Intense Muon Beam Accelerator R&D

Michael S. Zisman
CENTER FOR BEAM PHYSICS

Muon Collaboration Project Manager

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Outline

- Introduction
- Collaboration overview
- Neutrino factory ingredients
- R&D program progress
- MICE status
- R&D plans
- R&D budget
- Summary

Introduction

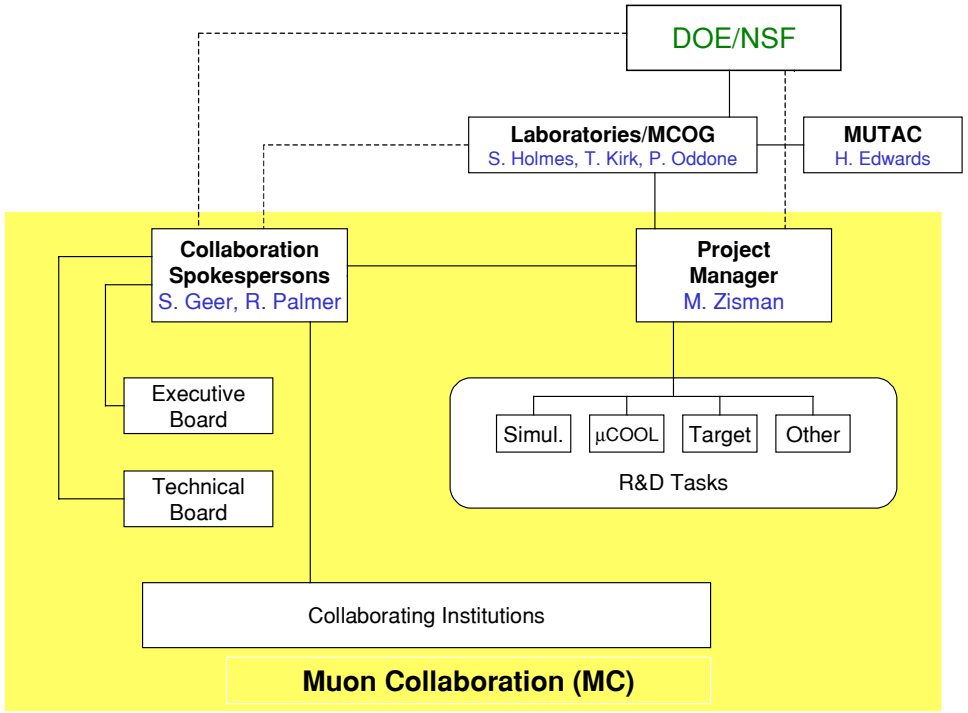
- For about 9 years now, there has been a focused R&D program to explore techniques for producing and accelerating intense muon beams
  - near-term focus: muon storage ring to serve as source of well characterized neutrinos ("Neutrino Factory") for long baseline experiments (≈3000 km)
  - longer term focus: Muon Collider
    - could be Higgs Factory operating at few hundred GeV or energy-frontier collider operating at several TeV
  - these machines are difficult but have high scientific potential
- Future muon beam facility requires extended accelerator R&D program
  - a feature common to most modern projects (PEP-II, NLC,...)
- Main technical challenges of muon accelerators
  - muon is unstable, with short decay time (2 μs at rest)
  - muon beam is created with very large 6D phase space

Introduction

- Neutrino Factory and Muon Collider Collaboration formed in 1995 to look into issues related to muon accelerators
  - mix of 128 accelerator and particle physicists from 30 institutions (National Labs, Universities, non-U.S. institutions)
- MC has three DOE "sponsoring Labs" (BNL, FNAL, LBNL); Cornell serves equivalent role for the NSF
- LBNL serves as Lead Lab for the MC, providing Project Manager
- Oversight of MC R&D provided by MCOG (Lab directorate level) and its Technical Advisory Committee (MUTAC)
- MC is attacking R&D problems of intense muon beams on a broad front
  - includes both component development and simulation studies
- Muon Ionization Cooling Experiment (MICE) activities are becoming a significant part of MC program
  - MICE will demonstrate the cooling technique

Collaboration Overview

- **Oversight role** of sponsoring Labs via **MCOG** (Directorate level)
  - MCOG appoints **Technical Advisory Committee** (**MUTAC**)
  - Project Manager responsible for R&D implementation, works closely with Spokesperson(s) on planning



Collaboration Overview

- MC (128 members; 30 institutions) has broad international community involvement (National Labs, Universities, non-U.S. institutions)
  - mix of particle and accelerator physicists

Executive Board:

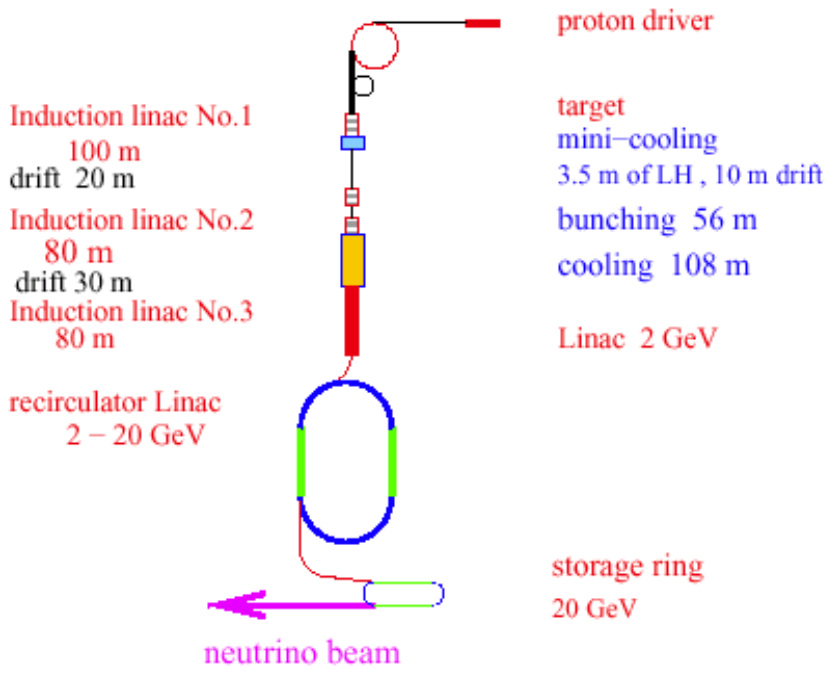
S. Geer, Fermilab (Co-Spokesperson)
R. Palmer, BNL (Co-Spokesperson)
M. Tigner, Cornell (Associate Spokesperson)
A. Sessler, LBNL (Associate Spokesperson)
M. Zisman, LBNL (Project Manager)
D. Cline, UCLA
D. Errede, U. Illinois-Urbana-Champaign
J. Gallardo, BNL (Secretary)
G. Hanson, UC-Riverside
D. Kaplan, Illinois Institute of Technology
K. McDonald, Princeton U.
A. Skrinsky, BINP
D. Summers, U. Mississippi
A. Tollestrup, Fermilab
W. Weng, BNL
J. Wurtele, LBNL/UC-Berkeley

Technical Board:

S. Geer, Fermilab (Co-Spokesperson)
R. Palmer, BNL (Co-Spokesperson)
M. Zisman, LBNL (Project Manager)
A. Bross, Fermilab
R. Fernow, BNL
M. Green, LBNL
D. Hartill, Cornell
H. Haseroth, CERN
D. Kaplan, IIT
H. Kirk, BNL
K. McDonald, Princeton
Y. Mori, KEK
D. Neuffer, Fermilab
J. Norem, ANL
R. Rimmer, Jlab
T. Roser, BNL

Neutrino Factory Ingredients

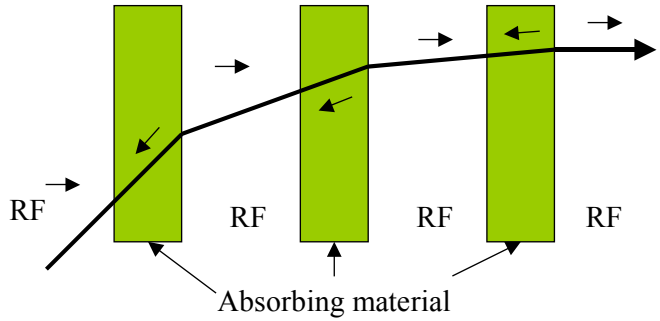
- Neutrino Factory comprises these sections (MC doing R&D on most)
  - **Proton Driver**
    (primary beam on production target)
  - **Target and Capture**
    (create π's; capture into decay channel)
  - **Phase Rotation**
    (reduce ΔE of bunch)
  - **Cooling**
    (reduce transverse emittance of beam)
    $\Rightarrow$Muon Ionization Cooling Experiment
  - **Acceleration**
    (130 MeV $\rightarrow$ 20–50 GeV with RLAs FFAGs, or pulsed synchrotrons)
  - **Storage Ring**
    (store muon beam for ≈500 turns; optimize yield with long straight section aimed in desired direction)



- Not an easy project, but no fundamental problems found

Neutrino Factory Ingredients

- **Ionization cooling** is a key feature of intense muon beam facilities
  - muon beam **must be cooled** (large initial emittance)…and **quickly** (2.2 μs lifetime)
- 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



Neutrino Factory Ingredients

- 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

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

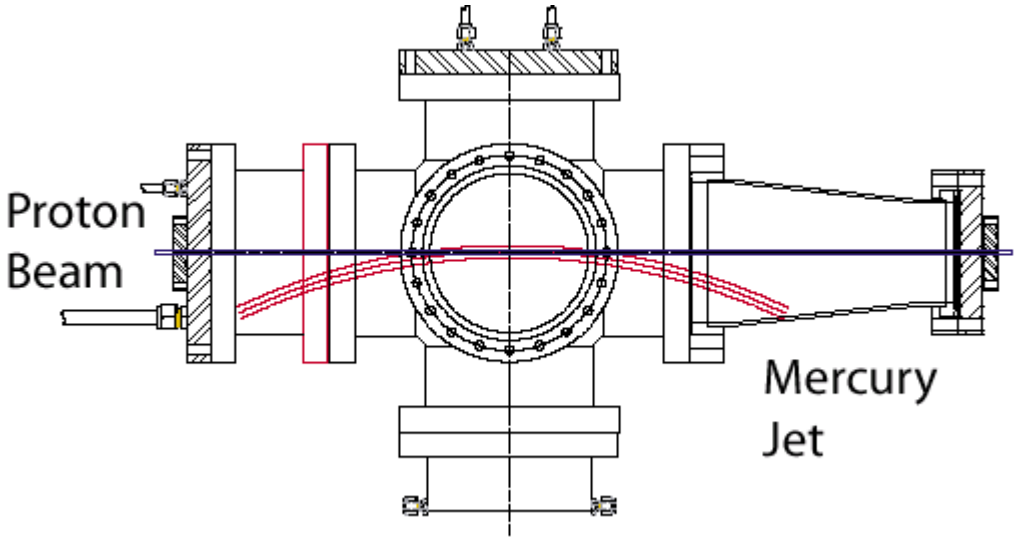
  - prefer low $\beta_\perp$ ($\Rightarrow$ strong focusing), large X_0 and dE/ds ($\Rightarrow$ H_2 best)

R&D Program Progress

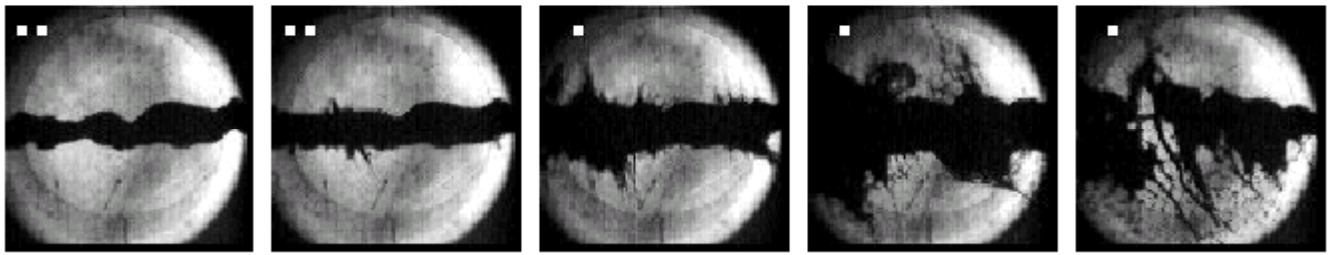
- Targetry
  - goal: develop targets capable of handling multi-MW proton beam without being quickly destroyed
    - concepts studied will be useful for producing neutrino Superbeams
  - initial beam tests of target (C rod and Hg jet) completed at the AGS (24 GeV)
  - key questions for Hg jet: injection into ≈20 T field; nonlinear jet dynamics at high proton intensity
    - fabricating test magnet to permit experimental study of its effects
    - designing Hg jet system capable of required 20–30 m/s velocity
    - continuing simulation program to predict and interpret effects
  - unavailability of AGS beam forcing us to look elsewhere for beam time

R&D Program Progress

- **Mercury-jet target tested at BNL**
  - **disruption occurs long after beam is gone**

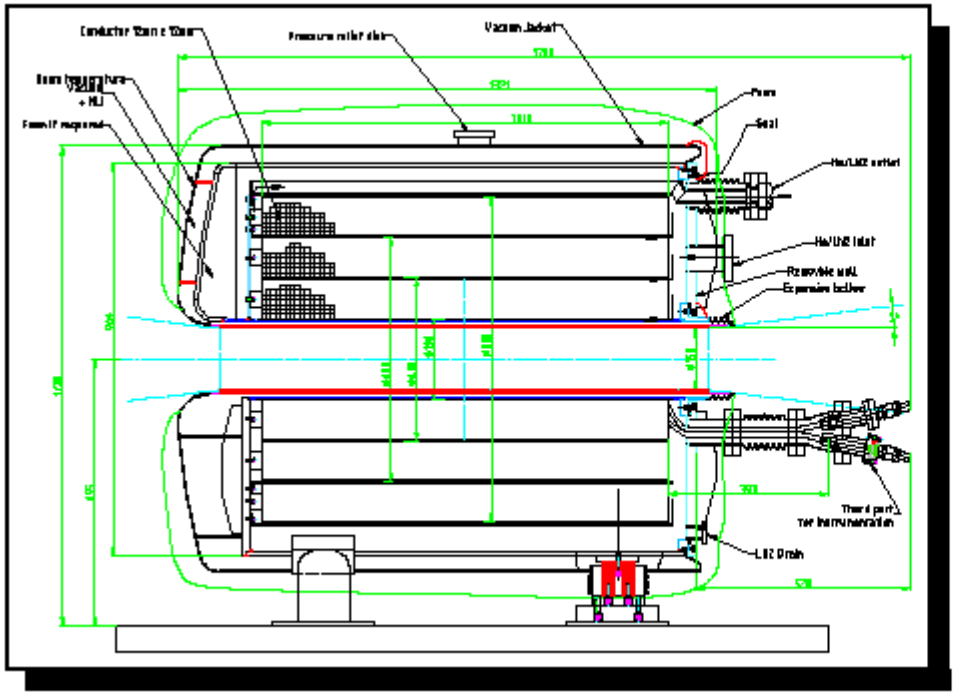


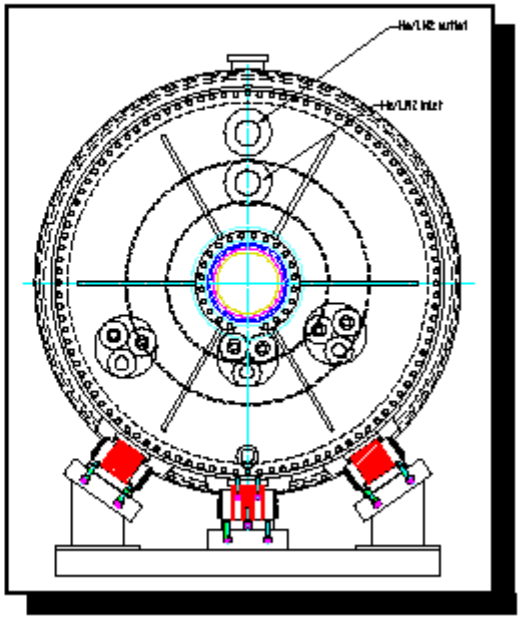
1-cm-diameter Hg jet in 2e12 protons at $t = 0, 0.75, 2, 7, 18$ ms.



R&D Program Progress

- **Contract awarded for 5–15 T magnet fabrication (for E951 at BNL ?)**



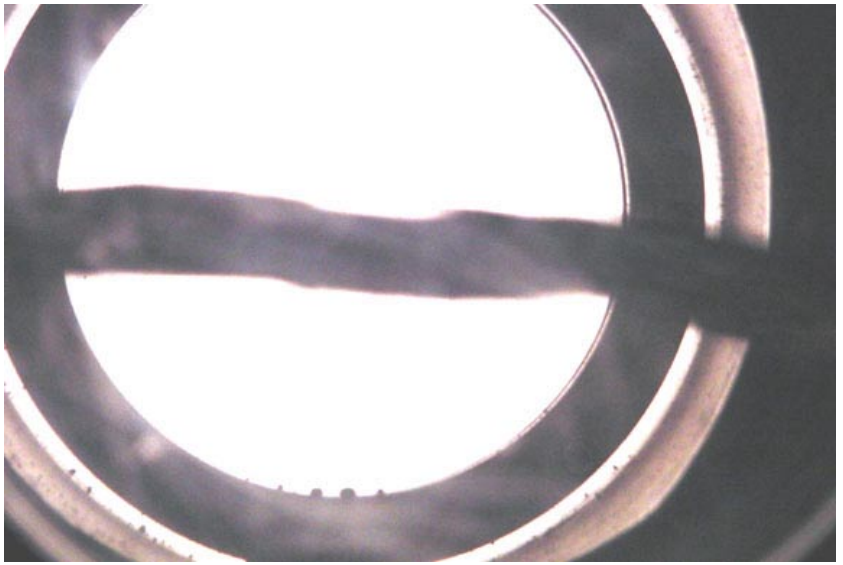


Stage	Field (T)	Power (MW)	Coolant	Temperature (K)
1	5	0.6	N_2	84
2	10	2.2	N_2	74
3	15	4.5	N_2	70

R&D Program Progress

- Developed a 2.5 m/s continuous Hg jet system for E951 at Princeton
  - never used with beam due to elimination of AGS HEP running
  - development of 20–30 m/s version just getting under way

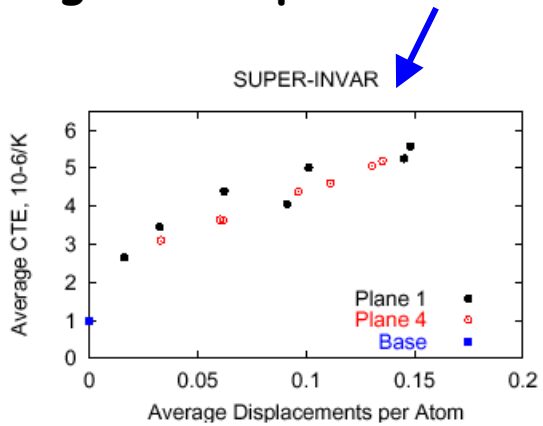
Test apparatus

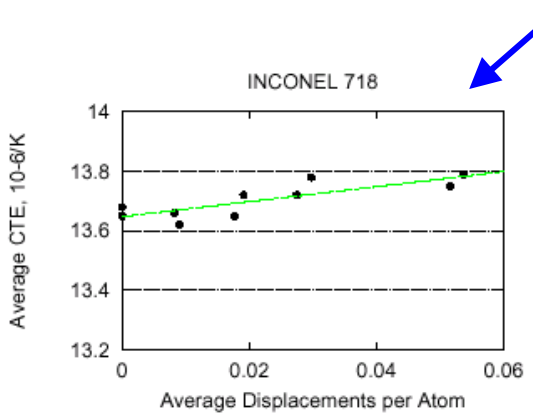


Mercury jet…on a good day

R&D Program Progress

- Radiation testing of candidate solid-target materials (Super-Invar and Inconel) carried out at BNL with 200 MeV p beam
  - looked at both CTE and tensile strength changes
    - big changes in Super-Invar CTE with dose, less with Inconel





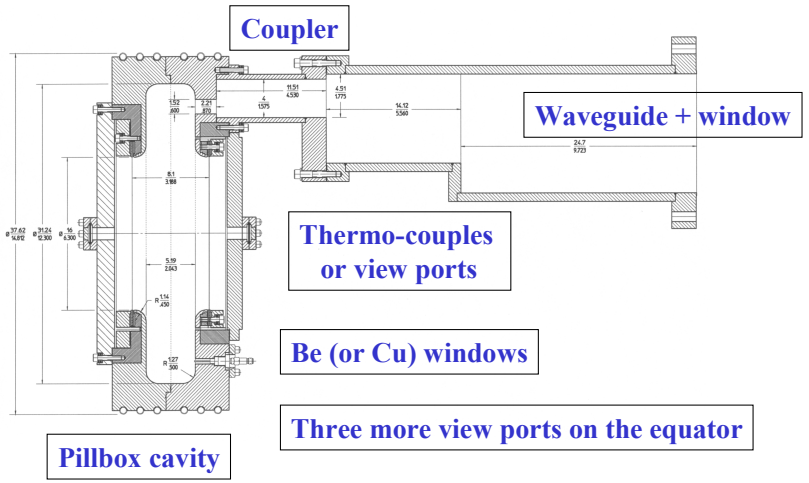
    - other promising materials will be investigated

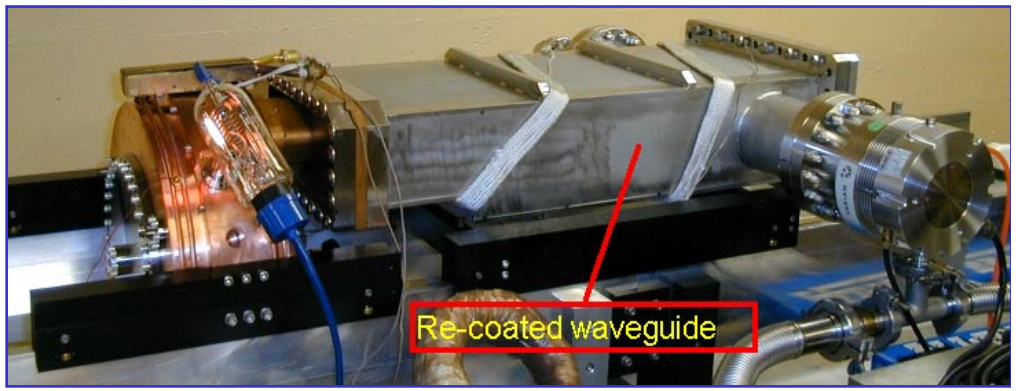
R&D Program Progress

- Cooling
  - simple concept, but difficult implementation
  - includes hardware R&D on rf cavities, absorbers, solenoids
  - rf work to date done at 805 MHz; 201 MHz cavity under construction
    - issue: limits to gradient in high magnetic field
  - absorber work going on in Illinois (ICAR supported) and Japan (U.S.-Japan funding)
    - issue: development of large diameter absorber with thin windows
    - hydrogen safety approach being developed in context of MICE
  - solenoid work is aimed mainly at mechanical engineering and integration issues
    - unable to begin fabrication due to funding limitations

R&D Program Progress

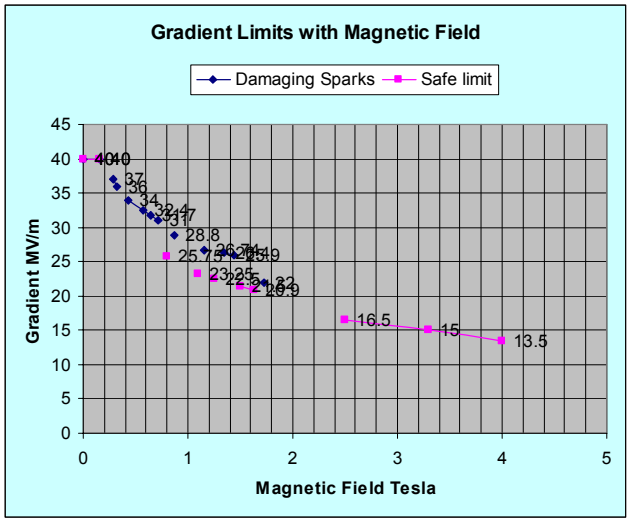
- Using 805 MHz pillbox cavity having replaceable windows (or grids) (Li)
  - cavity fits in bore of Lab G 5-T solenoid to mock up cooling channel configuration

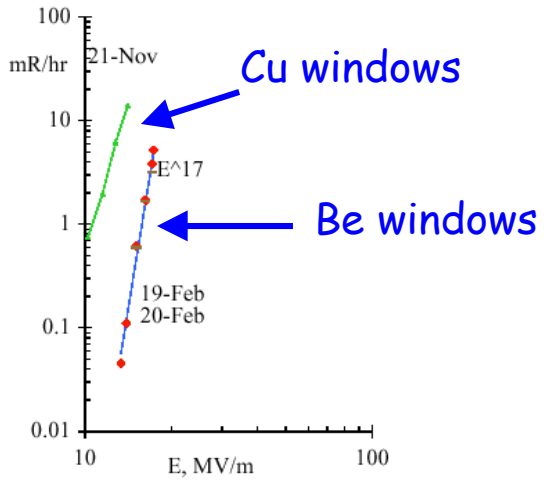




R&D Program Progress

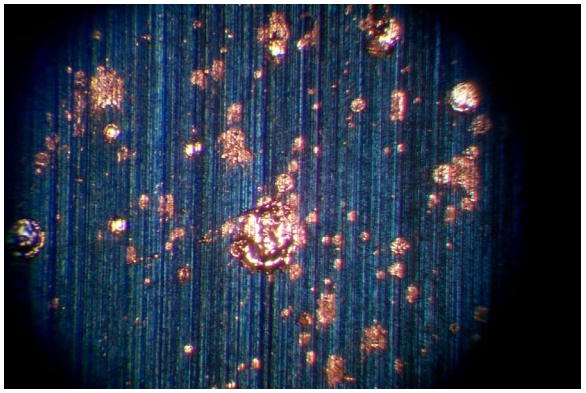
- Pillbox cavity reached 40 MV/m in Lab G using TiN-coated Be windows with no solenoid field
  - no conditioning problems seen without magnetic field
    - ⇒ "parallel plate" geometry does not cause big problems
- With solenoid, performance worse, radiation levels higher
  - field seemingly enhances likelihood of physical damage
  - background rates lower for Be than for Cu





R&D Program Progress

- Found no damage to Be surface, but sputtered Cu is present
  - suggests need to focus more on copper body than on windows

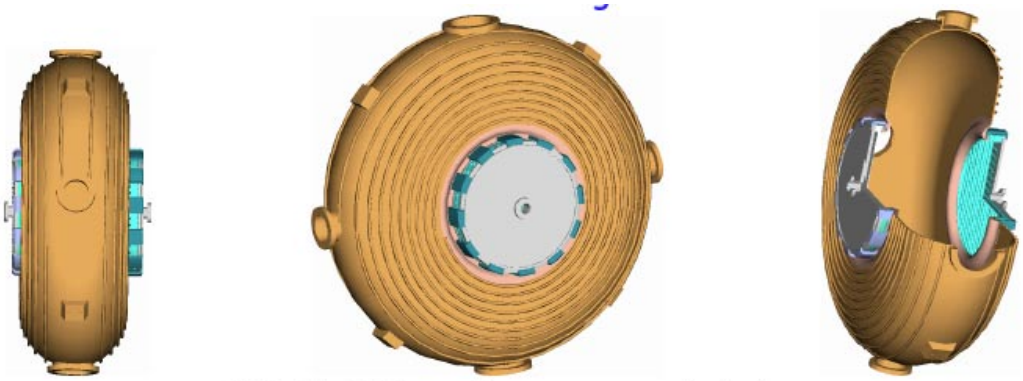


Be windows with sputtered copper

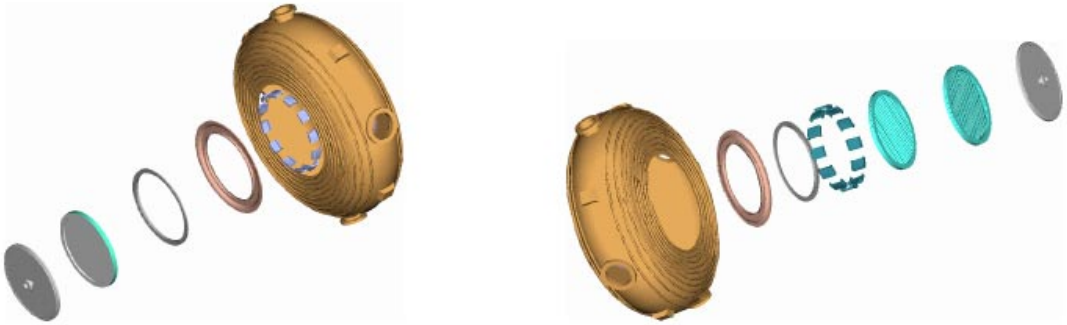
- Workshop on high-gradient rf limitations was held at ANL, October 7–9, 2003
  - URL: http://www.mice.iit.edu/rfworkshop/
- Study of rf cavities filled with high-pressure H_2 gas is also under way, supported by Muons, Inc. (SBIR/STTR funded)
  - concept also being applied to some cooling ring approaches

R&D Program Progress

- 201 MHz rf cavity under construction (Li, Virostek, Rimmer)



201.25 MHz cavity conceptual design

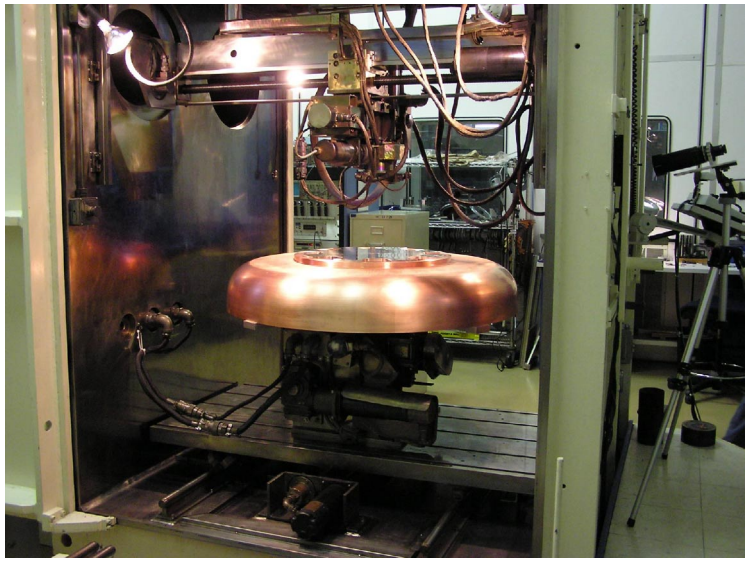


Exploded views showing foil and grid mounting hardware

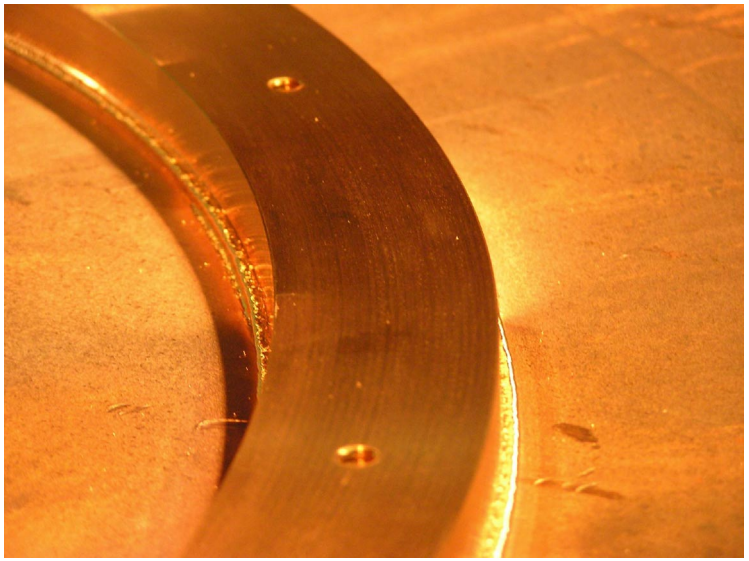
— options for either Be windows or grids are available

R&D Program Progress

- fabrication began this year; completion in about 1 year
  - Jlab and U-Miss collaborating on cavity fabrication



Setup for welding stiffener ring



After e-beam weld to half-shell

R&D Program Progress

- Muon cavity terminated with metallic windows to improve E_{acc}/E_{surf}
- Ideal termination would be perfectly conducting, transparent to muon beam, and rigid (to not affect cavity frequency)
  - present concept uses pre-curved Be foils that bow predictably
- Formed required shape for 805 MHz with stainless steel foil at LBNL
  - but failed with Be foil (cracked)

Stainless steel window

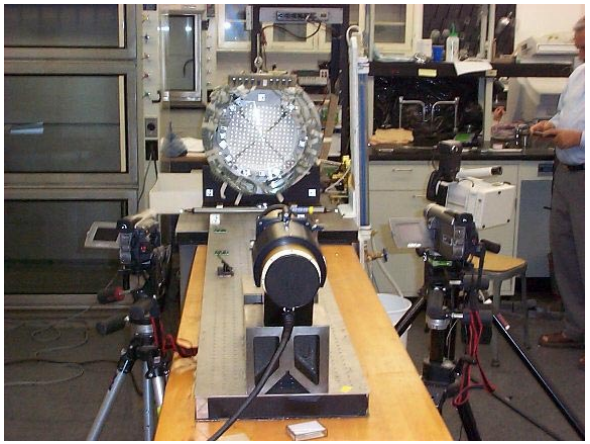
Be window

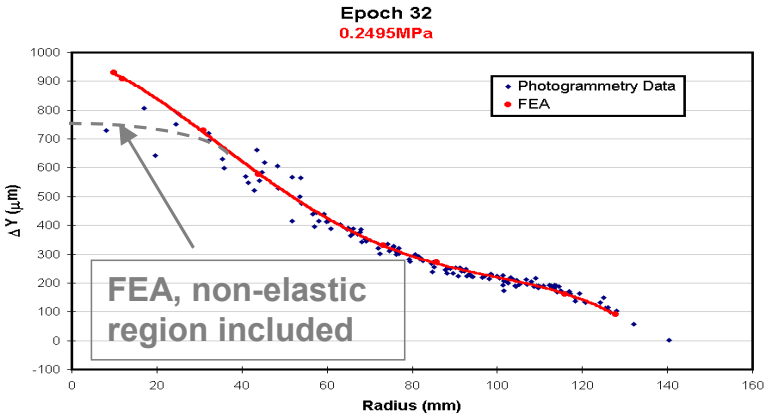
R&D Program Progress

- Ordered shaped Be foils from Brush-Wellman
  - they are confident they can make them
  - delivery due in early February
- Test these at 805 MHz before ordering the 201 MHz Be version

R&D Program Progress

- Absorber work focusing mainly on developing strong, thin windows for LH_2 containment (Cummings, Kaplan, Black)
  - use photogrammetry to characterize window behavior
    - goal is to verify FEA calculations (LH_2 safety requirement)

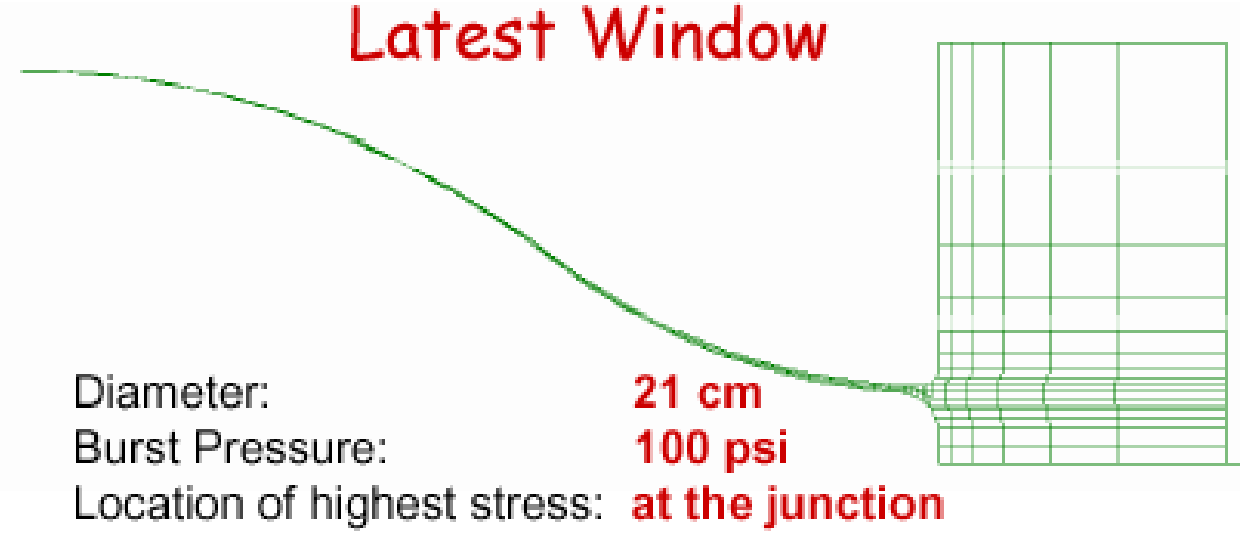




  - destruction tested at NIU (performance satisfactory)
    - 125 μm window broke at 44 psi (3 atm), 340 μm window at 120 psi (8 atm)

R&D Program Progress

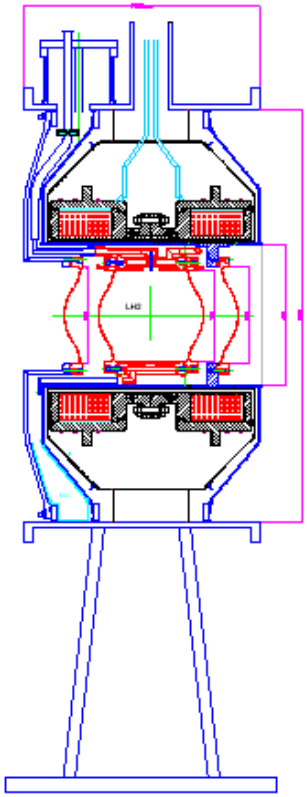
- New stronger (⇒ thinner) design (Lau) built and will be tested next
  - this concept was the seed for the rf window shape

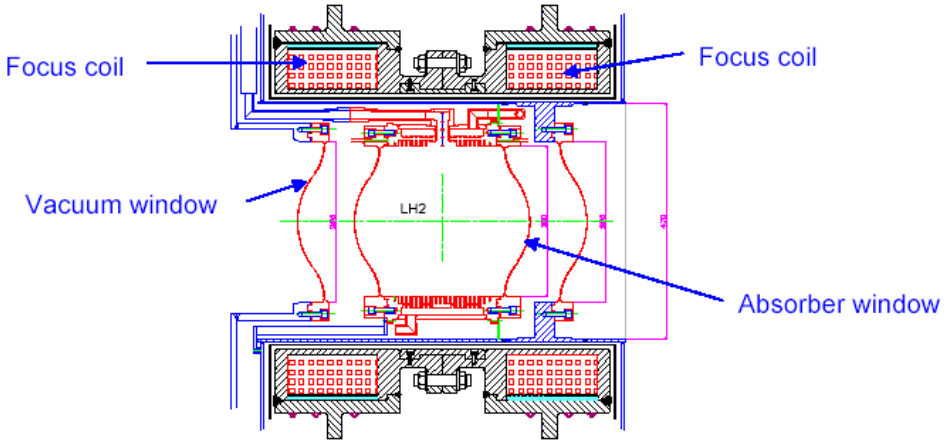


  - we must again destruction test a set of them to certify design

R&D Program Progress

- Solenoids (Green)
  - studying focus coil design that accommodates removable absorber and secondary vacuum isolation windows
    - absorber concept has passed its preliminary safety review





R&D Program Progress

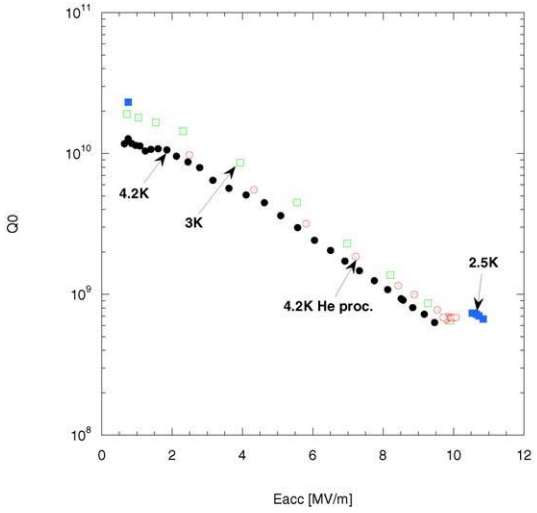
- To test hardware, built MUCOOL Test Area at Fermilab (Popovic)
  - absorber, solenoid, and 201 MHz rf cavity will be integrated here

Completed MTA (as seen by Project Manager)

Completed MTA (as seen by Lab Director)

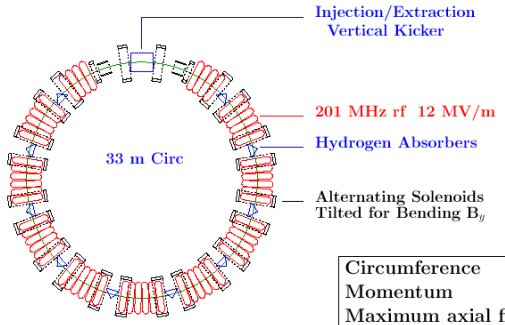
R&D Program Progress

- Work on 201 MHz scrf cavity for the acceleration system made good progress (Hartill, Padamsee; NSF)
  - focusing on achieving gradient, Q, mechanical stability
    - reached 11 MV/m after re-cleaning cavity at CERN (desire 16 MV/m)
    - low-power $Q_0 = 2 \times 10^{10}$ (at 2.5 K)
  - now trying to understand Q slope in terms of impurities and Nb coating properties

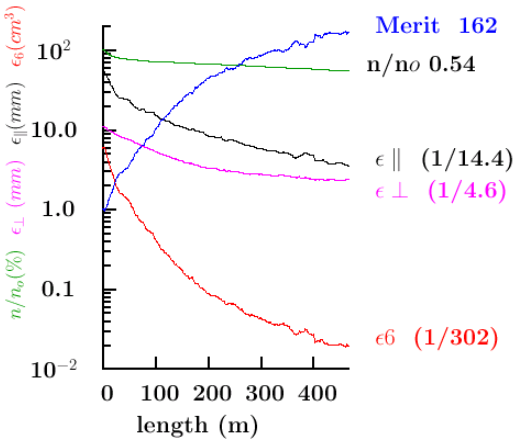


R&D Program Progress

- Simulations and Theory
  - focus on emittance exchange, as accomplished with cooling ring
  - many versions being studied
    (see http://www.cap.bnl.gov/mumu/conf/E-EX-040121/Agenda-E-EX-040121.html)
    - 6D cooling looks promising; injection/extraction an issue



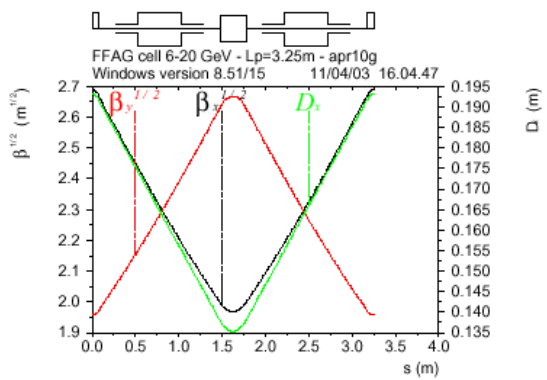
Circumference	m	33
Momentum	MeV/c	200
Maximum axial field	T	3
Ave. bending field	T	0.125
Hydrogen wedge thickness	cm	30
Wedge Angle	deg	100
RF frequency	MHz	201
RF Grad.	MV/m	12

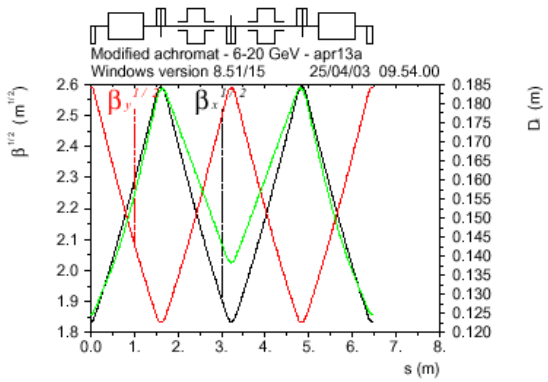


  - looking at RF schemes for bunching and phase rotation (to avoid costly induction linacs)
  - participating in APS Neutrino Physics Study (Palmer; Geer, MZ)

R&D Program Progress

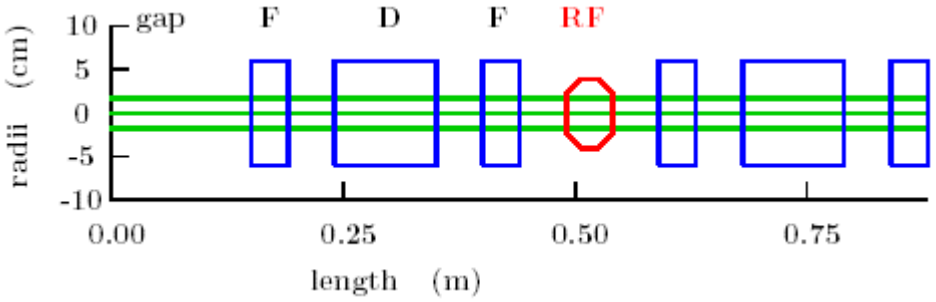
- Looking at acceleration schemes based on FFAG arcs (Berg, Johnstone, Keil, Sessler, Trbojevic)





- Discussion of building an electron model of FFAG has started
  - useful for studying proton or muon acceleration

Parameter	Value
Energy [MeV]	10-20
Diameter [m]	4.5
B_{peak} [T]	0.2
L_{cell} [cm]	44
Radial aperture [cm]	1.7
f_{rf} (muon version) [GHz]	3
f_{rf} (proton version) [MHz]	21

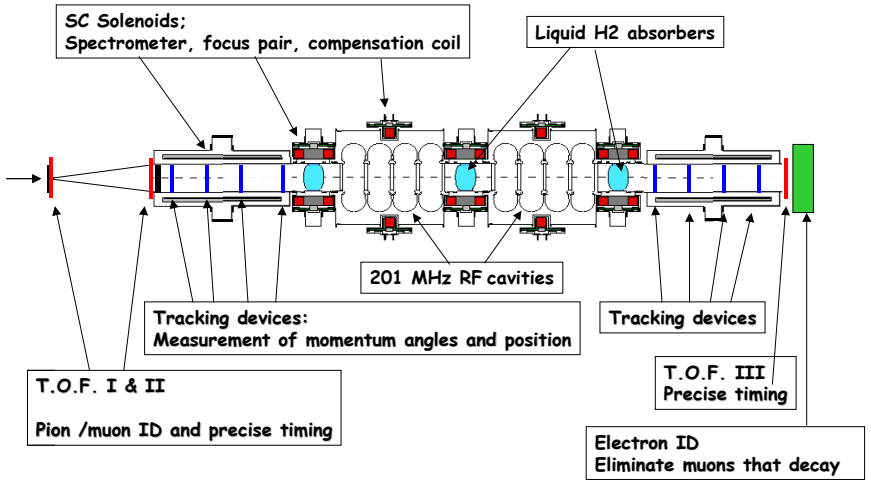


MICE Activities

- Motivation for MICE
  - straightforward physics, but not experimentally demonstrated
  - prudence dictates demonstration of key principle for expensive facility, $\mathcal{O}$($1B)
- MUTAC + MCOG strongly recommended MICE last two years
  - experiment considered "crucially important demonstration"
- MC participating in planning and organization of (international) MICE
  - Bross, Geer, Kaplan (U.S. Spokesperson), Torun, Zisman on Executive Board
    - Black, Bross, Kaplan, Torun, Zisman on Technical Board

MICE Activities

- Basic ingredients of MICE experiment:
  - absorbers to give energy loss (LH_2 capable of handling 100–300 W)
  - rf cavities to restore lost energy (up to 17 MV/m at 201 MHz)
  - solenoid magnets to contain the muons (up to 5 T)
  - diffuser to create large emittance sample
  - upstream diagnostics section to define initial emittance
  - downstream diagnostics section for final emittance and particle ID



MICE Activities

- **MICE status**
  - **proposal submitted in January 2003**
    - **international review held in February, 2003**
    - **review panel *"strongly recommends approval of the project"***

      " The Panel endorses the scientific case for MICE. It is a timely experiment and will provide a realistic prototype of an ionisation cooling channel for muons. This is an important piece of accelerator physics, and will remove many of the current uncertainties of performance and cost associated with this method of muon accumulation and cooling. The MICE experiment is therefore a crucial prerequisite in understanding the potential use of muons in a future Neutrino Factory or muon collider."

    - **scientific approval from RAL in October, 2003**

      "CCLRC accepts the strong endorsement of the proposal by the Astbury panel and consequently considers the proposal to have full scientific approval."

- **Funds for MICE being sought now in the UK, the U.S, and elsewhere**

R&D Plans

- To happen in a timely way, planned MC hardware activities require support beyond FY04 funding level
  - Targetry
    - complete target solenoid power supply
    - explore options for beam tests at CERN
  - MUCOOL
    - use MTA for RF and absorber testing
    - begin solenoid fabrication for 201-MHz cavity
  - Simulations
    - develop cost-optimized Neutrino Factory design in preparation for "World" Design Study (U.S., EU, Japan)
  - Acceleration
    - develop electron model of non-scaling FFAG

R&D Budget

- In FY03, the MC budget was halved
  - $2.809M→$1.429M

Year	DOE-base ($M)	DOE-MC ($M)	TOTAL ($M)
FY00	3.3	4.7	8.0
FY01	3.0	3.2	6.2
FY02	3.0	2.8	5.8
FY03	2.1	1.4	3.5
FY04	2.1	1.4	3.5

- Severe cut was surprising and demoralizing
  - after considerable technical progress, good MUTAC review, support from MCOG, and a favorable recommendation from HEPAP

"We support the decision to concentrate on the development of intense neutrino sources, and recommend continued R&D near the present level of $8M per year. This level of effort is well below what is required to make an aggressive attack on all of the technological problems on the path to a neutrino factory."

- Subsequent "flat-flat" profile not surprising…but still demoralizing

R&D Budget

- **Comments from January '03 MUTAC report**

"The committee notes with pleasure the enthusiasm evident at the MUTAC Review, and the refreshing ideas and progress made over the past year. This is particularly noteworthy since this progress has been made in the face of very difficult funding conditions."

"An additional ~$1M would make a considerable difference to the time scale on which a 200 MHz cavity could reach the testing stage."

"Overall, MUTAC was impressed by the accomplishments since the last meeting, particularly given the strained financial situation. MUTAC can enthusiastically assure MCOG that the limited funding is being well and carefully utilized. Present funding is substantially below the ~$8M level endorsed by the HEPAP Report. Additional funding would certainly be helpful in the implementation of the 200 MHz warm rf tests. However, the committee cannot make rational recommendations for increments at a time of total HEP funding limitations without knowing the impact on other HEP programs. We do however note that the Muon Collaboration is a fine example of laboratory–university collaboration on accelerator R&D. It also illustrates the need for increased accelerator R&D funding across the fields of HEP, NP, and BES."

R&D Budget

- **MCOG comments**

MCOG is concerned by the continuation of severe budget cuts in each of the last three years. These cuts in the level of support accorded to the muon R&D work of the Collaboration have severely impeded progress, especially in the attempts to advance the experimental work of Muon Cooling and High-Power Target R&D. Of particular concern is the projected level of support for FY 2003 and FY 2004, both in the explicit R&D funding directed to the Collaboration, and in the base program support provided by the supporting laboratories. MCOG has concluded that it is imperative that DOE seek to provide enhanced R&D funding for this work if it is to meet either the intent or the recommendations of the Long Range Plan laid out in the 2002 Gilman Report of HEPAP.

Summary

- Intense muon beam accelerator R&D program will determine whether a muon accelerator (Neutrino Factory or Muon Collider) is a realistic future option for HEP
  - long-term program, similar to the R&D efforts behind other state-of-the-art facilities (LHC, NLC, TESLA,…)
    - developing and demonstrating needed technologies and cost-effective solutions
  - this type of program is exactly why Advanced Accelerator R&D funds are important to the future of HEP
- R&D program has made excellent progress on all fronts in recent years
  - including being part of strong international effort for MICE
    - U.S. now developing components to serve as prototypes for MICE
- MC serves as "model" for collaboration of laboratories, universities, and international groups on major accelerator projects
  - opportunities for students to get hardware experience