2004 US-Japan Workshop for Heavy Ion Inertial Fusion
10 - 12 June 2004
Princeton Plasma Physics Laboratory

“Beam Stopping Issues and High Energy Density Physics”

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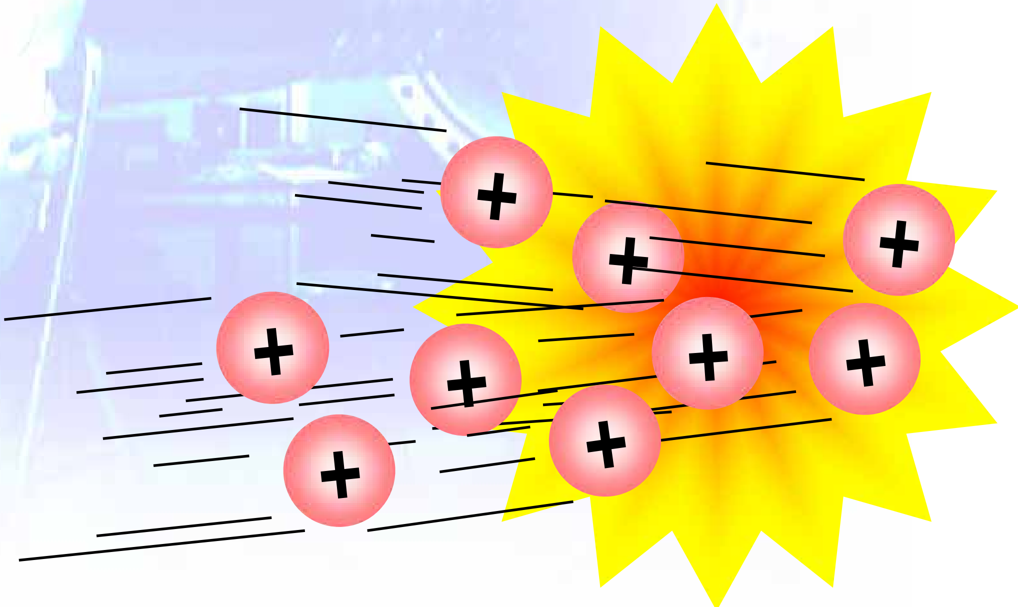
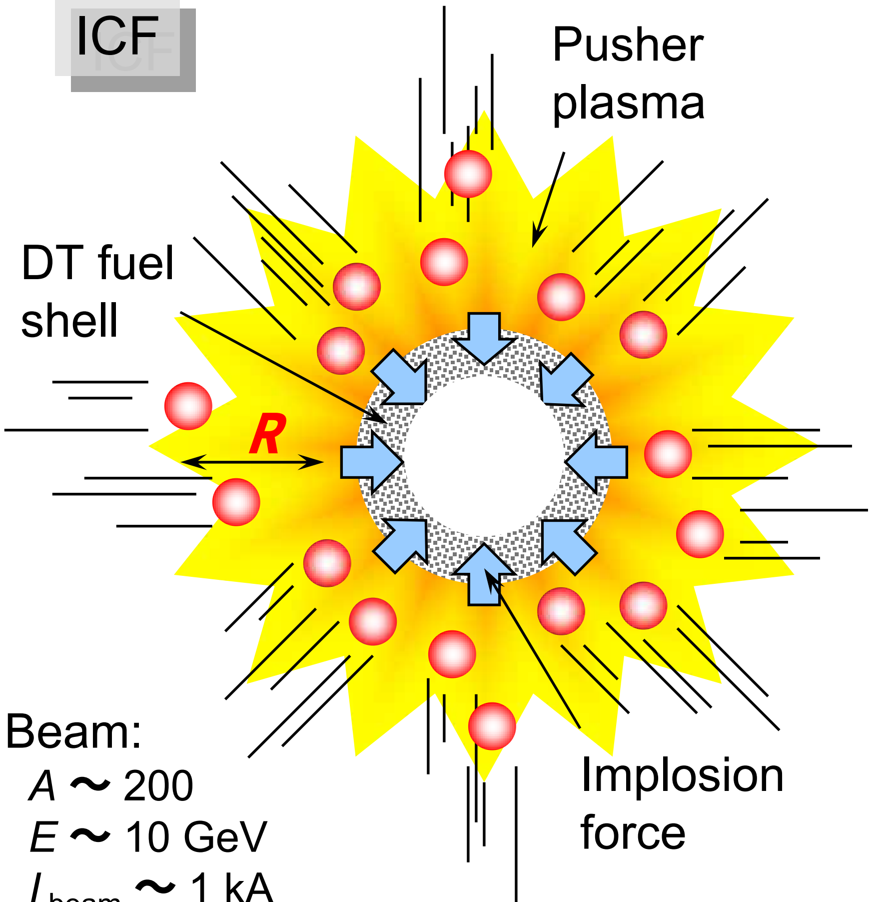


Knowledge on the beam-stopping is of importance to ICF as well as astrophysics.

- e.g., range of energetic ions R in plasmas:

ICF

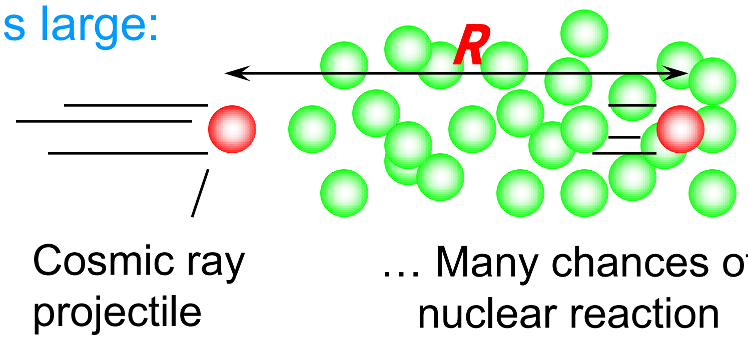


Beam:
$A \sim 200$
$E \sim 10$ GeV
$I_{beam} \sim 1$ kA
$\tau \sim 10$ ns

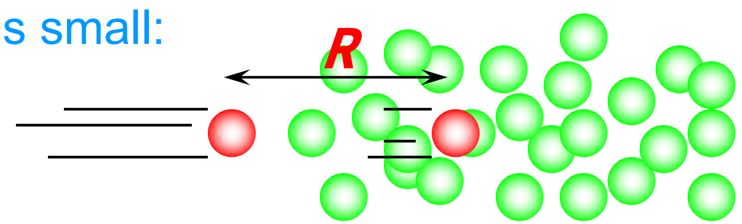
Astrophysics

Example:
Nucleosysnthesis in the early solar system

If R is large:



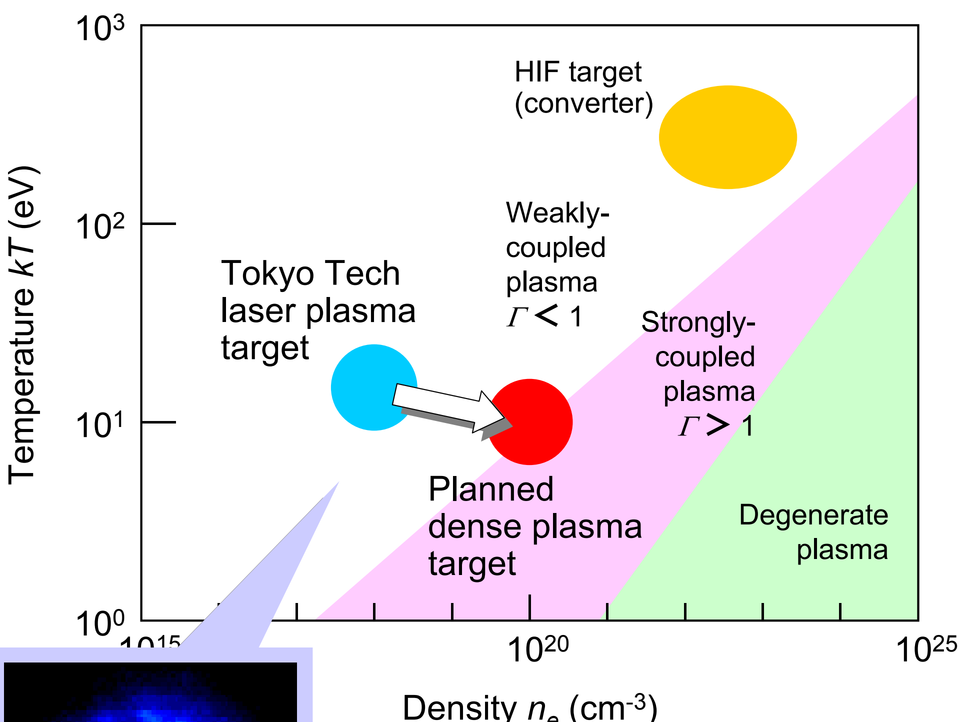
If R is small:

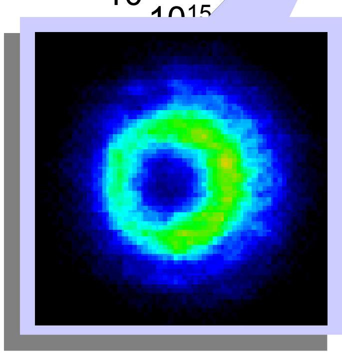


… Less chance of nuclear reaction

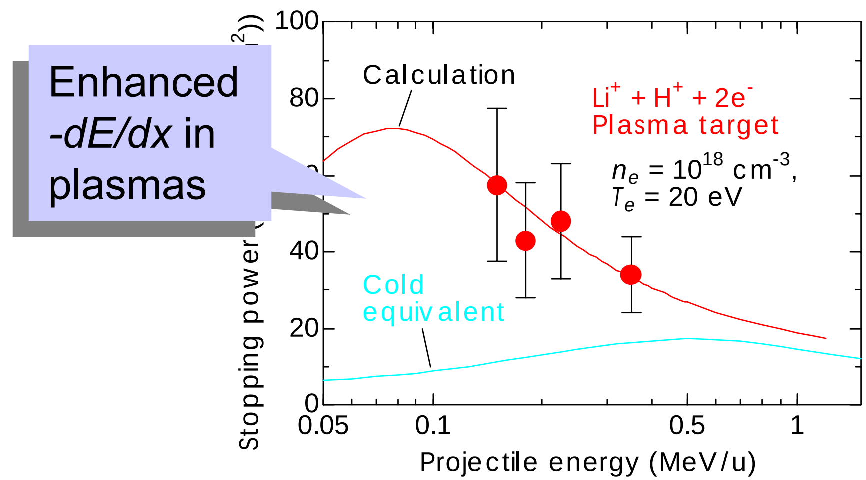
Beam-plasma interaction experiments with dense plasma targets are being planned at RLNR/Tokyo-Tech.

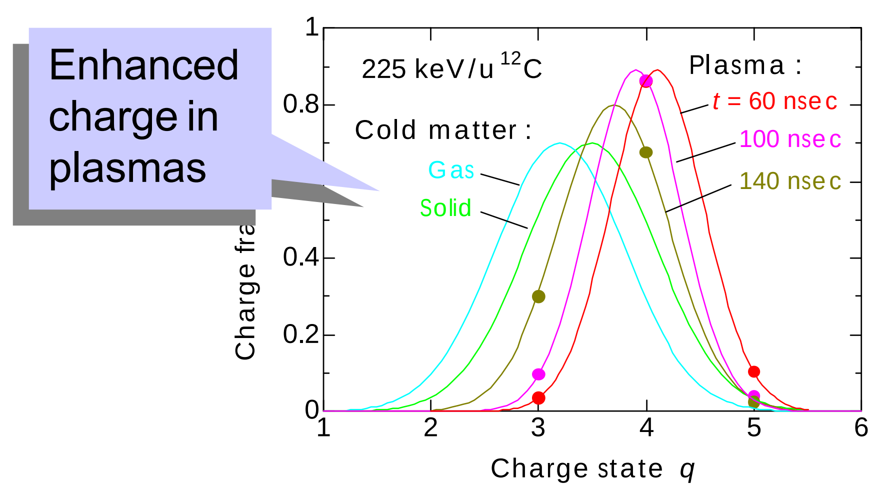
- Experiments performed so far using Tokyo-Tech 1.7 MV tandem accelerator:





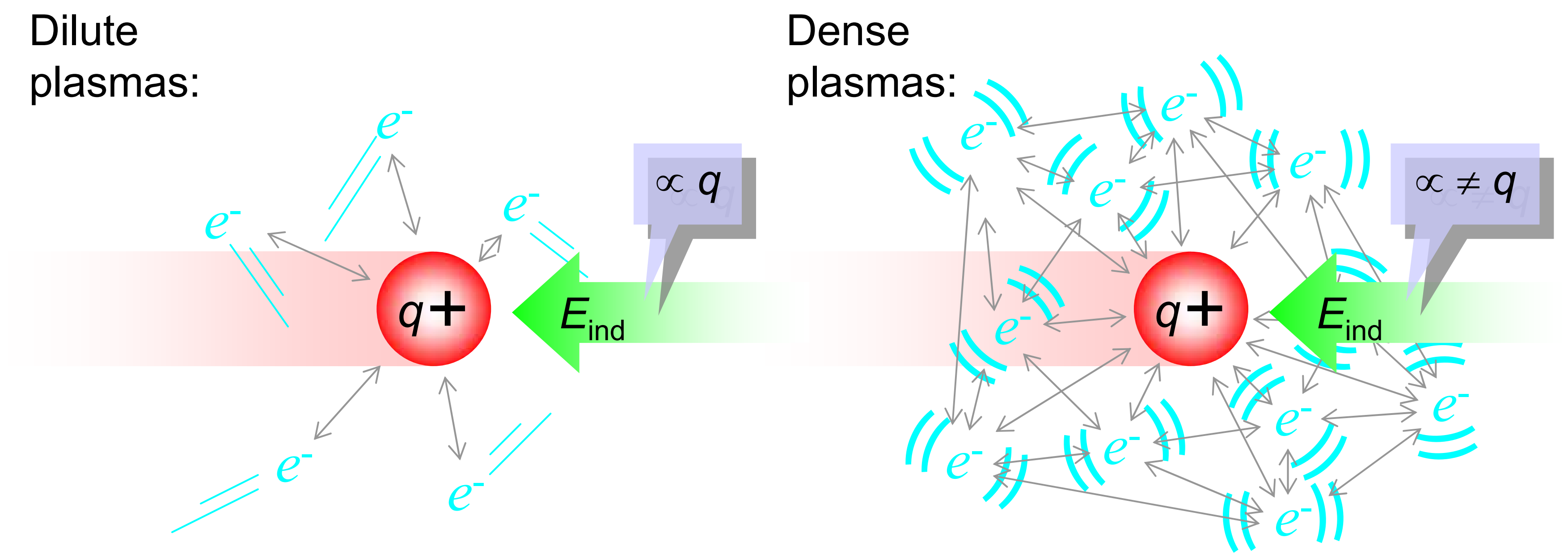
Plasma target ≈ $Li^+ + H^+ + 2e^-$,
$n_e \approx 10^{18}$ cm^{-3}, $kT \approx 10$ eV,





Nonlinear effects are expected for projectile stopping in HIF targets with solid density $(n_e \approx 10^{22}\ \mathrm{cm}^{-3})$.

- Dilute hot plasmas ・・・・・ Linear stopping:
  - Induced decelerating field $E_{ind} \propto q$
  - $-dE/dx = qe \times E_{ind} \propto q \times q = q^2$ (q: projectile charge state)
- Dense cold plasmas ・・・・・ Nonlinear stopping:
  - Induced decelerating field $E_{ind} \propto q^m$ ($m < 1$)
  - $-dE/dx = qe \times E_{ind} \propto q \times q^m = q^{1+m} \equiv q^n$ ($1 < n < 2$)



Non-ideality of the plasma target is measured by "plasma coupling constant" Γ.

- Potential energy ϕ and kinetic energy K of plasma particles:
  - Mean interparticle distance $\langle r\rangle$, mean Coulomb potential ϕ:

$$\langle r\rangle \equiv \sqrt[3]{\frac{3}{4\pi n_e}}, \quad \phi \equiv \frac{e^2}{4\pi\varepsilon_0\langle r\rangle}$$

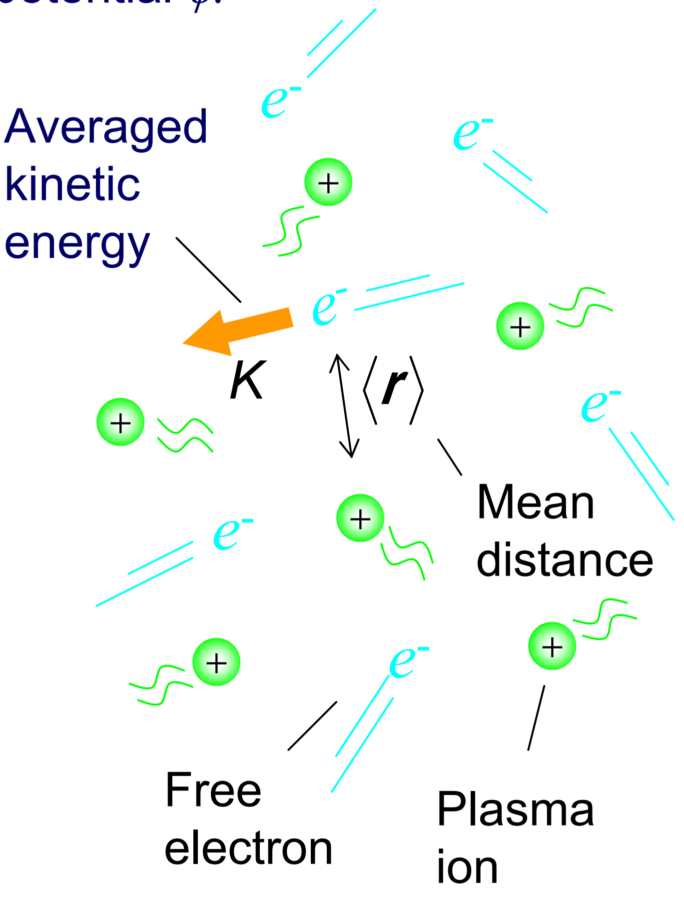
  - Averaged kinetic energy:

$$K \equiv kT$$

- Definition of "plasma coupling constant" Γ:
  - Ratio of potential energy to kinetic energy:

$$\Gamma \equiv \frac{\phi}{K} = \frac{e^2\sqrt[3]{4\pi n_e/3}}{4\pi\varepsilon_0 kT}$$

  - $\Gamma \approx 0$ → "Ideal plasma"
  - $\Gamma \neq 0$ → "Non-ideal plasma"
  - $\Gamma > 1$ → "Strongly-coupled plasma"

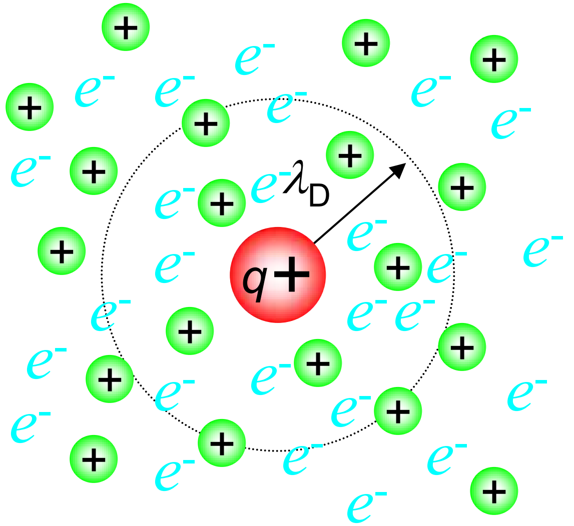


Strongly-coupled plasmas with Γ >> 1 are not always necessary for non-linear stopping experiments.

- Relationship between the projectile charge q and total charge of electrons which can interact with the projectile:
  - Range of Coulomb force by projectile ～ Debye length λ_D: $\lambda_D = \sqrt{\dfrac{\varepsilon_0 kT}{e^2 n_e}}$
  - Number of electrons in a Debye sphere N_D: $N_D = \dfrac{4\pi}{3}\lambda_D{}^3 n_e$
  - Particle distribution in the plasma is influenced by the projectile charge, if N_D << q, or,

$$\Xi \equiv \frac{q}{N_D} = 3^{3/2} q \Gamma^{3/2} >> 1$$

- Γ < 1 works, if q is very high.
- Effect of the projectile motion is not included in Ξ above.



A projectile-plasma coupling constant γ can be defined for projectiles moving in the plasma.

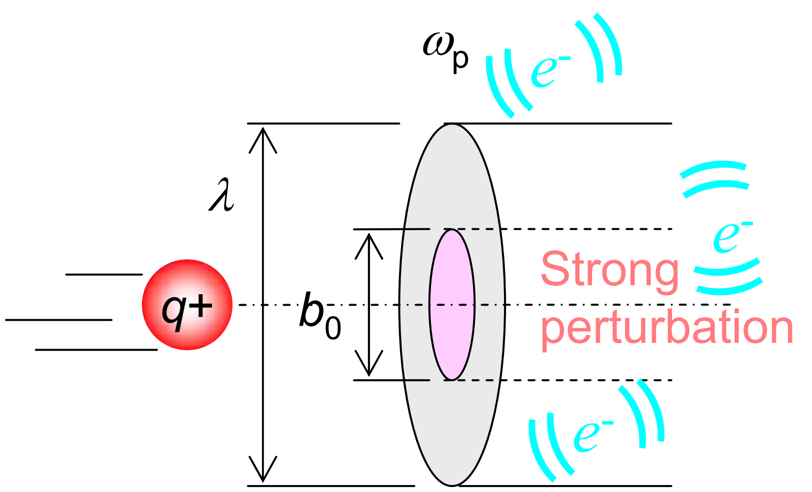
- Perturbations to the plasma electrons are possible only for the collision parameters b smaller than screening length λ :

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

  - $\langle v_r \rangle$: averaged relative energy

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

$$b < b_0 \equiv \frac{qe^2}{4\pi\varepsilon_0 m\langle v_r \rangle^2}$$

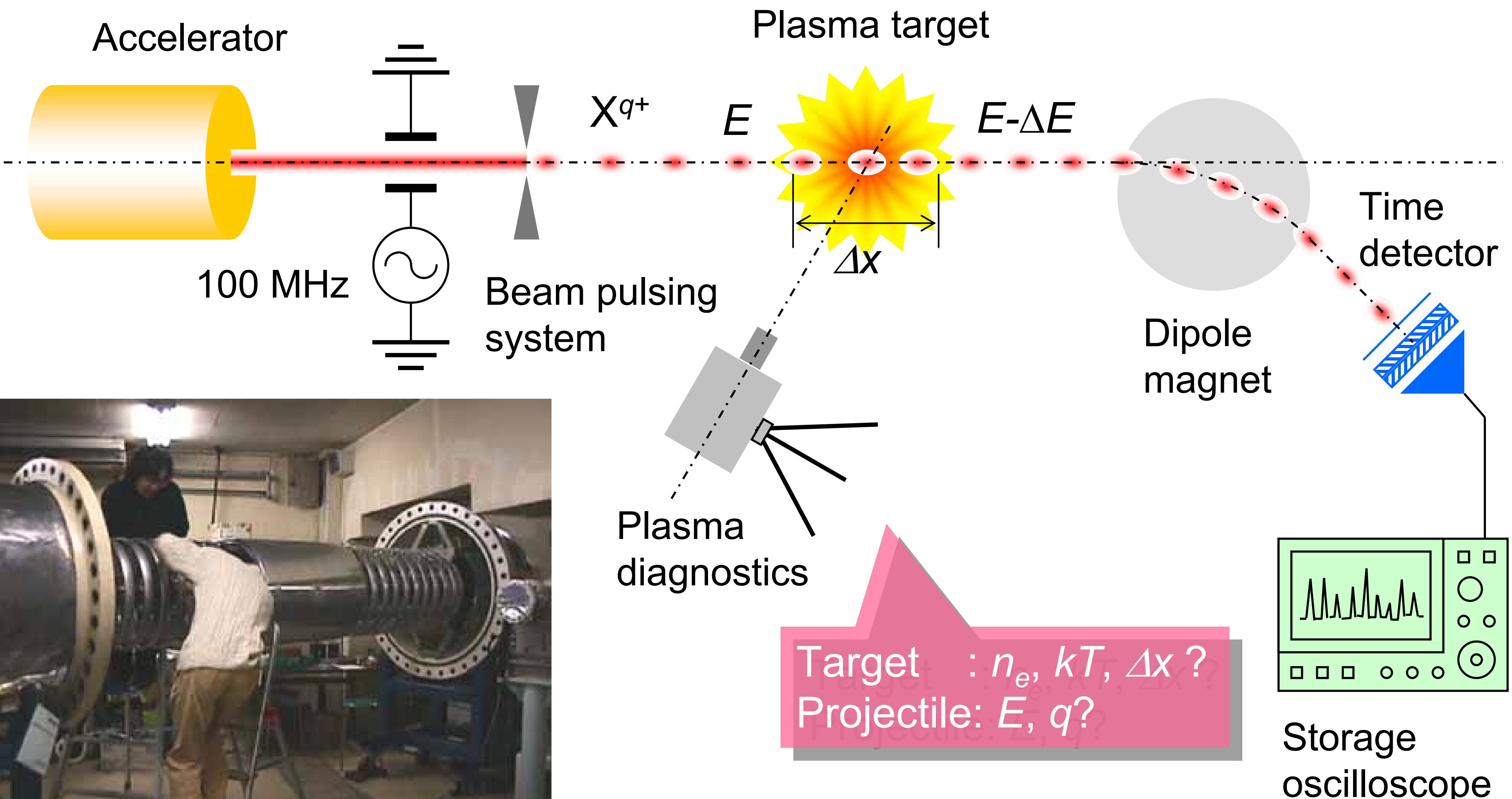


- The projectile-plasma coupling strength is estimated by the critical ratio $\gamma \equiv b_0/\lambda$:

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

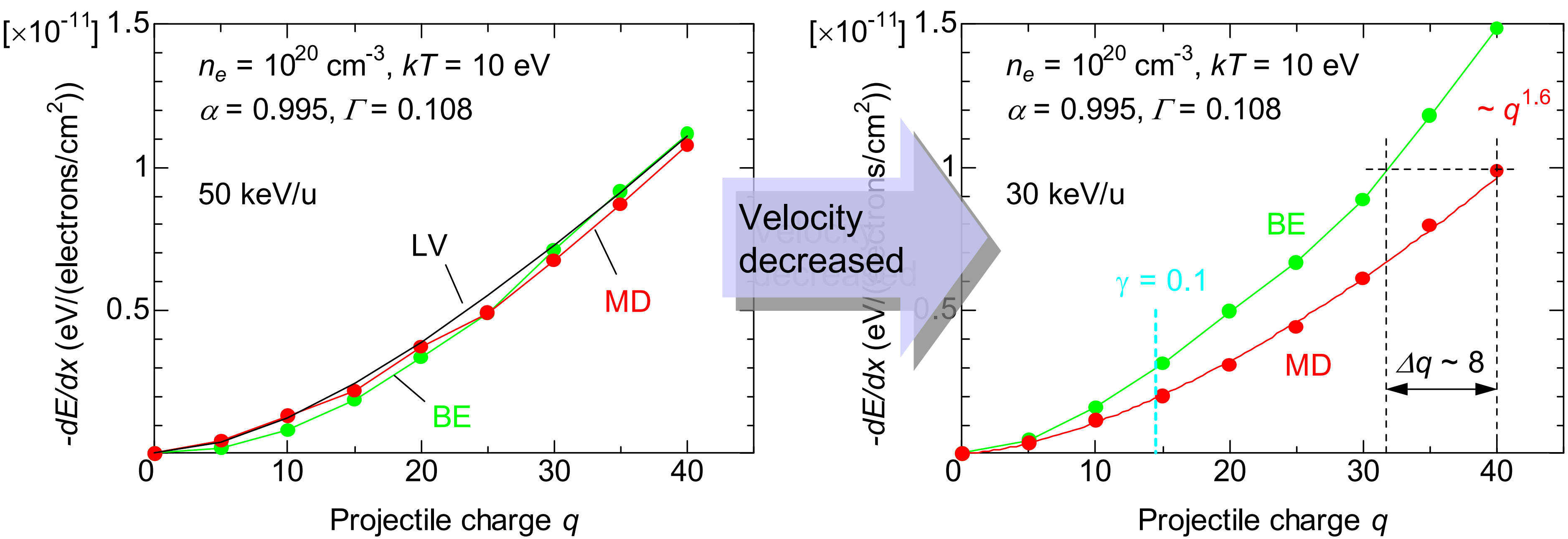
We are looking for appropriate experimental parameters to observe nonlinear effects.

- Energy loss measurement by Time-Of-Flight method:



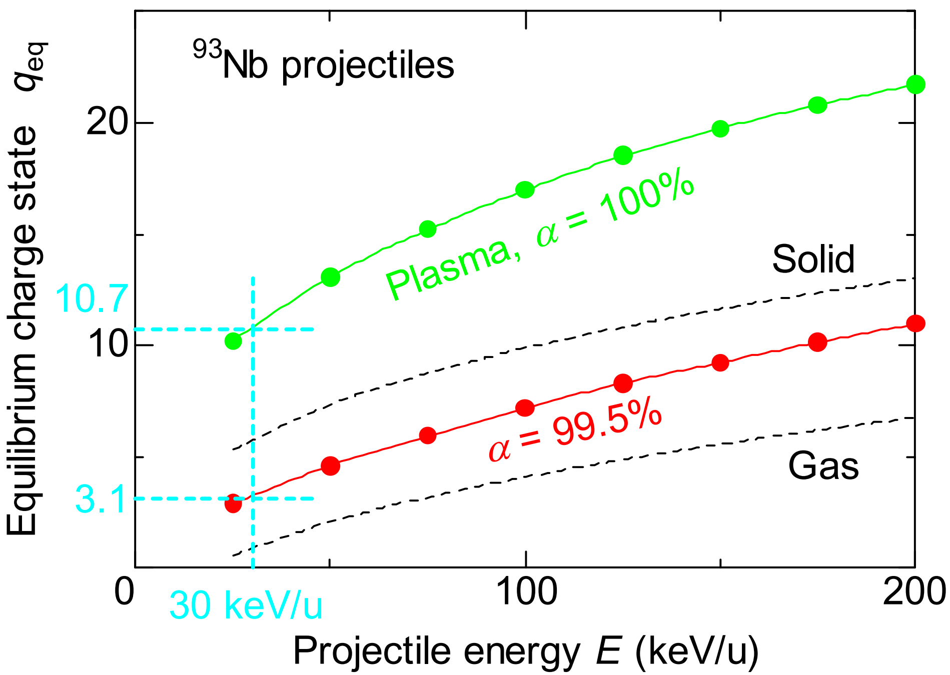
Nonlinear effect is remarkably increased by slightly decreasing the projectile velocity.

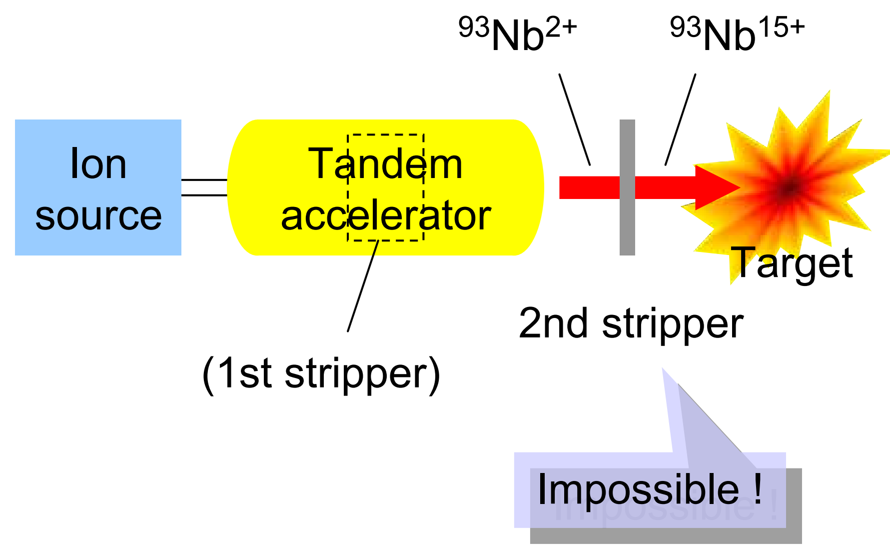
- 30 keV/u is acceptable, although lower projectile energies are not preferable as practical experimental conditions.
- $q > \approx 15+$ may be necessary to clearly observe the nonlinear effects.
- For q = 40+, the decrease of the projectile effective charge is ≈ 8.
  - At least 8 electrons are responsible for the screening ?



Experiments using a 30 keV/u ^{93}Nb beam from the tandem accelerator is very difficult.

- Charge state of the 30 keV/u ^{93}Nb beam from the accelerator is only q = 2+.
  $\rightarrow$ second stripper is necessary.
- At 30 keV/u, $q \approx$ 15+ is not available by ordinary stripping processes:
  - e.g., stripping of $_{41}$Nb by C-foil ➔ $q \approx 7$
  - Also plasma stripper does not work very well.

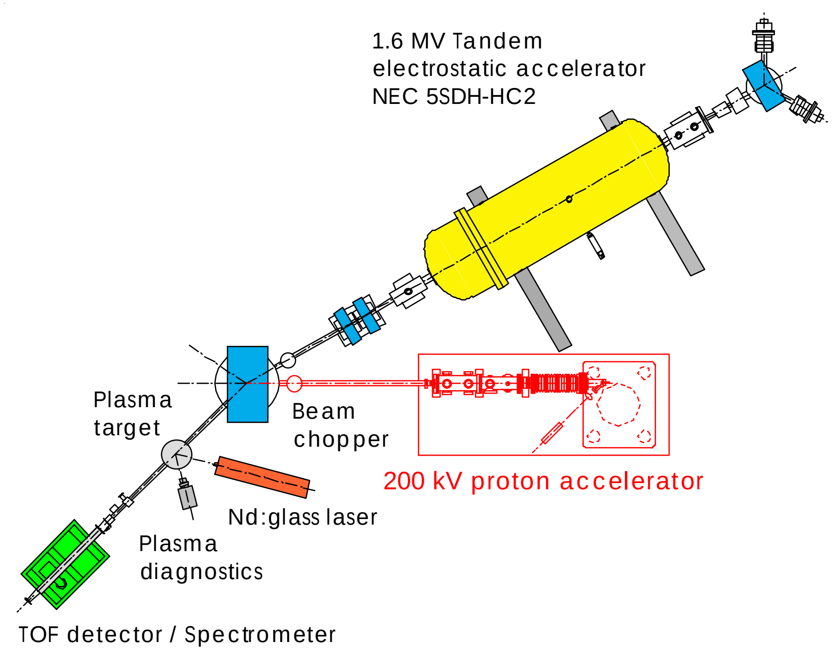


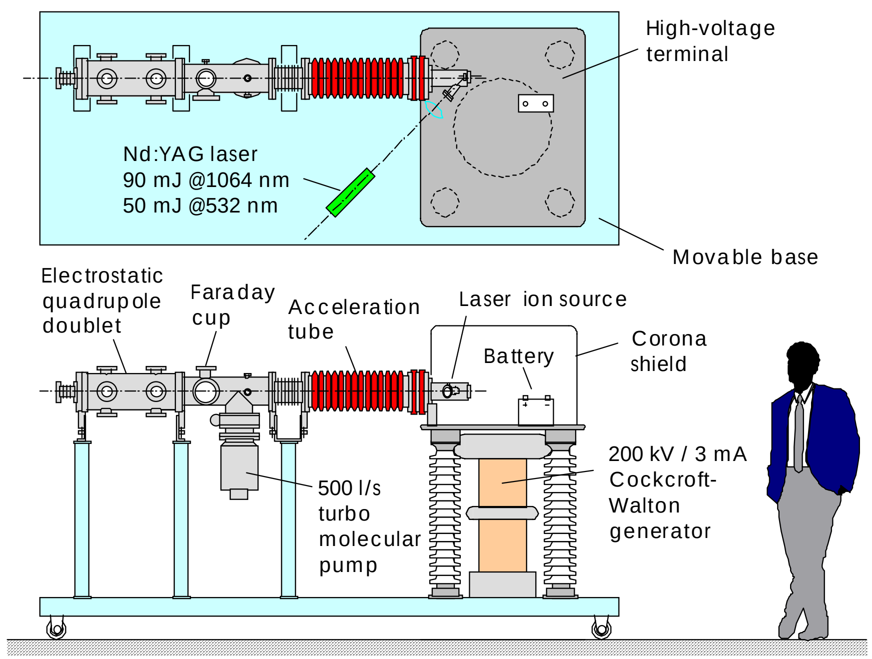


As an alternative, a single-ended low-energy machine with a source of highly-charged ions is considered.

- Originally designed for experiments using 100-200 keV protons for the measurement of Coulomb logarithm $\ln\Lambda$:
  - Laser Ion source (YAG-2ω, 50 mJ, 5 ns)
  - 180 MHz reentrant resonator cavity for beam bunching
- The beam is injected into the existing beam line.

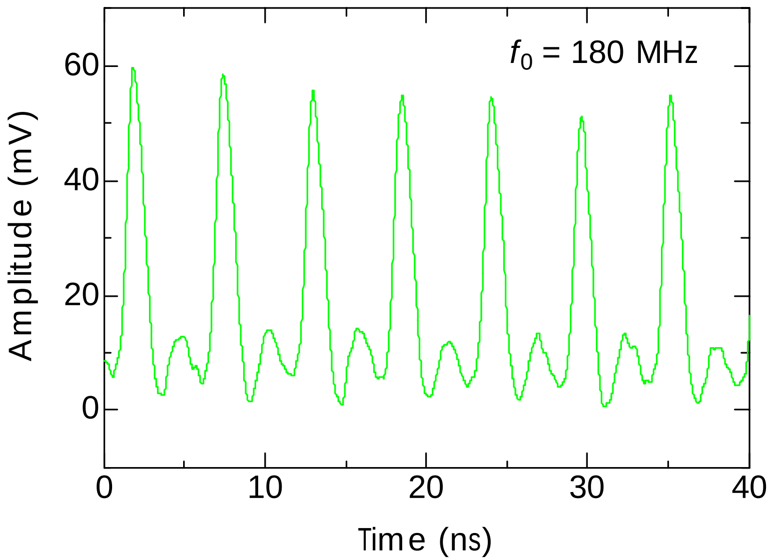
$$-dE/dx \propto q_{\mathrm{eff}}^2 \ln\Lambda$$





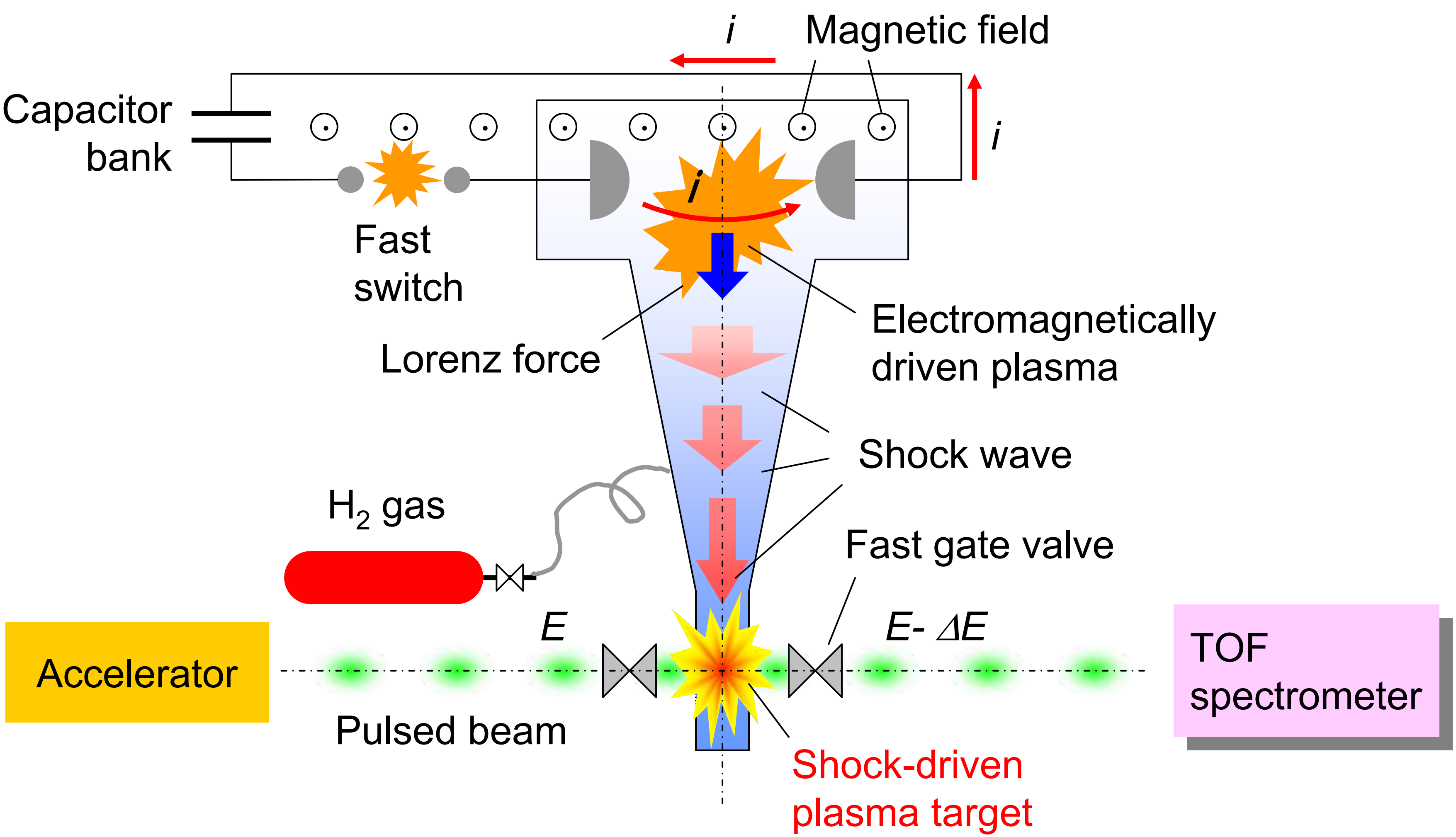
If the small YAG laser is changed to an existing glass laser, highly-charged projectiles will be obtained.

- By using the existing Nd:glass laser (1.05 μm, 4 J, 30 ns), irradiation of ≈ 10^{12} W/cm^2 is possible.
- If heavy ions with q = 15+ are available, experiments with the projectile energies up to 200 kV × 15e = 3.0 MeV are possible.
  - Cf. at CERN, 70 mA $^{181}Ta^{20+}$ by a 10^{12} W/cm^2 CO_2 laser.
- The machine is under the test of beam transport to the plasma target.



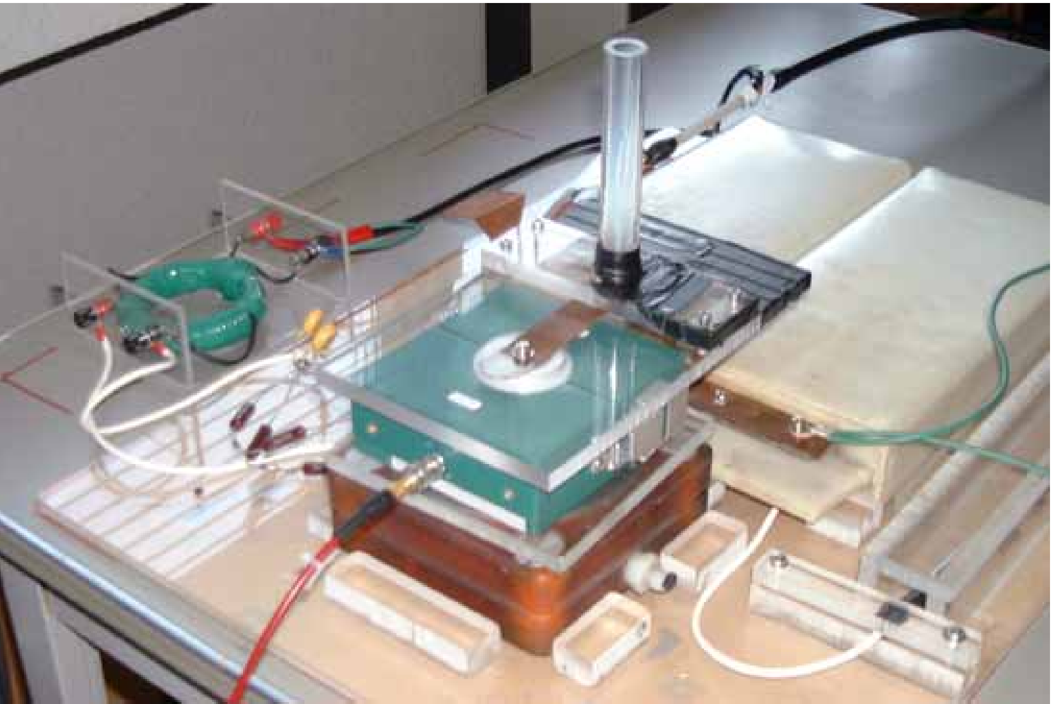
An electromagnetically-driven shock tube is being developed to produce cold dense plasma targets.

- Projectile energy loss is measured by a TOF method:



A prototype of the electromagnetic shock tube is being tested with air at the atmospheric pressure.

- Parameters of preliminary experiments:
  - Tube diameter / length = 14 mm / 140 mm
  - Capacitor bank C = 1 μF, V = 20 kV
  - Energy = 200 J
  - Time constant of discharge = 2.5 μs



V = 10 kV,
Exposure = 1μs