International
Muon Ionization Cooling Experiment

Michael S. Zisman
CENTER FOR BEAM PHYSICS

for the MICE Collaboration

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Introduction

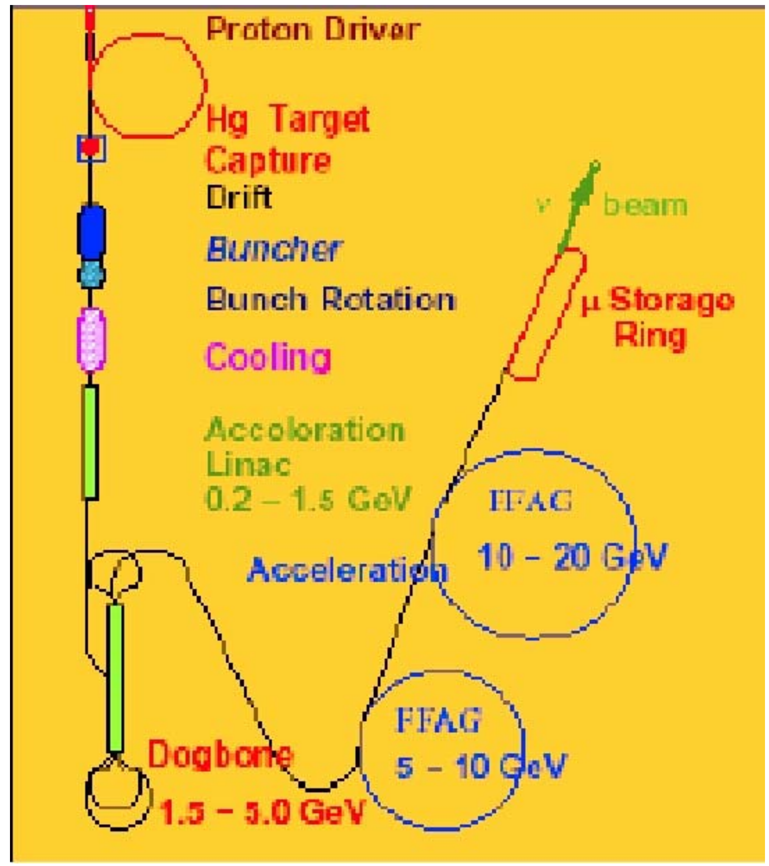
- Motivation for MICE
  - muon-based Neutrino Factory is most effective tool to probe neutrino sector and hopefully observe CP violation in lepton sector
    - results will test theories of neutrino masses and oscillation parameters, of importance for particle physics and cosmology
  - a high-performance Neutrino Factory ($\approx 4 \times 10^{20}$ ν_e aimed at far detector per 10^7 s year) depends on ionization cooling
    - straightforward physics, but not experimentally demonstrated
  - facility will be expensive ($\mathcal{O}$(€1B)), so prudence dictates a demonstration of the key principle
- Cooling demonstration aims:
  - to design, engineer, and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
  - to place this apparatus in a muon beam and measure its performance in a variety of modes of operation and beam conditions

Introduction

- Another aim
  - show that design tools (simulation codes) agree with experiment
    - gives confidence that we can optimize design of an actual facility
      - we test section of "a" cooling channel, not "the" cooling channel
        - simulations are the means to connect the two
- Both simulations and apparatus tested must be as realistic as possible
  - incorporate full engineering details of all components into simulation

Neutrino Factory Ingredients

- Neutrino Factory comprises these sections
  - Proton Driver
    (primary beam on production target)
  - Target and Capture
    (create π's; capture into decay channel)
  - Bunching and Phase Rotation
    (create bunches and reduce ΔE)
  - Cooling
    (reduce transverse emittance of beam)
    ⇒Muon Ionization Cooling Experiment
  - Acceleration
    (130 MeV → 20–50 GeV with RLAs/FFAGs)
  - Storage Ring
    (store muon beam for ≈500 turns; optimize yield with long straight section aimed in desired direction)

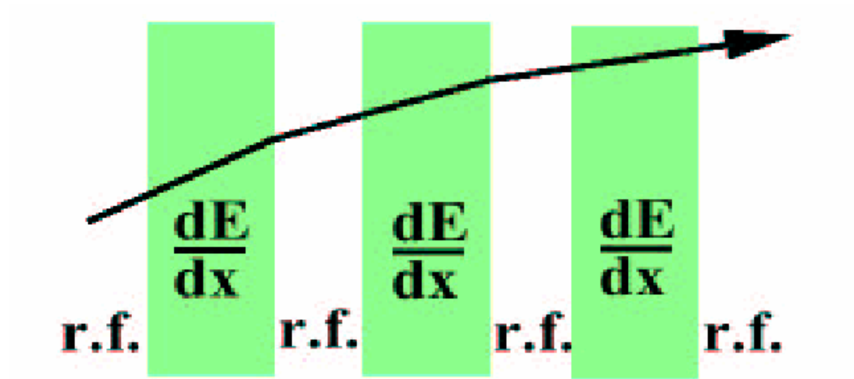


Study-IIa Neutrino Factory Layout

- Not an easy project, but no fundamental problems found to date

Cooling Description

- The need to cool the muons quickly dictates the approach to be used
  - muon lifetime in rest frame is 2.2 μs
    - "standard" stochastic cooling approach is much too slow
    - use novel technique of ionization cooling (tailor-made for muons)
- Analogous to familiar SR damping process in electron storage rings
  - energy loss (SR or *dE/dx*) reduces p_x, p_y, p_z
  - energy gain (RF cavities) restores only p_z
  - repeating this reduces $p_{x,y}/p_z$ and thus transverse emittance



Cooling Description

- There is also a heating term
  - with SR it is quantum excitation
  - with 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 $\beta_\perp$ ($\Rightarrow$ strong focusing), large X_0 and *dE/ds* ($\Rightarrow$ H_2 is best)

Cooling Description

- **Merit factors for candidate MICE absorbers (scaled as equilibrium emittance)**

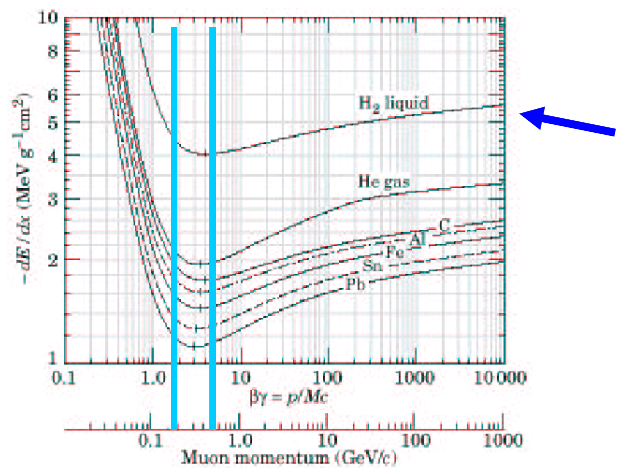
Material	$(dE/ds)_{min.}$ (MeV g^{-1} cm^2)	X_0 ($g\ cm^{-2}$)	Relative merit
Gaseous H_2	4.103	61.28	1.03
Liquid H_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18

— **requirements for Al windows and extended absorber with H_2 and He degrade these merit factors by roughly 30%**

- **H_2 is best, even with windows included**

Cooling Description

- Typical momentum chosen for transverse cooling is $p \approx$ 200 MeV/c
  - this is optimal in terms of muon production from thick target



Note benefits of LH_2 compared with other materials

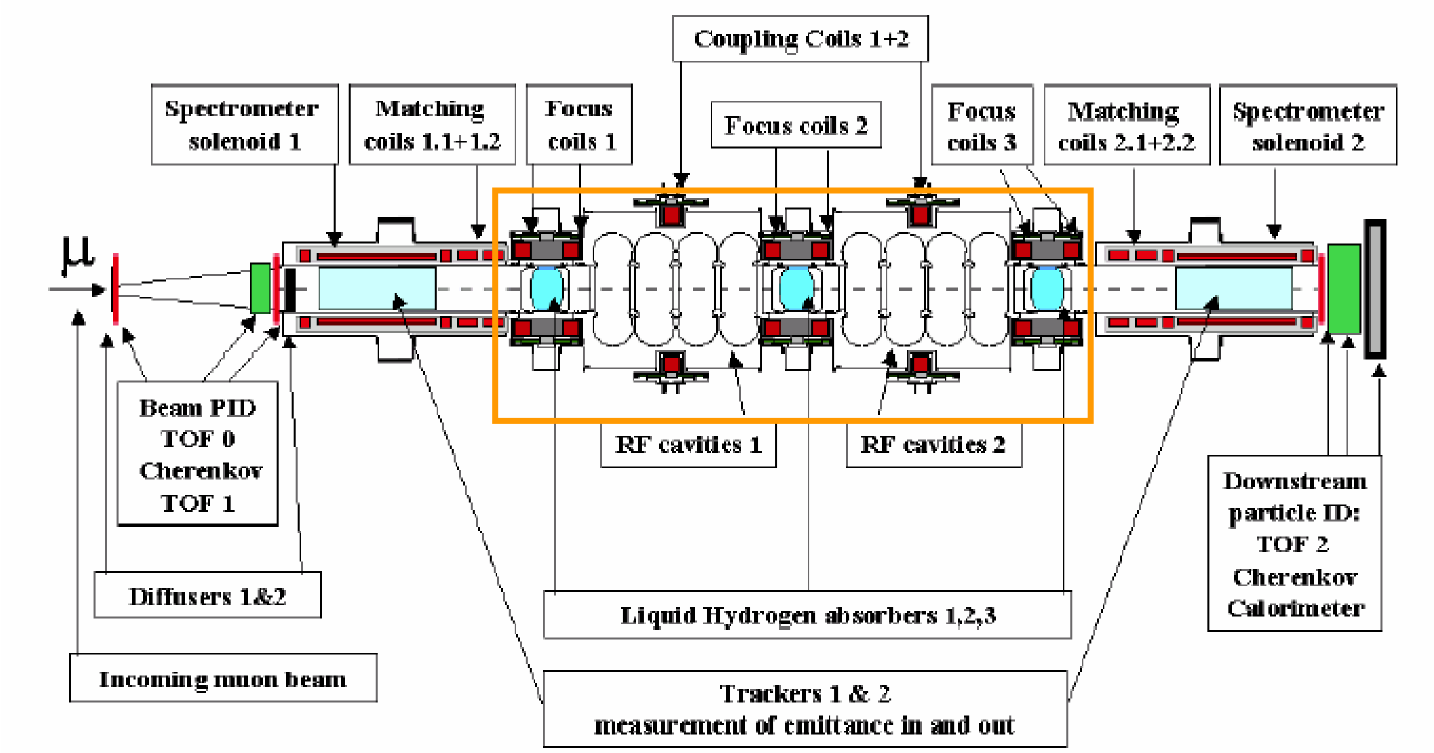
- Running below min. ionization energy increases longitudinal emittance
  - lower *E* particles have higher *dE/dx* than do higher *E* particles
- Running above min. ionization point disadvantageous for several reasons
  - more demanding RF and magnet requirements; more *E* straggling

Benefits of Cooling

- Why does a Neutrino Factory need cooling?
  - large phase space volume ("emittance") of initial muon beam is difficult to transport and accelerate efficiently
    - would require *very* large magnets and RF cavity apertures (possible in principle, but costly)
  - cooling increases muon density in a *given* acceptance by 4–10
    - the smaller the downstream acceptance, the larger the gain from cooling...and vice versa
- For many particle physicists, the Holy Grail of muon beam R&D is to build a Muon Collider
  - collider gives energy-frontier facility in small footprint
  - for this application, cooling is mandatory!

MICE Implementation

- Layout of MICE components
  - one lattice cell of cooling channel components (based on U.S. Study-II configuration) is indicated
  - note that cooling channel is simply a linac with absorber material added



MICE Implementation

- Basic ingredients of a cooling channel are:
  - solenoid magnets to contain muons as they traverse the channel ($B \approx 3$ T)
  - absorbers to give energy loss (LH_2, capable of handling ~100 W)
  - RF cavities to restore energy (16 MV/m gradient at 201 MHz)
    - power limitations (and probably background rates) preclude this gradient for MICE, which will typically operate at 8 MV/m
- For MICE, we add
  - diffuser to create large emittance sample
  - upstream diagnostics section to define initial emittance
  - downstream diagnostics section to determine final emittance and particle ID

MICE Implementation

- Simulations of MICE performance have been done
  - several tools developed/adapted for cooling simulations (ICOOL, Geant4)
  - simulations of nominal cooling channel performance done with ICOOL
  - full MICE simulations with all details are done with Geant (G4MICE)
- Typical parameters
  - beam

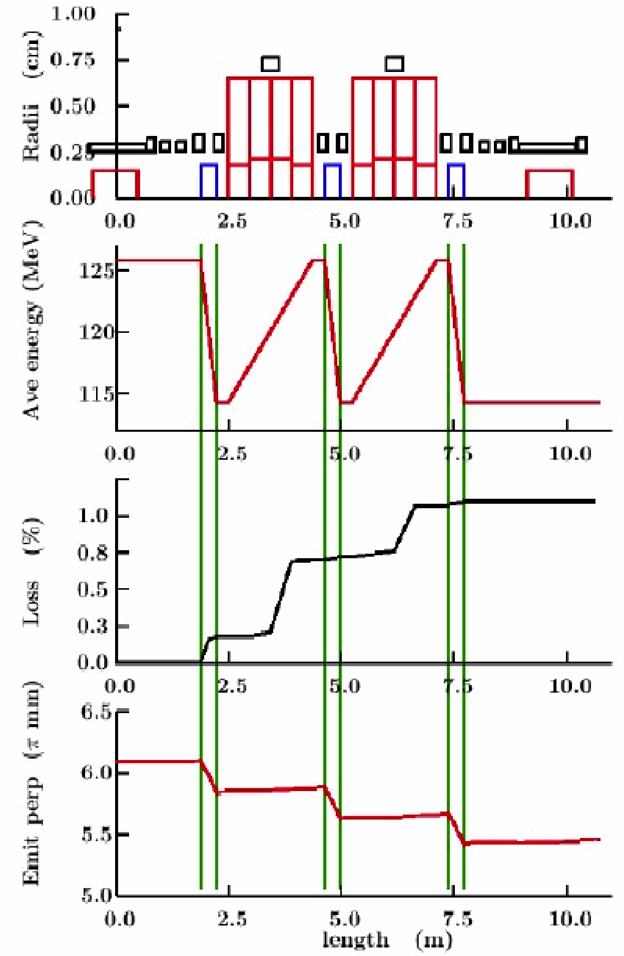
    momentum: 200 MeV/c (variable)
    momentum spread: $\pm$20 MeV/c
    $\sigma_{x,y} \approx$ 5 cm; $\sigma_{x',y'} \approx$ 150 mrad

  - channel

    solenoid field: $\approx$3 T
    $\beta_{\perp}$: 0.42 m
    cavity phase: 90° (on crest)

MICE Implementation

- ICOOL simulation of the MICE experiment shows transverse emittance reduction of ≈10%



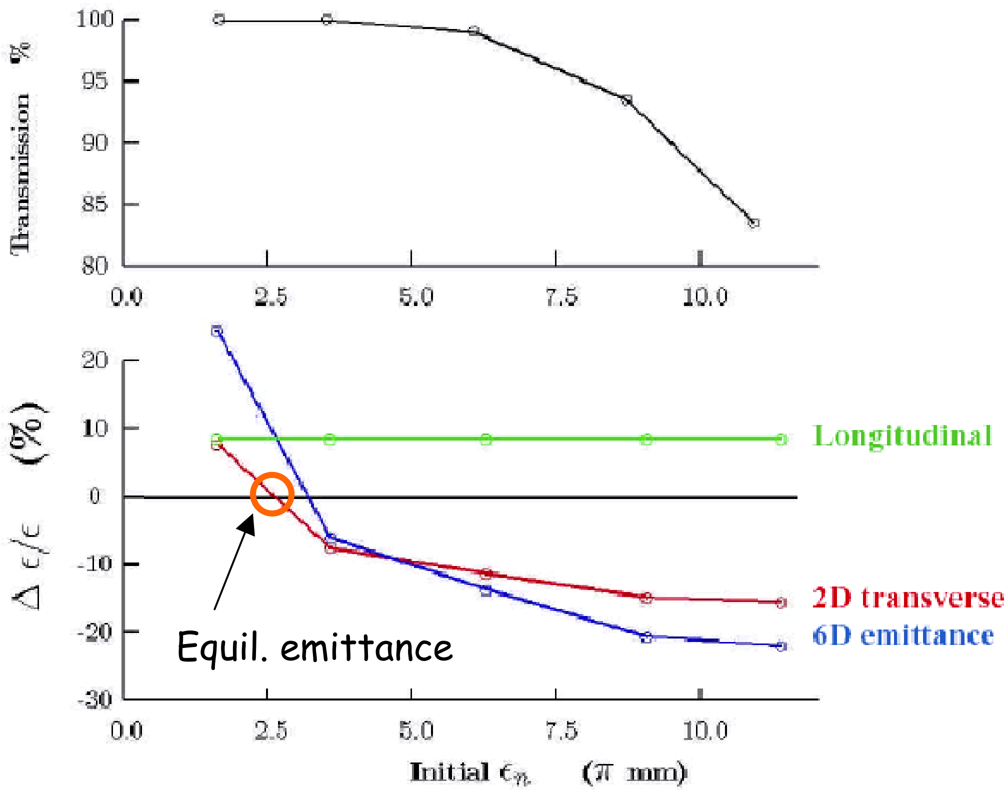
Energy variation

Particle loss

2D ε reduction

MICE Implementation

— virtual "scan" over input emittance locates the equilibrium emittance



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

— transmission is 100% for input emittance below 6 mm-rad

- high-emittance behavior reflects "scraping" as well as cooling

MICE Implementation

— important to test alternatives from baseline case to verify scaling

- different absorber materials (LHe, Li, Be,...); different beta functions

— these permit variation of heating and cooling terms, hence ε_{equil}.

- practical limit on reducing $\beta_\perp$ is current density in focusing coils
- doing low-beta tests at lower momentum avoids this limitation

Case	p (MeV/c)	$\beta_\perp$ (cm)
1a	200	42
1b	240	42
2	200	25.4
3	175	16.7
4	150	10.5
5	140	5.7

— operating with higher RF gradients (fewer cavities) or LN-temperature cavities is also possible

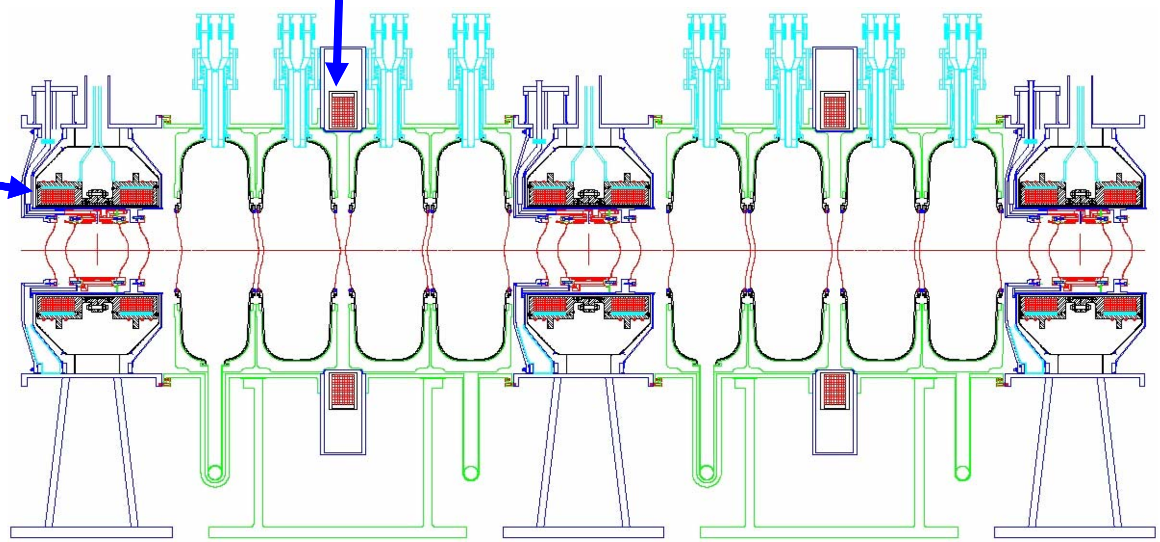
MICE Implementation

- Main challenge of MICE
  - for cost reasons, we use only a single cell of a cooling channel

    ⇒emittance reduction will be small in absolute terms ($\mathcal{O}$(10%))
    - wish to measure emittance reduction at level of 10^{-3}
- Other challenges
  - operating high-gradient RF cavities in solenoidal field and with field terminations (windows or grids)
  - operating LH_2 absorbers with very thin windows and consistent with safety regulations
  - integration of cooling channel components while maintaining operational functionality
  - these build upon R&D activities already under way outside of MICE
    - mainly under auspices of U.S. Neutrino Factory and Muon Collider Collaboration ("MC")

Cooling Hardware

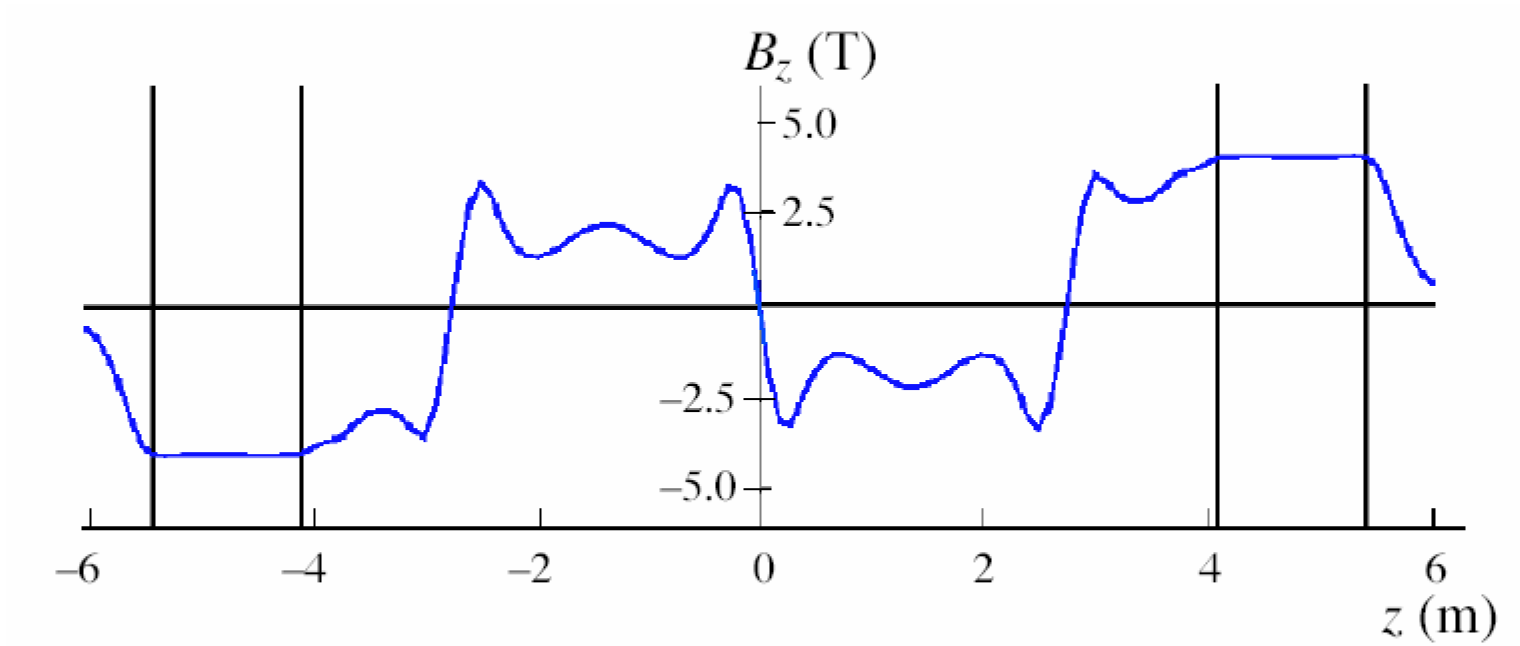
- Solenoid magnets
  - two types of coil required
    - focusing coils (integrated with absorber; cooled with cryocoolers)
    - coupling coils (outside of RF cavity module; also uses cryocoolers)



Note "complications" of actual implementation

Cooling Hardware

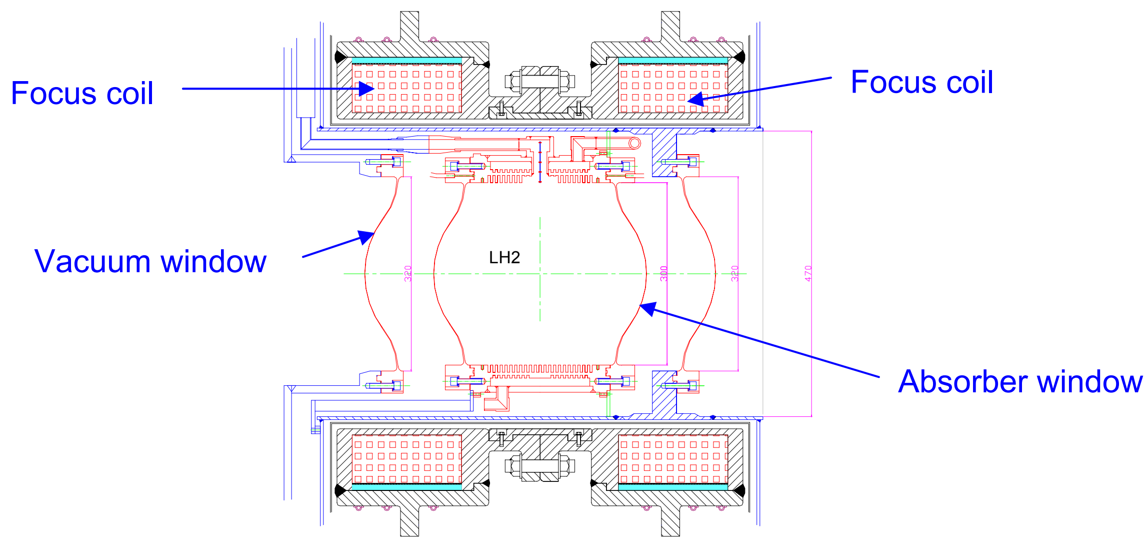
- Field profile used in the design simulations is based on the indicated coil configuration
  - — z = 0 is centerline of experiment (middle of central absorber)



- An alternative magnetic configuration with no field flip can also be tested

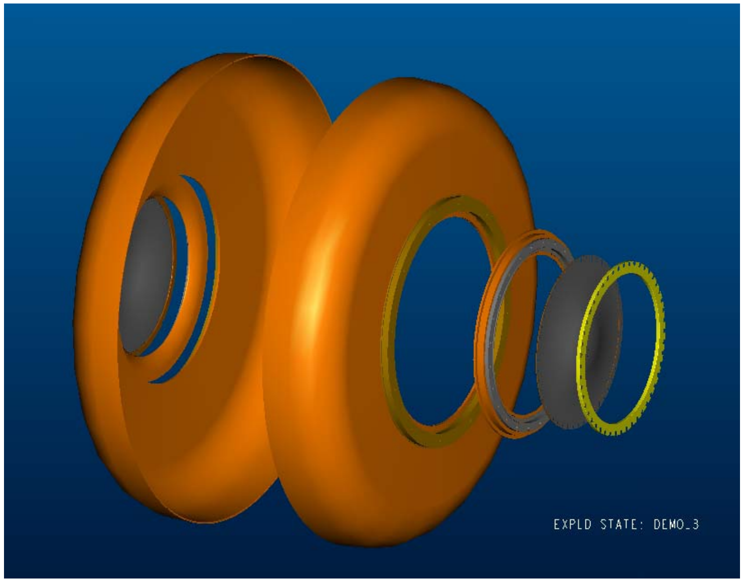
Cooling Hardware

- Absorbers
  - design based on LH_2 system with internal convection cooling
  - requires large diameter (300 mm), very thin (but strong!) Al windows
    - plus a second set of safety windows to form vacuum barrier
  - design tightly integrated with focusing coil package

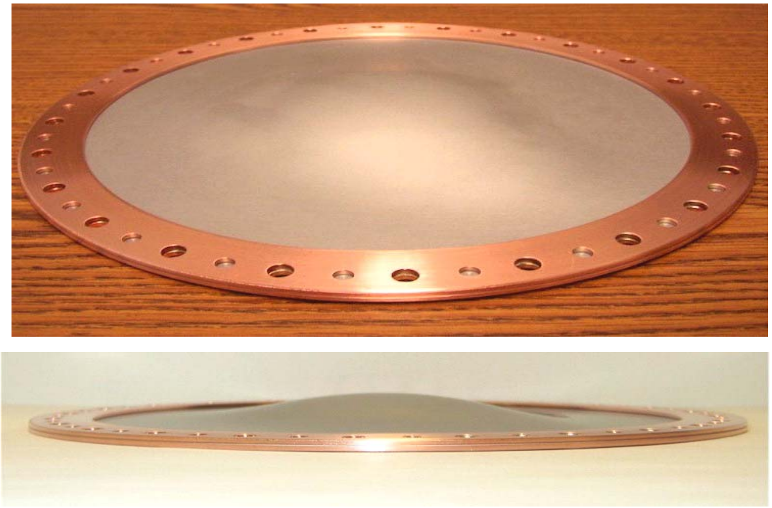


Cooling Hardware

- 201 MHz RF cavity
  - RF module comprises 4 cavities with individual tuner mechanisms
  - cavities use precurved Be foils to increase shunt impedance



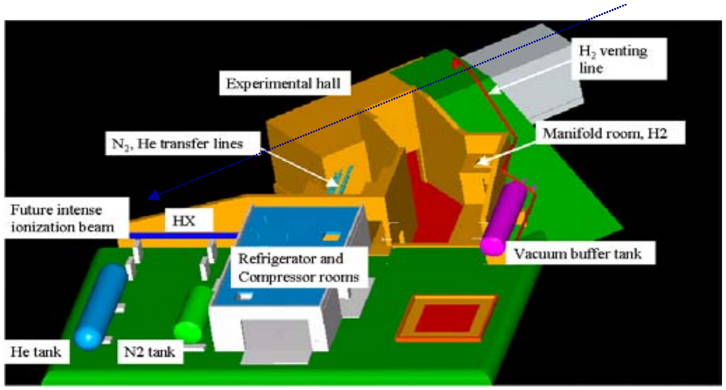
Exploded view of 201 MHz cavity
(1.2 m diameter)



805 MHz version of precurved Be window

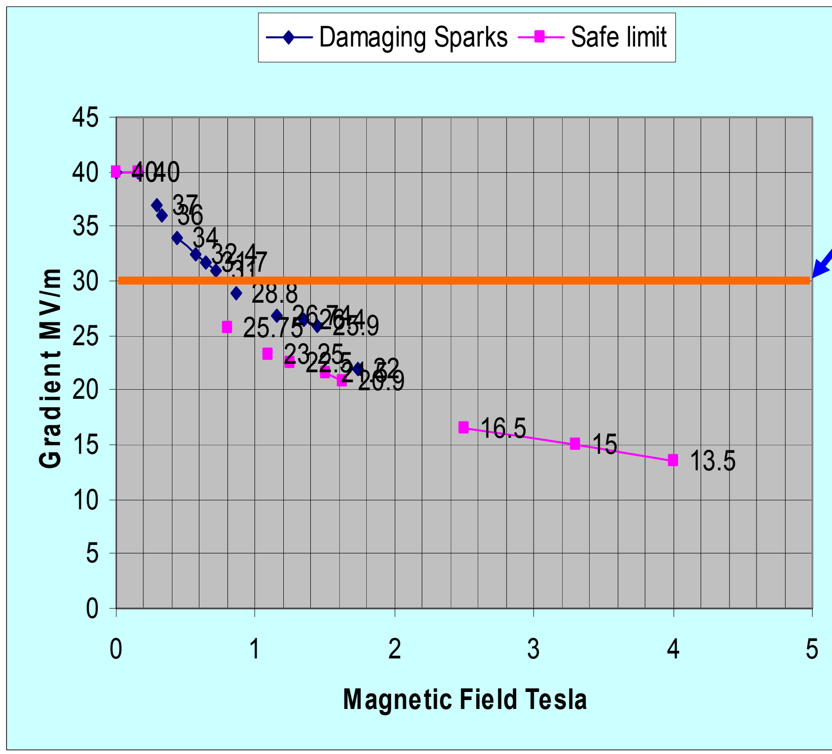
MUCOOL R&D Program

- Ability of MICE collaboration to achieve its goals greatly enhanced by hardware R&D programs under way worldwide
- U.S. MUCOOL R&D program has substantial effort in place to develop required hardware components for MICE
  - RF cavities, absorbers
- MUCOOL is building and testing prototypes of the absorber and 201-MHz RF cavity needed for MICE
  - a new area dedicated for component testing, the MUCOOL Test Area (MTA) is now in use at Fermilab



MUCOOL R&D Program

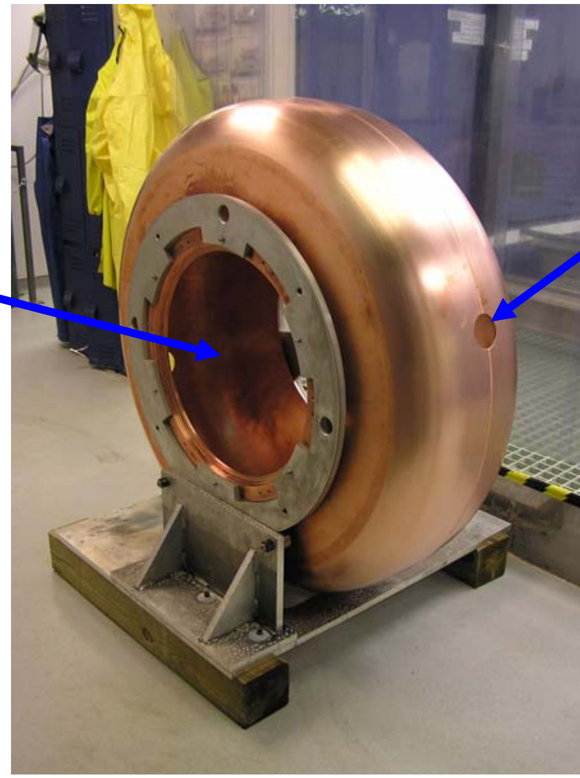
- Main RF challenge is to attain high gradient in the presence of a high magnetic field
  - increased breakdown and dark currents observed at 805 MHz
  - tests of different materials and coatings to mitigate effect will begin shortly



Desired gradient at 805 MHz

MUCOOL R&D Program

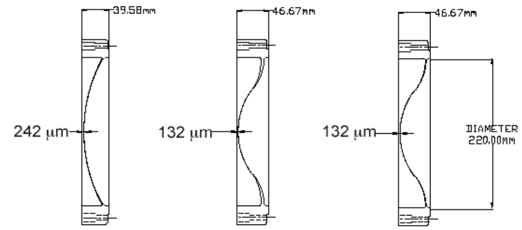
- Construction of 201 MHz RF cavity (LBNL, U-Miss., Jlab) is well along



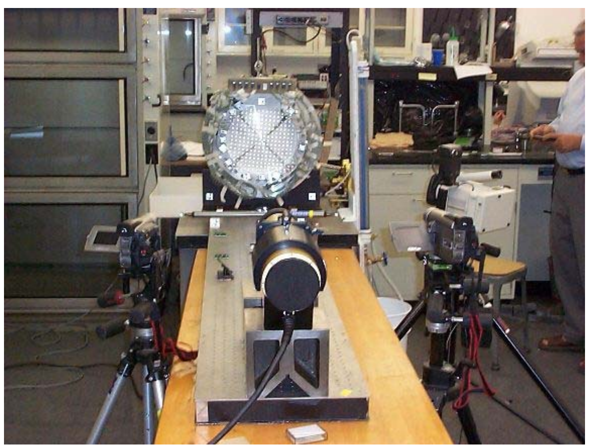
  - fabrication of prototype will be completed this year

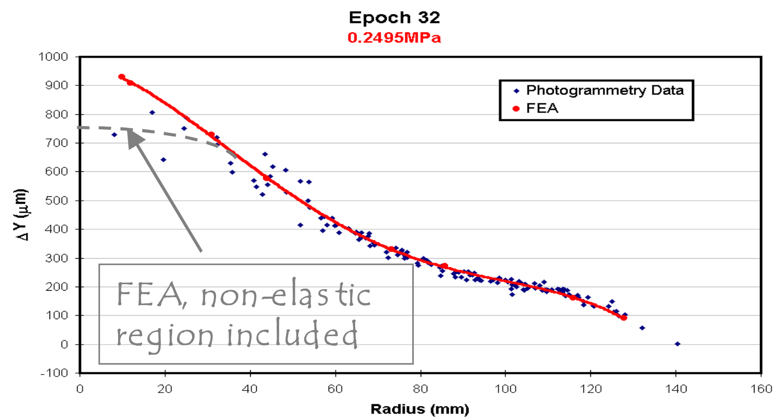
MUCOOL R&D Program

- Absorber work focusing mainly on developing strong, thin windows (IIT, NIU, Oxford, U-Miss.)
  - destruction tested windows at NIU (with satisfactory results)
    - 340 μm windows break at 120 psi (8 atm)
    - new inflected window shape is stronger and can be even thinner



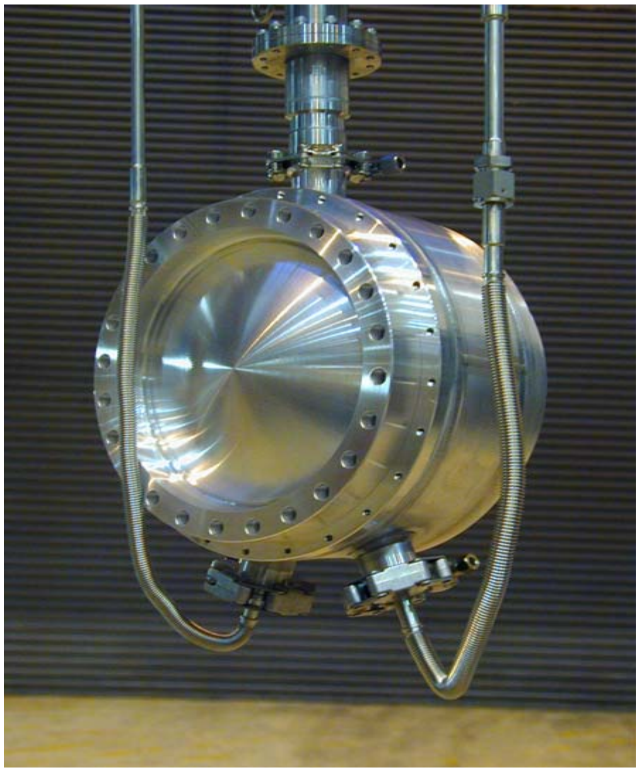
  - use photogrammetry to characterize window behavior and verify FEA calculations (LH_2 safety requirement)





MUCOOL R&D Program

- Convection-cooled absorber prototype fabricated at KEK
  - recently tested at Fermilab with LH_2 (with no leaks!)



Prototype LH_2 absorber

Test cryostat at MTA

MICE Instrumentation

- Parallel R&D effort on MICE instrumentation is under way
- Upstream PID
  - TOF (70 ps resolution) used for PID, trigger, timing with respect to RF phase; Milan
  - Cerenkov used for π/μ separation; U.-Mississippi
- Downstream PID
  - Electromagnetic calorimeter used for μ/e separation; Rome III
  - Cerenkov used for μ/e separation; Louvain
- Tracker (baseline option)
  - scintillating fiber tracker (5 stations, planar) used for 6D emittance measurement; Bari, Brunel, CERN, Edinburgh, FNAL, Geneva, IIT, Imperial College, KEK, Legnaro, Liverpool, Napoli, Osaka, UCLA, UC-Riverside

MICE Status

- MICE status
  - proposal submitted in January, 2003
    - international review held February, 2003 (recommended approval)
    - scientific approval from RAL in October, 2003
  - absorber system concept passed preliminary safety review by international review panel in December, 2003
  - estimated hardware cost is £11M (total cost £25M)
    - more than half of this is now in hand (mainly UK)
- In U.S., MUTAC + MCOG have strongly recommended MICE the past two years
  - experiment considered "crucially important demonstration"
- U.S. funding request submitted to NSF (under review)
  - stagnant funding makes it hard to launch new initiatives

MICE Status

- **Collaborating institutions**

Europe
Bari
Brunel
CERN
Edinburgh
Genève
Genova
Glasgow
Imperial College
Legnaro
Liverpool
LNF Frascati
Louvain la Neuve
Milano
Napoli
NIKHEF
Novosibirsk
Oxford
Padova
PSI
RAL
Roma III
Sheffield
Trieste

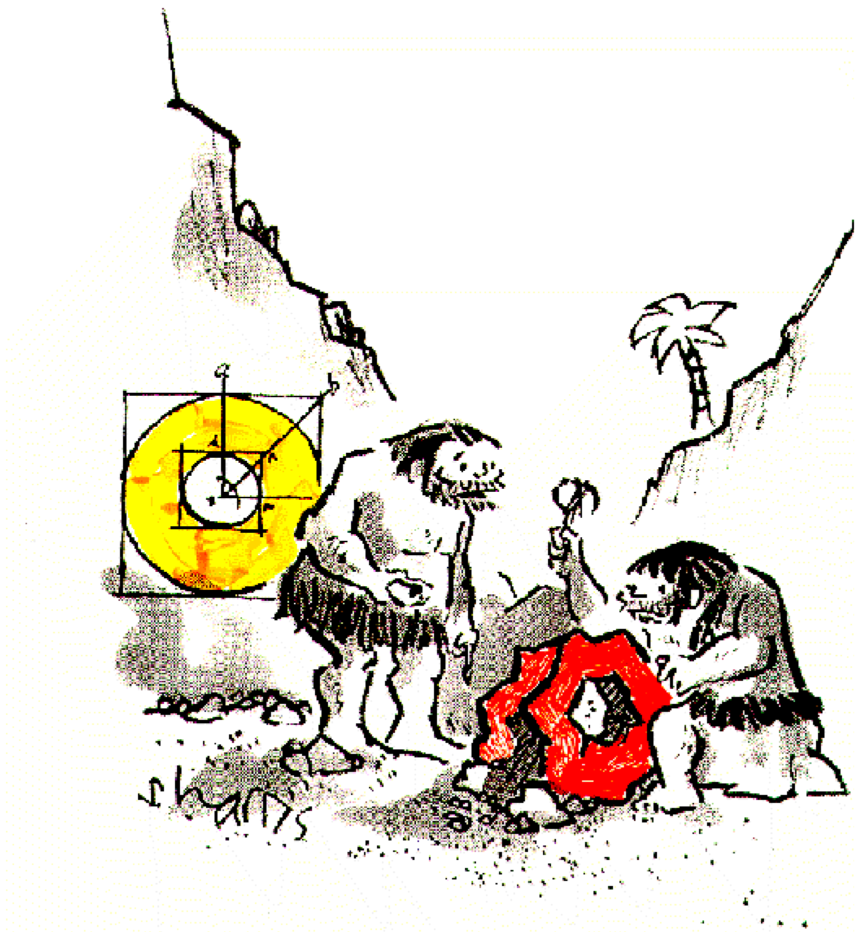
Japan
KEK
Osaka

U.S.
ANL
BNL
Chicago-Enrico Fermi Institute
FNAL
Illinois Institute of Technology
TJNAF
LBNL
Mississippi
Northern Illinois
UCLA
UC-Riverside

Summary

- R&D on required MICE components is already at an advanced stage
- MICE will assemble and test these components in a realistic beam environment
  - as new ideas mature, MICE will likely serve as a test-bed for other components
- MICE is a very challenging "linac R&D" program
  - additional collaborators are still very much welcome!
- Resultant demonstration of muon cooling will validate key concept of Neutrino Factory design
  - and put Muon Collider concept closer to realization
- Measured cooling performance will "calibrate" our design tools
  - permitting cost and performance optimization of future Neutrino Factory

...*the beam never lies!*



"I guess there'll <u>always</u> be a gap between science and technology."