International
Muon Ionization Cooling Experiment

Accelerator Physics Aspects

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MICE Review—RAL
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Outline

- Introduction
- Neutrino factory ingredients
- Cooling description
- Benefits of cooling
- MICE implementation
- Cooling hardware
- MUCOOL R&D program
- Summary
- Final remarks

Introduction

- Motivation for MICE
  - design of high-performance Neutrino Factory (≈4 x 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))
    - 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

- Other requirements
  - 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
- Thus, need both simulations and apparatus tested to be as close to reality as possible
  - incorporate full engineering details of all components into simulation

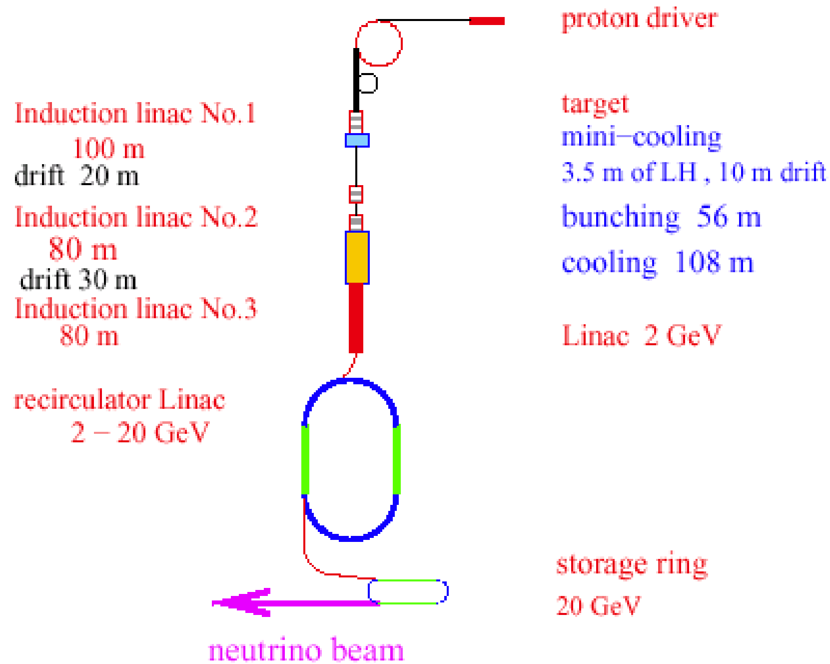
Introduction

- Challenge of MICE
  - for cost reasons, we use only a few cells of a cooling channel

    ⇒emittance reduction will be small in absolute terms ($\mathcal{O}$(10%))
    - need to measure emittance reduction at level of 10^{-3} (VP talk)
- 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

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)
  - Phase Rotation
    (reduce ΔE of bunch)
  - Cooling
    (reduce transverse emittance of beam)
    ⇒Muon Ionization Cooling Experiment
  - Acceleration
    (130 MeV → 20–50 GeV with RLAs)
  - Storage Ring
    (store muon beam for ≈500 turns; optimize yield with long straight section aimed in desired direction)

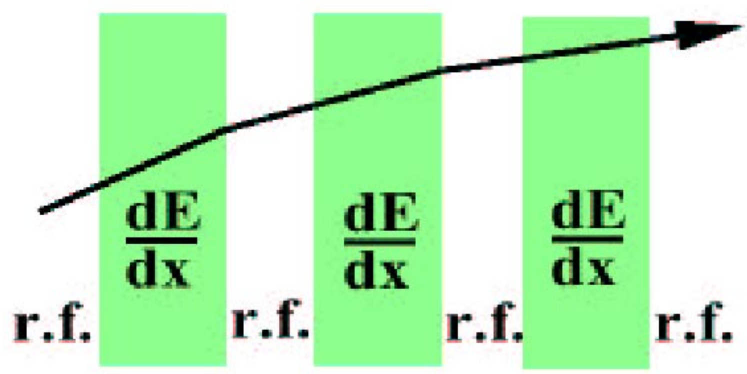


Study-II Neutrino Factory Layout

- 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

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

cooling heating

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

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

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Cooling Description

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

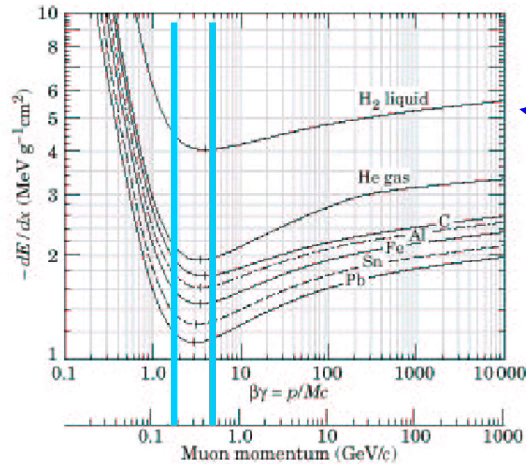
Material	$(dE/ds)_{min.}$ (MeV g^{-1} cm^2)	X_0 (g cm^{-2})	Relative merit
Gaseous H_2	4.103	61.28	1.03
Liquid H_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18

— 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

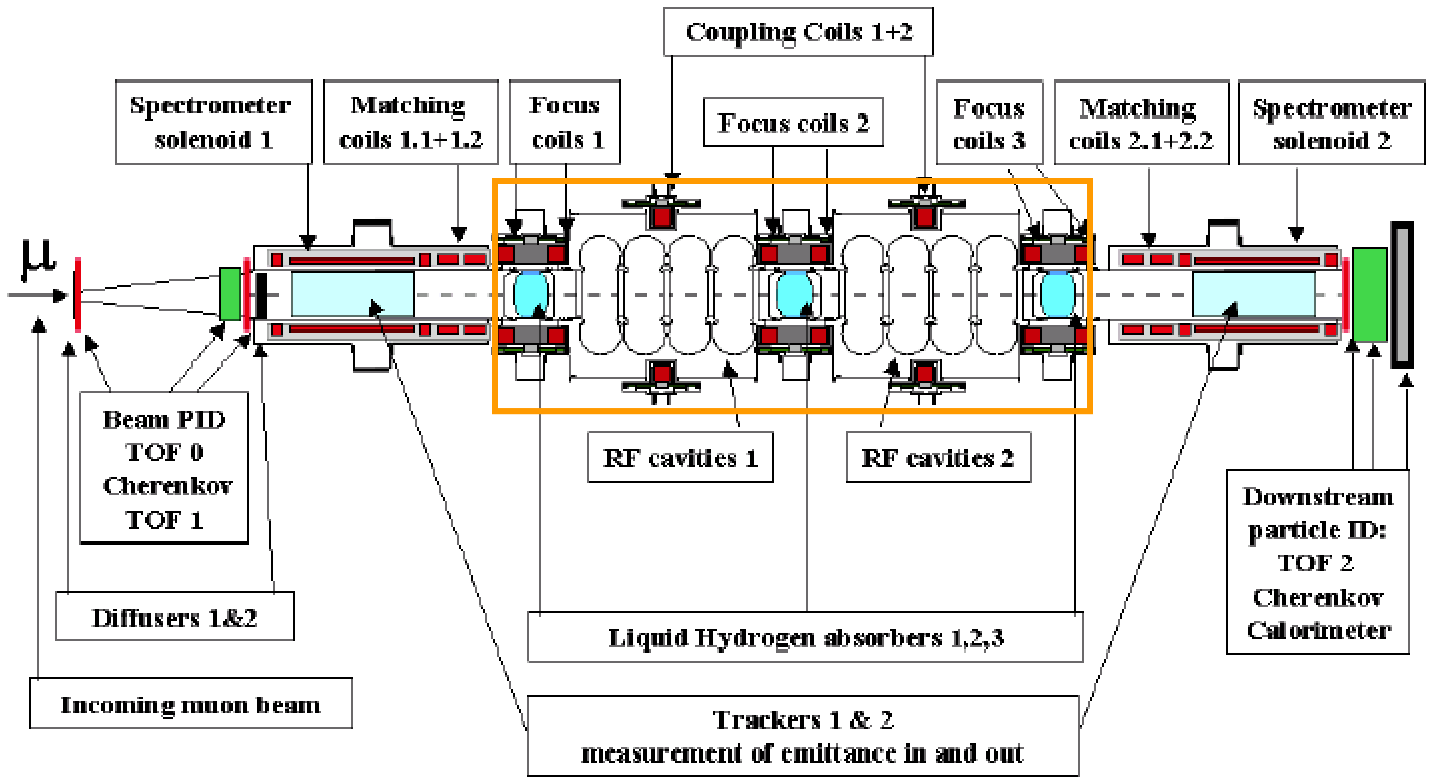
- Running below min. ionization energy increases longitudinal emittance
  - lower *E* particles have higher *dE/dx* than do higher *E* particles
- Running above min. ionization point disadvantageous for several reasons
  - more demanding RF and magnet requirements; more *E* straggling
- In general, lower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

Benefits of Cooling

- Why do we 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 very 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
- MICE calibrates cost and performance of actual cooling hardware
  - — permits quantitatively evaluating cost trade-offs between cooling and acceleration to arrive at a cost-optimized configuration
    - from Studies I and II, each acceleration stage costs €500M
- For many particle physicists, the Holy Grail of muon beam R&D is to build a Muon Collider, for which cooling is a necessity

MICE Implementation

- Layout of MICE components
  - one lattice cell of cooling channel components (based on U.S. Study-II configuration) is indicated



MICE Implementation

- Simulations of MICE performance have been done
  - several tools developed/adapted for cooling simulations (ICOOL, PATH, Geant)
  - codes have been cross checked and (now) give consistent results
  - full experimental simulations with all details are done with Geant
  - simulations of nominal cooling channel performance done with ICOOL
- Typical parameters
  - beam

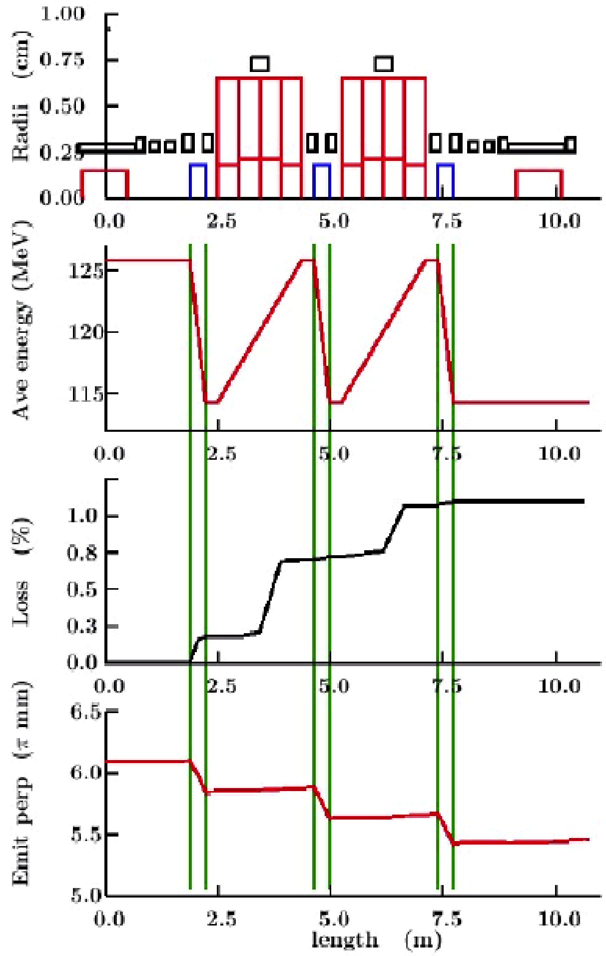
    momentum: 200 MeV/c (variable)
    momentum spread: ±20 MeV/c
    $\sigma_{x,y} \approx 5$ cm; $\sigma_{x',y'} \approx 150$ mrad

  - channel

    solenoid field: ≈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%



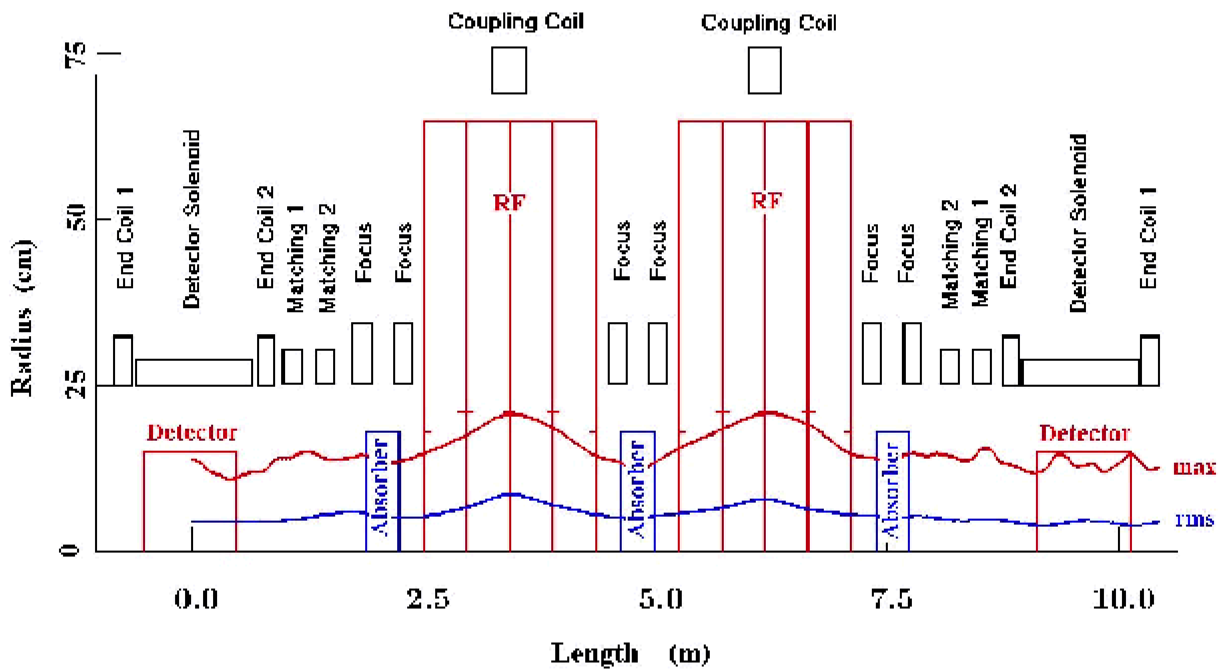
Energy variation

Particle loss

2D ε reduction

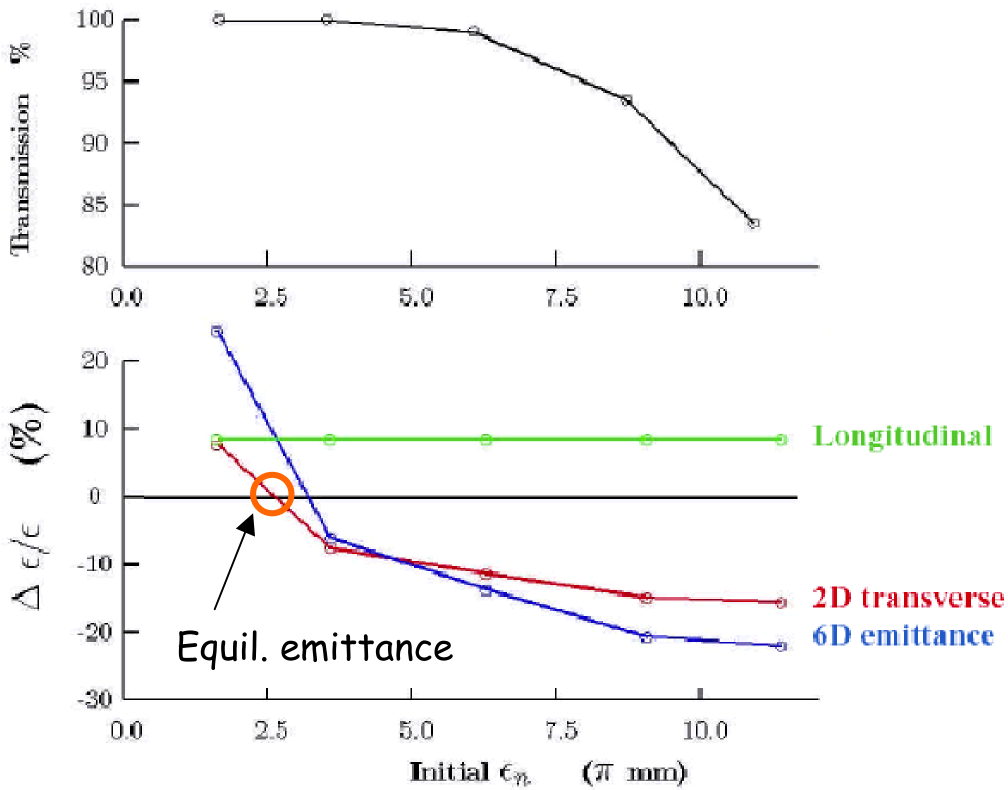
MICE Implementation

— cooling channel acceptance is limited by central RF cavity window dimension (21 cm)



MICE Implementation

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



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

— transmission is 100% for input emittance below 6 mm

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

MICE Implementation

— important to test alternatives from baseline case

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

— these permit variation of heating and cooling terms, hence $\varepsilon_{equil.}$

- 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

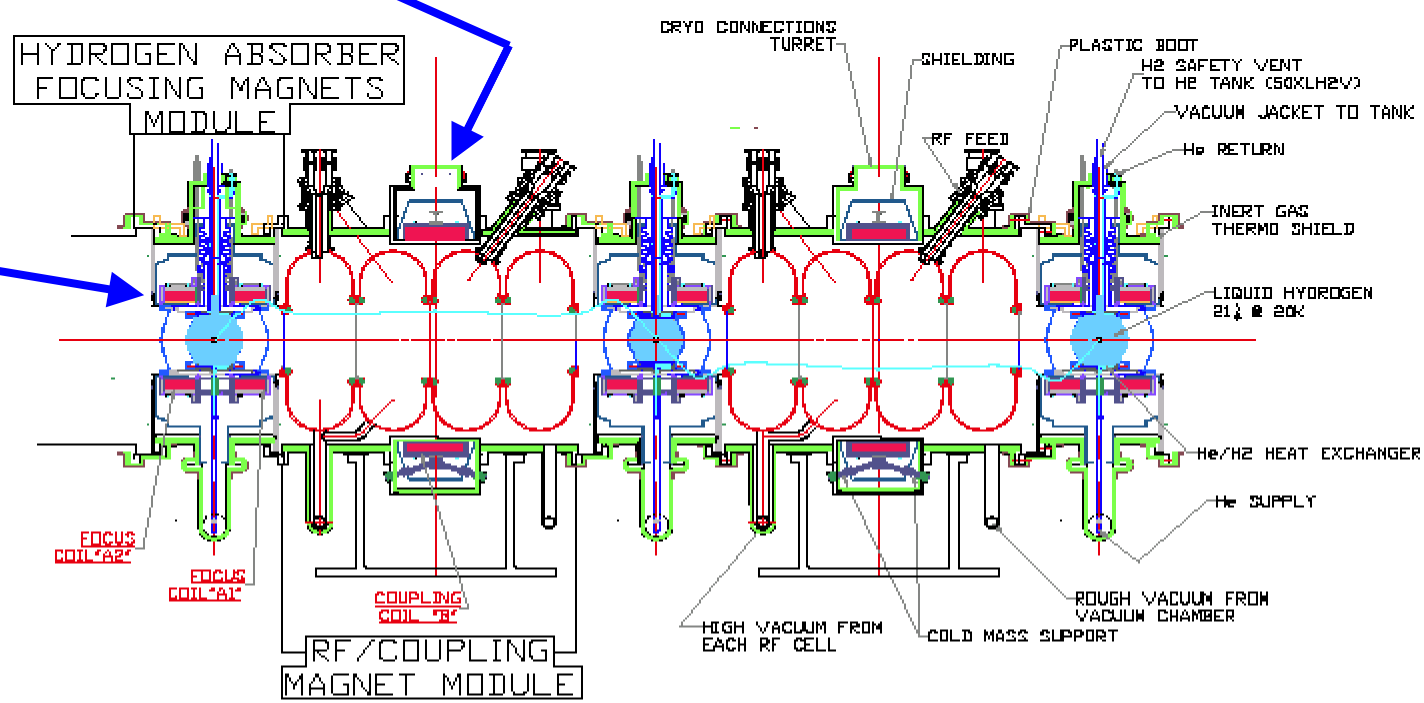
— operating with higher RF gradients (fewer cavities) or LN-temperature cavities is also possible

Cooling Hardware

- Basic ingredients of a cooling channel are:
  - absorbers to give energy loss (LH_2, capable of handling ~100 W)
  - RF cavities to restore energy lost in absorbers (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
  - solenoid magnets to contain the muons as they traverse the channel ($B \approx 5$ T)
- For MICE, we add (see VP talk)
  - diffuser to create large emittance sample
  - upstream diagnostics section to define initial emittance
  - downstream diagnostics section to determine final emittance and particle ID

Cooling Hardware

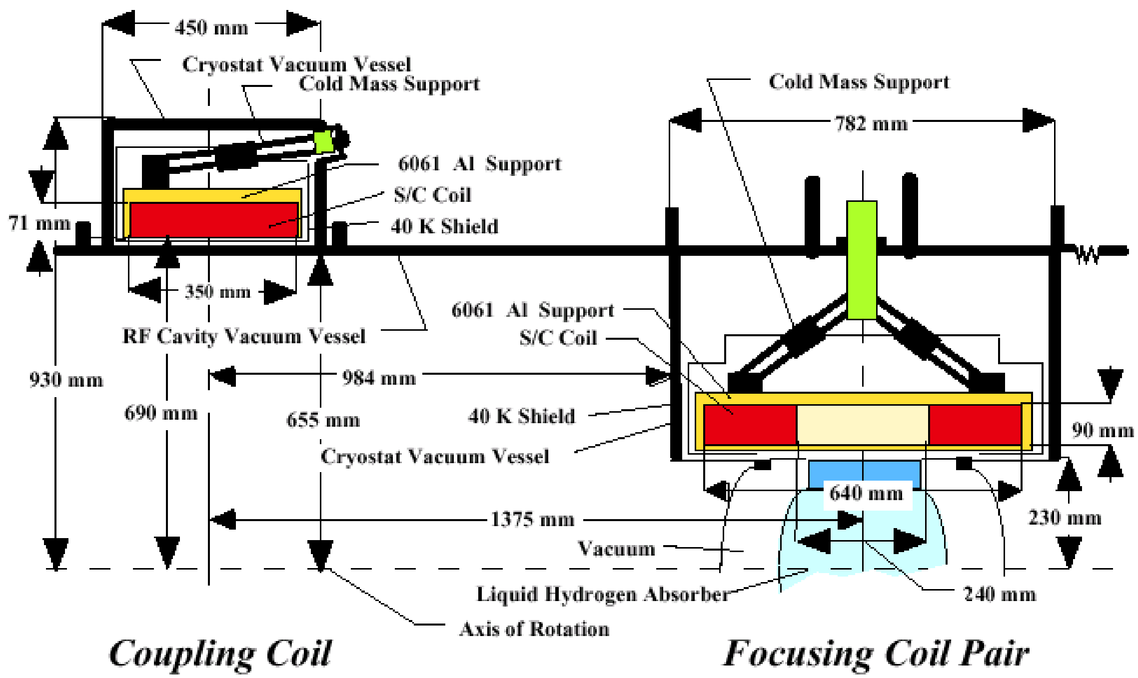
- Solenoid magnets
  - two types of coil required
    - focusing coils (integrated with absorber)
    - coupling coils (outside of RF cavity module)



Note "complications" of actual implementation

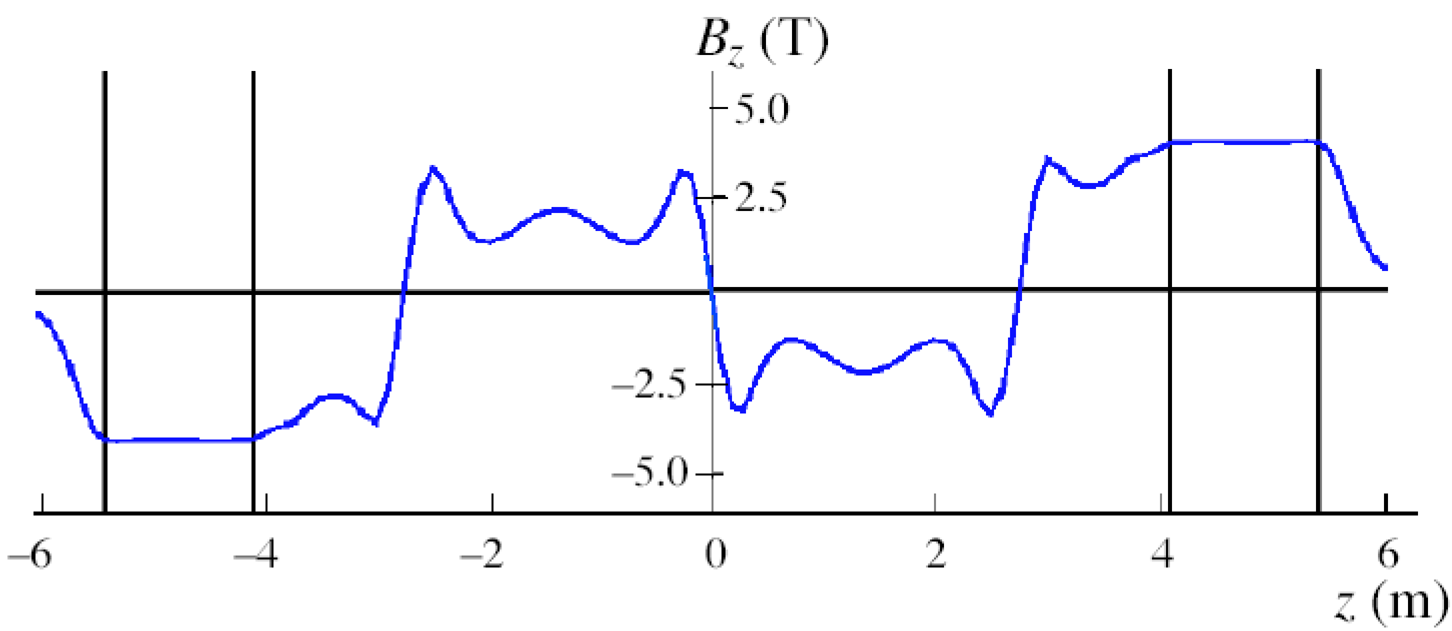
Cooling Hardware

- Magnets *per se* are within limits of today's technology
  - main issue is mechanical forces on coils during normal and off-normal conditions
    - support structures accommodate forces (few MN for focusing coil)
    - powering sets of like magnets in series reduces the number of off-normal possibilities to be analyzed



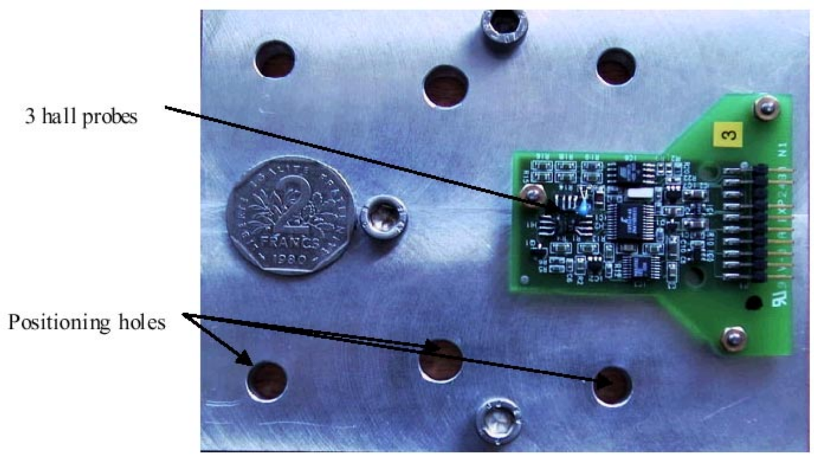
Cooling Hardware

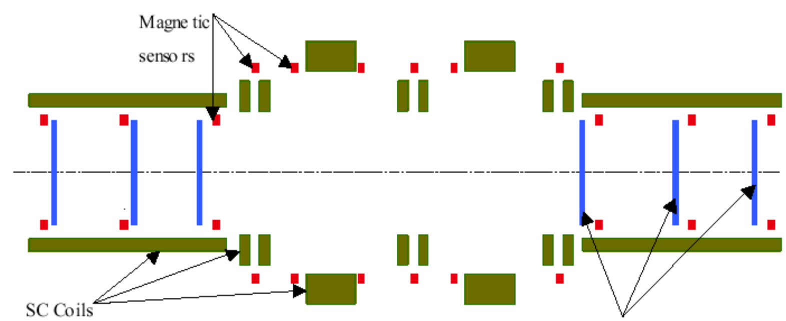
- Field profile used in the design simulations is based on the indicated coil configuration
  - z = 0 is centerline of experiment (middle of central absorber)



Cooling Hardware

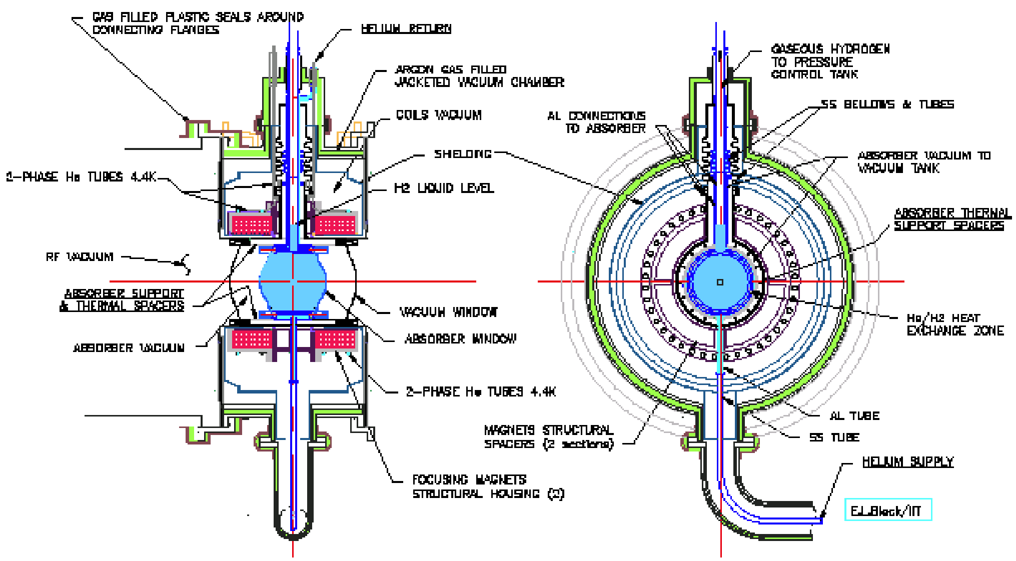
- Measurement technique based on existing ATLAS design
  - use calibrated Hall probes in precisely-known locations with respect to magnet coils
    - magnetic field requirement is higher than for ATLAS, so some upgrading of probes is needed (already under way for CMS)
  - probes located inside spectrometers, outside cooling channel magnets





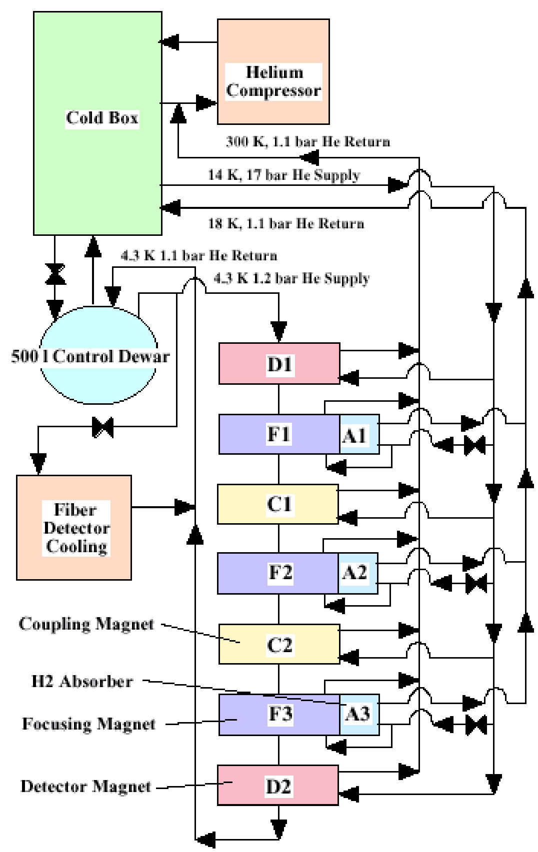
Cooling Hardware

- Absorbers
  - design based on LH_2 system with internal convection cooling
  - requires large diameter, very thin (but strong!) Al windows
    - plus a second set of safety windows to form vacuum barrier (and inert gas barrier to prevent O_2 ingress)
  - design tightly integrated with focusing coil package



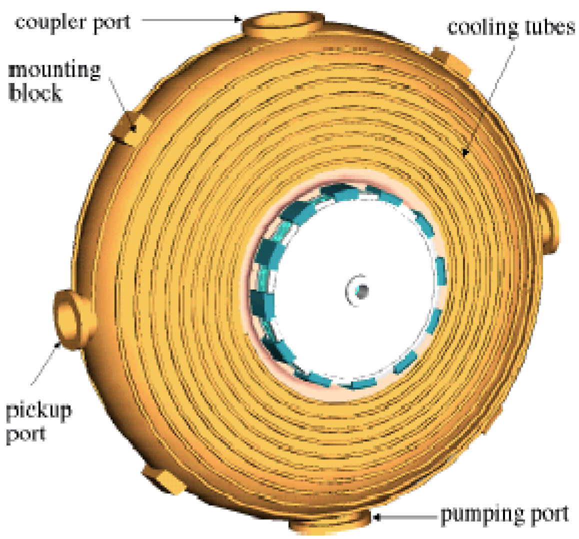
Cooling Hardware

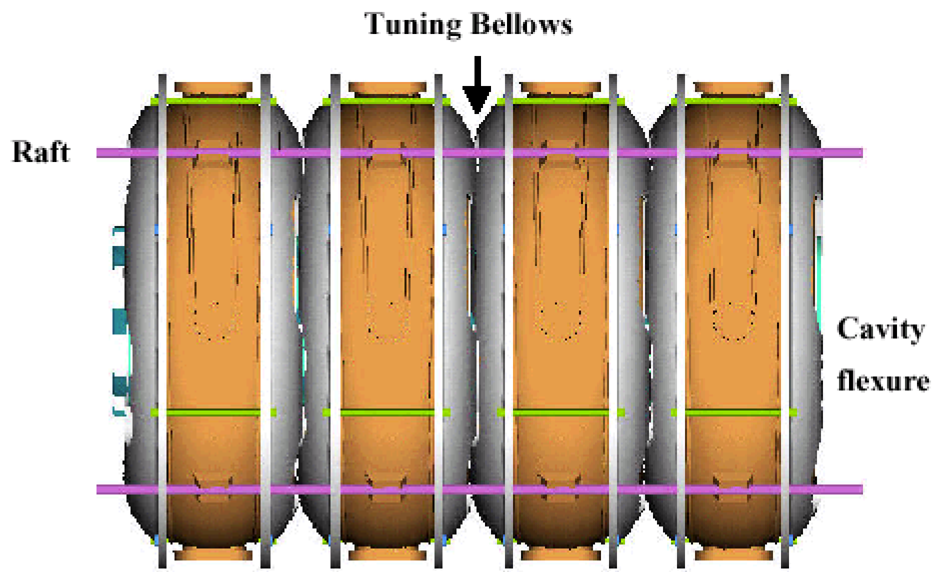
- Cryogenic system based on single 500-W He refrigerator
  - handles all cryo loads (magnets, absorber, detector electronics)
    - margin to accommodate filling absorbers with LHe if desired



Cooling Hardware

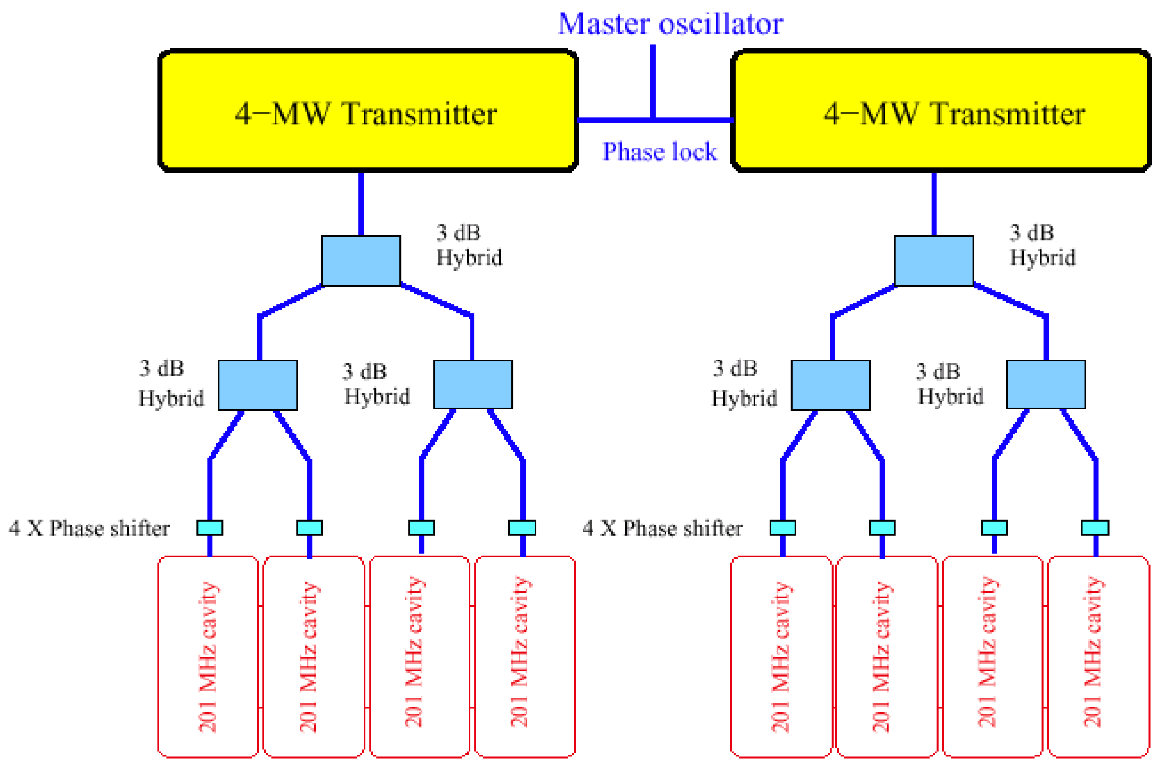
- 201 MHz RF cavity
  - RF module comprises 4 cavities with individual tuner mechanisms
  - cavities use Be foils to increase shunt impedance





Cooling Hardware

- Power source will provide 8 MW peak power
  - $V_{tot} \approx$ 21 MV (on crest); peak surf. field ≈12 MV/m (<1 Kilpatrick)
  - higher gradients can be tested if power applied to fewer cavities

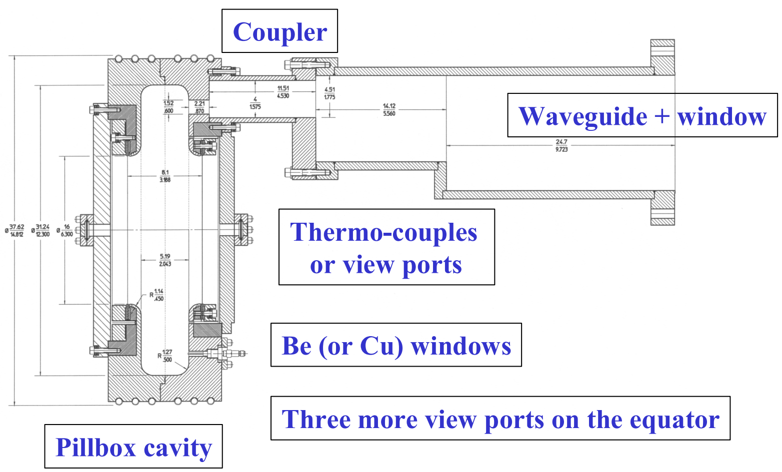


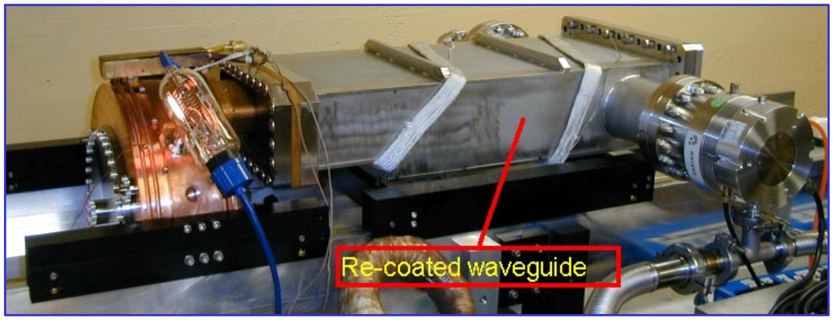
MUCOOL R&D Program

- 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
  - absorbers, RF cavities, magnets
  - $1–1.5M per year activity; 15–20 FTE
- MUCOOL anticipates building and testing prototypes of the absorber and 201-MHz RF cavity needed for MICE, and possibly the coupling coil as well
  - a solenoid similar to focusing coils has already been built and operated
  - a new area dedicated for component testing, the MUCOOL Test Area (MTA) is now under construction at Fermilab
    - this alone represents a $2M contribution in support of MICE

MUCOOL R&D Program

- 805 MHz cavity with foils being tested at Fermilab Lab G
  - gives advance information on:
    - behavior of a high-gradient RF cavity in a magnetic field
    - efficacy of Be window cavity termination

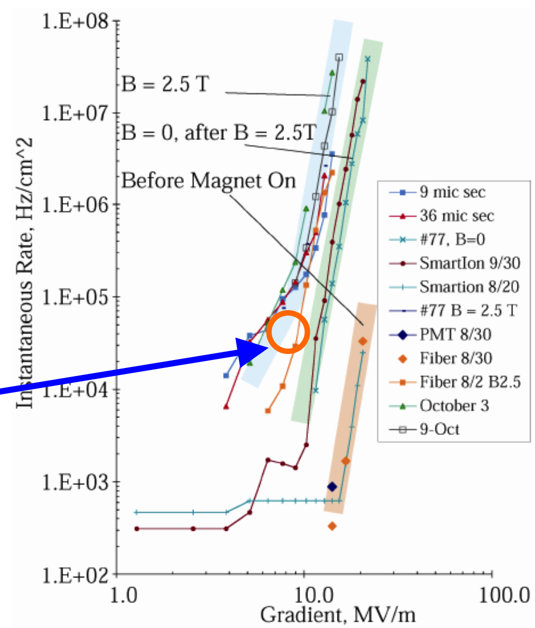




MUCOOL R&D Program

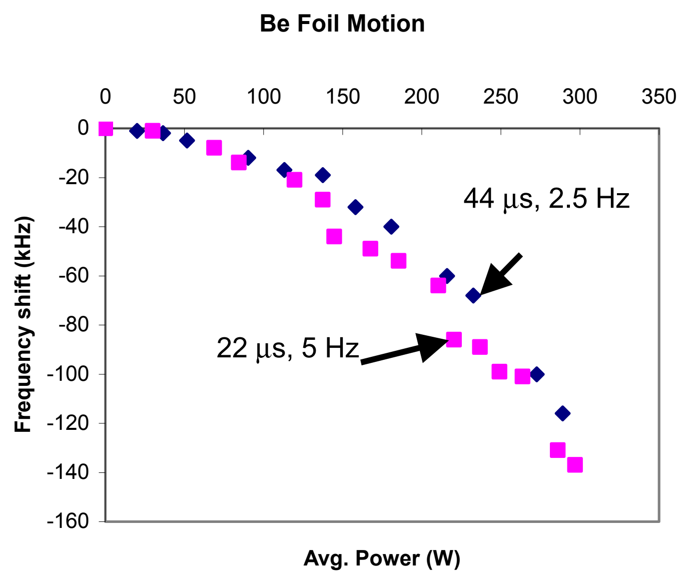
- **With copper windows and no magnetic field, cavity reached 34 MV/m (above its 30 MV/m design goal)**
  - **with B_{sol}, much more sparking and dark current generation observed**
  - **extrapolating to MICE baseline case, expected background rates are acceptable for the detectors (by 2-3 orders of magnitude)**
  - **further conditioning without B_{sol} significantly improved background rates with field on ("healing")**

Extrapolate from here



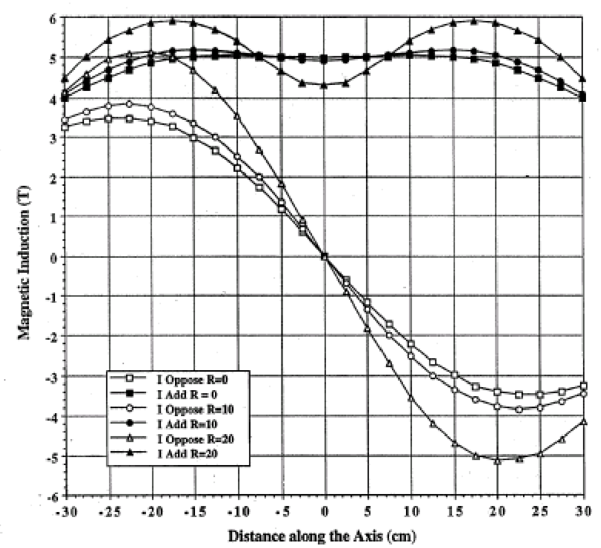
MUCOOL R&D Program

- Tests with thin Be windows (TiN coated) are now under way
  - no inordinate sparking activity observed without magnetic field
  - find evidence for foil motion due to heating
    - cavity frequency shifts depend on average input power
    - confirms need for tuners on MICE cavities



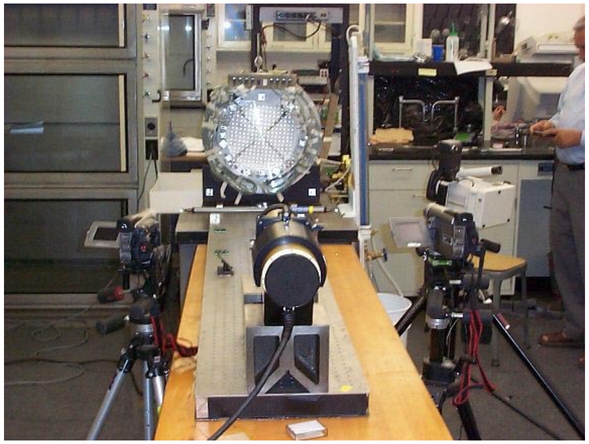
MUCOOL R&D Program

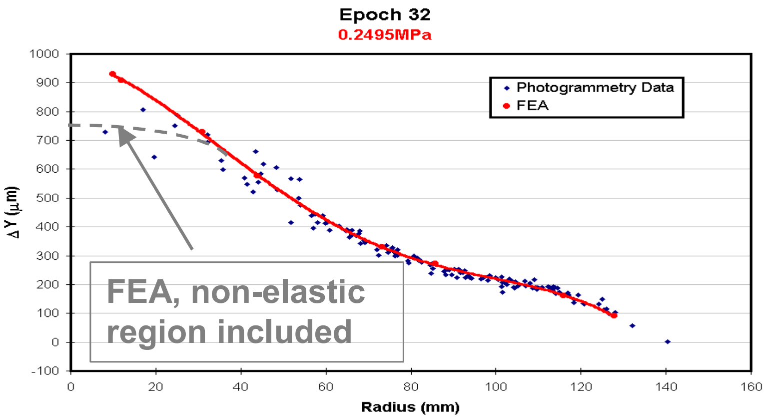
- Test solenoid representative of that needed for cooling channel has been built and tested
  - in "gradient mode" it has parameters similar to focusing coils
  - 805 MHz cavity being tested in this magnet
- Coupling coil prototype planned, but funding not yet available



MUCOOL R&D Program

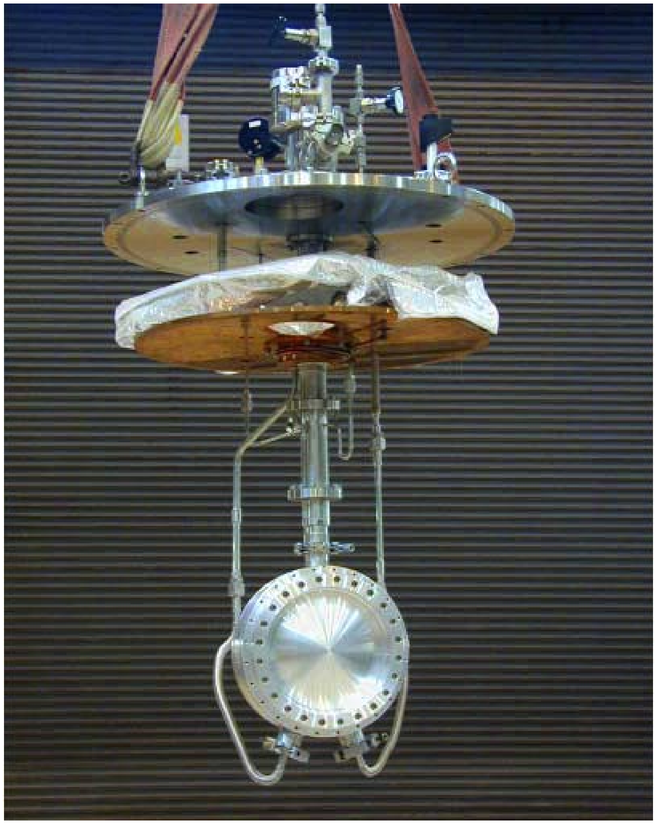
- Absorber work focusing mainly on developing strong, thin windows (IIT, NIU, Oxford, U-Miss.)
  - windows as thin as 125 μm machined from solid Al
  - destruction tested four windows at NIU (with satisfactory results)
    - 125 μm window broke at 44 psi (3 atm), 340 μm windows at 120 psi (8 atm)
  - use photogrammetry to characterize window behavior
    - goal is to verify FEA calculations (LH_2 safety requirement)

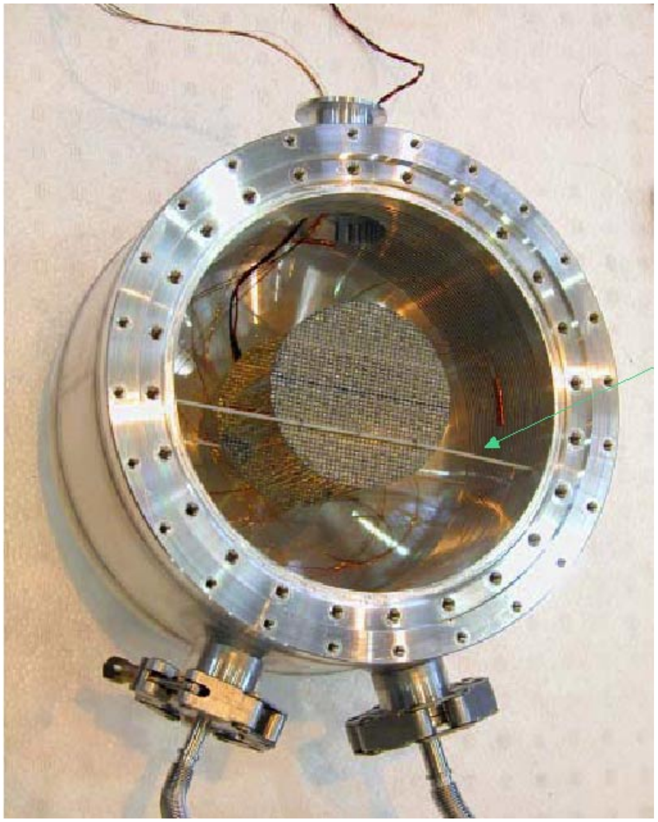




MUCOOL R&D Program

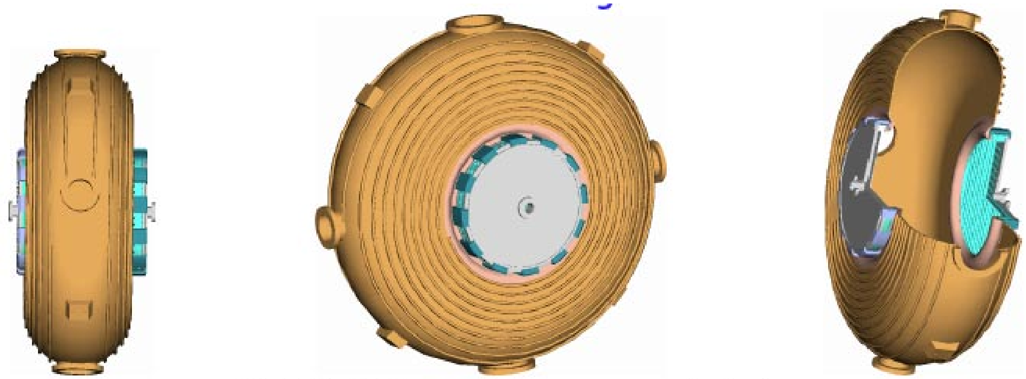
- Convection cooled absorber prototype fabricated and tested with LNe at KEK
  - plan to test at Fermilab with LH_2



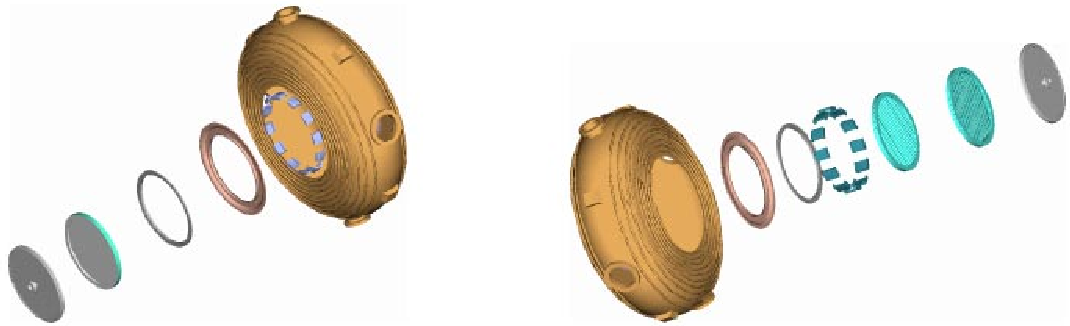


MUCOOL R&D Program

- 201 MHz RF cavity design is well along



201.25 MHz cavity conceptual design



Exploded views showing foil and grid mounting hardware

  — fabrication of prototype to begin this year

MUCOOL R&D Program

- To test hardware, building MUCOOL Test Area at Fermilab
  - absorber, solenoid, and 201 MHz RF cavity will be integrated here

Original area

Area after Phase I construction

What it will look like when completed

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
  - clearly these are not the "final" components of a Neutrino Factory
    - but they are valid prototypes and serve as proof-of-principle
  - note that, as new ideas mature (*e.g.*, cooling rings), MICE will likely serve as a test bed for other components
- Resultant demonstration of muon cooling will validate key concept of Neutrino Factory design
  - and put Muon Collider concept closer to being realized
- Measured cooling performance will "calibrate" our design tools
  - permitting cost and performance optimization of future Neutrino Factory

...*the beam never lies!*

Final Remarks

- MICE is necessary next step toward a proposal for a Neutrino Factory
  - time frame for experiment compatible with likely decision point on proceeding with new facility
- MICE collaboration is international from the outset
  - builds on worldwide expertise and interest in pursuing Neutrino Factory scientific program
- Goal of MICE is to bridge gap between cooling science and technology
- We seek:
  - approval to proceed with MICE experiment at RAL
- We believe that RAL is an ideal site for MICE
  - besides the beam, RAL offers a critical ingredient for success

    …*the support and enthusiasm of the local physicists!*