High-Power Targets
for Neutrino Beams and Muon Colliders

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Targets for 2-4 MW Proton Beams

- 5-50 GeV beam energy appropriate for Superbeams, Neutrino Factories and Muon Colliders.

  0.8-2.5 × 10^{15} pps; 0.8-2.5 × 10^{22} protons per year of 10^7 s.

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

  ⇒ Protons per pulse from 1.6 × 10^{13} to 1.25 × 10^{15}.

  ⇒ Energy per pulse from 80 kJ to 2 MJ.

- Small beam size preferred:

  ≈ 0.1 cm^2 for Neutrino Factory/Muon Collider, ≈ 1 cm^2 for Superbeam.

- Pulse width ≈ 1 μs OK for Superbeam, but < 3 ns desired for Neutrino Factory/Muon Collider.

⇒ 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!

⇒ No such thing as "solid-target-only" at this power level.

Radiation Damage

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

⇒ 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 flowing 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, SNS]
  - 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.

⇒ 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.

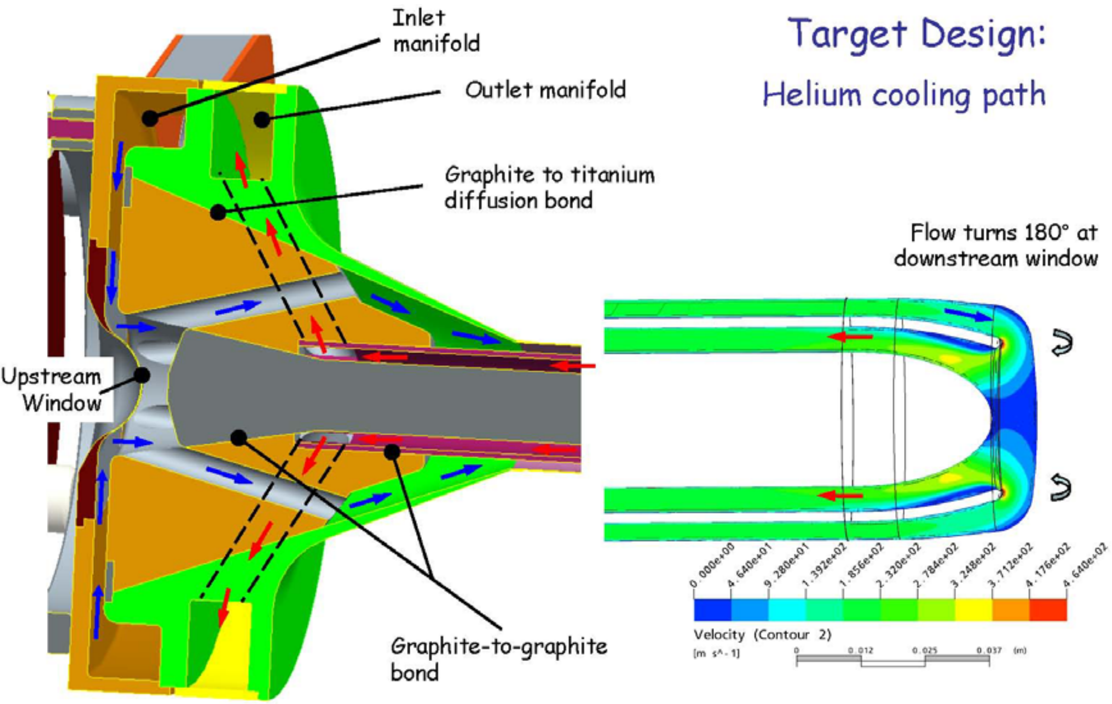
Cons:

- 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.

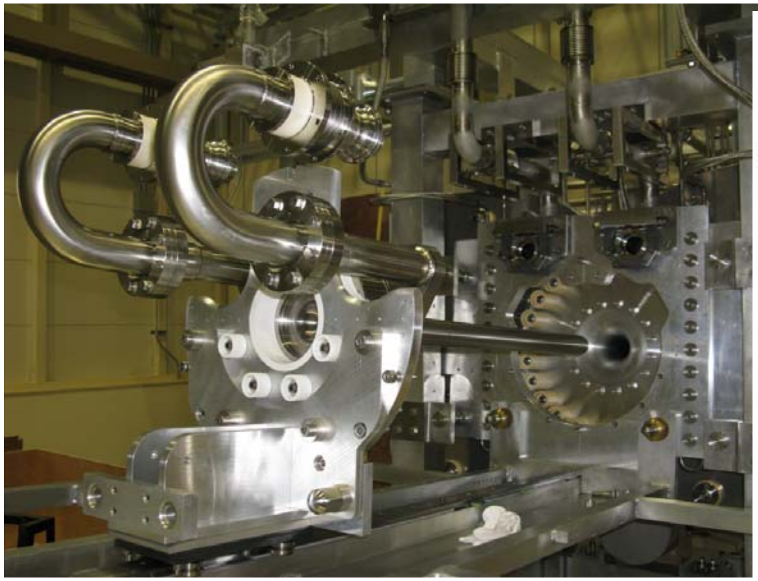
R&D: Proof of principle of a free liquid jet target has been established by the CERN MERIT Experiment. R&D would be useful to improve the jet quality, and to advance our understanding of systems design issues.

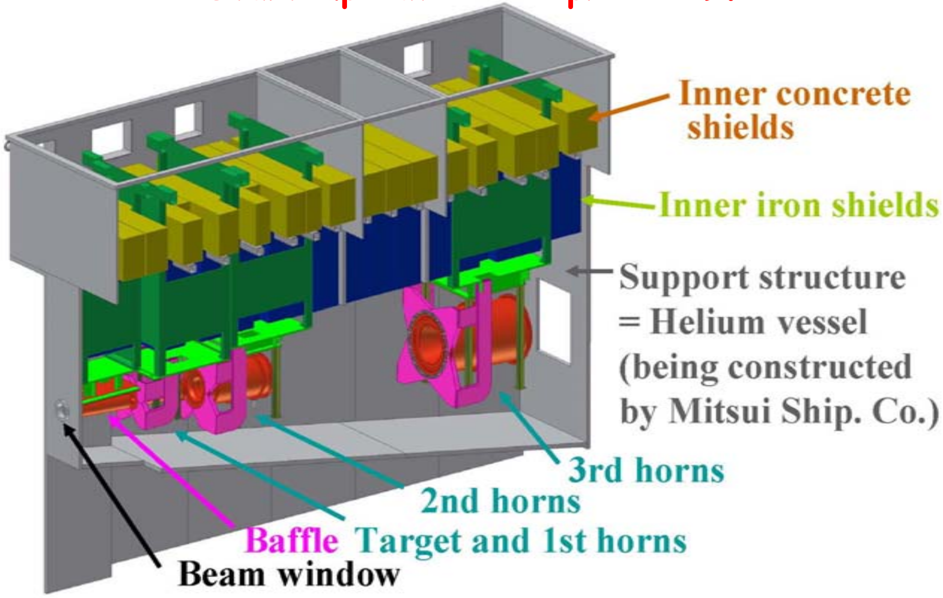
Personal view: This option deserves its status as the baseline for Neutrino Factories and Muon Colliders. For Superbeams that will be limited to less than 2 MW, static solid targets continue to be appealing.

T2K Target (C. Densham, *RAL*)

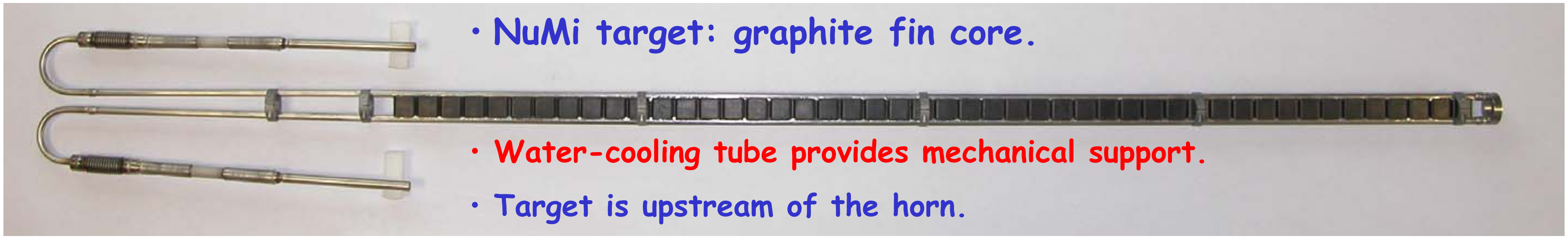


- Graphite rod, 900 mm (2 int.lengths) long, 26 mm (c.2σ) diameter.
- 20 kW of 750 kW Beam Power dissipated in target as heat.
- Helium cooled (i) to avoid shock waves from liquid coolant,s e.g., water and (ii) to allow higher operating temperature.
- Target rod completely encased in titanium to prevent 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.



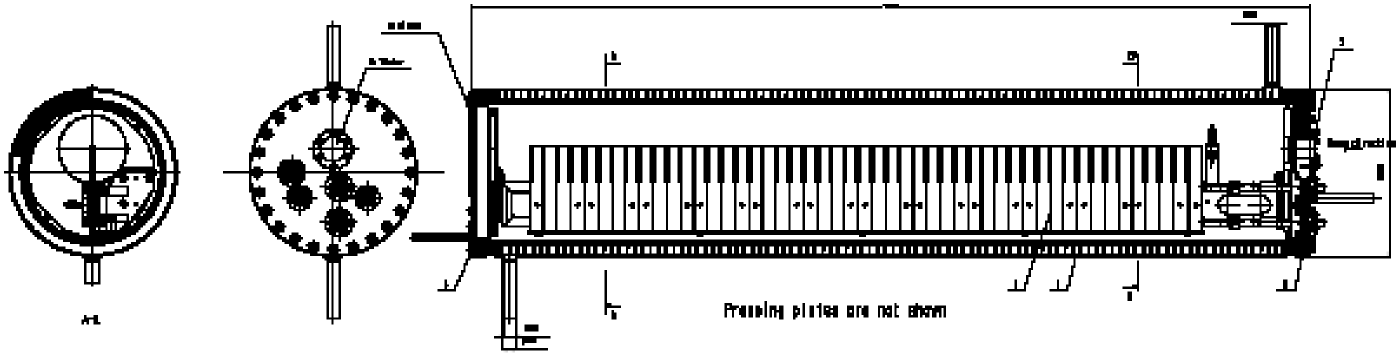


Extrapolating NuMI 0.3 MW Targeting to a 2 MW beam (J. Hylen, *FNAL*)

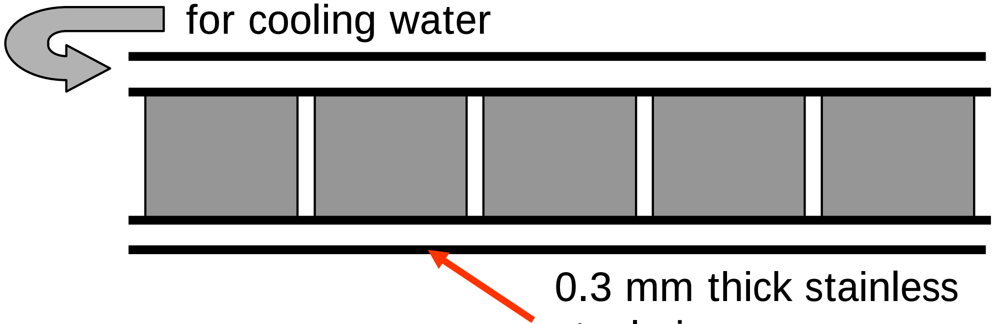


- NuMi target: graphite fin core.
- Water-cooling tube provides mechanical support.
- Target is upstream of the horn.

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

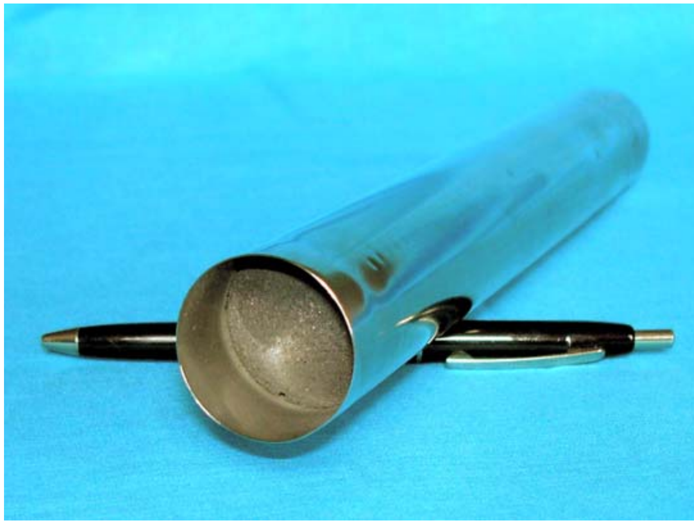


- DUSEL target for 2 MW.
- Embedded in horn.
- Graphite fins in water-cooled can should be viable to 2 MW.



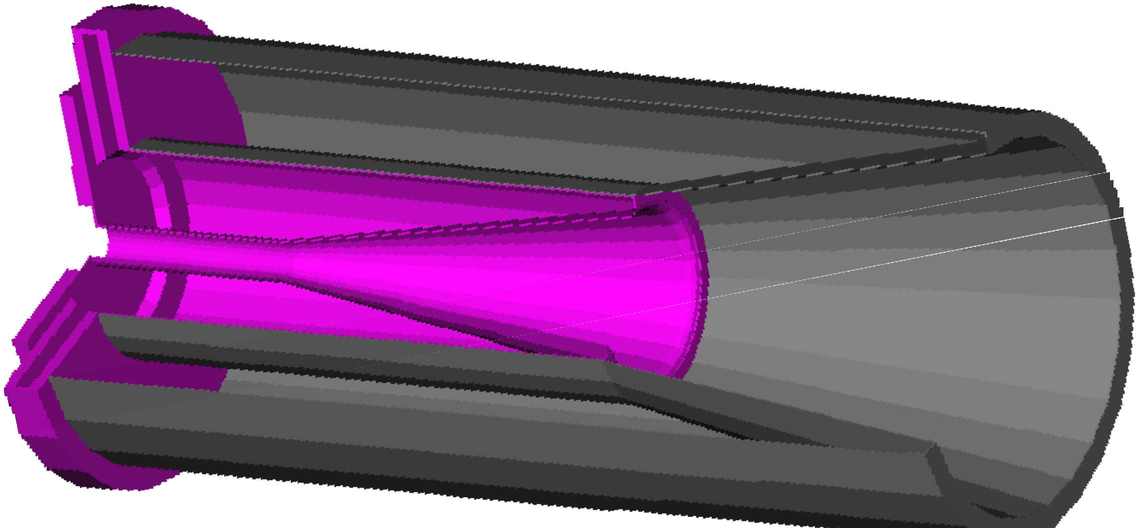
Annular channel (4 mm) for cooling water

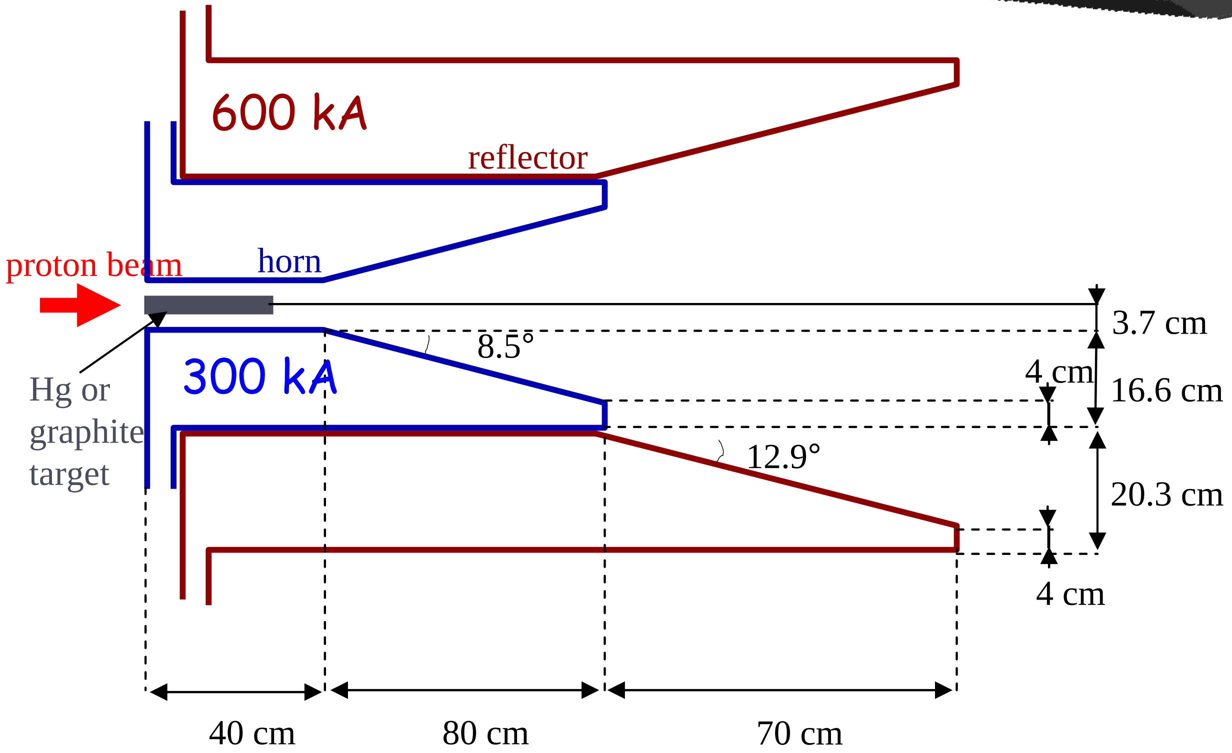
0.3 mm thick stainless steel pipe



Target for the CERN SPL at 2-4 GeV and 4 MW (A. Longhin, *Saclay*)

- 50-Hz beam ⇒ substantial electromechanical challenges for pulsed horn.
- Target inside horn.
- Hg jet target often considered, but a graphite (or flowing powder) target could work.

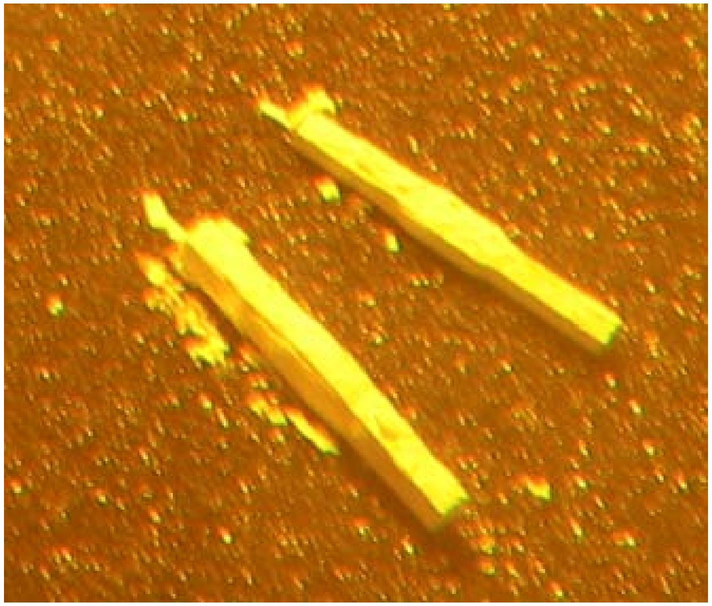




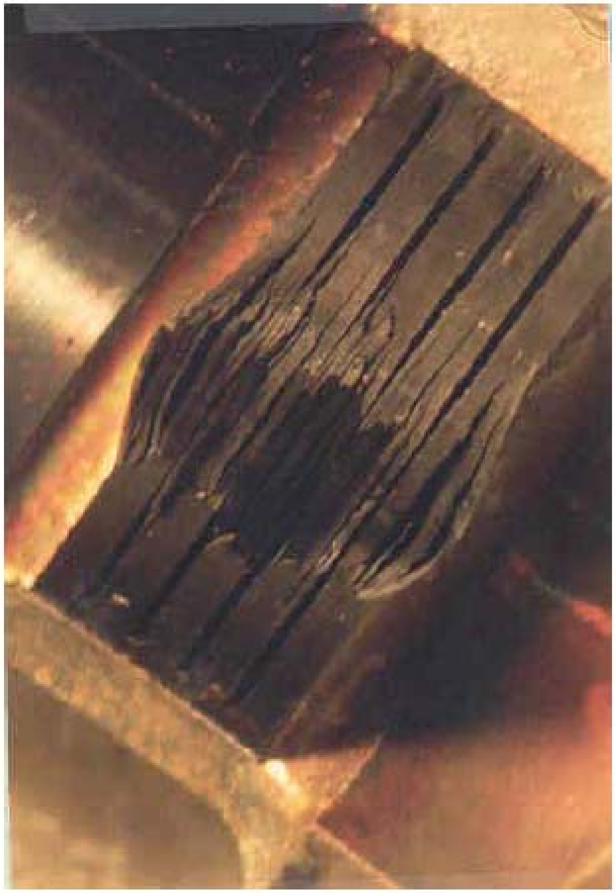
Material Irradiation Studies (Simos, *BNL*)

BNL BLP Studies:

Tantalum (0.25 dpa):

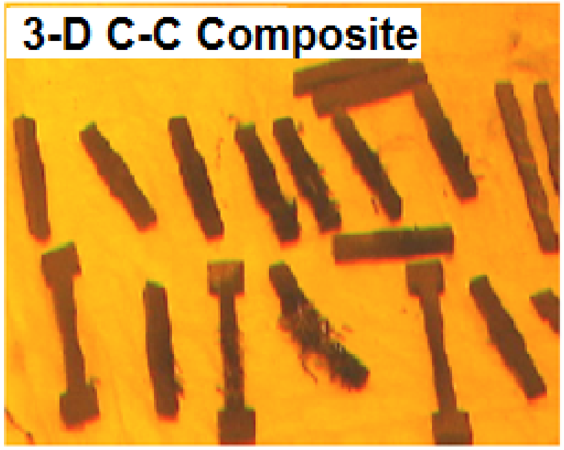


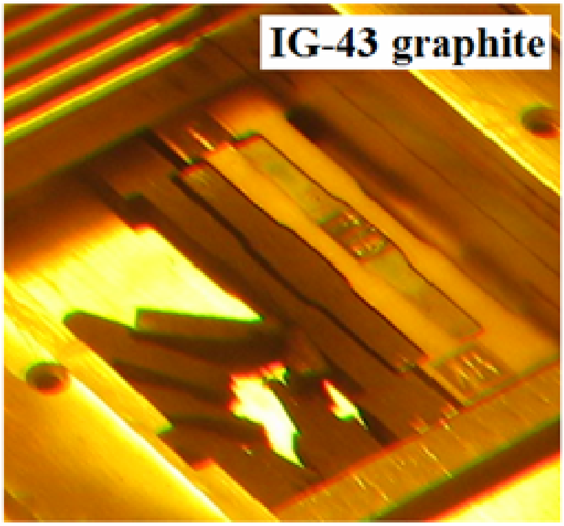
Water-cooled/Edge-cooled TRIUMF target (10^{22} *p*/cm^2):



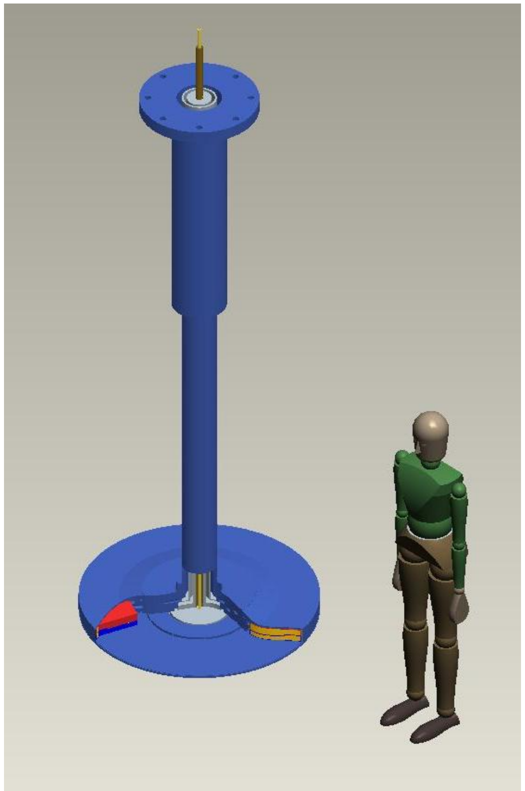
BNL BLP Studies:

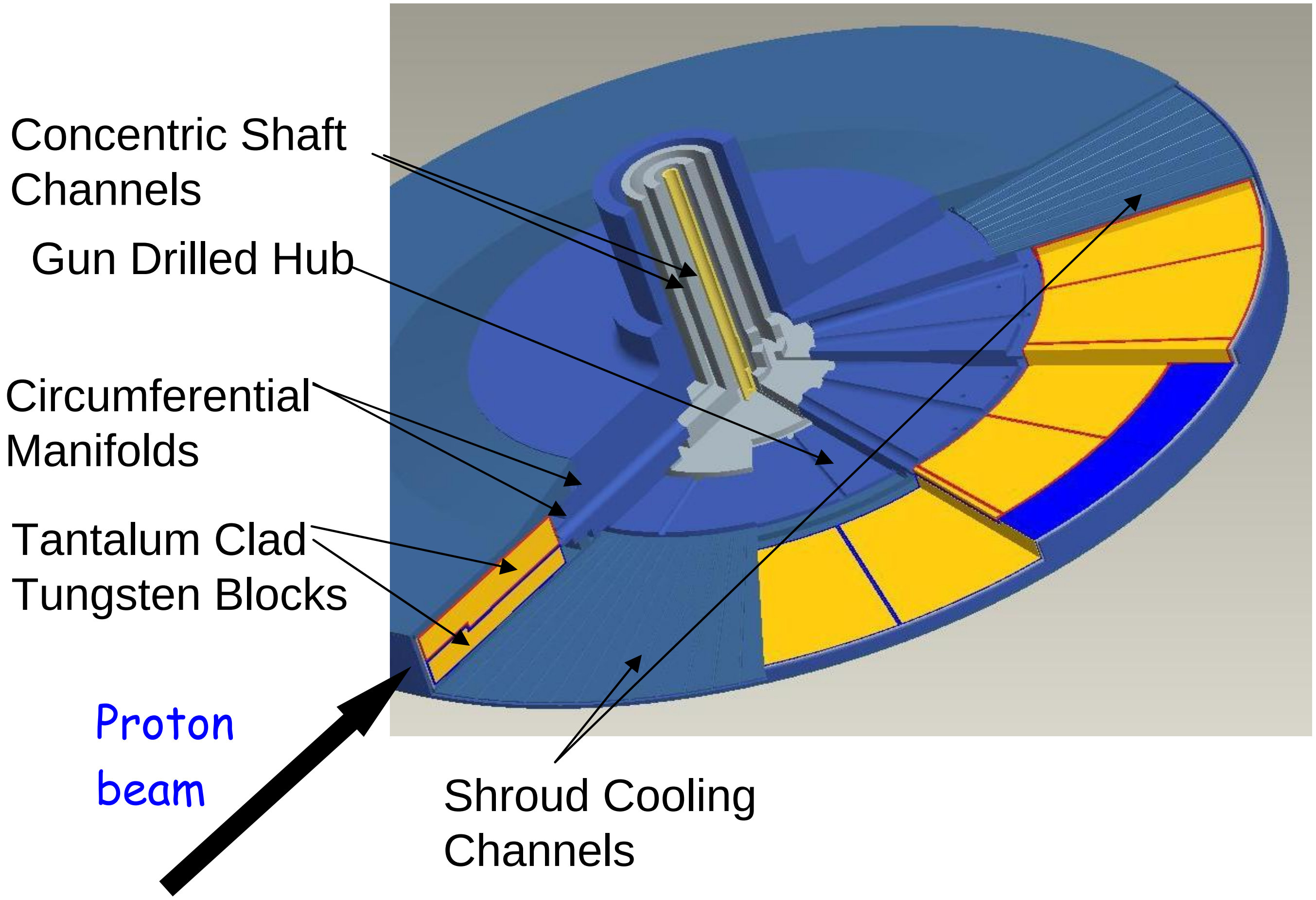
Carbon (0.25 dpa):





SNS (*ORNL*) 3-MW Target Option





Concentric Shaft Channels

Gun Drilled Hub

Circumferential Manifolds

Tantalum Clad Tungsten Blocks

Proton beam

Shroud Cooling Channels

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

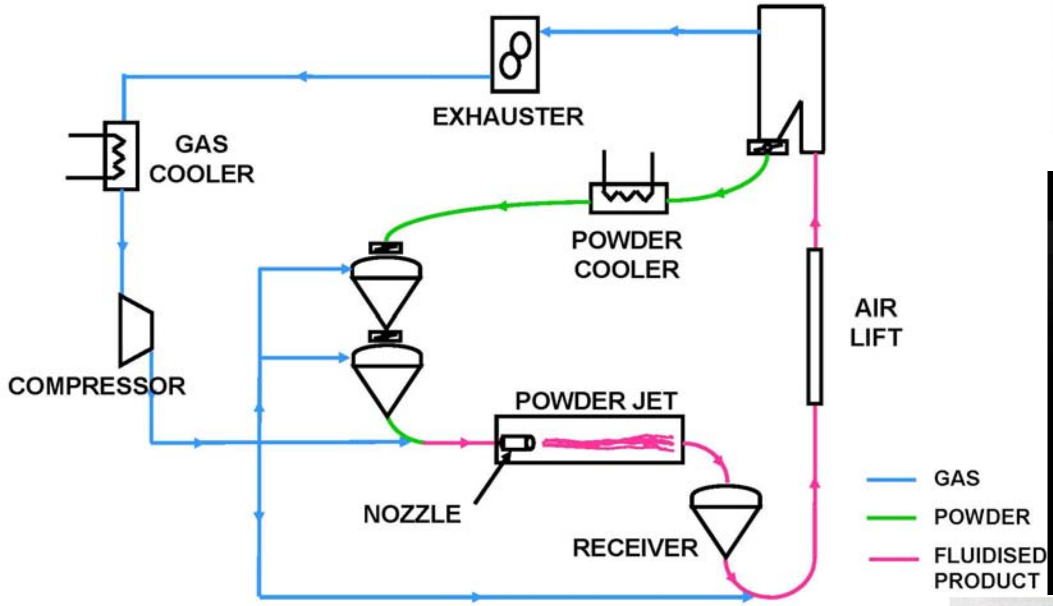
Water cooled by 10-gpm total flow.

Design life: 3 years.

This geometry is not suitable for ν Superbeam, ν Factory or Muon Collider.

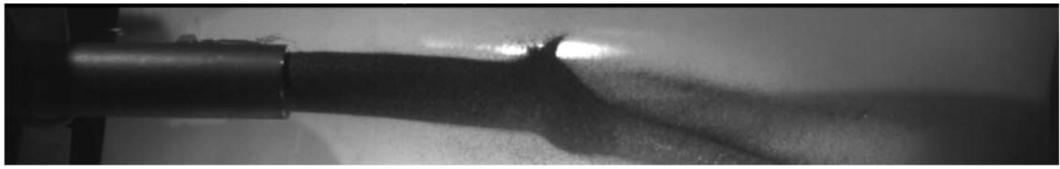
Fluidized Powder Targets (O, Caretta, *RAL*)

- 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. [Low density of high-Z target preferable for pion production (R. Bennett).]
- Flowing powder has surprising similarities to flowing liquids: turbulence, “surface”

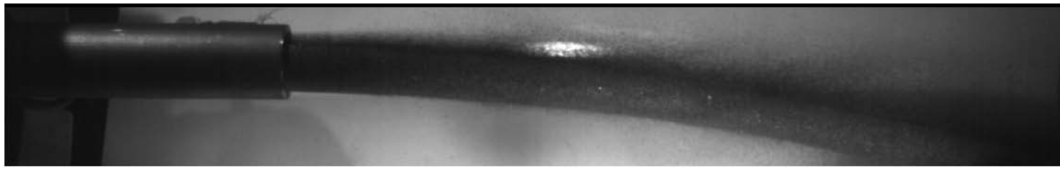


- Mechanics of a quasicontinuous flow system are intricate, but good industry support.
- Erosion a critical issue: ceramic inserts?

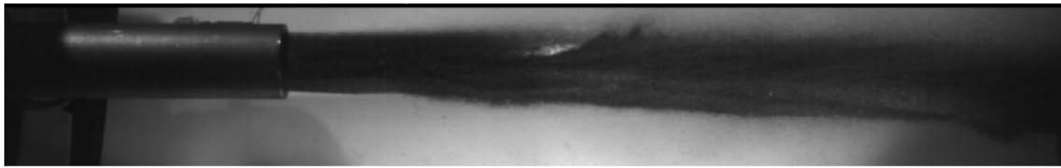
Carrier = helium at 1.5 bar



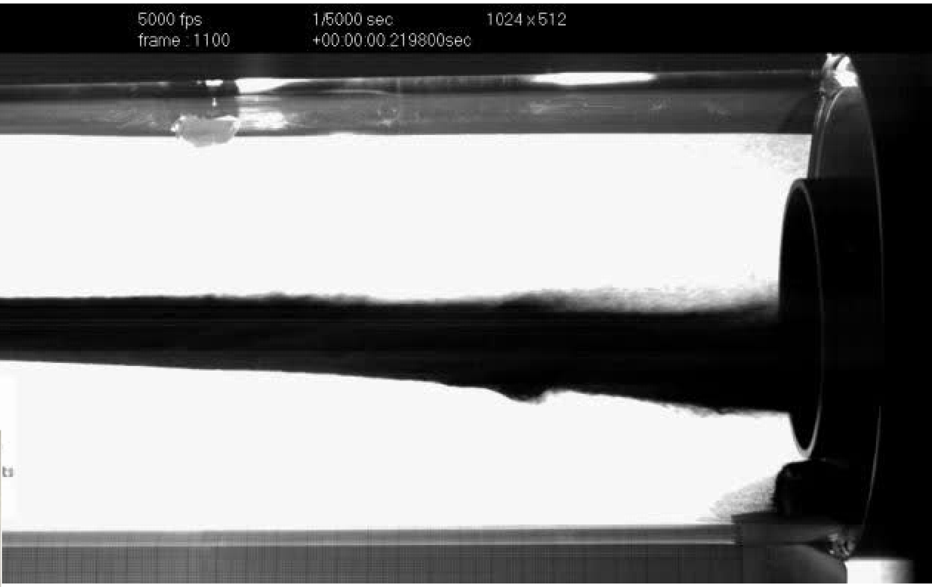
Carrier = helium at 2.5 bar



Carrier = helium at 3.5 bar



Carrier = air at 3 bar



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*, 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.

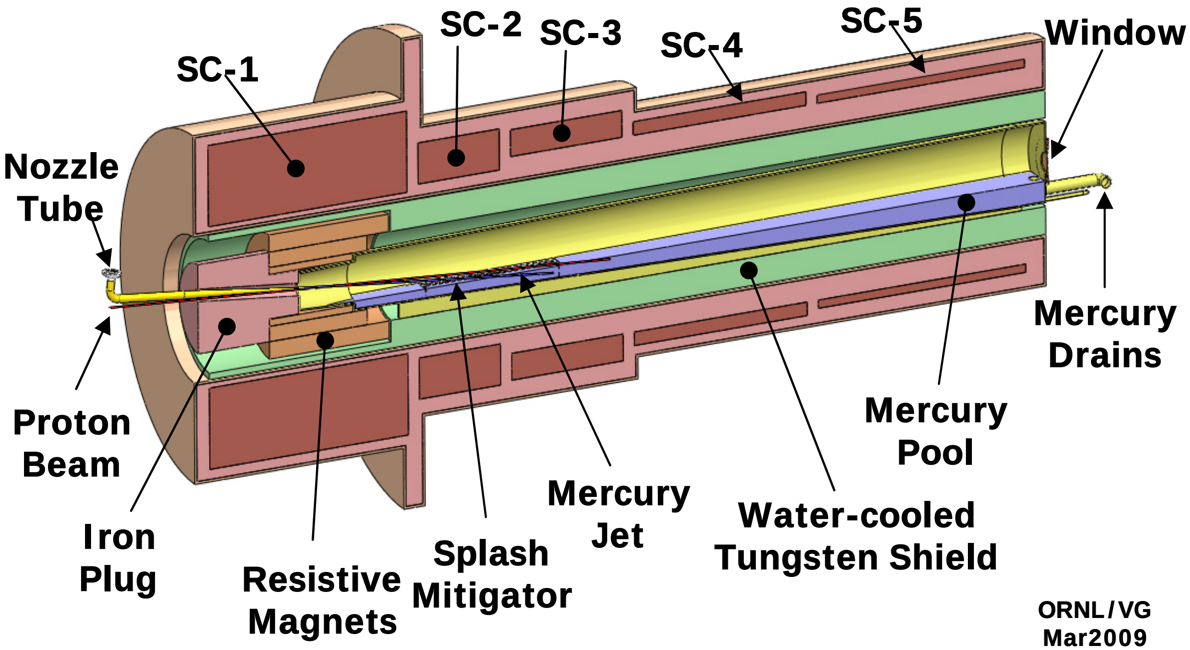
⇒ ≥ 4-year life against radiation damage at 4 MW.

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.

Neutrino Factory Study 2 Target Concept



Pion Production Issues for ν Factory/Muon Collider

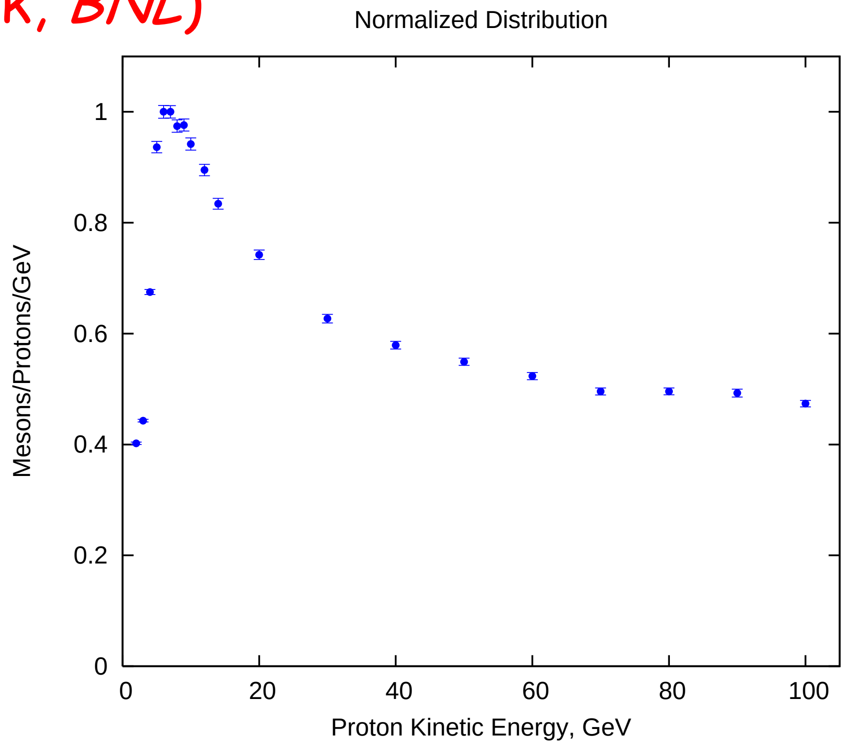
(X. Ding, *UCLA*, H. Kirk, *BNL*)

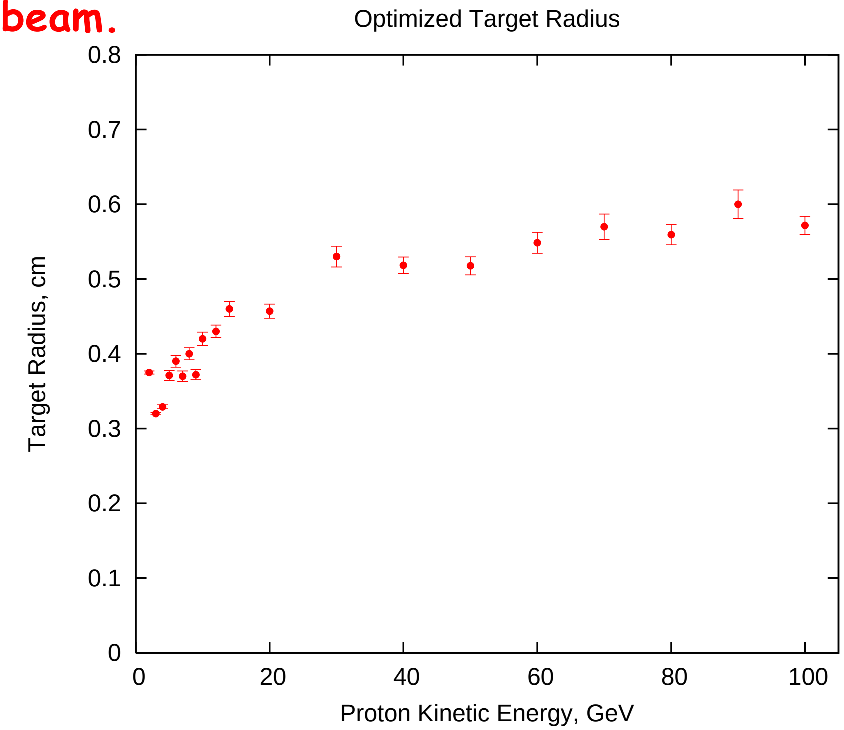
Only pions with $40 < KE_\pi < 180$ MeV are useful for later RF bunching/acceleration of their decay muons.

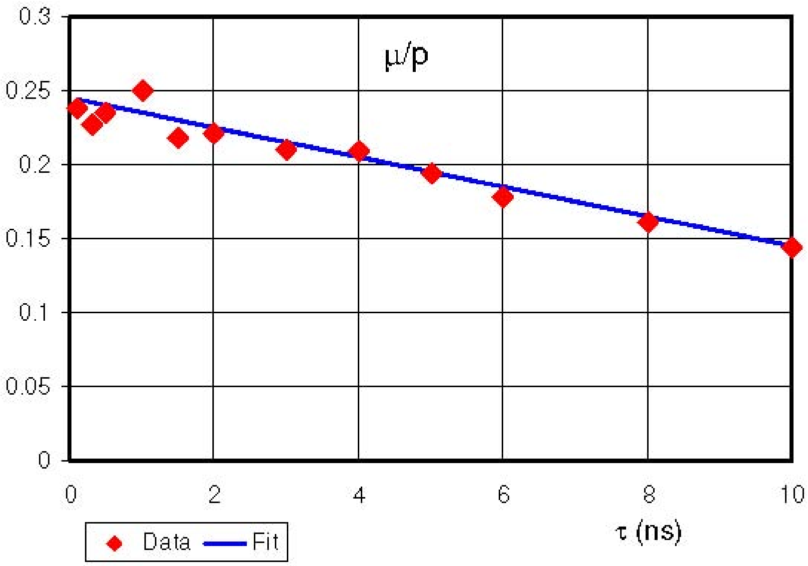
Production of such pions is optimized for a Hg target at E_p ~ 6-8 GeV, according to a MARS15 simulation. [Confirmation of low-energy dropoff by FLUKA highly desirable.]

But, to achieve this optimum, need proton beam radius of ~ 1.5 mm, and bunch length < 3 ns. This is challenging for low proton-beam energies!

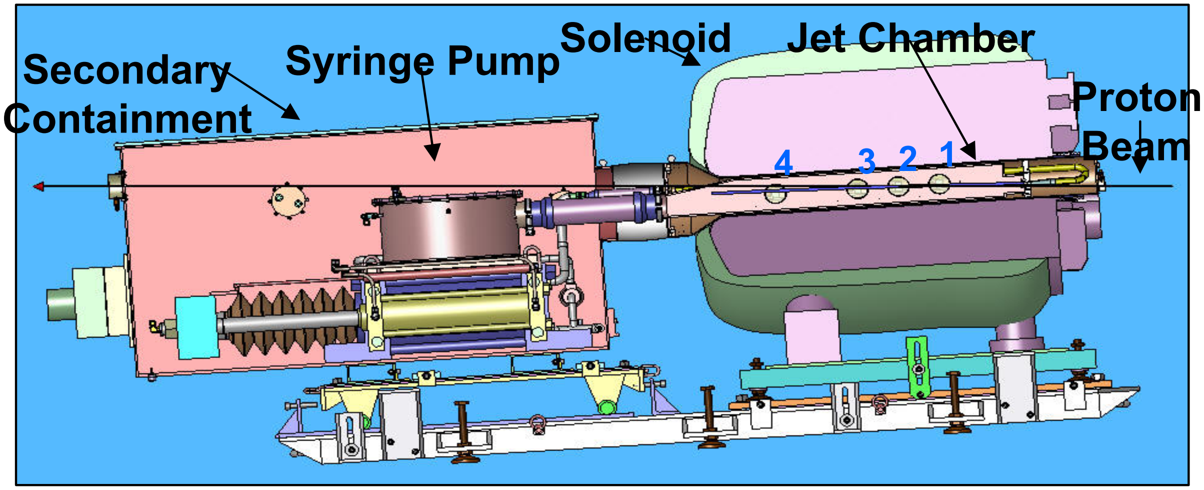
Hg better than graphite in producing low-energy pions, while graphite is better for higher energy pions as for a Superbeam.

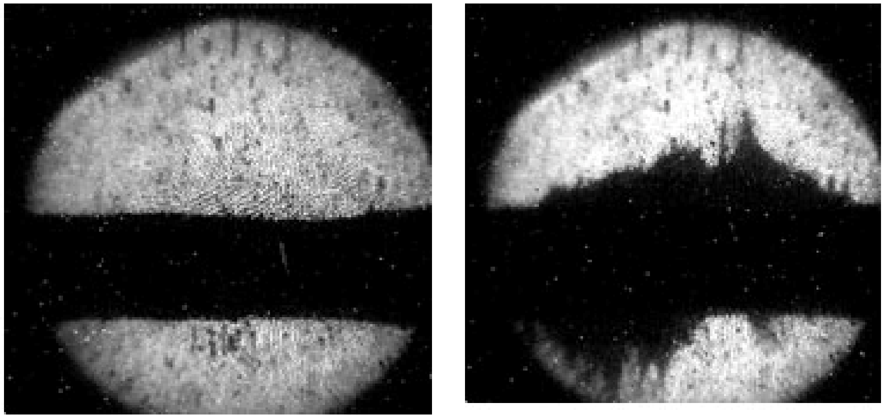






CERN MERIT Experiment (Nov 2007)





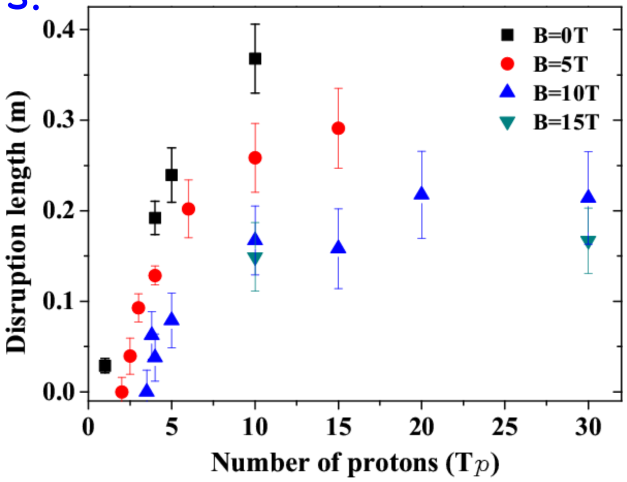
Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

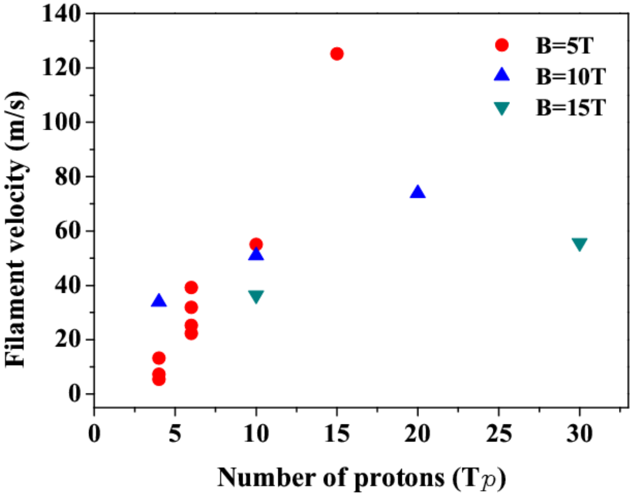
Pion production remains nominal for several hundred μs after first proton bunch of a train.

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

Region of disruption of the mercury jet is shorter than its overlap with the proton beam.

Filament velocity < 100 m/s.





R&D Issues for Hg Jet Target Option

- **Continue and extend simulations of mercury flow in and out of the nozzle.**
    - **Can we understand/mitigate the observed transverse growth of the jet out of the nozzle, which was largely independent of magnetic field.**
- **Examine the MERIT primary containment vessel for pitting by mercury droplets ejected from the jet by the proton beam.**
- **Extend the engineering study of a mercury loop + 20-T capture magnet, begun in ν Factory Study 2, in the context of the International Design Study.**
    - **Splash mitigation in the mercury beam dump,**
    - **Possible drain of mercury out upstream end of magnets.**
    - **Downstream beam window**
    - **Water-cooled tungsten-carbide shield of superconducting magnets.**
    - **High-TC fabrication of the superconducting magnets.**
- **Hardware prototype of a continuous mercury jet with improved nozzle.**

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.

⇒ Point-to-parallel focusing for

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

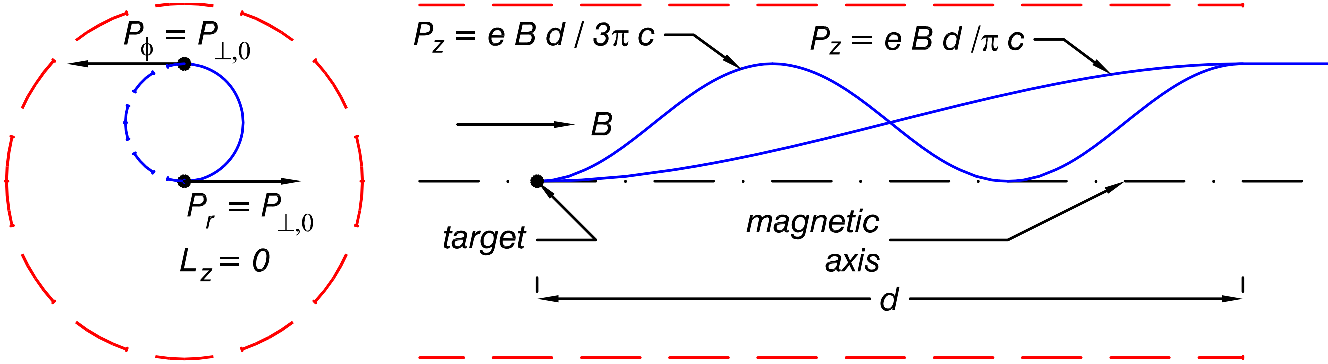
⇒Narrowband (less background) neutrino beams of energies

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

⇒ Can study several neutrino oscillation peaks at once,

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

(Marciano, hep-ph/0108181)



(KTM, physics/0312022)

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

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

⇒ MIND, TASD magnetized iron detectors

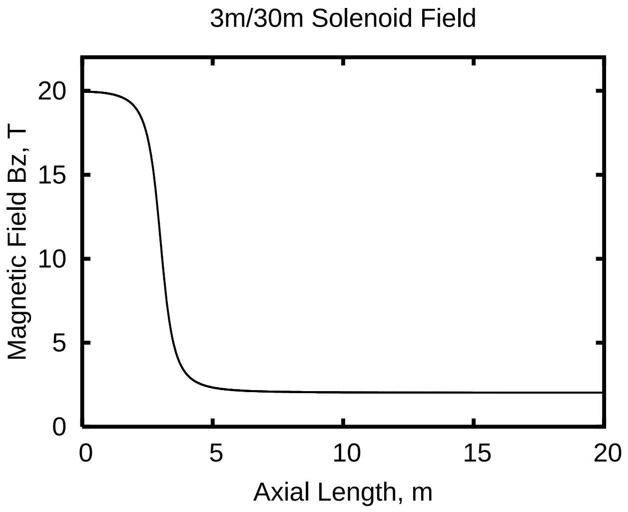
⇒ Liquid argon TPC that can identify slow protons:

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

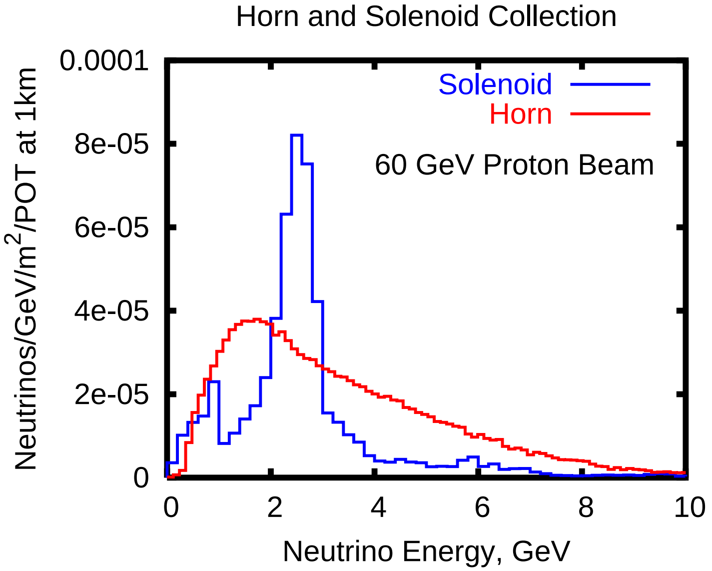
Simulation of Solenoid Horn

(H. Kirk and R. Palmer, *BNL*, NuFACT06)

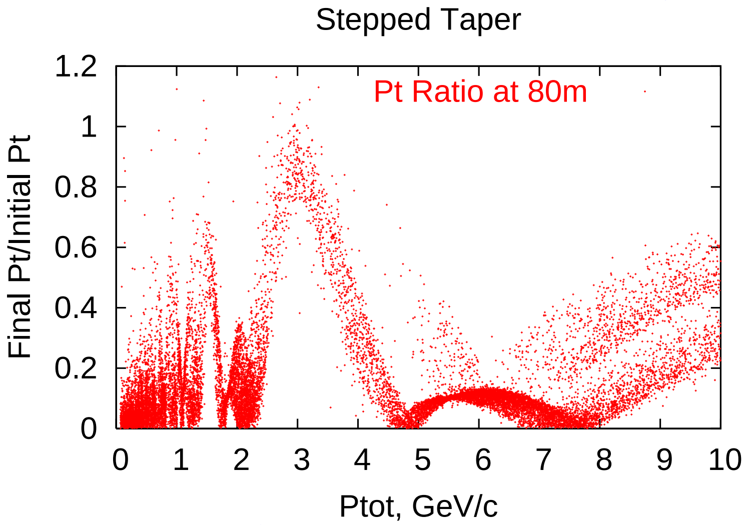
B vs. *z* for 3 + 30 m solenoid:



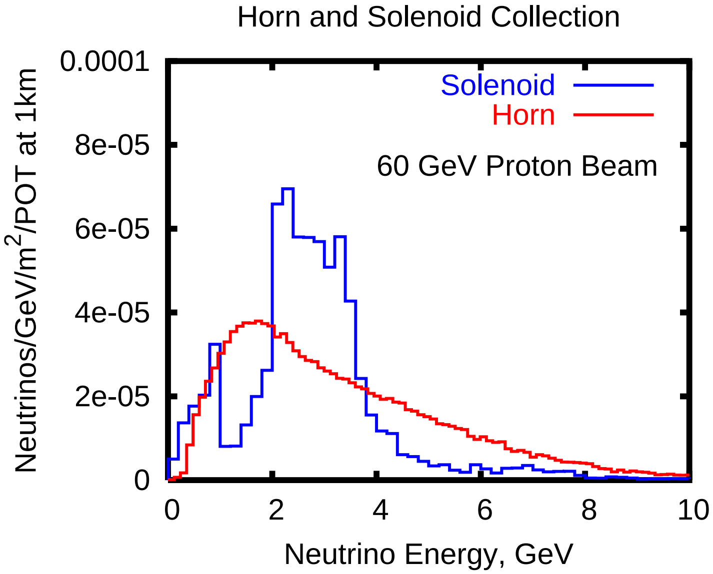
3-m solenoid gives
2 narrow peaks
in ν spectrum:



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



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



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