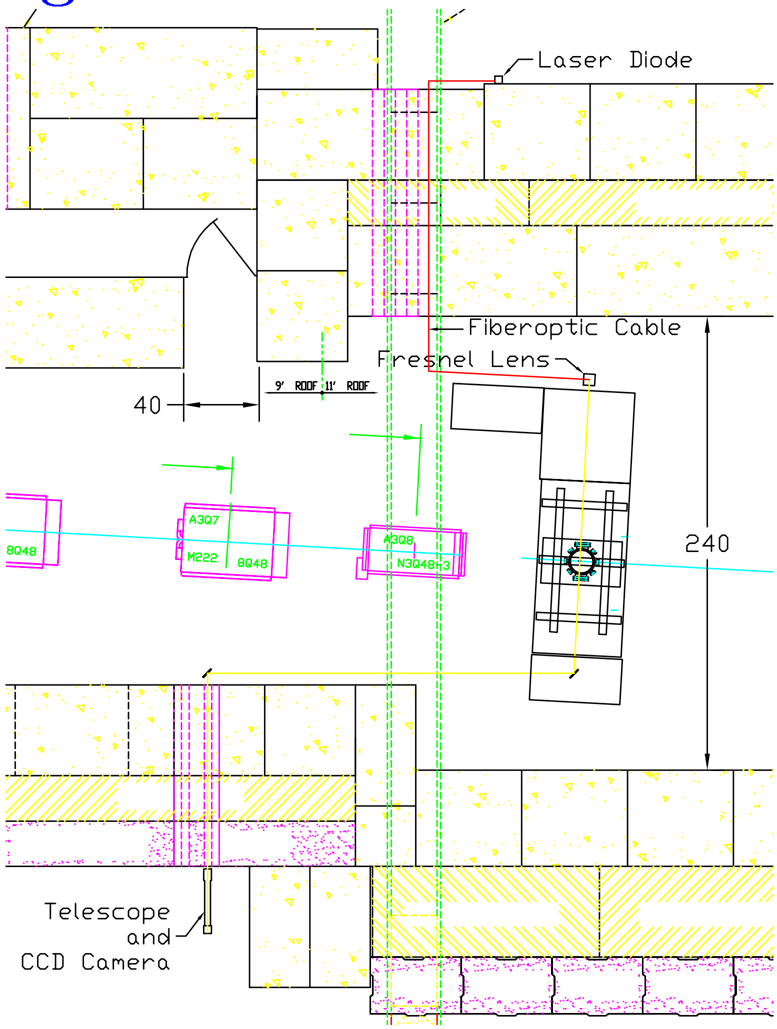
# Tests of Targets

# Interacting with an Intense Proton Pulse




K.T. McDonald

*Princeton U.*

December 15, 2000

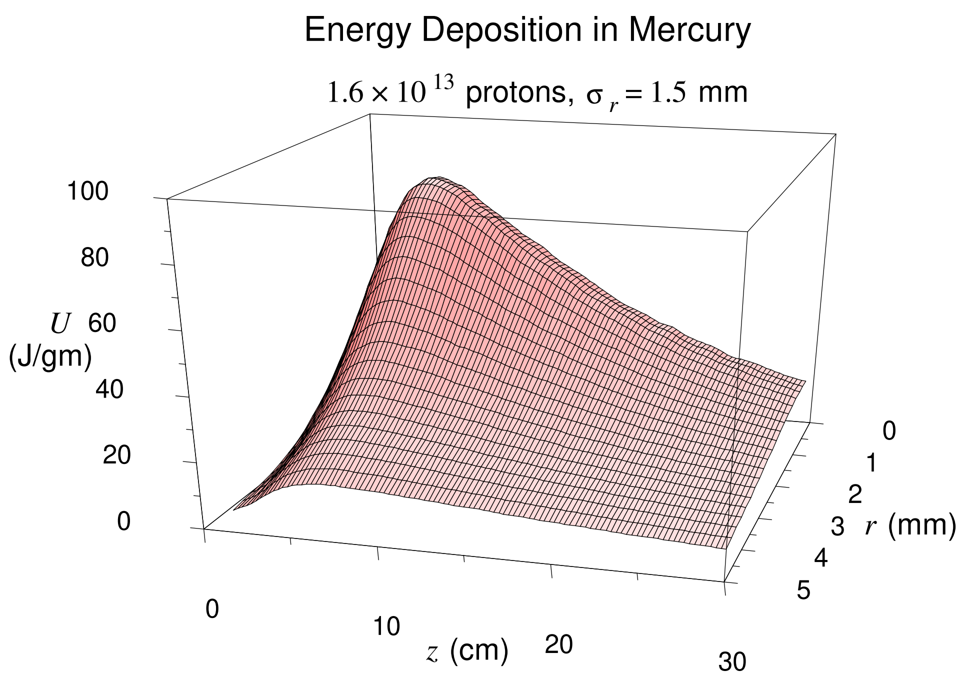
*Targetry Workshop, BNL*

http://puhep1.princeton.edu/mumu/target/

# The Need for a Moving Target

For high yield of pions from a target in a 24 GeV proton beam, use a high-$Z$ material of $\approx 1$ cm transverse dimension.

Peak energy deposition is $U \approx 100$ J/gm from a nsec pulse of $1.6 \times 10^{13}$ protons with radius $\sigma_r = 1.5$ mm.




$\Rightarrow$ A static, high-$Z$ target would melt after a few beam pulses, unless in contact with a massive heat sink.

But, massive heat sink $\Rightarrow$ poor pion collection efficiency.

Solution: a moving target, such as a **liquid metal jet**.

# Properties of Some Candidate Target Materials

| Element | $Z$ | Density<br>(g/cm$^3$) | Melting Temp.<br>(°C) | Boiling Temp.<br>(°C) | Heat Cap.<br>(J/g-°C) | Heat of Vapor.<br>(J/g) | Thermal Cond.<br>(W/cm-°C) | Resist.<br>($\mu\Omega$-cm) | Thermal Exp.<br>($10^{-5}$/°C) |
|---|---|---|---|---|---|---|---|---|---|
| Copper | 29 | 8.96 | 1087 | 2567 | 0.39 | 4796 | 4.01 | 1.7 | 1.7 |
| Zinc | 30 | 7.1 | 420 | 906 | 0.39 | 1733 | 1.16 | 6.0 | 3.1 |
| Gallium | 31 | 5.9 | 30 | 2204 | 0.33 | 3712 | 0.4 | 26$^\dagger$ | 12 |
| Indium | 49 | 7.3 | 156 | 2073 | 0.23 | 2016 | 0.82 | 10 | 3.2 |
| Tin | 50 | 7.3 | 232 | 2270 | 0.18 | 2487 | 0.67 | 13 | 2.2 |
| Mercury | 80 | 13.6 | −39 | 357 | 0.14 | 295 | 0.087 | 94$^\dagger$ | 6.1 |
| Lead | 82 | 11.35 | 327 | 1750 | 0.16 | 858 | 0.35 | 80$^\dagger$ | 2.9 |
| Bismuth | 83 | 9.7 | 271 | 1610 | 0.12 | 857 | 0.079 | 120 | 1.3 |

$^\dagger$ liquid

# Candidate Liquid Metals

| Approximate melting point, °C | Approximate composition, wt % |
|---|---|
| 185 | 48 bismuth, 52 thallium (eutectic) |
| 180 | 38 lead, 62 tin (eutectic) |
| 140 | 60 bismuth, 40 cadmium (eutectic) |
| 140 | 58 bismuth, 42 tin (eutectic) |
| 130 | 56 bismuth, 40 tin, 4 zinc (eutectic) |
| 125 | 44.5 bismuth, 55.5 lead (eutectic) |
| 120 | 25 cadmium, 75 indium (eutectic) |
| 117 | 48 tin, 52 indium (eutectic) |
| 105 | 48 bismuth, 28.5 lead, 14.5 tin, 9.0 antimony (matrix alloy) |
| 93 | 50 bismuth, 25 lead, 25 tin |
| 91.5 | 51.6 bismuth, 40.2 lead, 8.2 cadmium (eutectic) |
| 71.7-69.7 | 50 bismuth, 25 lead, 12.5 tin, 12.5 cadmium (Wood's metal) |
| 70 | 33 bismuth, 67 indium (eutectic) |
| 70 | 50 bismuth, 26.7 lead, 13.3 tin, 10 cadmium (eutectic) |
| 60.5 | 32.5 bismuth, 16.5 tin, 51 indium |
| 58.2 | 49.5 bismuth, 17.6 lead, 11.6 tin, 21.3 indium |
| 46.5 | 40.63 bismuth, 22.11 lead, 10.65 tin, 8.2 cadmium, 18.1 indium |
| 33 | 32 potassium, 68 rubidium (eutectic) |
| 17 | 12 tin, 6 zinc, 82 gallium (eutectic) |
| 10.8 | 12.5 tin, 17.6 indium, 69.8 gallium (eutectic) |
| 10.7 | 16 tin, 21.5 indium, 62.5 gallium (eutectic) |
| −8 | 8 sodium, 92 rubidium (eutectic) |
| −11 | 22 sodium, 78 potassium (eutectic) |
| −30 | 5 sodium, 95 cesium (eutectic) |
| −40 | 87 cesium, 13 rubidium (eutectic) |
| −48 | 23 potassium, 77 cesium (eutectic) |

# Lead Alloys

Attn: Kirk McDonald

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| PHYSICAL PROPERTIES & NOMINAL COMPOSITION | EUTECTIC ALLOYS: BELMONT ALLOY 2451 | EUTECTIC ALLOYS: BELMONT ALLOY 2491 | EUTECTIC ALLOYS: BELMONT ALLOY 2505 | EUTECTIC ALLOYS: BELMONT ALLOY 2562 | EUTECTIC ALLOYS: BELMONT ALLOY 2581 | NON EUTECTIC ALLOYS: BELMONT ALLOY 2431 | NON EUTECTIC ALLOYS: BELMONT ALLOY 2481 | NON EUTECTIC ALLOYS: BELMONT ALLOY 2405 |
|---|---|---|---|---|---|---|---|---|
| Melting Temperature (°F.) | ~~117~~ | ~~136~~ | ~~158~~ | ~~255~~ | ~~281~~ | (No definite melting point, see yield temp.) | | |
| Range (°F.) | 117-117 | 136-136 | 158-158 | 255-255 | 281-281 | 160-190 | 218-440 | 281-338 |
| Yield Temp. (°F.) | 117 | 136 | 158 | 255 | 281 | 162.5 | 240 | 302 |
| Weight Lb./In.$^3$ | .32 | .31 | .339 | .380 | .315 | .341 | .343 | .296 |
| Specific Gravity 20°C | 8.9 | 8.8 | 9.4 | 10.3 | 8.7 | 9.4 | 9.5 | 8.2 |
| Tensile Lb./In.$^2$ | 5400 | 6300 | 5990 | 6400 | 8000 | 5400 | 13000 | 8000 |
| *Elongation in 2" Slow Loading % | 1.5 | 50 | 200 | 60-70 | 200* | 220* | Less than 1% | 200* |
| Brinell Hardness # | 12 | 14 | 9.2 | 10.2 | 22 | 9 | 19 | 22 |
| *Specific Heat Liquid | .035 | .032 | .040 | .042 | .045 | .040 | .04 | .047 |
| *Specific Heat Solid | .035 | .032 | .040 | .03+ | .045 | .040 | .045 | .047 |
| *Latent Heat — Fusion Btu./LB. | 6 | 8 | 14 | 7.2 | 20 | 10 | | 22 |
| *Coefficient of Thermal Expansion | .000025/°C. | .000023/°C. | .000022/°C. | .000021/°C. | .000015/°C. | .000024/°C. | .000022/°C. | .000015/°C. |
| Thermal Conductivity (Solid) Cal/Cm$^2$/°C/Sec .94 = Copper | — | — | *.045 | *.04 | *.05 | *.05 | — | *.09 |
| Conductivity (Electrical) Compared with Pure Copper | 3.34% | 2.43% | 4.17% | 1.75% | 5.00% | 4.27% | 2.57% | 7.77% |
| Resistivity, OHMS based on volume standard (Meter, MM$^2$) | .5180 | .7081 | .4135 | .8825 | .3445 | .4037 | .6696 | .2219 |
| *Maximum Load — 30 Seconds Lb. — In.$^2$ | | | 10000 | 8000 | 15000 | 9000 | 16000 | 15000 |
| *Maximum Load — 5 Minutes Lb. — In.$^2$ | | | 4000 | 4000 | 9000 | 3800 | 10000 | 9500 |
| *Safe Load — Sustained Lb. — In.$^2$ | | | 300 | 300 | 500 | 300 | 300 | 500 |
| Volume Change (Liquid to Solid) | —1.4% | —1.35% | —1.7% | —1.5% | +0.77% | *—2.0% | —1.5% | *+0.5% |
| Volume Change (Linear growth after solidification.) | Less Than 0.05% | Less Than 0.05% | 0.6% | 0.3% | 0.05% | 0.3% | 0.5% | *0% |
| **GROWTH/SHRINKAGE CHARACTERISTICS TIME AFTER CASTING** | FIGURES INDICATED ARE IN INCHES PER INCH AS DETERMINED FROM CUMULATIVE GROWTH MEASURED AS THE DIFFERENCE IN LENGTH BETWEEN MOLD AND TEST BAR DIMENSIONS IN A TEST BAR ½" x ½" x 10". | | | | | | | |
| 2 Minutes | +.0005 | +.0003 | +.0025 | —.0008 | +.0007 | —.0004 | +.0008 | —.0001 |
| 6 Minutes | +.0002 | +.0002 | +.0027 | —.0011 | +.0007 | —.0007 | +.0014 | —.0001 |
| 30 Minutes | .0000 | +.0001 | +.0045 | —.0010 | +.0006 | —.0009 | +.0047 | —.0001 |
| 1 Hour | —.0001 | .0000 | +.0051 | —.0008 | +.0006 | .0000 | +.0048 | —.0001 |
| 2 Hours | —.0002 | —.0001 | +.0051 | —.0004 | +.0006 | +.0016 | +.0048 | —.0001 |
| 5 Hours | —.0002 | —.0002 | +.0051 | .0000 | +.0005 | +.0018 | +.0049 | —.0001 |
| 7 Hours | —.0002 | —.0002 | +.0051 | +.0001 | +.0005 | +.0019 | +.0050 | —.0001 |
| 10 Hours | —.0002 | —.0002 | +.0051 | +.0003 | +.0005 | +.0019 | +.0050 | —.0001 |
| 24 Hours | —.0002 | —.0002 | +.0051 | +.0008 | +.0005 | +.0022 | +.0051 | —.0001 |
| 96 Hours | —.0002 | —.0002 | +.0053 | +.0015 | +.0005 | +.0025 | +.0055 | —.0001 |
| 200 Hours | —.0002 | —.0002 | +.0055 | +.0019 | +.0005 | +.0025 | +.0058 | —.0001 |
| 500 Hours | —.0002 | —.0002 | +.0057 | +.0022 | +.0005 | +.0025 | +.0061 | —.0001 |
| Compositions (%): | | | | | | | | |
| Bismuth | 44.7 | 49.0 | 50.0 | 55.5 | 58.0 | 42.5 | 48.0 | 40.0 |
| Lead | 22.6 | 18.0 | 26.7 | 44.5 | | 37.7 | 28.5 | |
| Tin | 8.3 | 12.0 | 13.3 | | 42.0 | 11.3 | 14.5 | 60.0 |
| Cadmium | 5.3 | | 10.0 | | | 8.5 | | |
| Other | Indium 19.1 | Indium 21.0 | | | | | Antimony 9.0 | |

* APPROXIMATE VALUES

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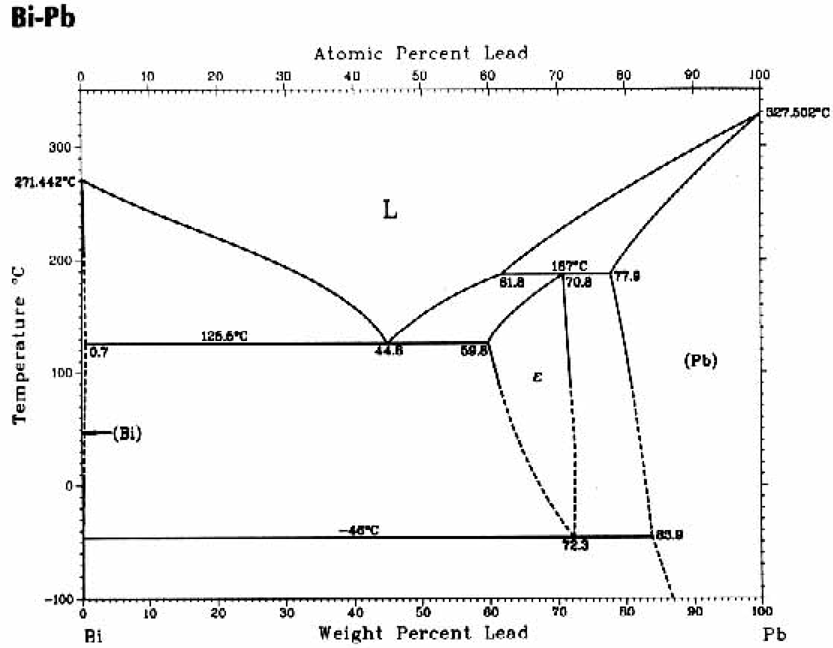
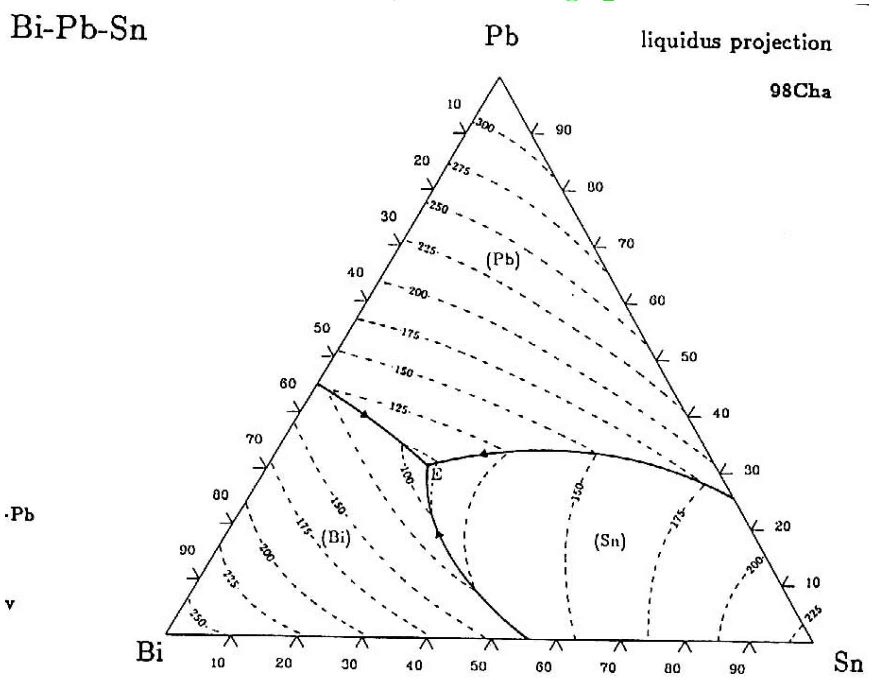
# Lead Alloy Phase Diagrams

## Lead-Bismuth, melting point = 126C:




## Lead-Tin-Bismuth, melting point = 95C:



# Beam-Induced Stress in Targets

Energy deposition $U$ (J/gm) $\quad\Rightarrow\quad$ Peak stress, $P \approx \dfrac{\alpha_V E_V U}{C}$,

where

$\alpha_V = 3\alpha$ is the volume coefficient of thermal expansion,

$E_V$ is the bulk modulus (inverse of compressibility),

$C$ is the heat capacity per unit mass.

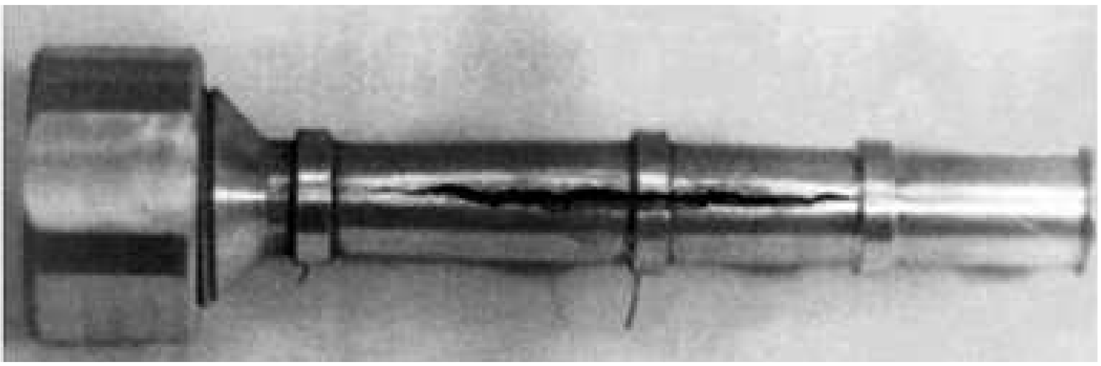
Mercury: $\alpha_V = 180 \times 10^{-6}$ K$^{-1}$, $E_V = 25$ GPa,

and $C = 138$ J K$^{-1}$ kg$^{-1}$.

Then, $U = 100$ J/gm $\Rightarrow P \approx 3000$ MPa, many times the tensile strength of steel.

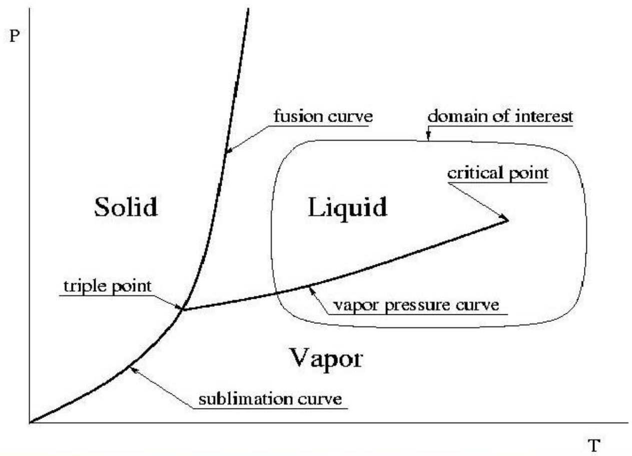
- Disruption of the jet by the beam is likely.
- The jet may break up into droplets.
- Propagation of the stress waves may lead to damage of any surface in contact with the jet, *i.e.*, pipes or nozzles.
- May be necessary to chop the jet into isolated segments.

# Pressure-Wave Damage to Liquid Targets in Pipes



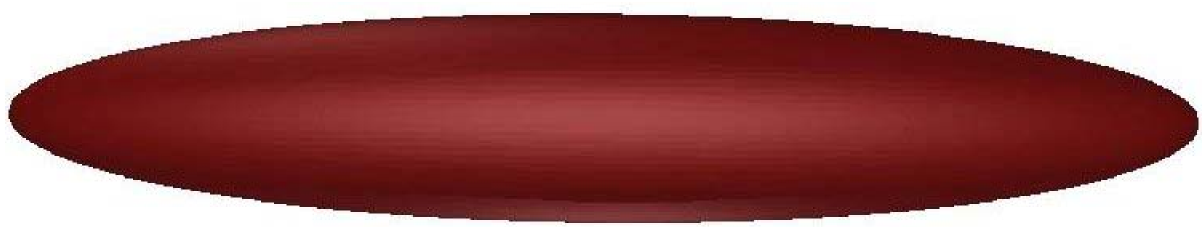
# FRONTIER Simulation of Beam-Jet Interaction

— R. Samulyak

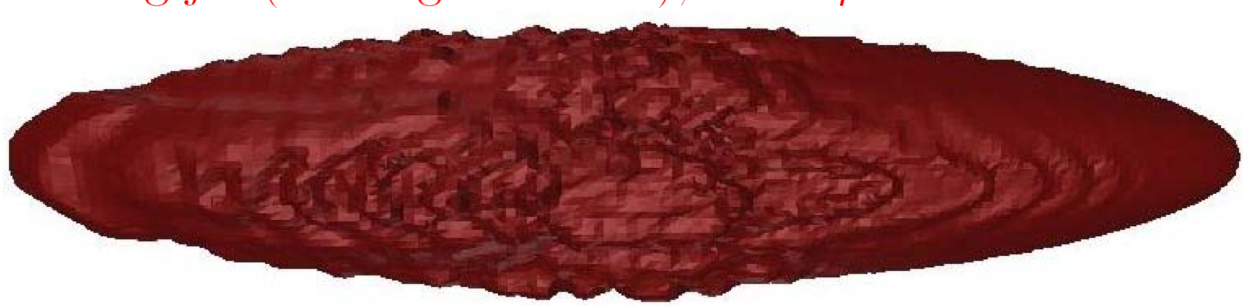



Critical point : $T_c = 1750\,\mathrm{K}$, $P_c = 172\,\mathrm{MPa}$, $V_c = 43\,\mathrm{cm^3 mol^{-1}}$
Boiling point : $T_b = 629.84\,\mathrm{K}$, $P_b = 0.1\,\mathrm{MPa}$, $\rho = 13.546\,\mathrm{g \cdot cm^{-3}}$

Beam + Hg jet (no magnetic field), $t = 0$:



Beam + Hg jet (no magnetic field), $t = 6\ \mu$s:



Magnetohydrodynamics being added to the code.

# Estimate of Droplet Velocity if the Jet Breaks Up

The pressure wave propagates to the surface in time
$\Delta t = r/v_s = (.005\text{ m})/(1300\text{ m/s}) = 4\ \mu\text{s}$ for mercury.

[$v_s$ may be temporarily reduced by the beam energy deposition.]

The radial expansion of the jet is $\Delta r \approx \dfrac{\alpha U r}{C}$.

$\Rightarrow$ Radial velocity of matter is $v_r \approx \dfrac{\Delta r}{\Delta t} \approx \dfrac{\alpha U v_s}{C} \approx 50\text{ m/s}.$

The target chamber windows must withstand the possible impact of tens of grams of liquid droplets with this velocity.

[Inside a strong magnetic field, the motion of the droplets would be damped.]

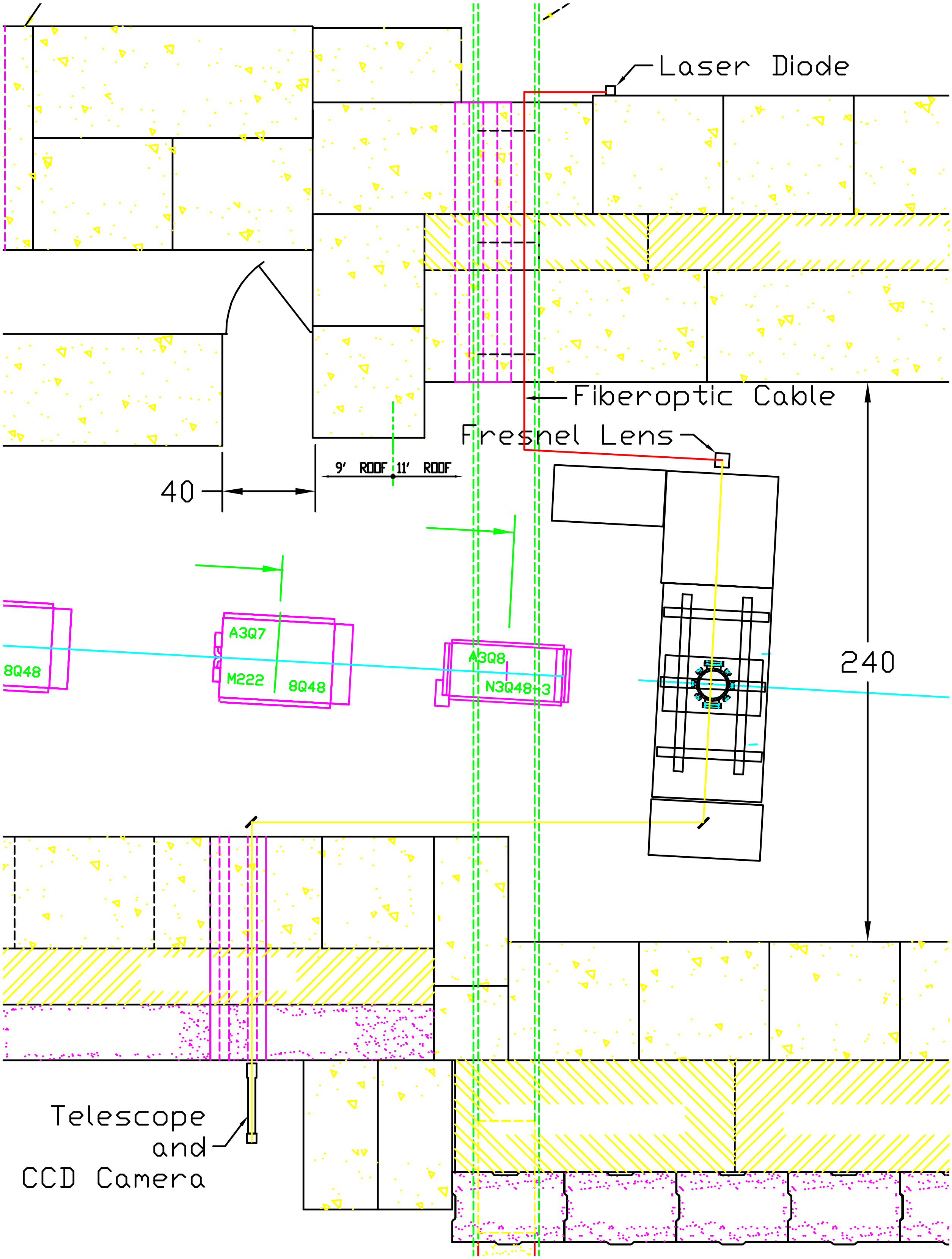
For a mercury target, some 10-20% of the material may be vaporized by a single pulse.

# Experiments Needed!

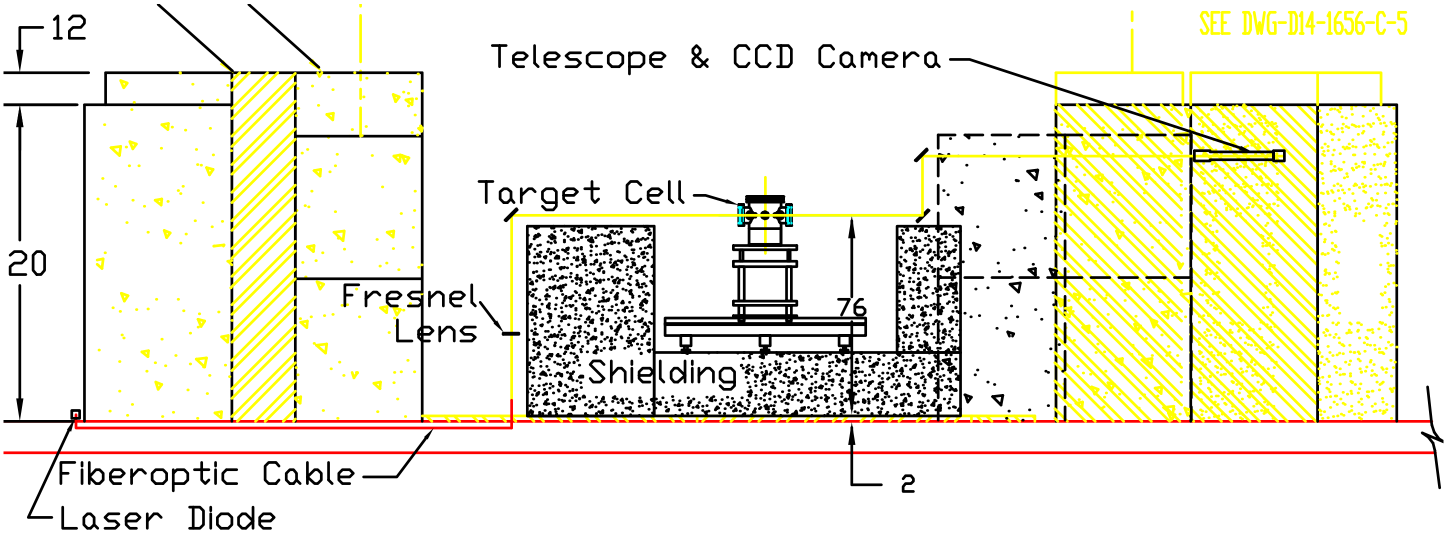
- A single intense proton pulse on a liquid target is an experiment by itself.
- "Pulse-on-demand" operation parasitic to other use of the AGS.
- A3 beamline with up to $1.6 \times 10^{13}$ protons/pulse.
- Pulse length $\approx$ 30 ns, $\sigma_r$ as small as 1 mm.
- Can have a train of 6 pulses, 30 msec apart.
- Primary diagnostic is visual, using a high-speed camera (16 frames in as little as 16 $\mu$sec) and shadow photography.
- Liquid metals other than mercury wet optical windows,
  $\Rightarrow$ May get only one chance to make a measurement.
- Containment of "splash" is a key operational issue.
- Each beam pulse delivers a dose of 5-50 krad to the inner optical window.

  Quartz good for 1 Grad, but "glass" browns at $\leq$ 1 Mrad.

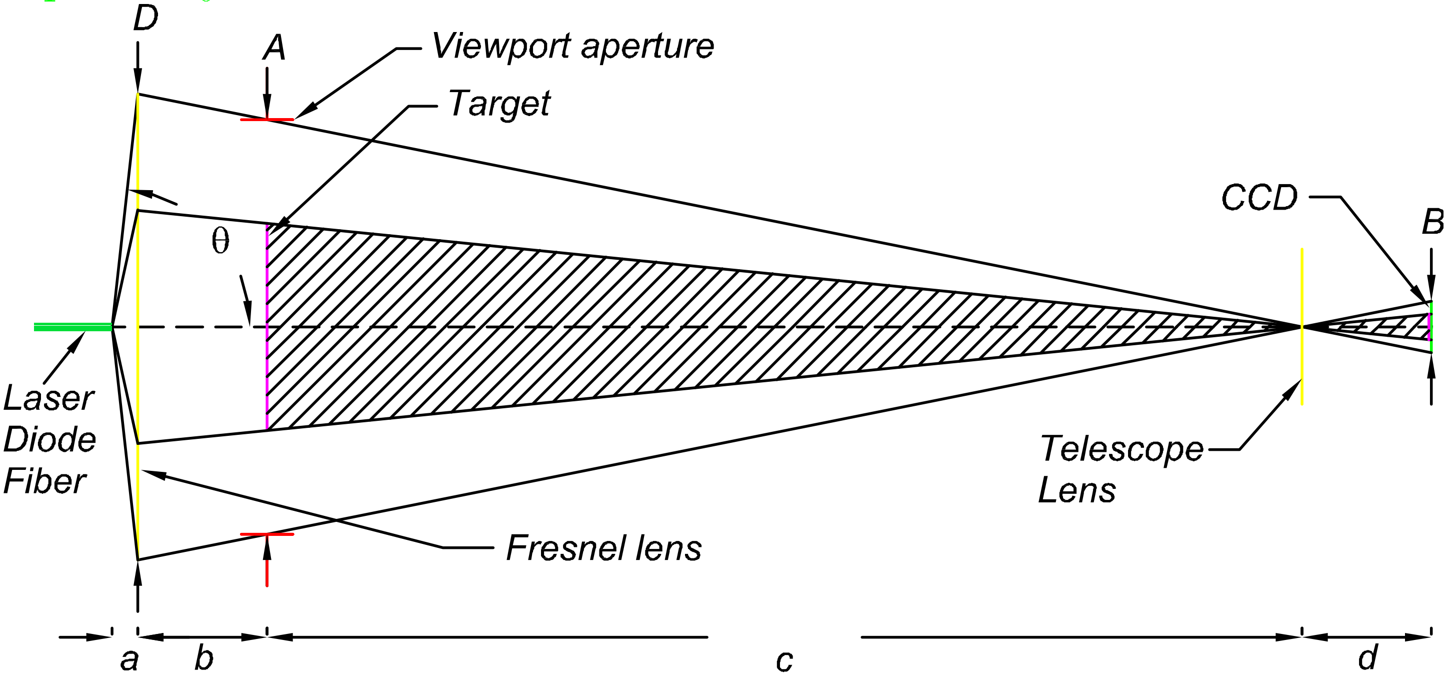
# Plan View of the A3 Beamline



# Elevation View of the A3 Beamline




## Optics layout:



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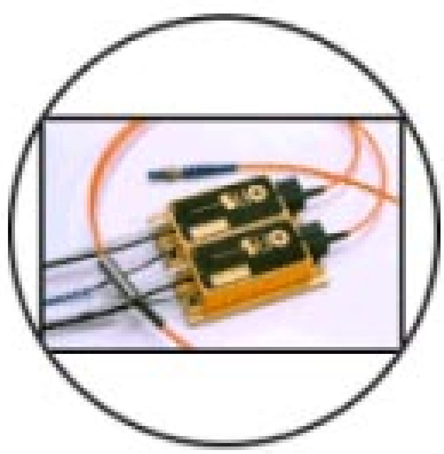
Pulsed laser diode for illumination (20W if CW):



# Target Test Program

1. Solid targets:
   - First tests: **carbon rod** at room temp, with strain sensors (ORNL).
   - Option for carbon rod at $\approx$ 2000C (BNL).
   - Option for test of material for a band target; should have strain sensors.
   - Option for Schlieren photography of stress waves in a quartz target (ANL).
2. Liquid targets:
   - **Horizontal mercury jet** (BNL).
   - Option for vertical mercury jet (BNL/Princeton).
   - Option for mercury in "trough" and/or pipe (Princeton).
   - Option for "Wood's metal" (Princeton/BNL).