Accelerator Requirements for a Neutrino Factory and Muon Collider

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Muon Accelerator Advantages

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

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

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

Produces high energy ν_e, above τ threshold

    - **decay kinematics well known**
      - **minimal hadronic uncertainties in the spectrum and flux**
    - **$\nu_e \to \nu_\mu$ 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
  - large energy spread and transverse phase space
    - 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!

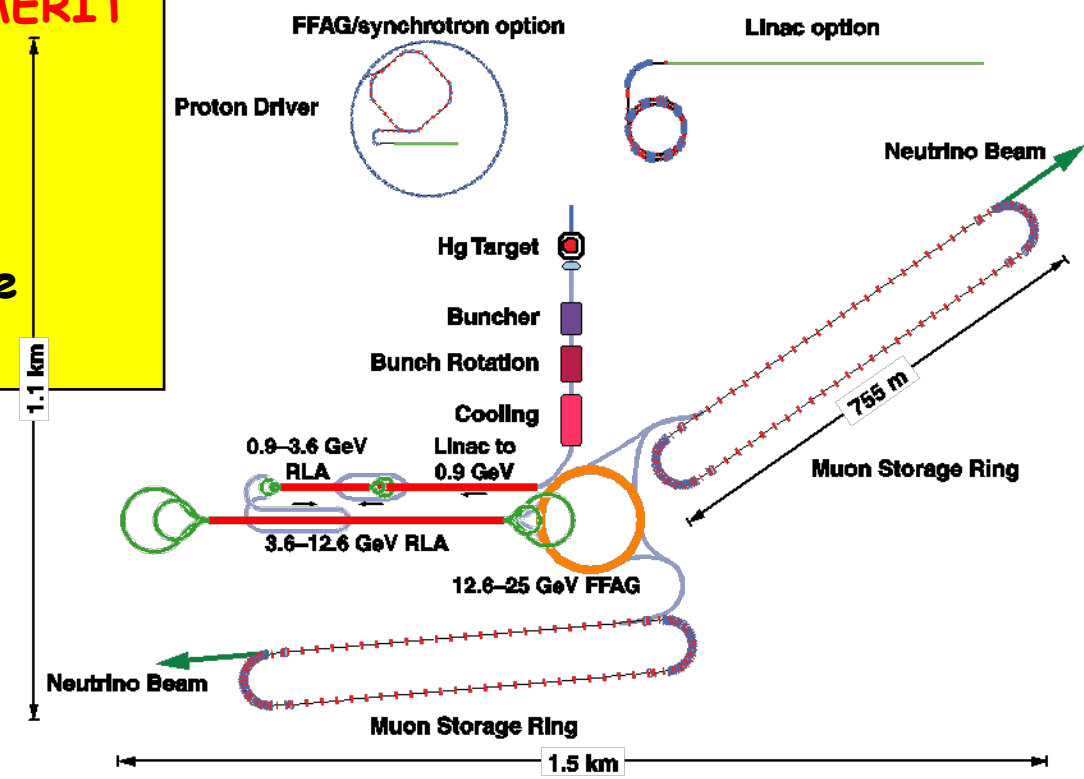
Muon Beam R&D Program

- Task: explore techniques for producing, accelerating, and storing intense muon beams
  - initial focus: muon storage ring to serve as source of well-characterized neutrinos ("Neutrino Factory") for long baseline experiments (~3000–7500 km)
  - ultimate focus: Muon Collider
    - Higgs Factory operating at few-hundred GeV or energy-frontier collider operating at several TeV
  - both types of machine are difficult, but have high scientific potential
- Recent attention from P5 and FNAL directorate have given Muon Collider R&D a higher profile in the U.S.
  - this is reflected in our recently submitted 5-year R&D plan

Neutrino Factory Ingredients

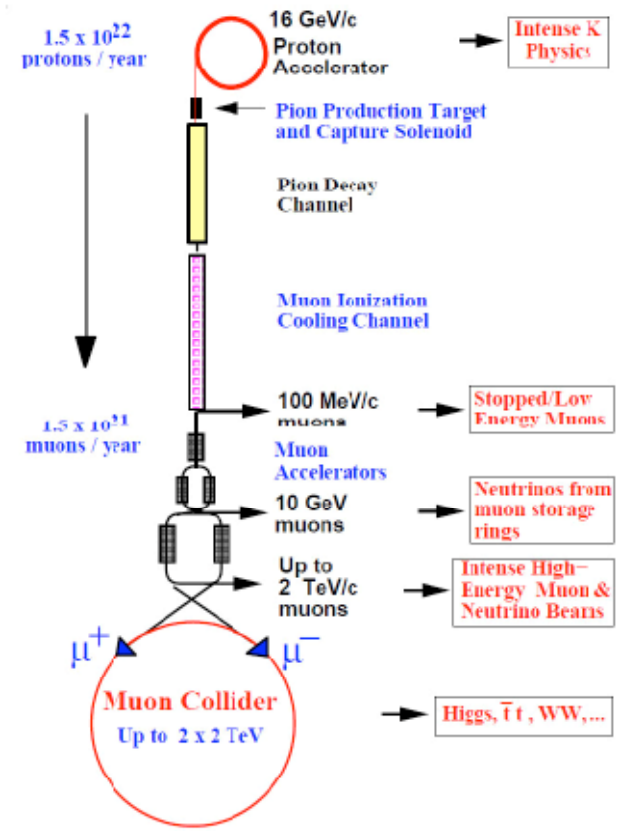
- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into $\mu \Rightarrow$ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance $\Rightarrow$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

IDS-NF Baseline Layout



Muon Collider Ingredients

- Muon Collider comprises these sections (similar to NF)
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into $\mu \Rightarrow$ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce long. and transverse emittance
      $\Rightarrow$ MICE $\rightarrow$ 6D experiment
  - Acceleration
    - 130 MeV $\rightarrow$ ~1 TeV
      with RLAs, FFAGs, or RCSs
  - Collider Ring
    - store for 500 turns



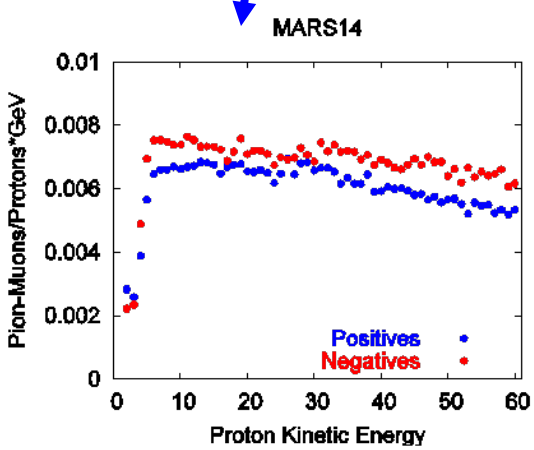
Much of Muon Collider R&D is common with Neutrino Factory R&D

Proton Driver Specifications

- **Specified only parameters, not design**
  - **implicitly assumes liquid-Hg target**

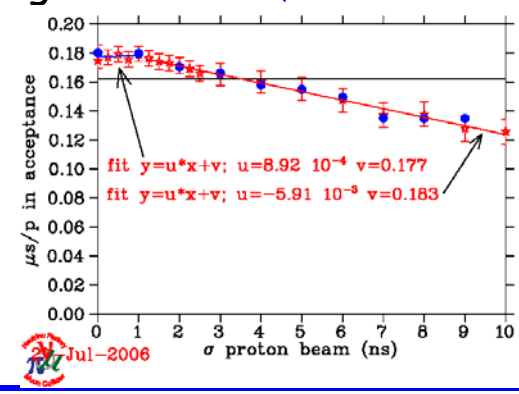
Parameter	Value
Energy (GeV)	10 ± 5
Beam power (MW)	4
Repetition rate (Hz)	≈50
No. of bunch trains	3[a)]
Bunch length, rms (ns)	2 ± 1
Beam duration[b)] (μs)	≈40

[a)] Values ranging from 1–5 possibly acceptable.
[b)] Maximum spill duration for liquid-metal target.



μ^-: 6 – 11 GeV

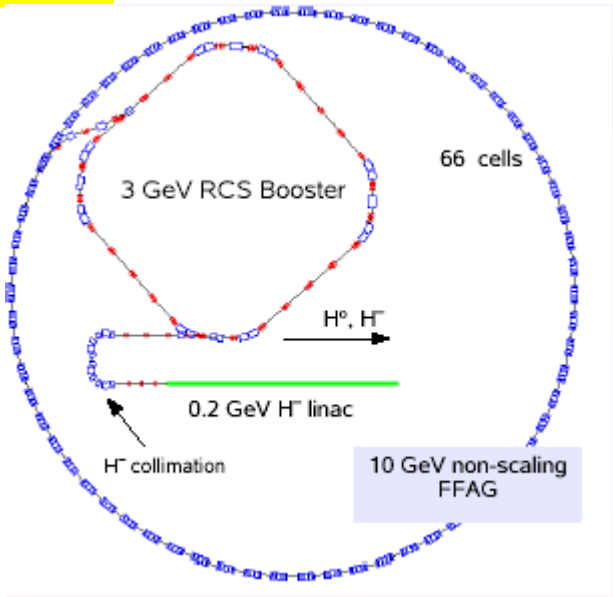
μ^+: 9 – 19 GeV

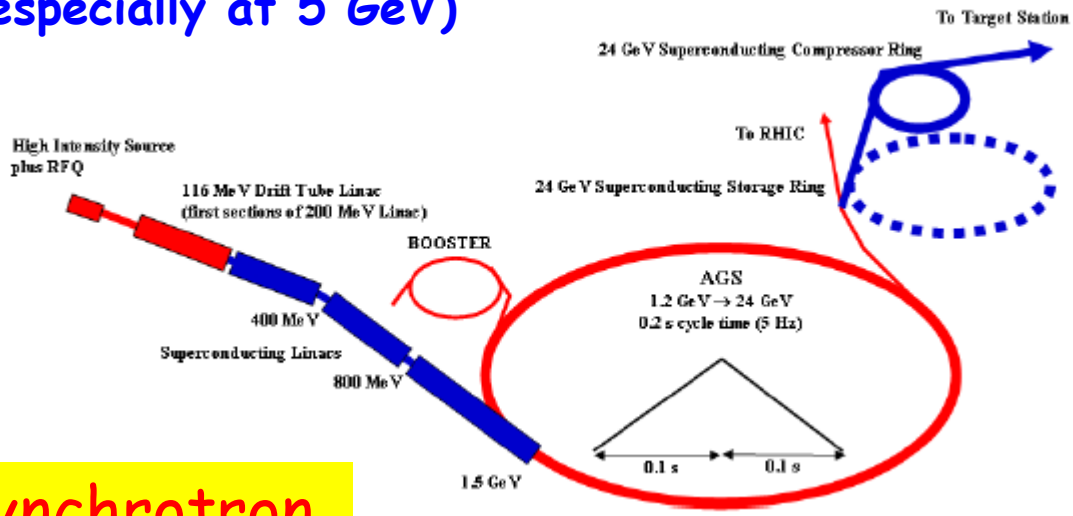


Proton Driver Options

- All options possible
- Issue is 1-3 ns bunch
  (especially at 5 GeV)

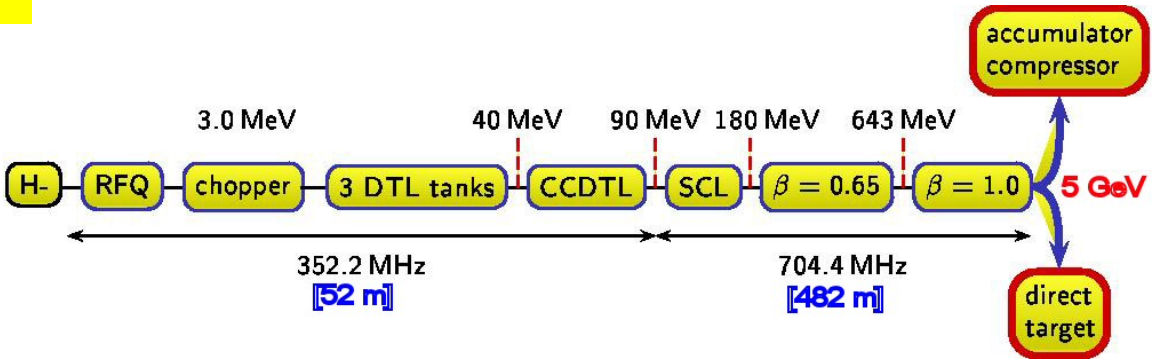
FFAG





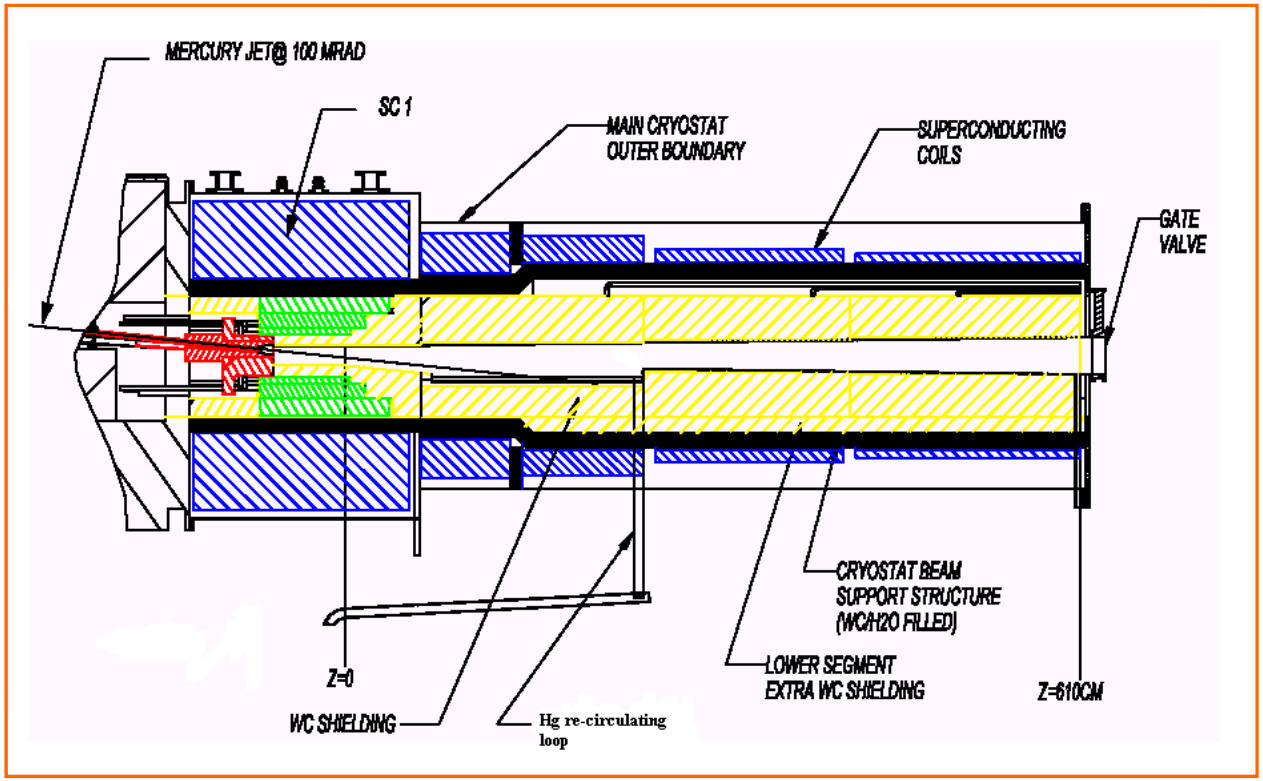
Synchrotron

Linac



Baseline Target System

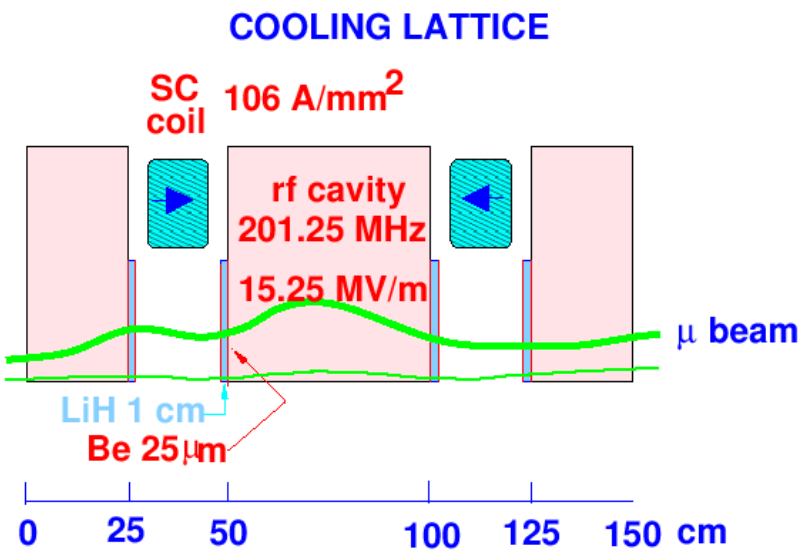
- Examined C and Hg, using 20 T solenoid capture system
  - Hg at 10 GeV gives best yield

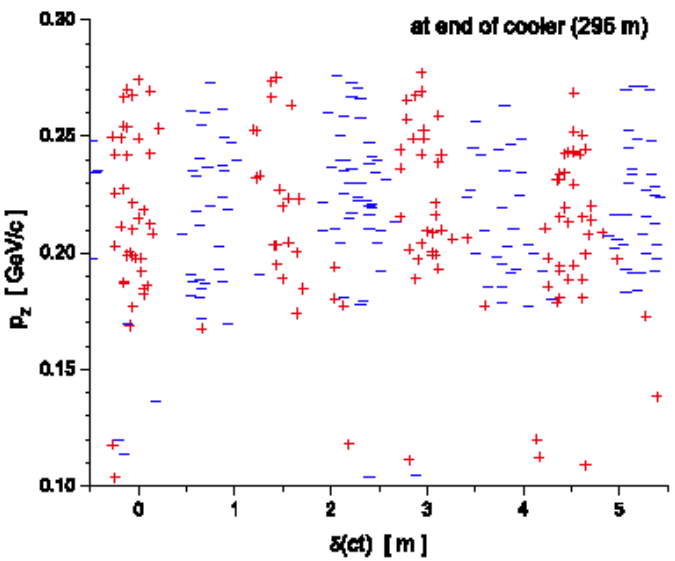


Field tapers from 20 T, 15 cm to 1.75 T, 60 cm over 20 m

Cooling Channel Baseline

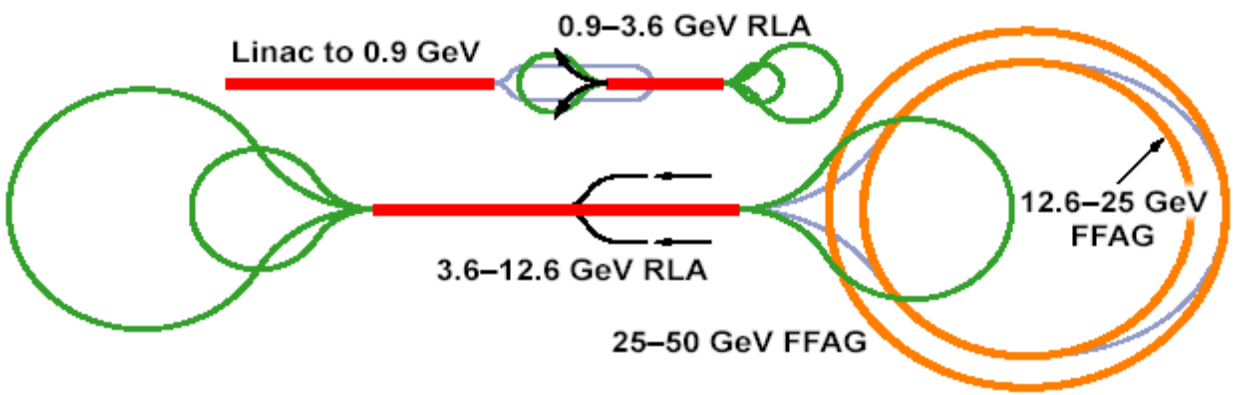
- Looked at all extant designs (Palmer)
  - FS2, FS2a, CERN, KEK channels
- Performance of FS2a channel is best
  - meets goal (with both signs) of 10^{21} useful decays per year
    - for 4 MW of 10 GeV protons (2 ns bunches)
      - some margin would be prudent
  - chose this as baseline configuration





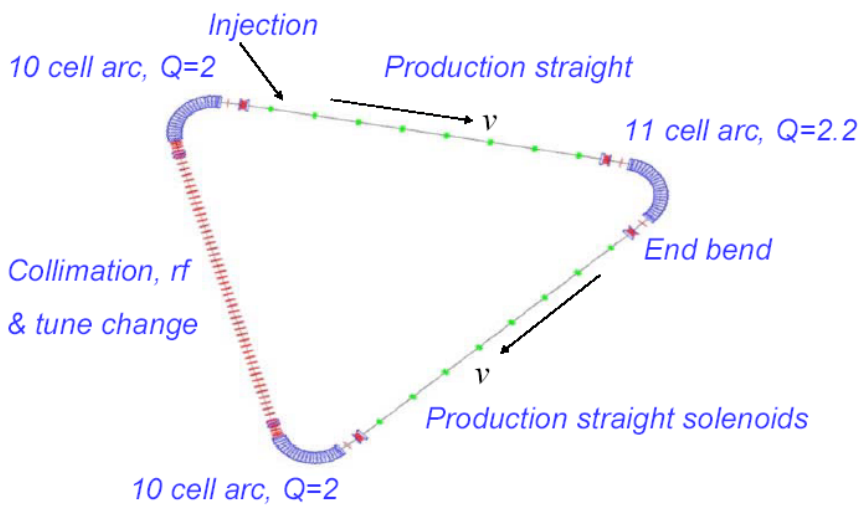
Acceleration

- Compared different schemes
  - RLA (dog bone preferred), scaling FFAG, non-scaling FFAG
    - considered implications of keeping both sign muons
- Looked at implications of 30 π mm-rad transverse acceptance
  - acceptance issues arose in non-scaling FFAG case
    - resulting in baseline scenario with only 1 FFAG (possibly 2)



Decay Ring Geometry (1)

- Both triangle and racetrack rings were examined
- 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



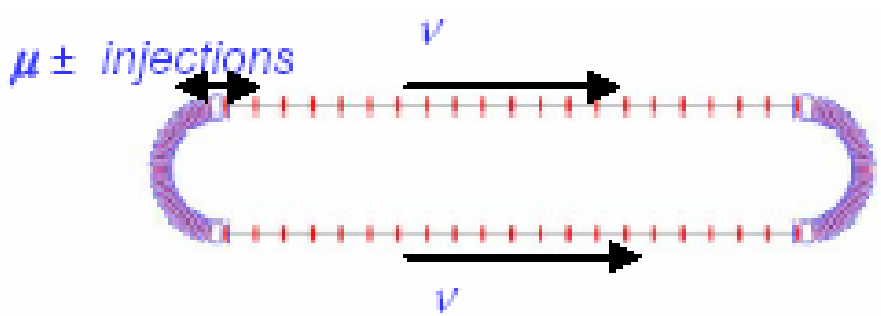
Depth ~500 m

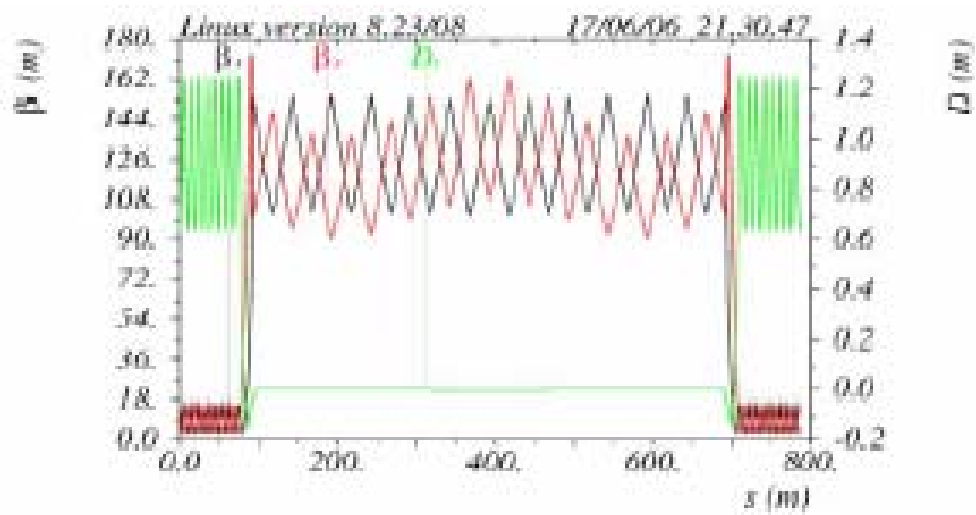
Rees, Prior

Decay Ring Geometry (2)

- 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

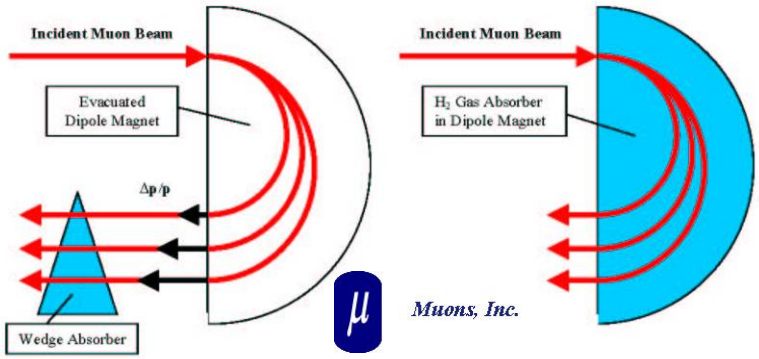
Collider Issues

- There are a few areas where collider requirements go beyond those of a Neutrino Factory
  - 6D cooling
  - final transverse cooling
  - collider ring design

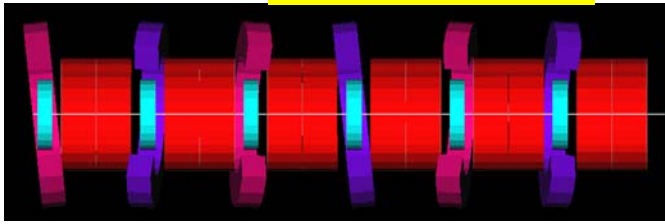
- Work on all of these is under way
  - mostly "paper studies" now
  - component tests and/or system tests are part of the longer-term R&D planning

6D Cooling

- For 6D cooling, add emittance exchange
  - increase energy loss for high-energy compared with low-energy muons
    - put wedge-shaped absorber in dispersive region
    - use extra path length in continuous absorber

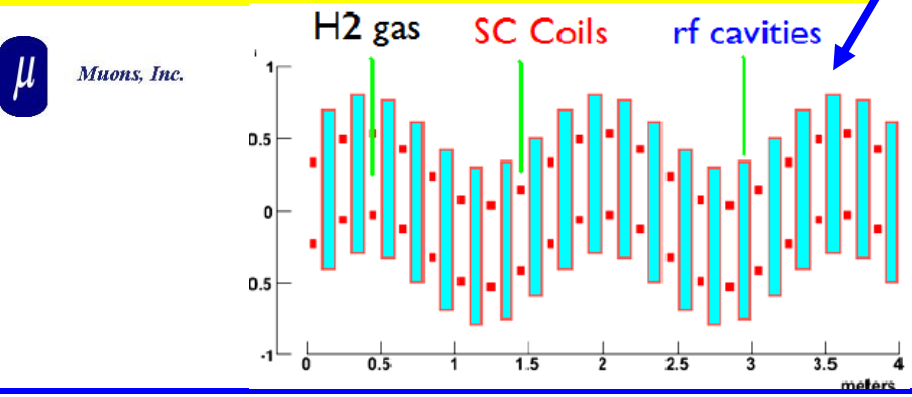


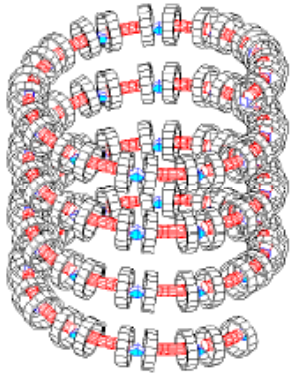
FOFO Snake (Alexahin)



Single pass; avoids ring injection/extraction issues

Helical cooling channel (Muons, Inc.)

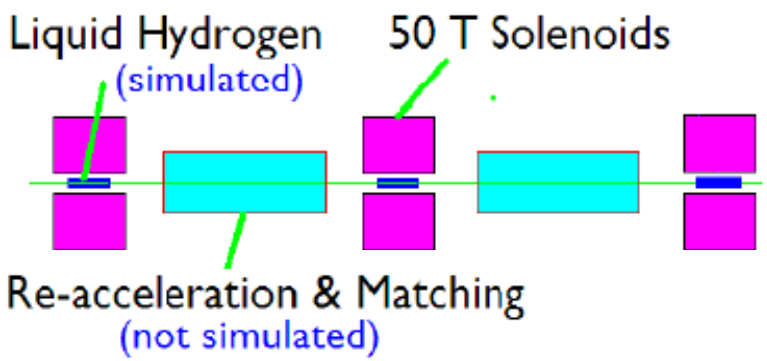




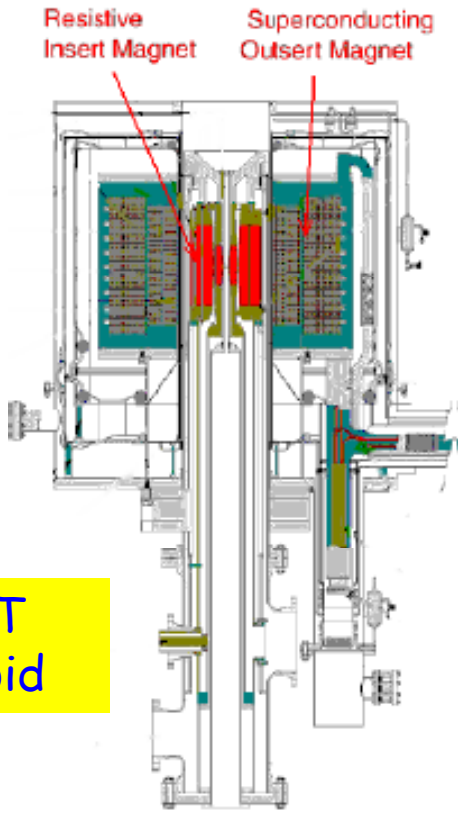
"Guggenheim" channel (Snopok)

Final Transverse Cooling

- To get to the lowest emittance values, we need very low beta function at the absorber location
  - present concept calls for up to 50 T solenoids (Palmer, Fernow)
    - there is an existence proof, more or less, but these are far from a "catalog item"



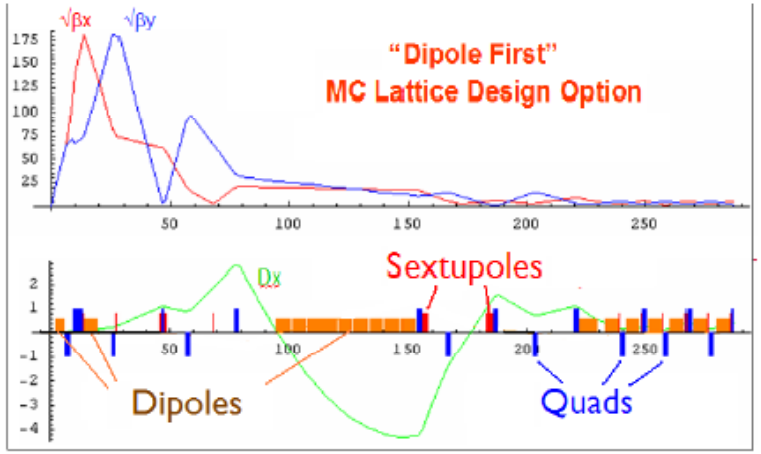
Final cooling section for MC



NHMFL 45-T hybrid solenoid

Collider Ring

- Collider lattice work ongoing (Alexahin, Gianfelice-Wendt)
  - several issues
    - low beta at IP with quadrupoles far away
      - can quadrupoles co-exist with detector?
    - dynamic aperture (for storage and for injection)
      - need to study with realistic errors
    - detector backgrounds ("MDI")
      - initial estimate indicated backgrounds are tolerable, but must revisit



Issue: do dipoles result in unacceptable backgrounds?

System Tests

- R&D program to validate design choices already well under way

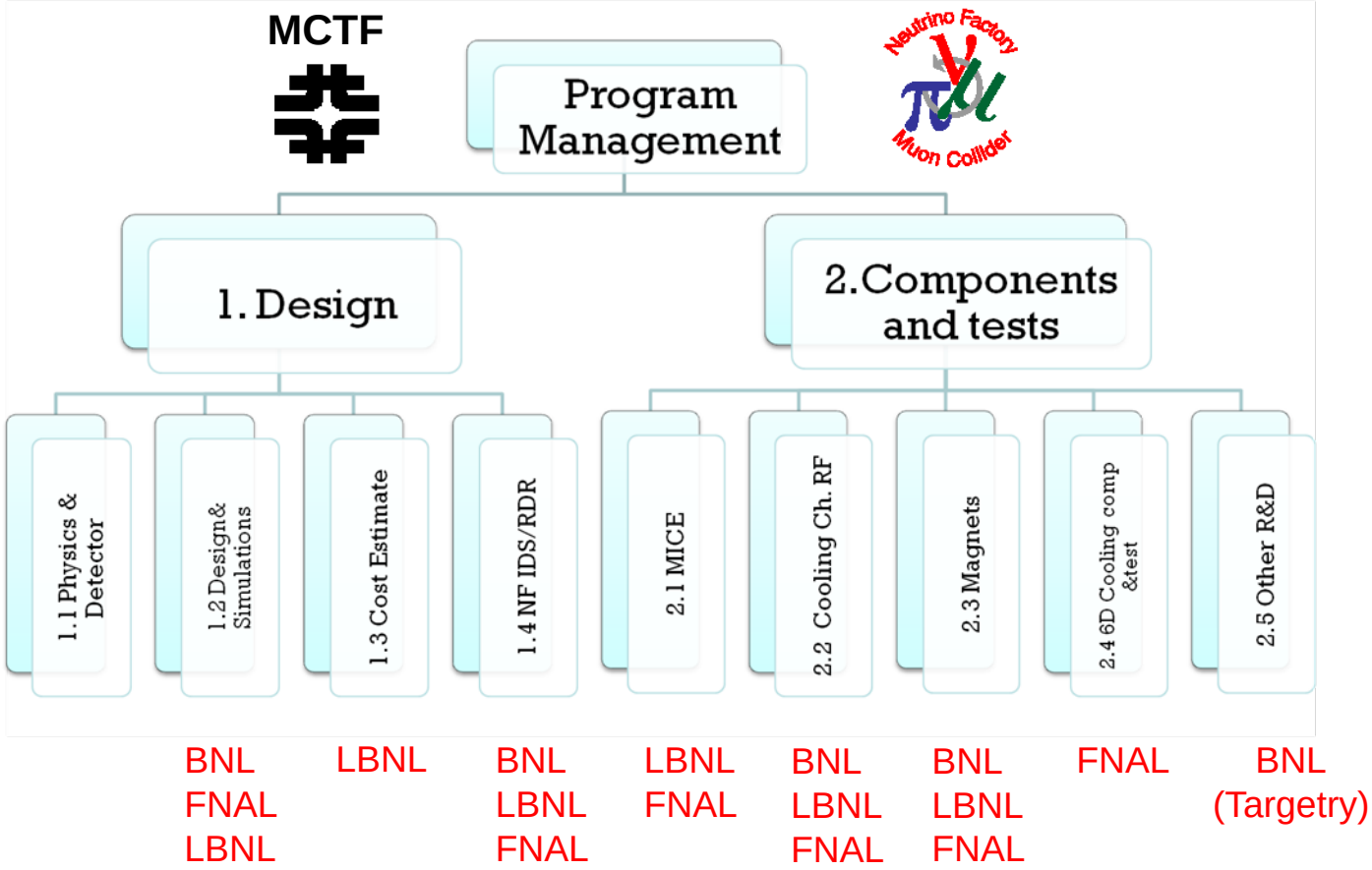
- System tests (carried out by international collaborations)
  - MERIT (high-power Hg-jet target) [completed; analysis ongoing]
  - MICE (ionization cooling demonstration)
  - EMMA (non-scaling FFAG electron model)
    - would validate potentially more cost-effective acceleration system

- Also need complementary component R&D
  - especially on high-gradient RF in a magnetic field

See backup slides for more information

5-year R&D Plan (1)

- **NFMCC and Fermilab MCTF have jointly proposed a 5-year R&D plan to DOE**



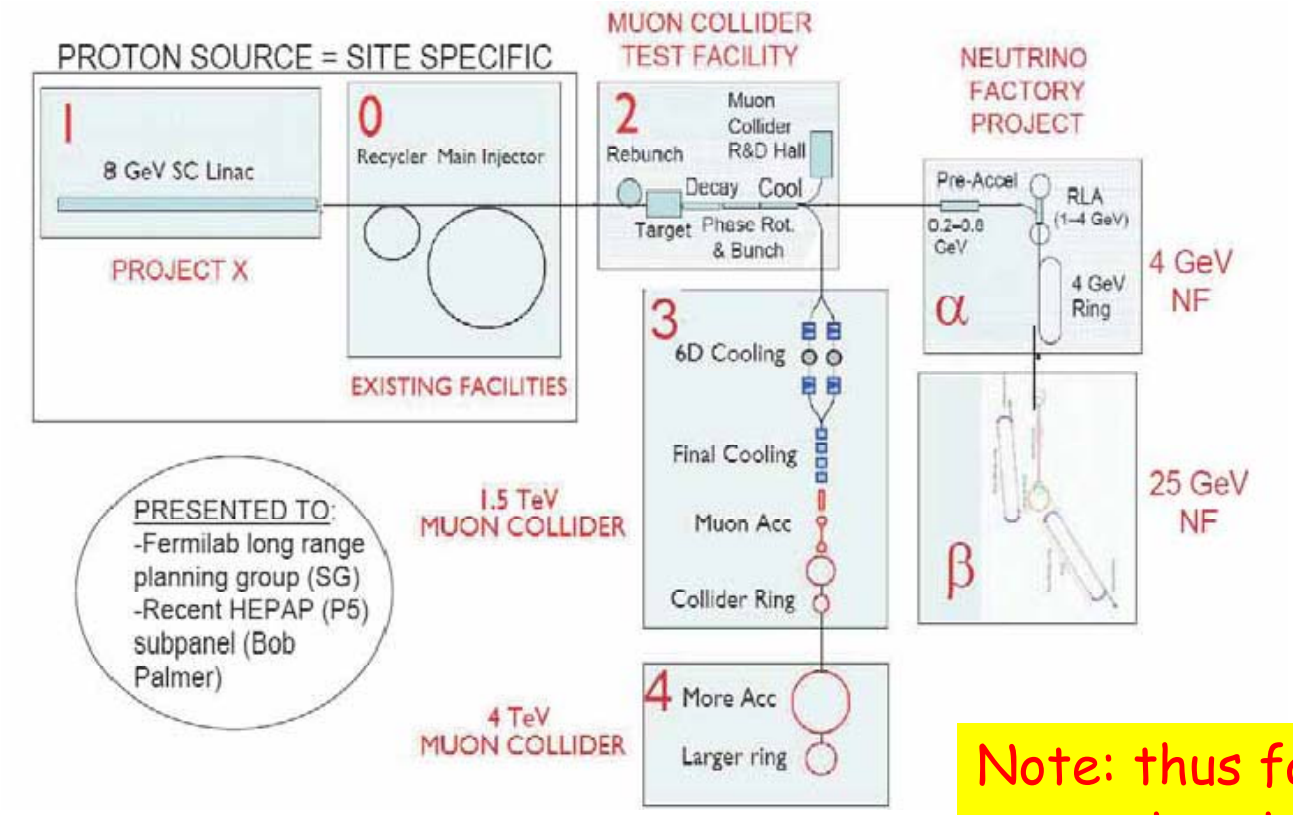
Sponsoring Laboratory participation

5-year R&D Plan (2)

- **Main deliverables**
  - design and simulations
    - MC Design Feasibility Study (DFS)
      - intended to be a "high-end" feasibility study
        - includes physics and detector studies
        - engineering and costing not fully detailed (component level costing, not bottom-up)
      - defines R&D program (extends beyond 5-yr plan)
    - NF RDR (under IDS-NF auspices)
      - help with engineering and costing (select areas)
      - participate in, and in some cases lead, accelerator design of various subsystems
  - component development and testing
    - demonstrate key technologies
    - allow down-selection of cooling channel schemes
      - may not pick unique optimal scheme, but will identify the most promising approaches

A U.S. Scenario

- **Possible muon beam evolution at Fermilab**



Note: thus far only a concept, not a proposal

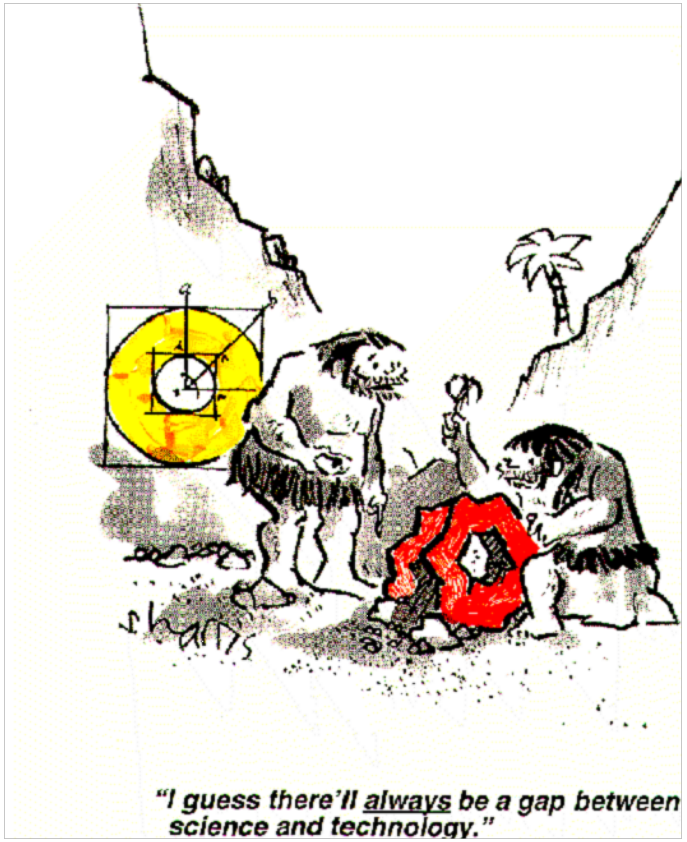
Summary

- Baseline NF design in place (<u>hardware cost</u> ~$2B in '04)
  - MC design being developed
- 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 being fabricated
- 5-year MC+NF R&D plan submitted for U.S. funding
  - deliverables include MC-DFS and NF-RDR, including cost estimates
  - if R&D results show promise, possible NF+MC scenario at Fermilab
- Development of muon-based accelerator facilities offers great scientific promise and remains a worthy—and challenging—goal to pursue

Final Thought

- **Challenges of a muon accelerator complex go well beyond those of standard facilities**
  - **developing solutions requires substantial R&D effort to specify**
    - **expected performance, technical feasibility/risk, cost (matters!)**

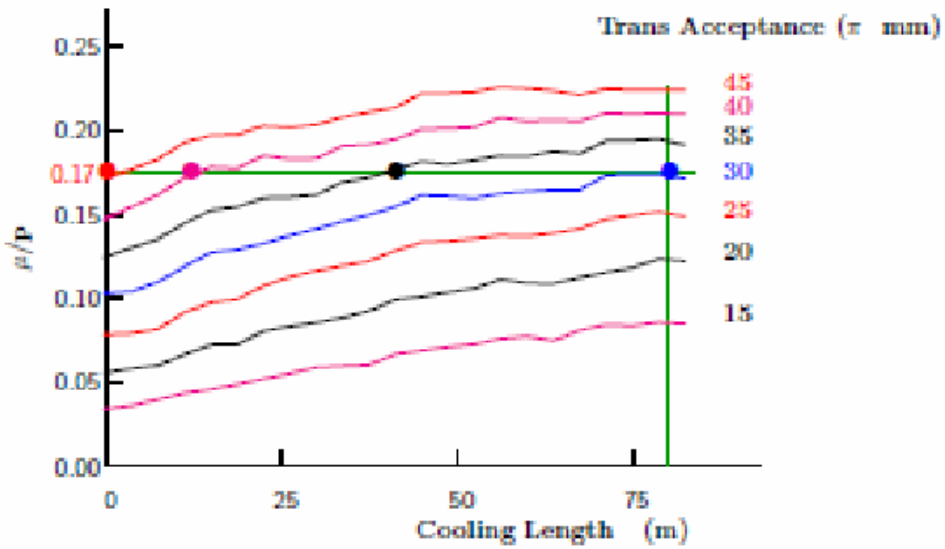
Critical to do experiments and build components.
Paper studies are not enough!



Backup slides

Front End

- 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 ≈ 30 π mm-rad seems practical limit
  - conclude that moderate cooling needed



FFAG Acceptance Issue

- Dynamics problem with non-scaling FFAGs related to dependence of revolution time on transverse amplitude (Machida, Berg)
  - larger amplitudes and bigger angles give longer path length
    - different flight times for different amplitudes lead to acceleration problems in FFAG
      - large-amplitude particles slip out of phase with RF and are not fully accelerated

- Present conclusions
  - 30 π mm-rad probably okay, but already a stretch
  - cascading several FFAG rings is harder than anticipated
    - two in series probably possible, but three in series looks impractical

IDS-NF

- Machine design for NF being carried out as international endeavor
  - International Design Study for a Neutrino Factory
    - 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

IDS-NF Leadership

Steering Group	Accelerator Group
K. Long (Chair) [ICL] A. Blondel [Geneva] Y. Kuno [Osaka] M. Zisman [LBNL]	J. S. Berg [BNL] Y. Mori [Kyoto] C. Prior [RAL/Oxford]
Detector Group	**Physics Group**
A. Bross [FNAL] P. Soler [Glasgow] N. Mondal [Mumbai] A. Cervera [Valencia]	A. Donini [Madrid] P. Huber [CERN] S. Pascoli [Durham] W. Winter [Würzburg] O. Yasuda [Tokyo Metro]

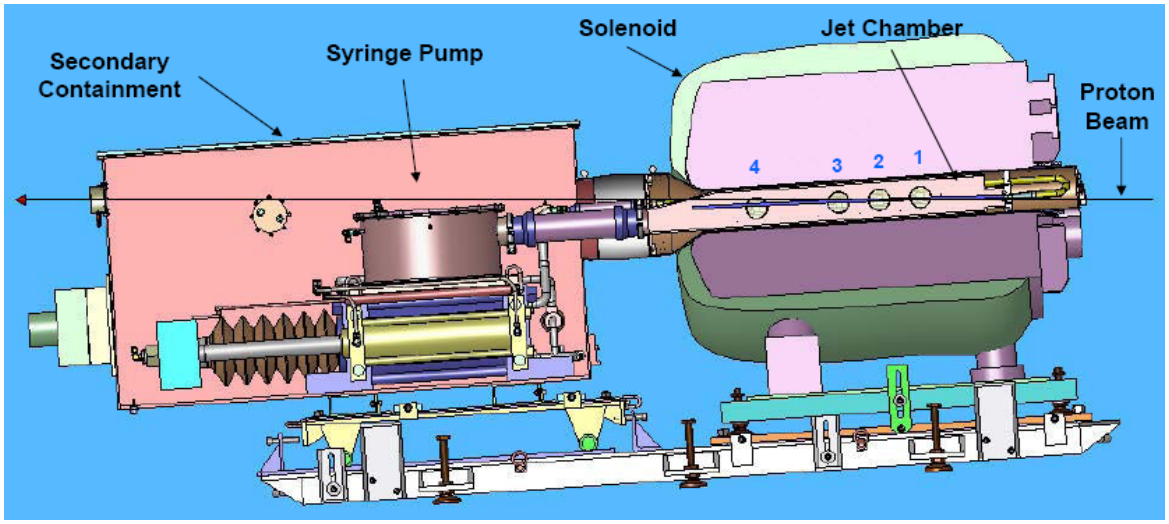
Muon Collider Parameters

- **Current parameters under study (Palmer)**
  - **a low-emittance version is also being studied by Muons, Inc.**

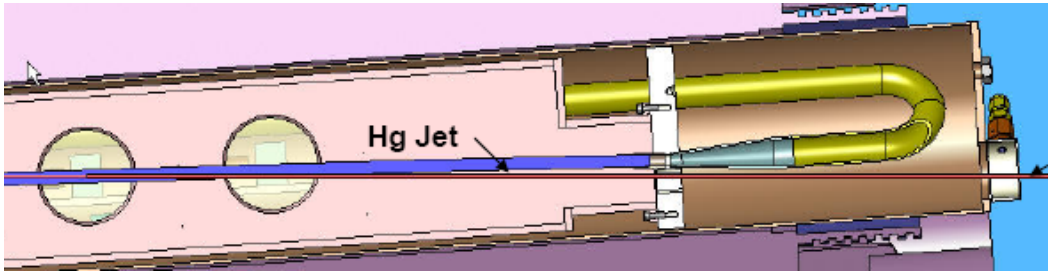
C of m Energy	1.5	4	TeV
Luminosity	1	4	10^{34} cm^{2}sec^{-1}
Muons/bunch	2	2	10^{12}
Ring circumference	3	8.1	km
Beta at IP $= \sigma_z$	10	3	mm
rms momentum spread	0.1	0.12	%
Required depth for ν rad	13	135	m
Repetition Rate	12	6	Hz
Proton Driver power	$\approx$4	$\approx$ 1.8	MW
Muon Trans Emittance	25	25	pi mm mrad
Muon Long Emittance	72,000	72,000	pi mm mrad

MERIT Experiment

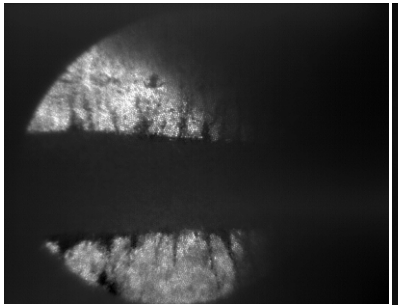
- MERIT completed beam test of Hg-jet target in 15-T magnetic field using CERN PS



Installation at CERN



Schematic of MERIT experimental setup



During After

10 Tp

MERIT Conclusions

- **Power handling of target is adequate**
  - disruption length of 28 cm ⇒ 70 Hz rep. rate at 20 m/s
  - 115 kJ per pulse x 70 Hz gives 8 MW of beam power
    - 4 MW design value seems "comfortable"

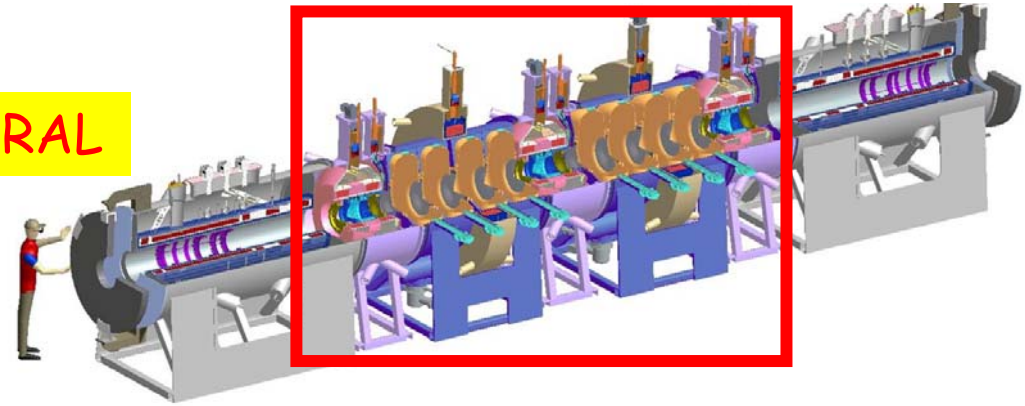
MERIT serves as a satisfactory proof-of-principle of Hg-jet concept

- **Issues to pursue (none require beam)**
  - look for damage to containment vessel from 60 m/s filaments
  - splash mitigation in Hg beam dump (from both beam and spent jet)
  - system aspects of continuous flow device

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 will teach 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

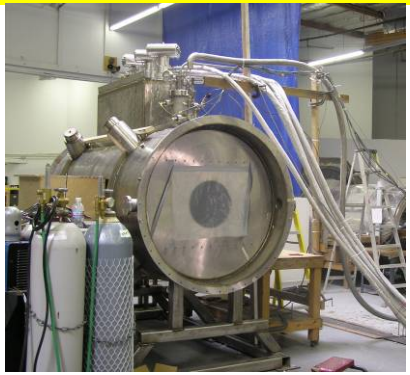
Experiment sited at RAL



Cooling Channel Components

- **All cooling channel components are now in production**

Spectrometer Solenoid (Wang NMR)

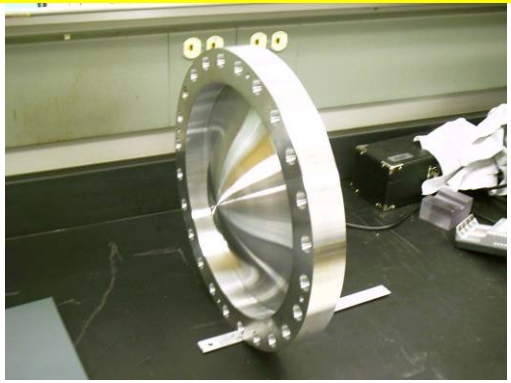


CC large test coil (HIT)

CC mandrel (Qihuan Co.)

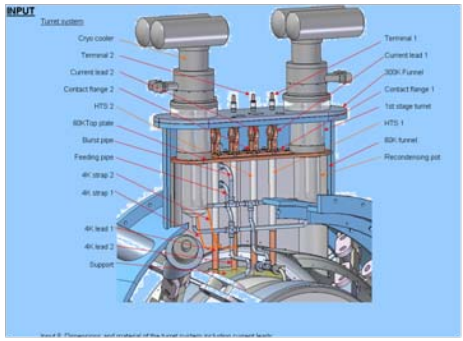
Absorber (KEK)

Absorber window (U-Miss)



Cavity half-shell (Acme)

FC (Tesla Eng., Ltd.)

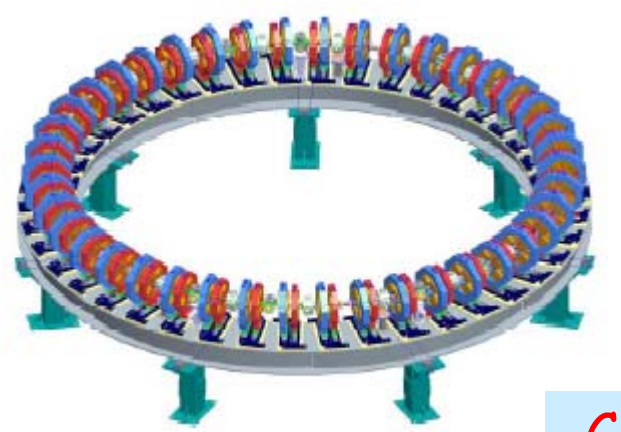


EMMA

- EMMA will test an electron model of a non-scaling FFAG
  - uses Daresbury ERLP as injector
  - aim:
    - demonstrate feasibility of non-scaling FFAG concept
      - investigate longitudinal dynamics, transmission, emittance growth, influence of resonances

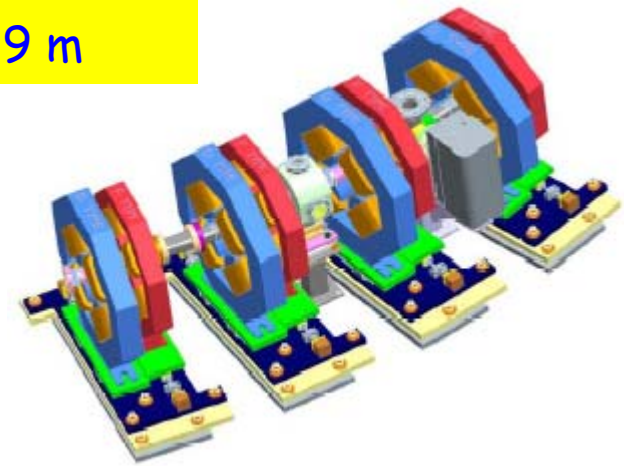
EMMA ring

C = 16.57 m



4 cells plus RF cavity

L_{cell} = 0.39 m



Components now being fabricated