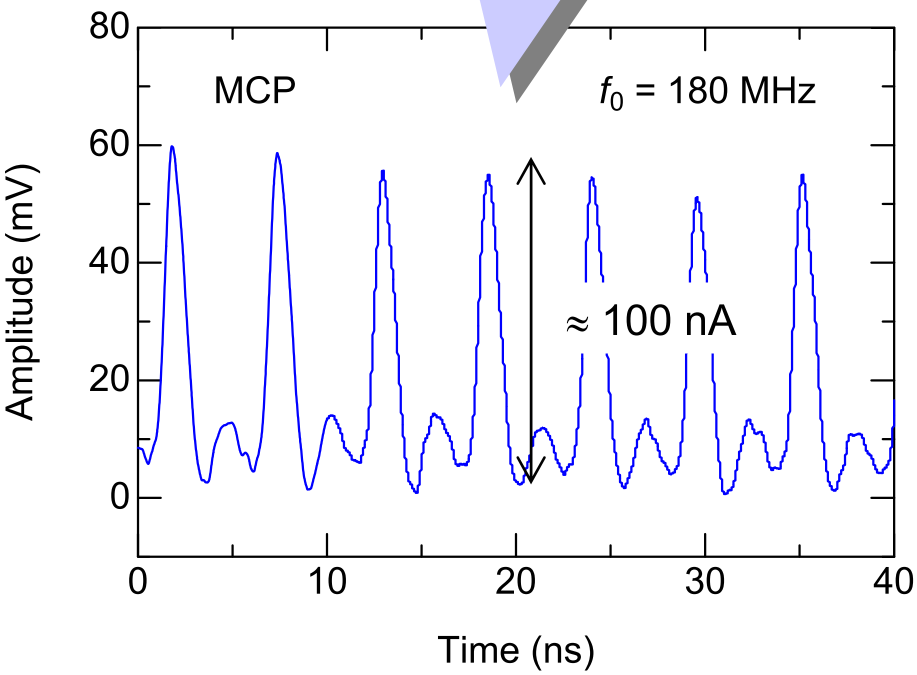
- The whole system is fixed on a movable base (frame) for precise alignment.



In previous measurements with a laser-plasma target, a TOF method using an MCP detector was applied.

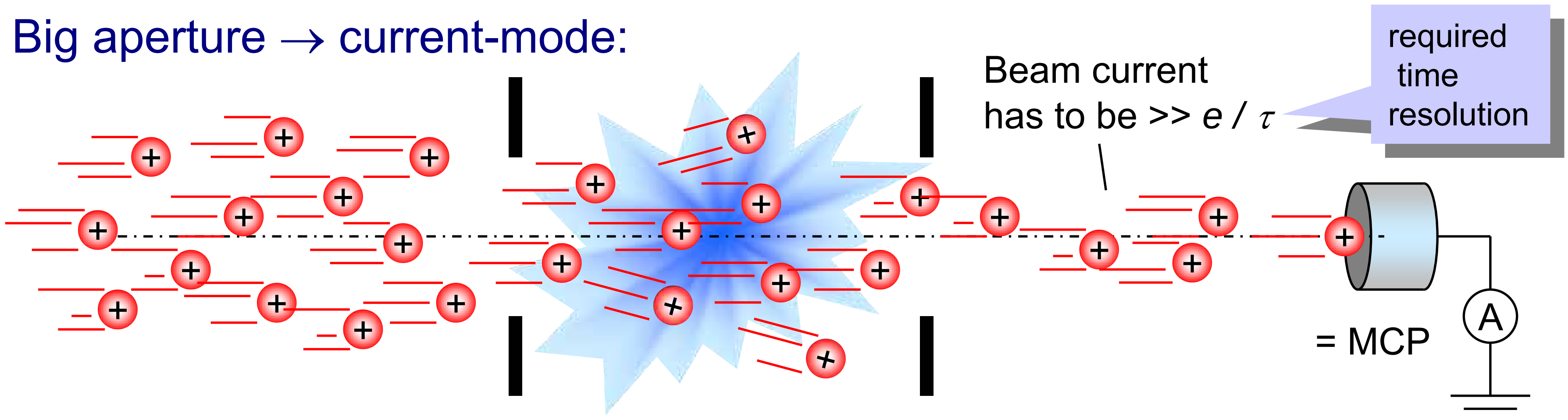
- MCPs for TOF (Time Of Flight) measurements:
  - High time resolution (< ns)
  - Sensitive to “beam current”, not to single-particle energy
  - Single-ion detection efficiency < 100%
  - Very sensitive to surface conditions
  - Noisy
  - Expensive

~ 100 nA is required to see clear signals

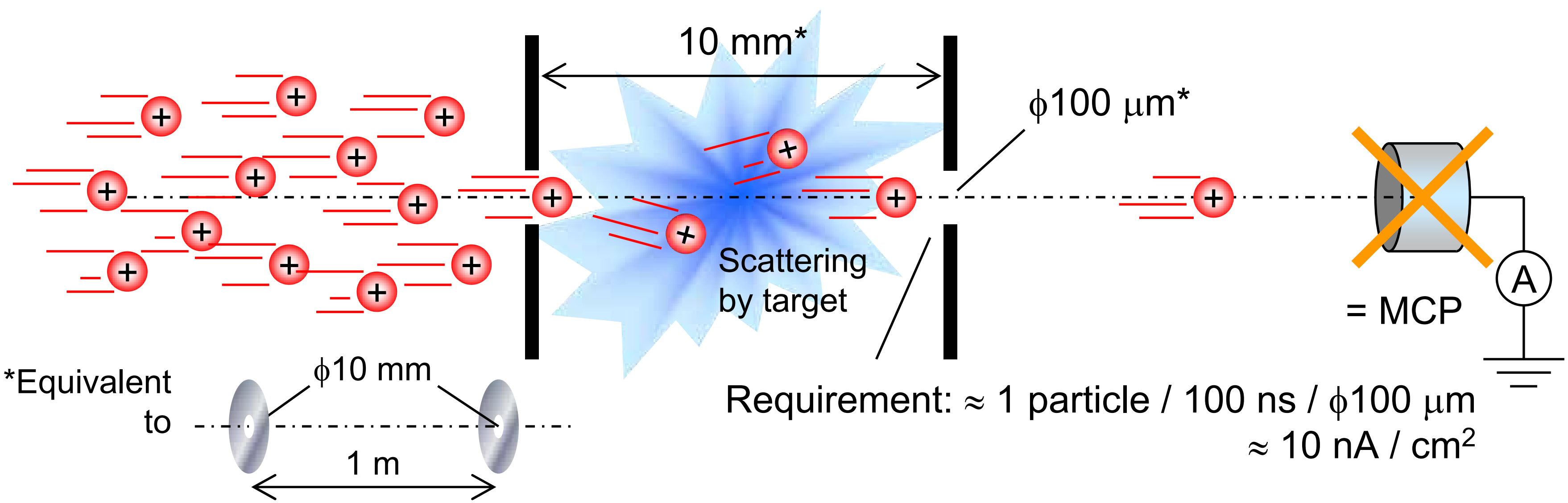


The beam transmission through ϕ100 μm apertures is too small to measure the beam as an electric current.

- Big aperture → current-mode:



- Small aperture → single-particle-mode:

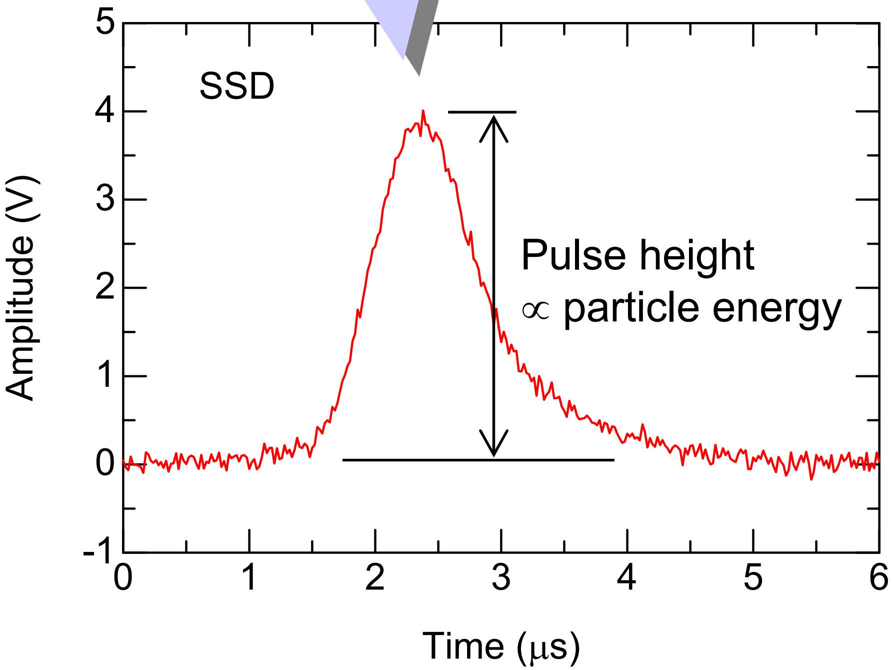


To measure low-intensity beams through small apertures, a Si surface-barrier detector was employed.

- Direct single-ion energy measurement by a Si surface-barrier semiconductor detector (SSD):
  - Energy-sensitive, single-particle detection
  - 100% detection efficiency
  - Much more robust than MCPs
  - Low time resolution (~ 1 μs)
  - No noise

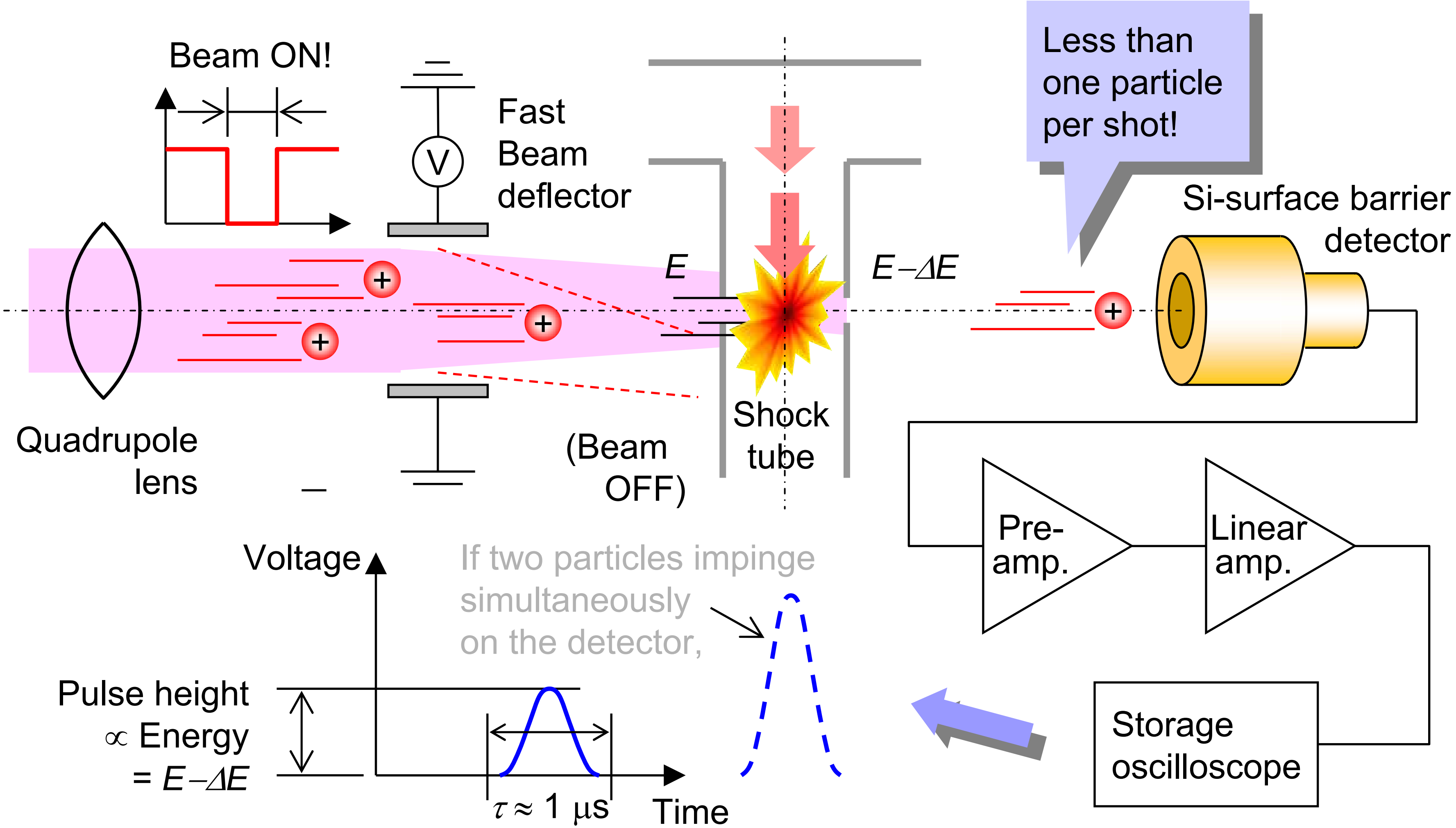
Active area: 50 mm^2
Sensitive depth: 300 μm
Surface Au thickness: < 40 μg/cm^2

Signal of an 800-keV single ^{16}O ion



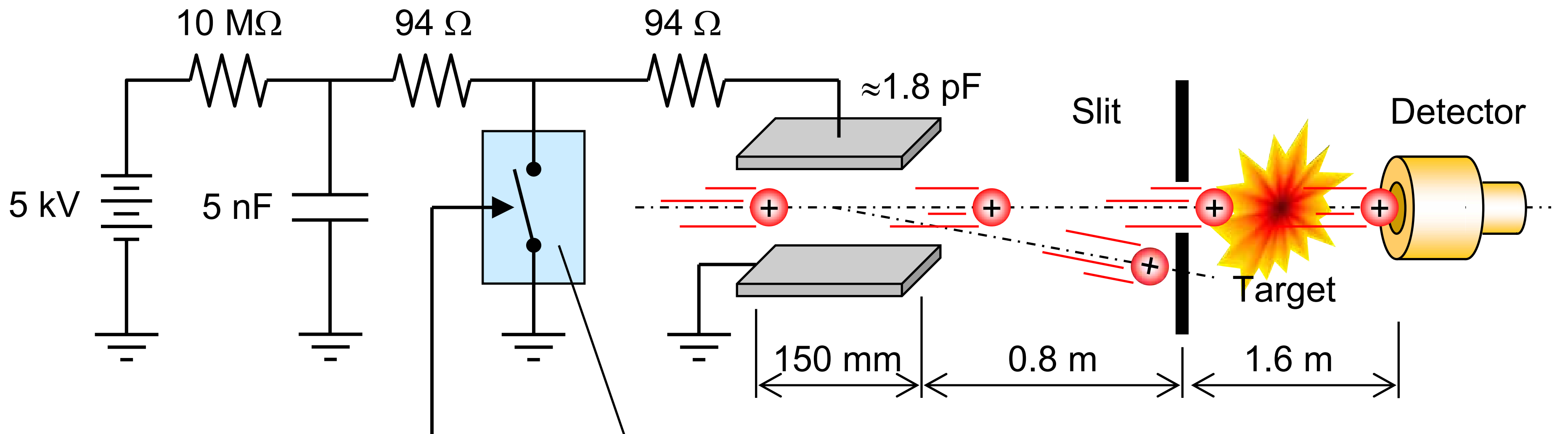
For time-resolved measurements, the SSD has to be used in combination with a fast beam deflector.

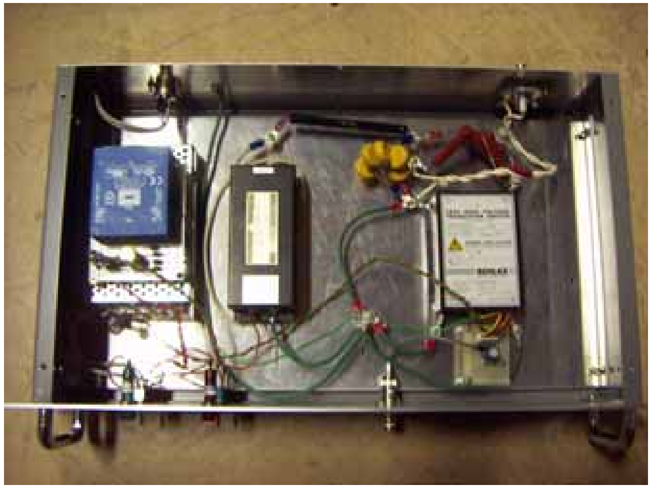
- Many shots are needed to detect one particle:



A pair of beam deflection plates and a beam slit were used to construct the fast beam kicker.

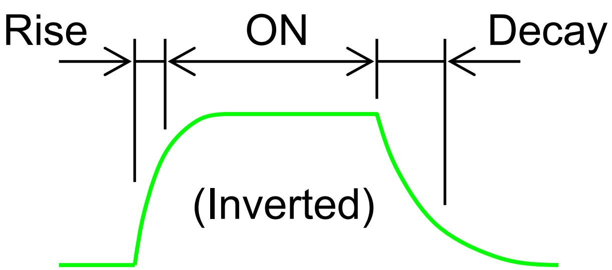
- A solid-state fast high-voltage switch was employed as the switching device:

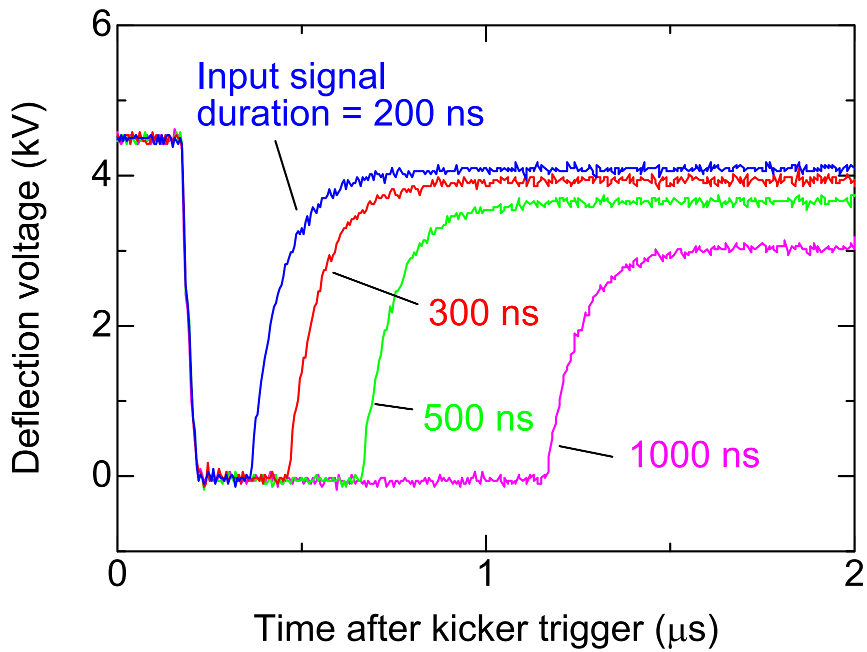


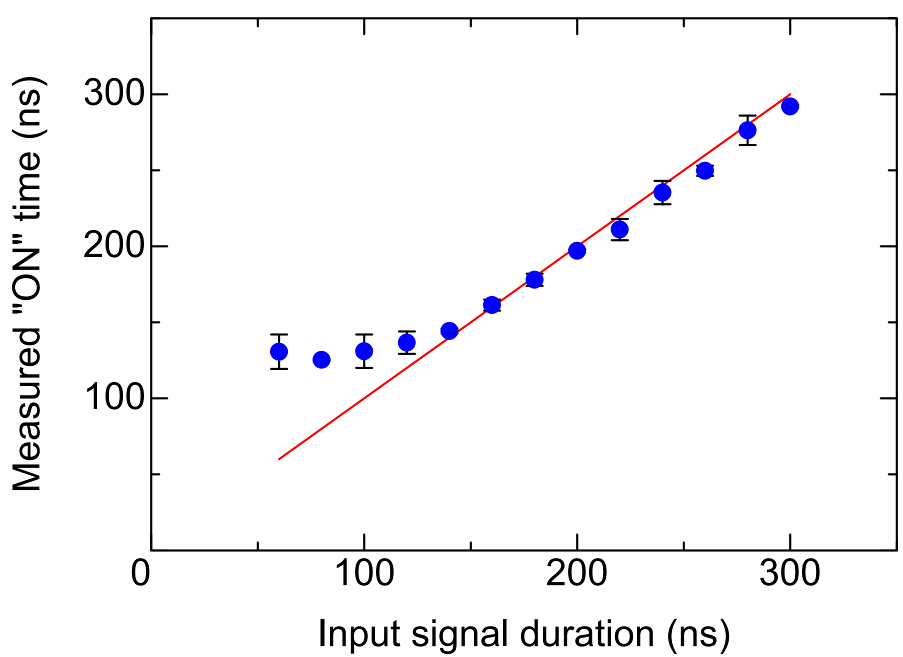


So far the minimum ON-time of the kicker is limited to ≈120 ns owing to the performance of the switch.

- Measured deflection voltage waveforms of the fast beam kicker:
  - Rise time ≈ 40 ns, decay time ≈ 200 ns
  - Measured ON-time = input pulse duration, down to ≈ 120 ns
  - The minimum ON-time of the switch in the catalog is 60 ns!

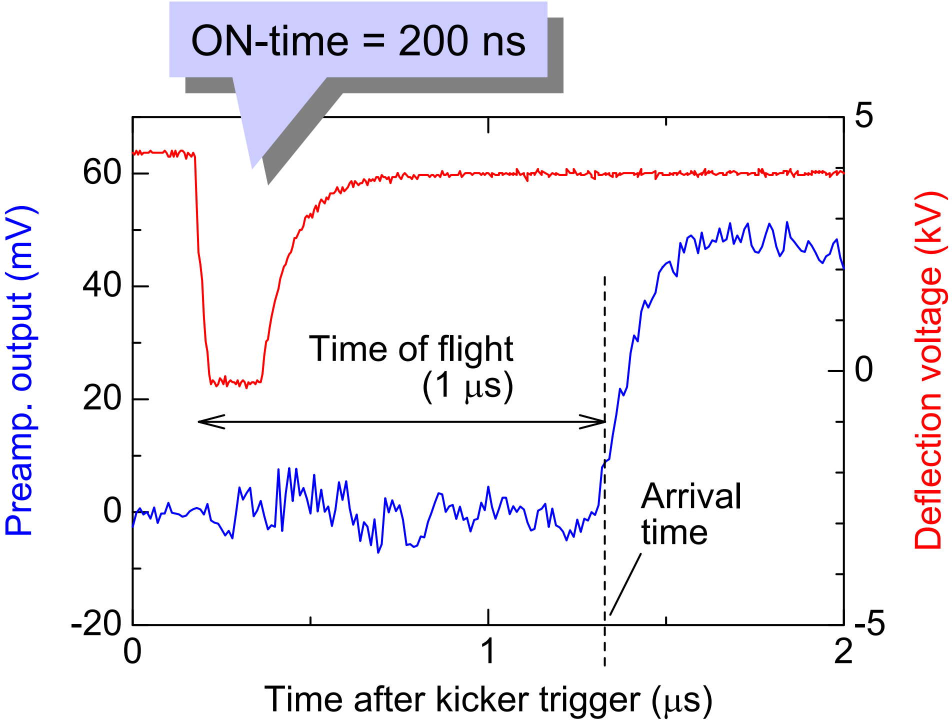


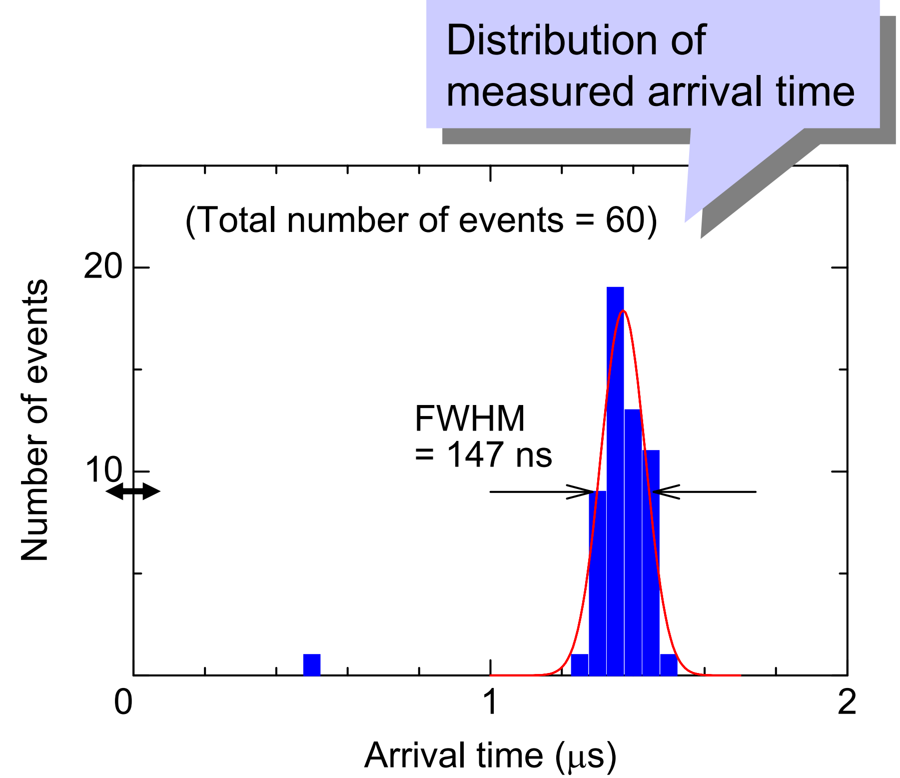




Synchronization were confirmed by measuring the distribution of the arrival time of ions.

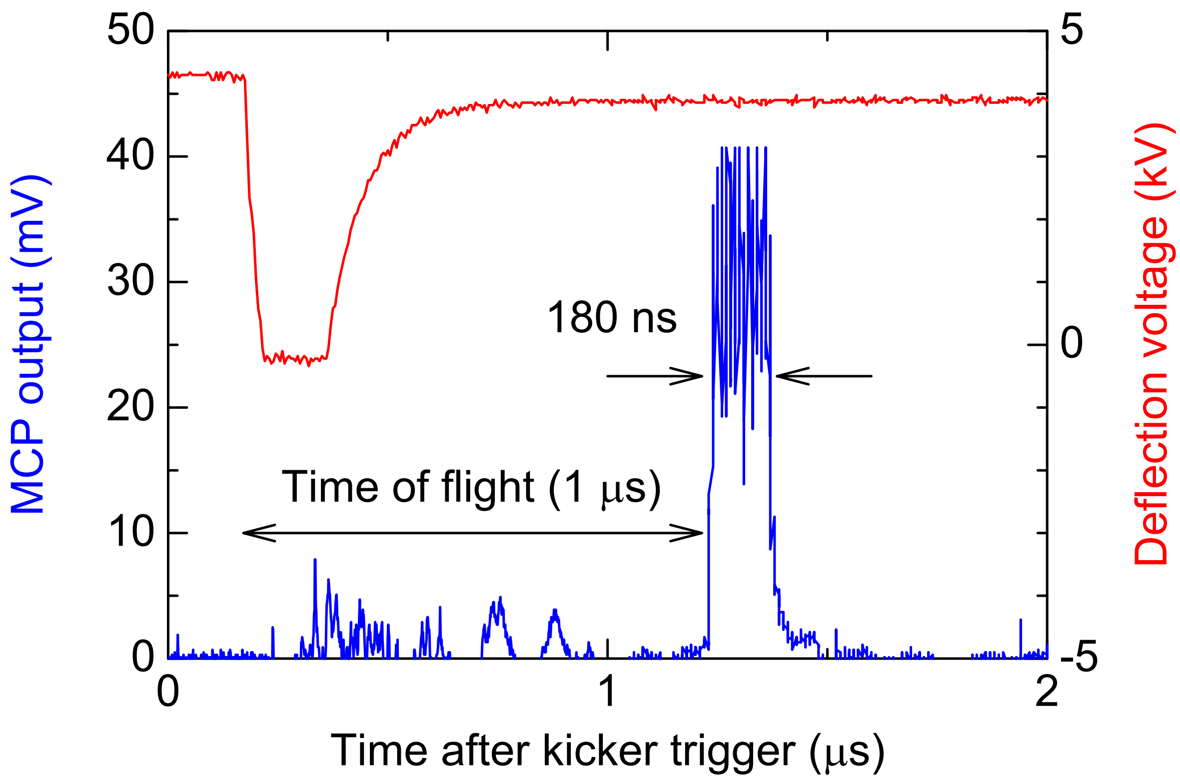
- The beam intensity was adjusted so that the count rate were less than one particle per shot.
  - The arrival time of 50 keV/u ^{79}Br projectile was directly measured using the “T-out”-signal* of the preamplifier. *Short rise time, but no information of particle energy
  - 90% of the all particles were detected during the 200 ns.





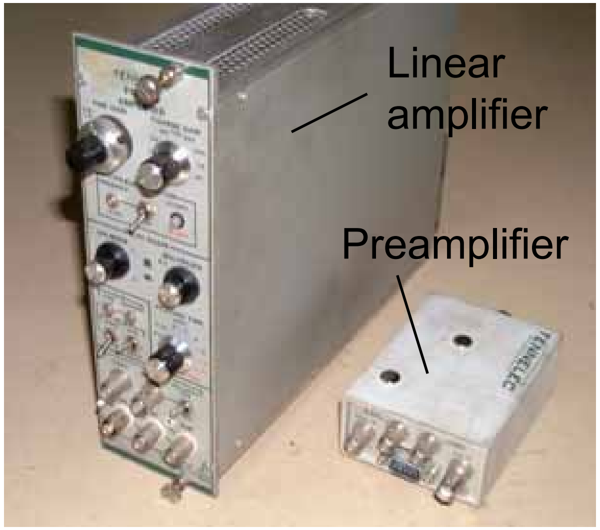
Duration of the ON-time of the kicker was cross-checked by measurement using an MCP detector.

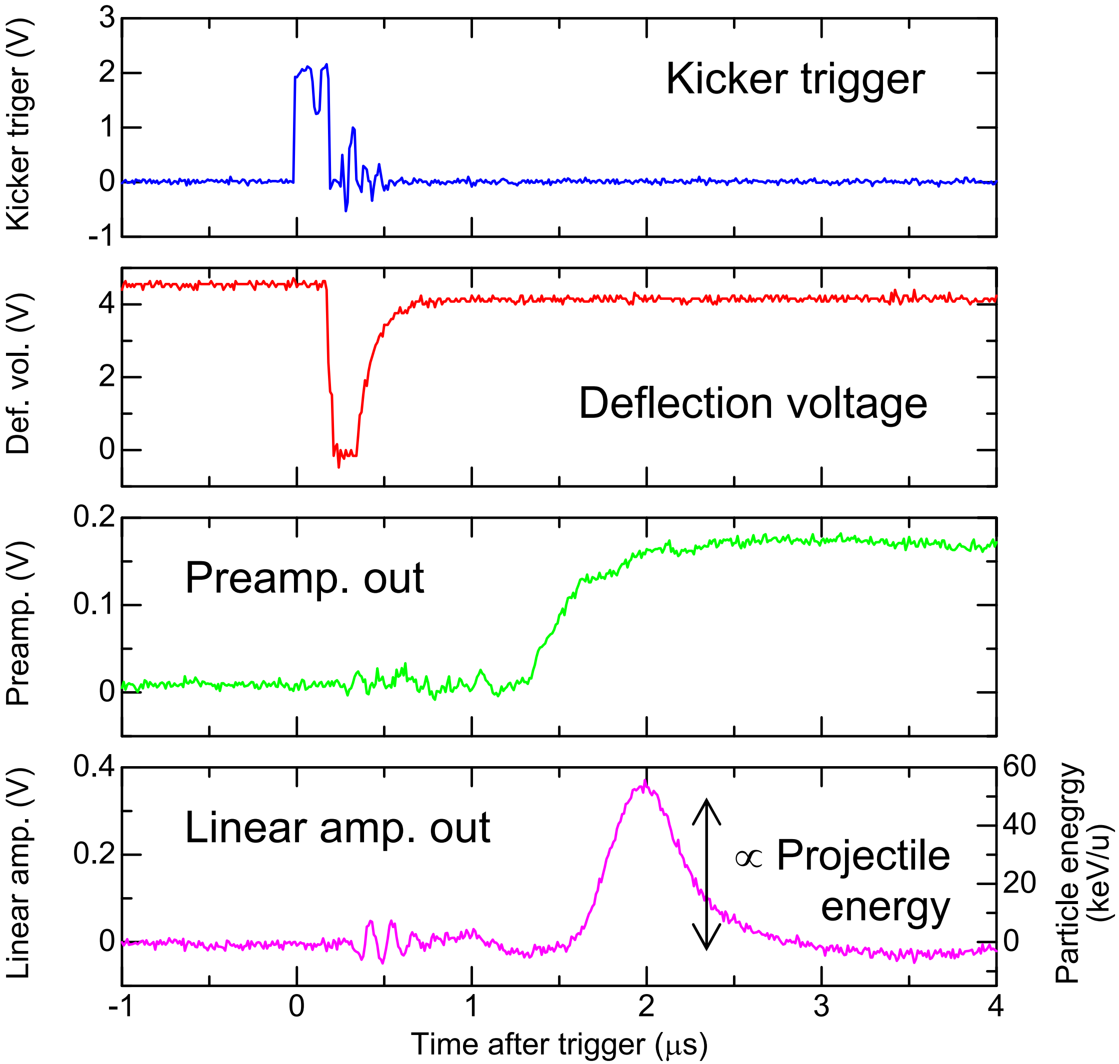
- Current waveform of the 50 kev/u ^{79}Br pulsed beam measured by an MCP:
  - The target aperture was removed so that ~10^3 ions can impinge on the detector per shot.
  - Measured pulse duration = 180 ns ≈ ON-time of the deflection voltage = 200 ns



Energy of projectiles behind the target is evaluated from the pulse height of the linear amplifier signal.

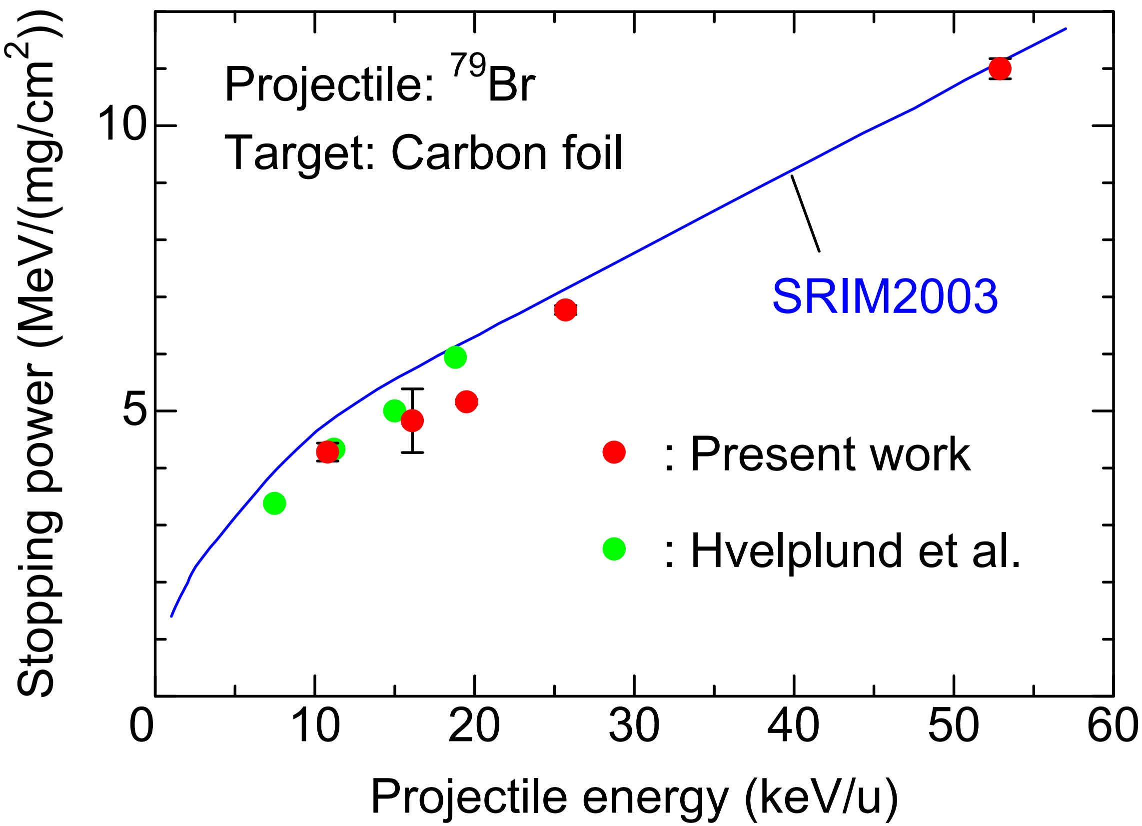
- Synchronization scheme between the beam injection by the kicker and detection of single ions:
  - Projectile: 50-keV/u ^{79}Br
  - Aperture size: ϕ1 mm
  - No target was used. (only apertures)





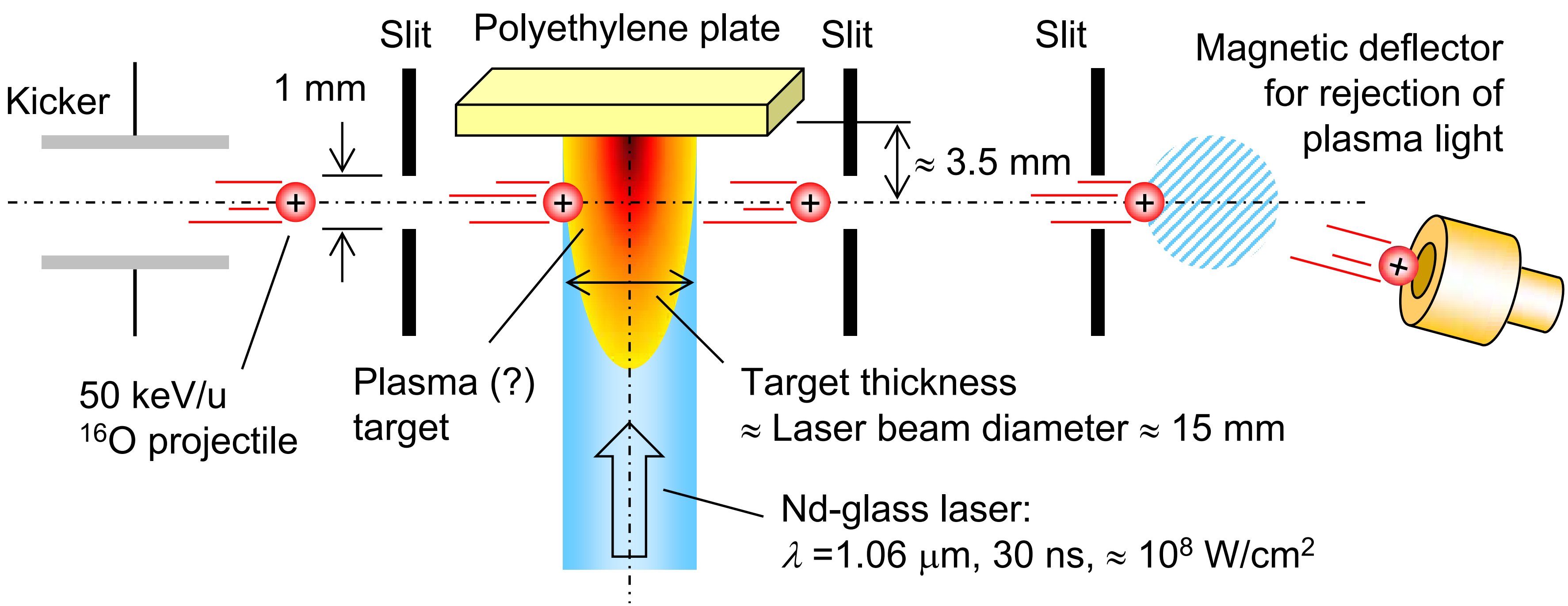
For static targets, the measured energy loss was in good agreement with other data.

- Comparison between the experimental results and other data:
  - Projectile: 10-50 keV/u ^{79}Br
  - Target: 10 μg/cm^2 carbon-foil



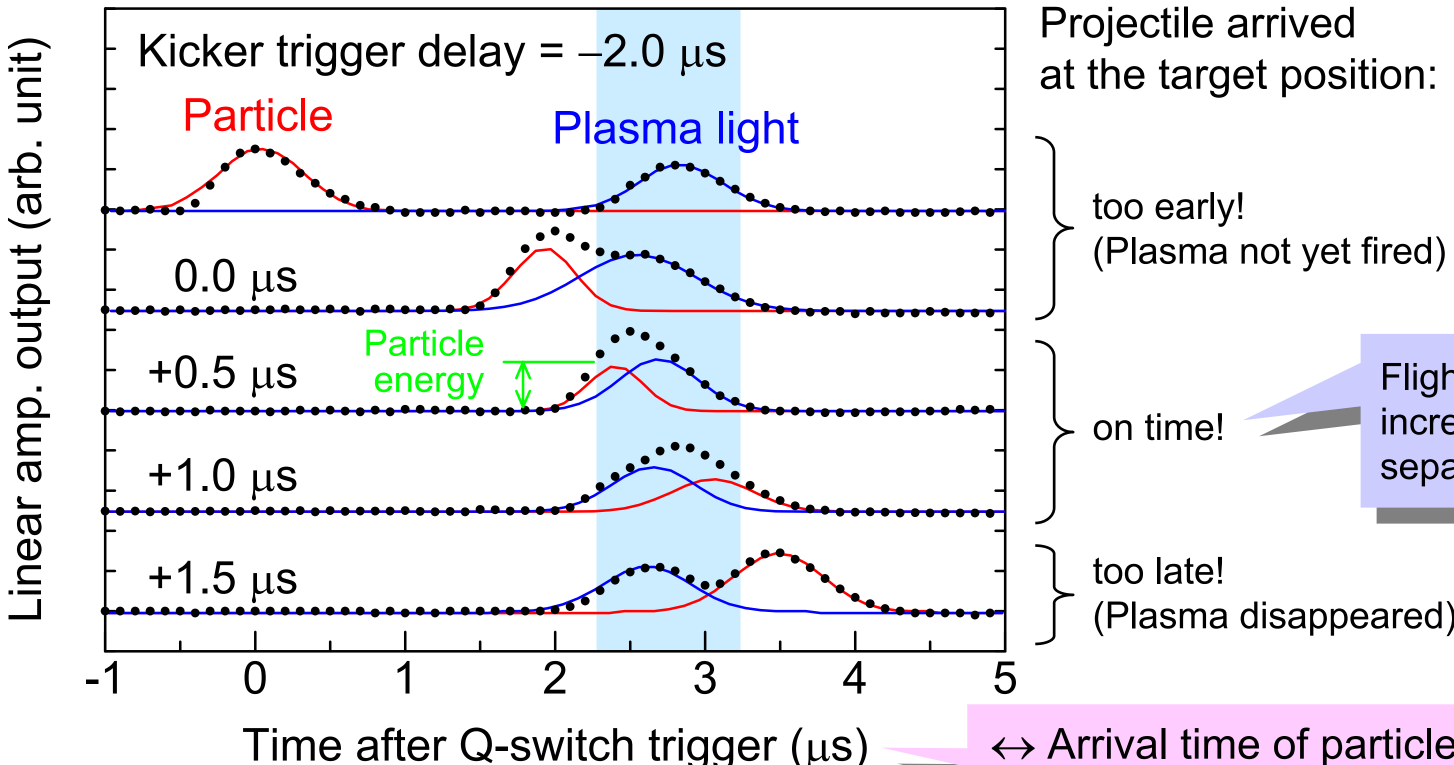
To test the timing performance of the system, projectile energy loss in a laser-plasma target was measured.

- The shock-driven plasma target and the differential pumping system is NOT YET installed in the beam line!
- As a substitute, a laser-plasma target was prepared as a short-lived target:
  - A polyethylene plate was irradiated with a pulsed laser to produce a plasma blow.
  - Diagnostic measurement of the plasma was not performed.



By using the difference of the arrival time, signals of the plasma light and the particle can be separated.

- Waveforms from the linear amplifier were fitted with two Gaussian functions:
  - Projectile: 50 keV/u ^{79}Br ions
  - Plasma light was not completely rejected by the dipole magnet
  - Particle energy was extracted from the height of particle component.



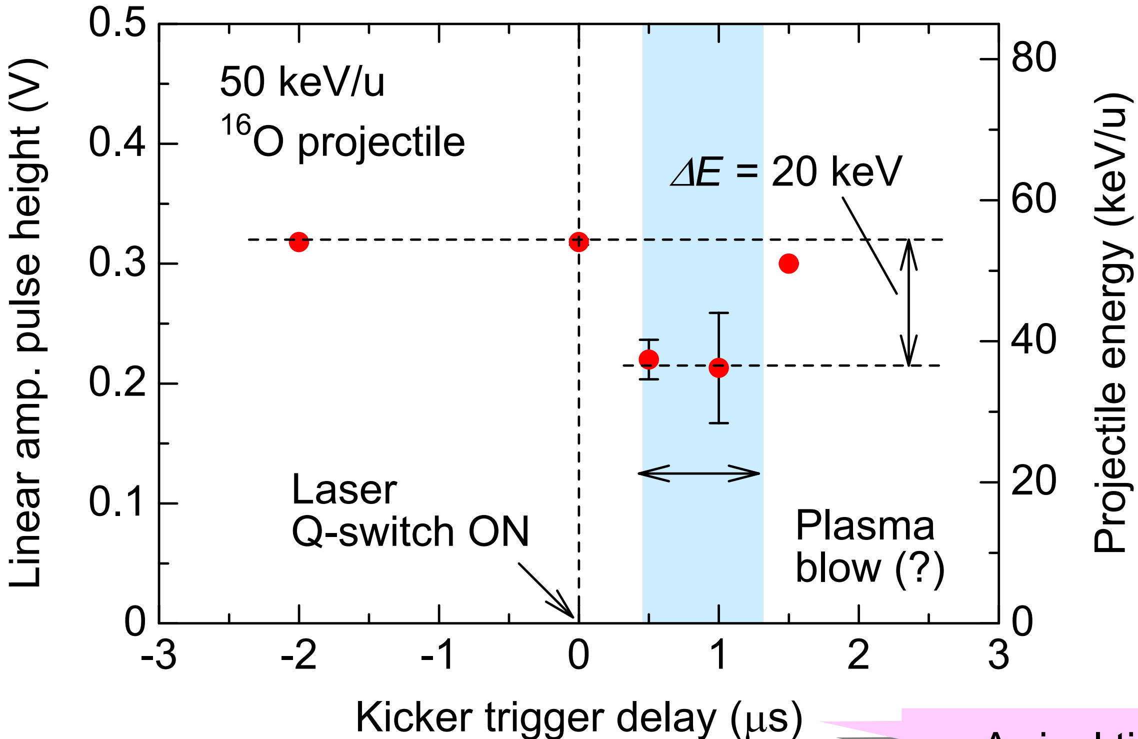
Flight length should be increased for complete separation.

↔ Arrival time of particle

We have succeeded in time-resolved measurement of projectile stopping power in the short-lived plasma blow.

- Preliminary result on the time-resolved energy loss measurement:
  - Energy loss $\Delta E \approx 20$ keV
  - Target thickness $\Delta x \approx 15$ mm
  - dE/dx(cold $(CH_2)_n$) ≈ 6 MeV/(mg/cm²)

  } → Target atomic density ~ 10^{18} cm^{-3} (?)



↔ Arrival time of particle

Concluding remarks

- The differential pumping system using two small thin apertures successfully confined the hydrogen gas in the shock tube as expected.
- By using a surface-barrier Si semiconductor charged-particle detector, we could measure –*dE/dx* of single ions of 10-50-keV/u ^{79}Br in thin carbon foils with acceptable accuracies.
- We have succeeded in time-resolved measurement of projectile energy loss in a laser plasma with a life of ~100 ns.
- The beam burst duration can be further reduced by employing a faster switch.
- Owing to the poor alignment performance, we have not yet succeeded in particle transport through 100-μm-double apertures.