Neutrino Factory and Muon Collider Collaboration R&D Program:

Progress, Plans, Budgets

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Outline

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

Introduction

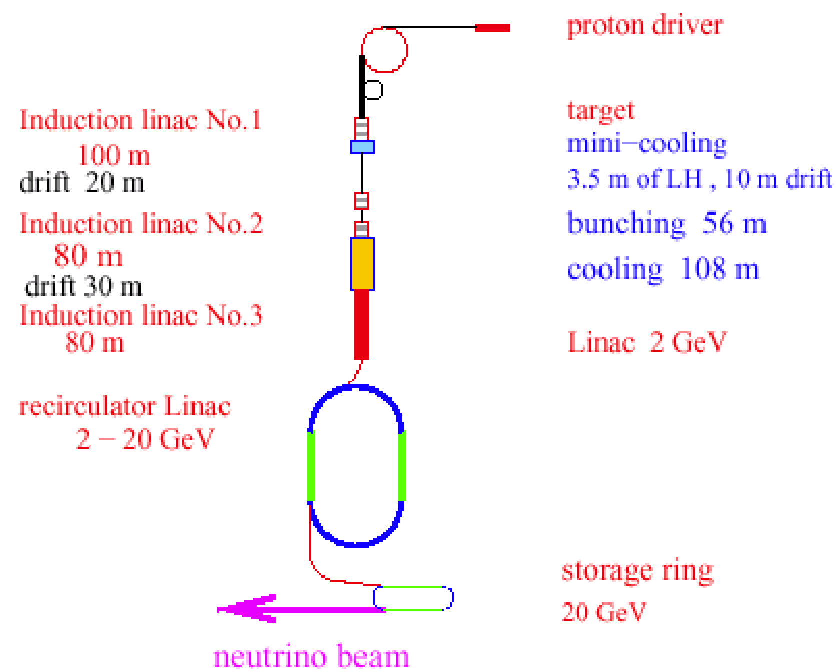
- MC is attacking R&D problems of a Neutrino Factory on a broad front
- MUTAC review has been very favorable for the past two years

  "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. ... Muon Collaboration is a fine example of laboratory -university collaboration on accelerator R&D."

- Hardware development is major focus (and major expense) for MC
  - simulation studies also important (Palmer talk)
    - ideas for cost-effective improvements begin here
      - ring cooler studies have potential for vastly improved designs
- MICE activities are becoming a significant part of MC program
- Here, I will summarize progress and discuss budgets

Neutrino Factory Ingredients

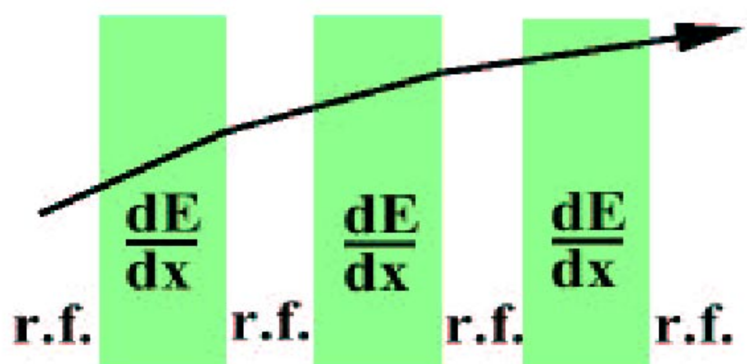
- Neutrino Factory comprises these sections (MC doing R&D on all)
  - **Proton Driver**
    (primary beam on production target)
  - **Target and Capture**
    (create π's; capture into decay channel)
  - **Phase Rotation**
    (reduce ΔE of bunch)
  - **Cooling**
    (reduce transverse emittance of beam)
    ⇒Muon Ionization Cooling Experiment
  - **Acceleration**
    (130 MeV → 20–50 GeV with RLAs 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 is created with very large emittance
  - must be cooled quickly (lifetime is 2.2 μs)
- 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

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

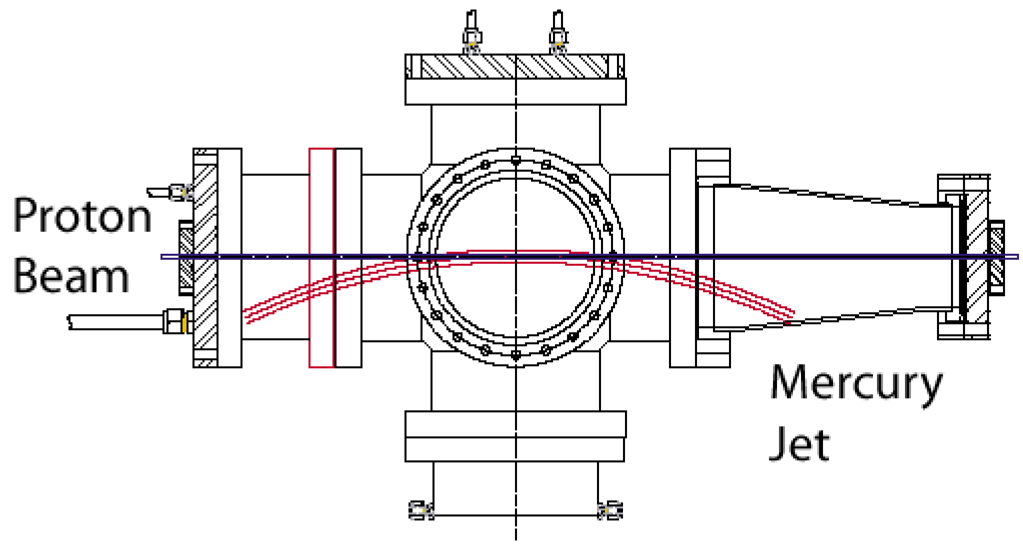
  - prefer low $\beta_\perp$ ($\Rightarrow$ strong focusing), large X_0 and dE/ds ($\Rightarrow$ H_2 best)

R&D Program Progress

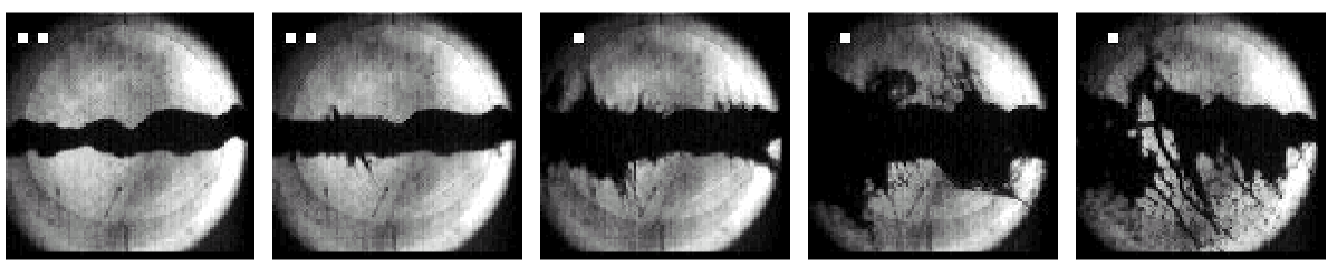
- Targetry
  - goal: develop targets capable of handling multi-MW proton beam without being quickly destroyed
    - in U.S., only MC working on targetry
    - concepts studied will be useful for producing neutrino Superbeams
  - initial beam tests of target (C rod and Hg jet) completed at the AGS (24 GeV)
  - open questions for Hg jet: injection into ≈20 T field and nonlinear jet dynamics at full proton intensity
    - designing 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
  - possible unavailability of AGS beam time forcing us to look elsewhere

R&D Program Progress

- Mercury-jet target tested at BNL

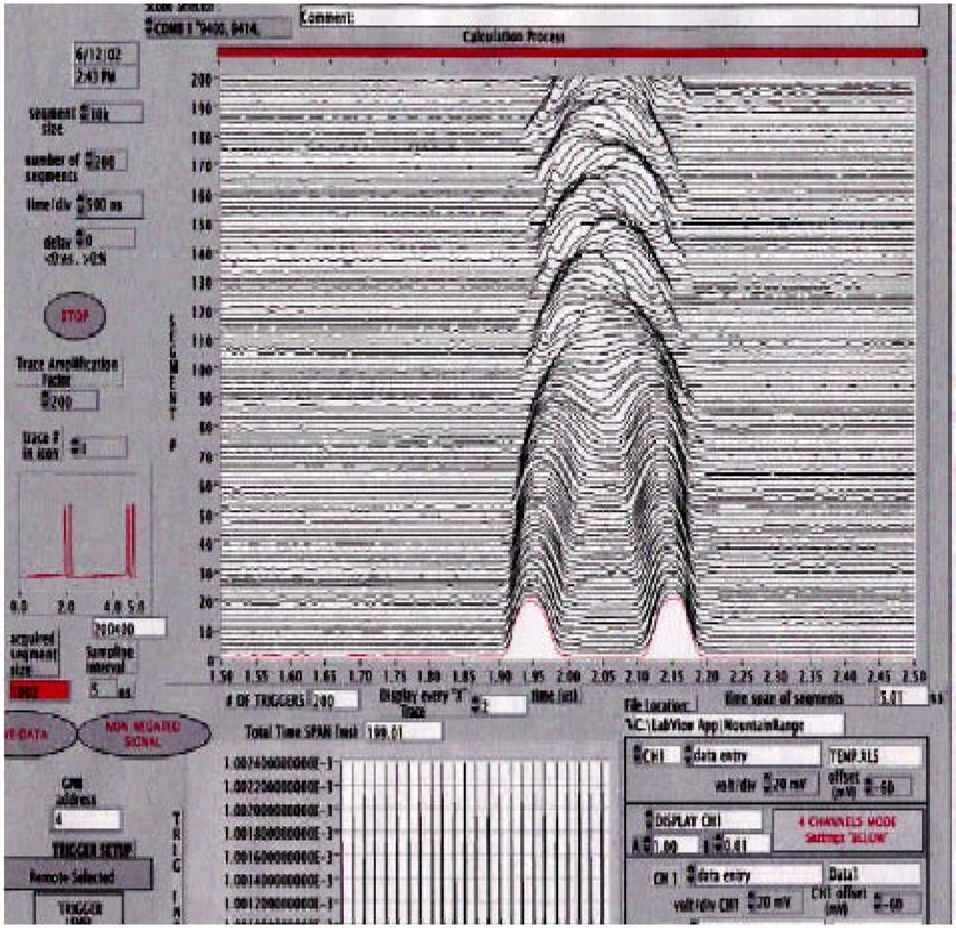


1-cm-diameter Hg jet in 2e12 protons at $t = 0, 0.75, 2, 7, 18$ ms.



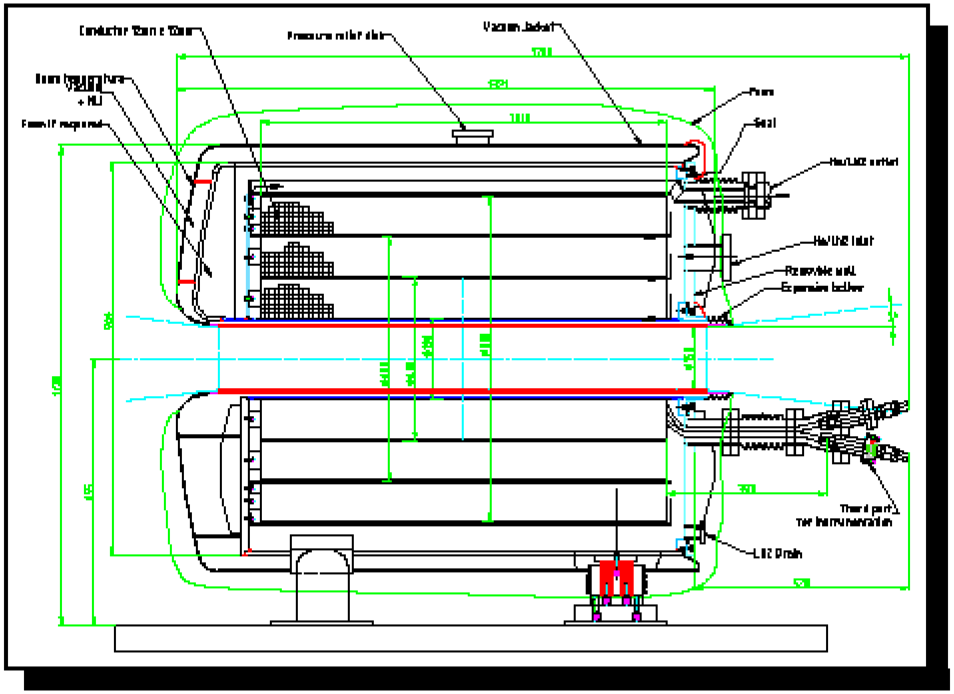
R&D Program Progress

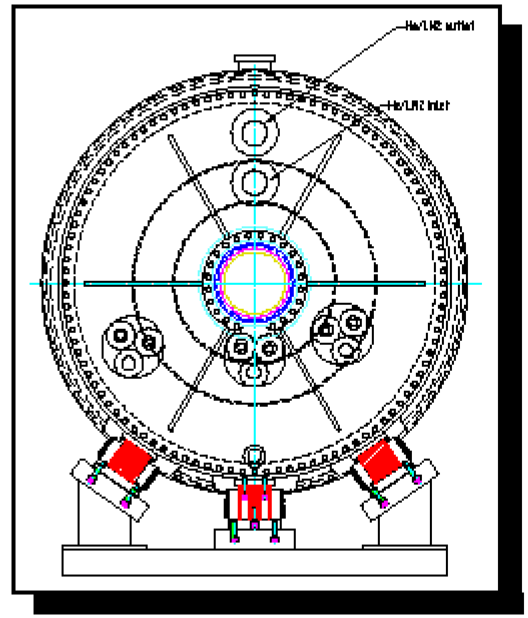
- Bunch merging (h = 12 → h = 6) at AGS gave extracted proton bunch of 10 Tp (desire 16 Tp)
  - — technique needs development, but is clearly workable



R&D Program Progress

- Engineering study of 5–14.5 T magnet for E951 at BNL completed





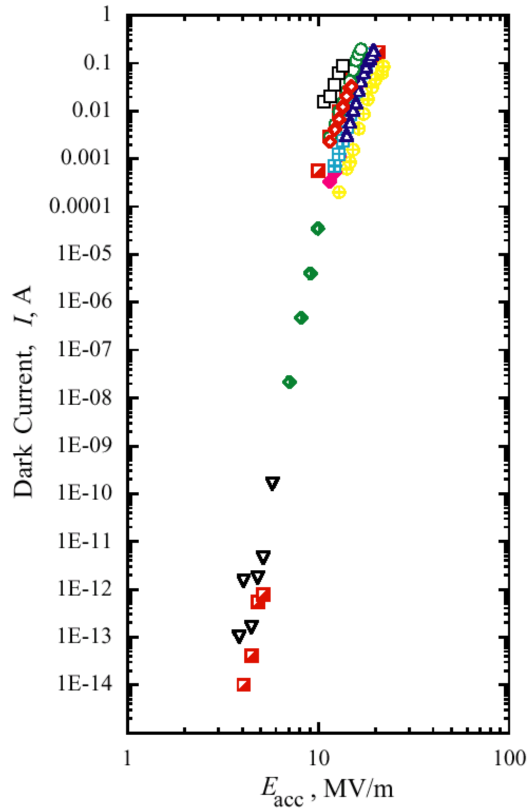
Stage	Field (T)	Power (MW)	Coolant	Temperature (K)
1	5	0.6	N_2	84
2	10	2.2	N_2	74
3	15	2.2	H_2	30
3a	15	4.5	N_2	70

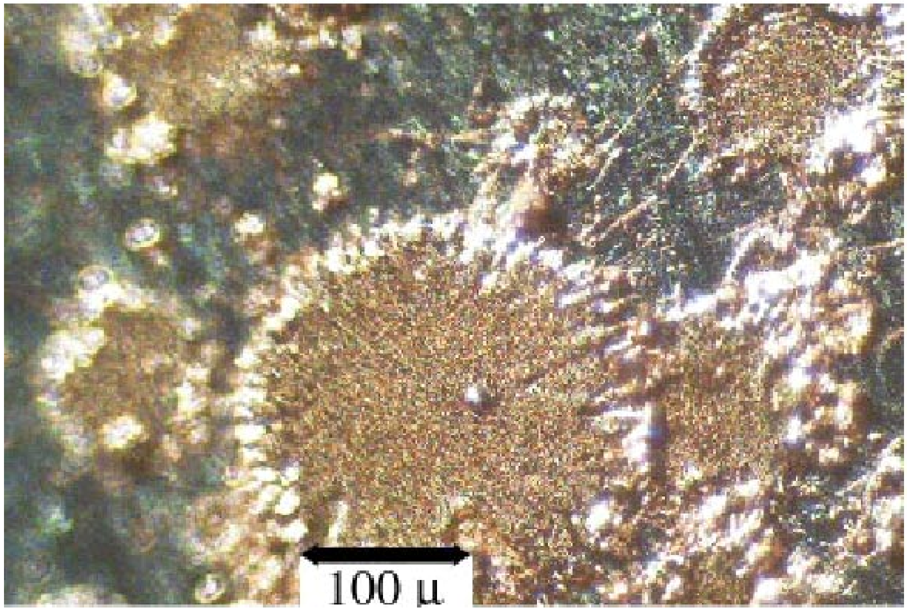
R&D Program Progress

- 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 (breakdown; dark current suppression)
  - absorber work going on in Illinois (ICAR supported) and Japan (U.S.-Japan funding)
    - focus is on development and testing of large, thin windows
    - consideration of hydrogen safety implications is well along
      - solutions being developed initially in the context of MICE
  - solenoid work is aimed mainly at cost and reliability issues
    - unable to begin fabrication due to funding limitations

R&D Program Progress

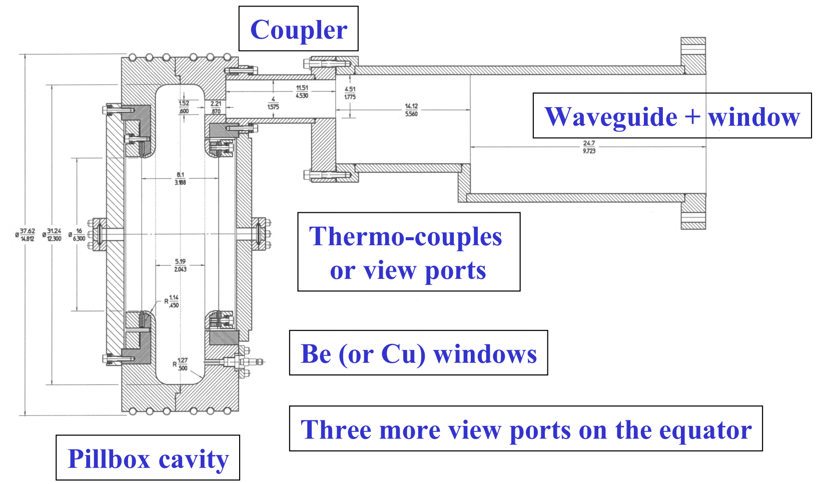
- **Initial tests of 805 MHz cavity in magnetic field (Moretti, Norem) showed large dark currents ($\propto E^{10}$)**
  - **copper splashes appear on window when solenoid field present**

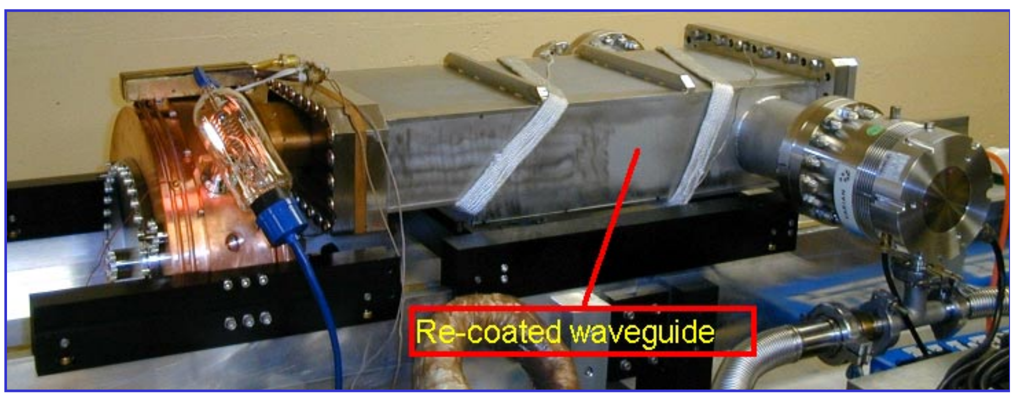




R&D Program Progress

- Focus now on pillbox cavity having replaceable windows (or grids) (Li)
  - cavity fits in bore of Lab G solenoid

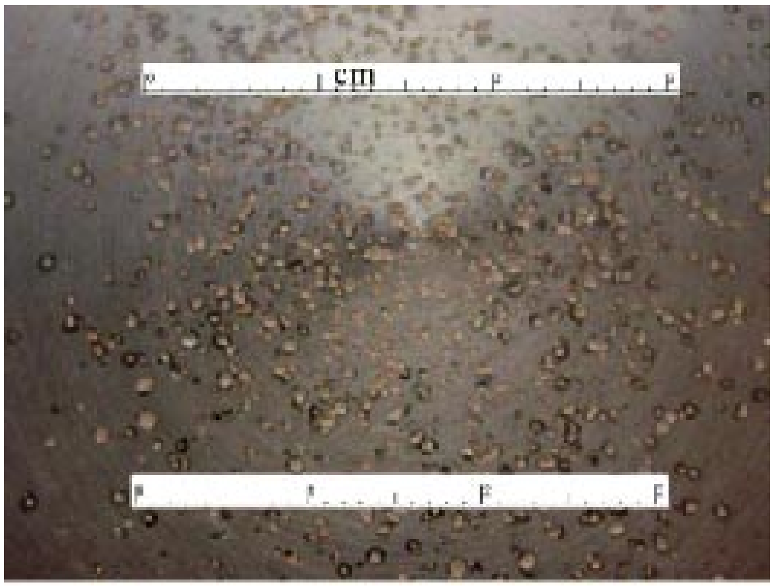




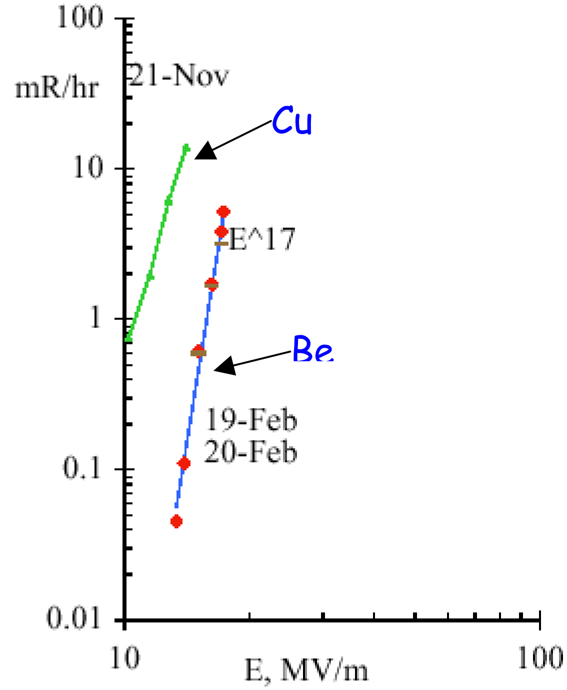
R&D Program Progress

- Pillbox cavity reached 34 MV/m in Lab G with no solenoid field
  - performance with solenoid is much lower and radiation levels higher
    - field seemingly enhances likelihood of "permanent" damage
      - but, evidence for healing when field is removed
- After initial operation, cavity disassembled to inspect windows and internal surfaces
  - some pitting of window seen, with copper "dust" at bottom of cavity
- TiN-coated Be windows next installed and tested
  - no conditioning problems seen without magnetic field
  - even with field on, background rates lower than for copper under comparable conditions

R&D Program Progress



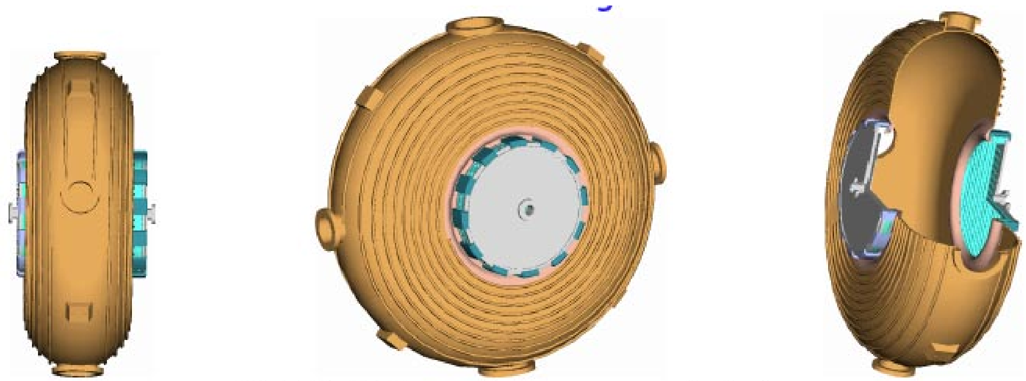
Copper window after using solenoid



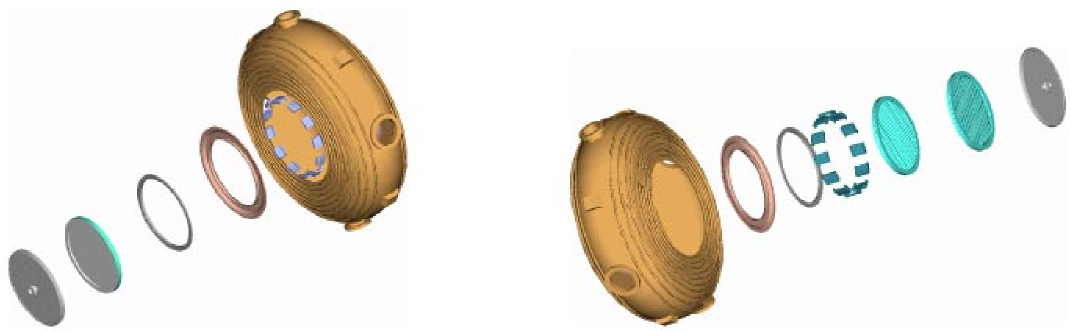
Radiation levels for Cu, Be windows

R&D Program Progress

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



201.25 MHz cavity conceptual design

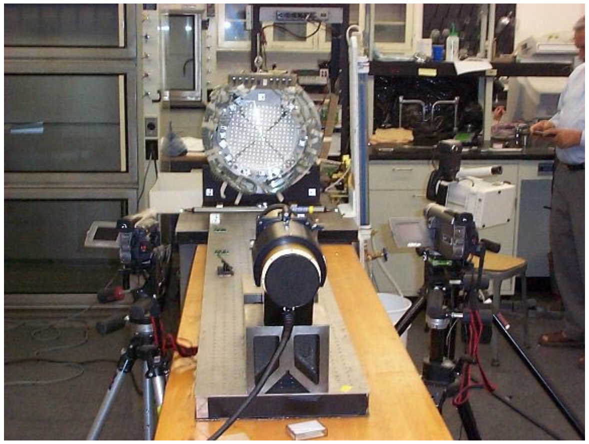


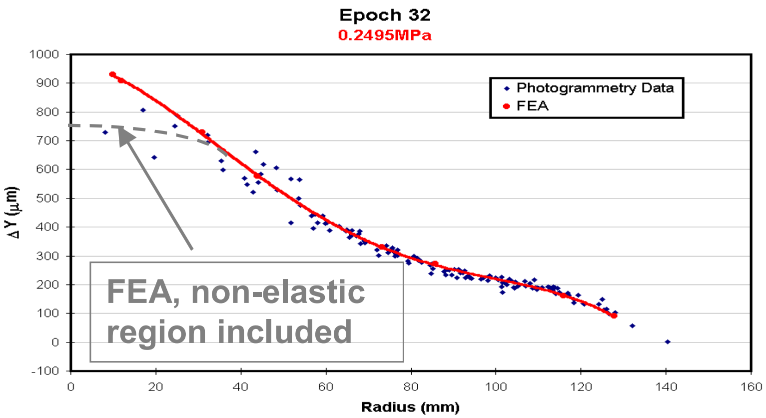
Exploded views showing foil and grid mounting hardware

  - collaboration between LBNL and Jlab
  - options for either Be windows or grids are available

R&D Program Progress

- Absorber work focusing mainly on developing strong, thin windows for LH_2 containment (Cummings, Kaplan)
  - windows as thin as 125 μm machined from solid Al
  - destruction tested at NIU (performance satisfactory)
    - 125 μm window broke at 44 psi (3 atm), 340 μm window at 120 psi (8 atm)
  - use photogrammetry to characterize window behavior
    - goal is to verify FEA calculations (LH_2 safety requirement)





R&D Program Progress

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

Original area

As of May, 2003

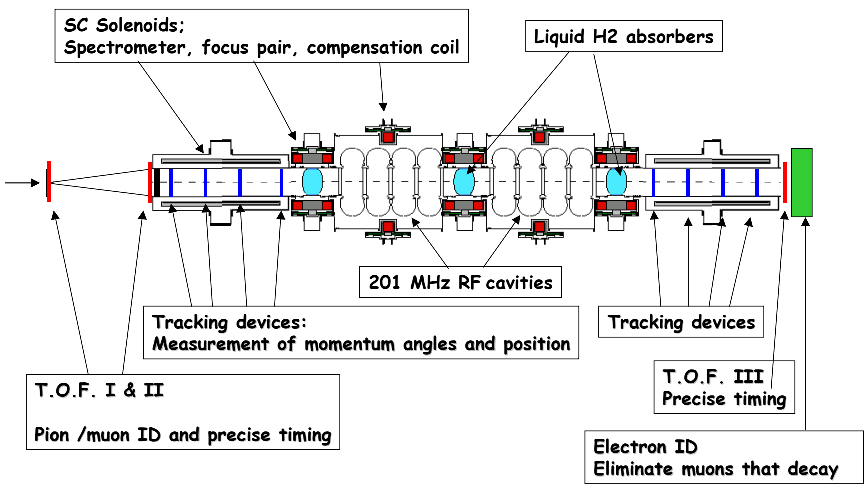
What it will look like when completed (September, 2003)

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 year (and this year)
  - experiment considered "crucially important demonstration"
- MC participating in planning and organization of (international) MICE
  - Kaplan (U.S. Spokesperson), Geer, and MZ on steering committee
    - technical conveners: Bross, Cummings, Green, Li, Norem, Palmer, Torun
- Why should we move forward expeditiously?
  - we have a motivated collaboration, an enthusiastic host lab, and a solid experiment design ⇒ the time to begin is now
  - experiment forces us to deal with operational and cost issues early

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
  - presentation of LOI to RAL on March 25 (McKigney, MZ$\rightarrow$Blondel)
    - RAL requested formal technical proposal to serve as host site
  - proposal submitted in January 2003
    - international review held February 17 (Blondel, MZ, Palladino, Edgecock)
    - 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."

MICE Activities

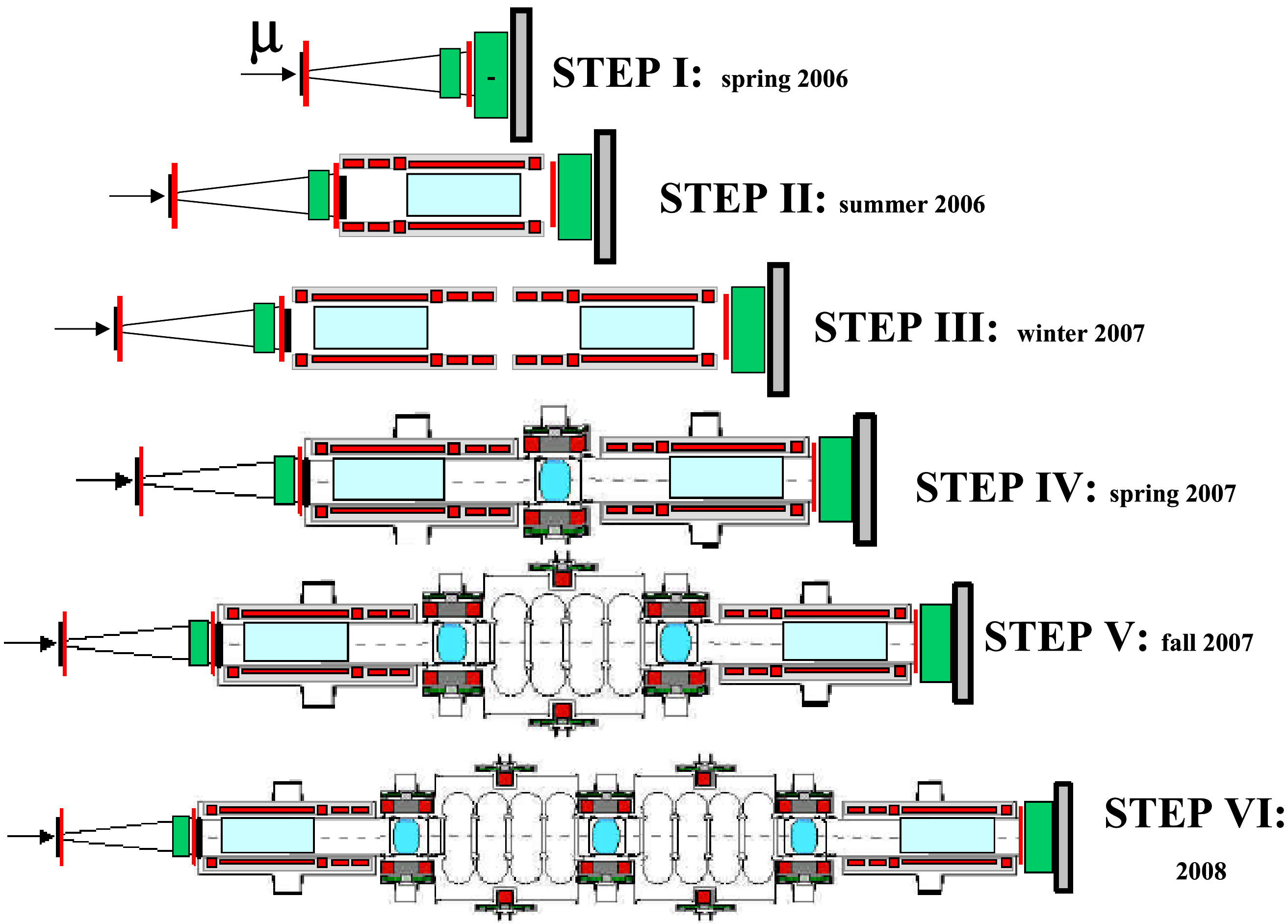
- funds are being sought now in the UK and elsewhere
- U.S. team submitted 5-year funding proposal to NSF for $24M
  - we hope DOE and NSF will coordinate on this request

• Hardware cost estimate in M€ (preliminary)

Item	Estimated cost	U.S.	Japan	Europe	UK
Cooling section	13.9	6.3	0.3	3.7	3.6
Spectrometer section	7.5	2.1	0.7	3.0	1.7
Ancillary items	3.8	0.1	0.0	0.5	3.2
Total	25.2	8.5	1.0	7.2	8.5
		(34%)	(4%)	(29%)	(34%)

MICE Activities

— anticipated schedule for staging experiment (depends on availability of support)



R&D Plans

- Future planned hardware activities require support well in excess of FY03 funding level
  - cost figures for major items given merely for guidance; *they do not represent detailed cost estimates*
- Targetry
  - fabricate 15 T magnet and test with AGS (or other) beam [≈$1.5M]
  - upgrade AGS extracted beam to reach 16 Tp on target
  - operate AGS for E951
    - requires 10 shifts for target tests [≈$1M if we are prime user]
  - present investment in AGS infrastructure ≈$3M

  Lack of AGS running for HEP in FY03 delayed program by 1 year

  if AGS running is not restored, we will seek beam elsewhere

R&D Plans

- MUCOOL
  - outfit MUCOOL Test Area (MTA) for rf and absorber experiments [≈$1M]
  - fabricate and test 201 MHz high-gradient cavity (17 MV/m) [≈$0.5M]
  - fabricate and test LH_2 absorbers (first convection-cooled, later externally cooled type) with all safety aspects [≈$0.2M]
  - fabricate and test solenoid "coupling coil" at full field [≈$1.5M]
  - carry out integration tests of all components operating together (cavity, absorber, solenoid)
  - upgrade MTA for 400 MeV p beam and test integrated system with beam ("blast test") [≈$0.5M]
  - present investment in Fermilab infrastructure ≈$3M

R&D Plans

- Acceleration (NSF supported)
  - develop full prototype of 201 MHz SCRF system (cavity, tuner, coupler, cryostat) and suitable low-level controls [≈$3–5M]
  - operate at high gradient (≈17 MV/m) with acceptable performance
  - present investment in Cornell infrastructure ≈$1M
- Ring coolers and FFAGs
  - develop prototypes of challenging magnets [≈$0.5M]
  - develop and test wedge absorbers [≈$0.2M]
- MICE
  - design, fabricate, and commission required beam line components for which the U.S. team is responsible (201 MHz rf cavities, solenoid coils, dark current and timing diagnostics, SciFi tracker, Cerenkov system) [≈$11M]
    - MICE funding anticipated to be separate from ongoing MC R&D program

R&D Budget

- FY03 *MC* budget is

Institution	COOLING	TARGETRY	COLLIDER	EFFORT[a]	RESERVE	TOTAL ($K)
BNL		300				300
FNAL	400					400
LBNL	204				26	230
ANL				144		144
IIT				75		75
Mississippi				50		50
Princeton		50				50
UCB			5			5
UCLA	25		50			75
UCR				90[b]		90
ORNL						0
JLab				10		10
TOTAL ($K)	**629**	**350**	**55**	**369**	**26**	**1429**

[a]Includes beam simulation and diagnostics effort.
[b]Support for simulations post-doc.

- **Also: salary support from BNL, FNAL, LBNL; support from NSF (mainly Cornell) of ≈$1M; and support from ICAR (≈15 FTE)**

R&D Budget

- In FY03, the MC budget was halved

Year	DOE-base ($M)	DOE-MC ($M)	TOTAL ($M)
FY99	2.8	2.2	5.0
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[a]	?	1.4	?

[a] Present guidance

- At this level, it is difficult to build components costing $\mathcal{O}$($1M) each
- Severe cut in FY03 was a shock
  - after considerable technical progress, a good MUTAC review, support from MCOG, and a favorable recommendation from HEPAP Subpanel

"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."

R&D Budget

- Budget issues
  - MC has no formal mechanism for giving DOE input on future funding needs
    - we do not formally submit FWP (but we sent one unsolicited!)
    - we do not get a DOE-HEP review as a "program"
  - we request to be reviewed as a program in future years
    - perhaps as part of LBNL program review
- We need to understand DOE's intentions regarding our program to do rational out-year planning
  - as noted by B&B Subpanel, $8M per year (direct + base program) would permit a solid program to address Neutrino Factory and Muon Collider R&D issues
- We based our R&D directions on the assumption of at least a return to FY02 levels in FY04
  - this optimism seems to have been misplaced

Summary

- MC program has made excellent progress on all fronts in the past few years
- MC and its interaction with colleagues worldwide serve as "model" for working together on major international projects
- MC is part of strong international planning effort for MICE
    - formal proposal to RAL completed, reviewed, and endorsed
    - international search for funds is under way
- MC is developing components that serve as prototypes for MICE
- Budget decline is causing significant morale problem
  - FY04 budget guidance inadequate for hardware development
    - seems at odds with community input
  - rectifying this, and keeping adequate funding levels in future years, are critical to maintaining a healthy U.S. muon beam R&D program