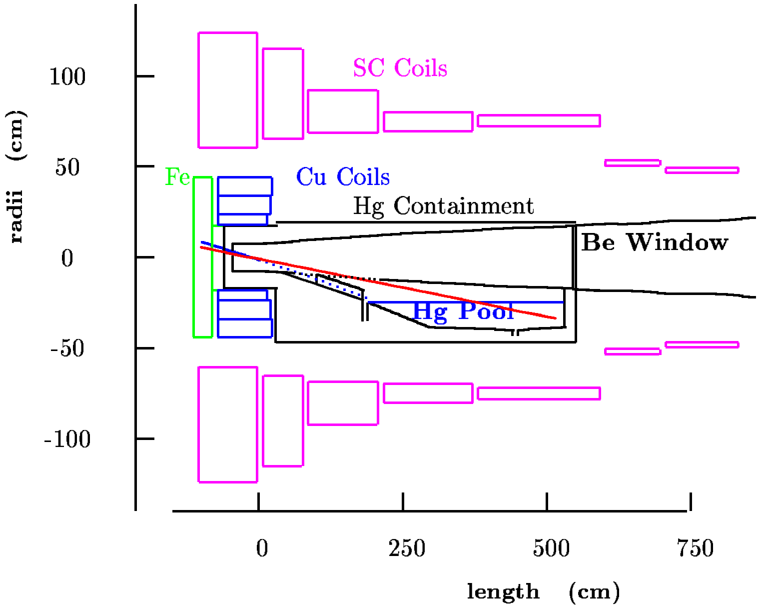
Targets for Neutrino Factories and Muon Colliders



K.T. McDonald

Princeton U.

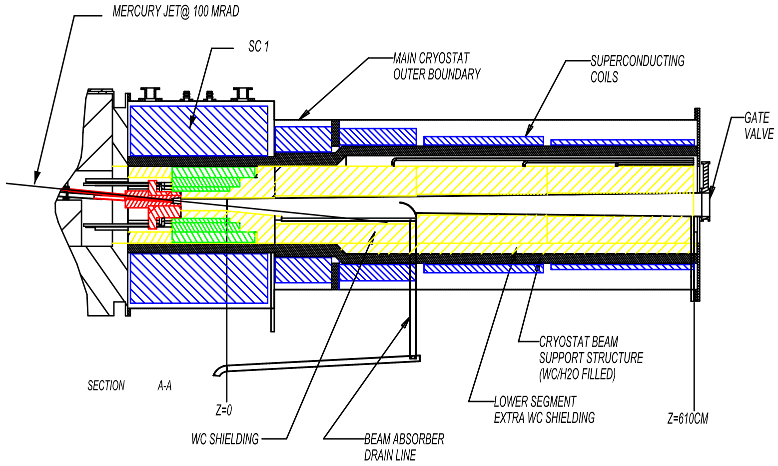
Muon Collaboration Meeting

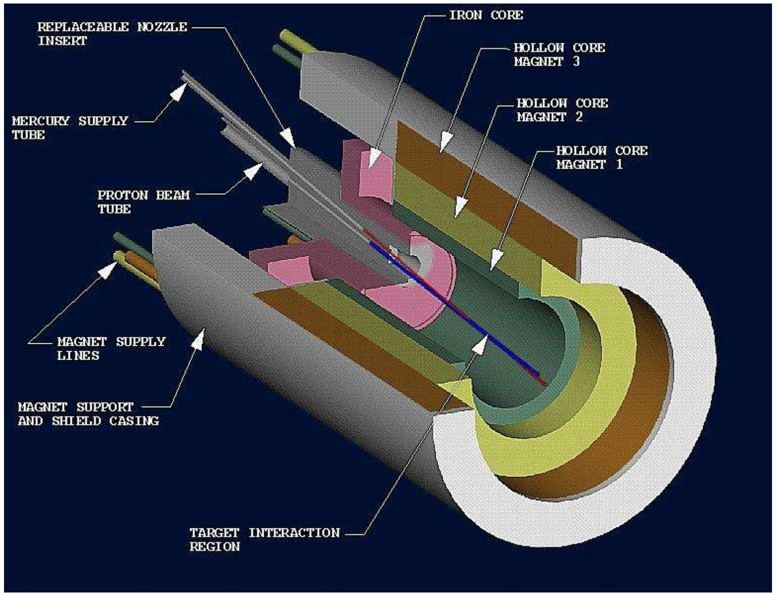
Riverside Mission Inn

January 29, 2004

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

Sketches of a 4-MW Target Station





High Performance Muon and Neutrino Beams Require a High Performance Source

- Existing target technologies can perhaps be extrapolated for use in 2 MW proton beams.
- High-power targetry important for muon colliders, neutrino factories, “conventional” secondary beams, accelerator production of tritium, accelerator transmutation of waste, fusion materials test facilities, ...
- Common targetry challenges explored in the Ronkonkoma Workshop (Sept. 2003, Harold Kirk).
- For modest extrapolation, key issues are materials properties after irradiation.
  $\Rightarrow$ Continuation of solid target studies at the BNL BLIP (Nick Simos).
- For use in $\gtrsim 2$ MW beams, need new options such as liquid metal jet targets.
- BNL/CERN tests of mercury + beam and mercury + 20-T magnet are encouraging,
  $\Rightarrow$ Make system test of mercury + magnet + beam (Peter Titus, Helmut Haseroth).
- Beam tests are supplemented by magnetohydrodynamic numerical simulations (Roman Samulyak).

Thermal Shock

When beam pulse length t is less than target radius r divided by speed of sound $v_{\rm sound}$, 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?

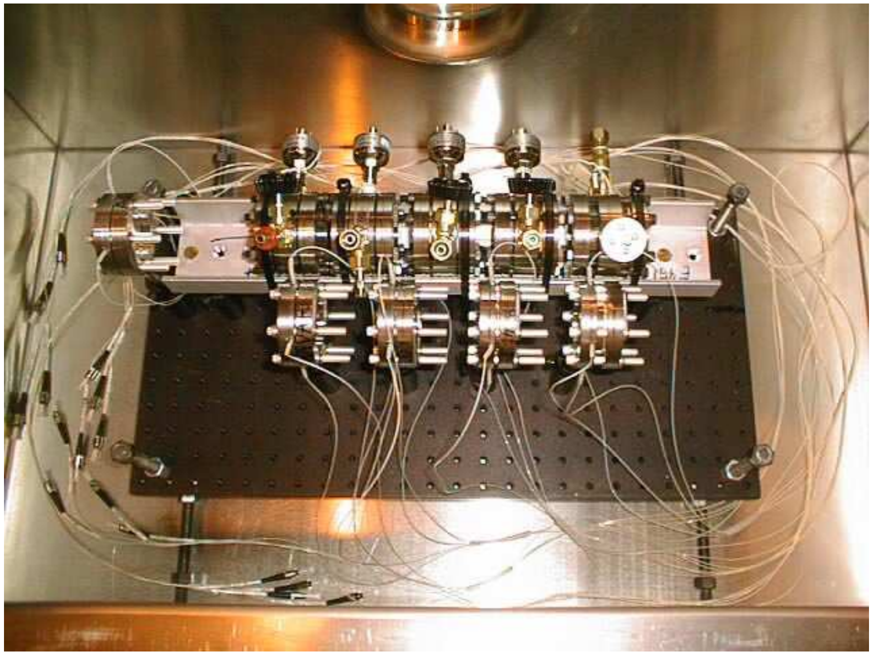
How many protons are required to deposit 60 J/g in a material? What is the maximum beam power this material can withstand without cracking, for a 10-GeV beam at 10 Hz with area 0.1 cm^2.

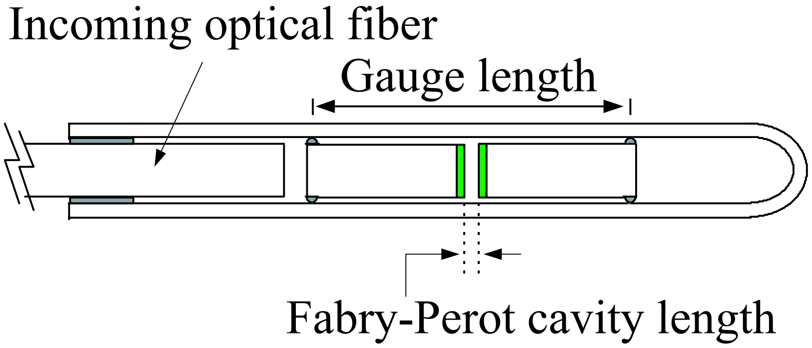
Ans. If we ignore "showers" in the material, we still have dE/dx ionization loss, of about 1.5 MeV/g/cm^2.
Now, 1 MeV $= 1.6 \times 10^{-13}$ J, so 60 J/ g requires a proton beam intensity of $60/(1.6 \times 10^{-13}) = 10^{15}/\text{cm}^2$.
Then, $P_{\max} \approx 10 \text{ Hz} \cdot 10^{10} \text{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

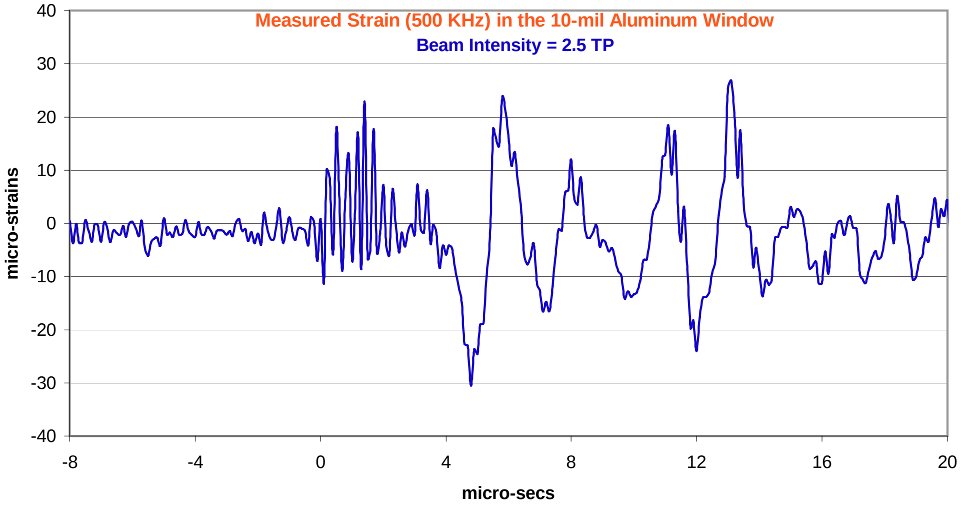
Solid targets are viable up to about 1.5 MW beam power!

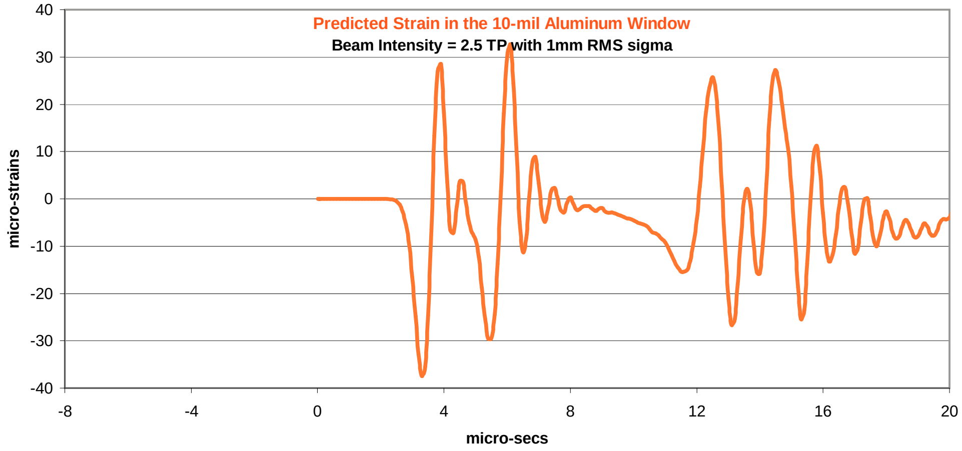
Window Tests (5e12 *p*pp, 24 GeV, 100 ns)

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



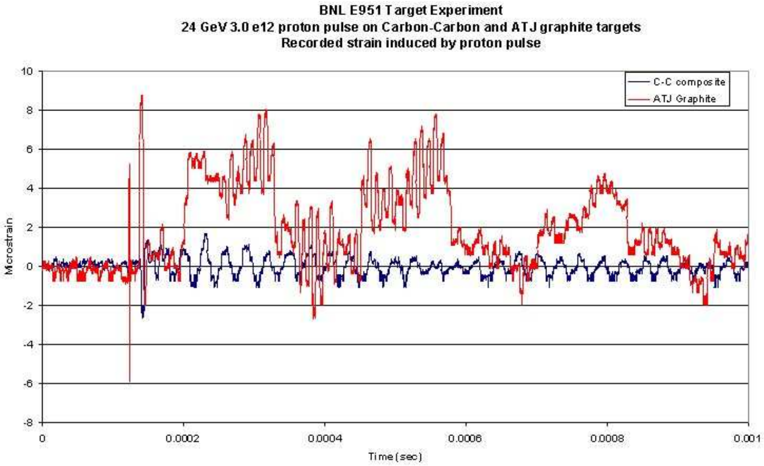




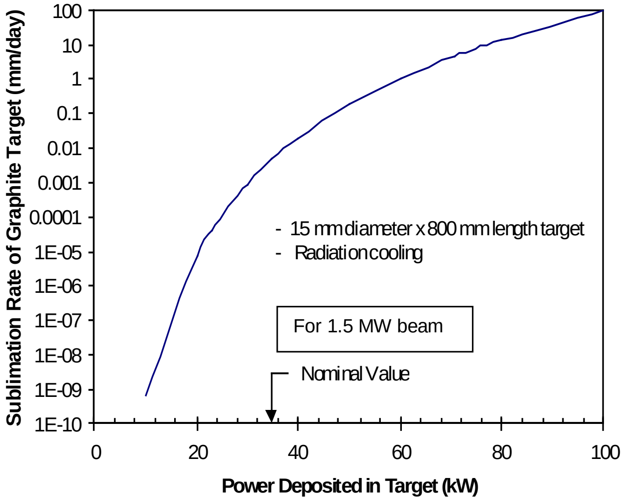


A Carbon Target is Feasible at 1-MW Beam Power

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.



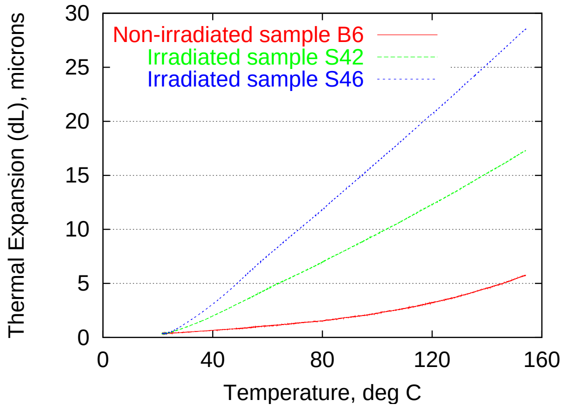
Sublimation of carbon is negligible in a helium atmosphere.

Tests underway at ORNL to confirm this.

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

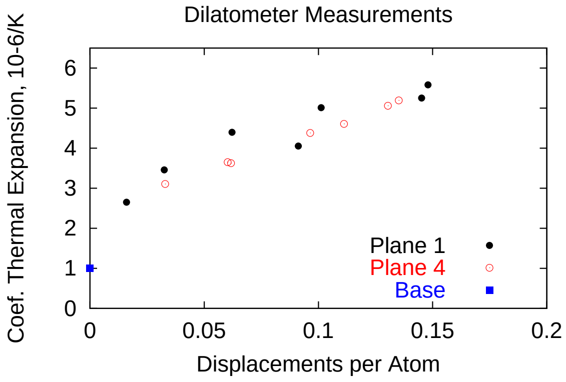
Effects of Radiation on SuperInvar

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



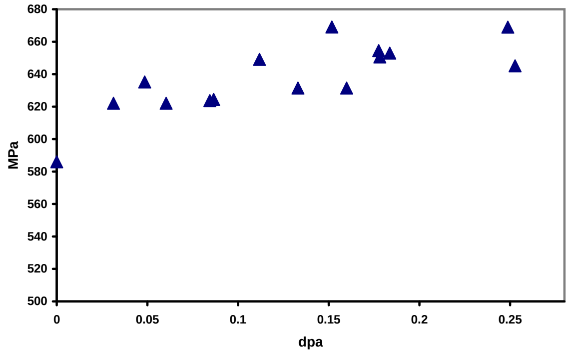
However, irradiation at the BNL BLIP facility show that the CTE increases rapidly with radiation dose.

CTE *vs.* dose ⇒



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

Yield strength *vs.* dose ⇒



New Round of Irradiation Studies

Are “high performance” alloys still high performance after irradiation?

Materials to be studied:

1. Vascomax 350 (high strength steel for bandsaw target).
2. Ti90Al6V4 (titanium alloy for linear collider positron target).
3. Toyota “gum” metal (low-thermal expansion titanium alloy).
4. AlBeMet (aluminum/beryllium alloy).
5. Graphite (baseline for J-PARC neutrino production target).
6. Carbon-carbon composite (3-d weave with low-thermal expansion).

Opportunity for a European Targetry R&D Project

A proposal to the European Union Sixth Framework Programme (FP6) for a "Design Study for Neutrino Factory Target R&D" will be submitted in March 2004.
Lead: R. Edgecock (RAL).

Topics:

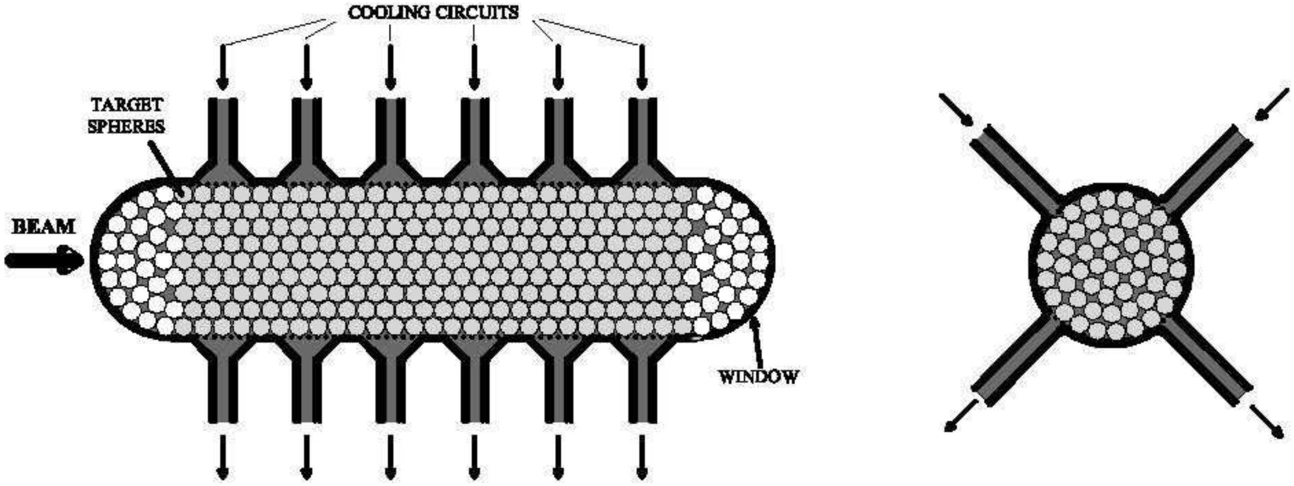
1. The Mercury Jet Target.
2. The Granular Target.
3. The Contained Metal Jet Target.
4. Target Station Design Studies.
5. Simulations of Beam/Target Interactions.

The Muon Collaboration Targetry Group will have an adjunct status on this proposal.

Our most immediate interest is topic 1, in the form of a beam test at CERN.

A Granular Target

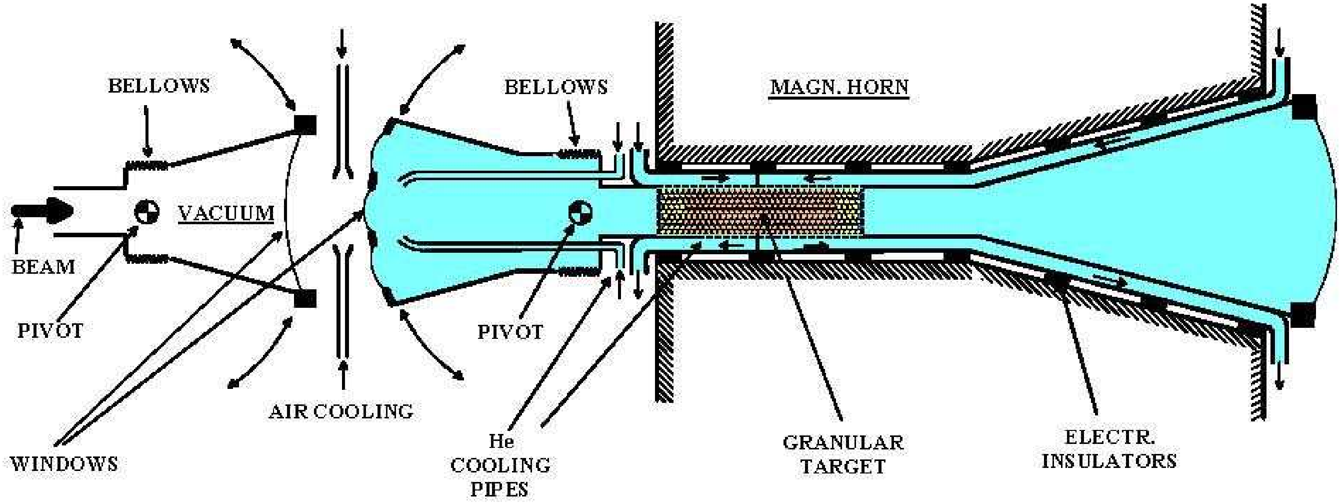
Target of pellets, cooled by flowing He gas.



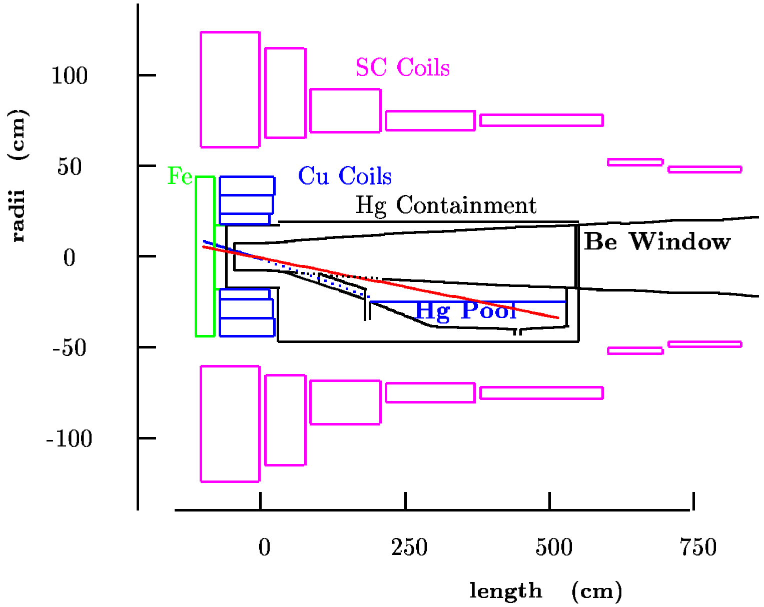
Beam entrance window an issue.

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

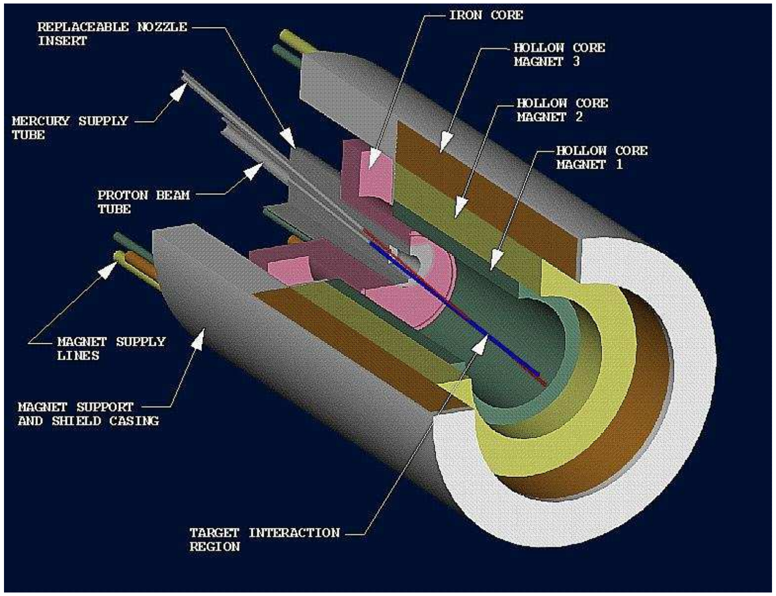
Inside a neutrino horn:



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.



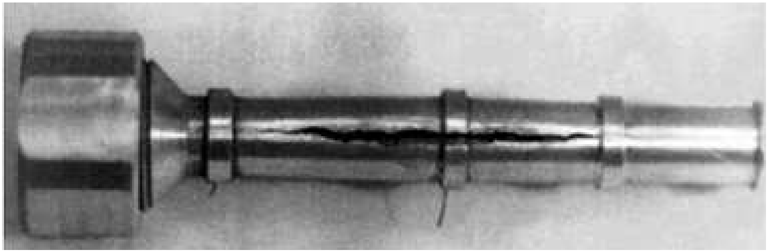
Mercury jet tilted by 100 mrad, proton beam by 67 mrad, to increase yield of soft pions.

Beam-Induced Cavitation in Liquids Can Break Pipes

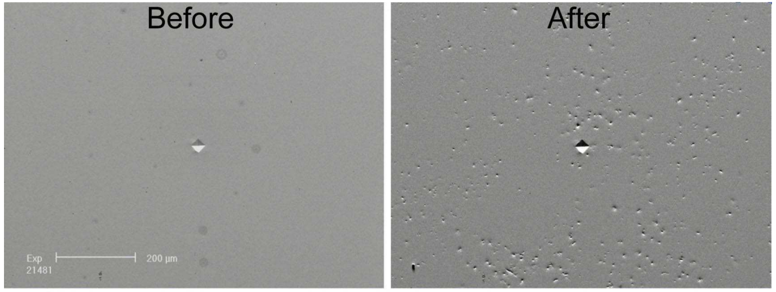
Snapping shrimp stun prey via cavitation bubbles.

ISOLDE:

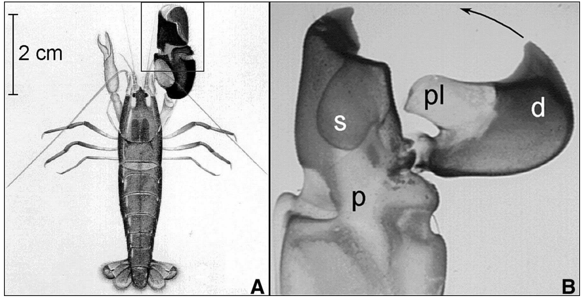
BINP:

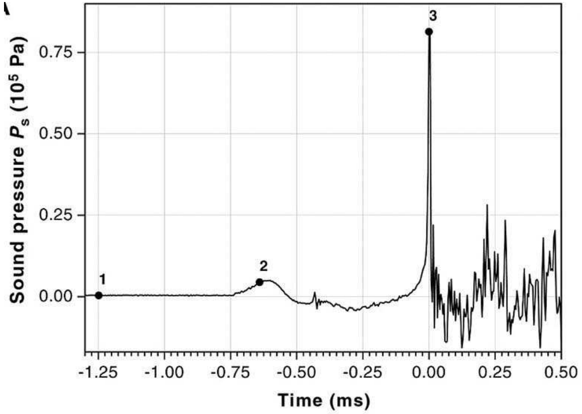


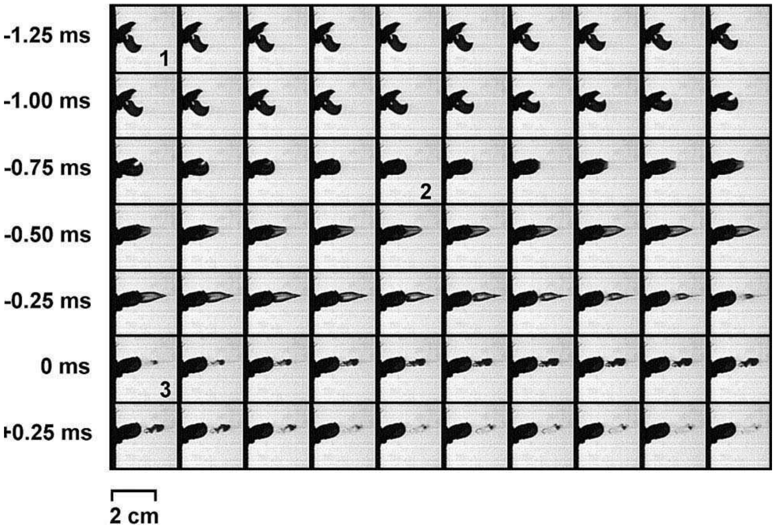
SNS:



TL - High Power Target
Specimen # 29754
Equivalent SNS Power Level = 2.5

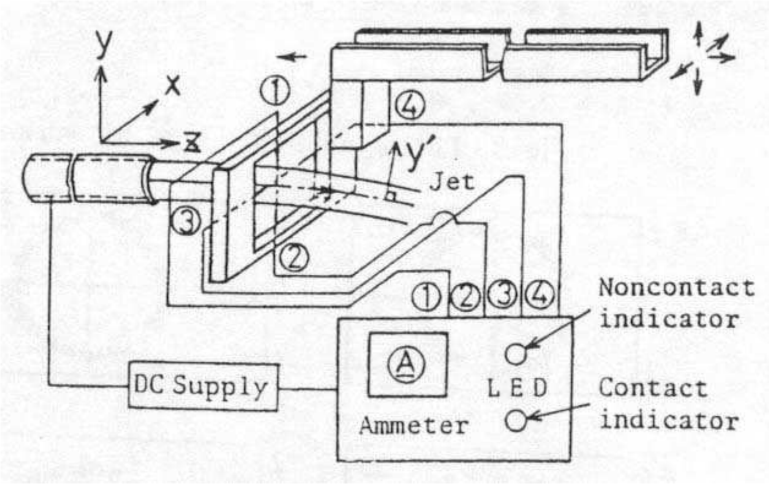


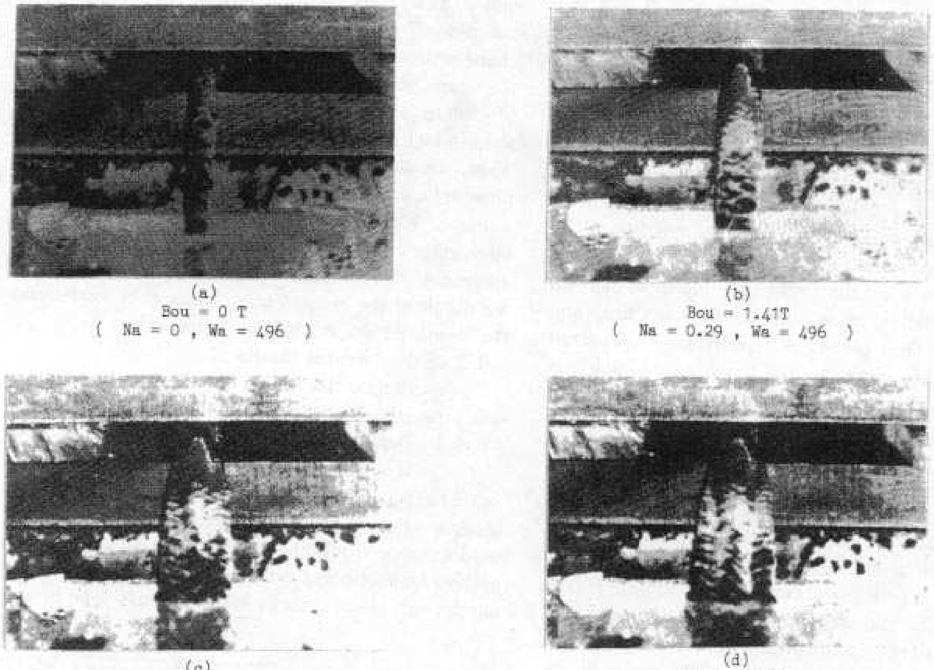




The Shape of a Liquid Metal Jet under a Non-uniform Magnetic Field

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





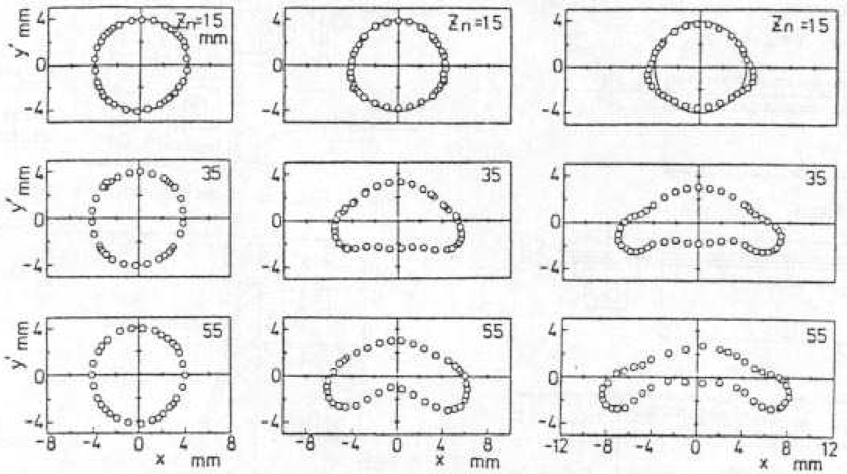
(a)
Bou = 0 T
(Na = 0 , Wa = 496)

(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 mag- netic field strengths



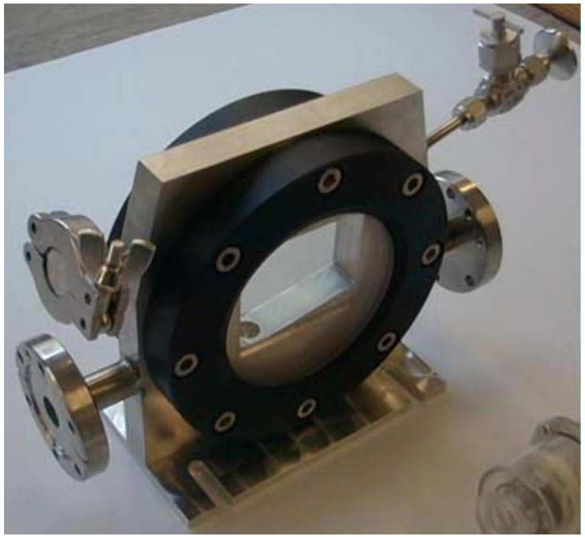
(a)
Bou = 0 T
(Na = 0 , Wa = 496)

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

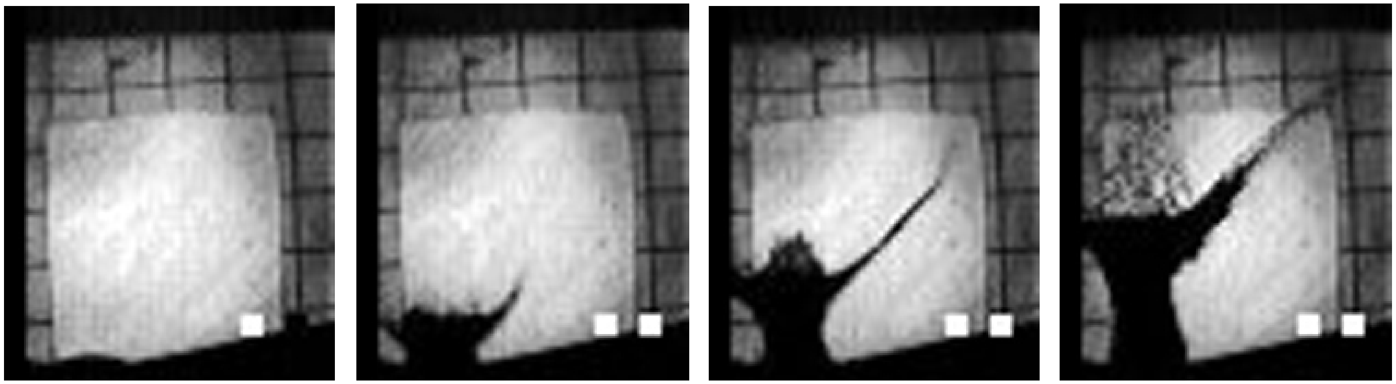
(c)
Bou = 1.88 T
(Na = 0.57 , Wa = 496)

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

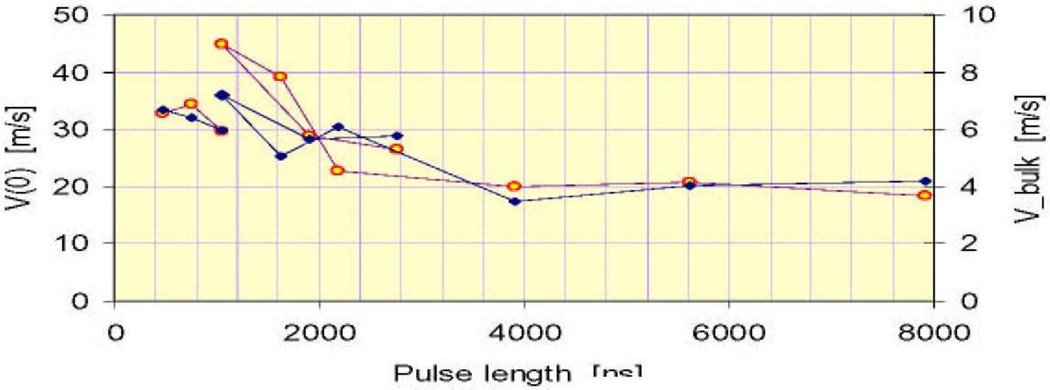
Passive Mercury Target Tests (BNL and CERN)



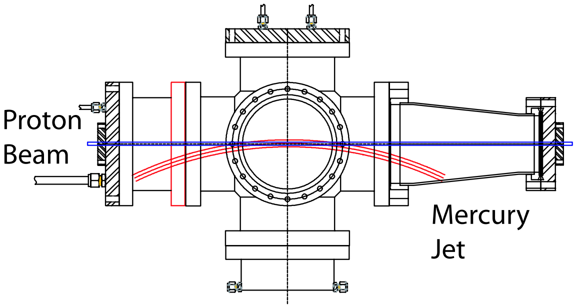
Exposures of 25 μs at
$t = 0, 0.5, 1.6, 3.4$ msec,
$\Rightarrow v_{\text{splash}} \approx 20 - 40$ m/s:

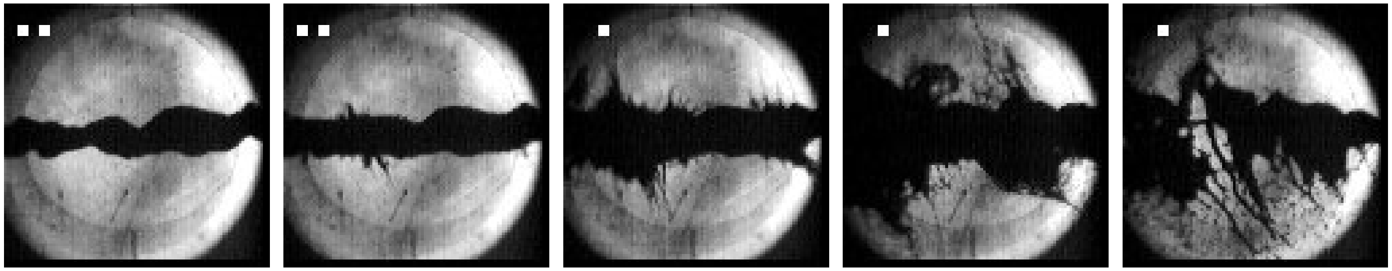


Two pulses of ≈ 250 ns give larger dispersal velocity only if separated by less than 3 μs.



Studies of Proton Beam + Mercury Jet (BNL)





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

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

for $U \approx 100$ J/g.

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

$v_{\rm dispersal}$ 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 $v_{\rm sound}$ very low.

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

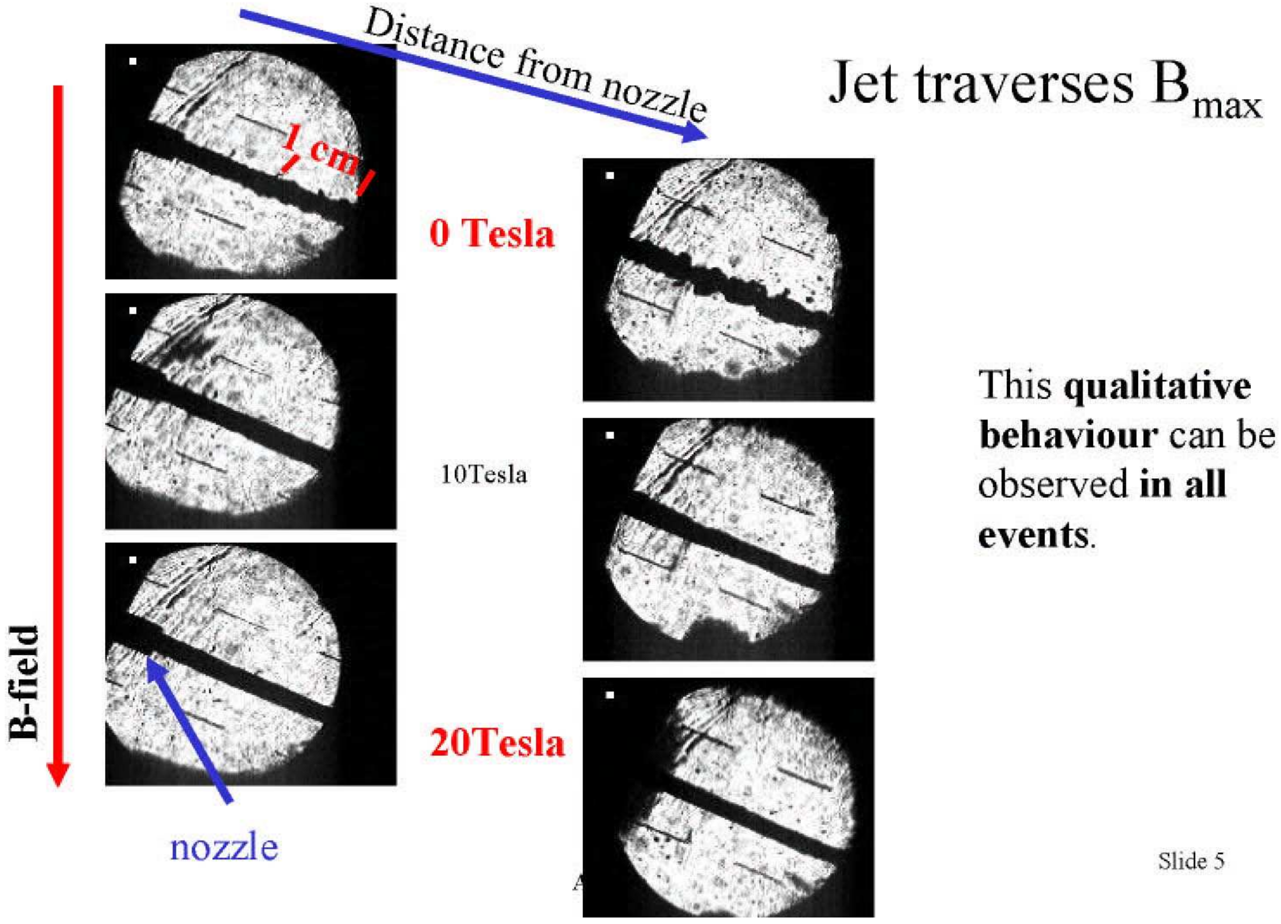
Eddy currents may distort the jet as it traverses the magnet.

Analytic model suggests little effect if jet nozzle inside field.

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

$\Rightarrow$ Damping of surface-tension waves (Rayleigh instability).

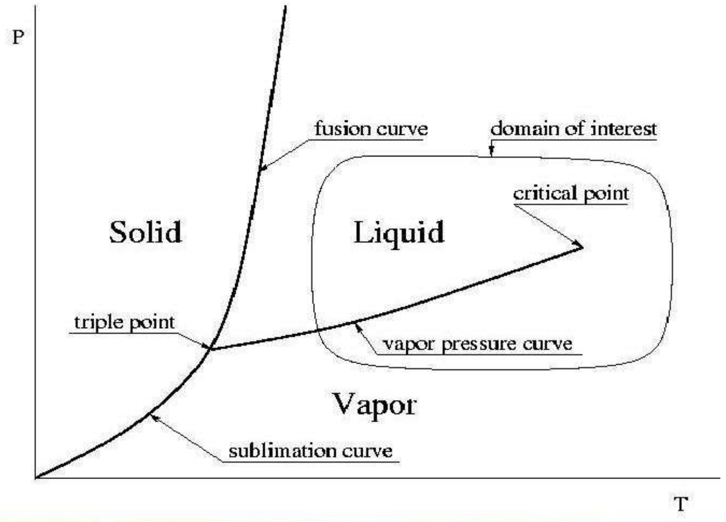
Will the beam-induced dispersal be damped also?

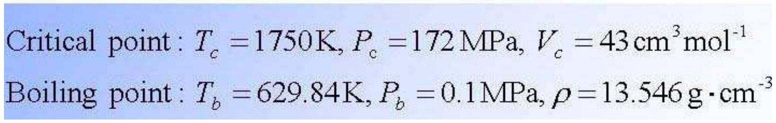


This **qualitative behaviour** can be observed **in all events**.

Computational Magnetohydrodynamics (R. Samulyak, Y. Pyrkarpatsky)

Use equation of state that supports negative pressures, but gives way to cavitation.

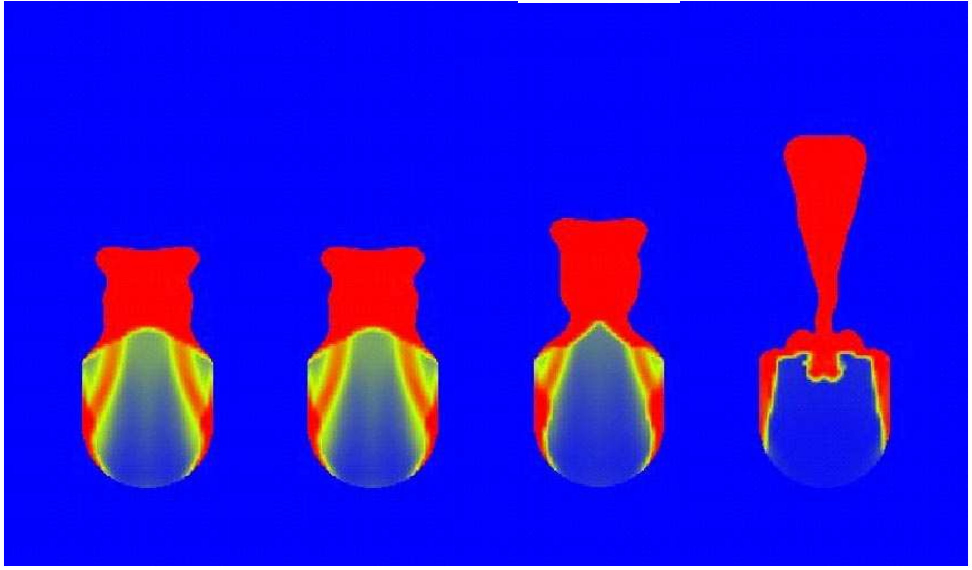




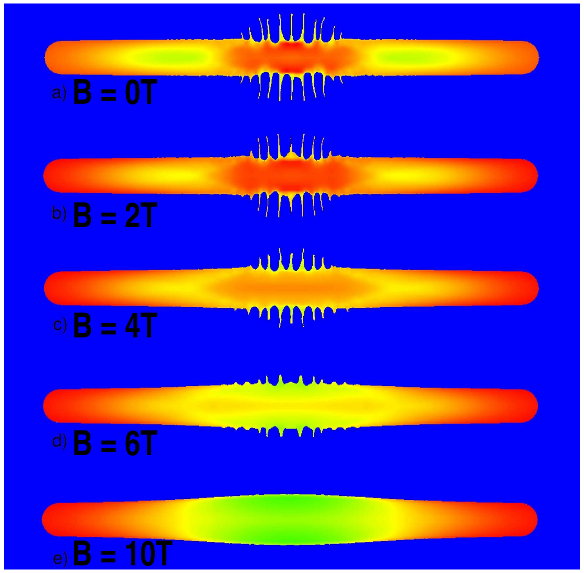
Critical point : $T_c = 1750\,\mathrm{K}$, $P_c = 172\,\mathrm{MPa}$, $V_c = 43\,\mathrm{cm}^3\mathrm{mol}^{-1}$

Boiling point : $T_b = 629.84\,\mathrm{K}$, $P_b = 0.1\,\mathrm{MPa}$, $\rho = 13.546\,\mathrm{g \cdot cm}^{-3}$

Thimble splash at 0.24, 0.48, 0.61, 1.01 μs



Magnetic damping of beam-induced filamentation:

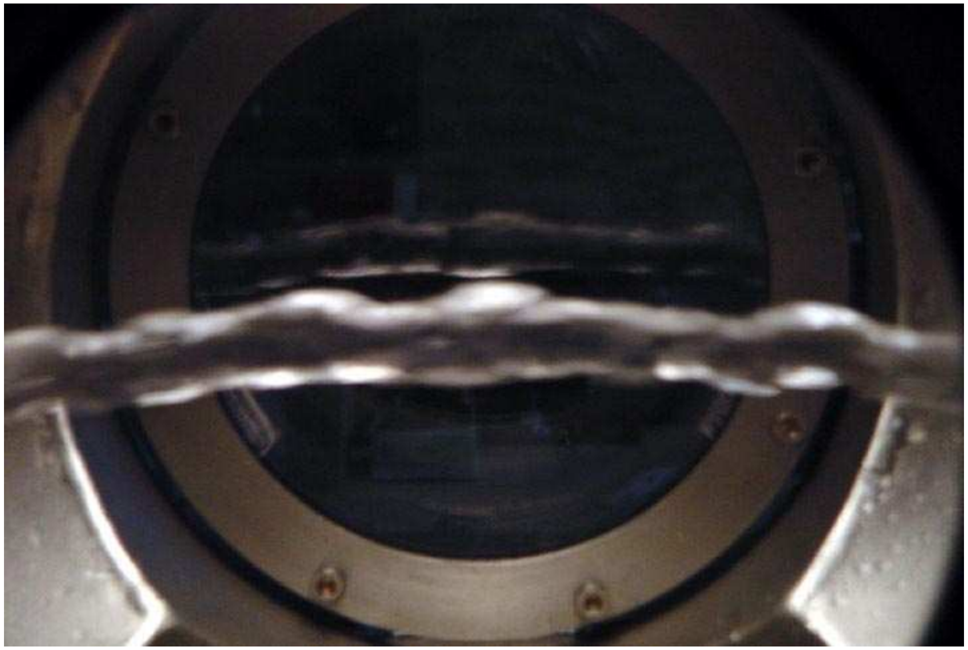


Issues for Further Targetry R&D

- 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 are constructing a 15-T pulsed magnet,
  that can be staged as a 5-T and 10-T magnet.

A 2-5 m/s Continuous Flow Mercury Jet

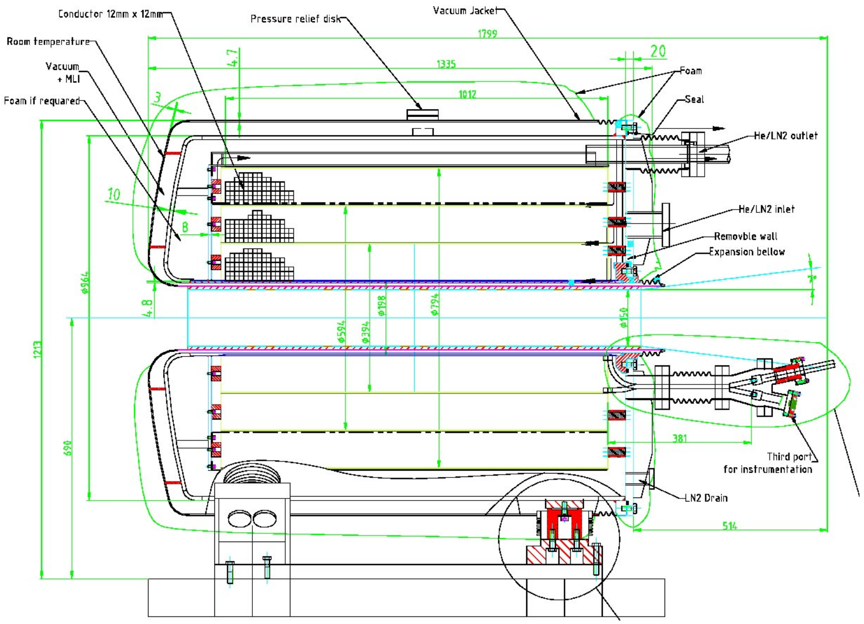
A 2.5-m/s, continuous-flow version of the free mercury jet target was constructed for use in the BNL A3 line.

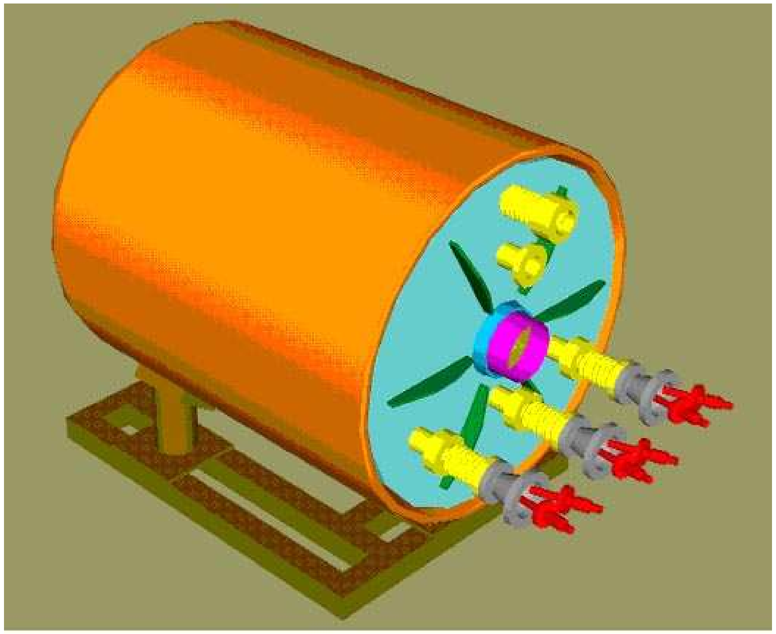


Completed Oct 2003. Now in storage.

Most components fabricated for a 2nd version using Wood's metal.
(However, the Wood's metal wets the quartz windows.)

A 15-T LN_2-Cooled Pulsed Solenoid



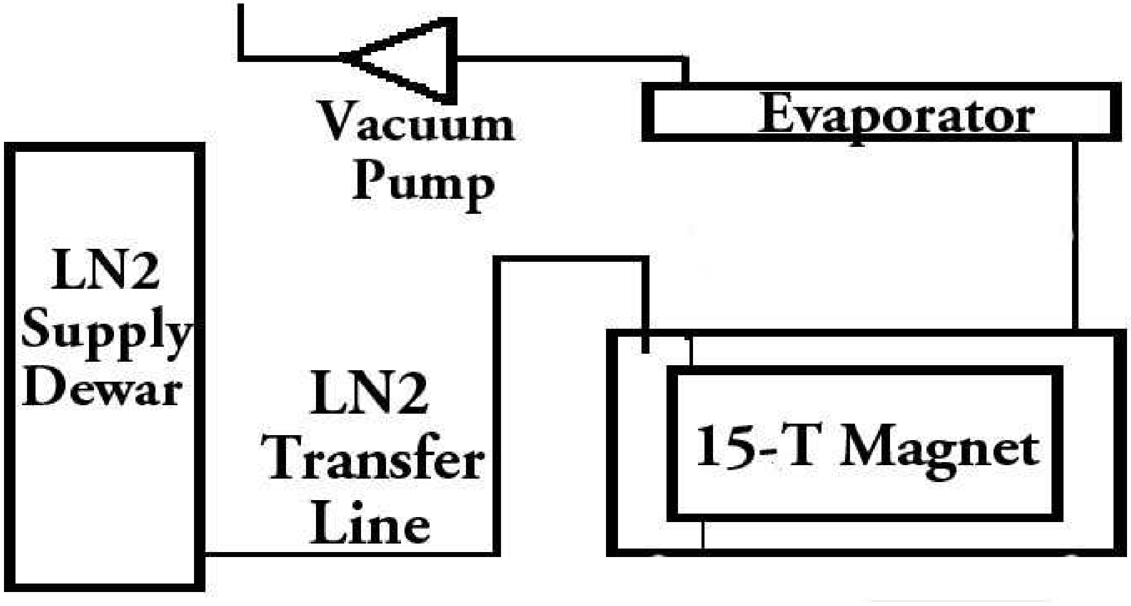


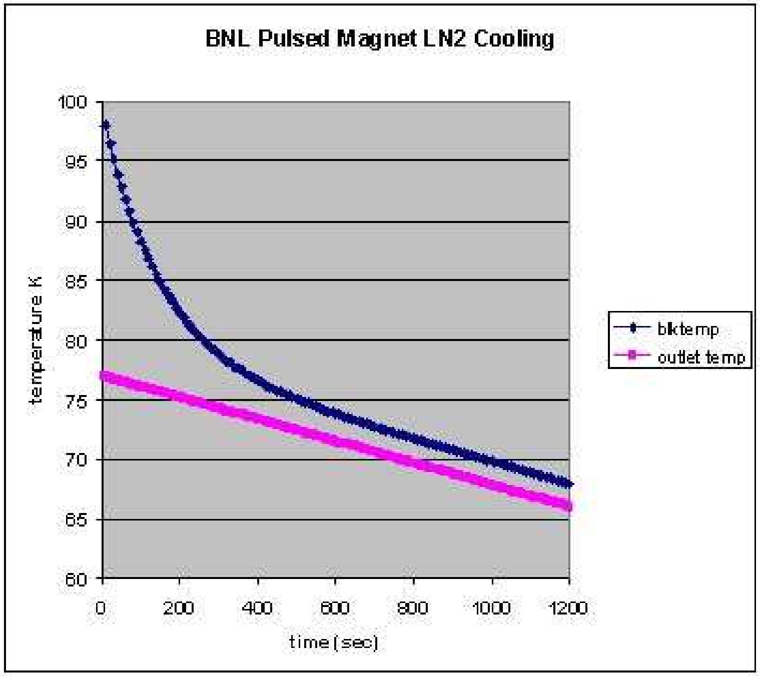
- Simple solenoid geometry with rectangular coil cross section and smooth bore (of 20 cm diameter)

- 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.)

Magnet Can Be Cooled by Forced Flow of LN_2



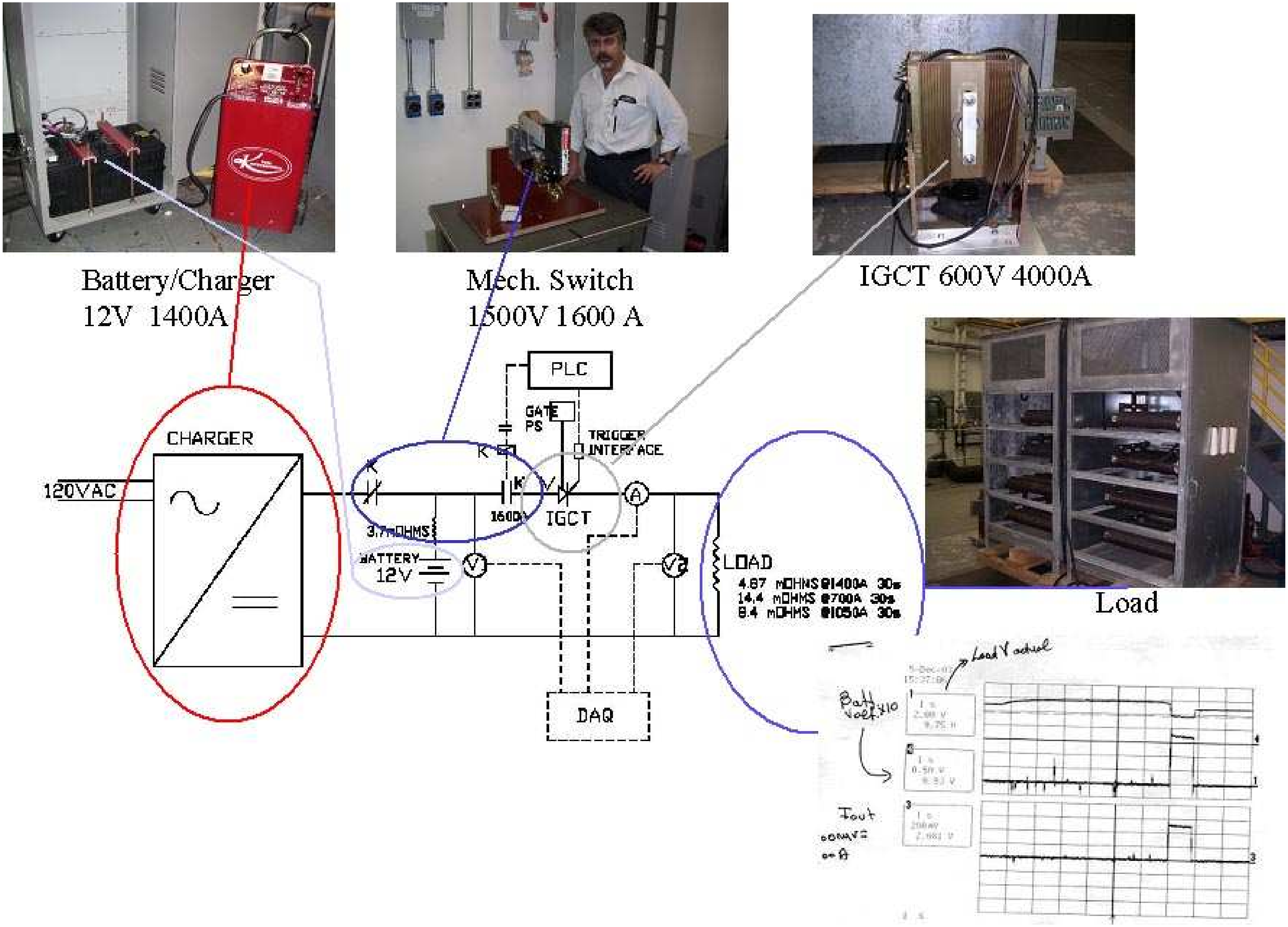


Force the LN_2 via pumping, ⇒ Can reduce temperature to 70K in 20 min.

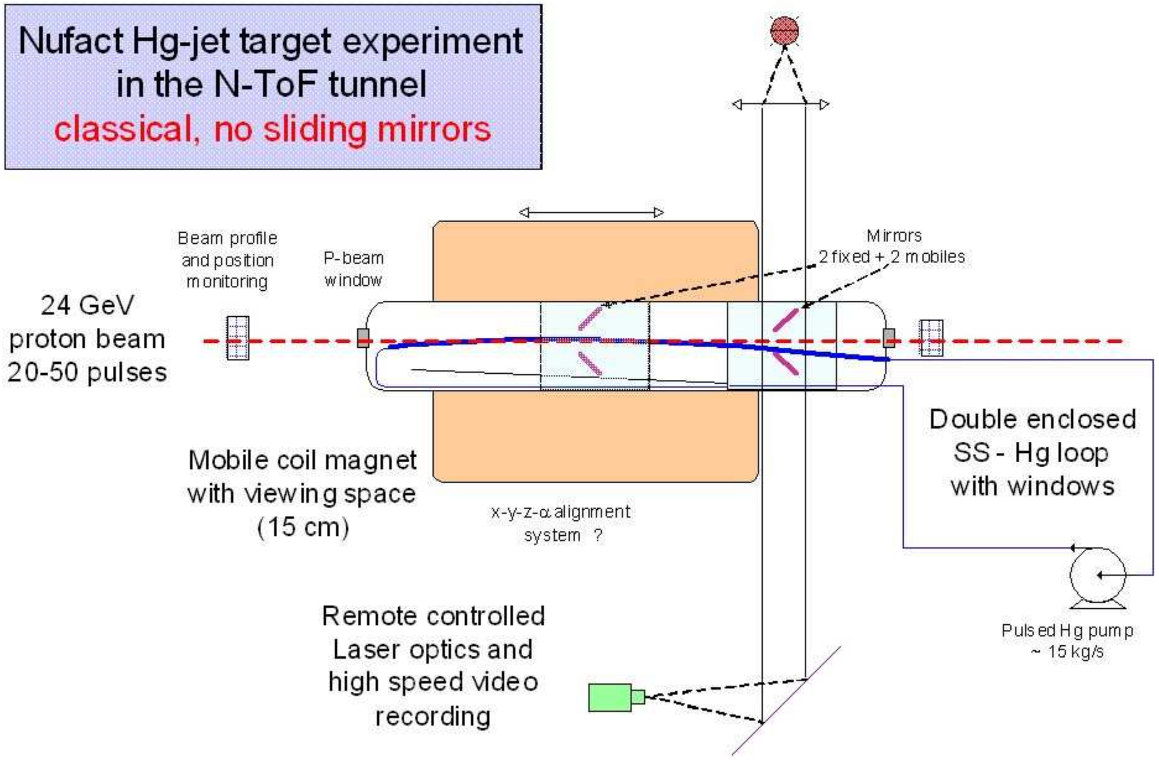
⇒ Can achieve 15 T with a 5-MW (battery) power supply.

Pump LN_2 completely out of magnet before pulsing, to minimize activation.

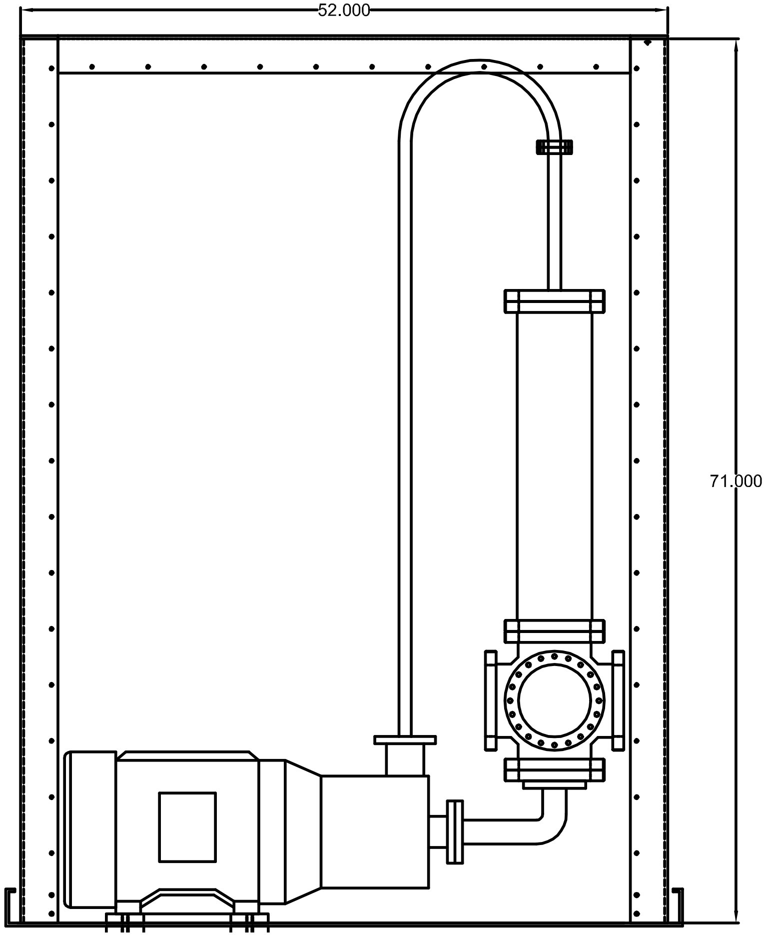
R&D for a 5-MW Battery Power Supply



Optical Diagnostics



Nufact Hg-jet target experiment in the N-ToF tunnel
classical, no sliding mirrors



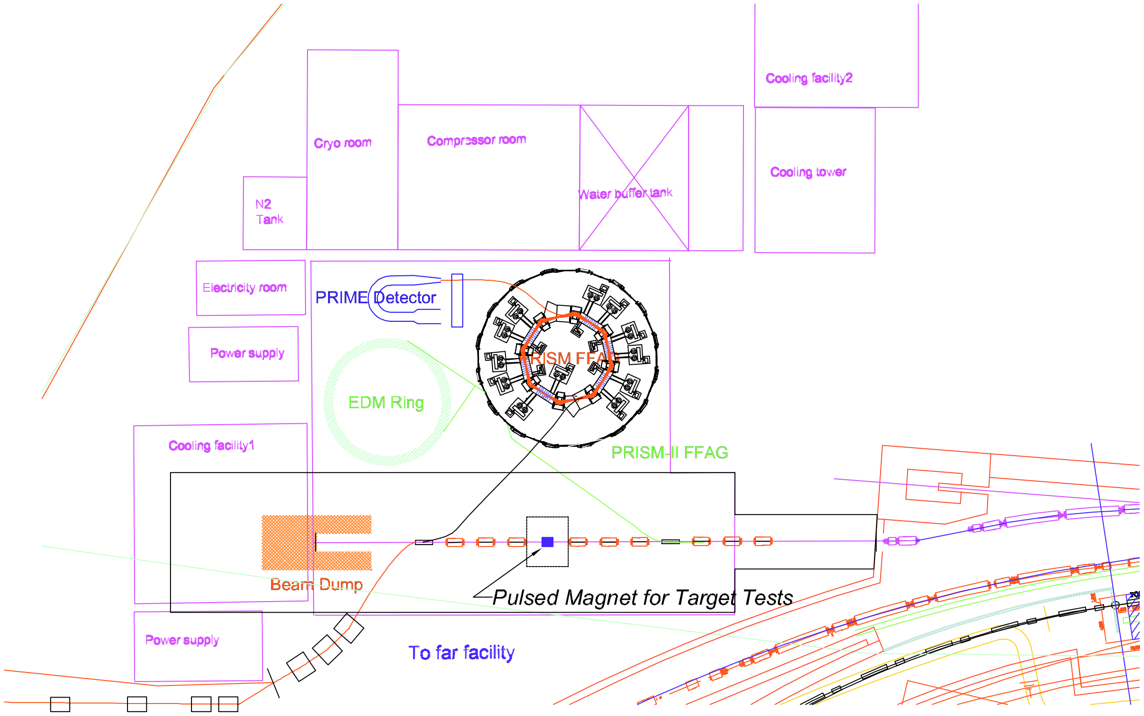
Need 20 m/s horizontal mercury jet.

Continuous or Pulsed?

20 m/s vertical continuous flow mercury jet under development:

Possible Sites of the Beam/Jet/Magnet Test

E-951 has existing setup in the BNL A3 line – but beam may be no longer available there.



J-PARC 50-GeV fast-extracted beam: (LOI 30, Jan 21, 2003)

CERN PS transfer line: CERN-INTC-2003-033 (Oct 23, 2003)