APPENDIX I

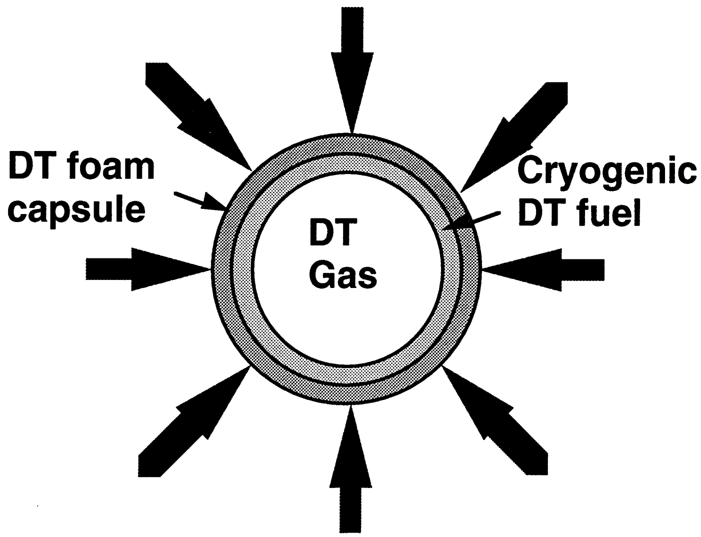
TARGET INJECTION AND TRACKING

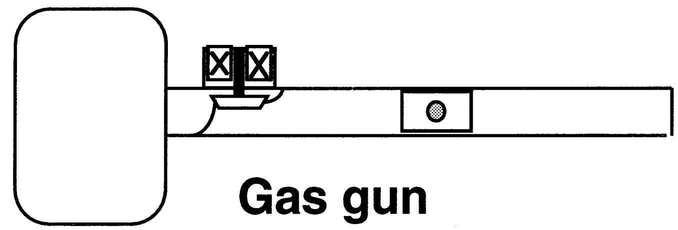
BY

RON PETZOLDT

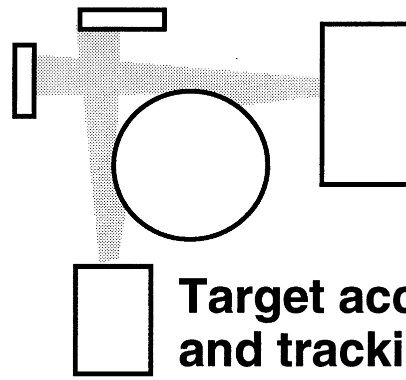
Direct drive target injection and tracking issues for IFE

Radiation and gas heating





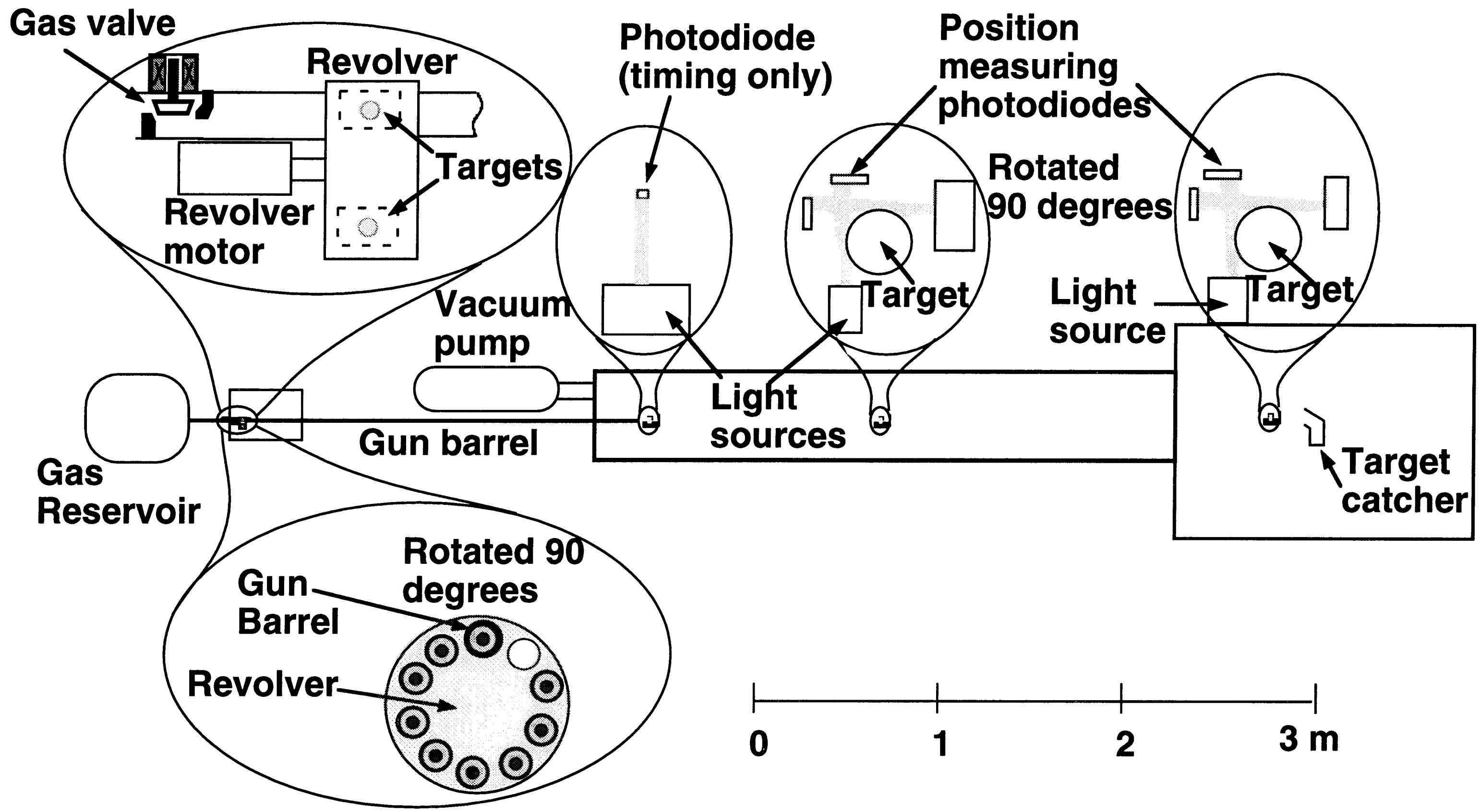
Gas gun acceleration



Target accuracy and tracking accuracy

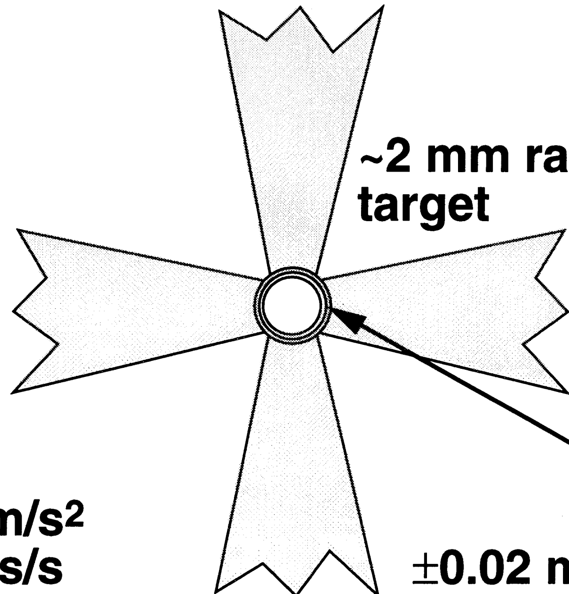
Ron Petzoldt
Direct Drive Target Workshop
15 September 1999

We have demonstrated the feasibility of accurate indirect drive target injection and tracking



Ref:
IFE Target Injection and Tracking Experiment
Fusion Technology Vol. 34 Nov. 1998 pp. 831-839

Targets must be precisely tracked into the reaction chamber at a speed of about 400 m/s



$v \sim 400$ m/s
$a \sim 10{,}000$ m/s^2
$f \sim 6$ targets/s
$L \sim 15$ m standoff

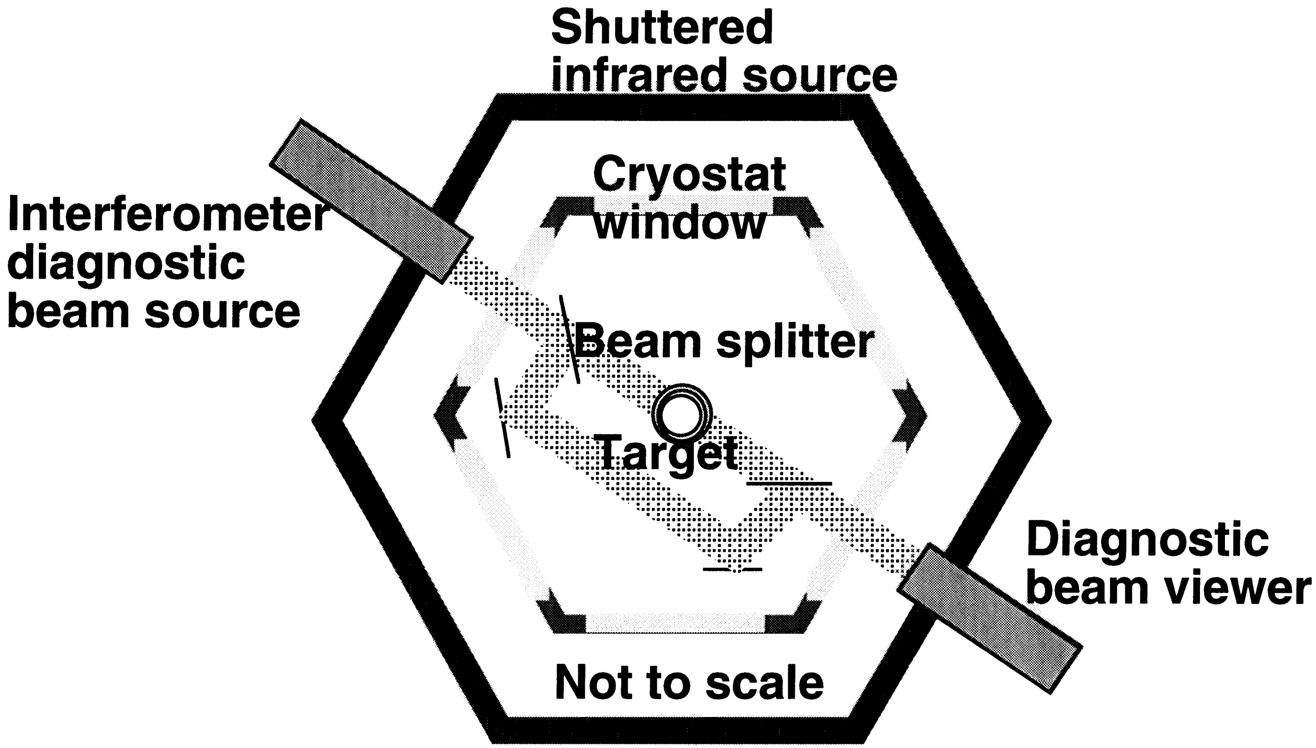
±0.02 mm position error (beam on target)
± 5 mm shot to shot position error

Total error of ± 0.02 mm { Target tracking error ± 0.014 mm; Beam pointing error ± 0.014 mm }

Total error of ± 0.02 mm		
	Target tracking error	± 0.014 mm
	Beam pointing error	± 0.014 mm

Cryogenic fuel temperature rise ~0.5 K at surface

Target response to a surface heat load should be measured



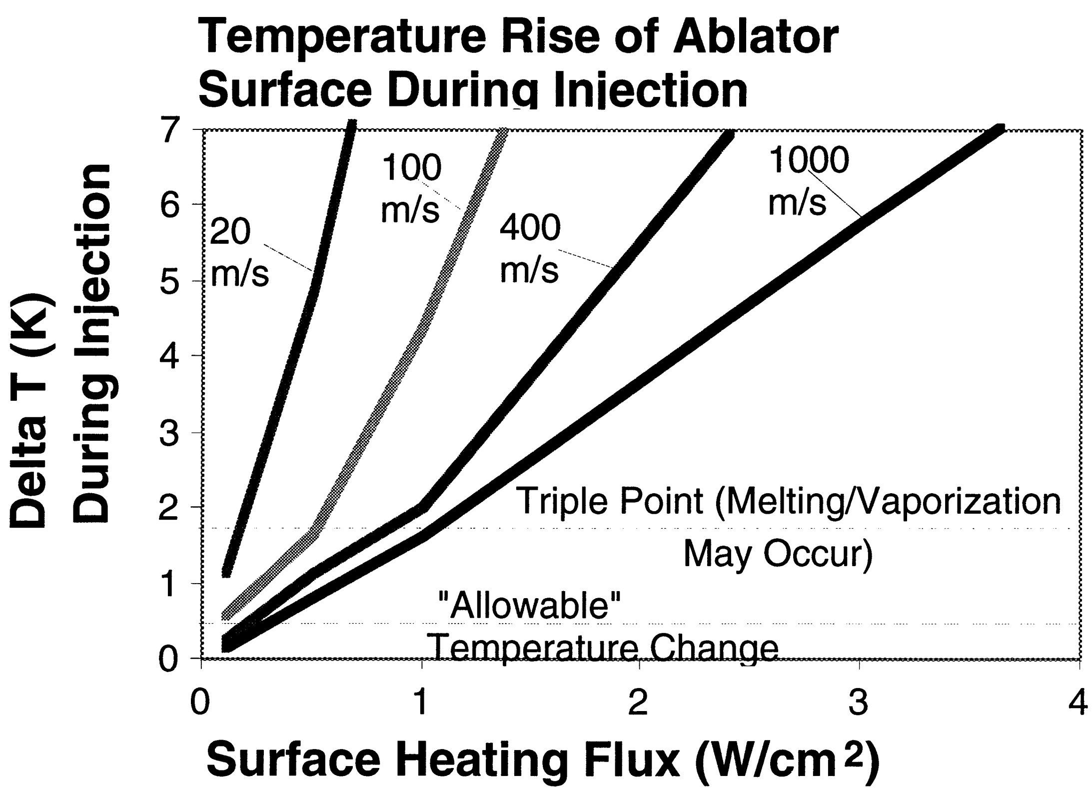
$$\dot{q}_{rad} = \varepsilon\sigma T^4$$

$$\approx (0.01)(5.67 \times 10^{-12}\,\mathrm{W/cm^2K^4})(1758\ \mathrm{K})^4$$

$$= 0.54\ \mathrm{W/cm^2}$$

radiative heat load exp

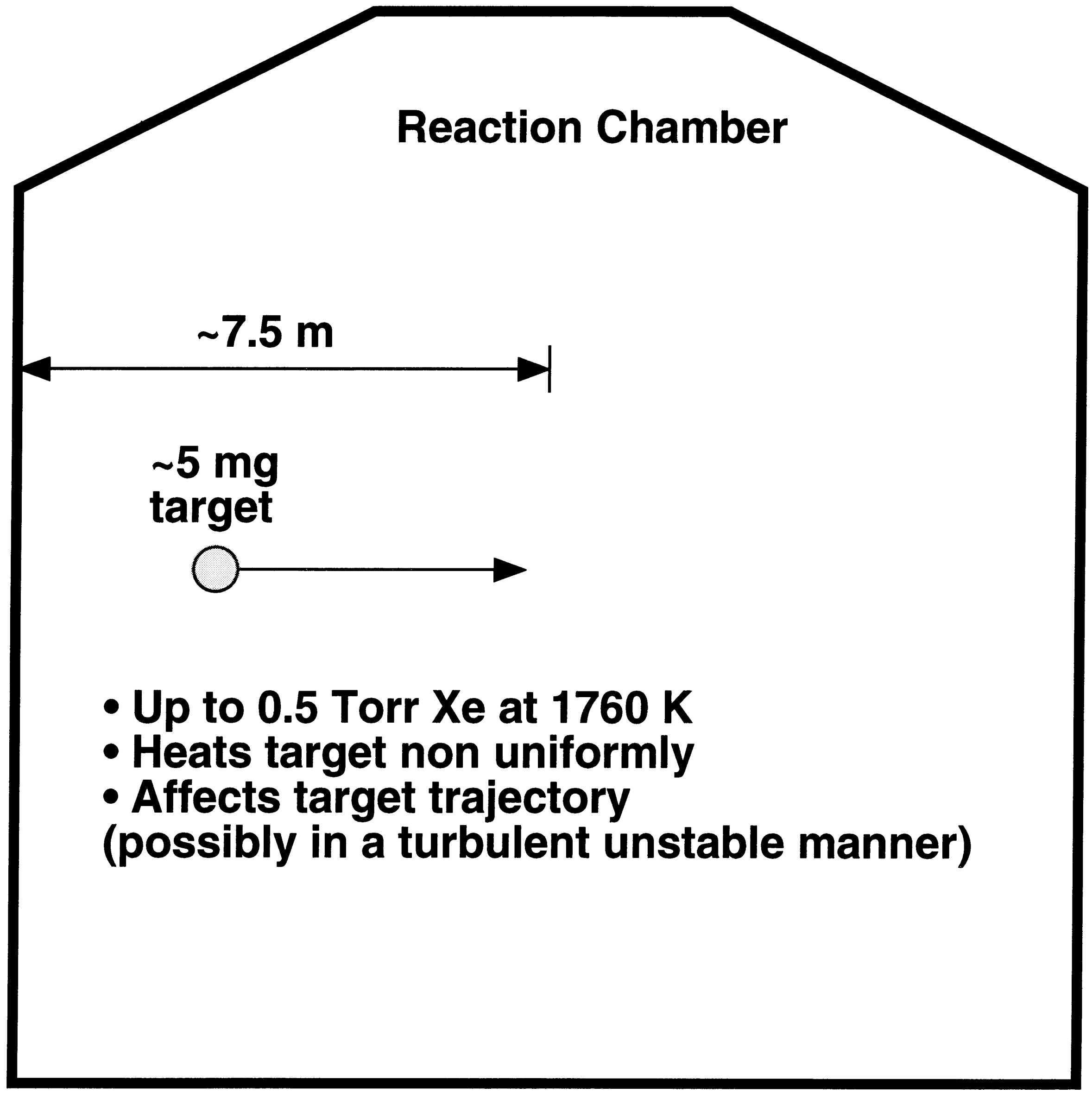
For constant heat flux, final surface temperature decreases little as speed increases above 400 m/s



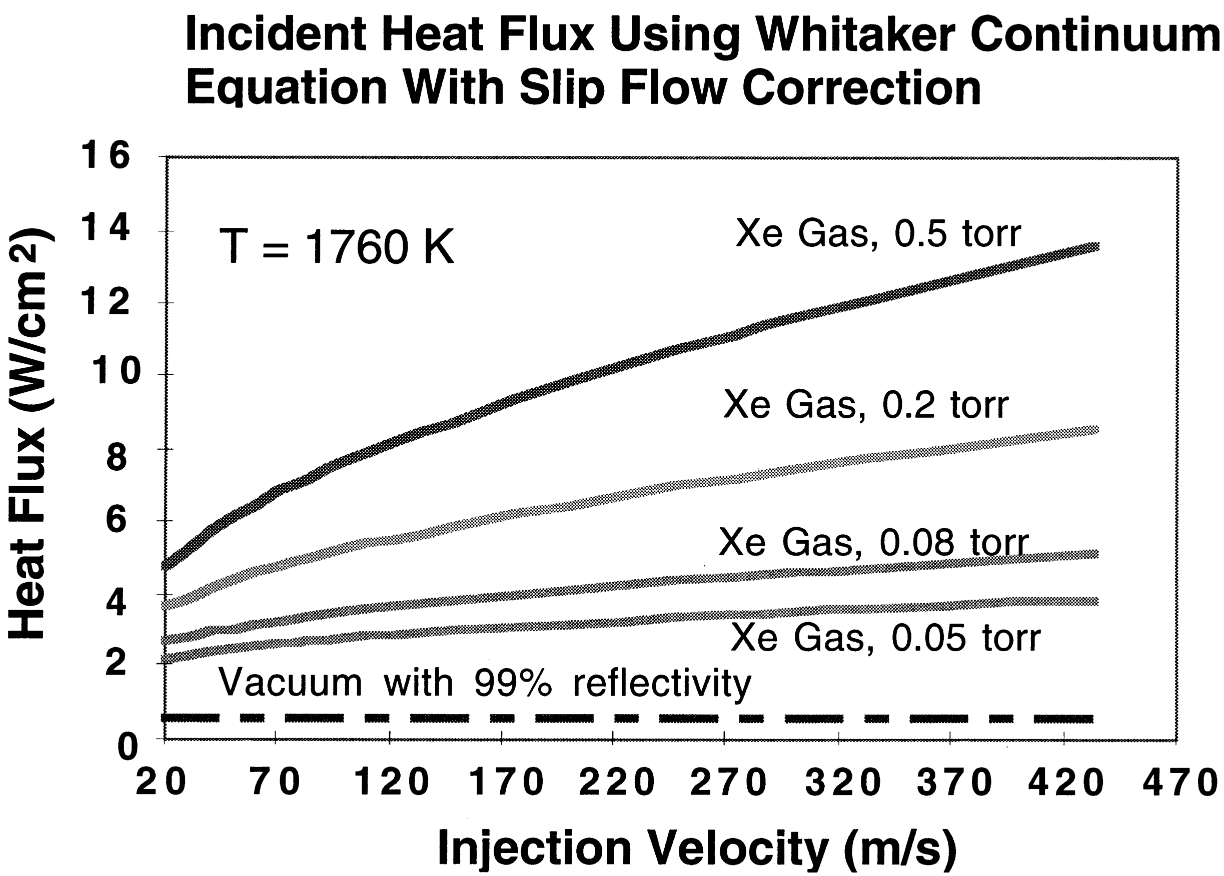
(Assumes 7 m chamber radius with NRL radiation preheat target)

Temp vs heat flux

Gas proposed to protect chamber walls will adversely affect direct drive targets



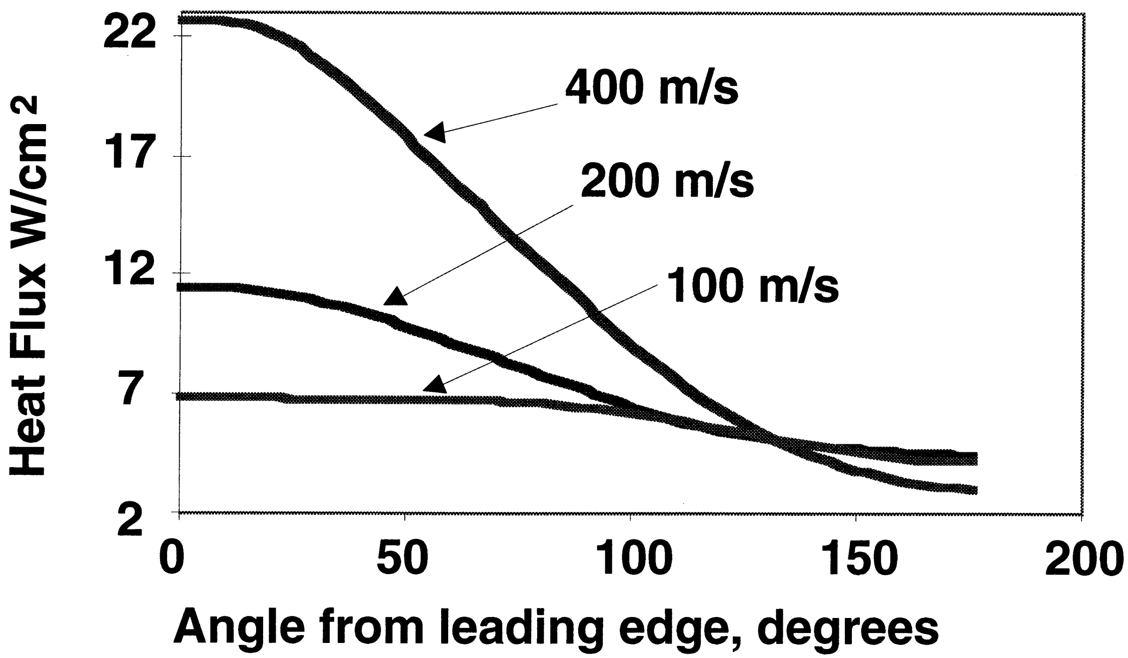
Gas heat loads are too high, even at 0.05 Torr, and increase with injection speed



Gas heat flux

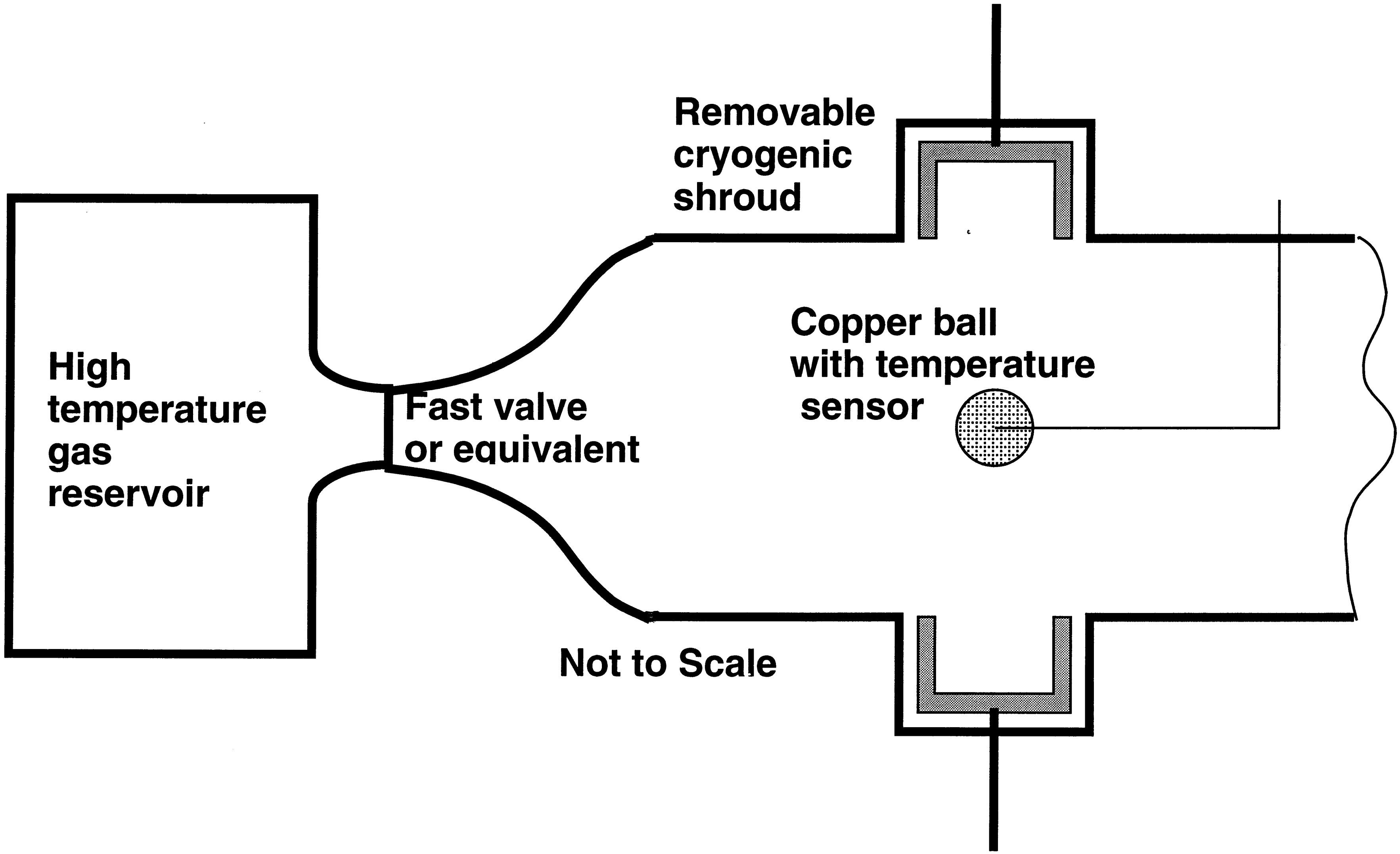
Gas heat loads are quite asymmetric

Heating distribution for direct-drive IFE target
Diameter= 3.904 mm, T=1758 K, P xenon=0.5 torr



Heat flux asymmetry

Gas heat flux calculations should be experimentally verified (if feasible)



Characteristic times for gas heating experiment look good

Assume 1 cm radius spherical copper ball at 20 K

with about 1 W / cm^2 average heat flux

$\rho = 9 g / cm^2$

$k = 105\ W / cm \cdot K$ at 20 K; $68\ W / cm \cdot K$ at 25 K

$c_p = 7\ mJ / g \cdot K$ at 20 K; $15\ mJ / g \cdot K$ at 25 K

$\alpha = k / \rho c = 1600\ cm^2 / s$ at 20 K

Characteristic thermal diffusion time

$$t_d = r^2 / k = \frac{(1\ cm)^2}{1600\ cm^2 / s} = 0.7\ ms$$

$m = \rho (4/3) \pi r^3 = 38\ g$

$E = mc\Delta T = (38\ g)(7\ mJ / g \cdot K)(1\ K) = 0.26\ J$

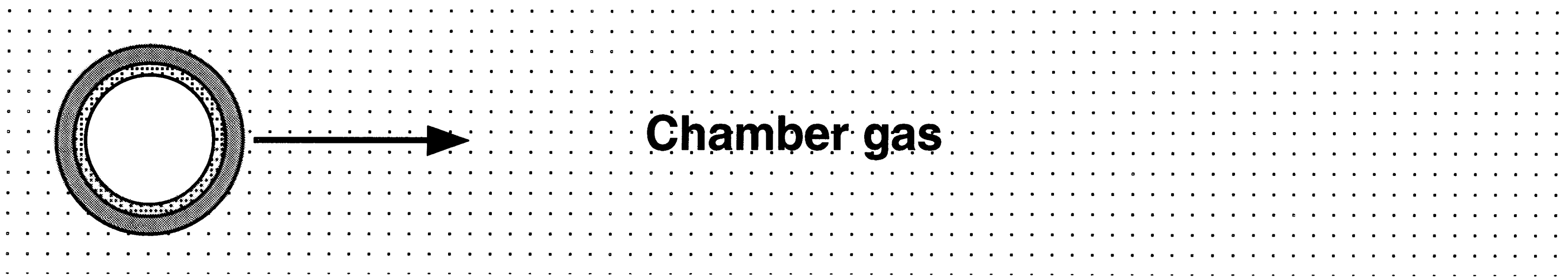
(for 1 K temperature increase)

$P = \phi 4 \pi r^2 = (1\ W / cm^2)(4)(3.14)(1\ cm)^2 = 12.6\ W$

Time for 1 K temperature increase

$t_{1K} = E / P = 0.26\ J / 12.6\ W = 21\ ms$

Chamber protection gas significantly affects direct drive target trajectory



The mass of gas in the target path is

$$m = \pi r_T^2 \rho r_c = 3.14(0.2\ \text{cm})^2 (4 \times 10^{-3}\ \text{mg/cm}^3)(750\ \text{cm}) = 0.38\ \text{mg}$$

The change in target position due to gas slowing in the chamber is

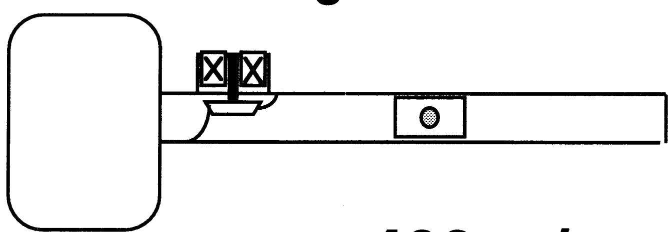
$$r_c \frac{\Delta v_{ave}}{v_{ave}} = r_c \frac{v_i - v_f}{2v_{ave}} \approx r_c \frac{m_g}{2(m_g + m_t)} = 750\ \text{cm} \frac{0.38}{10} = 28\ \text{cm}$$

There are possibilities for reducing the chamber gas pressure.

- Current target designs have reduced x-ray emissions
- Plasma debris could be redirected by magnetic fields
- Liquid surfaces could reduce the need for protective gases

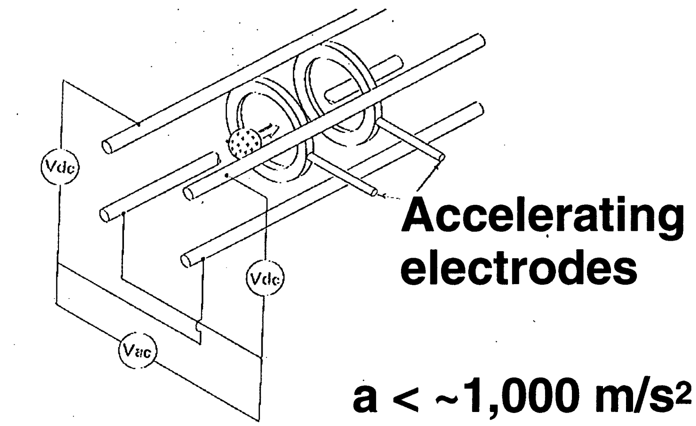
Among several possibilities, the gas gun is our recommended experimental target injector

Gas gun



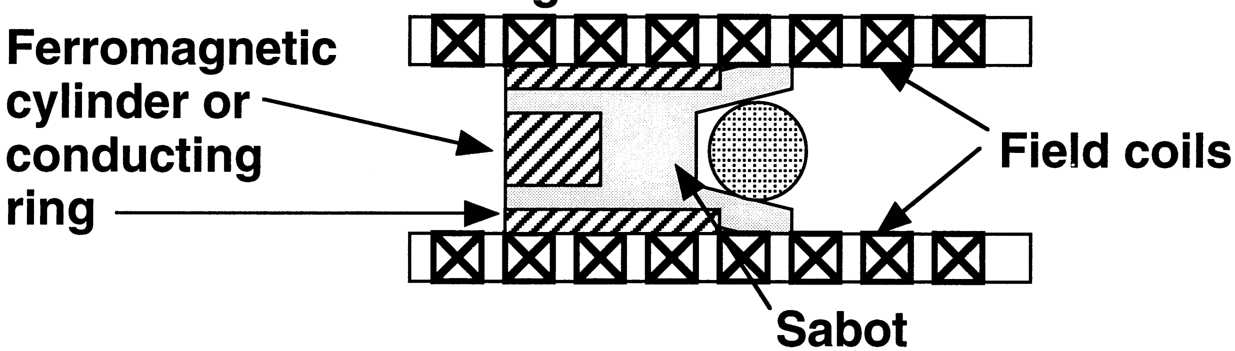
v < ~400 m/s

Electrostatic accelerator



$a < \sim 1{,}000\ m/s^2$

Magnetic accelerator



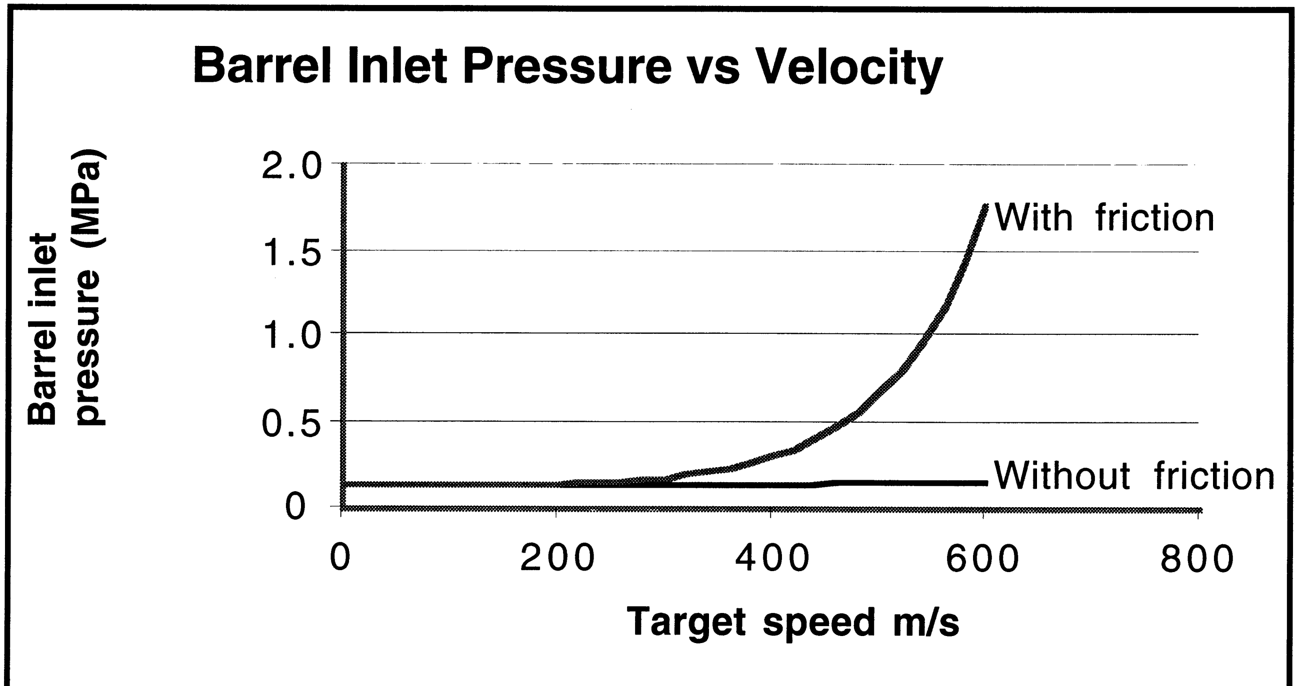
direct drive options

Gas friction increases faster than u^4
This limits max feasible speed

$$F_{fg} = \frac{m_g c_f u^2}{r_p} \qquad c_f \approx 0.049 N_{\mathrm{Re}}^{-1/5} \approx 0.005$$

$$p_i = p_a + p_f = p_0 + \frac{m_g \alpha}{A} + \frac{F_f}{A} = p_0 + \frac{m_g}{\pi r_p^2}\left(\alpha + \frac{c_f u^2}{r_p}\right)$$

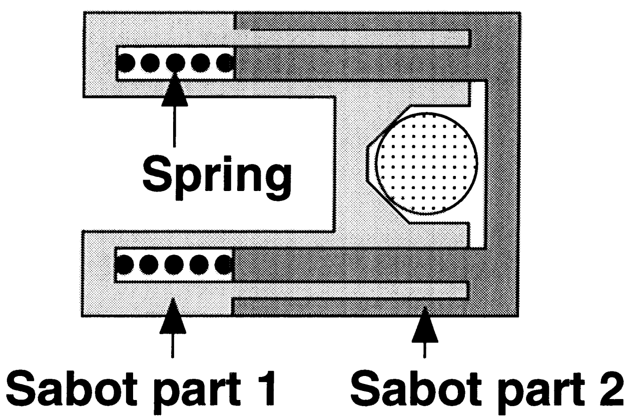
$$m_g = \int \rho dV = \pi r_p^2 \int_0^{x_p} \rho dx \qquad \rho = \rho_0 \left(\frac{p}{p_0}\right)^{\frac{1}{\gamma}}$$

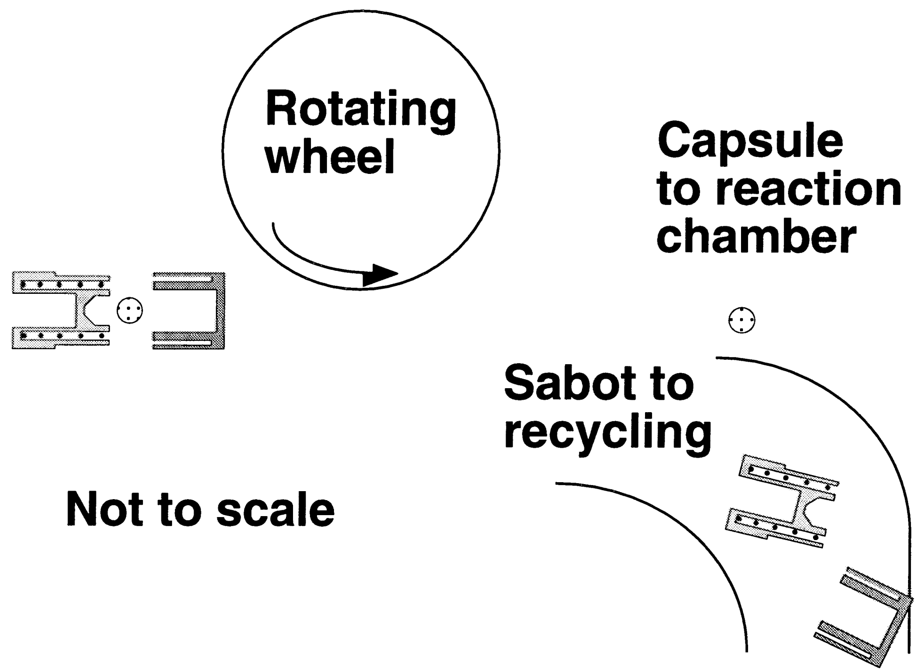


gas friction graph

1 g, 1 cm diameter target with 10,000 m/s^2 acceleration by room temperature hydrogen

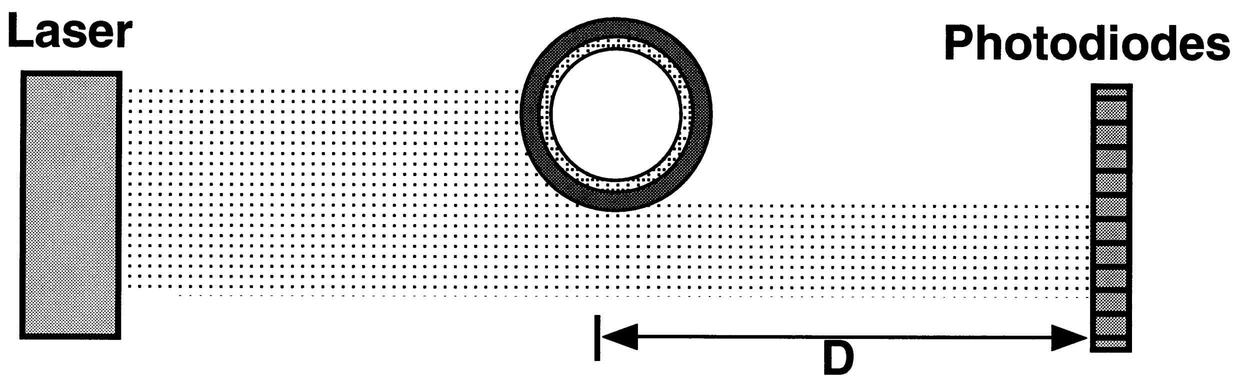
A spring loaded sabot could protect a capsule from gas heating during and immediately after acceleration





two piece sagot

Photodiode detector technology might achieve the required direct drive tracking accuracy



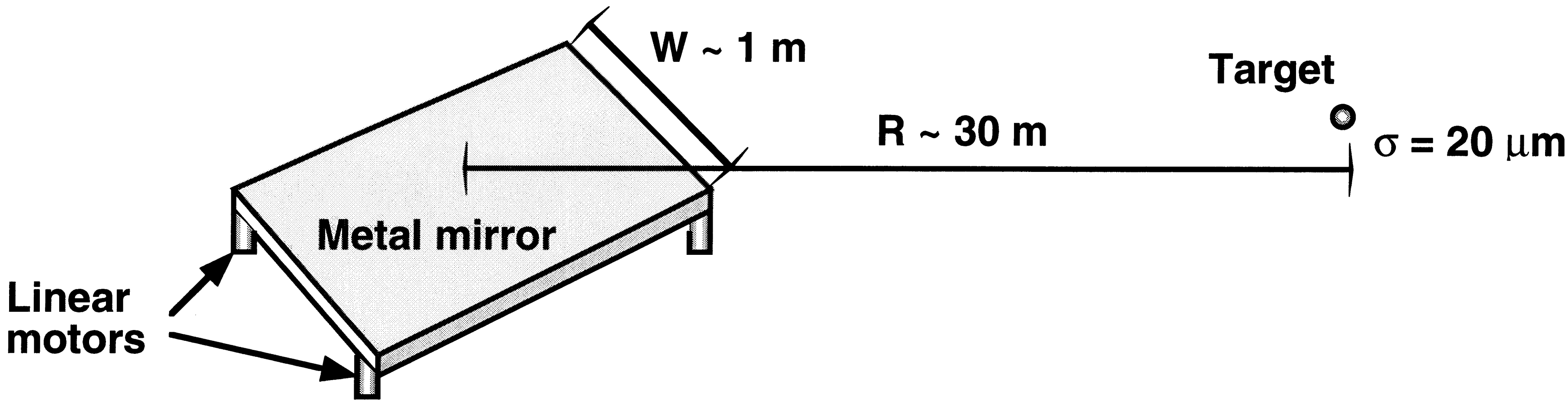
Measuring voltage output from several small photodiodes will increase position measurement sensitivity.

Sensor position control and/or feedback will be critical.

Required accuracy has yet to be demonstrated.

Diffraction will be important especially for large D
Shadow washout $d \sim \sqrt{D\lambda}$ **? I need to review this more.**

Linear motors with grazing incidence mirrors should provide adequate beam position control.



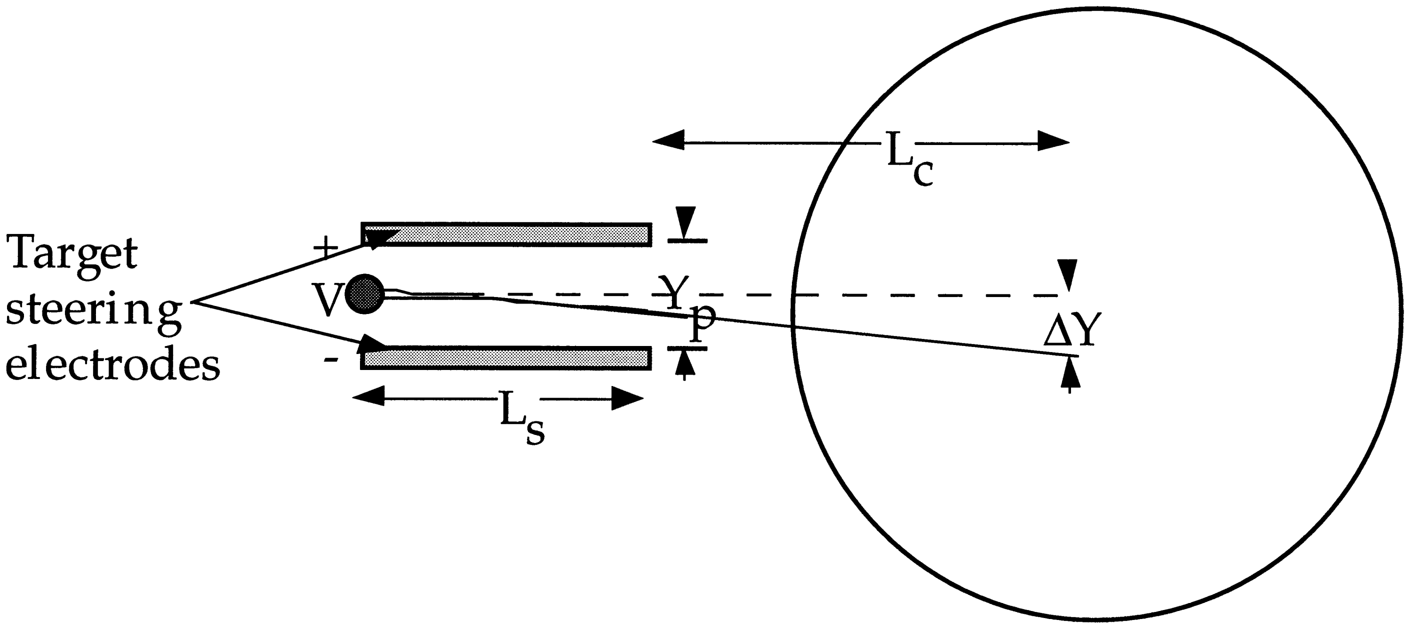
Required motor position accuracy $\approx \frac{W}{2}\frac{\sigma}{R} \approx \frac{1\text{ m}}{2}\frac{20\ \mu\text{m}}{30\text{ m}} = 0.3\ \mu\text{m}$

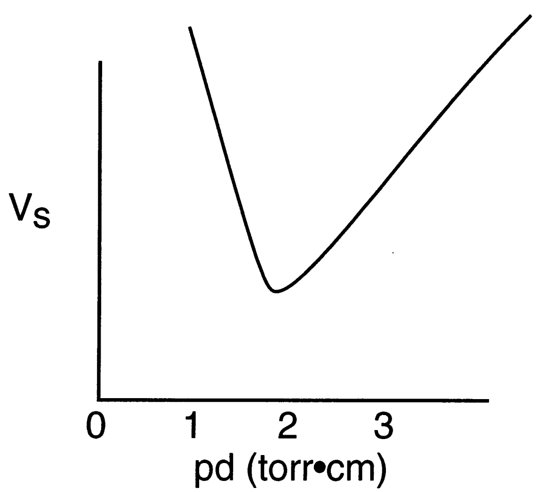
is well within state of the art motor accuracy of 0.02 μm. Required forces and response time are also within motor capabilities.

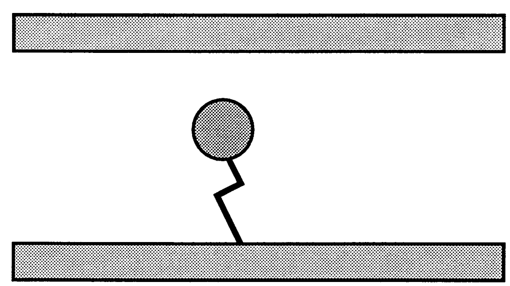
Remaining concerns for beam steering include position calibration and feed back.

Repositioning smaller optics early in beam might be preferred.

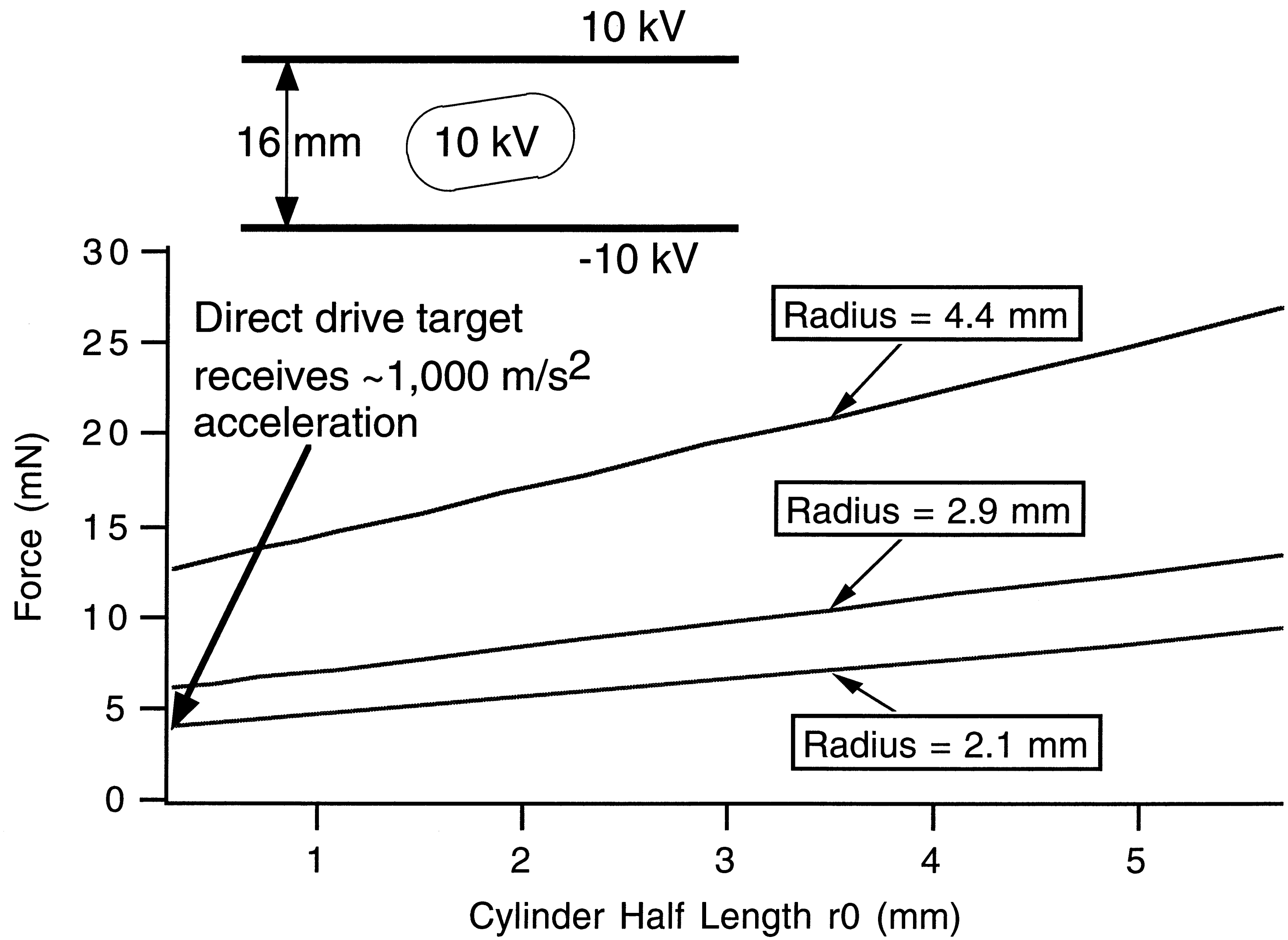
Electrostatic target steering is possible but electrical breakdown can occur especially with gases present





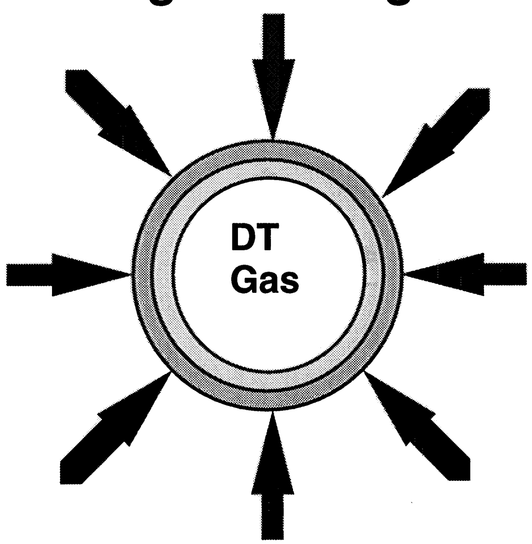


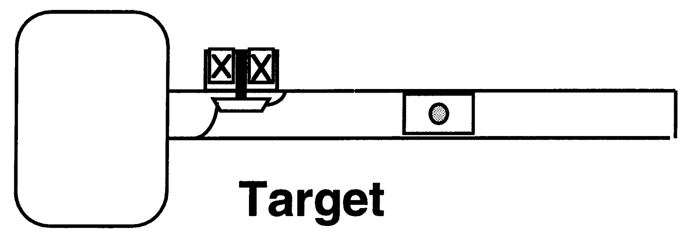
Target steering force due to 10 kV potentials was calculated



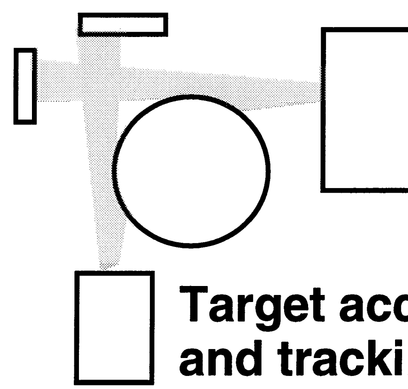
Conclusions:
Three significant issues facing direct drive IFE are target temperature limits and control, target injection and tracking accuracy, and allowable target acceleration. Resolving these issues will require significant analytical and experimental work.

Radiation and gas heating



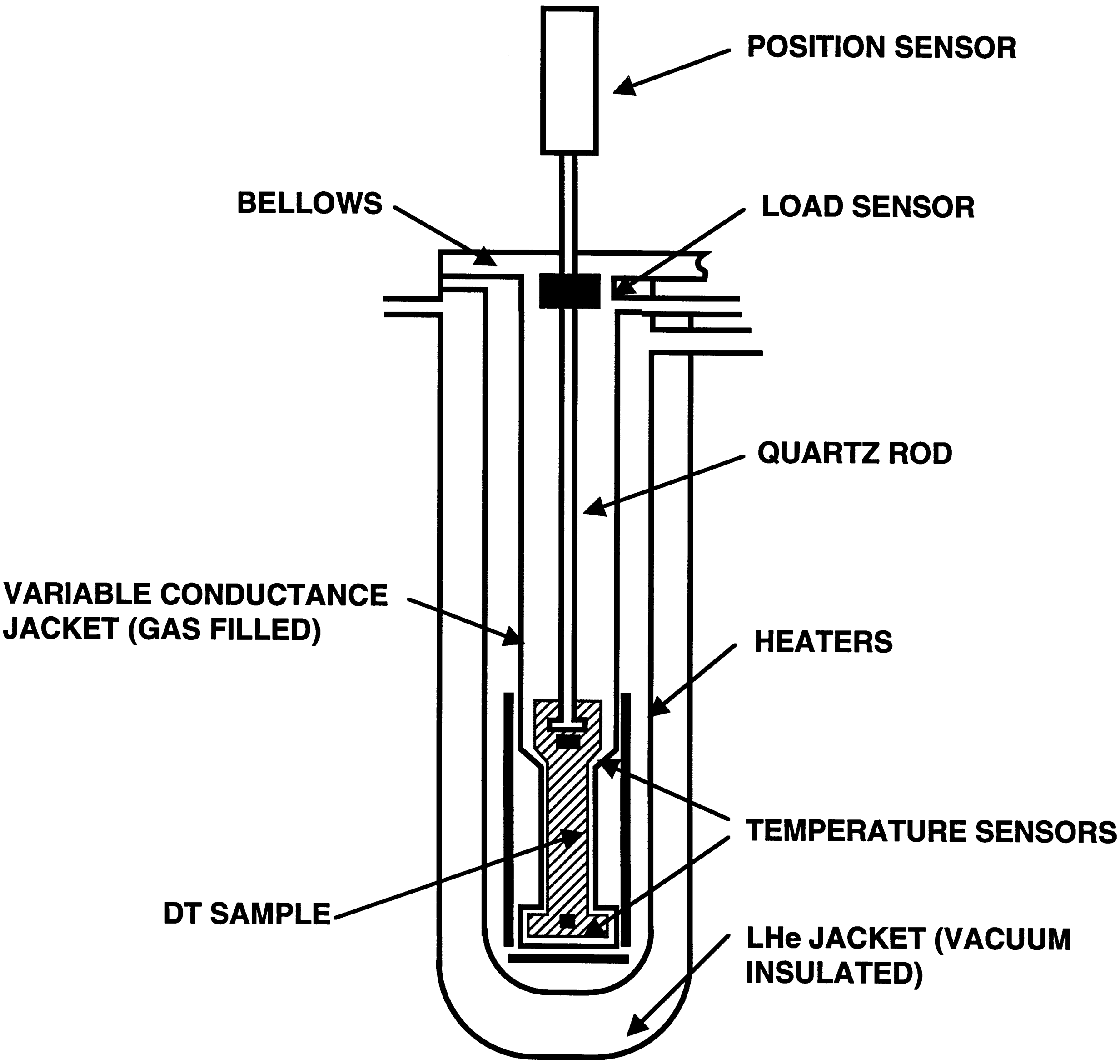


Target acceleration



Target accuracy and tracking accuracy

CONCEPTUAL LAYOUT OF DT STRENGTH MEASUREMENT EQUIPMENT



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GENERAL ATOMICS