Snowmass'01 M1 Working Group
Muon-Based Accelerators

Conveners: K.T. McDonald, A.M. Sessler

- A worldwide effort is under way to elucidate the unique particle physics opportunities presented by intense muon beams and the neutrino beams derived from their decay.
- Groups in Europe, Japan and the USA are engaged in a vigorous R&D program aimed at resolving the critical machine and beam design issues for both a Neutrino Factory based on a muon storage ring and a Muon Collider.
- To make progress in a time frame compatible with the needs of the physics program requires support of R&D at a level higher than present.

— From the Response to the Snowmass'01 M1 Working Group Charge.

Overview of this Plenary Talk

- Rich physics and technology led to joint sessions with E1, E3, E6, M6, P2, T2, T5, T7, T9.
- Several new ideas emerged at Snowmass'01, but most discussion was based on prior activities.
- This talk presents three major themes:

  1. Introduction to muon-based accelerators:
     A **Neutrino Factory** based on a muon storage ring, and a **Muon Collider** at the energy frontier and/or for S-channel Higgs production.
  2. R&D on accelerator physics and technology issues.
  3. A staged approach to the physics:
     A **Neutrino Superbeam Physics Program** is the first stage.

Why Muons?

- A muon is a heavy electron.

  $\Rightarrow$ Fundamental interest in the properties of the muon and of its decays.

- Muons live 2.2 μs when at rest.

  $\Rightarrow$ Muons of any energy live $\approx$ 1,000 turns in a 2-T magnetic field.

  $\Rightarrow$ Can use rings to accelerate, store and collide muons.

Why Now?

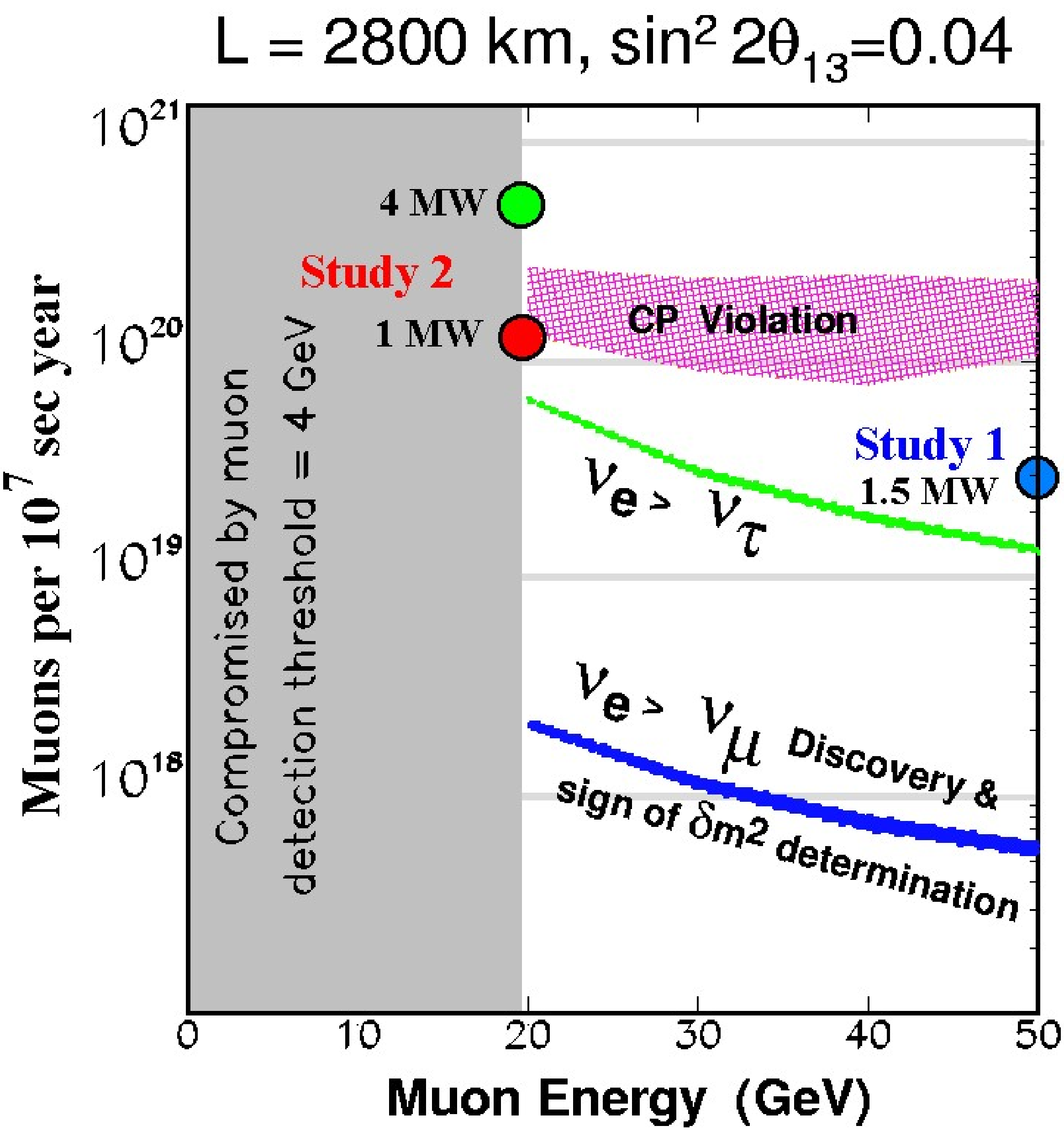
- $m_\mu = 205 m_e$ $\Rightarrow$ Initial state radiation suppressed in $\mu^+\mu^-$ collisions.

  $\Rightarrow$ Precision leptonic initial states up to 100 TeV.

- Muon decay, $\mu \to \nu_\mu e \overline{\nu}_e$, provides well-known fluxes of ν_μ, $\overline{\nu}_e$ ($\overline{\nu}_\mu$, ν_e) in equal amounts.

  $\Rightarrow$ Neutrino factory.

Discovery Potential of a Neutrino Factory



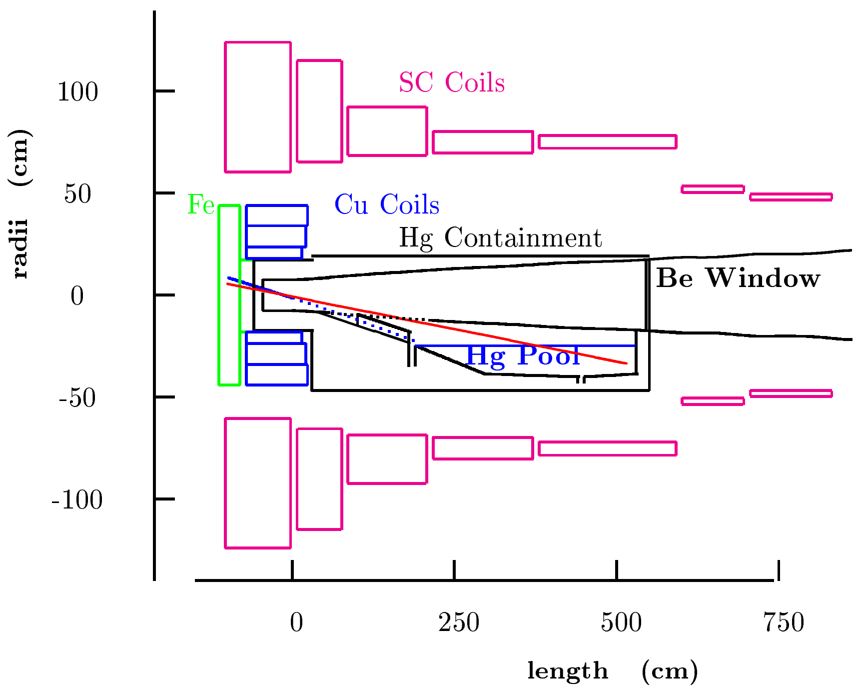
$$\frac{\text{Study II}}{\text{Study I}} = 6 \times \nu_\mu \text{ flux @ } 3/4 \text{ the cost.}$$

Non-τ physics can be done with low E_ν – and an appropriate detector.

Targetry Challenges

- Maximal production of soft pions $\rightarrow$ muons in a megawatt proton beam. Goal: $\mu/p = 0.1$ into the muon storage ring.

- Capture pions in a 20-T solenoid, followed by a 1.25-T decay channel.



- A carbon target is feasible for 1.5-MW proton beam power.

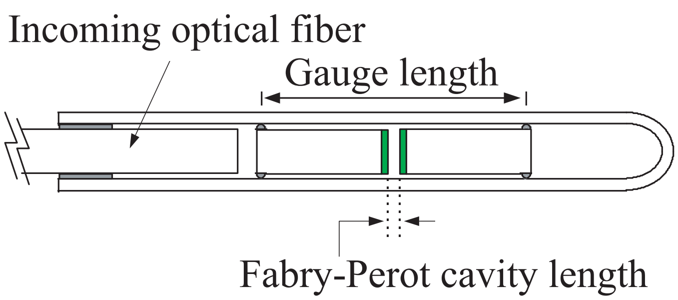
- For $E_p \gtrsim 16$ GeV, factor of 2 advantage with high-Z target.

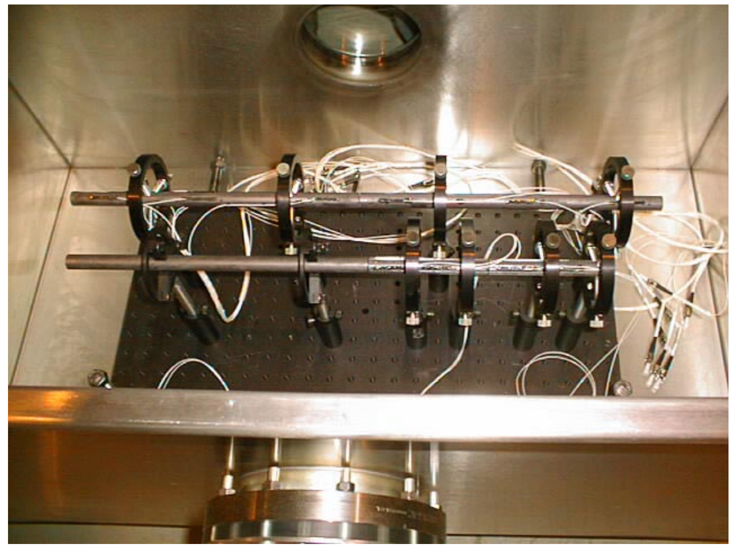
- Static high-Z target would melt, $\Rightarrow$ Moving target.

- A free mercury jet target is feasible for beam power of 4 MW (and more).

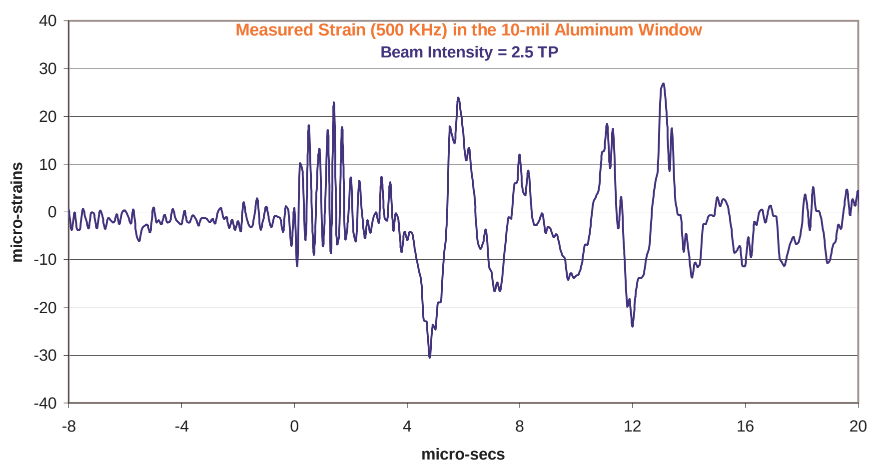
BNL E951: Solid Target Tests (5e12 $p$pp, 24 GeV)

Carbon, aluminum, Ti90Al6V4, Inconel 708, Havar, instrumented with fiberoptic strain sensors.

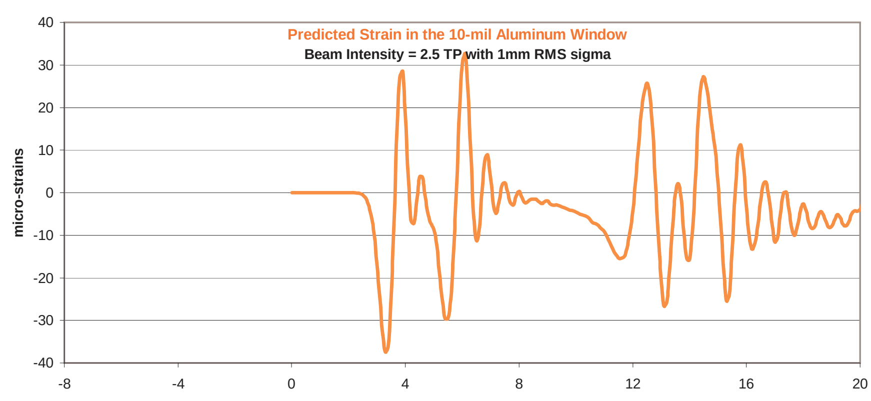




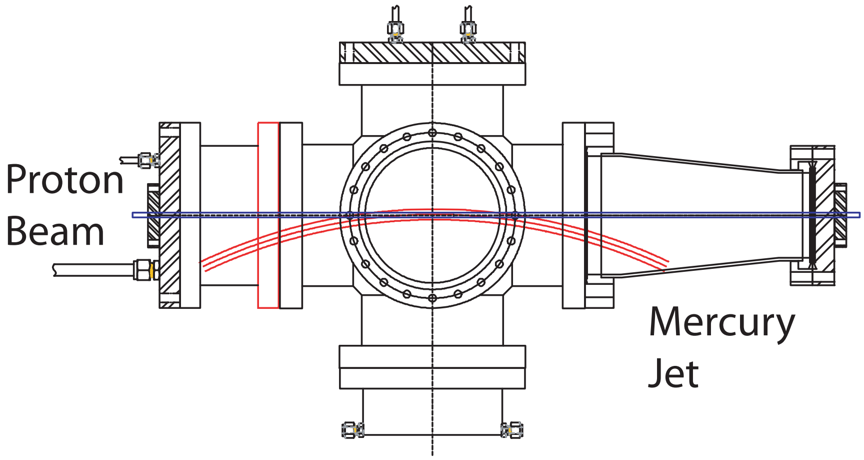
Data:



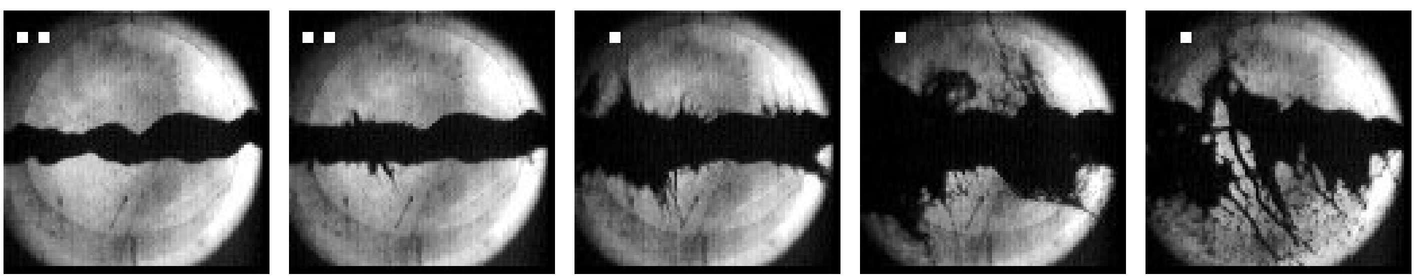
ANSYS model:



BNL E951: 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 $U \approx 100$ J/g.

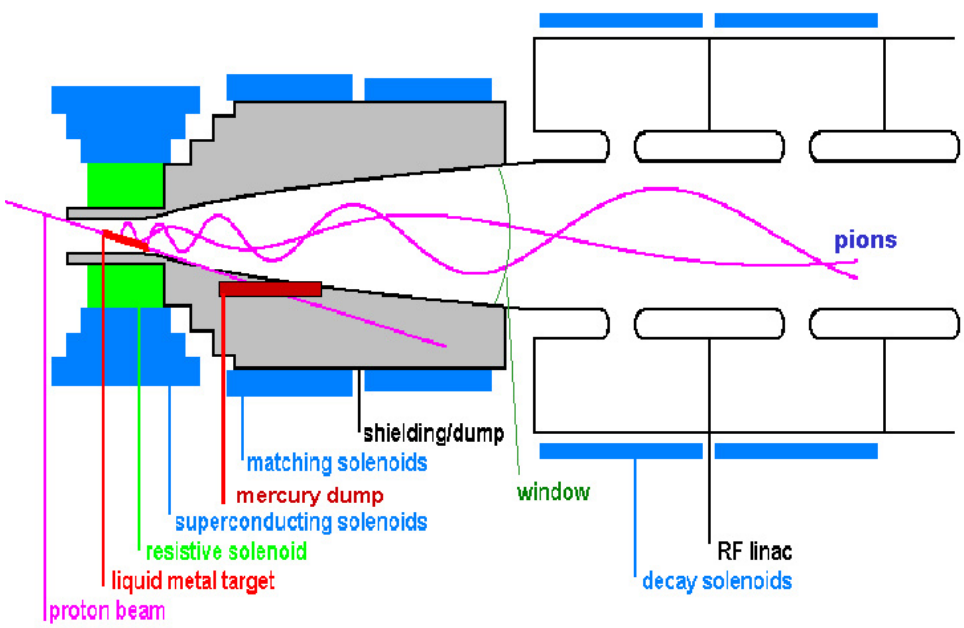
Data: $v_{\rm dispersal} \approx 10$ m/s for $U \approx 25$ J/g.

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

The dispersal is not destructive.

The Neutrino Horn Issue

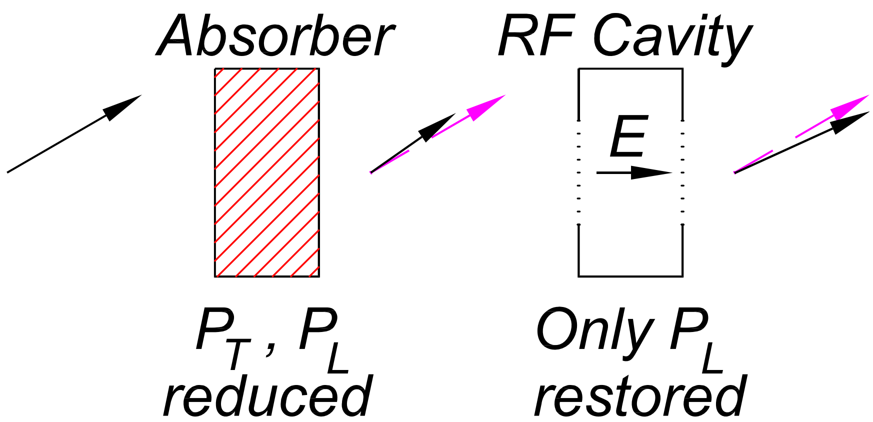
- 4 MW proton beams are achieved in both the BNL and FNAL (and CERN) scenarios via high rep rates: $\approx 10^6$/day.
- Classic neutrino horns based on high currents in conductors that intercept much of the secondary pions will have lifetimes of only a few days in this environment.
- Consider instead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



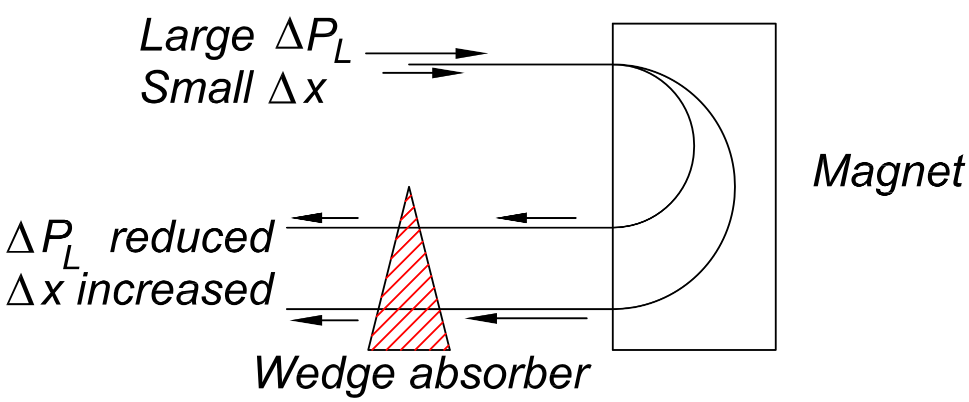
- Adiabatic drop in **B** with $z \Rightarrow p_\perp \propto \sqrt{B}$.

Fast Ionization Cooling of Muon Beams

- dE/dx loss cools both P_T and P_L.



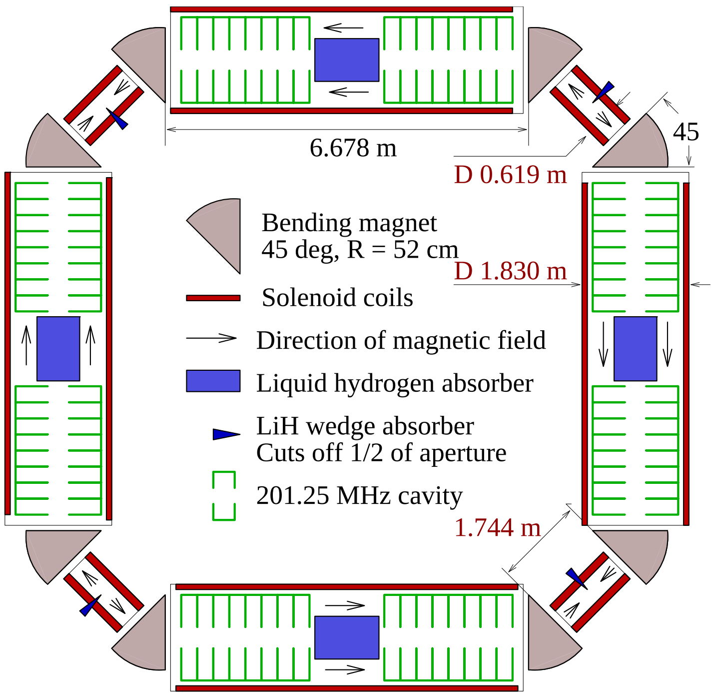
- Multiple scattering heats P_T, straggling heats P_L.
- With low-Z absorber can have net cooling of P_T, but P_L is heated.
- A magnet + wedge absorber can exchange transverse and longitudinal phase space.

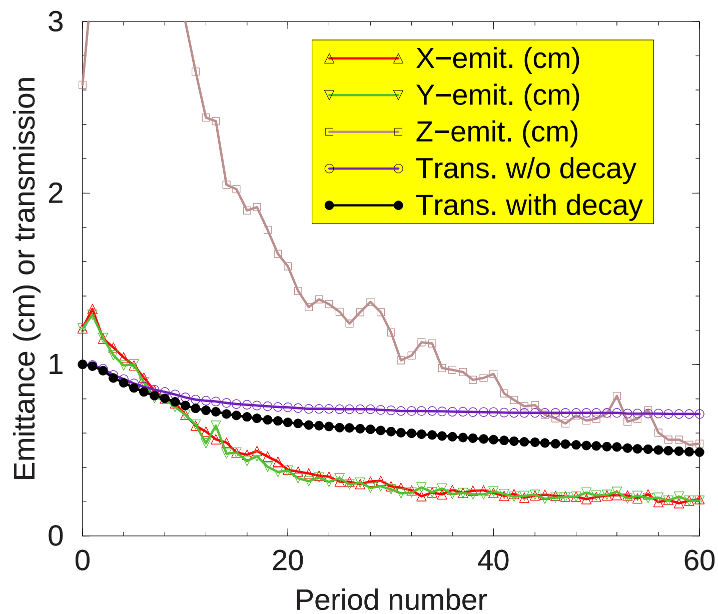


- Then cool transversely again....

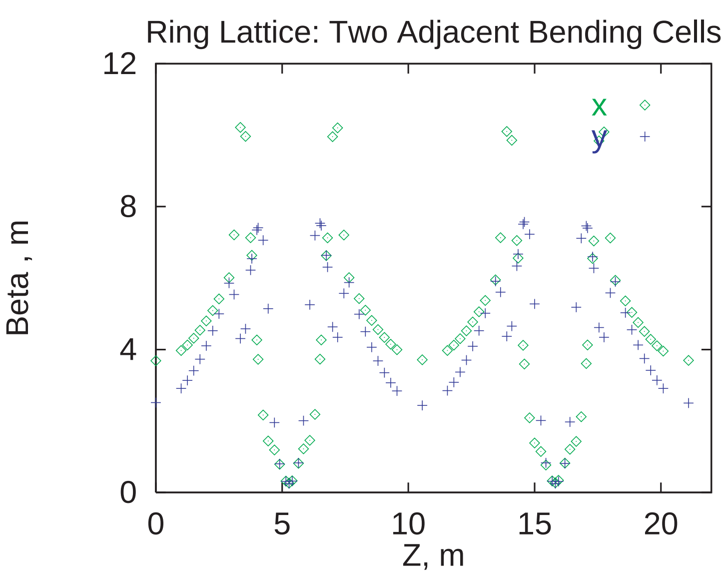
Ionization Cooling in Rings?

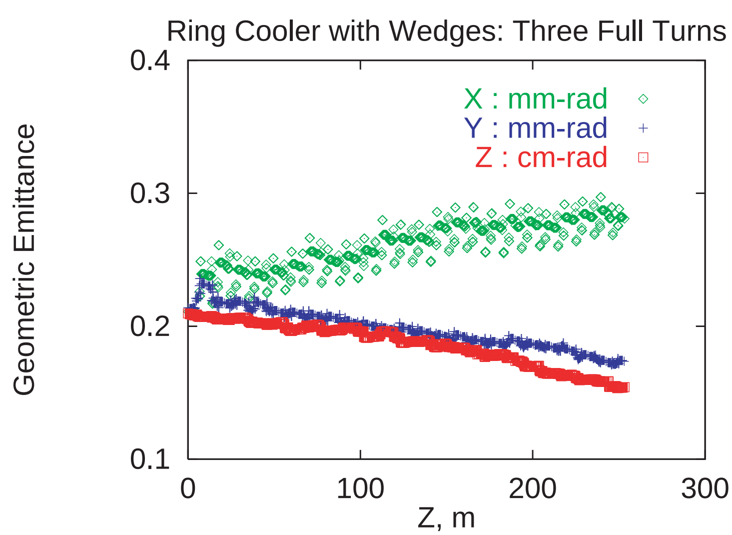
V. Balbekov *et al.*





A. Garren *et al.* (Snowmass'01)





Injection/ejection of large-emittance beams under study.

A Staged Scenario

- Lessons from Neutrino Factory Feasibility Studies I and II:
  - Proton driver upgrade from 1 to 4 MW is cost effective.
  - Acceleration of muon beams is expensive.
- These are incorporated in a staged scenario:
  1. A Neutrino superbeam from pion decay with 1-4 MW proton driver (+ $\approx$ 100 kton underground detector).
  2. A cooled muon beam at 200 MeV/c: muon EDM physics.
  3. A muon storage ring of 1-3 GeV: mini neutrino factory (aimed at the Stage 1 detector), $g-2$, ...
  4. A Neutrino Factory based on a 20-50 GeV storage ring (+ new 100+ kton detector at longer baseline).
  5. A Muon Collider operating as a Higgs factory, or at the energy frontier.

An E1/M1 Snowmass'01 Consensus

- The recent evidence for neutrino oscillations is a profound discovery.
- The US should strengthen its lepton flavor research program by expediting construction of a high-intensity conventional neutrino "superbeam" fed by a 1 - 4 MW proton source.
- A superbeam physics program will probe the neutrino mixing angles and mass hierarchy and may discover CP violation in the lepton sector.
- The full program will require neutrino beams at multiple energies and massive detectors at multiple baselines.
- These facilities will also support a rich program of other important physics, including proton decay, particle astrophysics and lepton CP- and flavor-violating processes.
- The ultimate laboratory for neutrino oscillation measurements is a neutrino factory, for which the superbeam facility serves as a strong foundation.
- The development of the additional needed technology for neutrino factories and muon colliders requires a ongoing vigorous R&D effort in which the US should be a leading partner.

Recommendations

- The most effective way to fully explore the opportunities of neutrino oscillation physics is to construct a Neutrino Factory.
- Fund accelerator R&D towards a neutrino factory based on a muon storage ring and a muon collider at a "success-oriented" level.
- Develop a Neutrino Superbeam Physics Program in the USA – with an upgrade path to a Neutrino Factory.