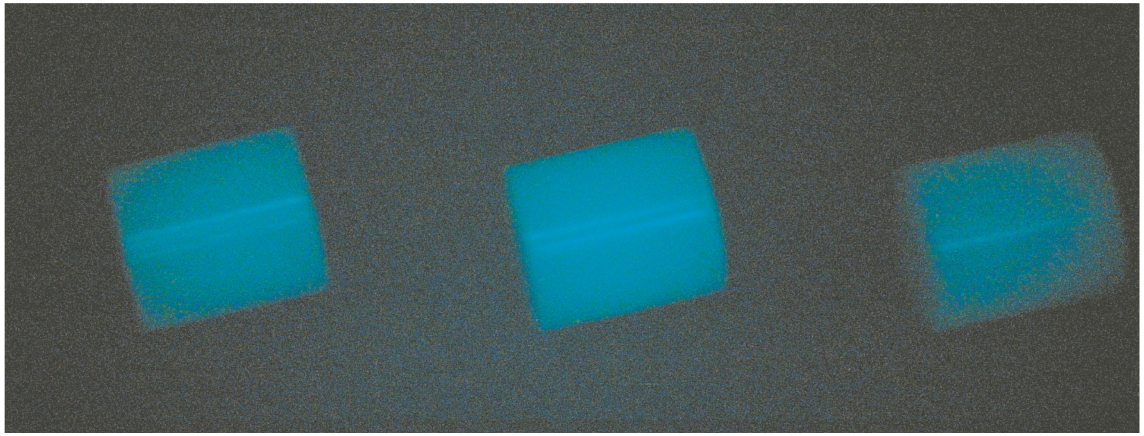
Preliminary Conceptual Design of Target Injector for Fast-Ignition Laser Fusion

Estimation of Target Acceleration
and
Simple Preliminary Experiments



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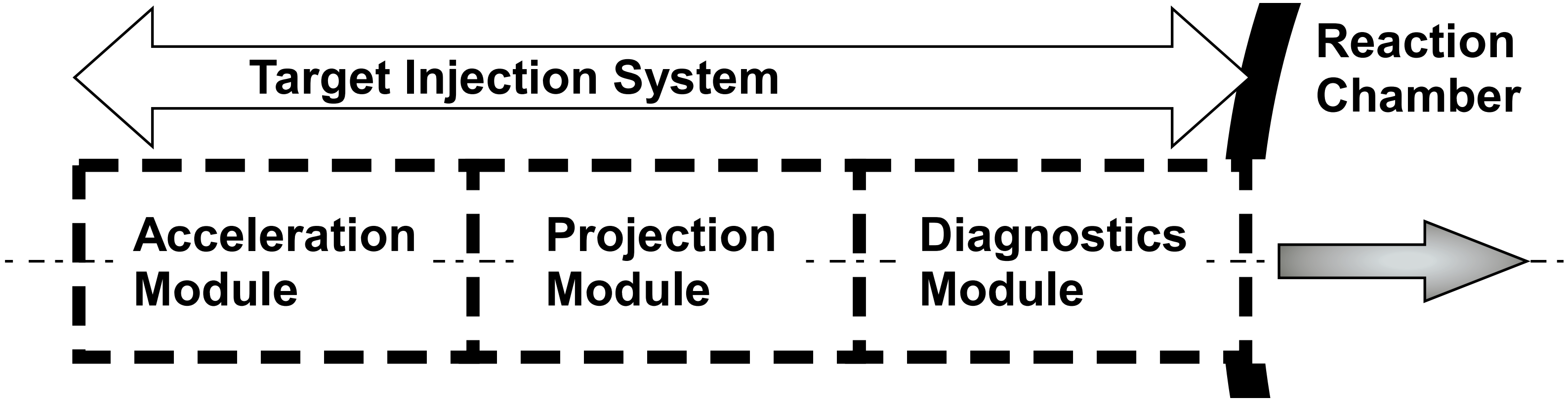
Outline

- Target Injection System
- Gas Dynamic Issues on Target Acceleration
- Simple Experiments on Target Acceleration

Target injection system consists of three modules



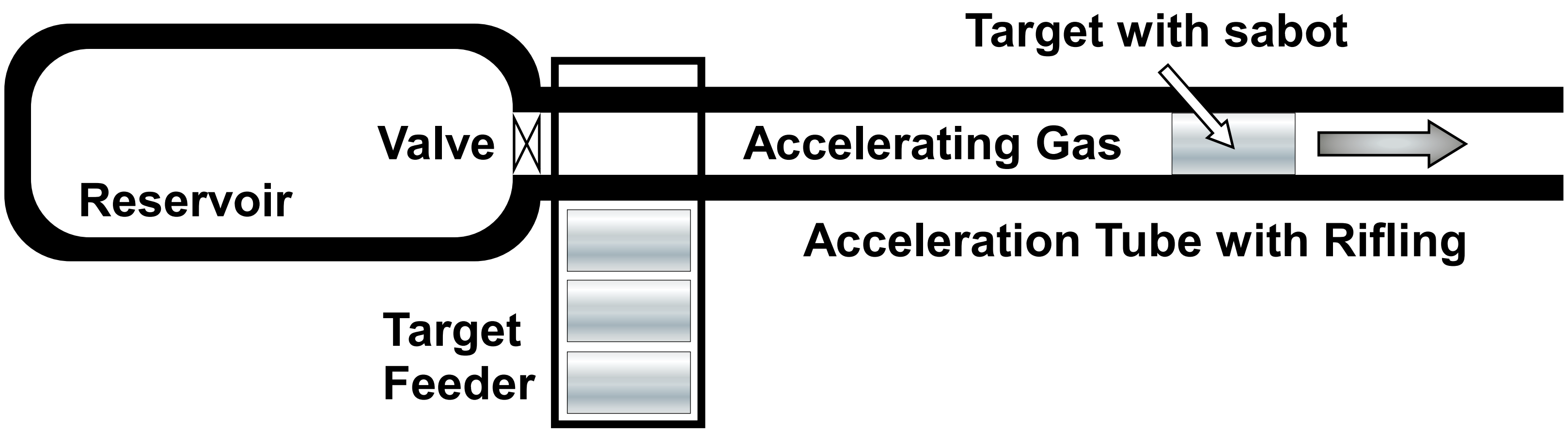
Acceleration Module
- To accelerate a target with a sabot by gas pressure
- Not to damage a target by adsorption, force, or heat

Projection Module
- To adjust the projecting direction
- To remove the sabot from the target
- To evacuate the accelerating gas

Diagnostics Module
- To measure the position and velocity of the target
- To transfer the target data to other modules and systems

Important Properties: Adjustability & Repeatability

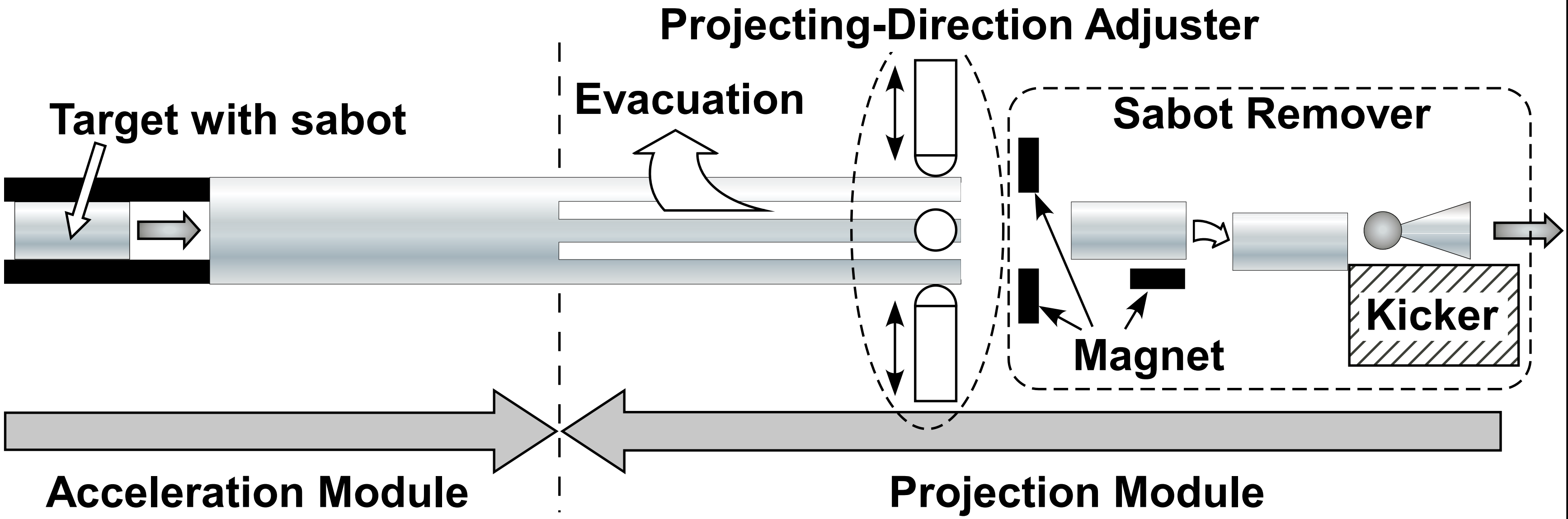
Reservoir pressure is limited by the DT-ice strength

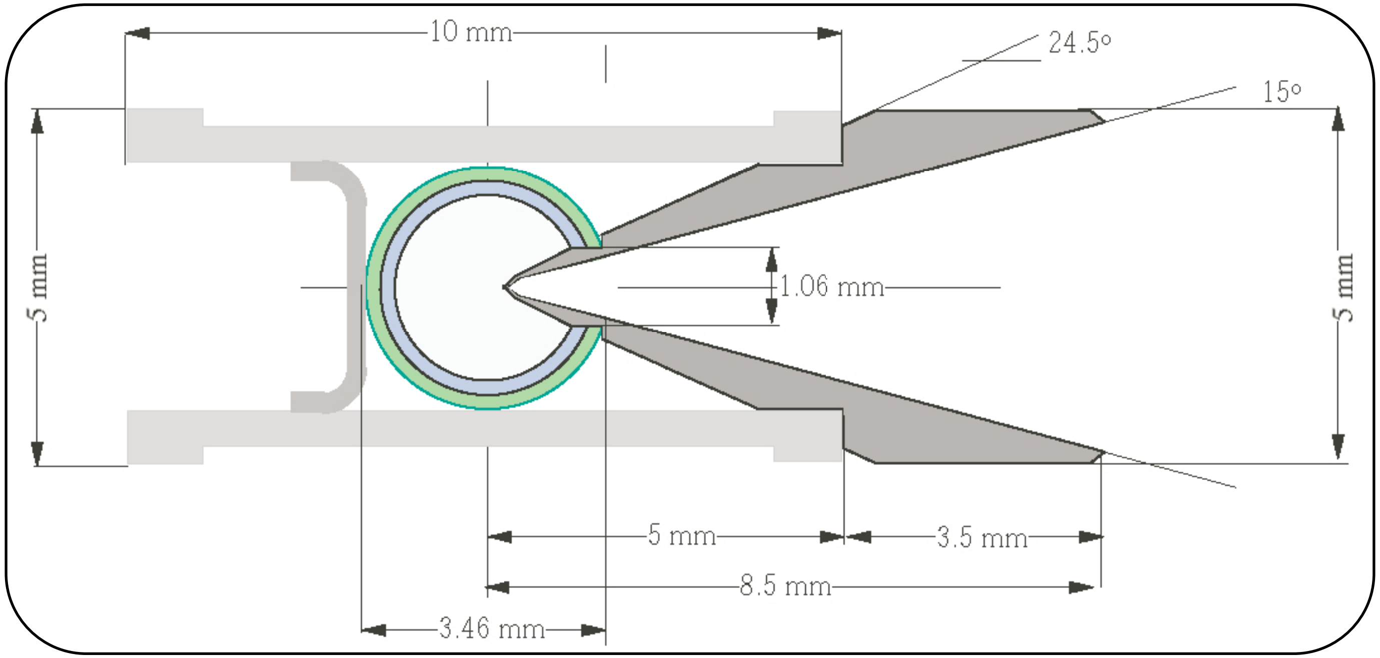


Constraints

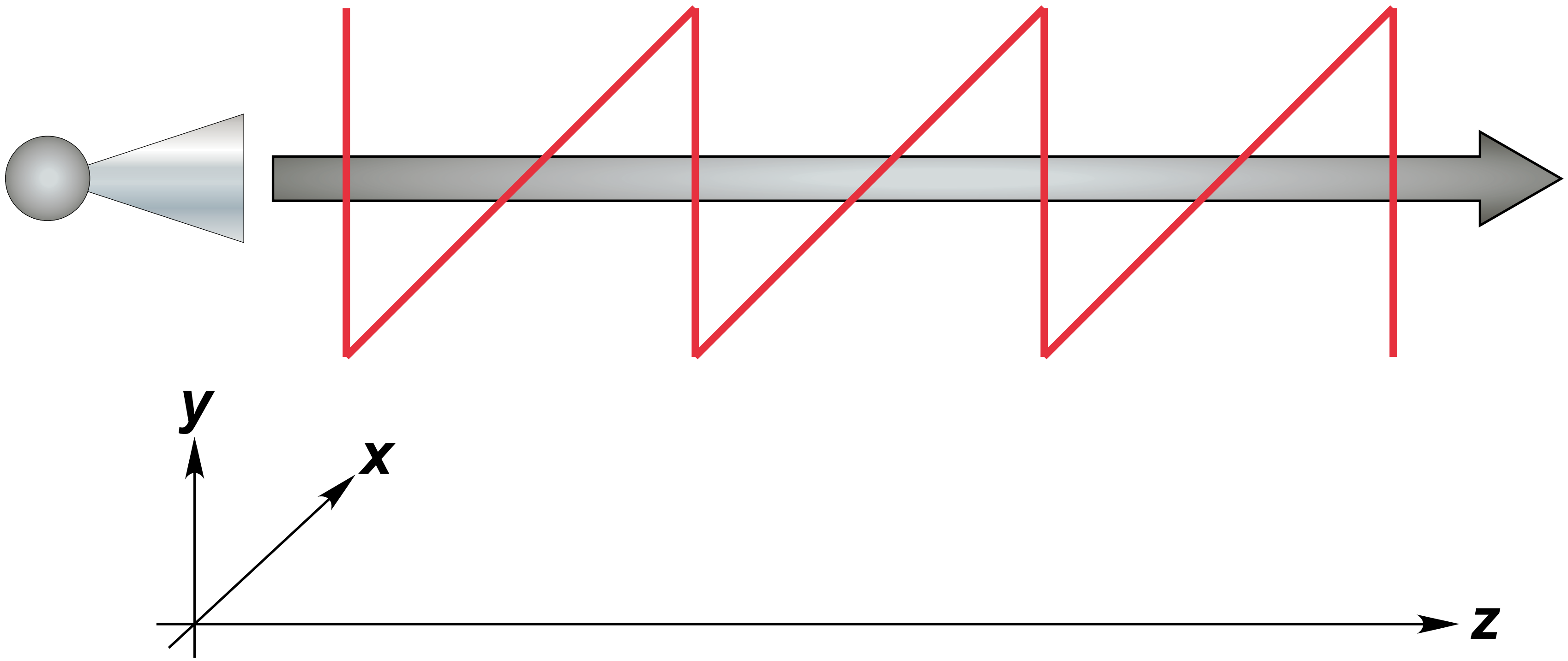
- To prevent the gas from being adsorbed by the target
  - ⇒ We have to select He gas as the accelerating gas.
- To prevent the target (DT ice) from being destroyed by the inertial force.
  - ⇒ We have to limit the acceleration of the target.
  - ⇒ We have to limit the reservoir pressure.

Projection module should be highly adjustable and repeatable





Diagnostics module had better be simple and speedy



Arrays of laser sheets in *x* and *y* directions transform the spatial information of the target into the timing information of the scattered light.

The DT-ice strength is a key parameter

0th-order Model: Isobaric accelerating gas, No resistance

U: Target Speed

p_{I}: Reservoir Pressure

m/A: Areal Mass Density of the Target

$$\Rightarrow \begin{cases} \dfrac{dU}{dt} = \dfrac{p_{\mathrm{I}}}{m/A} = \text{const.} \\ x = \dfrac{1}{2}\dfrac{m/A}{p_{\mathrm{I}}}U^2 \leftrightarrow U = \sqrt{2\dfrac{p_{\mathrm{I}}}{m/A}x} \\ t = \dfrac{m/A}{p_{\mathrm{I}}}U \end{cases}$$

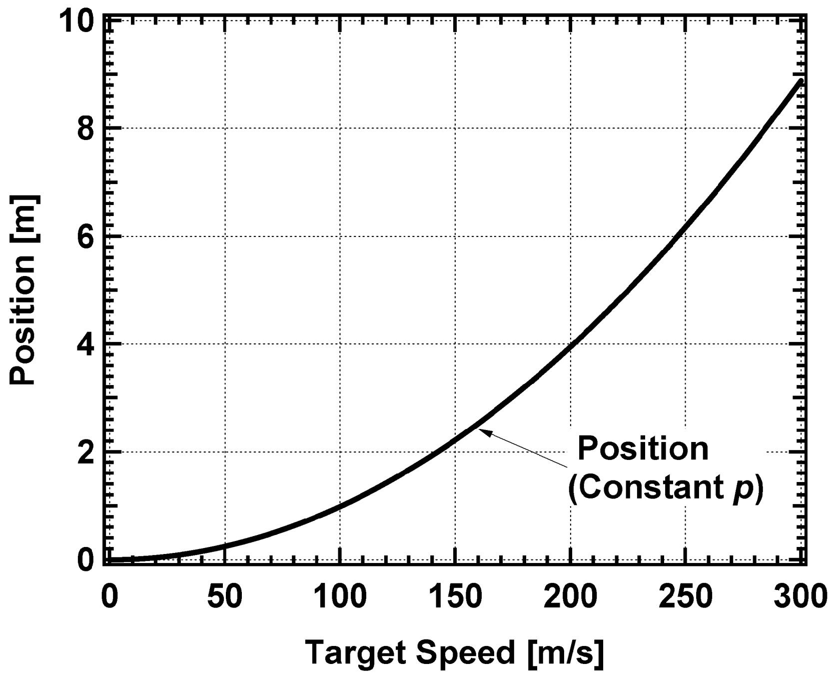
Conditions

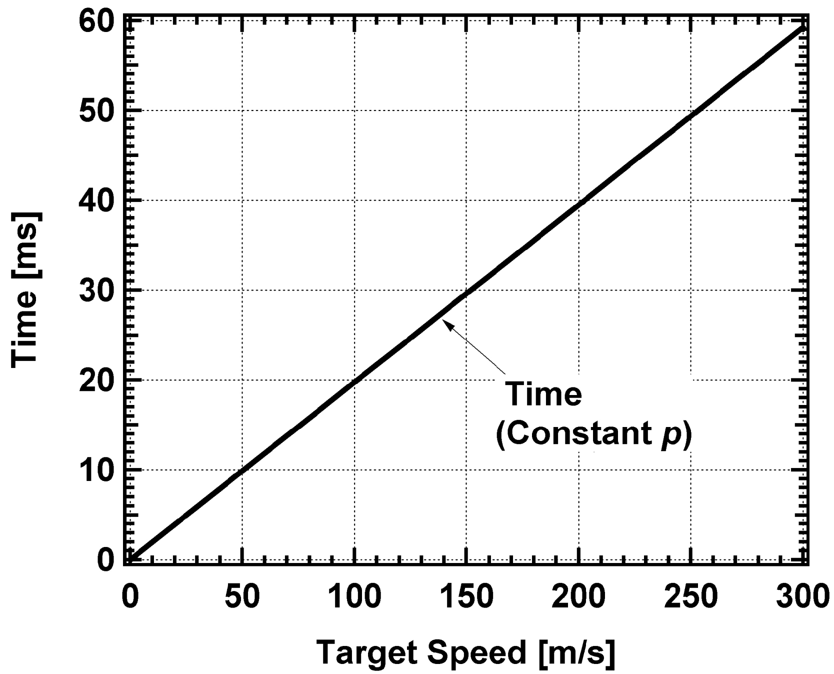
$$p_{\mathrm{I}} = 1\ \text{atm} \left[\text{corresponding to } \left(\frac{dU}{dt}\right)_{\max} \approx 500g \text{ when } m/A \approx 2\ \text{g/cm}^2 \right]$$

He gas, $T_{\mathrm{I}} = 300$ K

The DT-ice strength is a key parameter

0th-order Model: Isobaric accelerating gas, No resistance





Acceleration to 300 m/s needs *x* = 9 m and *t* = 60 ms.

Compressibility of the gas is not effective

1st-order Model: Expanded accelerating gas, No resistance
(We used relations for a self-similar rarefaction wave)

U: Target Speed

p_I: Reservoir Pressure

c_I: Reservoir Sonic Speed

γ: Specific-Heat Ratio

$u_{max} = \frac{2}{\gamma - 1} c_I$

m/A: Areal Mass Density of the Target

$$\Rightarrow \begin{cases} \frac{dU}{dt} = \frac{p_I}{m/A}\left(1 - \frac{U}{u_{max}}\right)^{\frac{2\gamma}{\gamma-1}} \\ x = \frac{2c_I^2}{\gamma+1}\frac{m/A}{p_I}\left\{1 - \left(1 - \frac{\gamma+1}{\gamma-1}\frac{U}{u_{max}}\right)\left(1 - \frac{U}{u_{max}}\right)^{-\frac{\gamma+1}{\gamma-1}}\right\} \\ t = \frac{2c_I}{\gamma+1}\frac{m/A}{p_I}\left[\left(1 - \frac{U}{u_{max}}\right)^{-\frac{\gamma+1}{\gamma-1}} - 1\right] \end{cases}$$

Conditions

$p_I = 1$ atm $\left[\text{corresponding to } \left(\frac{dU}{dt}\right)_{max} \approx 500g \text{ when } m/A \approx 2\ \text{g/cm}^2\right]$

He gas, $T_I = 300$ K

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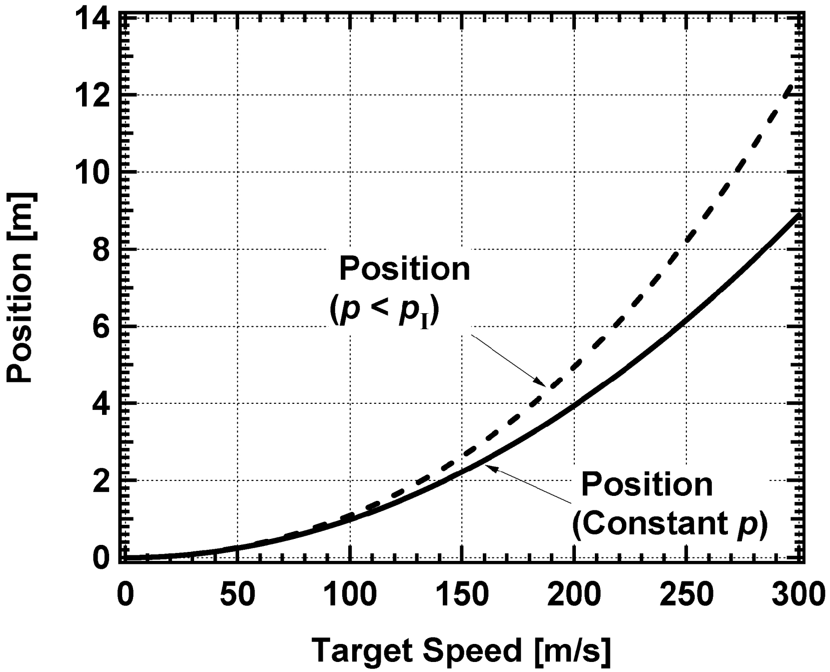
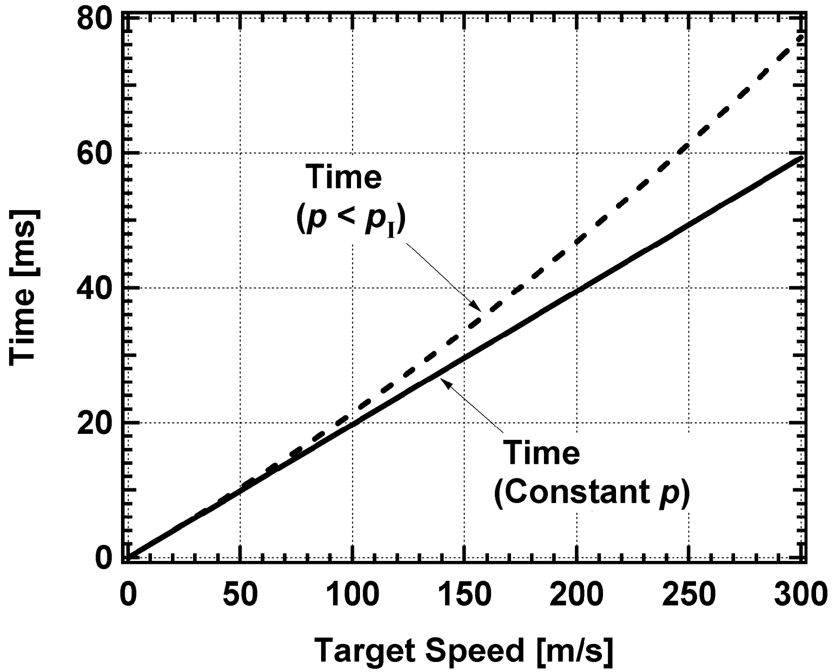
1st-order Model: Expanded accelerating gas, No resistance
(We used relations for a self-similar rarefaction wave)





Acceleration to 300 m/s needs x = 13 m and t = 80 ms.

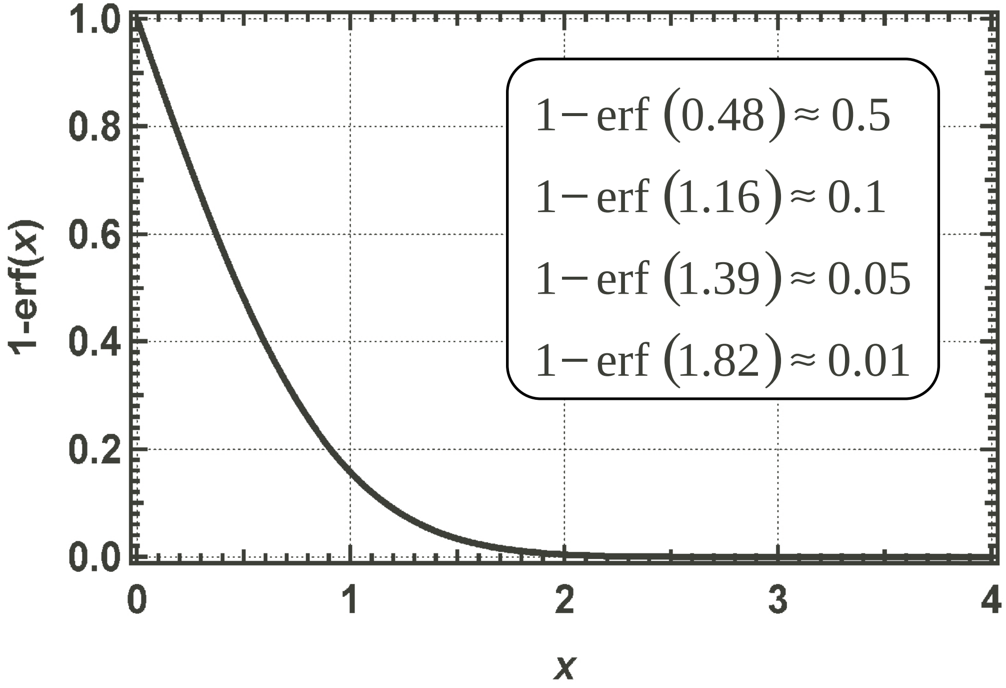
Acceleration efficiency is lowered by three factors

① **Friction & Rifling on the Acceleration Tube → Resistance**
② **Fluid Resistance in the Valve → Lowering Acceleration Pressure**
③ **Boundary Layer on the Acceleration Tube → Lowering Acceleration Pressure**

All of these may be compensated by raising the reservoir pressure.

- **Boundary-layer thickness (Incompressible flow on a flat wall)**

$$\frac{v_x(y,t)}{v_0} = 1 - \mathrm{erf}\left(\frac{y}{\sqrt{4\nu t}}\right), \qquad \left(\nu = \frac{\mu}{\rho}\right)$$

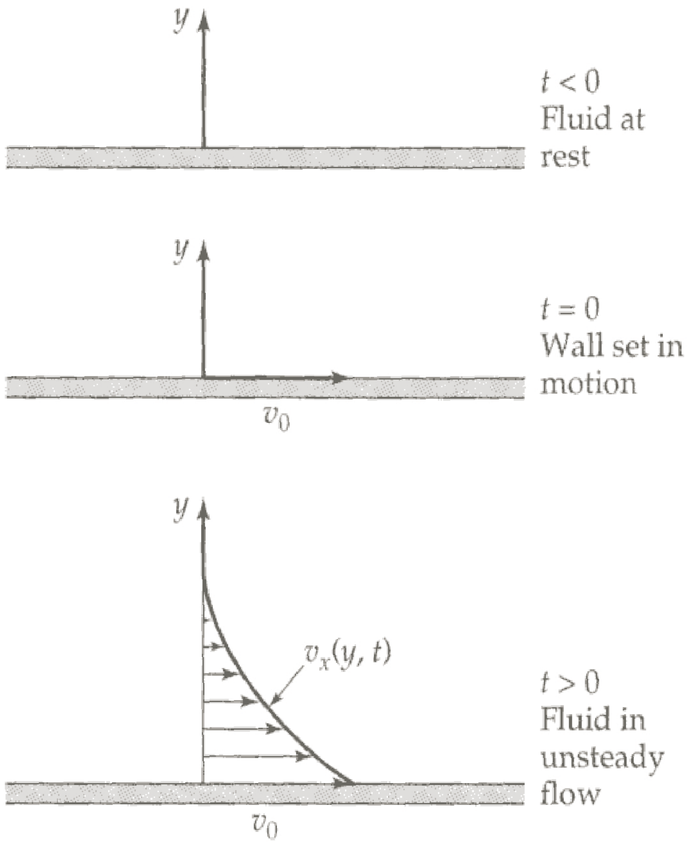


$1-\mathrm{erf}(0.48) \approx 0.5$

$1-\mathrm{erf}(1.16) \approx 0.1$

$1-\mathrm{erf}(1.39) \approx 0.05$

$1-\mathrm{erf}(1.82) \approx 0.01$



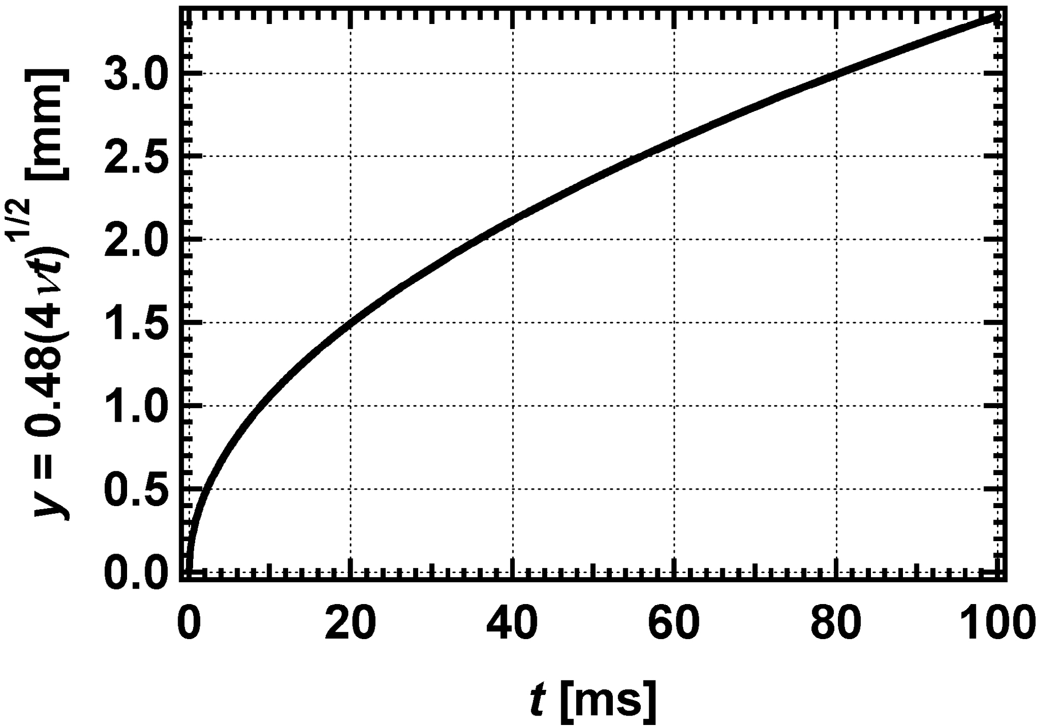
Boundary-layer thickness is comparable to the radius of the acceleration tube

He gas at 300 K $\mu = 2.0\times10^{-5}\ \ \mathrm{kg}/(\mathrm{m}\cdot\mathrm{s})$

$$p_{\mathrm{I}} = 1\ \mathrm{atm} \Rightarrow \nu = \mu/\rho = 1.2\times10^{-4}\ \ \mathrm{m}^2/\mathrm{s}$$

$$\frac{\upsilon_x(y,t)}{\upsilon_0} = 1 - \mathrm{erf}\left(\frac{y}{\sqrt{4\nu t}}\right) \approx 0.5 \Rightarrow \frac{y}{\sqrt{4\nu t}} = 0.48$$

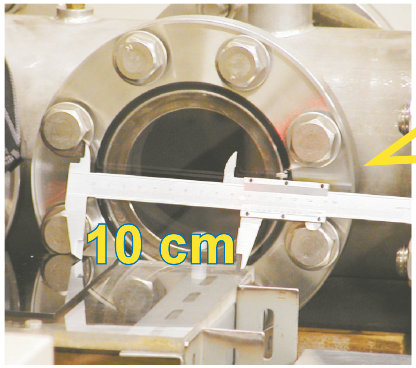
(Distance from the wall where flow velocity is lowered to a half by the friction)

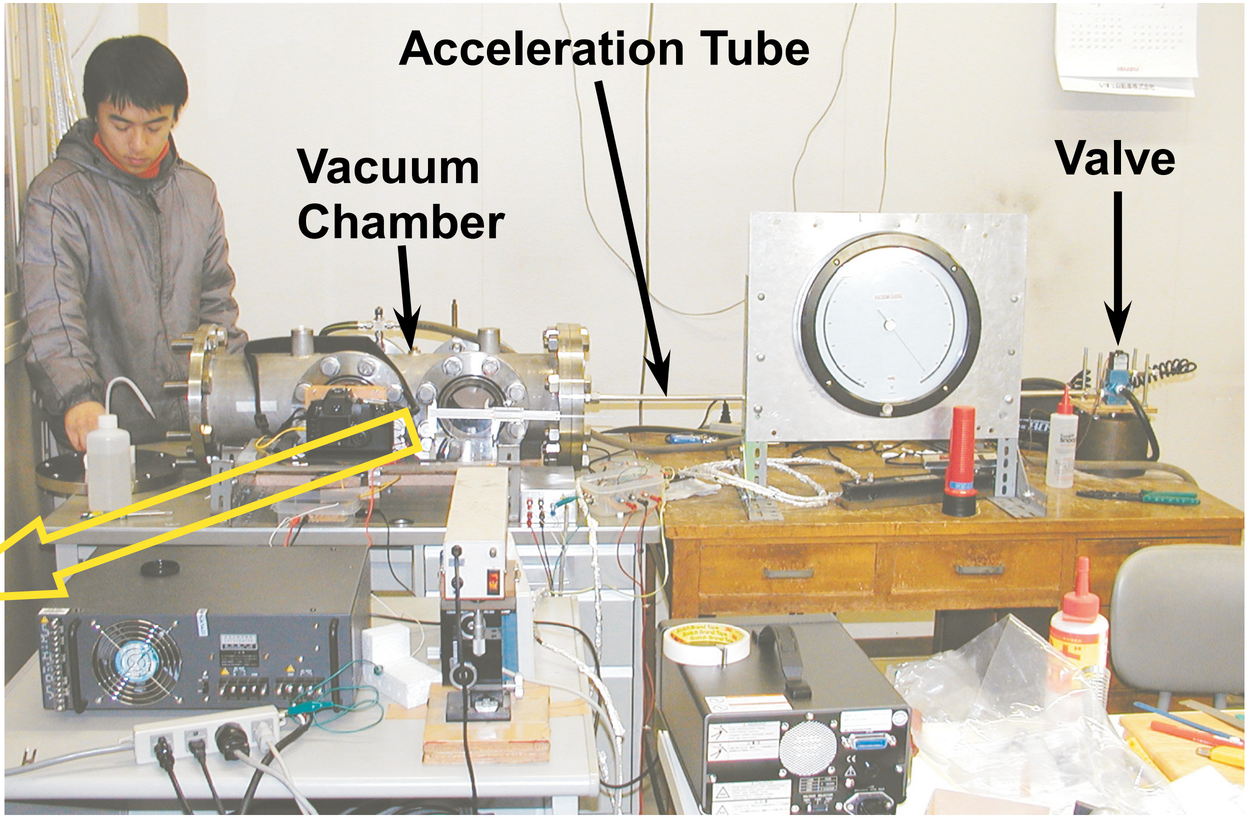


$$\left.\begin{array}{l} d = 5\ \mathrm{mm} \\ y = 1\ \mathrm{mm} \end{array}\right\} \Rightarrow \frac{\pi\left(\frac{d}{2} - y\right)^2}{\pi\left(\frac{d}{2}\right)^2} = 0.36$$

$$\left.\begin{array}{l} d = 5\ \mathrm{mm} \\ y = 2\ \mathrm{mm} \end{array}\right\} \Rightarrow \frac{\pi\left(\frac{d}{2} - y\right)^2}{\pi\left(\frac{d}{2}\right)^2} = 0.04$$

At all events we started target-acceleration experiments to accumulate experiences





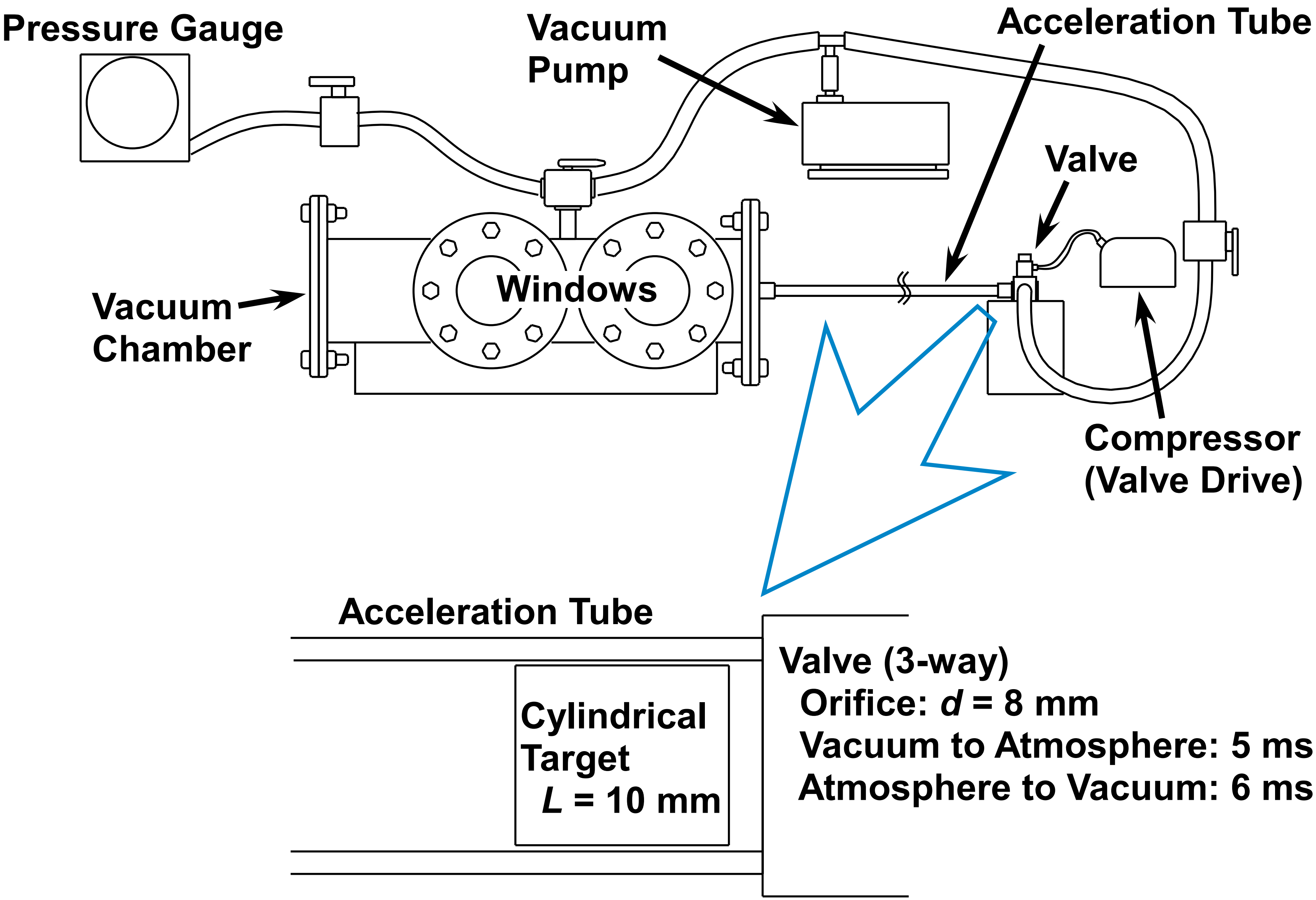
Acceleration Tube

Length:	1 m
Inner Diameter:	10 mm
Rifling:	No

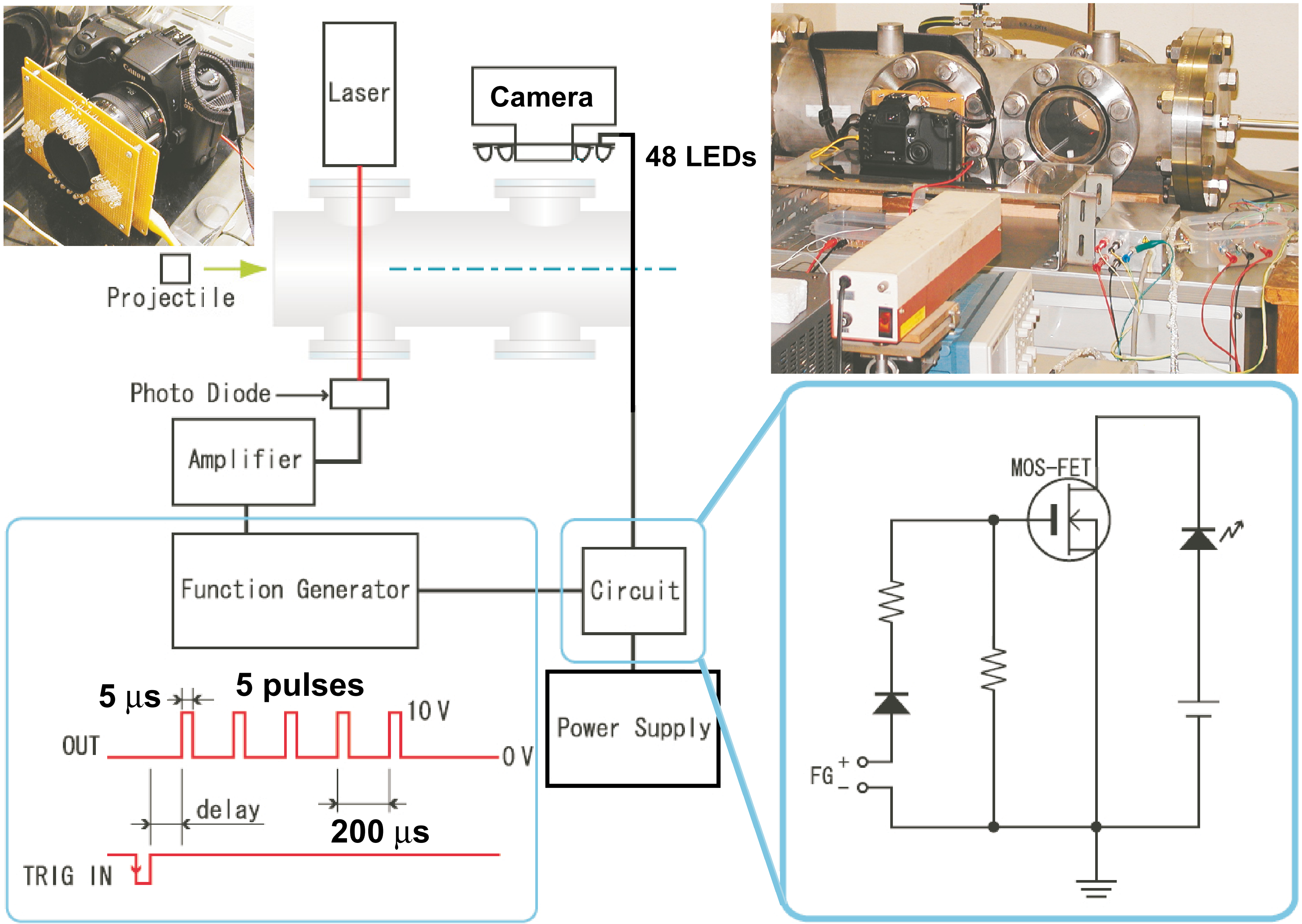
Reservoir (Room)

Pressure: 1 atm
Room Temperature
Air

We used polymer cylinders as accelerated targets



We used LEDs and a digital camera for diagnostics

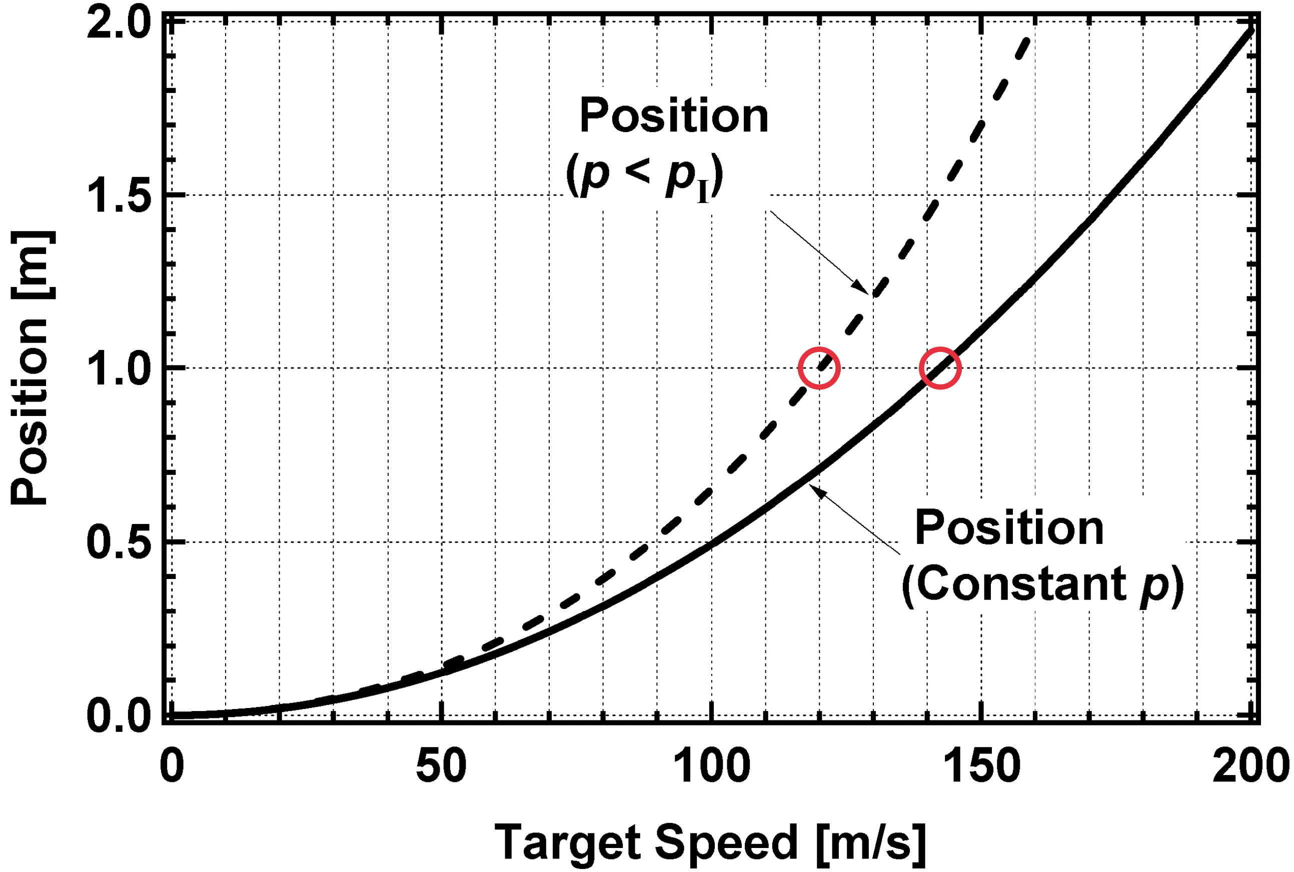


Expected target speed was 120 m/s (1st-order model) ~ 142 m/s (0th-order model)

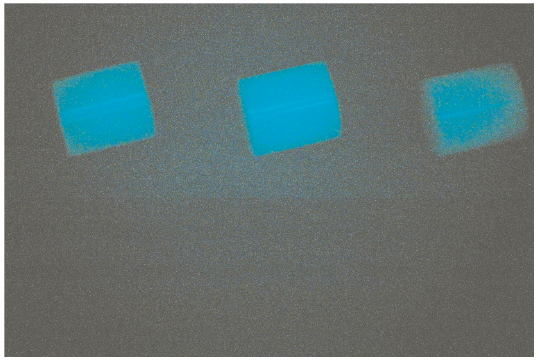
Experimental Conditions: $\text{Air}\ (28.8619\ \text{g/mol}),\quad \gamma = 7/5$

$p_\text{I} = 1\ \text{atm},\quad T_\text{I} = 300\ \text{K}$

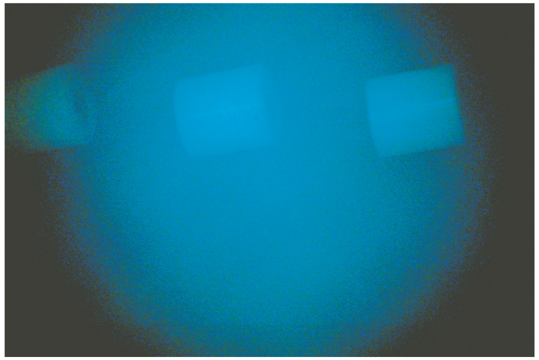
$m/A = 1\ \text{g/cm}^2$



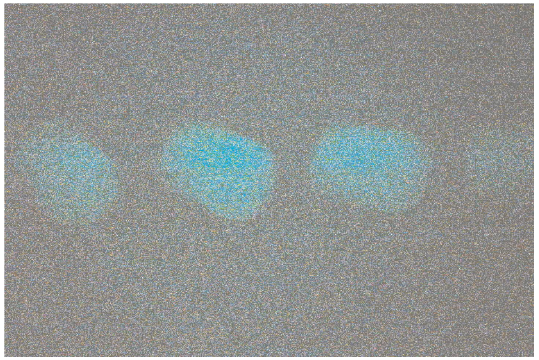
Measured target speeds were a little lower than the expected speed: 120 ～ 142 m/s



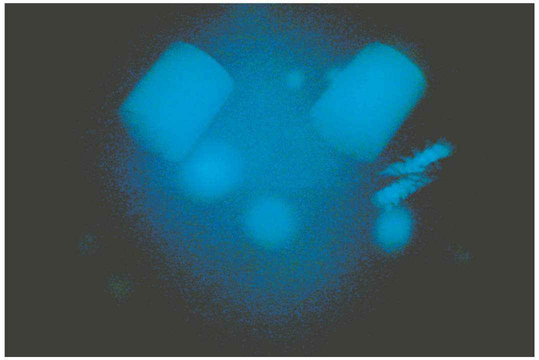
#030114-03, *d* = 9.60 mm, $p_{chamber}$ = 90 Torr, *U* = 109 m/s



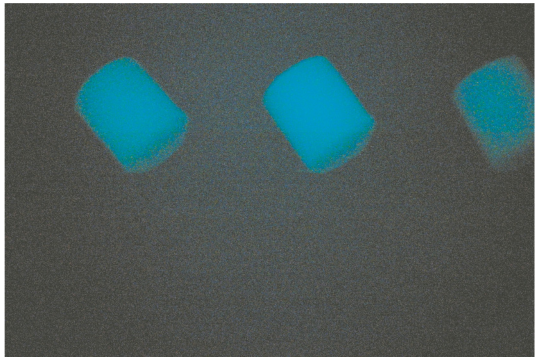
#030114-01, *d* = 9.80 mm, $p_{chamber}$ = 90 Torr, *U* = 113 m/s



#030109-02, *d* = 9.95 mm, $p_{chamber}$ = 90 Torr, *U* = 85 m/s



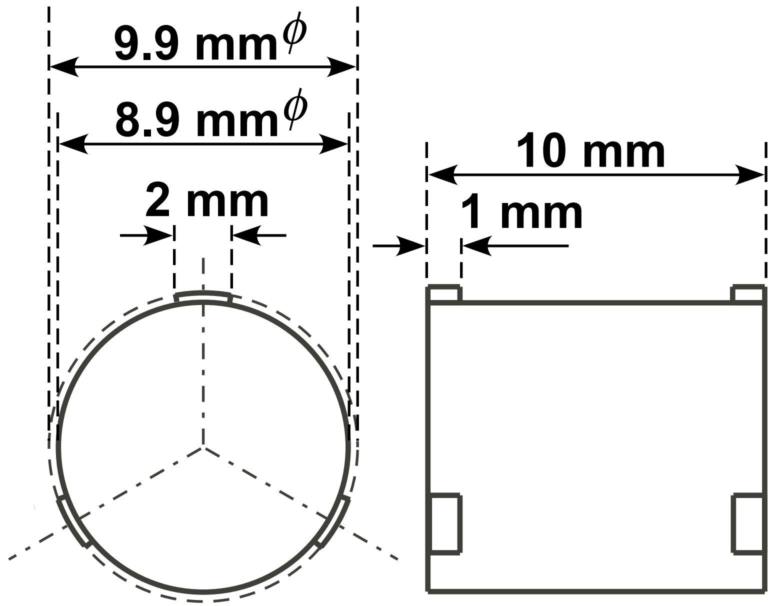
#030116-01, *d* = 9.60 mm, $p_{chamber}$ = 7 Torr, *U* = 116 m/s



#030116-02, *d* = 9.80 mm, $p_{chamber}$ = 8 Torr, *U* = 112 m/s

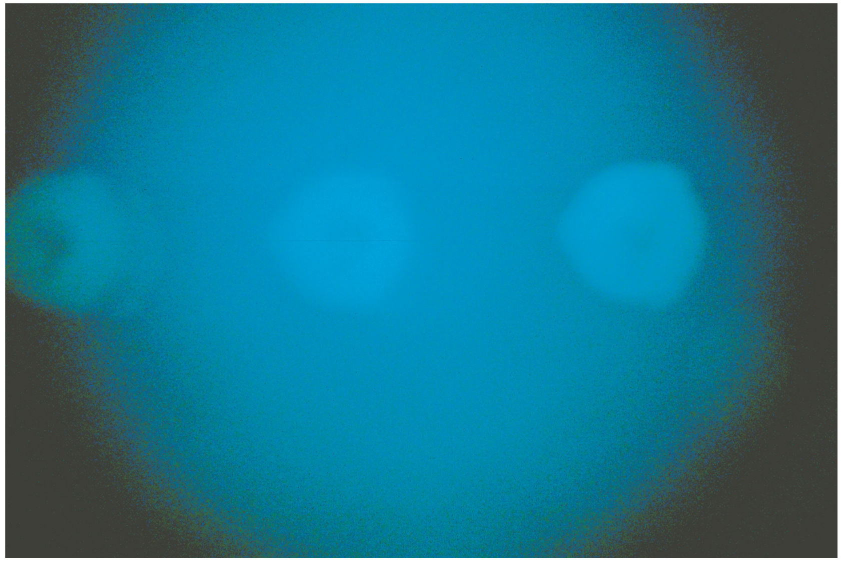
Targets were flying with rotation.

We tried to stop the target rotation. But it failed.



$m/A = 1.38\ \mathrm{g/cm^2}$

Expected target speed was 105 m/s (1st-order model) ～ 121 m/s (0th-order model).



#030131-03, *d* = 9.90 mm, $p_{chamber}$ = 70 Torr, *U* = 93 m/s

The target was flying with rotation.

Summary

- We discussed a target injection system which consisted of acceleration, projection and diagnostics modules.

- We discussed gas dynamic issues on target acceleration. The DT-ice strength is a key parameter. The quality of flying targets should be diagnosed, but it may be very difficult.

- We started simple experiments on target acceleration for accumulating experiences.
  To stop the target rotation, rifling may be necessary.