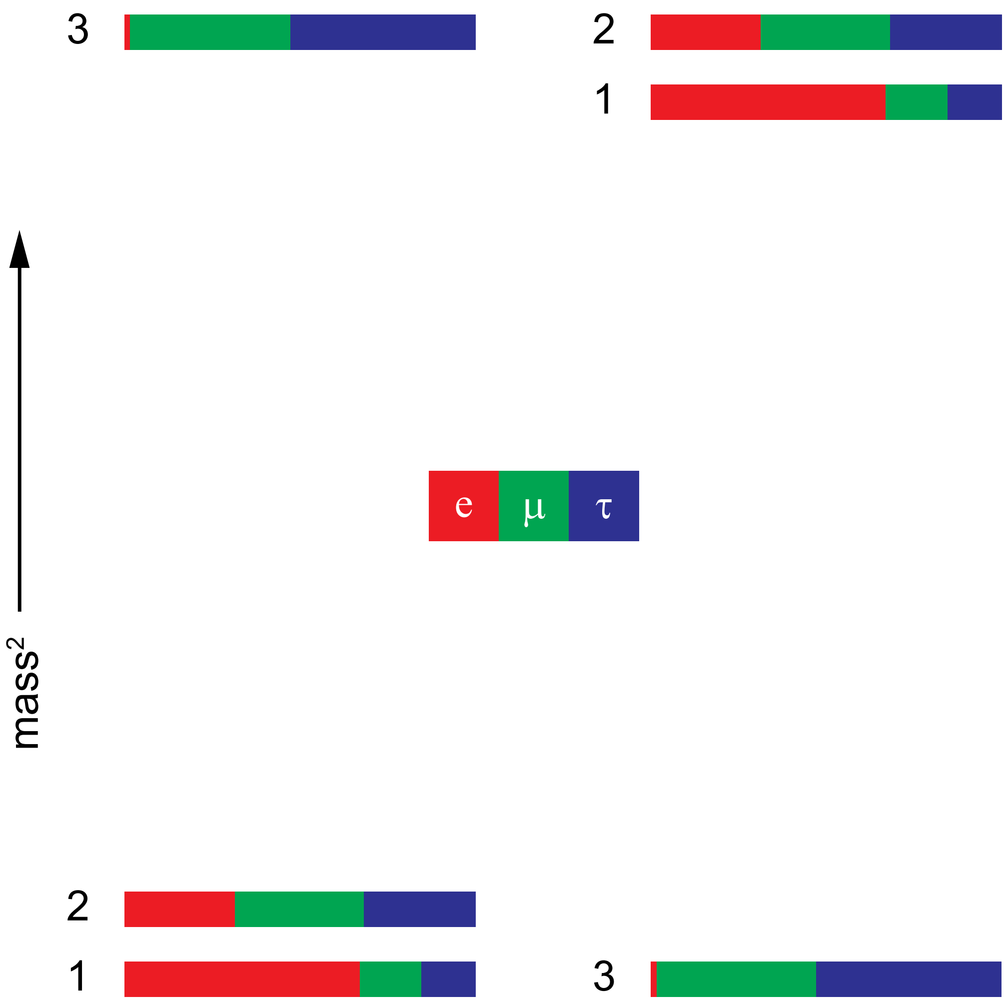
International Design Study of a Neutrino Factory

J. Scott Berg
Brookhaven National Laboratory
IPAC 2010
27 May 2010

Neutrino Physics

- Neutrinos have mass
- Mass and flavor eigenstates different
- Mixing matrix angles θ_{12}, θ_{23}, θ_{13}
  - θ_{13} possibly zero, θ_{23} near 45°
- CP-violating phase δ (irrelevant if θ_{13} zero)
- Squared mass differences
  - $|\Delta m^2_{21}| \ll |\Delta m^2_{31}|$
  - Sign of Δm^2_{31} unknown

Neutrino Properties



Long Baseline Neutrino Experiments

- Accelerator: make neutrinos in flavor eigenstate
  - Mixture of mass eigenstates
- Neutrinos propagate to far detector
  - Each mass eigenstate has different phase advance
  - Phase advance: square of mass
- Detector: detect flavor eigenstate
  - Detect corresponding lepton (e, μ)

Neutrino Factory Goals

- Create high-energy muon beam
- Decay in ring, directed through earth to far detector
- Well-defined spectrum from muon decay
  - μ^- creates ν_μ and $\bar{\nu}_e$
  - Distinguish by sign of detected leptons
    - Need magnetized detector

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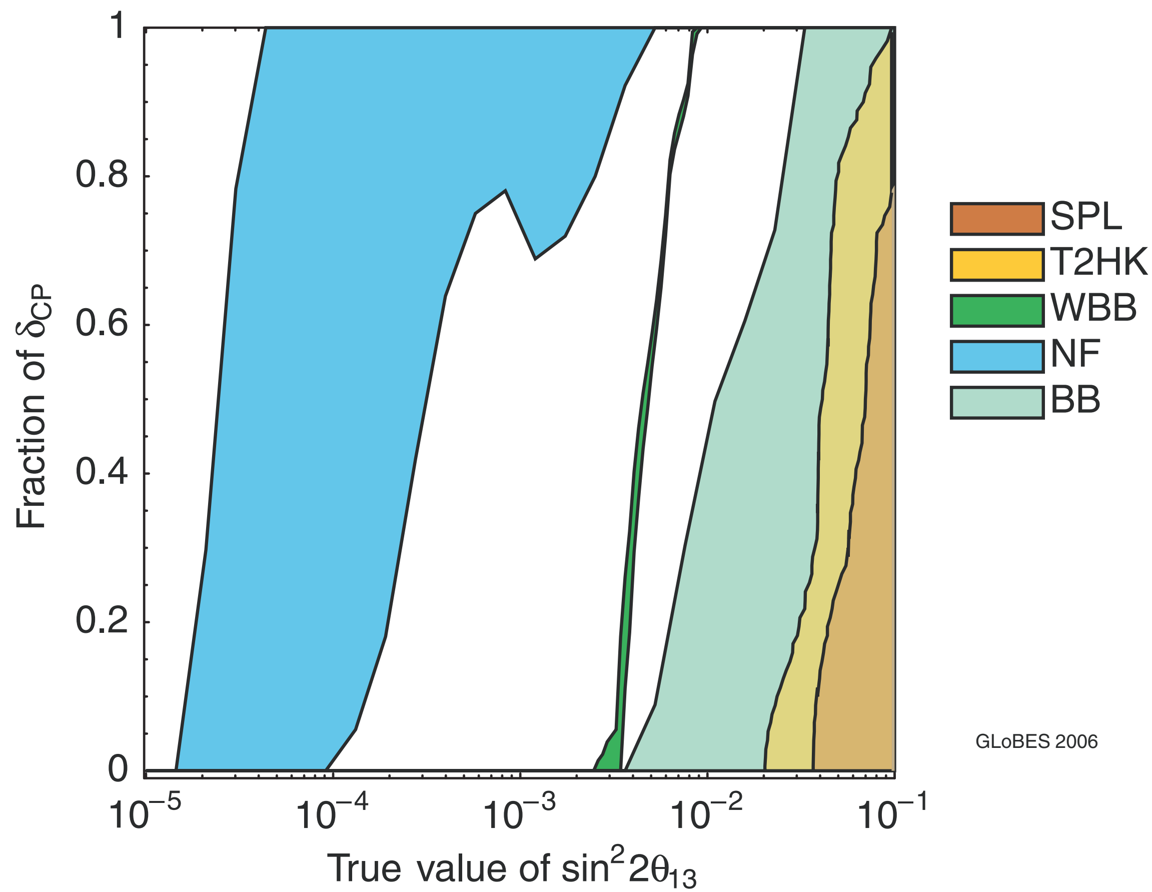
Neutrino Factory vs. Superbeams

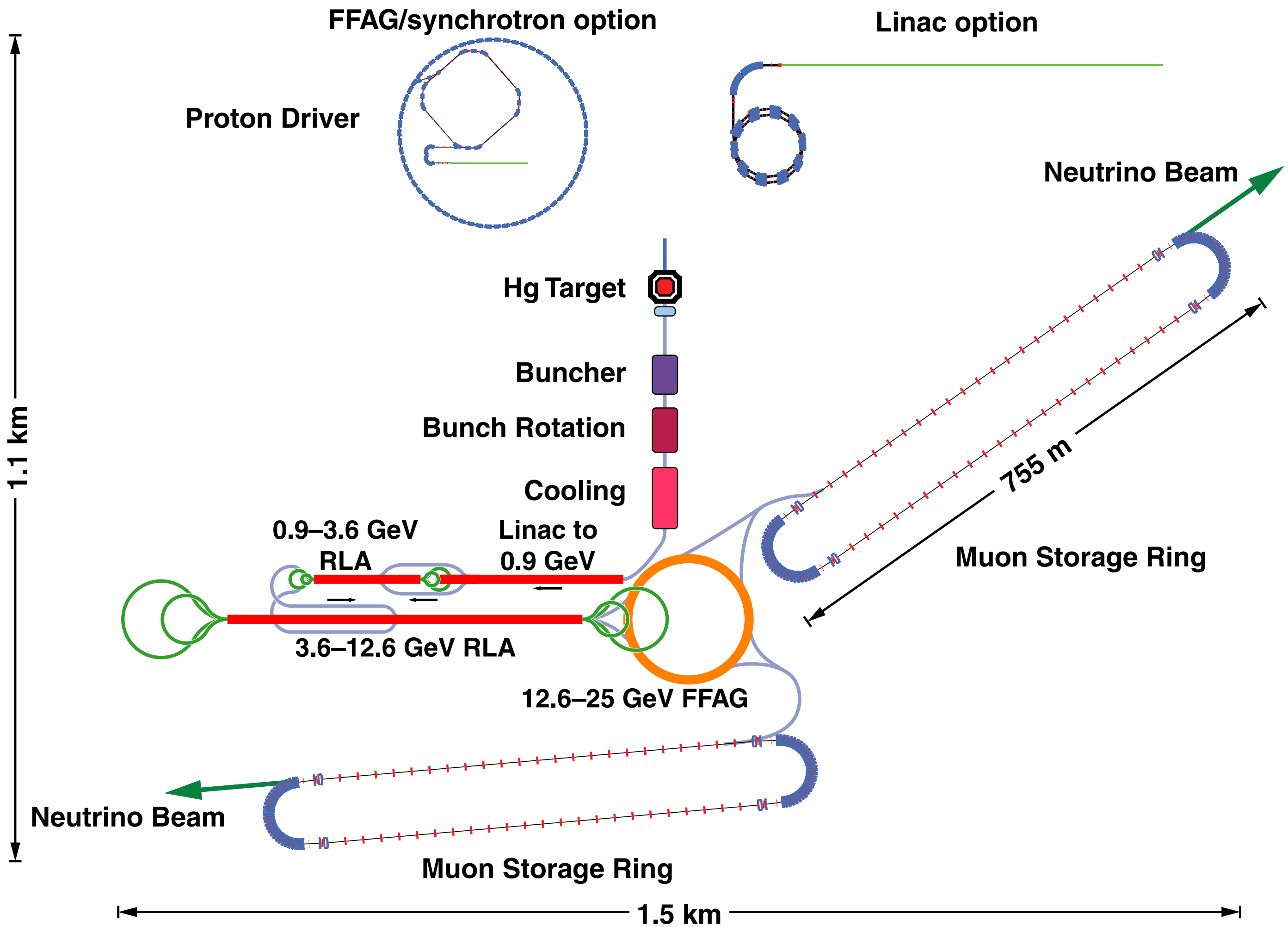
- Get results for smallest θ_{13}
- Better precision for mixing parameters
  - Especially interesting if nearly symmetric



Neutrino Factory Accelerator Complex

- High-power proton driver, protons hit
- Target, producing pions decaying to muons
- Front end, reshapes and intensifies beam
- Acceleration, increase energy to 25 GeV
- Decay ring, neutrinos produced decay toward far detectors

Neutrino Factory Accelerator Complex



International Design Study

- Goal: reference design report by end 2012
  - Basis for request to start project
  - Costs at 30% level
- Interim design report by end 2010
  - Move from design to engineering
  - Designs for all systems
  - Cost estimates at 50% level
- Focus on baseline: one design!

Baseline Parameters

- 25 GeV muon beam, both signs
- Detectors at two distances
  - 3000–5000 km
  - 7000–8000 km
- 5×10^{20} muon decays per year per baseline
- Muon beam divergence of $0.1/\gamma$

High-Power Proton Driver

- Supply protons to target to produce pions
- Basic specifications:
  - 4 MW proton beam power
  - Proton kinetic energy 5-15 GeV
  - RMS bunch length 1–3 ns
  - 50 Hz repetition rate
  - Three bunches, extracted up to 80 μs apart

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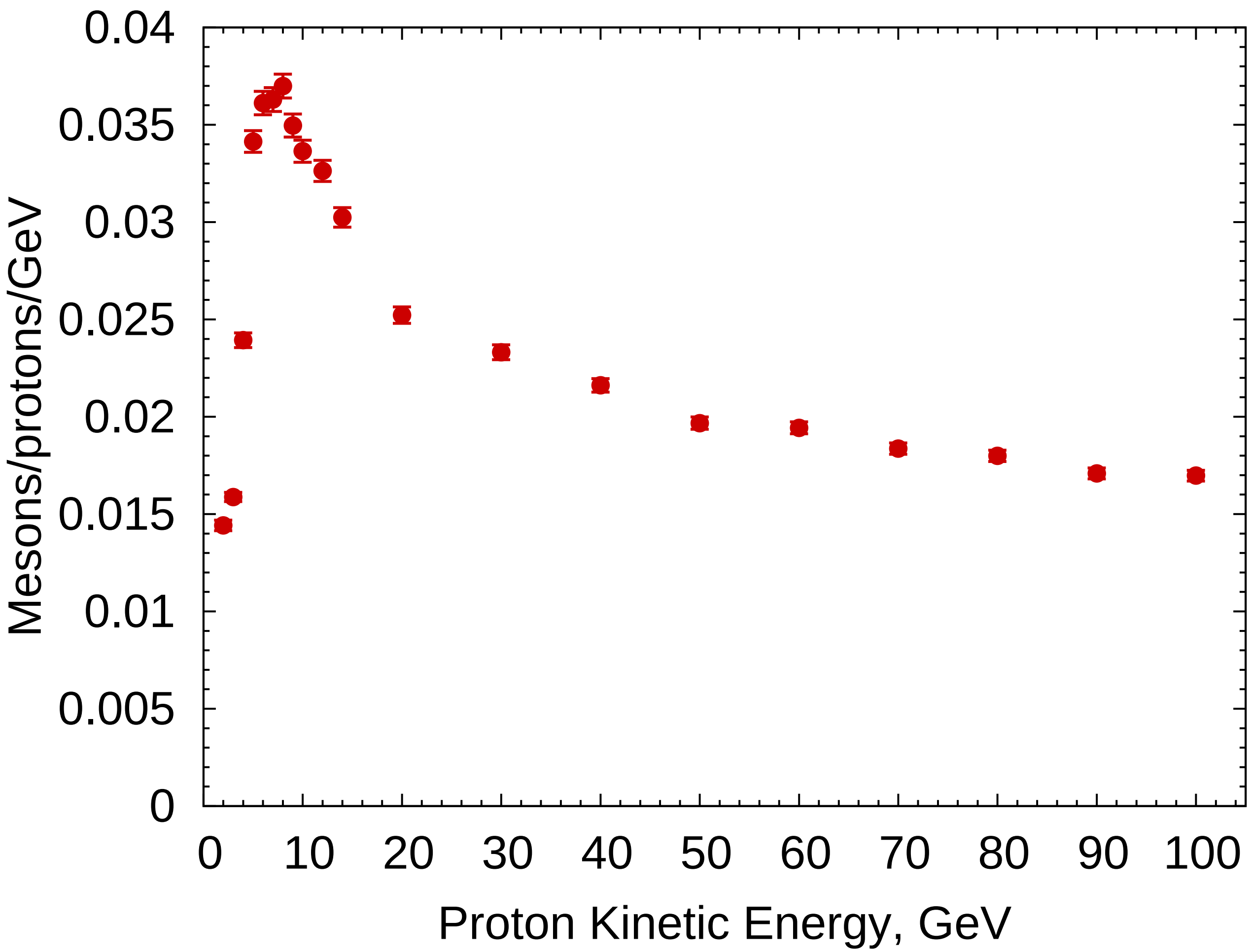
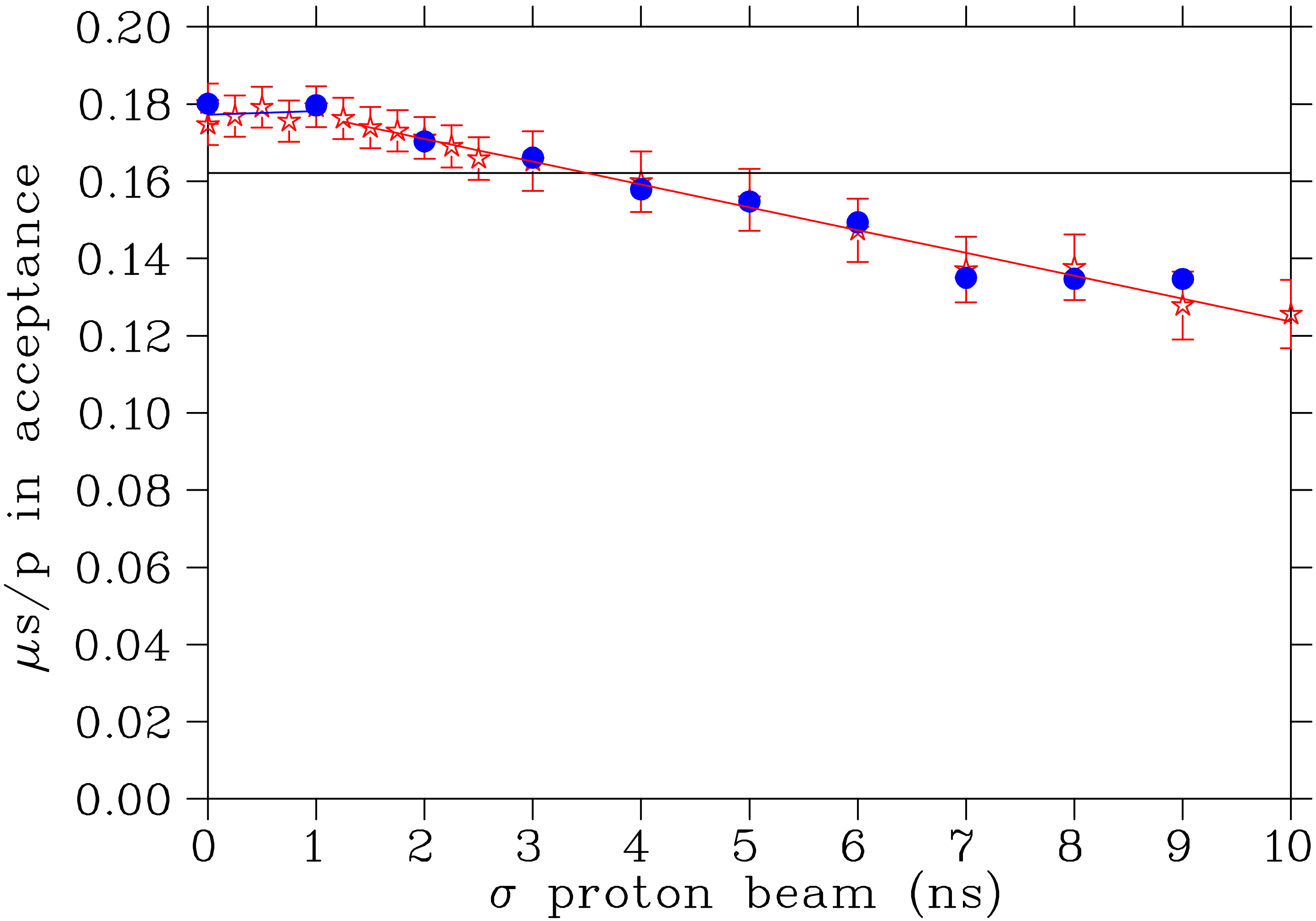
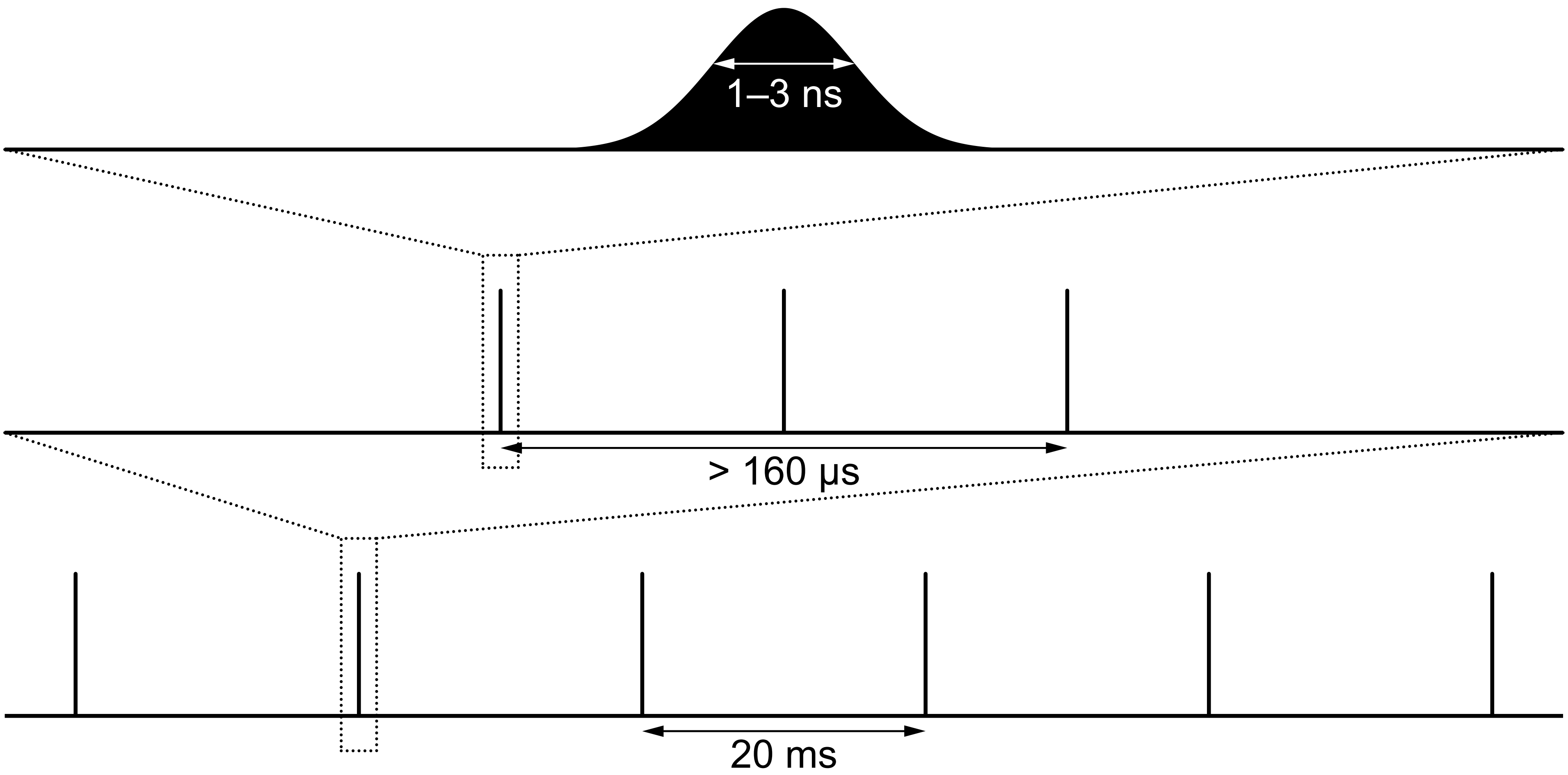
Muon Capture vs. Proton Energy



Muon Capture vs. Proton Bunch Length



Proton Bunch Structure



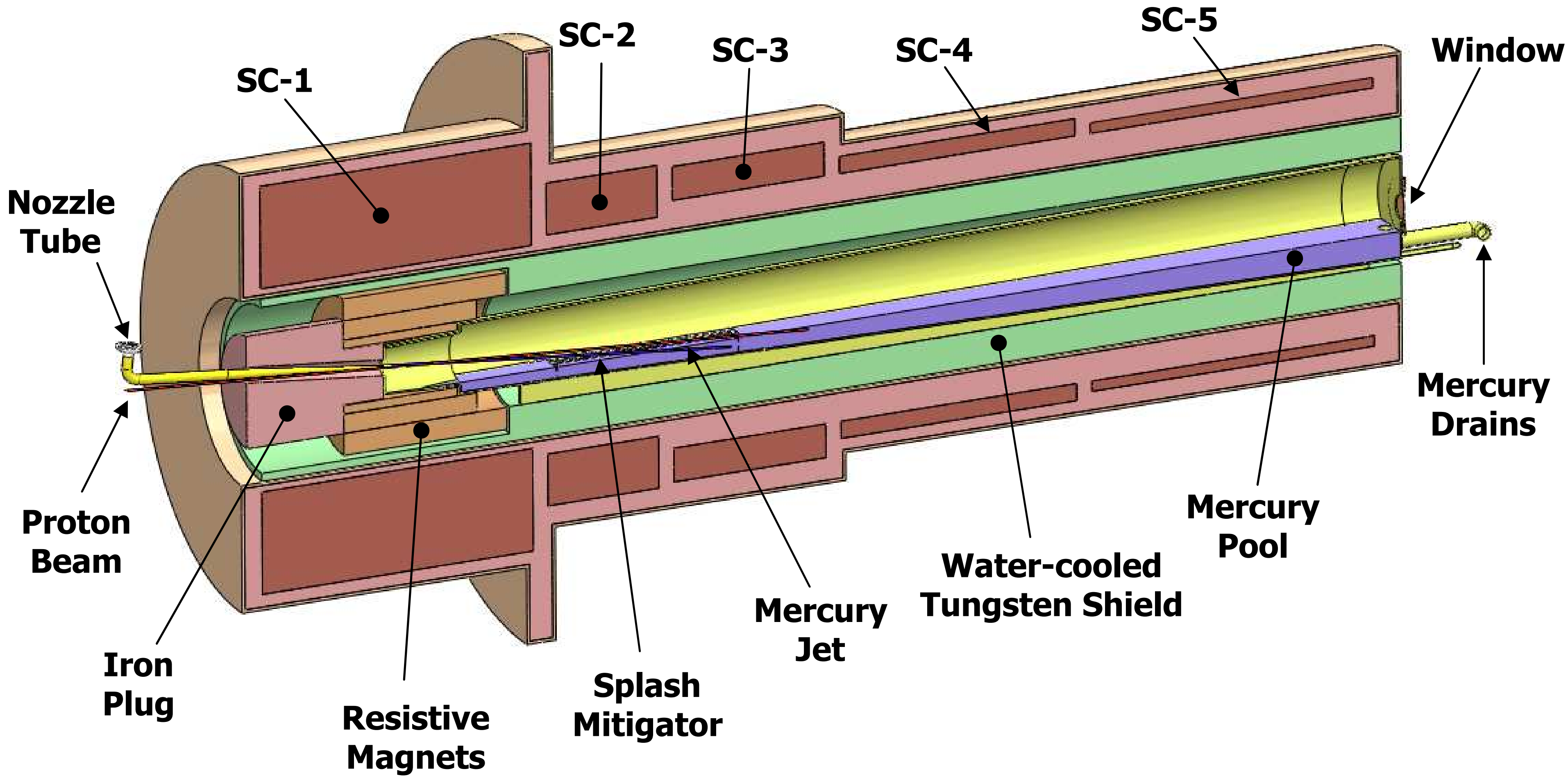
Proton Driver Plans

- Will be upgrade to existing facility
- Important to understand contribution to cost of neutrino factory
- Individual laboratories will contribute
  - Plan to upgrade to neutrino factory requirements
  - Corresponding cost estimate

Target

- Baseline is liquid mercury jet
  - Avoid target damage
- Target in 20 T field: pion capture
- Demonstrated in MERIT experiment
  - Proton beam pulses comparable to neutrino factory
  - Two bunches in rapid succession: no loss in production for second with spacing 350 μs or less

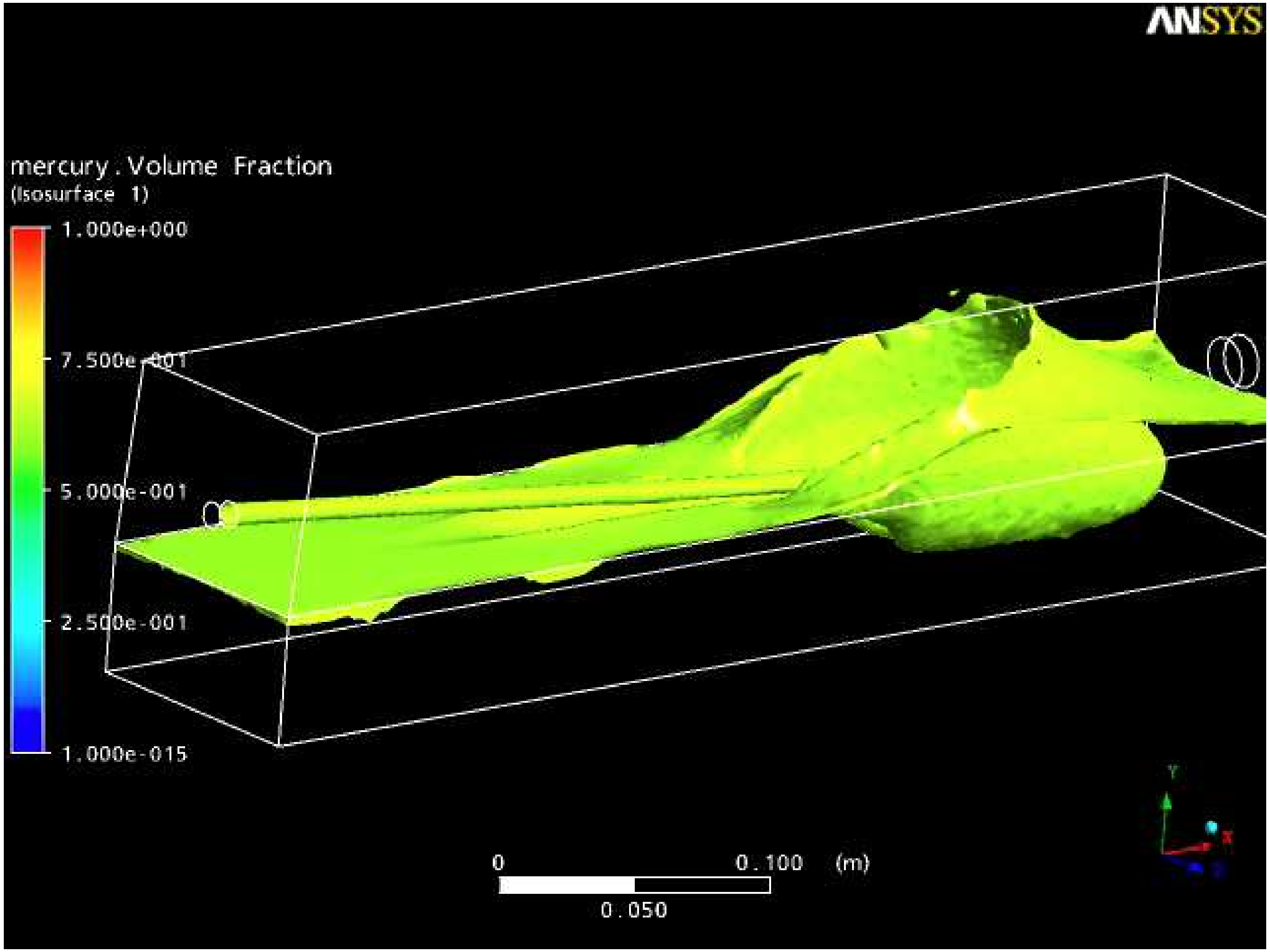
Mercury Jet Target Station



Target Plans

- Engineering of target station and components
- Jet nozzle: improve jet quality
- Ensure sufficient shielding of superconducting magnets
- Fluid dynamics/engineering of Hg pool
  - Acts as beam dump
  - Return Hg to loop

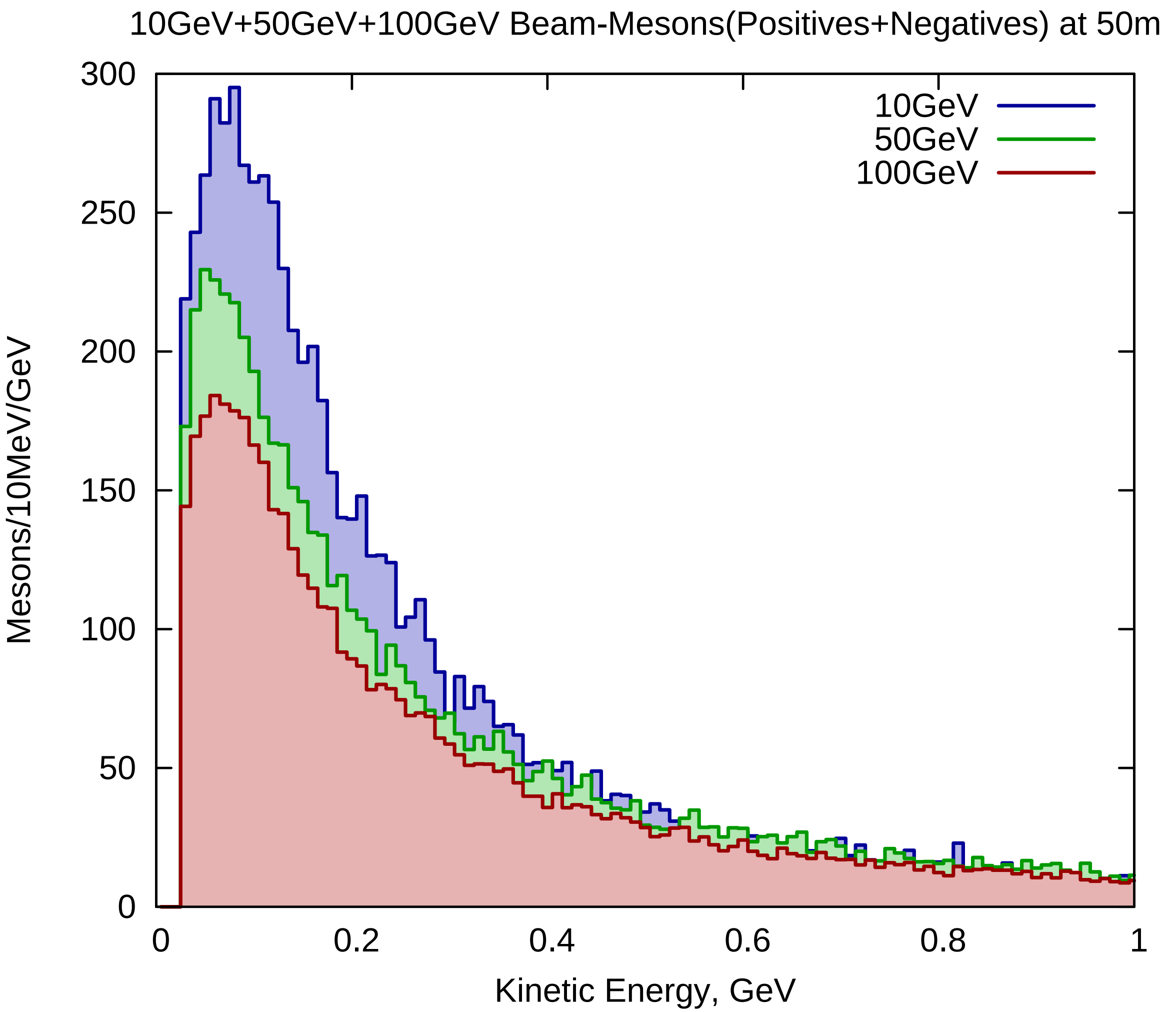
Mercury Pool Dynamics



Front End

- Pions (thus muons) start with large energy spread: reduce
  - "Neuffer" phase rotation
    - Uses high-frequency RF
    - Does both signs
  - Create 200 MHz bunch train
- Reduce transverse beam size
  - Ionization cooling

Pion Spectrum



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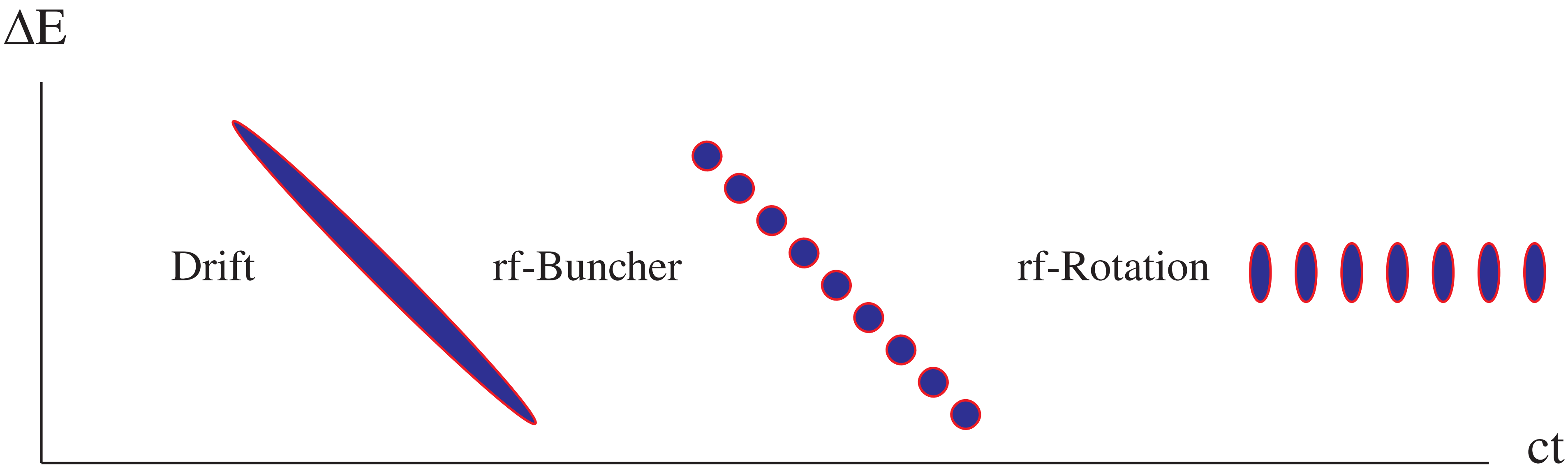
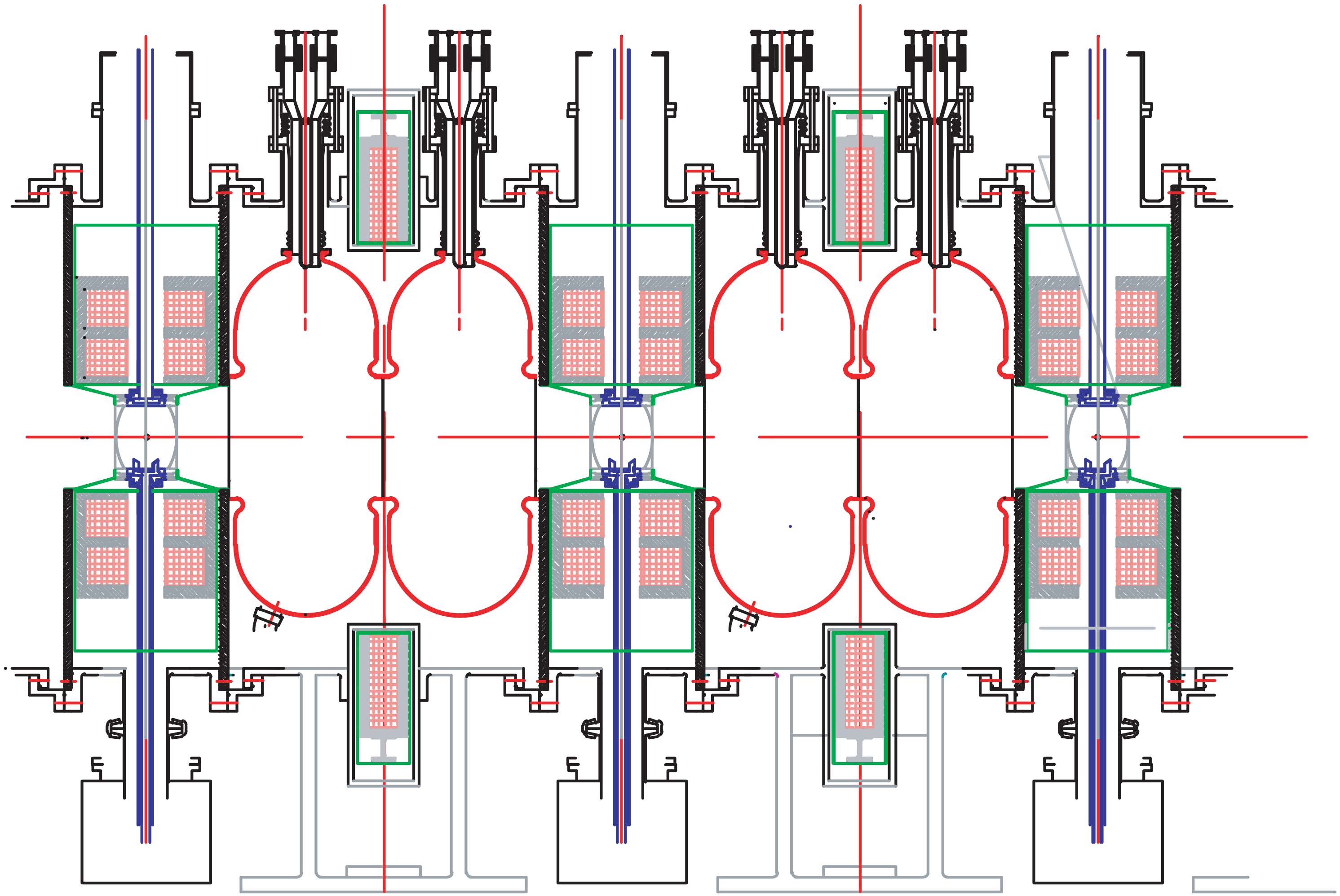
Phase Rotation



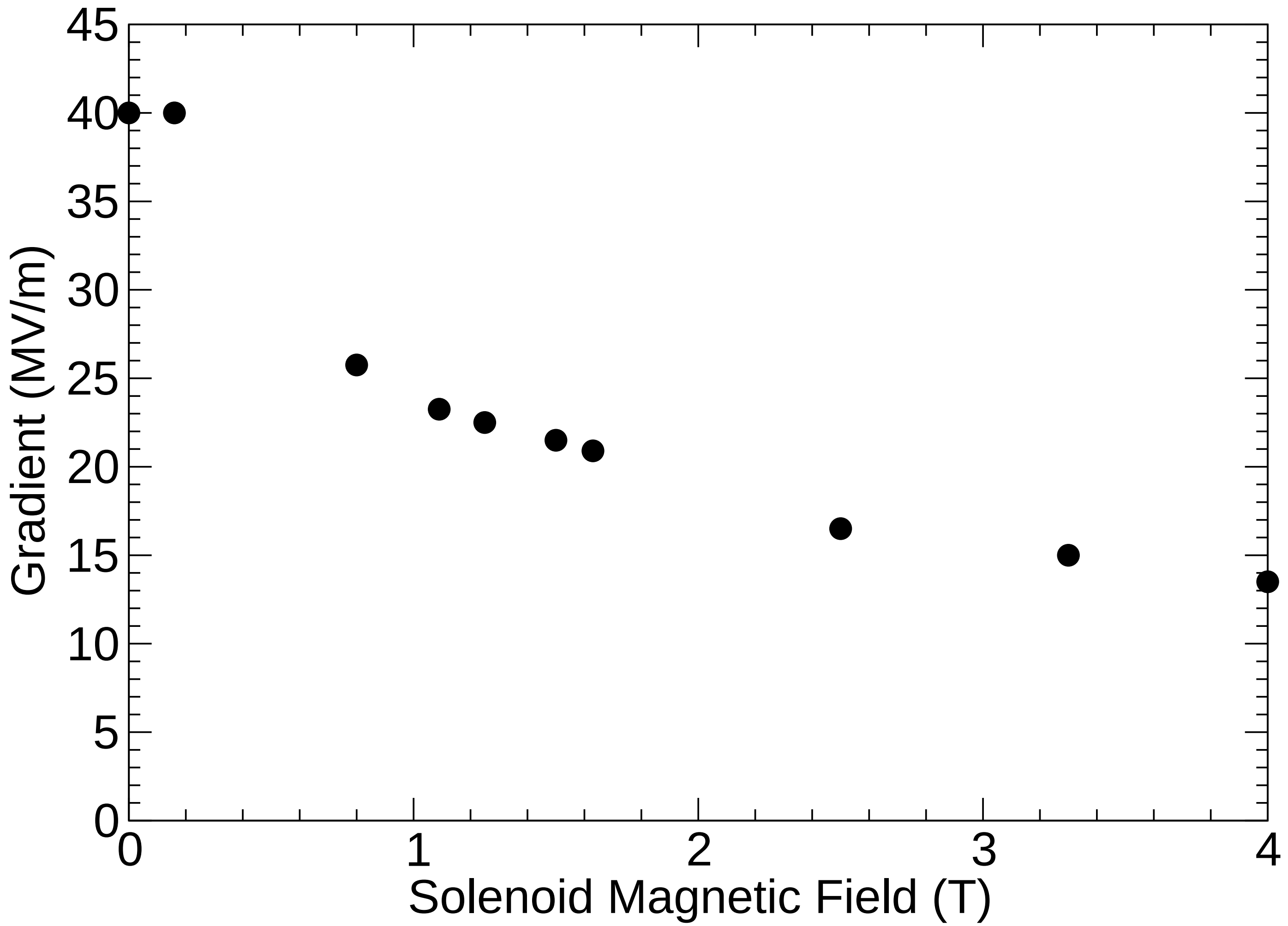
RF in Magnetic Field

- RF cavities in magnetic field
  - Large angular and energy acceptances
- Experiments: gradient reduced in magnetic field
- Don't have complete picture yet
- Ongoing experiments
  - Change magnetic field orientation w.r.t. surface
  - Gas-filled RF cavities
  - Test different surface materials

Ionization Cooling Lattice



Gradient vs. Magnetic Field



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Mitigation Strategies

- Reduce fields on cavities
  - Increase distance to magnets
  - Add bucking coils
  - Add shielding to solenoids
- Magnetically insulated lattice: high-E field surfaces parallel to B
- Make cavity from beryllium
- Fill cavities with pressurized hydrogen gas

Front End Plan

- Mitigation often reduces performance
- Operation limits of cavities still unknown
- Baseline: choose technically optimal design
  - Earlier “Study IIa” lattice
  - Improved Neuffer phase rotation
- One alternative to understand penalty/cost of mitigation

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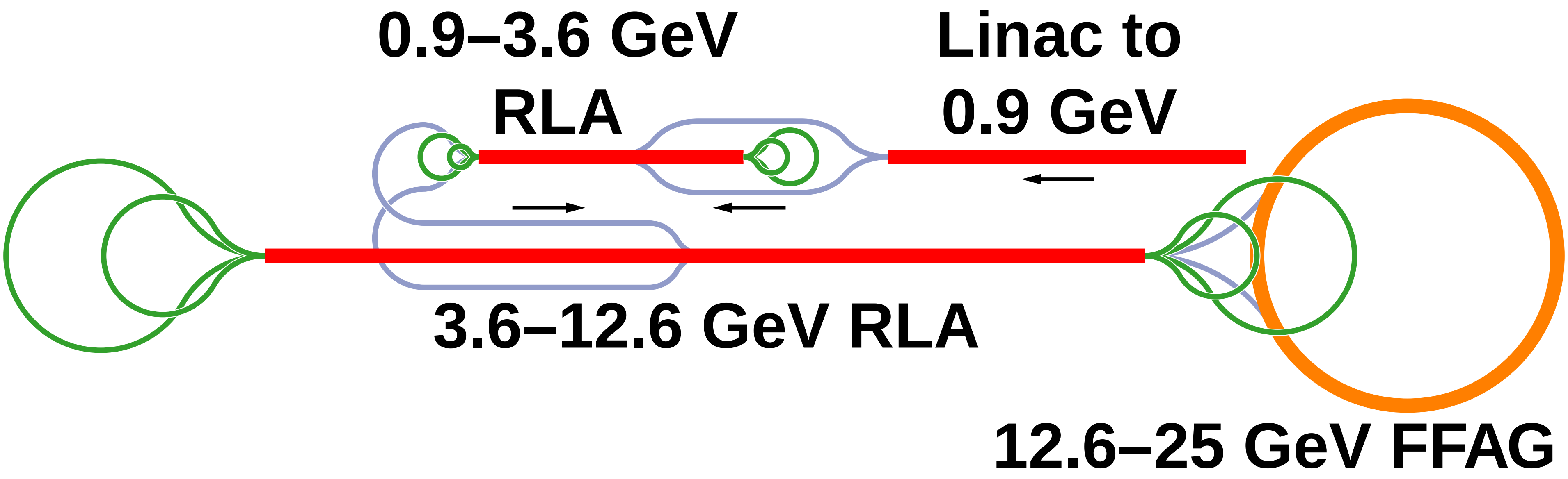
Acceleration

- Efficiency: maximize passes through RF
- Four stages to get good efficiency
  - Linac to 0.9 GeV
  - Two RLAs: to 3.6 GeV and 12.6 GeV (4.5 passes)
  - FFAG to 25 GeV (11 passes)
- Use 200 MHz SCRF

Acceleration



Acceleration
Linac and RLAs

- Lattices completely defined
- More detailed magnet designs
- Tracking beginning with soft ends

Acceleration FFAG

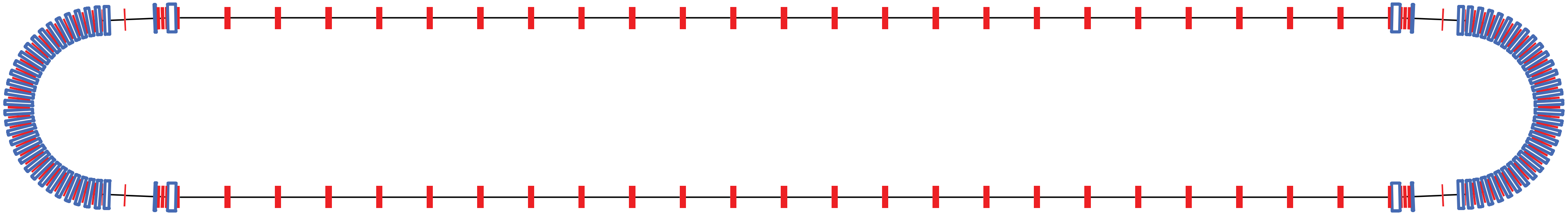
- Many passes (11): no switchyard
- Injection/extraction challenging
  - 15 cm radius, 0.09 T field, 7 needed, 546 m ring circumference
- Selected triplet lattice with long drifts
  - Longer drifts ease injection/extraction
  - Double cavity in long drift: better gradient
    - Reduce longitudinal distortion: large transverse amplitude

Acceleration FFAG

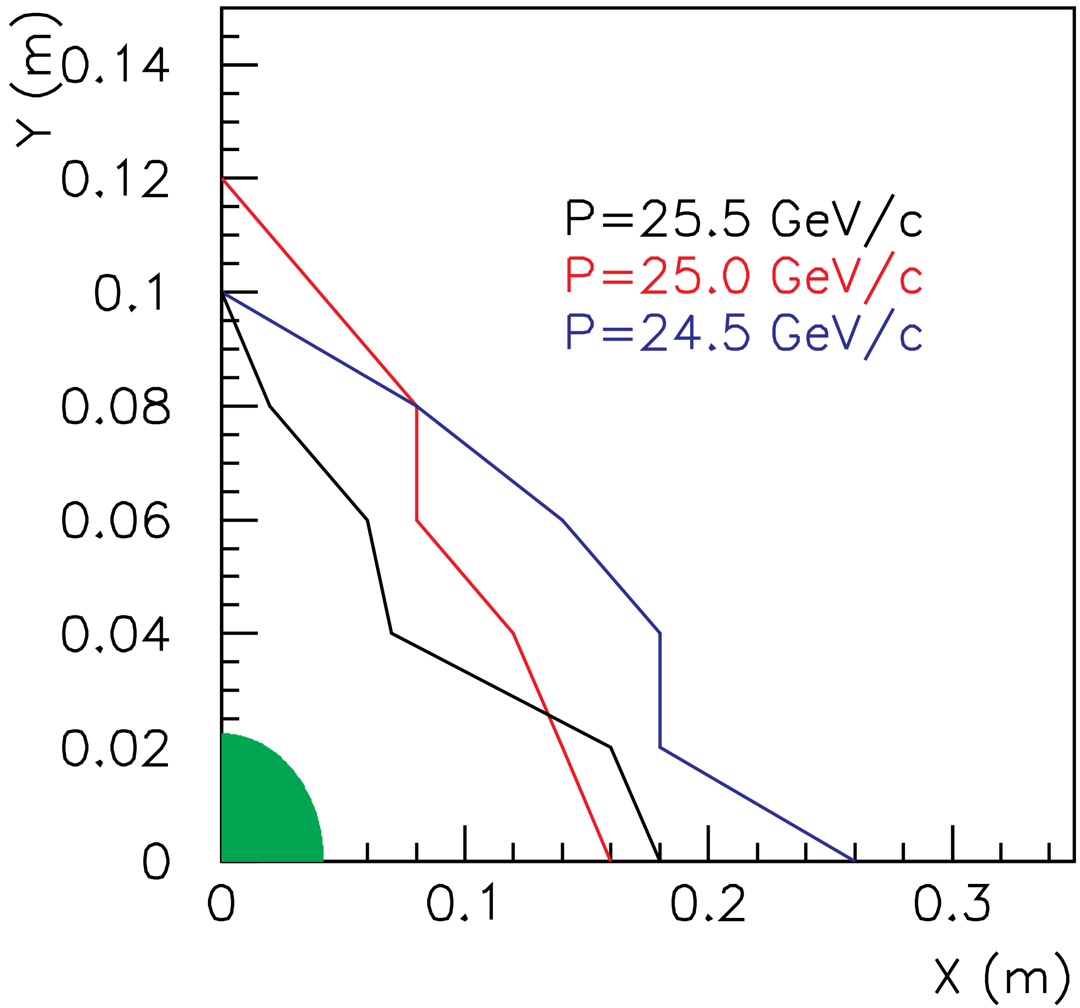
- Add some chromaticity correction
  - Modest amount: hurts dynamic aperture
  - Helps longitudinal distortion
- Design kicker systems (magnet, power supply)
- Study lattice dynamics in EMMA experiment

Decay Ring

- Long straights to maximize decays to detector
- High beta functions in straight: reduce divergence
  - Less divergence, less flux uncertainty for given divergence uncertainty
- Excellent dynamic aperture



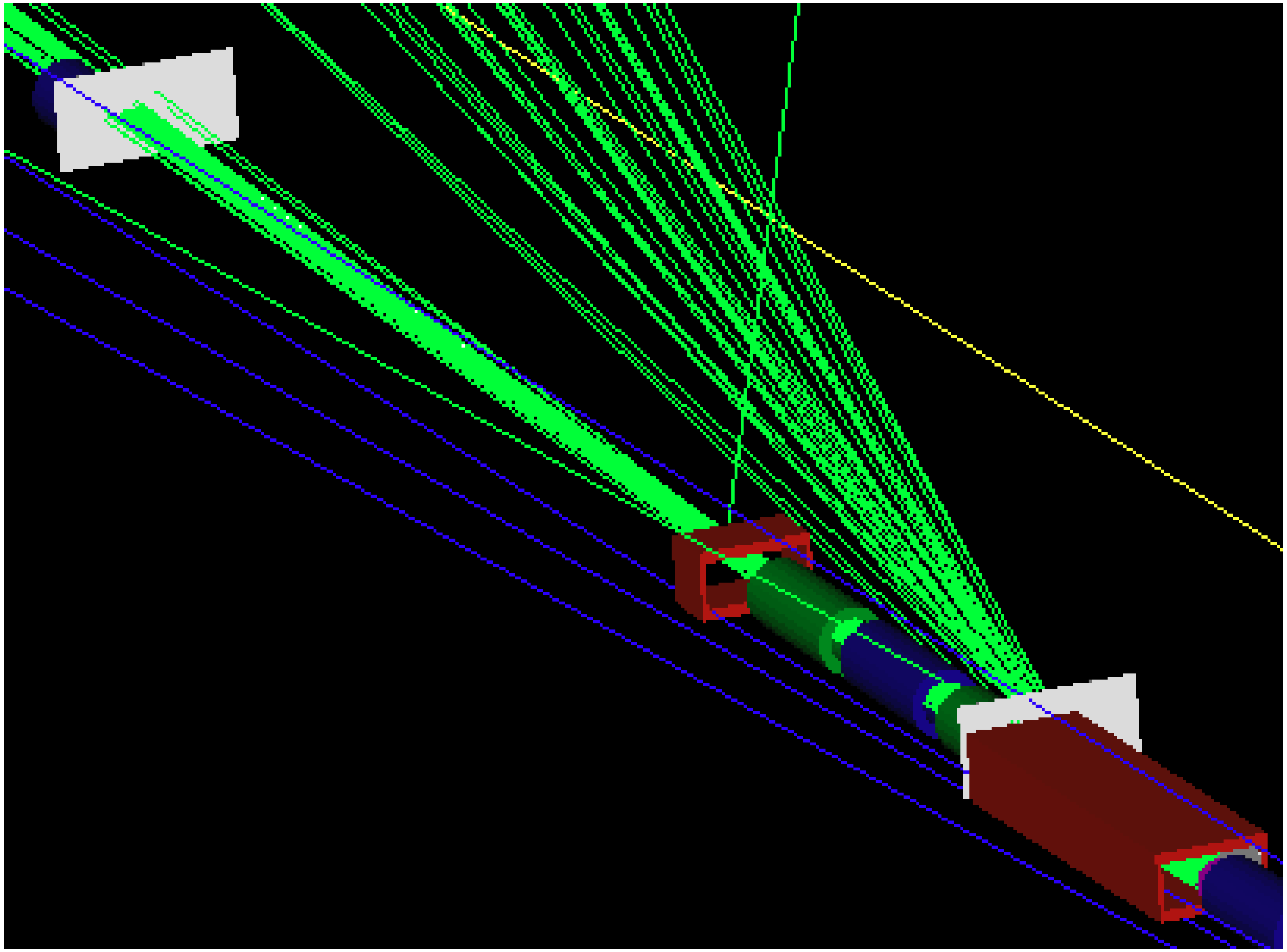
Decay Ring
Dynamic Aperture



Decay Ring Diagnostics

- Reduce flux spectrum uncertainty
- Polarimeter: measure decay electron spectrum
  - Neutrino flux depends on polarization
  - Detector transverse to beam, in matching section following weak bend
- In-beam He gas Cerenkov: beam divergence
  - Emittance growth: verify if acceptable

Decay Ring Polarimeter



Low-Energy Neutrino Factory

- Same as above but stopping acceleration earlier, different decay ring
- Competitive with high energy (and best superbeams) if θ_{13} large
- Interesting as part of staging
  - Start with low energy
  - Upgrade to high energy or larger detector depending on physics results
- Will be described in design reports

Conclusions

- Neutrino factory: precision measurements of neutrino mixing
- Well-defined scenario, lattices almost complete
- Continuing important R&D
  - RF cavities in magnetic fields
  - MICE cooling experiment
  - EMMA: FFAG dynamics
- Starting engineering of components