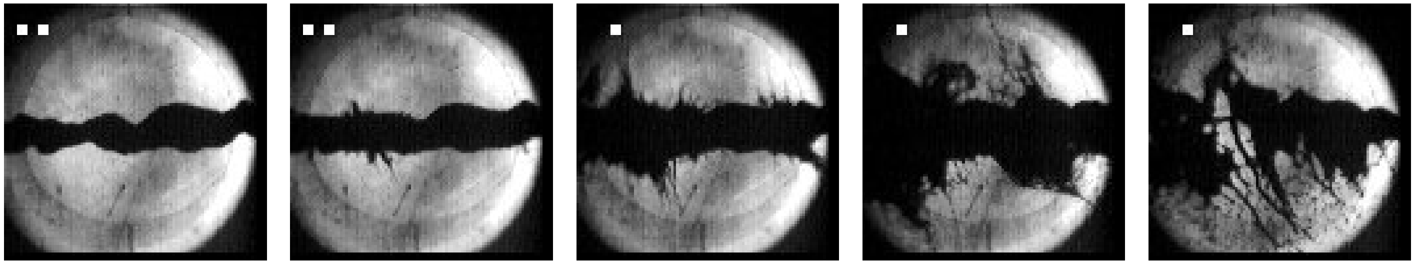
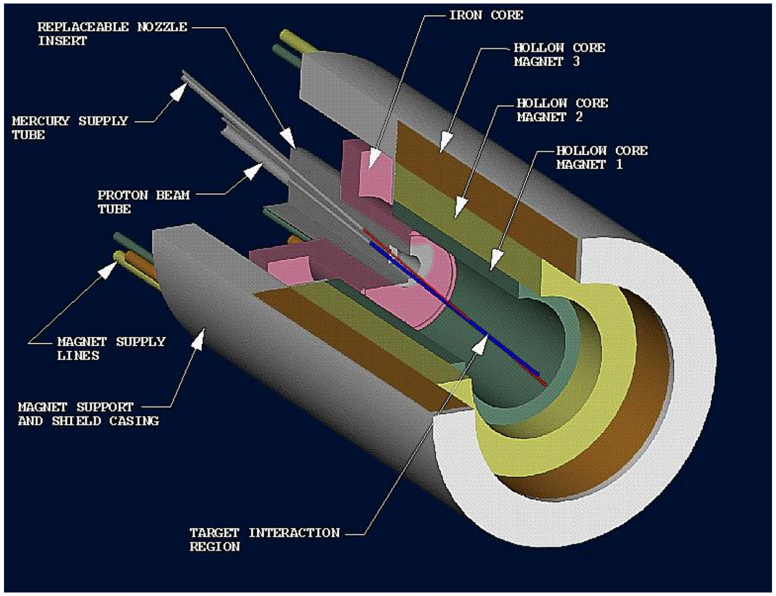
# High-Power Targets for Neutrino Superbeams, Neutrino Factories and Muon Colliders





**K.T. McDonald**
*Princeton U.*

*NFMCC Meeting*
*UCLA, January 29, 2007*

**Targetry Web Page:**
`http://puhep1.princeton.edu/mumu/target/`

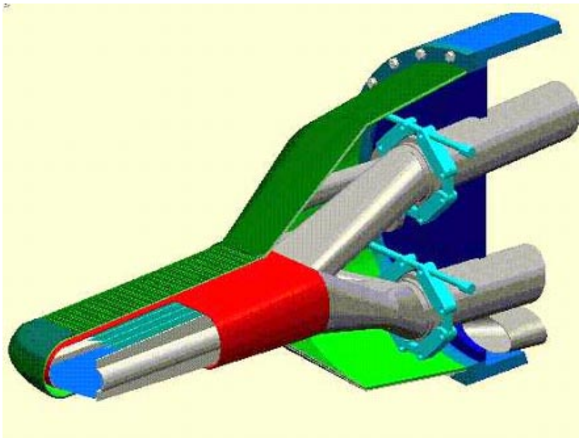
# Why Targetry?

- Targetry = the task of producing and capturing $\pi$'s and $\mu$'s from proton interactions with a nuclear target.
- At a muon 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.]
- Since its inception the Neutrino Factory/Muon Collider Collaboration has recognized the importance of high-performance targetry, and has dedicated considerable resources towards R&D on advanced targetry concepts.
- 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.

# High-Power Targets Essential for Many Future Facilties



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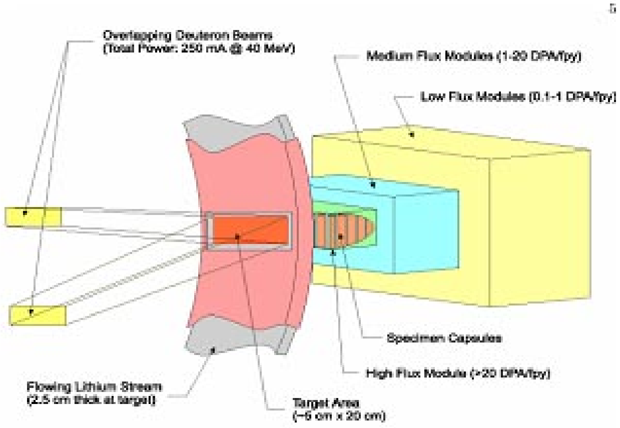

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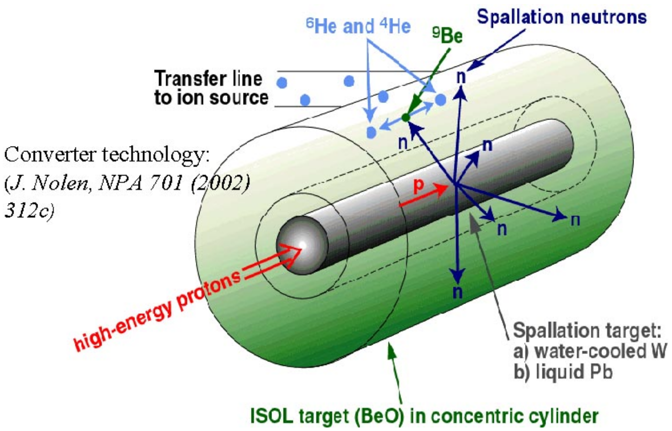
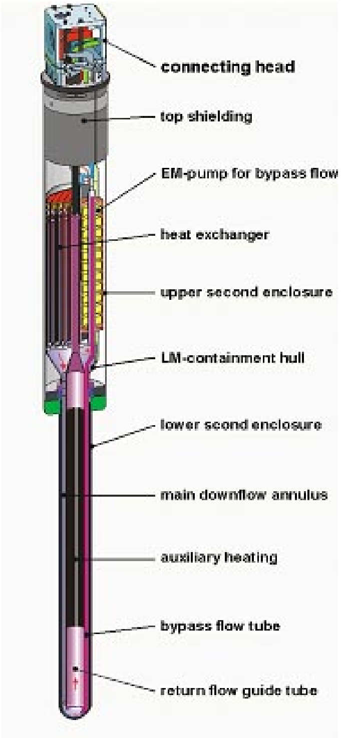


Converter technology:
*(J. Nolen, NPA 701 (2002) 312c)*

**ISOL/$\beta$ Beams**



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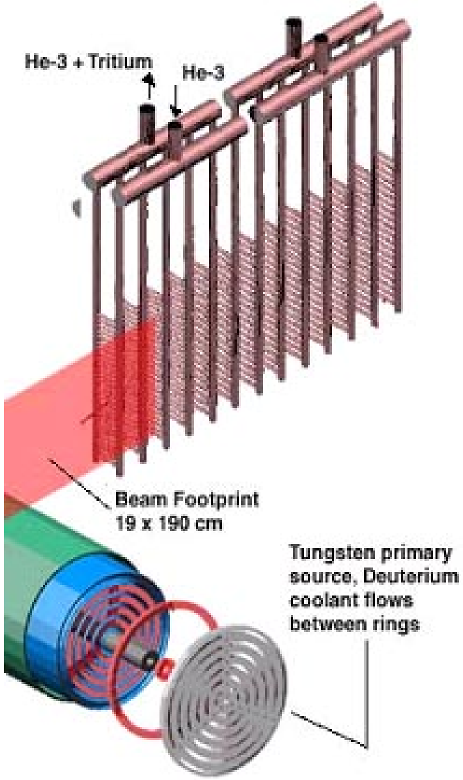

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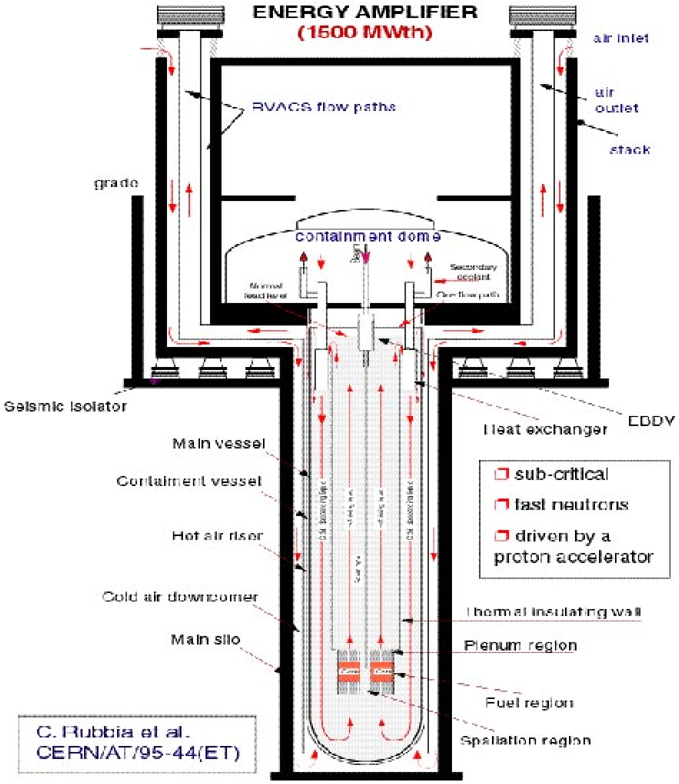


❐ sub-critical
❐ fast neutrons
❐ driven by a proton accelerator

C. Rubbia et al.
CERN/AT/95-44(ET)

**ATW**

# 4-MW Proton Beam

- **10-30 GeV appropriate for both Superbeam and Neutrino Factory.**

  ⇒ **0.8-2.5** $\times 10^{15}$ $p$**ps; 0.8-2.5** $\times 10^{22}$ **protons per year of** $10^7$ **s.**

- **Rep rate 15-50 Hz at Neutrino Factory, as low as 2 Hz for Superbeam.**

  ⇒ **Protons per pulse from 1.6** $\times 10^{13}$ **to 1.25** $\times 10^{15}$**.**

  ⇒ **Energy per pulse from 80 kJ to 2 MJ.**

- **Small beam size preferred:**

  ≈ **0.1 cm$^2$ for Neutrino Factory,** ≈ **0.2 cm$^2$ for Superbeam.**

⇒ **Severe materials issues for target AND beam dump.**

- **Radiation Damage.**
- **Melting.**
- **Cracking (due to single-pulse “thermal shock”.**

# Radiation Damage

The lifetime dose against radiation damage (embrittlement, cracking, ....) by protons for most solids is about $10^{22}$/cm$^2$.

⇒ Target lifetime of about 5-14 days at a Neutrino Factory (and 9-28 days at a Superbeam).

⇒ Mitigate by frequent target changes, moving target, liquid target, ...

# Remember the Beam Dump

Target of 2 interaction lengths ⇒ 1/7 of beam is passed on to the beam dump.

Long distance from target to dump at a Superbeam,
⇒ Beam is much less focused at the dump than at the target,
⇒ Radiation damage to the dump not a critical issue (Superbeam).

Short distance from target to dump at a Neutrino Factory,
⇒ Beam still tightly focused at the dump,
⇒ Frequent changes of the beam dump, or a moving dump, or a liquid dump.

A liquid beam dump is the most plausible option for a Neutrino Factory, independent of the choice of target. (This is so even for a 1-MW Neutrino Factory.)

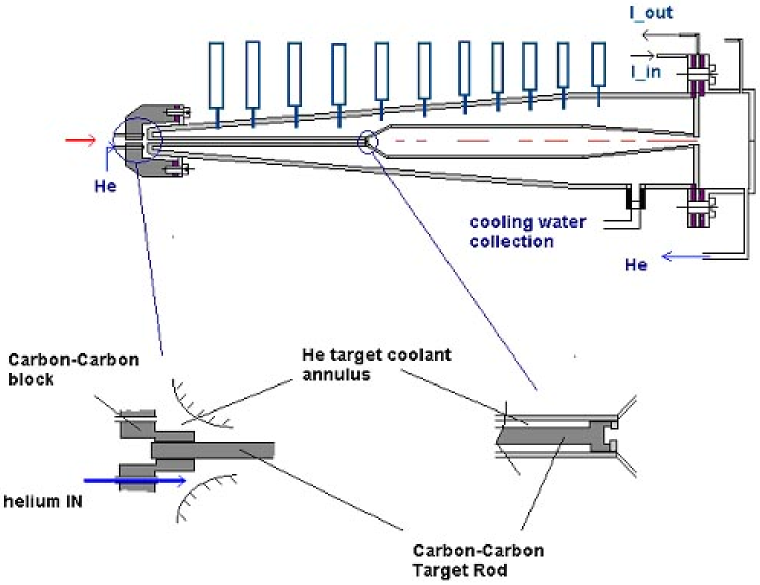
The proton beam should be tilted with respect to the axis of the capture system at a Neutrino Factory, so that the beam dump does not absorb the captured $\pi$'s and $\mu$'s.

# Target and Capture Topologies: Toroidal Horn

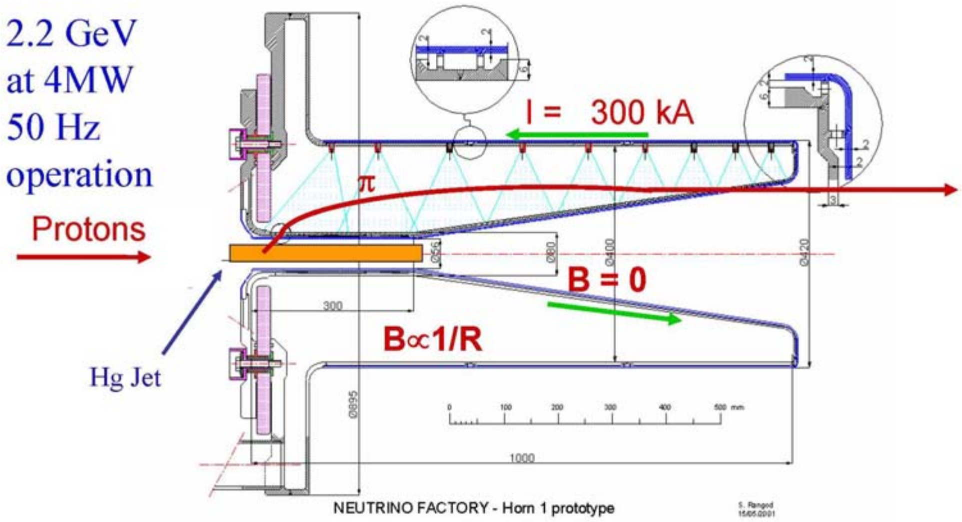
The traditional topology for efficient capture of secondary pions is a toroidal “horn” (Van der Meer, 1961).

- Collects only one sign, ⇒ Long data runs, but nonmagnetic detector (Superbeam).
- Inner conductor of toroid very close to proton beam.
  ⇒ Limited life due to radiation damage at 4 MW.
  ⇒ Beam, and beam dump, along magnetic axis.
  ⇒ More compatible with Superbeam than with Neutrino Factory.

Carbon composite target with He gas cooling (BNL study):



Mercury jet target (CERN SPL study):



If desire secondary pions with $E_\pi \lesssim 5$ GeV (Neutrino Factory), a high-$Z$ target is favored, but for $E_\pi \gtrsim 10$ GeV (some Superbeams), low $Z$ is preferred.

# Target and Capture Topologies: Solenoid

Palmer (1994) proposed a solenoidal capture system for a Neutrino Factory.

- Collects both signs of $\pi$'s and $\mu$'s, $\Rightarrow$ Shorter data runs (with magnetic detector).
- Solenoid coils can be some distance from proton beam.

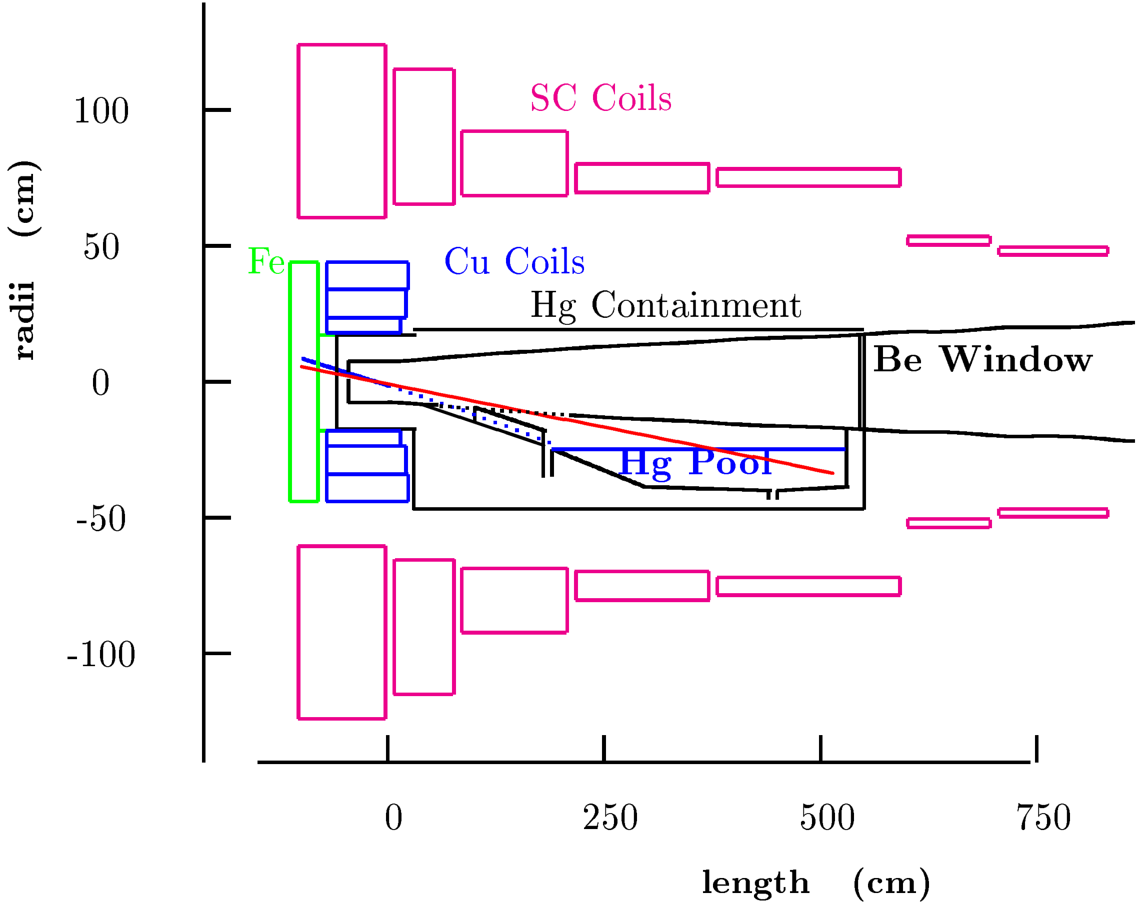
$\Rightarrow \gtrsim 4$ year life against radiation damage at 4 MW.

$\Rightarrow$ Proton beam readily tilted with respect to magnetic axis.

$\Rightarrow$ Beam dump out of the way of secondary $\pi$'s and $\mu$'s.

Mercury jet target and proton beam tilt downwards with respect to the horizontal magnetic axis of the capture system.

The mercury collects in a pool that serves as the beam dump (Neutrino Factory Study 2):



# A Neutrino Horn Based on a Solenoid Lens

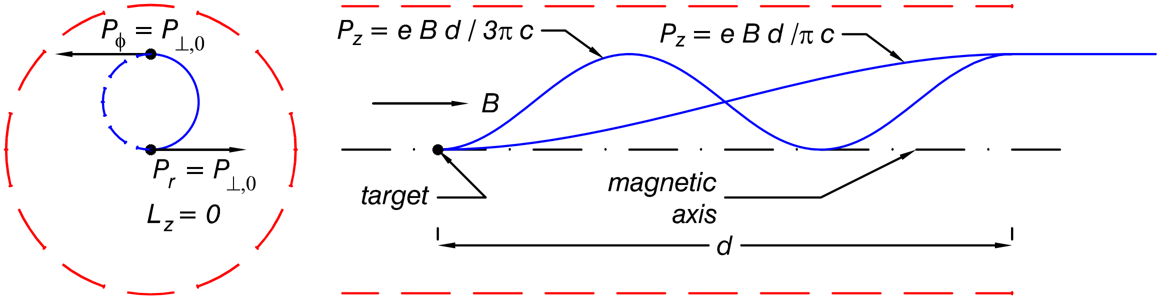
- **Pions produced on axis inside the (uniform) solenoid have zero canonical angular momentum, $L_z = r(P_\phi + eA_\phi/c) = 0$, $\Rightarrow P_\phi = 0$ on exiting the solenoid.**
- **If the pion has made exactly 1/2 turn on its helix when it reaches the end of the solenoid, then its initial $P_r$ has been rotated into a pure $P_\phi$, $\Rightarrow P_\perp = 0$ on exiting the solenoid.**

**⇒ Point-to-parallel focusing for**

$$P_\pi = eBd/(2n+1)\pi c.$$

**⇒ Narrowband (less background) neutrino beams of energies**

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



**(KTM, physics/0312022)**

**⇒ Can study several neutrino oscillation peaks at once,**

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

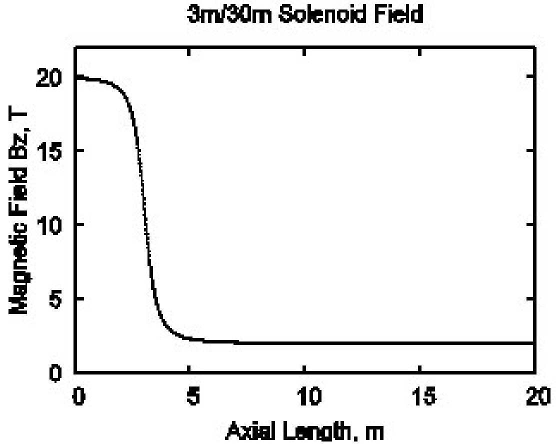
**(Marciano, hep-ph/0108181)**

**Study both $\nu$ and $\bar{\nu}$ at the same time.**
**⇒ Detector must identify sign of $\mu$ and $e$.**
**⇒ Magnetized liquid argon TPC.**
**(astro-ph/0105442).**

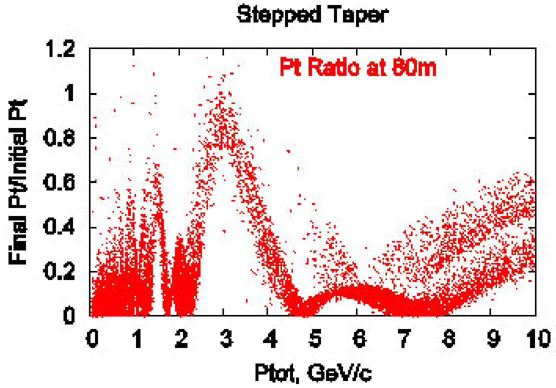
# Simulation of Solenoid Horn

## (H. Kirk and R. Palmer, NuFACT06)

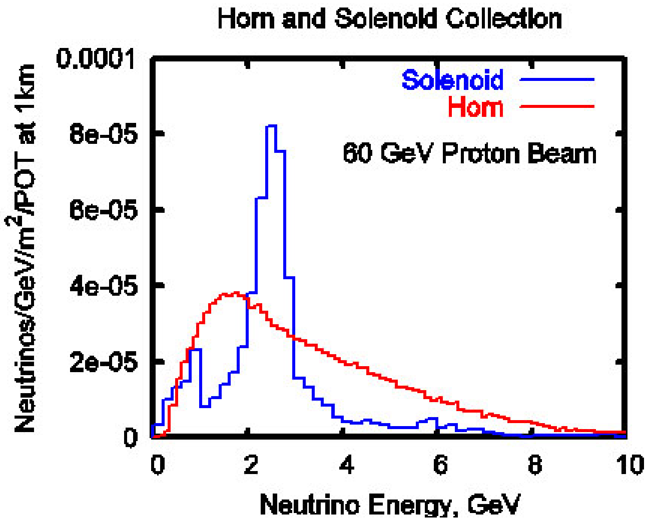
$B$ *vs.* $z$ for 3 + 30 m solenoid.



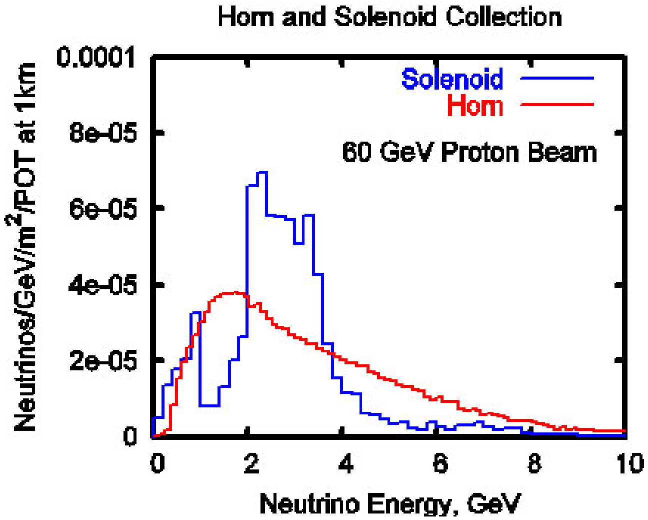
⇒ $P_\perp$ minimized at selected $P_{\mathrm{tot}}$.



3-m solenoid gives 2 narrow peaks in $\nu$ spectrum.



3-30-m solenoid broadens the higher energy peak.



Results very encouraging, but comparison with toroid horn needs confirmation.

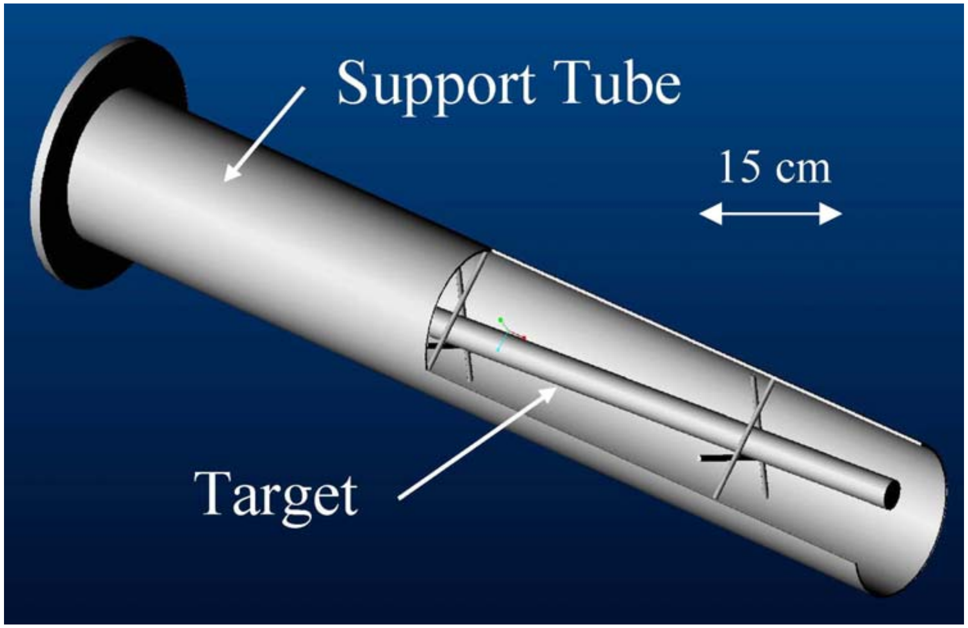
# Thermal Issues for Solid Targets (Superbeams), I

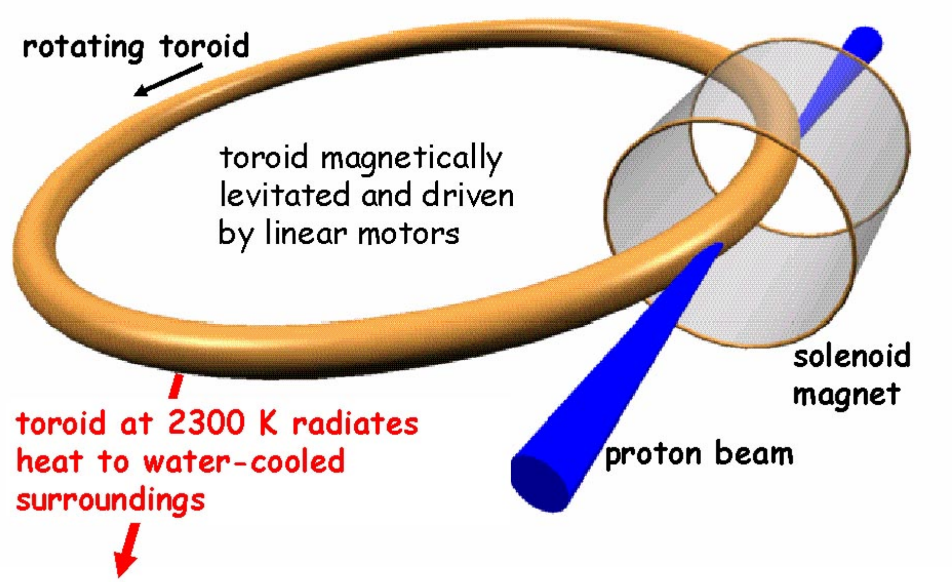
The quest for efficient capture of secondary pions precludes traditional schemes to cool a solid target by a liquid. (Absorption by plumbing; cavitation of liquid.)

A solid, radiation-cooled stationary target in a 4-MW beam will equilibrate at about 2500 C. ⇒ Carbon is only candidate for this type of target.

(Carbon target must be in He atmosphere to suppress sublimation.)

A moving band target (tantalum) could be considered (if capture system is toroidal).





# Thermal Issues for Solid Targets (Superbeams), II

**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 $\Delta T$ is given by**

$$\Delta T = \frac{U}{C}, \qquad \text{where } C = \text{heat capacity in Joules/g/K.}$$

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

$$\frac{\Delta r}{r} = \boldsymbol{\alpha}\Delta T = \frac{\boldsymbol{\alpha} U}{C}, \qquad \text{where } \boldsymbol{\alpha} = \text{thermal expansion coefficient.}$$

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

$$P = E\frac{\Delta r}{r} = \frac{E\boldsymbol{\alpha} U}{C}, \qquad \text{where } E = \text{modulus of elasticity.}$$

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

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

**⇒ Best candidates for solid targets have high strength (Vascomax, Inconel, TiAl6V4) and/or low thermal expansion (Superinvar, Toyota “gum metal”, carbon-carbon composite).**

# 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, 1.5 MeV** $= 2.46 \times 10^{-13}$ **J, so 60 J/ g requires a proton beam intensity of** $60/(2.4 \times 10^{-13}) = 2.4 \times 10^{14}$**/cm$^2$.**

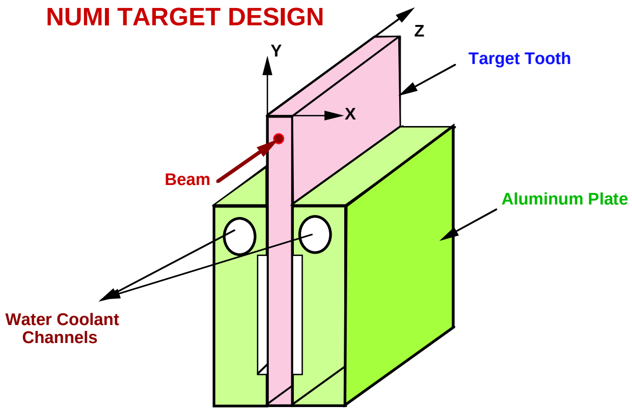
**So,** $P_{\rm max} \approx 10\ \mathbf{Hz} \cdot 10^{10}\ \mathbf{eV} \cdot 1.6 \times 10^{-19}\ \mathbf{J/eV} \cdot 2.4 \times 10^{14}/\mathbf{cm}^2 \cdot 0.1\ \mathbf{cm}^2 \approx 4 \times 10^5\ \mathbf{J/s} = \mathbf{0.4\ MW}$**.**

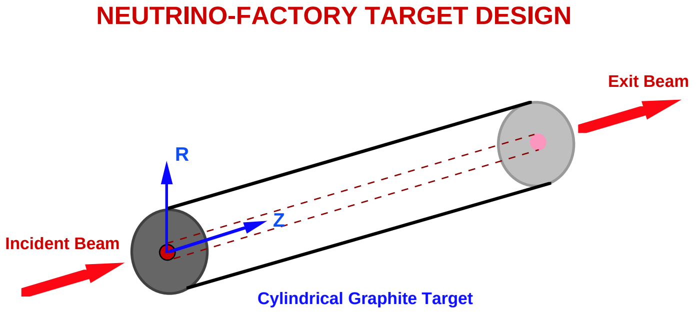
**If solid targets crack under singles pulses of 60 J/g, then safe up to only 0.4 MW beam power!**

**Empirical evidence is that some materials survive 500-1000 J/g,**
**$\Rightarrow$ May survive 4 MW if rep rate $\gtrsim$ 10 Hz.**

**Ni target in FNAL $p$bar source:**
**"damaged but not failed" for peak energy deposition of 1500 J/g.**

# A Carbon Target is Feasible at 1-MW Beam Power

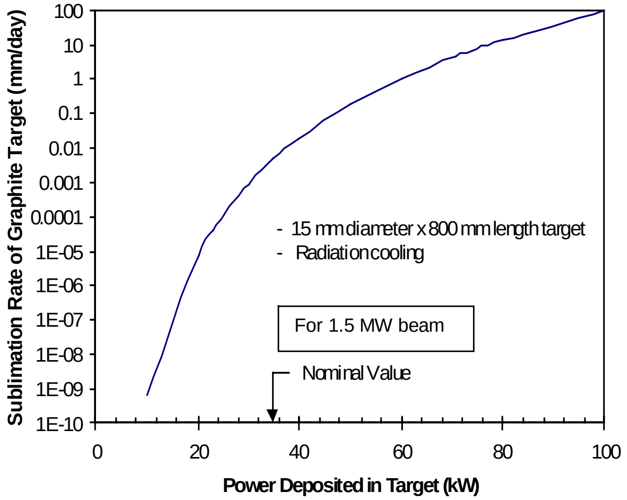

NUMI TARGET DESIGN


NEUTRINO-FACTORY TARGET DESIGN

HASSANEIN (ANL)

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

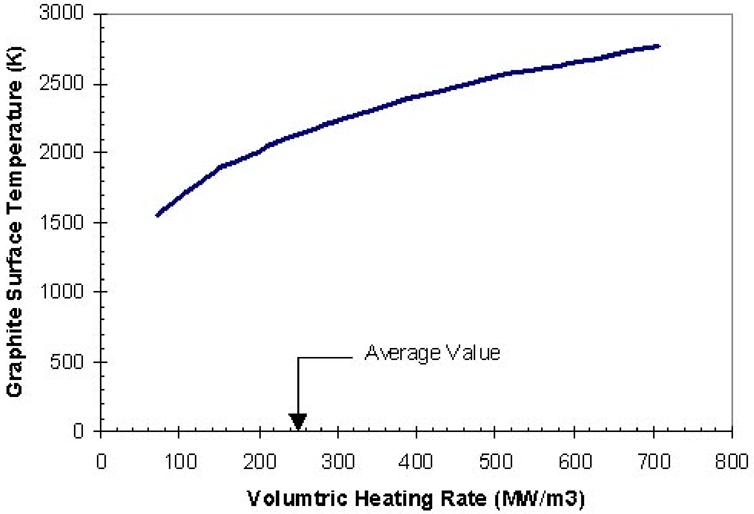
A carbon target in vacuum sublimates away in 1 day at 4 MW.



Sublimation of carbon is negligible in a helium atmosphere.

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

Equilibrium temperature of a carbon target of 1-cm-diameter as a function of beam power, assuming only radiation cooling.



## Radiation damage limit of materials?

Many materials turn to powder due to radiation damage once each atom has suffered $\approx$ one nuclear interaction $\equiv$ 1 DPA (displacement per atom).

The displacements are due to $\approx 10$-MeV neutrons.

In a thick target ($\gtrsim 1$ nuclear interaction length) have $\approx 10$ 10-MeV neutrons per beam proton.

$\sigma_{np} \approx 4\pi\bar{\lambda}^2 \approx 10^{-25}$ cm$^2$; $\sigma_{nA} \approx 10\sigma_{np} \approx 10^{-24}$ cm$^2$.

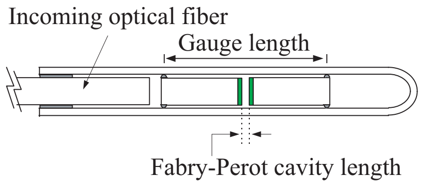
$\Rightarrow$ Need $\approx 10^{23}$ protons/cm$^2$ for 1 DPA.

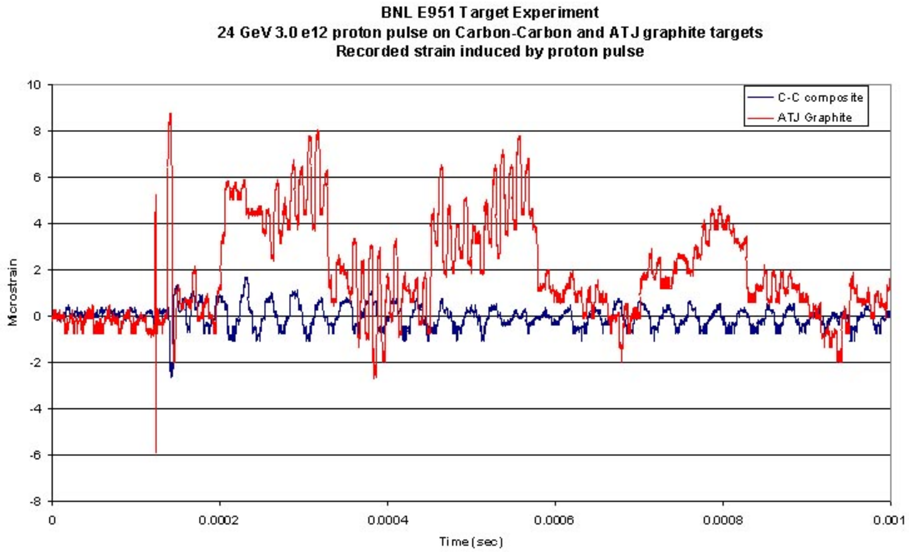
Empirical result: more like $10^{22}$/cm$^2$ for 1 DPA.

Ex: If 10 Hz of $10^{15}$ protons/pulse into 0.1 cm$^2$, need only $10^5$ pulses = 1 day for catastrophic radiation damage.

# Lower Thermal Shock If Lower Thermal Expansion Coefficient

ATJ graphite and a 3-D weave of carbon-carbon fibers instrumented with fiberoptic strain sensors, and exposed to pulses of $4 \times 10^{12}$ protons @ 24 Gev.

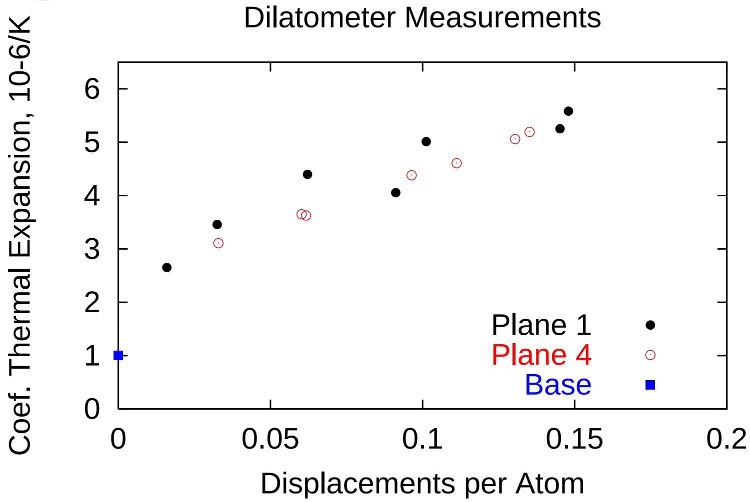




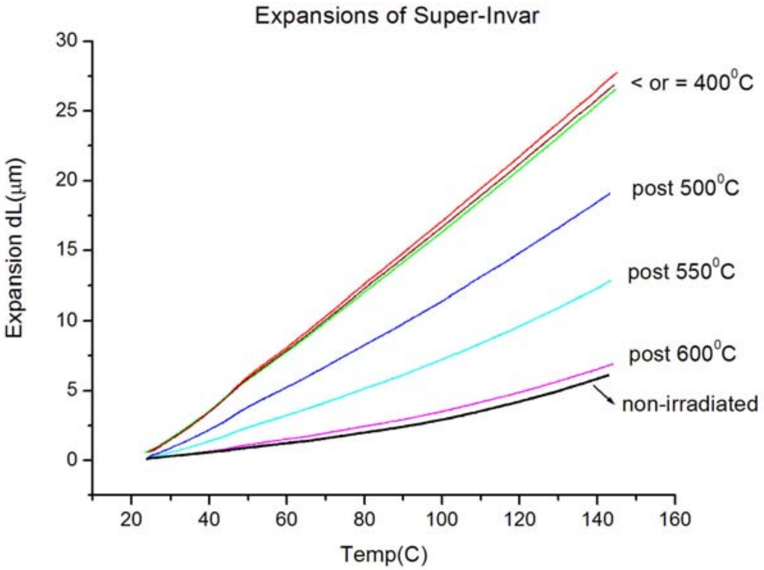
Carbon-carbon composite showed much lower strains than in the ordinary graphite – but readily damaged by radiation!

Thermal expansion coefficient of engineered materials is affected by radiation.

Super-Invar: CTE *vs.* dose:



Super-Invar: recovery of the CTE by thermal annealing:



# Recent/Ongoing Solid Target Projects

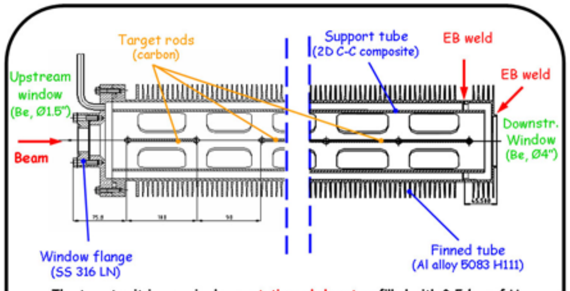
## CNGS Target System (R. Bruno, NuFact06)

Up to $7 \times 10^{13}$ 400-GeV protons every 6 s.

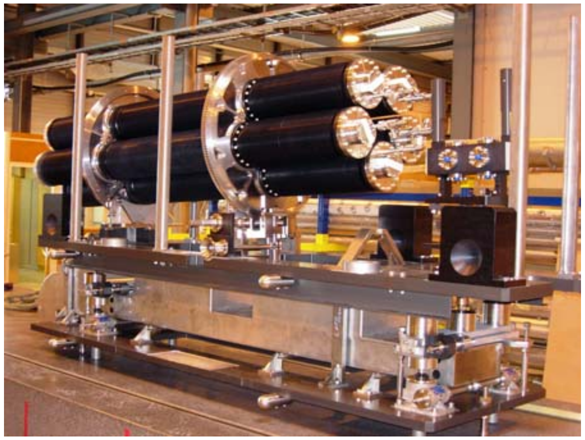
Beam $\sigma$ = 0.5 mm.

5 interchangeable graphite targets.

Designed for 0.75 MW.



The target unit is conceived as a static sealed system filled with 0.5 bar of He.
The tube has annular fins to enhance convective heat transfer.
Light materials are used to limit the heat load.



## JPARC $\nu$ Horn Target (Y. Hayato, NuFact06)

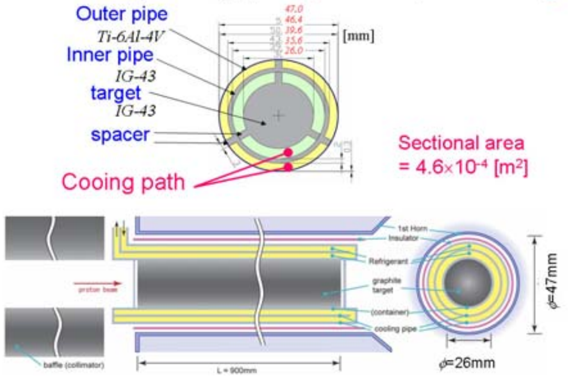
Up to $4 \times 10^{14}$ 50-GeV protons every 4 s.

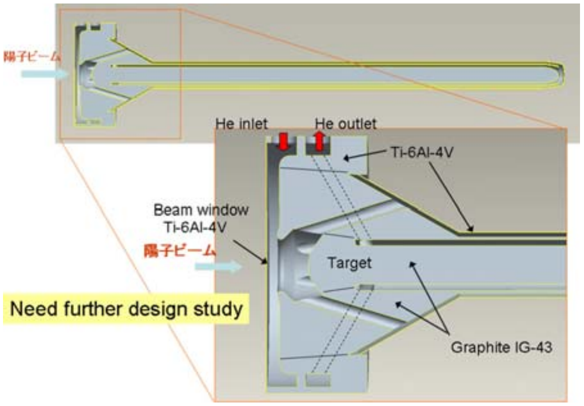
Beam $\sigma$ = 4 mm.

Designed for 0.75 MW.

He gas cooling.

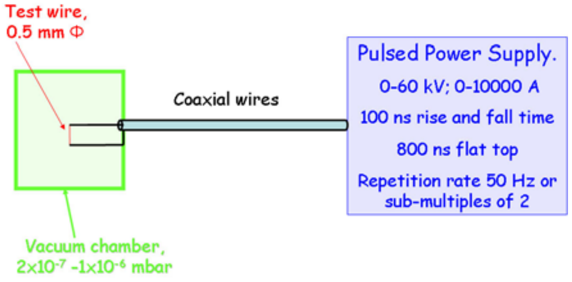
- Co-axial 2 layer cooling pipe: Graphite / Ti-6Al-4V, Helium cooling

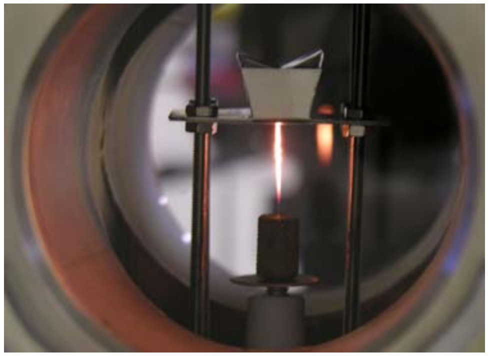


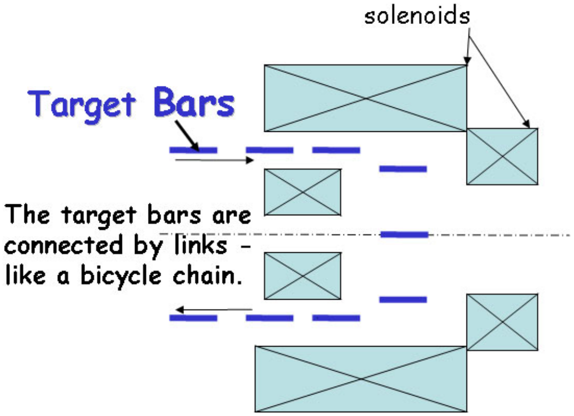


Need further design study

## Pulsed-Current Studies of Ta & W Wires at RAL (R. Bennett *et al.*)







The target bars are connected by links – like a bicycle chain.

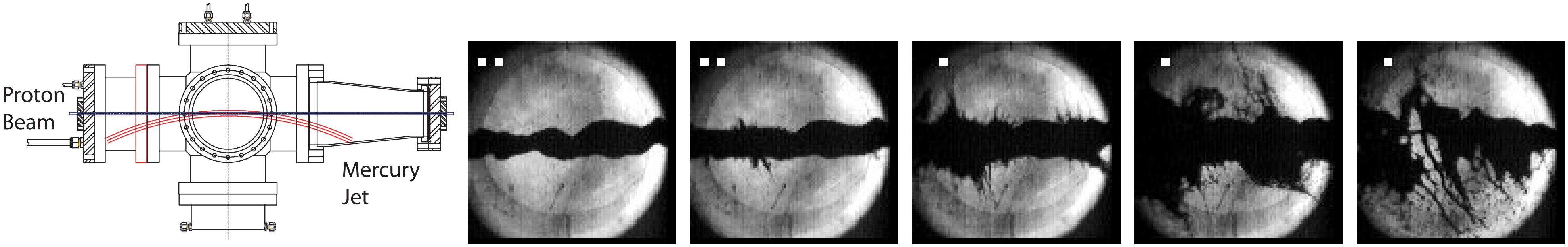
# Thermal Issues for Liquid Targets (Neutrino Factory)

**Liquid target/dump using mercury, or a Pb-Bi alloy.**

$\approx 400$ **J/gm to vaporize Hg (from room temp),**
$\Rightarrow$ **Need flow of** $> 10^4$ **g/s** $\approx 1$ **l/s in target/dump to avoid boiling in a 4-MW beam.**

**Neutrino Factory Study 2 design has 1.5 l/s flow of Hg, so no critical thermal issues.**

**Energy deposited in the mercury target (and dump) will cause dispersal, but at benign velocities (10-50 m/s).**

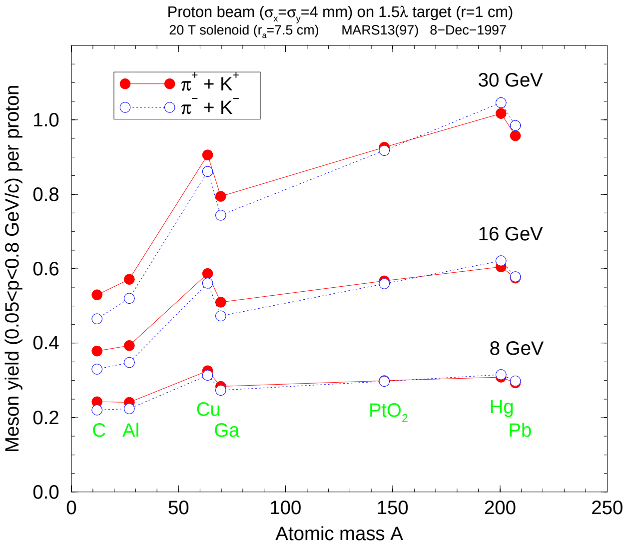


**1-cm-diameter Hg jet in 2e12 protons at** $t = 0$**, 0.75, 2, 7, 18 ms (BNL E-951, 2001).**

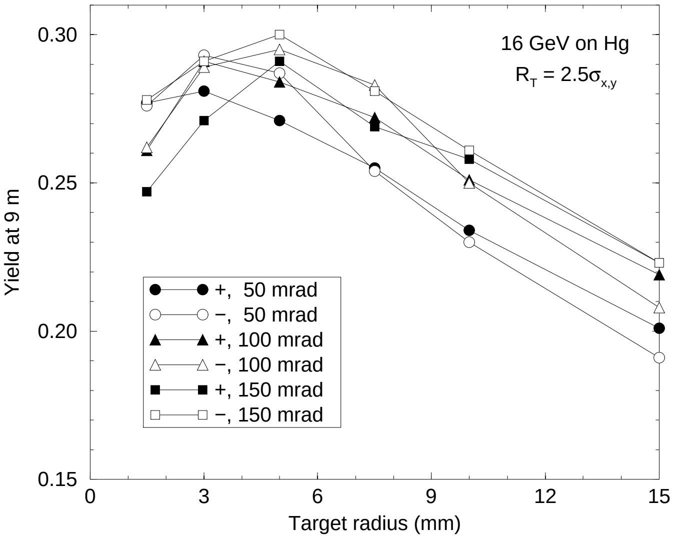
**Model (Sievers):** $$v_{\rm dispersal} = \frac{\Delta r}{\Delta t} = \frac{r\alpha\Delta T}{r/v_{\rm sound}} = \frac{\alpha U}{C} v_{\rm sound} \approx \textbf{12.5 m/s for } U \approx \textbf{25 J/g.}$$

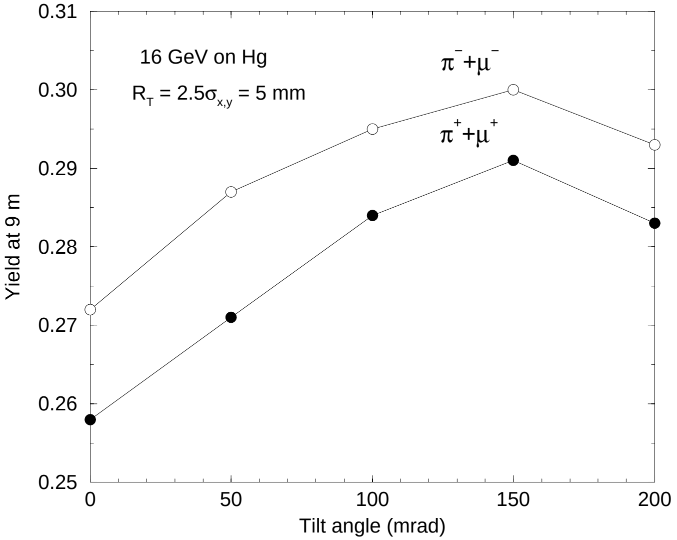
**Data:** $v_{\rm dispersal} \approx$ **10 m/s for** $U \approx$ **25 J/g.**

# Pion/Muon Yield



For $E_p \gtrsim 10$ GeV, more yield with high-$Z$ target (MARS calculations).

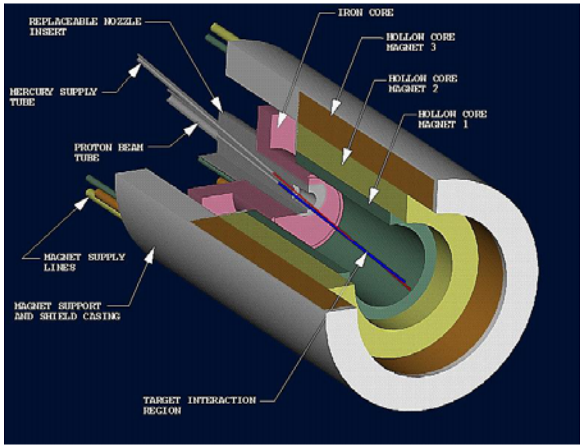




**Mercury target radius should be $\approx 5$ mm, with target axis tilted by $\approx 100$ mrad to the magnetic axis.**

**Can capture $\approx 0.3$ pion per proton with $50 < P_\pi < 400$ MeV/$c$.**

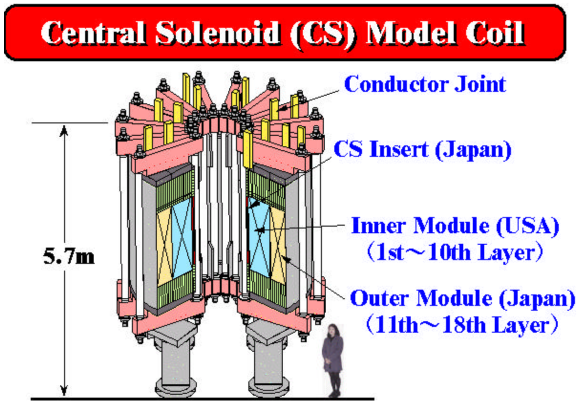
# 20-T Capture Magnet System

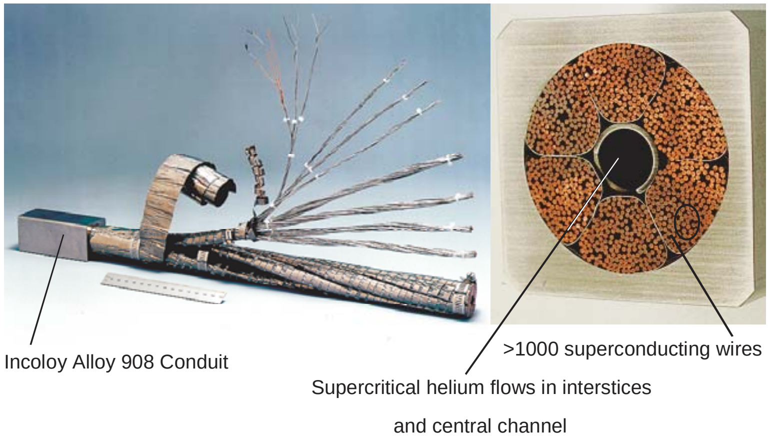


**Inner, hollow-conductor copper coils generate 6 T @ 12 MW:**

**Bitter-coil option less costly, but marginally feasible.**

**Outer, superconducting coils generate 14 T @ 600 MJ:**



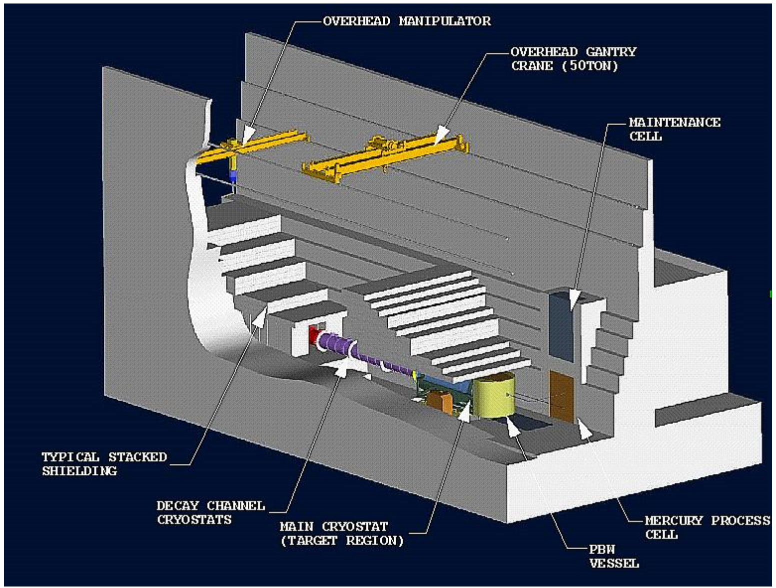


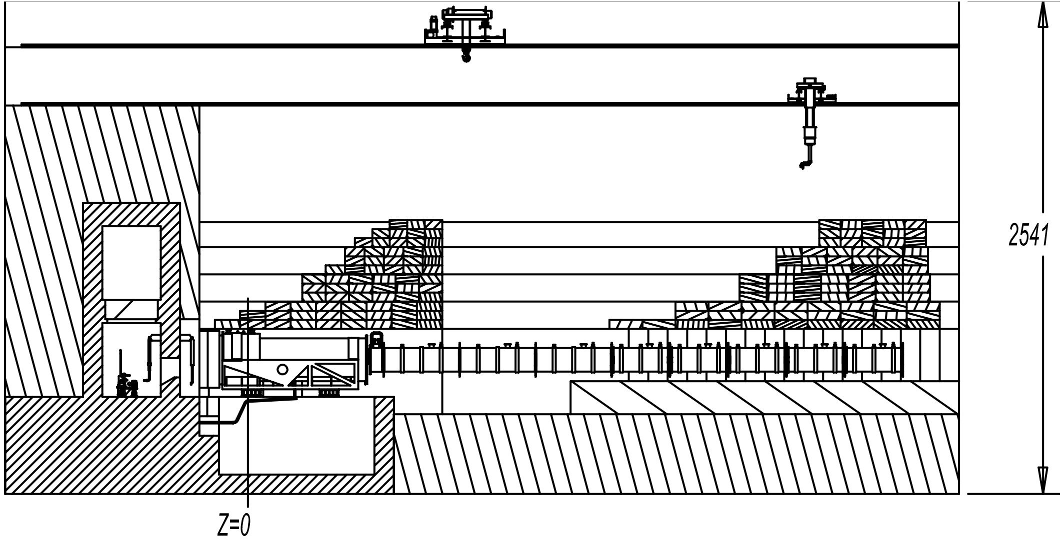
**Cable-in-conduit construction similar to ITER central solenoid.**

**Both coils shielded by tungsten-carbide/water.**

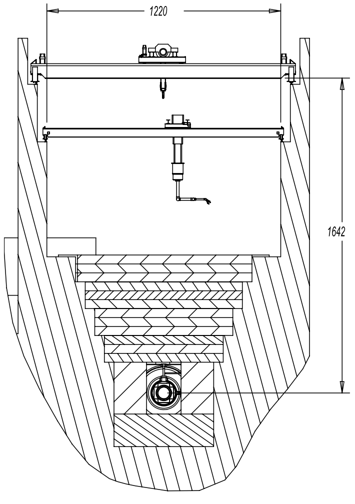
# Target System Support Facility

**Extensive shielding; remote handling capability.**



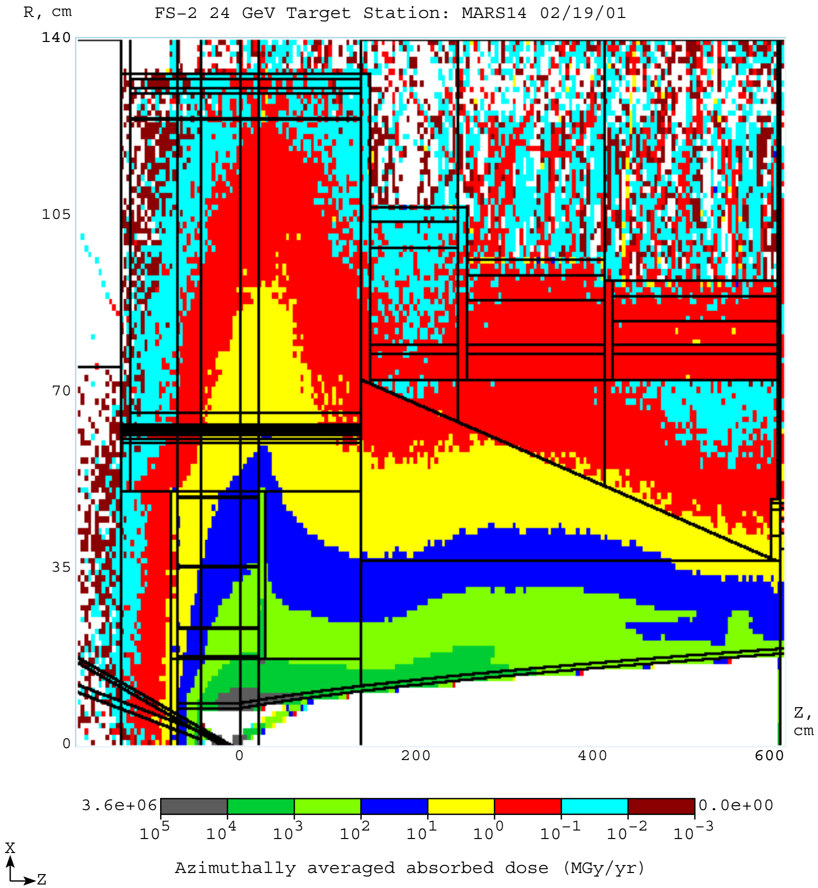


SECTION C-C



SECTION B-B
DECAY CHANNEL SHIELDING

# Lifetime of Components in the High Radiation Environment



Some components must be replaceable.

| Component | Radius (cm) | Dose/yr (Grays/$2 \times 10^7$ s) | Max allowed Dose (Grays) | 1 MW Life (years) | 4 MW life (years) |
|---|---|---|---|---|---|
| **Inner shielding** | **7.5** | $5 \times 10^{10}$ | $10^{12}$ | **20** | **5** |
| **Hg containment** | **18** | $10^9$ | $10^{11}$ | **100** | **25** |
| **Hollow conductor coil** | **18** | $10^9$ | $10^{11}$ | **100** | **25** |
| **Superconducting coil** | **65** | $5 \times 10^6$ | $10^8$ | **20** | **5** |

# Issues for Liquid Jet Targets

**1. Hydrodynamics. 2. Magnetic effects. 3. Beam-induced effects.**

**A. Calder, Paris (1937):**

# Hydrodynamics of Liquid Jet Targets

- **Diameter $d$ = 1 cm.**
- **Velocity $v$ = 20 m/s.**
- **The volume flow rate of mercury in the jet is**

$$\textbf{Flow Rate} = vA = 2000 \text{ cm/s} \cdot \frac{\pi}{4} d^2 = 1571 \text{ cm}^3\text{/s} = 1.57 \textbf{ l/s} = 0.412 \textbf{ gallon/s} = 94.2 \textbf{ l/min} = 24.7 \textbf{ gpm}. \quad (1)$$

- **The power in the jet (associated with its kinetic energy) is**

$$\textbf{Power} = \frac{1}{2}\rho \cdot \textbf{Flow Rate} \cdot v^2 = \frac{13.6 \times 10^3}{2} \cdot 0.00157 \cdot (20)^2 = 4270 \text{ W} = 5.73 \textbf{ hp}. \quad (2)$$

- **To produce the 20-m/s jet into air/vacuum out of a nozzle requires a pressure**

$$\textbf{Pressure} = \frac{1}{2}\rho v^2 = 27.2 \textbf{ atm} = 410 \textbf{ psi}, \quad (3)$$

**IF no dissipation of energy.**

- **The mercury jet flow is turbulent: the viscosity is $\mu_{\rm Hg} = 1.5$ cP (kinematic viscosity $\eta = \mu/\rho = 0.0011$ cm$^2$/s), so the Reynolds number is**

$$\mathcal{R} = \frac{\rho d v}{\mu} = \frac{dv}{\eta} = 1.8 \times 10^6. \quad (4)$$

- **The surface tension of mercury is $\tau$ = 465 dyne/cm (water = 73), ⇒**

$$\textbf{Weber number, } \mathcal{W} = \frac{\rho d v^2}{\tau} = 115,000. \quad (5)$$

# Nozzle Lore

## Hg jet for Neutrino Factory:

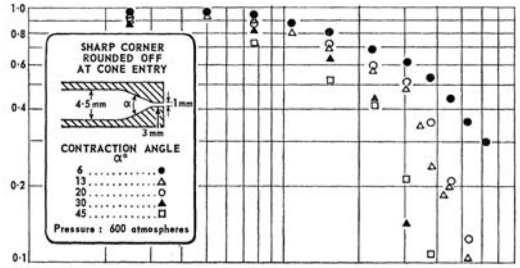
$v = 20$ m/s, $d = 1$ cm,

$\Rightarrow$ Turbulent flow.

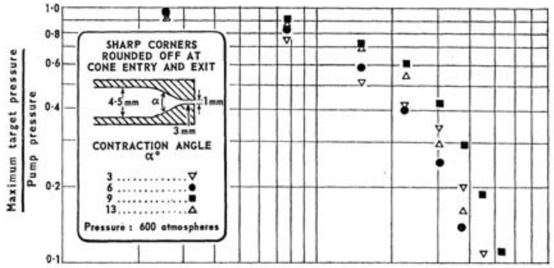
## Lore:

- Should be able to make a 1-cm-diameter Hg jet go 1-2 m before breakup.
- Area of feed should be $\gtrsim 10\times$ area of nozzle.
- $\approx 15^\circ$ nozzle taper is good.
- Nozzle tip should be straight, with $\approx 3:1$ aspect ratio.
- High-speed jets will have a halo of spray around a denser core.
- Low/zero surrounding gas pressure is better.

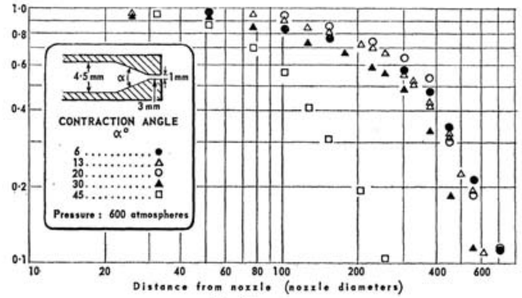
## Leach & Walker (1966):



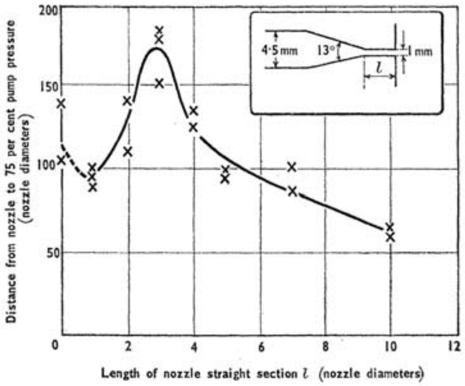
(a) Rounded inlet corners



(b) Rounded corners at both ends of contraction



(c) Sharp corners



## McCarthy & Molloy (1974):

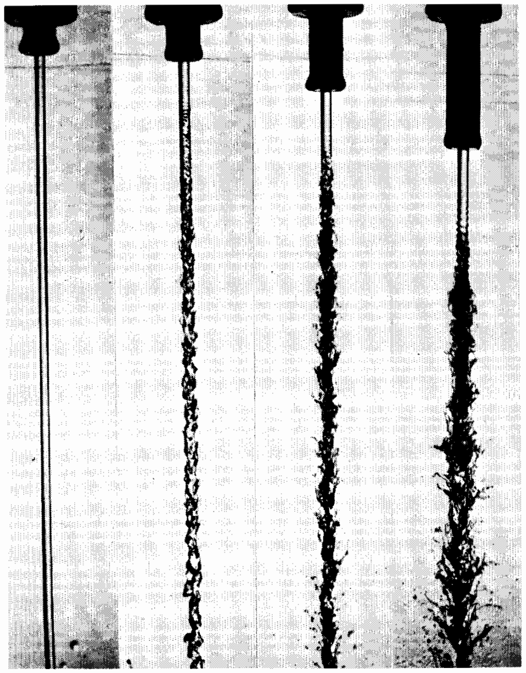
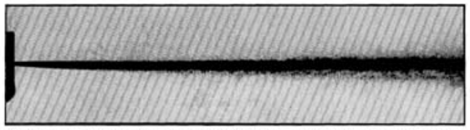


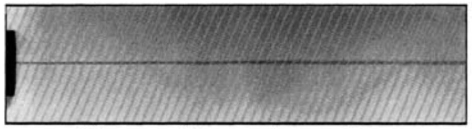
Fig. 5. Effect of nozzle design on the stability of glycerol–water jets.

| | |
|---|---|
| Jet viscosity | 11 cP |
| Jet velocity | 20 m $s^{-1}$ (approx.) |
| Nozzle diameter | 2.54 mm |
| Jet Reynolds no. | 4750 |
| Jet Ohnesorge no. | 0.026 |
| Exposure | 30 $\mu$sec |
| Nozzle aspect ratio | $AR = L/d$ (see Fig. 7) = 0, 1, 5, 10 L to R. |

## Leach & Walker:



(*d*) Spark source; parallel transmitted light ($\frac{1}{4}$ $\mu$s exposure); pressure 130 atm.



(*e*) X-ray source (5 min exposure); pressure 130 atm.

# Conservation of Energy *vs.* $\mathbf{F} = d\mathbf{P}/dt$ at a Contraction? (Borda, 1766)

**Incompressible fluid** $\Rightarrow V_1 A_1 = V_2 A_2$.

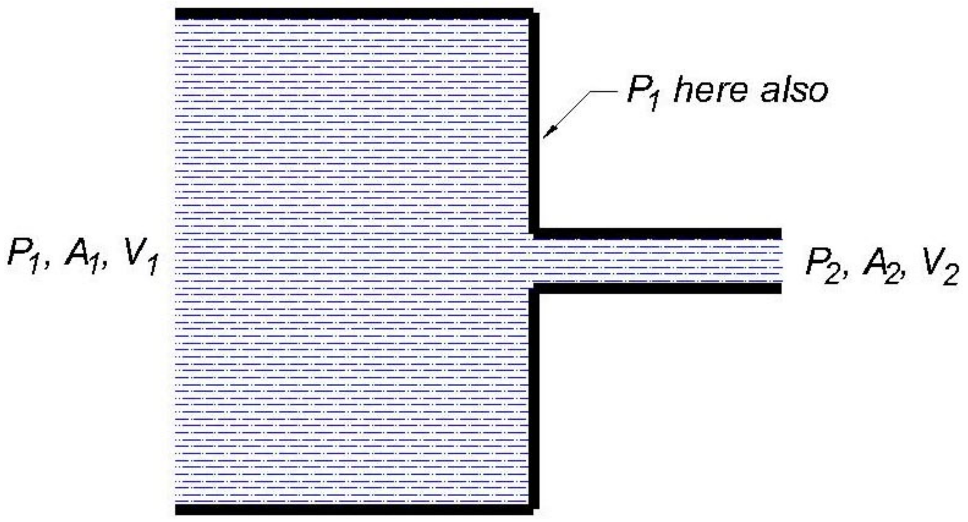
$$A_2 \ll A_1 \Rightarrow V_1 \ll V_2.$$

**Conservation of Energy** $\Rightarrow$ **Bernoulli's Law:**

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2.$$

$$V_1 \ll V_2 \Rightarrow \qquad V_2^2 \approx 2\frac{P_1 - P_2}{\rho}.$$

**Argument does not depend on the area.**



$\mathbf{F} = d\mathbf{P}/dt$:

**Mass flux** $= \rho V A$.

**Momentum flux** $= \rho V^2 A$.

**Net momentum flux** $= \rho(V_2^2 A_2 - V_1^2 A_1)$

$$= \rho V_2 A_2 (V_2 - V_1) \approx \rho V_2^2 A_2.$$

**Force** $\approx (P_1 - P_2) A_2$.

$$\mathbf{F} = \frac{d\mathbf{P}}{dt} \Rightarrow \qquad V_2^2 \approx \frac{P_1 - P_2}{\rho}.$$

**Consistency** $\Rightarrow$ **dissipative loss of energy, OR jet pulls away from the wall and contracts.**

# Vena Contracta

**Cavitation can be induced by a sharp-edged aperture.**

**A jet emerging from a small aperture in a reservoir contracts in area:**

$$A_{\text{jet}} = \frac{\pi}{\pi + 2} A_{\text{aperture}} = 0.62 A_{\text{aperture}}$$

$$d_{\text{jet}} = 0.78\ d_{\text{aperture}}$$

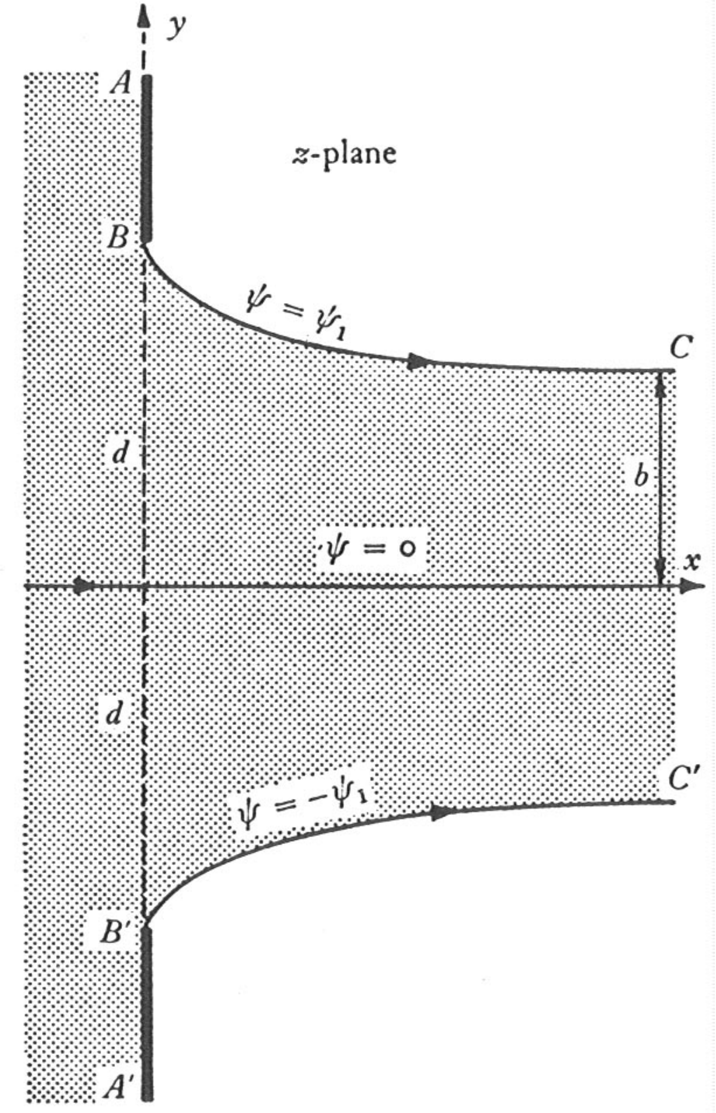
**2-d potential flow (conservation of energy) ⇒ analytic form:**

$$x = \frac{2d}{\pi + 2}(\tanh^{-1} \cos\theta - \cos\theta), \qquad y = d - \frac{2d}{\pi + 2}(1 + \sin\theta),$$

$$\theta = \text{angle of streamline}, \qquad -\frac{\pi}{2} < \theta < 0.$$

**90% of contraction occurs for $x < 0.8d$.**

**Good agreement between theory and experiment.**



# Magnetic Issues for Liquid Metal Jet Targets

Conducting materials that move through nonuniform magnetic field experience eddy-current effects, ⇒ Forces on entering or leaving a solenoid (but not at its center).

⇒ Free jet of radius $r$ cannot pass through a horizontal solenoid of diameter $D$ unless

$$v > \frac{3\pi\sigma r^2 B_0^2}{32\rho D} \approx 6\left[\frac{r}{1\ \text{cm}}\right]^2\ \text{m/s}, \qquad \text{for Hg or Pb-Bi jet, } D = 20\ \text{cm}, B_0 = 20\ \text{T}.$$

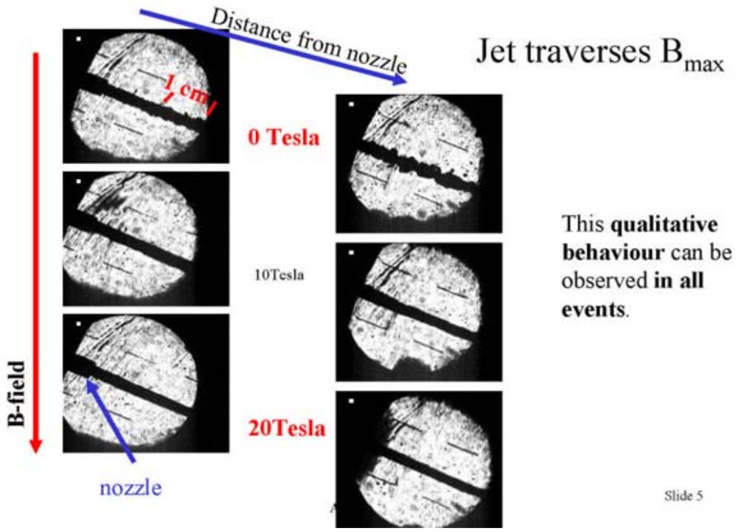
50-Hz rep rate requires $v = 20$ m/s for new target each pulse, so no problem for baseline design with $r = 0.5$ cm. The associated eddy-current heating is negligible.

[Small droplets pass even more easily, and can fall vertically with no retardation.]

A liquid jet experiences a quadrupole shape distortion if tilted with respect to the solenoid axis. This is mitigated by the upstream iron plug that makes the field more uniform.

Magnetic damping of surface-tension waves (Rayleigh instability) observed in CERN-Grenoble tests (2002).

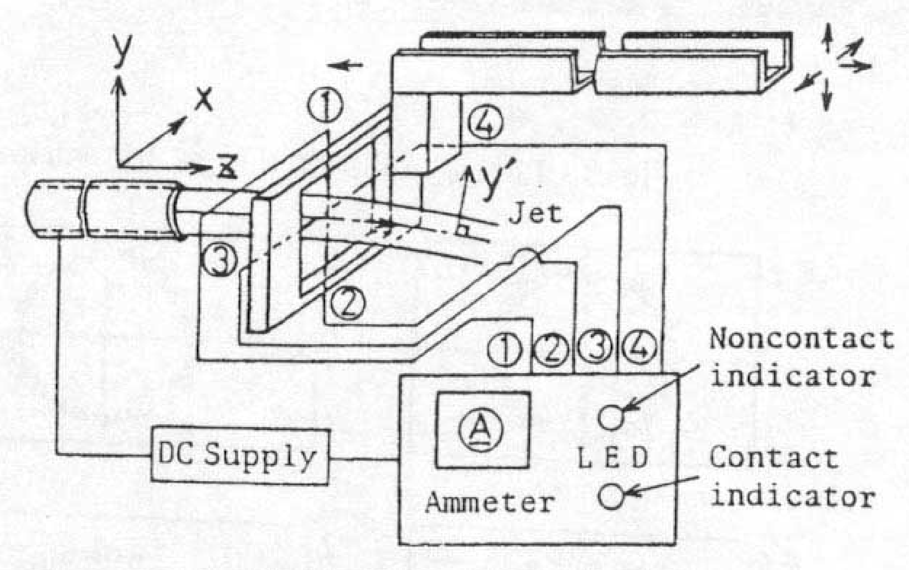
The beam-induced dispersal will be partially damped also (Samulyak).

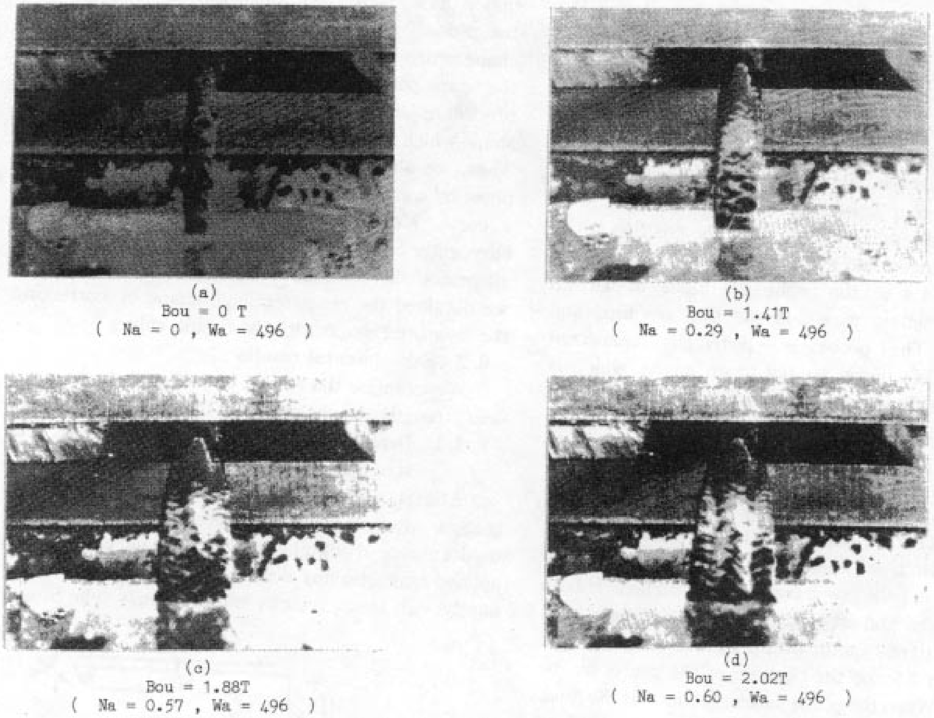


This qualitative behaviour can be observed in all events.

# The Shape of a Mercury Jet under a Non-uniform Magnetic Field

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



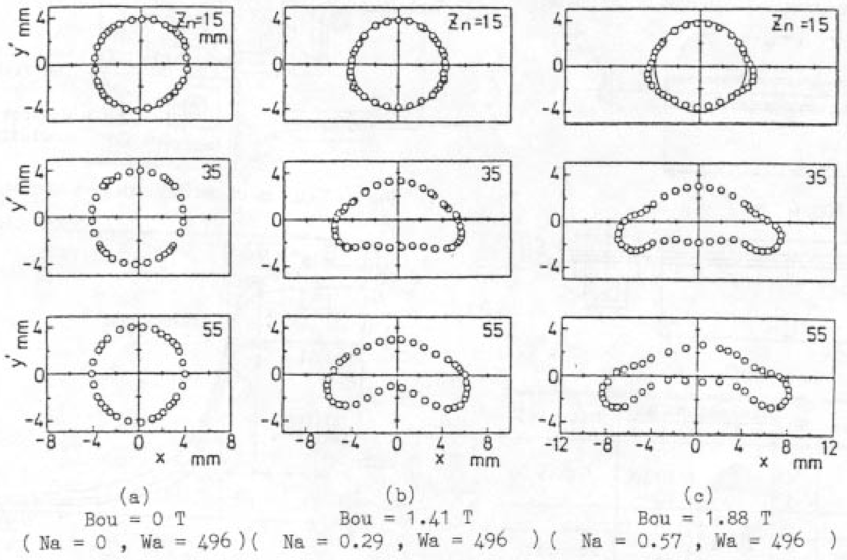

(a) Bou = 0 T ( Na = 0 , Wa = 496 )

(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 )

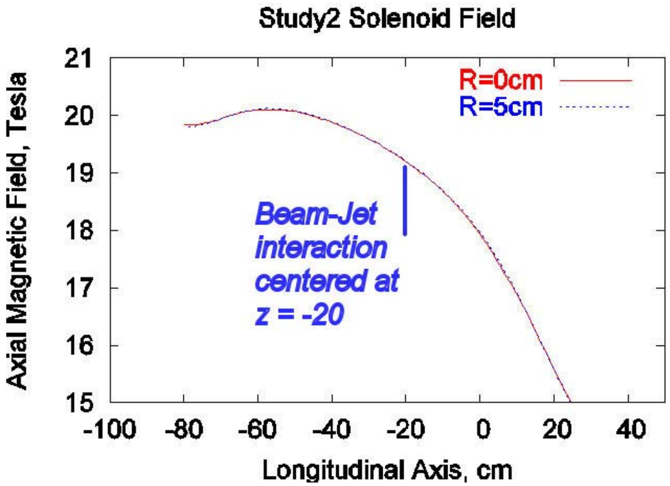
(c) Bou = 1.88 T ( Na = 0.57 , Wa = 496 )

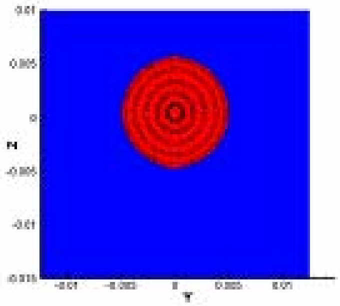
Fig. 10 Cross-sectional shape of the jet obtained by spot a electrode probe

# Simulations of Shape Distortion

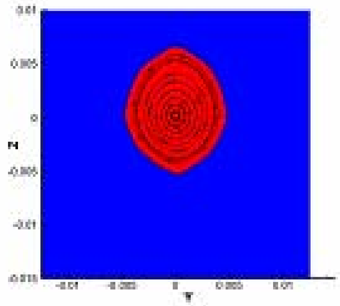
Incompressible code with free liquid surface confirms predictions of shape distortion of a liquid mercury jet that crosses magnetic field lines. (N. Morley, M. Narula; HIMAG).

Mitigate with good uniformity of magnetic field:

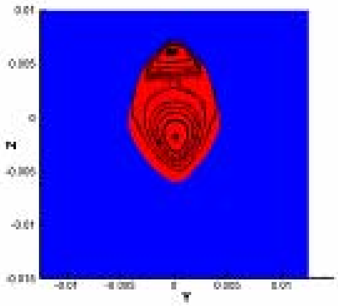




Jet section at inlet, current streamlines clockwise

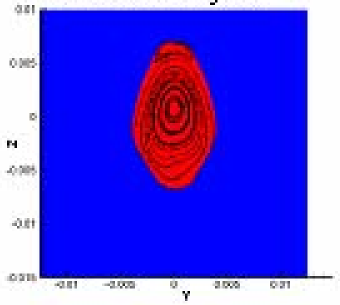


Jet section at X = 20cm, current streamlines clockwise

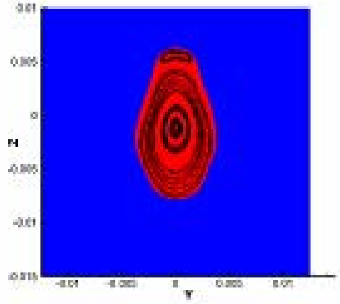


Jet section at X = 30cm, current streamlines clockwise, weird null

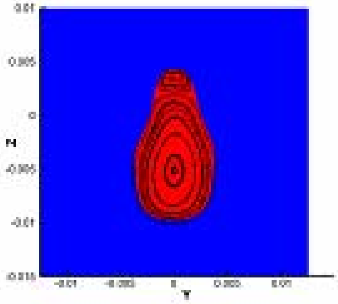
Jet section at X =40 cm , current streamlines anticlockwise, but clockwise secondary cell



Jet section at X = 50 cm , current streamlines anticlockwise



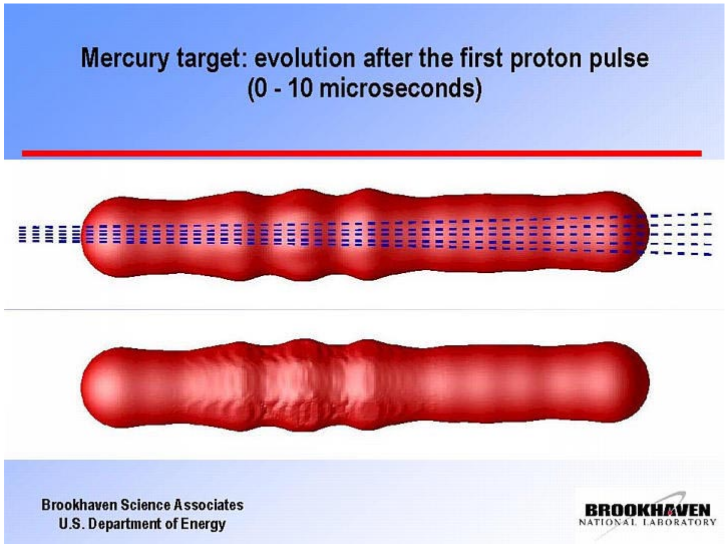
Jet section at X =60 cm , current streamlines anticlockwise



# Beam-Induced Effects on a Liquid Jet

Beam energy deposition may disperse the jet.

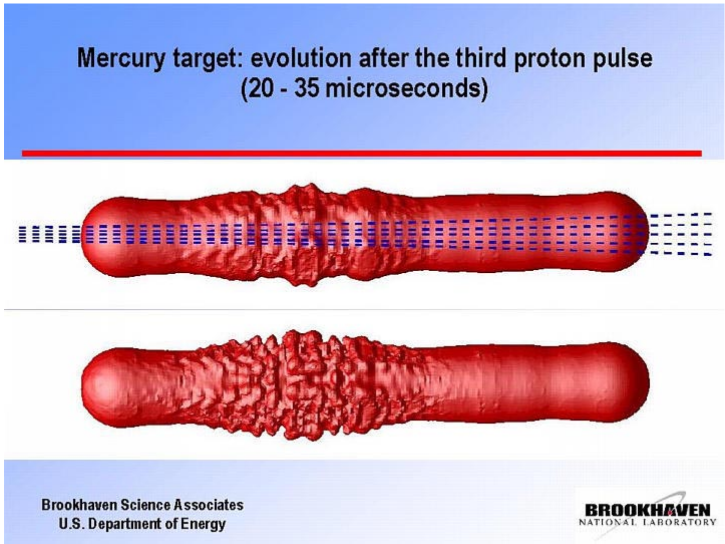
FRONTIER simulation predicts breakup via filamentation on mm scale:



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

Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN NATIONAL LABORATORY

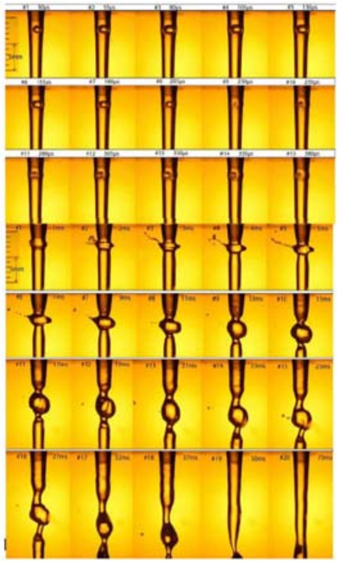


Mercury target: evolution after the third proton pulse
(20 - 35 microseconds)

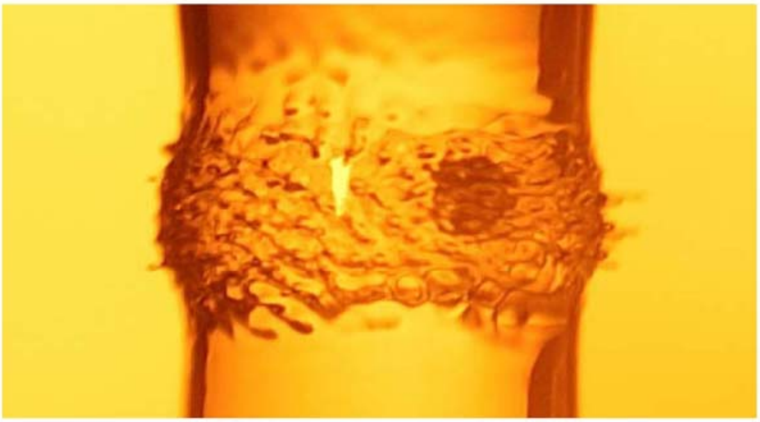
Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN NATIONAL LABORATORY

Laser-induced breakup of a water jet:
(J. Lettry, CERN)



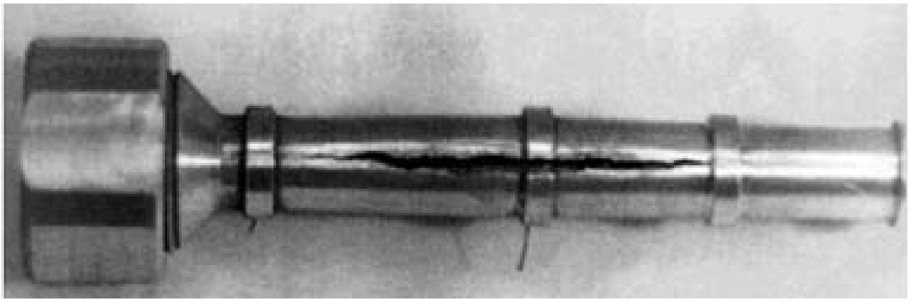
Water jet ripples generated by a 8 mJ Laser cavitation bubble



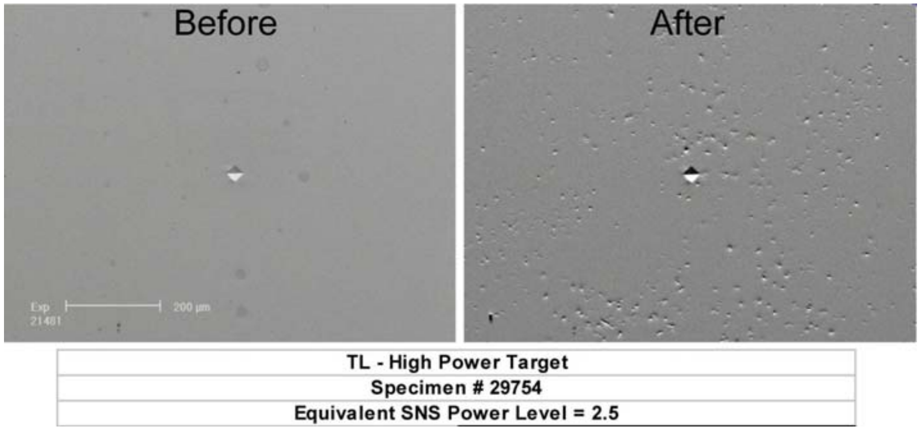
# Beam-Induced Cavitation in Liquids Can Break Pipes

**ISOLDE:**

**Hg in a pipe (BINP):**



**Cavitation pitting of SS wall surrounding Hg target after 100 pulses (SNS):**

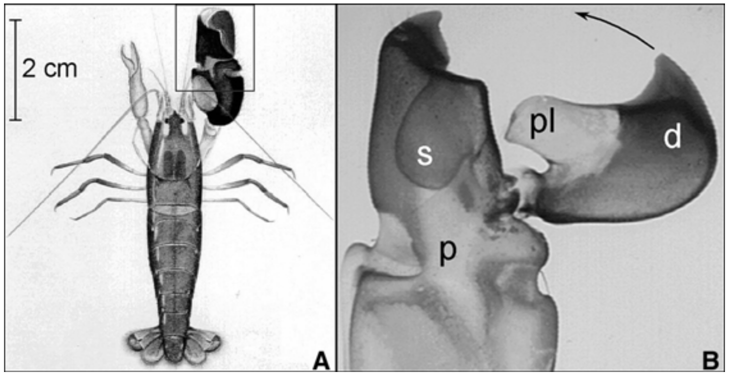


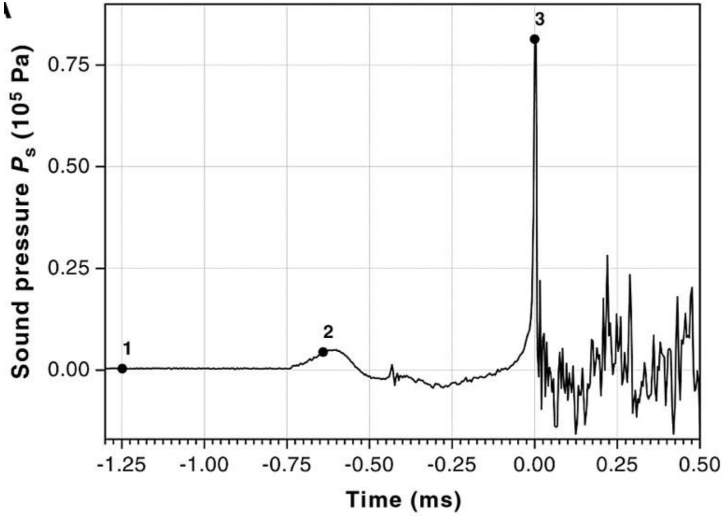
**Water jacket of NuMI target developed a leak after $\approx 1$ month. Likely due to beam-induced cavitation.**

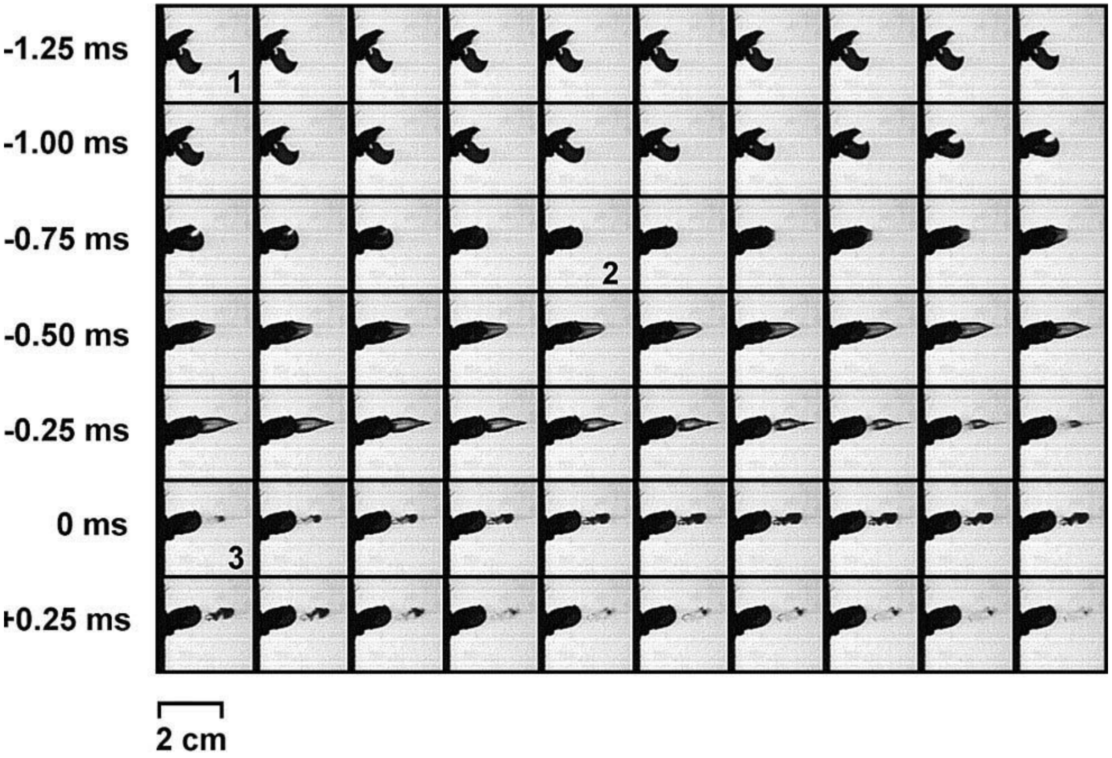
**$\Rightarrow$ Use free liquid jet if possible.**

# How Snapping Shrimp Snap: Through Cavitating Bubbles

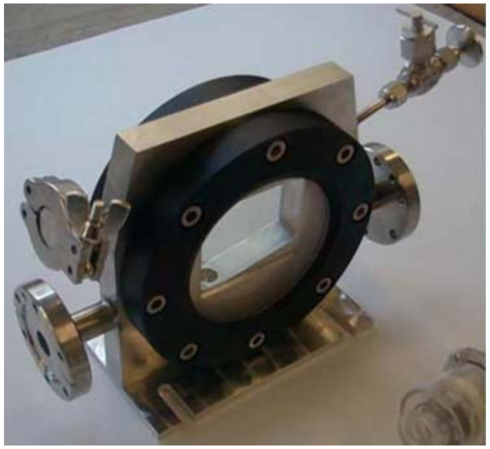
## M. Versluis, Science 289, 2114 (2000).



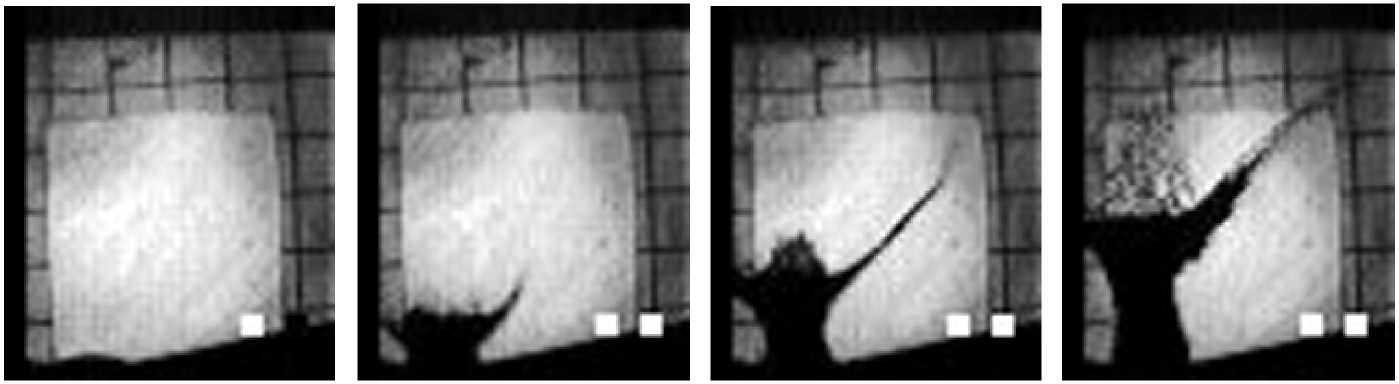




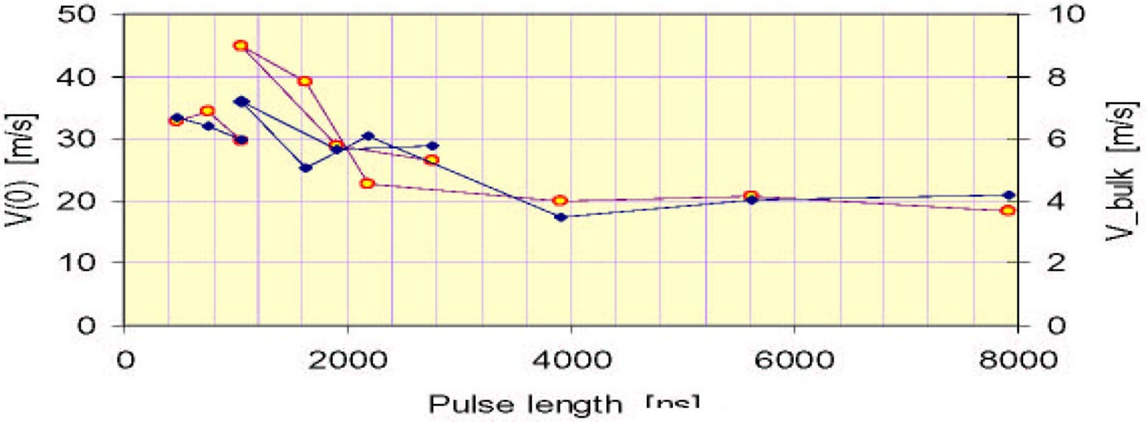
# Passive Mercury Target Tests



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

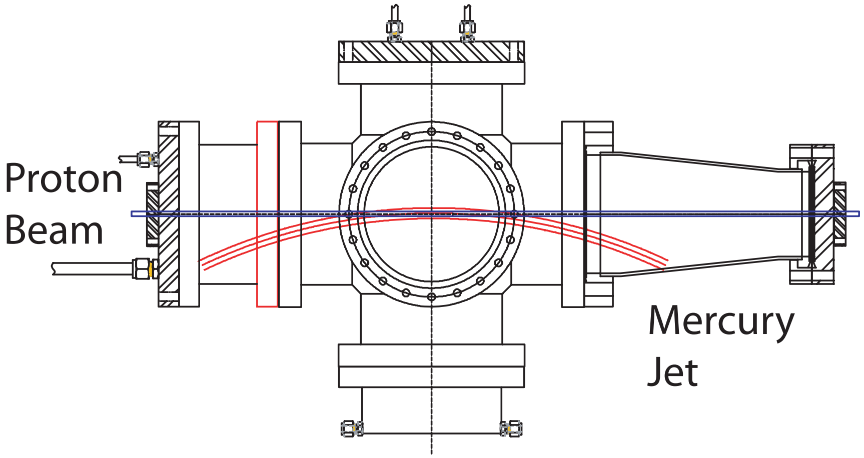


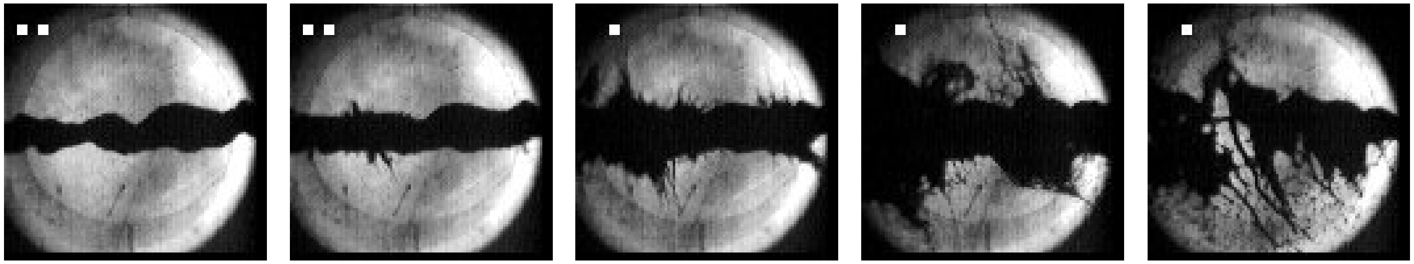
**Two pulses of $\approx 250$ ns give larger dispersal velocity only if separated by $< 3$ $\mu$s.**



# Studies of Proton Beam + Mercury Jet

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





**Model:** $v_{\rm dispersal} = \dfrac{\Delta r}{\Delta t} = \dfrac{r\alpha\Delta T}{r/v_{\rm sound}} = \dfrac{\alpha U}{C} v_{\rm sound} \approx 50$ **m/s for** $U \approx 100$ **J/g.**

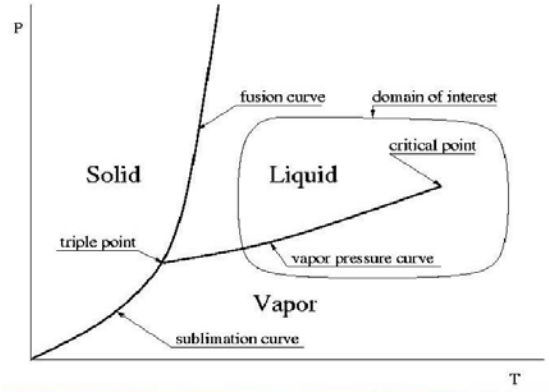
**Data:** $v_{\rm dispersal} \approx 10$ **m/s for** $U \approx 25$ **J/g.**

$v_{\rm dispersal}$ **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.**

# Computational Magnetohydrodynamics (R. Samulyak, J. Du)

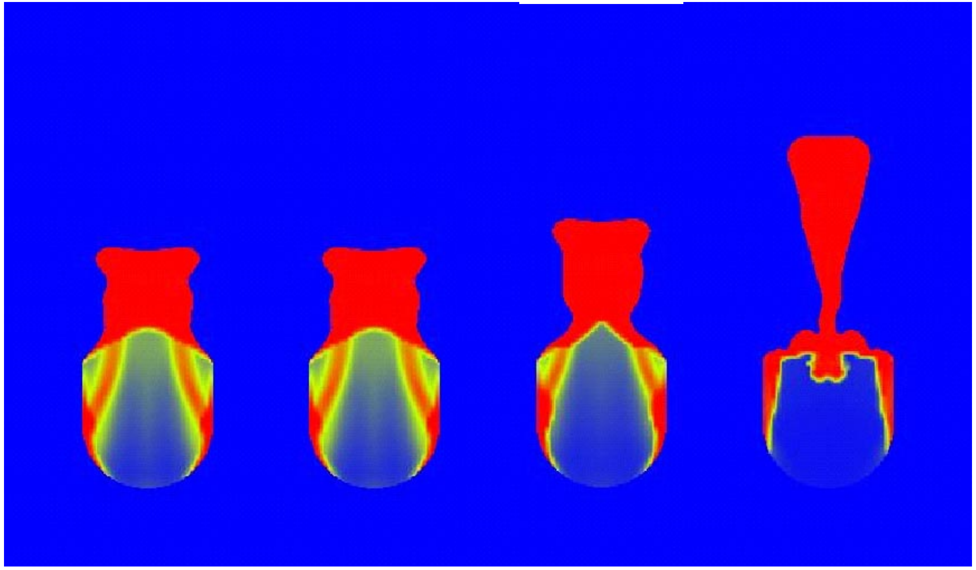


Critical point : $T_c = 1750\,\mathrm{K}$, $P_c = 172\,\mathrm{MPa}$, $V_c = 43\,\mathrm{cm^3 mol^{-1}}$

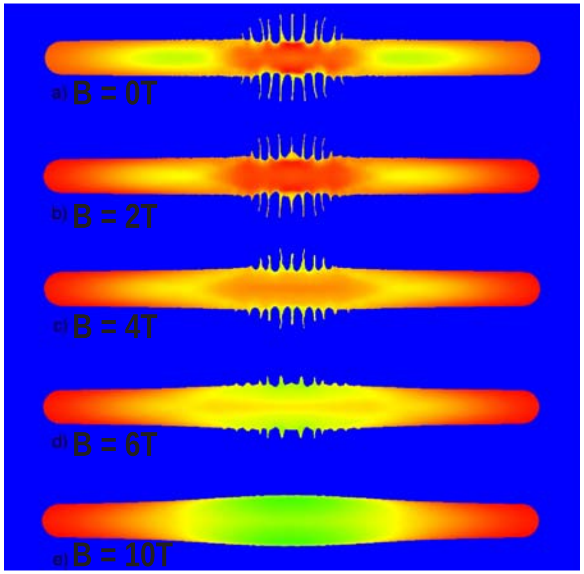
Bo

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

Thimble splash at 0.24, 0.48, 0.61, 1.01 $\mu$s



Magnetic damping of beam-induce filamentation



# What Have We Learned?

- Solid targets are viable in pulsed proton beams of up to 1-2 MW.
- Engineered materials with low coefficients of thermal expansion are desirable, but require further qualification for use at high radiation dose.
- A mercury jet appears to behave well in a proton beam at zero magnetic field, and in a high magnetic field without proton beam.

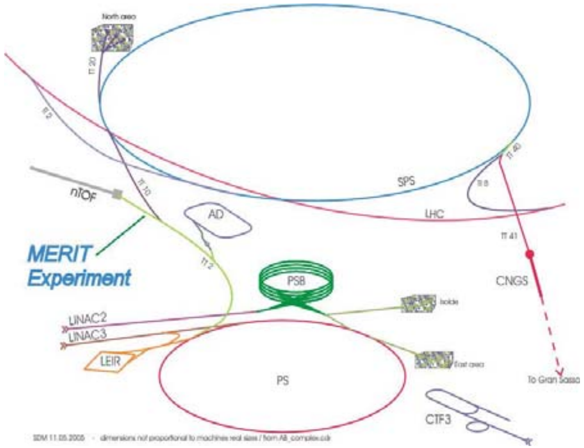
# Issues for Further Targetry R&D

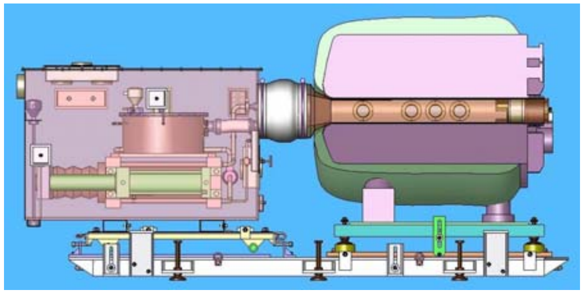
- Continue numerical simulations of MHD + beam-induced effects (J. Du).
- For solid targets, study radiation damage – and issues of heat removal from solid metal targets (carbon/carbon, Toyota Ti alloy, bands, chains, *etc.*) (N. Simos, R. Bennett).
- Proof-of-Principle test of an intense proton beam with a mercury jet inside a high-field magnet (CERN MERIT experiment, H. Kirk, V. Graves, H.-J. Park).
    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.
- Pb-Bi liquid metal targets: solid at room temp, less subject to boiling.

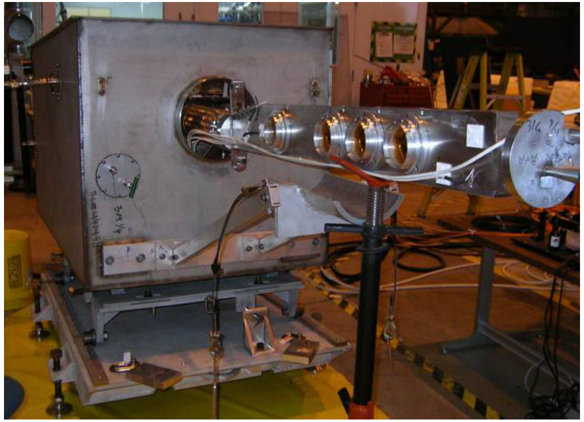
# CERN nToF11 Experiment (MERIT)

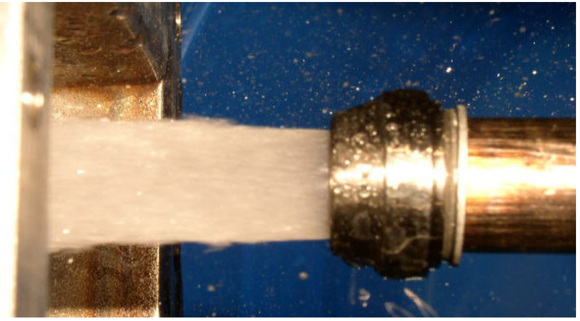
- **The MERIT experiment is a proof-of-principle demonstration of a free mercury jet target for a 4-megawatt proton beam, contained in a 15-T solenoid for maximal collection of soft secondary pions.**
- **MERIT = MERcury Intense Target.**
- **Key parameters:**
  - **24-GeV Proton beam pulses, up to 16) bunches/pulse, up to $2.5 \times 10^{12}$ $p$/bunch.**
  - **$\sigma_r$ of proton bunch = 1.2 mm, proton beam axis at 67 mrad to magnet axis.**
  - **Mercury jet of 1 cm diameter, $v = 20$ m/s, jet axis at 33 mrad to magnet axis.**
  - **$\Rightarrow$ Each proton intercepts the Hg jet over 30 cm = 2 interaction lengths.**
- **Every beam pulse is a separate experiment.**
  - **$\sim 100$ Beam pulses in total.**
  - **Vary bunch intensity, bunch spacing, number of bunches.**
  - **Vary magnetic field strength.**
  - **Vary beam-jet alignment, beam spot size.**

# CERN nToF11 Experiment (MERIT)









# Advertisement: High-Power Target Workshops

## Past Workshops sponsored by the NFMCC:

- Ronkonkoma (2003)
- ORNL (2005)

## Upcoming Workshops:

- EURISOL Target Workshop (CERN, Feb 22, 2007)
- PSI (Sept 10-14, 2007)