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

Target with sabot

Evacuation

Projecting-Direction Adjuster

Sabot Remover

Magnet

Kicker

Acceleration Module

Projection Module
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

\[ p = p_1 \]

Target with sabot

Valve

Accelerating Gas

Reservoir

Acceleration Tube with Rifling

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

\[
\frac{dU}{dt} = \frac{p_1}{m/A} = \text{const.}
\]

\[
x = \frac{1}{2} \frac{m/A}{p_1} U^2 \quad \leftrightarrow \quad U = \sqrt{2 \frac{p_1}{m/A} x}
\]

\[
t = \frac{m/A}{p_1} U
\]

Conditions

\[ p_1 = 1 \text{ atm} \]

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

He gas, \( T_1 = 300 \text{ K} \)
The DT-ice strength is a key parameter

\[ p = p_1 \]

Valve

Reservoir

Accelerating Gas \( p = p_1 \)

Target with sabot

Acceleration Tube with Rifling

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

\[ p = p_1 \]

Valve

\[ \text{Target with sabot} \]

Reservoir

[Image: Accelerating Gas]

\[ p < p_1 \]

[Image: Acceleration Tube with Rifling]

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

\[ U: \text{Target Speed} \]
\[ p_1: \text{Reservoir Pressure} \]
\[ c_1: \text{Reservoir Sonic Speed} \]
\[ \gamma: \text{Specific-Heat Ratio} \]
\[ \frac{2}{\gamma - 1} c_1 \]
\[ m/A: \text{Areal Mass Density of the Target} \]

\[
\frac{dU}{dt} = \frac{p_1}{m/A} \left( 1 - \frac{U}{u_{\text{max}}} \right)^{\frac{2\gamma}{\gamma - 1}}
\]

\[
\begin{align*}
x &= \frac{2c_1^2}{\gamma + 1} \frac{m/A}{p_1} \left[ 1 - \left( 1 - \frac{\gamma + 1}{\gamma - 1} \frac{U}{u_{\text{max}}} \right) \left( 1 - \frac{U}{u_{\text{max}}} \right)^{\frac{\gamma + 1}{\gamma - 1}} \right] \\
t &= \frac{2c_1}{\gamma + 1} \frac{m/A}{p_1} \left[ \left( 1 - \frac{U}{u_{\text{max}}} \right)^{\frac{\gamma + 1}{\gamma - 1}} - 1 \right]
\end{align*}
\]

Conditions

\[ p_1 = 1 \text{ atm} \quad \text{corresponding to} \quad \left( \frac{dU}{dt} \right)_{\text{max}} \approx 500 \text{ g when } m/A \approx 2 \text{ g/cm}^2 \]

He gas. \( T_1 = 300 \text{ K} \)
Compressibility of the gas is not effective

\[ p = p_1 \]

Target with sabot

Valve

\[ p < p_1 \]

Accelerating Gas

Reservoir

Acceleration Tube with Rifling

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)

\[
\frac{v_x(y, t)}{v_0} = 1 - \text{erf} \left( \frac{y}{\sqrt{4vt}} \right), \quad \left( v = \frac{\mu}{\rho} \right)
\]

\[
1 - \text{erf} (0.48) \approx 0.5
\]
\[
1 - \text{erf} (1.16) \approx 0.1
\]
\[
1 - \text{erf} (1.39) \approx 0.05
\]
\[
1 - \text{erf} (1.82) \approx 0.01
\]
Boundary-layer thickness is comparable to the radius of the acceleration tube

He gas at 300 K \( \mu = 2.0 \times 10^{-5} \text{ kg/(m\cdot s)} \)

\( p_1 = 1 \text{ atm} \Rightarrow v = \mu / \rho = 1.2 \times 10^{-4} \text{ m}^2/\text{s} \)

\( \frac{v_x(y,t)}{v_0} = 1 - \text{erf} \left( \frac{y}{\sqrt{4vt}} \right) \approx 0.5 \Rightarrow \frac{y}{\sqrt{4vt}} = 0.48 \)

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

\[
\begin{align*}
\text{Graph:} & \quad y = 0.48(4vt)^{1/2} \\
\text{Data:} & \quad d = 5 \text{ mm, } y = 1 \text{ mm} \\
& \Rightarrow \frac{\pi \left( \frac{d}{2} - y \right)^2}{\pi \left( \frac{d}{2} \right)^2} = 0.36 \\
& \quad \text{and} \\
& \quad d = 5 \text{ mm, } y = 2 \text{ mm} \\
& \Rightarrow \frac{\pi \left( \frac{d}{2} - y \right)^2}{\pi \left( \frac{d}{2} \right)^2} = 0.04
\end{align*}
\]
At all events we started target-acceleration experiments to accumulate experiences.
We used polymer cylinders as accelerated targets

Pressure Gauge

Vacuum Chamber

Vacuum Pump

Acceleration Tube

Valve

Compressor (Valve Drive)

Windows

Acceleration Tube

Cylindrical Target

$L = 10 \text{ mm}$

Valve (3-way)

Orifice: $d = 8 \text{ mm}$

Vacuum to Atmosphere: 5 ms

Atmosphere to Vacuum: 6 ms
We used LEDs and a digital camera for diagnostics.
Expected target speed was 120 m/s (1st-order model) \sim 142 \text{ m/s (0th-order model)}

Experimental Conditions: 
- \text{Air } (28.8619 \text{ g/mol}), \quad \gamma = 7/5
- p_i = 1 \text{ atm}, \quad T_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, \(p_{\text{chamber}} = 90\) Torr, \(U = 109\) m/s

#030114-01, \(d = 9.80\) mm, \(p_{\text{chamber}} = 90\) Torr, \(U = 113\) m/s

#030109-02, \(d = 9.95\) mm, \(p_{\text{chamber}} = 90\) Torr, \(U = 85\) m/s

#030116-01, \(d = 9.60\) mm, \(p_{\text{chamber}} = 7\) Torr, \(U = 116\) m/s

#030116-02, \(d = 9.80\) mm, \(p_{\text{chamber}} = 8\) Torr, \(U = 112\) m/s

Targets were flying with rotation.
We tried to stop the target rotation. But it failed.

\[ \frac{m}{A} = 1.38 \text{ g/cm}^2 \]

Expected target speed was 105 m/s (1st-order model)
\sim 121 \text{ m/s (0th-order model)}.

#030131-03, \( d = 9.90 \text{ mm} \),
\( p_{\text{chamber}} = 70 \text{ Torr} \),
\( U = 93 \text{ m/s} \)

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.