High-Power Targets for Neutrino Beams and Muon Colliders

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Princeton U.

NFMCC Collaboration Meeting
LBL, Jan 25-28, 2009

Targets for 2-4 MW Proton Beams

- 10-50 GeV beam energy appropriate for Superbeams, Neutrino Factories and Muon Colliders.

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

- Rep rate 15-50 Hz at Neutrino Factory/Muon Collider, as low as $\approx$ 2 Hz for Superbeam.

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

  $\Rightarrow$ Energy per pulse from 80 kJ to 2 MJ.

- Small beam size preferred:

  $\approx$ 0.1 cm^2 for Neutrino Factory/Muon Collider, $\approx$ 0.2 cm^2 for Superbeam.

- Pulse width $\approx$ 1 μs OK for Superbeam, but $\approx$ 1 ns desired for Neutrino Factory/Muon Collider.

$\Rightarrow$ Severe materials issues for target AND beam dump.

- Radiation Damage.
- Melting.
- Cracking (due to single-pulse "thermal shock").

- MW energy dissipation requires liquid coolant somewhere in system!

  $\Rightarrow$ No such thing as "solid target only option" at this power level.

Radiation Damage

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 4-MW Neutrino Factory
(and 9-28 days at a 2-MW Superbeam).

⇒ Mitigate by frequent target changes, moving target, liquid target, ...
[Mitigated in some materials by annealing/operation at elevated temperature.]

Remember the Beam Dump

Target of 2 interaction lengths ⇒ 1/7 of beam is passed on to the beam dump.
⇒ Energy deposited in dump by primary protons is same as in target.

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/Muon Collider,
⇒ 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.)

The proton beam should be tilted with respect to the axis of the capture system at a Neutrino Factory, so that the beam dump does not absorb the captured π's and μ's.

Target Options

- Static Solid Targets
  - Graphite (or carbon composite) cooled by water/gas/radiation [CNGS, NuMI, T2K]
  - Tungsten or Tantalum (discs/rods/beads) cooled by water/gas [PSI, LANL]

- Moving Solid Targets
  - Rotating wheels/cylinders cooled (or heated!) off to side [SLD, FNAL $\bar{p}$, Bennett]
  - Continuous or discrete belts/chains [King]
  - Flowing powder [Densham]

- Flowing liquid in a vessel with beam windows [SNS, ESS]

- Free liquid jet [Neutrino Factory Study 2]

Static Solid Targets

Pros:

- Tried and true – for low power beams.
- Will likely survive "thermal shock" of long beam pulses at 2 MW (Superbeam).

Cons:

- Radiation damage will lead to reduced particle production/mechanical failure on the scale of a few weeks at 2 MW.
- If liquid cooled, leakage of radioactive coolant anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

$\Rightarrow$ Must consider a "moving target" later if not sooner.

R&D: Test targets to failure in high-power beams to determine actual operational limits.

Moving Solid Targets

Pros:

- Can avoid radiation damage limit of static solid targets.
- Will likely survive "thermal shock" of long beam pulses at 2 MW (Superbeam).

Cons:

- Target geometry not very compatible with neutrino "horns" except when target is upstream of horn (high energy ν's: CNGS, NuMI).
- If liquid cooled, leakage of radioactive coolant anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

R&D:

- Engineering to clarify compatibility with a target station for Superbeams.
- Lab studies of erosion of nozzle by powders.

Personal view: this option is incompatible with Neutrino Factories.

Flowing Liquids in Vessels

Pros:

- The liquid flows through well-defined pipes.
- Radiation damage to the liquid is not an issue.

Cons:

- The vessel must include static solid beam windows, whose lifetime will be very short in the small proton spot sizes needed at Superbeams and Neutrino Factories.
- Cavitation in the liquid next to the beam windows is extremely destructive.
- Leakage of radioactive liquid anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

R&D: This option is not very plausible for Superbeams and Neutrino Factories, and no R&D is advocated.

Free Liquid Jet Targets

Pros:

- No static solid window in the intense proton beam.
- Radiation damage to the liquid is not an issue.

Cons:

- Never used before as a production target.
- Leakage of radioactive liquid anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

R&D: Proof of principle of a free liquid jet target has been established by the CERN MERIT Experiment. R&D would be useful to improve the jet quality, and to advance our understanding of systems design issues.

Personal view: This option deserves its status as the baseline for Neutrino Factories and Muon Colliders. For Superbeams that will be limited to less than 2 MW, static solid targets continue to be appealing.

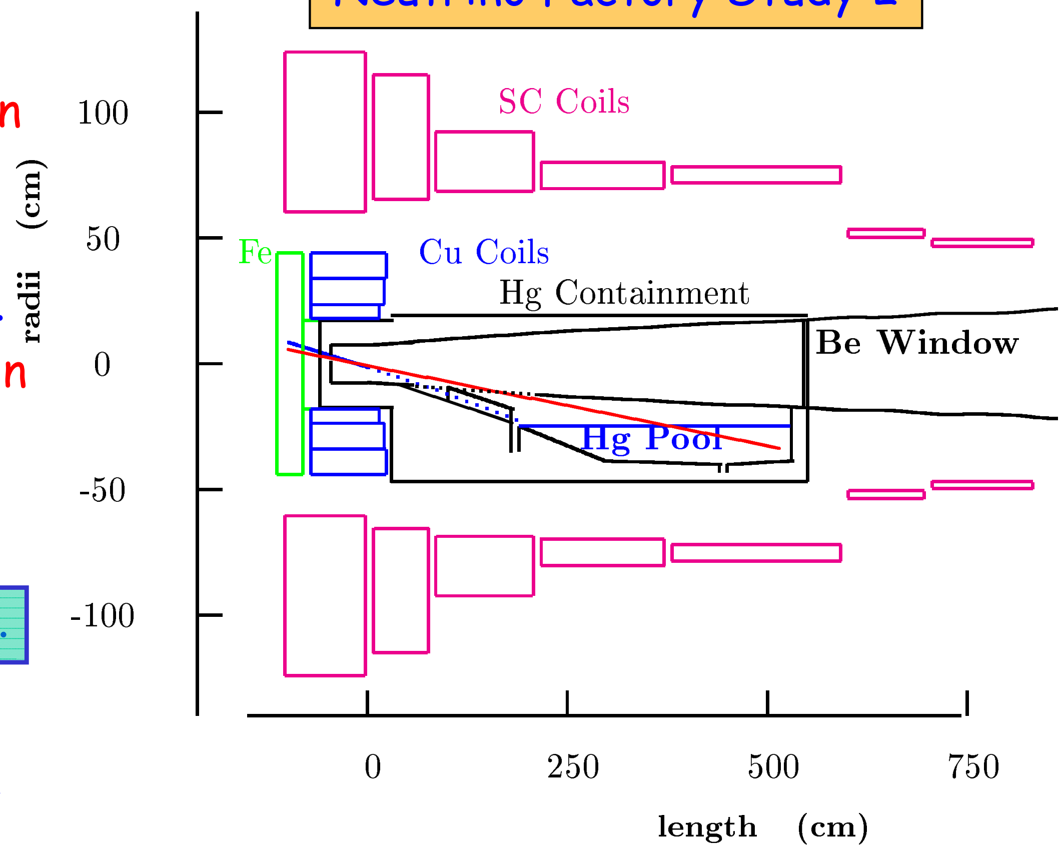
Target and Capture Topologies: Solenoid

Desire ≈ 10^{14} μ/s from ≈ 10^{15} p/s (≈ 4 MW proton beam).

Highest rate μ^{+} beam to date: PSI μE4 with ≈ 10^{9} μ/s from ≈ 10^{16} p/s at 600 MeV.

⇒ Some R&D needed!

R. Palmer (BNL)
Neutrino Factory Study 2



Palmer (1994) proposed a solenoidal capture system.

Low-energy π's collected from side of long, thin cylindrical target.

Collects both signs of π's and μ's,

⇒ Shorter data runs (with magnetic detector).

Solenoid coils can be some distance from proton beam.

⇒ ≥ 4-year life against radiation damage at 4 MW.

Liquid mercury jet target replaced every pulse.

Proton beam readily tilted with respect to magnetic axis.

⇒ Beam dump (mercury pool) out of the way of secondary π's and μ's.

Solenoid Capture System for a Superbeam

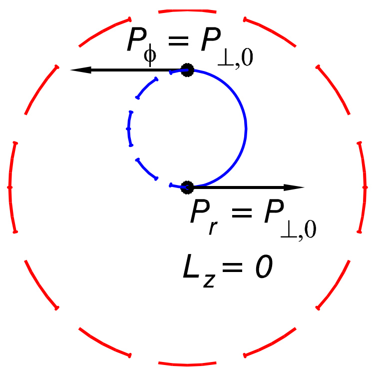
- Pions produced on axis inside the (uniform) solenoid have zero canonical angular momentum, $L_z = r(P_\varphi + eA_\varphi / c) = 0, \;\Rightarrow\; P_\varphi = 0$ on exiting the solenoid.
- If the pion has made exactly 1/2 turn on its helix when it reaches the end of the solenoid, then its initial P_r has been rotated into a pure P_φ, $\Rightarrow$ $P_r = 0$ on exiting the solenoid.

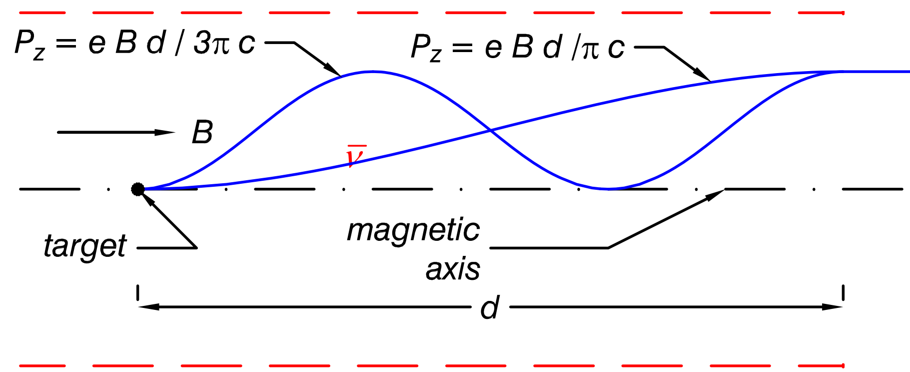
$\Rightarrow$ Point-to-parallel focusing for

$$P_\pi = eBd / (2n \underset{\bar{\nu}}{+} 1)\, \pi c.$$

$\Rightarrow$Narrowband (less background) neutrino beams of energies

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





(KTM, physics/0312022)

$\Rightarrow$ Can study several neutrino oscillation peaks at once,

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

(Marciano, hep-ph/0108181)

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

$\Rightarrow$ Detector must tell ν from $\bar{\nu}$.

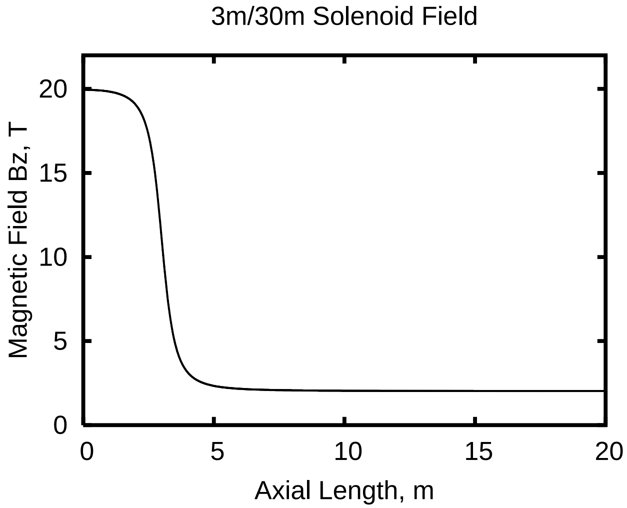
$\Rightarrow$ Liquid argon TPC that can identify slow protons:

$\nu\, n \rightarrow p\, e^- X \quad$ vs. $\quad \bar{\nu}\, p \rightarrow n\, e^+ X$

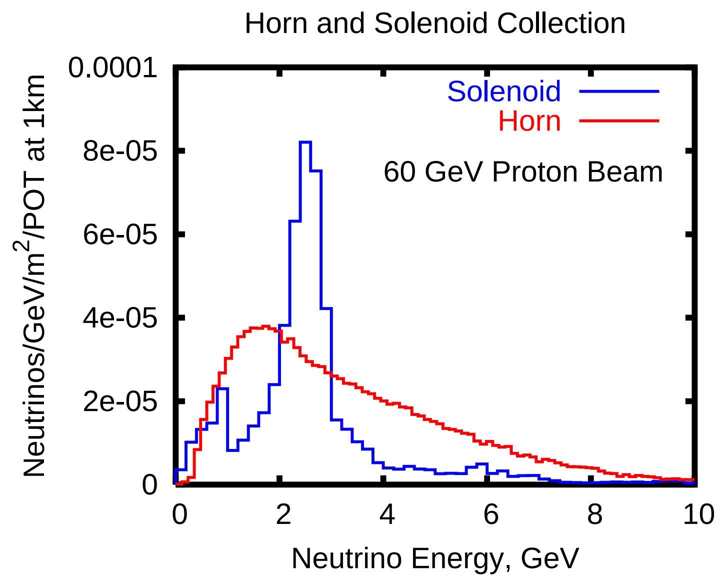
Simulation of Solenoid Horn

(H. Kirk and R. Palmer, NuFACT06)

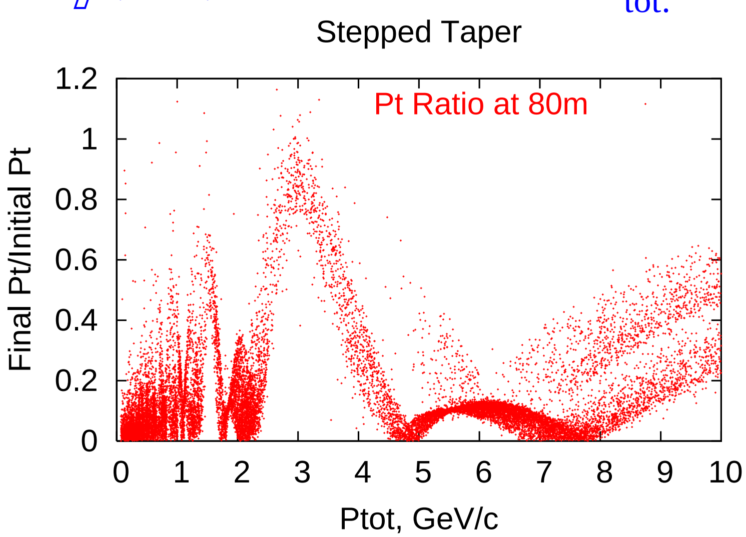
B vs. z for 3 + 30 m solenoid:



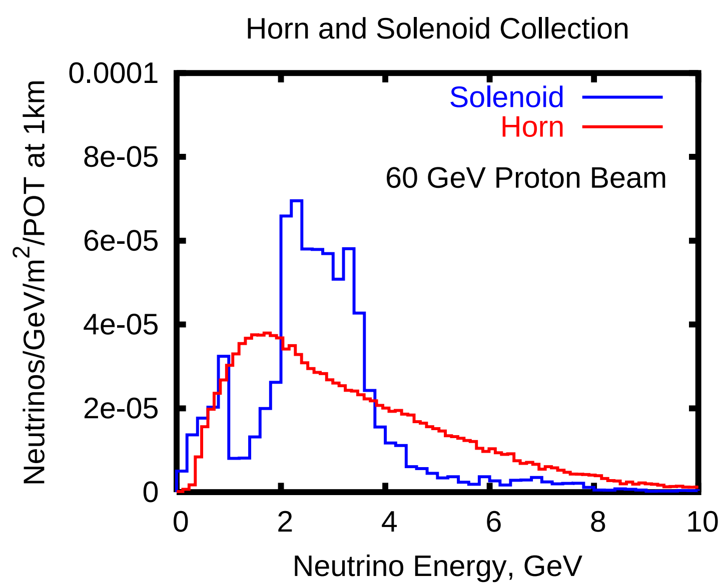
3-m solenoid gives
2 narrow peaks
in ν spectrum:



□ $P_{\perp}$ minimized at selected P_{tot}:



3+30-m solenoid
broadens the
higher energy
peak:



Results very encouraging, but comparison with toroid horn needs confirmation.

2nd Oxford-Princeton Workshop on High-Power Targets, Princeton, 6-7 Nov 2008

Thursday AM
1. McDonald: Introduction
2. Graves: Hg Containment Concepts
3. Ding: Hg Jet Optimization
4. Park. MERIT Results
5. Kadi: Eurisol Liquid Target Studies

Thursday PM
6. Rennich: SNS 3-MW Rotating Target
7. Fitton: T2K Target
8. Rooney: T2K Beam Window
9. Davenne:. Pelletized Target for ISIS
10. Hylen: DUSEL Target Options
11. Bennett: Solid Target Studies
12. Bennett: Absorption in Solid Targets
13. Skoro: Visar Studies for Solid Targets
14. Loveridge: Helmholz Coils for Wheel Target
15. Caretta: Tungsten Powder Jet Target
16. Brooks: Model for Production by Low-Density Targets
17. Brooks: Pion Production Update

Friday AM
18. Bricault: e- Targets
19. Samulyak: Hg Jet Simulations
20. Davenne: Hg Jet/Pool Simulations
21. Skoro: Simulations of Thermal Shock in Solids
22. Simos: Material Irradiation Studies
23. Efthymiopoulos: CERN Target Test Facilities
24. Hurh: Fermilab AP-0 Target Test Facility

Friday PM
25. Long: Discussion (IDS)

http://www.hep.princeton.edu/~mcdonald/mumu/target/index.html#2nd_OP_workshop

EUROnu WP2 Workshop, CERN, 15-17 Dec 2008

EUROnu WP2

from **Monday 15 December 2008 (14:00)**
to **Wednesday 17 December 2008 (16:00)**
Europe/Paris
at **CERN (*14-4-030*)**
chaired by: ***Marco Zito (IRFU-CEA) Marco Zito***
support: marcos.dracos@ires.in2p3.fr

Description: Meetings of Work Package 2 of European Project EUROnu

Monday 15 December 2008 | Tuesday 16 December 2008 | Wednesday 17 December 2008 |

http://indico.in2p3.fr/conferenceDisplay.py?confId=1586

Monday 15 December 2008

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15:00	Organisation (3h00')	All

Tuesday 16 December 2008

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09:00	CERN Proton Drivers (30') (Slides)	M. Martini (*CERN*)
09:30	Beam stability in the SPL-based accumulator: issues and planned studies (30') (Slides)	E. Benedetto
10:00	Harp Results on Hadroproduction (45') (Slides)	G. Catanesi
10:45	T2K neutrino spectra (45')	TBC
11:30	SPL neutrino spectra (30') (Slides)	Antoine Cazes (*IPNL-IN2P3*)
12:00	Discussion (30')	All
14:00	Dusel neutrino spectra (30') (Slides)	M. Bishai
14:30	Princeton/Oxford Meeting (45') (Slides)	Kirk Mc Donald (*Princeton University*)
15:15	CERN Target Test Area (45') (Slides)	Ilias Efthymiopoulos (*CERN*)
16:00	T2K Target (45') (Slides)	Chris Densham
16:45	Solid Target R&D (45') (Slides)	Roger Bennett
17:30	Powder Jet development (45') (Slides)	O. Caretta

Wednesday 17 December 2008

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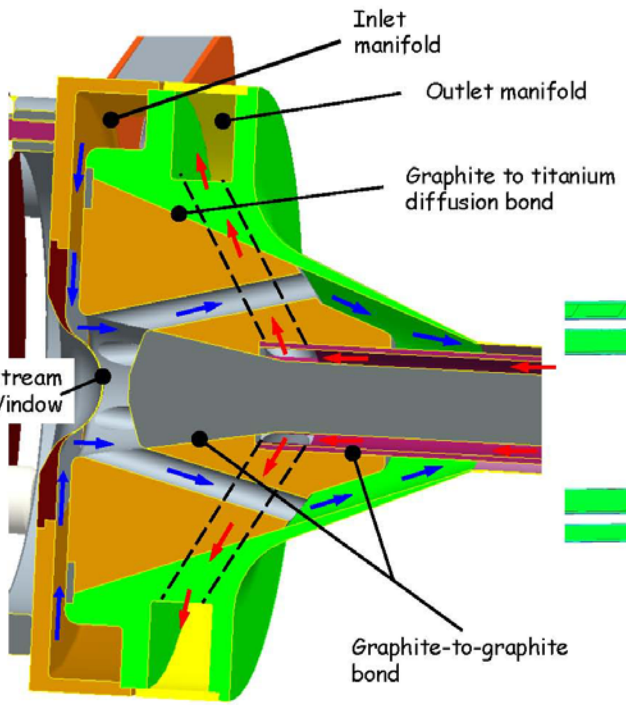
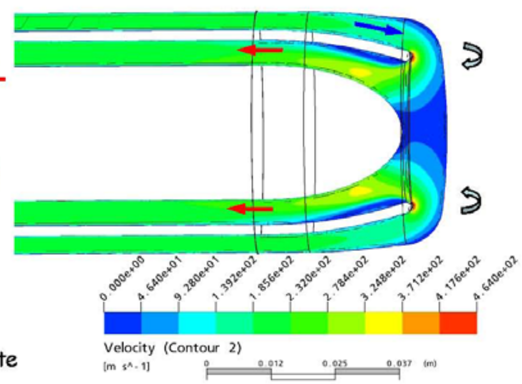
09:00	Target Imbed in Horn (45') (Slides)	Nikolaos Simos (*BNL*)
09:45	SPL Collection system (45') (Slides)	Marcos Dracos (*IPHC-IN2P3/CNRS*)
10:30	Design and Operational Features of a Mercury Target Facility (45') (Slides)	Van Graves
11:15	Hg Beam Dump issues (45') (Slides)	T. Davenne
12:00	Muon Production efficiency (45') (Slides)	Harold Kirk (*BNL*)
14:00	Workplan and summary (2h00') (document, pictures) (Room 112-R-028 PLEASE note room change !)	All

T2K Target (C. Densham, RAL)

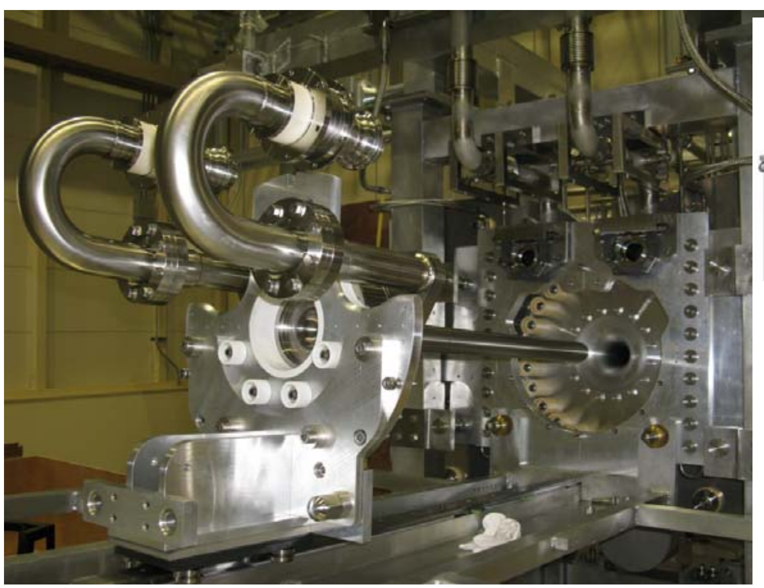


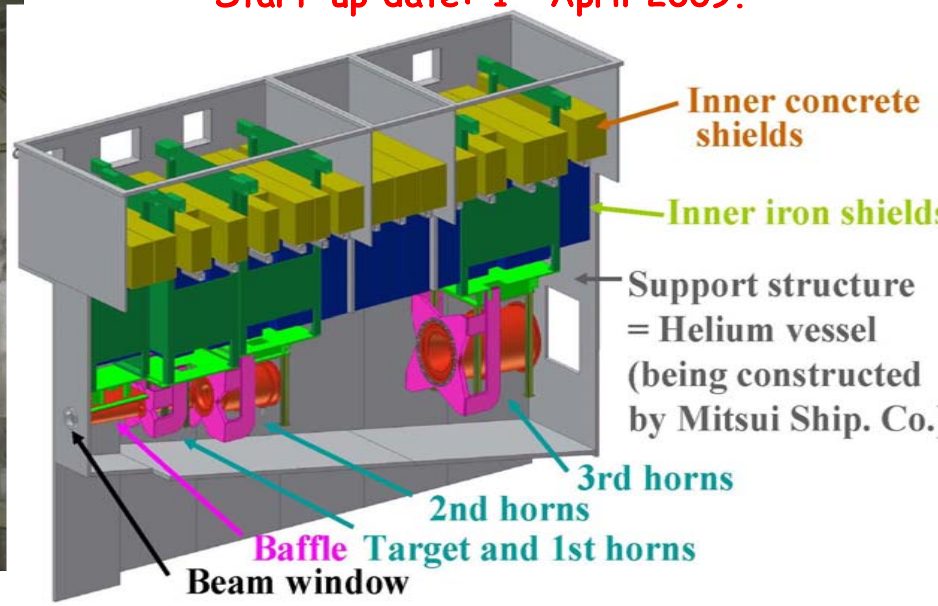
Target Design:

Helium cooling path

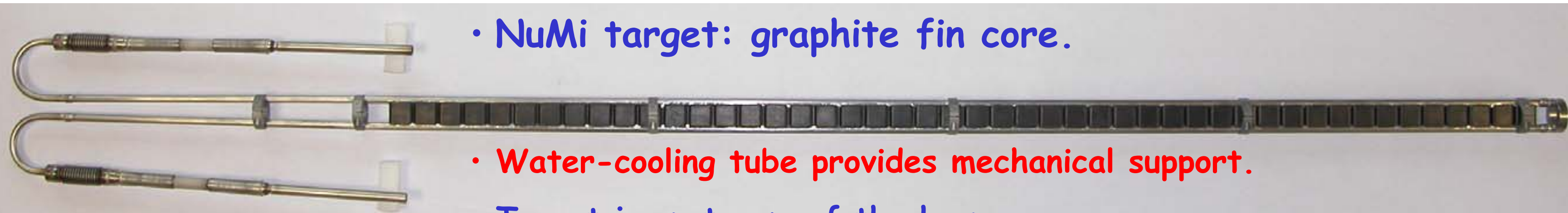


- Graphite rod, 900 mm (2 int.lengths) long, 26 mm (c.2σ) diameter.
- 20 kW of 750 kW Beam Power dissipated in target as heat.
- Helium cooled (i) to avoid shock waves from liquid coolant,s e.g., water and (ii) to allow higher operating temperature.
- Target rod completely encased in titanium to prevent oxidation of the graphite.
- Pressure drop ~ 0.8 bar available for flow rate of 32 g/s.
- Target to be uniformly cooled at ~400°C to reduce radiation damage.
- Can remotely change the target in the first horn.
- Start-up date: 1st April 2009.



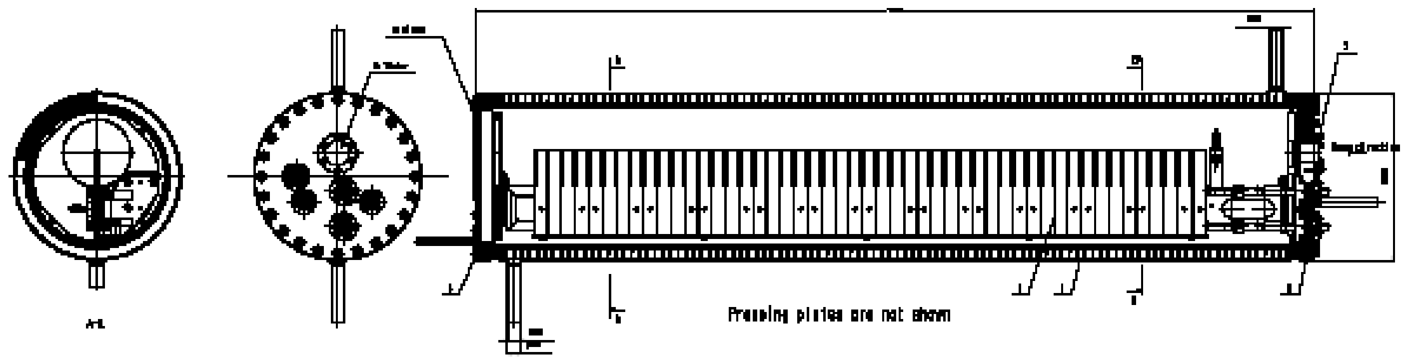


Extrapolating NuMI 0.3 MW Targeting to a 2 MW beam (J. Hylen,FNAL)

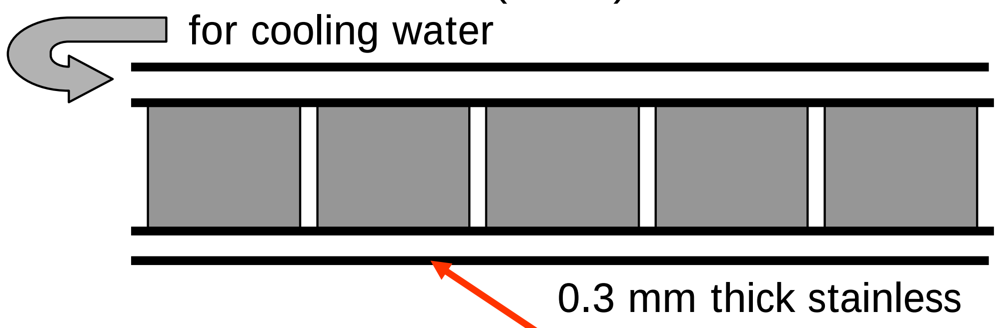


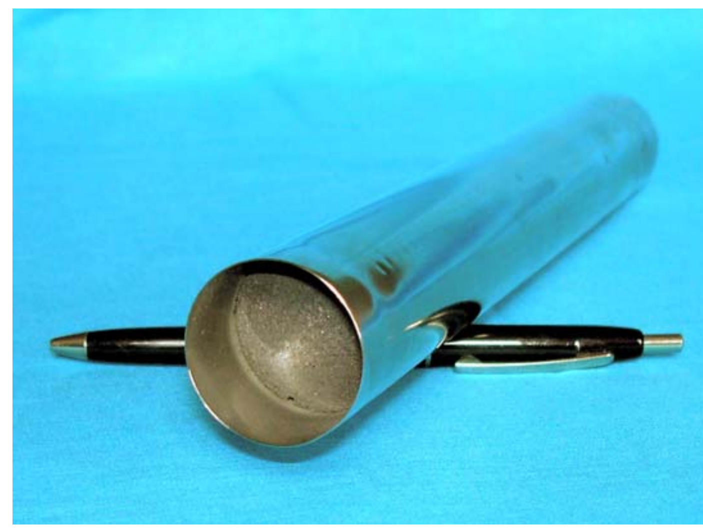
- NuMi target: graphite fin core.
- Water-cooling tube provides mechanical support.
- Target is upstream of the horn.

- Nova target for 0.7 MW.
- Upstream of horn.
- Graphite fins, 120 cm tota.l
- Water-cooled Al can.
- Proton beam σ = 1.3 mm.

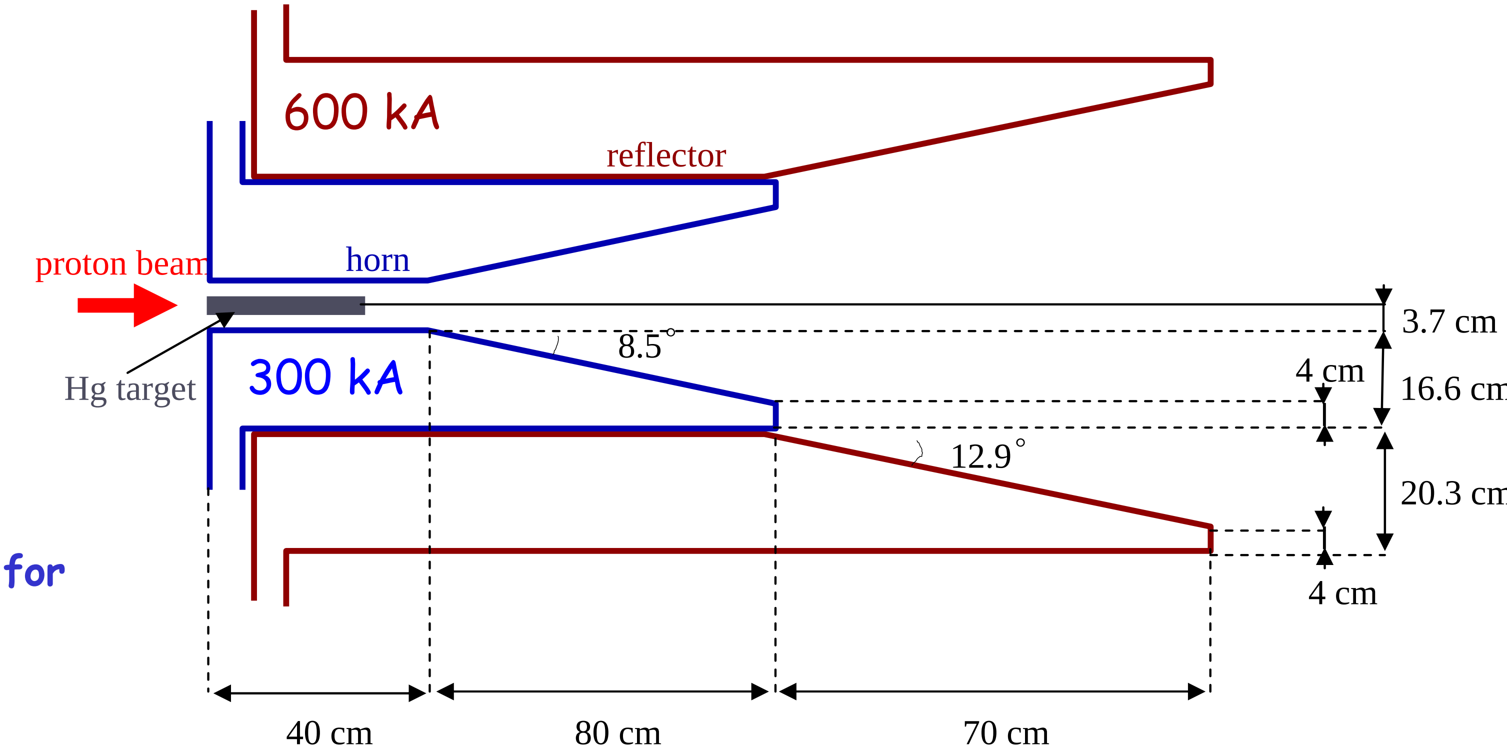


- DUSEL target for 2 MW.
- Embedded in horn.
- Graphite fins in water-cooled can should be viable to 2 MW.

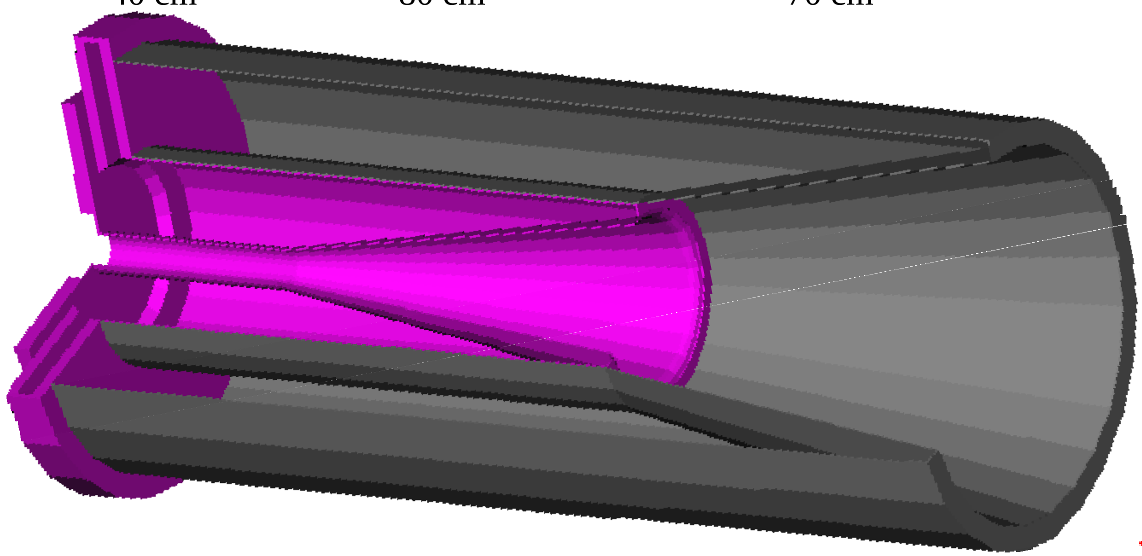




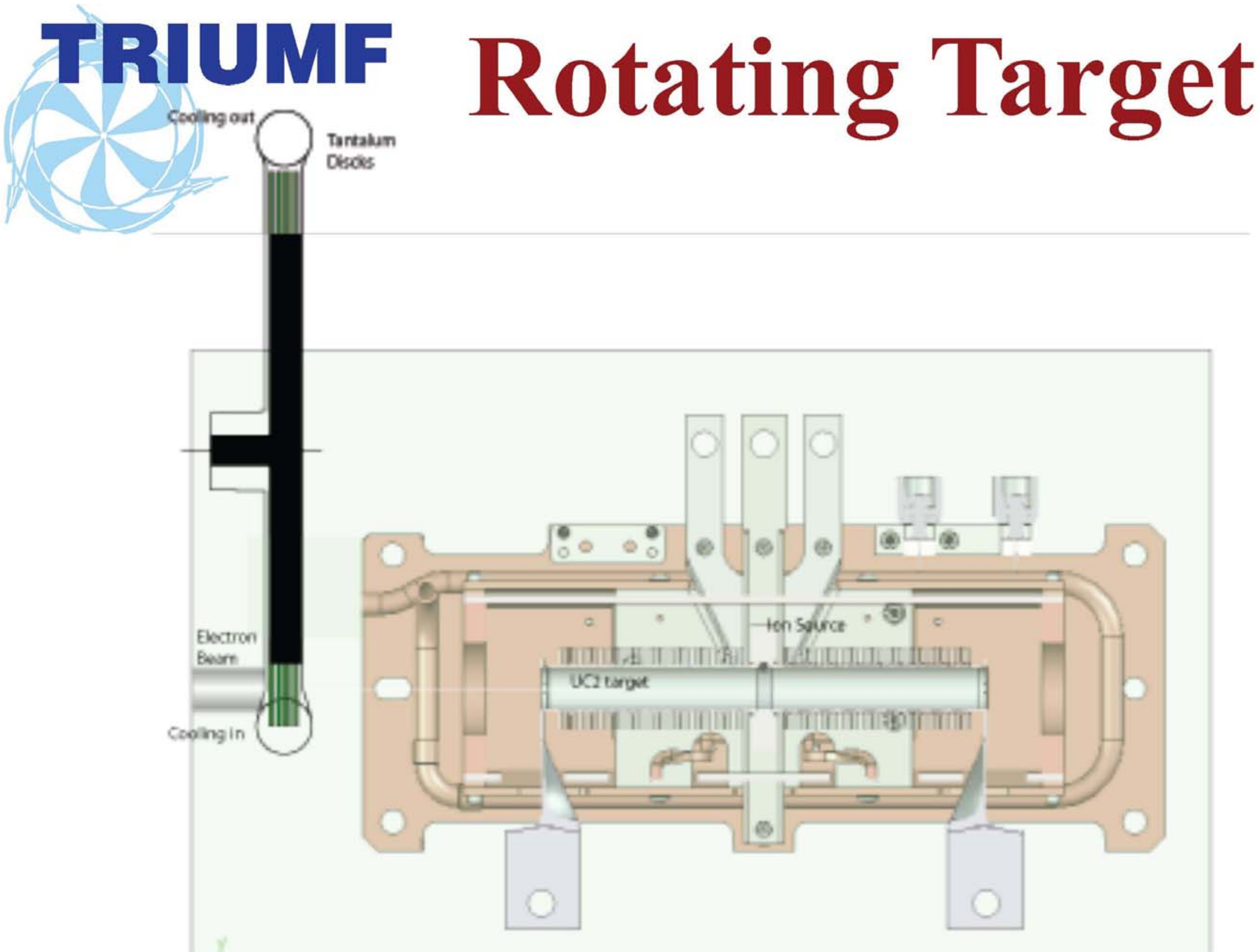
Target for the CERN SPL at 2.2 GeV and 4 MW (M. Dracos, Strasbourg)



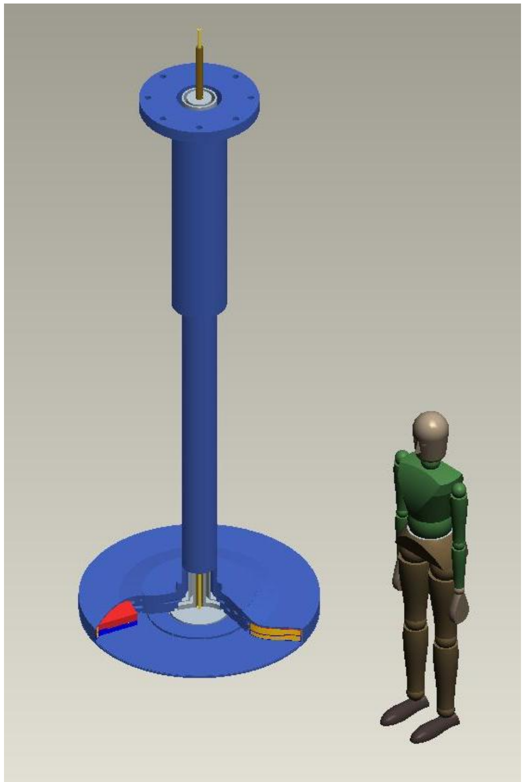
- 50-Hz beam ⇒ substantial electromechanical challenges for pulsed horn.
- Target inside horn.
- Hg jet target often considered, but would a solid (or powder target work?

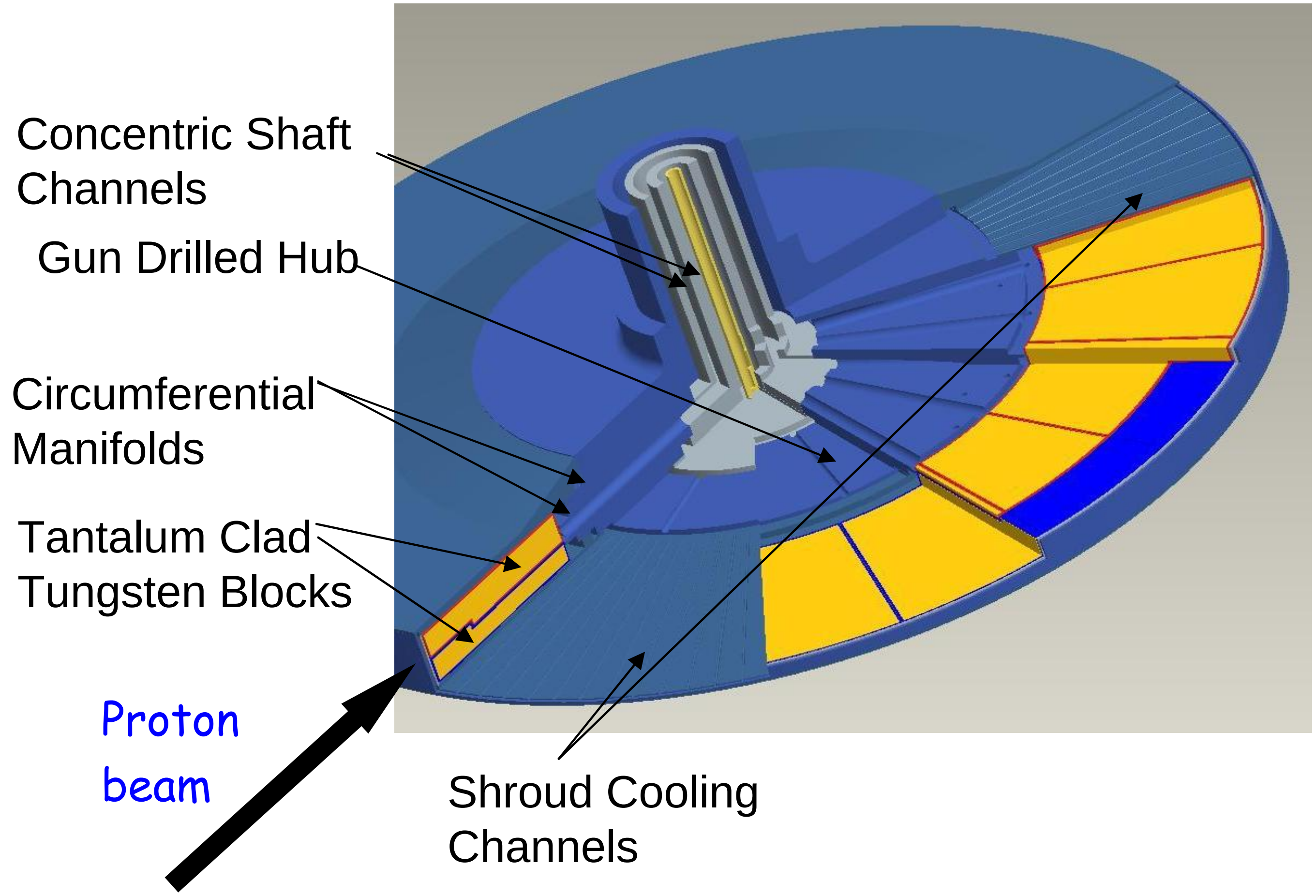


U Target for 0.5-MW e Beam (Bricault, TRIUMF)



SNS 3-MW Target Option (Rennich, ORNL)





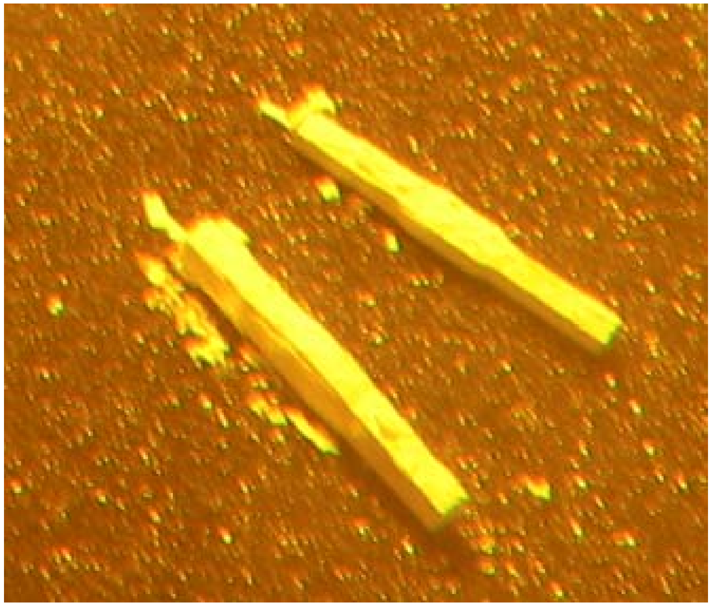
30 rpm with 20-Hz pulse frequency and 1-μs pulse length, 7-cm diameter.

Water cooled by 10-gpm total flow.

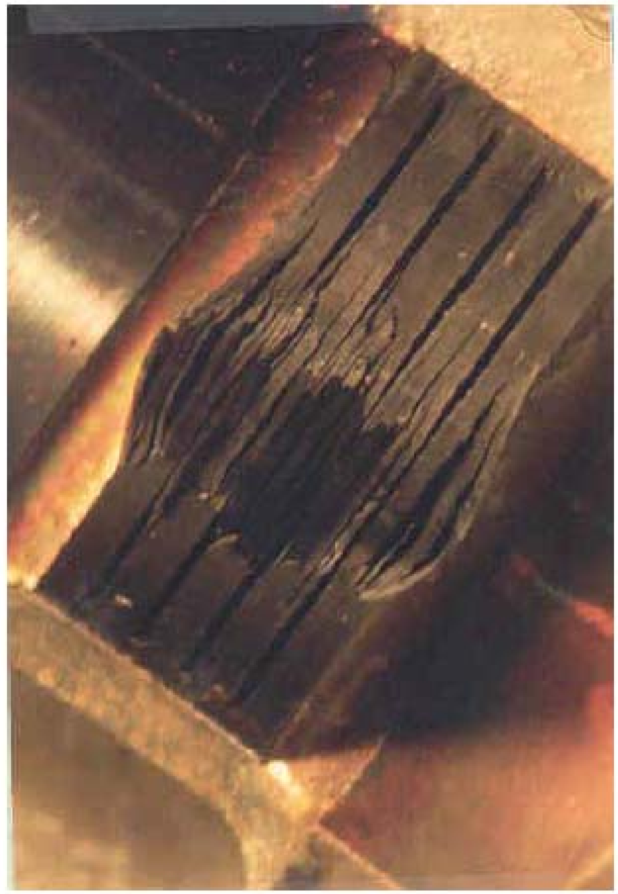
Design life: 3 years.

Material Irradiation Studies (Simos, BNL)

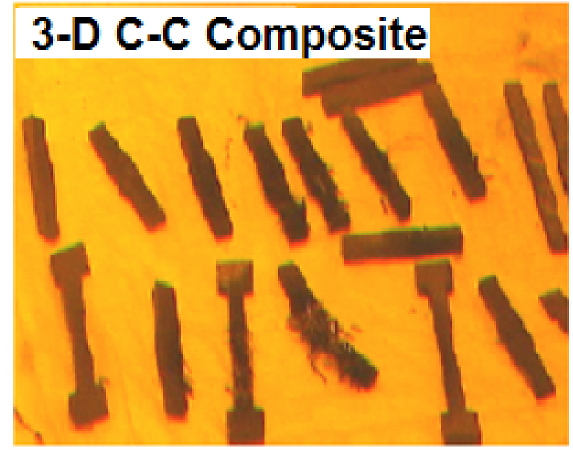
BNL BLP Studies:
Tantalum (0.25 dpa):

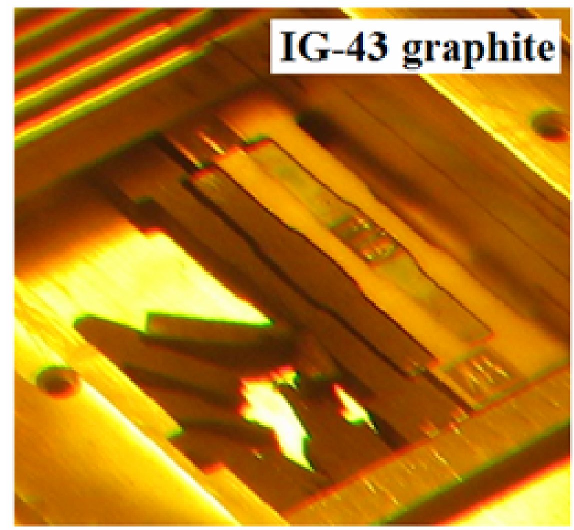


Water-cooled/Edge-cooled
TRIUMF target (10^{22} p/cm2):

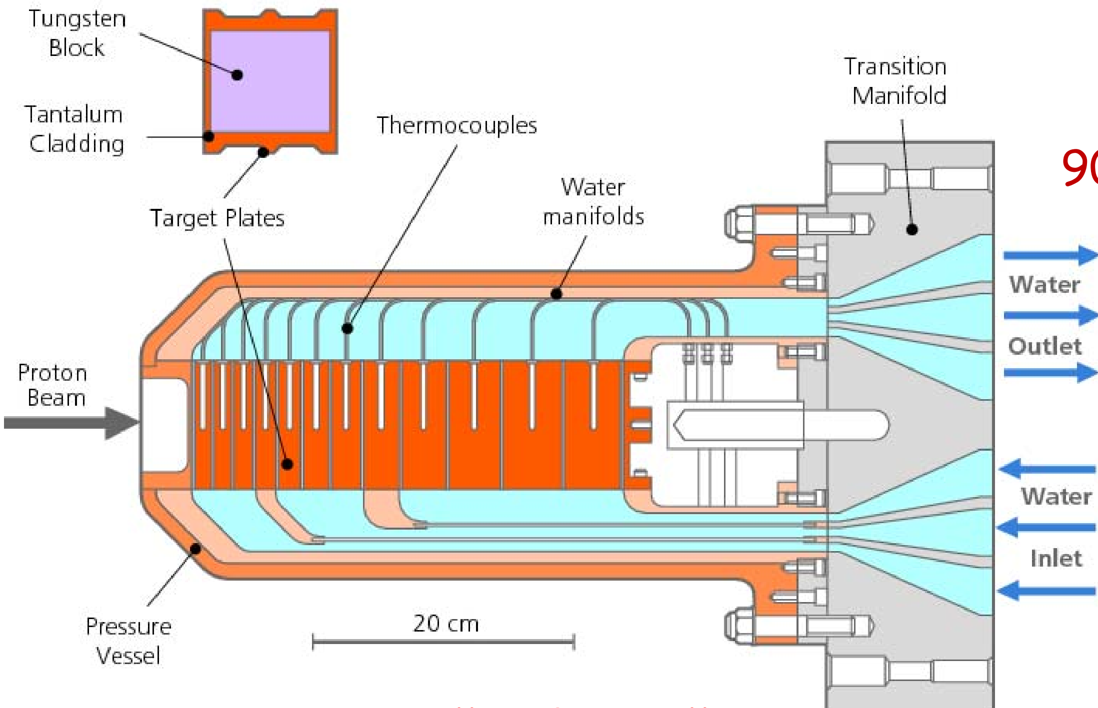


BNL BLP Studies:
Carbon (0.25 dpa):





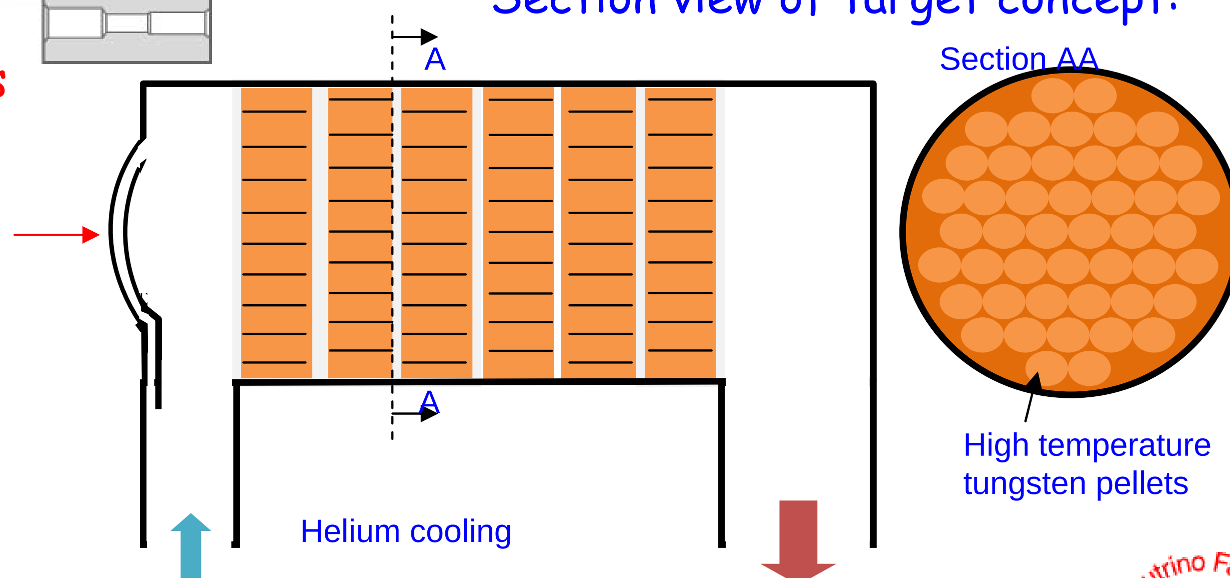
Pelletized Target Option for ISIS (T. Davenne, RAL)



800MeV, 160kW, 50Hz

90kW heat removed in water

Section view of target concept:



Target being in pellet form allows high temp operation without high stresses

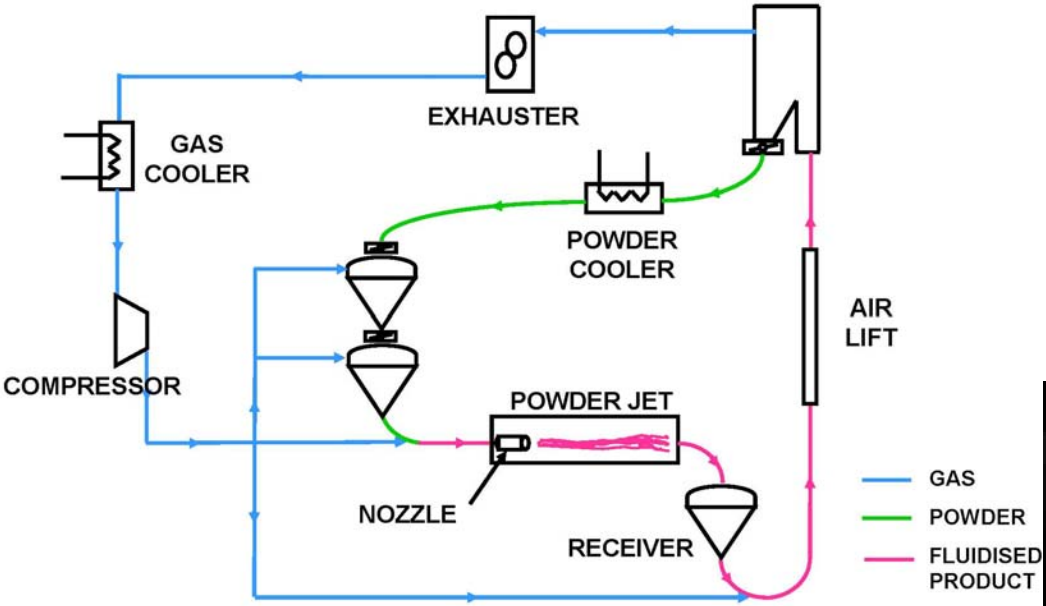
No cooling water to moderate neutron flux

Scope for more than 160kW?

Ref: Sievers (2003)

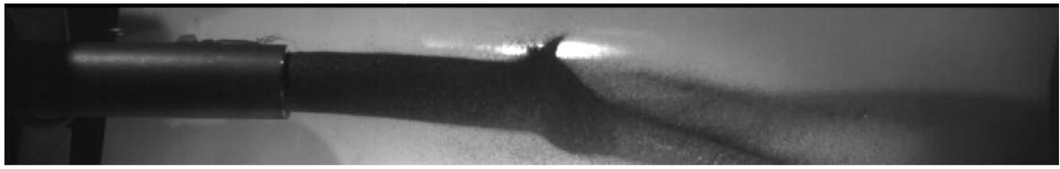
Fluidized Powder Targets (O, Caretta, RAL)

- Powders propelled (fluidized) by a carrier gas flow somewhat like liquids.
- Powder grains largely unaffected by magnetic fields (eddy currents).
- Flowing powder density ~ 30% of solid.

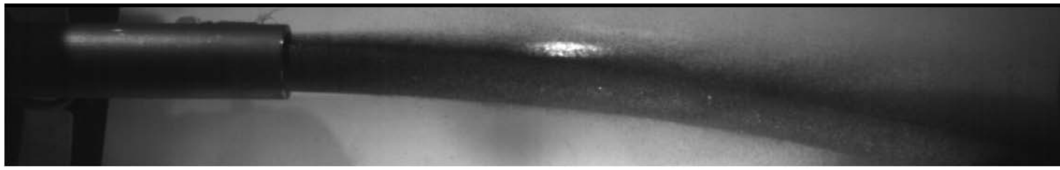


- Mechanics of a quasicontinuous flow system are intricate, but good industry support.
- Erosion a critical issue: ceramic inserts?

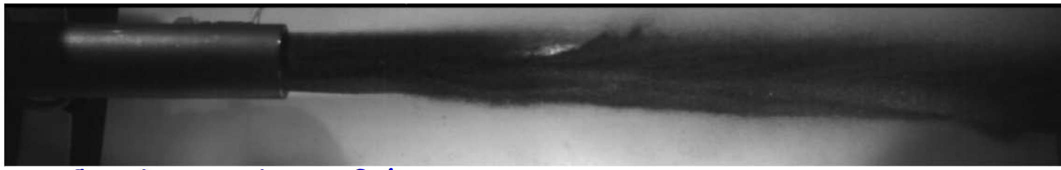
Carrier = helium at 1.5 bar



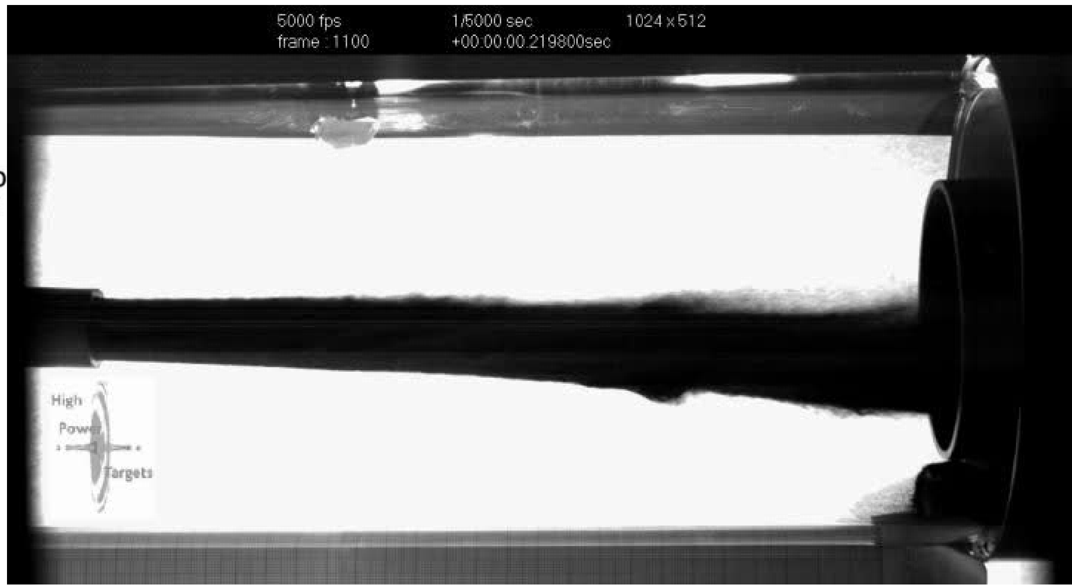
Carrier = helium at 2.5 bar



Carrier = helium at 3.5 bar



Carrier = air at 3 bar



Solid and Powder Target Studies (R. Bennett, RAL)

• Studies with fine tungsten wires pulsed by high currents indicate that such wires could survive the "shock" from 4 MW proton pulses if the target is operated at high temperature ⇒ continual annealing.

• A Static tungsten target would melt in a 4 MW beam, so need moving target (wheel?).

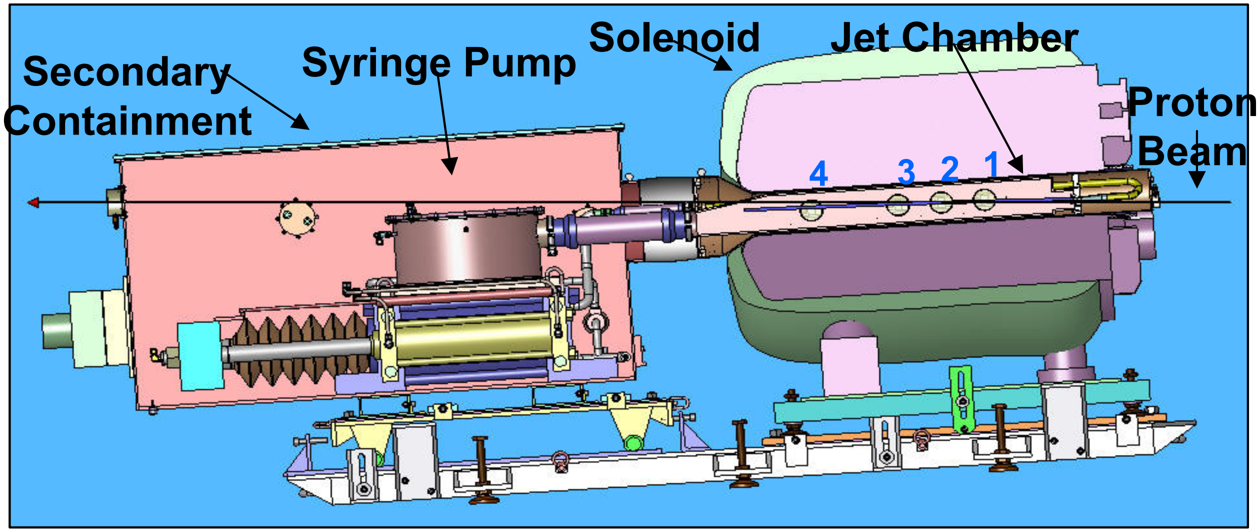
• A low-density powder target can be advantageous for a high-Z material with large pion absorption.

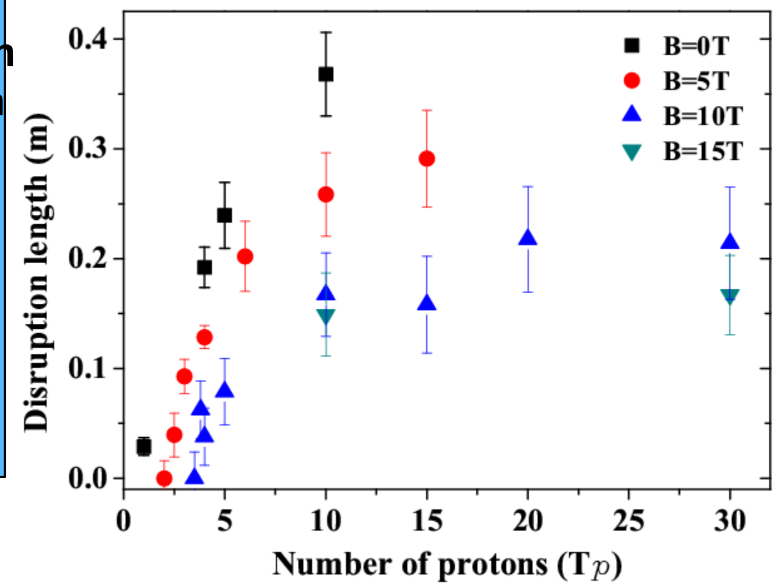
• Model: if p = pion production in nominal density target, and a = fraction of pions absorbed in this target, then the yield is

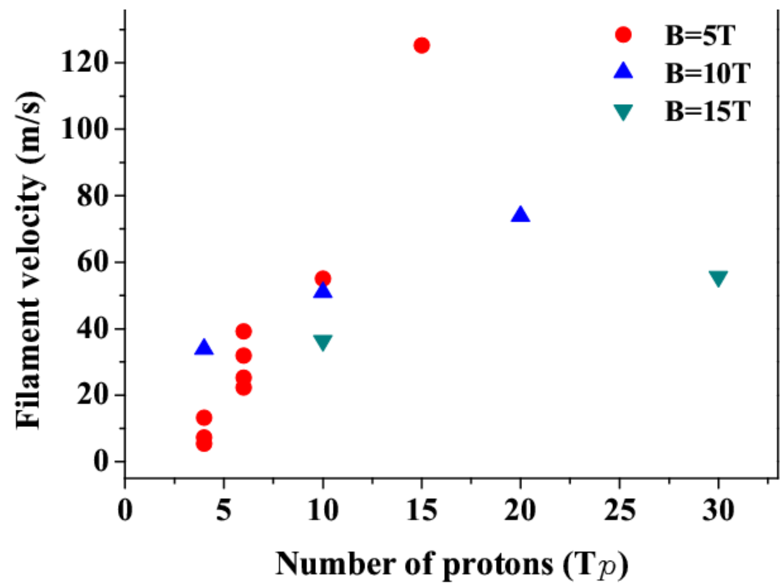
$Y(f) = f\ p\ (1 - f\ a)$ where f = fraction of nominal density.

Y is maximal for $f = 1 / 2a$, so if $a > \frac{1}{2}$, better to use $f < 1$.

CERN MERIT Experiment (Park, BNL)







Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

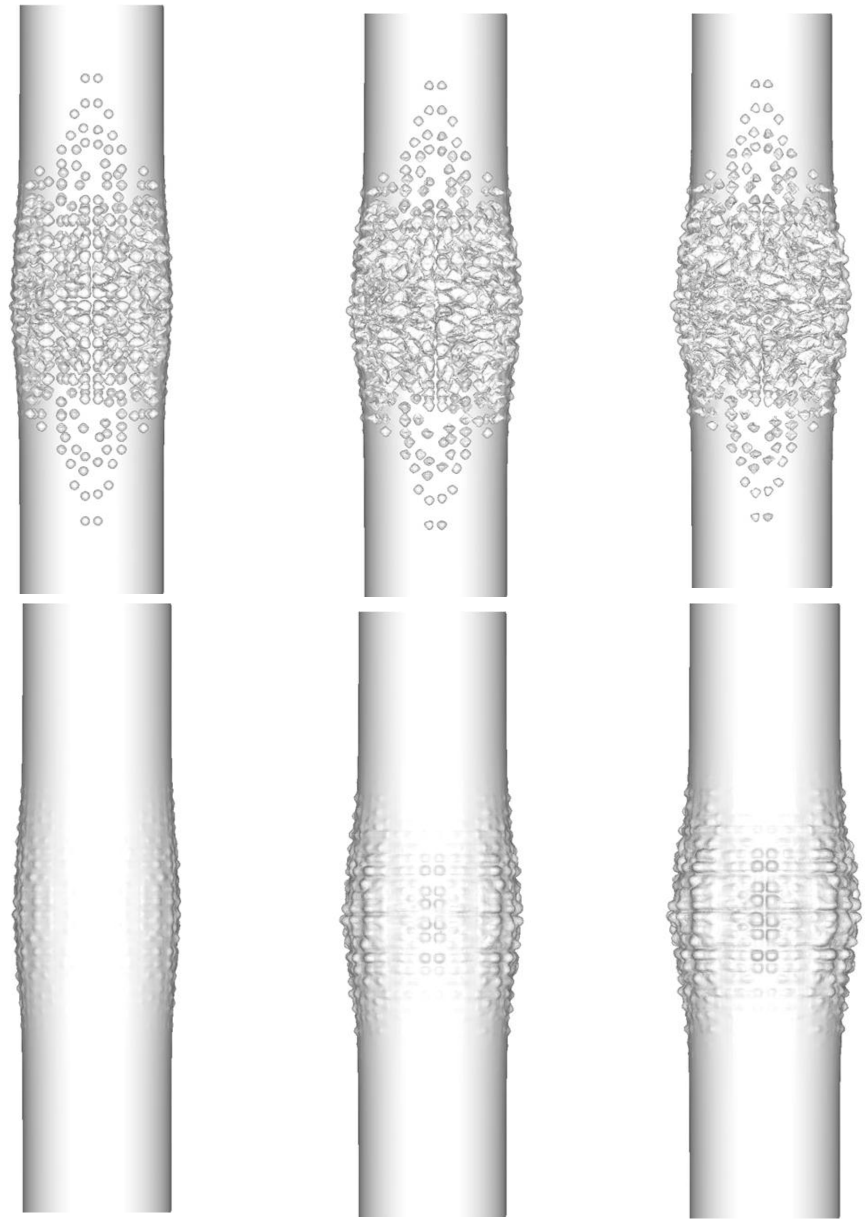
Jet disruption suppressed (but not eliminated by high magnetic field.

Particle production remains nominal for several hundred μs after first proton bunch of a train.

Hg Cavitation Simulations (Samulyak, BNL)

"Transparent mercury":

Exterior view:

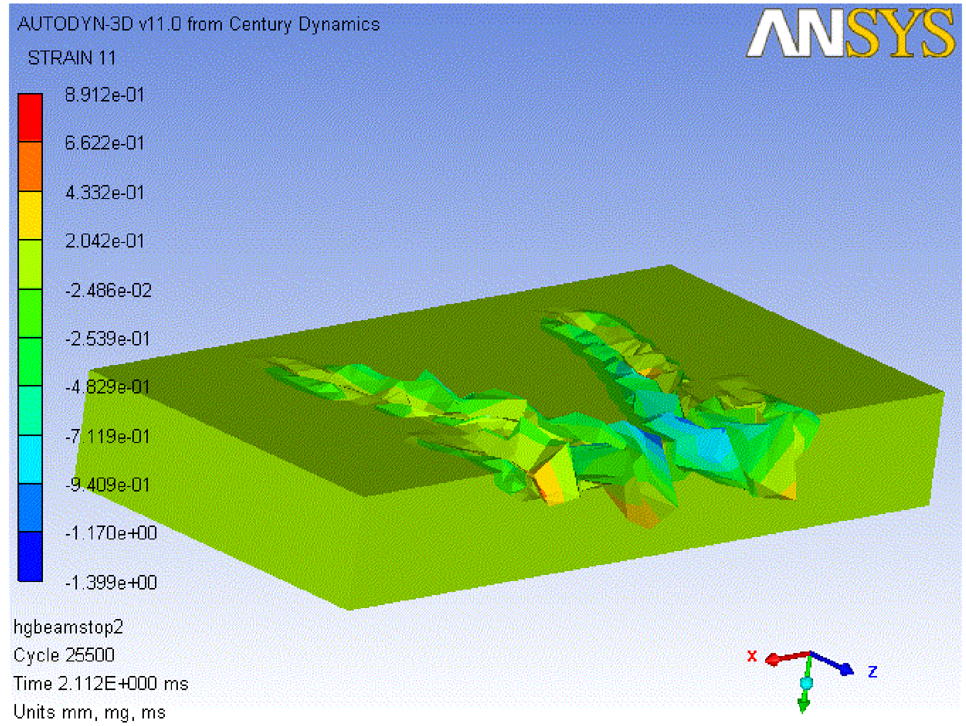


15 μs 30 μs 45 μs

Damage by Mercury Droplets (Davenne, RAL)

A 3-mm-diameter mercury droplet impacting a stainless steel plate at 75 m/s is predicted to cause significant damage.

Ti-6Al-4V is predicted to be more resistant to damage due to higher ultimate strength and shear strength.



Model: A drop of radius r and density ρ vith velocity v causes pressure
$P = F / A \sim (\Delta p / \Delta t) / \pi r^2 \sim [2 m v / (r/v)] / \pi r^2 \sim 8 \pi r^3 \rho v^2 / 3 \pi r^3$,
$\Rightarrow P \sim 8 \rho v^2 / 3$ independent of the radius!

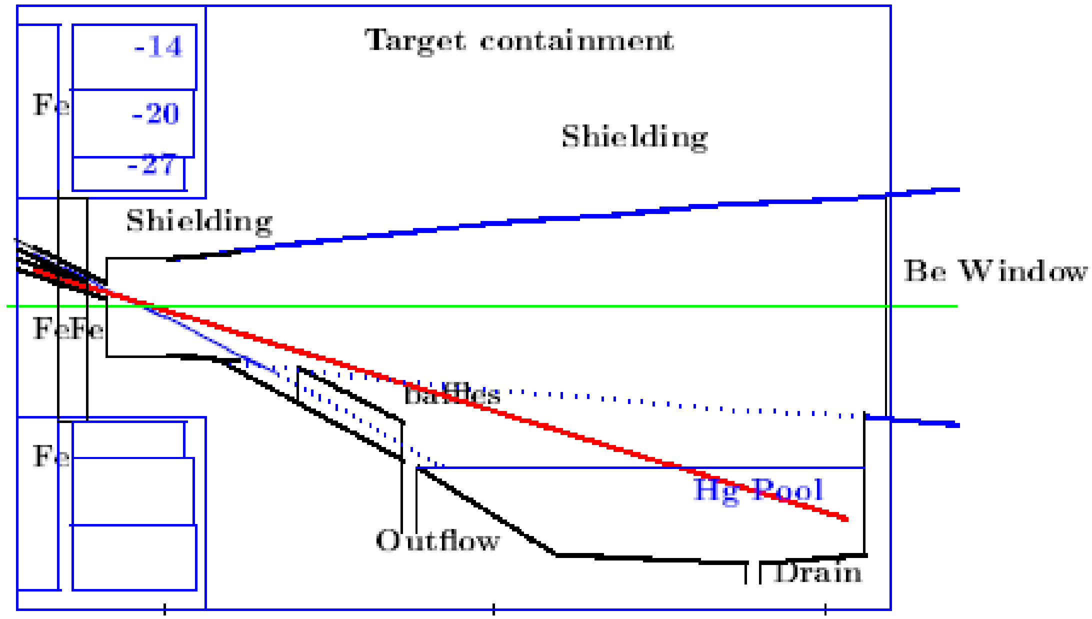
Example: $\rho_{\mathrm{mercury}} = 13.6e3$, $v = 100$ m/s $\Rightarrow P \sim 325$ MPa ~ tensile strength of steel.

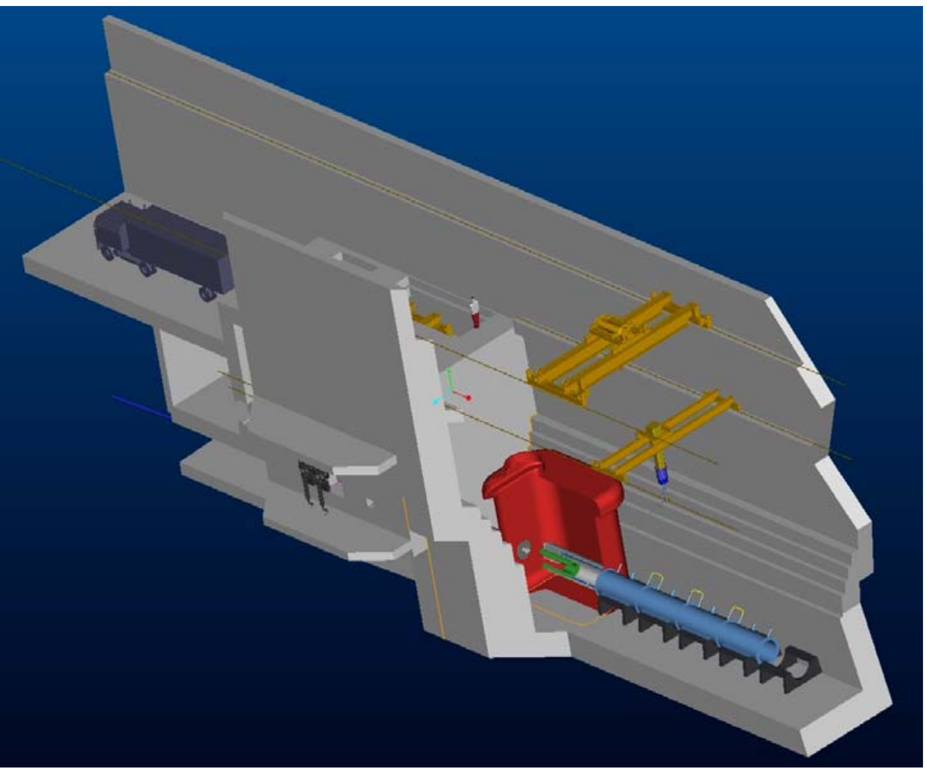
The velocity of an atom of mercury vapor at room temperature is 200 m/s.

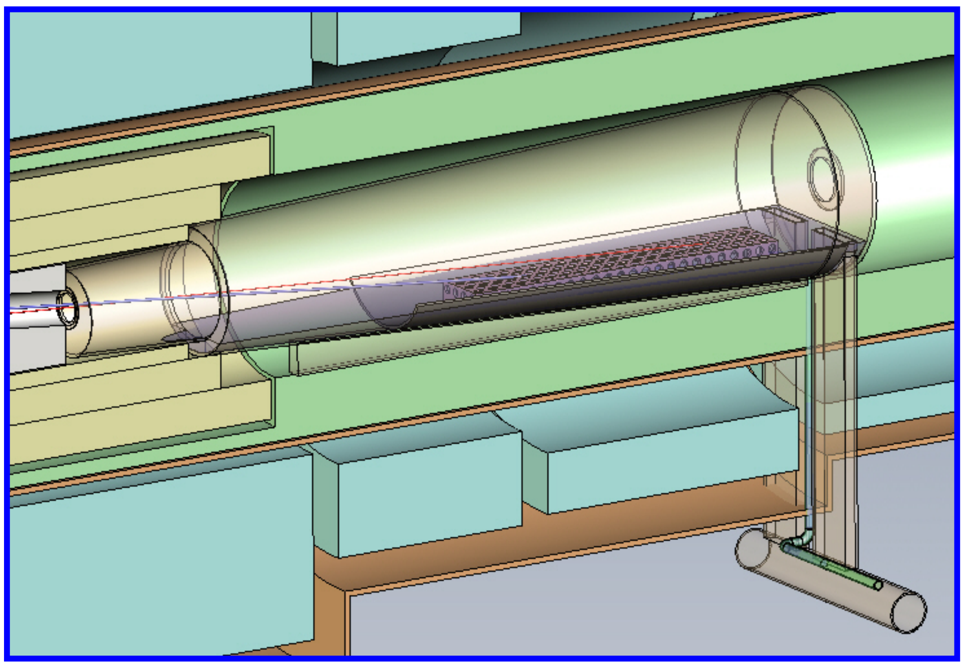
Mercury Target Facility Issues (V. Graves, ORNL)

ORNL can extend the studies of a mercury target facility, begun in Neutrino Factory Study 2, in the context of the International Design Study for a Neutrino Factory.

A small effort in underway to design a mercury collection pool (beam dump)

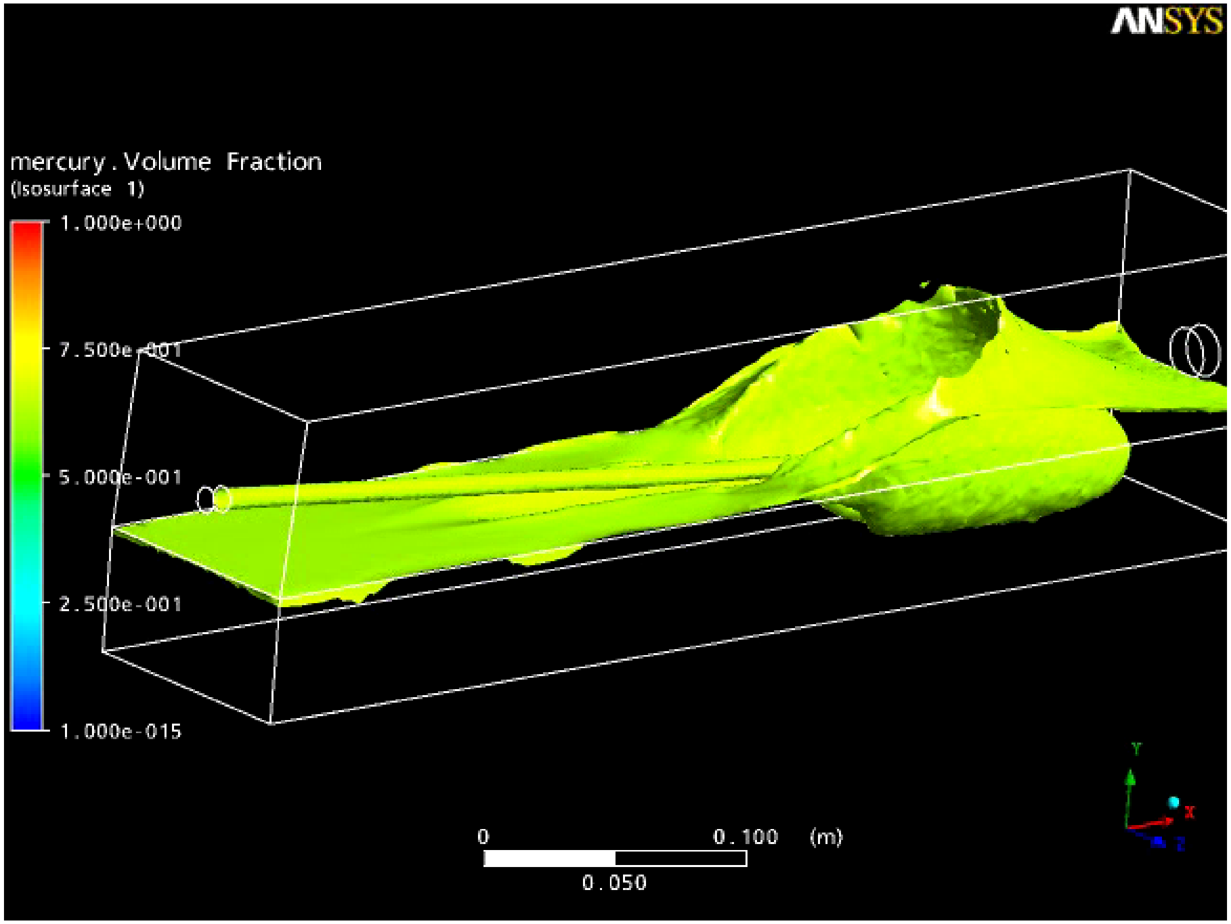


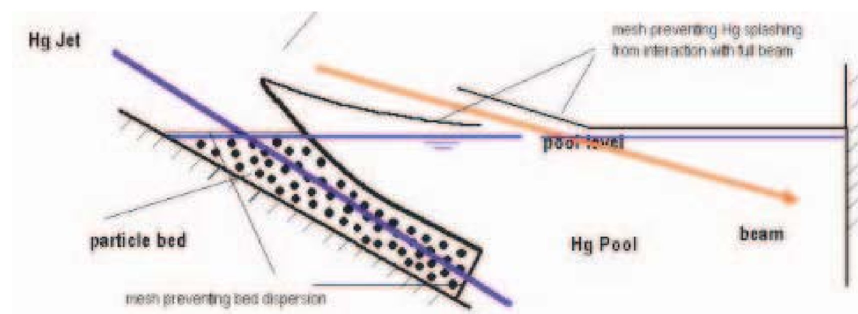




Mercury Beam Dump Simulations (T. Davenne, RAL)

A 20-m/s mercury jet causes significant agitation as it enters the mercury collection pool.



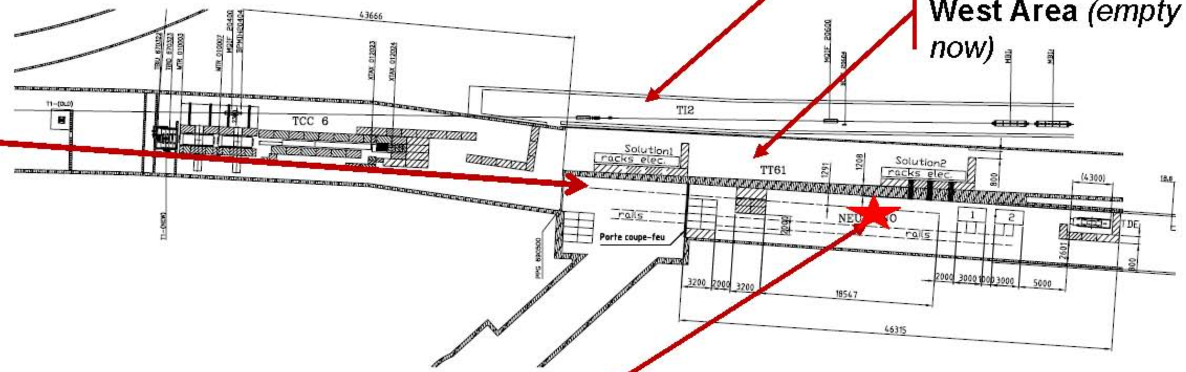


Mitigation of this agitation by baffles or a pebble bed (Study 2) should be (re)considered.

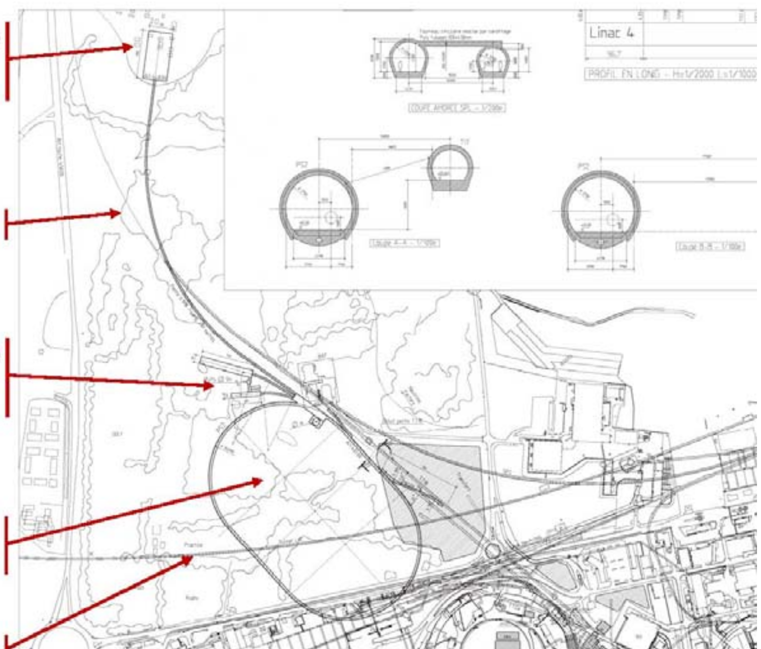
Future Target Test Facilities at CERN (I. Efthymiopoulos, CERN)

Options include:

Old WANF tunnel:



A new area associated with the PS2 (2016):



AP-0 Target Test Facility (Hurh, FNAL)

- A future, limited, Target Test Facility is still possible at FNAL using the AP-0 (p-bar source) Target Hall after Collider Run II (2010).
- Possible beam parameter ranges: 8-120 GeV, 0-4e13 ppp (1.7e14, Project X), up to 700 kW (ANU) or 2.3 MW (Project X), sigma down to 0.12 mm.
- Parasitic running with Minerva, Minos, & NOvA required. This may practically limit testing to pulse testing rather than irradiation studies.
- Need proposals for specific experiments (talk to P. Hurh or A. Leveling).
- Act soon; Current plan is to De-commission!

Option for Follow-On Studies (without Beam) at ORNL (V. Graves, ORNL)

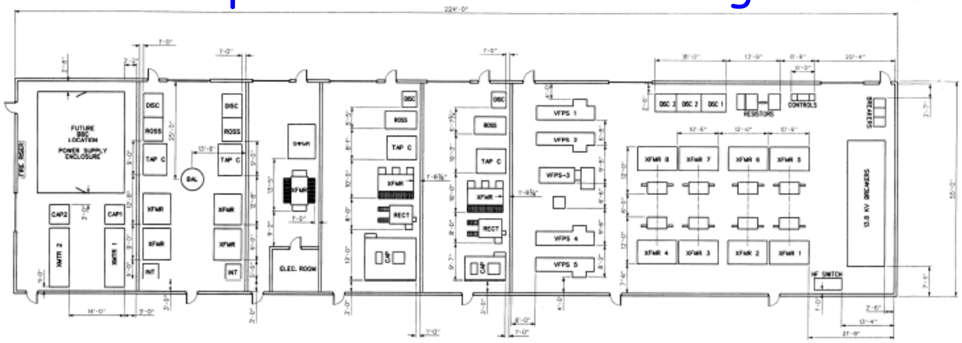
A new fusion test facility in bldgs 7625, 7627 will be completed in late 2008.

Several 10-MW power supplies available.

LN_2 dewar 20-t overhead crane, equipment pit.

Could begin with zero field studies (nozzle optimatization, Hg splash in pool,….)

Eventual option to use MERIT magnet at 15 (or 20!) T.



ELECTRICAL EQUIPMENT LAYOUT

Vertical field power supplies (capability of each)
650V peak
15,000 A pulsed > 5 sec
Voltage and/or current can be controlled by SCR gate waveform control