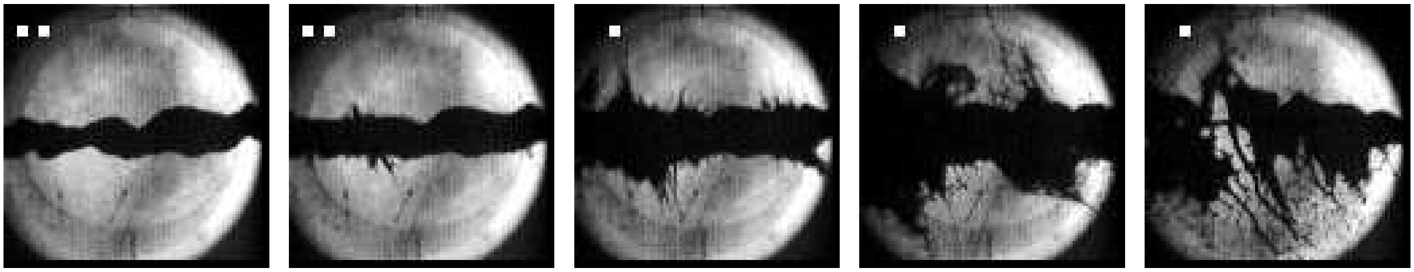
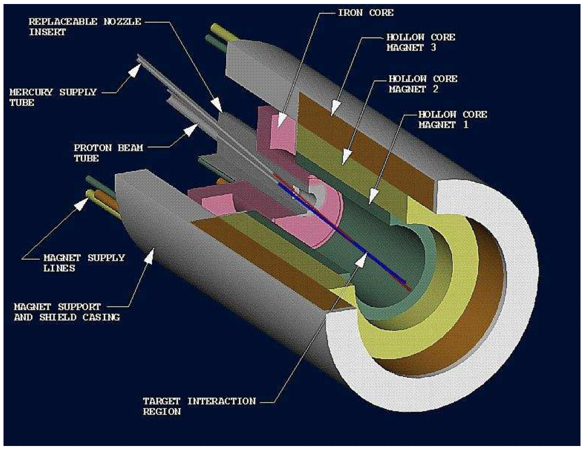
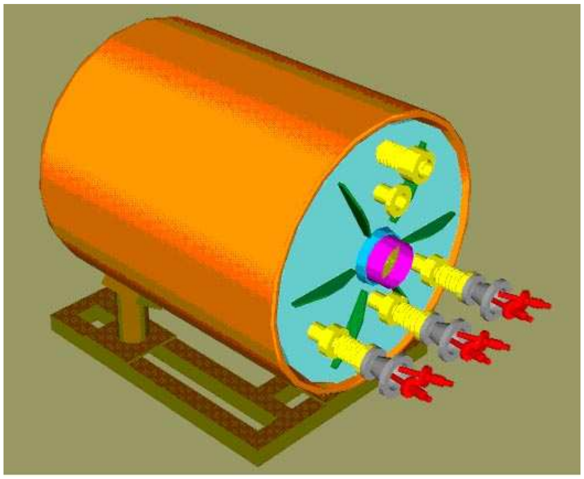
The R&D Program for a 4 MW Target Station for a Neutrino Factory and Muon Collider Source

(BNL E951)







K.T. McDonald

Princeton U.

RHIC/AGS Users Meeting

BNL, May 16, 2003

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

Why Targetry?

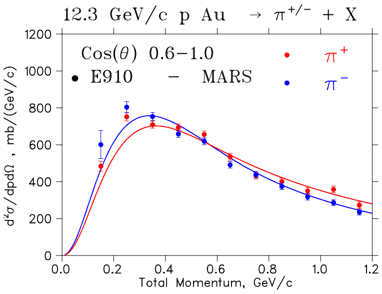
- **Targetry** = the task of producing and capturing π's and μ's from proton interactions with a nuclear target.
- At a **muon collider** the key parameter is **luminosity**:

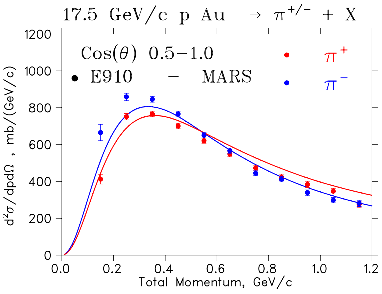
$$\mathcal{L} = \frac{N_1 N_2 f}{A}\,\mathrm{s}^{-1}\mathrm{cm}^{-2},$$

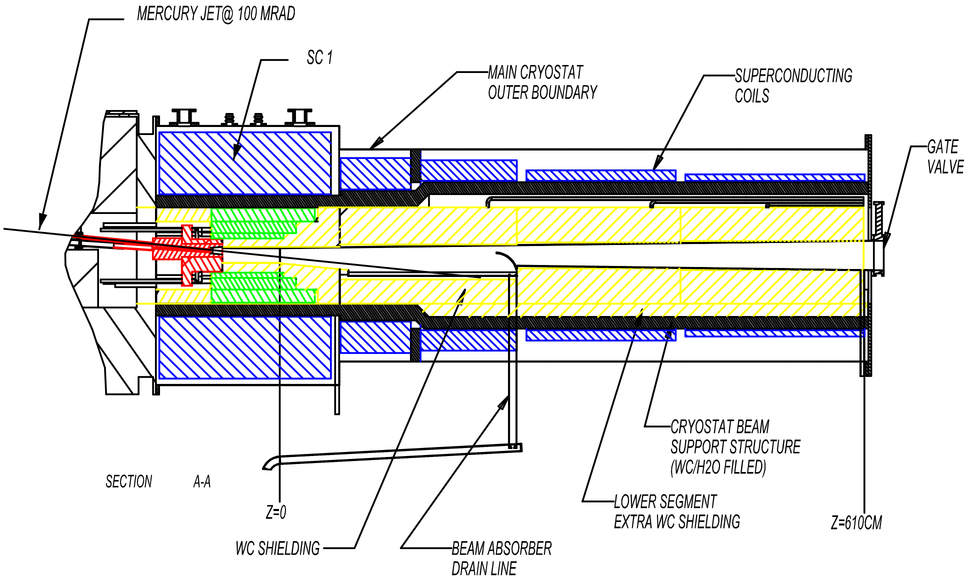
  ⇒ Gain as square of source strength (targetry),
  but small beam area (cooling) is also critical.
- At a **neutrino factory** the key parameter is **neutrino flux**,
  ⇒ Source strength (targetry) is of pre-eminent concern.
  [Beam cooling important mainly to be sure the beam fits in the pipe.]
- Since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

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 (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).

Why Targetry R&D?

- More π's, μ's and ν's are needed to expand the frontiers of high energy physics.
- Proton drivers are foreseen with beam power up to 4 MW, $>$ 10 times that of present HEP drivers.
- It appears most cost effective to maximize yield at the source (confirmed by Neutrino Factory Feasibility Studies 1 and 2).
- At 4-MW beam power, targets must survive intense heating, intense mechanical shock, and severe radiation damage.
- A disposable (moving) target suggests itself.
- For beam energy above ≈ 6 GeV, yield is enhanced for a high-Z target, ⇒ Liquid metal target: mercury, Pb-Bi, ...
- Secondary particle yield peaks at low momentum, ⇒ **Capture in tapered high-field solenoid magnet**.
- Although "feasible", these target concepts are beyond the state of the art.

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.

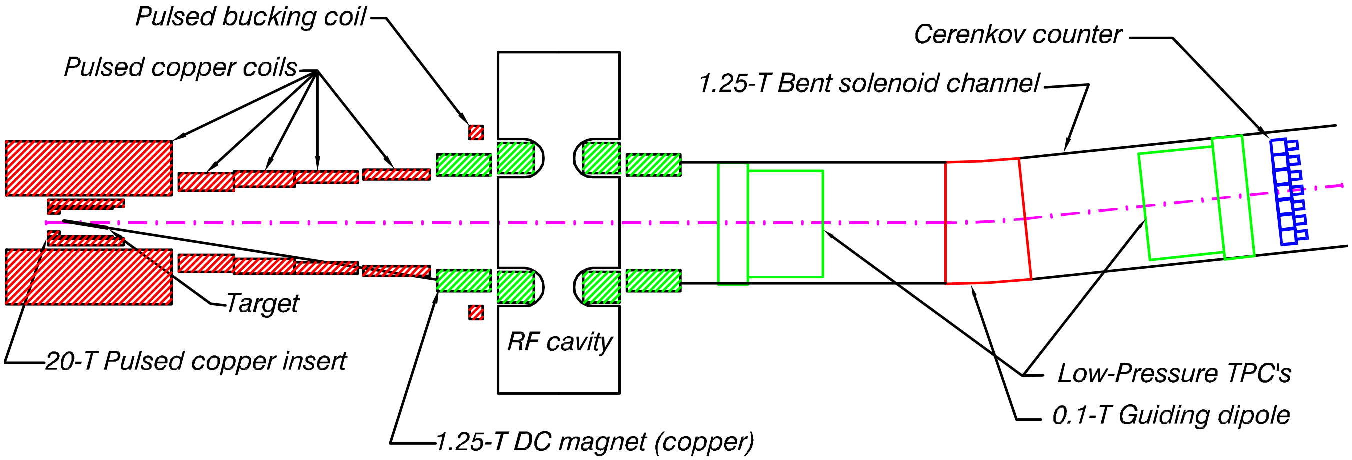
  See, http://pubweb.bnl.gov/users/kahn/www/talks/Homestake.pdf

BNL 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 BNL E951 Collaboration

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Summary of Targetry Activities To Date

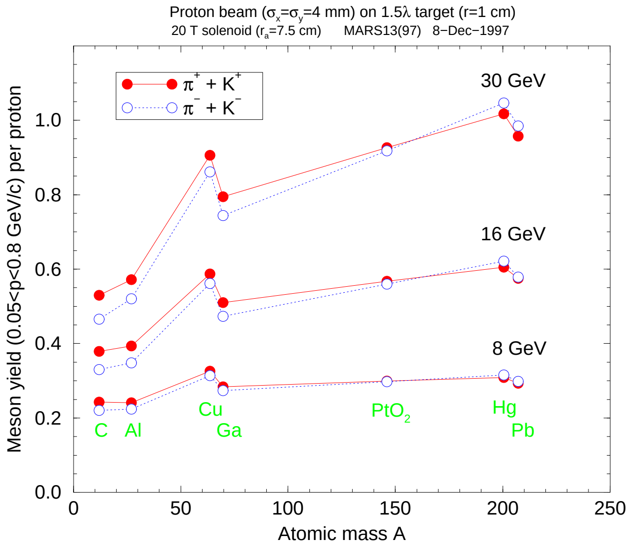
- Liquid metal targets in vessels show beam-induced cavitation damage to entrance window (ISOLDE, 1995, LANL, 2001).
- Beam tests of large passive mercury target for SNS (BNL 1998, LANL 2000) suggest velocity of sound may be reduced temporarily by beam-induced microcavitation).
- MARS simulations of 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).
- Target systems issues (hybrid-magnet design, beam dump, activation, radiation damage, shielding, remote handling, ...) addressed during Neutrino Factory Studies 1 & 2 (Millier, Pearson, Spampinato, Weggel).
- 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.

Targetry Activities, cont'd; BNL E951

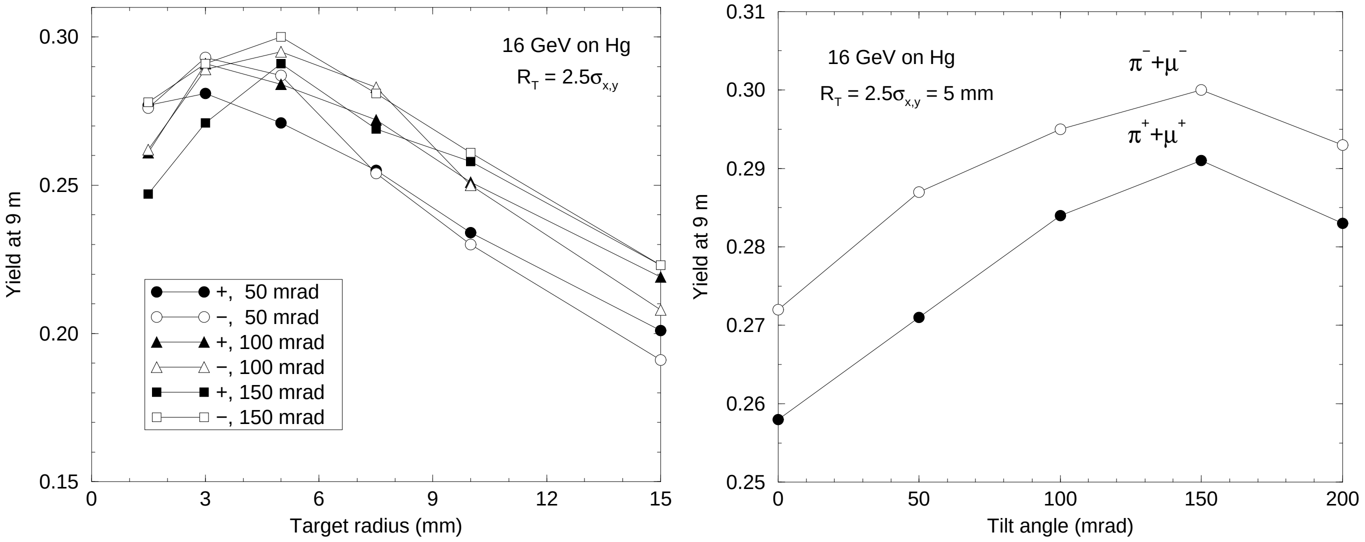
- Beam tests of high-strength solid targets show good agreement between strain-sensor data and ANSYS simulation, and suggest that they can survive single-pulse stresses up to Study-2 design intensity, = 16 TP / 8 mm^2 (BNL, March '01).
- Calculation and experiment indicate that a carbon target could survive against sublimation in a He atmosphere in a 4 MW beam (Haines, Thieberger).
- 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.
- Engineering design essentially complete for a 15-T pulsed solenoid magnet (+ GHe/LN2 cryo system + power supply) to test combined effects of beam + magnetic field on a mercury jet.

Pion/Muon Yield

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



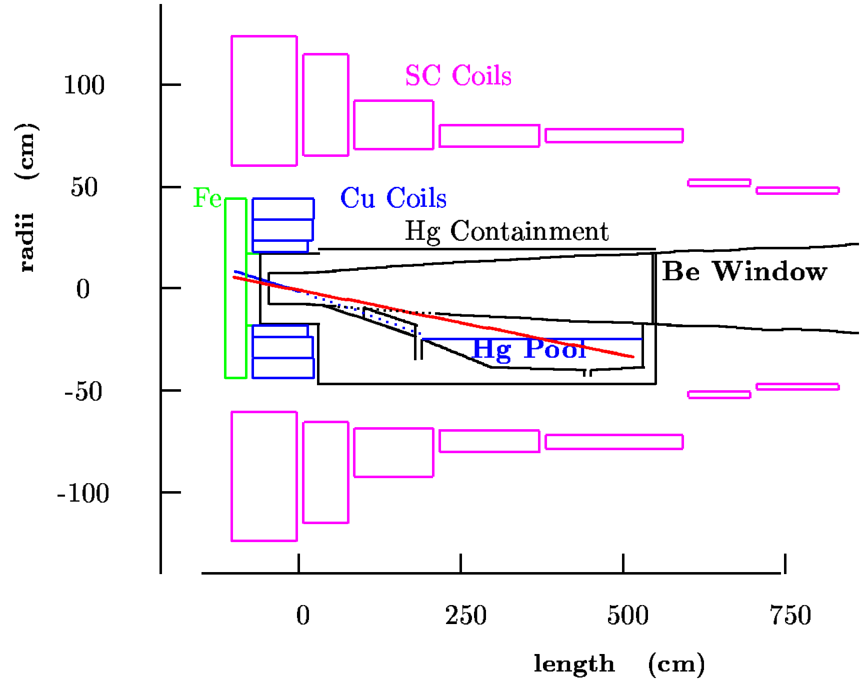
Mercury target radius should be ≈ 5 mm,
with target axis tilted by ≈ 100 mrad to the magnetic axis.



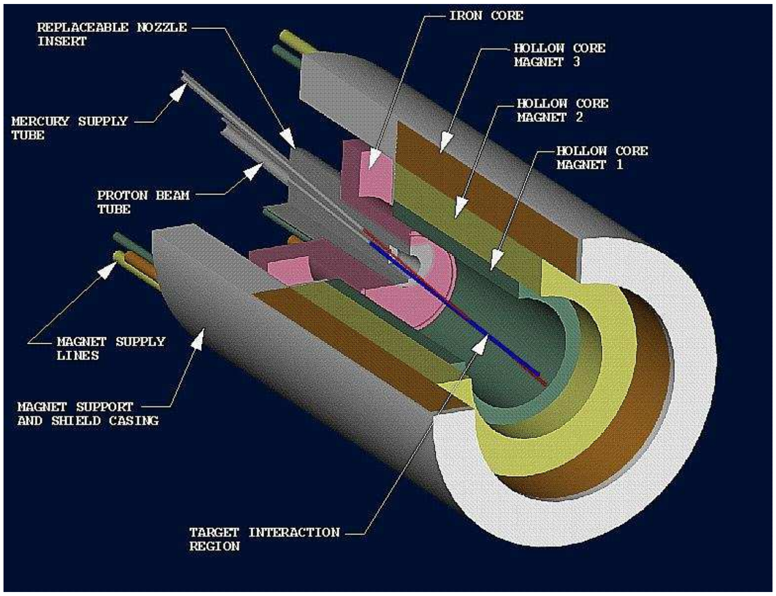
Can capture ≈ 0.3 pion per proton with $50 < P_\pi < 400$ MeV$/c$.

Target System Layout

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

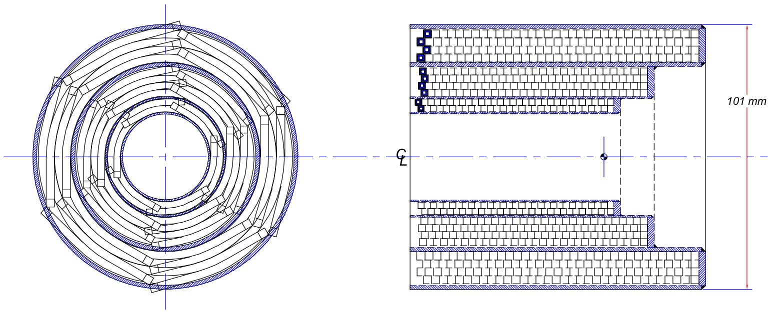


Mercury jet tilted by 100 mrad, proton beam by 67 mrad.



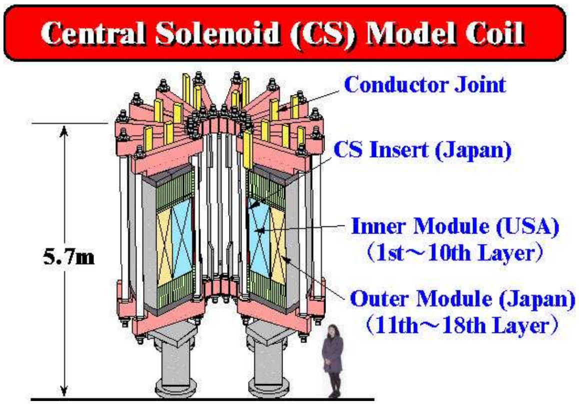
20-T Capture Magnet System

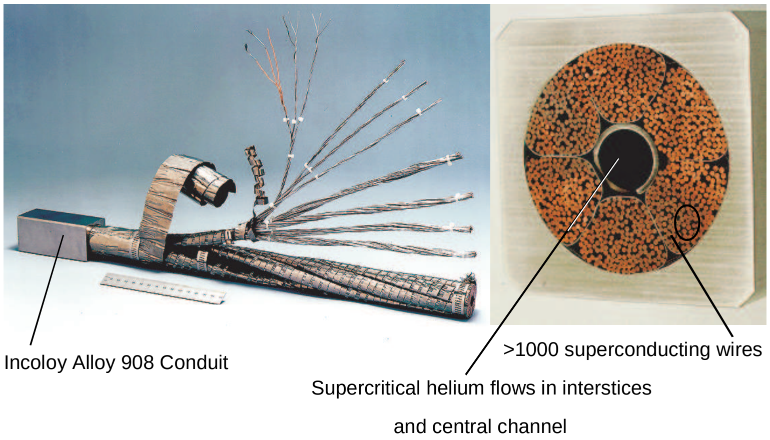
Inner, hollow-conductor copper coils generate 6 T @ 12 MW:



Bitter-coil option less costly, but marginally feasible.

Outer, superconducting coils generate 14 T @ 600 MJ:



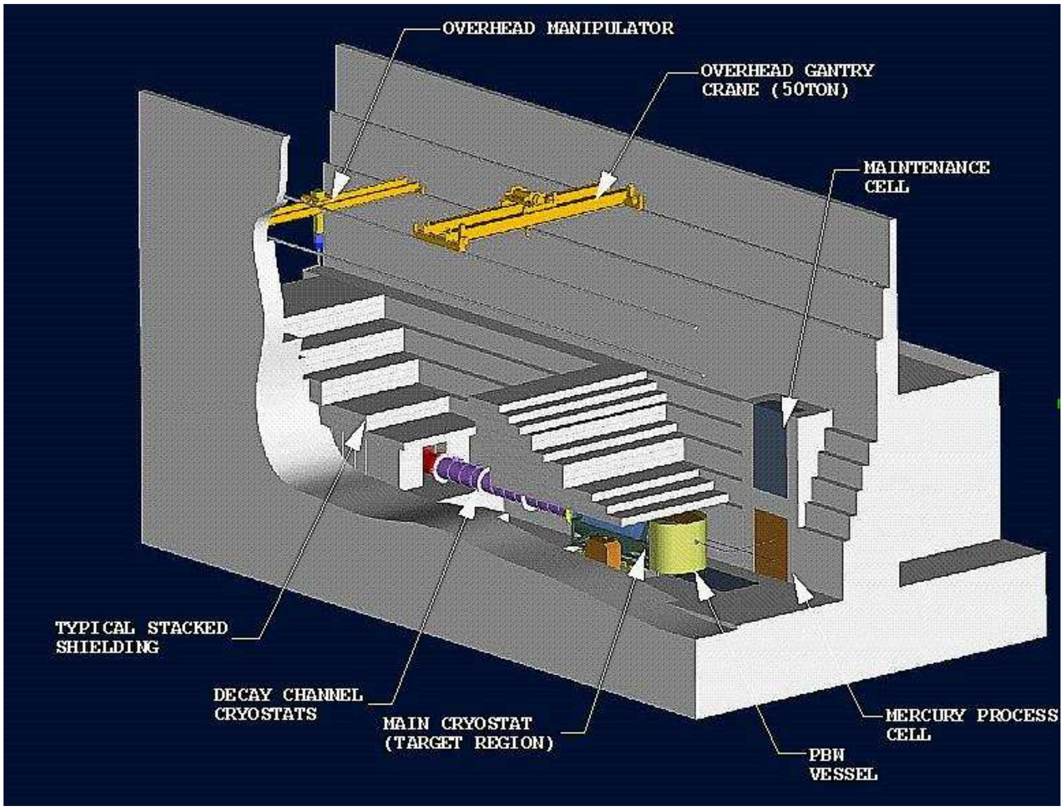


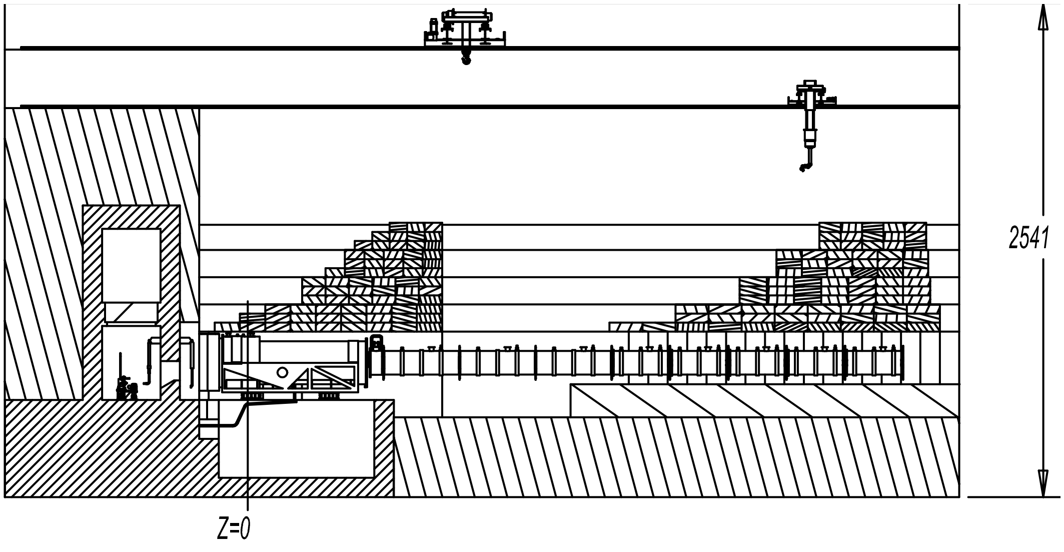
Cable-in-conduit construction similar to ITER central solenoid.

Both coils shielded by tungsten-carbide/water.

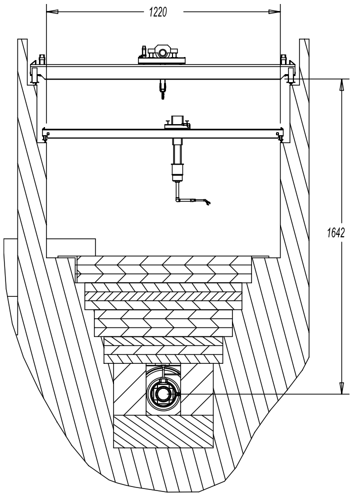
Target System Support Facility

Extensive shielding; remote handling capability.



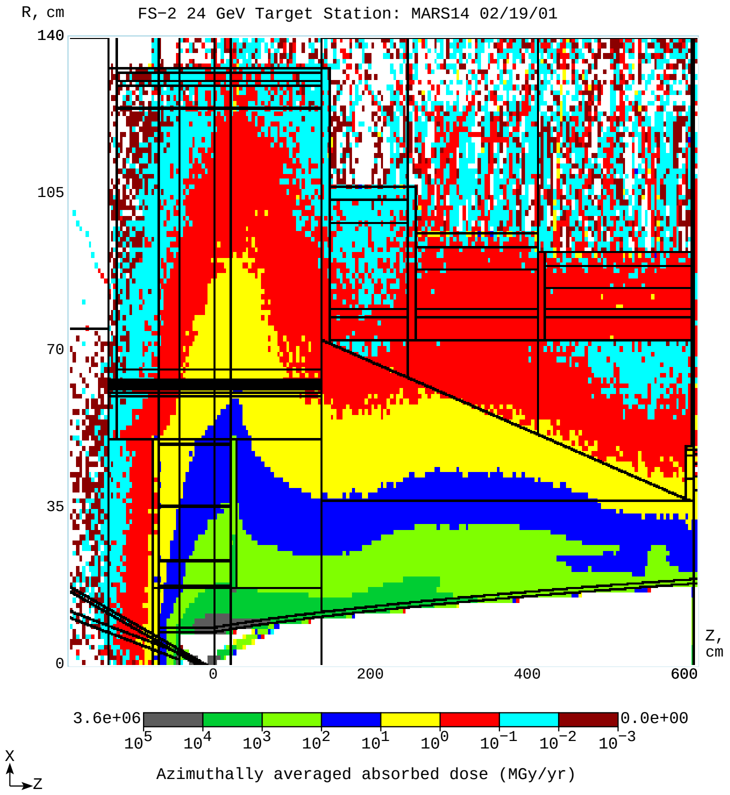


SECTION C-C



SECTION B-B
DECAY CHANNEL SHIELDING

Lifetime of Components in the High Radiation Environment

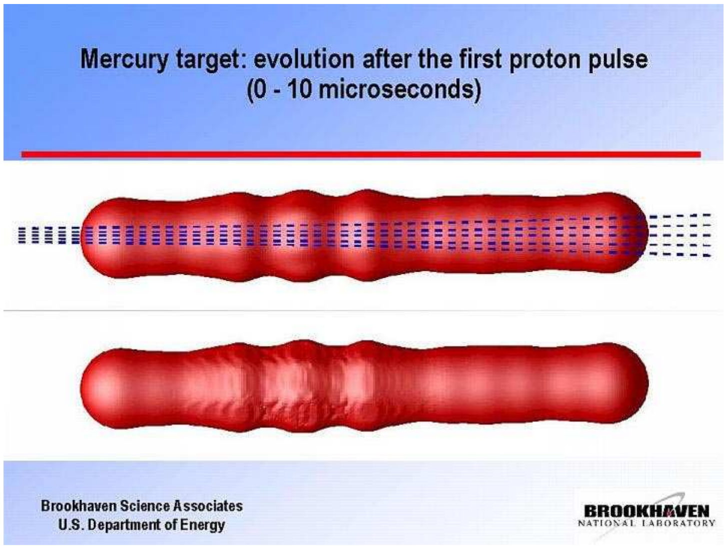


Component	Radius (cm)	Dose/yr (Grays/2×10^7 s)	Max allowed Dose (Grays)	1 MW Life (years)	4 MW life (years)
Inner shielding	7.5	5×10^{10}	10^{12}	20	5
Hg containment	18	10^9	10^{11}	100	25
Hollow conductor coil	18	10^9	10^{11}	100	25
Superconducting coil	65	5×10^6	10^8	20	5

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)

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U.S. Department of Energy

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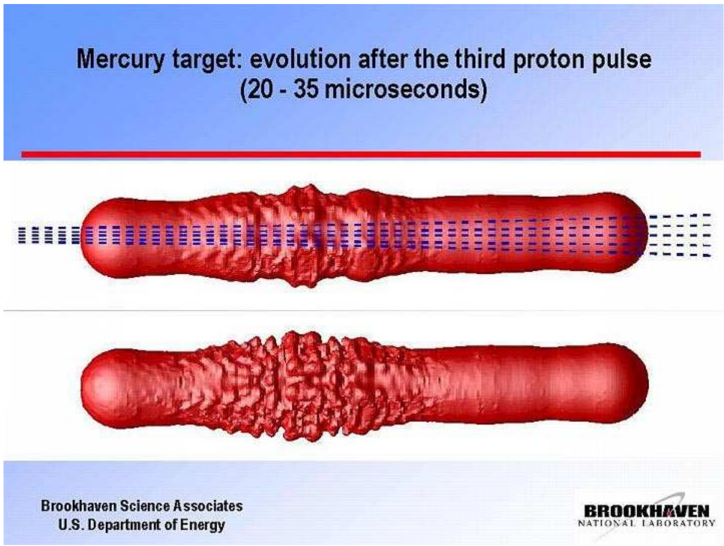

Mercury target: evolution after the third proton pulse (20 - 35 microseconds)

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U.S. Department of Energy

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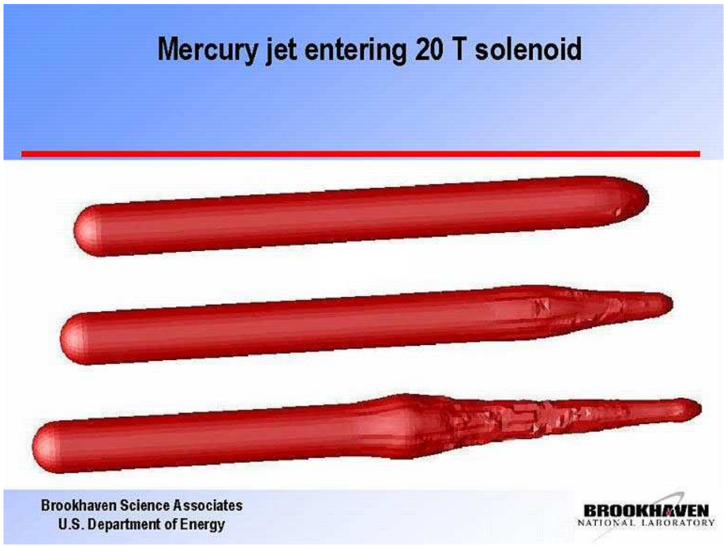
- Eddy currents may distort the jet as it traverses the magnet.



Mercury jet entering 20 T solenoid

Brookhaven Science Associates
U.S. Department of Energy

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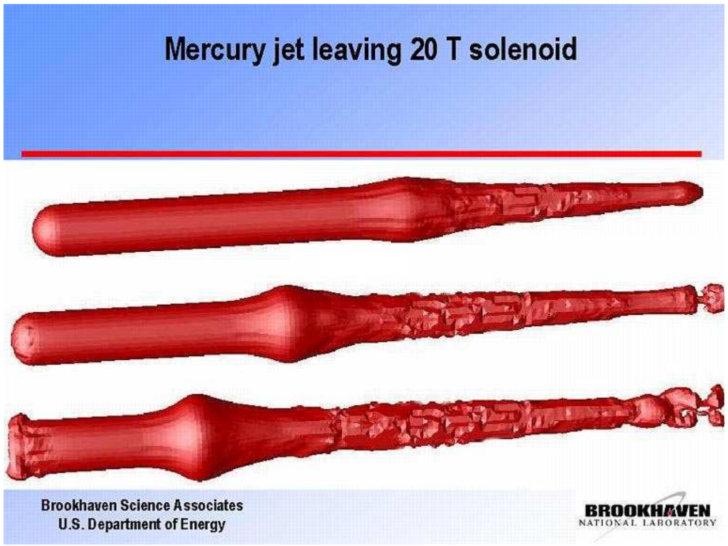

Mercury jet leaving 20 T solenoid

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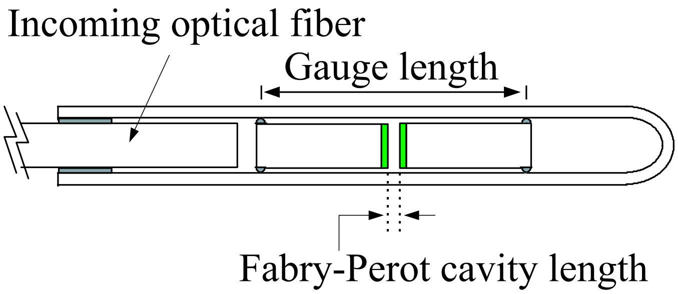
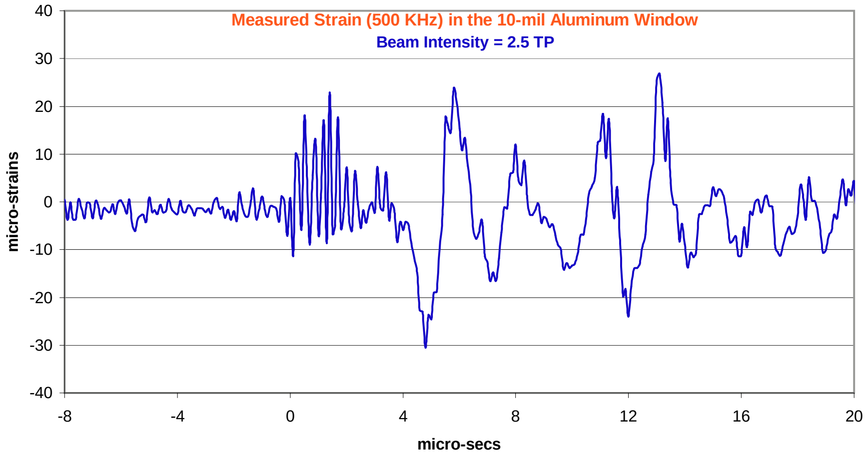
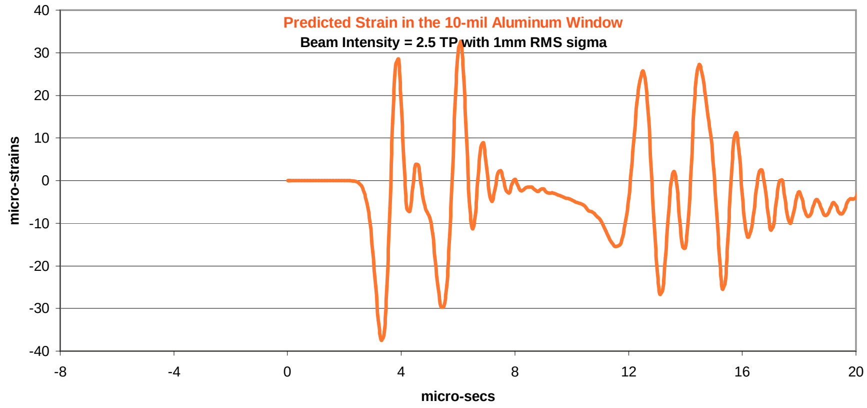
- Computational challenge: to include negative pressure and cavitation in a magnetohydrodynamic (MHD) simulation of a liquid metal with a free surface.

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

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

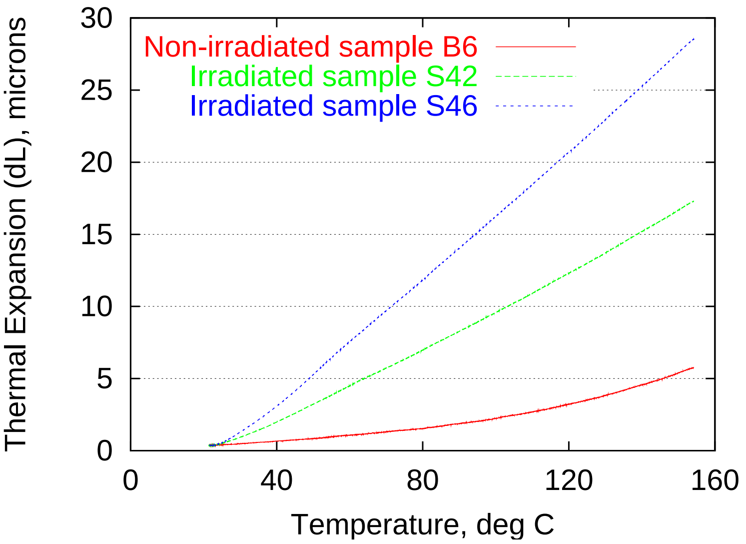






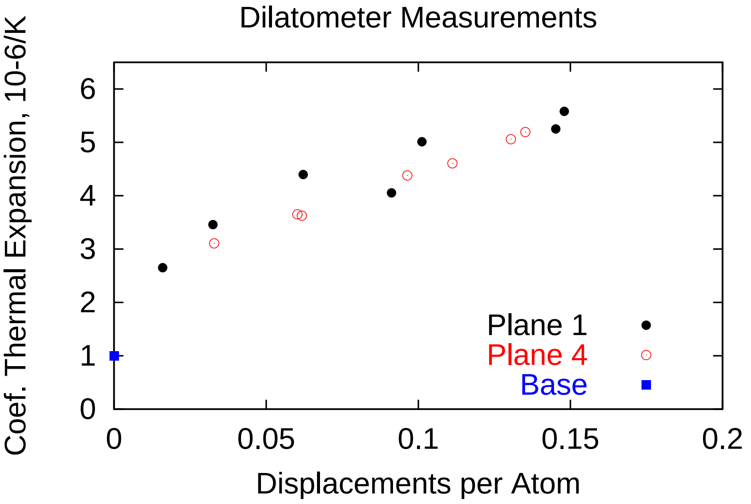
Effects of Radiation on SuperInvar

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



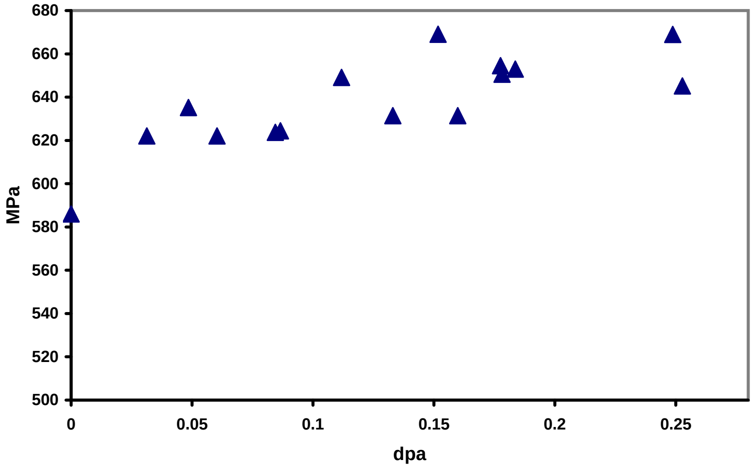
However, irradiation at the BNL BLIP facility show that the CTA increases rapidly with radiation dose.

CTA *vs.* dose ⇒

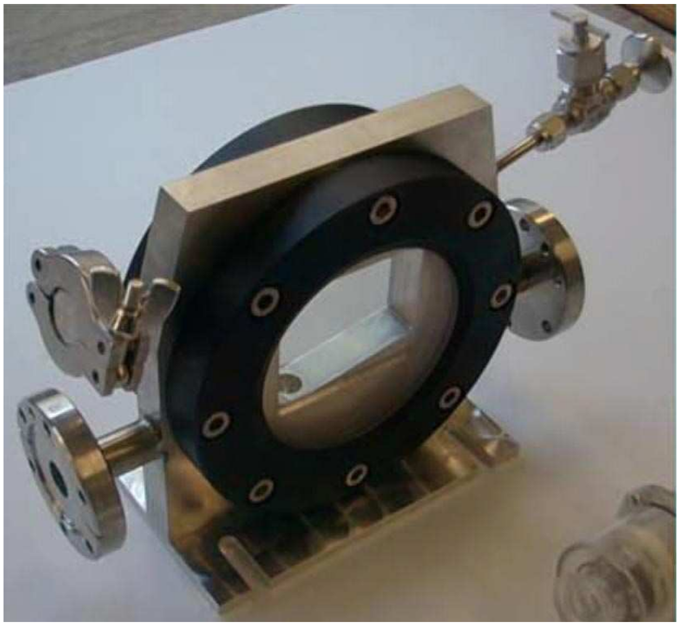


SuperInvar is made stronger by moderate radiation doses (like many materials).

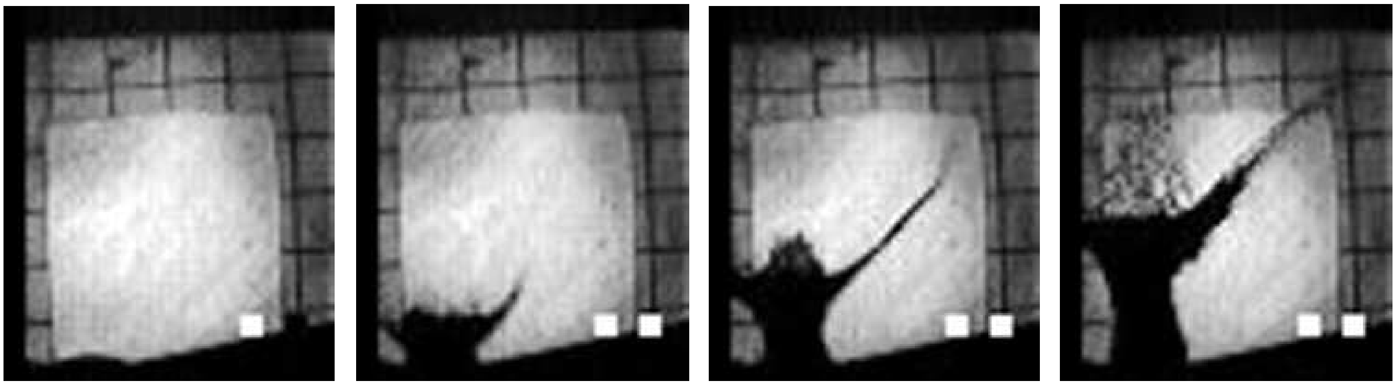
Yield strength *vs.* dose ⇒



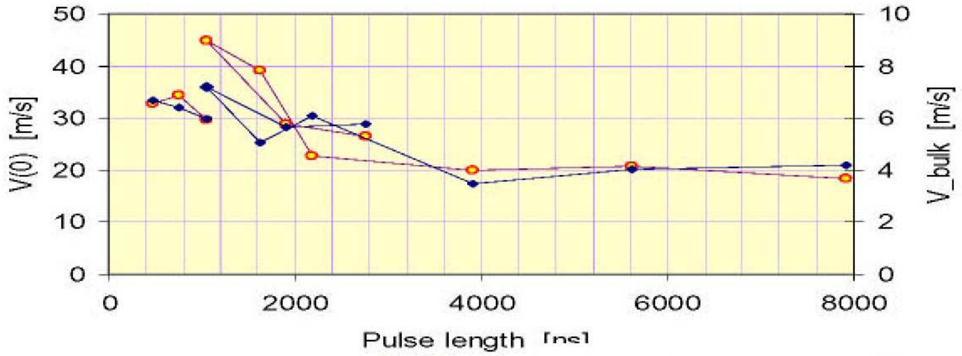
Passive Mercury Target Tests



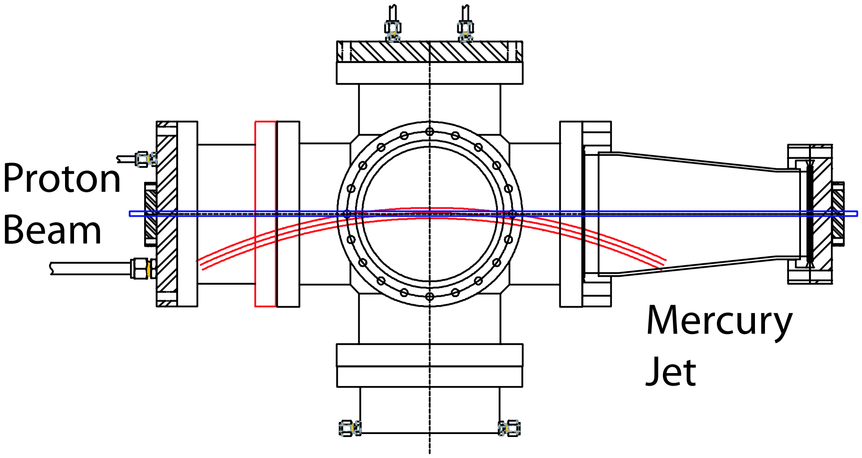
Exposures of 25 μs at
$t = 0, 0.5, 1.6, 3.4$ msec,
$\Rightarrow v_{\text{splash}} \approx 20 - 40$ m/s:



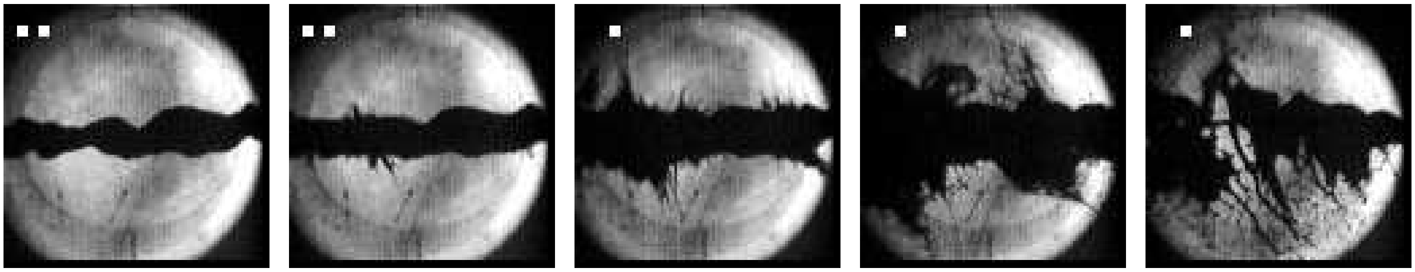
Two pulses of ≈ 250 ns give larger dispersal velocity only if separated by less than 3 μs.



Studies of Proton Beam + Mercury Jet



1-cm-diameter Hg jet in 2e12 protons at $t = 0, 0.75, 2, 7, 18$ ms.



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

for $U \approx 100$ J/g.

Data: $v_{\text{dispersal}} \approx 10$ m/s for $U \approx 25$ J/g.

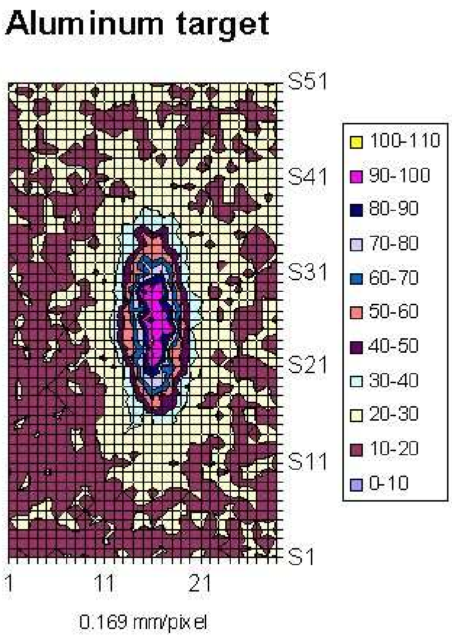
$v_{\text{dispersal}}$ appears to scale with proton intensity.

The dispersal is not destructive.

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

AGS Proton Pulse Intensity

Mercury jets tests done with 4-5e12 protons in spot 0.7×2.0 mm^2.



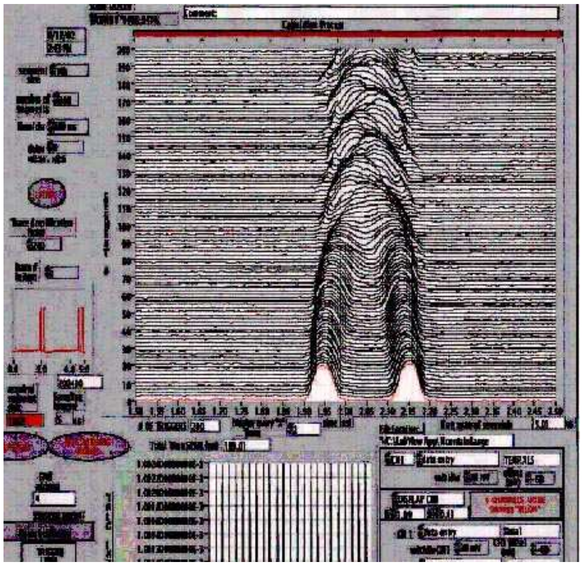
Legend
🟨 100-110
🟪 90-100
■ 80-90
☐ 70-80
🟦 60-70
🟥 50-60
■ 40-50
☐ 30-40
☐ 20-30
■ 10-20
☐ 0-10

This is 1/4 no. of protons/bunch desired for a neutrino factory, but same no. of protons/mm^2.

Goal: Test mercury jet in 1.6e13 protons/pulse, where increased beam energy may lead to boiling (in addition to dispersal via pressure waves).

Improvements underway to AGS horizontal sextupoles (better control of bunches during transition), and vertical sextupole (used in fast extraction.

Preliminary test of rf bunch merging at 24 GeV yielded bunches of 1e13 protons.

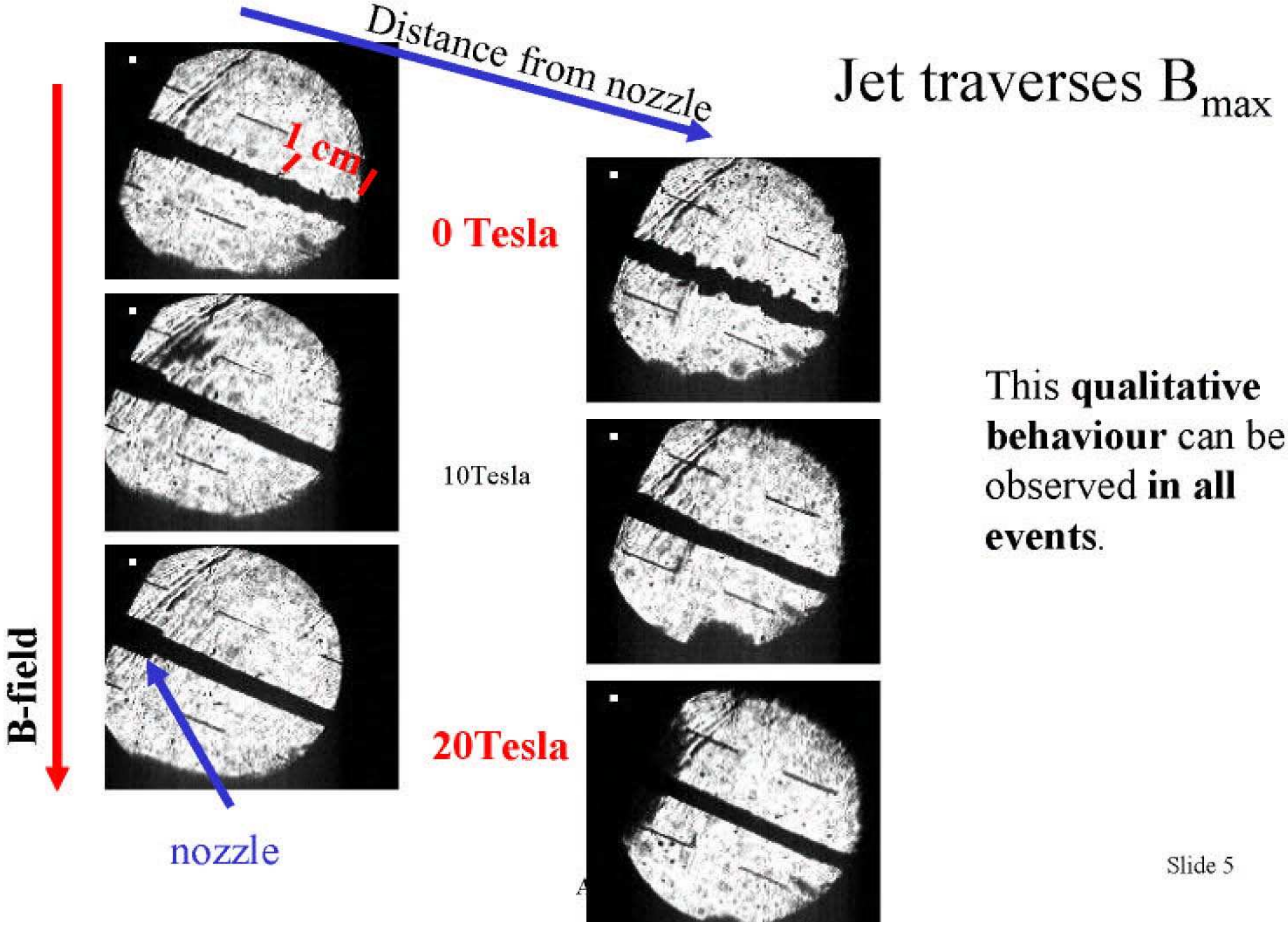


Tests of a Mercury Jet in a 20-T Magnetic Field (CERN/Grenoble, A. Fabich, Ph.D. Thesis)

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.



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

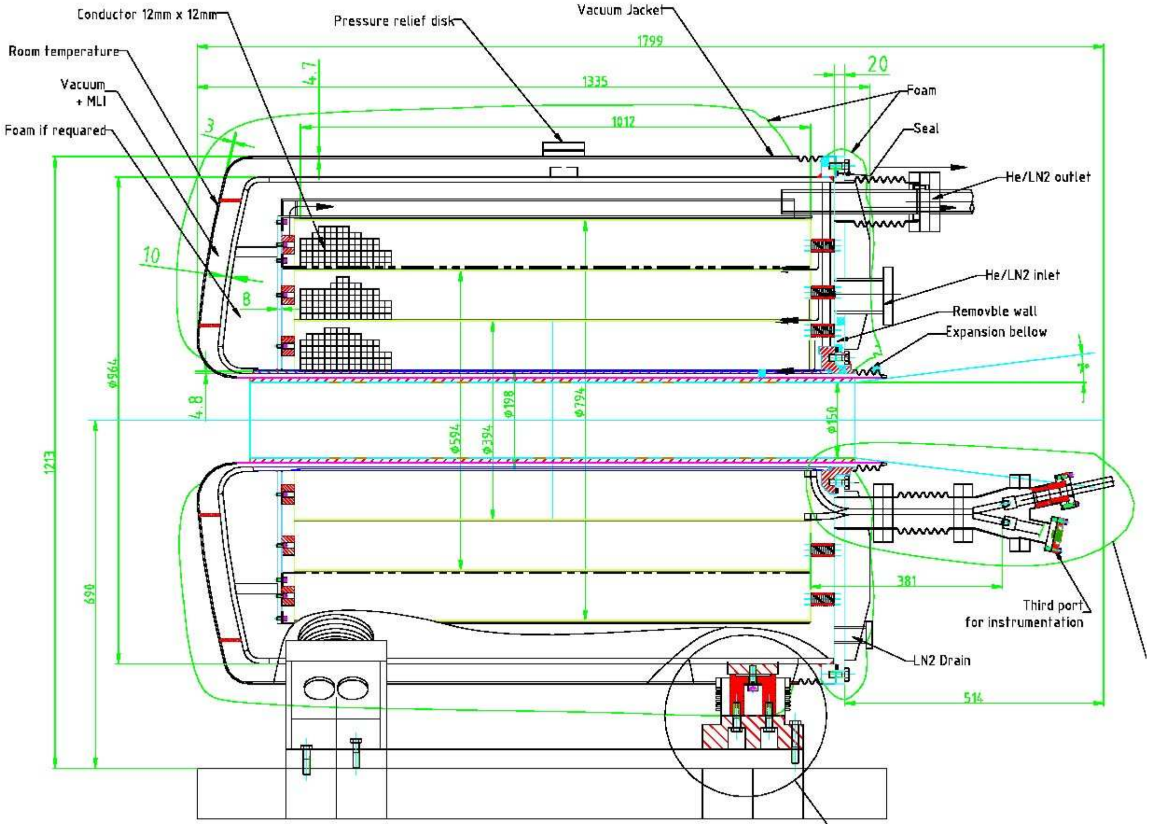
⇒ Damping of surface tension waves (Rayleigh instability).

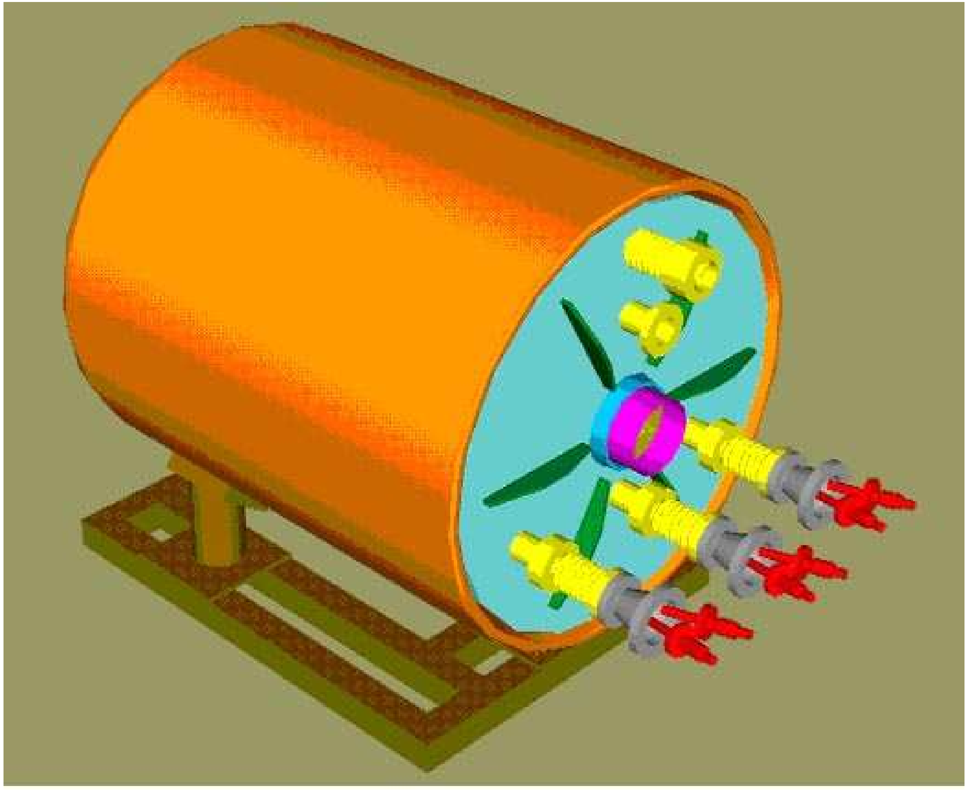
Will the beam-induced dispersal be damped also?

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.

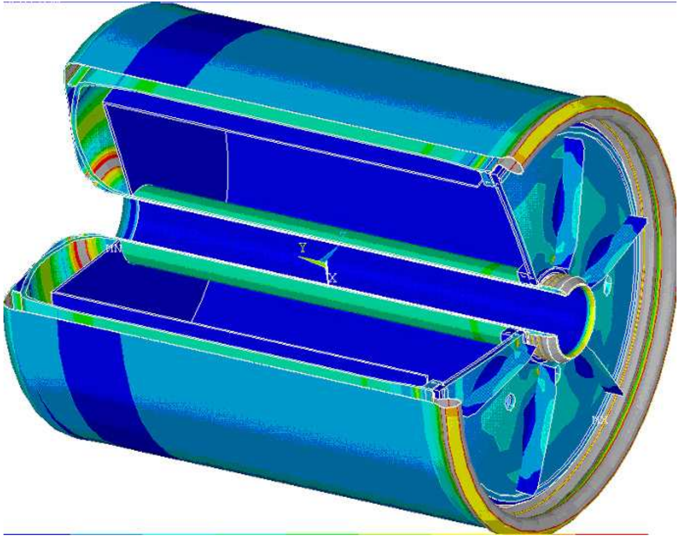
A 15-T LN_2-Cooled Pulsed Solenoid

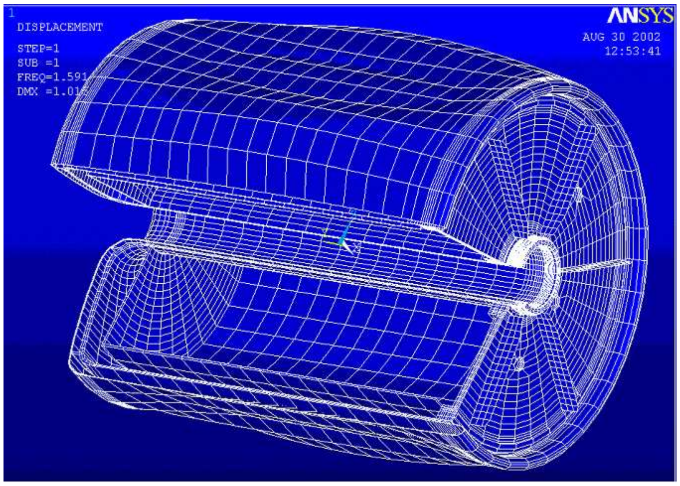




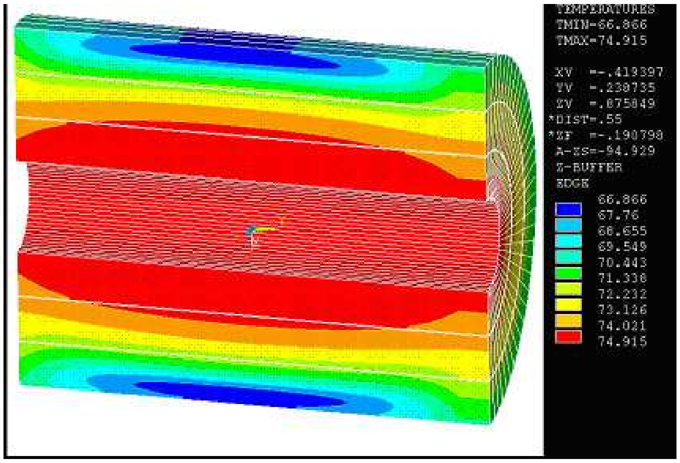
Structural and Thermal Analyses of the Magnet

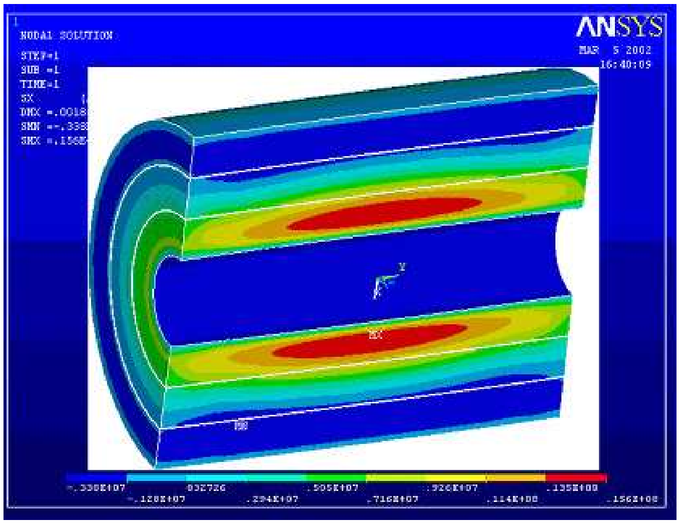
Cryostat:





Magnet coils:





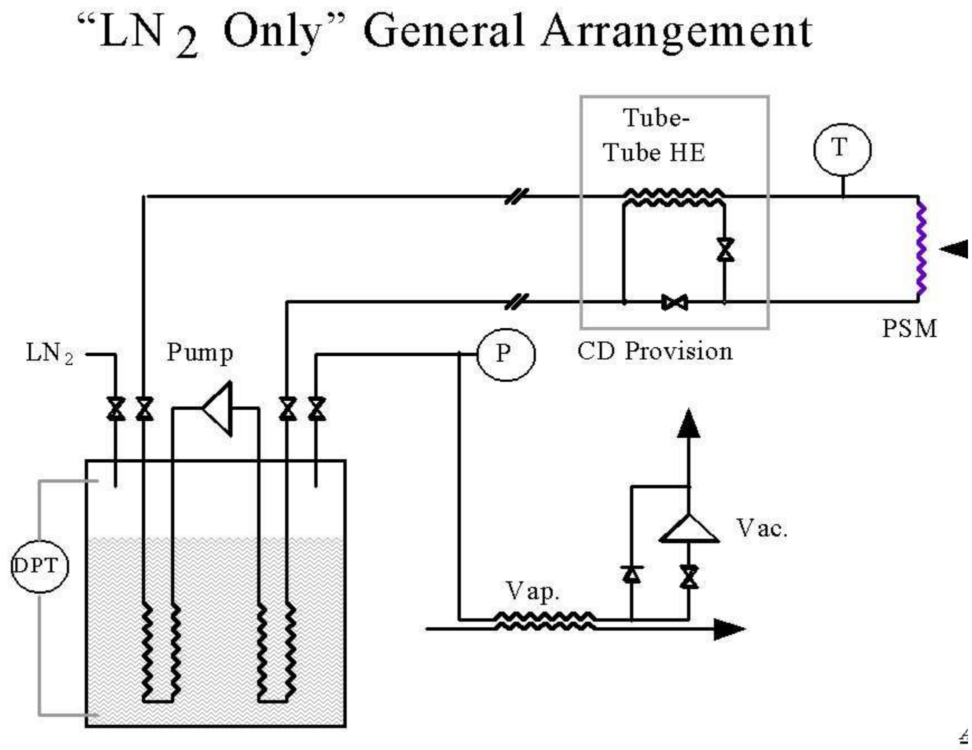
Keeping Costs Low

- 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

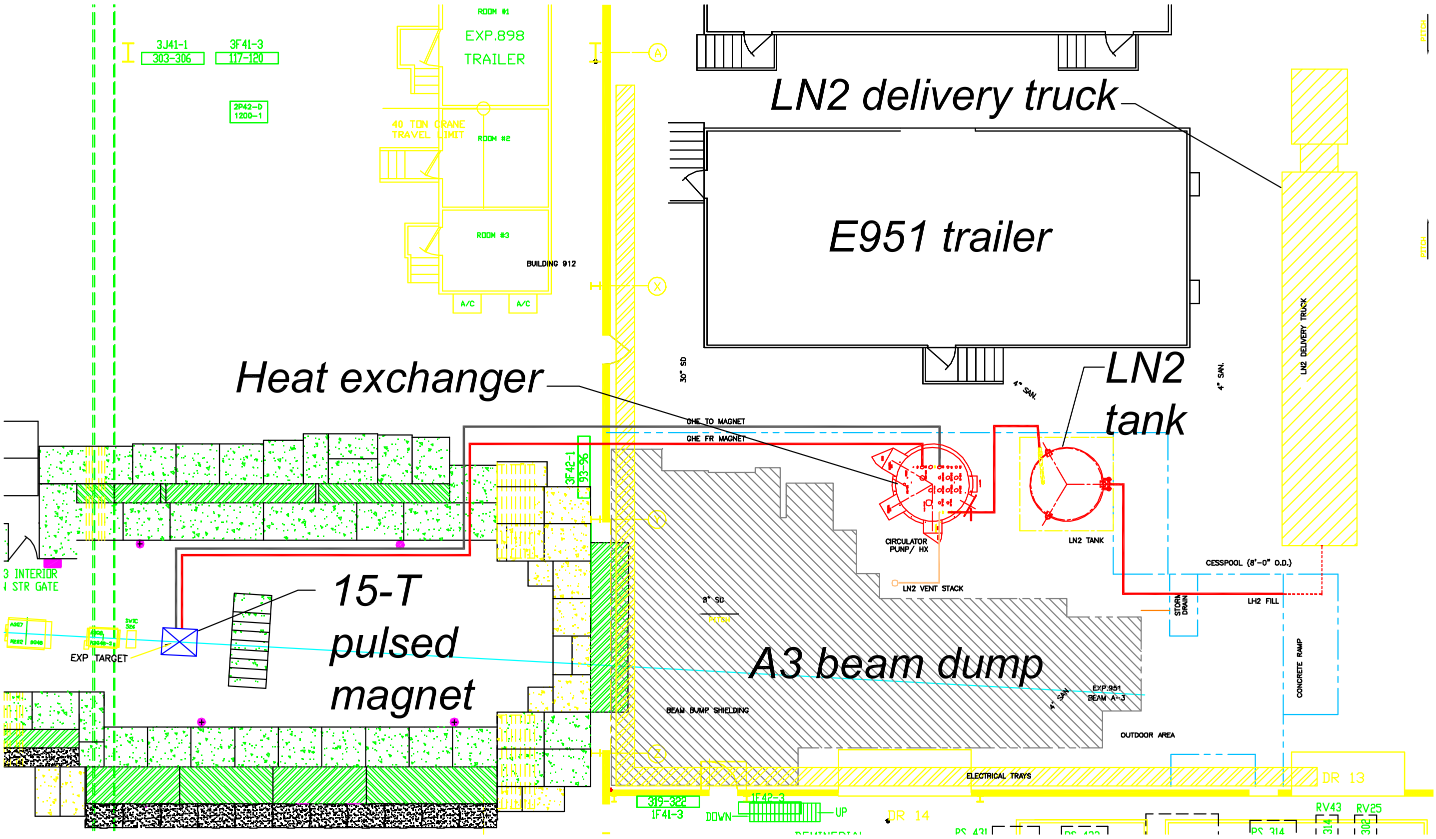
- Can build a 2.2-MW power supply out of 4 existing 540-kVA supplies at BNL [Marneris].
- Most cost effective to build a 4.5-MW supply out of “car” batteries! (We need at most 1,000 pulses of the magnet.)

Cooling via He Gas + LN_2 Heat Exchanger



Heat exchanger recylced 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.