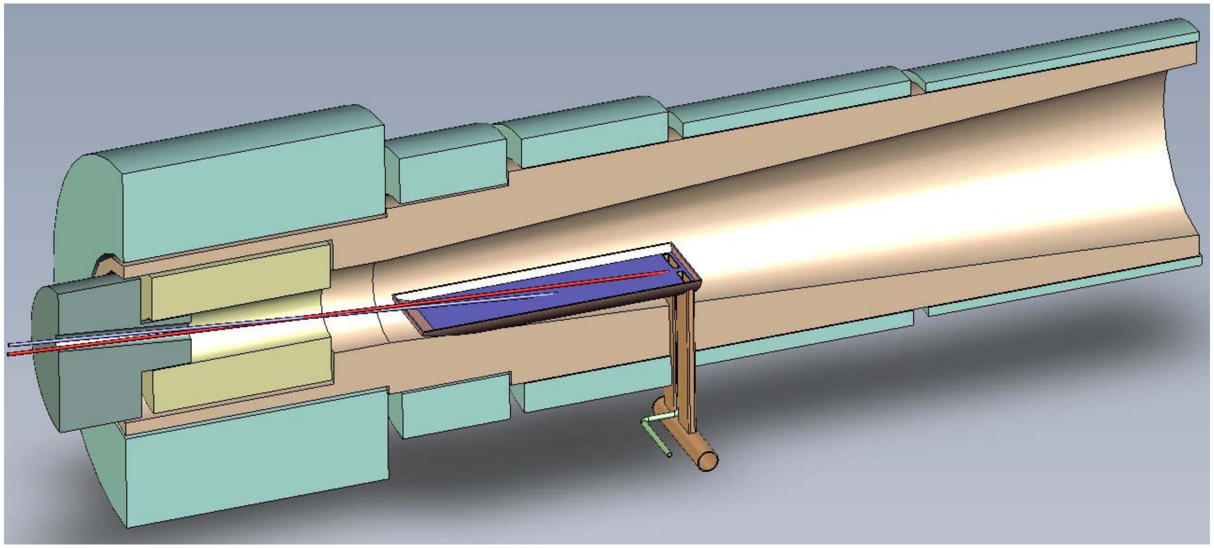
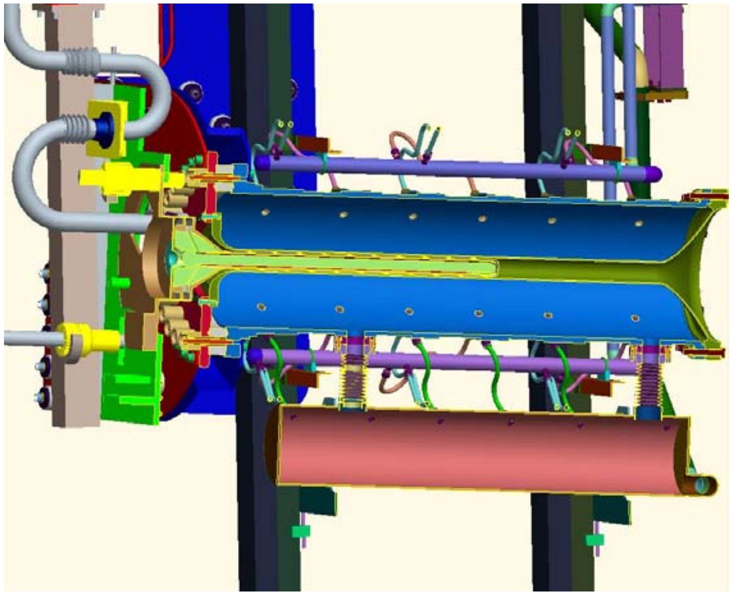
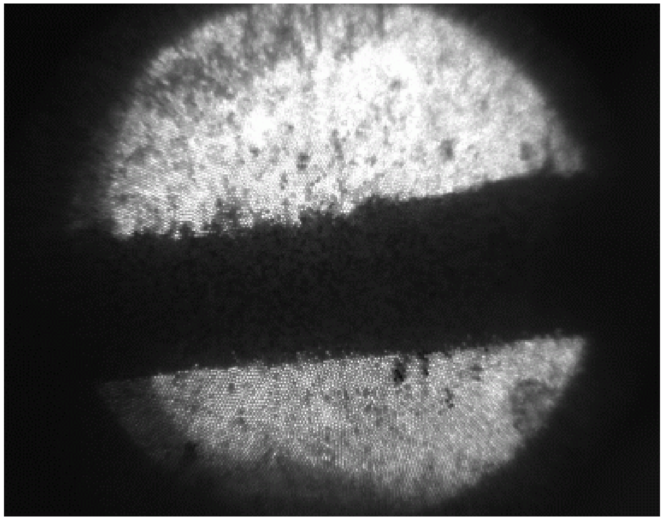
High-Power Targets for Superbeams and Neutrino Factories

(and Muon Colliders)







K.T. McDonald
Princeton U.

2nd Oxford-Princeton Targetry Workshop
Princeton, Nov 6, 2008

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

The Context

- **Physics:** Nature presents us with the opportunity to explore the richness of the mixing of massive neutrinos using neutrino beams: Mass hierarchy, $\sin^2\theta_{13}$, *CP* violation.

- **Neutrino Beams:**
  - Superbeam neutrinos from $\pi^\pm \to \mu^\pm \nu_\mu(\bar{\nu}_\mu)$ (Pions from $pA \to \pi^\pm X$.)
  - Factory neutrinos from $\mu^\pm \to e^\pm \bar{\nu}_\mu \nu_e (\nu_\mu \bar{\nu}_e)$ (Muons from $\pi^\pm \to \mu^\pm \nu_\mu(\bar{\nu}_\mu)$.)
  - β-beam neutrinos from $^6\mathrm{He} \to {}^6\mathrm{Li}\ e^- \nu_e$, $^{18}\mathrm{Ne} \to {}^{18}\mathrm{F}\ e^+ \nu_e$ (not discussed here).

- **Detectors:** Cheapest large detectors are calorimeters with no magnetic field.
  - ⇒ Cheapest to study $\nu_\mu \to \nu_e$ oscillations with a sign-selected source.
  - ⇒ Long time to study both neutrino and antineutrino oscillations.

Alternatives to permit simultaneous studies of neutrinos and antineutrinos:

- Magnetized iron calorimeter with Neutrino Factory ($\mu^\pm$ only).
- Magnetized liquid argon detector with Superbeam and/or Neutrino Factory.

(Only magnetized fine-grain detector {LAr, TASD, …] can distinguish $e^\pm$.)

(Neutrino Factory needs magnetized detector even if sign-selected beam.)

Targetry

The exciting results from atmospheric, solar and reactor neutrino programs (Super-K, SNO, Borexino, KamLAND, …) reinforce the opportunity for neutrino physics with intense accelerator neutrino beams, where targetry is a major challenge.

Targetry = the task of producing and capturing π's and μ's from proton interactions with a nuclear target.

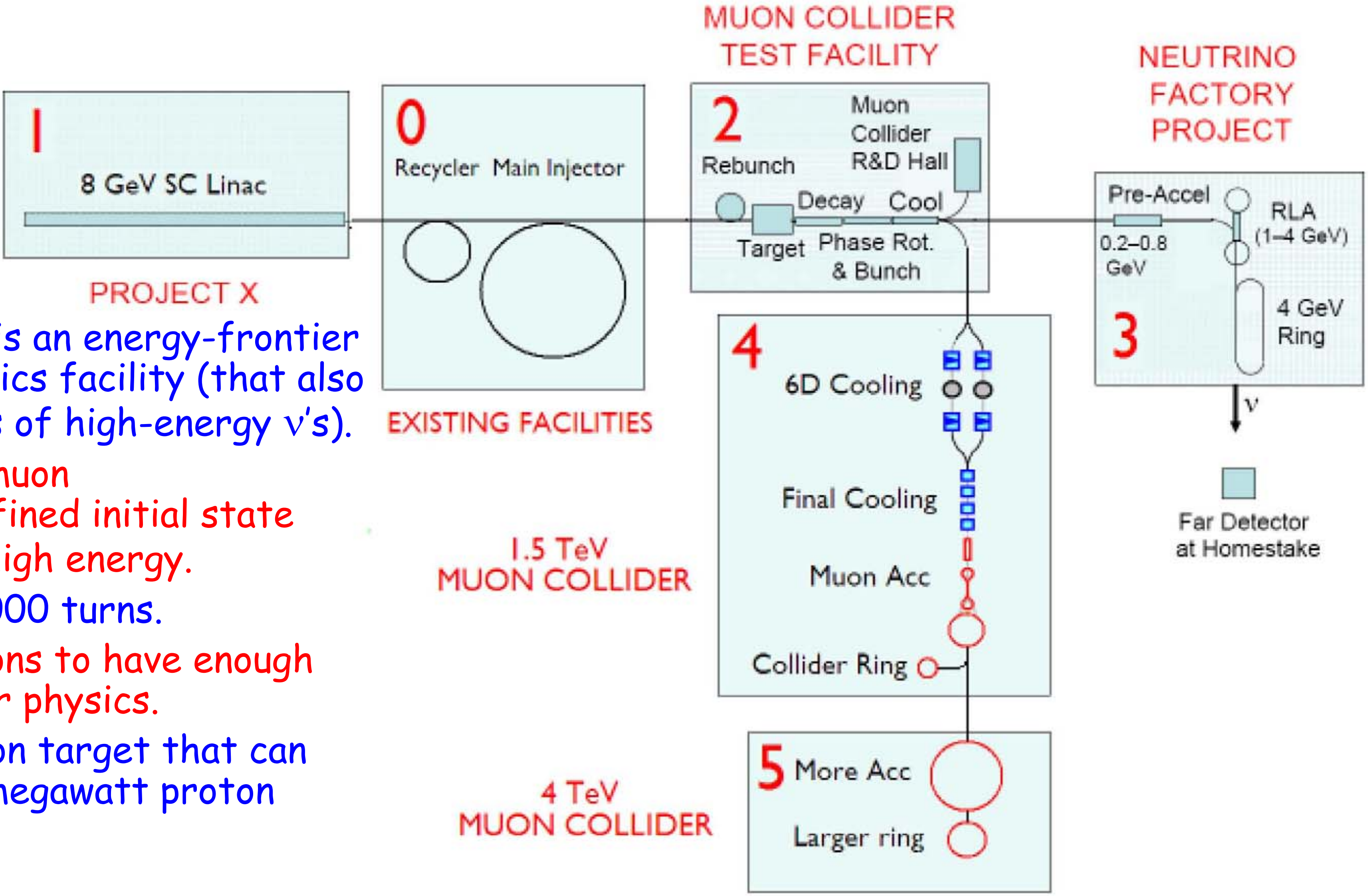
At a muon collider the key parameter is luminosity: $\mathcal{L} = \dfrac{N_1 N_2 f}{A}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$,

$\Rightarrow$ Gain as square of source strength (targetry) [but small beam area (cooling) is also critical].

At a neutrino superbeam and a neutrino factory the key parameter is neutrino flux,
$\Rightarrow$ Source strength (targetry) is of pre-eminent concern.

[Beam cooling important mainly to be sure the beam fits in the pipe.]

The Target is Pivotal between a Proton Driver and ν or μ Beams



A Muon Collider is an energy-frontier particle-physics facility (that also produces lots of high-energy ν's).

Higher mass of muon
⇒ Better defined initial state than e^+e^- at high energy.

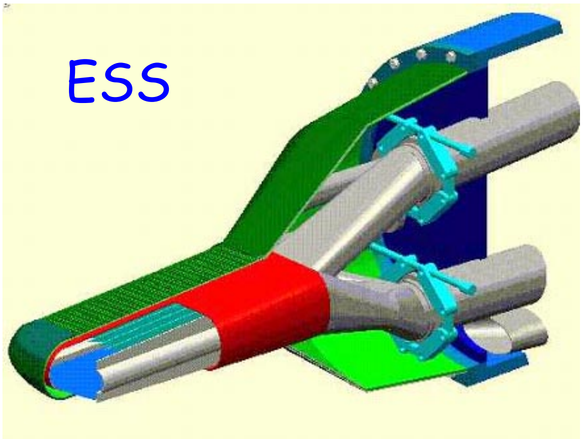
A muon lives ≈ 1000 turns.

Need lots of muons to have enough luminosity for physics.

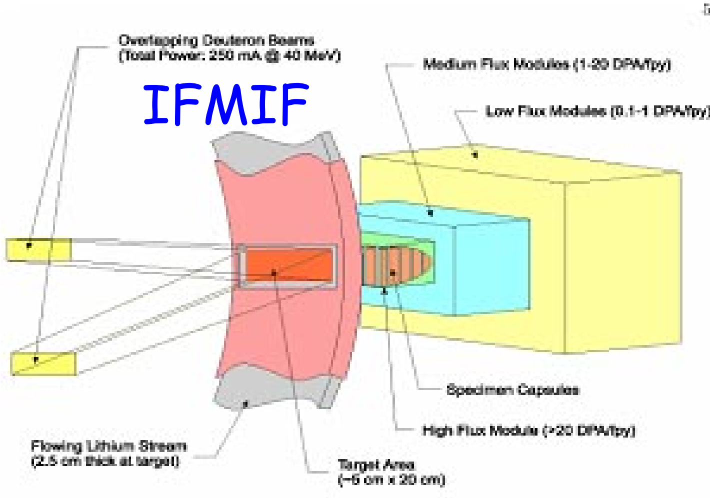
Need a production target that can survive multmegawatt proton beams.

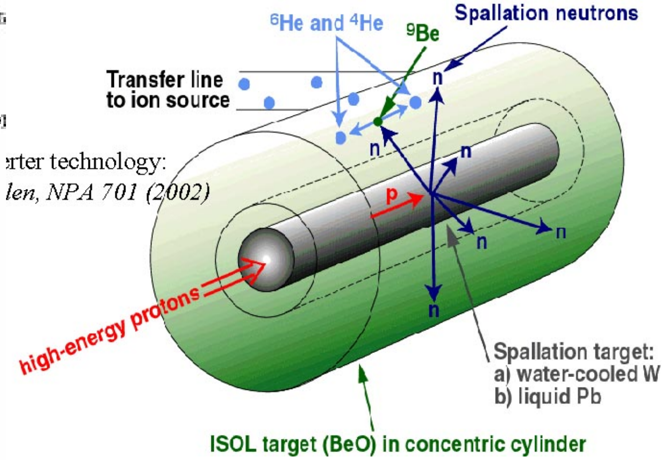
High-Power Targets Essential for Many Future Facilities

ESS



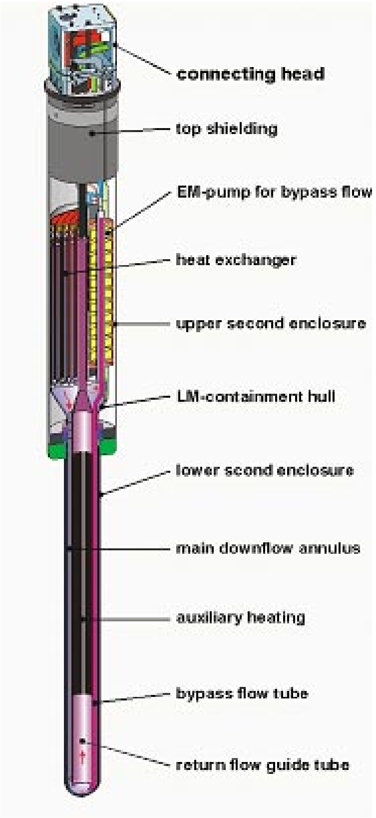
IFMIF



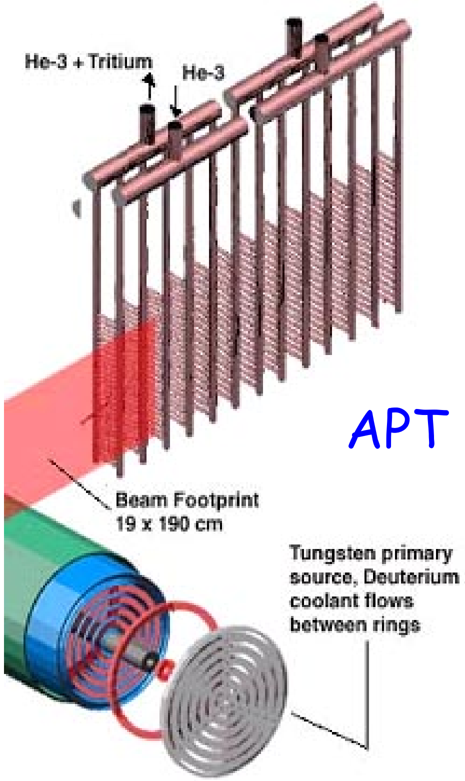


ISOL/β Beams

PSI



APT



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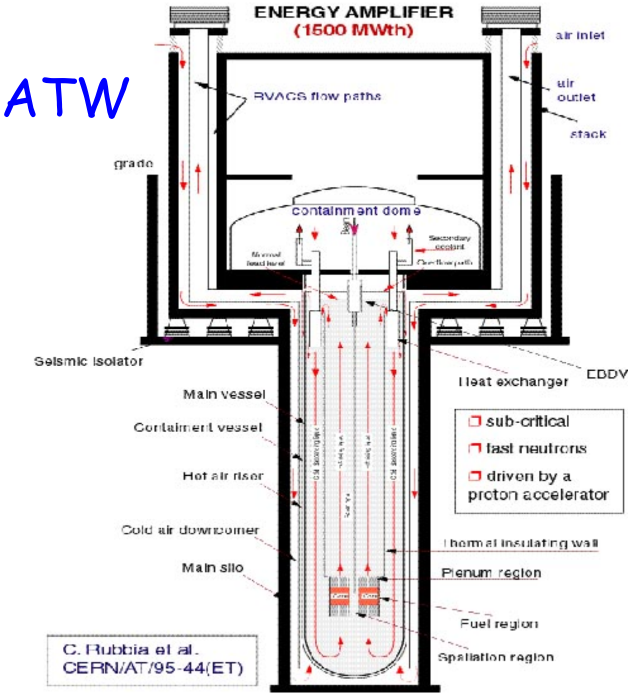


C. Rubbia et al.
CERN/AT/95-44(ET)

2-4 MW Proton Beams

- 10-50 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, ≈ 0.2 cm^2 for Superbeam.

- Pulse width ≈ 1 μs OK for Superbeam, but ≈ 1 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 option" at this power level.

Radiation Damage

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

⇒ 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.)

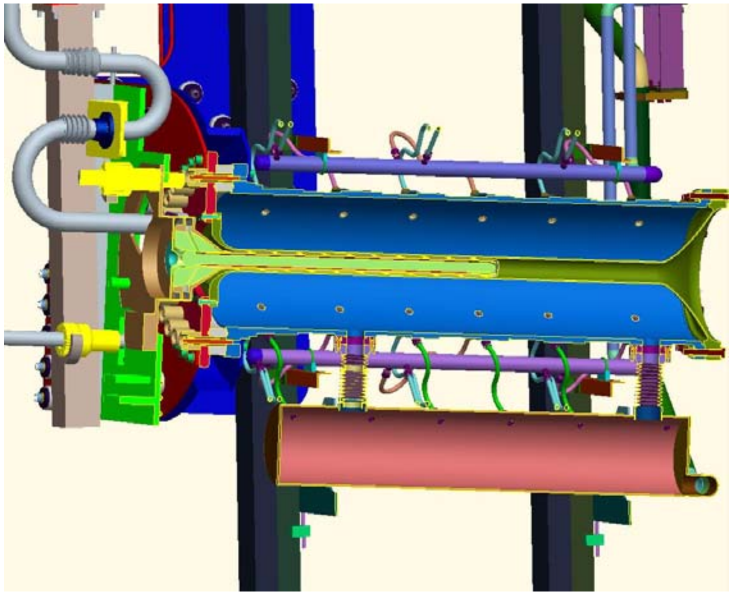
The proton beam should be tilted with respect to the axis of the capture system at a Neutrino Factory, so that the beam dump does not absorb the captured π's and μ's.

Target and Capture Topologies: Toroidal Horn

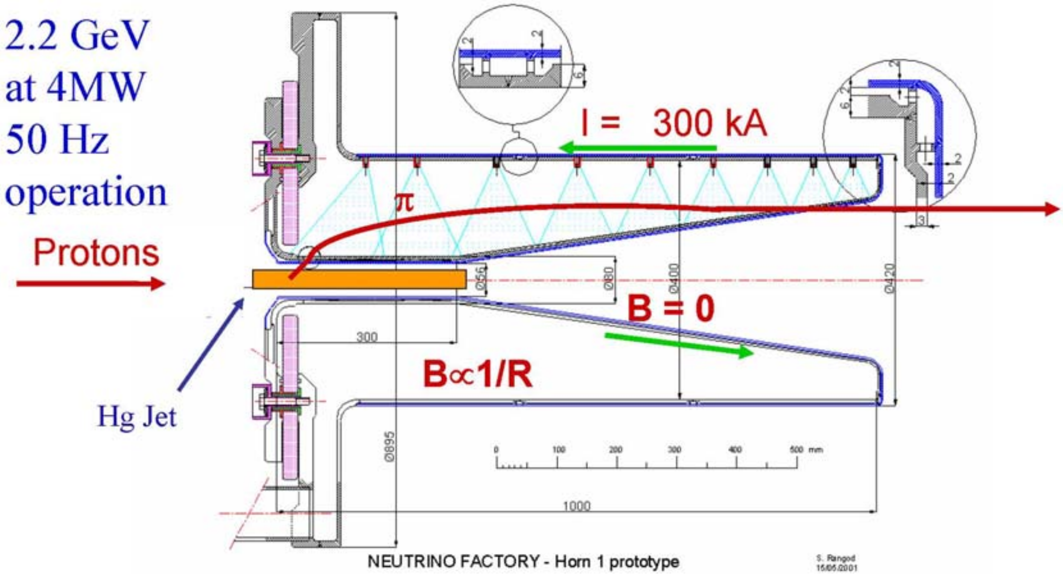
The traditional topology for efficient capture of secondary pions is a toroidal “horn” (Van der Meer, 1961).

- Collects only one sign, ⇒ Longer 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/Muon Collider.

0.75-MW Graphite target with He gas cooling (T2K):



Mercury jet target (CERN SPL study):



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

Target and Capture Topologies: Solenoid

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

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

⇒ Some R&D needed!

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.

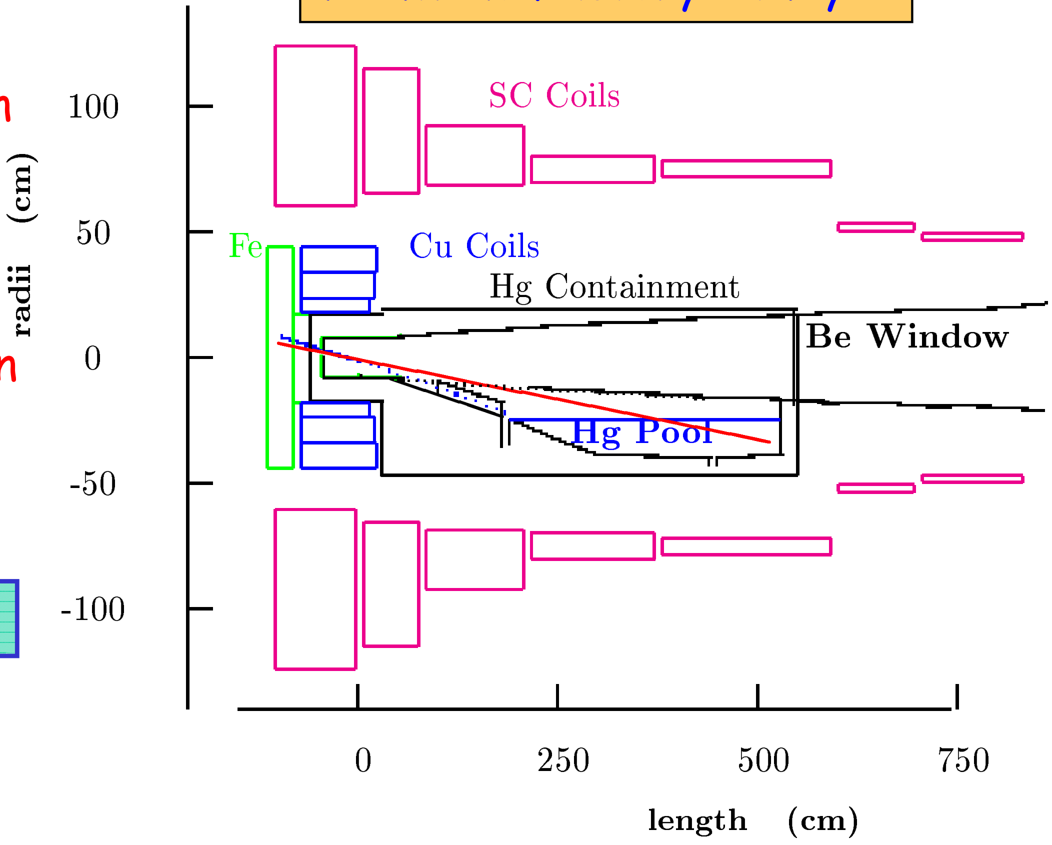
⇒ $\geq$ 4-year life against radiation damage at 4 MW.

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.

R. Palmer (BNL)
Neutrino Factory Study 2



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

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

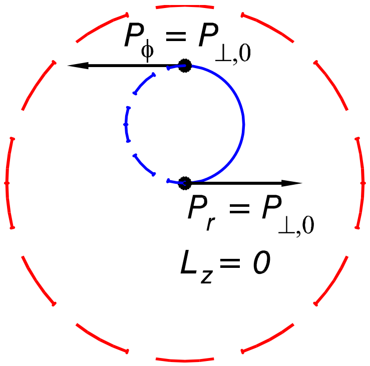
⇒Narrowband (less background) neutrino beams of energies

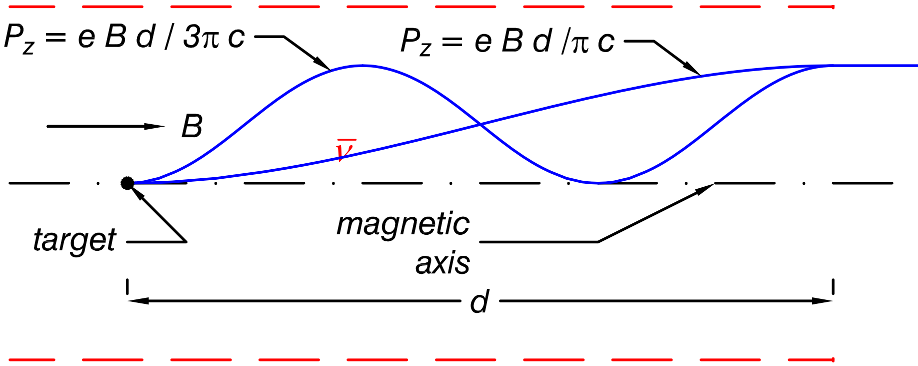
$$E_\nu \approx \frac{P_\pi}{2} = \frac{eBd}{(2n+1)2\pi c}.$$

⇒ Can study several neutrino oscillation peaks at once,

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

(Marciano, hep-ph/0108181)





(KTM, physics/0312022)

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

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

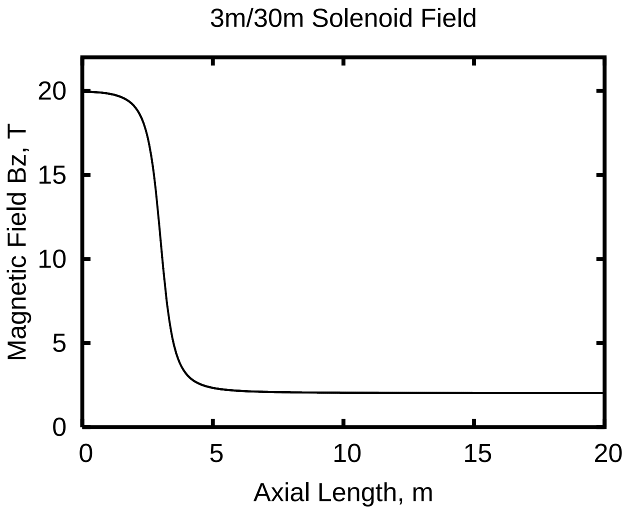
⇒ Liquid argon TPC that can identify slow protons:

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

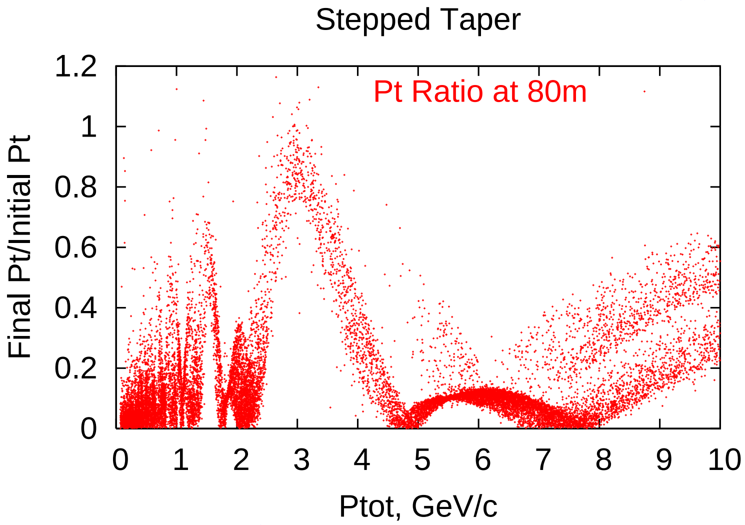
Simulation of Solenoid Horn

(H. Kirk and R. Palmer, NuFACT06)

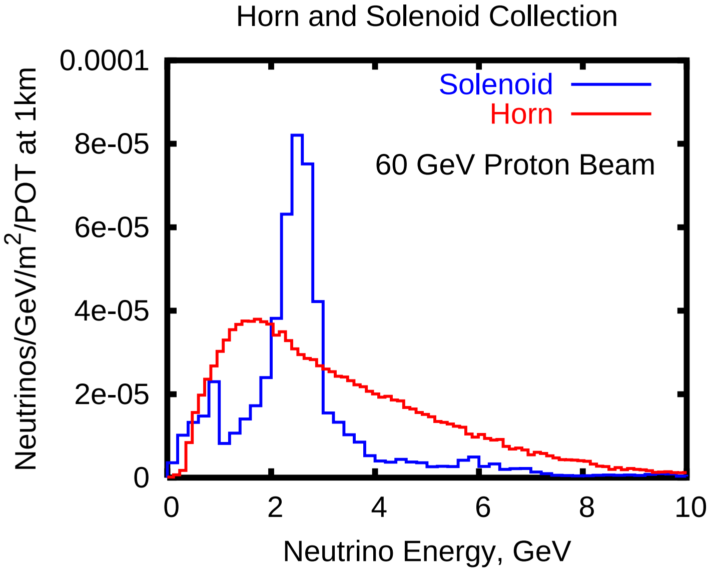
B vs. z for 3 + 30 m solenoid:



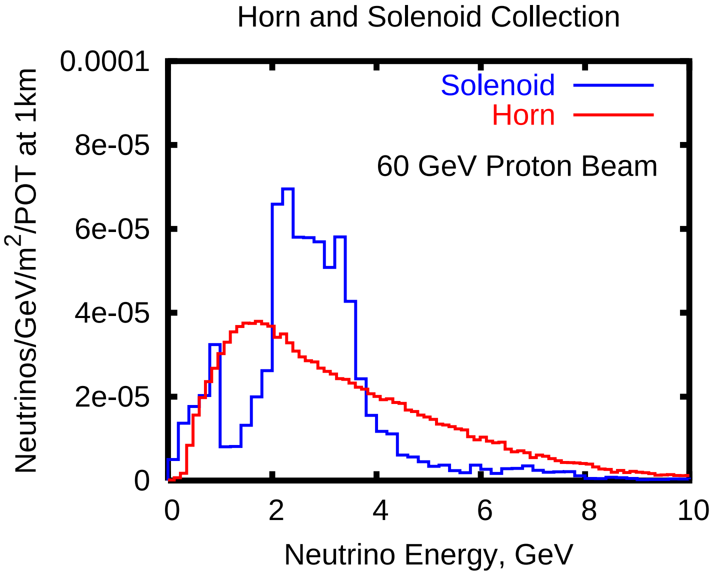
$\Rightarrow P_\perp$ minimized at selected $P_{\rm tot}$:



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



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



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

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 $\overline{p}$, 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.

⇒ 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.

Future Mercury Target System R&D

Analysis (and simulation) of MERIT data is ongoing, but the success of the experiment already provides proof-of-principle of a free mercury jet target for megawatt proton beams.

Considerable system engineering is needed before an actual jet target station could be built: 20-T magnet, tungsten-carbide(?) shield, mercury delivery and collection system, remote handling system, radioisotope processing, ……..

Desirable to improve jet quality, and to explore viability of jet axis at 100 mrad to magnetic axis, as proposed in Feasibility Study 2. Would also be good to verify feasibility of recovery of the mercury jet in an open pool.

An opportunity exists to conduct non-beam studies with the MERIT equipment after it is shipped from CERN to ORNL ~ Jan 2009 (presentation by V. Graves).

Such studies would begin with no magnetic field (jet quality, Hg pool), followed by studies with the MERIT magnet powered to 15 (or even 20) T at a new fusion power test facility at ORNL.