Neutrino Factory: Downstream Systems

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Outline

- Introduction
- Muon accelerator pros & cons
- Neutrino factory ingredients
- Bunching and phase rotation
- Ionization cooling
- Acceleration
- Decay ring
- R&D program
- R&D issues
- Help wanted
- Possible U.S. scenario
- Summary

Introduction

- Muon-based neutrino factory will be a powerful tool in the experimentalist's arsenal
- Design and performance evaluations for such a facility have been ongoing for nearly 10 years
  - fully international effort
    - U.S.
      - Neutrino Factory and Muon Collider Collaboration (NFMCC)
    - EU
      - UK Neutrino Factory group
      - EUROnu Design Study
    - Asia
      - Japan Neutrino Factory Working Group
- Here we will consider the "downstream" systems
  - bunching, phase rotation, cooling, acceleration, decay rings

Muon Accelerator Advantages

- Muon-beam accelerators can address several of the outstanding accelerator-related particle physics questions
  - neutrino sector
    - Neutrino Factory beam properties

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\% \bar{\nu}_e + 50\% \nu_\mu$$

Produces high energy ν_e, above τ threshold

    - decay kinematics well known
      - minimal hadronic uncertainties in the spectrum and flux
    - $\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable "wrong-sign" μ (low background)

Unmatched sensitivity for CP violation, mass hierarchy, and unitarity

  - energy frontier
    - point particle makes full beam energy available for particle production
      - couples strongly to Higgs sector
    - Muon Collider has almost no synchrotron radiation
      - narrow energy spread at IP compared with e^+e^- collider
      - uses expensive RF equipment efficiently ($\Rightarrow$ fits on existing Lab sites)

Muon Beam Challenges

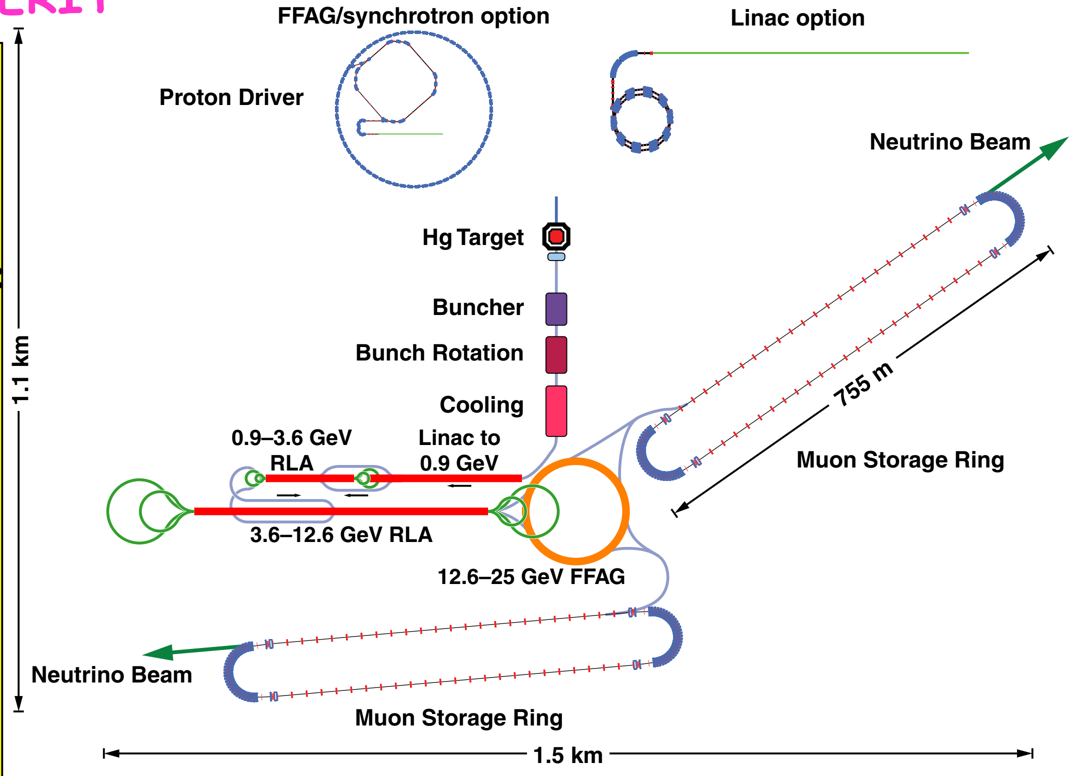
- Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
  - low production rate
    - need target that can tolerate multi-MW beam (+ source to provide it!)
  - large energy spread and transverse phase space
    - need solenoidal focusing for the low energy portions of the facility
      - solenoids focus in both planes simultaneously
    - need emittance cooling
    - high-acceptance acceleration system and decay ring
- Muons have short lifetime (2.2 μs at rest)
  - puts premium on rapid beam manipulations
    - high-gradient RF cavities (in magnetic field) for cooling
    - presently untested ionization cooling technique
    - fast acceleration system
- Decay electrons give rise to heat load in magnets and backgrounds in collider detector

If intense muon beams were easy to produce, we'd already have them!

Neutrino Factory Ingredients

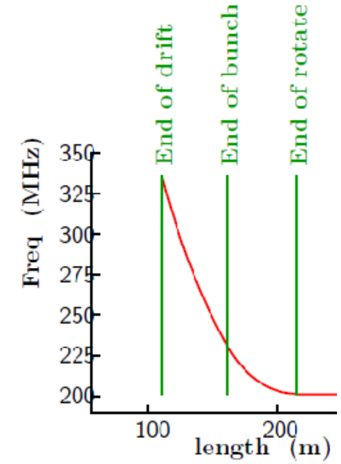
- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into μ ⇒ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance ⇒ MICE
  - Acceleration
    - 130 MeV → 25 GeV with RLAs+FFAGs ⇒ EMMA
  - Decay Ring
    - store for 500 turns; long straight sections

IDS-NF Baseline Layout

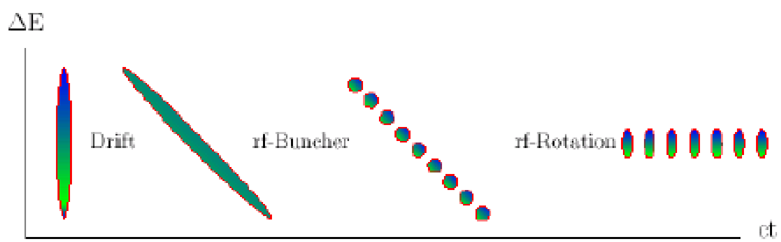


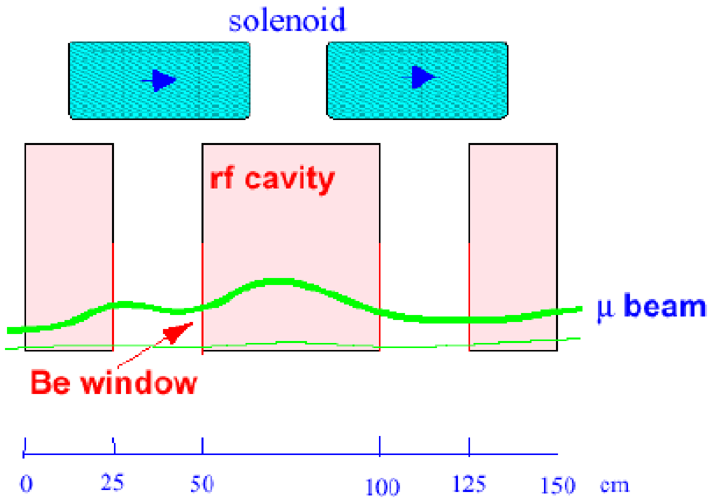
Bunching and Phase Rotation

- **Beam from target unsuitable for downstream accelerators**
  - **must be "conditioned" before use**
    - **reduce energy spread**
    - **create beam bunches for RF acceleration (201 MHz)**
  - **accomplished with RF system with many frequencies**
    - **has same RF issues as cooling channel (covered later)**
  - **optimization of length and performance under way**



Neuffer scheme

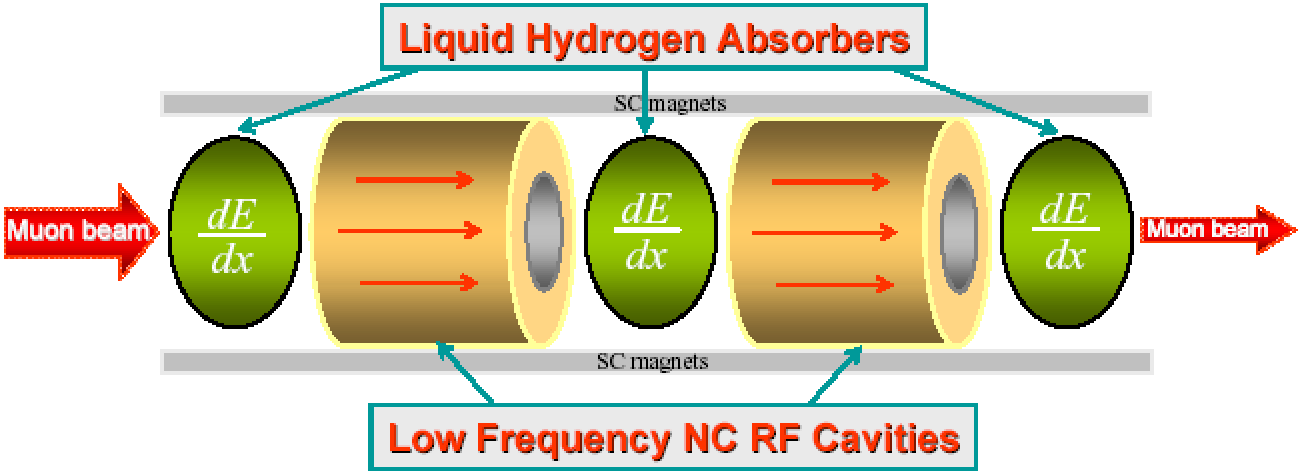




Ionization Cooling (1)

- Ionization cooling analogous to familiar SR damping process in electron storage rings
  - energy loss (SR or *dE/ds*) reduces p_x, p_y, p_z
  - energy gain (RF cavities) restores only p_z
  - repeating this reduces $p_{x,y}/p_z$ (⇒ 4D cooling)

  - presence of LH_2 near RF cavities is an engineering challenge
    - we get lots of "design help" from Lab safety committees!



Ionization Cooling (2)

- There is also a heating term
  - for SR it is quantum excitation
  - for ionization cooling it is multiple scattering

- Balance between heating and cooling gives equilibrium emittance

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left|\frac{dE_\mu}{ds}\right|\frac{\varepsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

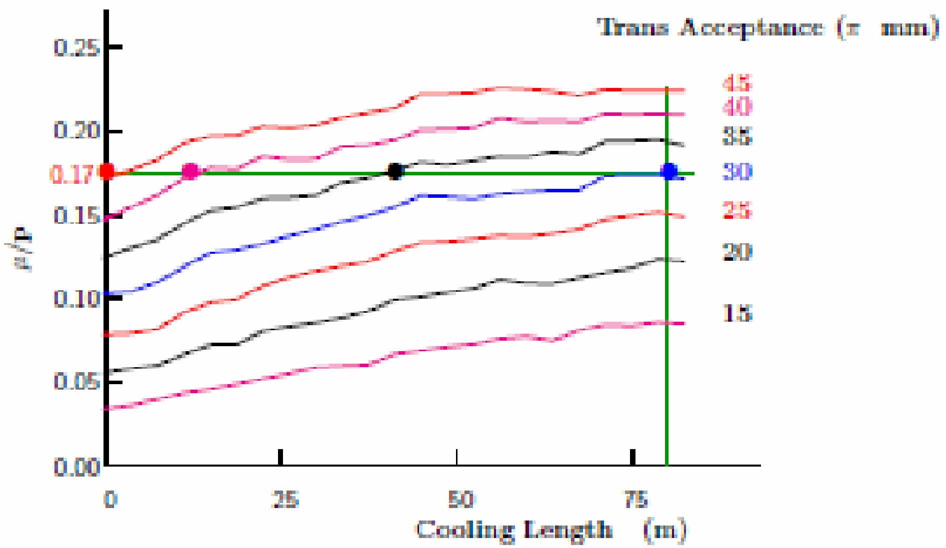
Cooling Heating

$$\varepsilon_{x,N,equil.} = \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta m_\mu X_0 \left|\frac{dE_\mu}{ds}\right|}$$

  - prefer low $\beta_\perp$ (strong focusing), large X_0 and dE/ds (H_2 is best)

Is Cooling Needed?

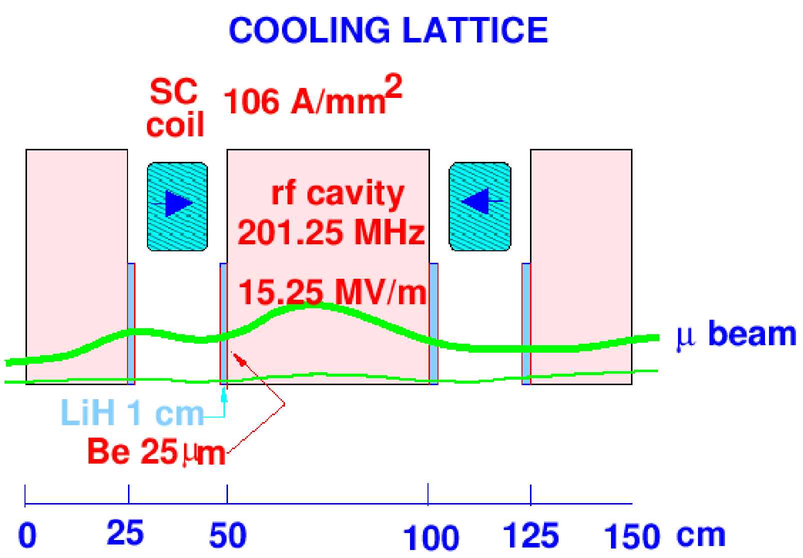
- Evaluated trade-offs between cooling efficacy and downstream acceptance (Palmer)
  - increasing from 30 to 35 π mm-rad halves the required length of cooling channel
    - at 45 π mm-rad, no cooling needed
- At present, $A \approx 30\ \pi$ mm-rad seems practical limit
  - conclude that moderate cooling needed

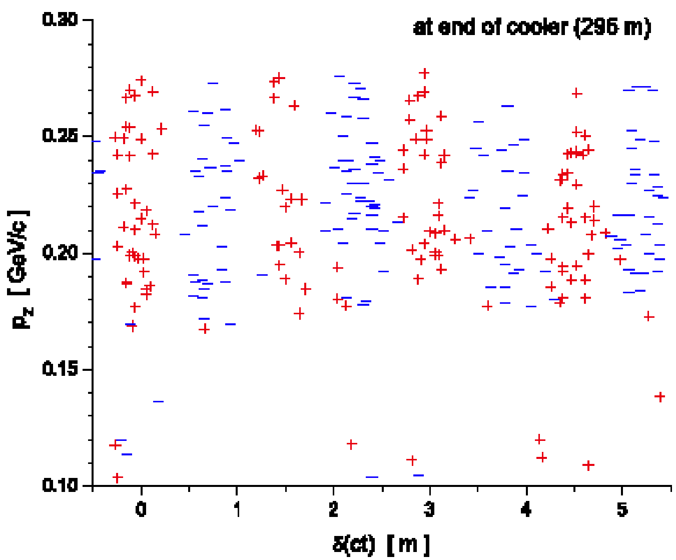


Baseline Cooling Channel

- ISS compared all extant designs (Palmer)
  - FS2, FS2a, CERN, KEK channels

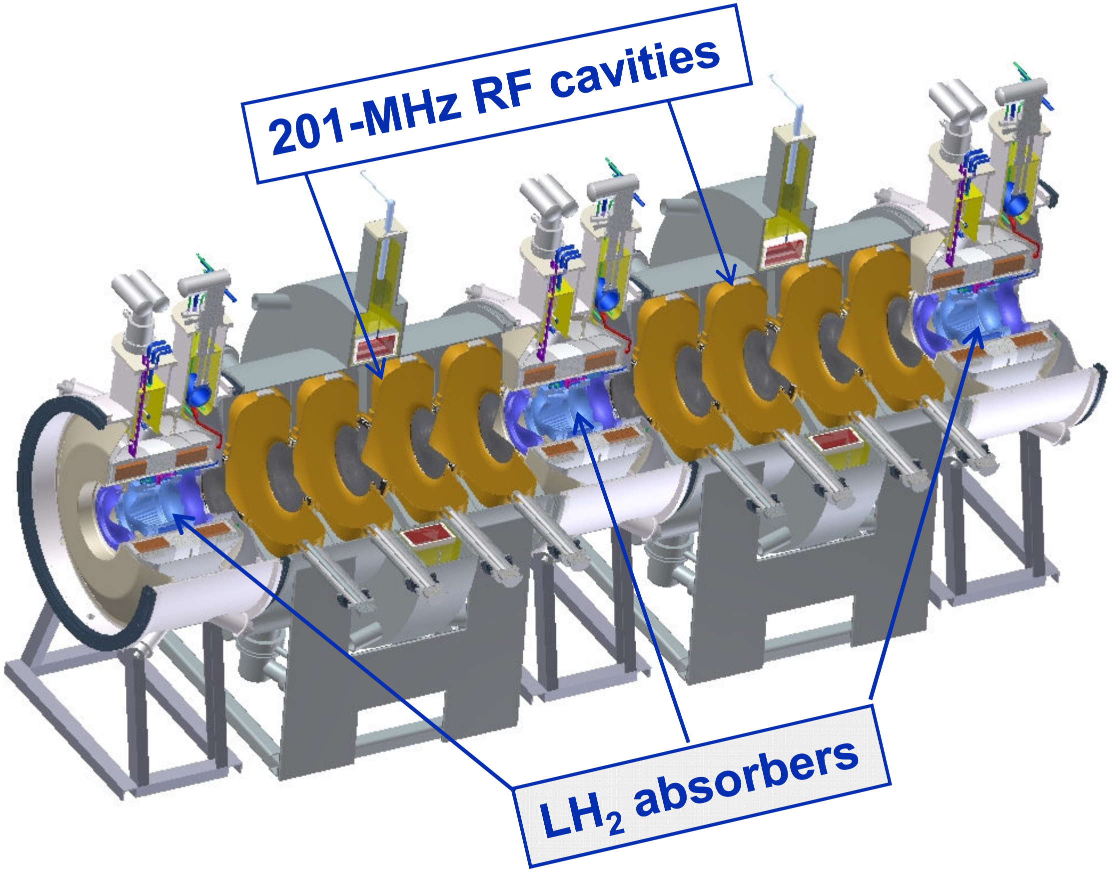
- Performance of FS2a channel found to be best
  - meets goal (with both signs) of 10^{21} useful decays per year
    - for ~4 MW of 5–15 GeV protons (2 ns bunches)
      - some margin in beam power would be prudent
  - chose this as baseline configuration





Cooling Channel Implementation

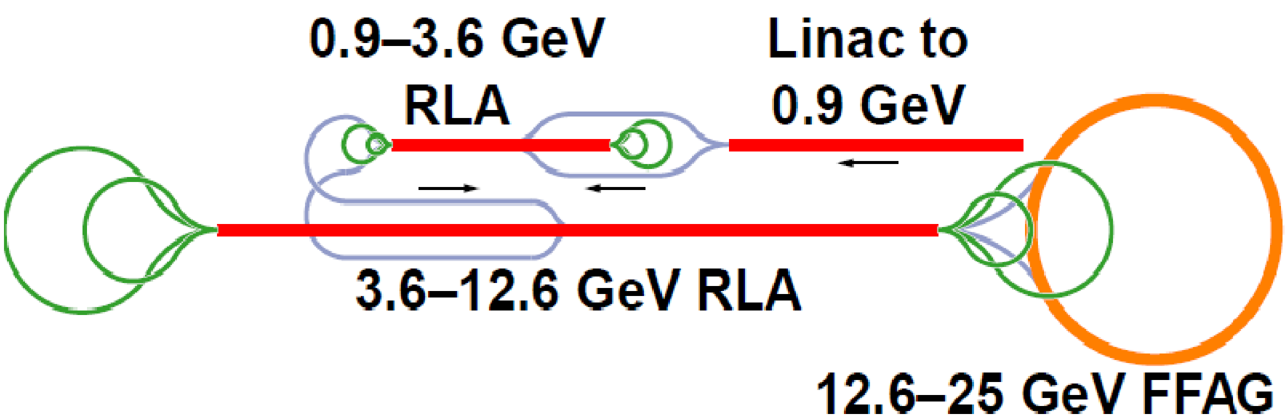
- Actual implementation is complex
  - example shown (from MICE) is earlier cooling channel design
    - baseline design subsequently simplified (somewhat)



Acceleration (1)

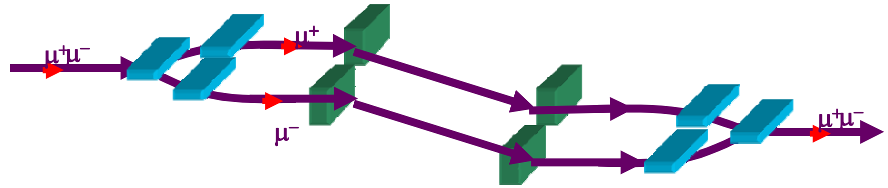
- **Baseline scheme**
  - **linac followed by two dog bone RLAs, then non-scaling FFAG**
    - **keeps both muon signs**
  - **system accommodates 30 mm transverse and 150 mm longitudinal acceptance**

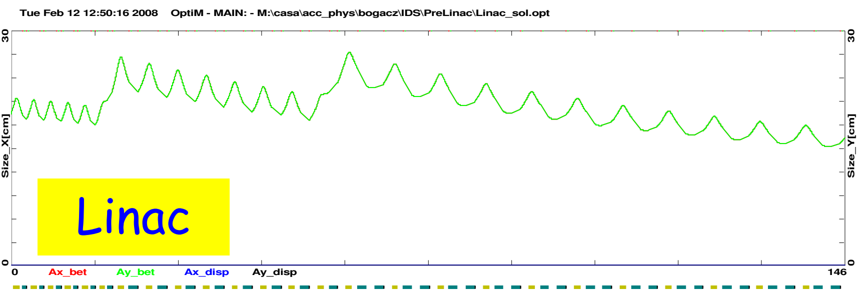
Bogacz

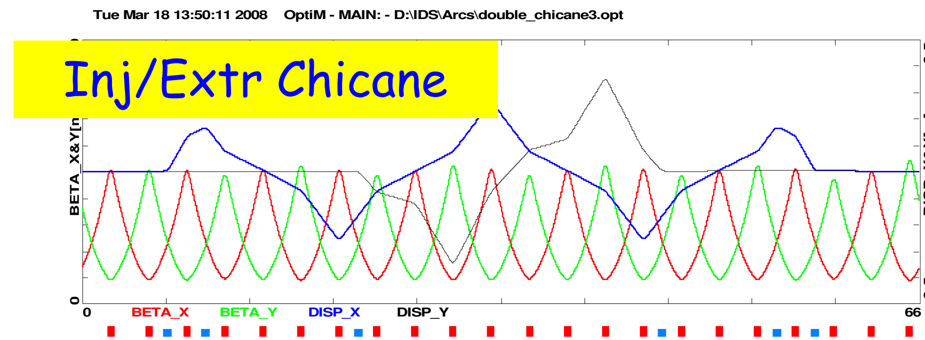


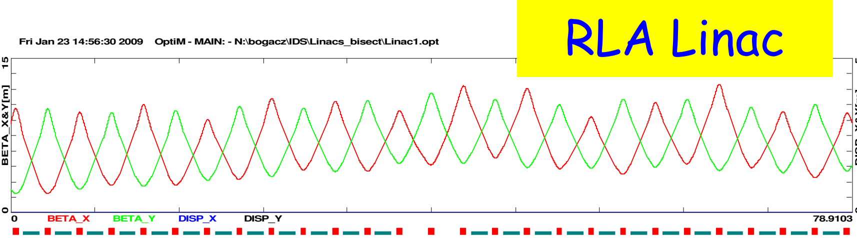
Acceleration (2)

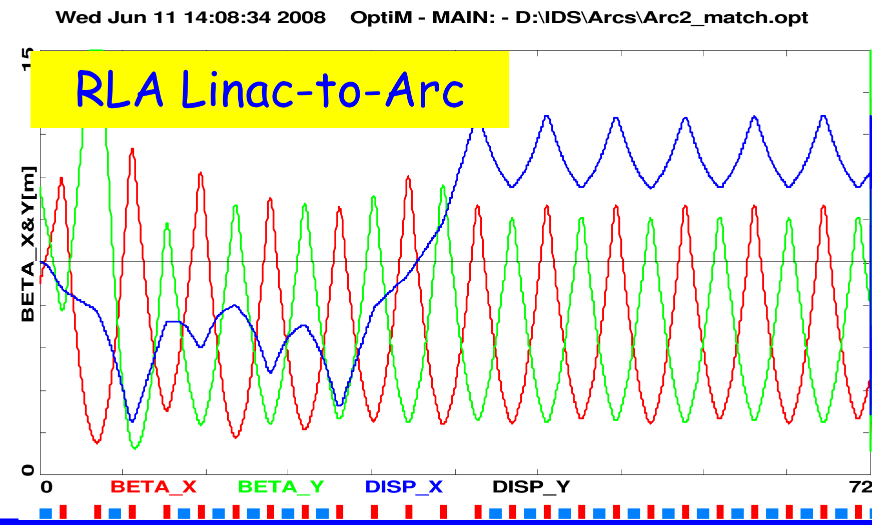
- Optics for linac, both RLAs, and transfer lines all completed (Bogacz)
  - including injection chicanes

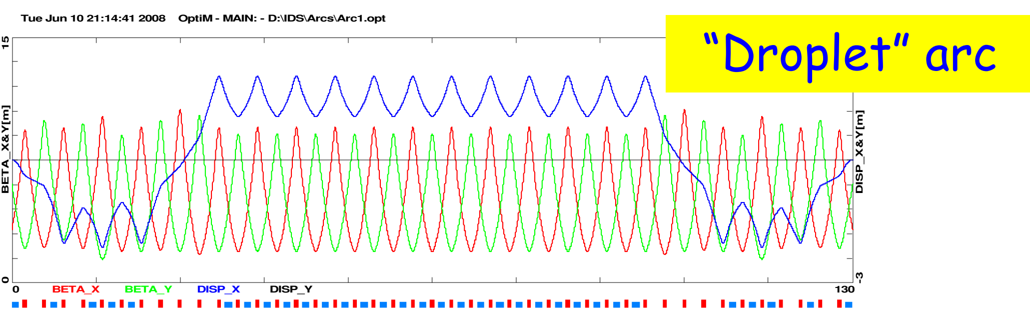








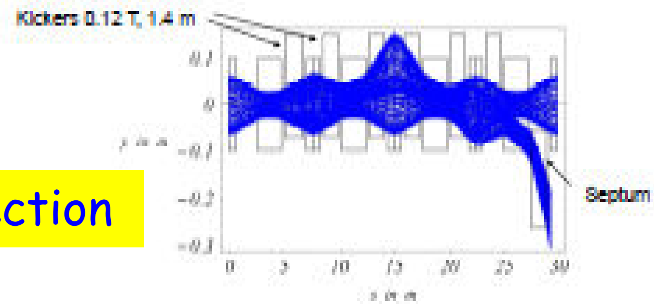




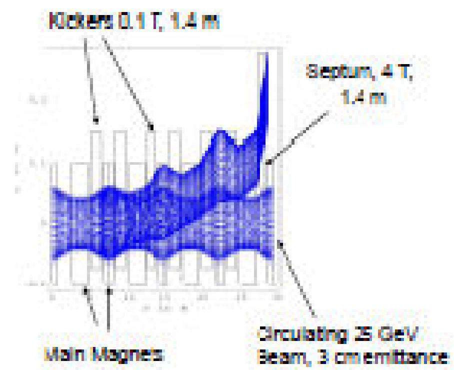
Acceleration (3)

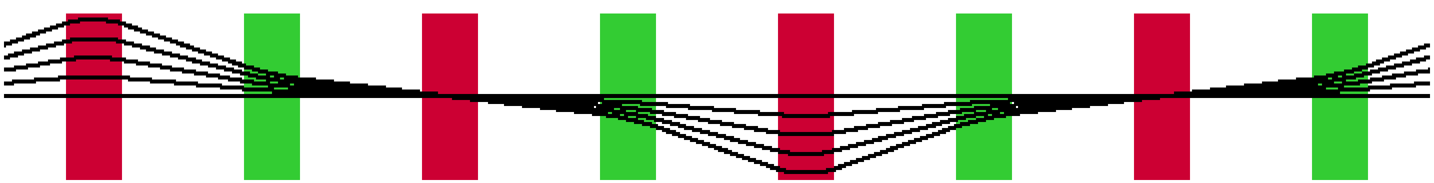
- Non-scaling FFAG ring has two main issues
  - coupling between transverse and longitudinal dynamics (Berg, Machida)
    - larger amplitudes and bigger angles give longer path length
      - different flight times for different amplitudes lead to acceleration problems in non-scaling FFAG
        - large-amplitude particles slip out of phase with RF and are not fully accelerated
    - partial chromatic correction is workable
  - injection and extraction (Pasternak)
    - large beams, not much space
      - optics done
      - kicker and septum magnets daunting

Injection



Extraction





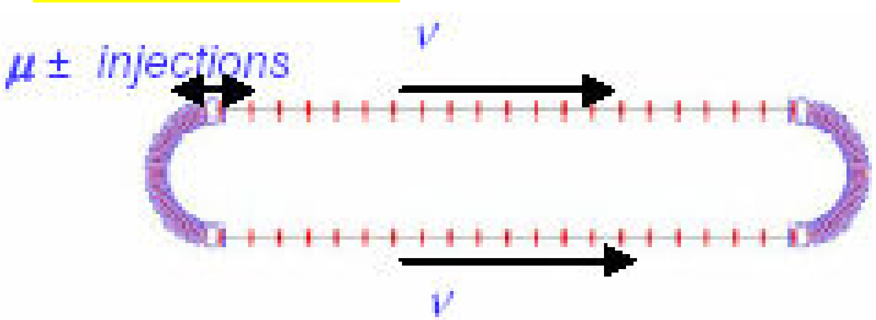
Decay Ring

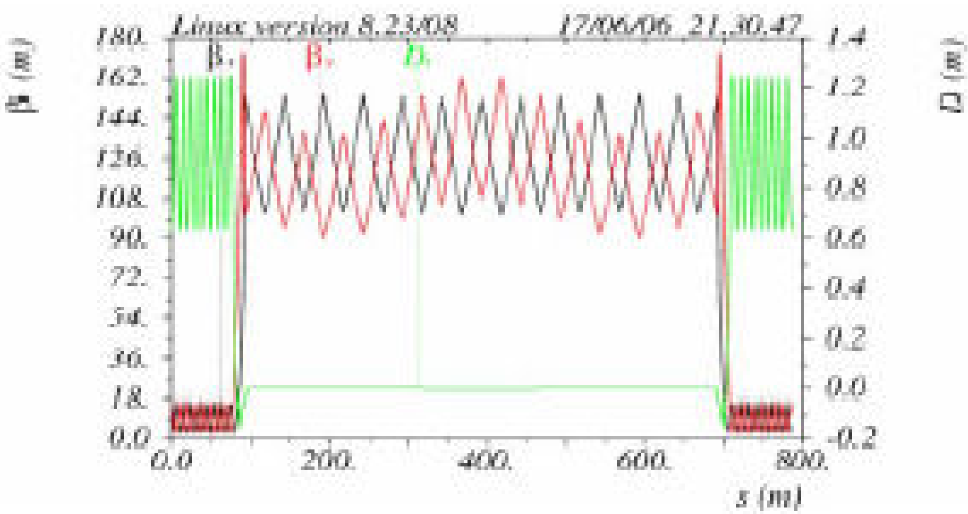
- Both triangle and racetrack rings possible
  - depth of ring is potential issue for both styles
    - especially for 7500 km baseline case
      - reaches ~500 m
  - shorter rings may be possible
    - will require RF to keep bunch trains separated
      - topic for IDS-NF to consider

Decay Ring Geometry (1)

- Racetrack rings have two long straight sections that can be aimed at a single detector site
  - alternately store one species in each ring
    - or could store μ^+ and μ^- together in one ring
- More flexibility than triangle, but likely more expensive
  - can stage the rings if one detector is ready first
  - can point to two sites without constraints
  - adopted as baseline configuration

Johnstone

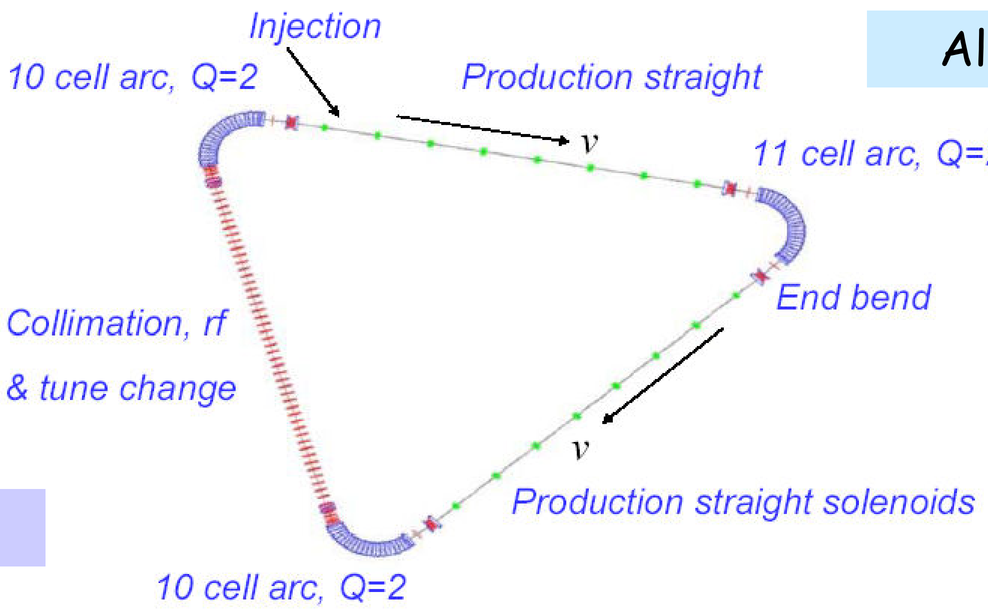




Depth ~500 m

Decay Ring Geometry (2)

- Triangle rings would be stacked side by side in tunnel
  - one ring stores μ^+ and one ring stores μ^-
    - permits illuminating two detectors with (interleaved) neutrinos and anti-neutrinos simultaneously
  - triangle ring more efficient than racetrack ring for two suitable detector sites
    - for single site, or sites in same direction from ring, racetrack is better



Alternative design

Rees, Prior

Depth ~500 m

R&D Program

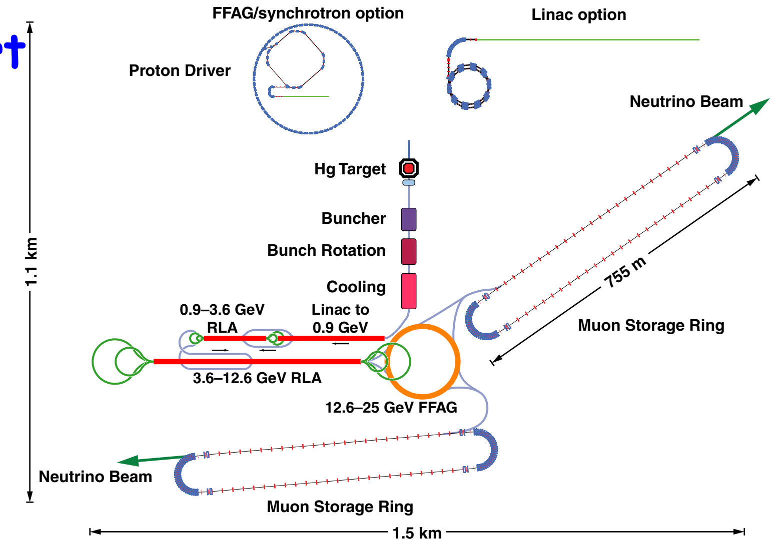
- To validate design choices, need substantial R&D program
  - three categories (simulations, component development, system tests)
  - under way in many places
    - loose, but effective, international coordination
- Simulations include design and performance optimization
  - now under IDS-NF auspices (Berg, Pozimski, Prior)
- Component R&D includes development of RF, magnets, absorbers (MuCool program)
  - especially high-gradient RF in a magnetic field (Bross, Torun, Li, Moretti, Palmer, Huang, Norem, ...)
- System tests carried out by international collaborations
  - proof-of-concept tests to validate overall performance and cost

R&D Issues

- Main Neutrino Factory R&D issues include:
  - simulations
    - optimization of subsystem designs
    - end-to-end tracking of entire facility
  - components
    - operation of normal conducting RF in an axial magnetic field
    - development of low-frequency SRF cavities
    - development of wide-aperture kicker magnets for FFAG ring
    - decay ring magnets that can withstand the mid-plane heat load from muon decay products
  - system tests
    - high-power target proof-of-concept [MERIT]
    - ionization cooling channel proof-of-concept [MICE]
    - non-scaling FFAG proof-of-concept [EMMA]

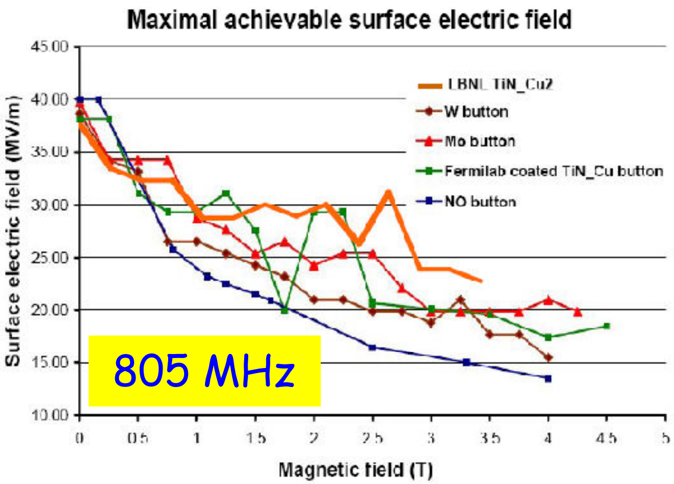
- Machine design for NF being carried out as international endeavor
  - International Design Study for a Neutrino Factory [Pozimski talk]
    - goal: deliver a Reference Design Report in which the physics performance of the Neutrino Factory is detailed and the specification of each of the accelerator, diagnostic, and detector systems that make up the facility is defined
      - also develop cost estimate for project
  - complete RDR in 2012/13 time frame
  - present baseline is a result of this effort

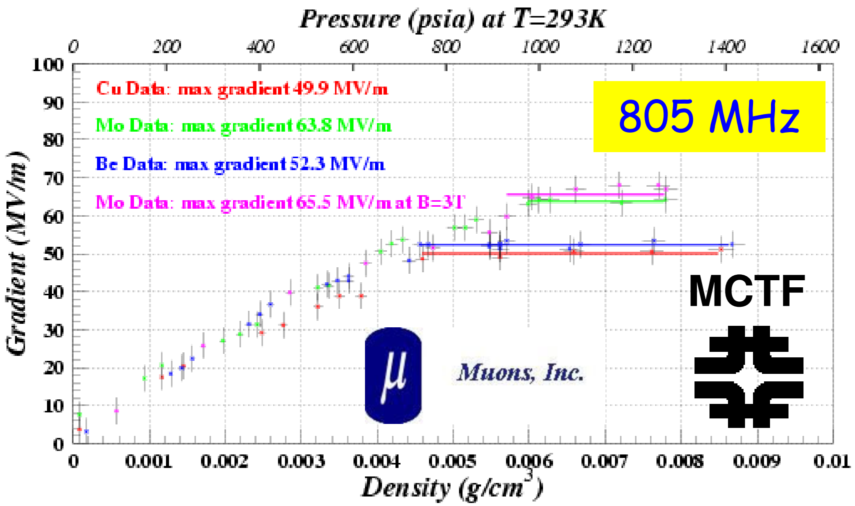
Strong EU contribution via EUROnu activity



NCRF Issue

- Main challenge for cooling channel is operation of RF in axial magnetic field
  - applies equally to bunching and phase rotation section
- R&D has shown that maximum gradient degrades in magnetic field for "vacuum" RF
  - HPRF does not show this effect
  - evaluating different cavity materials and response of HPRF to beam

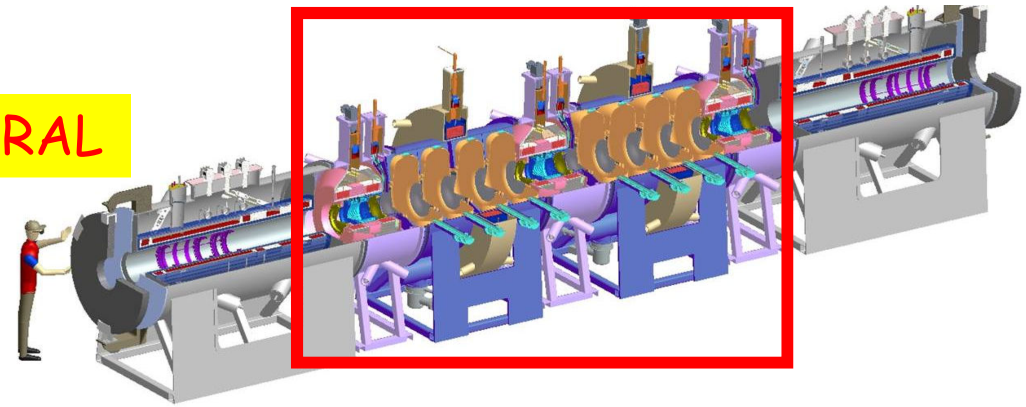




MICE

- Cooling demonstration aims to:
  - design, engineer, and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
  - place this apparatus in a muon beam and measure its performance in a variety of modes of operation and beam conditions
- Another key aim:
  - show that design tools (simulation codes) agree with experiment
    - gives confidence that we can optimize design of an actual facility
- Getting the components fabricated and operating properly is teaching us a lot about both the cost and complexity of a muon cooling channel
  - measuring the "expected" cooling will serve as a proof of principle for the ionization cooling technique

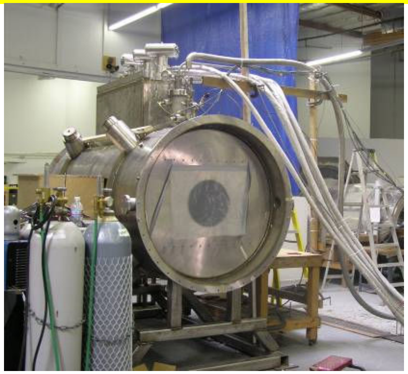
Experiment sited at RAL



MICE Components

- All MICE cooling channel components are now in production

Spectrometer Solenoid (Wang NMR)

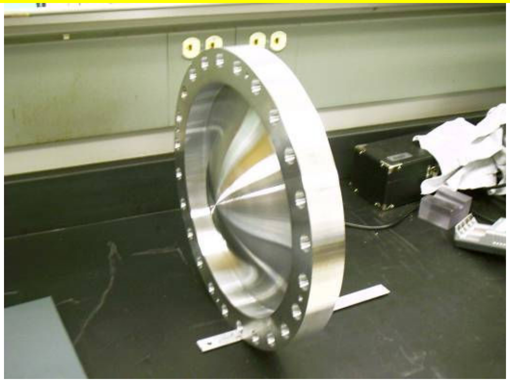


CC large test coil (HIT)

CC mandrel (Qi Huan Co.)

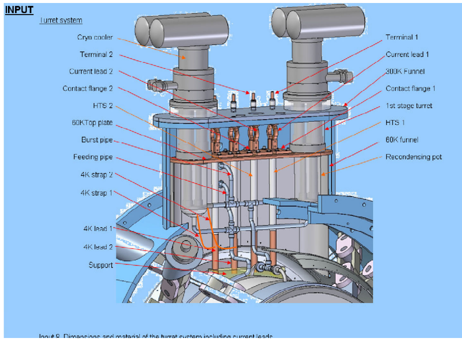
Absorber (KEK)

Absorber window (U-Miss)



Cavities (Applied Fusion)

FC (Tesla Eng., Ltd.)

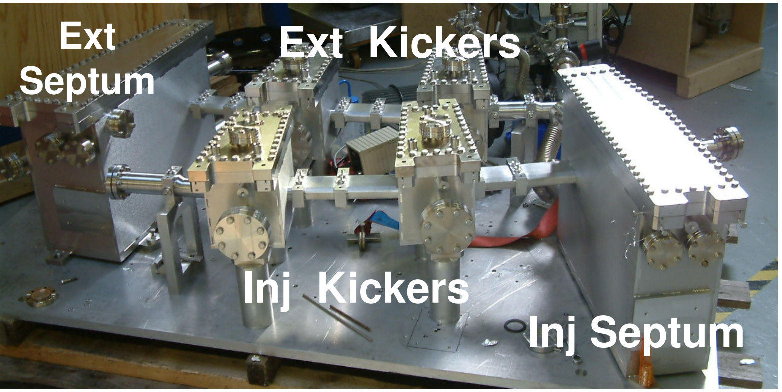


EMMA

- **EMMA will test an electron model of a non-scaling FFAG**
  - uses Daresbury ERLP (ALICE) as injector
  - aim:
    - demonstrate feasibility of non-scaling FFAG concept
      - investigate longitudinal dynamics, transmission, emittance growth, influence of resonances
  - commissioning begins early 2010

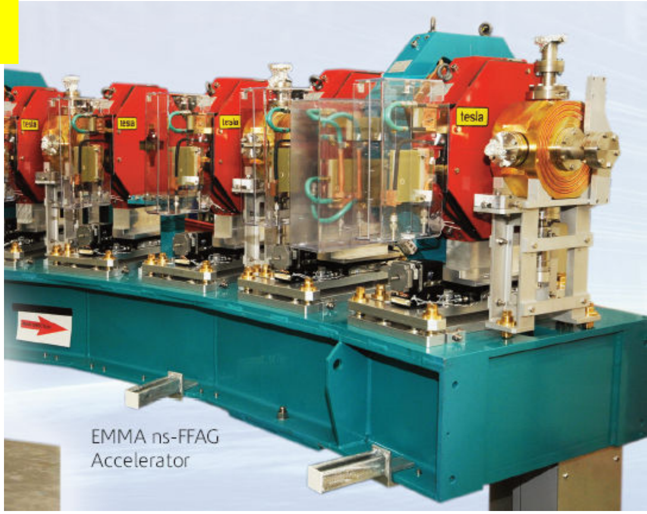
Primarily EU effort

EMMA injection/extraction components



1.3 GHz RF cavity

Assembled girder



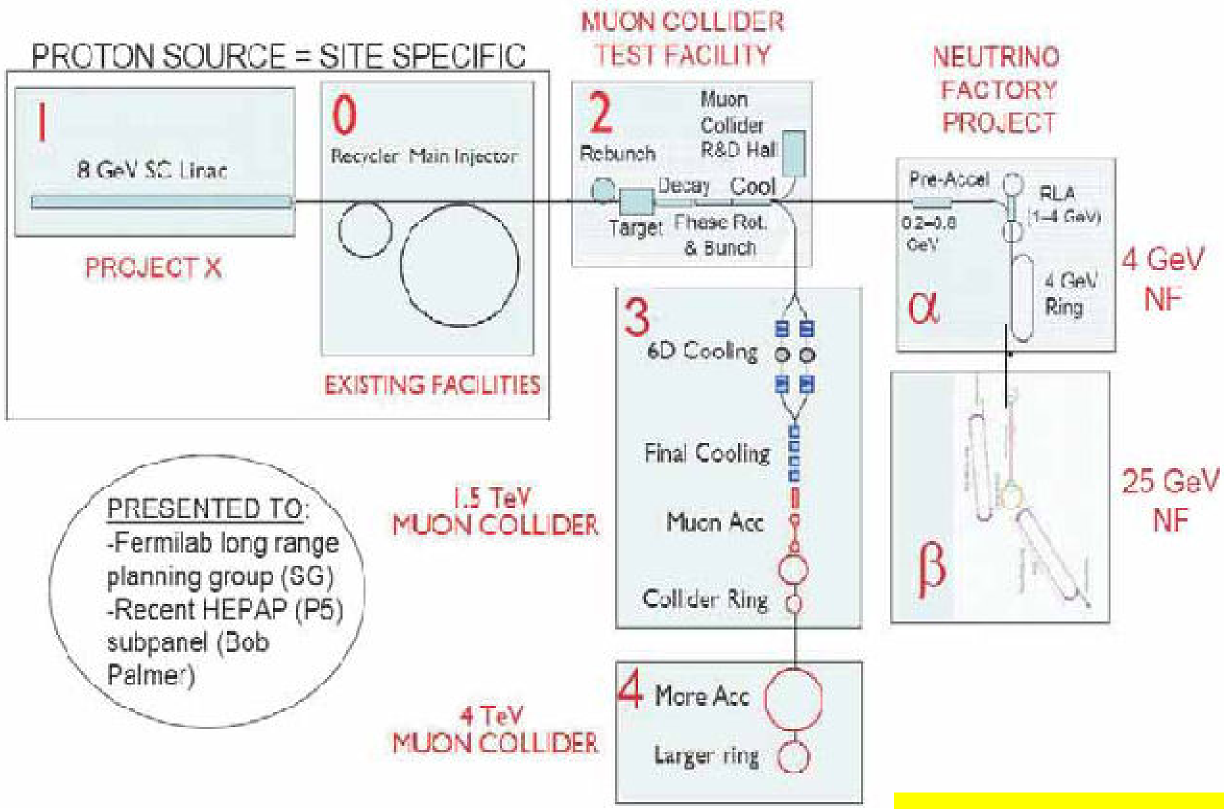
Components now mostly fabricated

Help Wanted

- There are many areas where expertise from CERN could make substantial—and necessary—contributions
  - target facility design, e.g., shielding estimates
  - site-specific proton driver design (SPL-based, ~4 MW, ~2 ns bunches)
  - engineering and costing of key components
    - NCRF systems; SRF systems; FFAG kickers; cryogenic systems; SC magnets;...
      - LHC engineering staff are world experts in all of these areas!
  - simulation effort for IDS-NF
    - CERN scientific staff made key contributions to NF design and MICE in the "early days"
      - that intellectual effort is sorely missed
        - and still badly needed
  - in the longer term, participation in a 6D cooling experiment would be of great value to the international scientific community
    - Muon Collider would also be an international endeavor

Possible U.S. Scenario

- **Possible muon beam evolution at Fermilab**



Note: this is thus far only a *concept*, there is no formal request for funding.

Summary

- R&D toward a NF and MC making steady progress
  - MERIT established ability of Hg-jet to tolerate >4 MW of protons
  - MICE is progressing (major components all in production)
    - looking forward to first ionization cooling measurements in a few years!
  - EMMA components mostly fabricated; commissioning in early 2010
  - strong EU contributions to all of these!
- CERN help in engineering and costing of key components will be critical
  - simulation effort would also be of great value
  - as would participation in a future 6D cooling experiment
- Development of muon-based accelerator facilities offers great scientific promise and remains a worthy—and challenging—goal to pursue