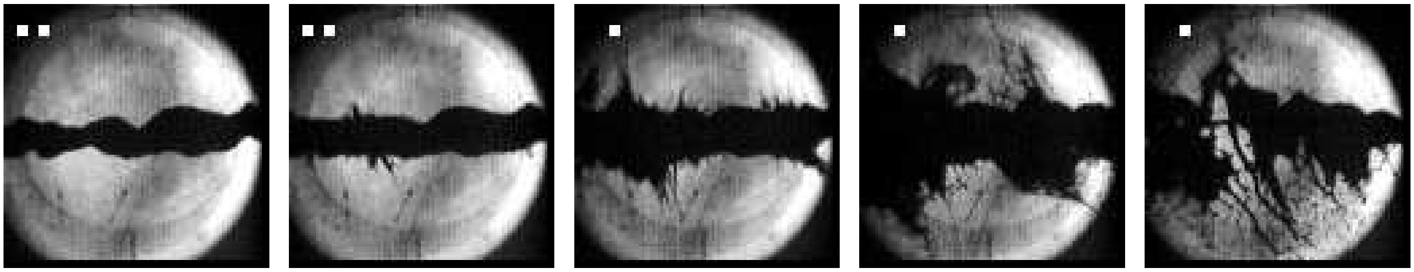
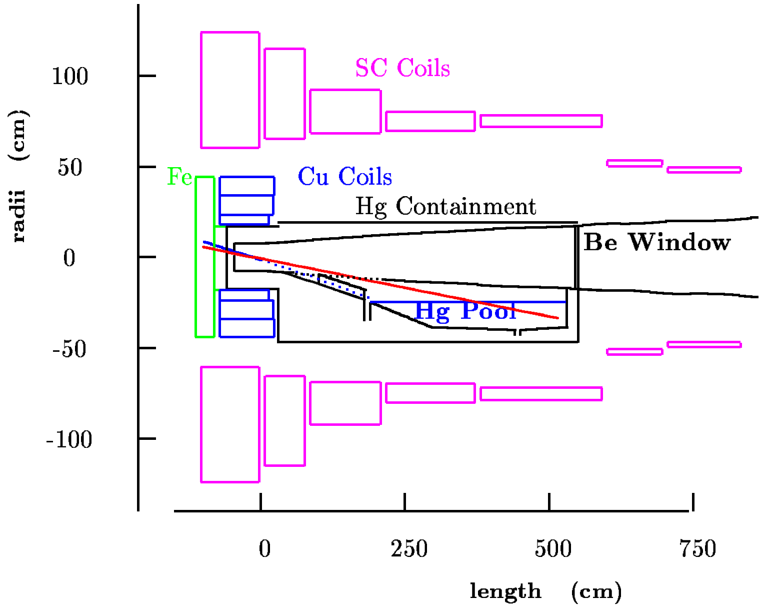
Muon Collaboration

THE NEUTRINO FACTORY AND MUON COLLIDER COLLABORATION

A Short Course on Targetry for a Neutrino Factory and Muon Collider





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NuFact03 Summer Institute

Shelter Island, June 4, 2003

Targetry Web Page:

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

Various Physics Examples:

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

A Short Course on Targetry

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, ≈ 1 kW/m^2.]

A metaphysics question: Why do people enjoy getting sunburned?

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**:

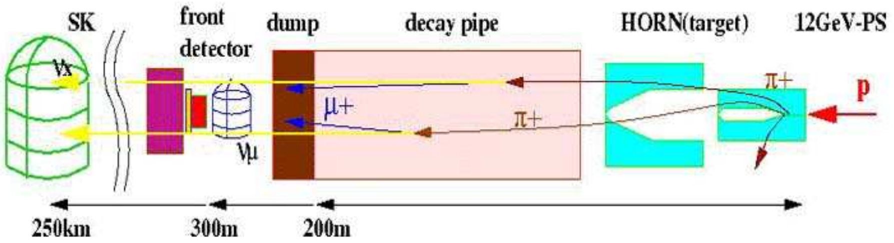
$$\mathcal{L} = \frac{N_1 N_2 f}{A}\,\mathrm{s}^{-1}\mathrm{cm}^{-2},$$

  ⇒ 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**.

Exercises

1. Give an expression for the luminosity of beams that collide with a nonzero crossing angle α.

2. A typical high-energy neutrino beam is made from the decay of π mesons that have been produced in proton interactions on a target, as sketched in the figure below.



Suppose that only positively charged particles are collected by the "horn". The main source of neutrinos is then the decay $\pi^+ \to \mu^+ \nu_\mu$.

1. Give a simple estimate of the relative number of other types of neutrinos than ν_μ in the beam.
2. If the decay pions have energy $E_\pi \gg m_\pi$, what is the characteristic angle θ_C of the decay neutrinos with respect to the direction of the π^+?
3. If a neutrino is produced with energy $E_\nu \gg m_\pi$, what is the maximum angle $\theta_{\max}(E_\nu)$ between it and the direction of its parent pion (which can have any energy)? What is the maximum energy E_ν at which a neutrino can be produced in the decay of a pion if it appears at a given angle θ with respect to the pion's direction?

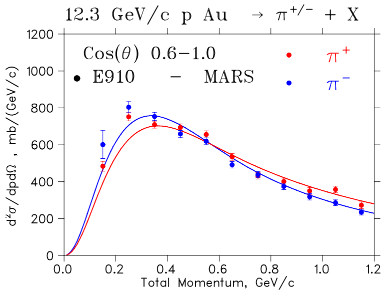
   Parts 4 and 6 explore consequences of the existence of these maxima.
4. Deduce an analytic expression for the energy-angle spectrum $d^2N/dE_\nu d\Omega$ for neutrinos produced at angle $\theta \le \theta_C$ to the proton beam. You may suppose that $E_\nu \gg m_\pi$, that the pions are produced with an energy spectrum $dN/dE_\pi \propto (E_p - E_\pi)^5$, where E_p is the energy of the proton beam, and that the "horn" makes all pion momenta parallel to that of the proton beam.
5. At what energy $E_{\nu,\text{peak}}$ does the neutrino spectrum peak for $\theta = 0$?
6. Compare the characteristics of a neutrino beam at $\theta = 0$ with an off-axis beam at angle θ such that $E_{\nu,\max}(\theta)$ is less than $E_{\nu,\text{peak}}(\theta = 0)$.

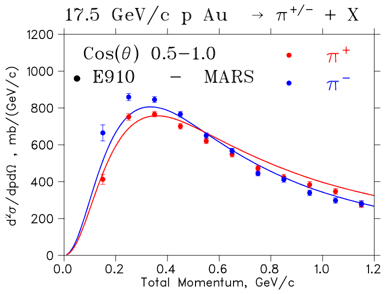
Facts: $m_\pi = 139.6$ MeV/c^2, $\tau_\pi = 26$ ns, $m_\mu = 105.7$ MeV/c^2, $\tau_\mu = 2.2$ μs. In this problem, neutrinos can be taken as massless.

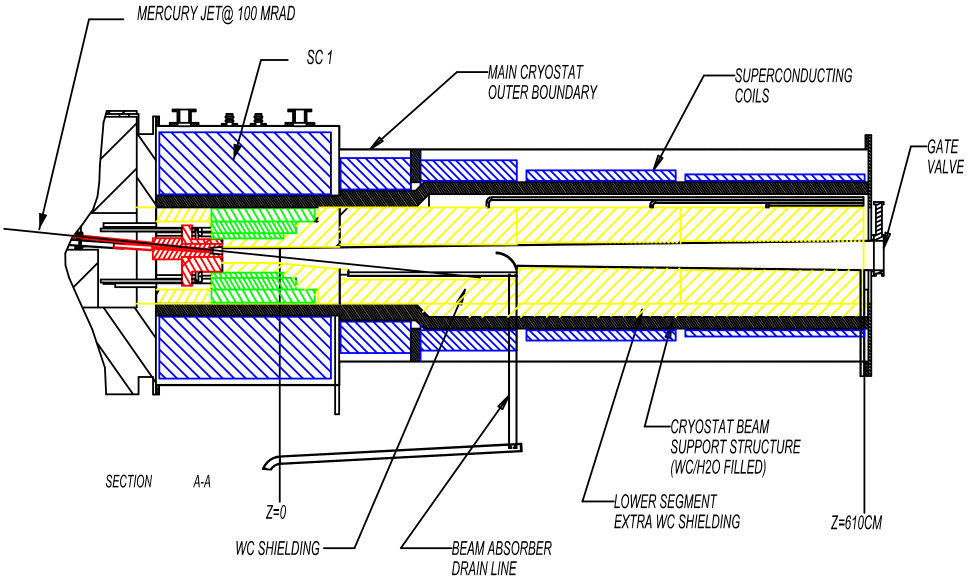
See, http://puhep1.princeton.edu/˜mcdonald/examples/offaxisbeam.pdf

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).

Exercises

3. A charged particle moves in a plane perpendicular to a uniform magnetic field **B**. Show that if **B** changes slowly with time, the magnetic moment produced by the orbital motion of the charge remains constant. Show also that the magnetic flux through the orbit, $\Phi = \pi r^2 B$ is constant. These results are sometimes given the fancy name of **adiabatic invariants** of the motion.

See, prob. 1a of http://puhep1.princeton.edu/˜mcdonald/examples/ph501set5.pdf

4. **The Magnetic Mirror**. Suppose instead, that the magnetic field is slightly non-uniform such that B_z increases with z. Then, if the charged particle has a small velocity in the z direction, it slowly moves into a stronger field. Again, we would expect the flux through the orbit to remain constant, which means that the orbital radius must decrease and the orbital velocity must increase. However, magnetic fields which are constant in *time* cannot change the magnitude of the velocity, therefore v_z must decrease. If B_z increases enough, v_z will go to zero, and the particle is "trapped" by the magnetic field. Write

$$v^2 = v_z^2 + v_\perp^2 = v_0^2 \, , \tag{1}$$

where $v_\perp$ is the orbital velocity and v_0 is constant. Use the result of exercise 3 to show that

$$v_z^2(z) \approx v_0^2 - v_\perp^2(0) \frac{B_z(z)}{B_z(0)} \, . \tag{2}$$

Suppose a particle is created on the axis of a cylindrically symmetric magnetic field $\mathbf{B}_z(z)$ with initial longitudinal momentum P_{z0} and initial transverse momentum $P_{\perp,0}$ at a point where the field strength is B_0. What are the longitudinal and transverse momenta of the particle, and the radius of its helical trajectory, as a function of z as it moves adiabatically through the field.

(Since B_z varies with z, there must also be a radial component B_r to the field, according to $\nabla \cdot \mathbf{B} = 0$. In the adiabatic approximation, one ignores the small radial field component.)

See, prob. 1b of http://puhep1.princeton.edu/˜mcdonald/examples/ph501set5.pdf

Exercise

5. Consider particle with charge e and momentum $\mathbf{P} = \mathbf{P}_z + \mathbf{P}_\perp$ ($P_\perp \neq 0$) that is moving on average in the z direction inside a solenoid magnet whose symmetry axis is the z axis and whose magnetic field strength is B_z. Inside the solenoid, the particle's trajectory is a helix of radius R, whose center is at distance R_0 from the magnet axis.

The longitudinal momentum P_z is so large that when the particle reaches the end of the solenoid coil, it exits the field with little change in its transverse coordinates. This behavior is far from the adiabatic limit in which the trajectory spirals around a field line.

When the particle exits the solenoid, the radial component of the magnetic "fringe" field exerts azimuthal forces on the particle, and, in general, leaves it with a nonzero azimuthal momentum, P_ϕ. Deduce a condition on the motion of the particle when within the solenoid, *i.e.*, on R, R_0, P_z, $P_\perp$, and B_z, such that the azimuthal momentum vanishes as the particle leaves the magnetic field region. Your result should be independent of the azimuthal phase of the trajectory when it reaches the end of the solenoid coil.

Hint: Consider the canonical momentum and/or angular momentum.

Answer: The particle has zero canonical angular momentum if and only if its trajectory passes through the magnetic axis.

This result shows that a solenoid can act as a lens – for particles of a given momentum. For example, if the particles are created in a target the lies on the magnetic axis, they will have zero azimuthal momentum, $P_\phi = 0$, after they leave the magnet. If they also have zero radial momentum, $P_r = 0$, then the particles would form a parallel beam, and we could say that the target was at a focus of the solenoid "lens".

The radial momentum is unchanged as the particle leaves the magnet (in the "impulse approximation" that the solenoid field drops quickly to zero at the edge of the magnet). Hence, the particles will be focused into a parallel beam if they have zero radial momentum when they reach the edge of the magnet.

Note that if the particles execute exactly 1/2 revolution (or $(2n+1)/2$ revolutions) on their helical trajectories while in the magnet, their intimal radial momentum P_r is completely transformed into (mechanical) azimuthal momentum $P_{\phi,M}$ (which is equal and opposite to the azimuthal electromagnetic momentum, so that the canonical azimuthal momentum is zero); the radial momentum is now zero as desired. Since the cyclotron frequency of the helical motion is $\omega = eB_z/mc$, the distance L from the target to the edge of the solenoid should be $L = v_z \Delta t = (2n+1)\pi v_z/\omega = (2n+1)\pi m v_z c/eB_z = (2n+1)\pi c P_z/eB_z$. Thus, the solenoid is "focusing" only for particles of (odd multiples of) a particular longitudinal momentum.

See, http://puhep1.princeton.edu/~mcdonald/examples/canon.pdf

The Neutrino Horn Issue

- 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.
- Adiabatic reduction of the solenoid field along the axis,
  $\Rightarrow$ Adiabatic reduction of pion transverse momentum,
  $\Rightarrow$ Focusing.
- Or, use a uniform solenoid to produce a narrow-band beam of (odd multiples of) a desired central momentum.

See, http://pubweb.bnl.gov/users/kahn/www/talks/Homestake.pdf

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

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

Exercises

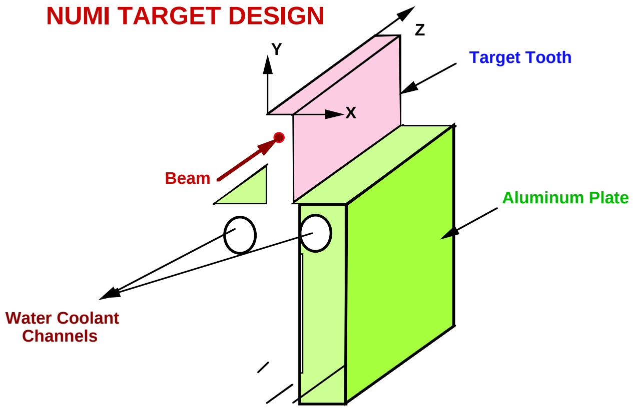
6. Estimate C, α, E and the tensile strength P using a simplified model of atoms.

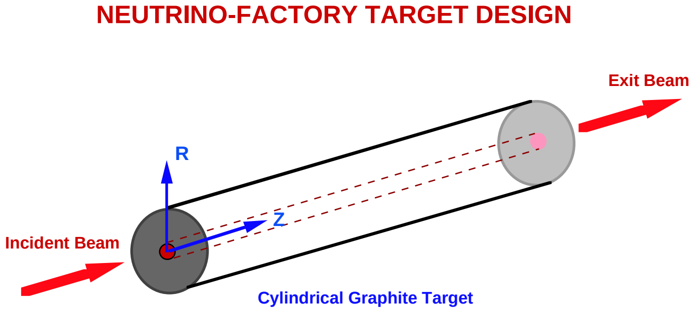
7. How many protons are required to deposit 60 J/g in a material? What is the maximum beam power this material can withstand without cracking, for a 10-GeV beam at 10 Hz with area 0.1 cm^2.

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 $60/(1.6 \times 10^{-13}) = 10^{15}/\mathrm{cm}^2$.
Then, $P_{\max} \approx 10\ \mathrm{Hz} \cdot 10^{10}\ \mathrm{eV} \cdot 1.6 \times 10^{-19}\ \mathrm{J/eV} \cdot 10^{15}/\mathrm{cm}^2 \cdot 0.1\ \mathrm{cm}^2$
$\approx 1.6 \times 10^6$ 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

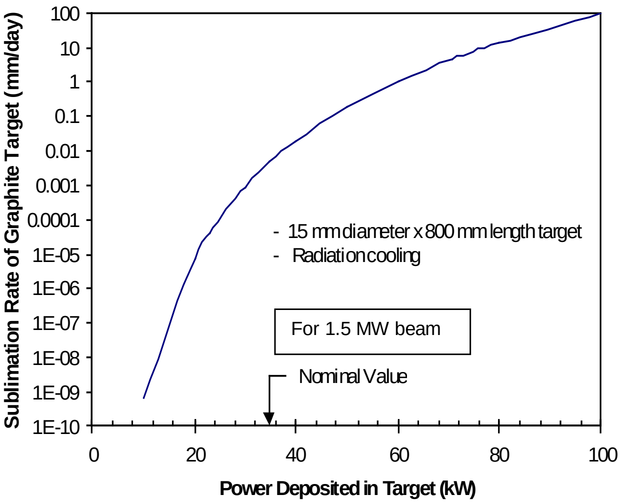




HASSANEIN (ANL)

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.

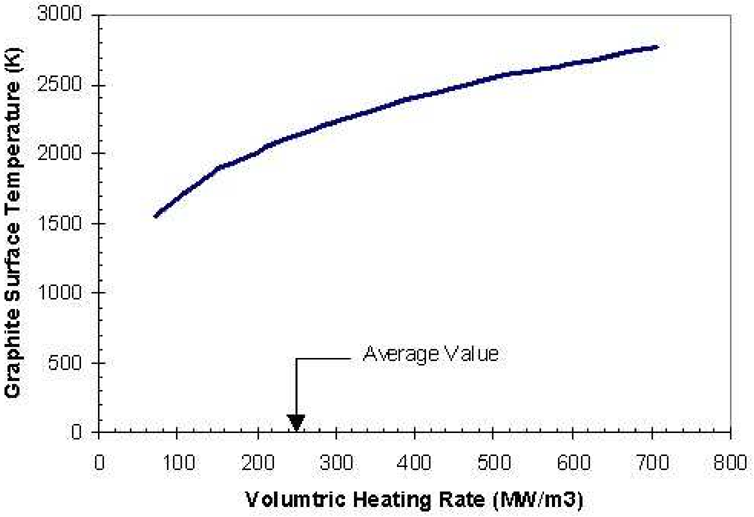
See, http://www-mucool.fnal.gov/mcnotes/public/pdf/muc0186/muc0186.pdf

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

Exercises

8. What is the equilibrium temperature of a carbon target of 1-cm-diameter as a function of beam power, assuming only radiation cooling?

Ans:



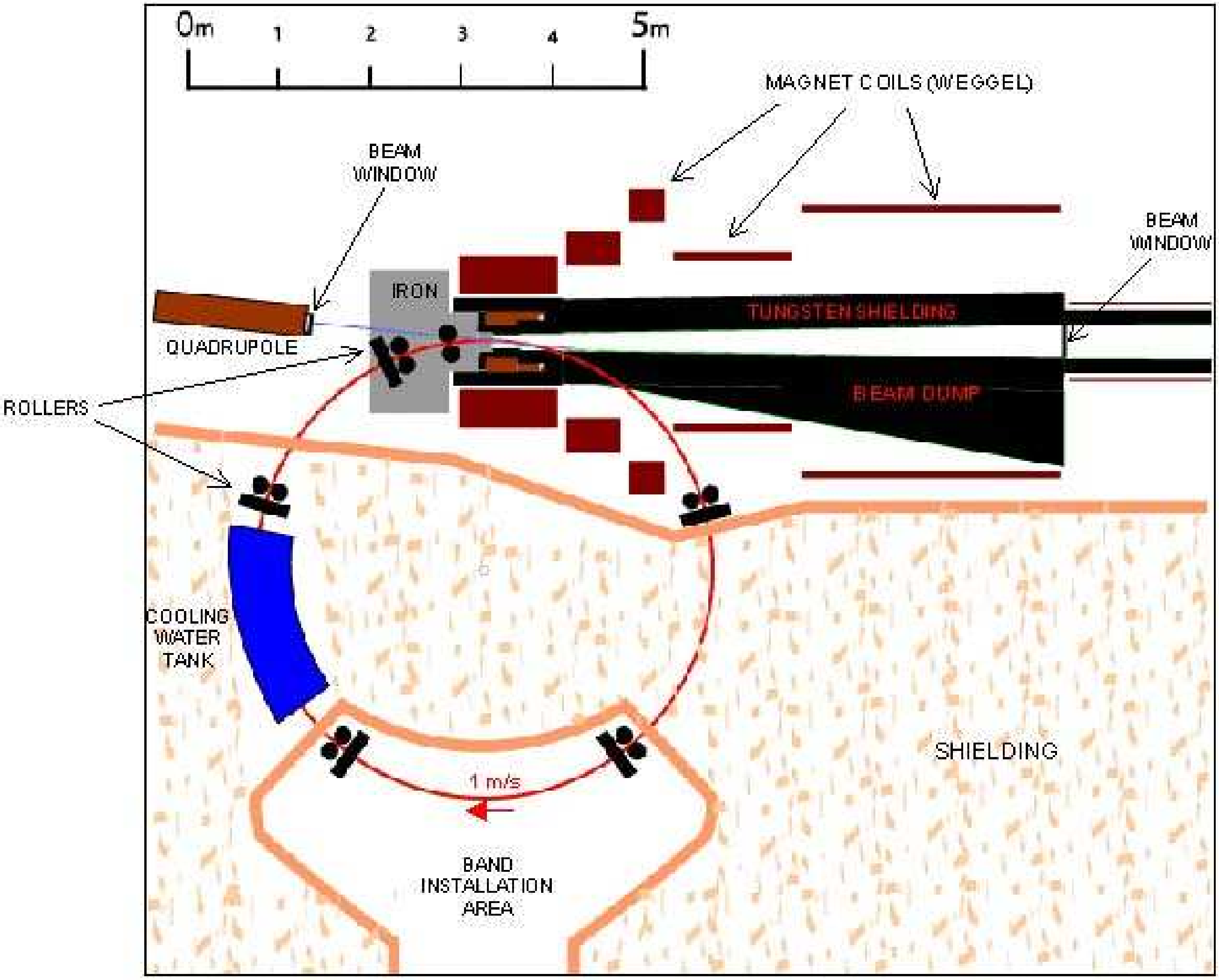
From http://www.hep.princeton.edu/mumu/catalina/Catalina_Mtg.ppt

9. What is the radiation damage limit of materials?

Ans: Materials turn to powder due to radiation damage once each atom has suffered ≈ one nuclear interaction ≡ 1 DPA (displacement per atom).
The displacements are due to ≈ 10-MeV neutrons.
In a thick target ($\gtrsim$ 1 nuclear interaction length) have ≈ 10 10-MeV neutrons per beam proton.
$\sigma_{np} \approx 4\pi\lambdabar^2 \approx 10^{-25}$ cm^2; $\sigma_{nA} \approx 10\sigma_{np} \approx 10^{-24}$ cm^2.
$\Rightarrow$ Need ≈ 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.

Maybe Can Use a Moving Solid Target

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

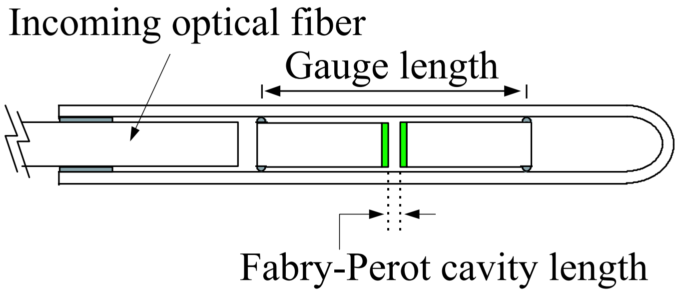


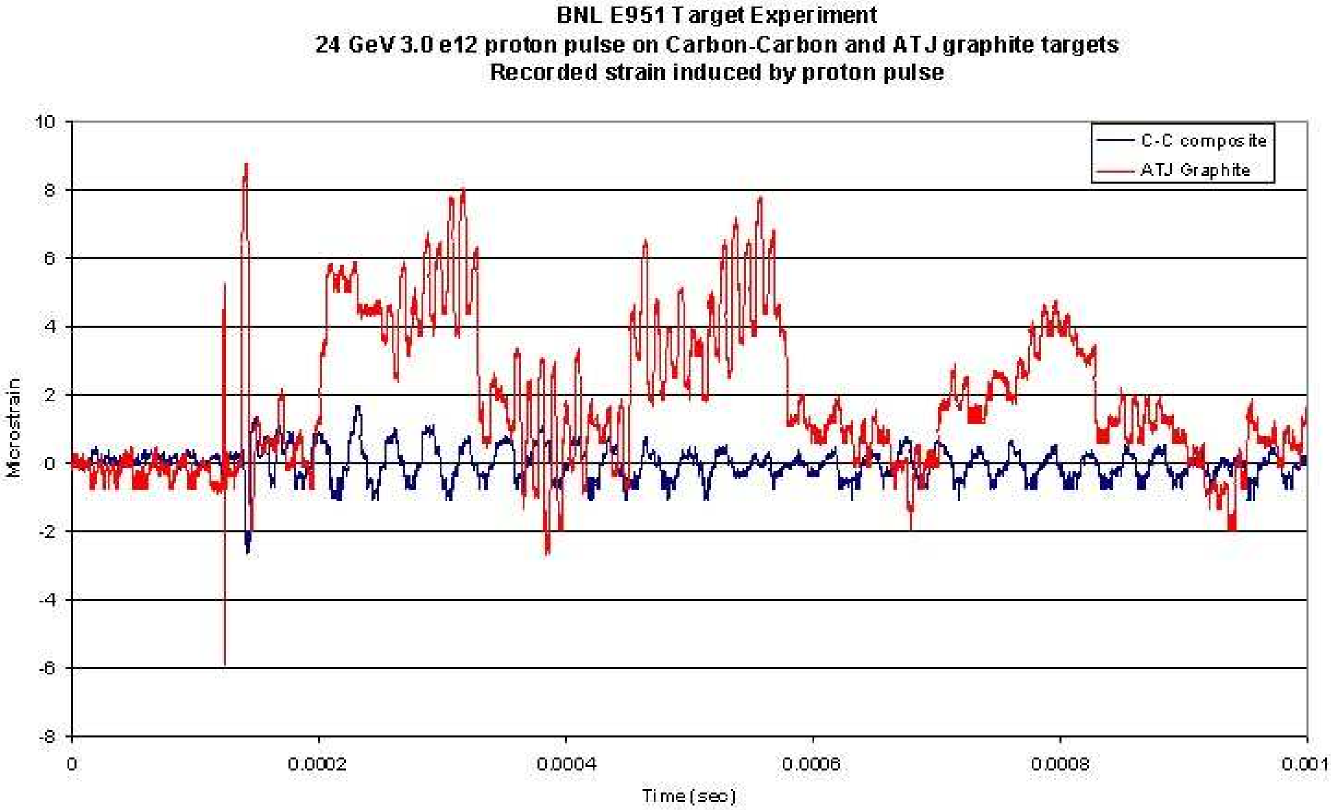
Compatibility of the rotating band with a capture solenoid magnet?

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

Lower Thermal Shock If Lower Thermal Expansion Coefficient

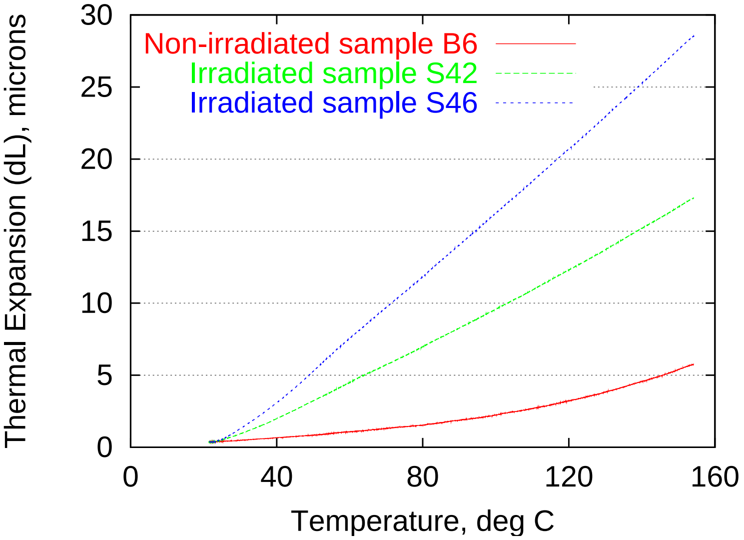
ATJ graphite and a 3-d weave of carbon-carbon fibers instrumented with fiberoptic strain sensors.





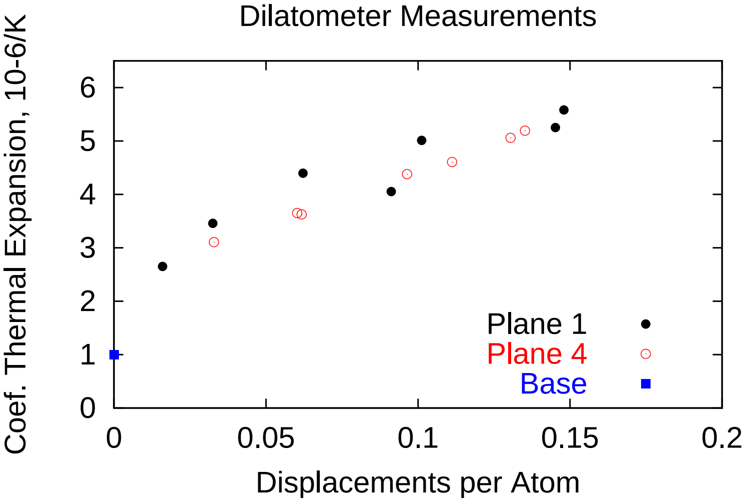
Effects of Radiation on SuperInvar

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



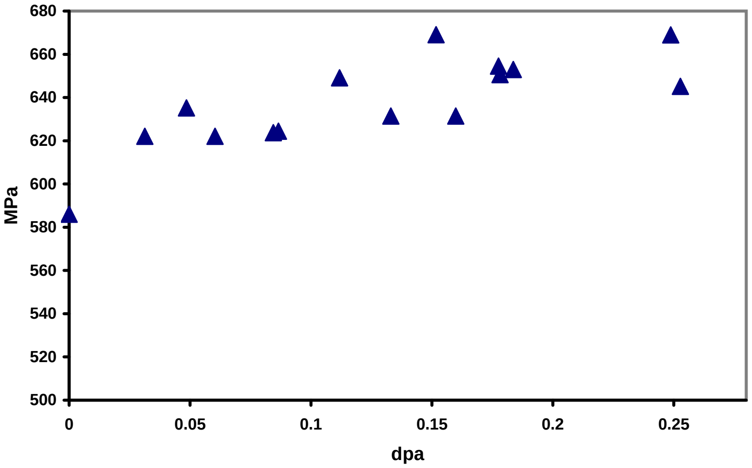
However, irradiation at the BNL BLIP facility show that the CTA increases rapidly with radiation dose.

CTA *vs.* dose ⇒



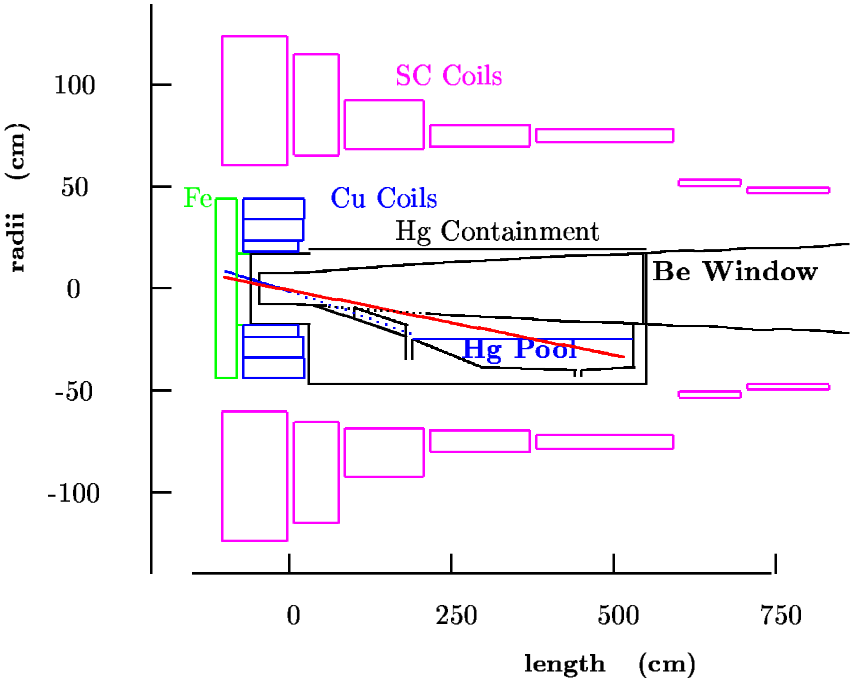
SuperInvar is made stronger by moderate radiation doses (like many materials).

Yield strength *vs.* dose ⇒

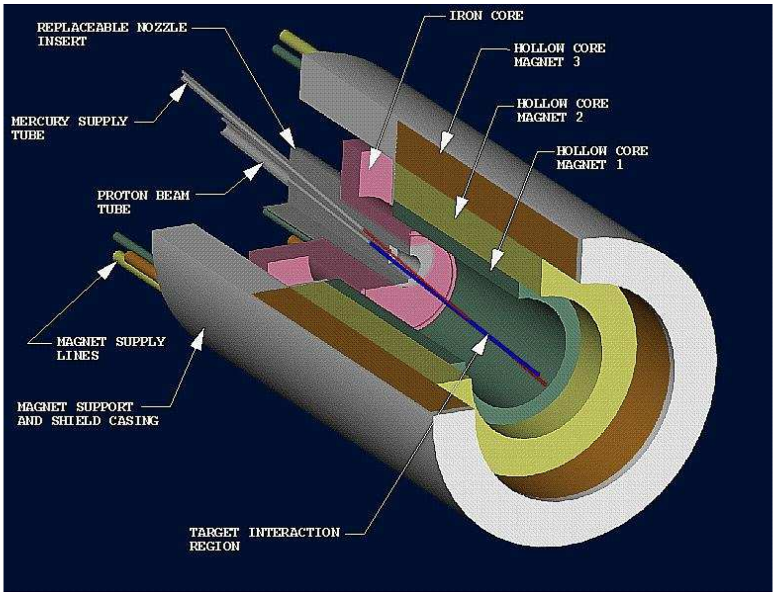


A Liquid Metal Jet May Be the Best Moving Target

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

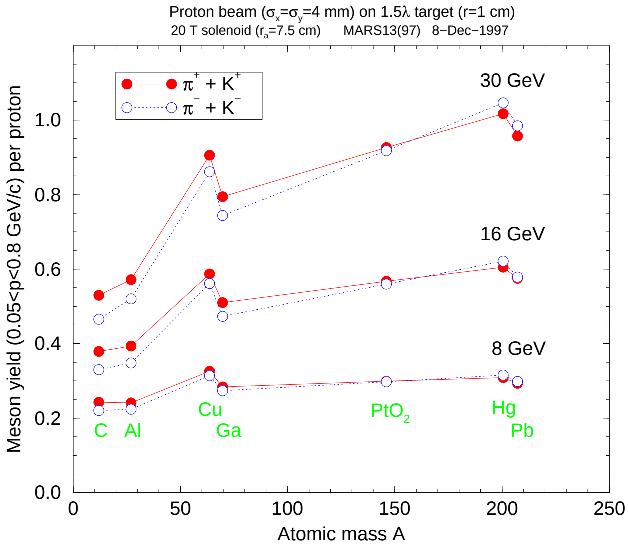


Mercury jet tilted by 100 mrad, proton beam by 67 mrad.

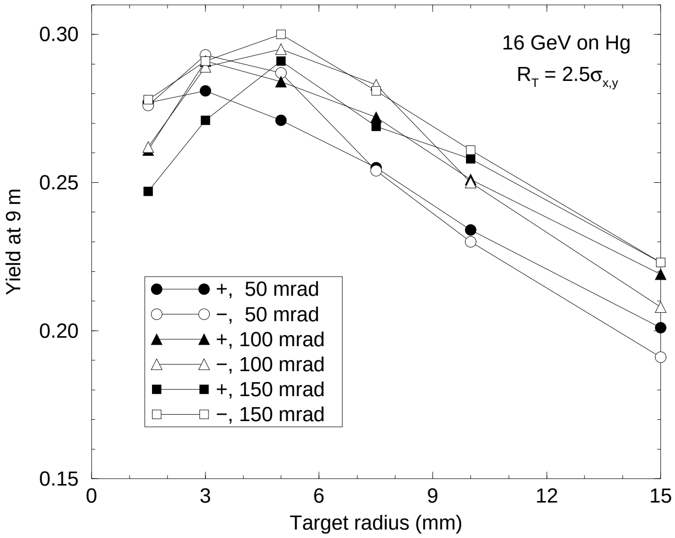


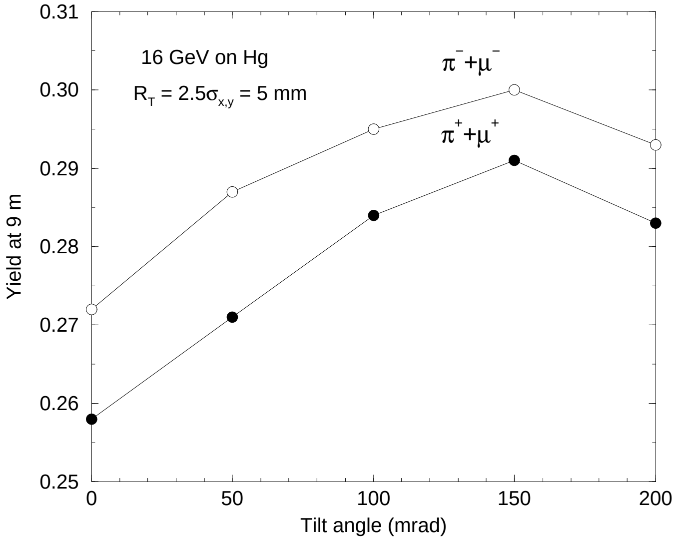
Pion/Muon Yield

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.

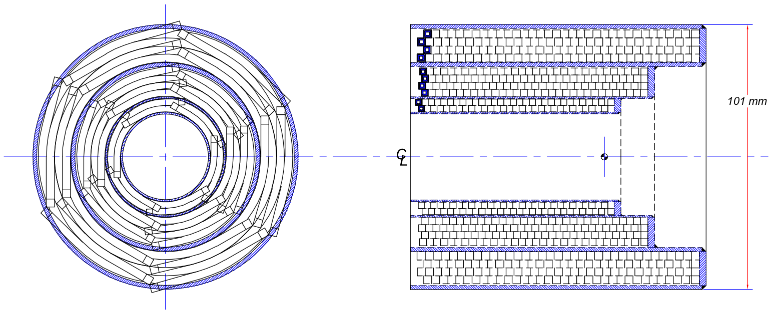




Can capture ≈ 0.3 pion per proton with $50 < P_\pi < 400$ MeV$/c$.

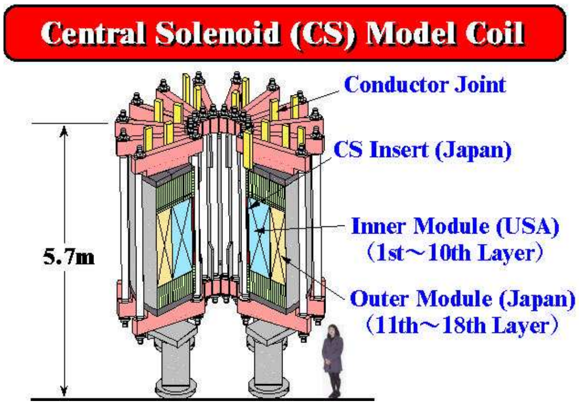
20-T Capture Magnet System

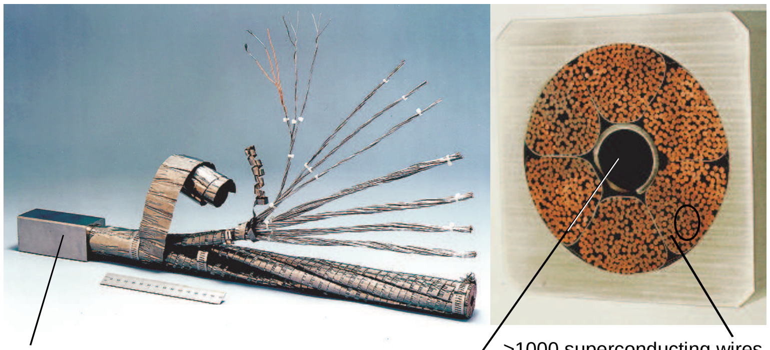
Inner, hollow-conductor copper coils generate 6 T @ 12 MW:



Bitter-coil option less costly, but marginally feasible.

Outer, superconducting coils generate 14 T @ 600 MJ:





Incoloy Alloy 908 Conduit

>1000 superconducting wires

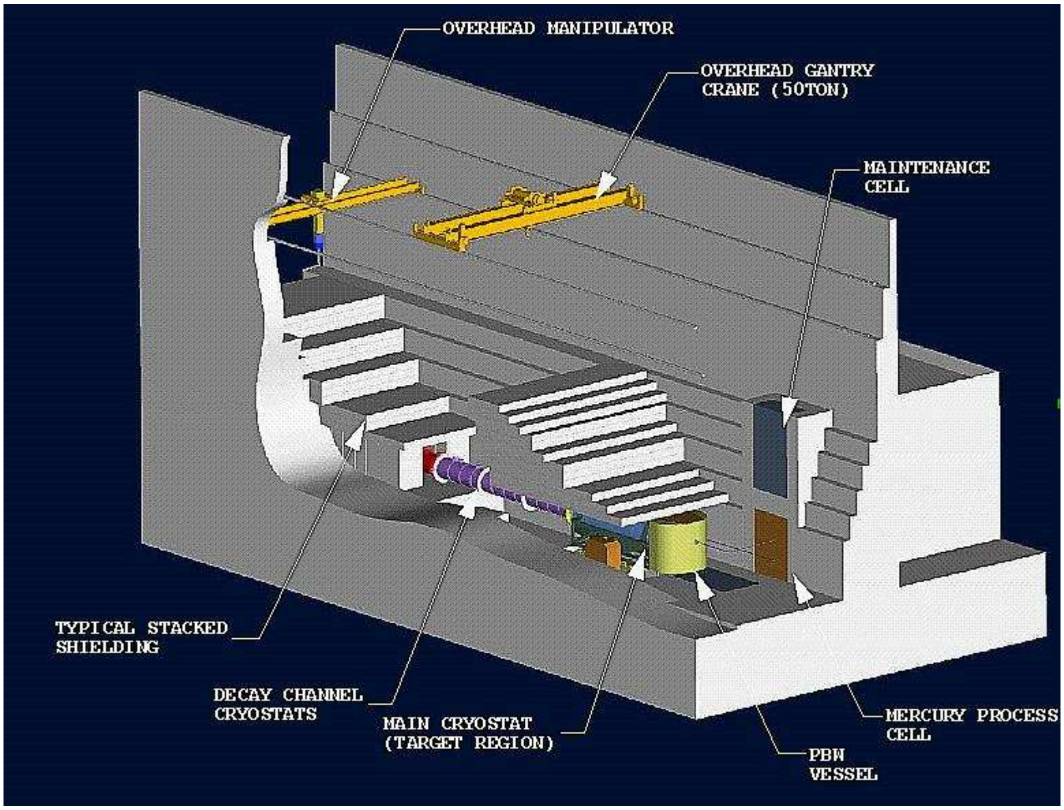
Supercritical helium flows in interstices
and central channel

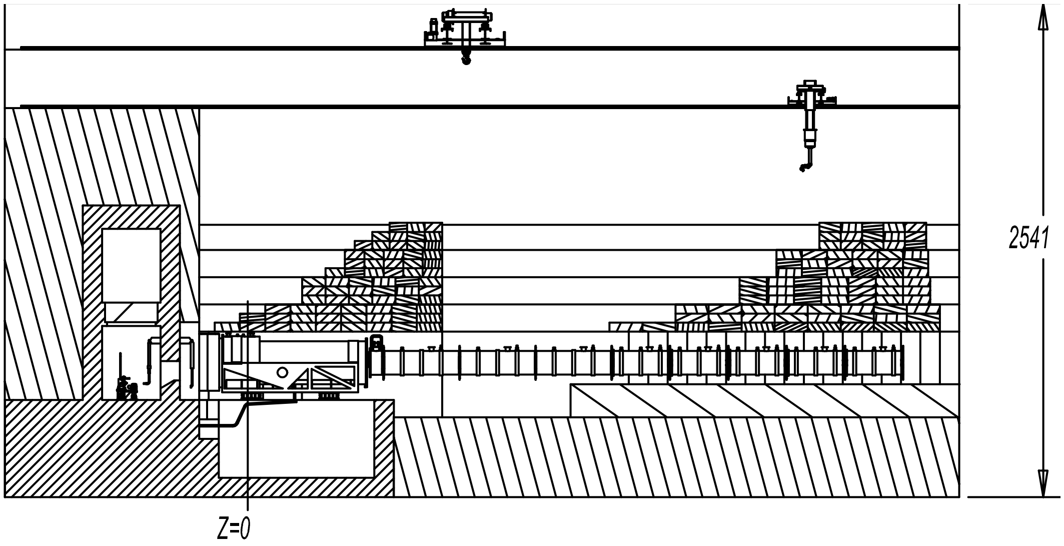
Cable-in-conduit construction similar to ITER central solenoid.

Both coils shielded by tungsten-carbide/water.

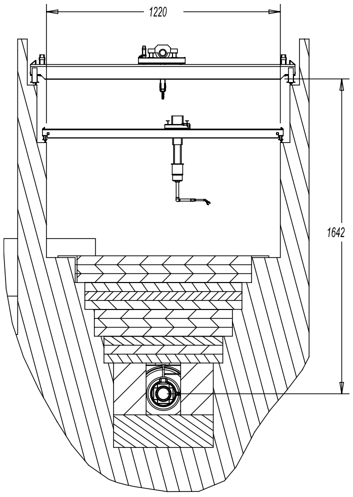
Target System Support Facility

Extensive shielding; remote handling capability.



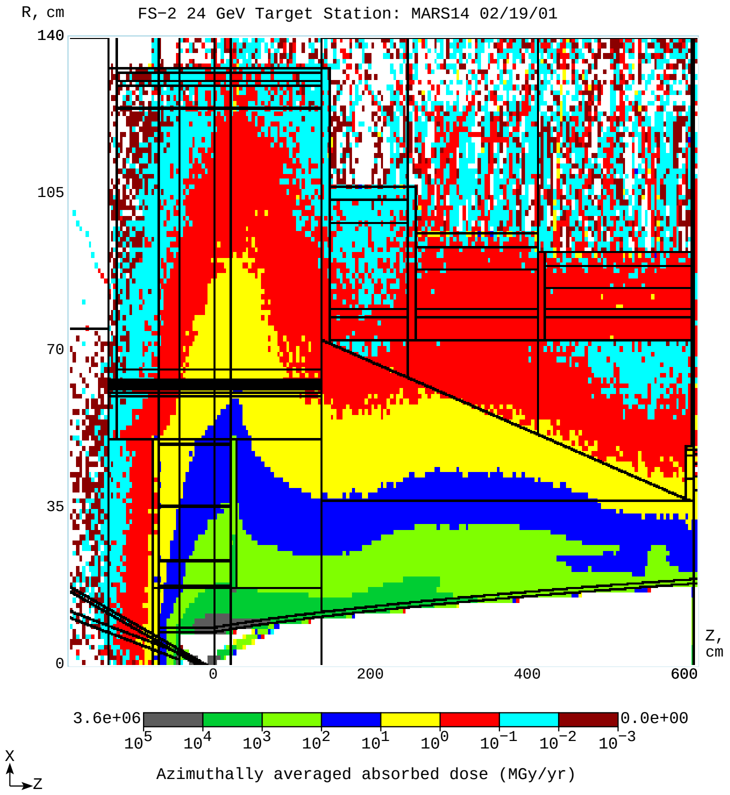


SECTION C-C



SECTION B-B
DECAY CHANNEL SHIELDING

Lifetime of Components in the High Radiation Environment

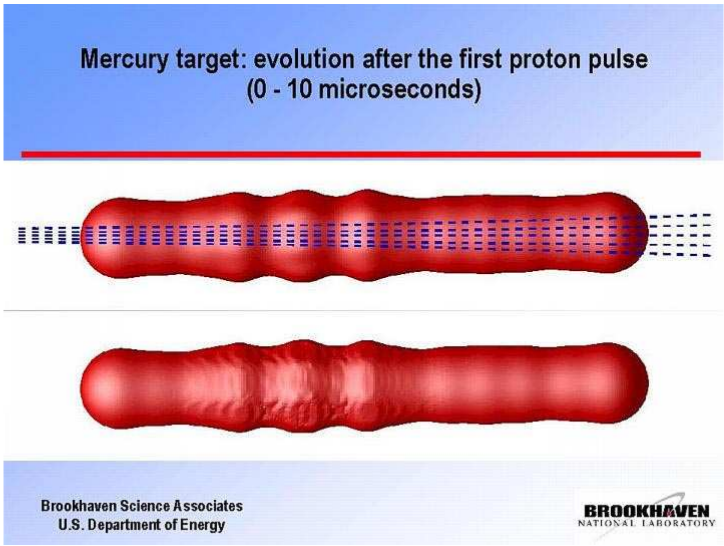


Component	Radius (cm)	Dose/yr (Grays/2×10^7 s)	Max allowed Dose (Grays)	1 MW Life (years)	4 MW life (years)
Inner shielding	7.5	5×10^{10}	10^{12}	20	5
Hg containment	18	10^9	10^{11}	100	25
Hollow conductor coil	18	10^9	10^{11}	100	25
Superconducting coil	65	5×10^6	10^8	20	5

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

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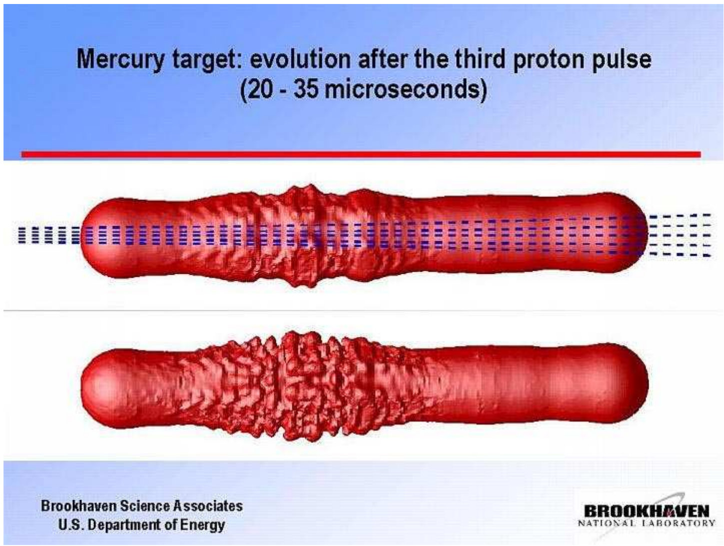

Mercury target: evolution after the third proton pulse
(20 - 35 microseconds)

Brookhaven Science Associates
U.S. Department of Energy

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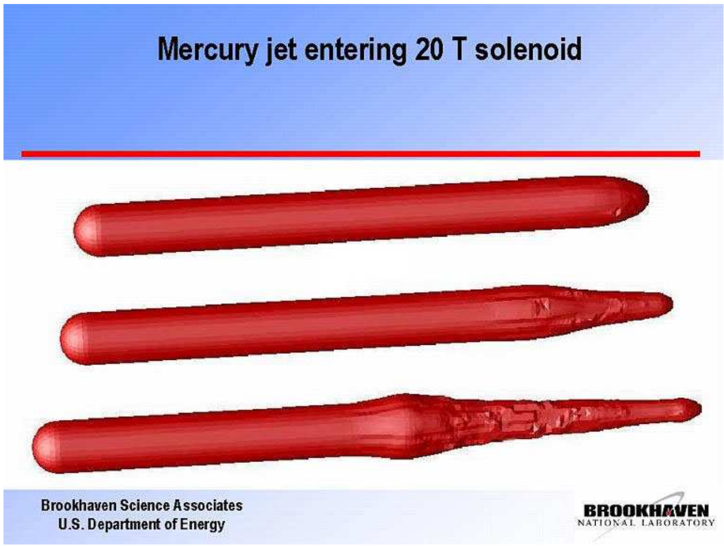
- Eddy currents may distort the jet as it traverses the magnet.



Mercury jet entering 20 T solenoid

Brookhaven Science Associates
U.S. Department of Energy

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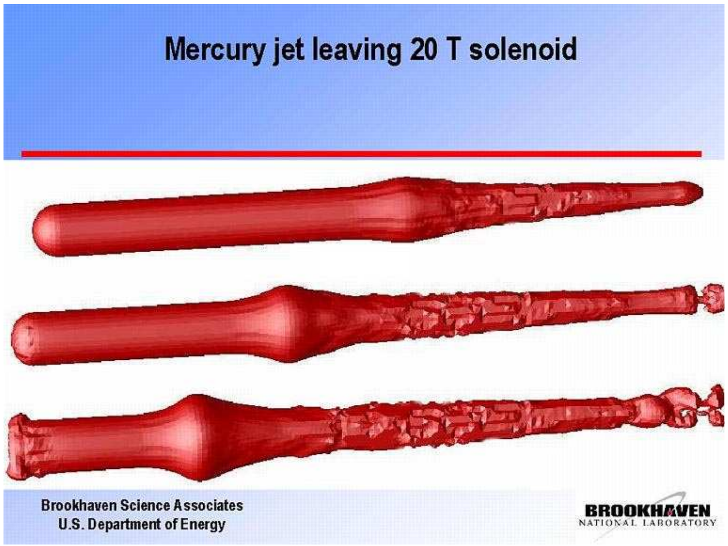

Mercury jet leaving 20 T solenoid

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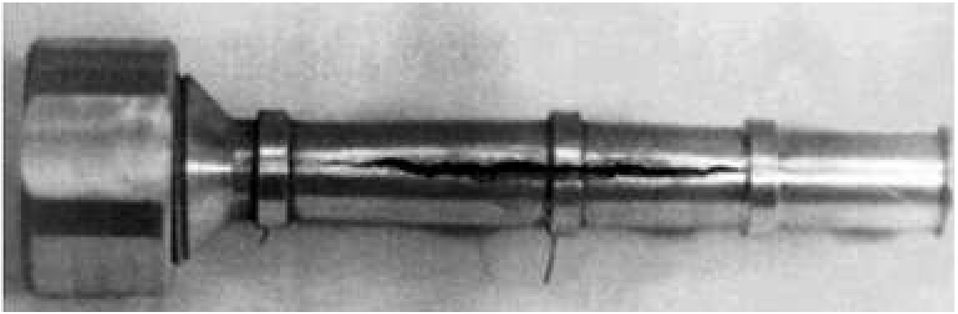
- Computational challenge: to include negative pressure and cavitation in a magnetohydrodynamic (MHD) simulation of a liquid metal with a free surface.

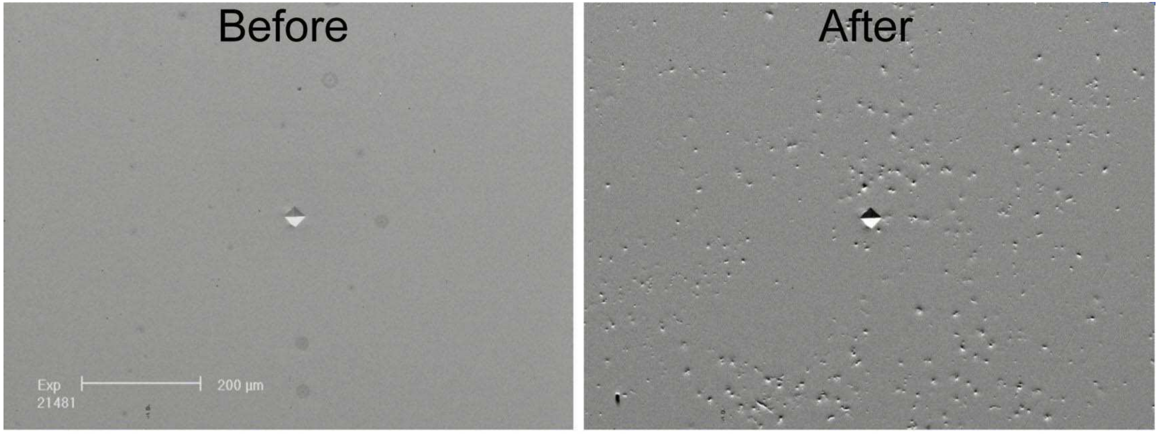
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

BINP:



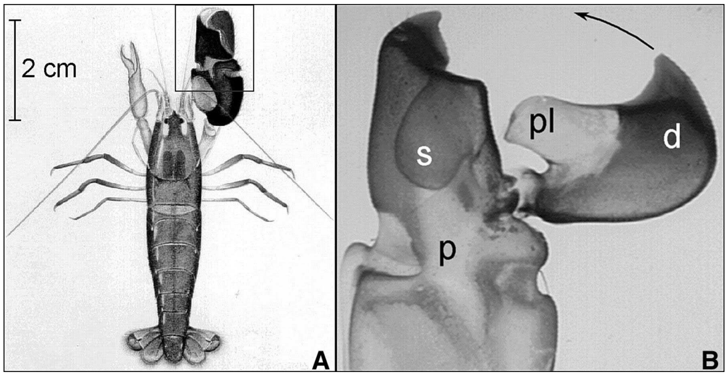
SNS:

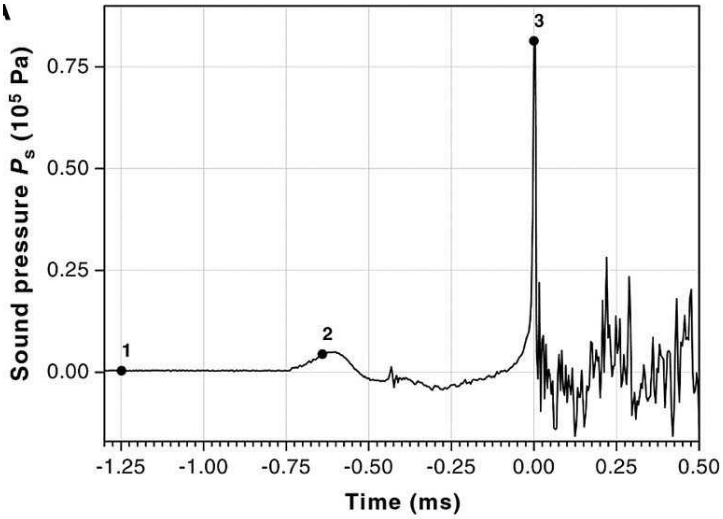


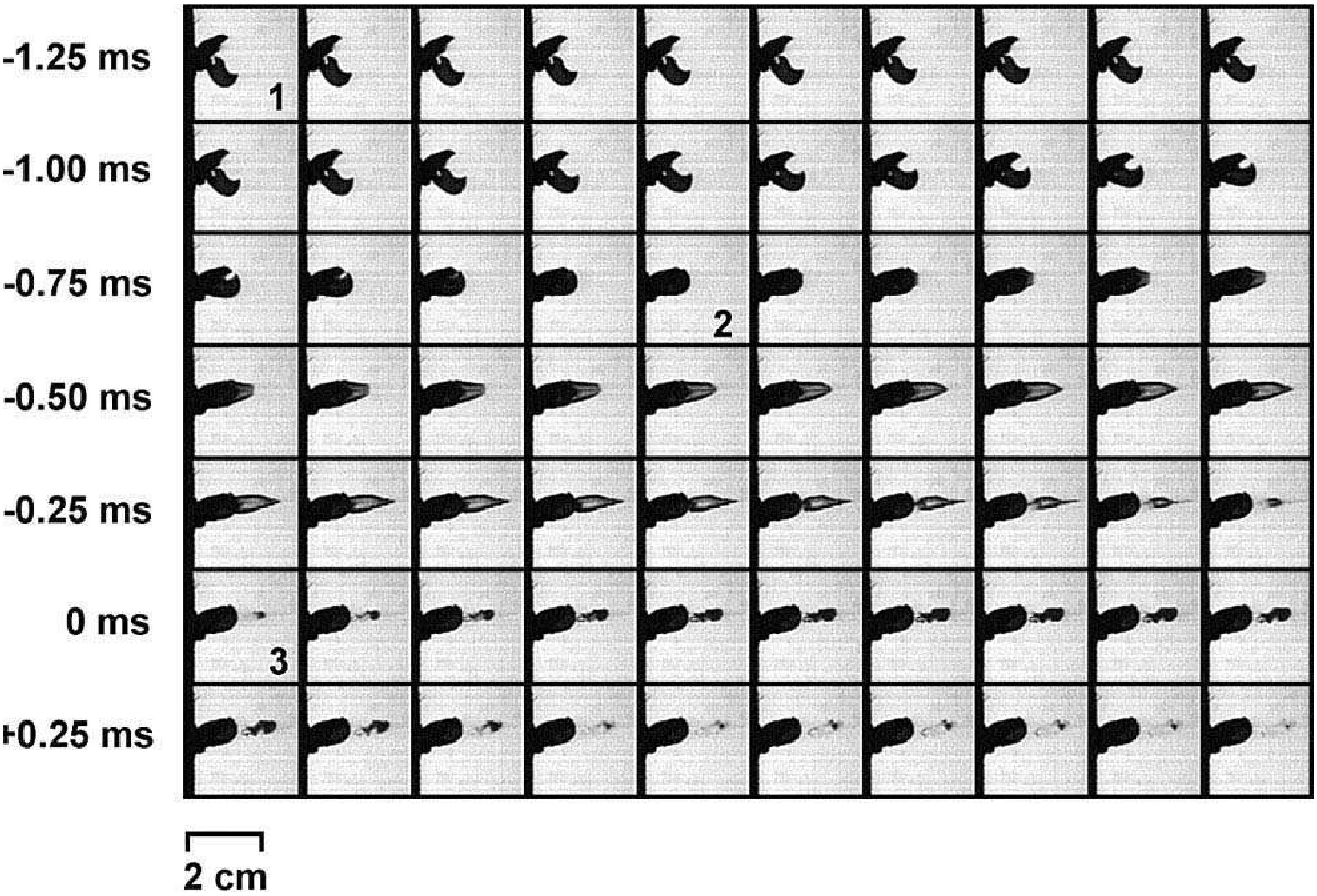
TL - High Power Target
Specimen # 29754
Equivalent SNS Power Level = 2.5

How Snapping Shrimp Snap: Through Cavitating Bubbles

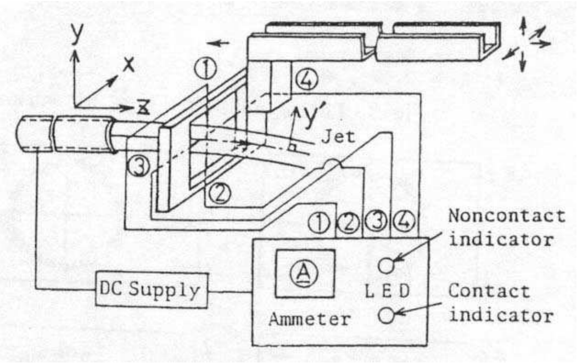
M. Versluis , Science **289**, 2114 (2000).



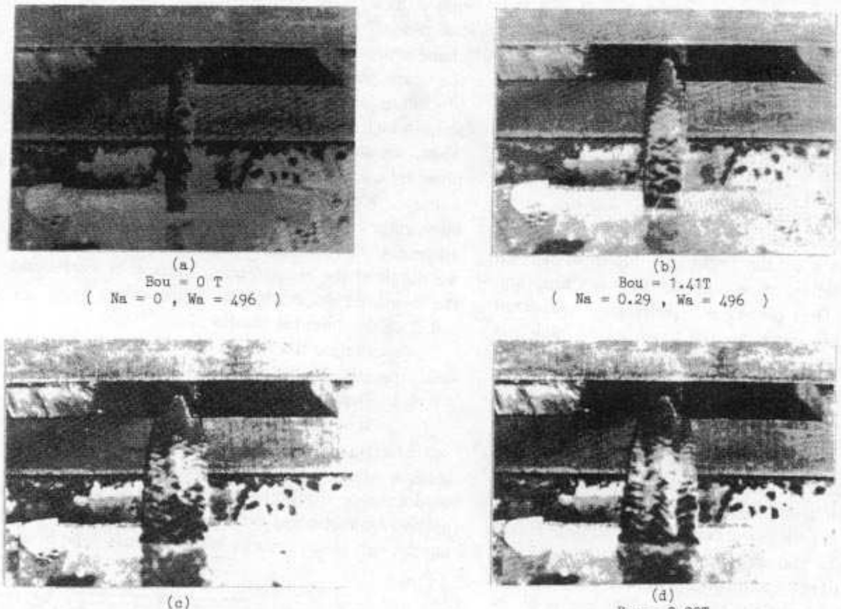




The Shape of a Liquid Metal Jet under a Non-uniform Magnetic Field



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



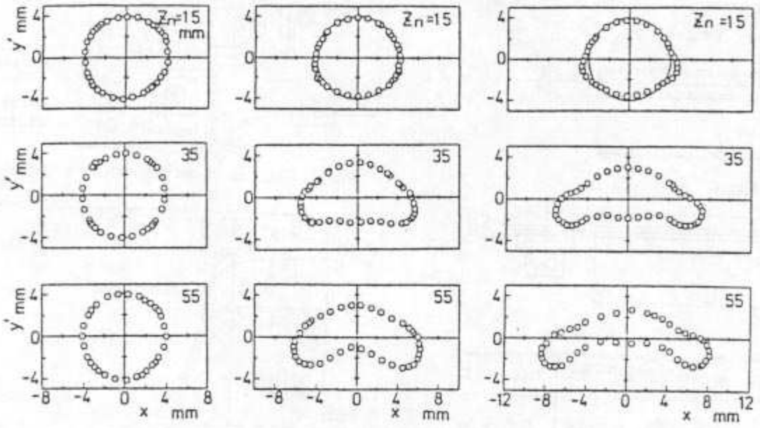
(a)
Bou = 0 T
(Na = 0 , Wa = 496)

(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 magnetic field strengths



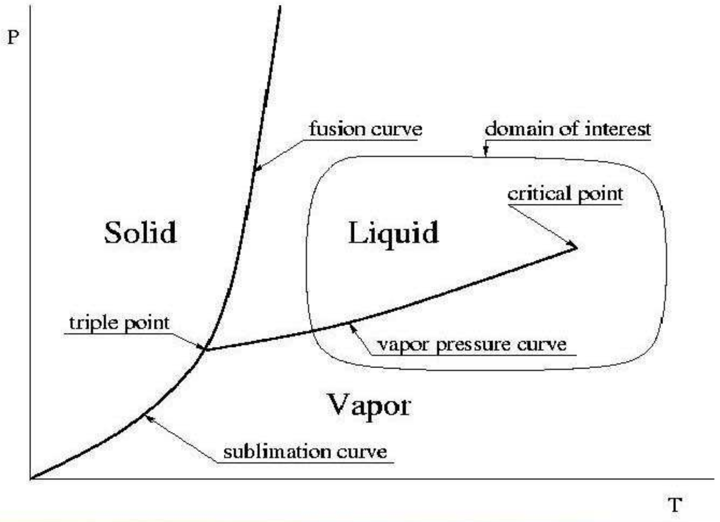
(a)
Bou = 0 T
(Na = 0 , Wa = 496)

(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

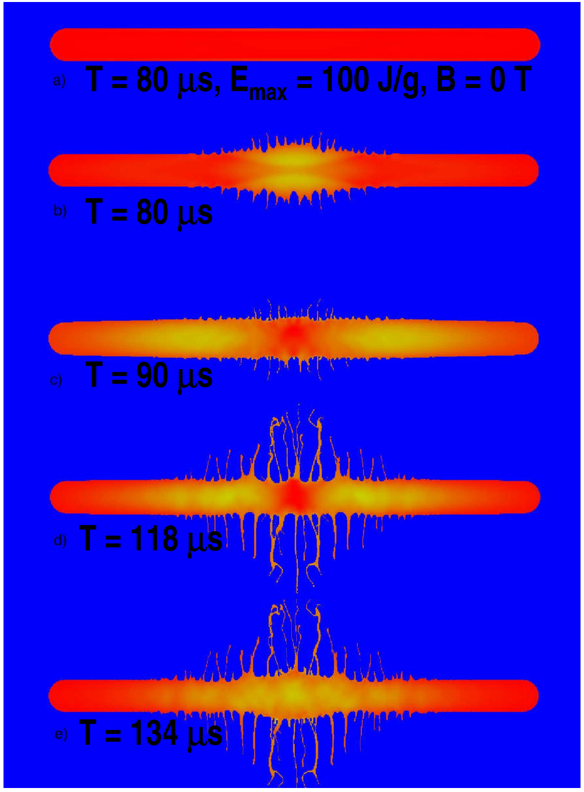
Computational Magnetohydrodynamics (R. Samulyak)

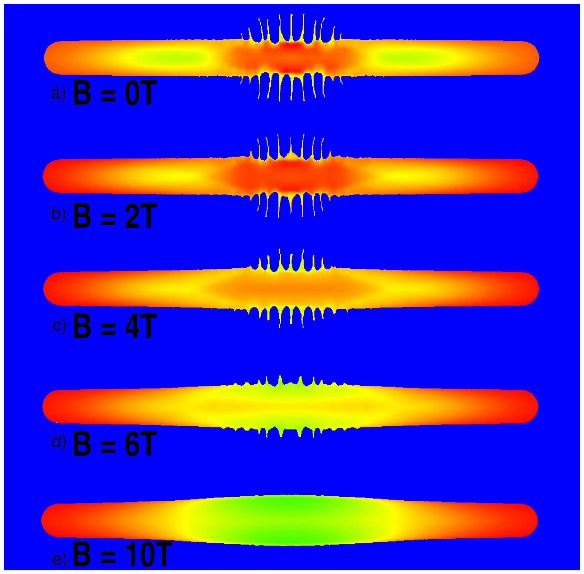


Critical point : $T_c = 1750\,\mathrm{K}$, $P_c = 172\,\mathrm{MPa}$, $V_c = 43\,\mathrm{cm}^3\mathrm{mol}^{-1}$

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.





Exercises

9. Estimate the dispersal velocity of a liquid jet into which a proton beam deposits U J/g.

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

for $U \approx 100$ J/g.

10. In the phenomenon of single-bubble sonoluminescence, a water bubble of initial radius of 40 μm is observed to emit light when its radius collapses to about 0.5 μm under one atmosphere pressure. Approximately 6×10^6 photons are emitted in the energy range 1-6 eV, with a bremsstrahlung-like spectrum of the form $dN \propto dE/E$ where E is the photon energy. (Water is opaque to photons above about 6 eV.)

In this problem the bubble can assumed to contain vacuum.

a) Suppose that all the kinetic energy of the collapsing bubble is converted to photons with the spectrum $dN \propto dE/E$. What would be the maximum photon energy emitted?

b) At what radius does the velocity of the inner surface of the bubble reach the speed of sound in water, 1,500 m/s?

See, http://puhep1.princeton.edu/~mcdonald/examples/sonobubble.pdf

11. When an electron (or positronium atom) is injected into liquid helium with nearly zero energy, a bubble quickly forms around it. This phenomenon (which also occurs in liquid hydrogen, liquid neon and possibly in solid helium) lowers the mobility of the electron to a value similar to that for a positive ion.

Estimate the radius of the bubble at zero pressure and temperature.

If the liquid is held in a state of negative pressure, the bubble will expand beyond the radius at zero pressure. Estimate the negative pressure such that a bubble once formed will grow without limit.

Hint: Consider the pressure associated with the zero-point energy of an electron in a bubble (dark energy?).

See, http://puhep1.princeton.edu/~mcdonald/examples/hebubble.pdf

12. If one pitches a penny into a large magnet, eddy currents are induced in the penny, and their interaction with the magnetic field results in a repulsive force, according to Lenz' law. Estimate the minimum velocity needed for a penny to enter a long, 1-T solenoid magnet whose diameter is 10 cm.

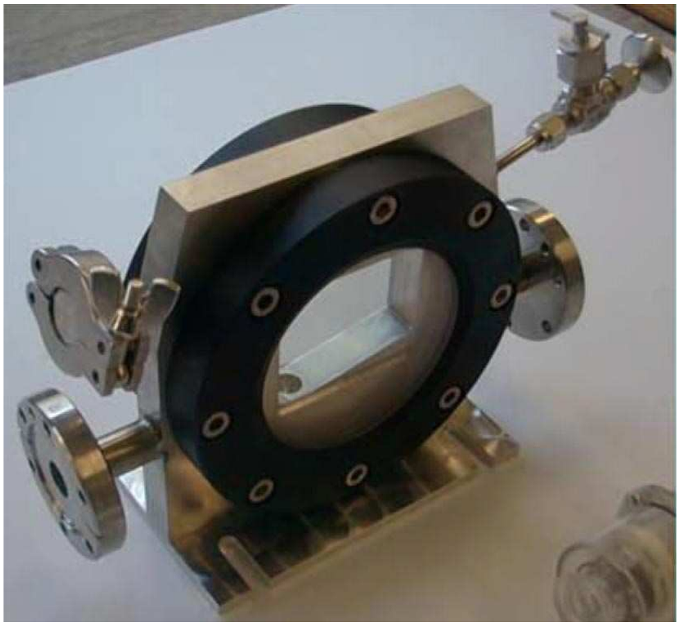
You may suppose that the penny moves so that its axis always coincides with that of the magnet, and that gravity may be ignored. The speed of the penny is low enough that the magnetic field caused by the eddy currents may be neglected compared to that of the solenoid. Equivalently, you may assume that the magnetic diffusion time is small.

See, prob. 1b of http://puhep1.princeton.edu/~mcdonald/examples/ph501set5.pdf

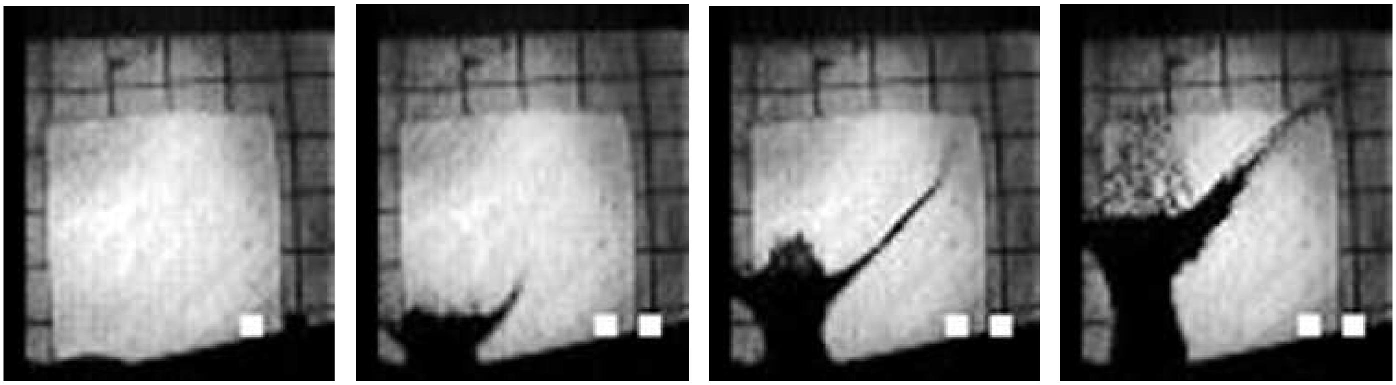
13. Extend the analysis of exercise 10 to the case where the penny (liquid metal jet) enters the magnet at angle θ to the field axis.

See, http://www.hep.princeton.edu/~mcdonald/mumu/target/jet.pdf

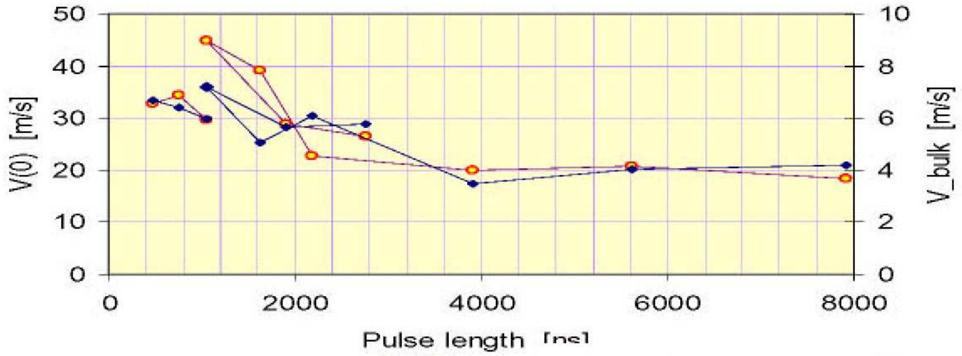
Passive Mercury Target Tests



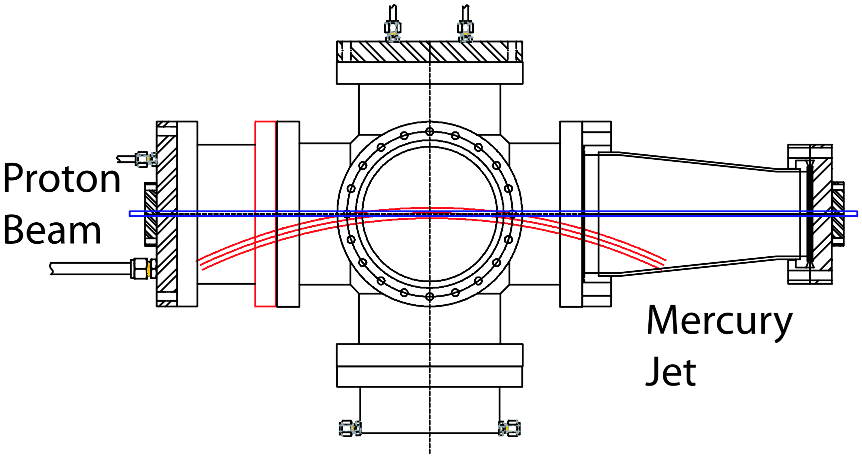
Exposures of 25 μs at $t = 0, 0.5, 1.6, 3.4$ msec, $\Rightarrow v_{\rm splash} \approx 20 - 40$ m/s:



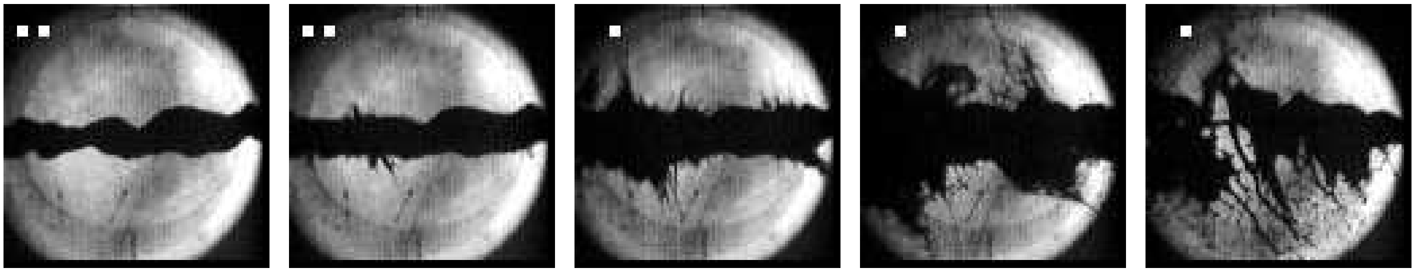
Two pulses of ≈ 250 ns give larger dispersal velocity only if separated by less than 3 μs.



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.

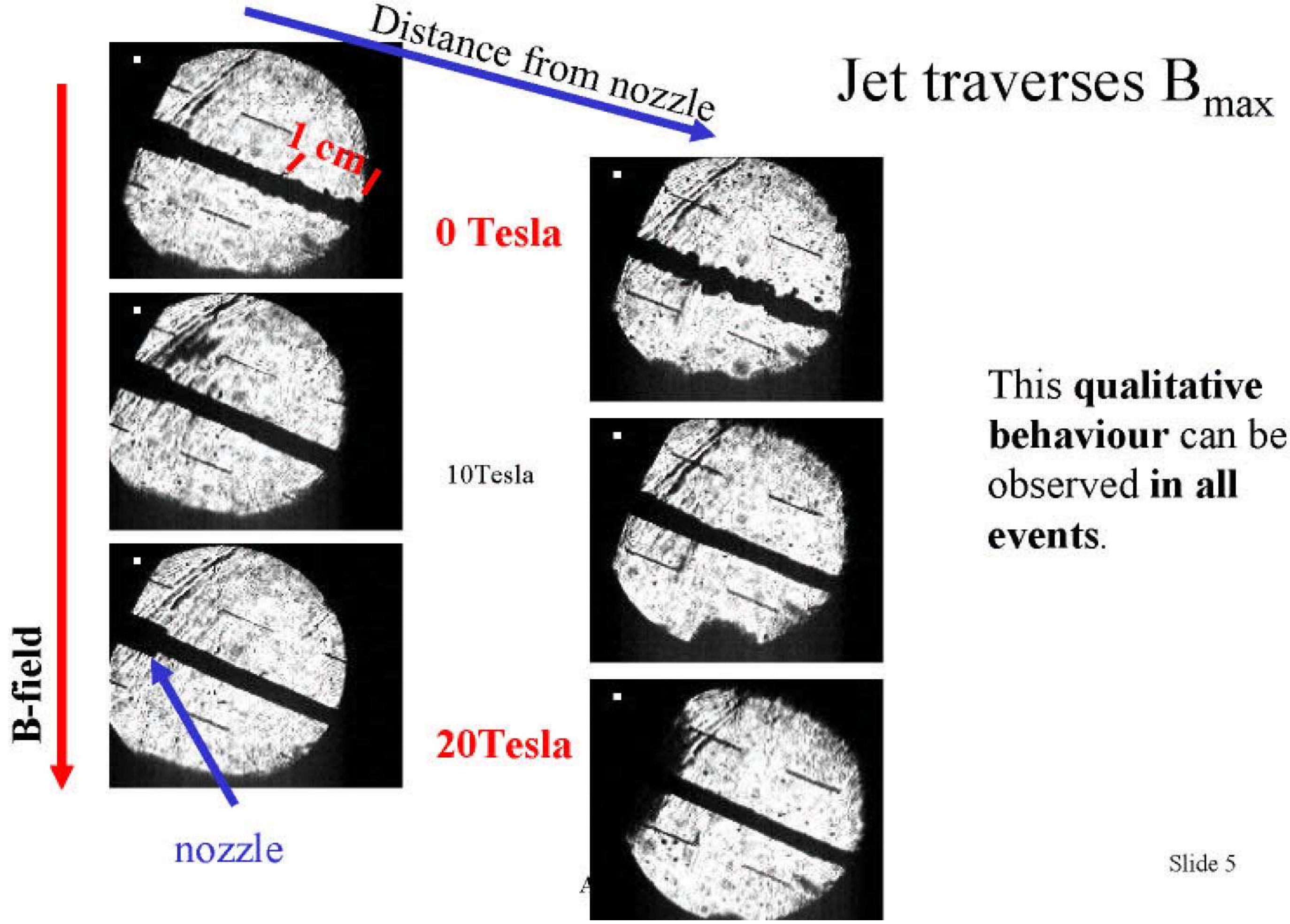
Filaments appear only $\approx 40\ \mu$s after beam, $\Rightarrow$ after several bounces of waves, or v_{sound} very low.

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

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

Analytic model suggests little effect if jet nozzle inside field.

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



Jet traverses B_{max}

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

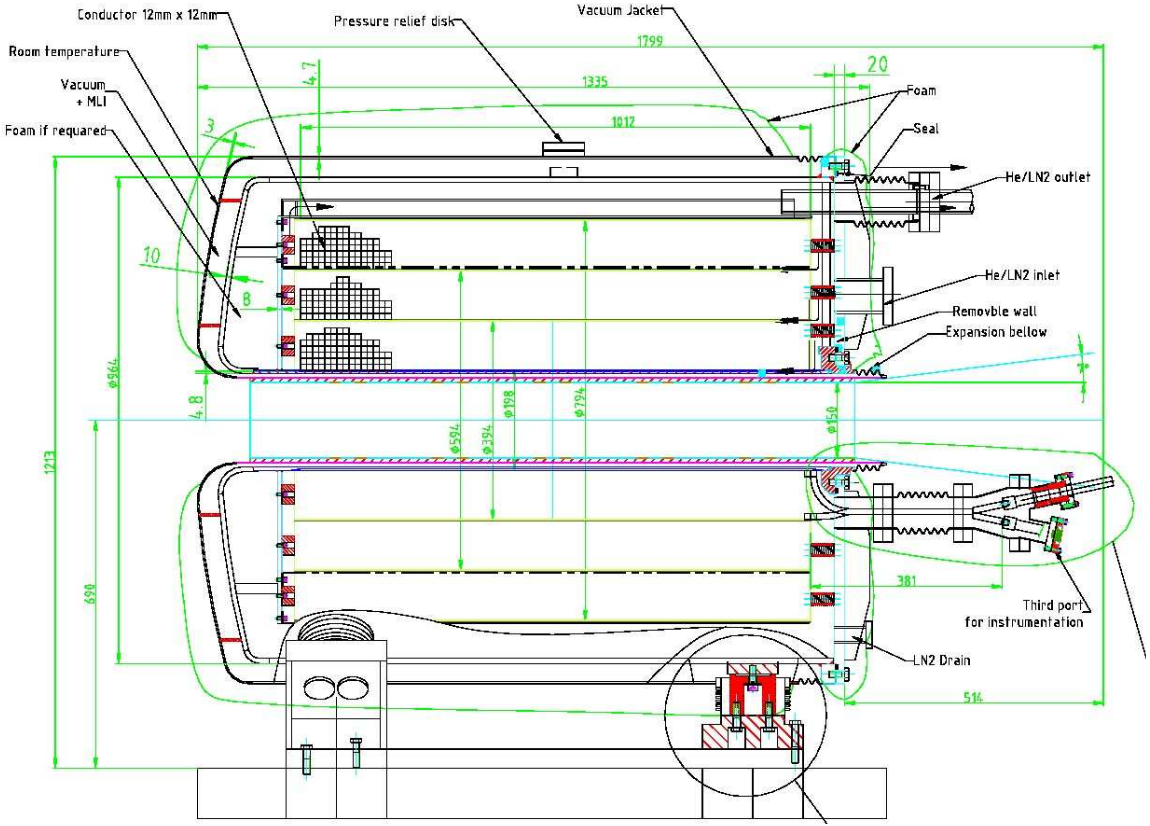
⇒ Damping of surface tension waves (Rayleigh instability).

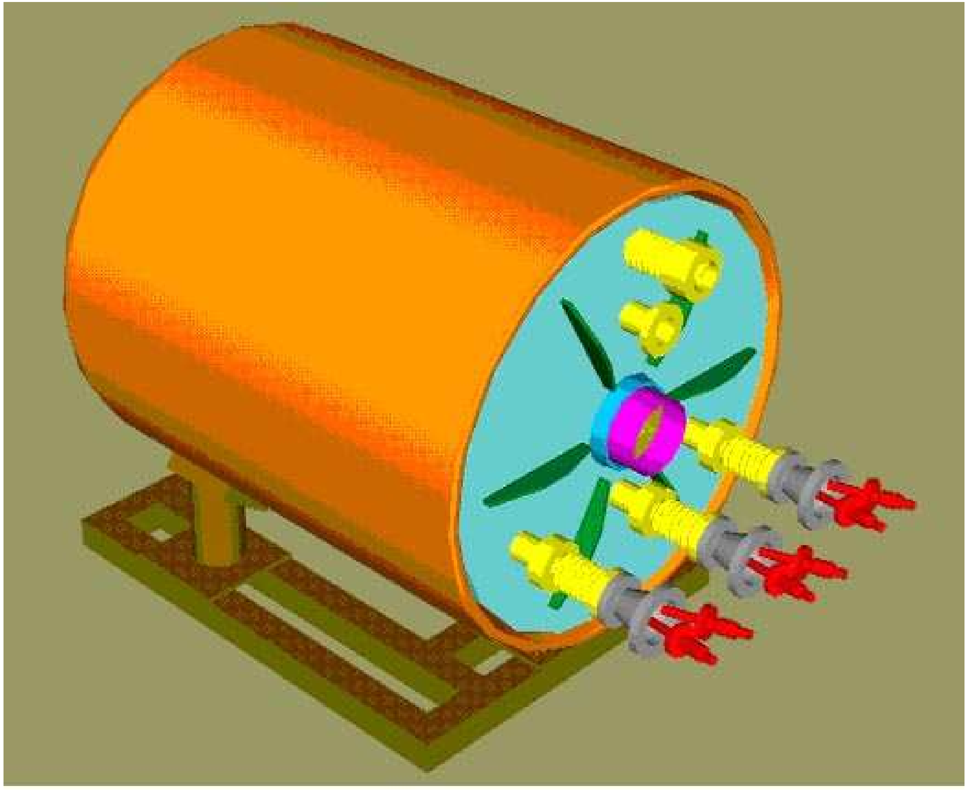
Will the beam-induced dispersal be damped also?

Issues for Further Targetry R&D

- Continue numerical simulations of MHD + beam-induced effects [Samulyak].
- Continue tests of mercury jet entering magnet [CERN, Grenoble – but funding exhausted].
- 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.

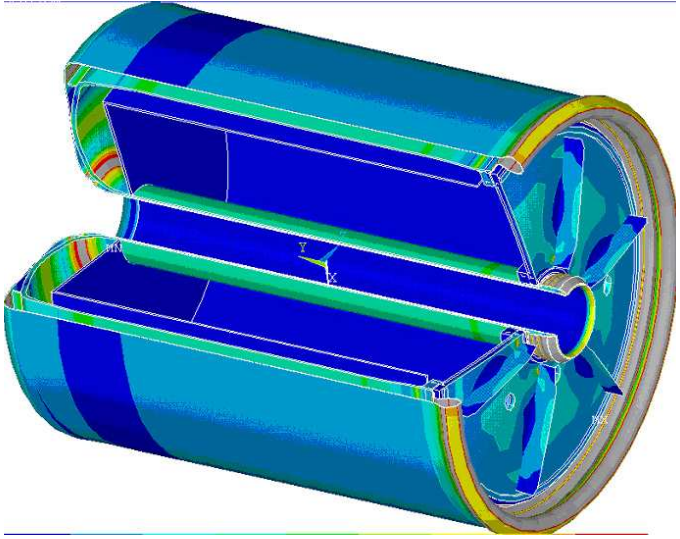
A 15-T LN_2-Cooled Pulsed Solenoid

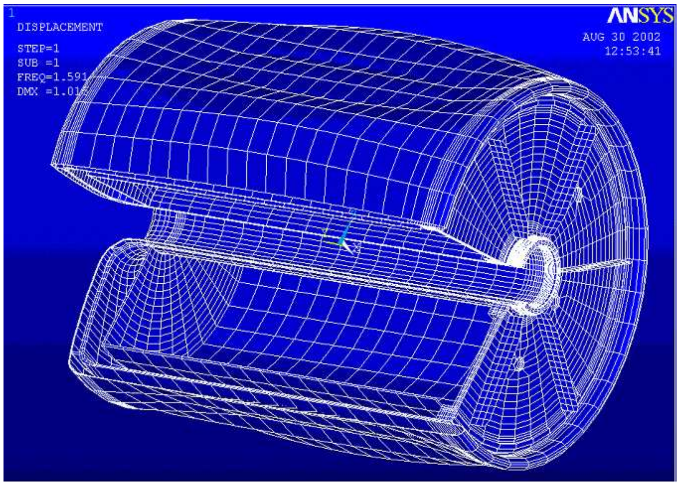




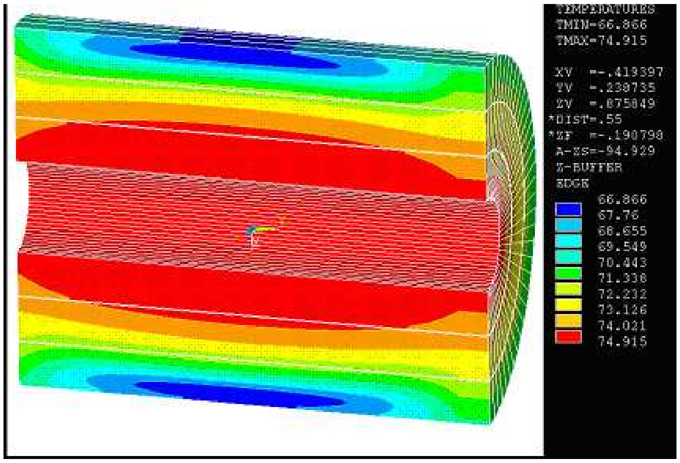
Structural and Thermal Analyses of the Magnet

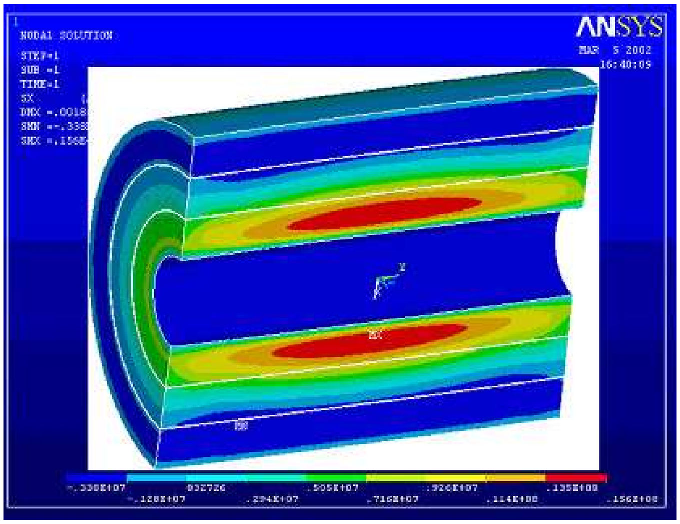
Cryostat:





Magnet coils:





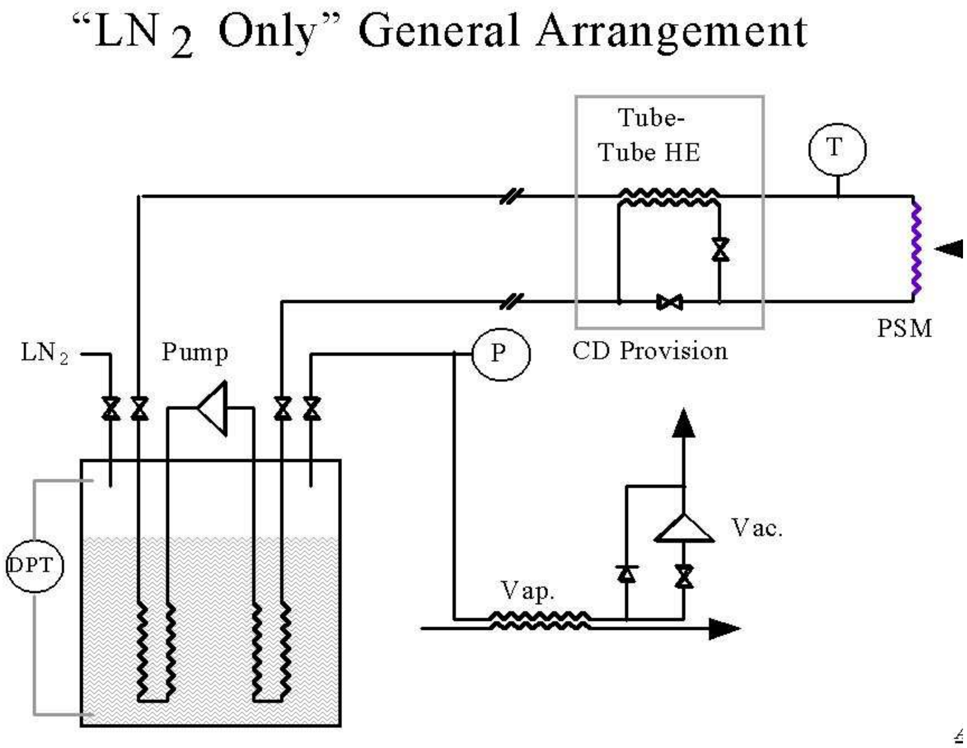
Keeping Costs Low

- Simple solenoid geometry with rectangular coil cross section and smooth bore (of 20 cm diameter) [Weggel, Titus].
- Cryogenic system reduces coil resistance to give high field at relatively low current [Iarocci, Mulholland].
  - Circulating coolant is gaseous He to minimize activation, and to avoid need to purge coolant before pulsing magnet.
  - Heat exchanger recycled from the SSC.
  - Cooling via N_2 boiloff.

Phase	Field	Power	Coolant	Temp.
1	5 T	0.6 MW	N_2	84 K
2	10 T	2.2 MW	N_2	74 K
3	15 T	4.5 MW	N_2	70 K

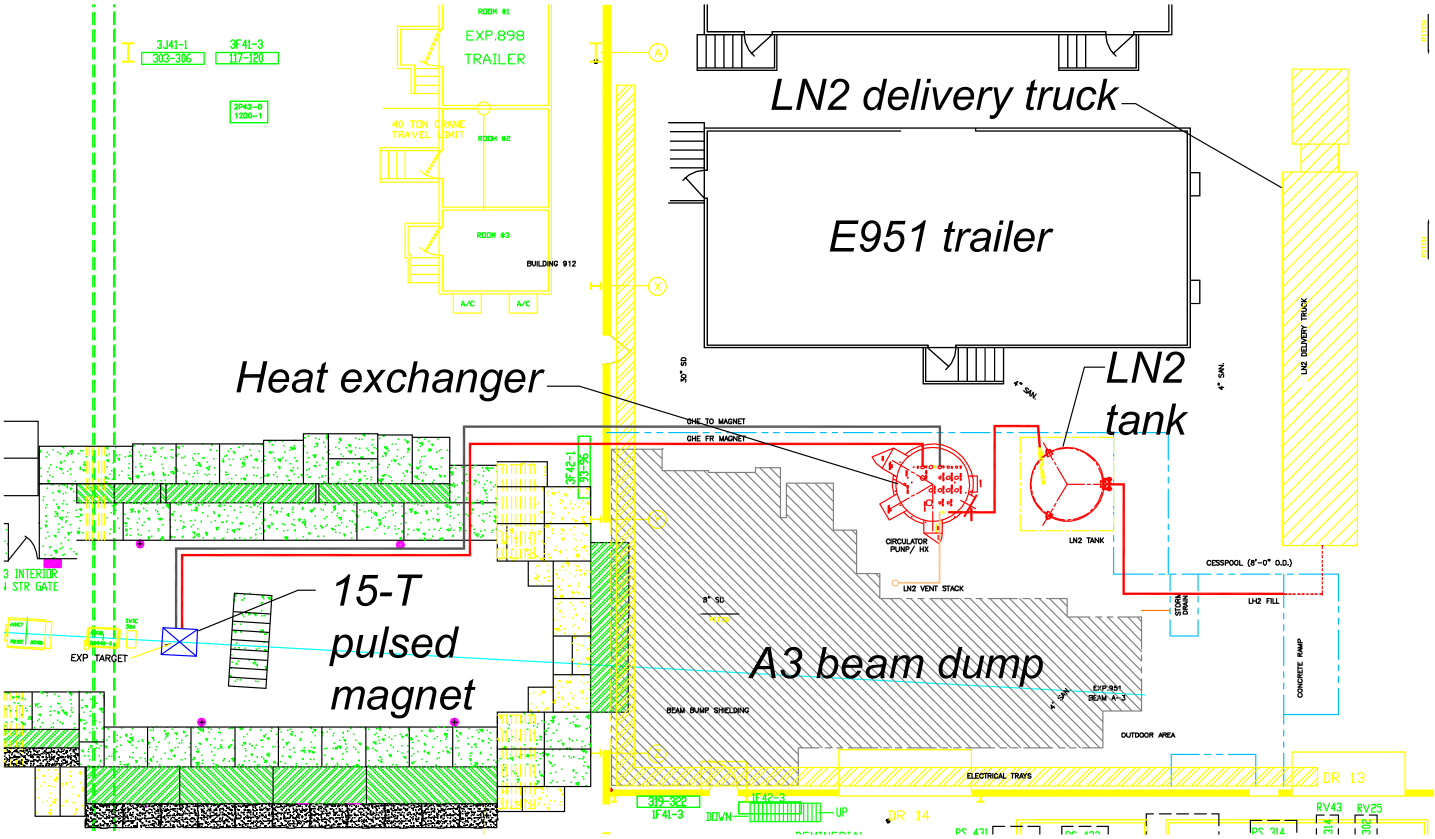
- Can build a 2.2-MW power supply out of 4 existing 540-kVA supplies at BNL [Marneris].
- Most cost effective to build a 4.5-MW supply out of “car” batteries! (We need at most 1,000 pulses of the magnet.)

Cooling via He Gas + LN$_2$ Heat Exchanger



Heat exchanger recycled from the SSC:

Pulsed Magnet System Layout at the AGS



- Locate the 4 x 540 kVA power supplies (or batteries) on the east side of the A3 cave, feed power in via the trench.
- Use only LN2 to cool the GHe in the heat exchanger, ⇒ Need 4.5 MW power supply to reach 15 T.

Alternatives to AGS Running

DOE HEP support of AGS running was zeroed out for FY03, and may not be restored.

Parameter	Muon Collider	BNL AGS	FNAL Booster	CERN PS	LANSCE PSR	KEK MR	JHF RCS	JHF MR
Proton Energy (GeV)	16-24	24	8.9	24	0.8	12	3	50
p/bunch	5×10^{13}	1.6×10^{13}	6×10^{10}	4×10^{12}	3×10^{13}	7×10^{11}	4×10^{13}	4×10^{13}
No. of bunches	2	6	84	8	1	9	2	8
p/cycle	1×10^{14}	1×10^{14}	5×10^{12}	3×10^{13}	3×10^{13}	6×10^{12}	8×10^{13}	3×10^{14}
Bunch spacing (ns)	≈ 1000	440	18.9	250	–	140	600	600
Bunch train length (μs)	≈ 1	2.2	1.6	2.0	0.25	1.1	0.6	4.2
RMS Bunch length (ns)	≈ 1	≈ 10	≈ 1	≈ 10	≈ 60	≈ 10	≈ 10	≈ 10

The JHF (now J-PARC) 50-GeV proton beam is well suited for high power targetry studies.

J-PARC has strong interest in a 4-MW source for a neutrino superbeam/factory.

Prospects for collaboration are excellent; J-PARC Letter of Intent No. 30 submitted 21 Jan 2003.

⇒ Timely to start fabrication of pulsed magnet coils (then cryo system and power supply), despite uncertainly as to AGS schedule.