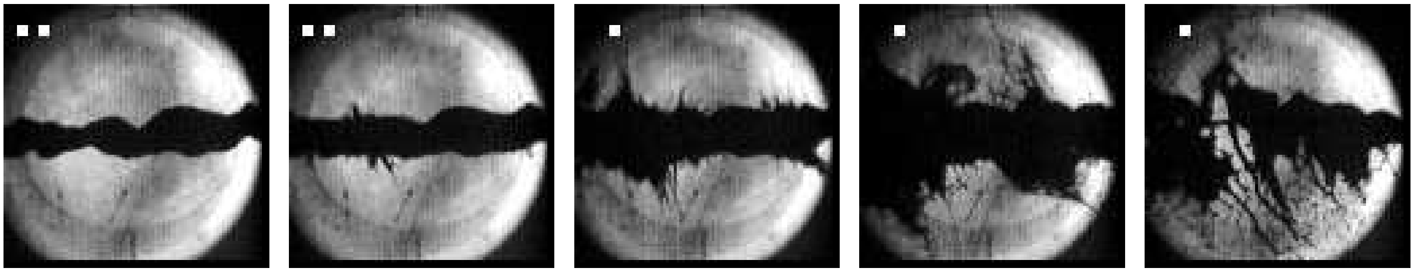
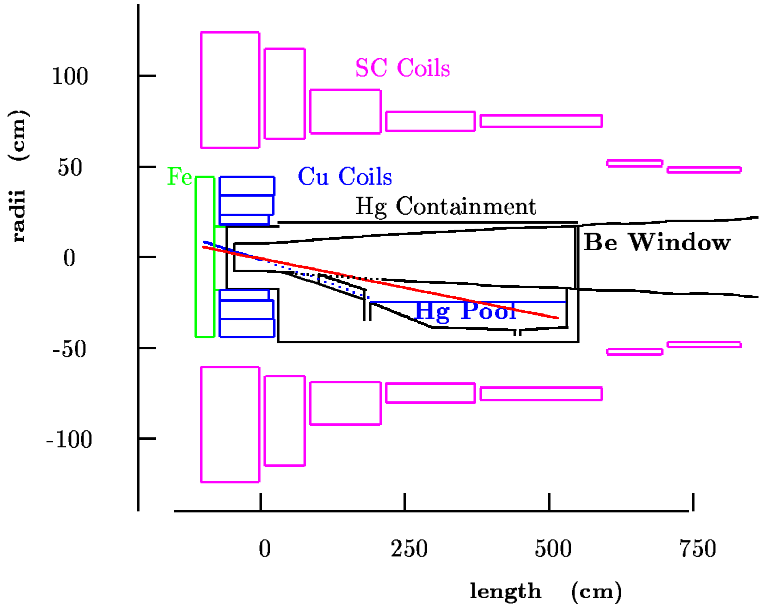
Targetry for a Neutrino Factory and Muon Collider





K.T. McDonald

Princeton U.

NuFact03

Columbia U., June 9, 2003

Targetry Web Page:

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

Various Physics Examples:

`http://puhep1.princeton.edu/~mcdonald/examples/`

A Short Course on Targetry

presented at the NuFact03 Summer Institute

June 4, 2003

E. Fermi: “I can calculate anything to 20% in 20 minutes.”

An everyday targetry physics question: What is the threshold intensity of sunlight to damage human skin?

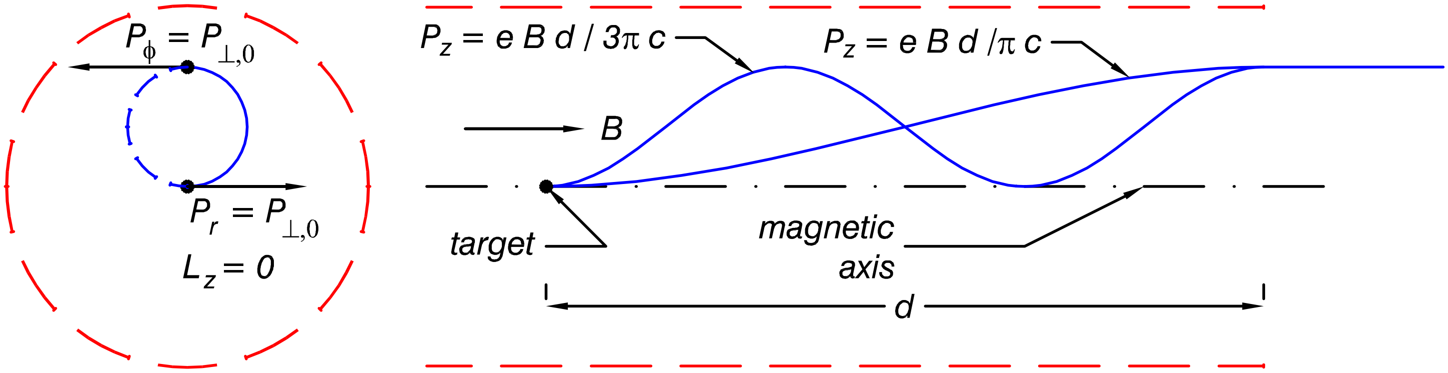
[Ans: Bright sunlight, $\approx$ *1 kW/m*^{2}*.]*

A metaphysics question: Why do people enjoy getting sunburned?

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.

Why Targetry?

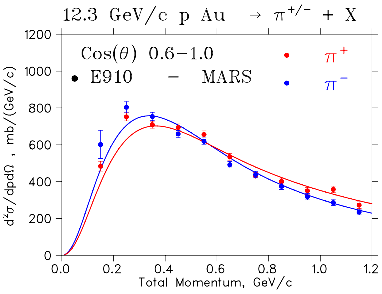
- **Targetry** = the task of producing and capturing π's and μ's from proton interactions with a nuclear target.
- At a **muon collider** the key parameter is **luminosity**:

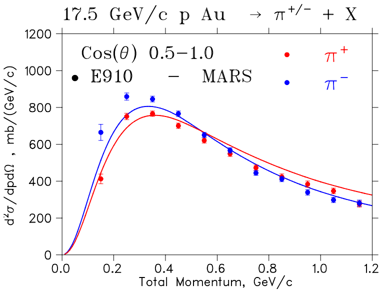
$$\mathcal{L} = \frac{N_1 N_2 f}{A}\,\mathrm{s}^{-1}\mathrm{cm}^{-2},$$

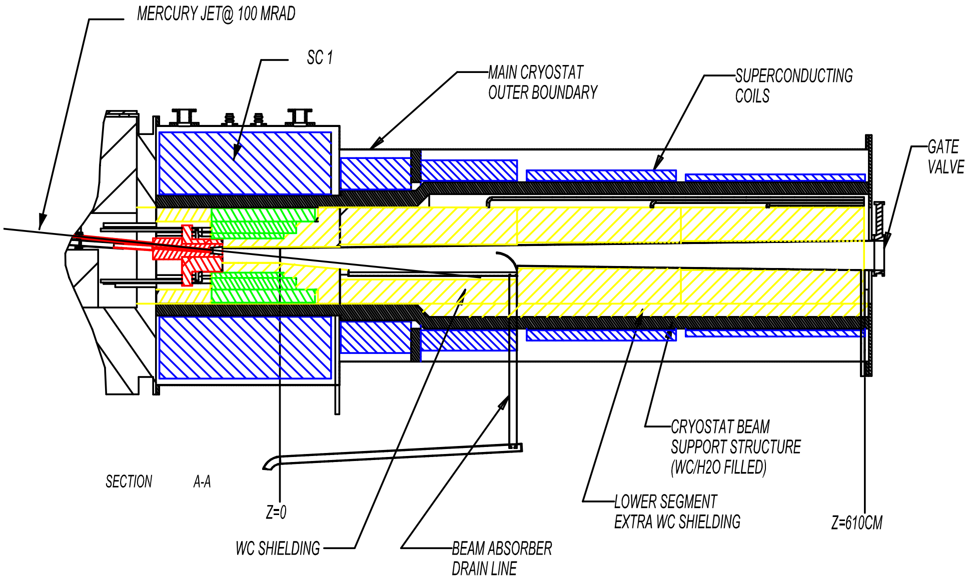
  ⇒ Gain as square of source strength (targetry), but small beam area (cooling) is also critical.
- At a **neutrino factory** the key parameter is **neutrino flux**, ⇒ Source strength (targetry) is of pre-eminent concern. [Beam cooling important mainly to be sure the beam fits in the pipe.]
- Since its 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 the major challenge**.

Targetry Challenges

- Use of a multimegawatt proton beam for maximal production of soft pions → muons.
- Capture pions in a 20-T solenoid, followed by a 1.25-T decay channel (with beam and target tilted by 100 mrad w.r.t. magnetic axis).







- A carbon target is feasible for 1.5-MW proton beam power.
- For $E_p \gtrsim 16$ GeV, factor of 2 advantage with high-Z target.
- Static high-Z target would melt, ⇒ Moving target.
- A free mercury jet target is feasible for beam power of 4 MW (and more).

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

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

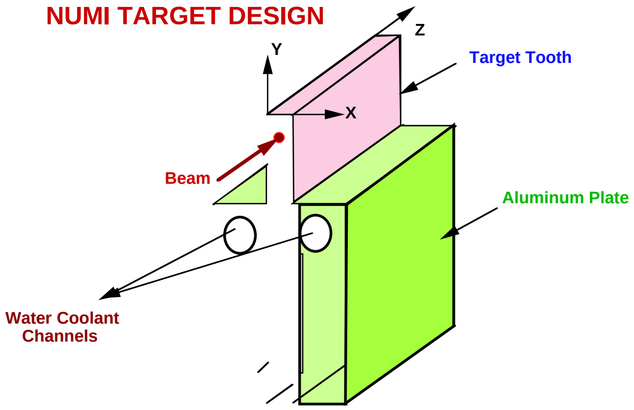
How Much Beam Power Can a Solid Target Stand?

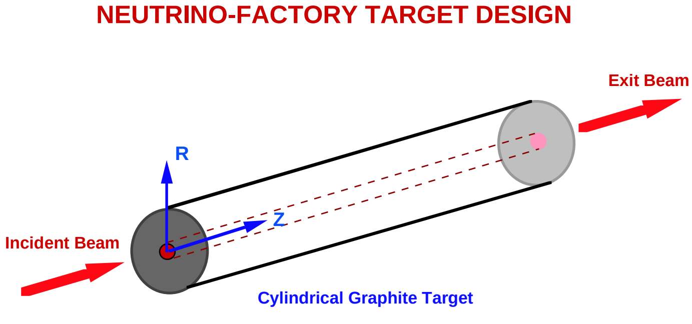
How many protons are required to deposit 60 J/g in a material? What is the maximum beam power this material can withstand without cracking, for a 10-GeV beam at 10 Hz with area 0.1 cm^2.

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, $P_{\text{max}} \approx 10\ \text{Hz} \cdot 10^{10}\ \text{eV} \cdot 1.6 \times 10^{-19}\ \text{J/eV} \cdot 10^{15}/\text{cm}^2 \cdot 0.1\ \text{cm}^2$
$\approx 1.6 \times 10^6$ J/s $=$ 1.6 MW.

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

A Carbon Target is Feasible at 1-MW Beam Power

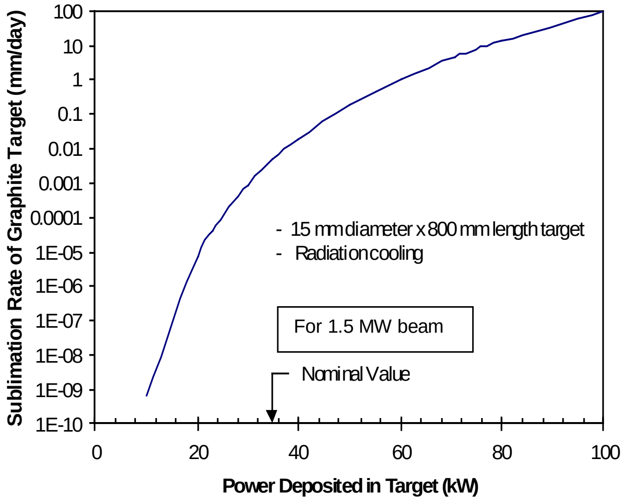




HASSANEIN (ANL)

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.

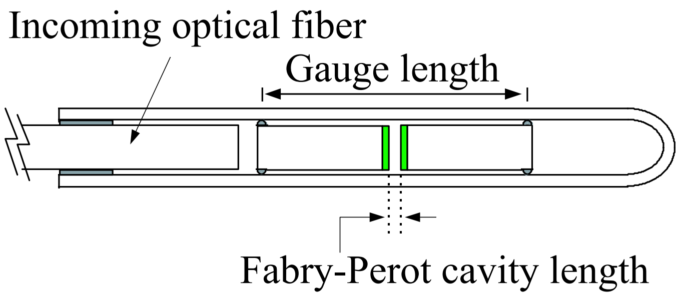


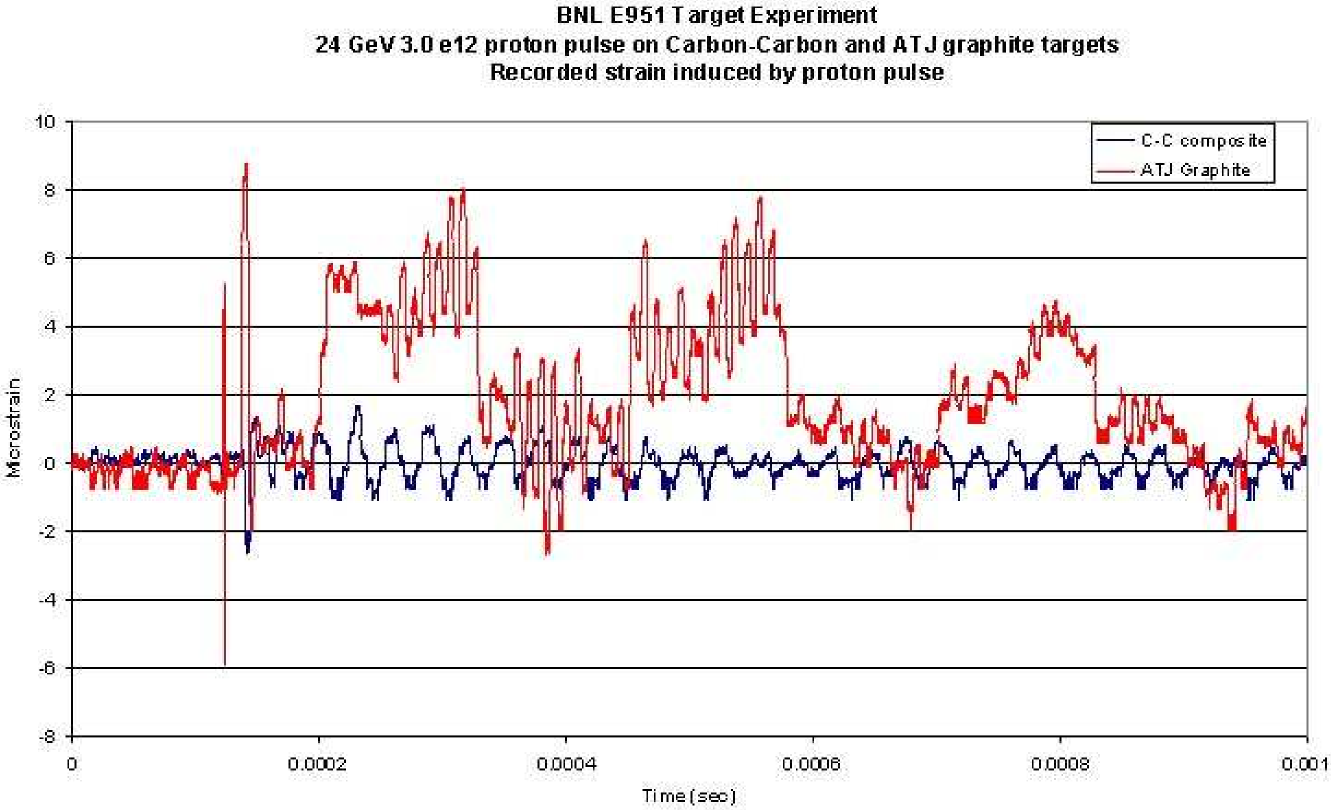
Sublimation of carbon is negligible in a helium atmosphere. (P. Thieberger) Tests underway at ORNL to confirm this.

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

Lower Thermal Shock If Lower Thermal Expansion Coefficient

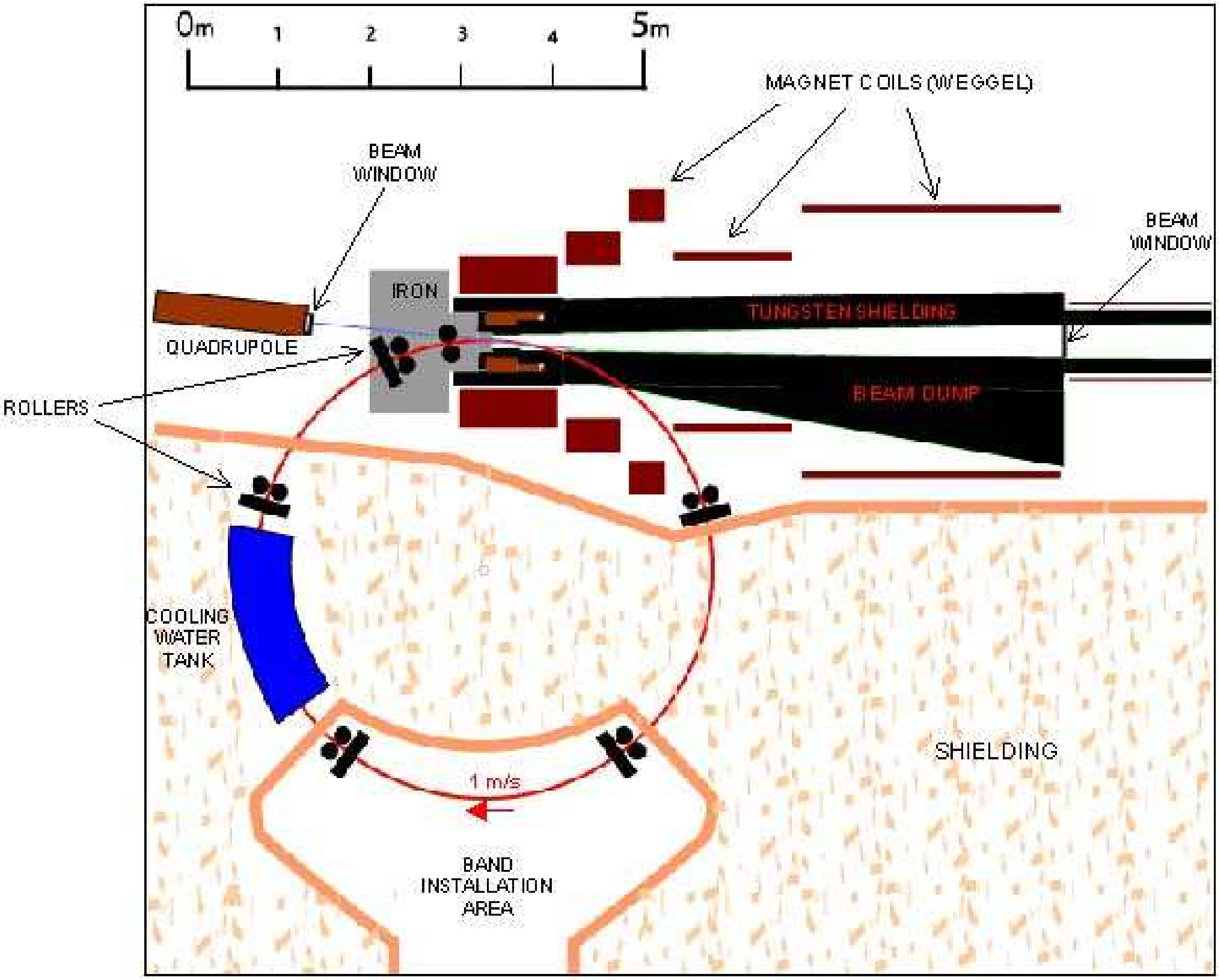
Proton beams studies of ATJ graphite and a 3-d weave of carbon-carbon fibers, instrumented with fiberoptic strain sensors:




BNL E951 Target Experiment
24 GeV 3.0 e12 proton pulse on Carbon-Carbon and ATJ graphite targets
Recorded strain induced by proton pulse

Maybe Can Use a Moving Solid Target

Ex. Rotating band that increases radiation damage life by 1000:

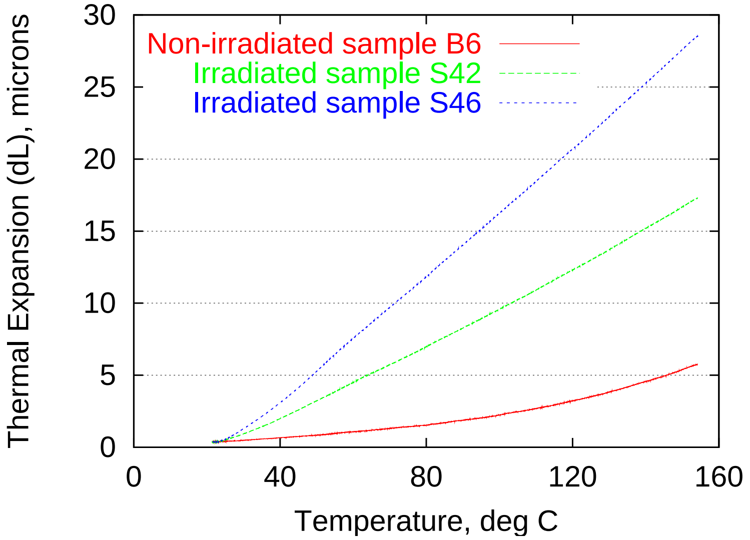


Compatibility of the rotating band with a capture solenoid magnet?

Single-pulse thermal shock still an issue, so maybe use SuperInvar, a material with a very low thermal expansion coefficient.

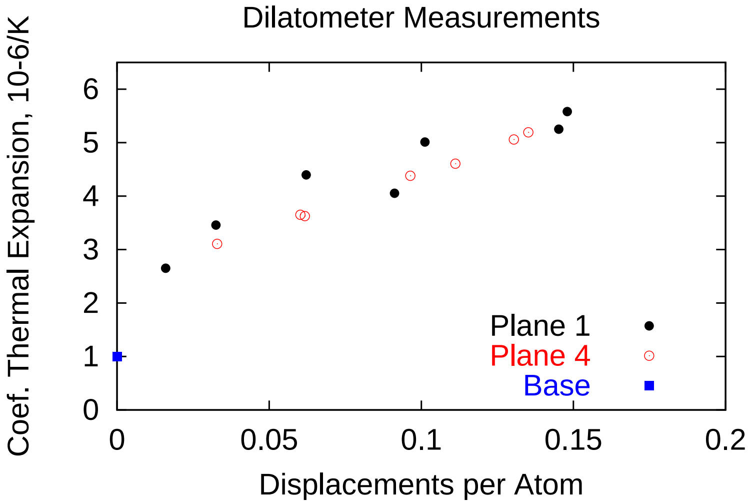
Effects of Radiation on SuperInvar

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



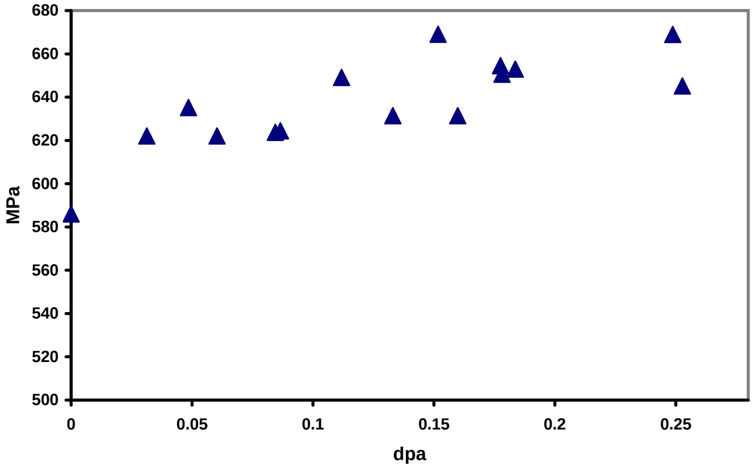
However, irradiation at the BNL BLIP facility show that the CTA increases rapidly with radiation dose.

CTA *vs.* dose ⇒



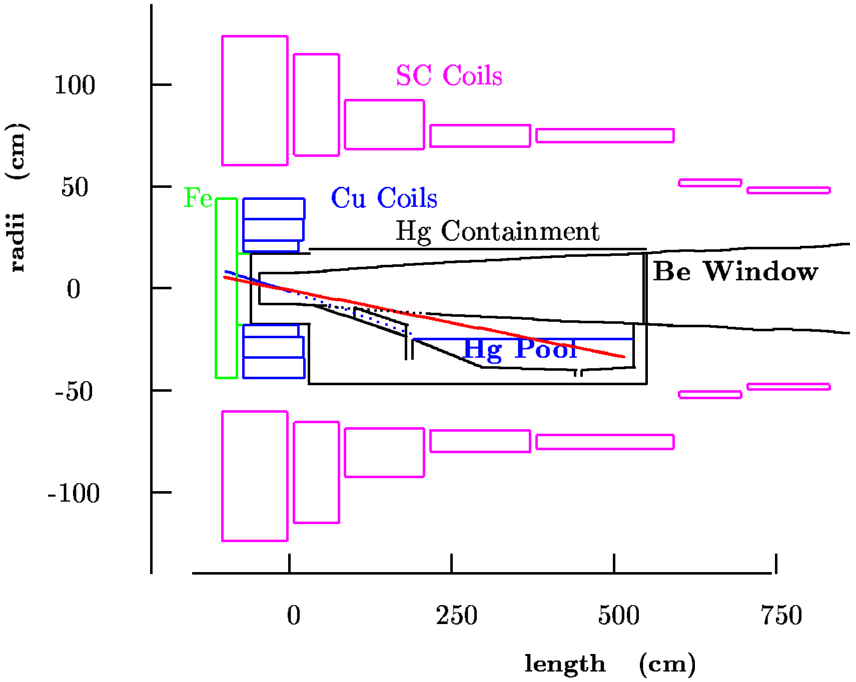
SuperInvar is made stronger by moderate radiation doses (like many materials).

Yield strength *vs.* dose ⇒

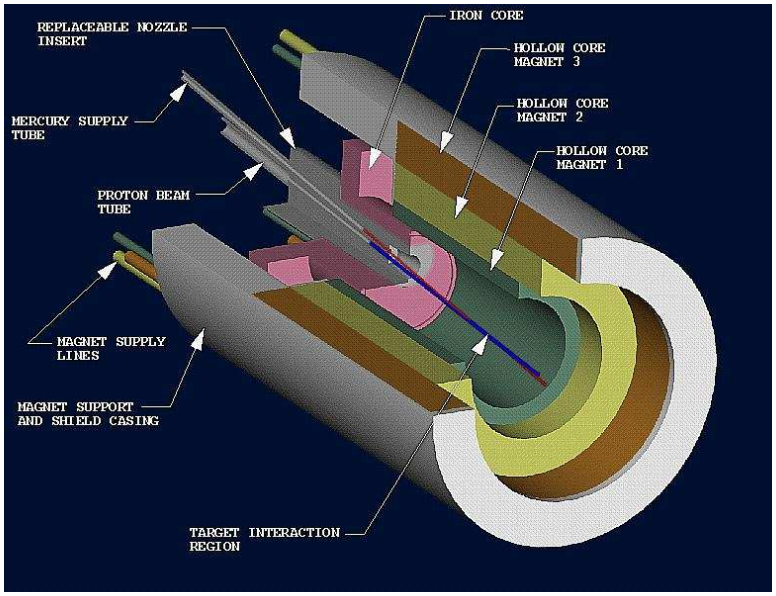


A Liquid Metal Jet May Be the Best Moving Target

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

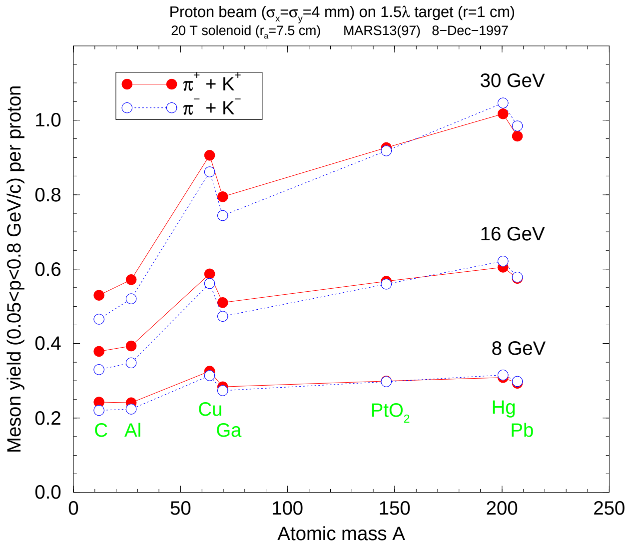


Mercury jet tilted by 100 mrad, proton beam by 67 mrad.

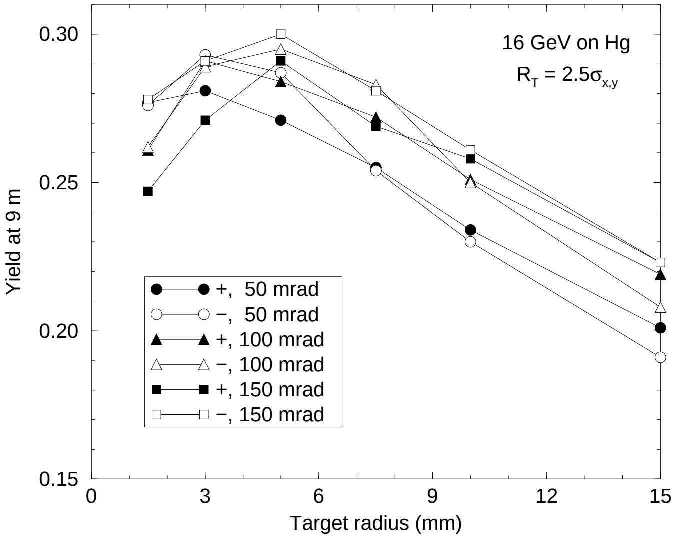


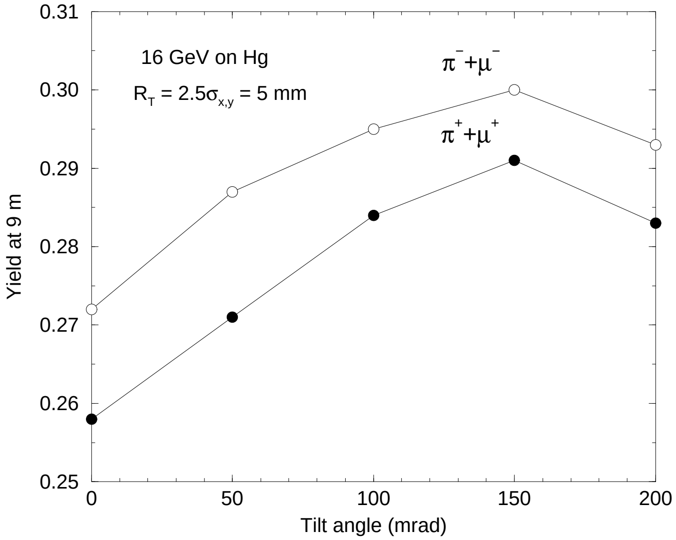
Pion/Muon Yield

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



Mercury target radius should be ≈ 5 mm,
with target axis tilted by ≈ 100 mrad to the magnetic axis.

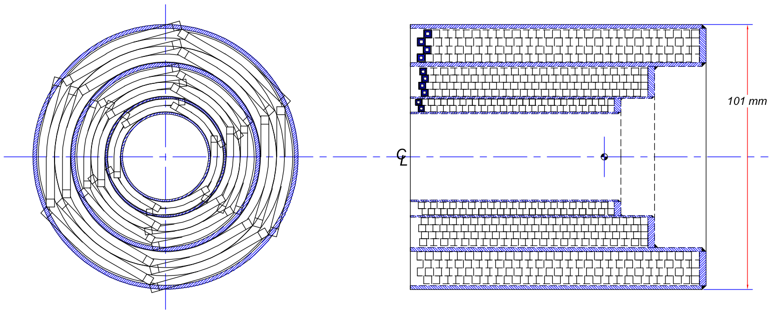




Can capture ≈ 0.3 pion per proton with $50 < P_\pi < 400$ MeV/c.

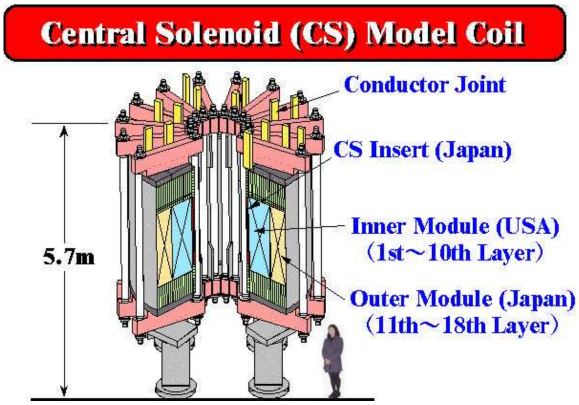
20-T Capture Magnet System

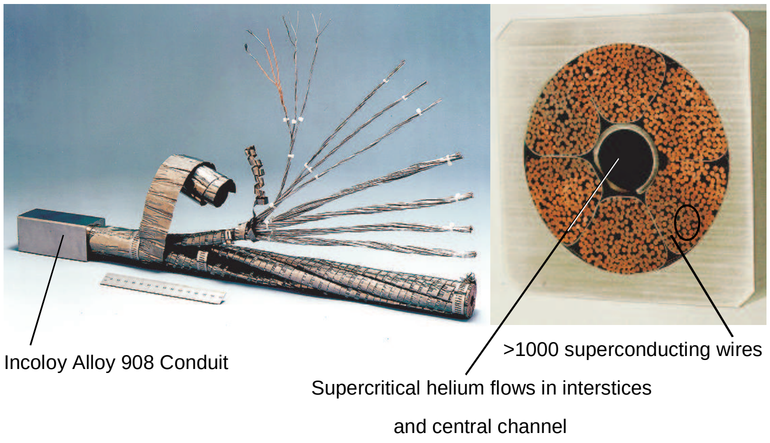
Inner, hollow-conductor copper coils generate 6 T @ 12 MW:



Bitter-coil option less costly, but marginally feasible.

Outer, superconducting coils generate 14 T @ 600 MJ:



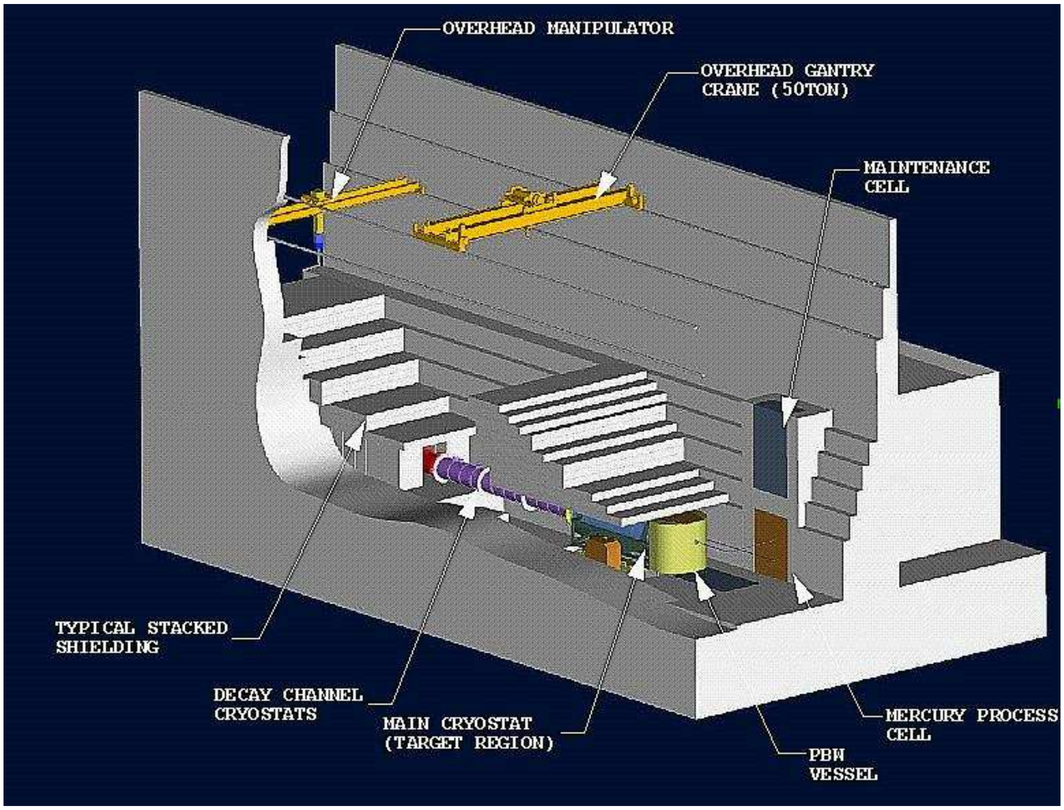


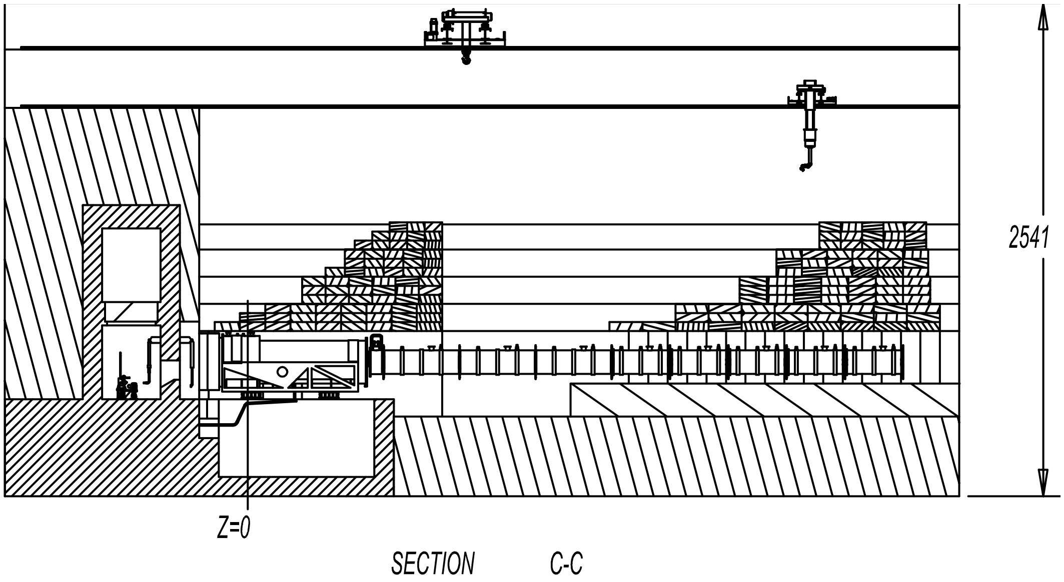
Cable-in-conduit construction similar to ITER central solenoid.

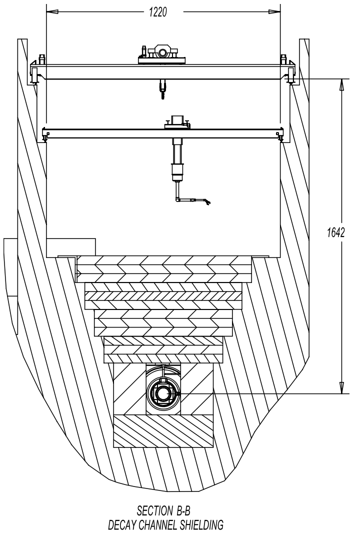
Both coils shielded by tungsten-carbide/water.

Target System Support Facility

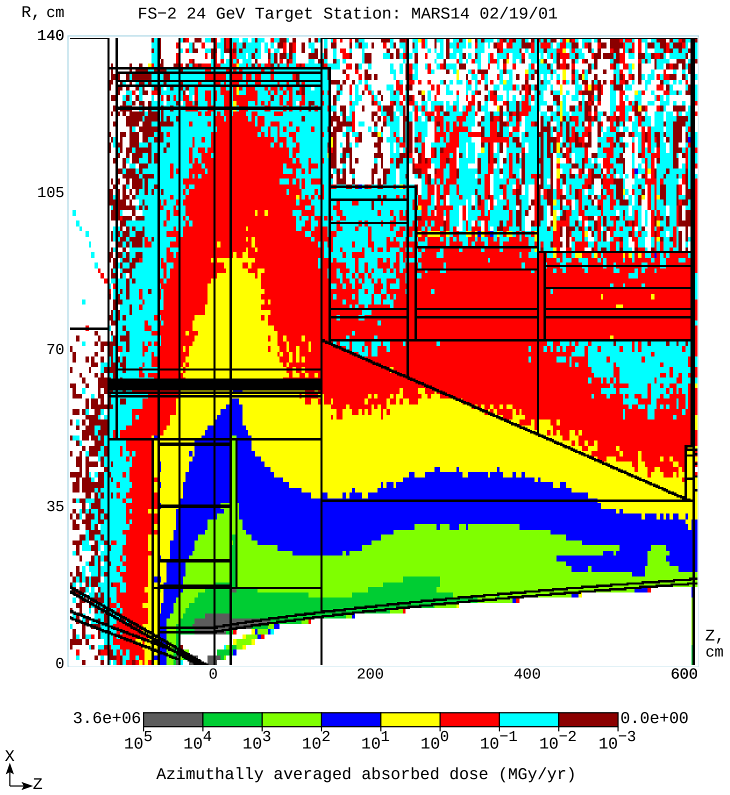
Extensive shielding; remote handling capability.







Lifetime of Components in the High Radiation Environment

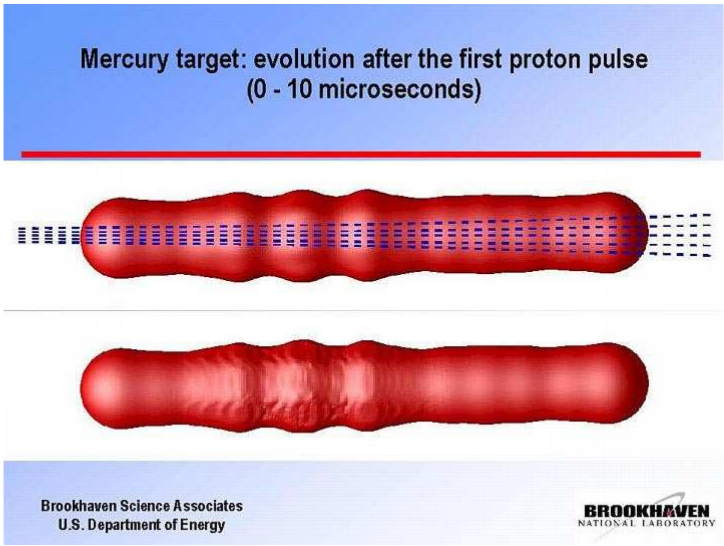


Component	Radius	Dose/yr	Max allowed Dose	1 MW Life	4 MW life
	(cm)	(Grays/2×10^7 s)	(Grays)	(years)	(years)
Inner shielding	7.5	5×10^{10}	10^{12}	20	5
Hg containment	18	10^9	10^{11}	100	25
Hollow conductor coil	18	10^9	10^{11}	100	25
Superconducting coil	65	5×10^6	10^8	20	5

Some components must be replaceable.

Viability of Targetry and Capture For a Single Pulse

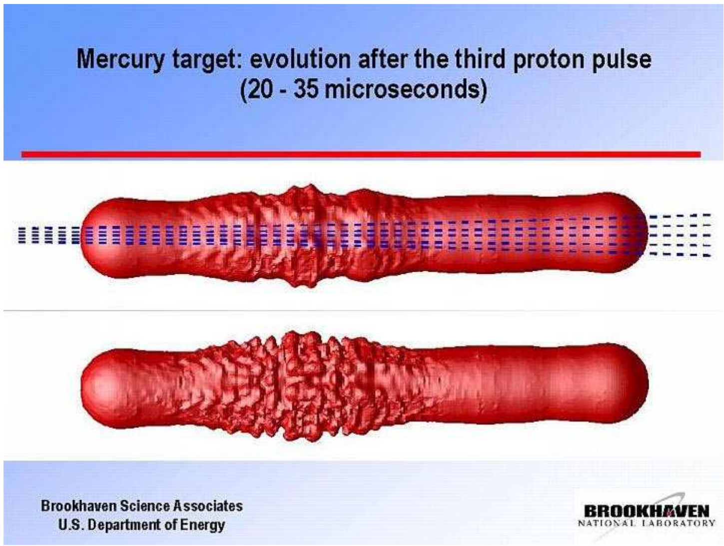
- Beam energy deposition may disperse the jet.



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

Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN NATIONAL LABORATORY

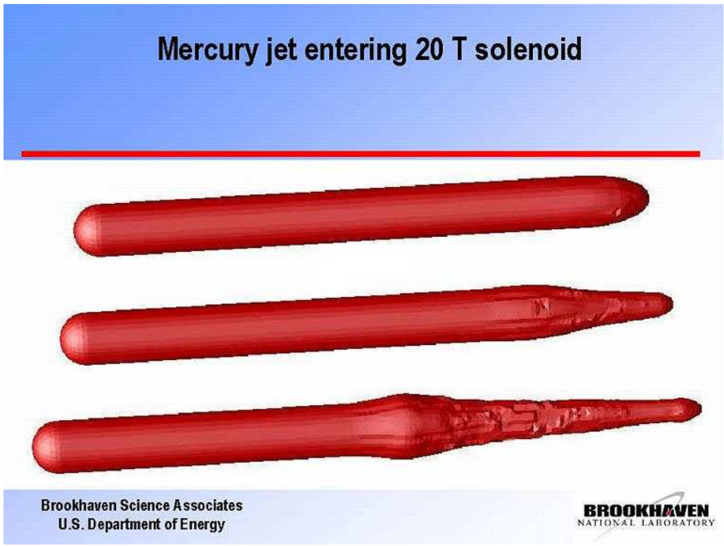


Mercury target: evolution after the third proton pulse
(20 - 35 microseconds)

Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN NATIONAL LABORATORY

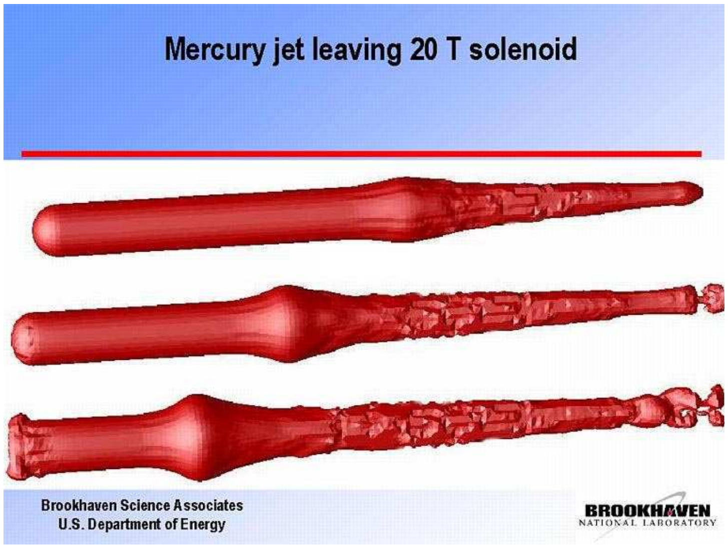
- Eddy currents may distort the jet as it traverses the magnet.



Mercury jet entering 20 T solenoid

Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN NATIONAL LABORATORY



Mercury jet leaving 20 T solenoid

Brookhaven Science Associates
U.S. Department of Energy

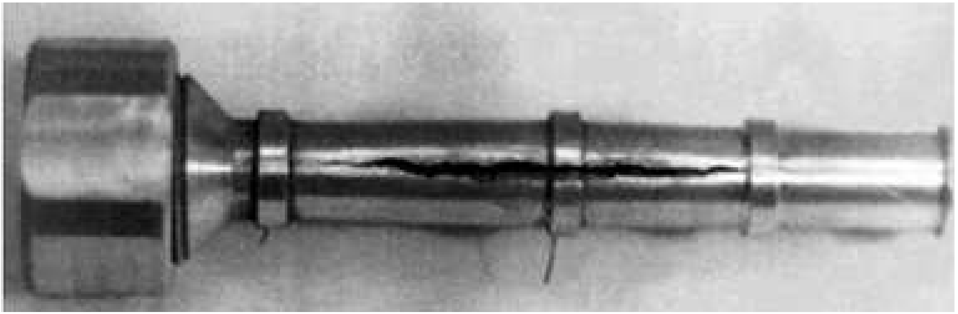
BROOKHAVEN NATIONAL LABORATORY

- Computational challenge: to include negative pressure and cavitation in a magnetohydrodynamic (MHD) simulation of a liquid metal with a free surface.

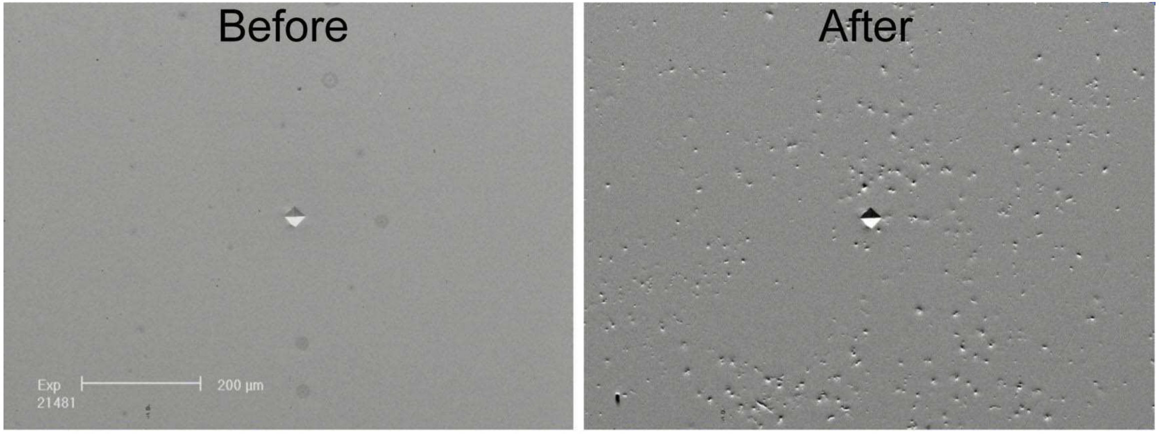
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

BINP:



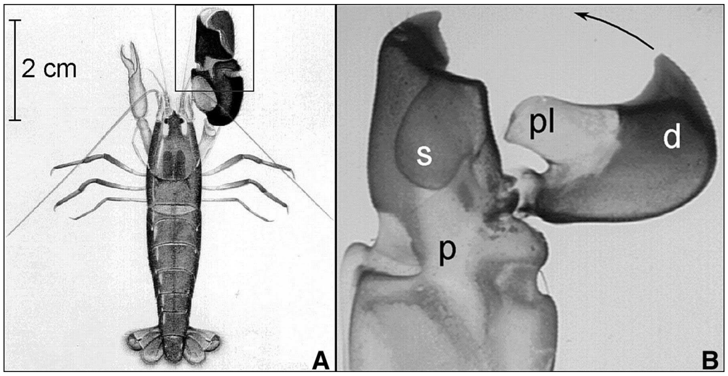
SNS:

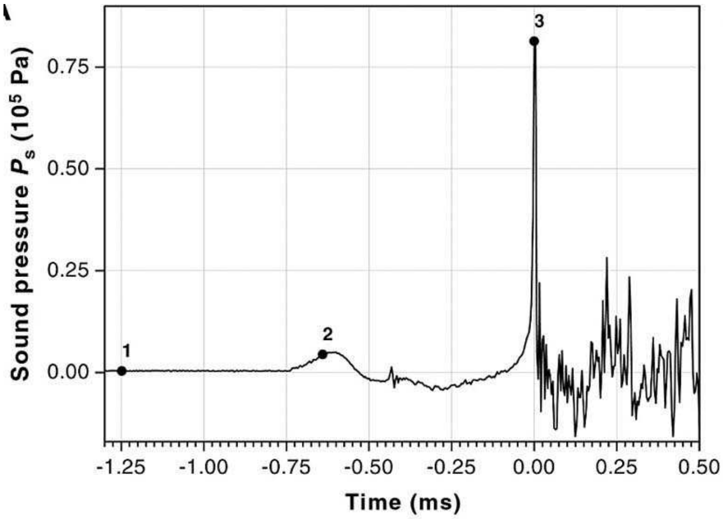


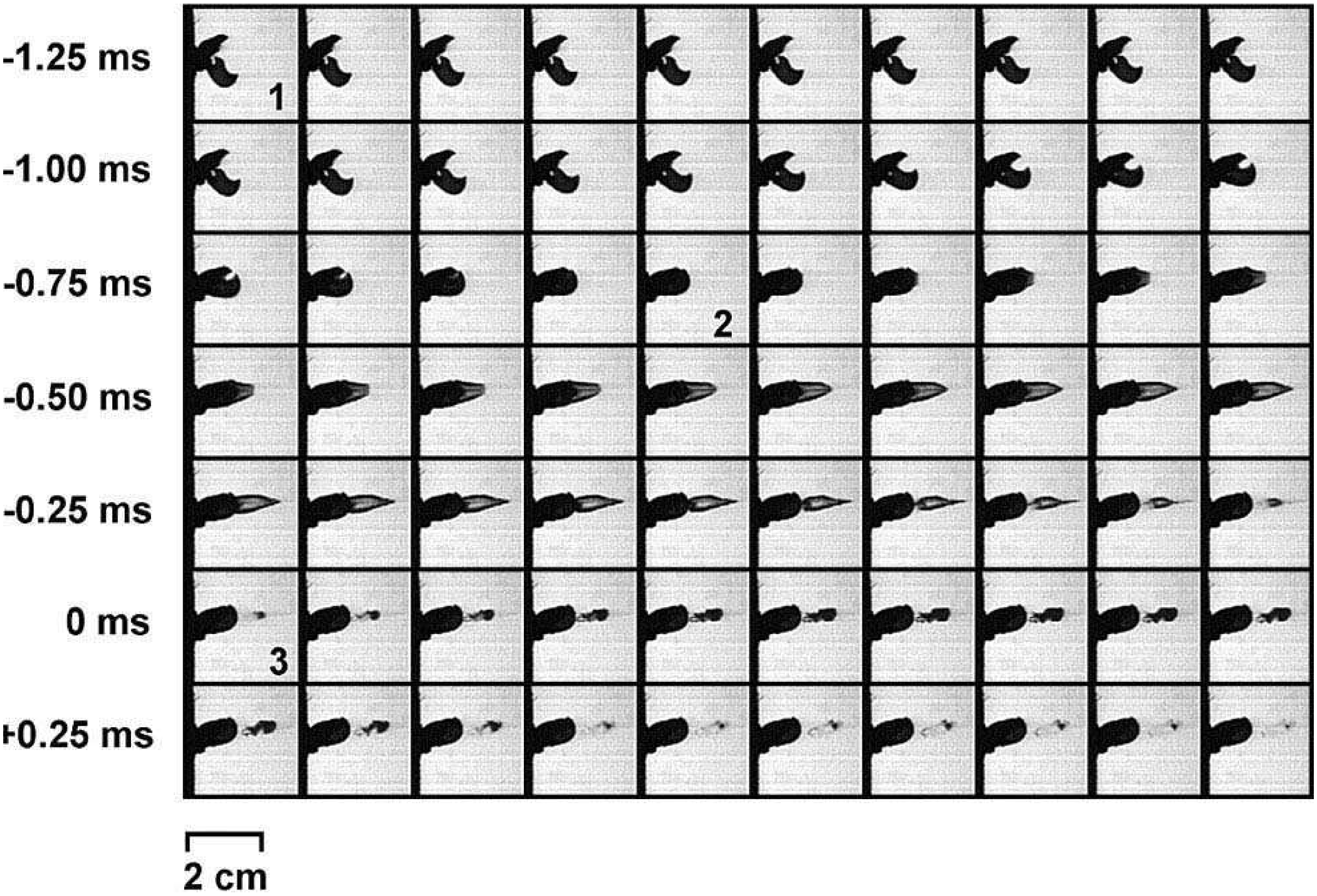
TL - High Power Target
Specimen # 29754
Equivalent SNS Power Level = 2.5

How Snapping Shrimp Snap: Through Cavitating Bubbles

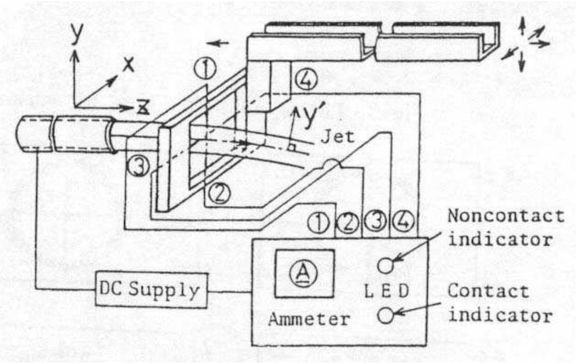
M. Versluis , Science **289**, 2114 (2000).



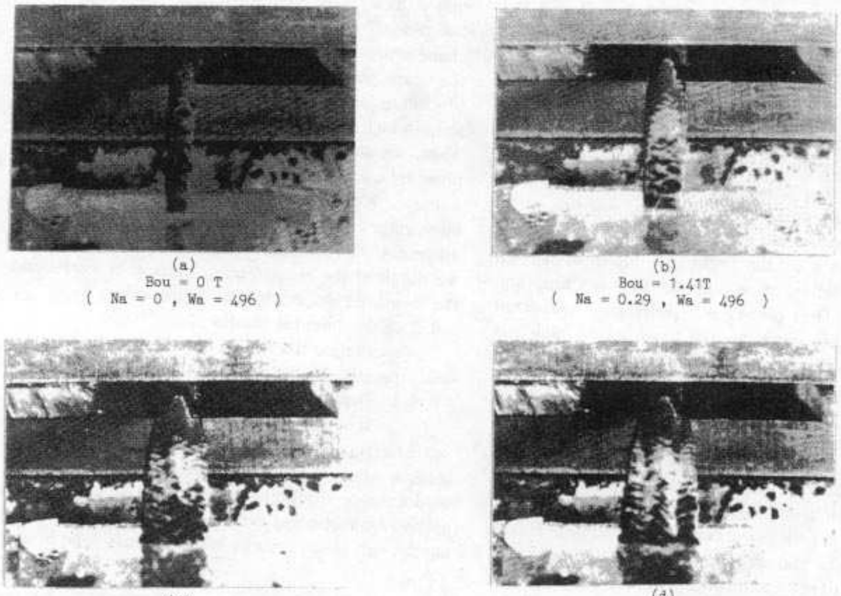




The Shape of a Liquid Metal Jet under a Non-uniform Magnetic Field



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



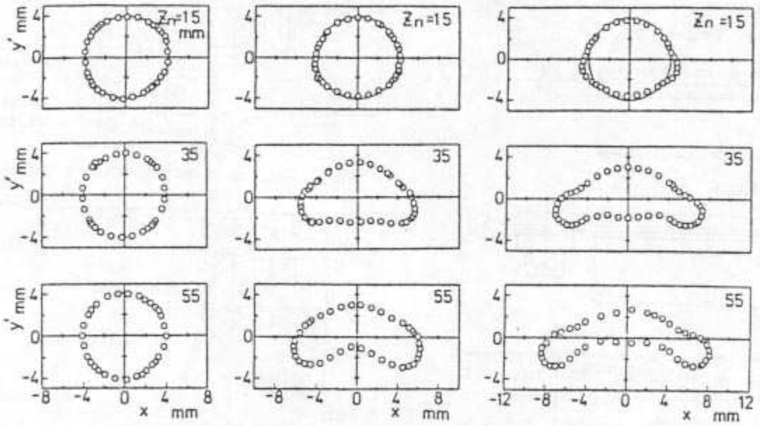
(a)
Bou = 0 T
(Na = 0 , Wa = 496)

(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



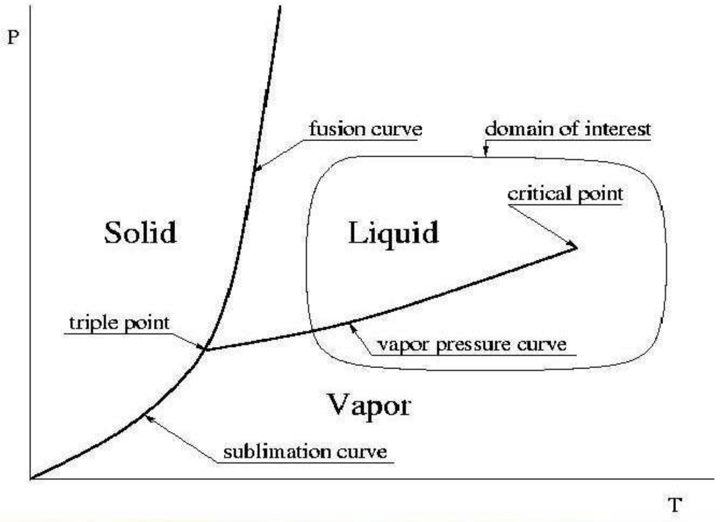
(a)
Bou = 0 T
(Na = 0 , Wa = 496)

(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

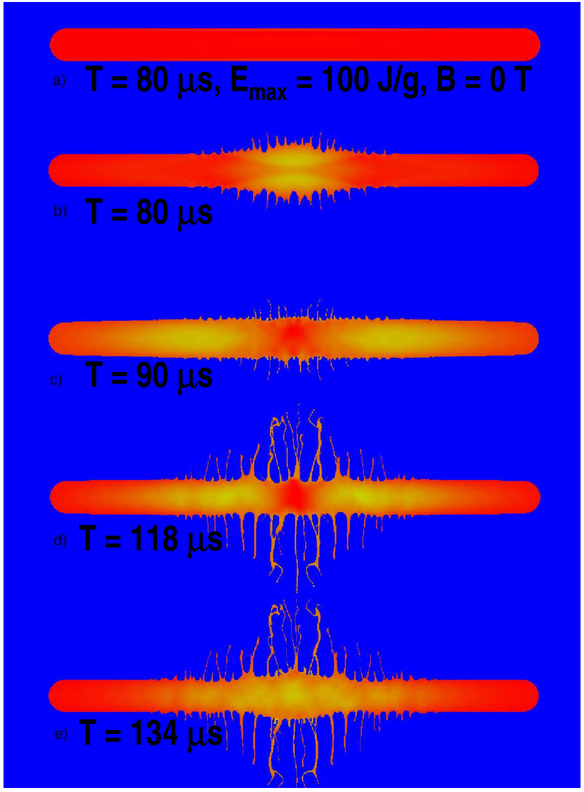
Computational Magnetohydrodynamics (R. Samulyak)

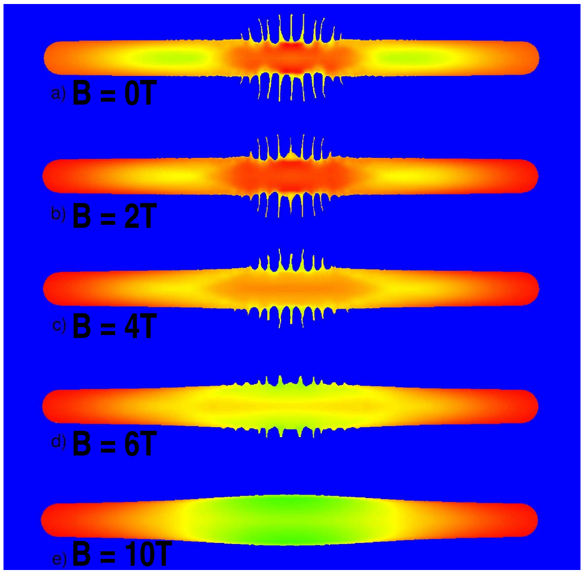


Critical point : $T_c = 1750\,\mathrm{K}$, $P_c = 172\,\mathrm{MPa}$, $V_c = 43\,\mathrm{cm}^3\mathrm{mol}^{-1}$

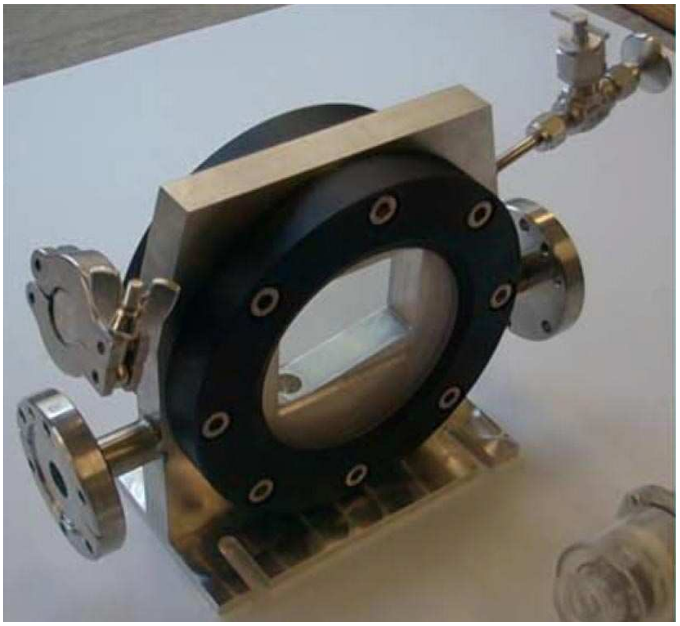
Boiling point : $T_b = 629.84\,\mathrm{K}$, $P_b = 0.1\,\mathrm{MPa}$, $\rho = 13.546\,\mathrm{g \cdot cm}^{-3}$

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

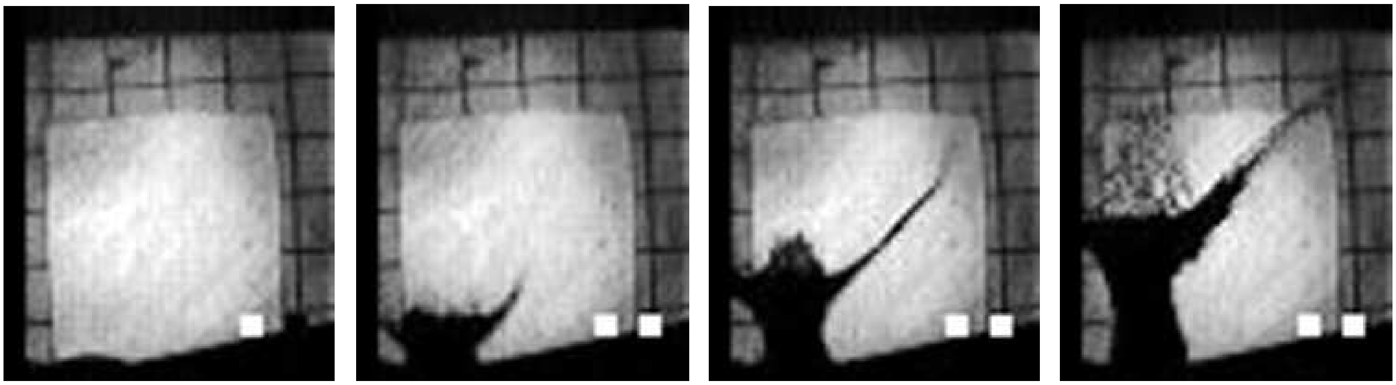




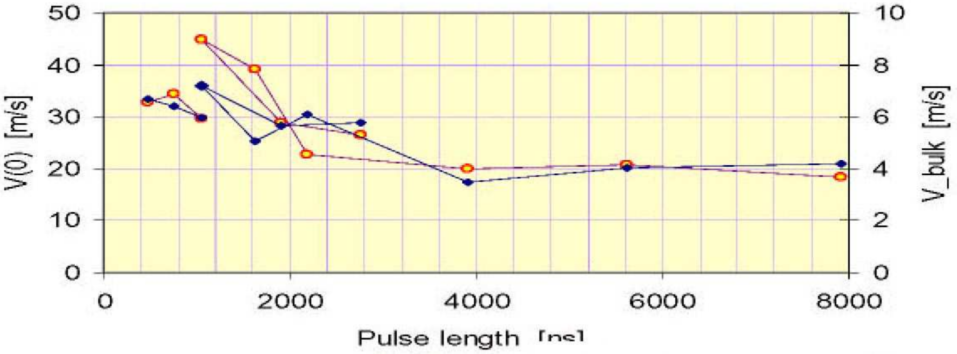
Passive Mercury Target Tests



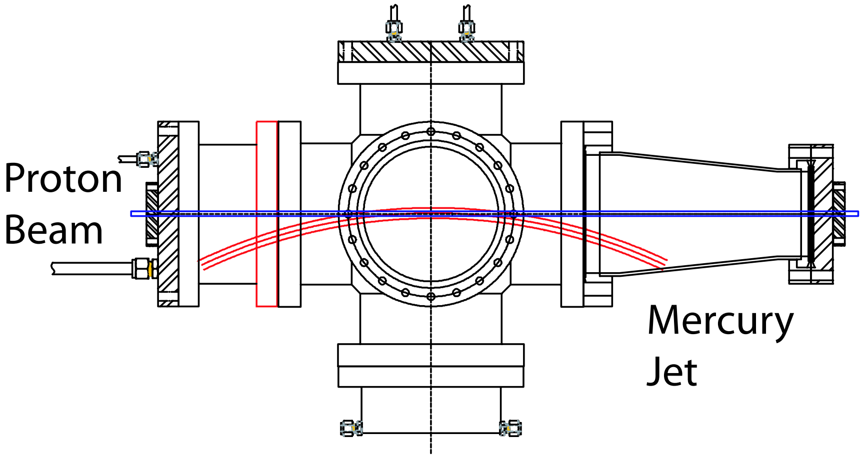
Exposures of 25 μs at $t = 0, 0.5, 1.6, 3.4$ msec,
$\Rightarrow v_{\text{splash}} \approx 20 - 40$ m/s:



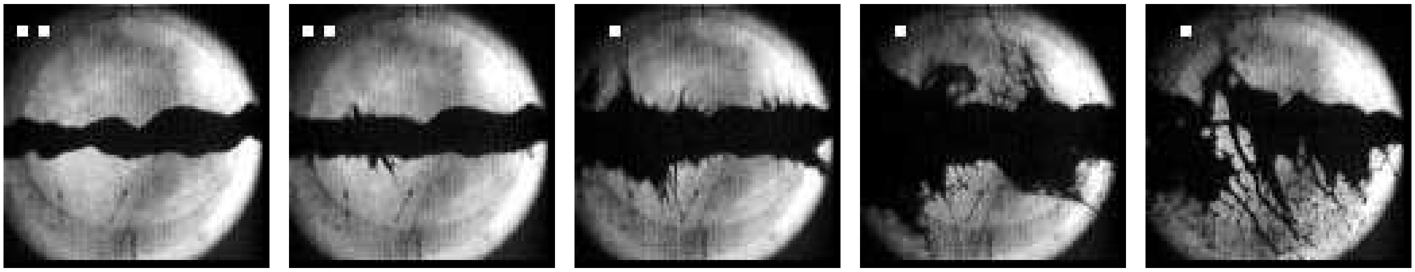
Two pulses of ≈ 250 ns give larger dispersal velocity only if separated by less than 3 μs.



Studies of Proton Beam + Mercury Jet



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.

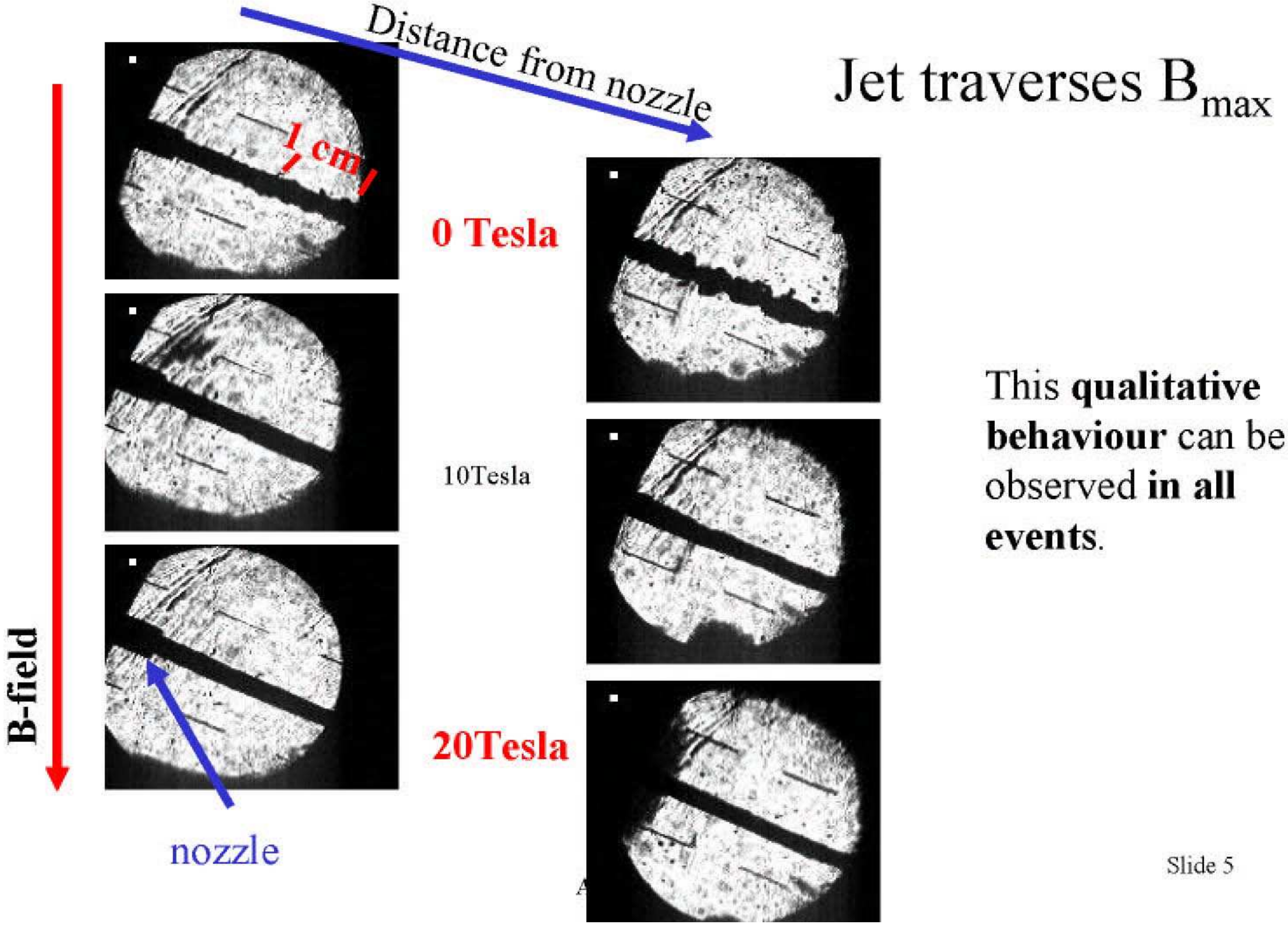
Filaments appear only $\approx 40\ \mu$s after beam, ⇒ after several bounces of waves, or v_{sound} very low.

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.



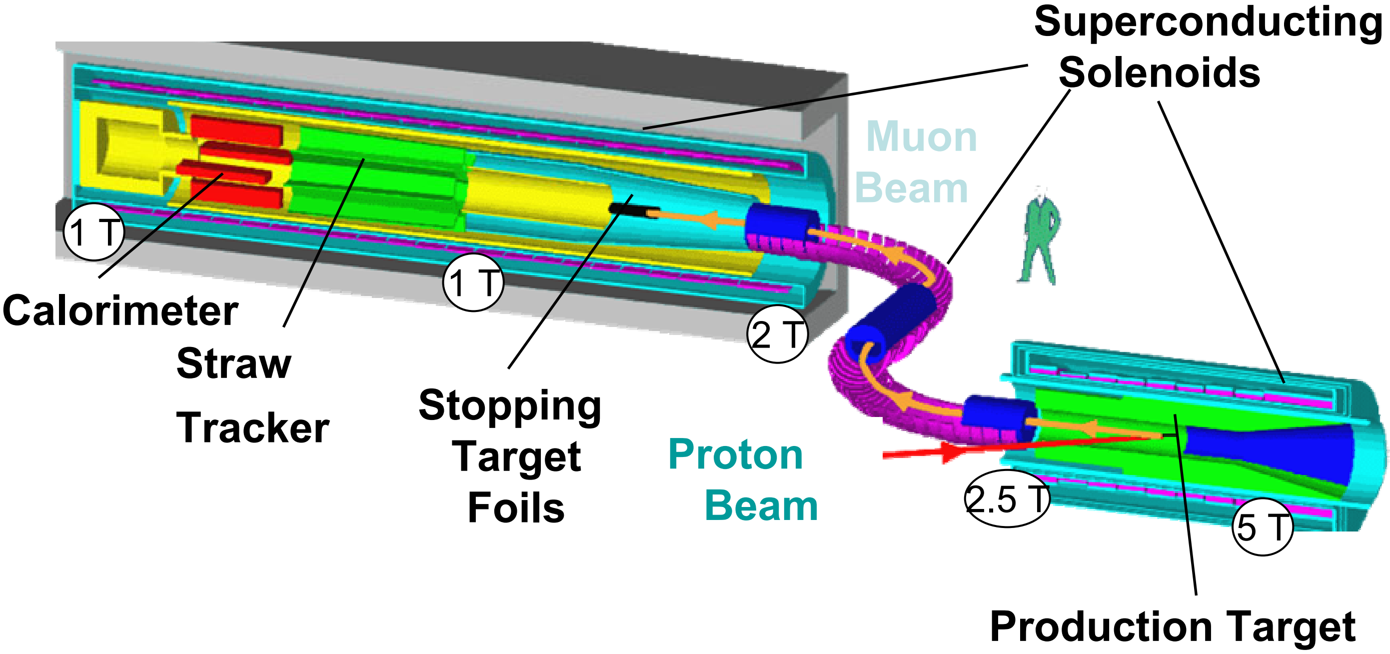
Jet traverses B_{max}

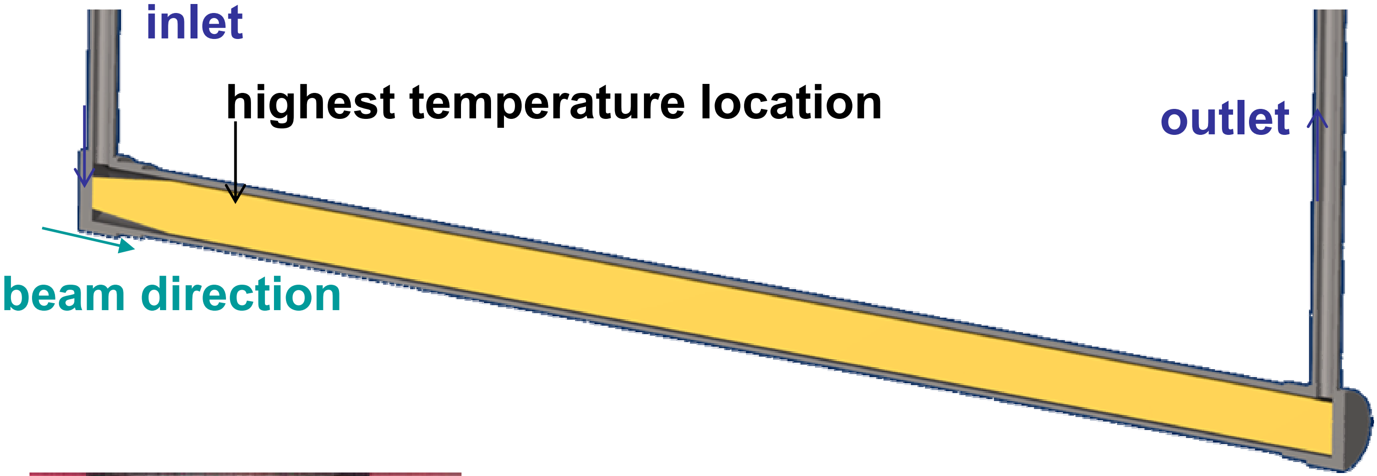
This **qualitative behaviour** can be observed **in all events**.

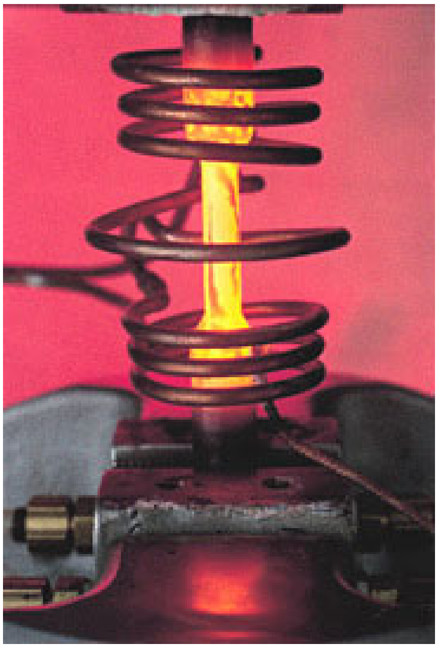
⇒ Damping of surface tension waves (Rayleigh instability).

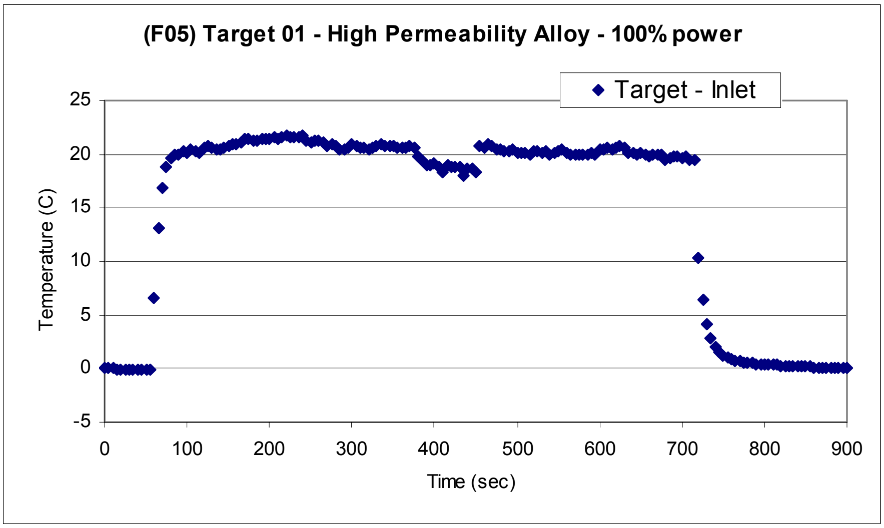
Will the beam-induced dispersal be damped also?

MECO Target R&D, *J. Popp*



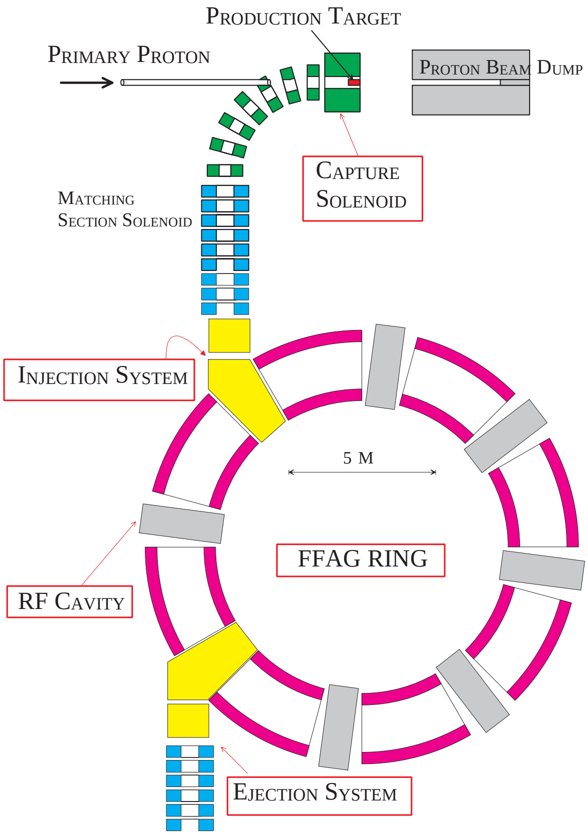


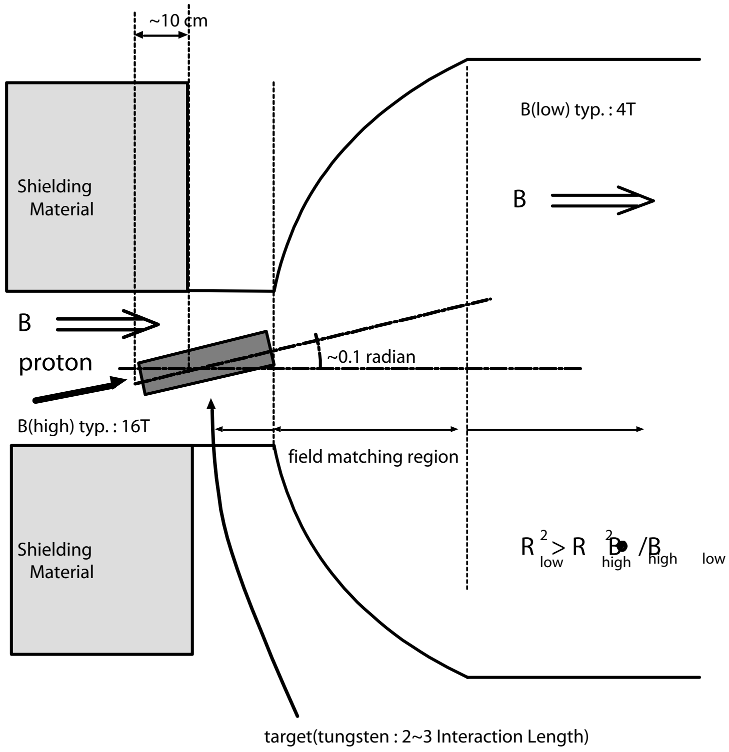




PRISM Target R&D

H. Ohnishi, Y, Yamanoi, K. Yoshimura





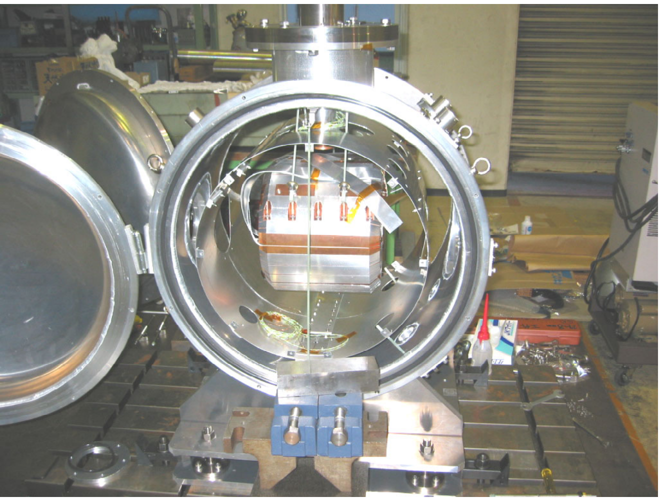
Target concept similar to Neutrino Factory Study 2.

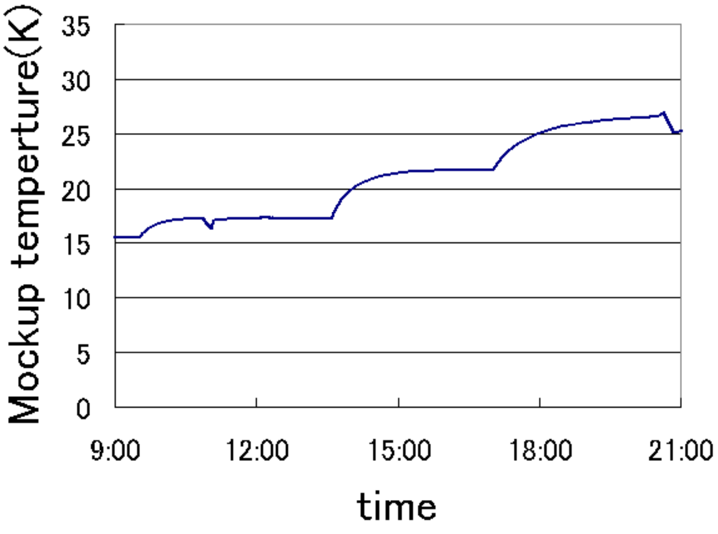
10.9-T Prototype magnet, 6-cm warm bore;

hybrid coil (NbTi, Nb3Sn, HiTc)

Graphite target.

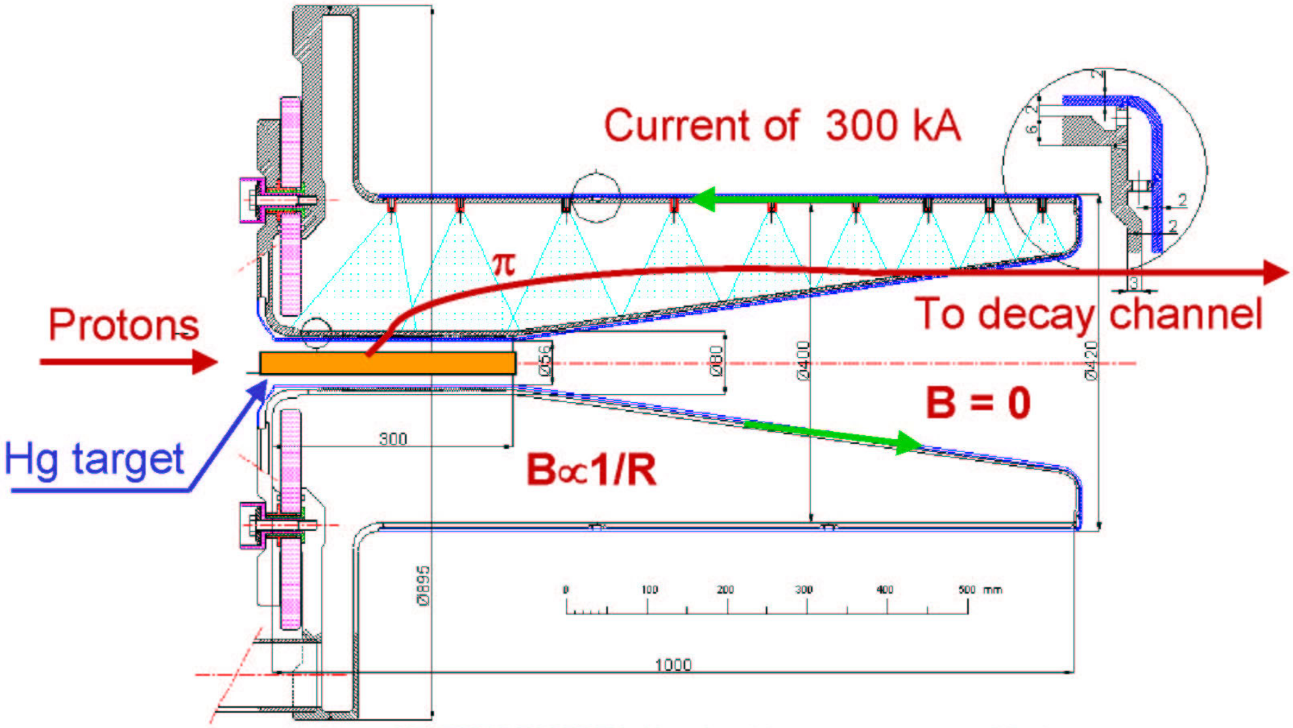
Beam test of coil mockup at KEK with 12-GeV protons, 10^{11}/s.





Neutrino Horn + Target R&D at CERN

S. Gilardoni *et al.*



NEUTRINO FACTORY - Horn 1 prototype

S. Rangod
16/06/2001

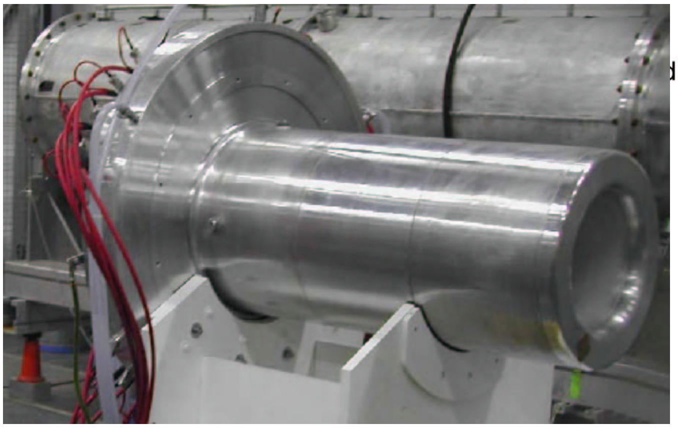
- First “inner” horn 1:1 prototype
- Power supply for Test One:
  30 kA and 1 Hz, pulse 100 μs long
  - ✓ First mechanical measurements
  - ➢ Test of numerical results for vibration
  - ✓ Test of cooling system

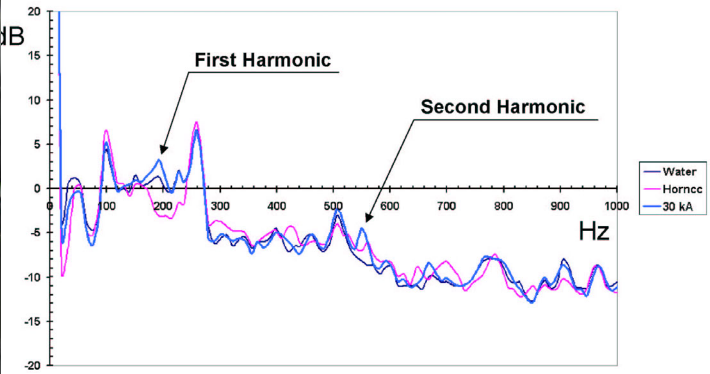
done

- Test Two: 100 kA and 0.5 Hz
  - – Testing during this week
- Last test: 300 kA and 50 Hz

Unknown schedule

Goal: Horn Life-Time 6 weeks ($2*10^8$ pulses)





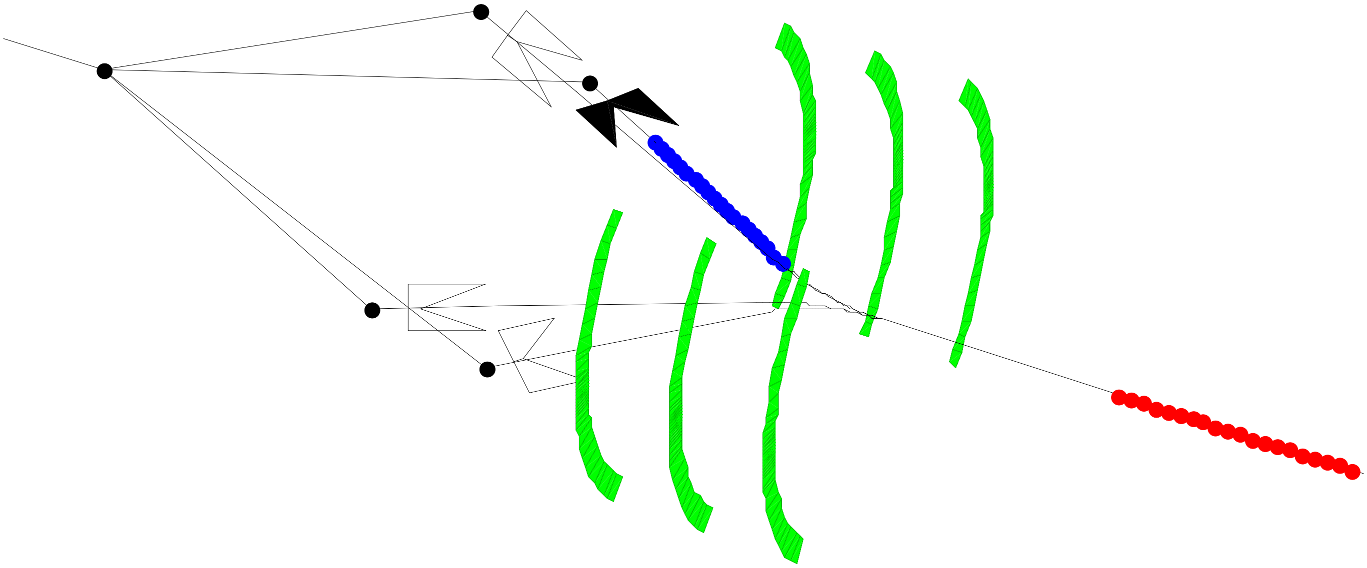
eigenfrequencies from horn “sound”

Funneling π's and μ's

B. Autin, P. Sievers, A. Verdier, F. Méot

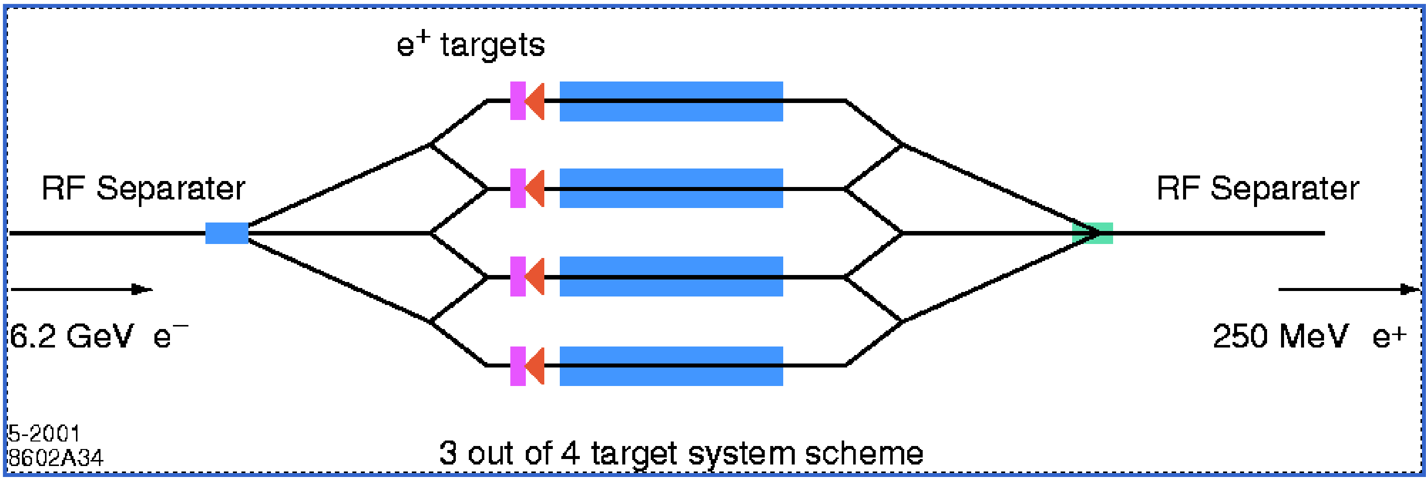
If one neutrino horn is good, 4 horns are better!

Use rotating dipoles to direct beam pulses into four beamlines, each with its own horn.



Undulator Based Production of Polarized Positrons

Would need multiple “conventional” positron production targets at a linear collider.

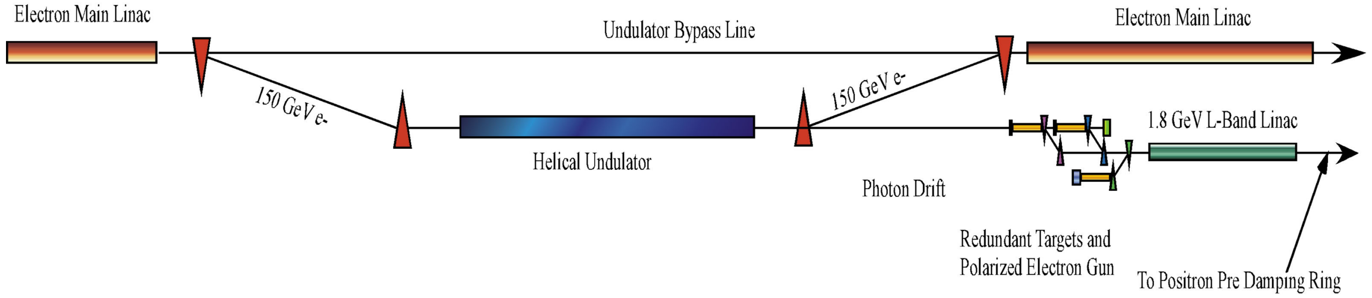


3 out of 4 target system scheme

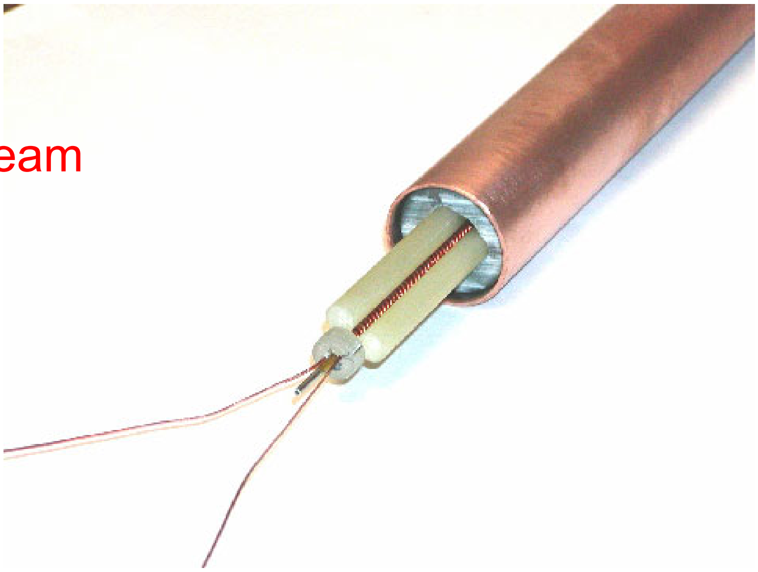
Mikhailichenko: Electron beam + helical undulator

=> Circularly polarized photons of ~ 10 MeV.

=> Longitudinally polarized positrons out of thin target.



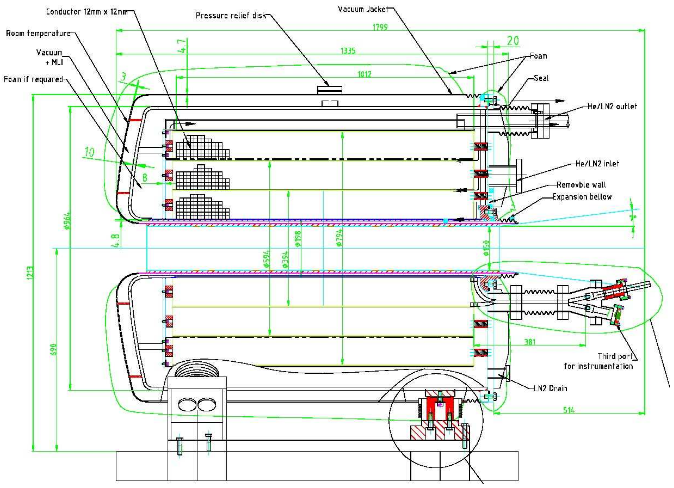
Demonstration proposed at SLAC (E-166) using the 50-GeV Final Focus Test Beam + 1-m-long, 1-mm-diameter pulsed helical undulator.

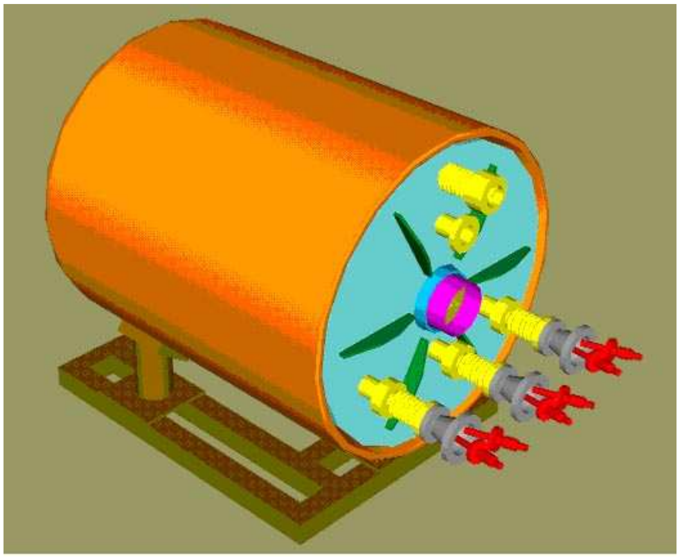


Issues for Further Targetry R&D

- 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 (bands, chains, *etc.*).
- Confirm manageable mercury-jet dispersal in beams up to full Study-2 intensity – 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.)

Beam + Jet + Magnet at the AGS or J-PARC