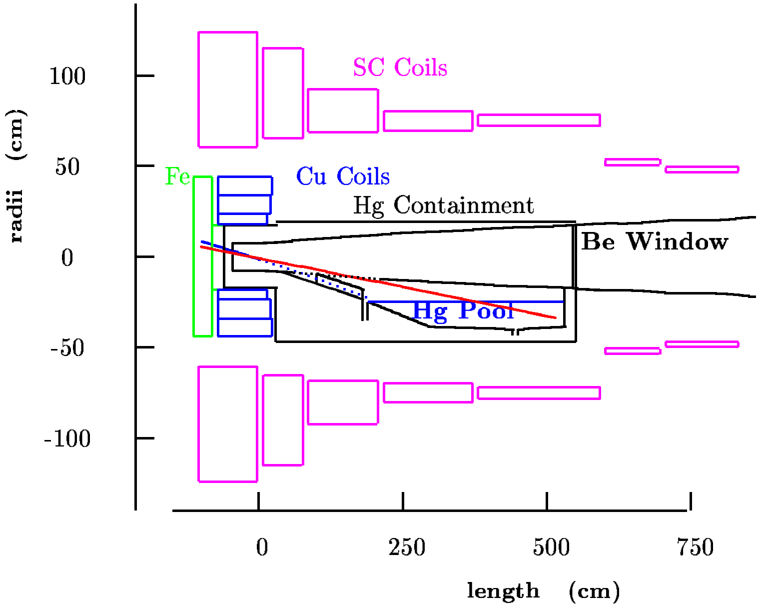
Targets for Multimegawatt Proton Beams



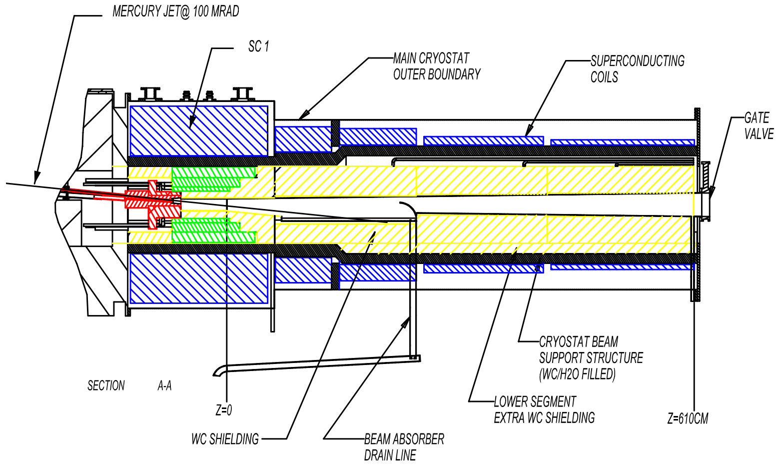
K.T. McDonald

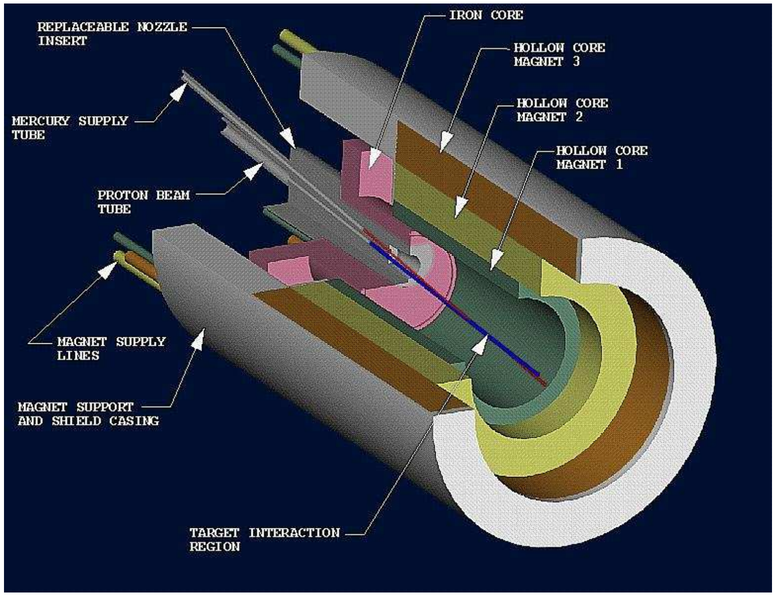
Princeton U.

Fermilab, August 8, 2003

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

Sketches of a 4-MW Target Station





Overview

- Why **targetry**? = R&D of high power targets for accelerators.
- Targets in a solenoid horn.
- Targets in a conventional (toroidal) neutrino horn.
- How much power can a pulsed target withstand?
- Solid target studies, including band targets and granular targets.
- Liquid target studies.
- Continuing R&D (including targets for linear colliders).

Why Targetry?

- **Targetry** = the task of producing and capturing π's and μ's from proton interactions with a nuclear target.
- At a **lepton collider** the key parameter is **luminosity**:

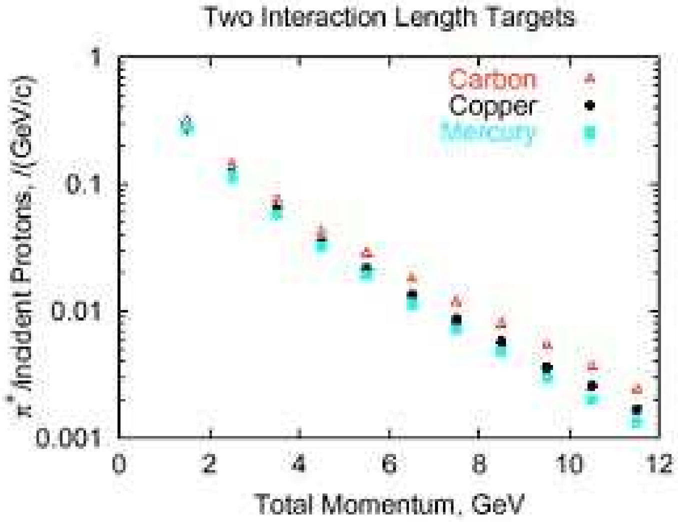
$$\mathcal{L} = \frac{N_1 N_2 f}{A}\,\mathrm{s}^{-1}\mathrm{cm}^{-2},$$

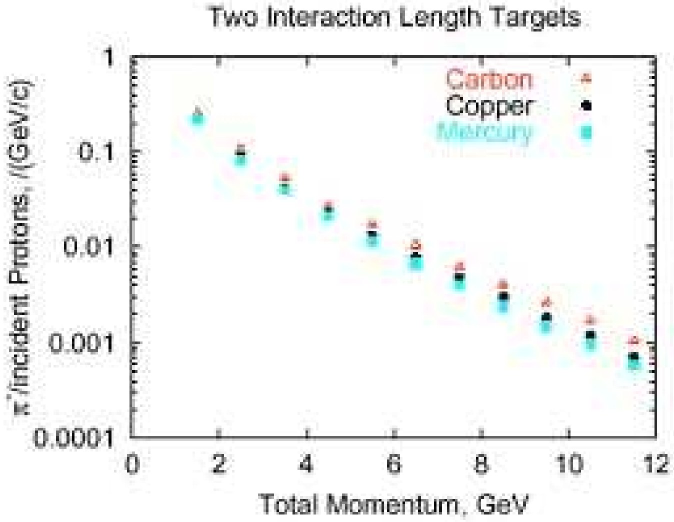
  ⇒ Gain as square of source strength (targetry),
  but small beam area (cooling) is also critical.

- At a **neutrino factory** the key parameter is **neutrino flux**, ⇒ Source strength (targetry) is of pre-eminent concern.
  [Beam cooling important mainly to be sure the beam fits in the pipe.]
- The exciting results from atmospheric and reactor neutrino programs (Super-K, SNO, KamLAND) reinforce the opportunity for neutrino physics with intense accelerator neutrino beams, where **targetry is a major challenge**.

A “Conventional” Neutrino Horn

If desire secondary pions with $E_\pi \lesssim 0.5$ GeV (neutrino factories), a high-Z target is favored, but for $E_\pi \gtrsim 1$ Gev (“conventional” neutrino beams), low Z is preferred.

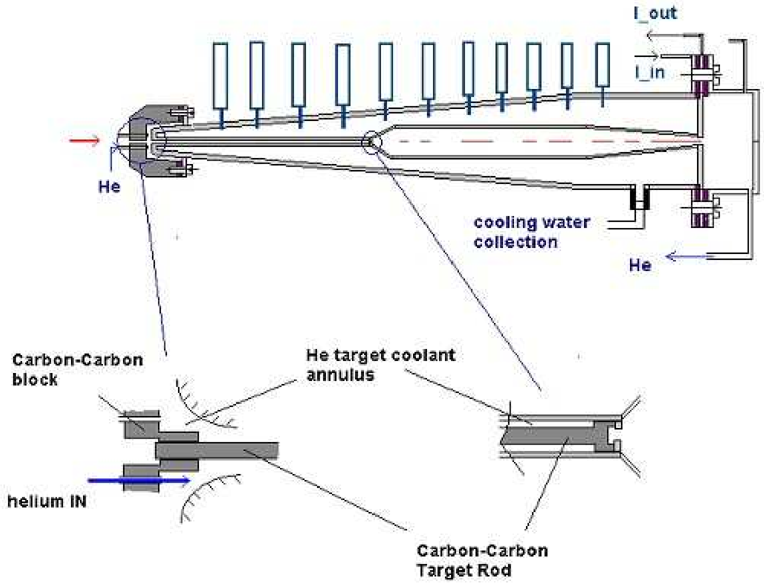




A conventional neutrino horn works better with a point target (high-Z).

Small horn ID is desirable $\Rightarrow$ challenge to provide target cooling for high beam intensity.

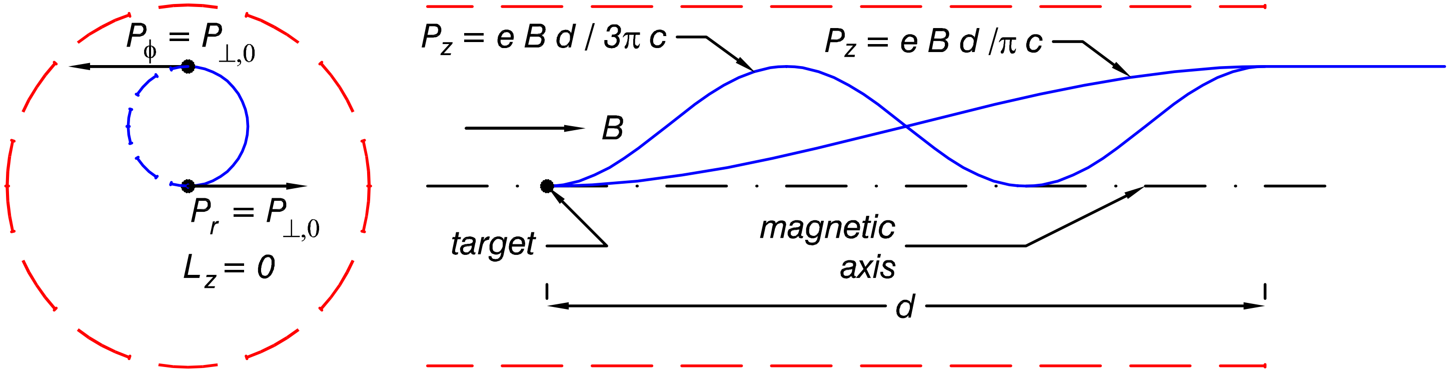
Aggressive design: carbon-carbon target with He gas cooling:



A Solenoidal Targetry System for a Superbeam

- A precursor to a Neutrino Factory is a Neutrino Superbeam based on decay of pions from a multimegawatt proton target station.
- 4 MW proton beams are achieved in both the BNL and FNAL (and CERN) scenarios via high rep rates: $\approx 10^6$/day.
- Classic neutrino horns based on high currents in conductors that intercept much of the secondary pions will have lifetimes of only a few days in this environment.
- Consider instead a solenoid "horn" with conductors at larger radii than the pions of interest – similar to the Neutrino Factory capture solenoid.
- Pions produced on axis inside the solenoid have zero
(canonical) angular mometum, $L_z = r(P_\phi + eA_\phi/c) = 0$,
$\Rightarrow P_\phi = 0$ on exiting the solenoid.
- If the pion has made exactly 1/2 turn on its helix when it reaches the end of the solenoid, then its initial P_r has been rotated into a pure P_ϕ, $\Rightarrow P_\perp = 0$ on exiting the solenoid,
$\Rightarrow$ Point-to-parallel focusing.

Narrowband Beam via Solenoid Focusing



- The point-to-parallel focusing occurs for $P_\pi = eBd/(2n+1)\pi c$.
- $\Rightarrow$ Narrowbeam neutrino beam with peaks at

$$E_\nu \approx \frac{eBd}{(2n+1)2\pi c}\,.$$

- $\Rightarrow$ Can study several neutrino oscillation peaks at once, at

$$\frac{1.27 M_{23}^2[\mathrm{eV}^2]\ L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]} = \frac{(2n+1)\pi}{2}\,.$$

- Get both ν and $\bar{\nu}$ at the same time,
  $\Rightarrow$ Must use detector that can identify sign of μ and e,
  $\Rightarrow$ Magnetized liquid argon TPC.

Thermal Shock

When beam pulse length t is less than target radius r divided by speed of sound v_{sound}, beam-induced pressure waves (thermal shock) are a major issue.

Simple model: if U = beam energy deposition in, say, Joules/g, then the instantaneous temperature rise ΔT is given by

$$\Delta T = \frac{U}{C},$$

where C = heat capacity in Joules/g/K.

The temperature rise leads to a strain $\Delta r/r$ given by

$$\frac{\Delta r}{r} = \alpha \Delta T = \frac{\alpha U}{C},$$

where α = thermal expansion coefficient.

The strain leads to a stress P (= force/area) given by

$$P = E\frac{\Delta r}{r} = \frac{E\alpha U}{C},$$

where E is the modulus of elasticity.

In many metals, the tensile strength obeys $P \approx 0.002E$, $\alpha \approx 10^{-5}$, and $C \approx 0.3$ J/g/K, in which case

$$U_{\max} \approx \frac{PC}{E\alpha} \approx \frac{0.002 \cdot 0.3}{10^{-}5} \approx 60 \text{ J / g}.$$

How Much Beam Power Can a Solid Target Stand?

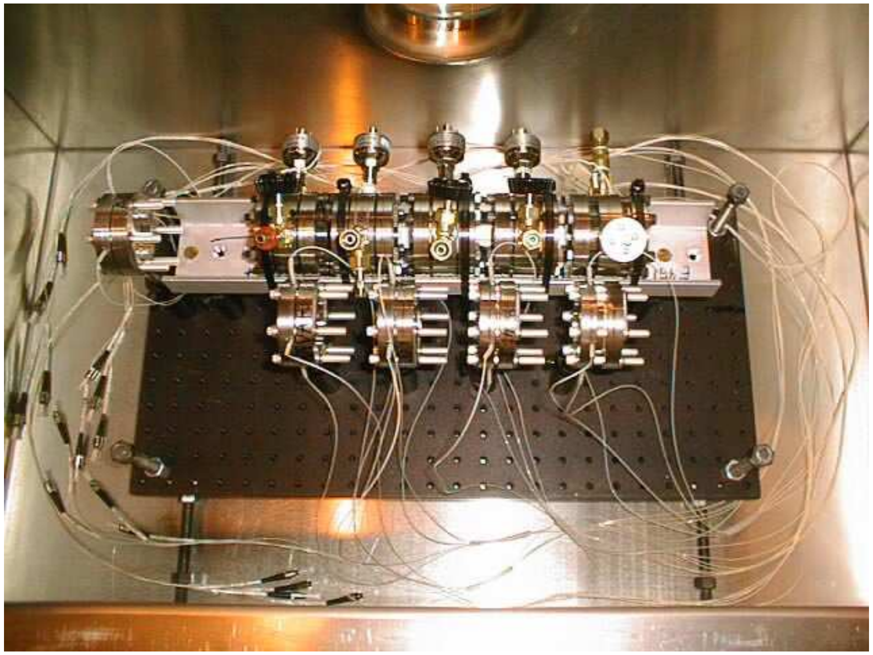
How many protons are required to deposit 60 J/g in a material? What is the maximum beam power this material can withstand without cracking, for a 10-GeV beam at 10 Hz with area 0.1 cm^2.

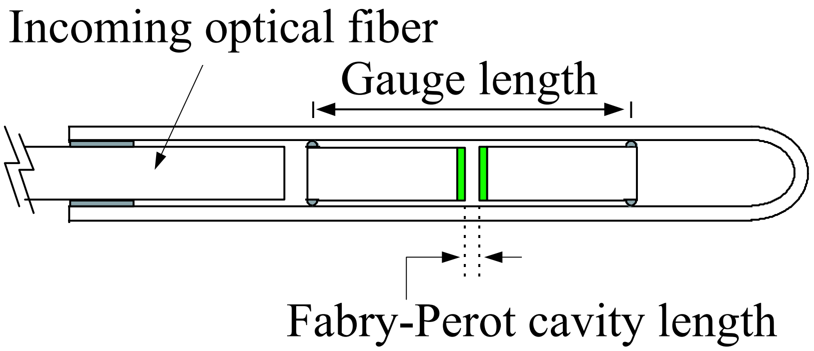
Ans. If we ignore "showers" in the material, we still have dE/dx ionization loss, of about 1.5 MeV/g/cm^2.
Now, 1 MeV $= 1.6 \times 10^{-13}$ J, so 60 J/ g requires a proton beam intensity of $60/(1.6 \times 10^{-13}) = 10^{15}/\text{cm}^2$.
Then, $P_{\max} \approx 10 \text{ Hz} \cdot 10^{10} \text{ eV} \cdot 1.6 \times 10^{-19} \text{ J/eV} \cdot 10^{15}/\text{cm}^2 \cdot 0.1 \text{ cm}^2$
$\approx 1.6 \times 10^6 \text{ J/s} = 1.6$ MW.

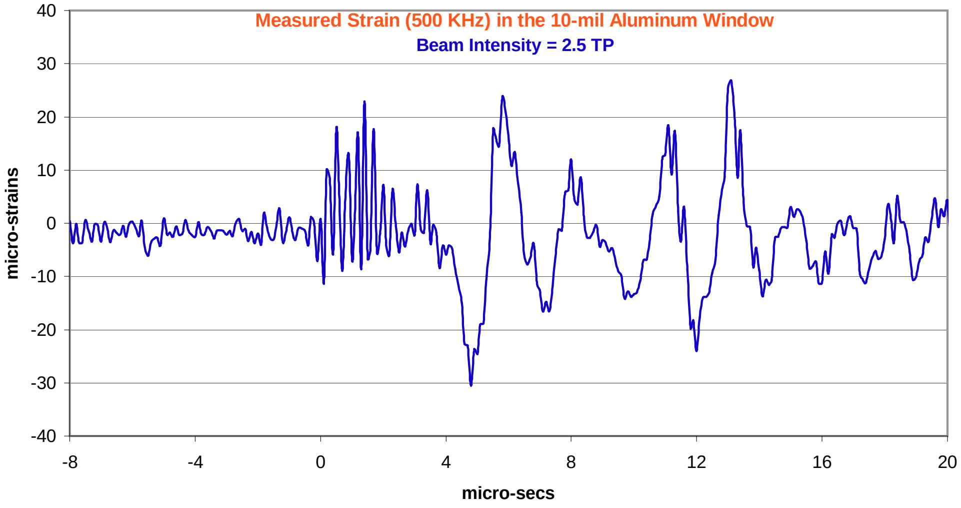
Solid targets are viable up to about 1.5 MW beam power!

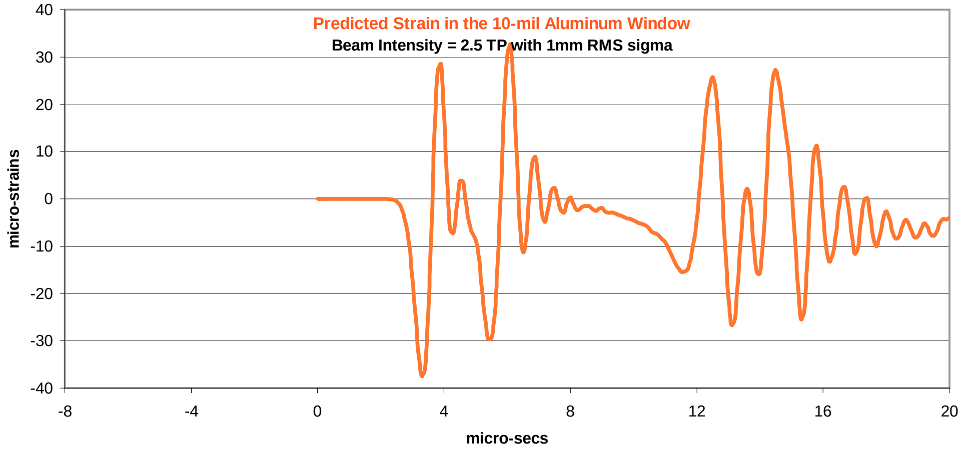
Window Tests (5e12 $p$pp, 24 GeV, 100 ns)

Aluminum, Ti90Al6V4, Inconel 708, Havar, instrumented with fiberoptic strain sensors.



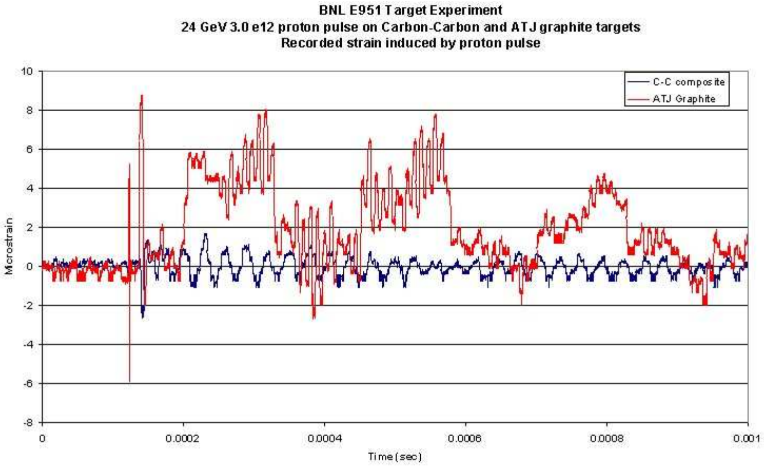




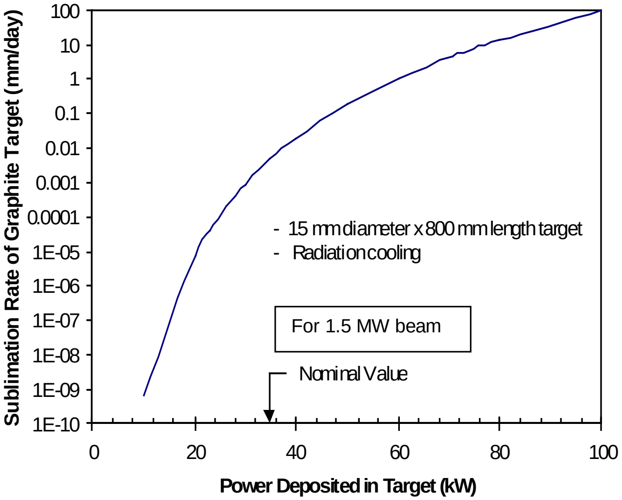


A Carbon Target is Feasible at 1-MW Beam Power

A carbon-carbon composite with near-zero thermal expansion is largely immune to beam-induced pressure waves.



A carbon target in vacuum sublimates away in 1 day at 4 MW.

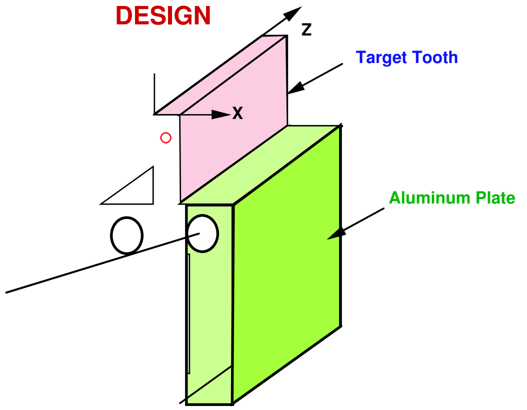


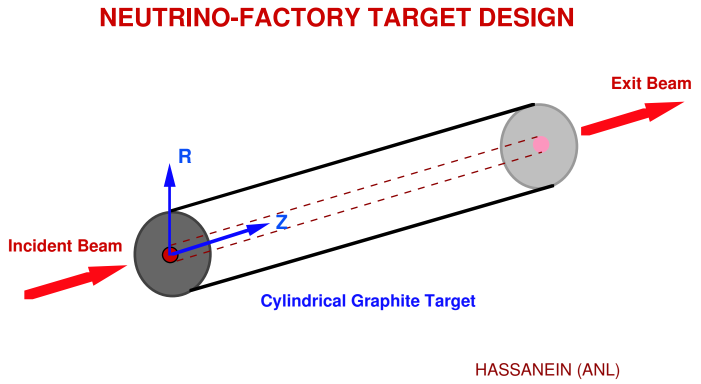
Sublimation of carbon is negligible in a helium atmosphere.

Tests underway at ORNL to confirm this.

Radiation damage is limiting factor: ≈ 12 weeks at 1 MW.

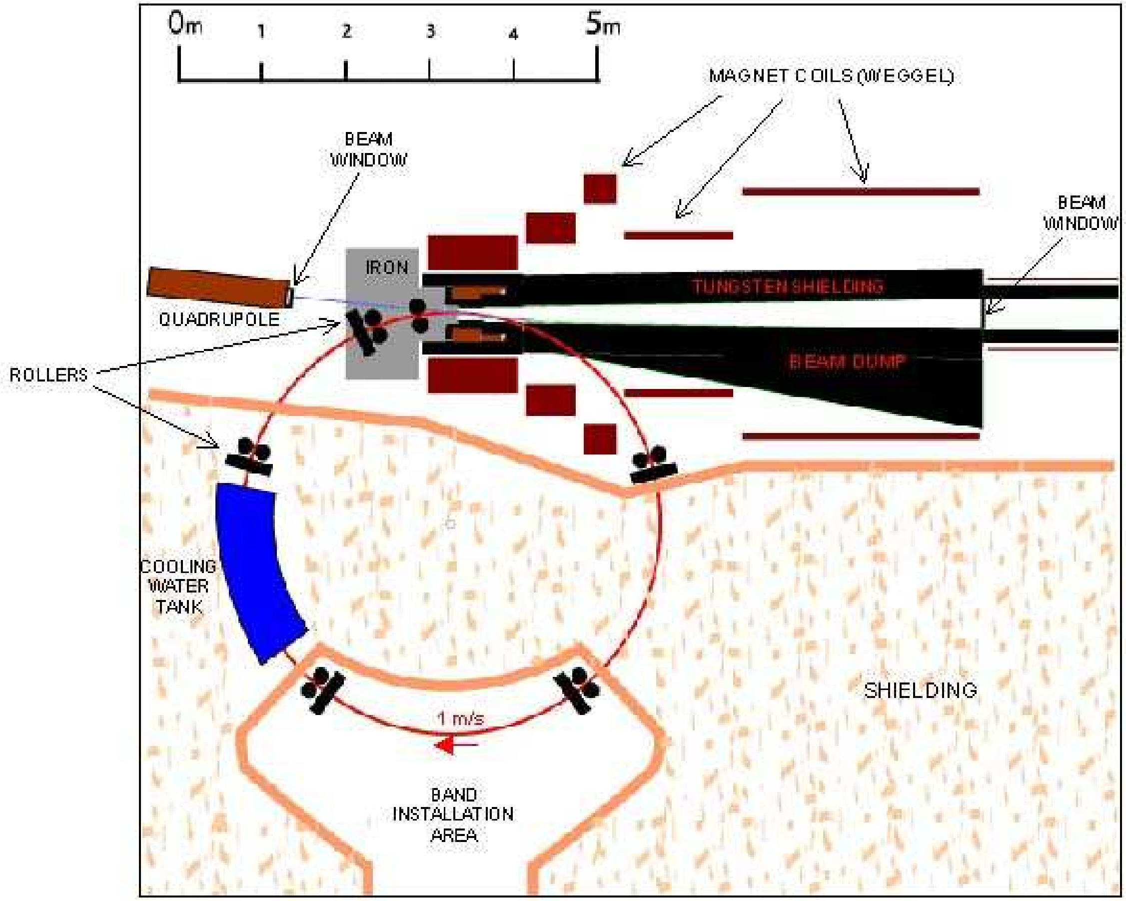
Solid Target Designs





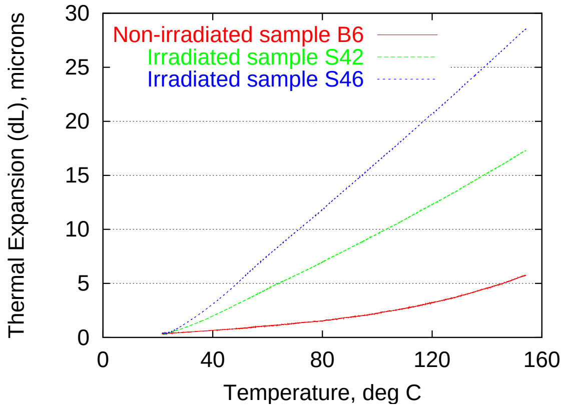
A rotating band target is another option:

Could use Fe or Ni alloys.



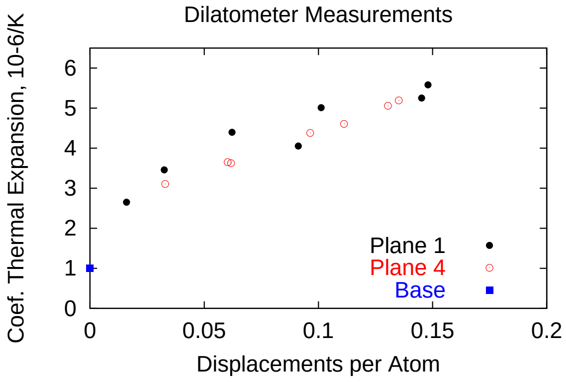
Effects of Radiation on SuperInvar

SuperInvar has a very low coefficient of thermal expansion (CTA),
⇒ Resistant to "thermal shock" of a proton beam.



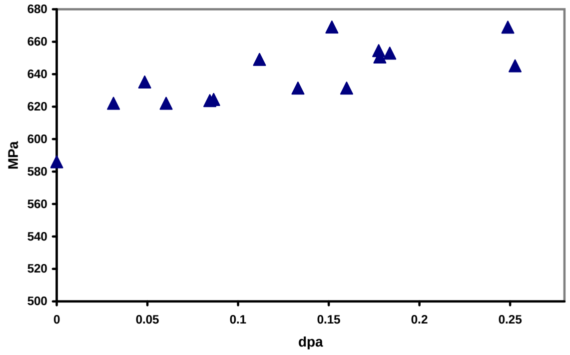
However, irradiation at the BNL BLIP facility show that the CTA increases rapidly with radiation dose.

CTA *vs.* dose ⇒



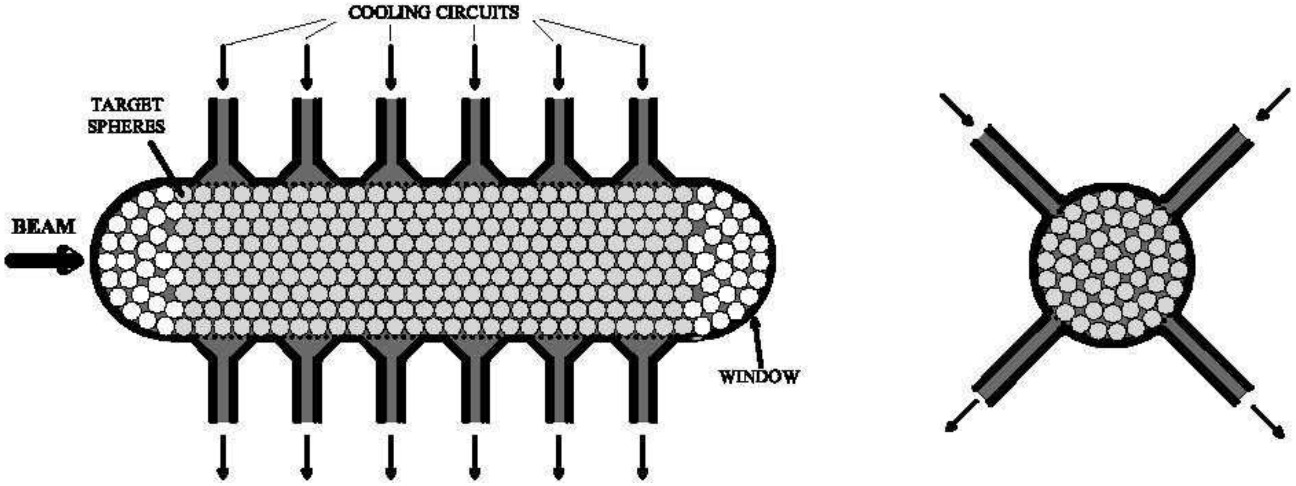
SuperInvar is made stronger by moderate radiation doses (like many materials).

Yield strength *vs.* dose ⇒



A Granular Target

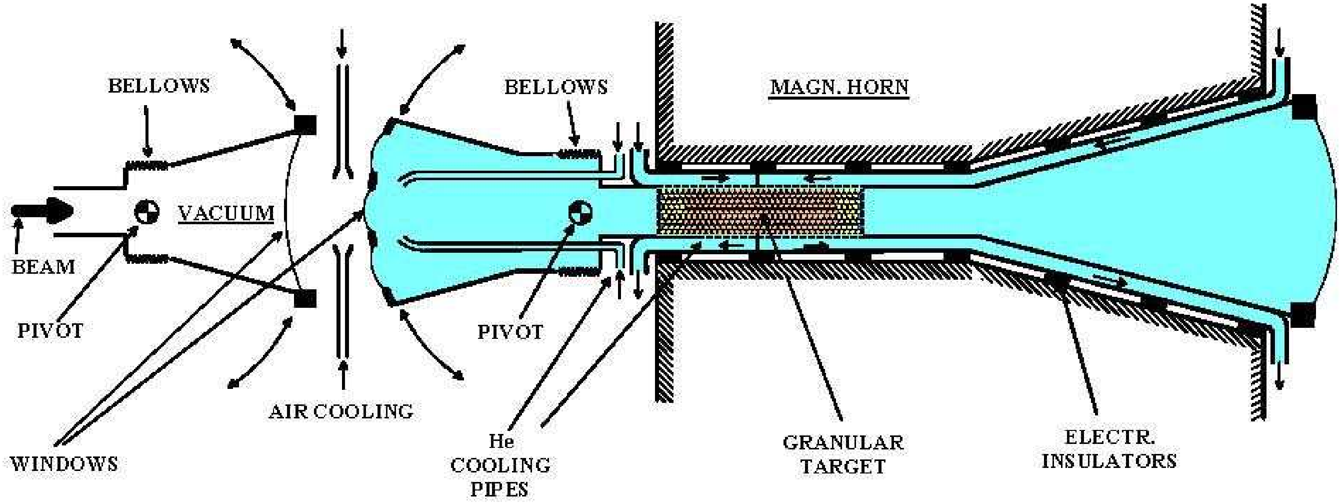
Target of pellets, cooled by flowing He gas.



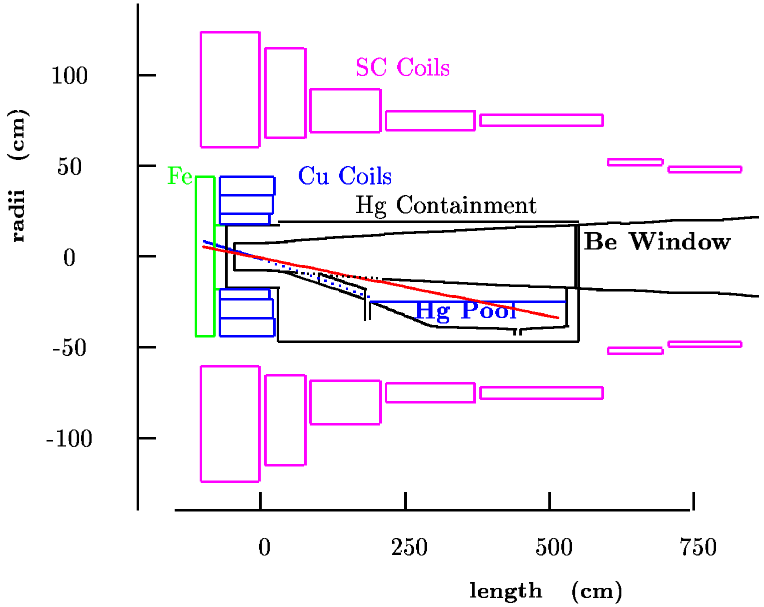
Beam entrance window an issue.

P. Sievers, http://molat.home.cern.ch/molat/neutrino/nf127.pdf

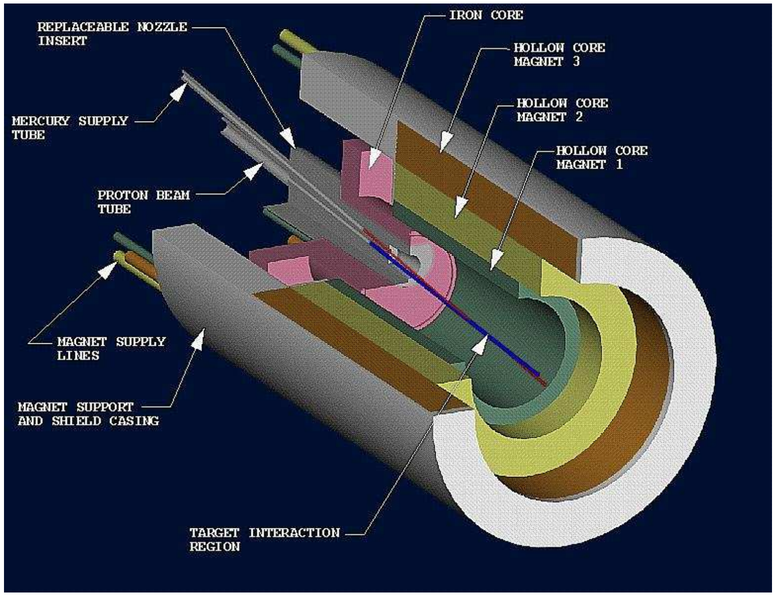
Inside a neutrino horn:



A Liquid Metal Jet May Be the Best Target for Beam Power above 1.5 MW

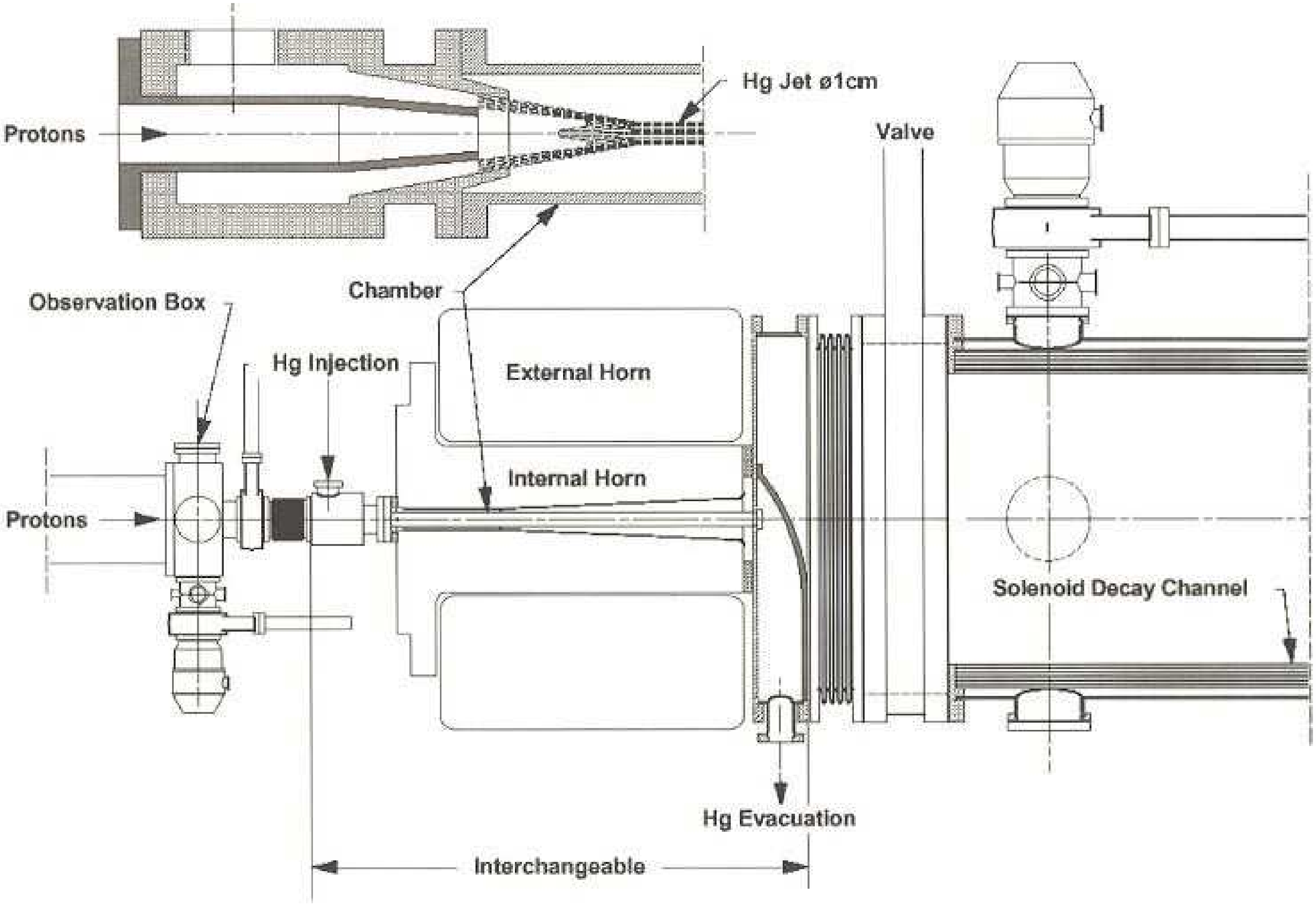


Mercury jet target inside a magnetic bottle: 20-T around target, dropping to 1.25 T in the pion decay channel.



Mercury jet tilted by 100 mrad, proton beam by 67 mrad, to increase yield of soft pions.

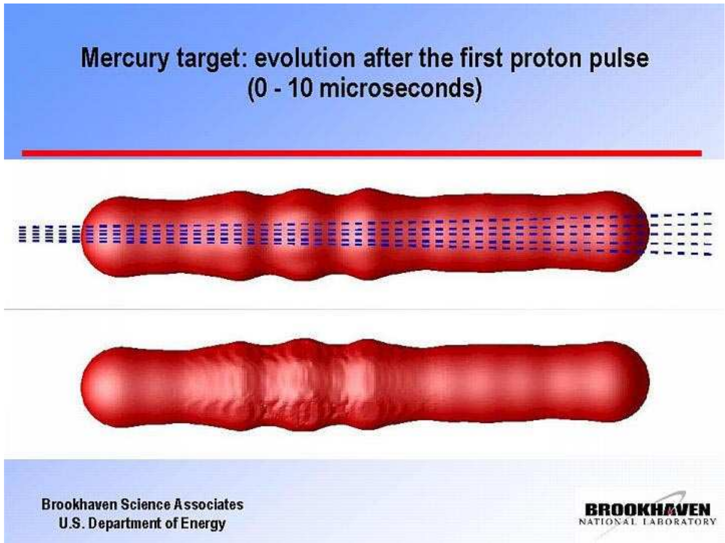
Mercury Jet Concept for the CERN 2-GeV Neutrino Horn



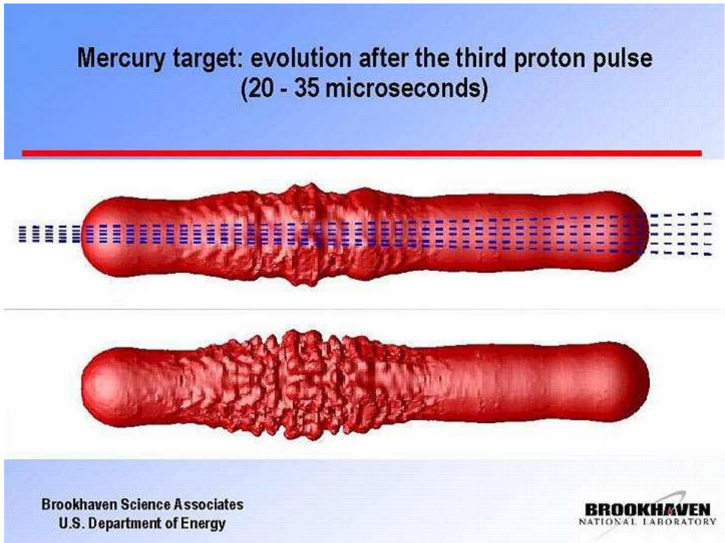
Recent schematic of the CERN Target

Viability of Targetry and Capture For a Single Pulse

- Beam energy deposition may disperse the jet.

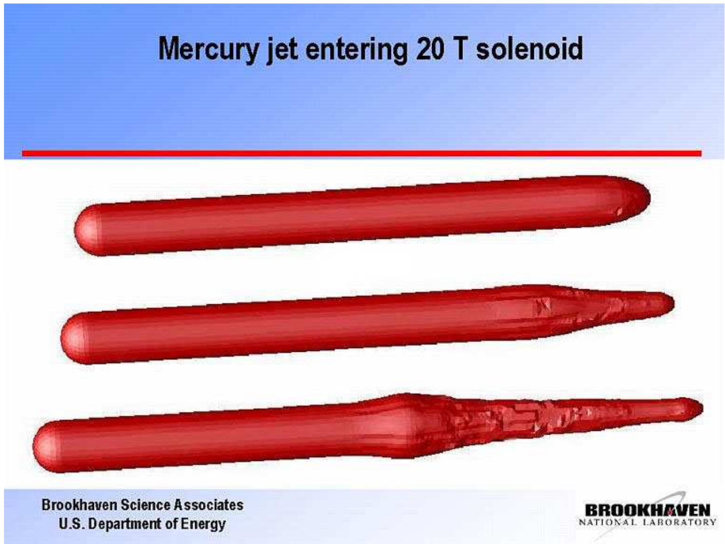

Mercury target: evolution after the first proton pulse
(0 - 10 microseconds)

Brookhaven Science Associates
U.S. Department of Energy

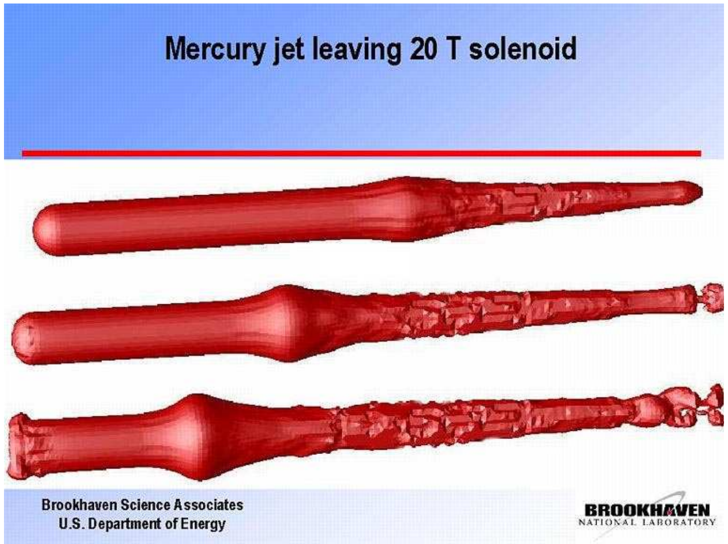

Mercury target: evolution after the third proton pulse
(20 - 35 microseconds)

Brookhaven Science Associates
U.S. Department of Energy

- Eddy currents may distort the jet as it traverses the magnet.


Mercury jet entering 20 T solenoid

Brookhaven Science Associates
U.S. Department of Energy

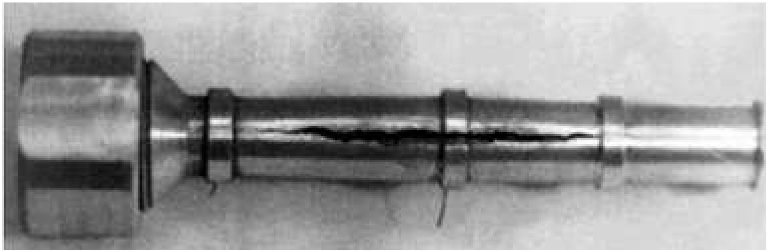

Mercury jet leaving 20 T solenoid

Brookhaven Science Associates
U.S. Department of Energy

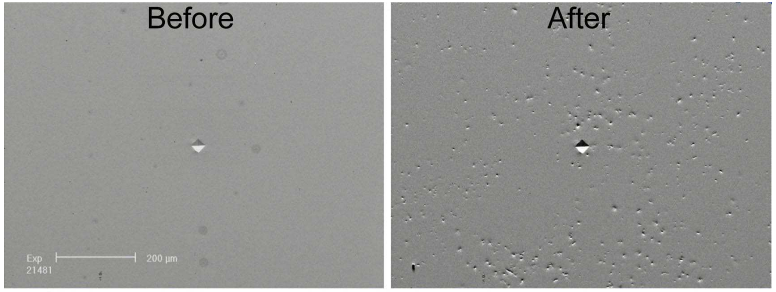
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

BINP:



SNS:

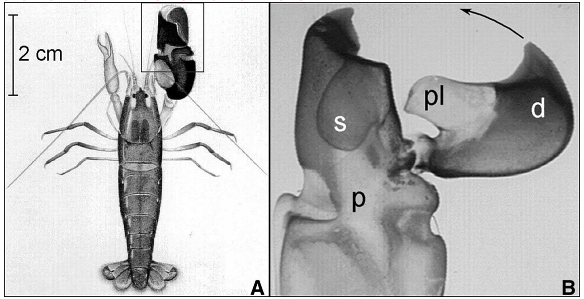


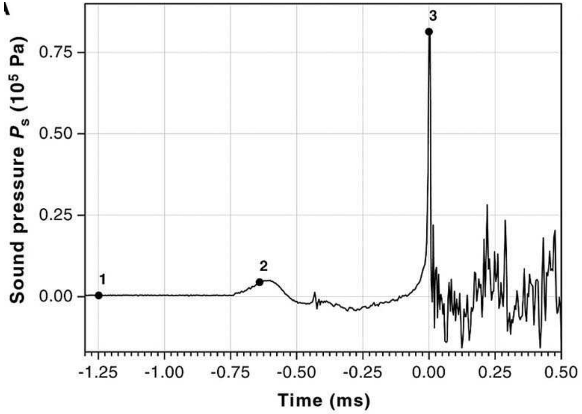
TL - High Power Target

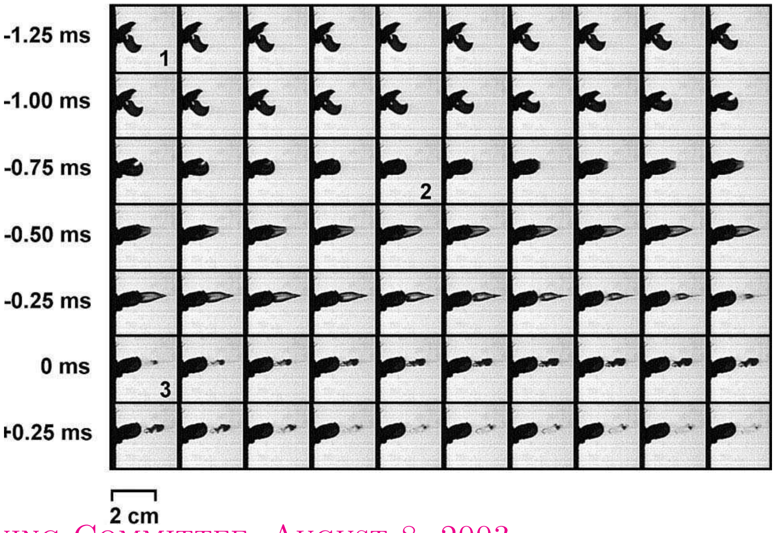
Specimen # 29754

Equivalent SNS Power Level = 2.5

Snapping shrimp stun prey via cavitation bubbles.

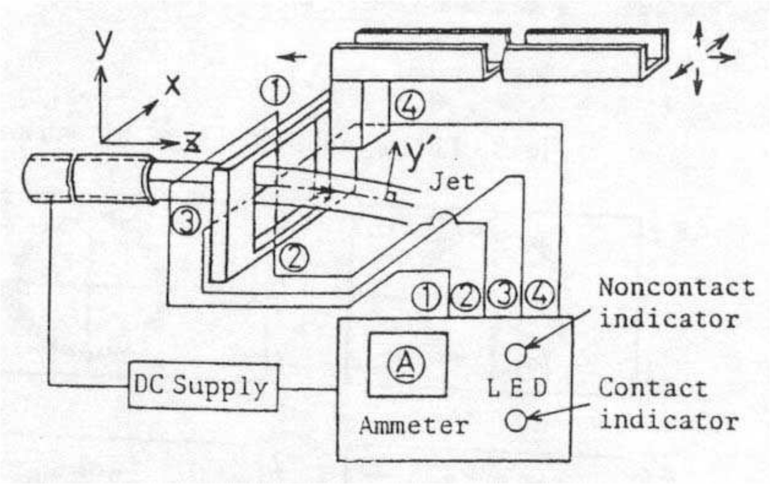


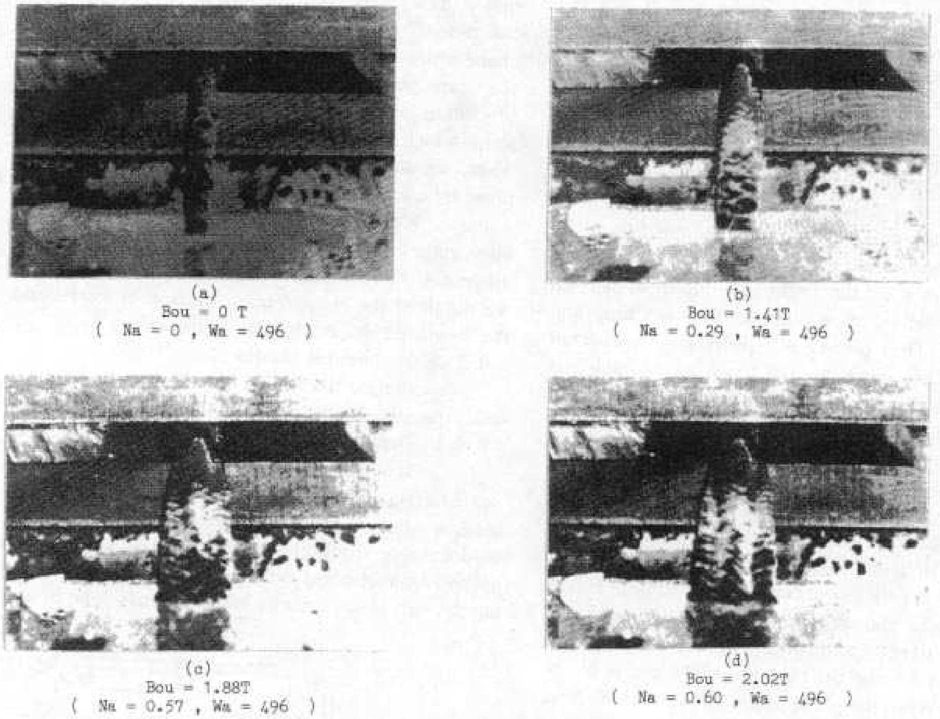




The Shape of a Liquid Metal Jet under a Non-uniform Magnetic Field

S. Oshima *et al.*, JSME Int. J. **30**, 437 (1987).



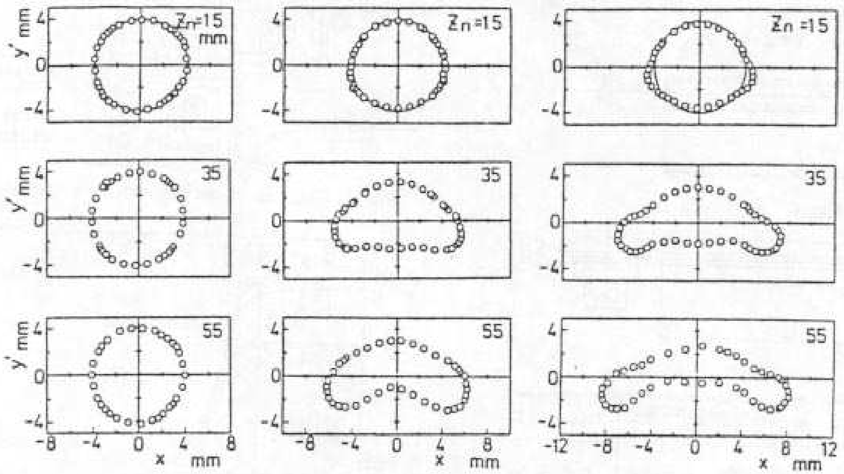

(a) Bou = 0 T (Na = 0 , Wa = 496)

(b) Bou = 1.41T (Na = 0.29 , Wa = 496)

(c) Bou = 1.88T (Na = 0.57 , Wa = 496)

(d) Bou = 2.02T (Na = 0.60 , Wa = 496)

Fig. 9 Photographs of the jet for various applied magnetic field strengths



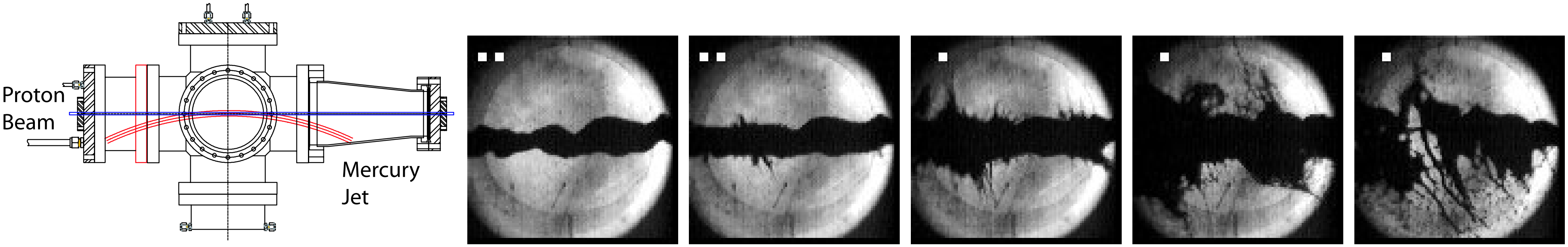
(a) Bou = 0 T (Na = 0 , Wa = 496)

(b) Bou = 1.41 T (Na = 0.29 , Wa = 496)

(c) Bou = 1.88 T (Na = 0.57 , Wa = 496)

Fig. 10 Cross-sectional shape of the jet obtained by spot a electrode probe

Studies of Proton Beam + Mercury Jet (BNL)



1-cm-diameter Hg jet in 2e12 protons at $t = 0$, 0.75, 2, 7, 18 ms.

$$\text{Model:} \qquad v_{\text{dispersal}} = \frac{\Delta r}{\Delta t} = \frac{r\alpha\Delta T}{r/v_{\text{sound}}} = \frac{\alpha U}{C} v_{\text{sound}} \approx 50 \text{ m/s}$$

for $U \approx 100$ J/g.

Data: $v_{\text{dispersal}} \approx 10$ m/s for $U \approx 25$ J/g.

$v_{\text{dispersal}}$ appears to scale with proton intensity.

The dispersal is not destructive.

Filaments appear only $\approx 40\ \mu$s after beam,

$\Rightarrow$ after several bounces of waves, or v_{sound} very low.

Tests of a Mercury Jet in a 20-T Magnetic Field
(CERN/Grenoble, A. Fabich, Ph.D. Thesis)

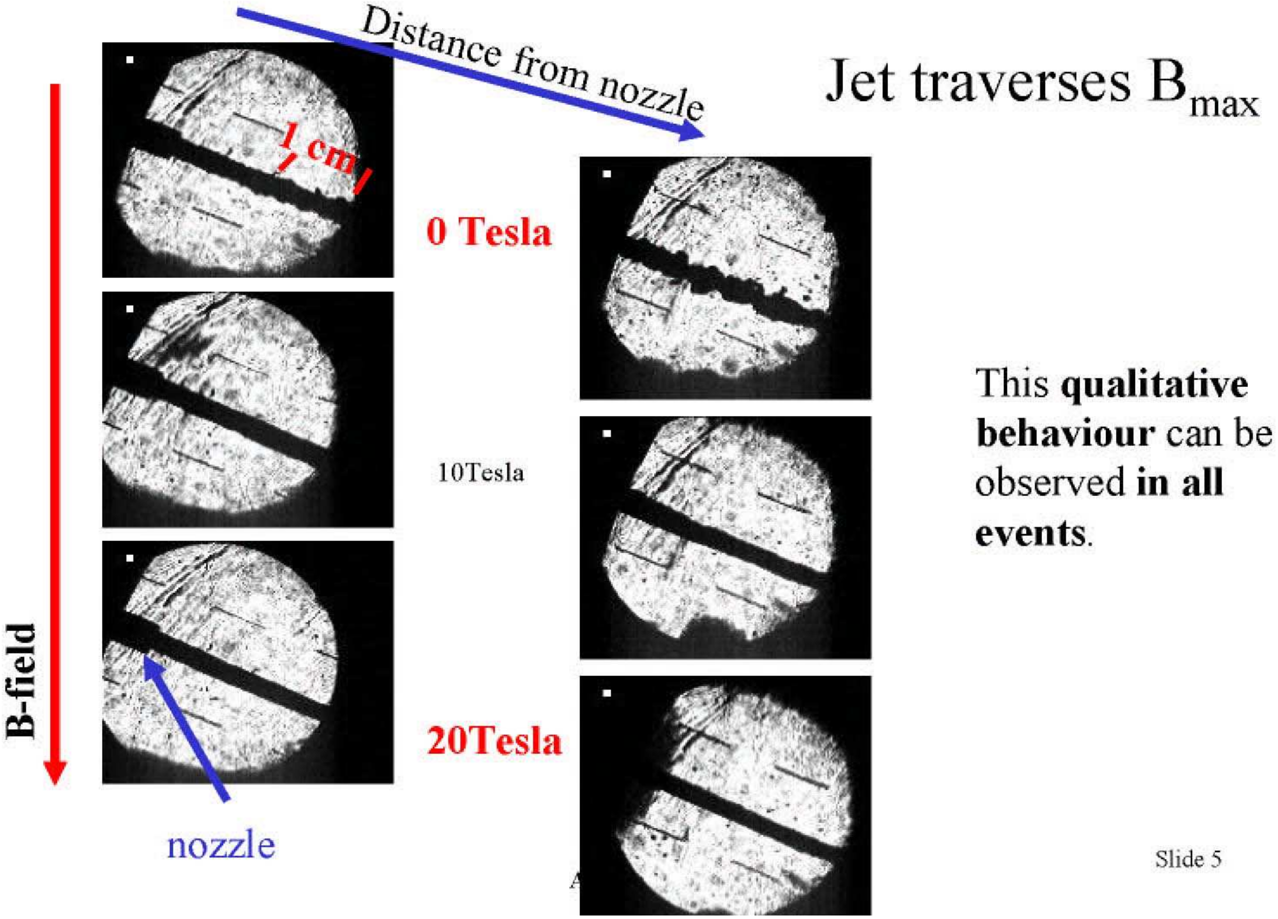
Eddy currents may distort the jet as it traverses the magnet.

Analytic model suggests little effect if jet nozzle inside field.

4 mm diam. jet, $v \approx 12$ m/s, $B = 0, 10, 20$ T.

⇒ Damping of surface tension waves (Rayleigh instability).

Will the beam-induced dispersal be damped also?

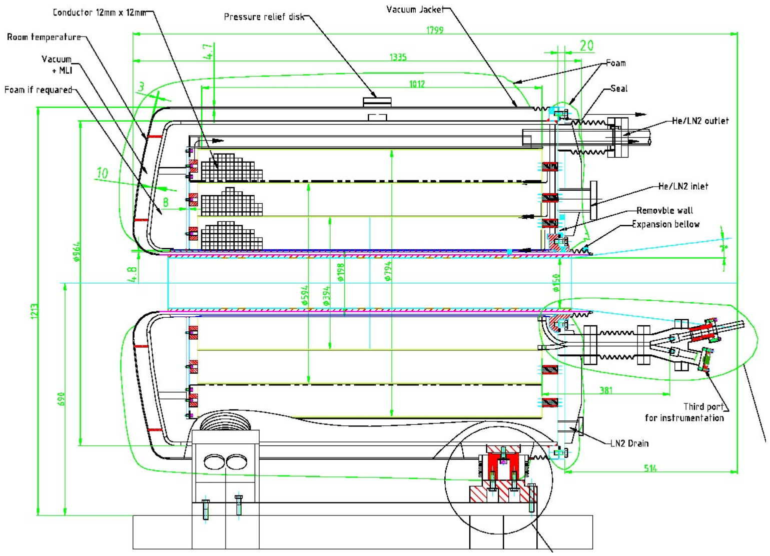


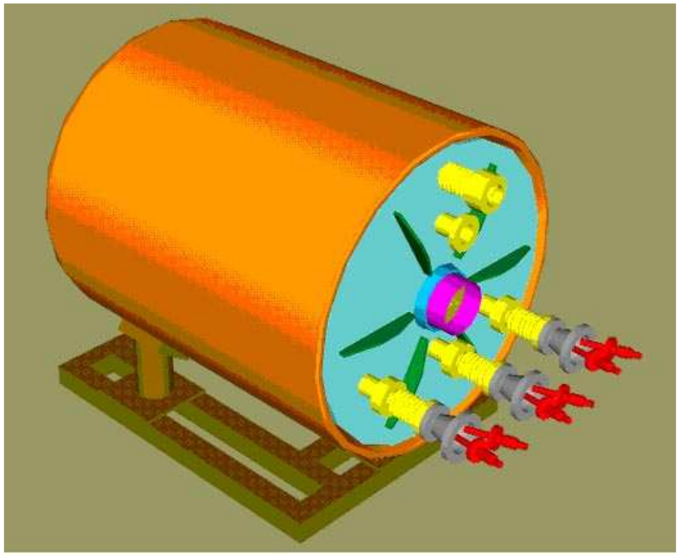
This **qualitative behaviour** can be observed **in all events**.

Issues for Further Targetry R&D

- Continue numerical simulations of MHD + beam-induced effects.
- Continue tests of mercury jet entering magnet.
- For solid targets, study radiation damage – and issues of heat removal from solid metal targets (carbon/carbon, Toyota Ti alloy, bands, chains, *etc.*).
- Confirm manageable mercury-jet dispersal in beams up to 10^{14} protons/pulse – for which single-pulse vaporization may also occur. Test Pb-Bi alloy jet.
- Study issues when combine intense proton beam with mercury jet inside a high-field magnet.
    1. MHD effects in a **prototype target configuration**.
    2. Magnetic damping of mercury-jet dispersal.
    3. Beam-induced damage to jet nozzle – in the magnetic field.
- ⇒ We propose to construct a 15-T pulsed magnet, that can be staged as a 5-T and 10-T magnet.

A 15-T LN_2-Cooled Pulsed Solenoid





- Simple solenoid geometry with rectangular coil cross section and smooth bore (of 20 cm diameter)
- Cryogenic system reduces coil resistance to give high field at relatively low current.
  - Circulating coolant is gaseous He to minimize activation, and to avoid need to purge coolant before pulsing magnet.
  - Cooling via N_2 boiloff.
- Most cost effective to build the 4.5-MW supply out of “car” batteries! (We need at most 1,000 pulses of the magnet.)

Addendum: Targetry Issues for Positron Production at a Linear Collider

Goal: 1 positron per electron.

A conventional thick target is overstressed by the requirements of NLC/TESLA – and the e^+ are unpolarized.

Option: use e_- beam + helical undulator to produce 10-MeV polarized γ's, which are converted to polarized e^+ in a thin target.

$\approx$ 1/10 the power density in target with the undulator scheme.

SLAC E-166 recently approved to demonstrate undulator-based production of polarized positrons.