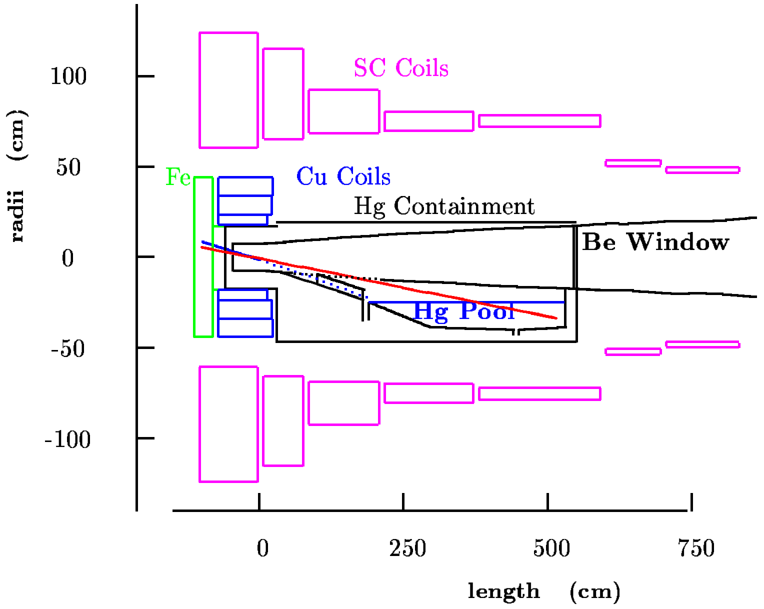
Targets for Neutrino Factories and Muon Colliders



K.T. McDonald

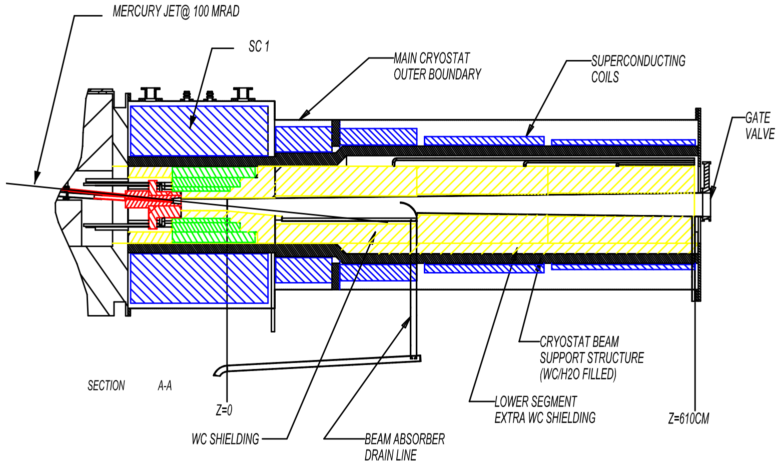
Princeton U.

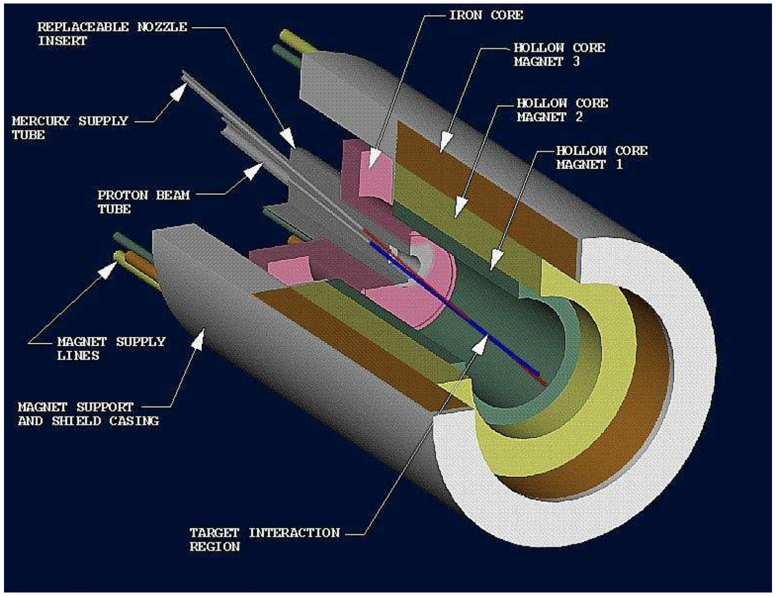
Workshop on High-Power Targets for Future Accelerators

Ronkonkoma, NY, September 10, 2003

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

Sketches of a 4-MW Target Station





The BNL E951 Collaboration

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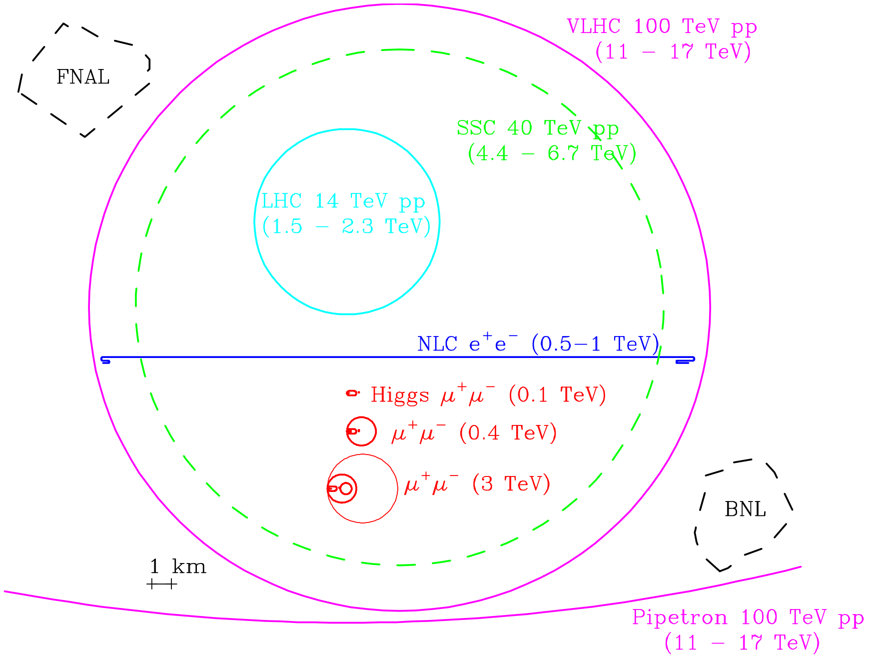
What is a Muon Collider?

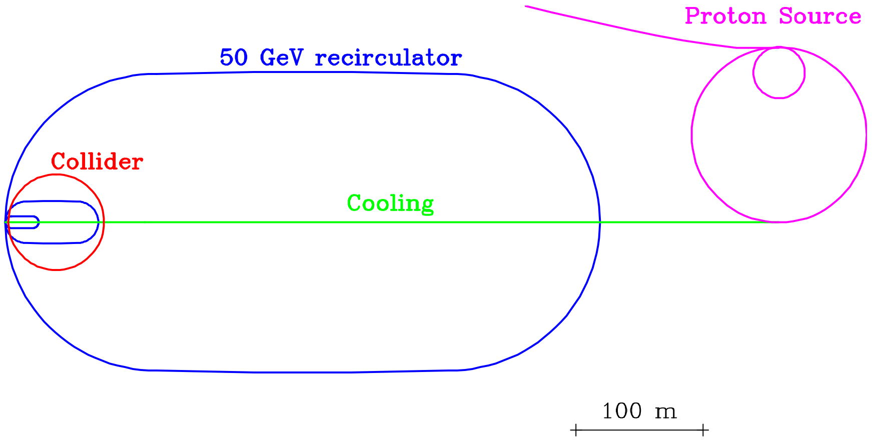
An accelerator complex in which

- The initial state is even more precise than e^+e^- (because muons radiate less than electrons).
- Muons (both μ^+ and μ^-) are collected from pion decay following a pN interaction.
- Muon phase volume is reduced by 10^6 by ionization cooling.
- The cooled muons are accelerated and then stored in a ring.
- $\mu^+\mu^-$ collisions are observed over the useful muon life of $\approx$ 1000 turns at any energy.
- Intense neutrino beams and spallation neutron beams are available as byproducts.

TeV Colliders:



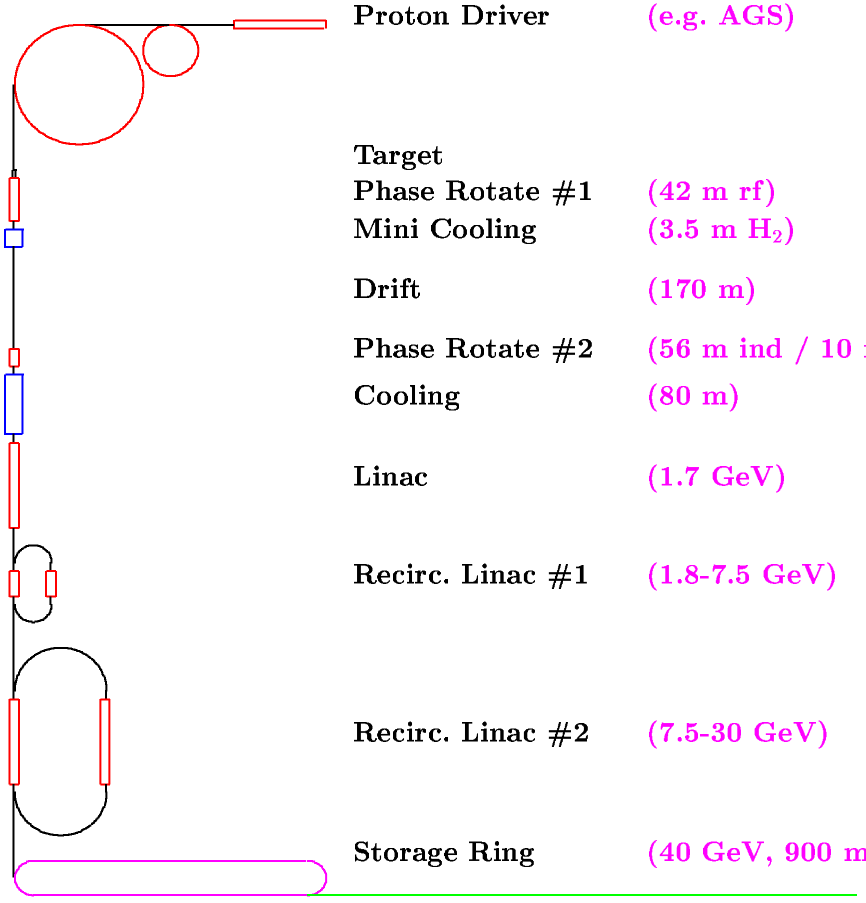
A light-Higgs factory:



A Neutrino Factory Based on a Muon Storage Ring

- Many elements in common with the front end of a muon collider.
- Maximize $\pi/\mu/\nu$ yield by collecting low-energy ($\approx$ 400 MeV) charged secondaries.
- Let pions decay to muons, then accelerate the muons and store them in a ring to obtain decay neutrinos of desired energy.
- Accelerator components more effective if only a few Hz of intense beam pulses.
- Study neutrino mixing, including CP violation via CP-conjugate initial states:

$$\mu^+ \to e^+ \overline{\nu}_\mu \nu_e, \qquad \mu^- \to e^- \nu_\mu \overline{\nu}_e.$$



Proton Driver	**(e.g. AGS)**
Target	
Phase Rotate #1	**(42 m rf)**
Mini Cooling	**(3.5 m H_2)**
Drift	**(170 m)**
Phase Rotate #2	**(56 m ind / 10 m rf)**
Cooling	**(80 m)**
Linac	**(1.7 GeV)**
Recirc. Linac #1	**(1.8-7.5 GeV)**
Recirc. Linac #2	**(7.5-30 GeV)**
Storage Ring	**(40 GeV, 900 m circ)**

Neutrino Beam

Targetry for Muon Colliders and Neutrino Factories

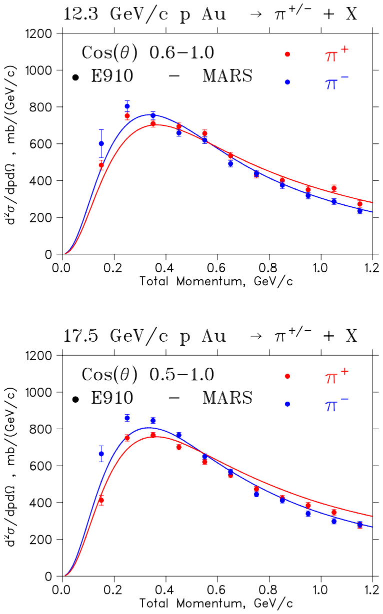
- **Targetry** = the task of producing and capturing π's and μ's from proton interactions with a nuclear target.
- At a **lepton collider** the key parameter is **luminosity**:

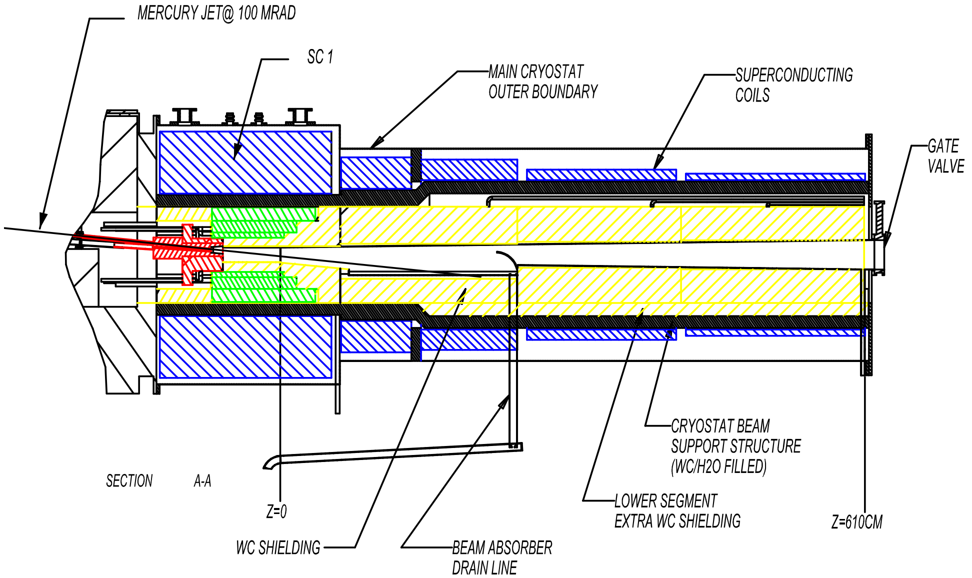
  $$\mathcal{L} = \frac{N_1 N_2 f}{A} \, \mathrm{s}^{-1}\mathrm{cm}^{-2},$$

  ⇒ 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**.

Targetry Challenges for Intense Muon and Neutrino Beams

- Use of a multimegawatt proton beam for maximal production of soft pions → muons.
- Capture pions in a 15-20-T solenoid, followed by a 1.25-T decay channel (with beam and target tilted by 100 mrad w.r.t. magnetic axis).

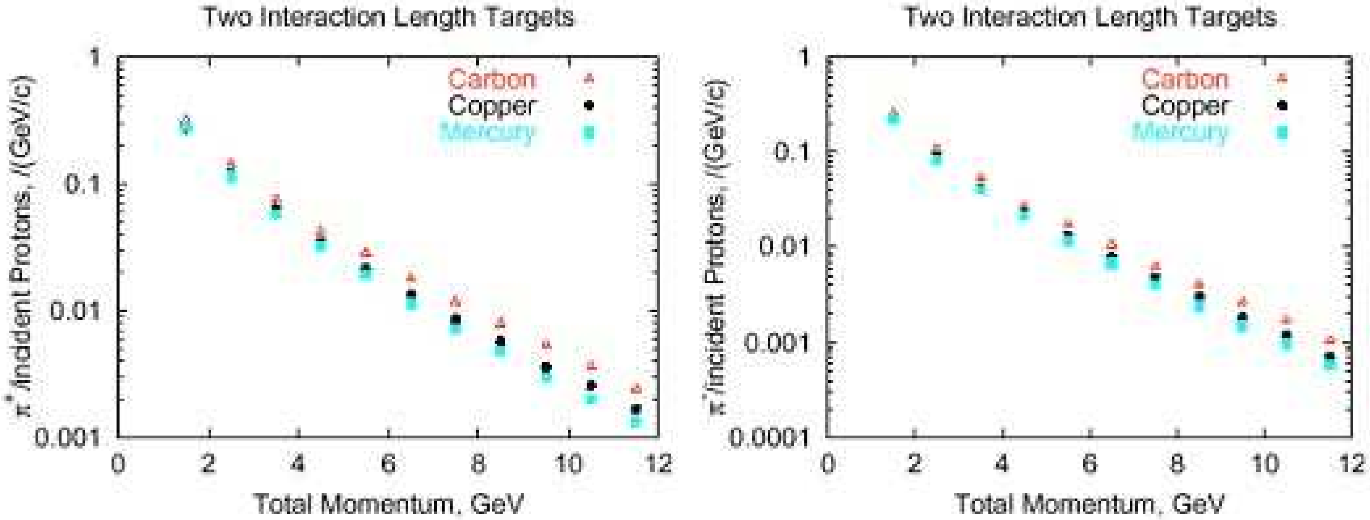




- A carbon target is feasible for 1.5-MW proton beam power.
- For $E_p \gtrsim 16$ GeV, factor of 2 advantage with high-Z target.
- Static high-Z target would melt, ⇒ **Moving target**.
- A free mercury jet target is feasible for beam power of 4 MW (and more).

A "Conventional" Neutrino Horn + Target

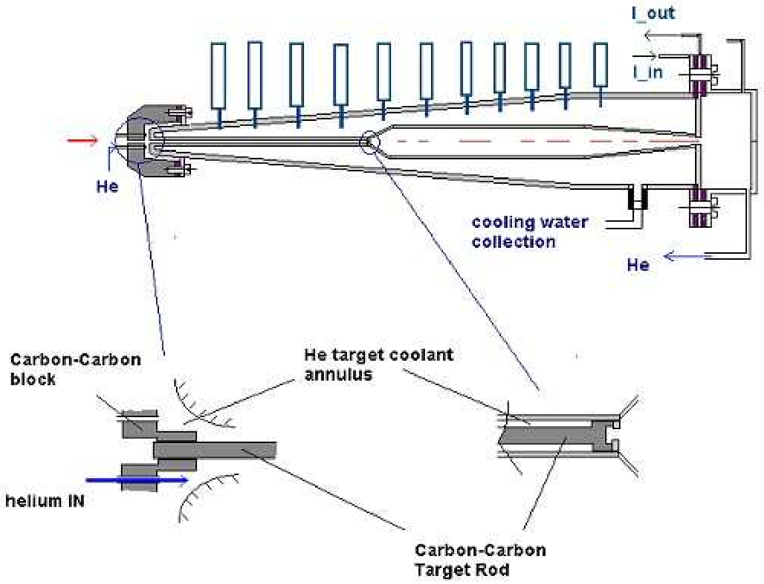
If desire secondary pions with $E_\pi \lesssim 0.5$ GeV (neutrino factories), a high-Z target is favored, but for $E_\pi \gtrsim 1$ Gev ("conventional" neutrino beams), low Z is preferred.



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

Small horn ID is desirable ⇒ challenge to provide target cooling for high beam intensity.

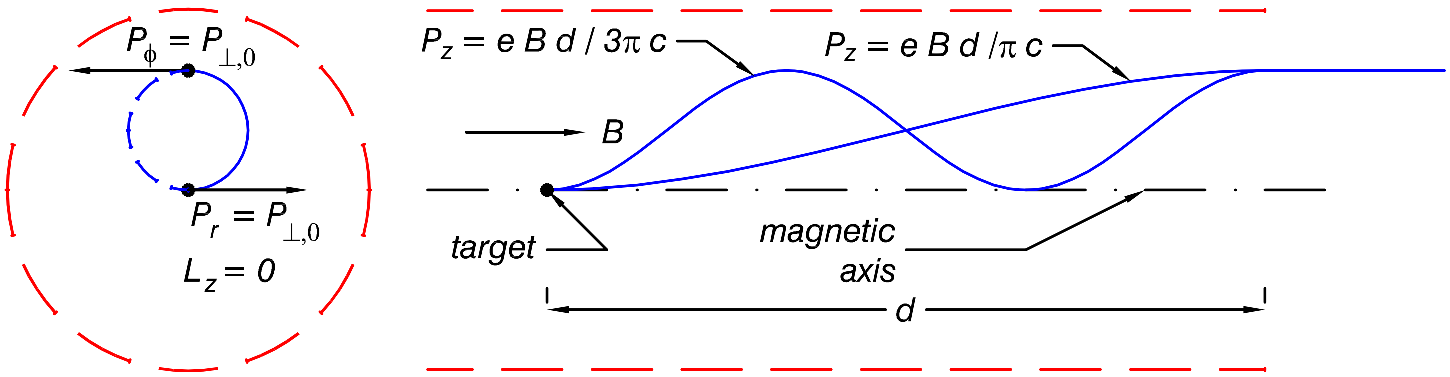
Aggressive design: carbon-carbon target with He gas cooling:



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 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_ϕ, $\Rightarrow P_\perp = 0$ on exiting the solenoid,
  $\Rightarrow$ **Point-to-parallel focusing**.

Narrowband Neutrino Beams via Solenoid Focusing



- The point-to-parallel focusing occurs for $P_\pi = eBd/(2n+1)\pi c$.
- $\Rightarrow$ Narrowband neutrino beams of energies

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

- $\Rightarrow$ Can study several neutrino oscillation peaks at once (Marciano, hep-ph/0108181),

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

- 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 (astro-ph/0105442).

Thermal Shock is a Major Issue in High-Power Pulsed Beams

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.

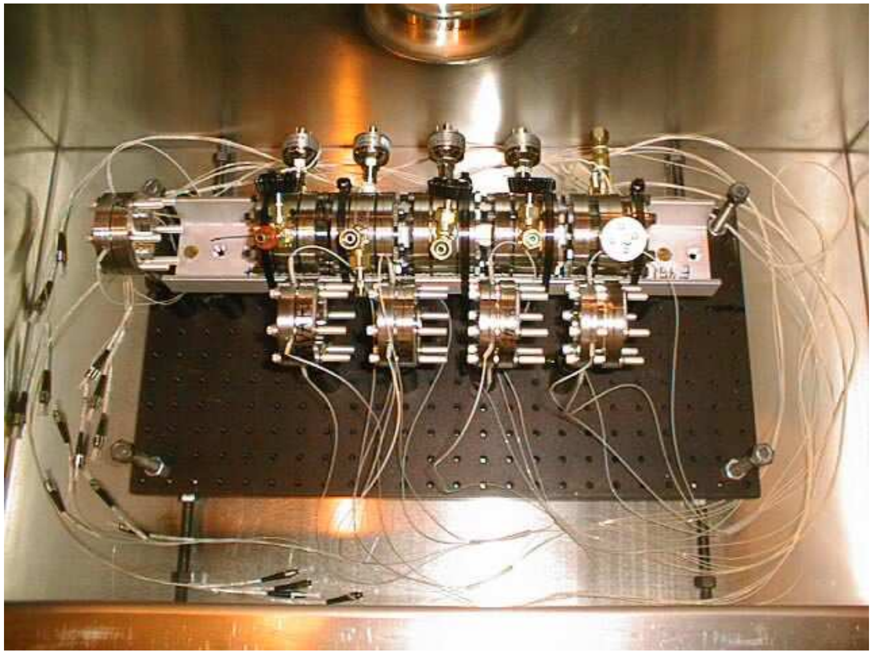
Ans. If we ignore "showers" in the material, we still have dE/dx ionization loss, of about 1.5 MeV/g/cm^2.
Now, 1 MeV $= 1.6 \times 10^{-13}$ J, so 60 J/ g requires a proton beam intensity of $60/(1.6 \times 10^{-13}) = 10^{15}/\text{cm}^2$.
Then, $P_{\max} \approx 10 \text{ Hz} \cdot 10^{10} \text{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

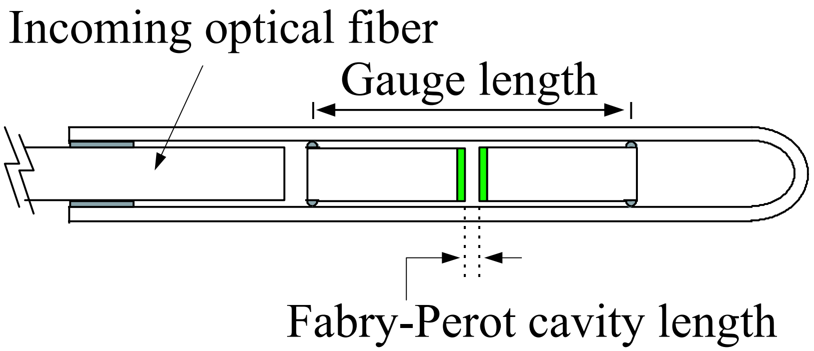
Solid targets are viable up to about 1.5 MW beam power!

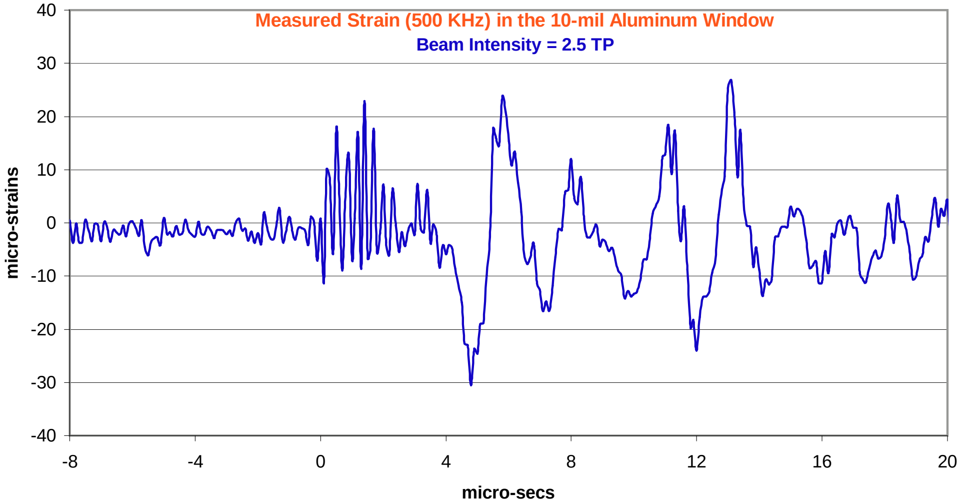
Window Tests (BNL E-951, 5e12 $p$pp, 24 GeV, 100 ns)

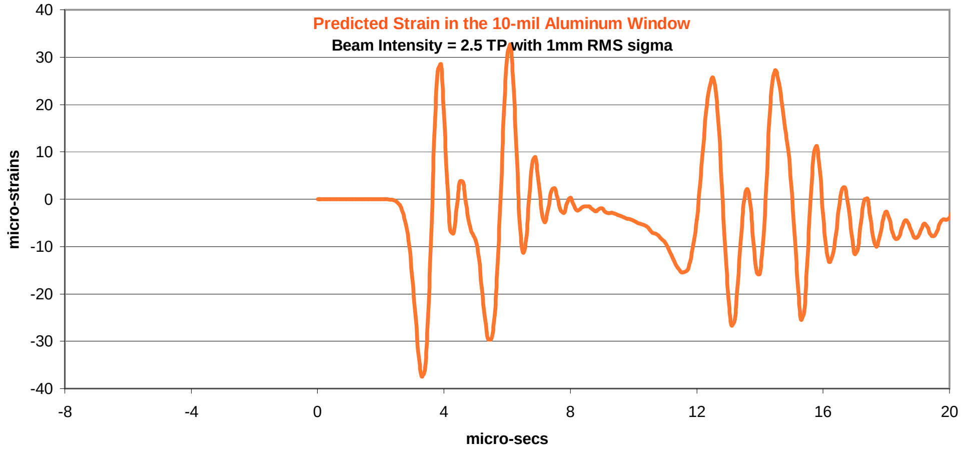
Aluminum, Ti90Al6V4, Inconel 708, Havar, instrumented with fiberoptic strain sensors.

[Thanks to our ORNL colleagues.]



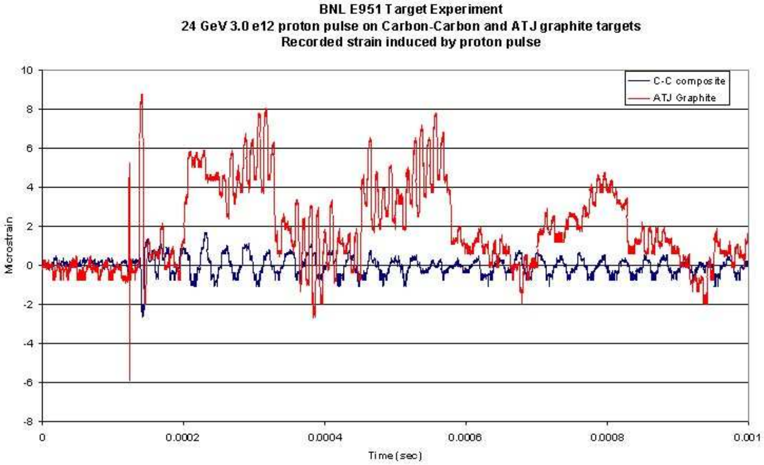






A Carbon Target is Feasible at 1-MW Beam Power

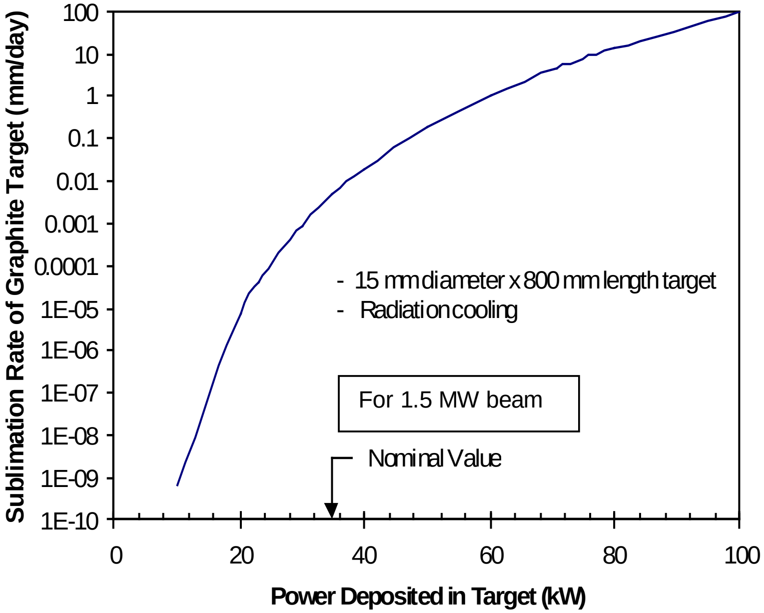
A **carbon-carbon composite** with near-zero thermal expansion is largely immune to beam-induced pressure waves.



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

Sublimation of carbon may be negligible in a helium atmosphere.

Tests underway at ORNL to confirm this.

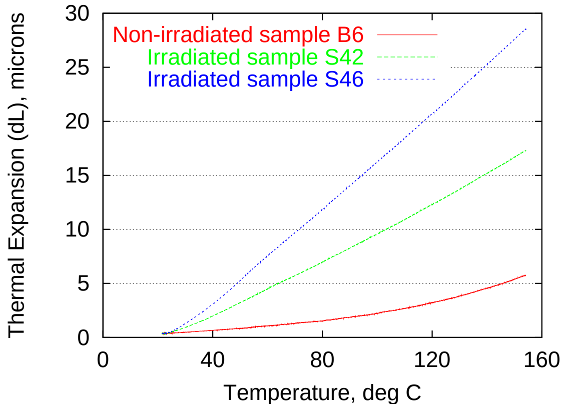


Radiation damage is limiting factor: ≈ 12 weeks at 1 MW.

Will radiation damage ruin the low thermal expansion coefficient?

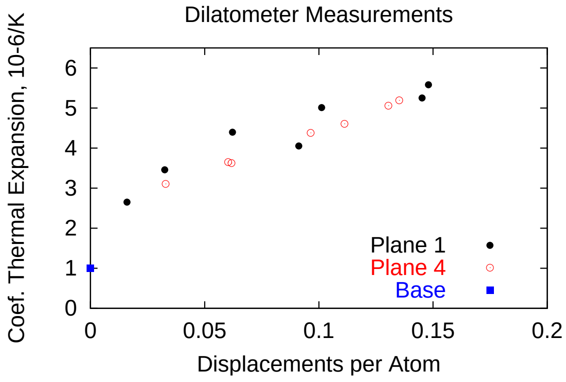
Effects of Radiation on SuperInvar

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



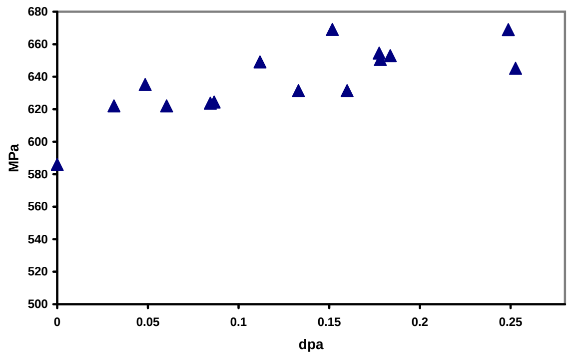
However, irradiation at the BNL BLIP facility show that the CTA increases rapidly with radiation dose.

CTA *vs.* dose ⇒



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

Yield strength *vs.* dose ⇒



High-Performance Titanium Alloy Developed by Toyota

T. Saito *et al.*, Science **300**, 464 (2003)

"We describe a group of alloys that exhibit super properties, such as ultralow elastic modulus, ultrahigh strength, super elasticity, and super plasticity, at room temperature and that show Elinvar and Invar behavior. These super properties are attributable to a dislocation-free plastic deformation mechanism. In cold-worked alloys, this mechanism forms elastic strain fields of hierarchical structure that range in size from the nanometer scale to several tens of micrometers. The resultant elastic strain energy leads to a number of enhanced material properties."

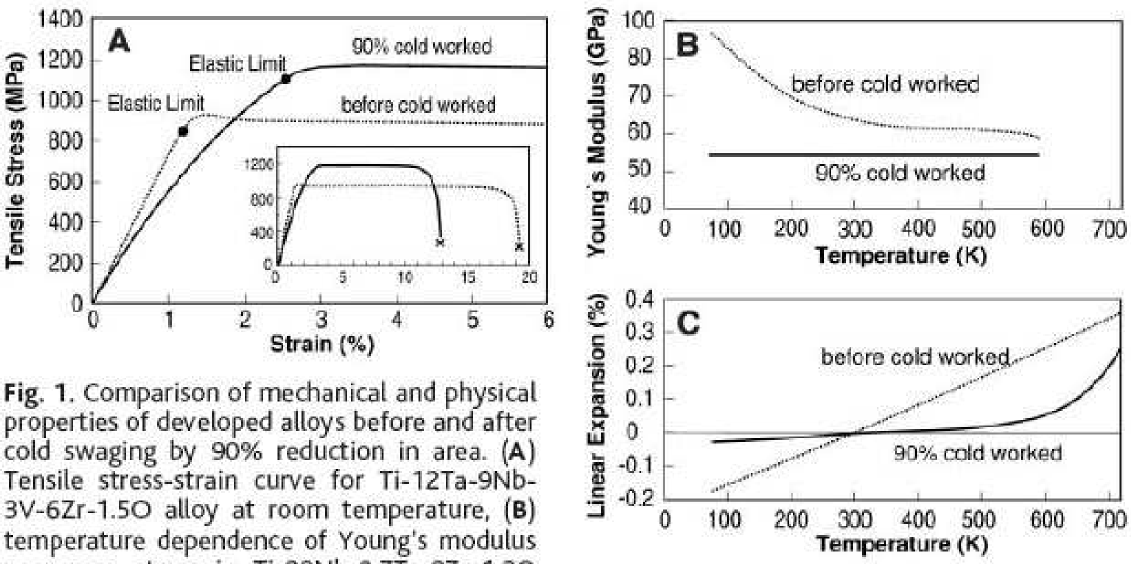


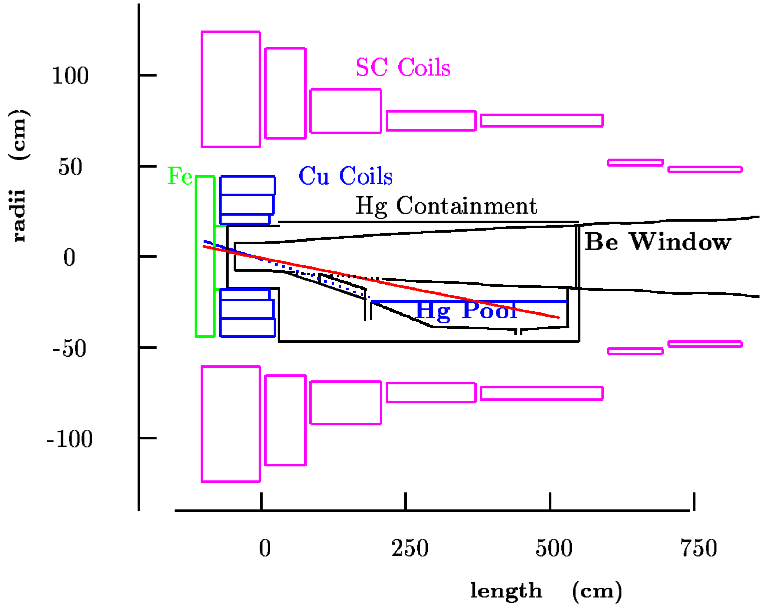
Fig. 1. Comparison of mechanical and physical properties of developed alloys before and after cold swaging by 90% reduction in area. (**A**) Tensile stress-strain curve for Ti-12Ta-9Nb-3V-6Zr-1.5O alloy at room temperature, (**B**) temperature dependence of Young's modulus near zero stress in Ti-23Nb-0.7Ta-2Zr-1.2O alloy, and (**C**) temperature dependence of linear expansion in Ti-23Nb-0.7Ta-2Zr-1.2O alloy.

Cold working of this Ti alloy [Ti-23Nb-0.7Ta-2Zr-1.2O] is favorable 3 ways:

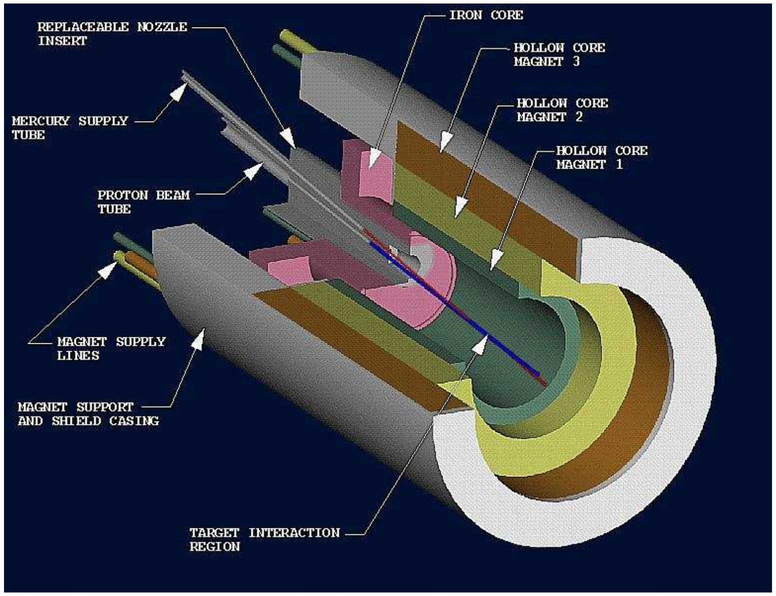
higher tensile strength, lower Young's modulus, and lower thermal expansion coefficient.

Are these advantages robust against radiation damage? Will test at BLIP in FY04.

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



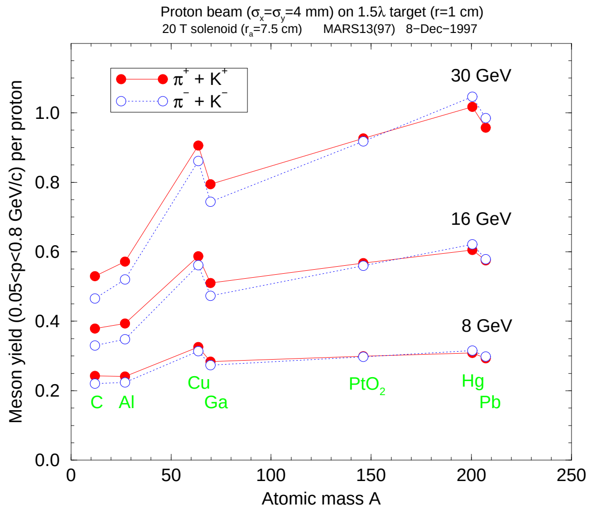
Mercury jet target inside a magnetic bottle: 20-T around target, dropping to 1.25 T in the pion decay channel.



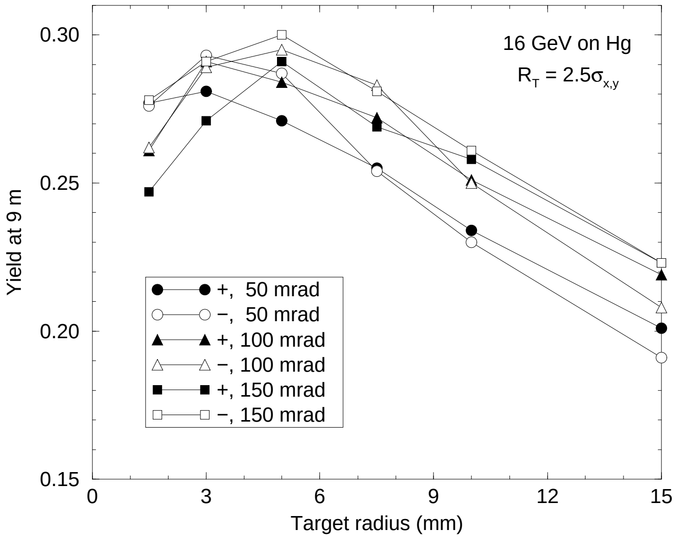
Mercury jet tilted by 100 mrad, proton beam by 67 mrad, to increase yield of soft pions.

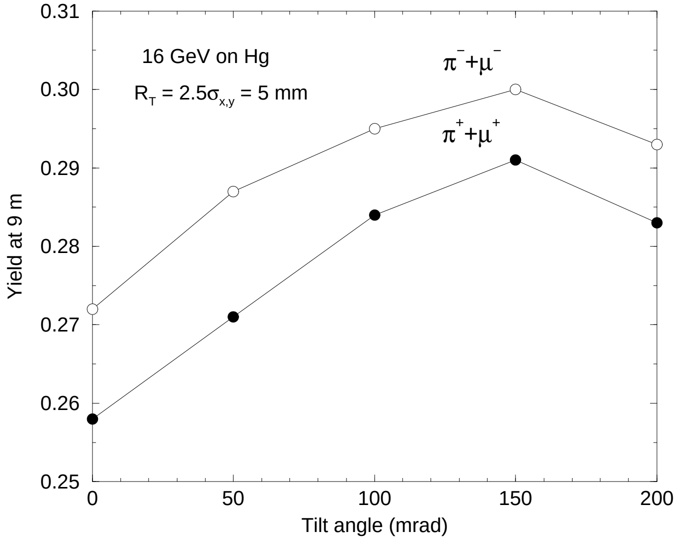
Pion/Muon Yield

For $E_p \gtrsim 10$ GeV,
more yield
with high-Z target.
[MARS calculations:]



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

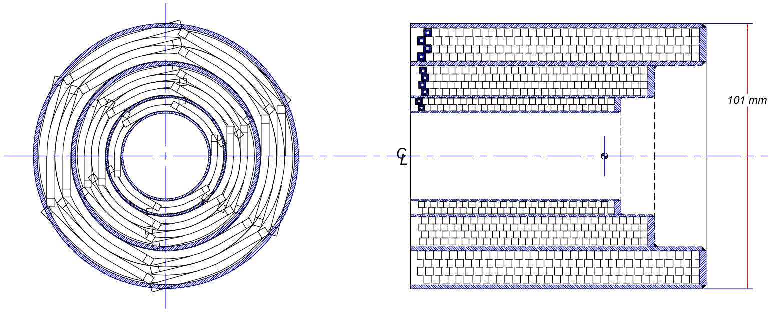




Can capture ≈ 0.3 pion per proton with $50 < P_\pi < 400$ MeV/c.

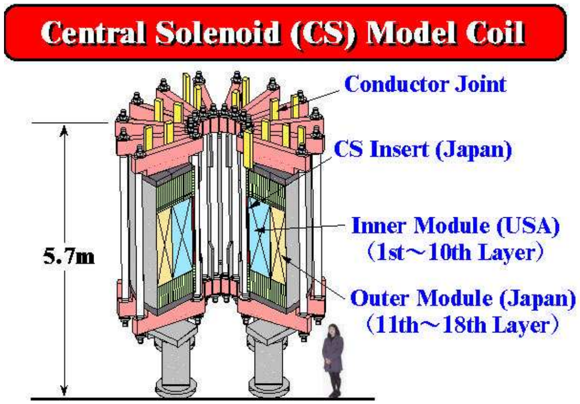
20-T Capture Magnet System

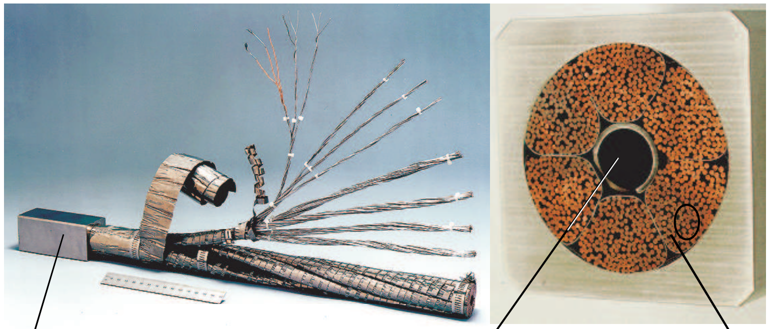
Inner, hollow-conductor copper coils generate 6 T @ 12 MW:



Bitter-coil option less costly, but marginally feasible.

Outer, superconducting coils generate 14 T @ 600 MJ:



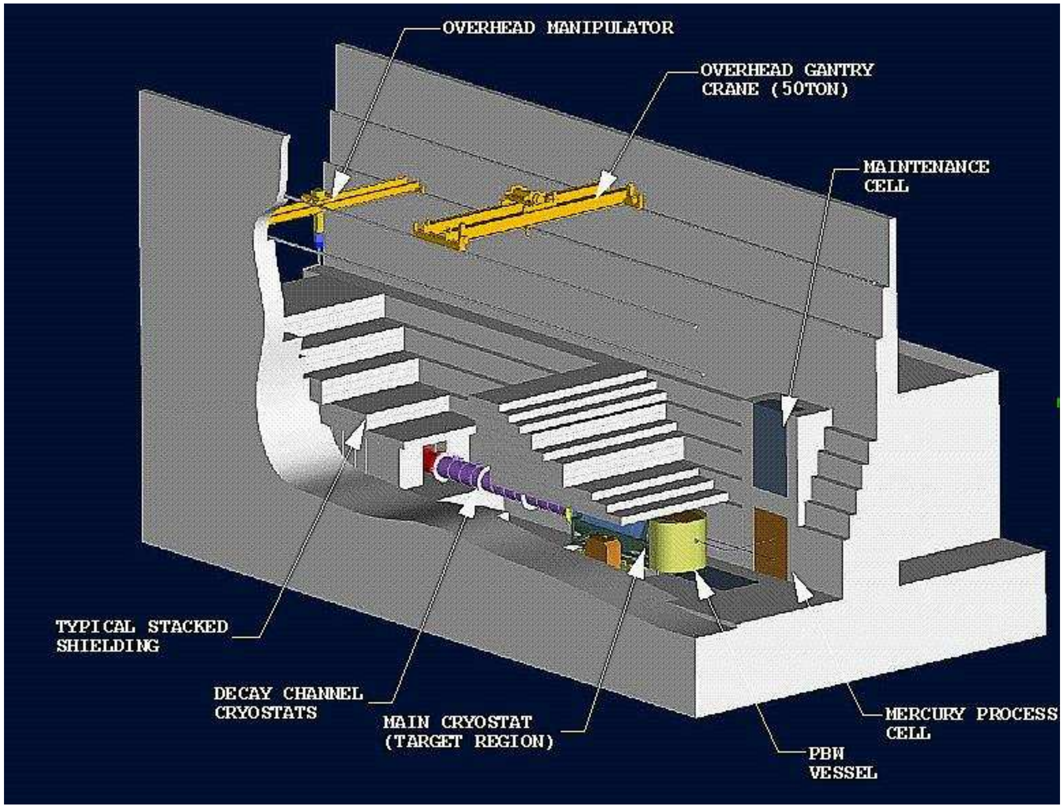


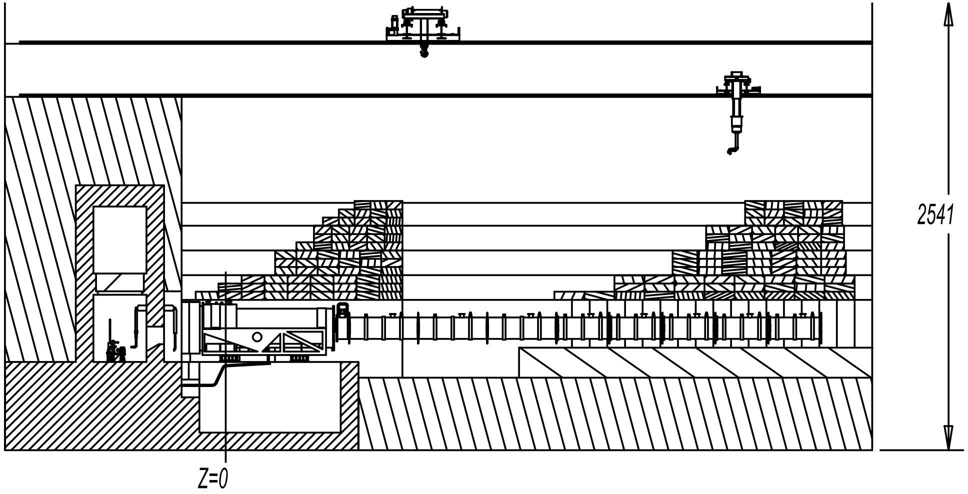
Cable-in-conduit construction similar to ITER central solenoid.

Both coils shielded by tungsten-carbide/water.

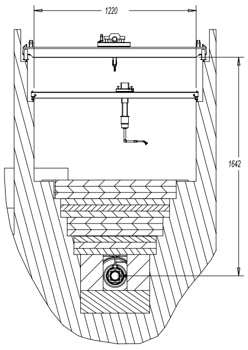
Target System Support Facility

Extensive shielding and remote handling capability. [Spampinato *et al.*, *Neutrino Factory Feasibility Study 2* (2001)]





SECTION C-C



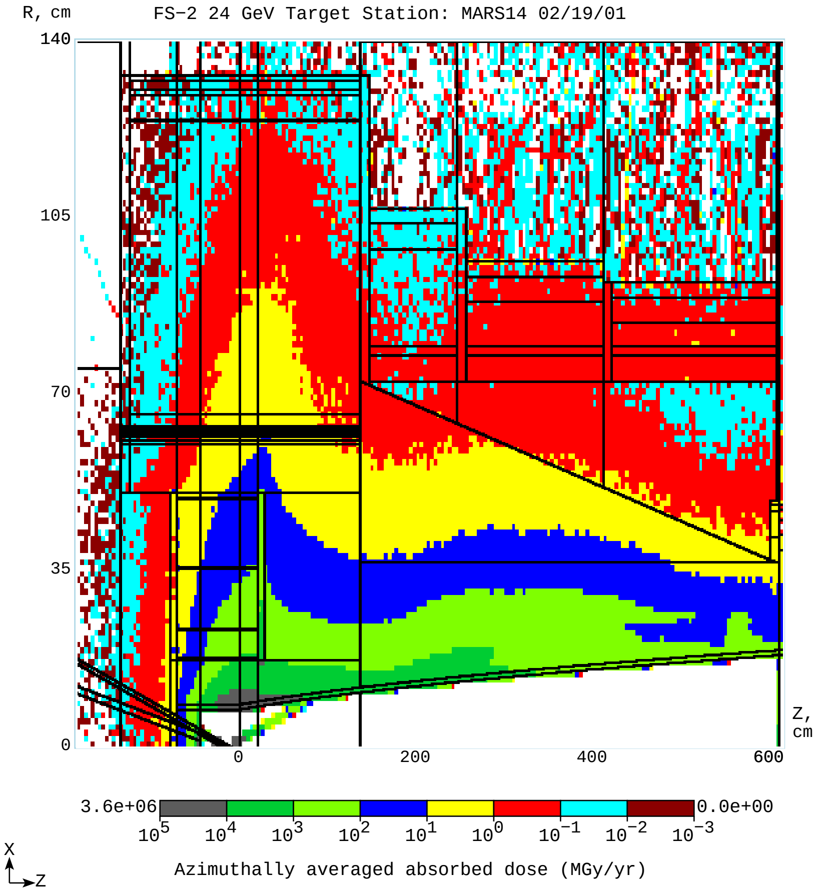
SECTION B-B
DECAY CHANNEL SHIELDING

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

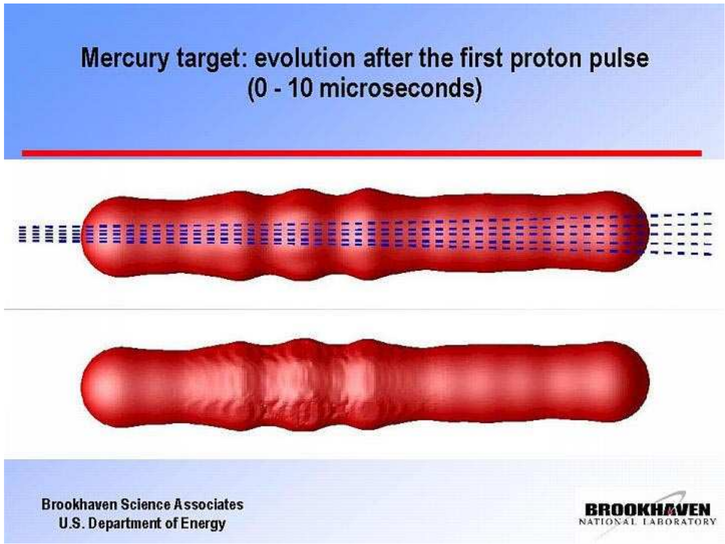
Some components must be replaceable.

[MARS calculations:]

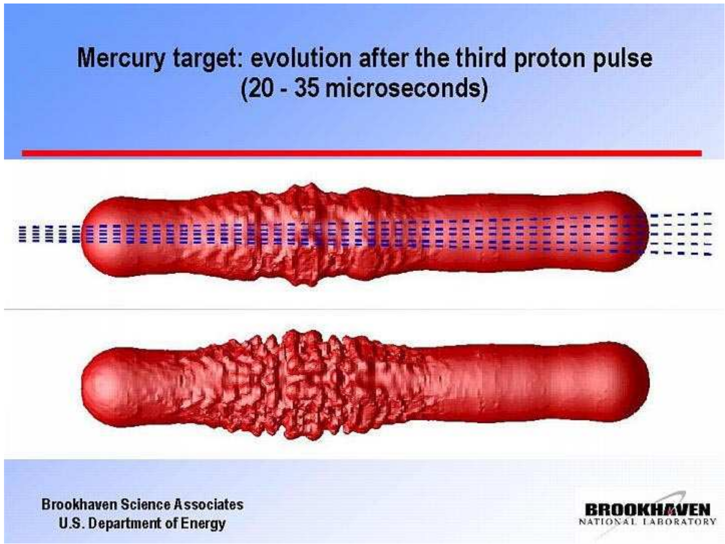


Viability of Targetry and Capture For a Single Pulse

- Beam energy deposition may disperse the jet. [FRONTIER calculations]

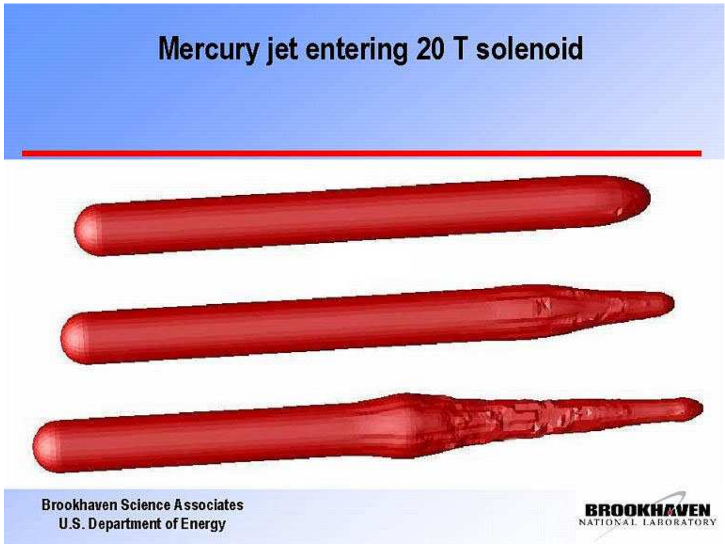

Mercury target: evolution after the first proton pulse
(0 - 10 microseconds)

Brookhaven Science Associates
U.S. Department of Energy

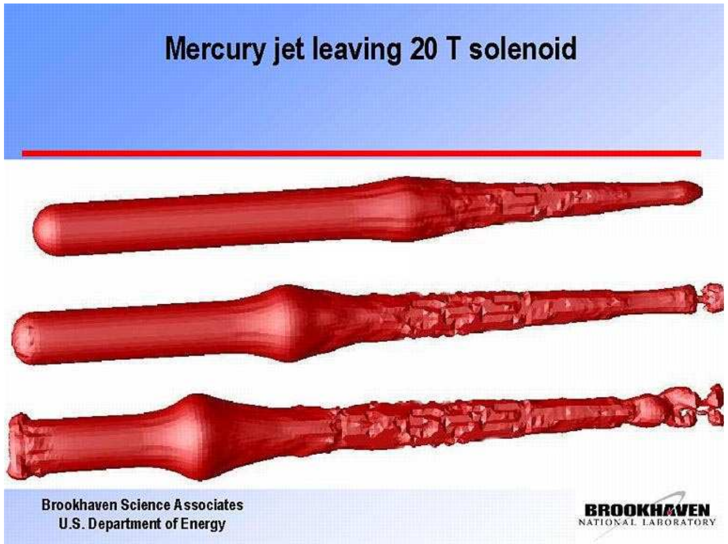

Mercury target: evolution after the third proton pulse
(20 - 35 microseconds)

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

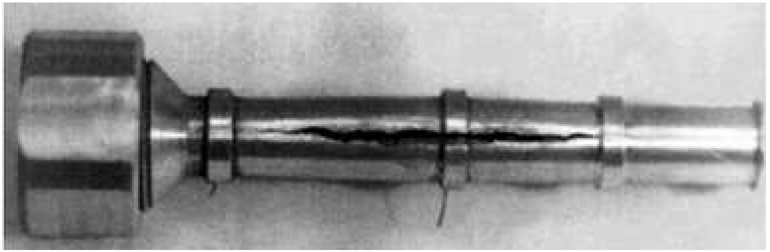
Brookhaven Science Associates
U.S. Department of Energy

Beam-Induced Cavitation in Liquids Can Break Pipes

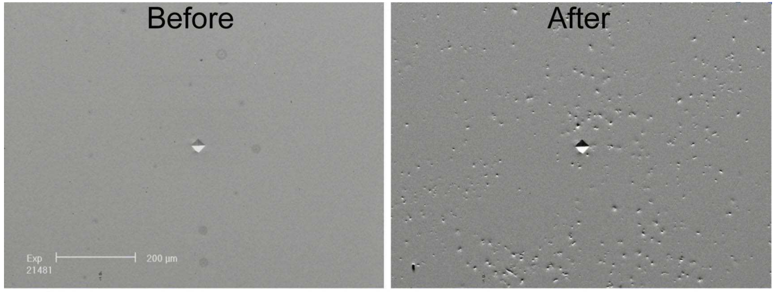
Snapping shrimp stun prey via cavitation bubbles.

ISOLDE:

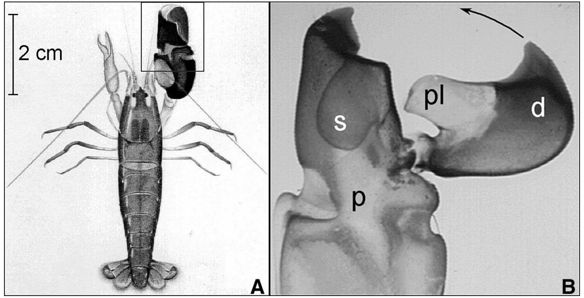
BINP:

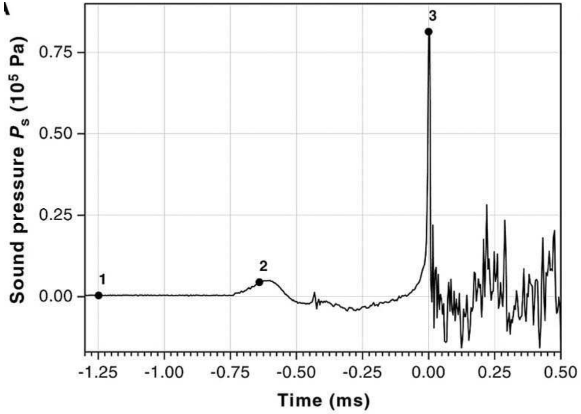


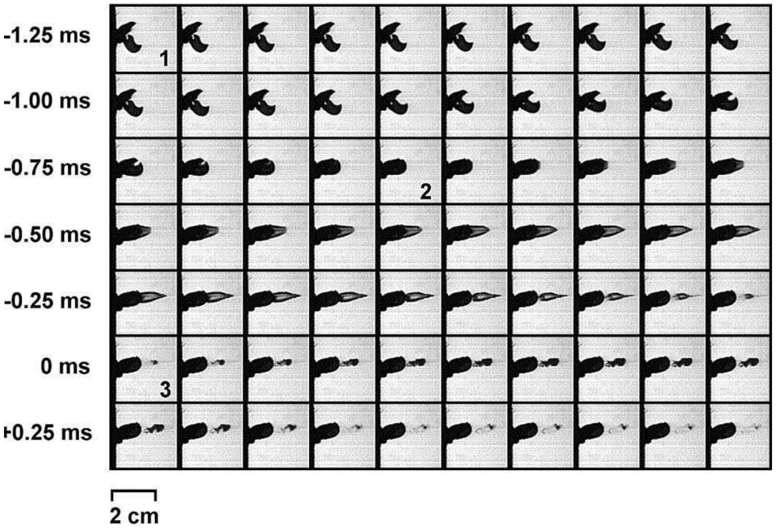
SNS:



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

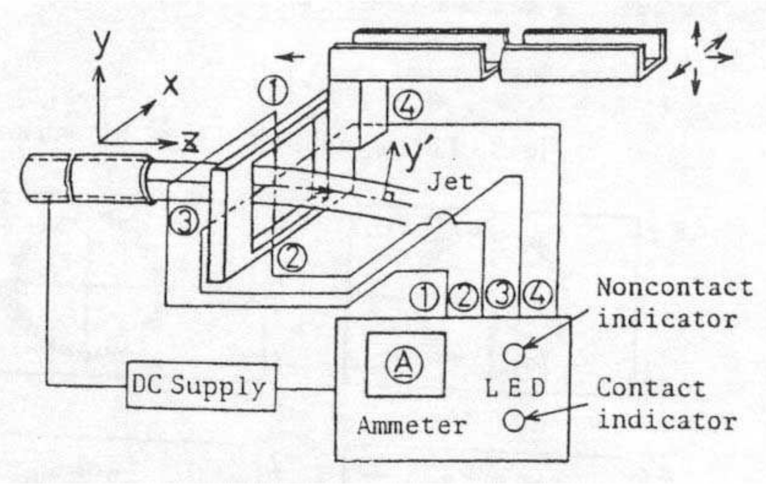


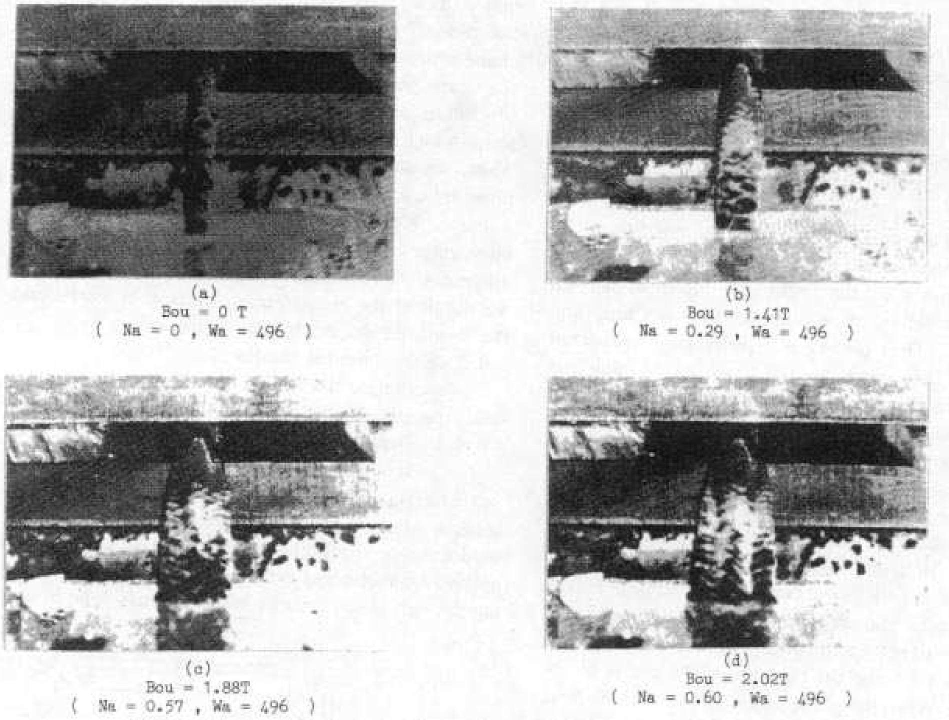




The Shape of a Liquid Metal Jet under a Non-uniform Magnetic Field

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



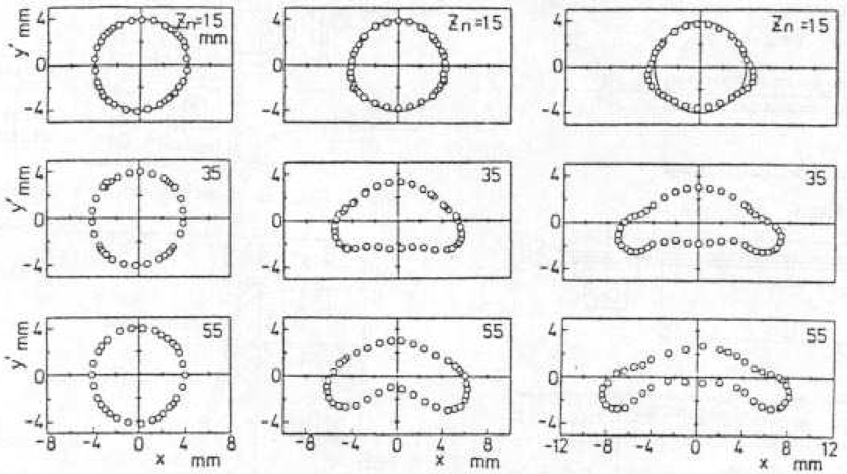

(a) Bou = 0 T (Na = 0 , Wa = 496)

(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 magnetic field strengths



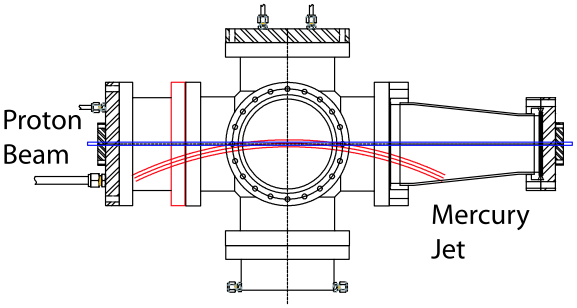
(a) Bou = 0 T (Na = 0 , Wa = 496)

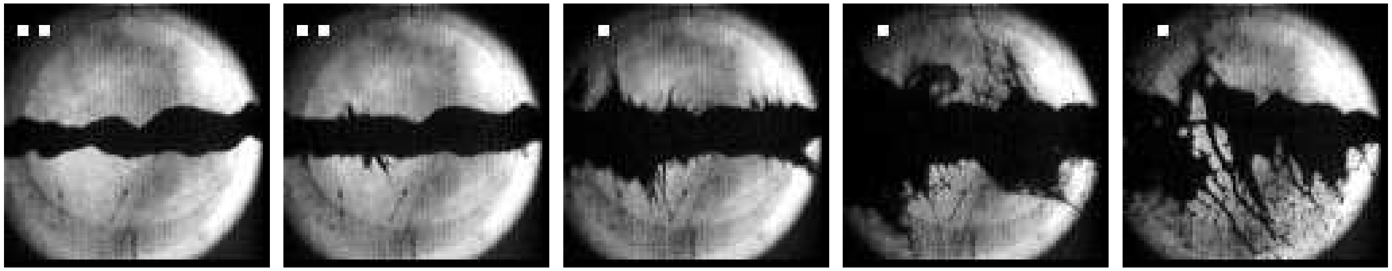
(b) Bou = 1.41 T (Na = 0.29 , Wa = 496)

(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.

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)

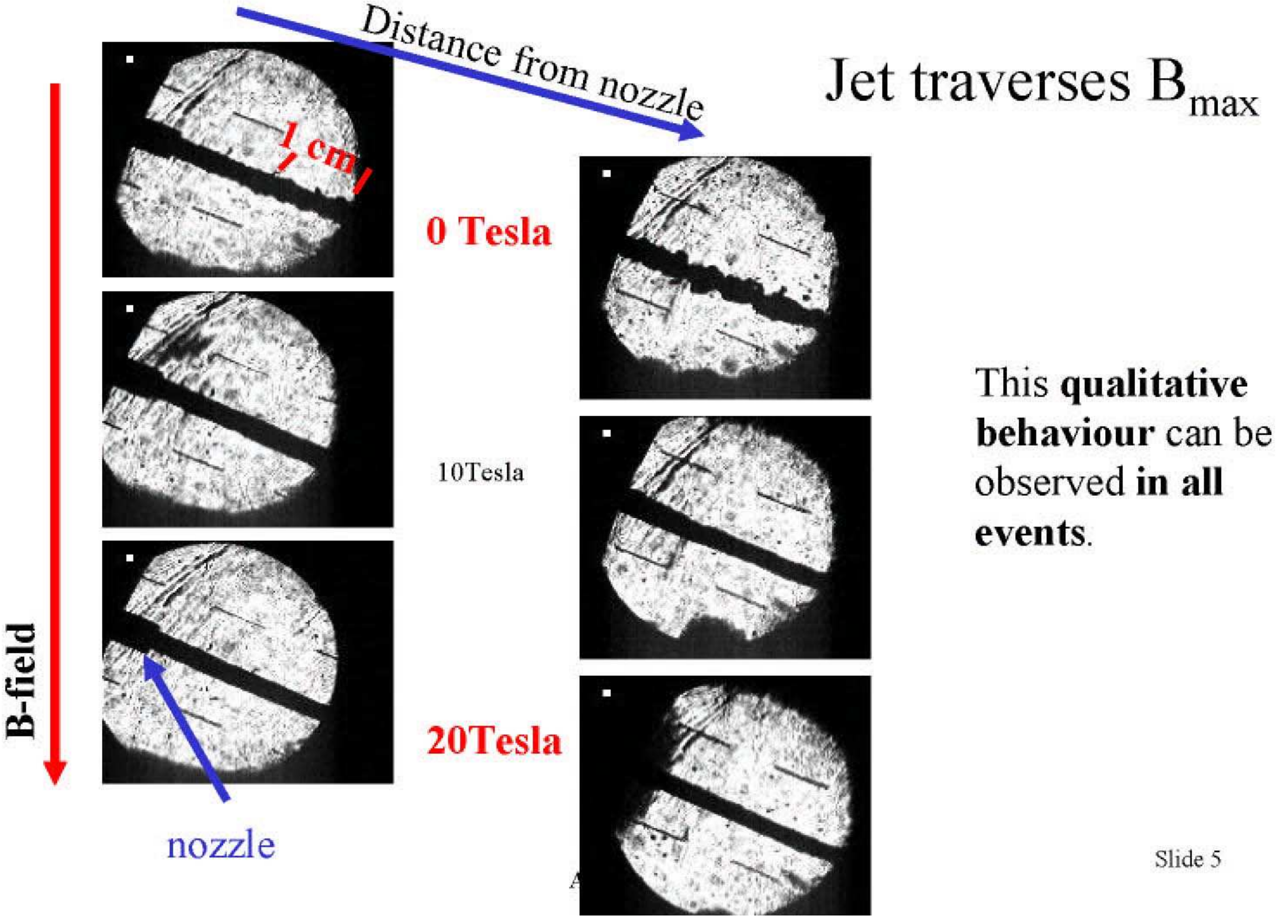
Eddy currents may distort the jet as it traverses the magnet.

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?

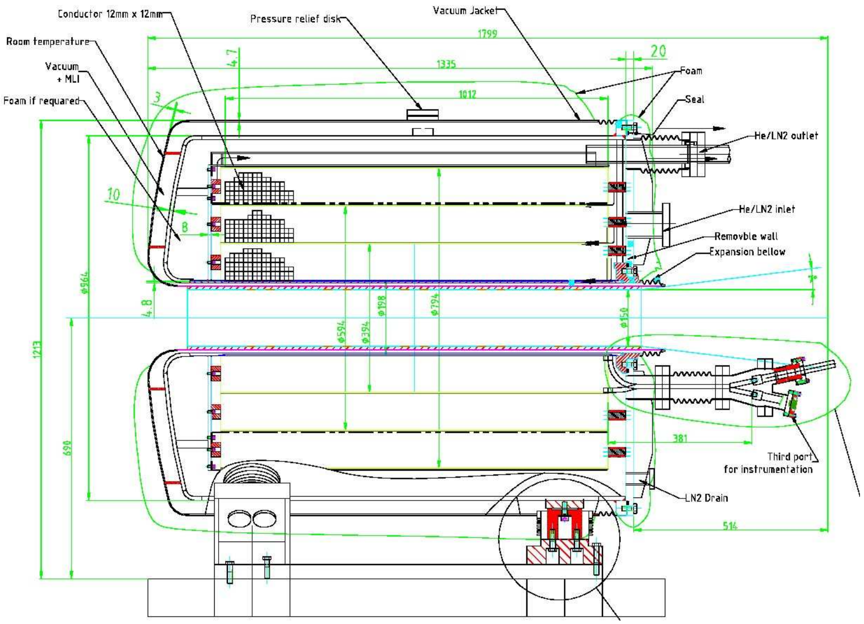


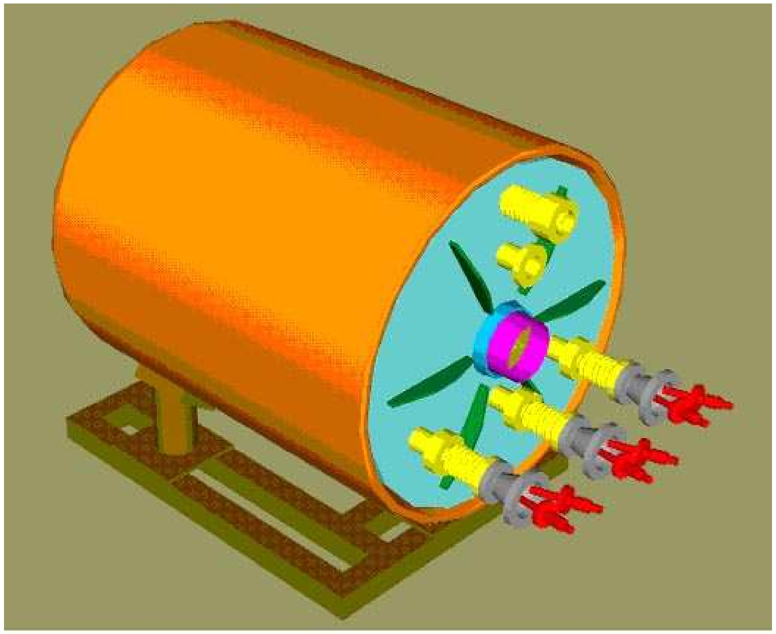
This **qualitative behaviour** can be observed **in all events**.

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)

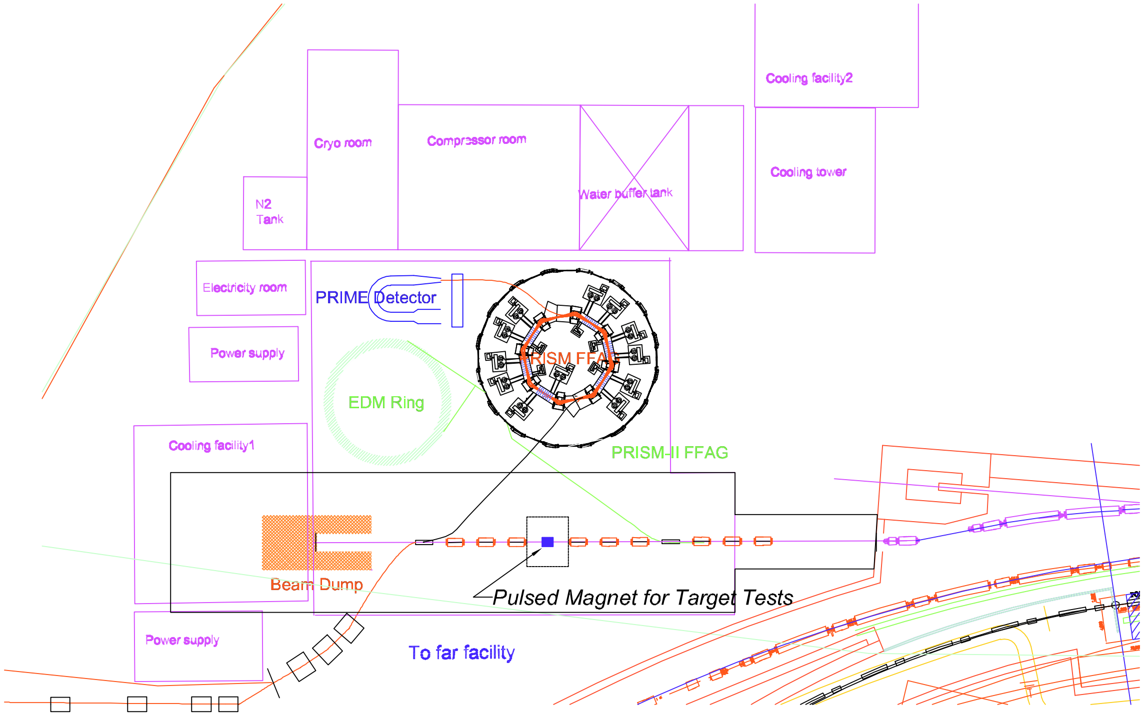
- Cryogenic system reduces coil resistance to give high field at relatively low current.
  - Circulating coolant is gaseous He to minimize activation, and to avoid need to purge coolant before pulsing magnet.
  - Cooling via N_2 boiloff.

- Most cost effective to build the 4.5-MW supply out of “car” batteries! (We need at most 1,000 pulses of the magnet.)

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)



CERN PS transfer line: