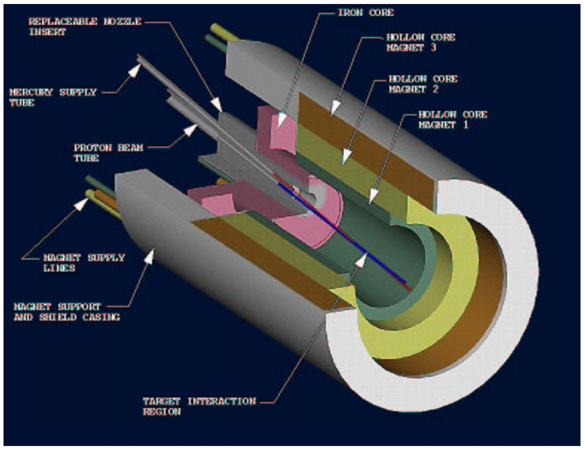
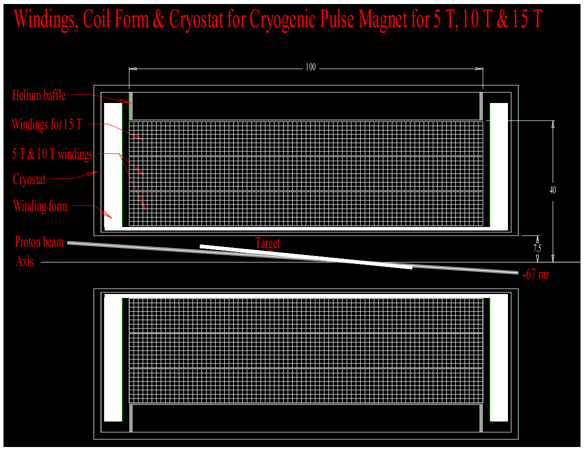
THE NEUTRINO FACTORY AND MUON COLLIDER COLLABORATION

The E-951 15-T Pulsed Solenoid Magnet R&D Facility for a Neutrino Factory / Muon Collider Source




Windings, Coil Form & Cryostat for Cryogenic Pulse Magnet for 5 T, 10 T & 15 T

K.T. McDonald

Princeton U.

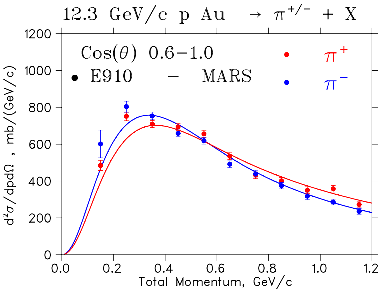
C-AD Safety Review

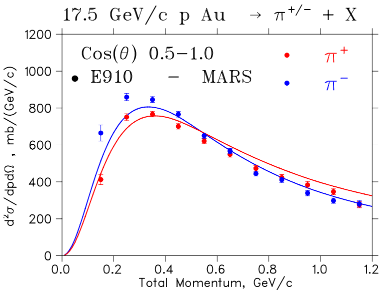
BNL, Sept. 6, 2002

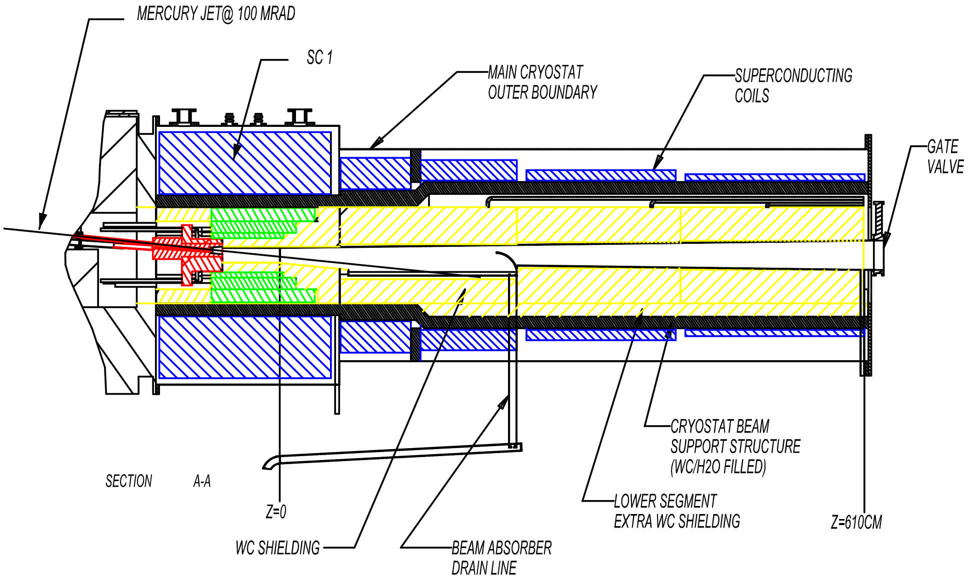
`http://puhep1.princeton.edu/mumu/target/`

Challenges

- Maximal production of soft pions → 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, ⇒ Moving target.
- A free mercury jet target is feasible for beam power of 4 MW (and more).

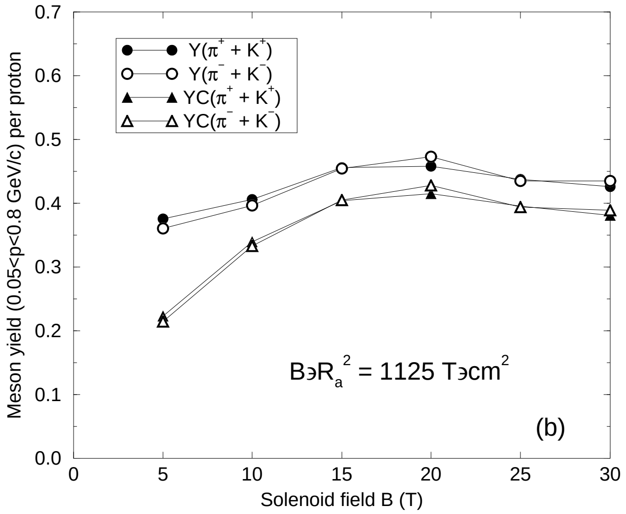
The Neutrino Horn Issue

- 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

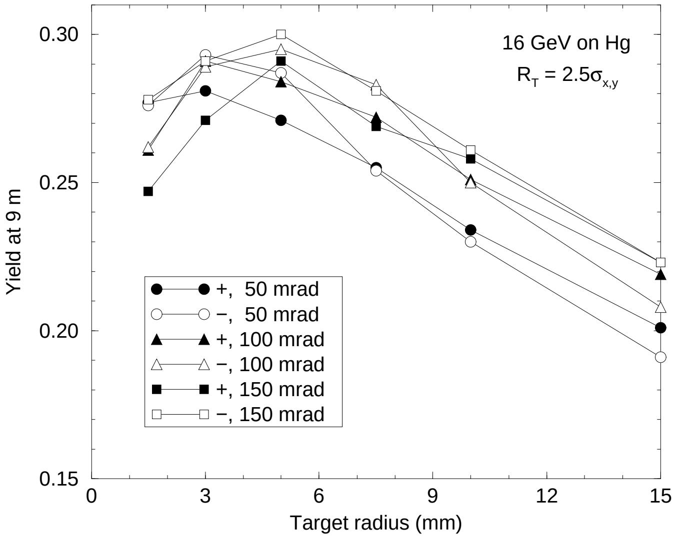
Pion/Muon Yield

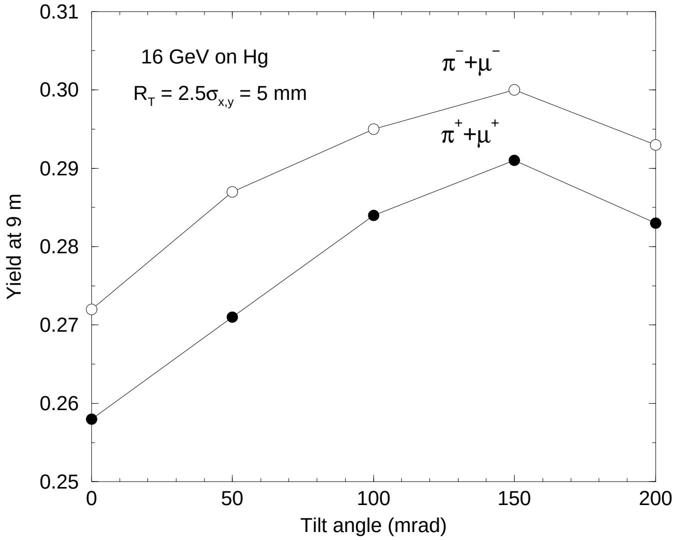
For $E_p \gtrsim 10$ GeV, more yield with high-Z target.



Mercury target radius should be ≈ 5 mm,

with target axis tilted by ≈ 100 mrad to the magnetic axis.

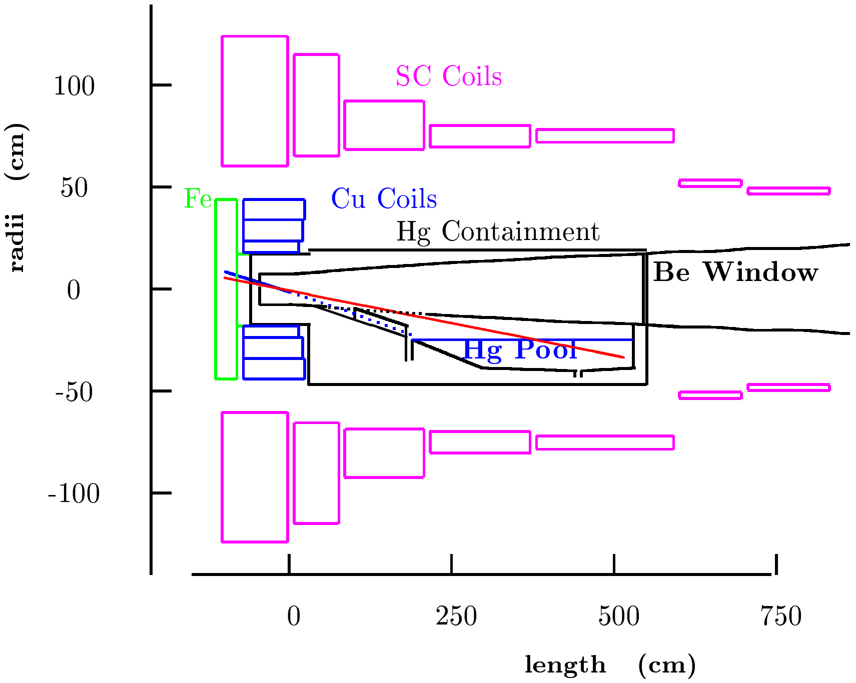




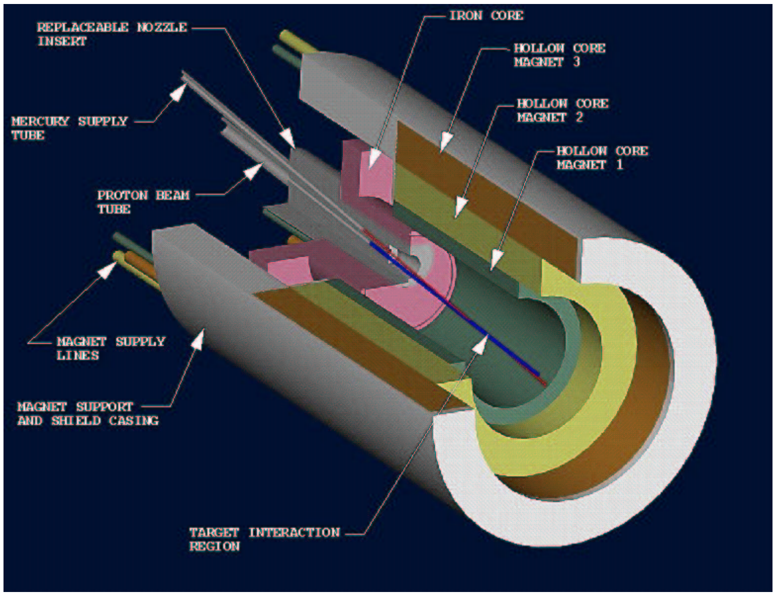
Can capture ≈ 0.3 pion per proton with $50 < P_\pi < 400$ MeV/c.

Target System Layout

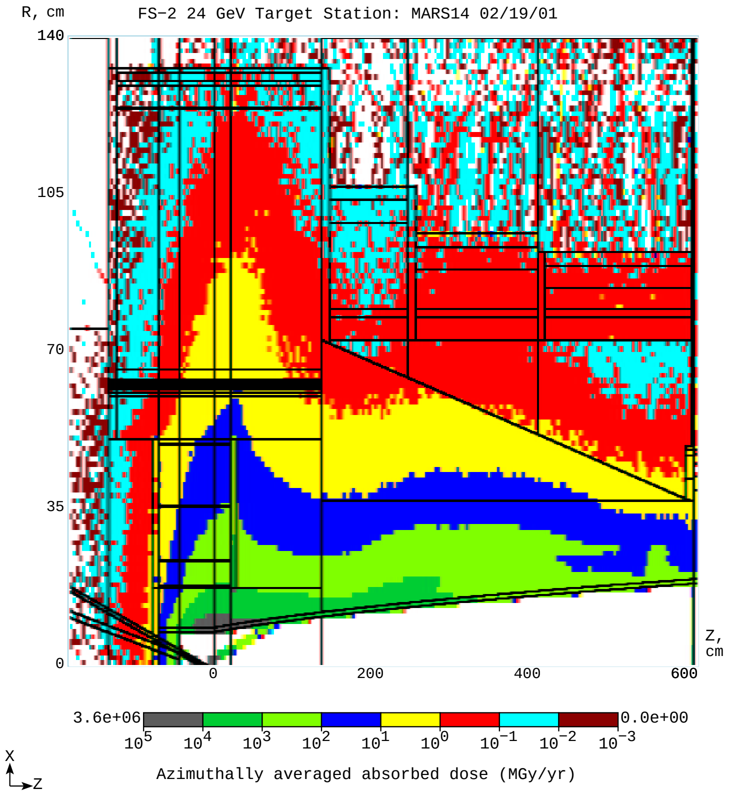
Mercury jet target inside a magnetic bottle: 20-T around target, dropping to 1.25 T in the pion decay channel.



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



Lifetime of Components in the High Radiation Environment

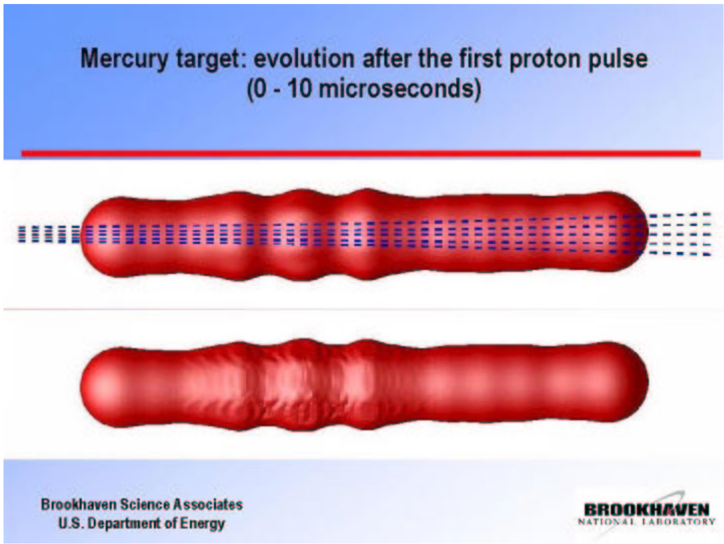


Component	Radius (cm)	Dose/yr (Grays/2×10^7 s)	Max allowed Dose (Grays)	1 MW Life (years)	4 MW life (years)
Inner shielding	7.5	5×10^{10}	10^{12}	20	5
Hg containment	18	10^9	10^{11}	100	25
Hollow conductor coil	18	10^9	10^{11}	100	25
Superconducting coil	65	5×10^6	10^8	20	5

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)

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U.S. Department of Energy

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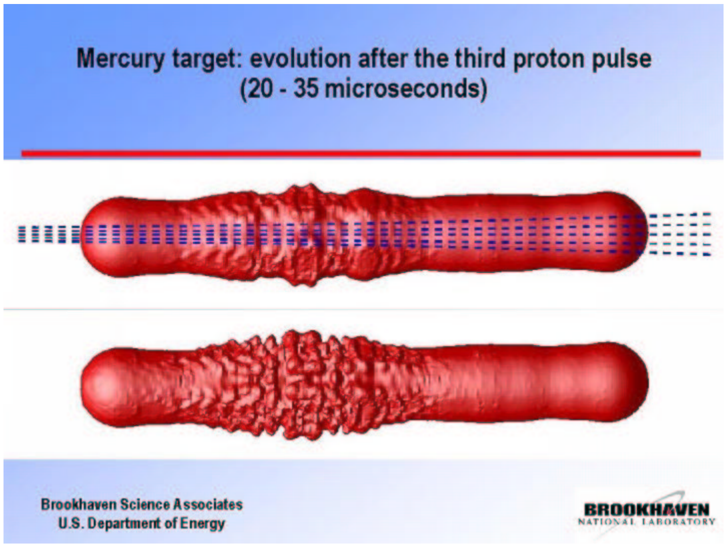

Mercury target: evolution after the third proton pulse
(20 - 35 microseconds)

Brookhaven Science Associates
U.S. Department of Energy

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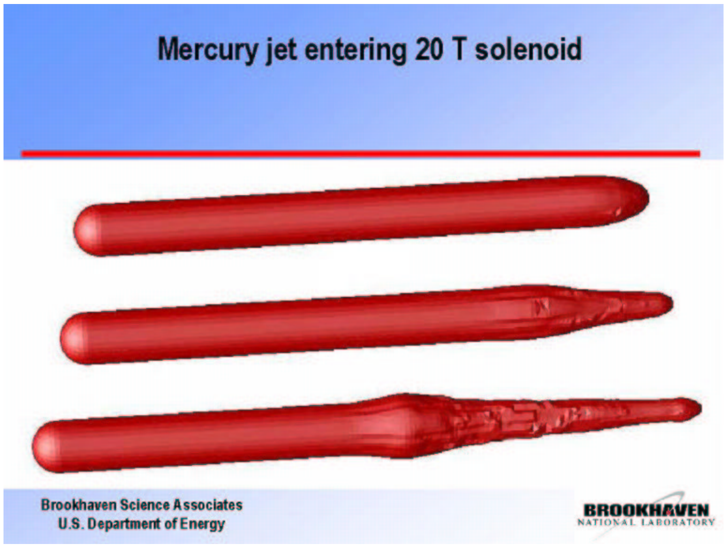
- Eddy currents may distort the jet as it traverses the magnet.



Mercury jet entering 20 T solenoid

Brookhaven Science Associates
U.S. Department of Energy

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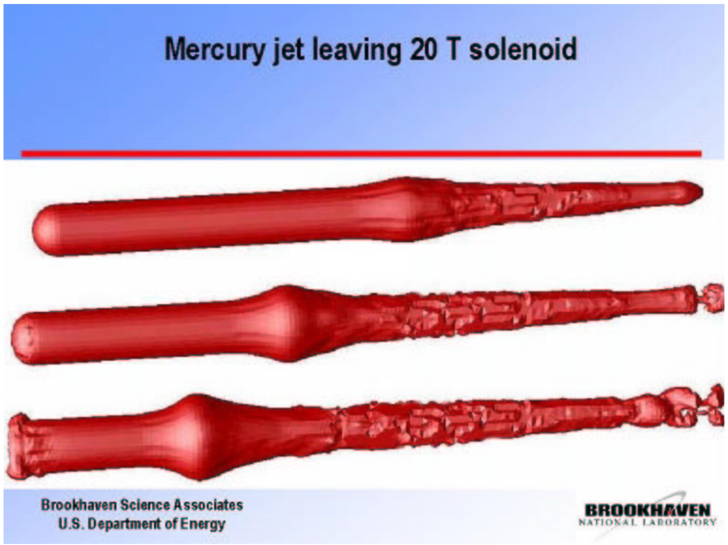

Mercury jet leaving 20 T solenoid

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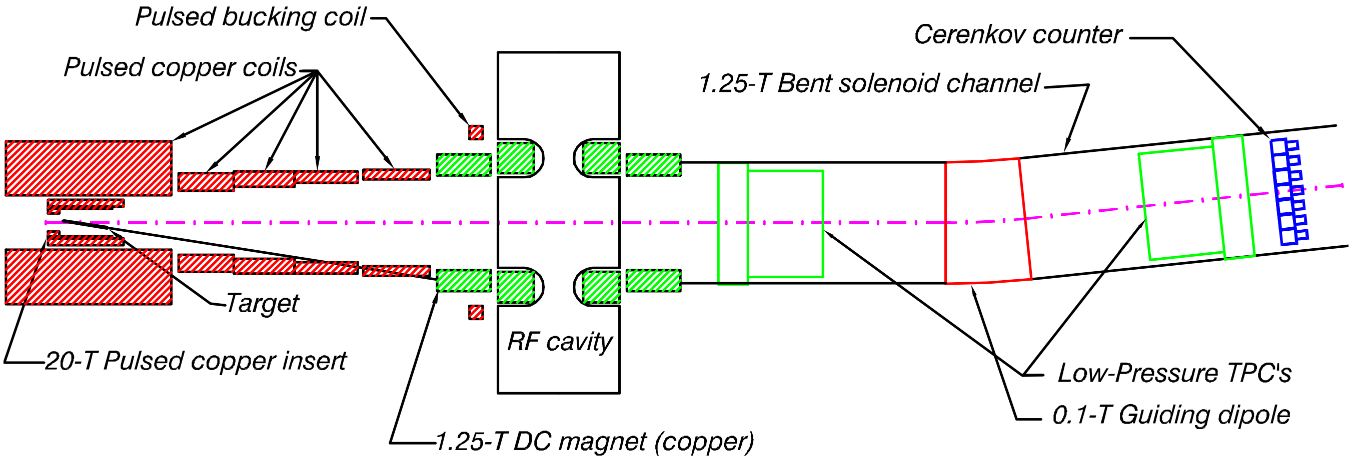
E951 Studies the Single Pulse Issues

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.



We are now beginning the "Mid Term" phase, but with a more affordable 15-T magnet.

The E951 Collaboration

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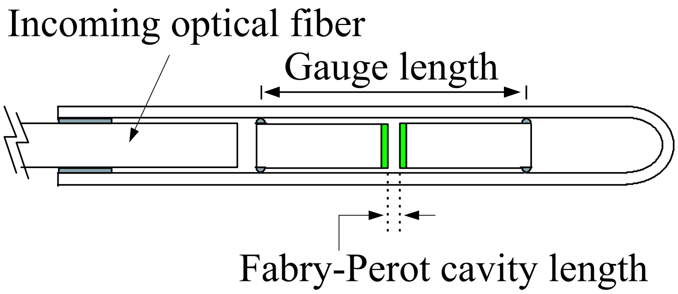
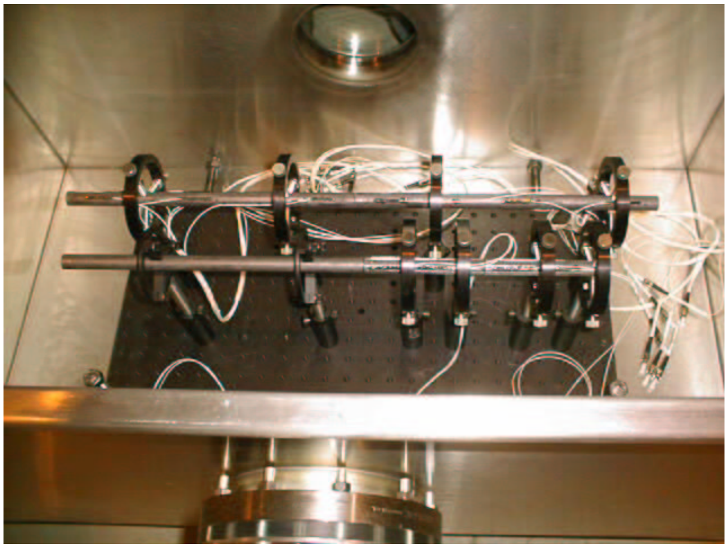
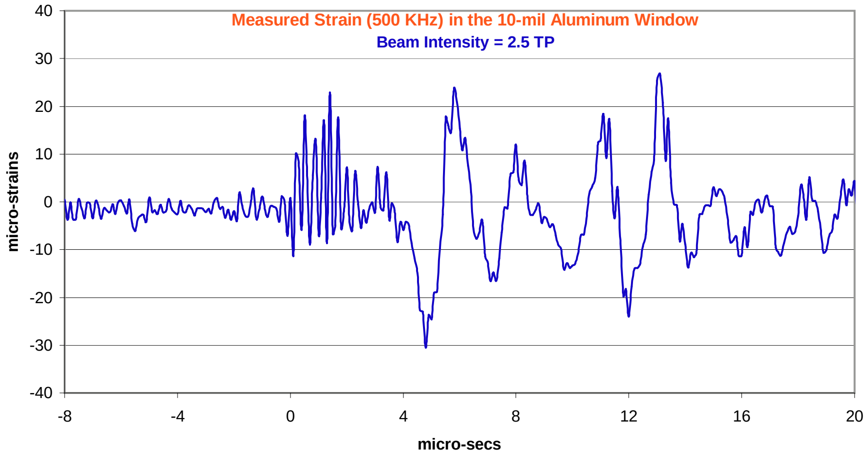
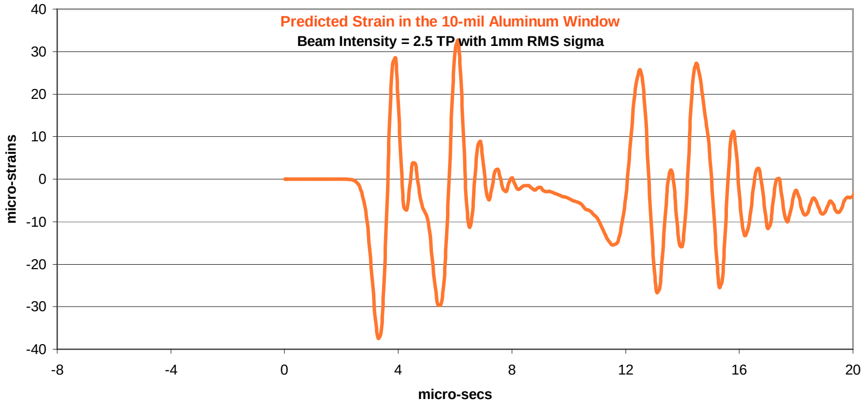
Solid Target Tests (5e12 *p*pp, 24 GeV, 100 ns)

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

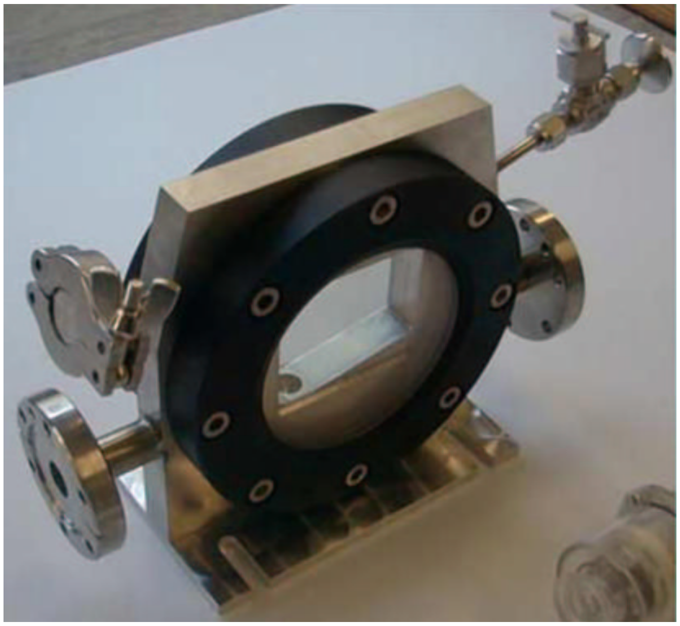




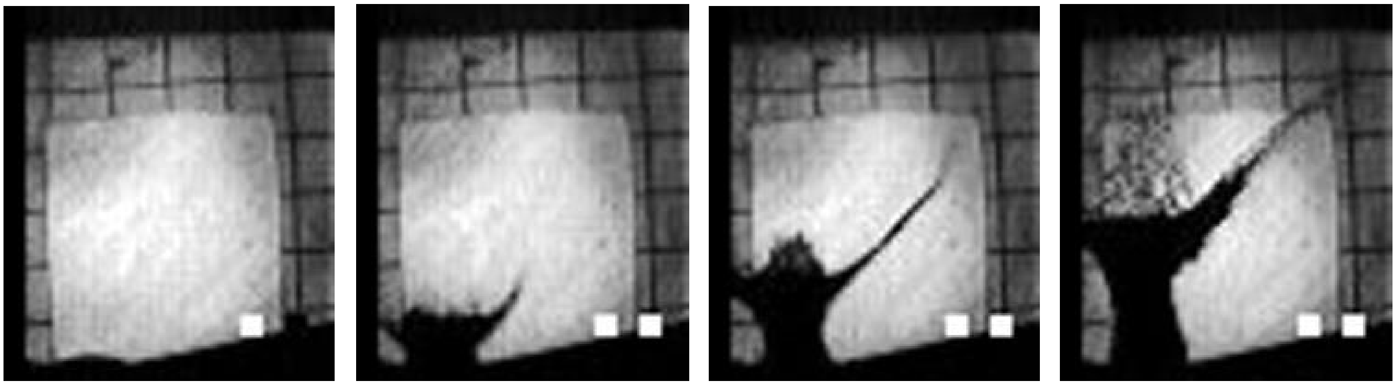




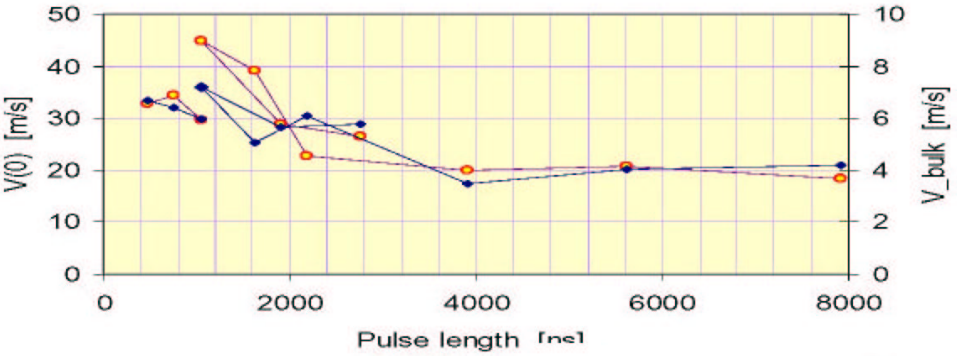
Passive Mercury Target Tests



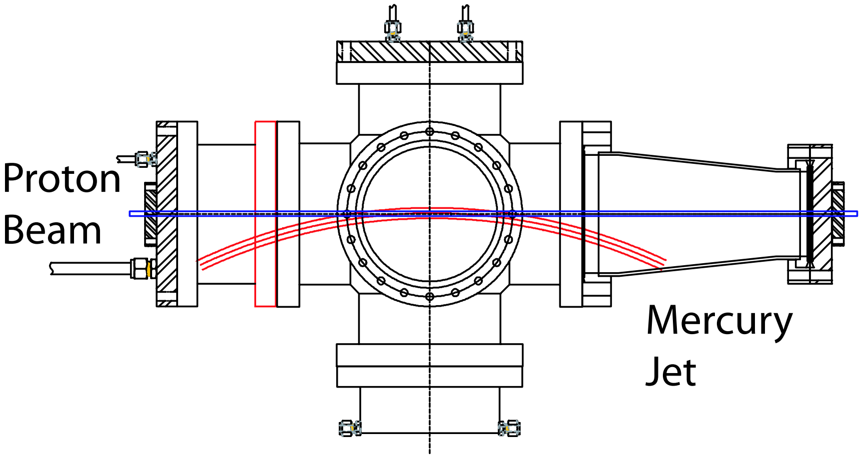
Exposures of 25 μs at
$t = 0, 0.5, 1.6, 3.4$ msec,
$\Rightarrow v_{\text{splash}} \approx 20 - 40$ m/s:



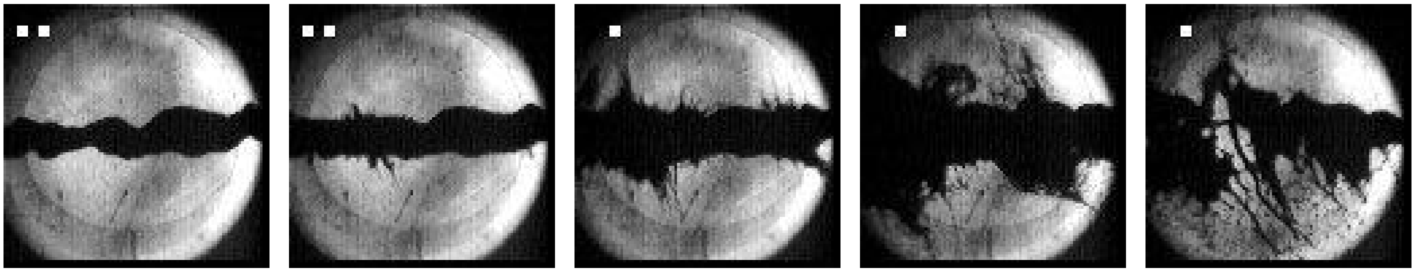
Two pulses of ≈ 250 ns give larger dispersal velocity only if separated by less than 3 μs.



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.

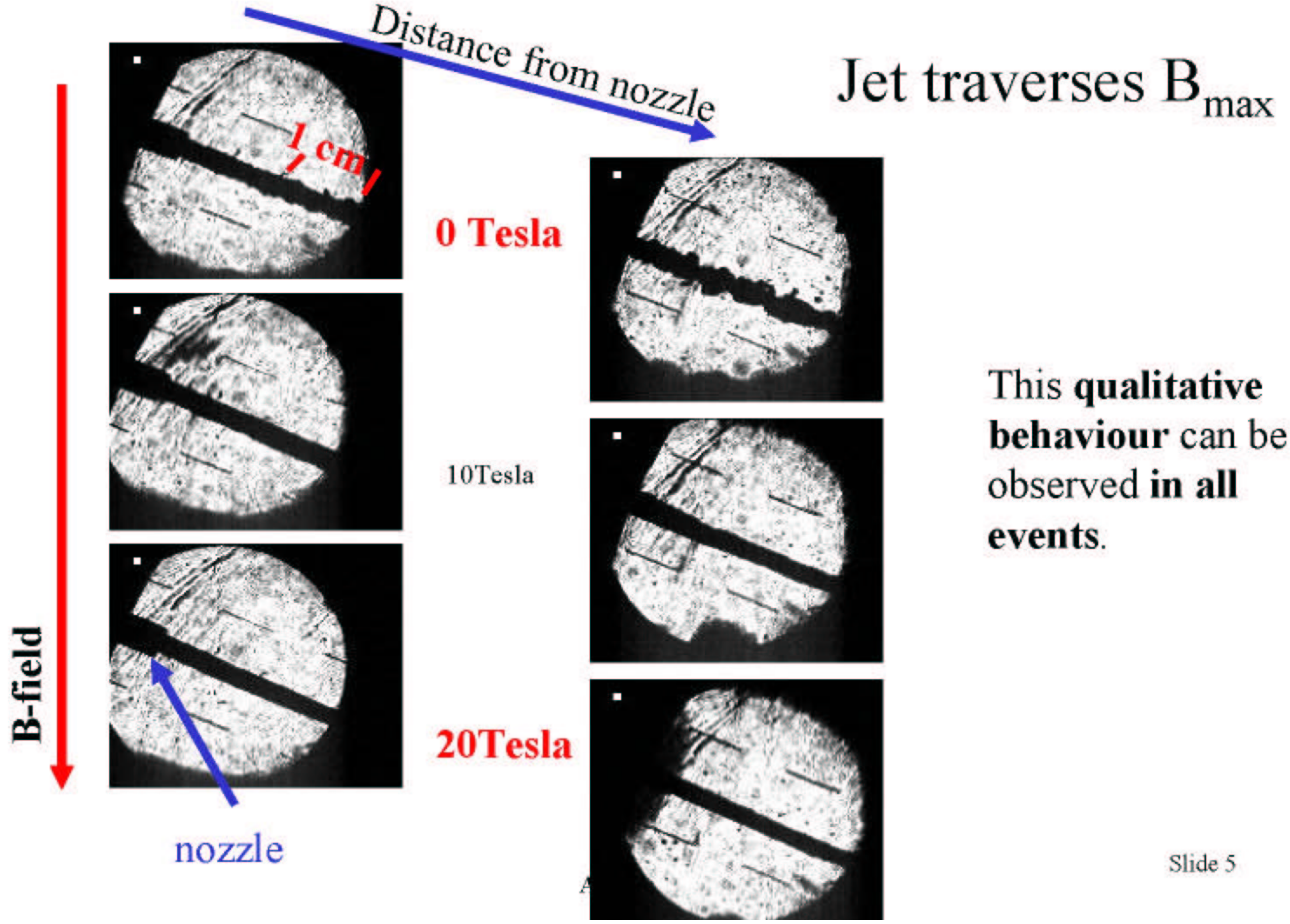
The dispersal is not destructive.

Tests of a Mercury Jet in a 20-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, $v \approx 12$ m/s, $B = 0$, 10, 20 T.



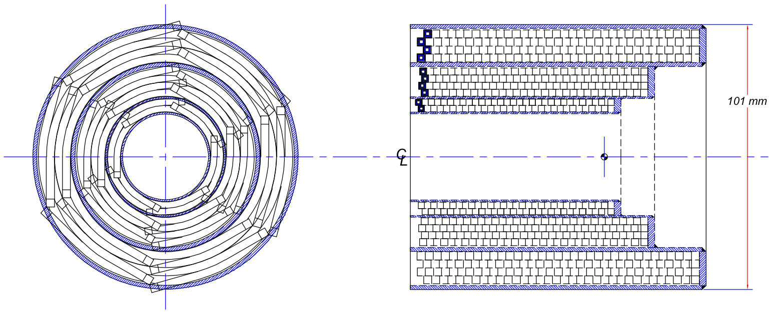
This **qualitative behaviour** can be observed **in all events**.

⇒ Damping of surface tension waves (Rayleigh instability).

Will the beam-induced dispersal be damped also?

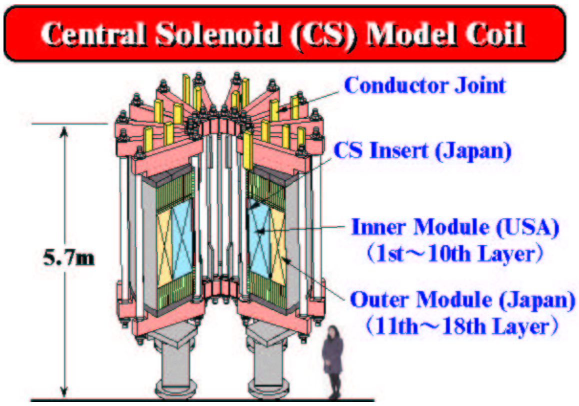
20-T Capture Magnet System

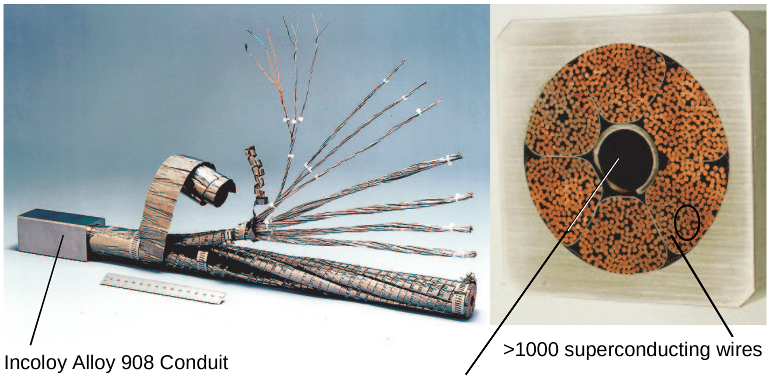
Inner, hollow-conductor copper coils generate 6 T @ 12 MW:



Bitter-coil option less costly, but marginally feasible.

Outer, superconducting coils generate 14 T @ 600 MJ:



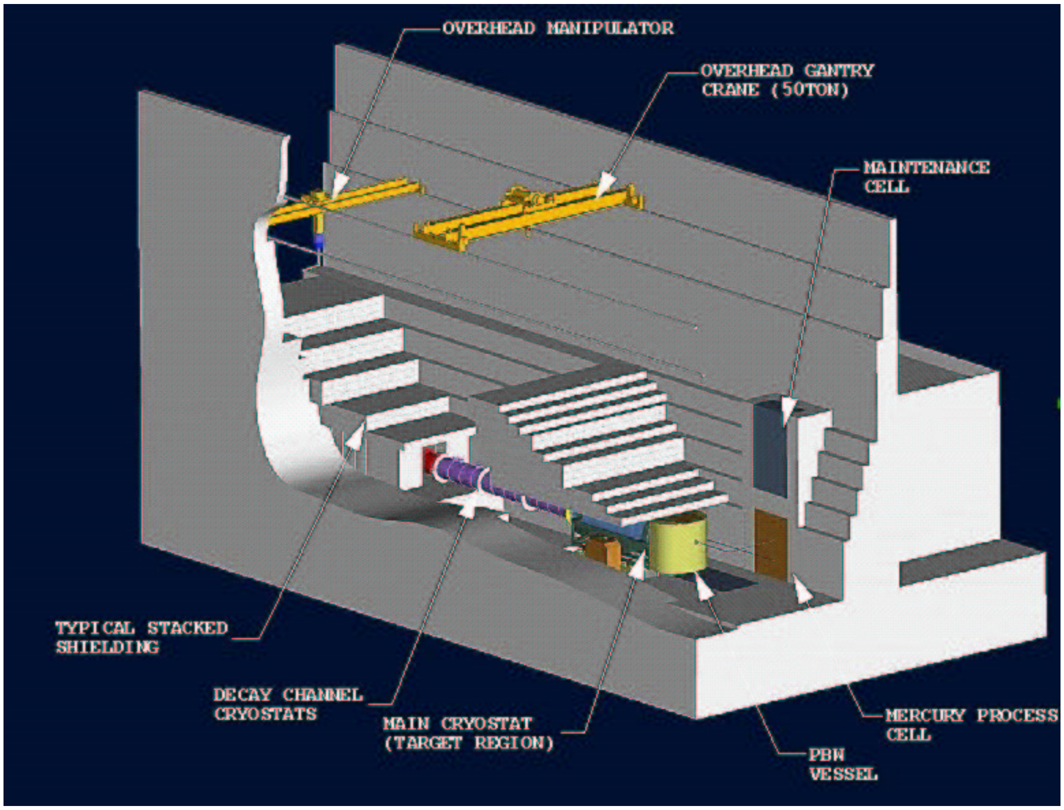


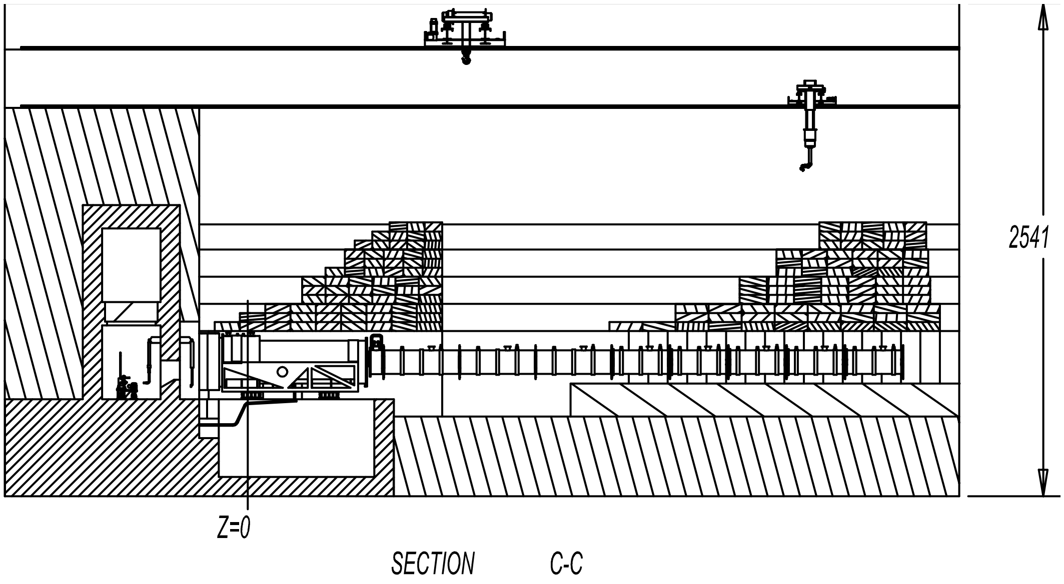
Cable-in-conduit construction similar to ITER central solenoid.

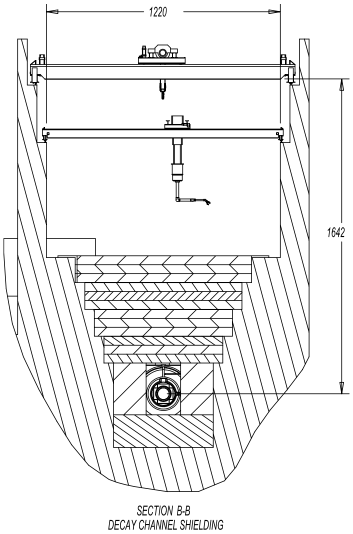
Both coils shielded by tungsten-carbide/water.

Target System Support Facility

Extensive shielding; remote handling capability.







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 ⇒ 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 suggest little problem if nozzle within field (CERN, Grenoble, 2002).
- Superinvar samples irradiated in BLIP facility to study effect of radiation damage on the very low thermal expansion coef.

Issues for Further Targetry R&D

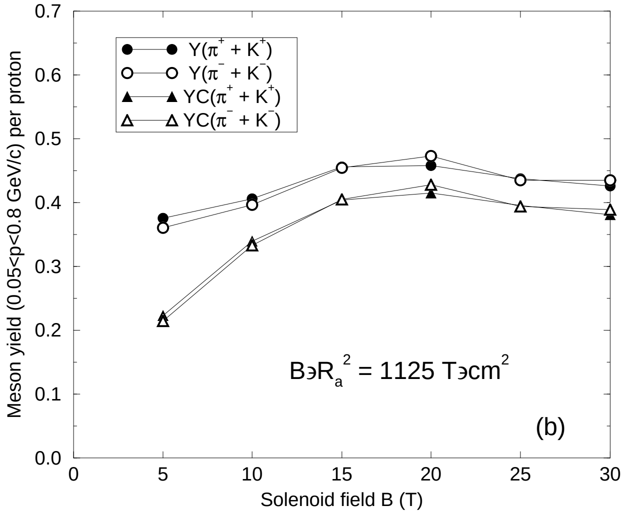
- Continue numerical simulations of MHD + beam-induced effects [Samulyak].
- Continue tests of mercury jet entering magnet [CERN, Grenoble].
- For solid targets, study radiation damage – and issues of heat removal from solid metal targets (bands, chains, *etc.*).
- Confirm manageable mercury-jet dispersal 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 (Begun June 2002).
- 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.]

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.

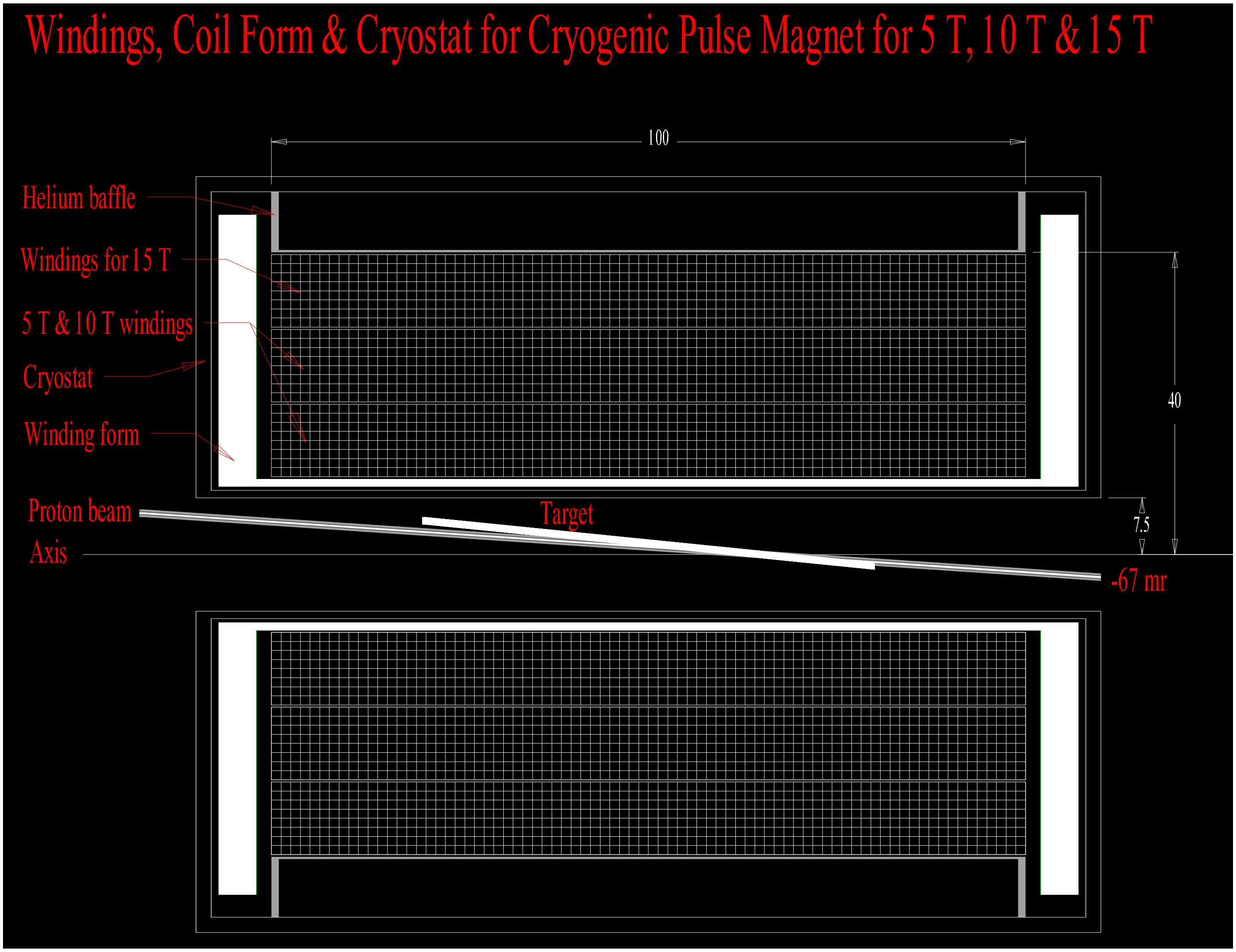
A capture solenoid for a superbeam needs a larger bore to trap higher $P_\perp$ pions, for which 14 T is then sufficient.

$\Rightarrow$ 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 15-T pulsed magnet for about twice the cost of a 5-T pulsed magnet.
- ⇒ We propose to construct a 15-T pulsed magnet, that can be staged as a 5-T and 10-T magnet.

A 15-T Pulsed Magnet with 5- and 10-T Phased Options

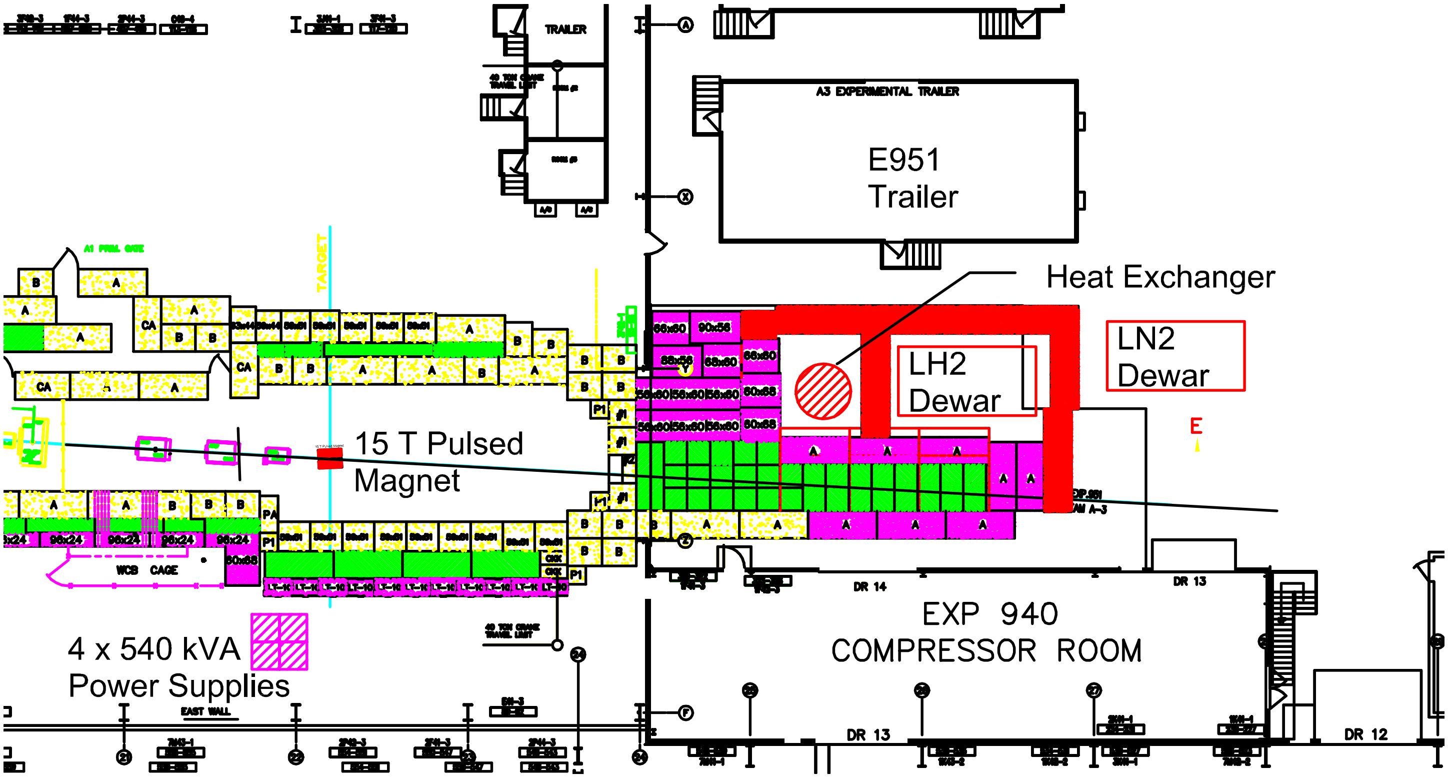


Phase	No. of PS	Coolant	Temp.	Field
1	1	N_2	84 K	5 T
2	4	N_2	74 K	10 T
3	4	H_2	30 K	15 T

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, 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.
  - 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.

Presentations

- P. Titus (MIT): Pulsed Solenoid Magnet Engineering.
- G. Mulholland (ACT): Cryogenic Systems.
- I. Marneris (BNL): Electrical Systems.
- J. Scaduto (BNL): ODH Considerations.