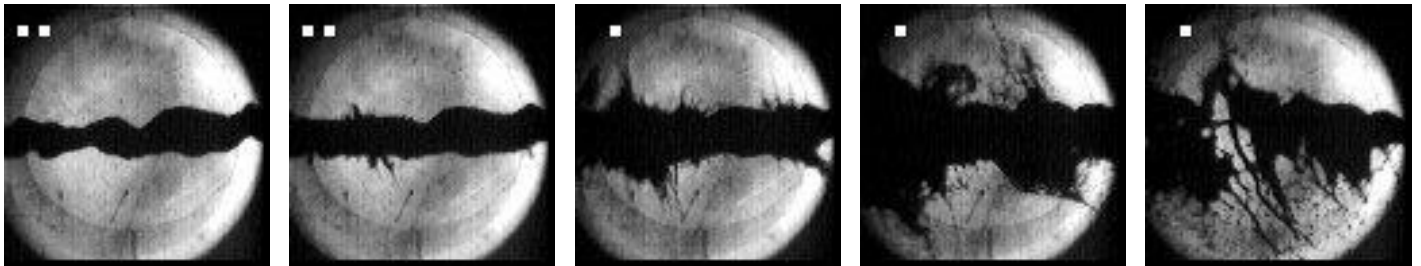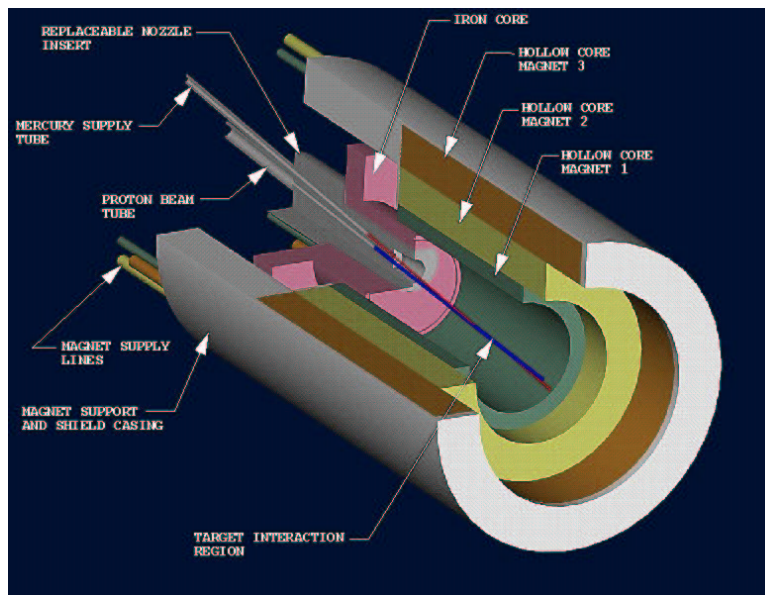# Carbon and Mercury Targets for Neutrino Beams and a Muon Collider Source

(BNL E951)

K.T. McDonald

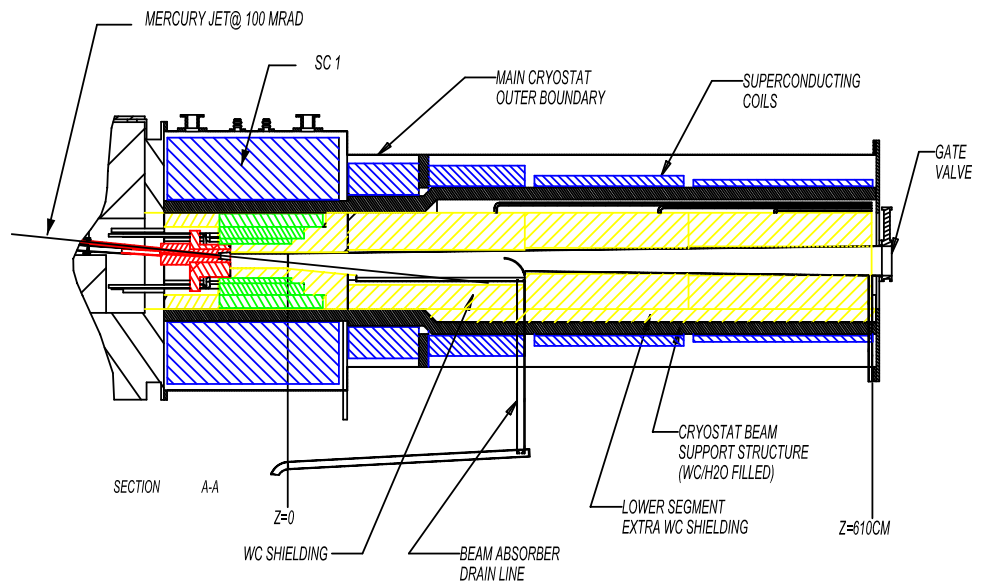*Princeton U.*

Muon Collider and Neutrino Factory Collaboration Meeting

Shelter Island, May 9, 2002

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

Challenges

- Maximal production of soft pions $\rightarrow$ muons in a megawatt proton beam.

- Capture pions in a 20-T solenoid, followed by a 1.25-T decay channel.
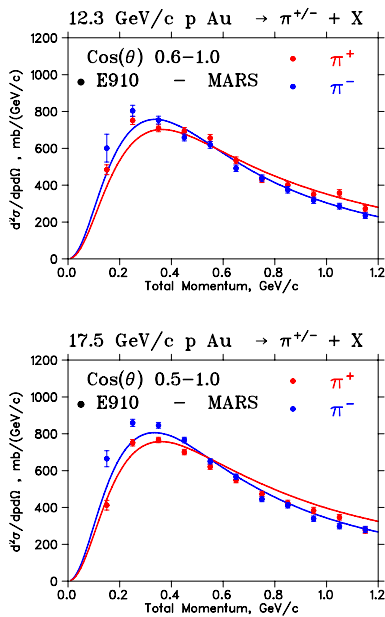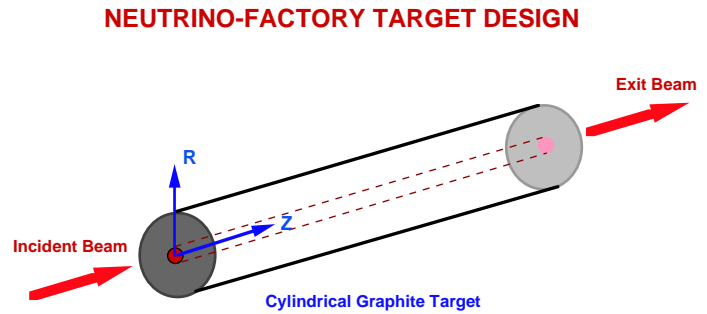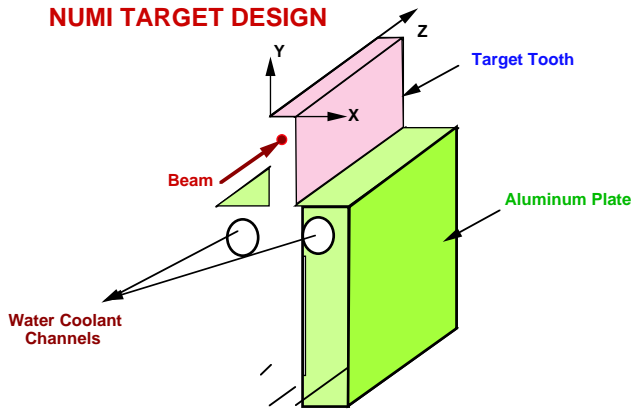

- A carbon target is feasible for 1.5-MW proton beam power.

- For $E_p \gtrsim 16$ GeV, factor of 2 advantage with high-Z target.

- Static high-Z target would melt, $\Rightarrow$ Moving target.

- A free mercury jet target is feasible for beam power of 4 MW (and more).

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.

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

ν fact
π μ
Muon Collaboration

A Carbon Target is Feasible at 1-MW Beam Power

NUMI TARGET DESIGN

NEUTRINO-FACTORY TARGET DESIGN

Target Tooth

Beam

Aluminum Plate

Water Coolant Channels

Exit Beam

R

Incident Beam
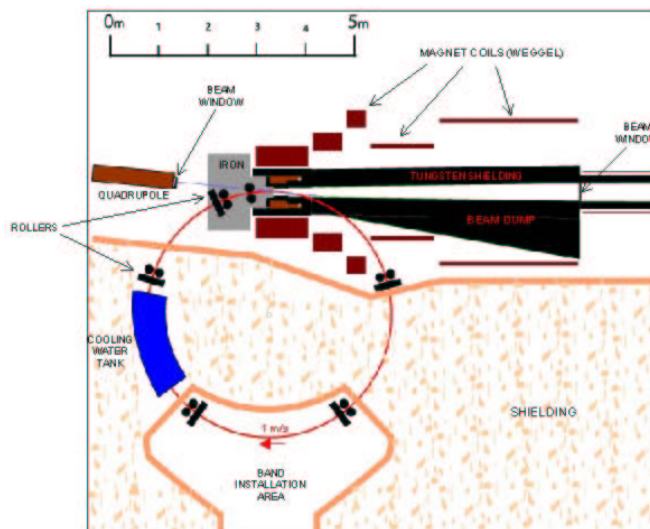
Z

Cylindrical Graphite Target

HASSANEIN (ANL)

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

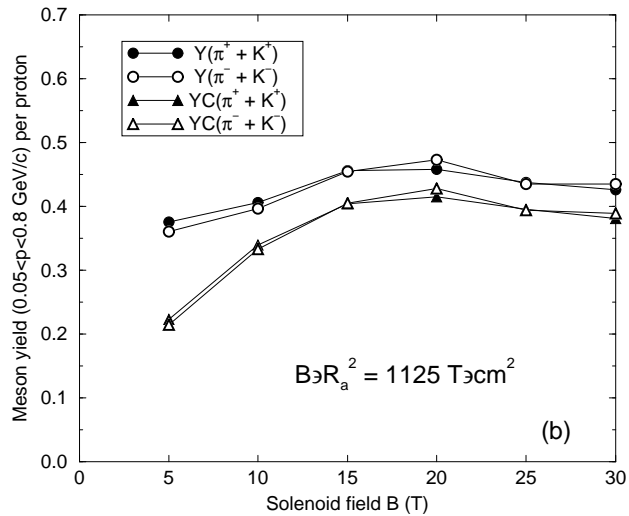Sublimation of carbon is negligible in a helium atmosphere.

Radiation damage is limiting factor: $\approx$ 12 weeks at 1 MW.
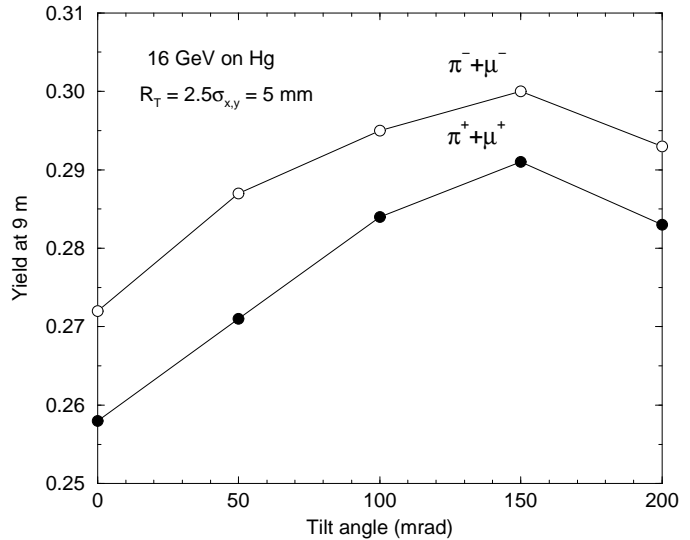
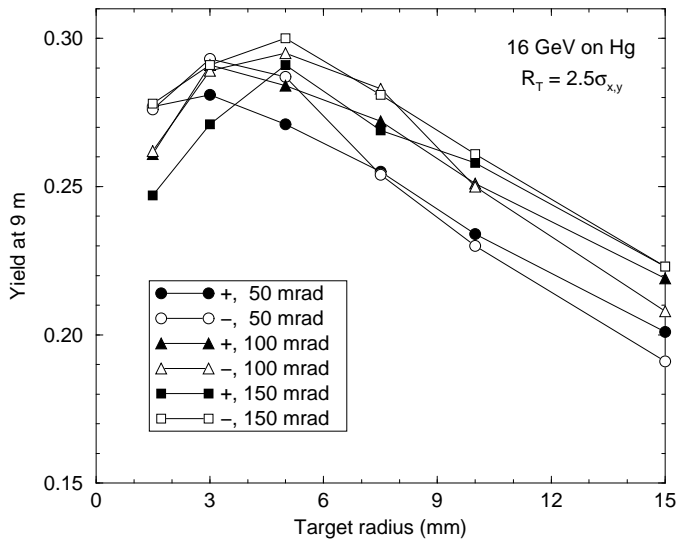A rotating band target is another option:

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.

Target System Layout
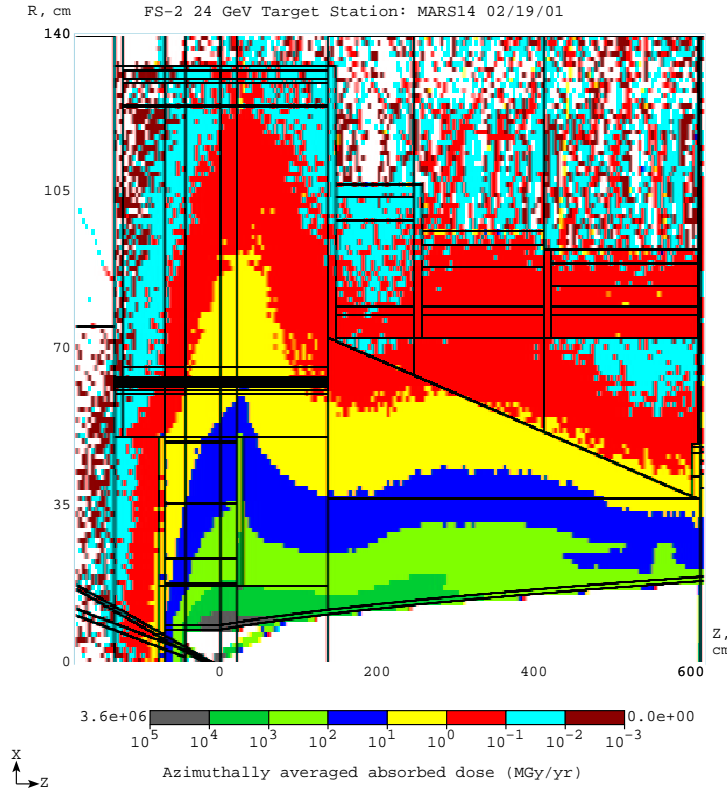
Mercury jet target inside a magnetic bottle: 20-T around target, dropping to 1.25 T in the pion decay channel.
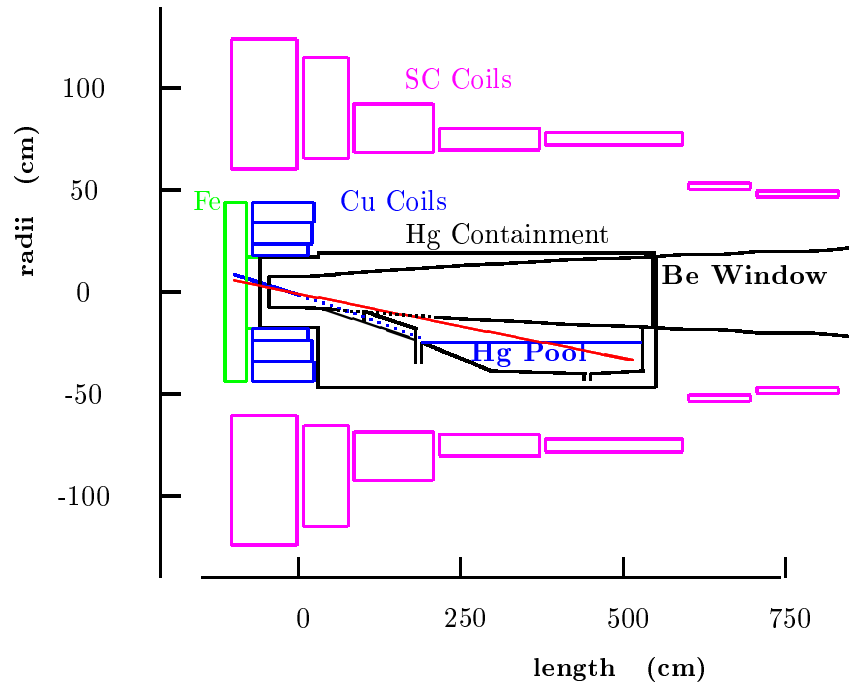
Mercury jet tilted by 100 mrad, proton beam by 67 mrad.
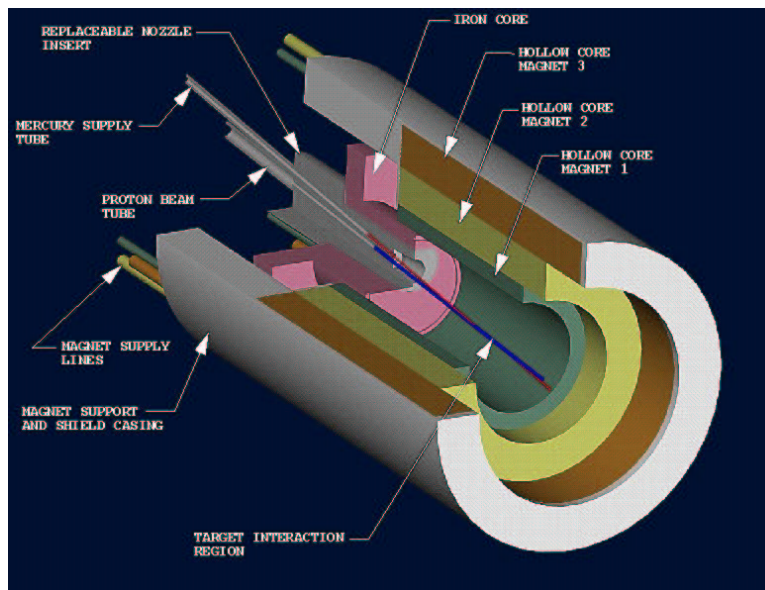
Lifetime of Components in the High Radiation Environment

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.**

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

Muon Collaboration
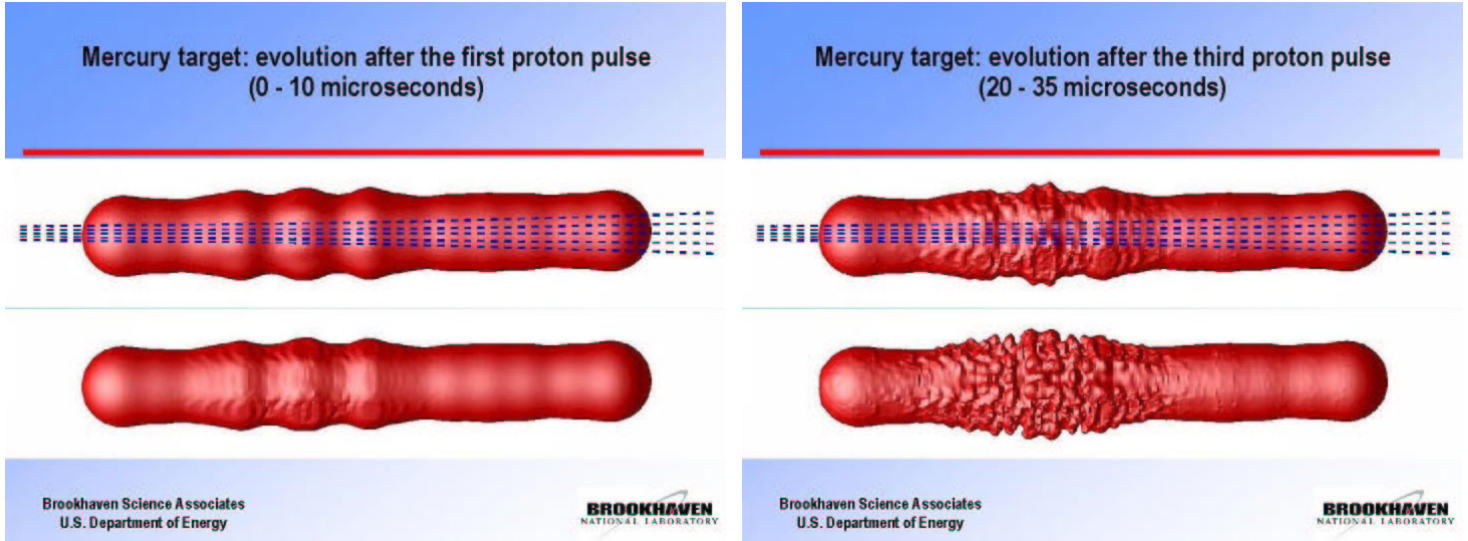
E951 Studies the Single Pulse Issues

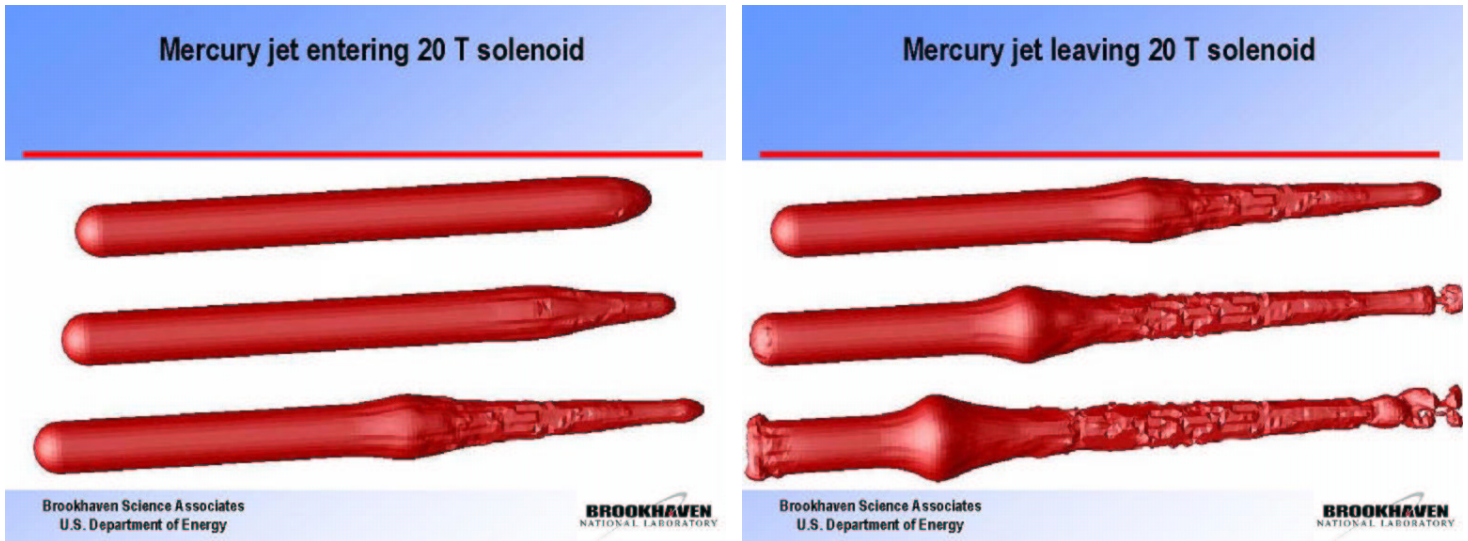**Overall Goal:** Test key components of the front-end of a neutrino factory in realistic single-pulse beam conditions.

Near Term (1-2 years): Explore viability of a liquid metal jet target in intense, short proton pulses and (separately) in strong magnetic fields.

Mid Term (3-4 years): Add 20-T magnet to beam tests; Test 70-MHz rf cavity (+ 1.25-T magnet) 3 m from target; Characterize pion yield.
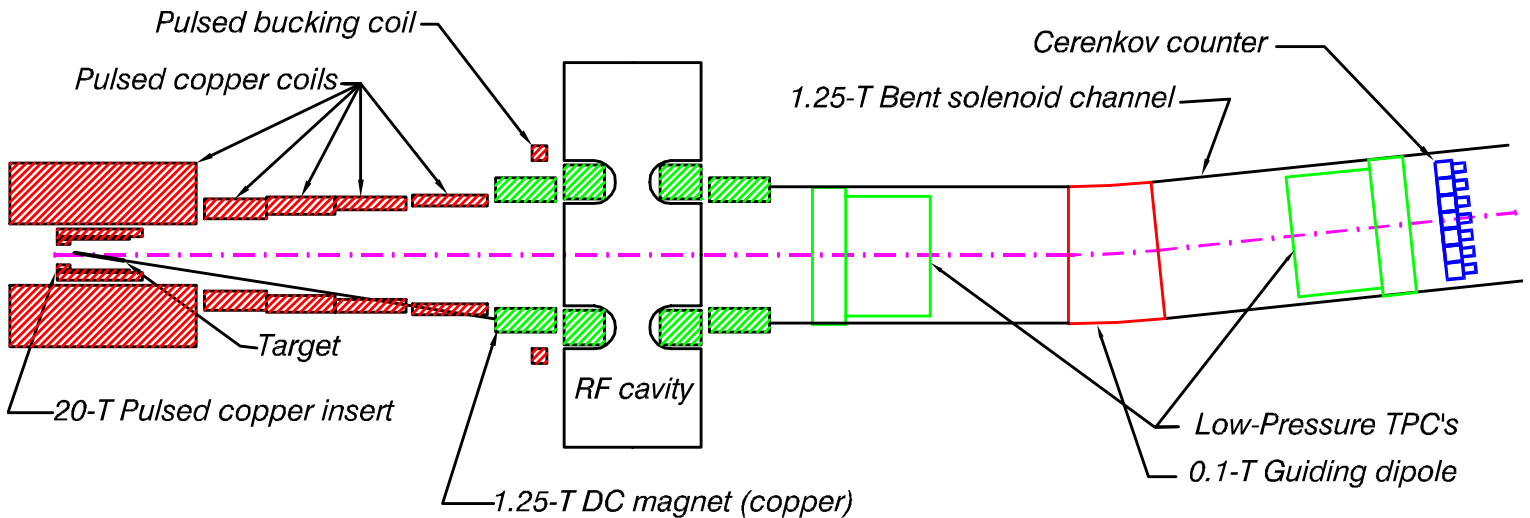
The E951 Collaboration

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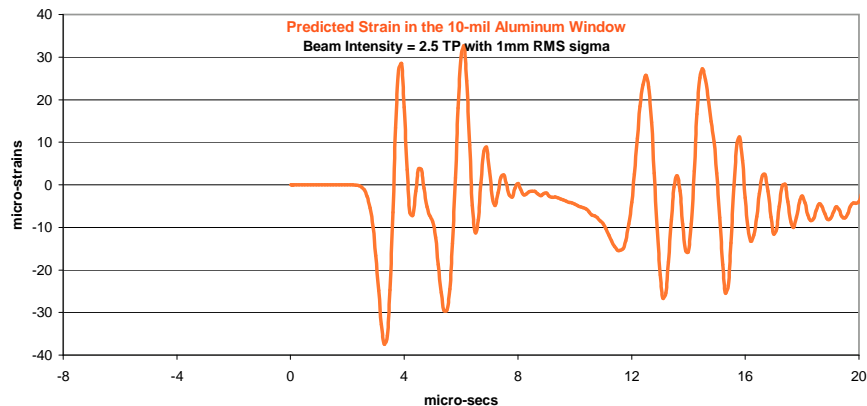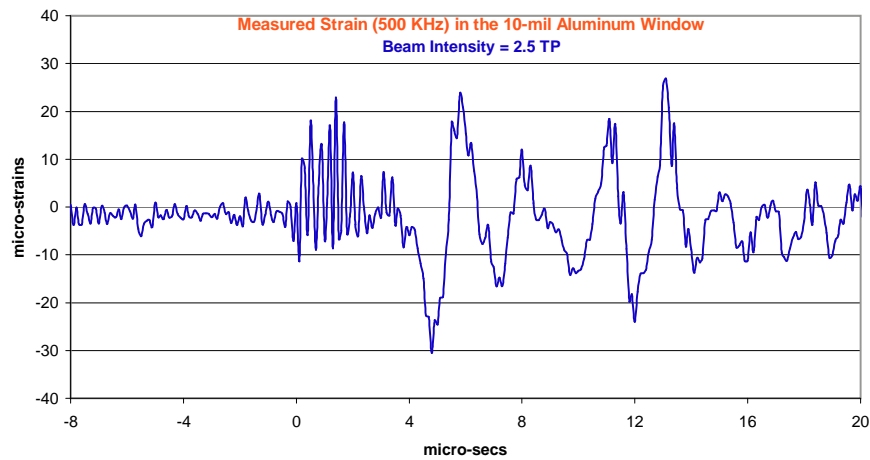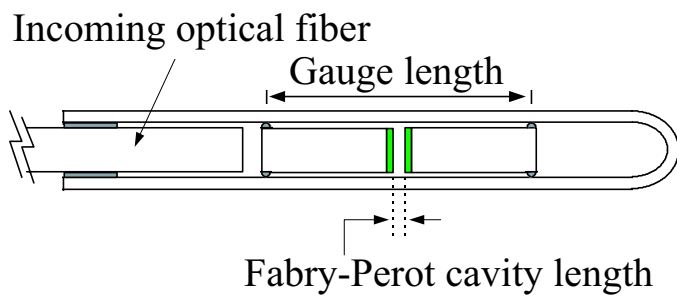[i]Oak Ridge National Laboratory, Oak Ridge, TN 37831
[j]Princeton University, Princeton, NJ 08544

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[2]Spokesperson. Email: mcdonald@puphep.princeton.edu

Muon Collaboration

Solid Target Tests (5e12 $p$pp, 24 GeV, 100 ns)

Carbon, aluminum, Ti90Al6V4, Inconel 708, Havar, instrumented with fiberoptic strain sensors.

Incoming optical fiber

Gauge length

Fabry-Perot cavity length

Measured Strain (500 KHz) in the 10-mil Aluminum Window
Beam Intensity = 2.5 TP

Predicted Strain in the 10-mil Aluminum Window
Beam Intensity = 2.5 TP with 1mm RMS sigma

Passive Mercury Target Tests
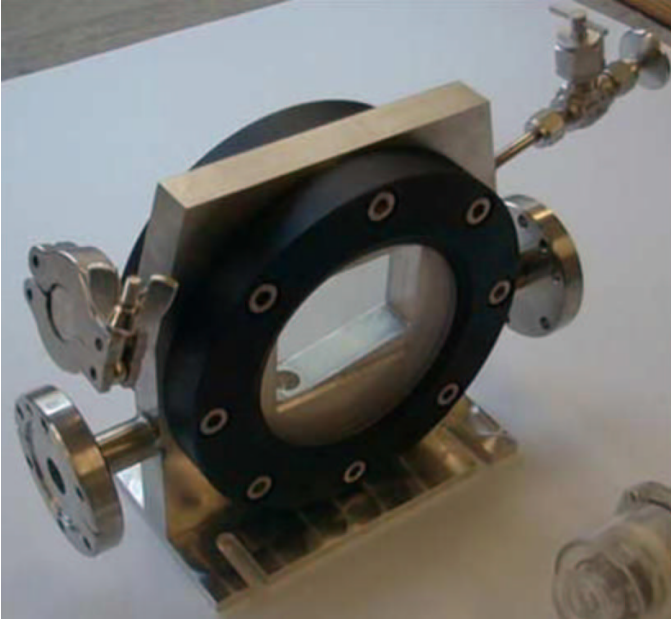
Exposures of 25 μs at
$t = 0,\ 0.5,\ 1.6,\ 3.4$ msec,
$\Rightarrow v_{\text{splash}} \approx 20 - 40$ m/s:
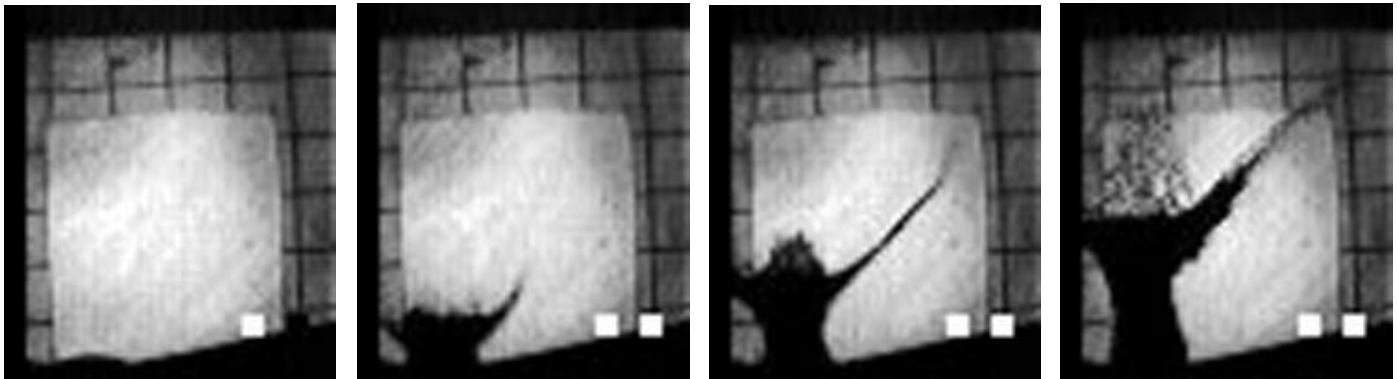
Two pulses of ≈ 250 ns give larger dispersal velocity only if separated by less than 3 μs.

Studies of Proton Beam + Mercury Jet
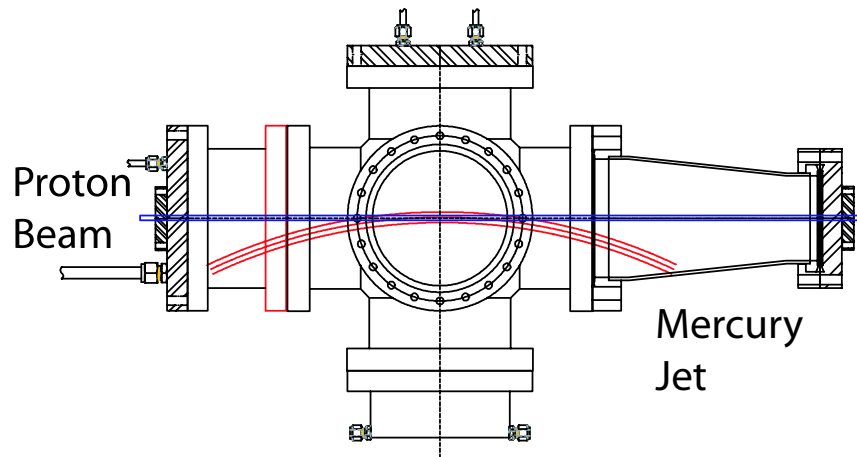
1-cm-diameter Hg jet in 2e12 protons at $t = 0, 0.75, 2, 7, 18$ ms.

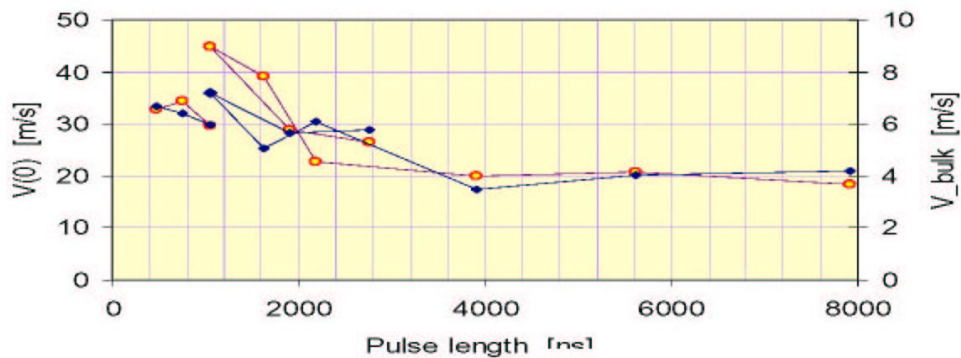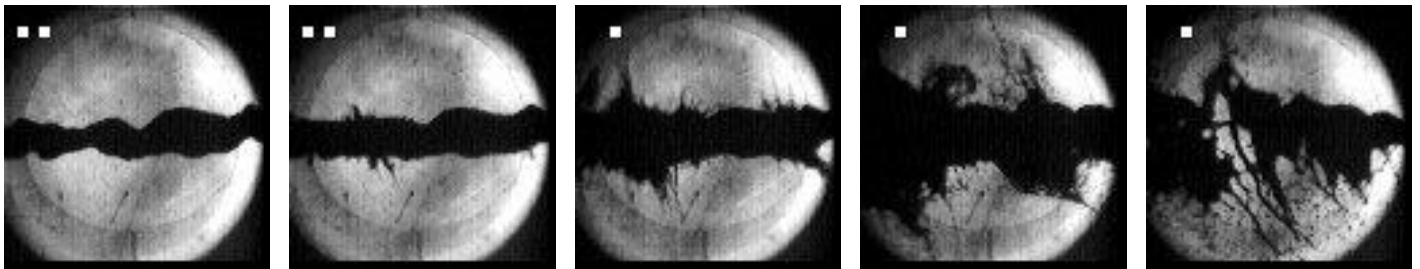Model: $v_{\text{dispersal}} = \dfrac{\Delta r}{\Delta t} = \dfrac{r\alpha\Delta T}{r/v_{\text{sound}}} = \dfrac{\alpha U}{C}v_{\text{sound}} \approx 50$ m/s

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.

Tests of a Mercury Jet in a 13 T Magnetic Field

(CERN/Grenoble High Magnetic Field Laboratory)

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

Analytic model suggests little effect if jet nozzle inside field.
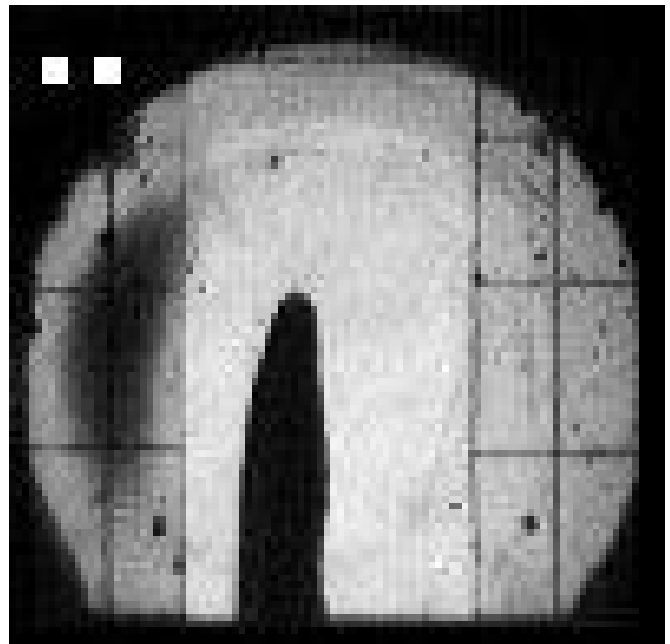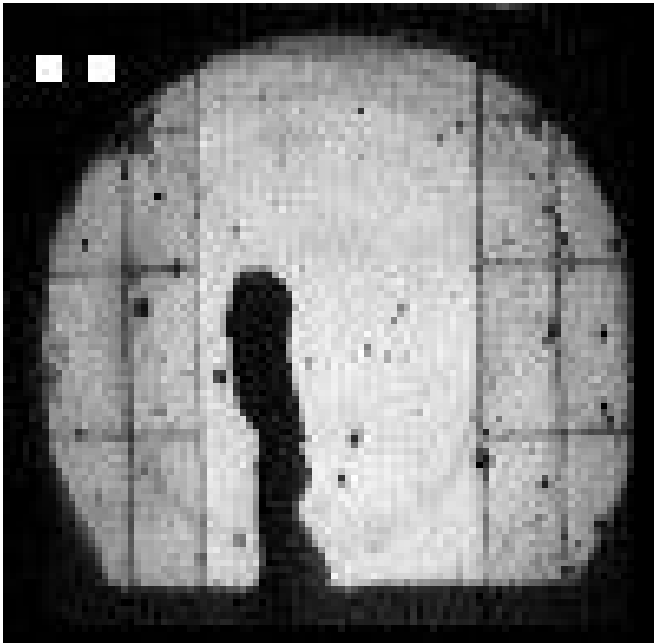
4 mm diam. jet, $v = 4.6$ m/s, $B = 0$ T; $v = 4.0$ m/s, $B = 13$ T:

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

20-T Capture Magnet System

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

101 mm
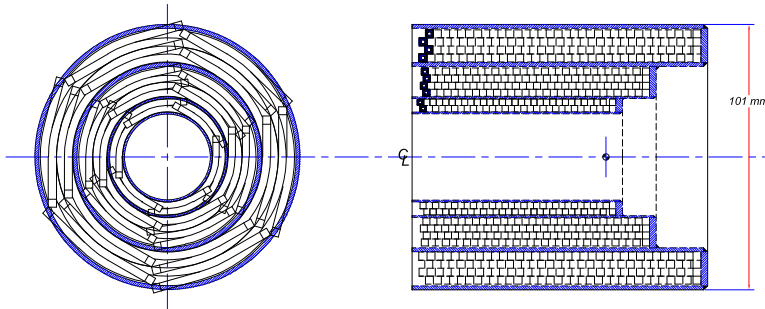
Bitter-coil option less costly, but marginally feasible.

Outer, superconducting coils generate 14 T @ 600 MJ:

Central Solenoid (CS) Model Coil

Conductor Joint

CS Insert (Japan)

Inner Module (USA)
(1st～10th Layer)

Outer Module (Japan)
(11th～18th Layer)

5.7m

Incoloy Alloy 908 Conduit

>1000 superconducting wires

Supercritical helium flows in interstices
and central channel
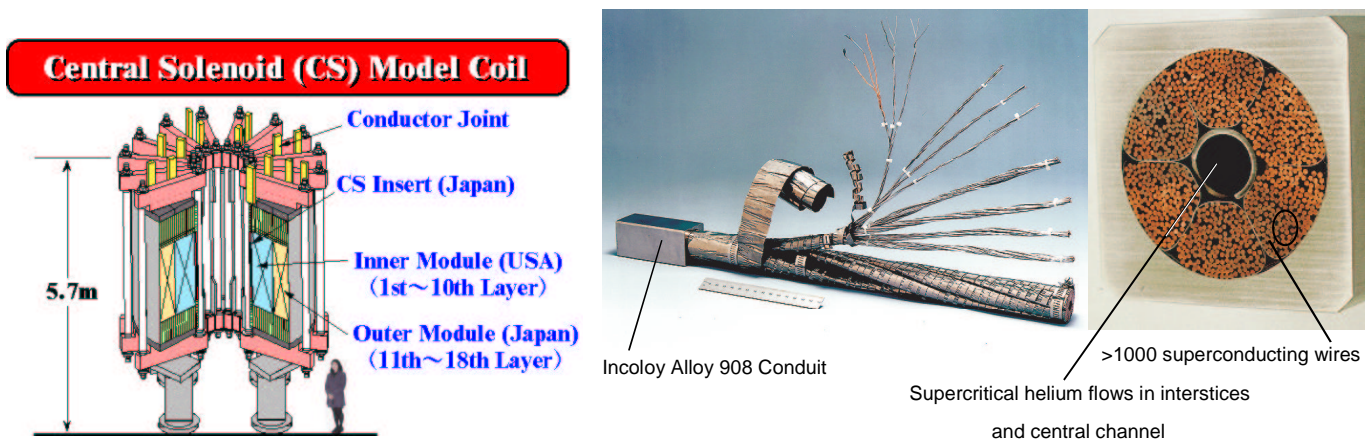
Cable-in-conduit construction similar to ITER central solenoid.

Both coils shielded by tungsten-carbide/water.

Target System Support Facility

Extensive shielding; remote handling capability.
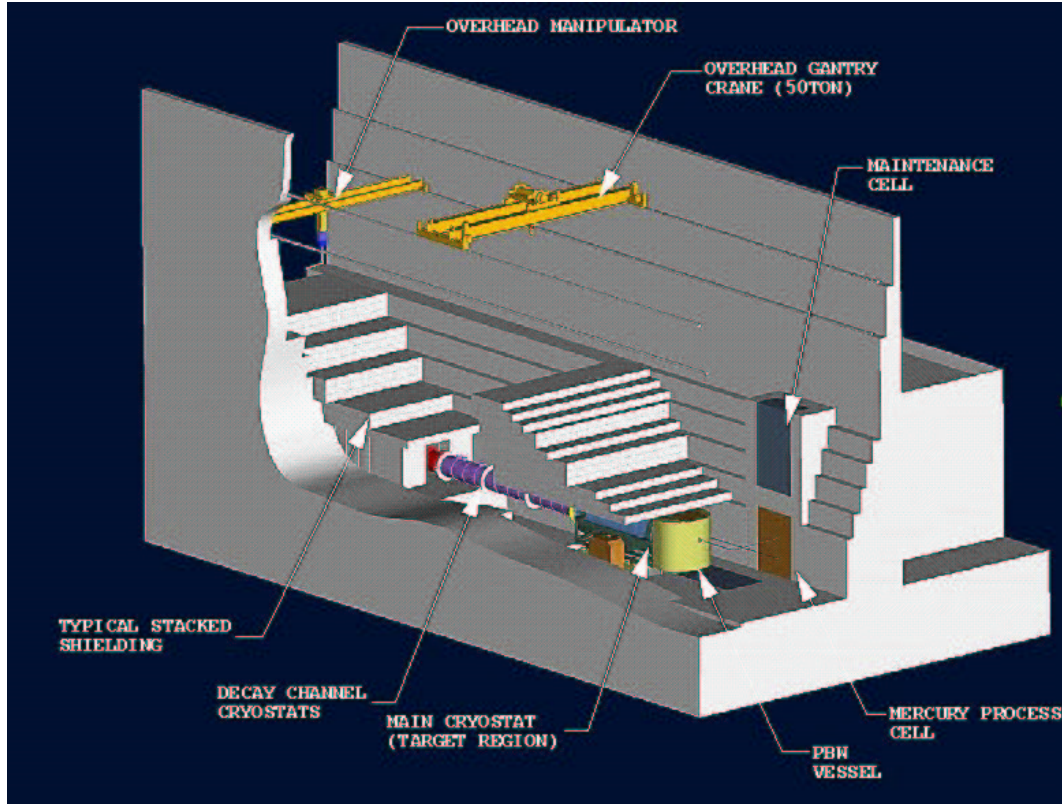
Summary of Targetry Activities Through FY01

- Liquid metal targets in vessels show beam-induced cavitation damage to entrance window (ISOLDE, 1995, LANL, 2001).

- Beam tests of large passive mercury target for SNS (BNL 1998, LANL 2000) suggest velocity of sound may be reduced temporarily by beam-induced microcavitation).

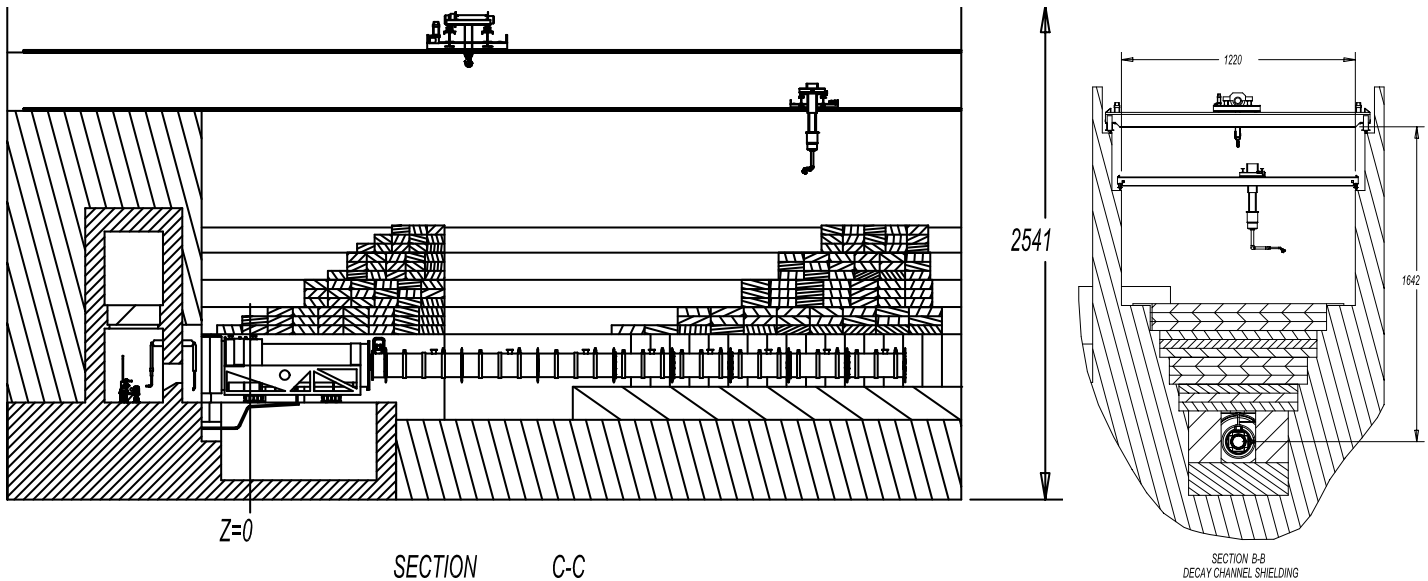- MARS simulations of beam-target interactions $\Rightarrow$ advantage of high-Z target, of high-field capture solenoid, of tilted beam and target, and disadvantages of high radiation dose (Mokhov).

- Analytic simulations of beam-induced pressure waves in target (Sievers), and of MHD effects of mercury jet entering magnet (KTM, Palmer, Weggel) indicate "feasibility", but need for R&D.

- Numerical simulations (Hassanein, Samulyak) tend to confirm these analytic estimates.

- Beam tests of high-strength solid targets show good agreement between strain-sensor data and ANSYS simulation, and suggest that they can survive single-pulse stresses up to Study-2 design intensity, $= 16$ TP / 8 mm^2 (BNL, March '01).

- Calculation and experiment indicate that a carbon target could survive against sublimation in a He atmosphere in a 4 MW beam (Thieberger, ORNL).

- Beam tests of active and passive mercury targets indicate dispersal velocities of manageable size, proportional to proton pulse energy (BNL, April '01; ISOLDE, Aug. '01).

- Tests of mercury jets entering a high-field solenoid not yet definitive (CERN, Grenoble, 2001).

Issues for Further Targetry R&D

- Continue numerical simulations of MHD + beam-induced effects [Samulyak].

- Continue tests of mercury jet entering magnet [CERN, Grenoble].

- 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 prototype target configuration.

  2. Magnetic damping of mercury-jet dispersal.

 3. Beam-induced damage to jet nozzle – in the magnetic field.

Further Beam Studies without High-Field Magnet

- Studies of production of mercury jets up to 20 m/s. Jet quality is the issue.

- Construction of new liquid metal jet targets with continuous flow: mercury and Wood's metal.

- Upgrade AGS to 8/16 TP single pulses [Roser].

  1. Improve control of fast extraction with bipolar power supply for a key vertical sextupole.

  2. Improve control of chromaticity of bunches during transition with heftier power supply for main ring horizontal sextupoles.

  3. Explore schemes for 2:1 bunch merging at 24 GeV via rf manipulation.

- Test the continuous-flow targets in beam once at least 8 TP per pulse are available.

- [Radiation damage studies of solid targets at BNL booster.]

Further Beam Studies with a High-Field Magnet

- Study jet dispersal, and possible damage to nozzle, as a function of beam intensity, magnetic field strength, and nozzle position.

- Online diagnostics will primarily be optical (+ possible use of fiberoptic strain sensors).
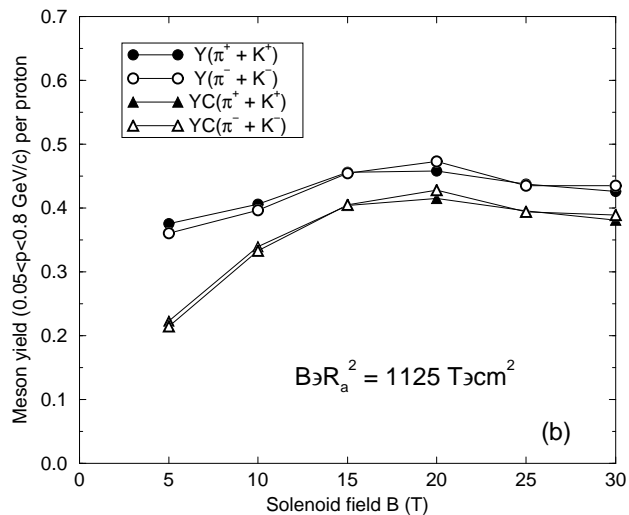
CERN/Grenoble optical system that fits in 20-cm magnet bore:
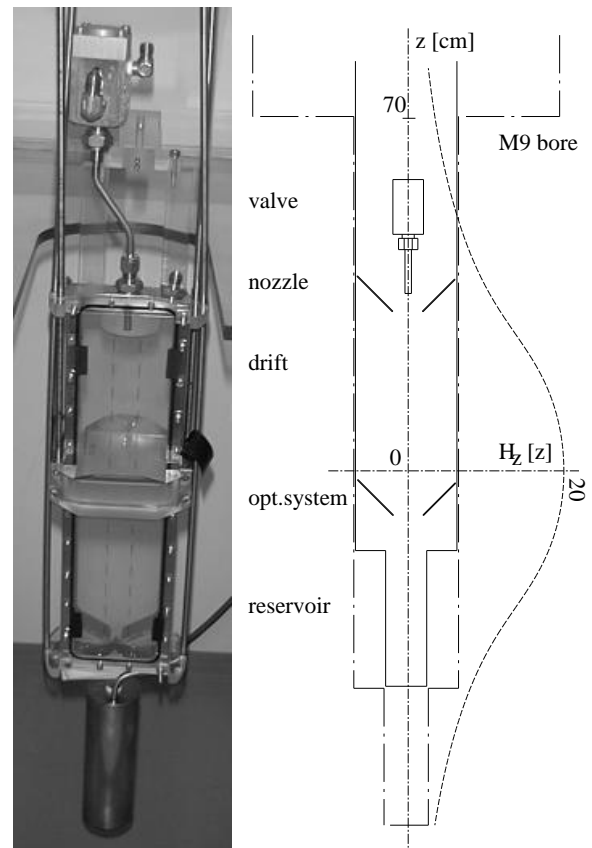
- To be affordable, construct a 15-T pulsed solenoid magnet.

What Magnetic Field Strength is Appropriate?

- Our muon collider and neutrino factory designs have long called for a 20-T capture solenoid.

A 20-T magnet must be a hybrid: 6-T copper "insert" + 14-T superconducting "outsert".

The small gain in performance from 14 to 20 T may not warrant the cost and complexity of the hybrid magnet.

A capture solenoid for a superbeam needs a larger bore to trap higher $P_\perp$ pions, for which 14 T is then sufficient.

$\Rightarrow$ Our physics goals are well satisfied by a 14-T capture solenoid.

Should the Pulsed R&D Magnet have Lower Field?

- Most magnetic-field effects on the mercury jet scale as the magnetic pressure $B^2/8\pi$ (for a fixed geometry).

- Thus, a study using a 5-T magnet would require a factor of 8 extrapolation to the desired performance at 14 T.

- Present cost estimates indicate that we can build a 14-T pulsed magnet for about twice the cost of a 5-T pulsed magnet.

- $\Rightarrow$ We propose to construct a 14.5-T pulsed magnet, that can be staged as a 5-T and 10-T magnet.

A 14.5-T Pulsed Magnet with 5- and 10-T Phased Options

14.5-T Pulsed Magnet (using all 3 coils)
*5- or 10-T magnet using inner 2 coils*
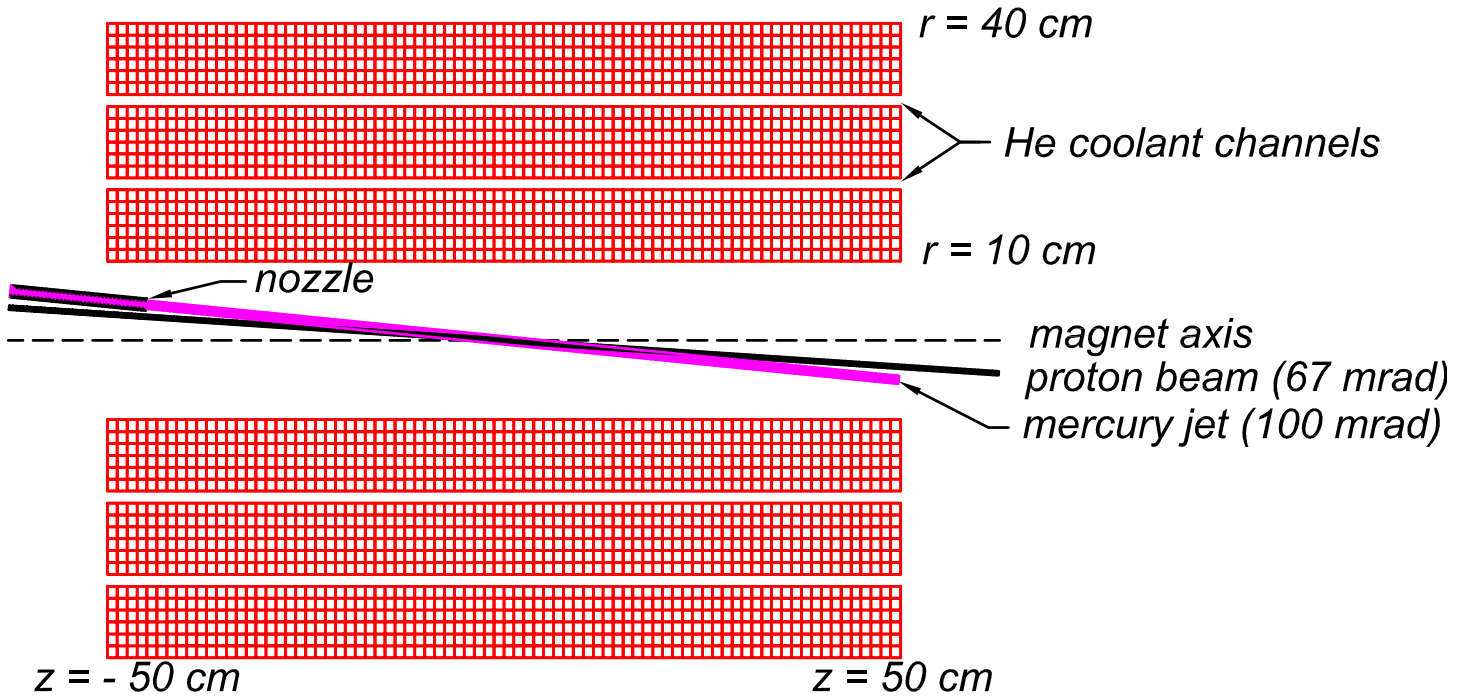
Phase	No. of PS	Coolant	Temp.	Field
1	1	N_2	84 K	5 T
2	4	N_2	74 K	10 T
3	4	H_2	30 K	14.5 T

Keeping Costs Low

- Simple solenoid geometry with rectangular coil cross section and smooth bore (of 20 cm diameter) [Weggel, Titus].

- Power supply built out of 4 existing 540 kVA supplies that can be fed by a single, existing substation [Marneris].

- Cryogenic system reduces coil resistance to give high field at relatively low current [Iarocci].

  – Circulating coolant is gaseous He to minimize activation, and to avoid need to purge coolant before pulsing magnet.

  – Heat exchanger recycled from the SSC.

 – Phase 1 & 2 cooling via N_2 boiloff; Phase 3 via H_2.

Pulsed Magnet System Layout at the AGS
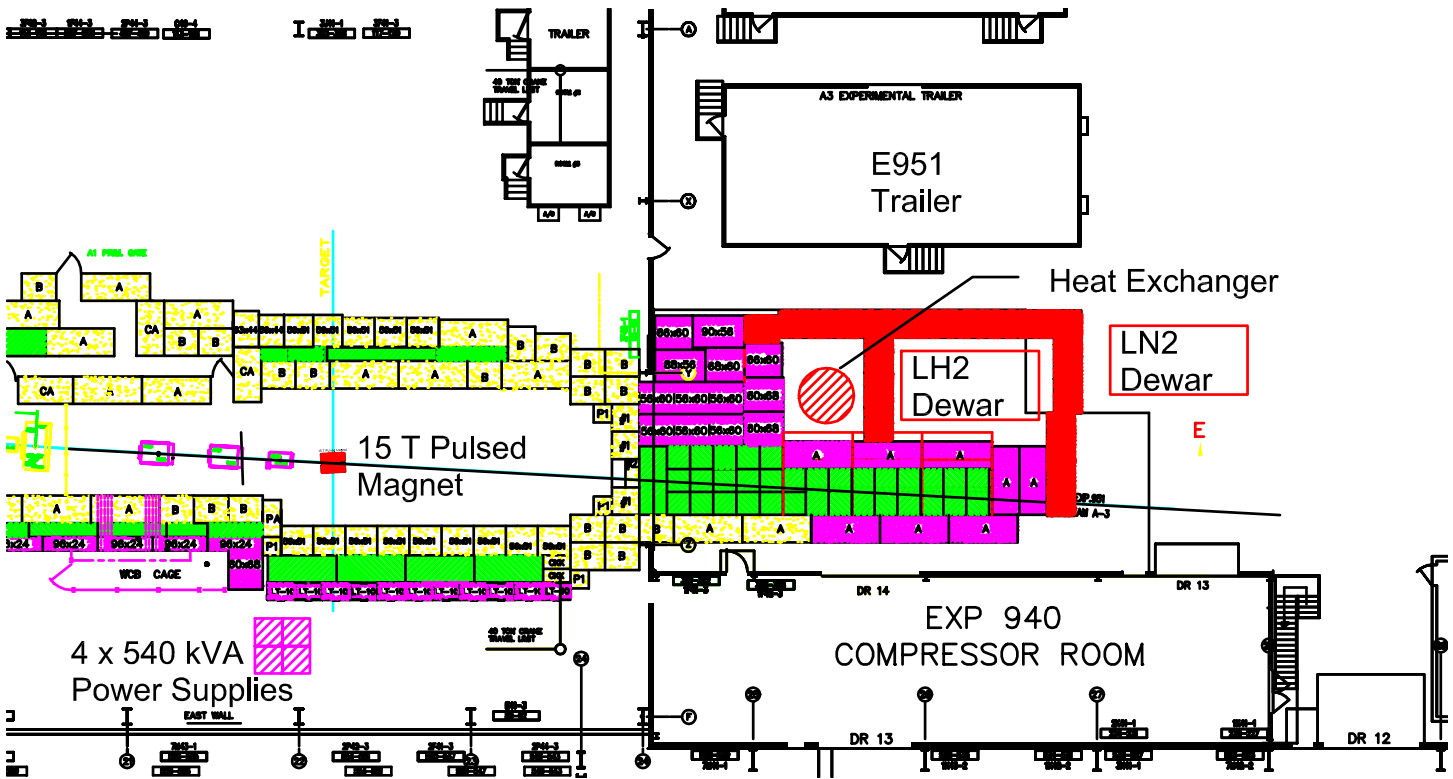
- Locate the 4 x 540 kVA power supplies on the east side of the A3 cave, feed power in via the trench.

- If satisfactory to Safety Committee, locate the heat exchanger and LH$_2$ dewar in a concrete enclosure that extends the present A3 beam stop.

Other Works in Progress

- AGS sextupole power supply upgrades (Brown, Sandberg).

- $2 \to 1$ AGS bunch merging via rf manipulation (Brown, Brennan).

- 2nd round of liquid metal jets: $2.5 \to 20$ m/s; Hg and Pb/Bi alloy (Kirk, McDonald).
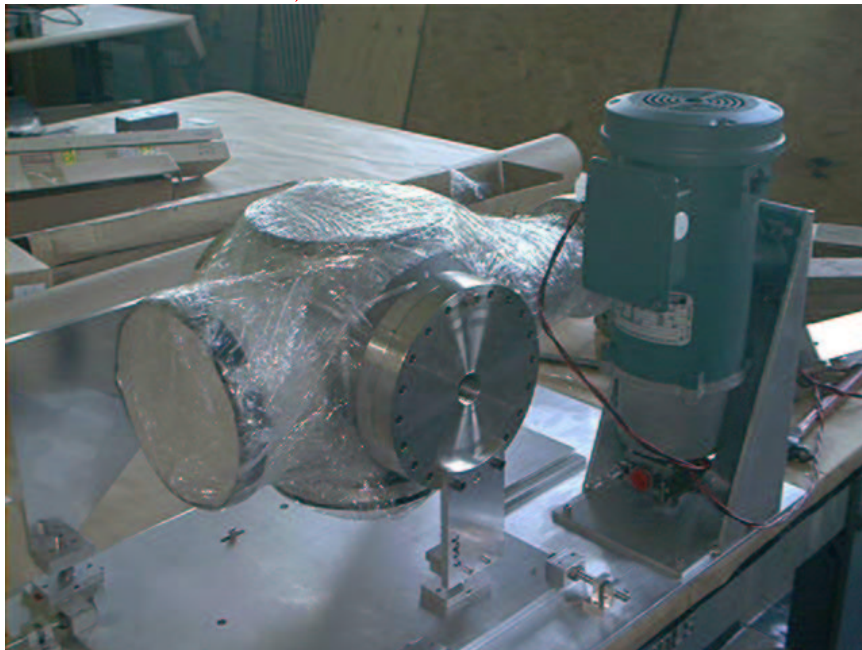
- Radiation damage studies of Invar at BLIP (Thieberger, Weggel).

- Graphite sublimation in a He atmosphere (Haines, Spampinato).

- FEA simulations (Samulyak).