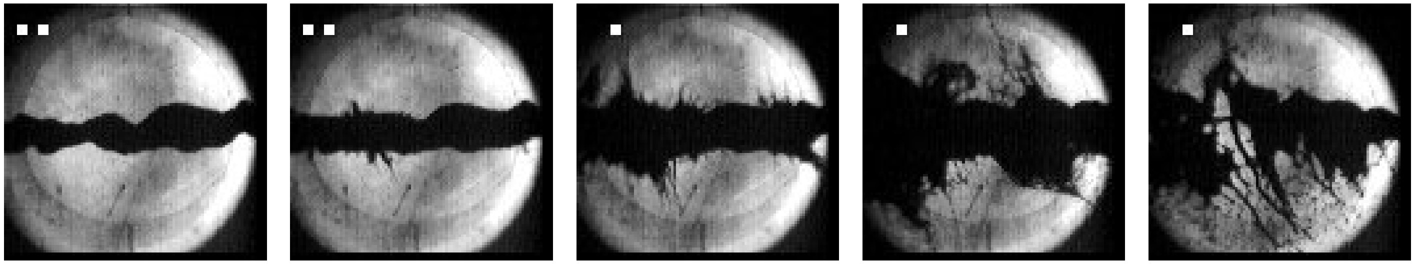
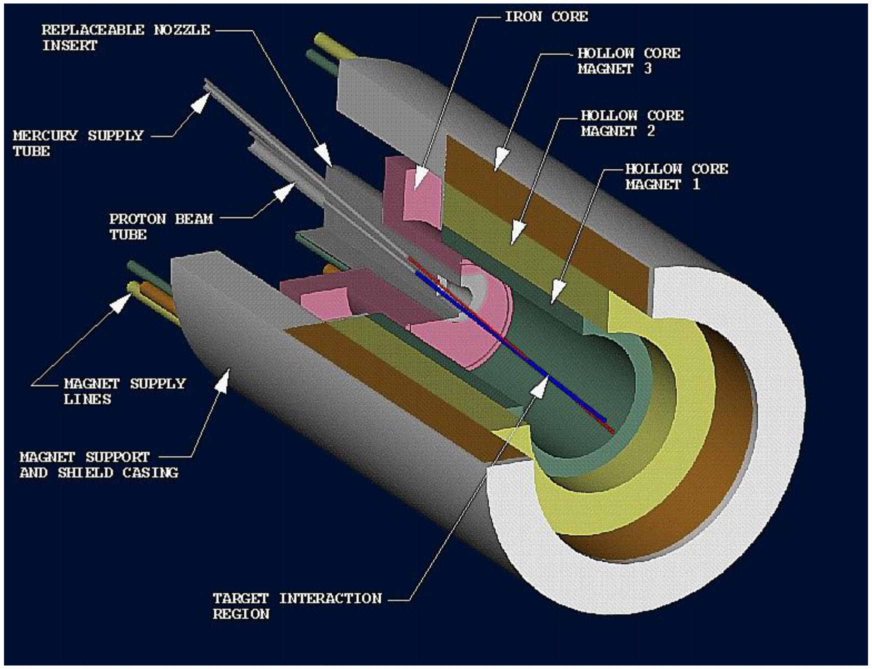
High-Power Targets for Project X – and Beyond

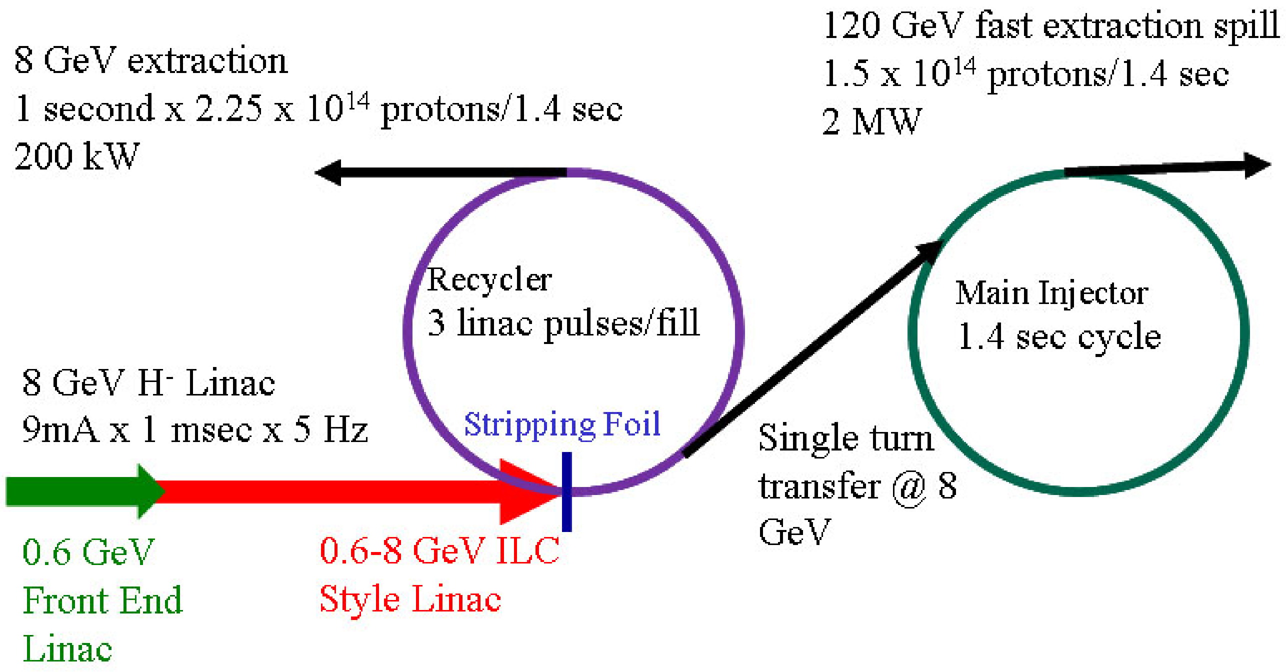




K.T. McDonald
Princeton U.
Project X Workshop
Fermilab, November 13, 2007

Targetry Web Page: `http://puhep1.princeton.edu/mumu/target/`

Targetry Challenges at Project X – and Beyond



- **8 GeV superconducting proton linac:**

  Baseline: 9 mA $\times$ 1 ms $\times$ 5 Hz = 360 kW at 8 GeV

  Future: 27 mA $\times$ 1 ms $\times$ 10 Hz = 2100 kW at 8 GeV

- **Proton Synchrotron:**

  Baseline: 1.5×10^{14} **in 10 μs spill every 1.4 s @ 120 GeV = 2 MW**

  Future(?): 2 MW linac, 90% transfer efficiency, 20 GeV synchrotron = 4 MW, *etc.*

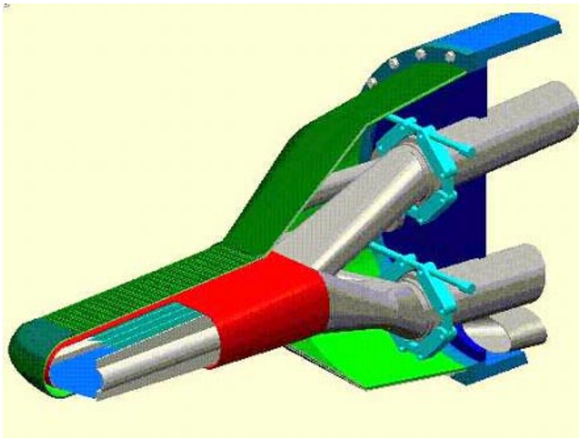
- **"Conventional" ν superbeam, ν Factory, Muon Collider, ...**

- **Can the secondary production target withstand the proton beam power?**

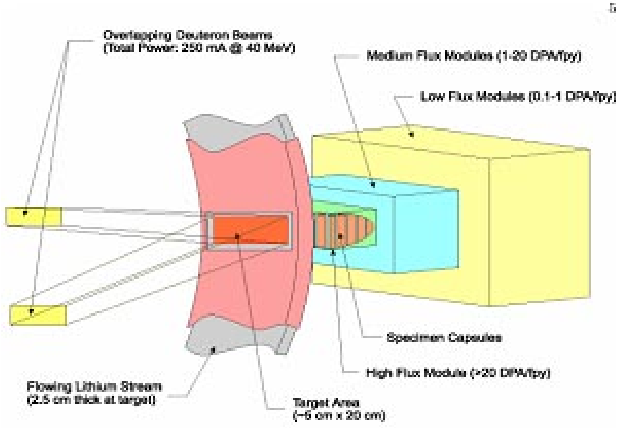
Target Survival

- Plausible that a new "conventional" graphite target (+ toroidal ν horn) could survive pulsed-beam-induced stresses at 2 MW (Hylen).
  http://projectx.fnal.gov/AACReview/ProjectXTargetingAAC_Hylen.pdf
  - Graphite target should be in helium atmosphere to avoid rapid destruction by sublimation, $\Rightarrow$ Cool target by helium gas flow (Simos).
  - Radiation damage will require target replacement $\approx$ monthly.
  - Graphite target less and less plausible beyond 2 MW.
  - Secondary particle collection favors shorter target, $\Rightarrow$ High-Z materials.
- High-Z targets for > 2 MW should be replaced every pulse!
  - $\Rightarrow$ Flowing liquid target: mercury, lead-bismuth, ...
  - Pulsed beam + liquid in pipe $\Rightarrow$ Destruction of pipe by cavitation bubbles, $\Rightarrow$ Use free liquid jet.
  - Free liquid metal jets are stabilized by a strong longitudinal magnetic field.
  - Strong solenoid field around target favorable for collection of low-energy secondaries, as needed for ν Factory and Muon Collider.
  - $\Rightarrow$ High-power liquid jet target R&D over last 10 years, sponsored by the Neutrino Factory and Muon Collider Collaboration.

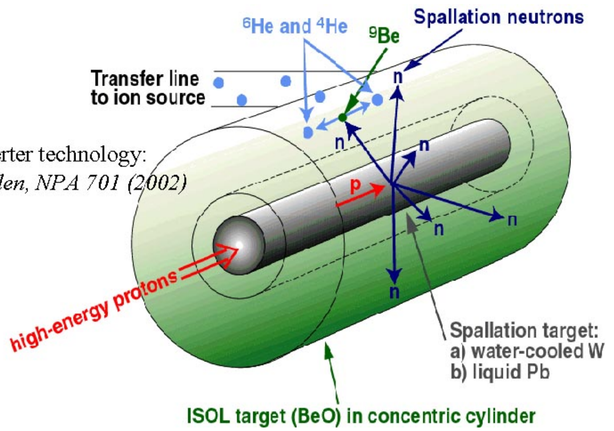
High-Power Targets Essential for Many Other Future Facilties



ESS

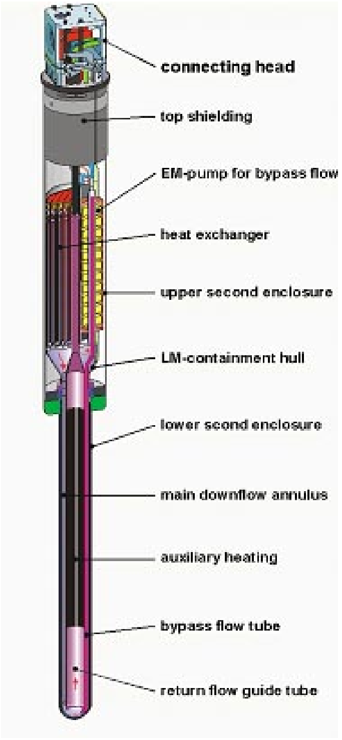


IFMIF

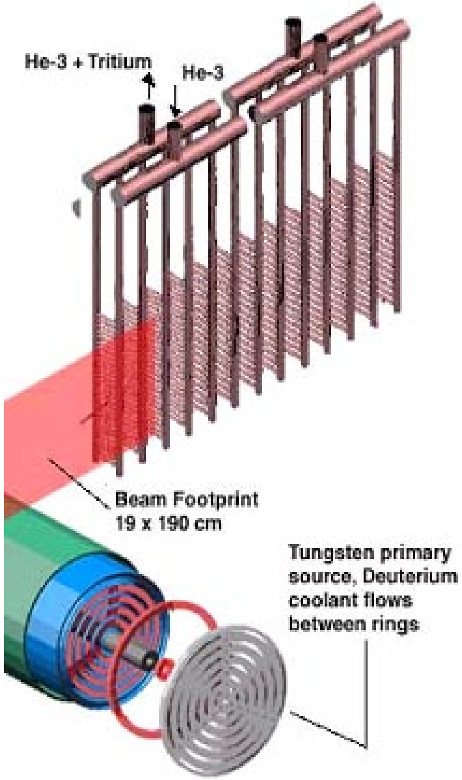


Converter technology:
(J. Nolen, NPA 701 (2002) 312c)

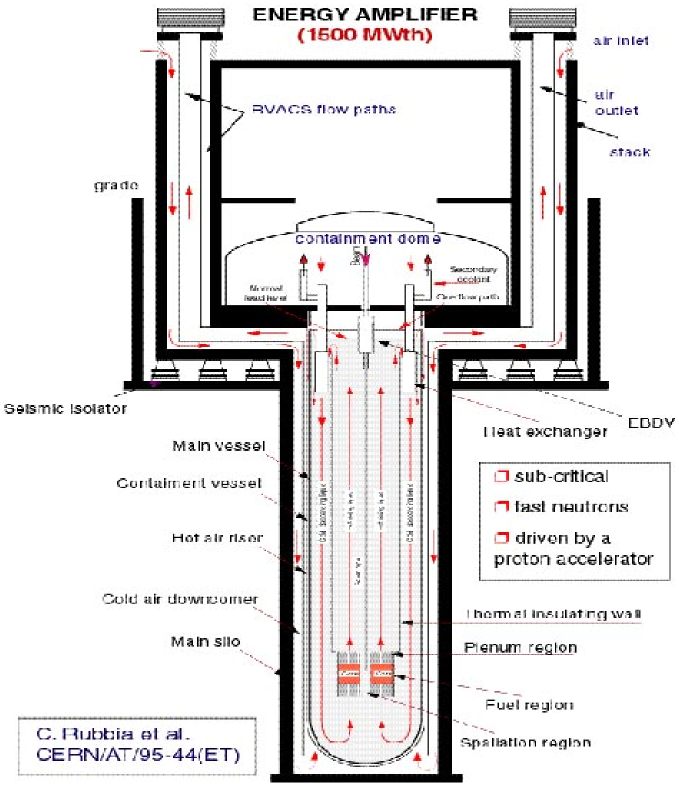
ISOL/β Beams



PSI



APT



C. Rubbia et al.
CERN/AT/95-44(ET)

ATW

The Challenges of High-Power Targetry

4-MW Proton Beam

- 10-30 GeV appropriate for both Superbeam and Neutrino Factory.

  ⇒ 0.8-2.5 $\times 10^{15}$ $p$ps; 0.8-2.5 $\times 10^{22}$ protons per year of 10^7 s.

- Rep rate 15-50 Hz at Neutrino Factory, as low as 2 Hz for Superbeam.

  ⇒ Protons per pulse from 1.6 $\times 10^{13}$ to 1.25 $\times 10^{15}$.

  ⇒ Energy per pulse from 80 kJ to 2 MJ.

- Small beam size preferred:

  ≈ 0.1 cm^2 for Neutrino Factory, ≈ 0.2 cm^2 for Superbeam.

⇒ Severe materials issues for target AND beam dump.

- Radiation Damage.
- Melting.
- Cracking (due to single-pulse “thermal shock”.

Radiation Damage is the Ultimate Limit

The lifetime dose against radiation damage (embrittlement, cracking, ...) by protons for most solids is about 10^{22}/cm^2.

⇒ Target lifetime of about 5-14 days at a Neutrino Factory (and 9-28 days at a Superbeam).

⇒ Mitigate by frequent target changes, moving target, liquid target, ...

Remember the Beam Dump

Target of 2 interaction lengths ⇒ 1/7 of beam is passed on to the beam dump.

Long distance from target to dump at a Superbeam,
⇒ Beam is much less focused at the dump than at the target,
⇒ Radiation damage to the dump not a critical issue (Superbeam).

Short distance from target to dump at a Neutrino Factory,
⇒ Beam still tightly focused at the dump,
⇒ Frequent changes of the beam dump, or a moving dump, or a liquid dump.

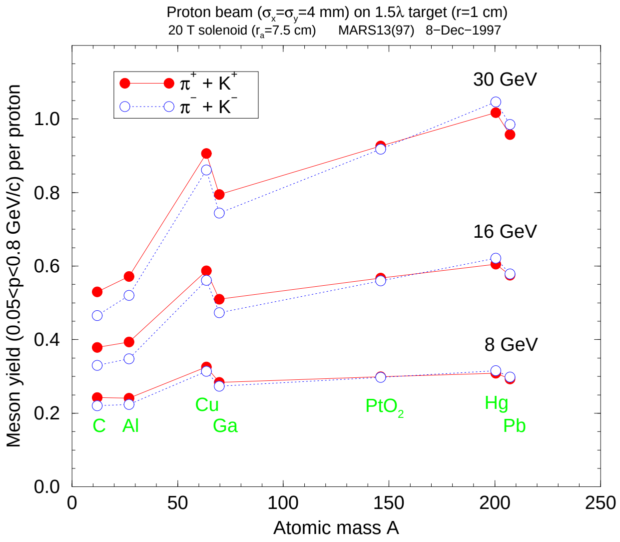
A liquid beam dump is the most plausible option for a Neutrino Factory, independent of the choice of target. (This is so even for a 1-MW Neutrino Factory.)

Pion Yield

Pion/Muon Yield, I

ν Superbeams need $E_\pi \approx 0.5$-5 GeV, ν Factories need $E_\pi < 0.5$ Gev.

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

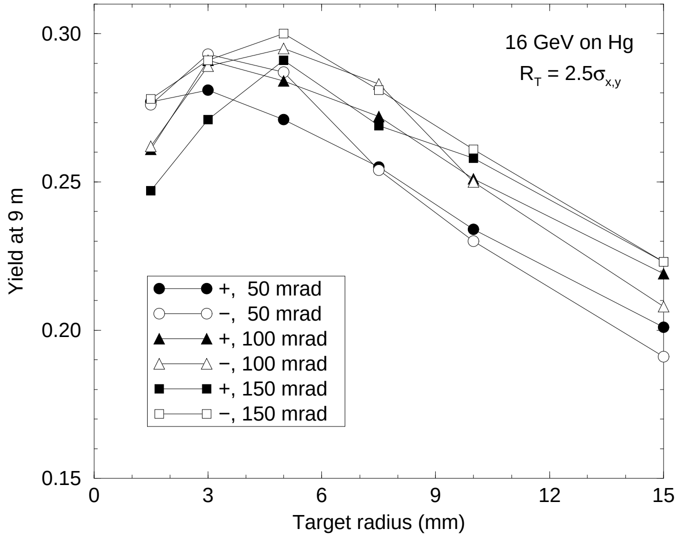


$$\frac{N^+_{10GeV}}{N^+_{24GeV}} = 1.07 \qquad \frac{N^-_{10GeV}}{N^-_{24GeV}} = 1.10$$

$$\frac{N^+_{5GeV}}{N^+_{24GeV}} = 1.90 \qquad \frac{N^-_{5GeV}}{N^-_{24GeV}} = 1.77$$

$$\frac{N^+_{Hg-10GeV}}{N^+_{C-5GeV}} = 1.18 \qquad \frac{N^-_{Hg-10GeV}}{N^-_{C-5GeV}} = 1.22$$

Yield *vs.* target radius:

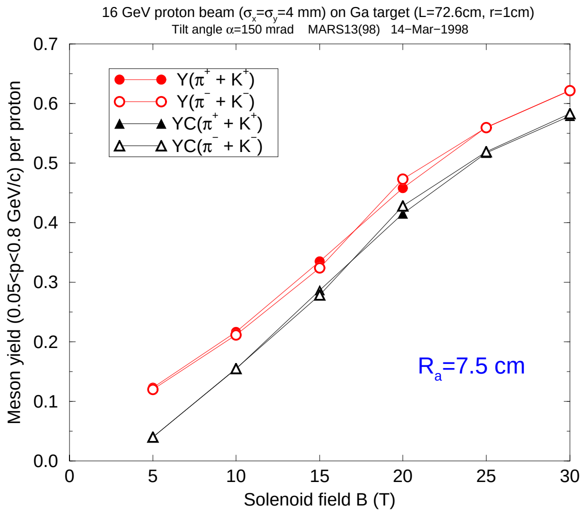


Ex: Mercury target radius should be ≈ 5 mm.

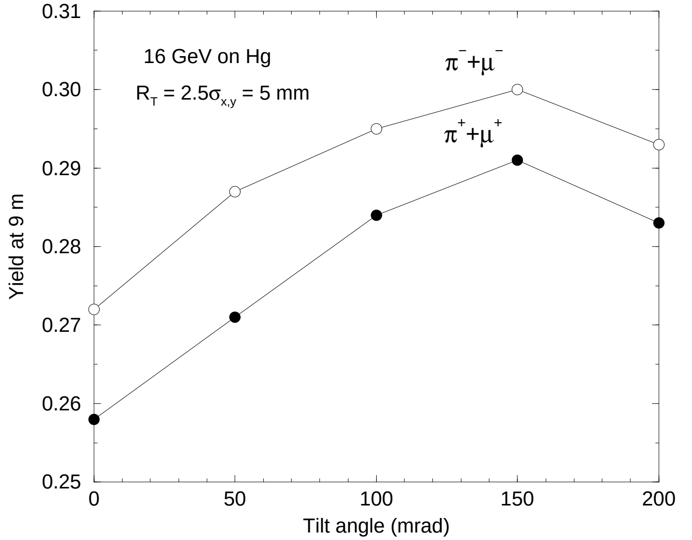
Pion/Muon Yield, II: Solenoid Capture

IF capture pions in a solenoid channel, should begin with a high-field “magnetic bottle”.

Yield *vs.* magnetic field for 15-cm bore:



Yield *vs.* target tilt:



Tilt target axis by ≈ 100 mrad to the magnetic axis to increase yield of soft, large-angle pions.

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

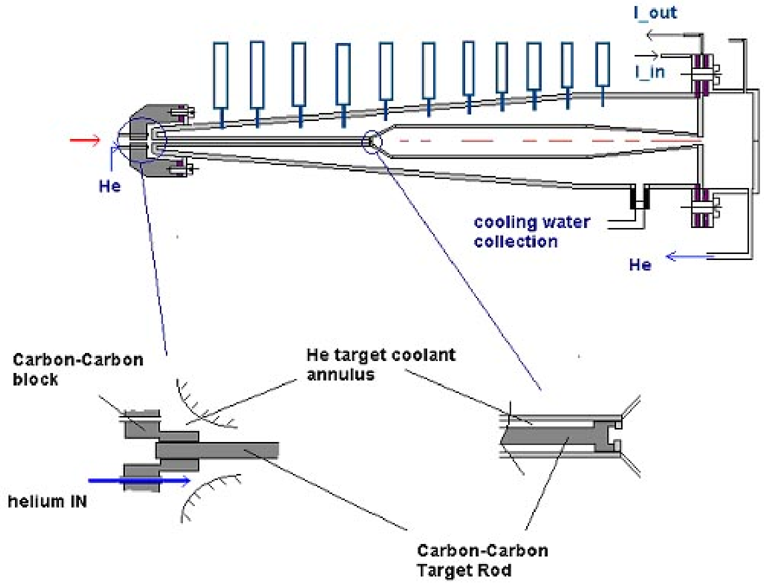
Target Topologies

Target and Capture Topologies: Toroidal Horn

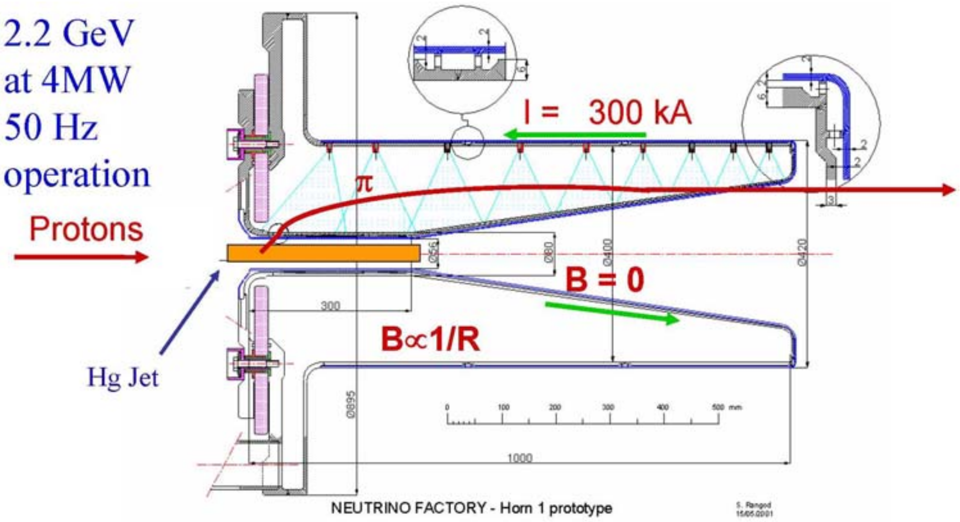
The traditional topology for efficient capture of secondary pions is a toroidal “horn” (Van der Meer, 1961).

- Collects only one sign, ⇒ Long data runs, but nonmagnetic detector (Superbeam).
- Inner conductor of toroid very close to proton beam.
  ⇒ Limited life due to radiation damage at 4 MW.
  ⇒ Beam, and beam dump, along magnetic axis.
  ⇒ More compatible with Superbeam than with Neutrino Factory.

Carbon composite target with He gas cooling (BNL study):



Mercury jet target (CERN SPL study):


2.2 GeV
at 4MW
50 Hz
operation

If desire secondary pions with $E_\pi \lesssim 5$ GeV (Neutrino Factory), a high-Z target is favored, but for $E_\pi \gtrsim 10$ GeV (some Superbeams), low Z is preferred.

Target and Capture Topologies: Solenoid

Palmer (1994) proposed a solenoidal capture system for a Neutrino Factory.

- Collects both signs of π's and μ's, $\Rightarrow$ Shorter data runs (with magnetic detector).
- Solenoid coils can be some distance from proton beam.

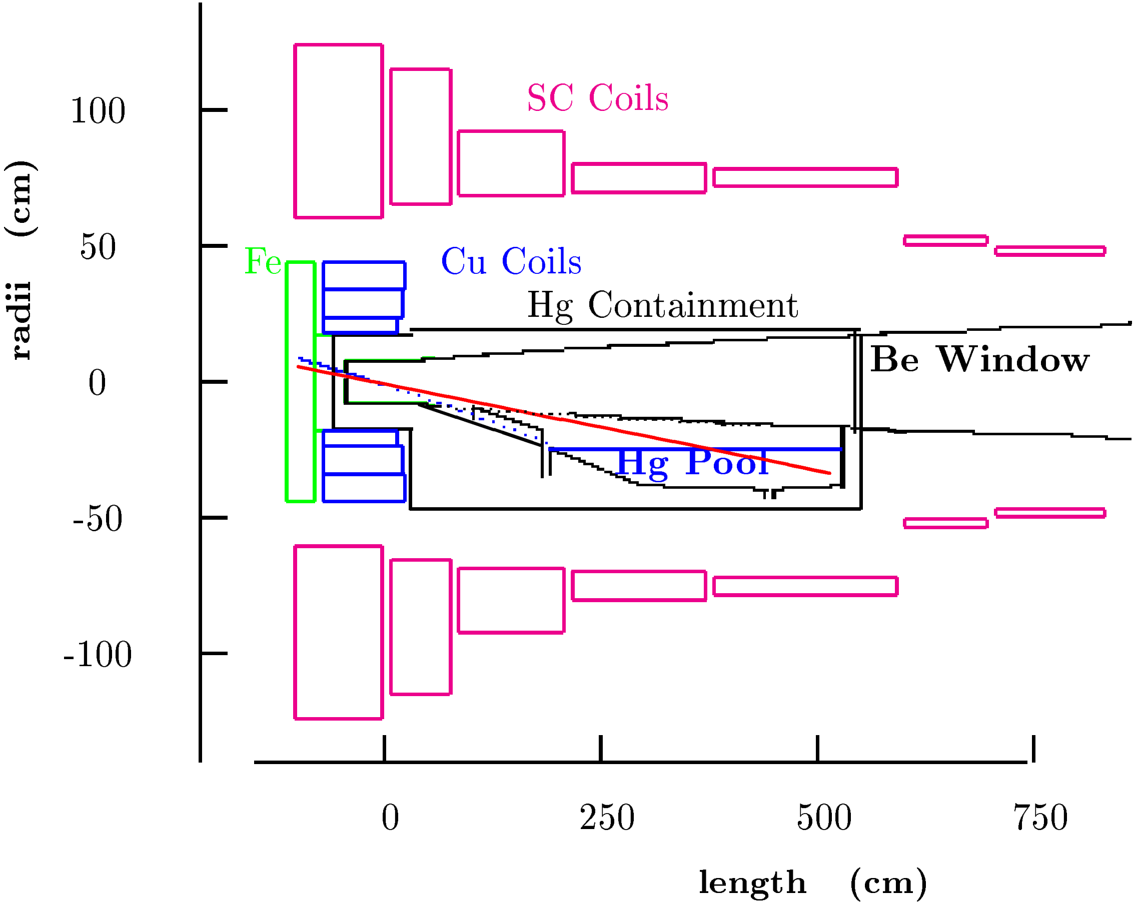
$\Rightarrow$ $\gtrsim$ 4 year life against radiation damage at 4 MW.

$\Rightarrow$ Proton beam readily tilted with respect to magnetic axis.

$\Rightarrow$ Beam dump out of the way of secondary π's and μ's.

Mercury jet target and proton beam tilt downwards with respect to the horizontal magnetic axis of the capture system.

The mercury collects in a pool that serves as the beam dump (Neutrino Factory Study 2):



A Neutrino Horn Based on a Solenoid Lens

Point-to-parallel focusing for

$$P_\pi = eBd/(2n+1)\pi c.$$

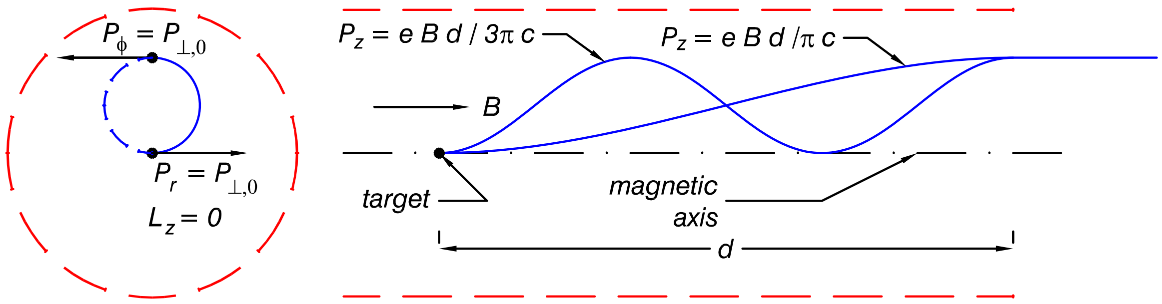
⇒ Narrowband (less background) neutrino beams of energies

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

⇒ Can study several neutrino oscillation peaks at once,

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

(Marciano, hep-ph/0108181)



(KTM, physics/0312022)

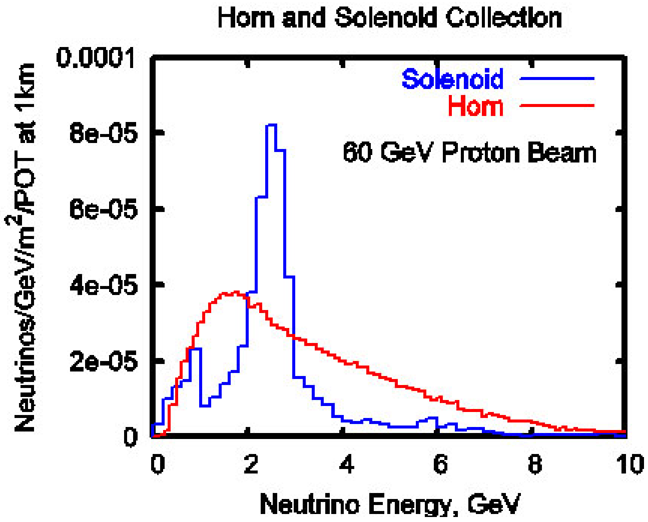
⇒ Study both ν and $\bar{\nu}$ at the same time.

⇒ Detector must identify sign of μ and e.

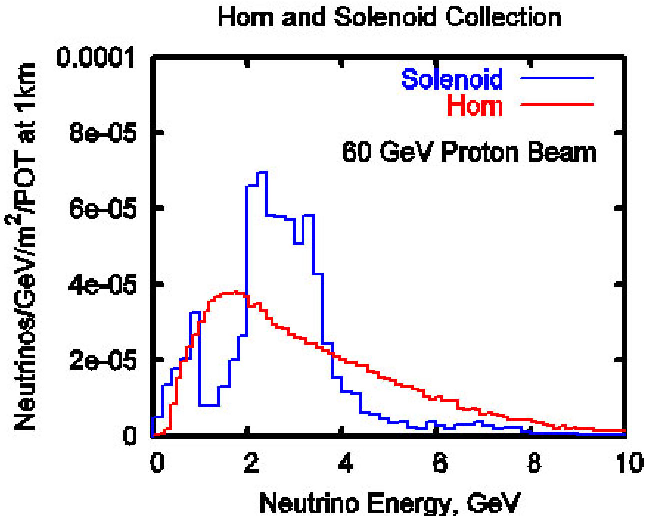
⇒ Magnetized liquid argon TPC. (astro-ph/0105442).

(H. Kirk and R. Palmer, NuFACT06):

3-m solenoid gives 2 narrow peaks in ν spectrum.



3-30-m solenoid broadens the higher energy peak.



Solid Targets

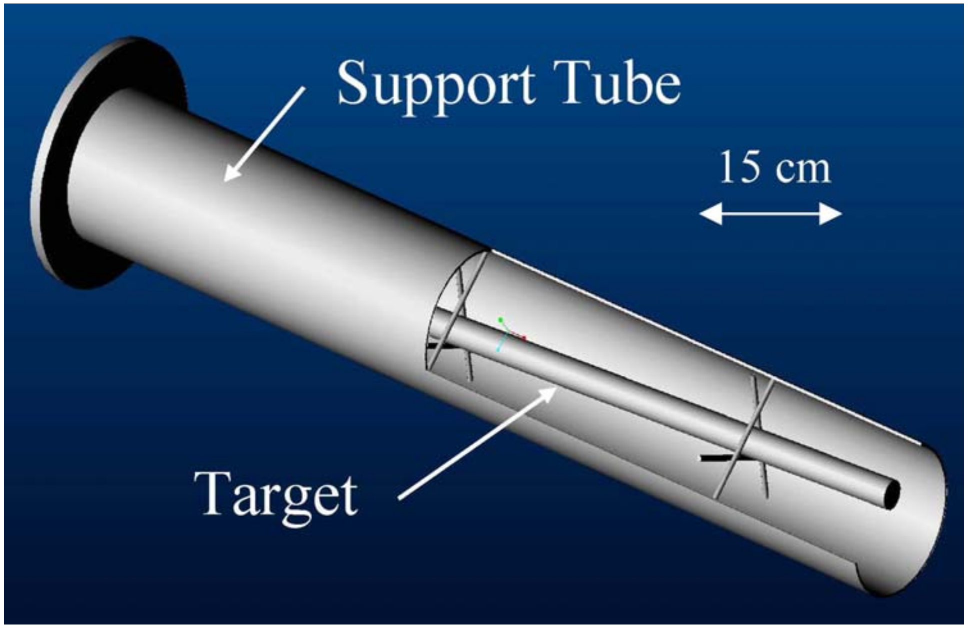
Thermal Issues for Solid Targets, I

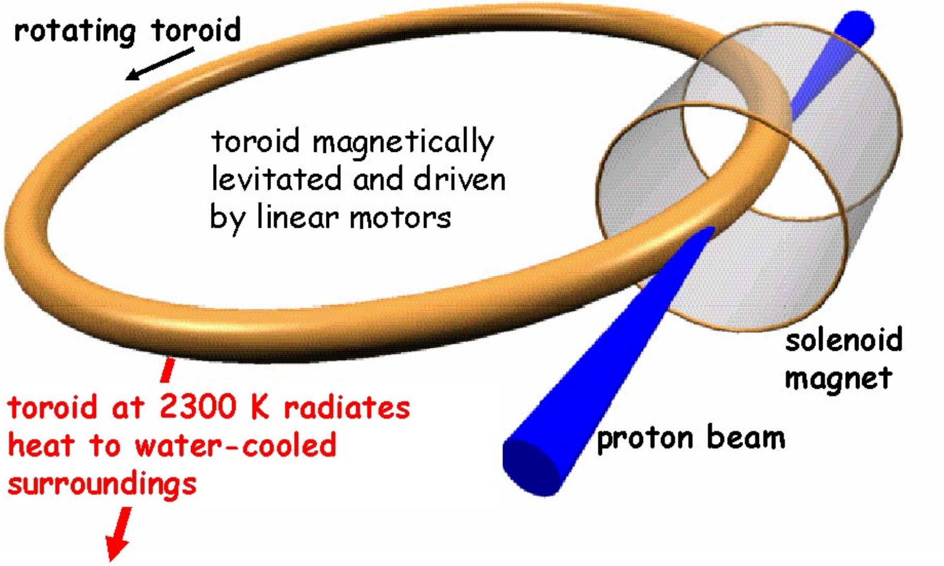
The quest for efficient capture of secondary pions precludes traditional schemes to cool a solid target by a liquid. (Absorption by plumbing; cavitation of liquid.)

A solid, radiation-cooled stationary target in a 4-MW beam will equilibrate at about 2500 C. ⇒ Carbon is only candidate for this type of target.

(Carbon target must be in He atmosphere to suppress sublimation.)

A moving band target (Ta, W, ...) could be considered (if capture system is toroidal).





Thermal Issues for Solid Targets, II

When beam pulse length t is less than target radius r divided by speed of sound $v_{\rm sound}$, beam-induced pressure waves (thermal shock) are a major issue.

Simple model: if U = beam energy deposition in, say, Joules/g, then the instantaneous temperature rise ΔT is given by

$$\Delta T = \frac{U}{C}, \qquad \text{where } C = \text{heat capacity in Joules/g/K.}$$

The temperature rise leads to a strain $\Delta r/r$ given by

$$\frac{\Delta r}{r} = \boldsymbol{\alpha}\Delta T = \frac{\boldsymbol{\alpha} U}{C}, \qquad \text{where } \boldsymbol{\alpha} = \text{thermal expansion coefficient.}$$

The strain leads to a stress P (= force/area) given by

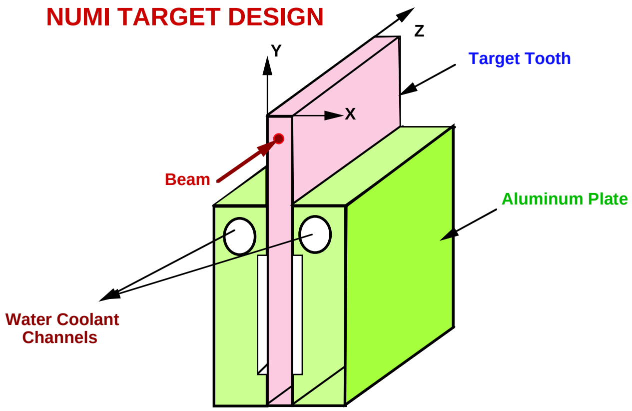
$$P = E\frac{\Delta r}{r} = \frac{E\boldsymbol{\alpha} U}{C}, \qquad \text{where } E = \text{modulus of elasticity.}$$

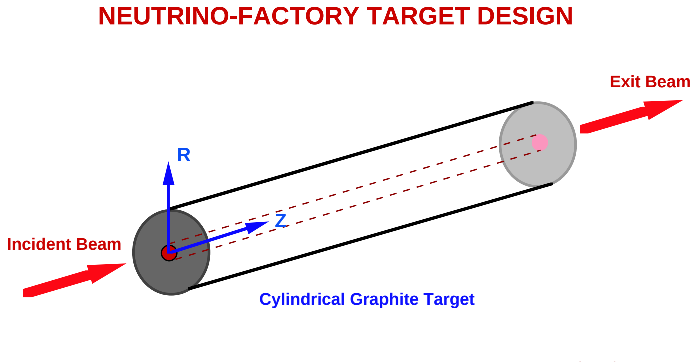
In many metals, the tensile strength obeys $P \approx 0.002E$, $\boldsymbol{\alpha} \approx 10^{-5}$, and $C \approx 0.3$ J/g/K, in which case

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

⇒ Best candidates for solid targets have high strength (Vascomax, Inconel, TiAl6V4) and/or low thermal expansion (Superinvar, Toyota "gum metal", carbon-carbon composite).

A Carbon Target is Feasible at 1-2 MW Beam Power





HASSANEIN (ANL)

Low energy deposition per gram and low thermal expansion coefficient reduce thermal “shock” in carbon.

Operating temperature > 2000C if use only radiation cooling.

A carbon target in vacuum would sublimate away in 1 day at 4 MW, but sublimation of carbon is negligible in a helium atmosphere.

Radiation damage is limiting factor: $\approx$ 12 weeks at 1 MW.

⇒ Carbon target is baseline design for most neutrino superbeams.

Useful pion capture increased by compact, high-Z target,
⇒ Continued R&D on solid targets.

How Much Beam Power Can a Solid Target Stand?

How many protons are required to deposit 60 J/g in a material?

What is the maximum beam power this material can withstand without cracking, for a 10-GeV beam at 10 Hz with area 0.1 cm^2.

Ans: If we ignore "showers" in the material, we still have dE/dx ionization loss, of about 1.5 MeV/g/cm^2.

Now, 1.5 MeV $= 2.46 \times 10^{-13}$ J, so 60 J/ g requires a proton beam intensity of $60/(2.4 \times 10^{-13}) = 2.4 \times 10^{14}$/cm^2.

So, $P_{\rm max} \approx 10\ \mathbf{Hz} \cdot 10^{10}\ \mathbf{eV} \cdot 1.6 \times 10^{-19}\ \mathbf{J/eV} \cdot 2.4 \times 10^{14}/\mathbf{cm}^2 \cdot 0.1\ \mathbf{cm}^2 \approx 4 \times 10^5\ \mathbf{J/s} = \mathbf{0.4\ MW}$.

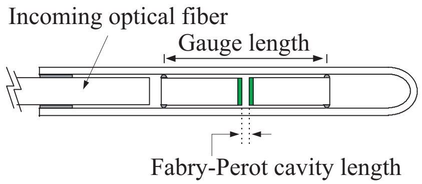
If solid targets crack under singles pulses of 60 J/g, then safe up to only 0.4 MW beam power!

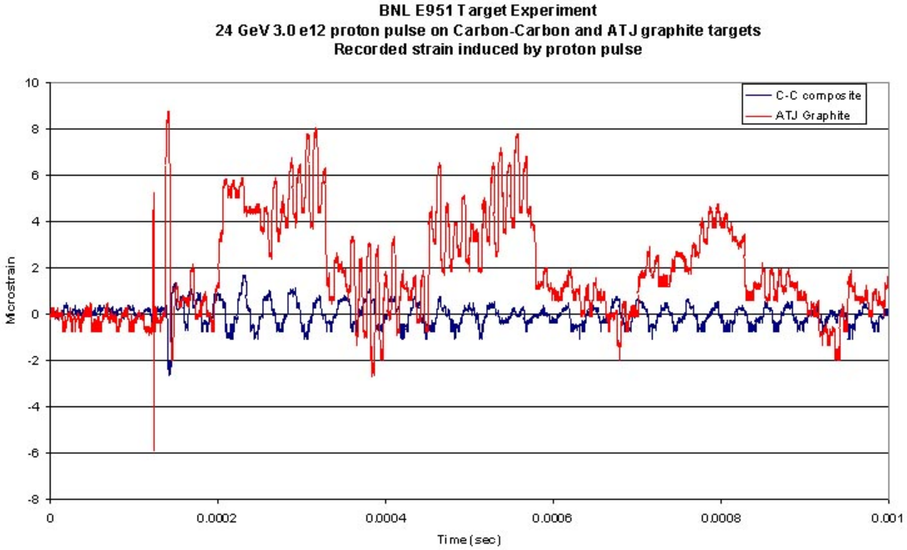
Empirical evidence is that some materials survive 500-1000 J/g,
$\Rightarrow$ May survive 4 MW if rep rate $\gtrsim$ 10 Hz.

Ni target in FNAL $p$bar source:
"damaged but not failed" for peak energy deposition of 1500 J/g.

Lower Thermal Shock If Lower Thermal Expansion Coefficient

ATJ graphite and a 3-D weave of carbon-carbon fibers instrumented with fiberoptic strain sensors, and exposed to pulses of 4×10^{12} protons @ 24 Gev.

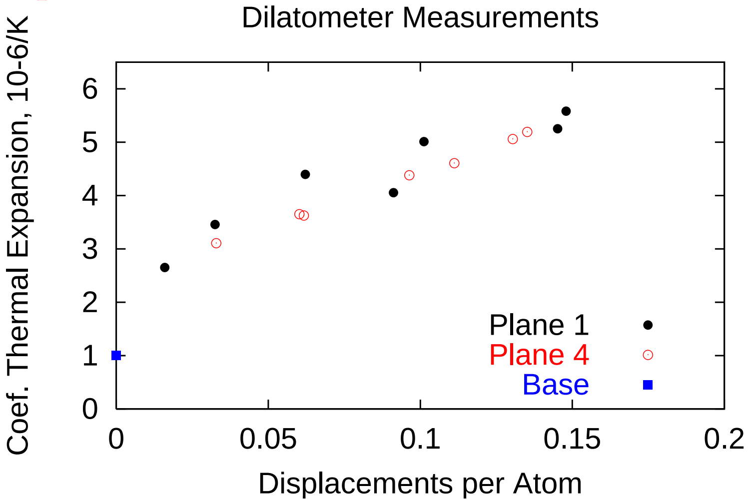




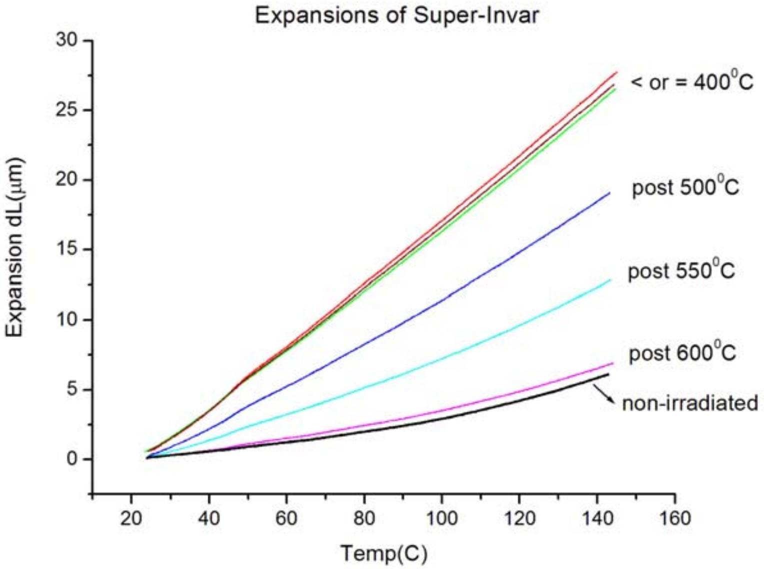
Carbon-carbon composite showed much lower strains than in the ordinary graphite – but readily damaged by radiation!

Thermal expansion coefficient of engineered materials is affected by radiation.

Super-Invar: CTE *vs.* dose:

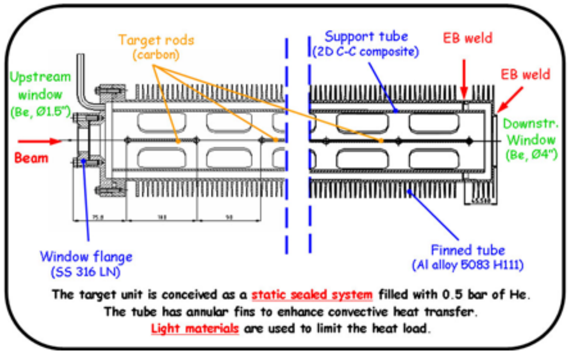


Super-Invar: recovery of the CTE by thermal annealing:

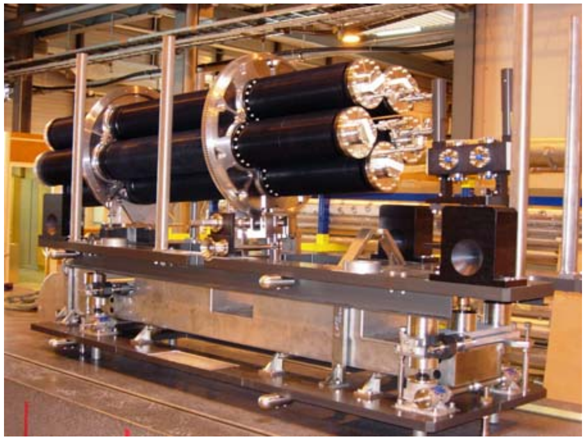


Recent/Ongoing Solid Target Projects

CNGS Target System
(R. Bruno, NuFact06)
Up to 7×10^{13} 400-GeV protons every 6 s.
Beam σ = 0.5 mm.
5 interchangeable graphite targets.
Designed for 0.75 MW.

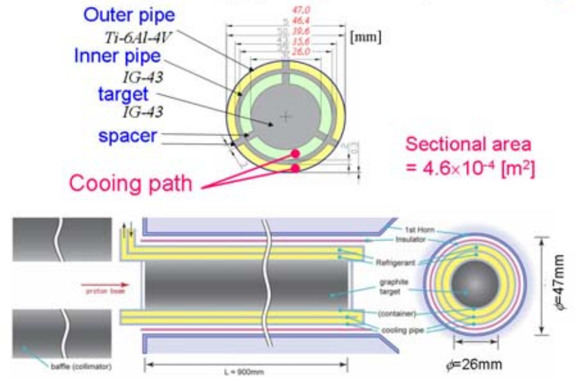


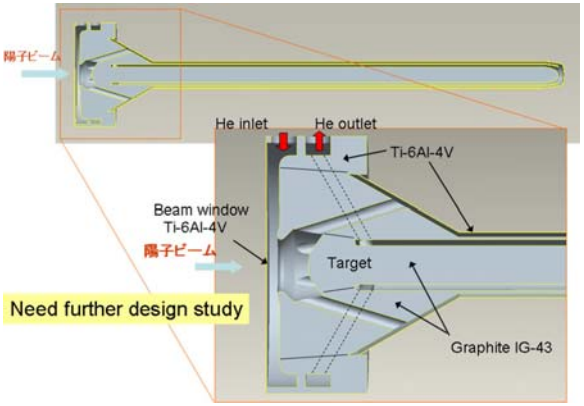
The target unit is conceived as a static sealed system filled with 0.5 bar of He.
The tube has annular fins to enhance convective heat transfer.
Light materials are used to limit the heat load.



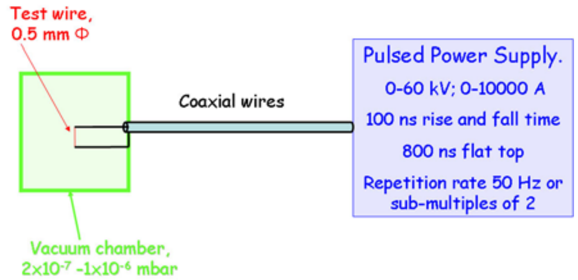
JPARC ν Horn Target
(Y. Hayato, NuFact06)
Up to 4×10^{14} 50-GeV protons every 4 s.
Beam σ = 4 mm.
Designed for 0.75 MW.
He gas cooling.

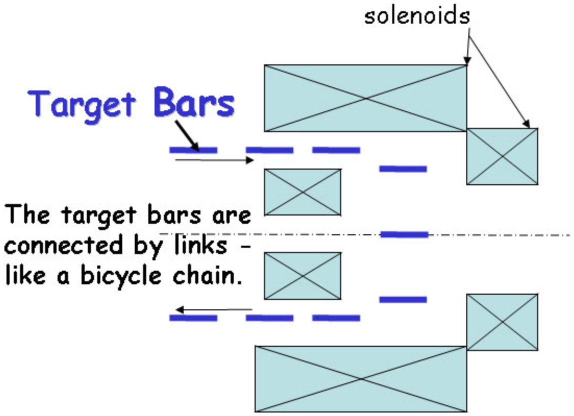
- Co-axial 2 layer cooling pipe: Graphite / Ti-6Al-4V, Helium cooling





Pulsed-Current Studies of Ta & W Wires at RAL
(R. Bennett *et al.*)





The target bars are connected by links – like a bicycle chain.

New: Flowing Tungsten Powder Targets
(C. Densham *et al.*, RAL)

Liquid Jet Targets

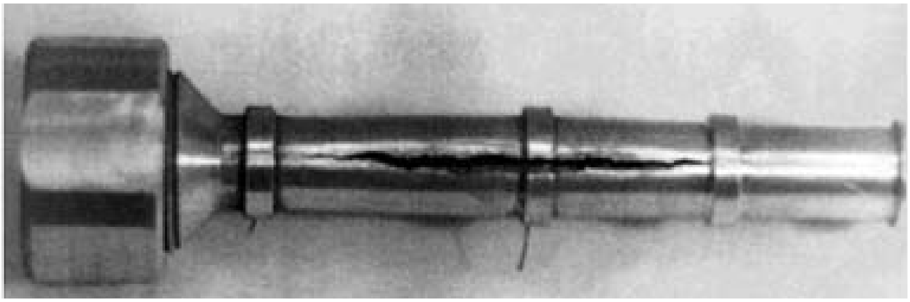
A. Calder, Paris (1937):

Now at Fundació Joan Miró, Barcelona

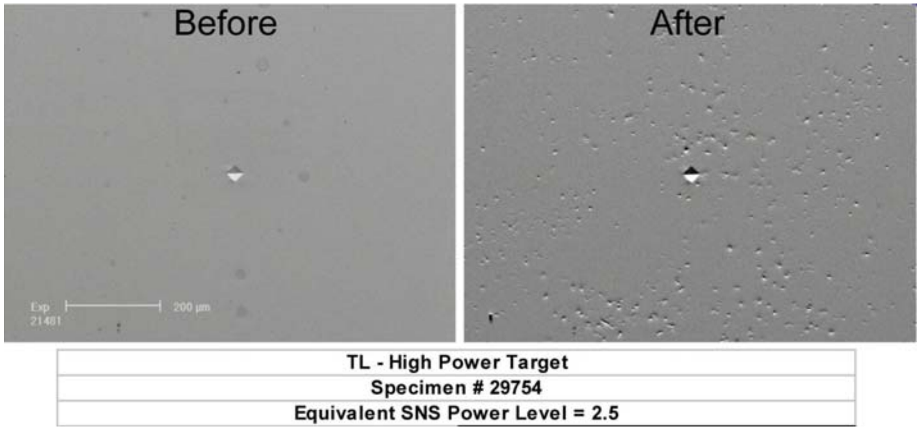
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

Hg in a pipe (BINP):



Cavitation pitting of SS wall surrounding Hg target after 100 pulses (SNS):



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

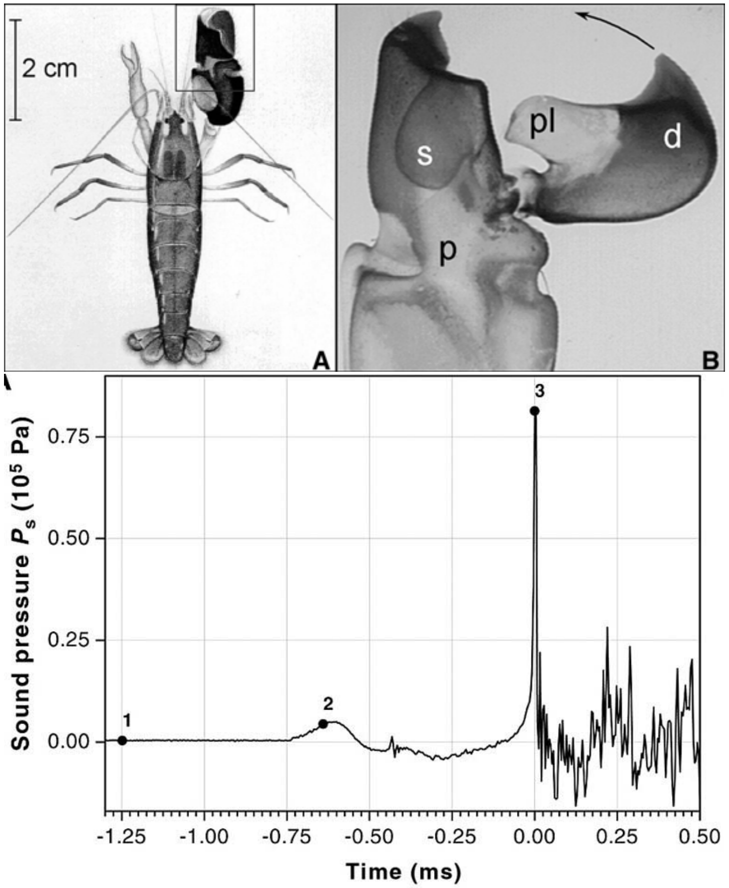
Water jacket of NuMI target developed a leak after ≈ 1 month.
Likely due to beam-induced cavitation.

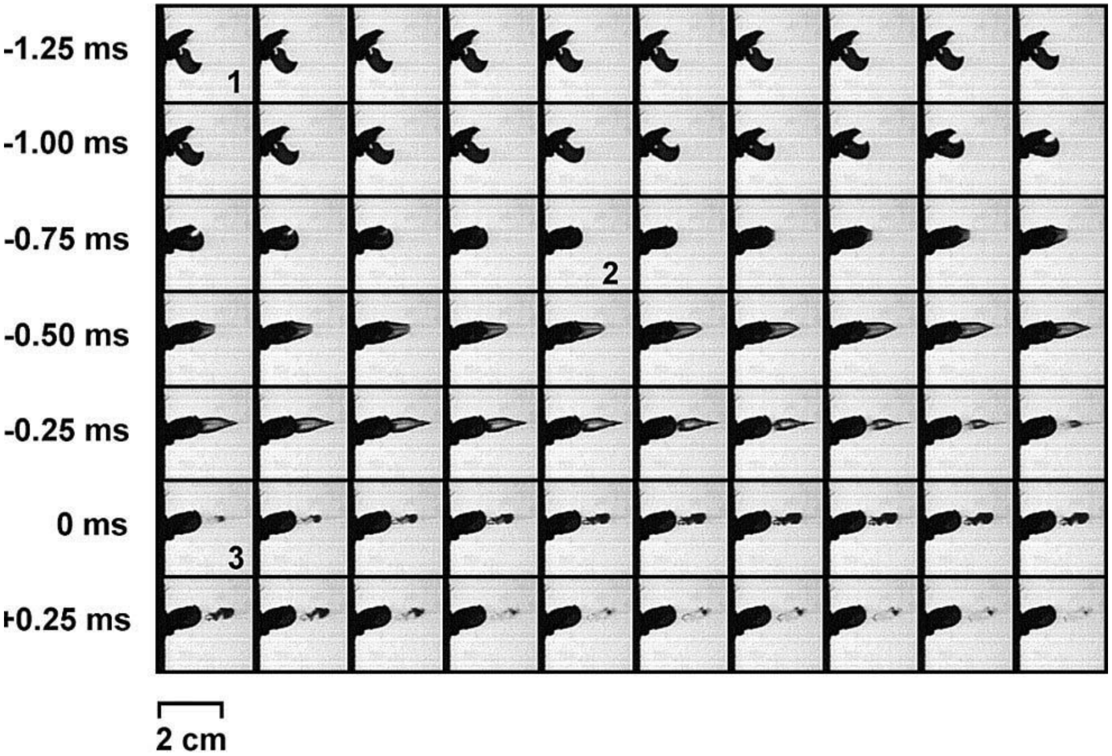
Ceramic drainpipe/voltage standoff of water cooling system of CNGS horn failed after 2 days operation at high beam power. (Not directly a beam-induced failure.)

⇒ Use free liquid jet if possible.

How Snapping Shrimp Snap: Through Cavitating Bubbles

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

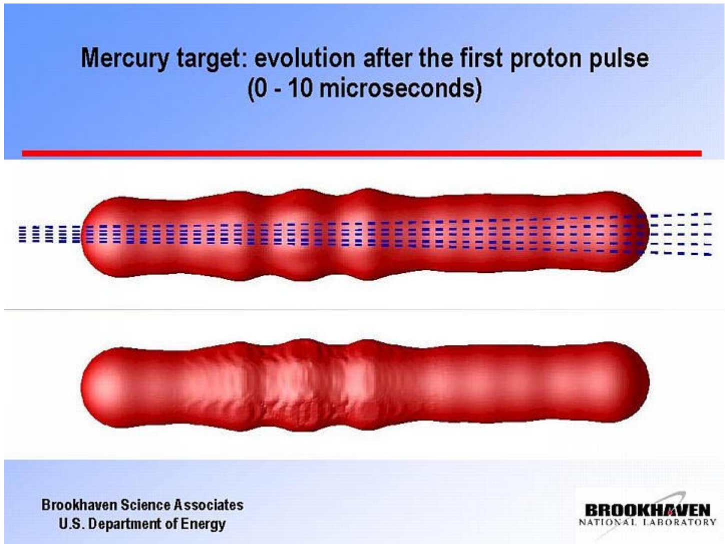




Beam-Induced Effects on a Free Liquid Jet

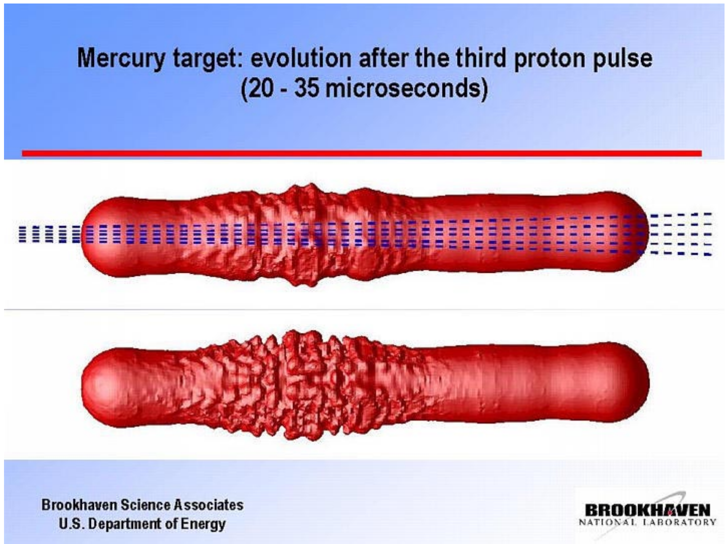
Beam energy deposition may disperse the jet.

FRONTIER simulation predicts breakup via filamentation on mm scale:


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

Brookhaven Science Associates
U.S. Department of Energy

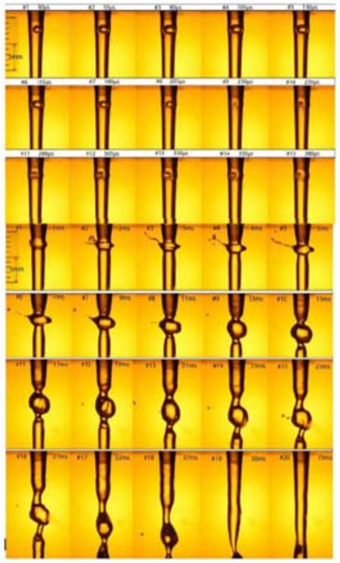
BROOKHAVEN
NATIONAL LABORATORY


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

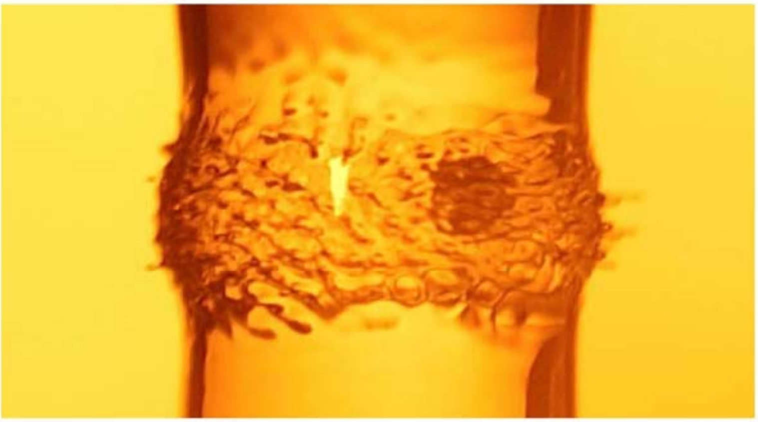
Brookhaven Science Associates
U.S. Department of Energy

BROOKHAVEN
NATIONAL LABORATORY

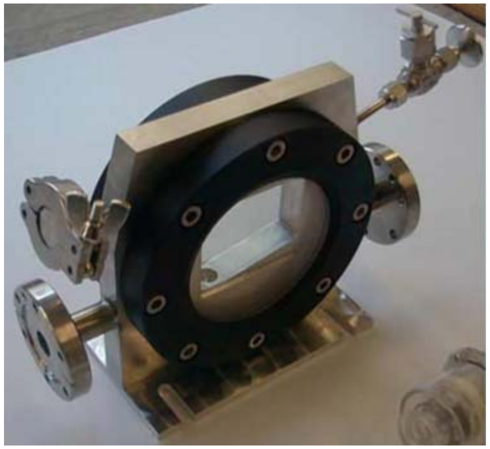
Laser-induced breakup of a water jet:
(J. Lettry, CERN)



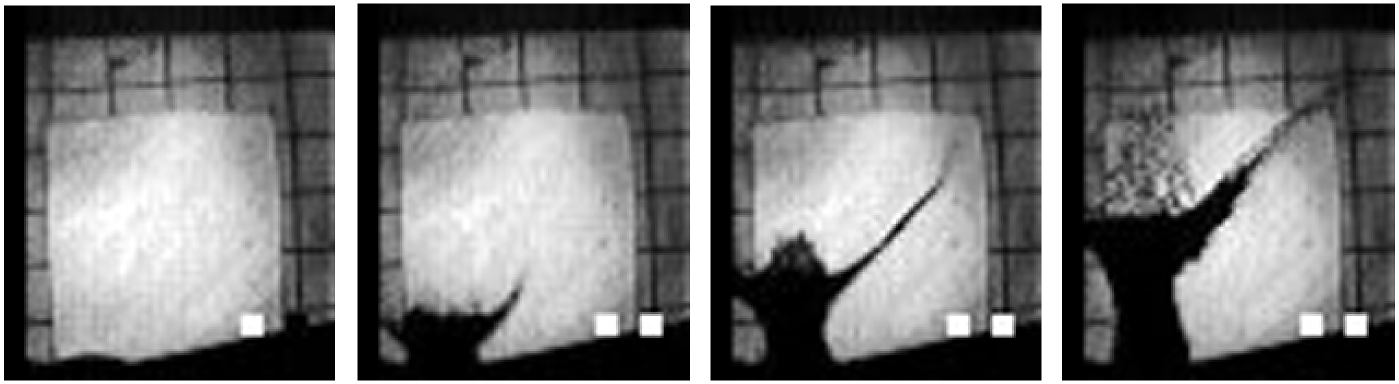
Water jet ripples generated by a
8 mJ Laser cavitation bubble



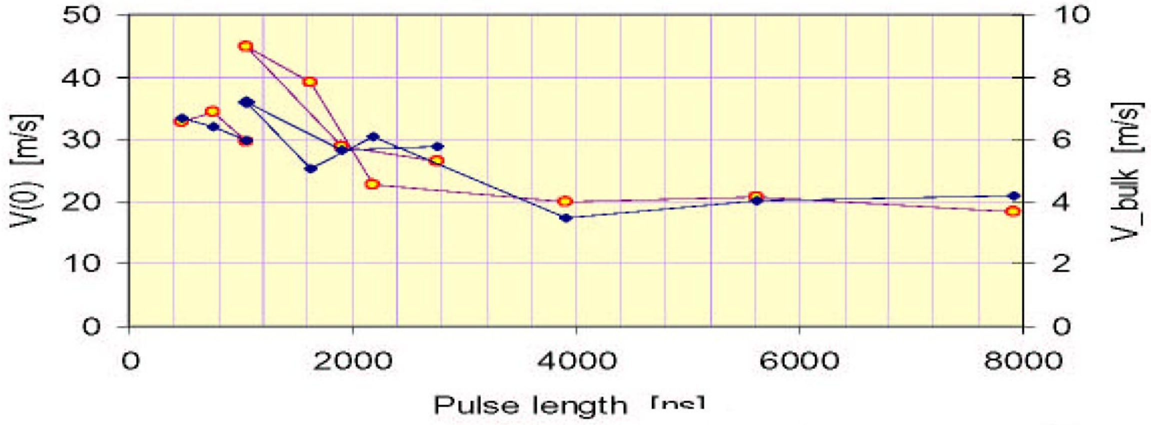
Passive Mercury Target Tests (BNL-CERN, 2001-2002)



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

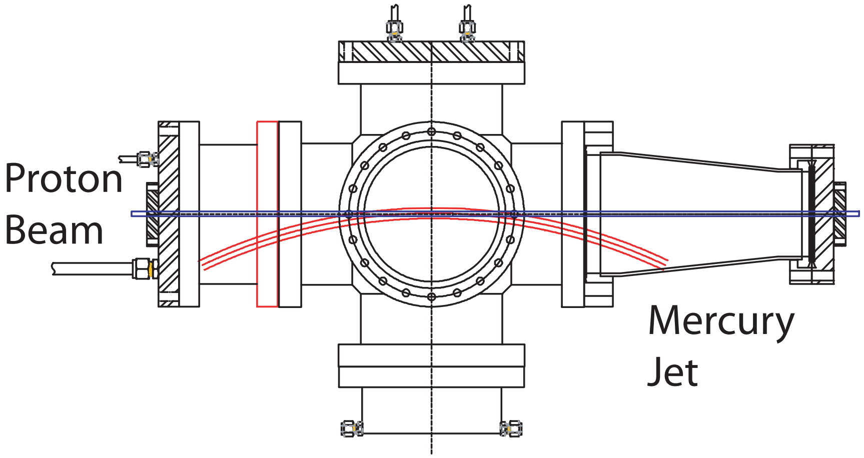


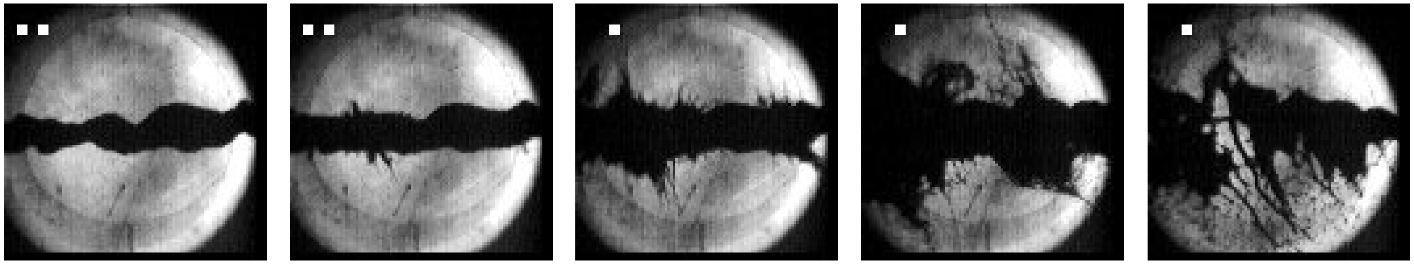
Two pulses of ≈ 250 ns give larger dispersal velocity only if separated by $< 3\ \mu$s.



Studies of Proton Beam + Mercury Jet

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





Model: $$v_{\rm dispersal} = \frac{\Delta r}{\Delta t} = \frac{r\alpha\Delta T}{r/v_{\rm sound}} = \frac{\alpha U}{C} v_{\rm sound} \approx 50 \text{ m/s for } U \approx 100 \text{ J/g}.$$

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

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

The dispersal is not destructive.

Filaments appear only ≈ 40 μs after beam,
$\Rightarrow$ After several bounces of waves, OR $v_{\rm sound}$ very low.

Hydrodynamics of Liquid Jet Targets

- **Diameter d = 1 cm.**
- **Velocity v = 20 m/s.**
- **The volume flow rate of mercury in the jet is**

$$\textbf{Flow Rate} = vA = 2000\ \mathrm{cm/s} \cdot \frac{\pi}{4} d^2 = 1571\ \mathrm{cm}^3/\mathrm{s} = 1.57\ \textbf{l/s} = 0.412\ \textbf{gallon/s} = 94.2\ \textbf{l/min} = 24.7\ \textbf{gpm}. \qquad (1)$$

- **The power in the jet (associated with its kinetic energy) is**

$$\textbf{Power} = \frac{1}{2}\rho \cdot \textbf{Flow Rate} \cdot v^2 = \frac{13.6 \times 10^3}{2} \cdot 0.00157 \cdot (20)^2 = 4270\ \mathrm{W} = 5.73\ \textbf{hp}. \qquad (2)$$

- **To produce the 20-m/s jet into air/vacuum out of a nozzle requires a pressure**

$$\textbf{Pressure} = \frac{1}{2}\rho v^2 = 27.2\ \textbf{atm} = 410\ \textbf{psi}, \qquad (3)$$

IF no dissipation of energy.

- **The mercury jet flow is turbulent: the viscosity is $\mu_{\mathrm{Hg}} = 1.5$ cP (kinematic viscosity $\eta = \mu/\rho = 0.0011$ cm^2/s), so the Reynolds number is**

$$\mathcal{R} = \frac{\rho d v}{\mu} = \frac{dv}{\eta} = 1.8 \times 10^6. \qquad (4)$$

- **The surface tension of mercury is τ = 465 dyne/cm (water = 73), ⇒**

$$\textbf{Weber number, } \mathcal{W} = \frac{\rho d v^2}{\tau} = 115,000. \qquad (5)$$

Nozzle Lore

Hg jet for Neutrino Factory:

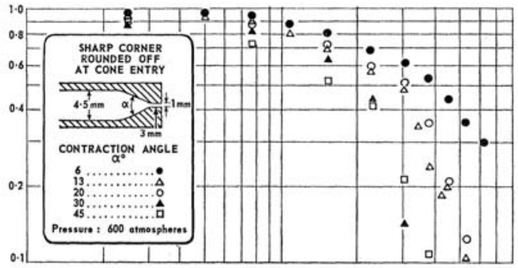
$v = 20$ m/s, $d = 1$ cm,

$\Rightarrow$ Turbulent flow.

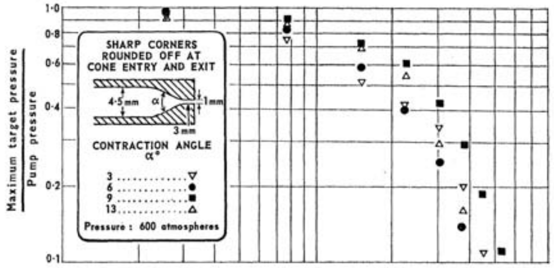
Lore:

- Should be able to make a 1-cm-diameter Hg jet go 1-2 m before breakup.
- Area of feed should be $\gtrsim 10\times$ area of nozzle.
- $\approx 15^\circ$ nozzle taper is good.
- Nozzle tip should be straight, with $\approx 3:1$ aspect ratio.
- High-speed jets will have a halo of spray around a denser core.
- Low/zero surrounding gas pressure is better.

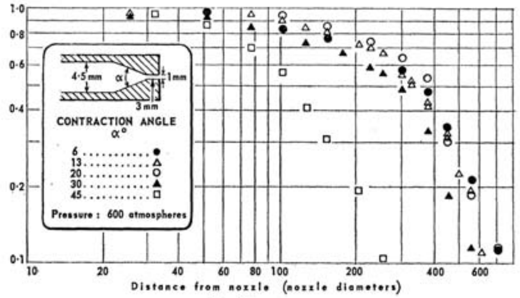
Leach & Walker (1966):



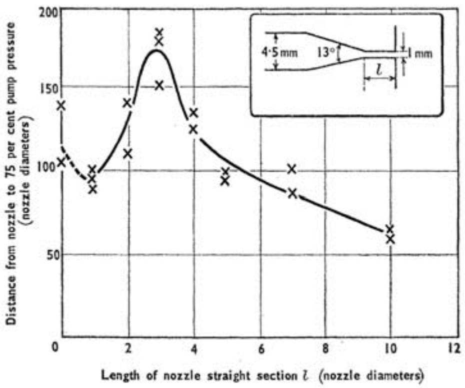
(a) Rounded inlet corners



(b) Rounded corners at both ends of contraction



(c) Sharp corners



McCarthy & Molloy (1974):

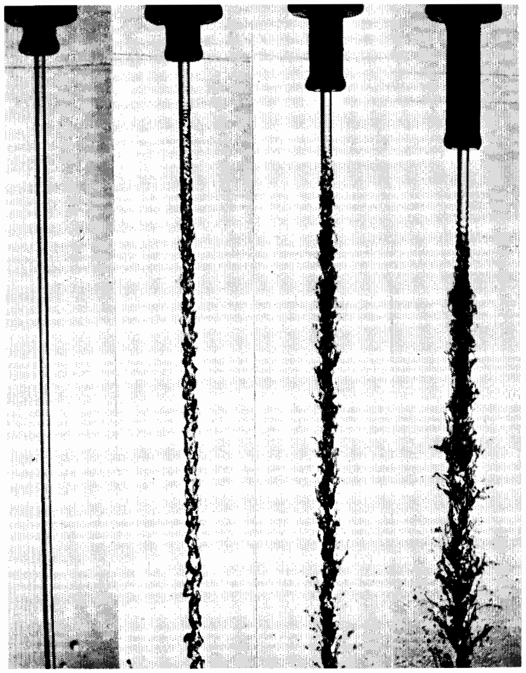
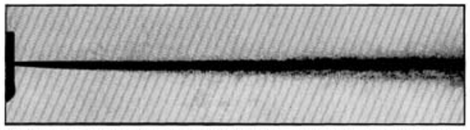


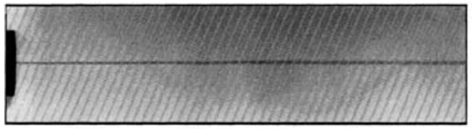
Fig. 5. Effect of nozzle design on the stability of glycerol–water jets.

Jet viscosity	11 cP
Jet velocity	20 m s^{-1} (approx.)
Nozzle diameter	2.54 mm
Jet Reynolds no.	4750
Jet Ohnesorge no.	0.026
Exposure	30 μsec
Nozzle aspect ratio	$AR = L/d$ (see Fig. 7) = 0, 1, 5, 10 L to R.

Leach & Walker:



(*d*) Spark source; parallel transmitted light ($\frac{1}{2}$ μs exposure); pressure 130 atm.



(*e*) X-ray source (5 min exposure); pressure 130 atm.

Magnetic Issues for Liquid Metal Jet Targets

Conducting materials that move through nonuniform magnetic field experience eddy-current effects, ⇒ Forces on entering or leaving a solenoid (but not at its center).

⇒ Free jet of radius r cannot pass through a horizontal solenoid of diameter D unless

$$v > \frac{3\pi\sigma r^2 B_0^2}{32\rho D} \approx 6\left[\frac{r}{1\ \text{cm}}\right]^2\ \text{m/s}, \qquad \text{for Hg or Pb-Bi jet, } D = 20\ \text{cm}, B_0 = 20\ \text{T}.$$

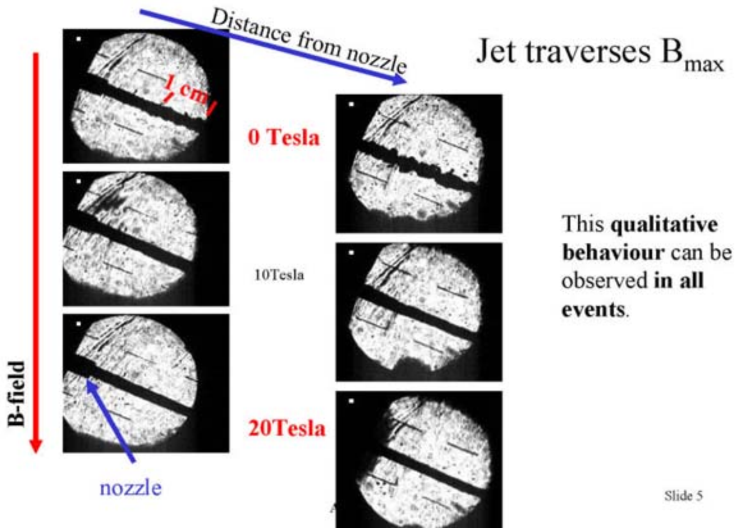
50-Hz rep rate requires $v = 20$ m/s for new target each pulse, so no problem for baseline design with $r = 0.5$ cm. The associated eddy-current heating is negligible.

[Small droplets pass even more easily, and can fall vertically with no retardation.]

A liquid jet experiences a quadrupole shape distortion if tilted with respect to the solenoid axis. This is mitigated by the upstream iron plug that makes the field more uniform.

Magnetic damping of surface-tension waves (Rayleigh instability) observed in CERN-Grenoble tests (2002).

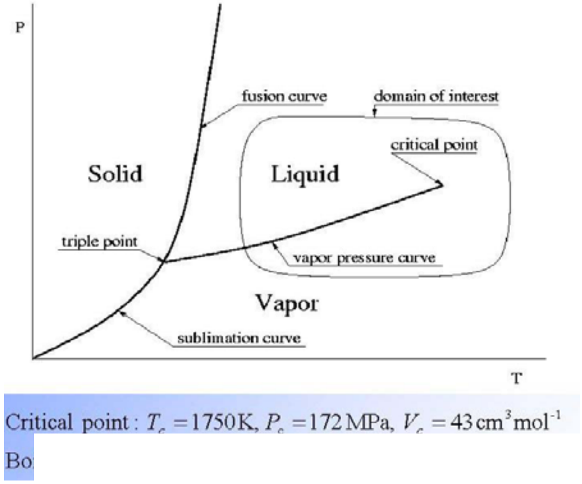
The beam-induced dispersal will be partially damped also (Samulyak).



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

Computational Magnetohydrodynamics (R. Samulyak, J. Du)

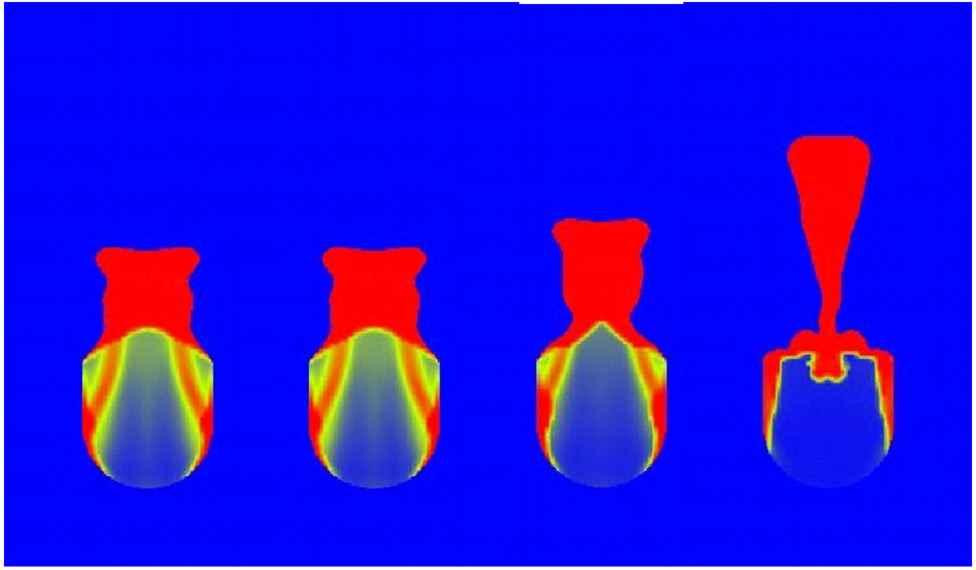
Use an equation of state that supports negative pressures, but gives way to cavitation.



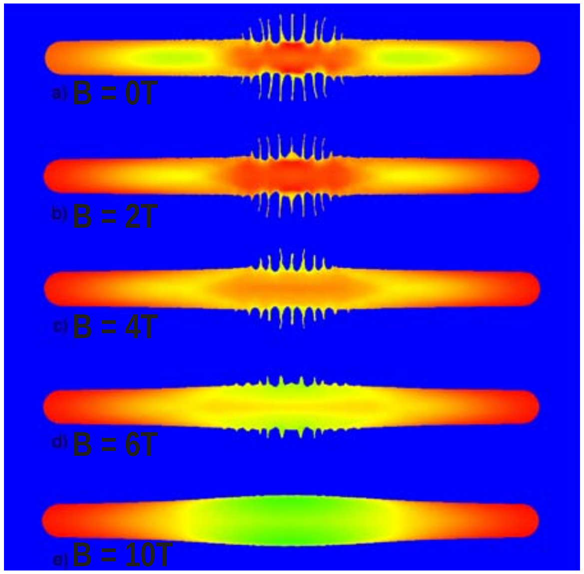
Critical point : $T_c = 1750\,\mathrm{K}$, $P_c = 172\,\mathrm{MPa}$, $V_c = 43\,\mathrm{cm}^3\mathrm{mol}^{-1}$

Bo

Thimble splash at 0.24, 0.48, 0.61, 1.01 μs

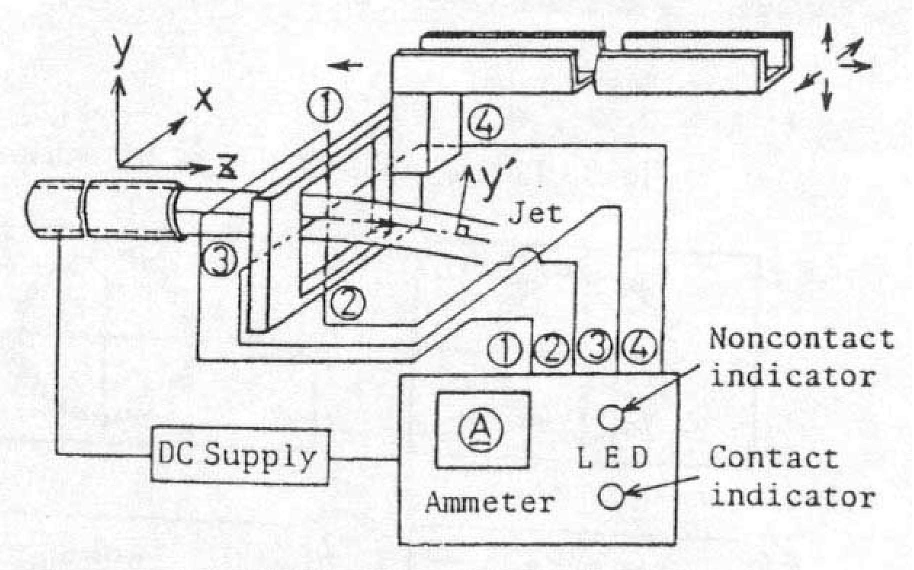


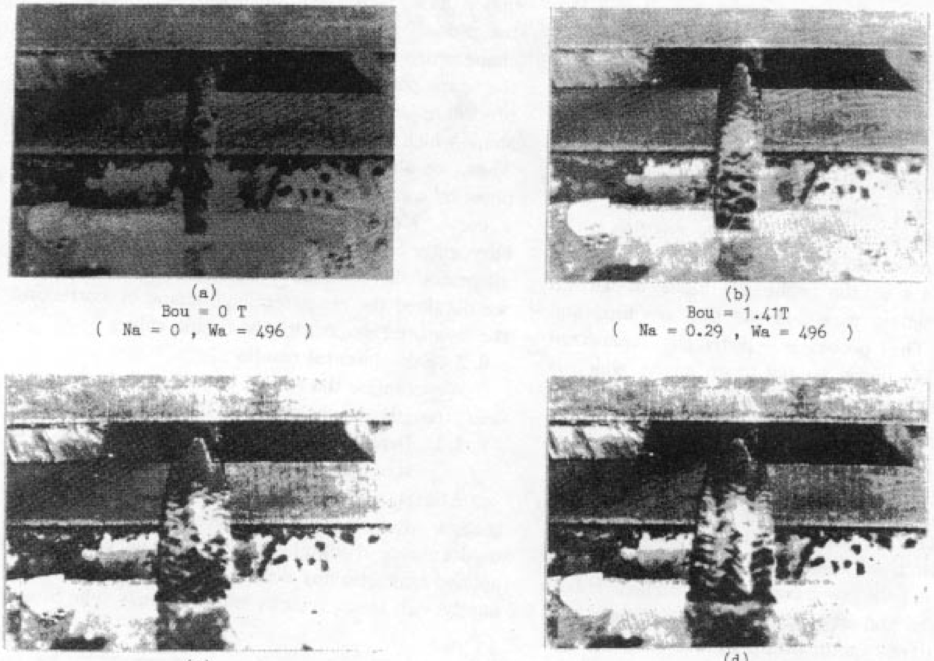
Magnetic damping of beam-induced filamentation:



The Shape of a Mercury Jet under a Non-uniform Magnetic Field

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



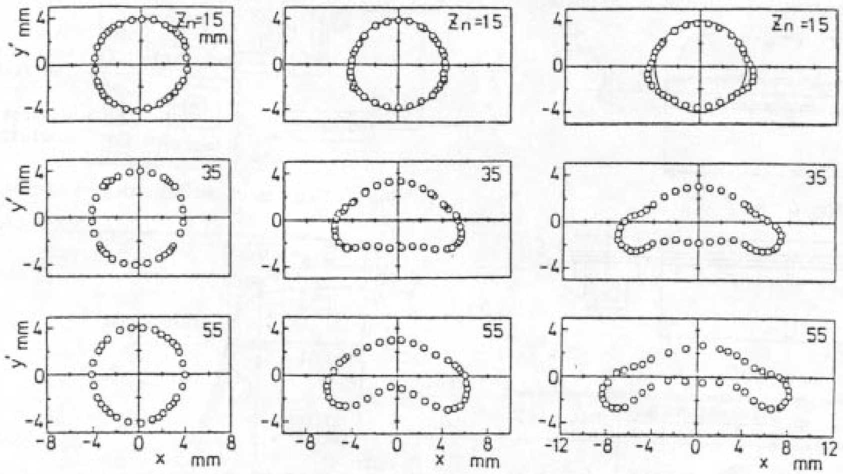

(a) Bou = 0 T (Na = 0 , Wa = 496)

(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 mag- netic field strengths



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

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

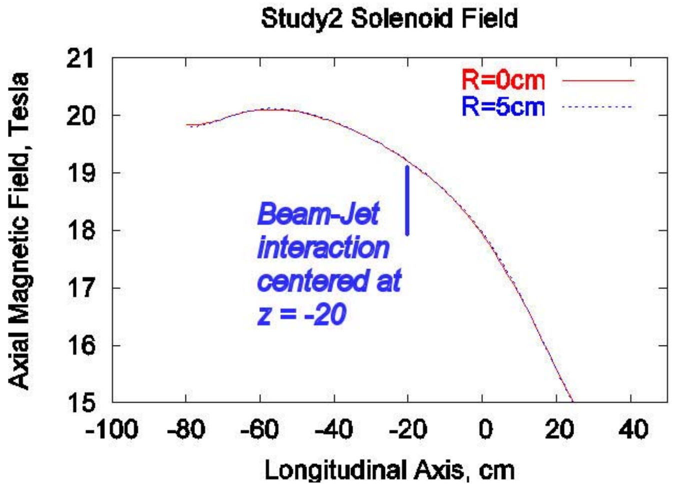
(c) Bou = 1.88 T (Na = 0.57 , Wa = 496)

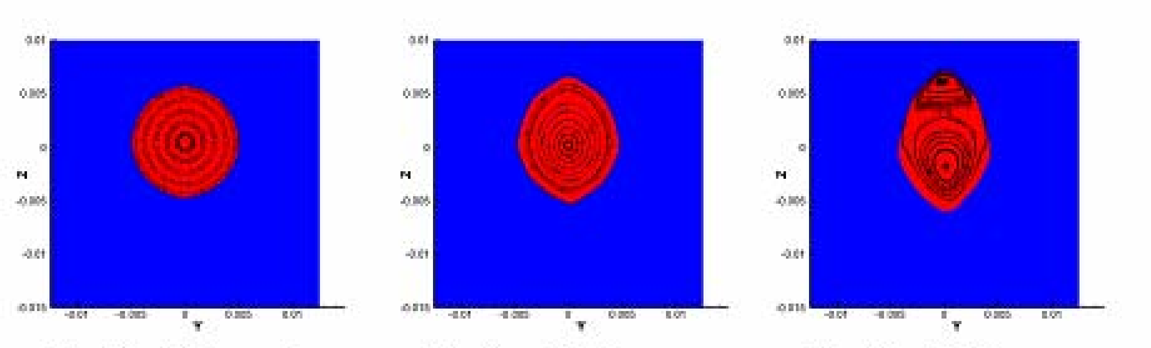
Fig. 10 Cross-sectional shape of the jet obtained by spot a electrode probe

Simulations of Shape Distortion

Incompressible code with free liquid surface confirms predictions of shape distortion of a liquid mercury jet that crosses magnetic field lines. (N. Morley, M. Narula; HIMAG).

Mitigate with good uniformity of magnetic field:





Jet section at inlet, current streamlines clockwise

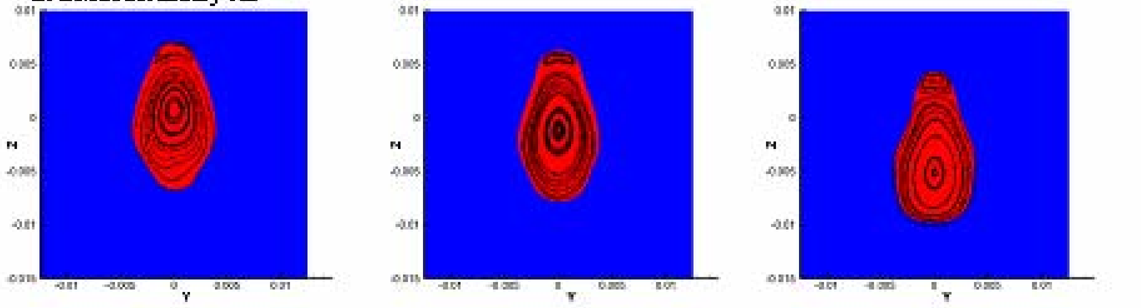
Jet section at X = 20cm, current streamlines clockwise

Jet section at X = 30cm, current streamlines clockwise, weird null

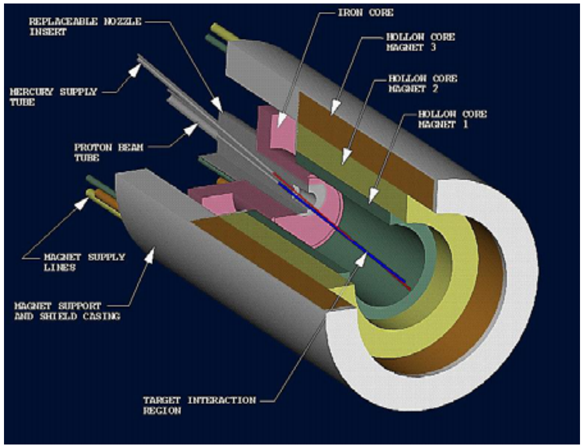
Jet section at X =40 cm , current streamlines anticlockwise, but clockwise secondary cell

Jet section at X = 50 cm , current streamlines anticlockwise

Jet section at X =60 cm , current streamlines anticlockwise



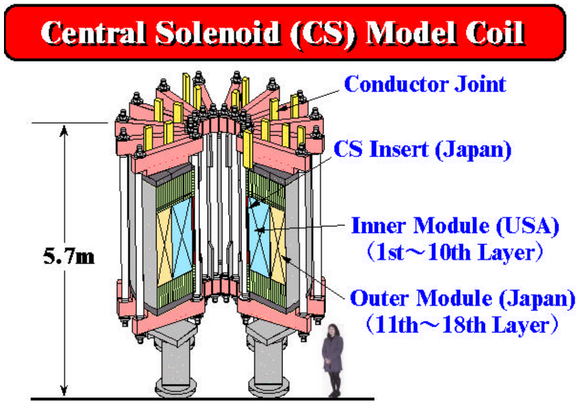
20-T Capture Magnet System (ν Factory Study 2)



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:

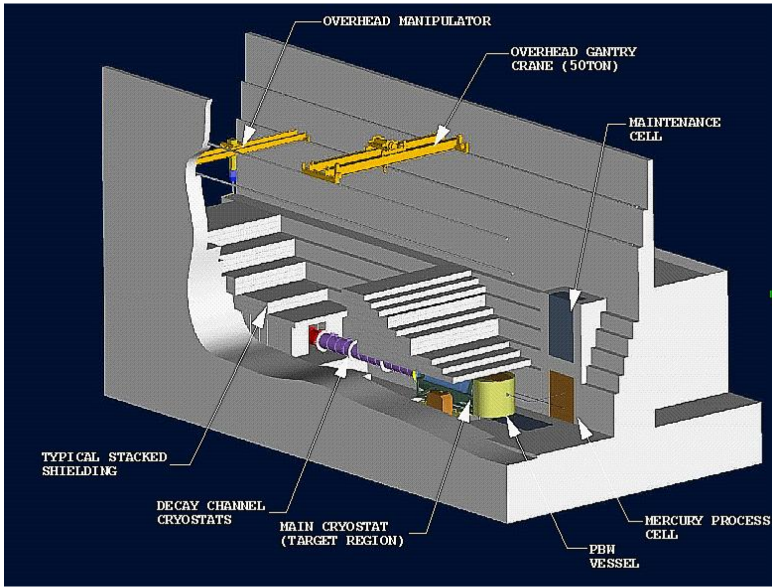


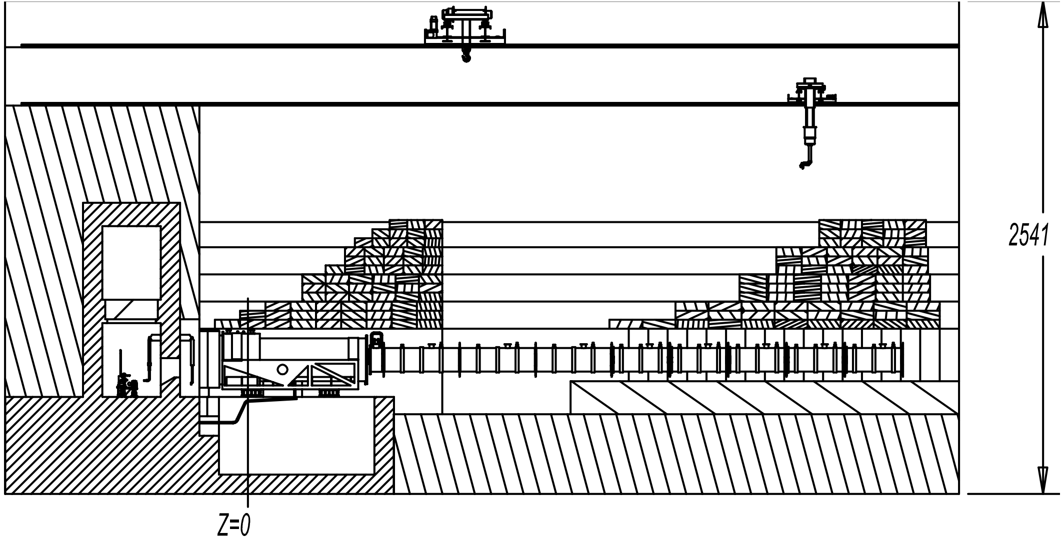
Cable-in-conduit construction similar to ITER central solenoid.

Both coils shielded by tungsten-carbide/water.

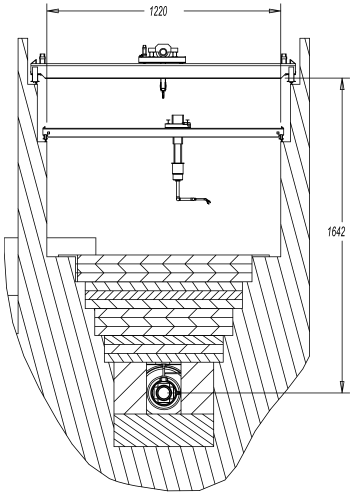
Target System Support Facility

Extensive shielding; remote handling capability.



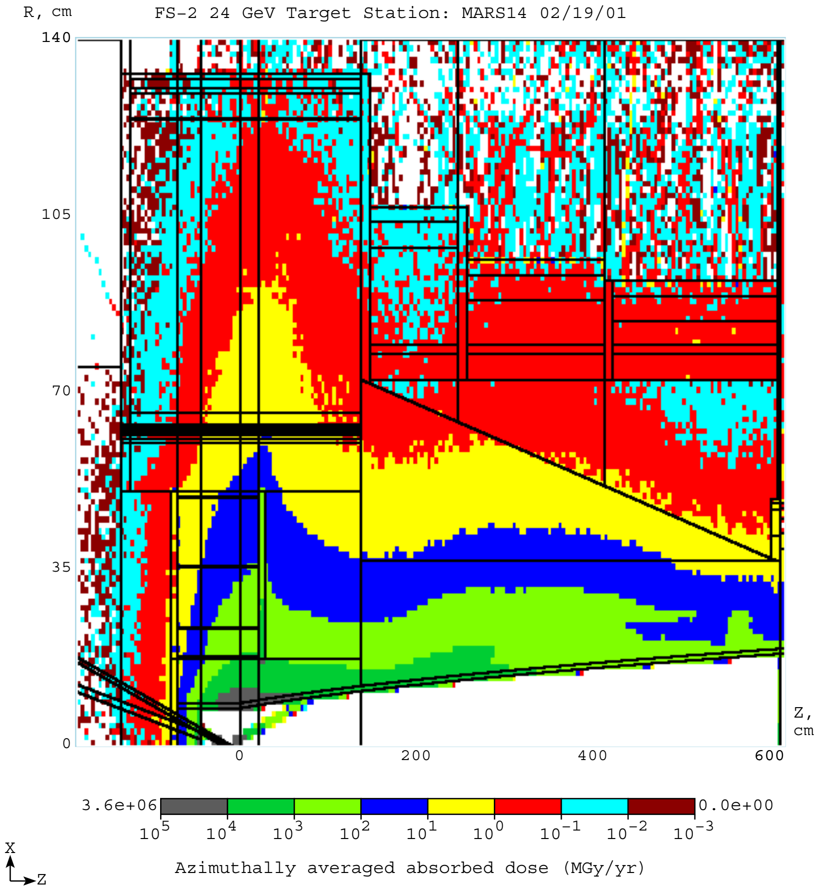


SECTION C-C



SECTION B-B
DECAY CHANNEL SHIELDING

Lifetime of Components in the High Radiation Environment



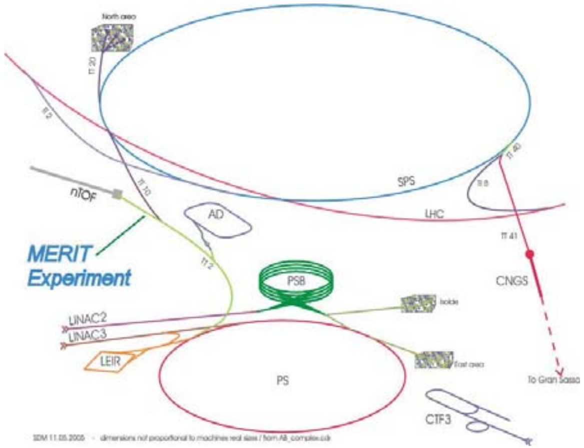
Some components must be replaceable.

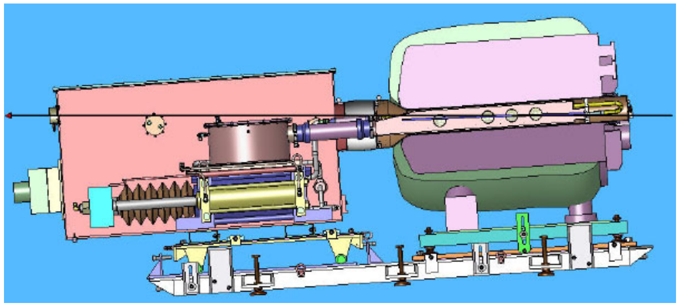
Component	Radius (cm)	Dose/yr (Grays/2×10^7 s)	Max allowed Dose (Grays)	1 MW Life (years)	4 MW life (years)
Inner shielding	**7.5**	5×10^{10}	10^{12}	**20**	**5**
Hg containment	**18**	10^9	10^{11}	**100**	**25**
Hollow conductor coil	**18**	10^9	10^{11}	**100**	**25**
Superconducting coil	**65**	5×10^6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

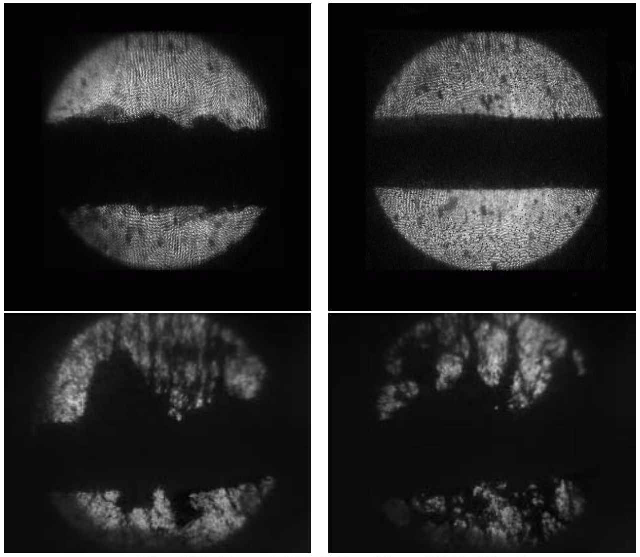
CERN MERIT Experiment

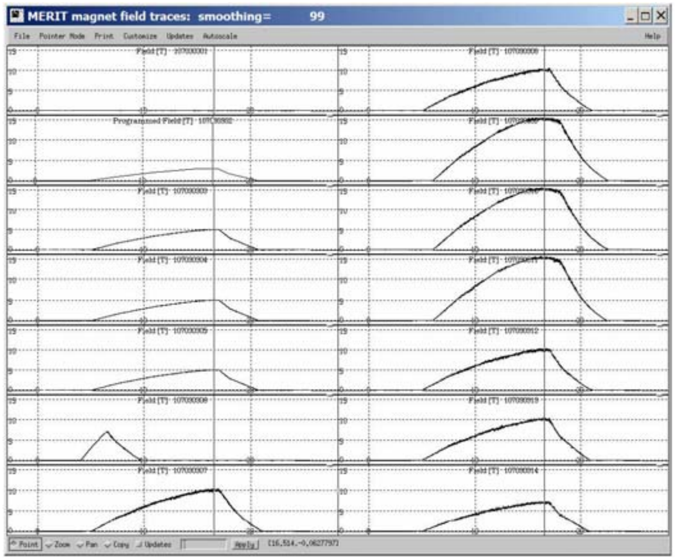
CERN nToF11 Experiment (MERIT)

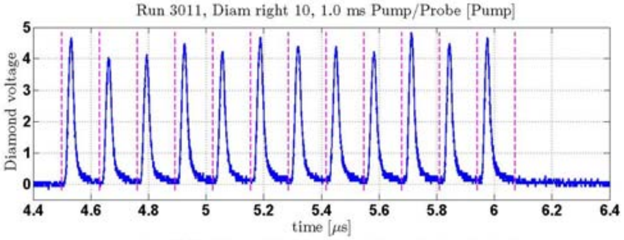
- The MERIT experiment is a proof-of-principle demonstration of a free mercury jet target for a 4-megawatt proton beam, contained in a 15-T solenoid for maximal collection of soft secondary pions.
- MERIT = MERcury Intense Target.
- Key parameters:
  - 24-GeV Proton beam pulses, up to 16) bunches/pulse, up to 2.5×10^{12} p/bunch.
  - σ_r of proton bunch = 1.2 mm, proton beam axis at 67 mrad to magnet axis.
  - Mercury jet of 1 cm diameter, $v = 20$ m/s, jet axis at 33 mrad to magnet axis.
  - ⇒ Each proton intercepts the Hg jet over 30 cm = 2 interaction lengths.
- Every beam pulse is a separate experiment.
  - ~ 100 Beam pulses in total.
  - Vary bunch intensity, bunch spacing, number of bunches.
  - Vary magnetic field strength.
  - Vary beam-jet alignment, beam spot size.

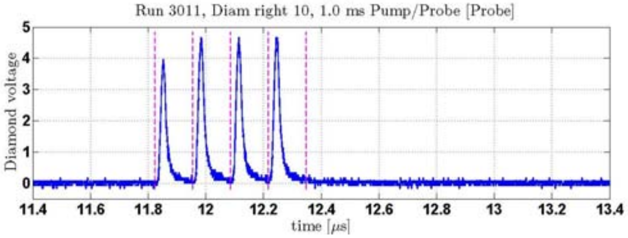

North area
TT20
E2
TT10
nTOF
AD
SPS
LHC
TT40
TT60
TT41
CNGS
MERIT Experiment
TT2
PSB
ISOLDE
LINAC2
LINAC3
LEIR
PS
East area
To Gran Sasso
CTF3
SDM 11.05.2005 · dimensions not proportional to machines real sizes / from AB_complex.cdr






MERIT magnet field traces: smoothing= 99
File Pointer Mode Print Customize Updates Autoscale
Help
Field [T]
Programmed Field [T]
Point Zoom Pan Copy Updates Apply


Run 3011, Diam right 10, 1.0 ms Pump/Probe [Pump]
Diamond voltage
0
1
2
3
4
5
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
6.2
6.4
time [μs]


Run 3011, Diam right 10, 1.0 ms Pump/Probe [Probe]
Diamond voltage
0
1
2
3
4
5
11.4
11.6
11.8
12
12.2
12.4
12.6
12.8
13
13.2
13.4
time [μs]

CERN nToF11 Experiment (MERIT), II

- **Data taken Oct. 22 – Nov. 12, 2007 with mercury jet velocities of 15 & 20 m/s, magnetic fields up to 15 T, and proton pulses of up to 3×10^{13} in 2.5 μs.**
- **As expected, beam-induced jet breakup is relatively benign, and somewhat suppressed at high magnetic field.**
- **"Pump-Probe" studies with bunches separated by up to 700 μs indicated that the jet would hold together during, say, a 1-ms-long 8-GeV linac pulse.**
- **$\Rightarrow$ Good success as proof-of-principle of liquid metal jet target in strong magnetic fields for use with intense pulsed proton beams.**