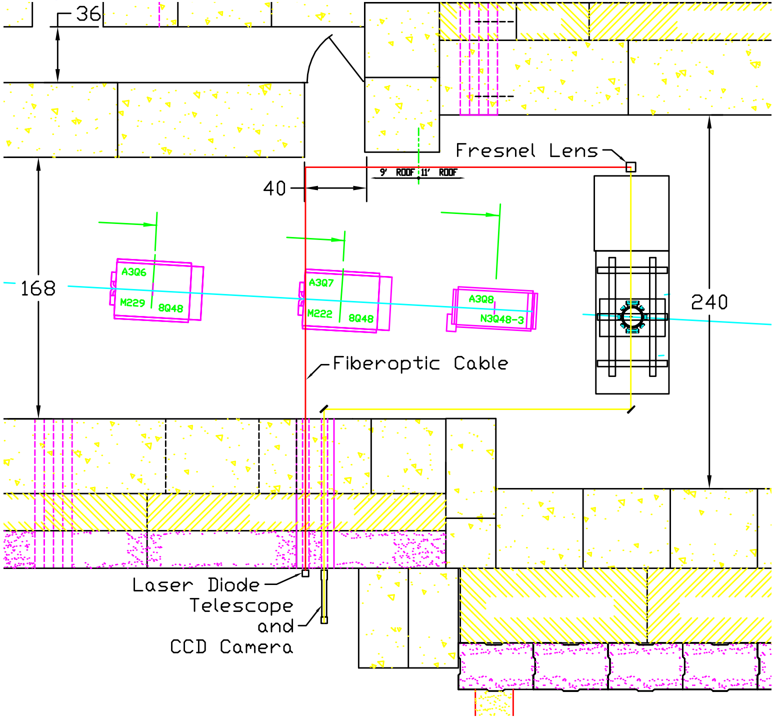
Tests of Targets Interacting with an Intense Proton Pulse



K.T. McDonald

Princeton U.

December 15, 2000

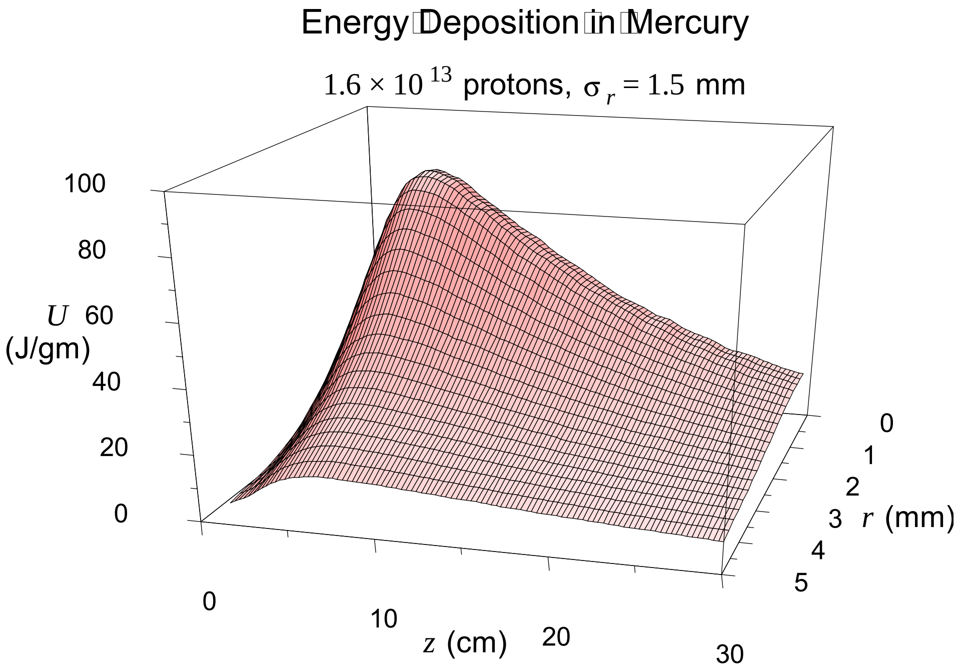
Targetry Workshop, BNL

`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 ≈ 1 cm transverse dimension.

Peak energy deposition is $U \approx 100$ J/gm from a nsec pulse of 1.6×10^{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.

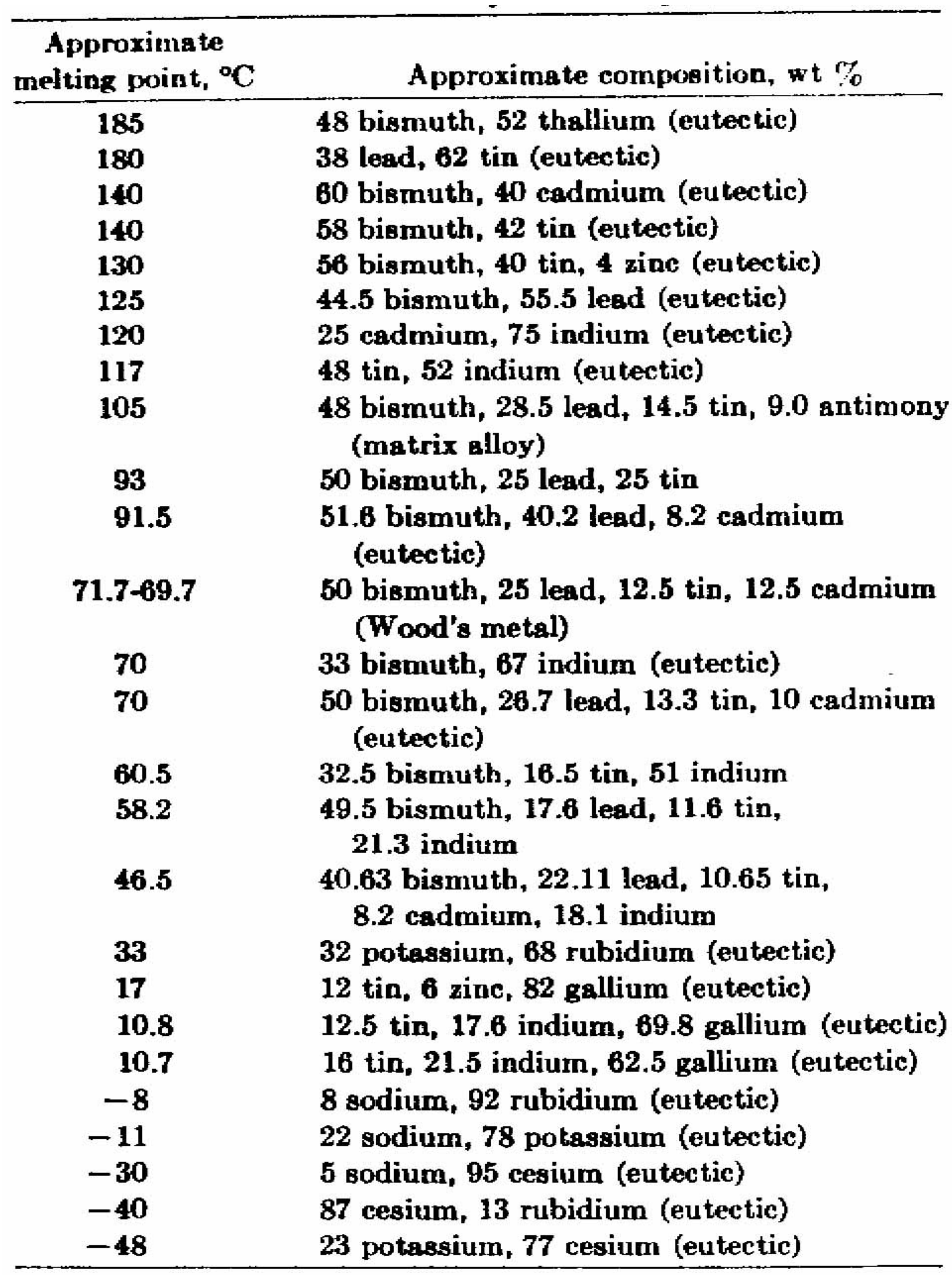
Solution: a moving target, such as a **liquid metal jet**.

Properties of Some Candidate Target Materials

Element	Z	Density (g/cm^3)	Melting Temp. (°C)	Boiling Temp. (°C)	Heat Cap. (J/g-°C)	Heat of Vapor. (J/g)	Thermal Cond. (W/cm-°C)	Resist. ($\mu\Omega$-cm)	Thermal Exp. (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†	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†	6.1
Lead	82	11.35	327	1750	0.16	858	0.35	80†	2.9
Bismuth	83	9.7	271	1610	0.12	857	0.079	120	1.3

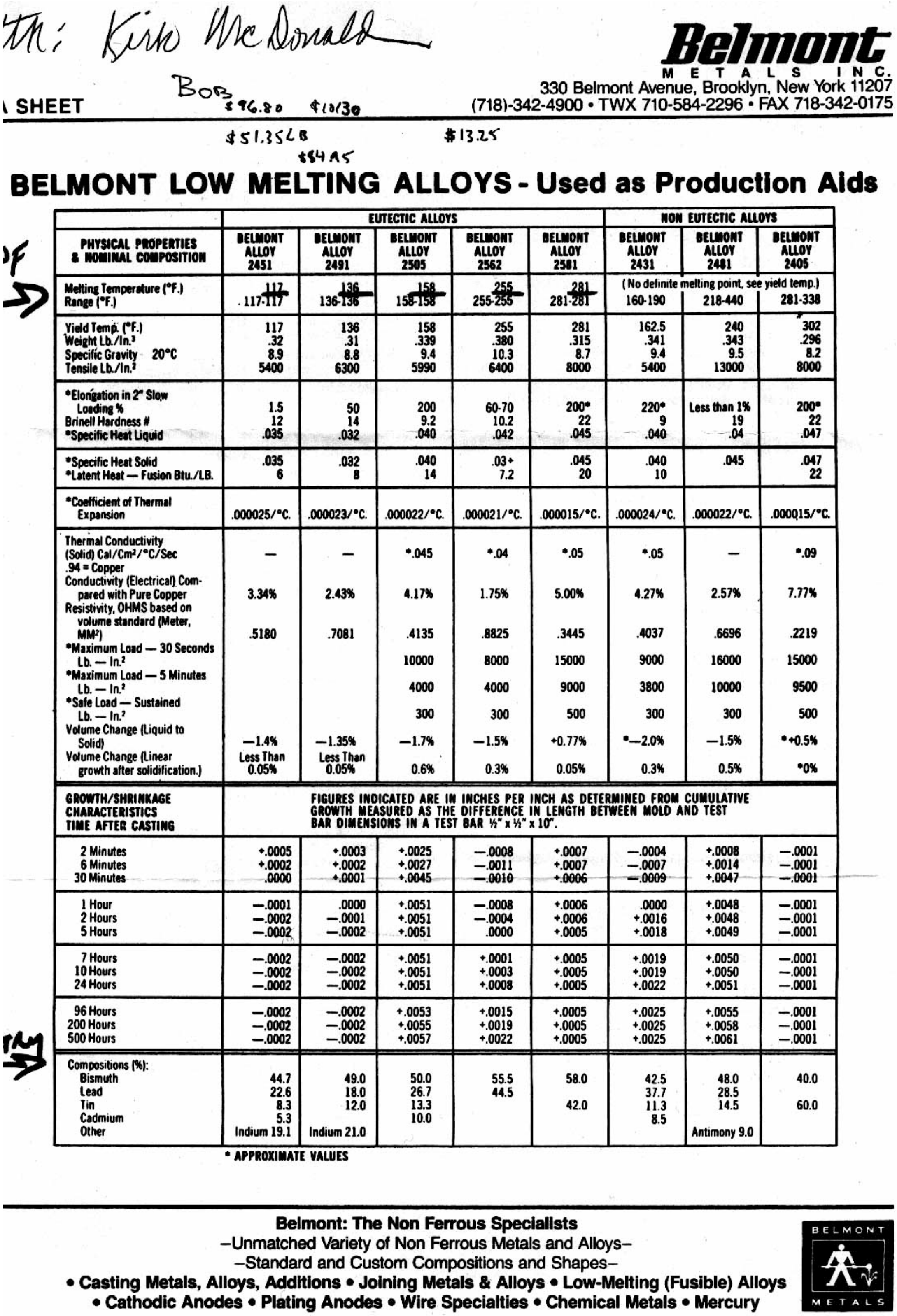
† liquid

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



tn: Kirk McDonald

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PHYSICAL PROPERTIES & NOMINAL COMPOSITION	EUTECTIC ALLOYS					NON EUTECTIC ALLOYS		
	BELMONT ALLOY 2451	BELMONT ALLOY 2491	BELMONT ALLOY 2505	BELMONT ALLOY 2562	BELMONT ALLOY 2581	BELMONT ALLOY 2431	BELMONT ALLOY 2481	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/Cm²/°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, MM²)	.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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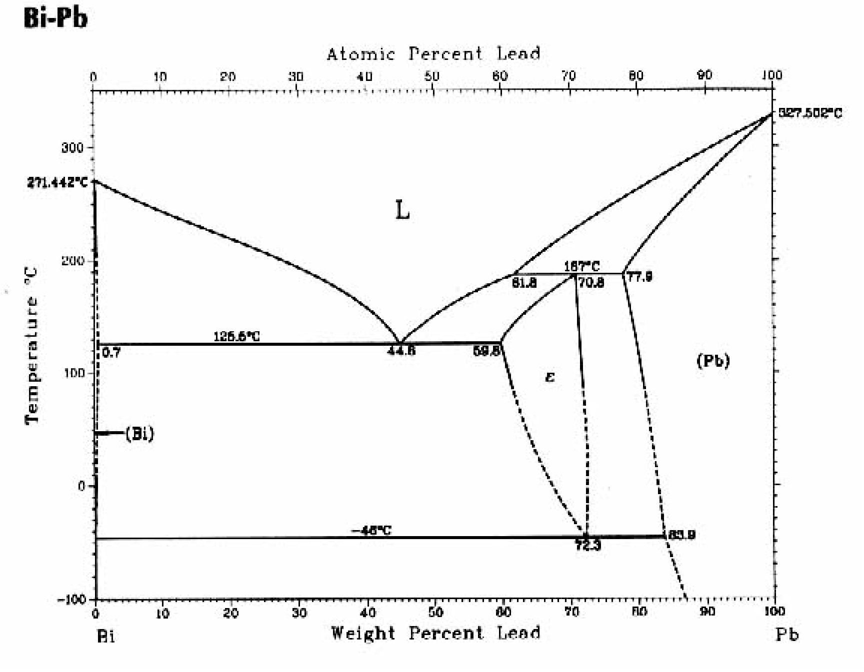
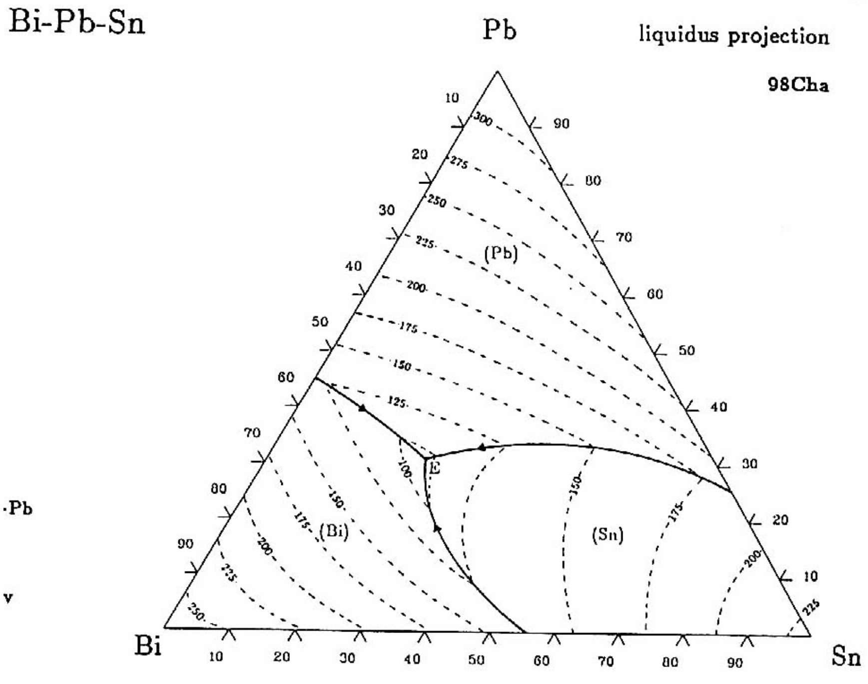
Lead Alloy Phase Diagrams

Lead-Bismuth, melting point = 126C:



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



Beam-Induced Stress in Targets

Energy deposition U (J/gm) $\Rightarrow$ 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.

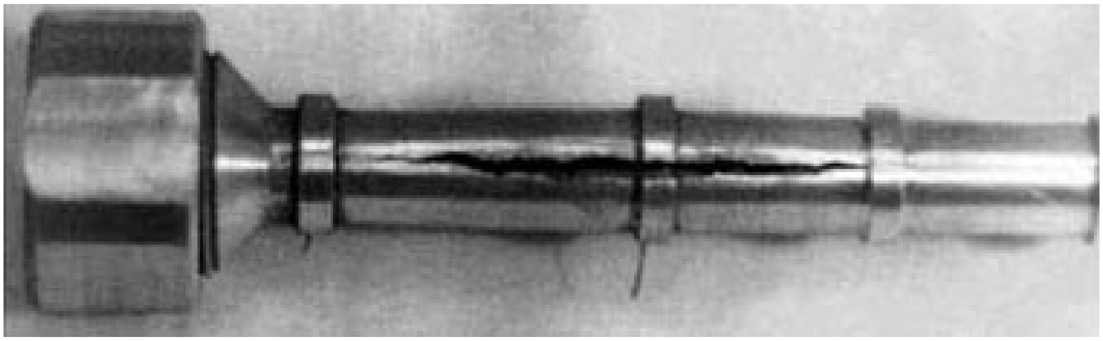
Mercury: $\alpha_V = 180 \times 10^{-6}$ K^{-1}, $E_V = 25$ GPa,

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.

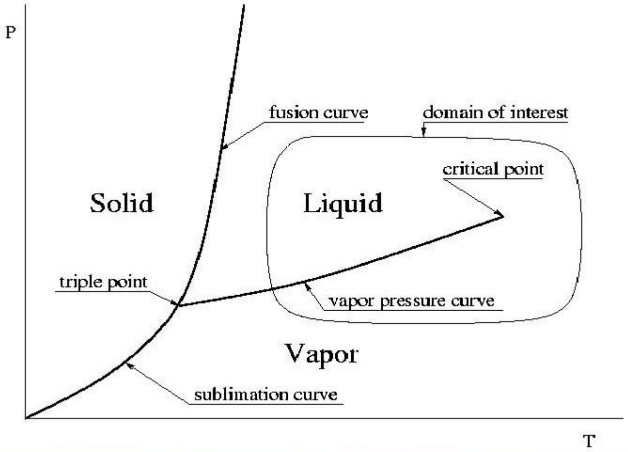
- Disruption of the jet by the beam is likely.
- The jet may break up into droplets.
- Propagation of the stress waves may lead to damage of any surface in contact with the jet, *i.e.*, pipes or nozzles.
- May be necessary to chop the jet into isolated segments.

Pressure-Wave Damage to Liquid Targets in Pipes



FRONTIER Simulation of Beam-Jet Interaction

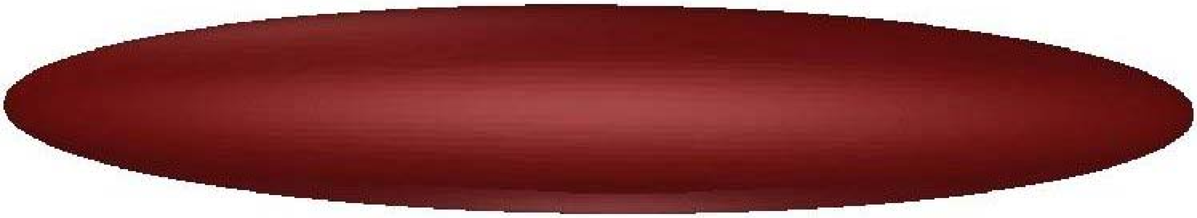
— R. Samulyak



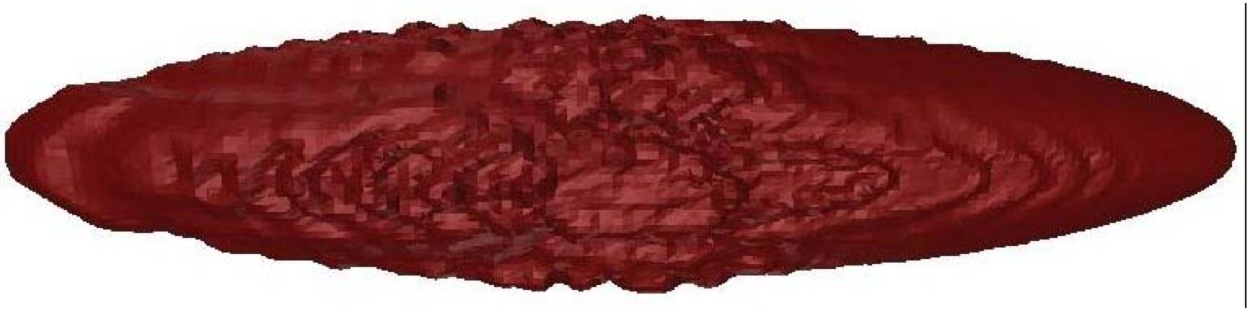
Critical point : $T_c = 1750\,\mathrm{K}$, $P_c = 172\,\mathrm{MPa}$, $V_c = 43\,\mathrm{cm^3 mol^{-1}}$

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), $t = 6$ μs:



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 $$\Delta r \approx \frac{\alpha U r}{C}.$$

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

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.]

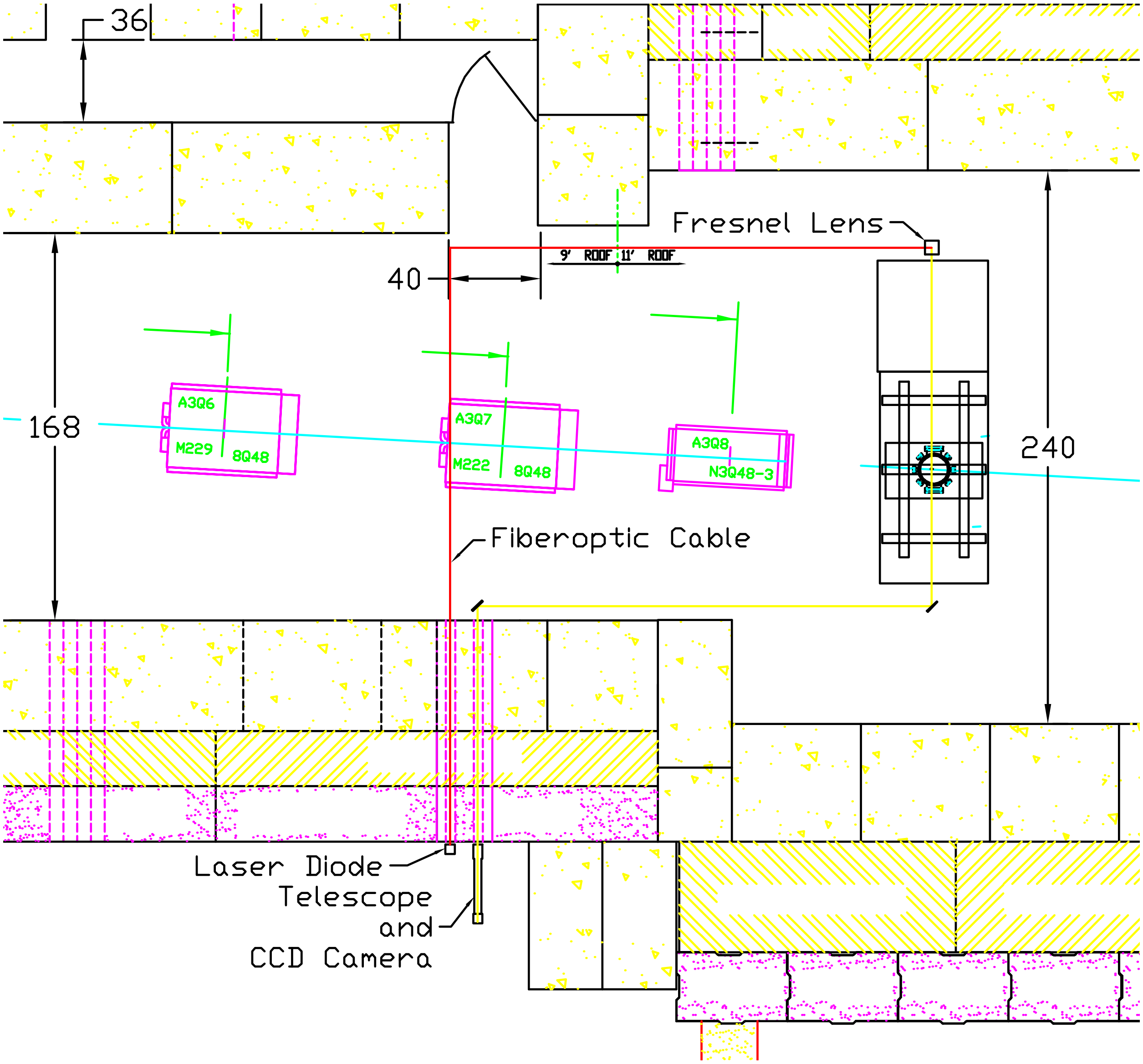
For a mercury target, some 10-20% of the material may be vaporized by a single pulse.

Experiments Needed!

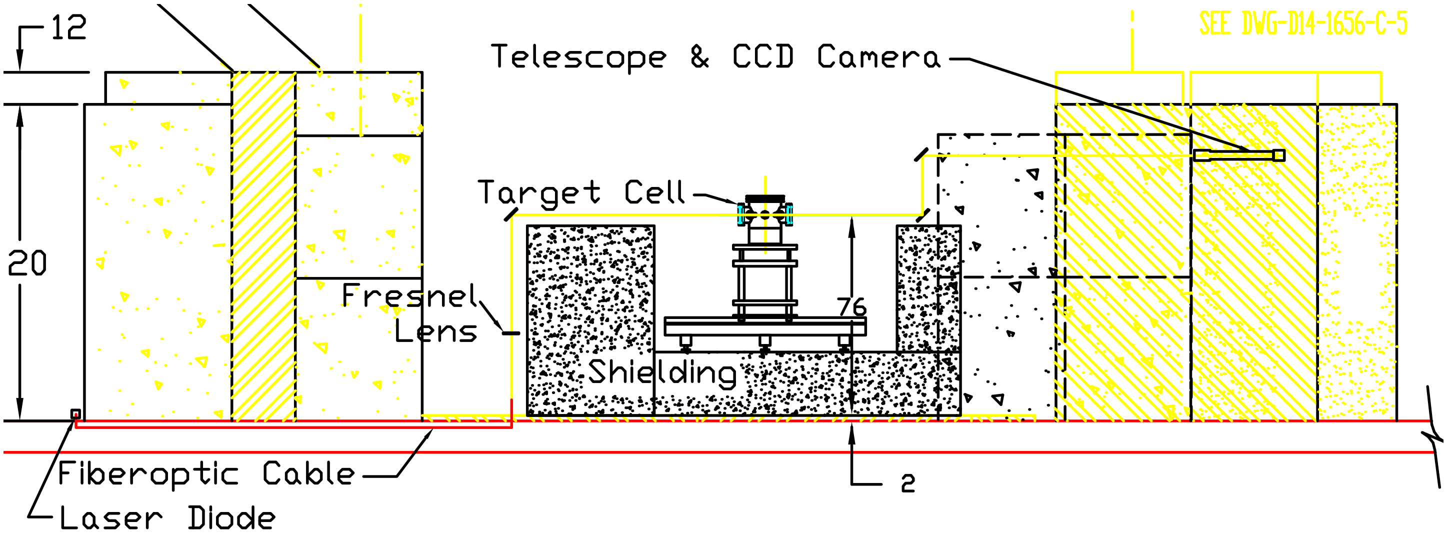
- A single intense proton pulse on a liquid target is an experiment by itself.
- "Pulse-on-demand" operation parasitic to other use of the AGS.
- A3 beamline with up to 1.6×10^{13} protons/pulse.
- Pulse length ≈ 30 ns, σ_r as small as 1 mm.
- Can have a train of 6 pulses, 30 msec apart.
- Primary diagnostic is visual, using a high-speed camera (16 frames in as little as 16 μsec) 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 ≤ 1 Mrad.

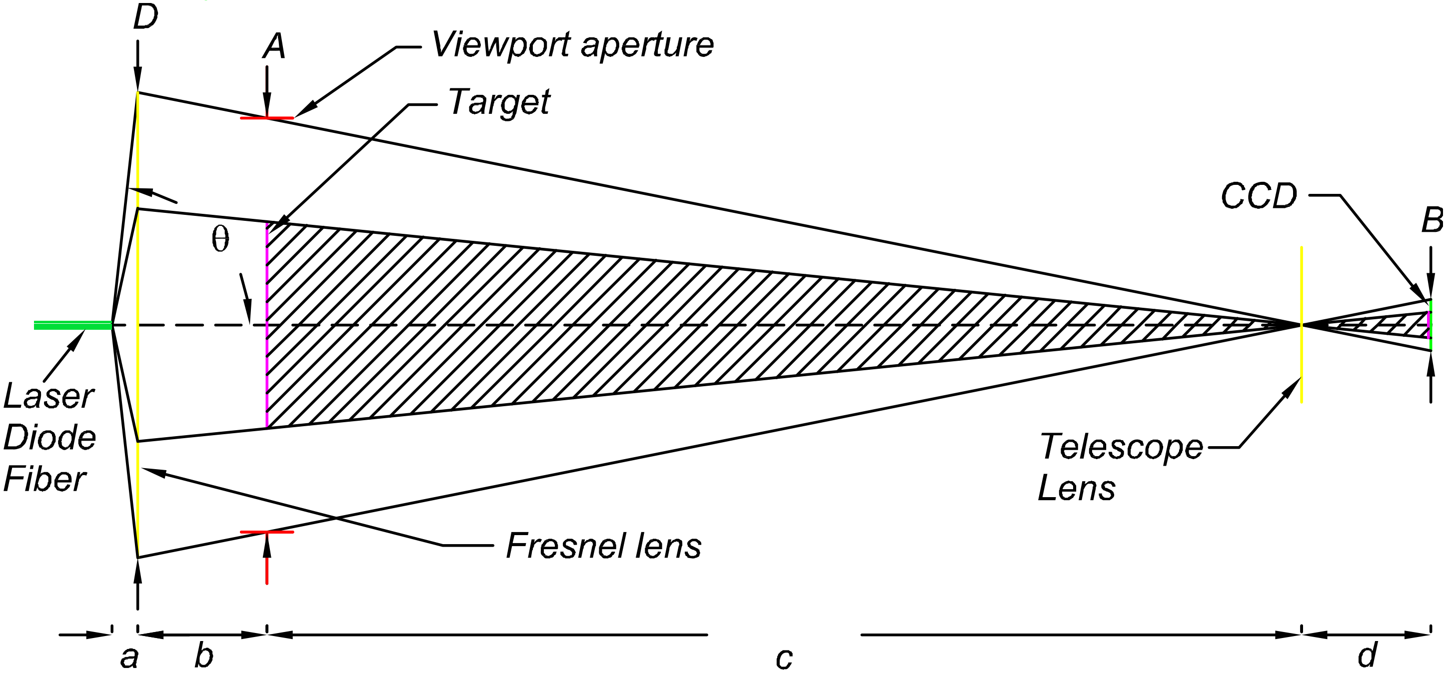
Plan View of the A3 Beamline



Elevation View of the A3 Beamline



Optics layout:



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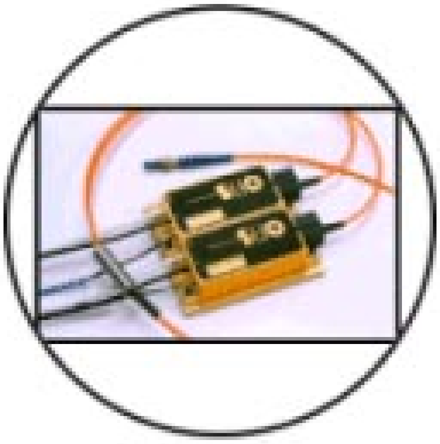
Pulsed laser diode for illumination (20W if CW):



Target Test Program

1. Solid targets:
    - First tests: **carbon rod** at room temp, with strain sensors (ORNL).
    - Option for carbon rod at ≈ 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).