A Neutrino Superbeam Physics Program as a First Stage of a Neutrino Factory

K.T. McDonald, Princeton University, July 14, 2001

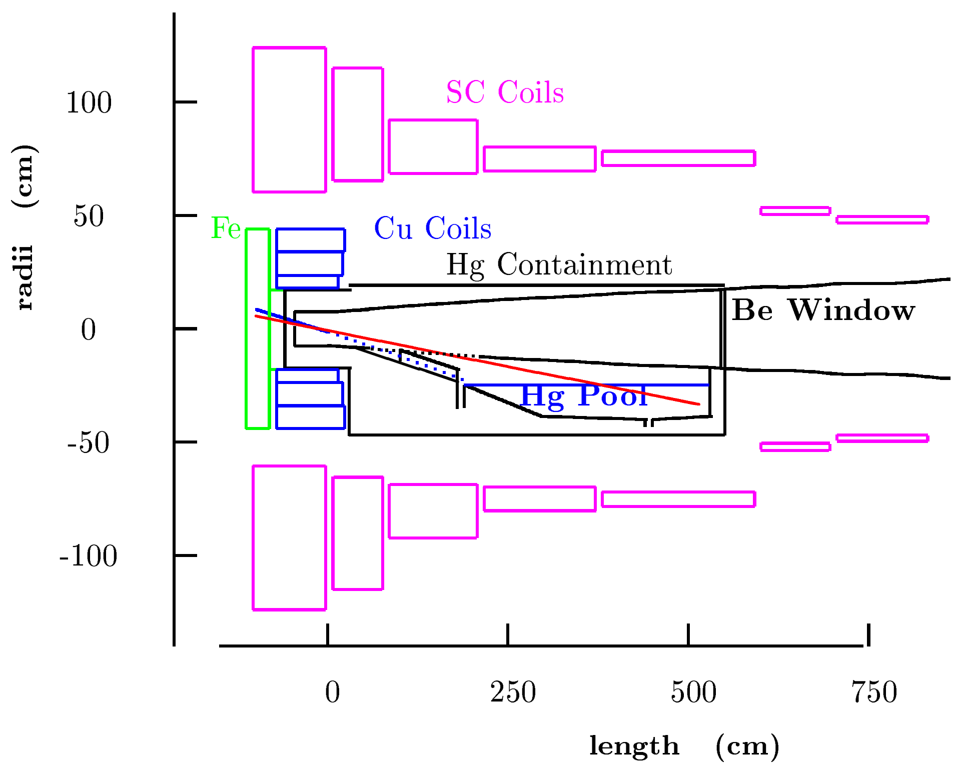
- This scenario is based on the premise that a neutrino factory will play an eventual prominent role in neutrino physics – *i.e.*, that the LMA solution to the solar neutrino problem is correct.
- Hence, physics reach and compatibility between a superbeam and a neutrino factory is given greater emphasis than incremental improvement on existing experiments.
- The LSND result is discounted.
- A viable level of R&D for a neutrino factory is likely only if this becomes coupled to a neutrino superbeam physics program.

The Basic Scenario

- Lessons from Neutrino Factory Feasibility Studies I and II:
  - Proton driver upgrade from 1 to 4 MW is very cost effective.
  - Acceleration of muon beams is very expensive.
- This suggests (at least) 3 stages towards a neutrino factory:
  1. Neutrino superbeam from pion decay with 4 MW proton driver. (Stages 1a, 1b, 1c might be 1, 2, 4 MW.)
  2. Add a muon capture channel + storage ring to produce muon decay neutrinos of same central energy as in Stage 1.
     - Same beam energy in Stages 1 and 2 $\Rightarrow$ same detector and baseline.
     - ν_μ rate from muon decay $\sim 1/3$ that from pion decay, but ν_e rate much greater.
     - To keep costs low, the energy of the Stage 1 and 2 neutrino beams should be low.
  3. Add muon acceleration to higher energy (20 GeV?), a new storage ring, and a new detector at a new, longer baseline.

The Neutrino Horn Issue

- 4 MW proton beams are achieved in both the BNL and FNAL (and CERN) scenarios via high rep rates: $\approx 10^6$/day.
- Classic neutrino horns based on high currents in conductors that intercept much of the secondary pions will have lifetimes of only a few days in this environment.
- Consider instead a solenoid horn with conductors at larger radii than the pions of interest – similar to the neutrino factory capture solenoid.



]

- Reduce magnetic field adiabatically in z from B_{max} to B_{min}.

- $\Phi_B = BR^2$ is an adiabatic invariant, where R = radius of helical trajectory.
- Also, $R \propto P_\perp / B$.
- Hence, $P_\perp^2 / B$ is also an adiabatic invariant.
- Thus, $p_{\perp,\text{final}} = p_{\perp,\text{initial}} \sqrt{B_\text{min}/B_\text{max}}$.
- Ex: $B_\text{max} = 20$ T, $B_\text{min} = 0.1$ T
  $\Rightarrow \langle p_{\perp,\text{final}} \rangle = \langle p_{\perp,\text{initial}} \rangle /14 \approx 300/14 = 20$ MeV$/c$.
- Length of solenoid should be less than $8 \langle \gamma_\pi \rangle$ m.
- Compatible with off-axis beams to select a narrow energy spread.
- **The solenoid horn beam is NOT sign selected.**
- **The detector must identify the sign of the lepton.**

Detector Issues

- Detector mass should be $\gtrsim$ 100 kton to be competitive.
- Detector for neutrino factory should identify sign of muons – as should a superbeam detector if use solenoid horn.
- For greater reach in study of CP violation, detector should identify sign of electron/positron.
- Magnetized liquid argon detector is only choice for $\mu^\pm$, $e^\pm$ identification – for $E_\nu \lesssim 1$ GeV, $B \sim 0.5$ T.
- R&D needed to confirm efficiency/rejection of lepton sign identification in a magnetized liquid argon detector.

Detector Siting Issues

- Distance L to accelerator should be ≈ 400 km $\times \langle E_\nu \rangle$ [GeV] (based on ΔM^2_{23}).
- For $e^\pm$ ID with $B \sim 0.5$, need $L \lesssim 400$ km, $\langle E_\nu \rangle \lesssim 1$ GeV.
- For accelerator beam physics, the detector could be on or near the surface.
- Siting at $2000'$-$3000'$ depth would permit proton decay and astrophysical neutrino studies as well.
- The additional physics reach of a moderately deep site justifies this choice.
- While a deep site with horizontal access is preferable (and possible within range of BNL), siting with 2 large vertical shafts is a viable option.

Summary

- Competitive study of neutrino physics with accelerators requires a superbeam as a first stage, with natural evolution of the accelerator/detector to a neutrino factory.
- CP violation physics, and probable need for a solenoid horn at a 4 MW proton driver, require a detectors with $\mu^{\pm}$, $e^{\pm}$ identification.
- Costs of the proton driver and first stage of a neutrino factory, as well as requirement of $e^{\pm}$ ID, lead to $\langle E_{\nu} \rangle \lesssim 1$ GeV and baseline $L \lesssim 400$ km.
- The obvious detector technology for this is a ≈ 100 kton magnetized liquid argon device.
- Siting at depths below $2000'$ adds capability to study neutrino astrophysics and proton decay to 10^{35} years lifetime.