# Neutrino Factory and Muon Collider R&D: Status and Plans

**Michael S. Zisman**
*CENTER FOR BEAM PHYSICS*

*Project Manager, Neutrino Factory and Muon Collider Collaboration*

BNL Seminar
January 17, 2007

# Outline

- Organization
- History
- International perspective
- U.S. R&D partners
- Physics context
- Facility description
- Ionization cooling
- R&D overview
- R&D accomplishments (Simulations, Targetry, RF cavity, Absorber, SCRF)
- MICE
- Future plans
- Summary

# Organization

- U.S. Neutrino Factory and Muon Collider Collaboration broadly based
  - more than 100 scientists and engineers from about 30 institutions
- NFMCC is a mix of accelerator and particle physicists
  - from both National Labs and Universities
- We also greatly benefit from collaborators in Europe and Asia
- Main funding support from DOE, including valuable SBIR grants
  - some U.S. support has come from NSF
- Program oversight by Muon Collaboration Oversight Group (MCOG)
  - Laboratory directorate level (BNL, Fermilab, LBNL)
- MCOG appoints technical review committee (MUTAC)
  - chaired by Bob Kephart

# History

- NFMCC began as informal group of ≈100 people investigating feasibility of building a high-energy Muon Collider
  - see "Muon Collider Feasibility Study Report" Snowmass 1996 (BNL-52503, FNAL-Conf-96/092, LBNL-38946; 480 pages)
- Oversight/review structure initiated by DOE and Lab Directors when organization formalized
- First MUTAC review recommended that NFMCC focus on one facility and conduct end-to-end technical study
  - choice was Neutrino Factory (viewed as technically simpler)
- In 1999–2000, Fermilab director sponsored Feasibility Study I (~$1M engineering effort)
  - concluded that Neutrino Factory is feasible but expensive (~$2B)
- In 2000–2001, BNL director + NFMCC sponsored Feasibility Study II
  - intensity improvement (5x Study I), but still expensive

# International Perspective

- International Neutrino Factory community has held annual "NuFact" workshops since 1999
  - provides opportunity for physics, detector, and accelerator groups to plan and coordinate R&D efforts at "grass roots" level
  - venue rotates among geographical regions (Europe, Japan, U.S.)

| Year | Conference Venue |
|---|---|
| 1999 | Lyon, France |
| 2000 | Monterey, CA |
| 2001 | Tsukuba, Japan |
| 2002 | London, England |
| 2003 | New York, NY |
| 2004 | Osaka, Japan |
| 2005 | Frascati, Italy |
| 2006 | Irvine, CA |
| 2007 | Okayama, Japan |

# International Perspective

- Activities in Europe
  - European Neutrino Factory Feasibility Study completed in 2002
  - ECFA report encouraged R&D effort; EMCOG set up (Spring 2002)
  - Beams for European Neutrino Experiments launched in 2004 (Chair: Vittorio Palladino)
  - International Scoping Study (ISS) of Future Neutrino Factory and Superbeam Facility launched at NuFact05
    - hosted by RAL; sponsored by BENE, NFMCC, NuFact-J, UKNF
    - first phase completed at NuFact06
    - International Design Study (IDS) being launched as ISS follow-on
      - organizational meeting at CERN in February 2007

# International Perspective

- Activities in Japan (KEK, Kyoto, Osaka)
  - Japanese Neutrino Factory Feasibility Study completed in 2001
  - contributing to NFMCC effort (absorbers and FFAG studies)
  - also to ISS
- Two "global" experiments launched (MICE, MERIT)
  - China (ICST, Harbin) has recently joined MICE collaboration
- Another experiment in which we hope to be involved is EMMA
  - recently funded in the UK to build electron model of non-scaling FFAG

# U.S. R&D Partners

- Collaborating with Muons, Inc. and FNAL MCTF on Muon Collider R&D
  - MCTF goals (subject to funding constraints) include
    - FY07
      - design 1.5 TeV low-emittance Muon Collider
      - prepare plan for MTA high-power proton beam
      - prepare development plan for 50-T HTS solenoid
      - begin design of 50-T solenoid
    - FY08
      - test high-pressure RF cavity with proton beam
      - develop and install muon beam line, including target
      - test 5-T HTS insert in 15-T solenoid
      - design and prototype helical cooling channel elements
    - FY09
      - commission muon beam line
      - begin fabrication of helical cooling channel magnets
      - complete engineering design for 50-T HTS solenoid
    - FY10
      - complete helical cooling channel magnets and begin MANX
      - complete prototype 50-T HTS solenoid
      - prepare report on helical cooling channel

# Physics Context

- NFMCC focus on Neutrino Factory and Muon Collider driven by physics
  - for Neutrino Factory
    - exciting evidence for neutrino oscillations, with parameters within reach of future accelerator experiments
    - beam properties

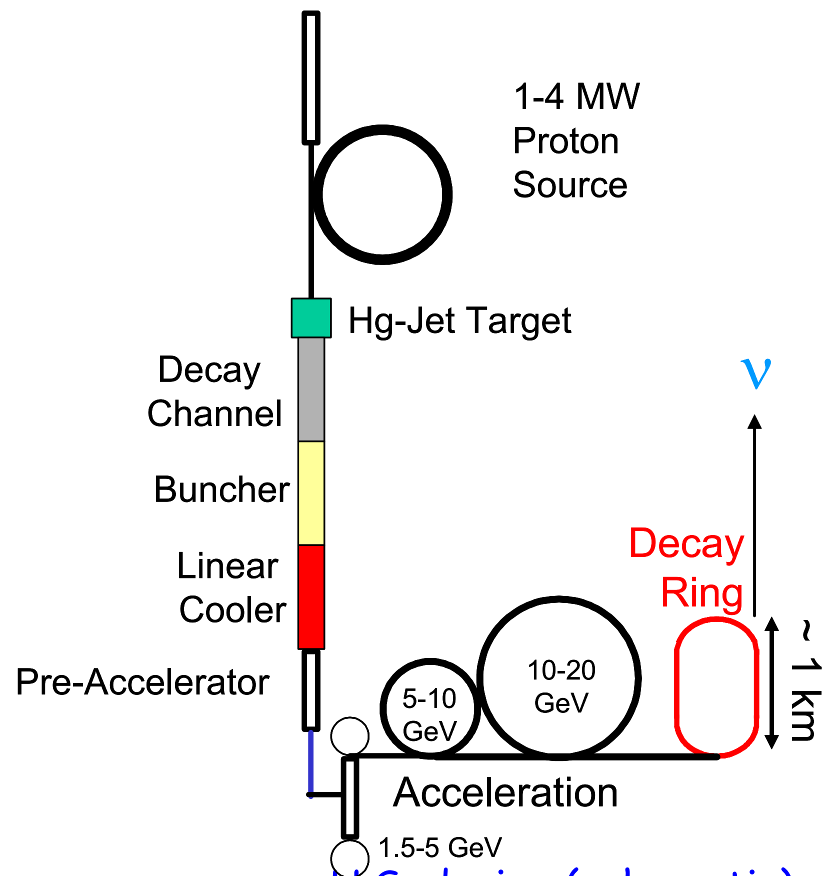
$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \overline{\nu}_\mu$$

$$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu \Rightarrow 50\% \overline{\nu}_e + 50\% \nu_\mu$$

    - decay kinematics well known (minimal hadronic uncertainties in spectrum, flux, and comparison of $\mu^+$ and $\mu^-$ results)
    - $\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable "wrong-sign" muons
  - for Muon Collider
    - no bremsstrahlung or beamstrahlung; fits on existing site
    - 10x higher energy reach than similar energy proton collider

# Facility Description

- Neutrino Factory comprises these sections (NFMCC doing R&D on most)
  - **Proton Driver**
    (primary beam on production target)
  - **Target and Capture**
    (create π's; capture into decay channel) ⇒ MERIT
  - **Bunching and Phase Rotation**
    (reduce $\Delta E$ of bunch)
  - **Cooling**
    (reduce transverse emittance of beam) ⇒ MICE
  - **Acceleration**
    (130 MeV → 20–50 GeV with RLAs or FFAGs)
  - **Decay Ring**
    (store muon beam for ≈500 turns; optimize yield with long straight section aimed in desired direction)

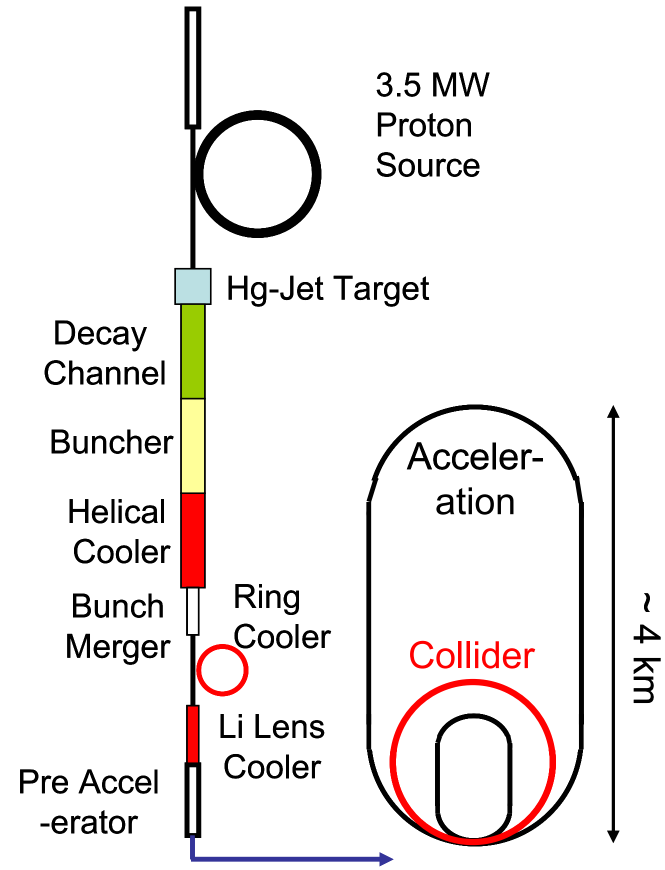


U.S. design (schematic)

- **Not an easy project, but no fundamental problems found**

# Facility Description

- Muon Collider comprises these sections (similar to Neutrino Factory)
  - Proton Driver
    (primary beam on production target)
  - Target and Capture
    (create π's; capture into decay channel) ⇒ MERIT
  - Phase Rotation
    (reduce $\Delta E$ of bunch)
  - Cooling
    (reduce longitudinal & transverse emittance of beam) ⇒ MICE → MANX
  - Acceleration
    (130 MeV → 1.5 TeV with RLAs or FFAGs)
  - Collider Ring
    (store muon beam for ≈500 turns; 1 IP)



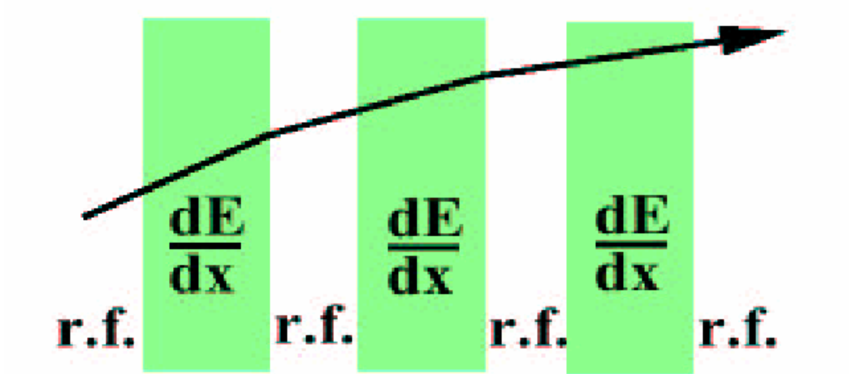

- Much of Muon Collider R&D is common with Neutrino Factory R&D
  - carried out by Muons, Inc., NFMCC, and newly formed MCTF at FNAL

# Facility Description

- Challenges of a muon-based facility (Neutrino Factory or Collider)
  - muons have short lifetime (2.2 μs at rest)
    - puts premium on rapid beam manipulations
      - high-gradient NCRF (in magnetic field) for cooling
      - presently untested ionization cooling technique
      - fast acceleration system
  - muons are created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
    - low production rate ⇒
      - target that can handle multi-MW beam
    - large muon beam transverse phase space and energy spread ⇒
      - ionization cooling
      - high-acceptance acceleration system and decay ring
- Cooling requirements for Muon Collider much more stringent than for Neutrino Factory

# Ionization Cooling

- 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



# Ionization Cooling

- 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)

# Ionization Cooling

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

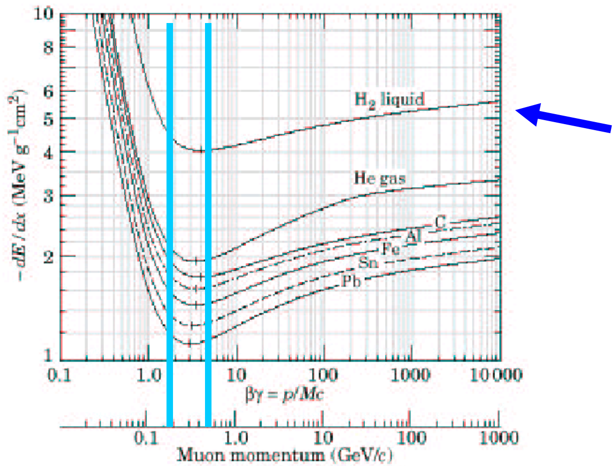
| **Material** | **$(dE/ds)_{min.}$ (MeV g$^{-1}$ cm$^2$)** | **$X_0$ (g cm$^{-2}$)** | **Relative merit** |
|---|---|---|---|
| Gaseous $H_2$ | 4.103 | 61.28 | 1.03 |
| Liquid $H_2$ | 4.034 | 61.28 | 1 |
| He | 1.937 | 94.32 | 0.55 |
| LiH | 1.94 | 86.9 | 0.47 |
| Li | 1.639 | 82.76 | 0.30 |
| $CH_4$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

# Ionization Cooling

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

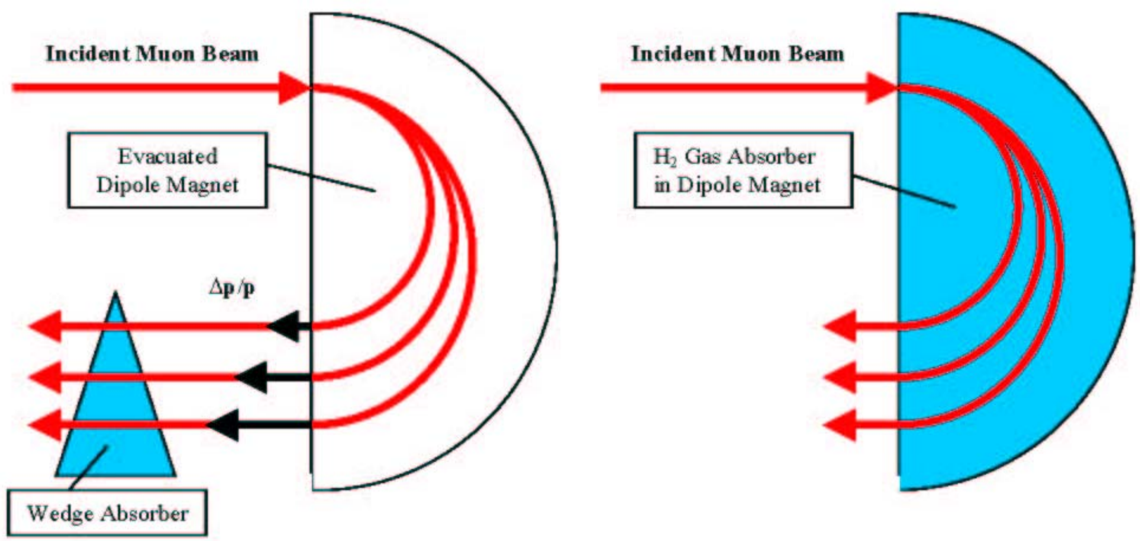



Note benefits of $LH_2$ compared with other materials

- 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

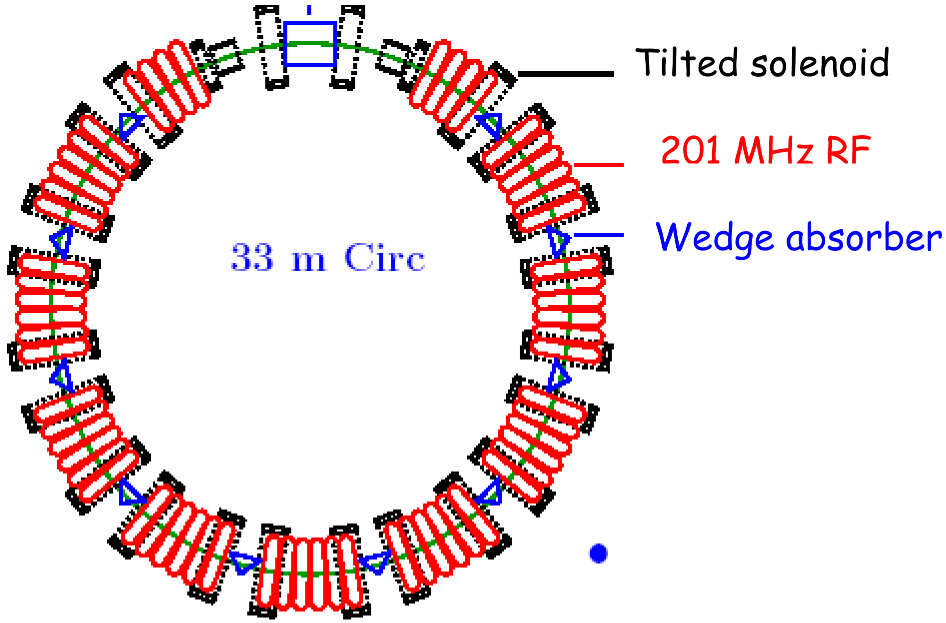
# Ionization Cooling

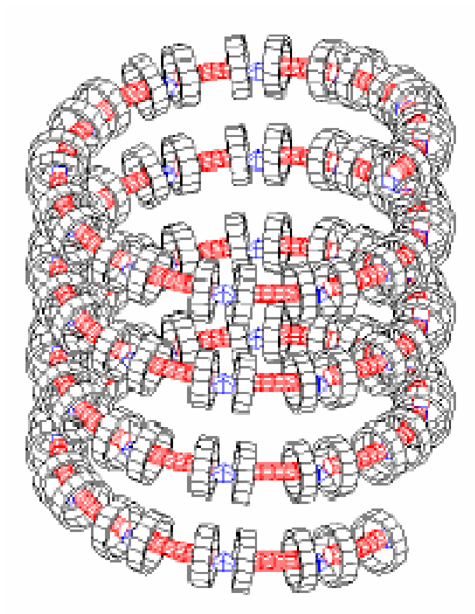
- To carry out 6D cooling, add emittance exchange to the mix
  - create increased energy loss for high energy muons compared with low-energy muons
    - put wedge-shaped absorber in a dispersive region
    - use additional path length in continuous absorber for high energy muons



# Ionization Cooling

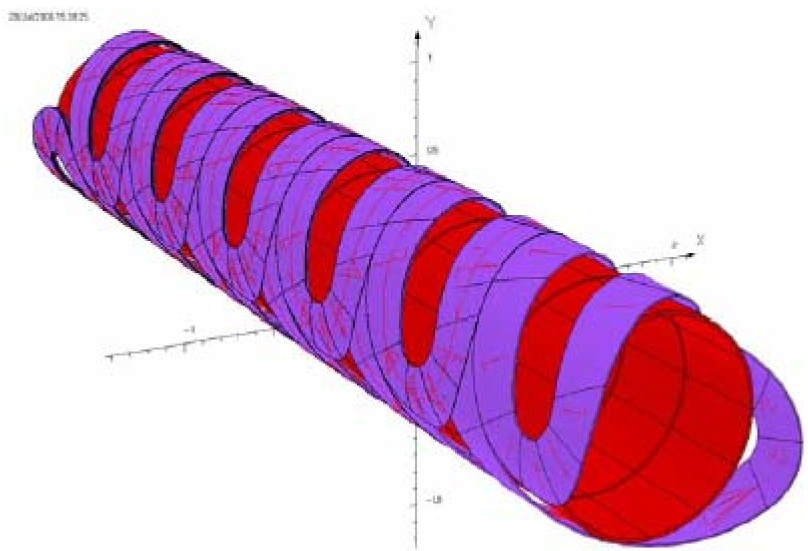
- Dispersion can be created with a cooling ring or so-called "Guggenheim" arrangement of a single-pass channel
  - Guggenheim structure avoids difficult injection and extraction issues and permits modification of channel parameters as cooling proceeds
    - at the expense of more hardware



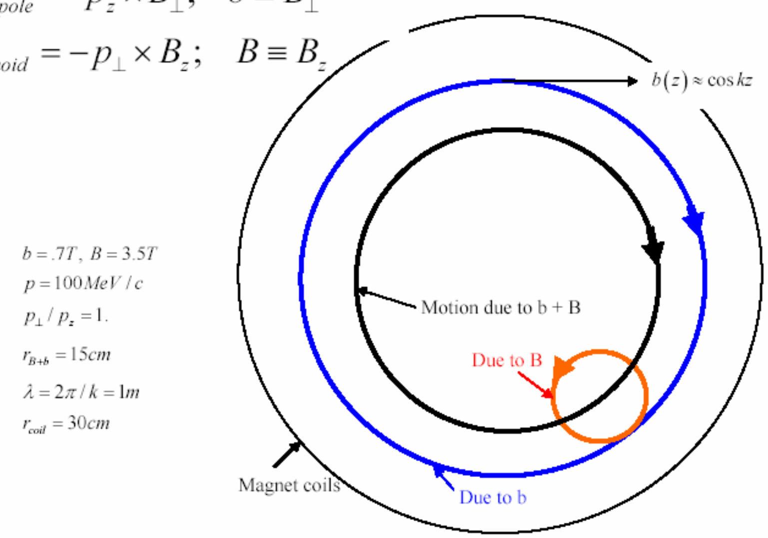
# Ionization Cooling

- **Gas filled helical channel can also be used as a compact 6D cooling channel**
  - **superposition of helical dipole and solenoidal fields gives increased path length for higher momentum particles**



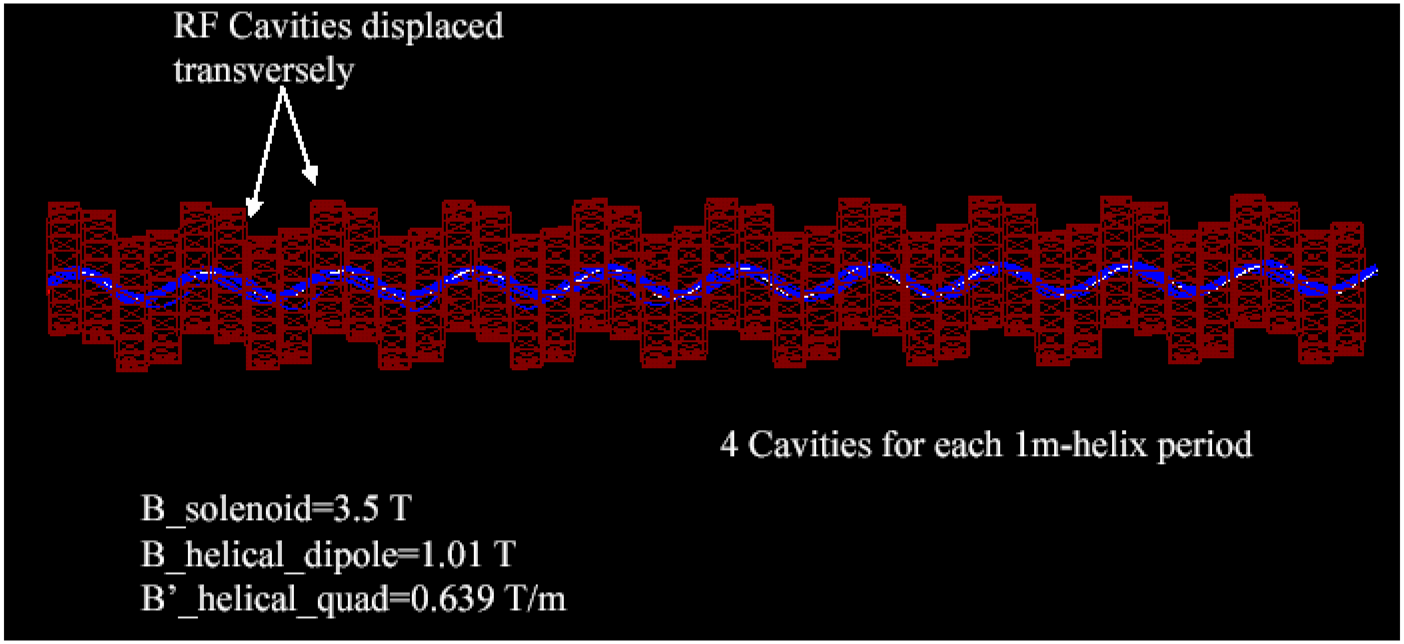
$$F_{h-dipole} = p_z \times B_\perp; \quad b \equiv B_\perp$$

$$F_{solenoid} = -p_\perp \times B_z; \quad B \equiv B_z$$



# Ionization Cooling

— still need RF cavities, either internal to magnetic channel or in separate interleaved sections



# R&D Overview

- NFMCC R&D program has the following components:
  - simulation and theory effort in support of Neutrino Factory and Muon Collider design (incl. MCTF, FFAG/EMMA)
  - development of high-power target technology (Targetry)
  - hardware development of cooling channel components (MUCOOL)
- NFMCC also participates in three international endeavors:
  - MICE (ionization cooling demonstration)
  - MERIT (high-power Hg-jet target)
  - ISS → IDS (simulation studies of Neutrino Factory design)
- Hardware development continues as major focus of NFMCC activity
- Simulation effort aimed at reducing Neutrino Factory cost ("Study IIa") gave good results in APS neutrino study
  - increased performance, lower cost

# Design and Simulations

- Simulations
  - a main focus recently was participation in APS Multi-Divisional Neutrino Study (http://www.aps.org/policy/reports/multidivisional/neutrino/index.cfm)
  - detailed report written by "Neutrino Factory and Beta Beams Experiments and Development Working Group"
    - http://www.aps.org/policy/reports/multidivisional/neutrino/upload/Neutrino_Factory_and_Beta_Beam_Experiments_and_Development_Working_Group.pdf
    - considerable progress made in simplifying front-end systems while maintaining performance
  - have now completed one year ISS to follow up on the improvements
  - making progress on studies of 6D cooling (emittance exchange) motivated by collider design
    - several cooling ring designs look workable
    - innovative helical "linear" channel also being investigated (with MCTF and Muons, Inc.)

# Design and Simulations

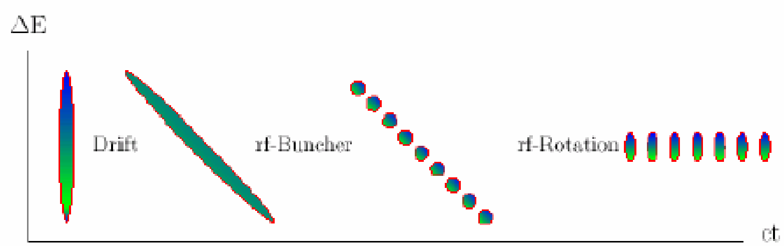
- **Substantial cost savings predicted from reoptimization of Study II design**
  - **at the same throughput for one sign of muon as Study II**
  - **both signs now available, so facility performance effectively doubled**

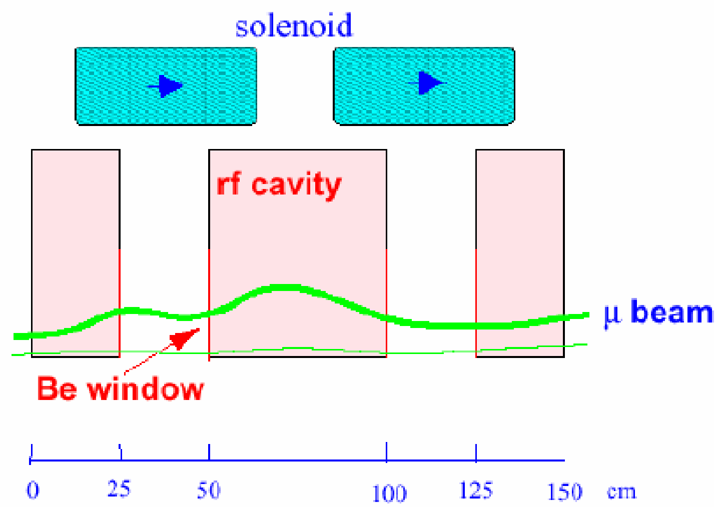
| System | Cost reduction (Study IIa vs. II) |
|---|---|
| Target and Capture | 0.99 |
| Bunching and Phase Rotation | 0.38 |
| Cooling | 0.60 |
| Acceleration | 0.77 |
| Aggregate | 0.65 |

  - **main savings accrued from**
    - **developing RF bunching and phase rotation scheme**
    - **developing large acceptance FFAG scheme for final acceleration stages**
    - **simplifying cooling channel (takes advantage of larger downstream acceptance)**

# Design and Simulations

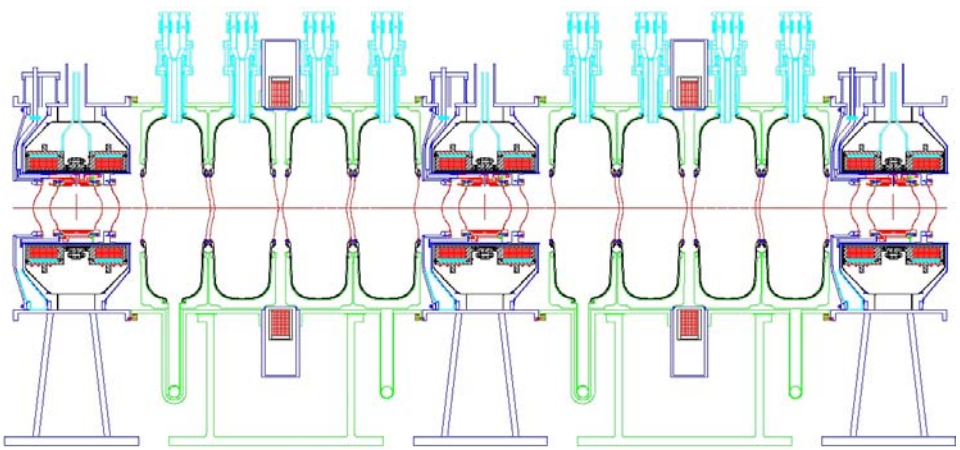
- Use RF to bunch, then to phase rotate
  - performance acceptable and less expensive than induction linacs
    - uses "standard" cooling channel components
    - keeps both $\mu^+$ and $\mu^-$
  - RF frequencies vary along the beam channel



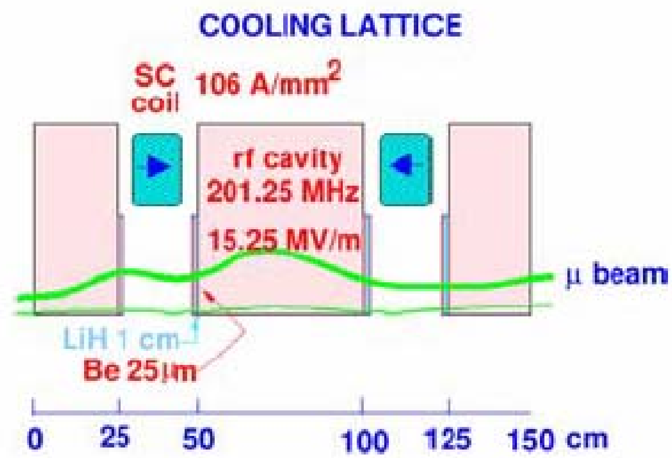



# Design and Simulations

- Use simplified cooling channel
  - shorter, fewer magnets and cavities, simpler absorbers (replace $LH_2$ with LiH)



Study II channel

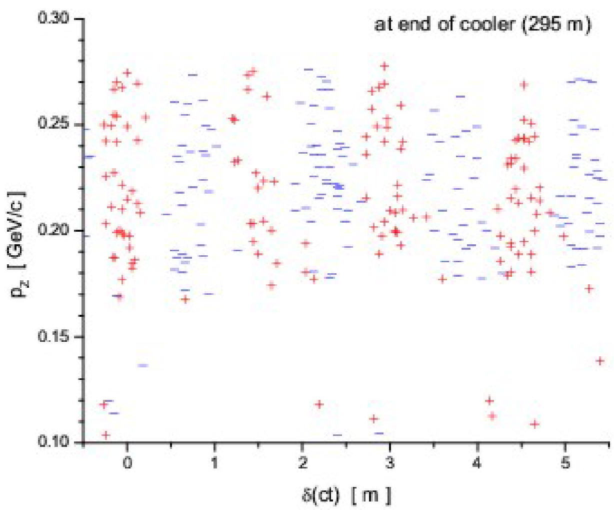


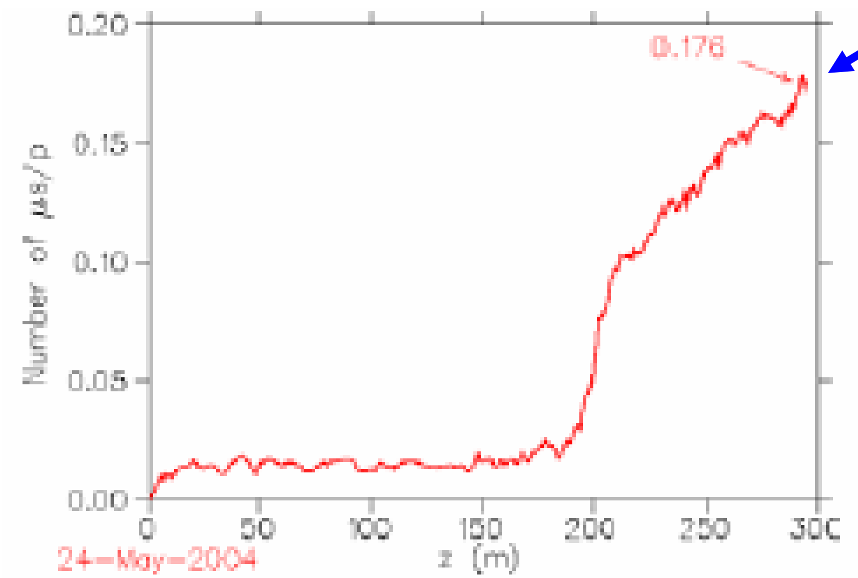

Study IIa channel

## Design and Simulations

– simpler channel performs acceptably for both $\mu^+$ and $\mu^-$ (with larger downstream acceptance)

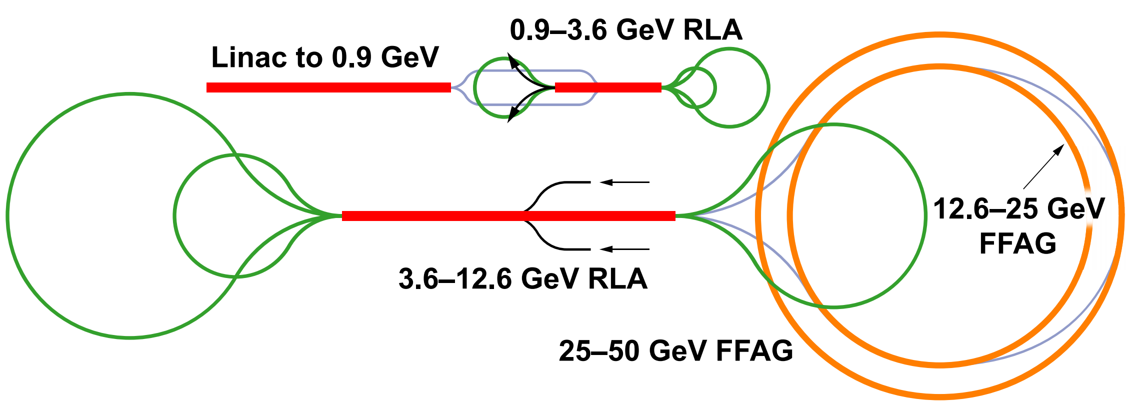
Same as Study II



# Design and Simulations

- Developed non-scaling FFAG scheme for cost-effective large acceptance acceleration
  - below 12.6 GeV, linac + cascaded "dog-bone" RLA scheme is more cost effective
  - at higher energies, use non-scaling FFAG rings
    - electron model of FFAG (EMMA) recently funded in UK

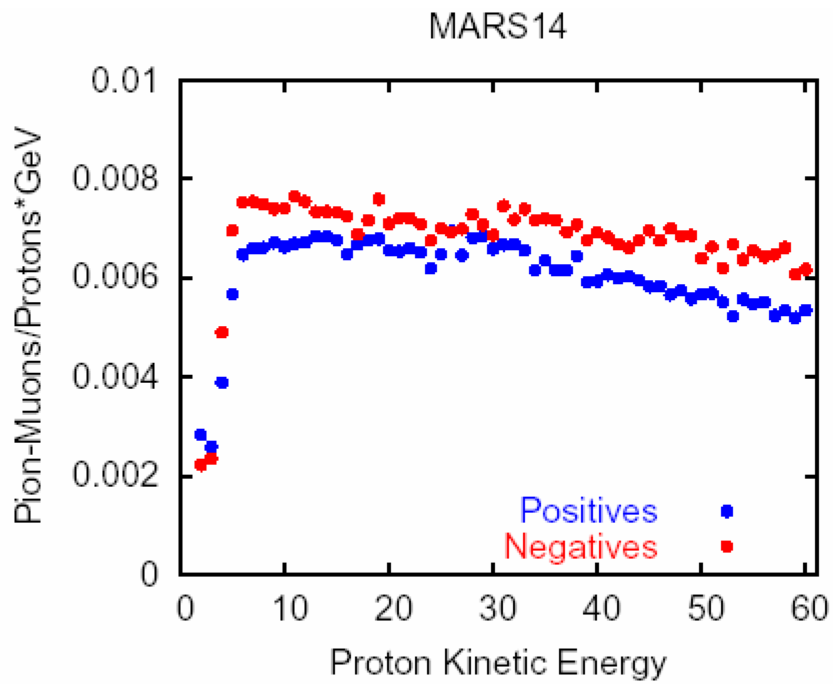


## Design and Simulations

- Summary of main findings from ISS (report in preparation)
  - preferred proton driver energy is 10 ± 5 GeV
  - Hg-jet target gives optimal muon production for protons in preferred energy range
  - Study IIa front end design is preferred, using simultaneous operation with both muon signs
  - non-scaling FFAG beam dynamics limits performance, so preferred approach will use only one, or at most two, such systems
  - both racetrack and triangular rings possible (two rings needed in either case)
    - triangle more efficient if two suitable sites are operating simultaneously
    - racetrack better for a single detector site, and has no directional constraints

# Design and Simulations

- Preferred energy (simulations by H. Kirk)
  - also need short bunches, 1–3 ns is preferred range




$\mu^-$: 6 – 11 GeV

$\mu^+$: 9 – 19 GeV

We adopted 10 $\pm$ 5 GeV as representative range

# Design and Simulations

- **Target comparisons done for Hg and C**
  - **conclude that Hg is best**

Results from H. Kirk

Compare Meson production for Hg at 24 GeV and 10 GeV

$$\frac{N^{+}{}_{10GeV}}{N^{+}{}_{24GeV}} = 1.07 \qquad \frac{N^{-}{}_{10GeV}}{N^{-}{}_{24GeV}} = 1.10$$

Compare Meson production for C at 24 GeV and 5 GeV

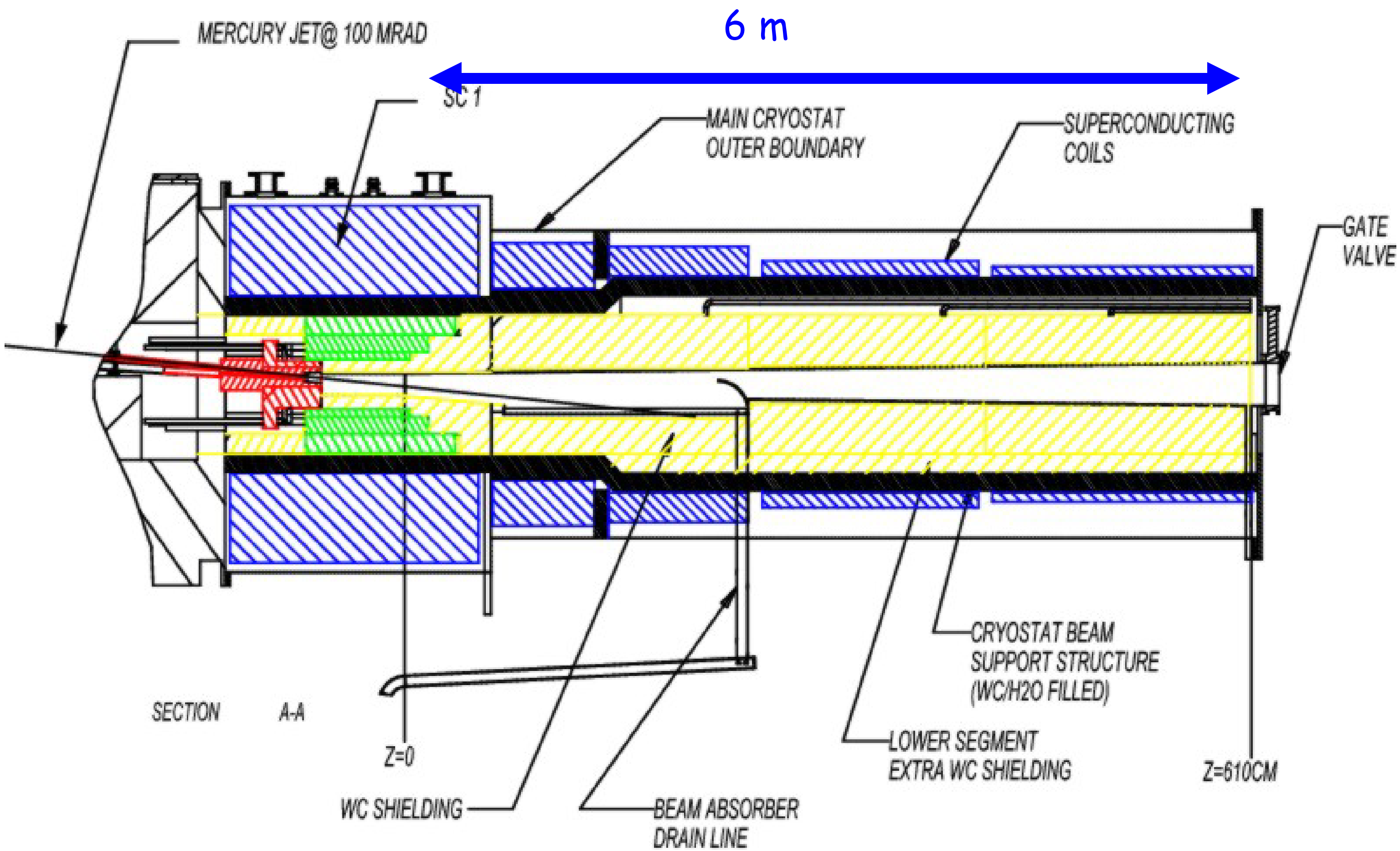
$$\frac{N^{+}{}_{5GeV}}{N^{+}{}_{24GeV}} = 1.90 \qquad \frac{N^{-}{}_{5GeV}}{N^{-}{}_{24GeV}} = 1.77$$

Compare Meson production for Hg at 10 GeV and C at 5 GeV

$$\frac{N^{+}{}_{Hg-10GeV}}{N^{+}{}_{C-5GeV}} = 1.18 \qquad \frac{N^{-}{}_{Hg-10GeV}}{N^{-}{}_{C-5GeV}} = 1.22$$

# Targetry R&D

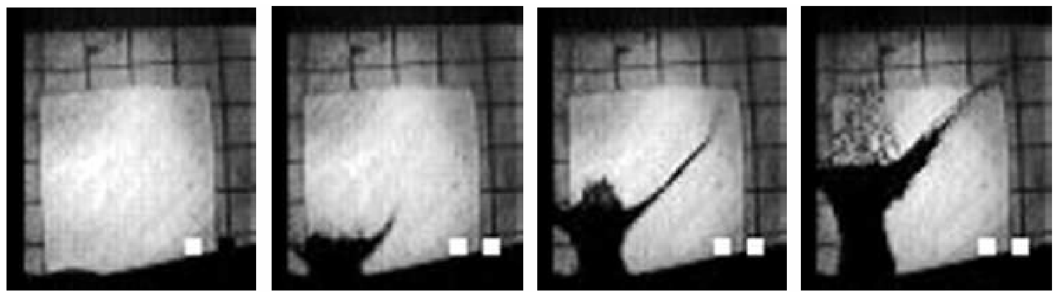
- Target concept based on free Hg jet in 20-T solenoidal field
  - jet velocity of 20 m/s establishes "new" target each beam pulse



# Targetry R&D

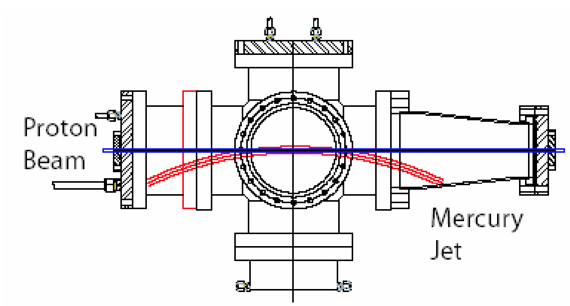
- Targetry effort focused mainly on validating efficacy of Hg-jet target
  - E951 experiment at BNL looked at both stationary and moving Hg

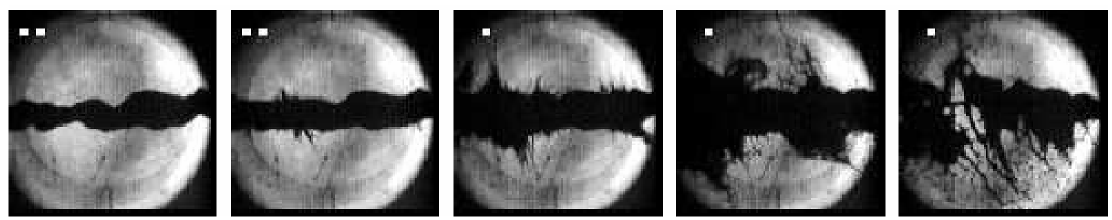
Hg thimble



*t* = 0 0.5 1.6 3.4 ms

Hg jet



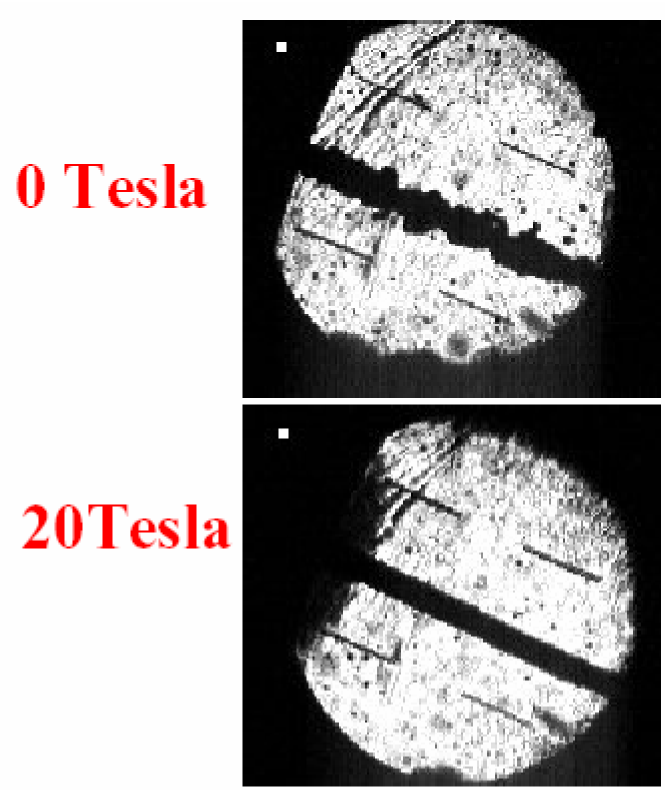



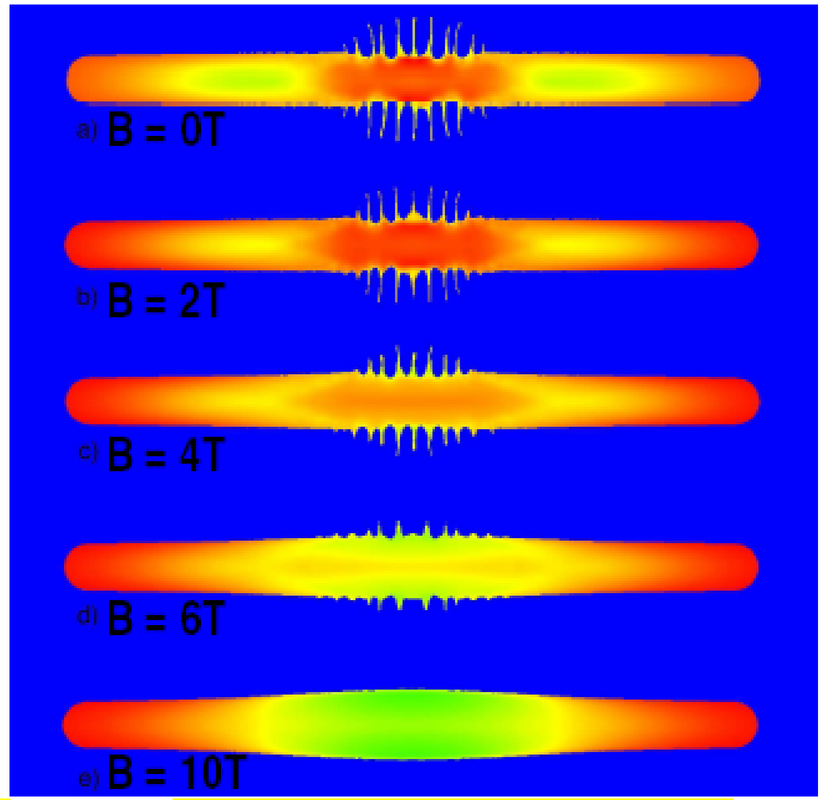
*t* = 0 0.75 2 7 18 ms

- Without magnetic field, Hg jet looks workable

# Targetry R&D

- With magnetic field, surface instabilities are stabilized

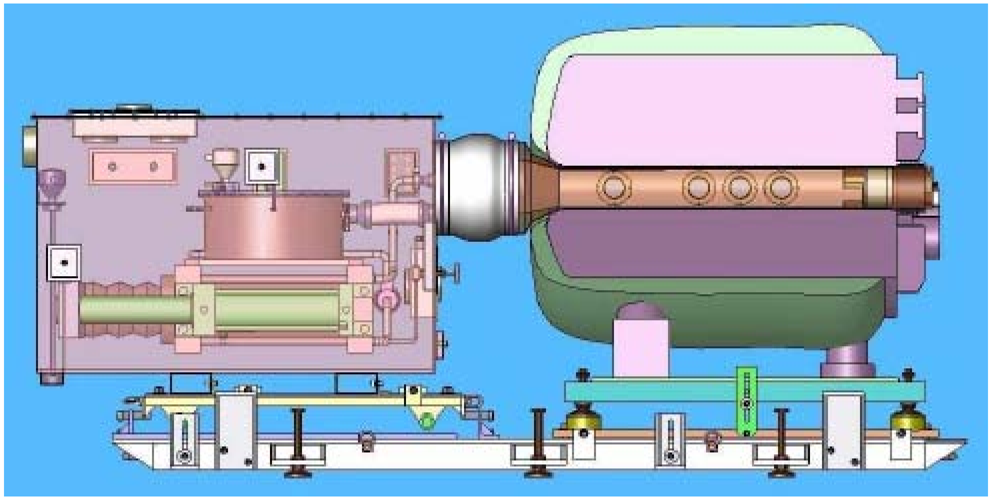


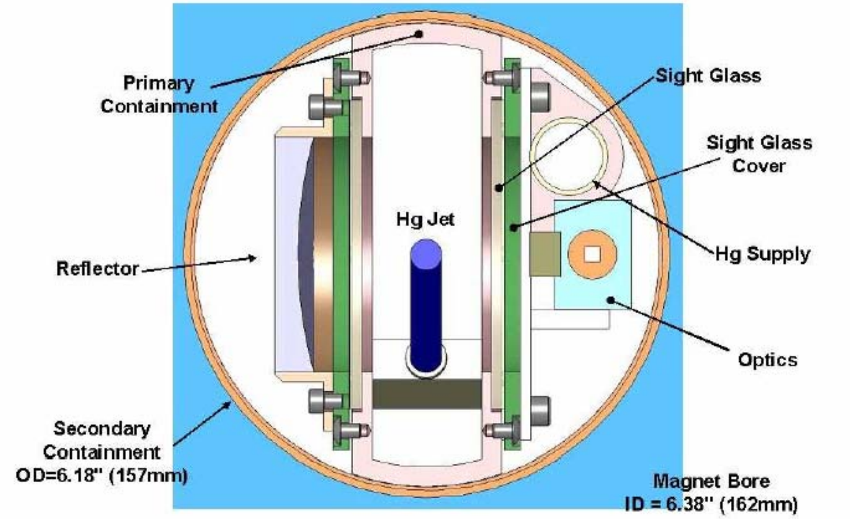




Experiment (Fabich) MHD simulation (Samulyak)

# Targetry R&D

- To do beam test of Hg jet with magnetic field, MERIT proposal submitted to CERN April, 2004 (approved April 2005)
  - located in TT2A tunnel to ISR, in nTOF beam line
  - first beam from CERN PS ~July, 2007

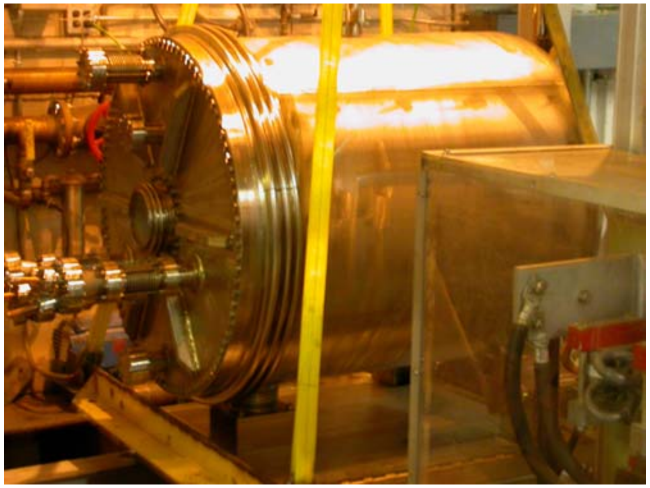




# Targetry R&D

- Fabrication of 15 T magnet completed
  - operates at 80 K (cryogenic but not superconducting)
    - repetition rate ~ 0.001 Hz (20 minute cycle)
  - Hg jet system capable of 20 m/s completed at ORNL

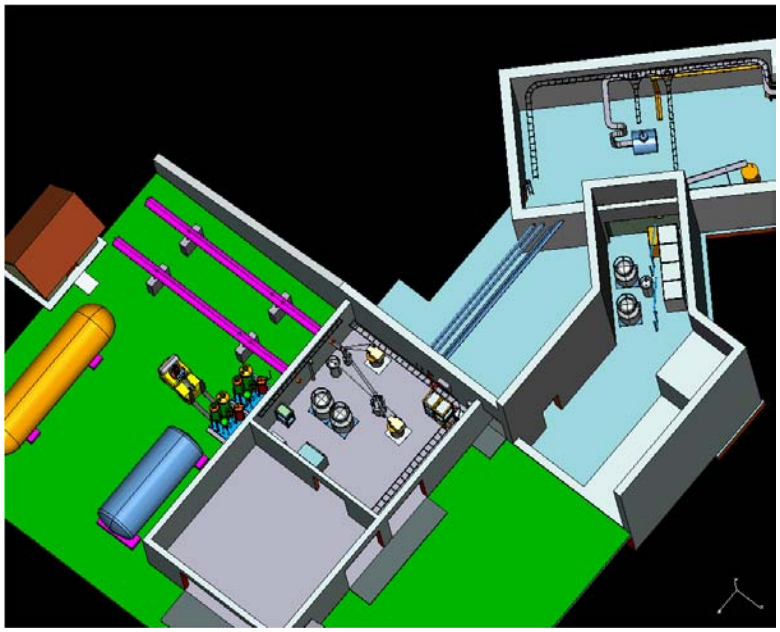
15-T solenoid in test location at MIT



Hg jet system at ORNL

# Cavity R&D (MUCOOL)

- Cooling component tests (rf cavities and absorbers) carried out in newly constructed area at Fermilab
  - MUCOOL Test Area (MTA, funded by NFMCC)
    - located at end of 400 MeV linac; will initially be used for beam tests (“blast” tests)
      - MCTF exploring plans to add muon beam line for 6D cooling

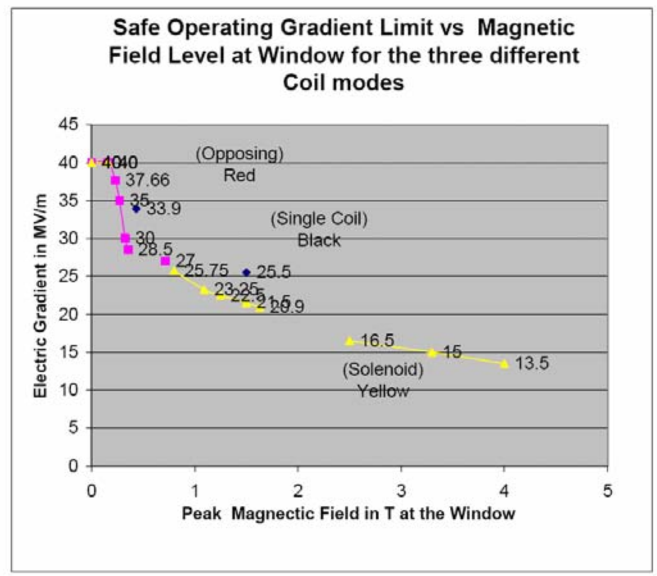


# Cavity R&D (MUCOOL)

- **Motivation for RF test program: observed degradation in cavity performance when strong magnetic field is applied**
  - **open-cell cavity did not exhibit such a limit, so problem does not seem fundamental**

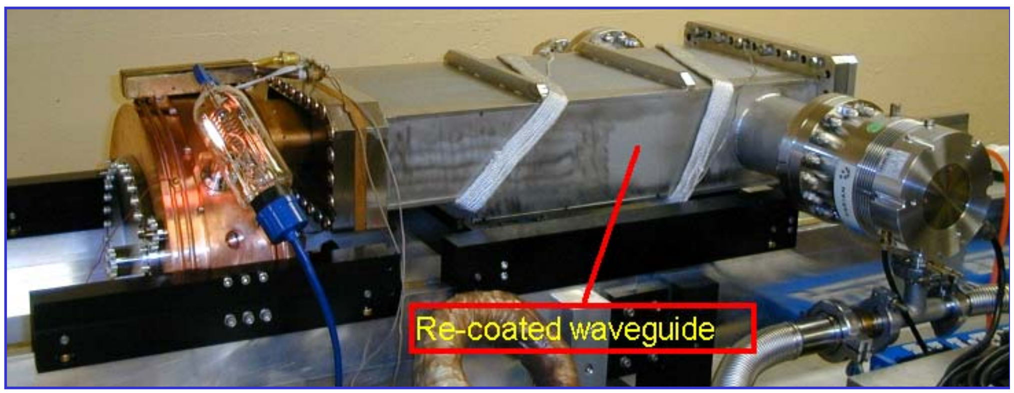
201 MHz cavity

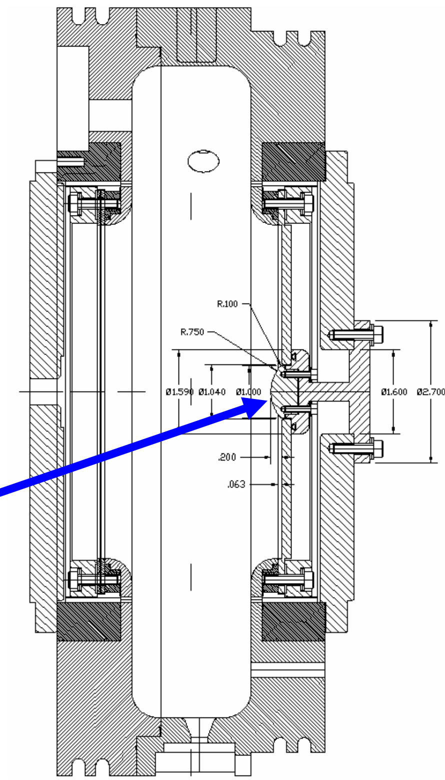
5-T solenoid +
805-MHz cavity



# Cavity R&D (MUCOOL)

- Materials tests will use 805-MHz pillbox cavity with replaceable windows or "buttons"
  - cavity fits in bore of MTA solenoid
  - generate field enhancement at buttons to test performance of materials and/or coatings



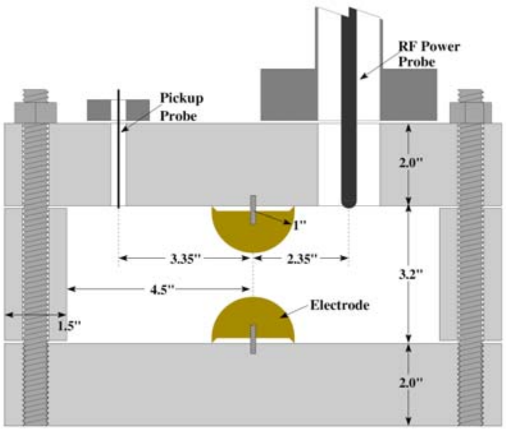



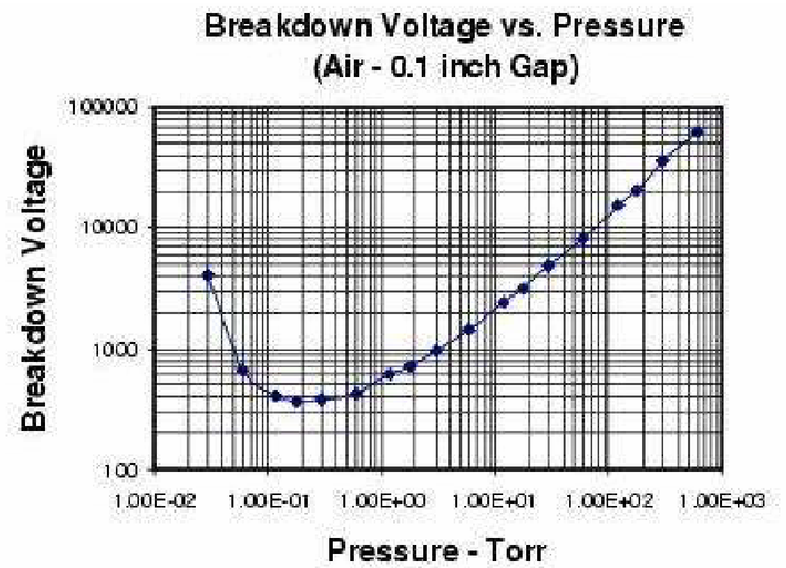

"Button" for materials tests

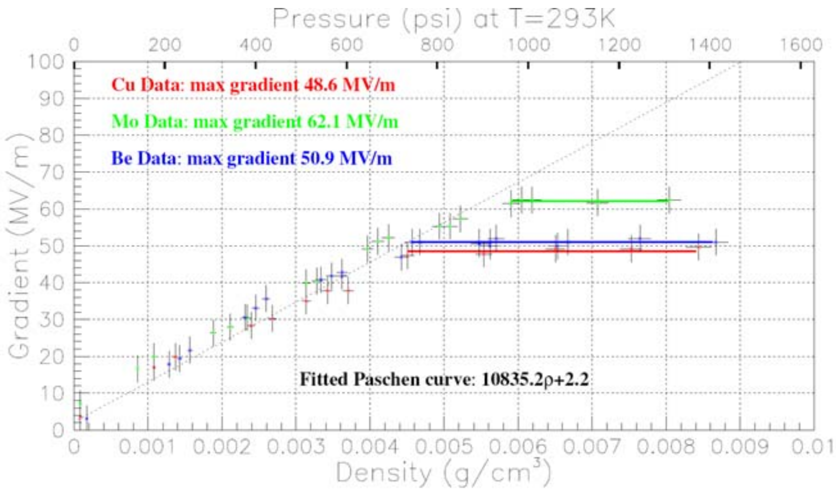
# Cavity R&D (MUCOOL)

- Tested pressurized version of button cavity (Muons, Inc.)

— use high pressure $H_2$ gas to limit breakdown



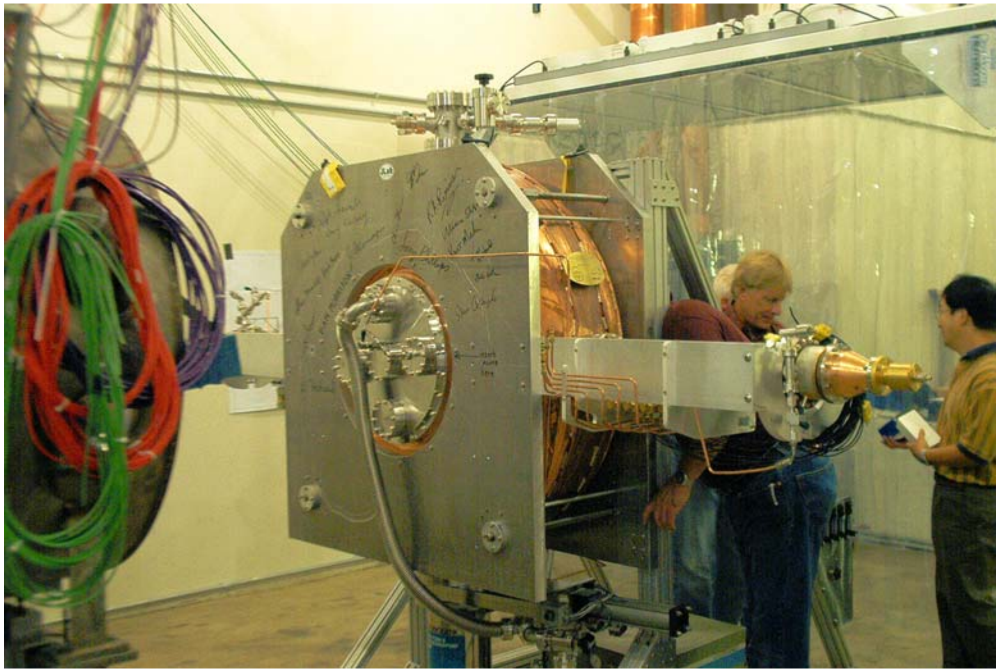



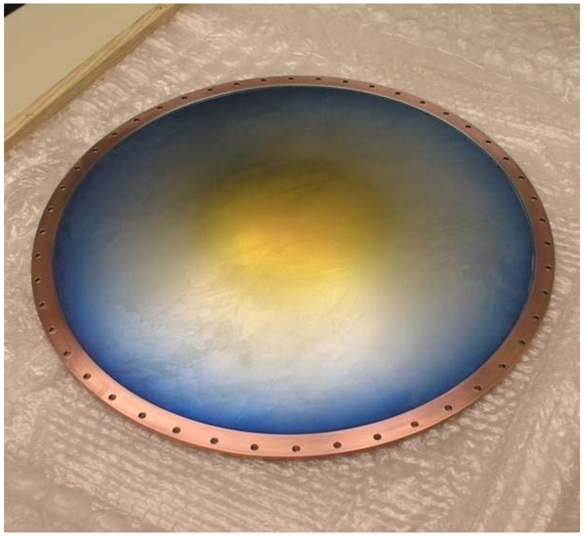
# Cavity R&D (MUCOOL)

- Initial tests of 201 MHz cavity have commenced

— LBNL, Jlab, and U-Miss collaborated on cavity fabrication

  - reached 16 MV/m easily (without magnetic field)

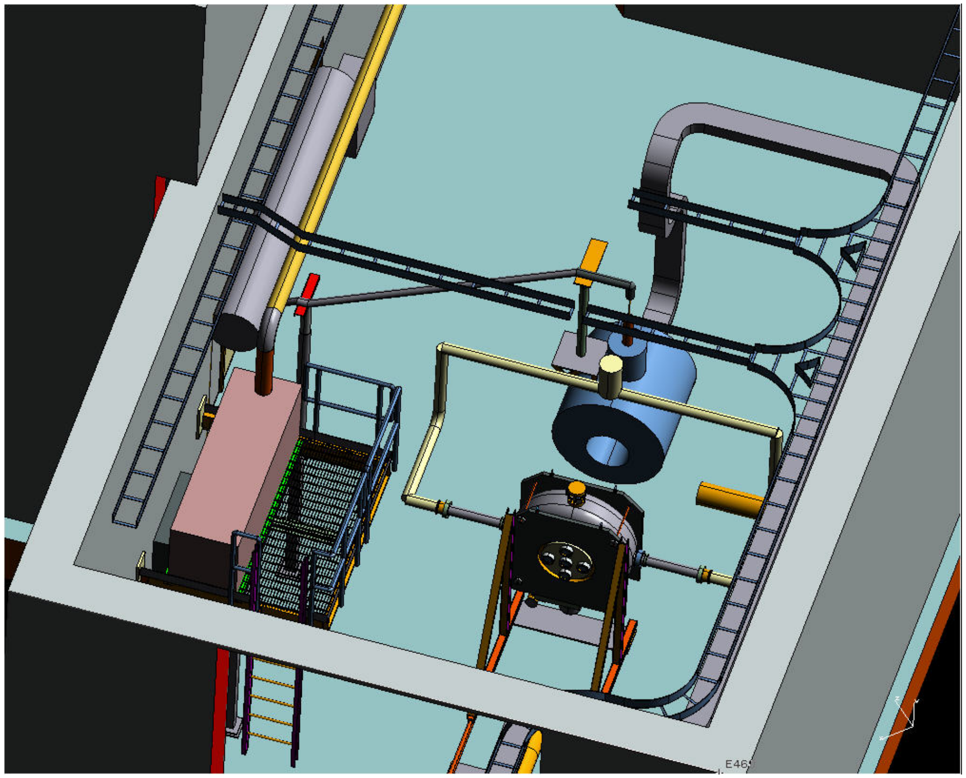




42-cm curved Be window

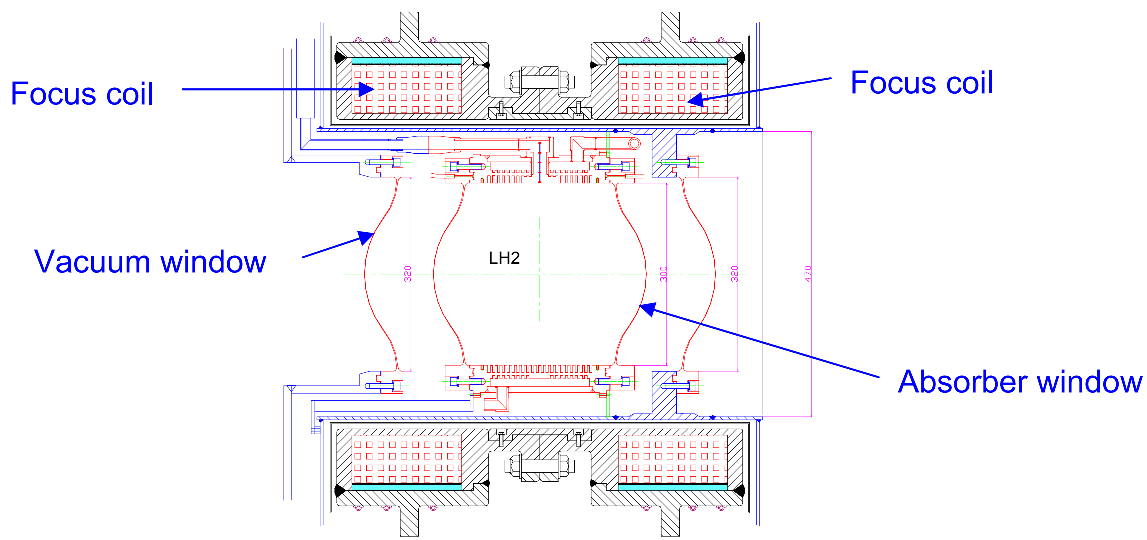
# Cavity R&D (MUCOOL)

- 201-MHz cavity can be tested in close proximity to 5-T solenoid to provide some magnetic field
  - — more realistic field configuration requires large diameter coupling coil (awaiting sufficient funding to acquire this)
    - discussions with Harbin ICST group took place in December



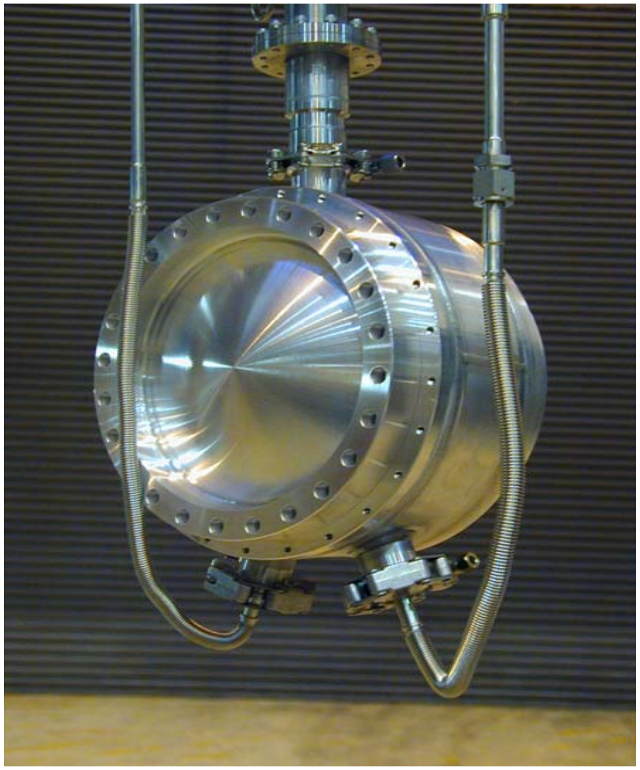
# Absorber R&D (MUCOOL)

- Absorbers for cooling channel tests
  - 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



# Absorber R&D (MUCOOL)

- Initial absorber $LH_2$ filling tests carried out at MTA last summer
  - convection-cooled absorber prototype fabricated at KEK
  - plan to also test IIT/Fermilab forced-flow absorber design here

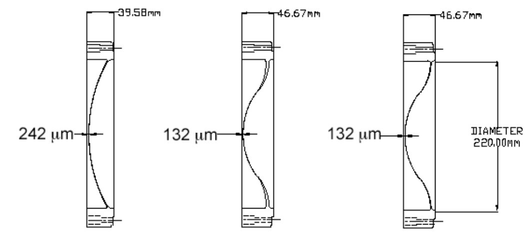


Prototype $LH_2$ absorber

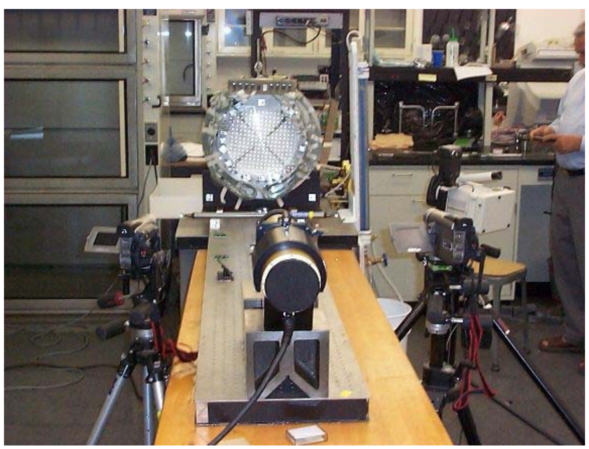
Test cryostat at MTA

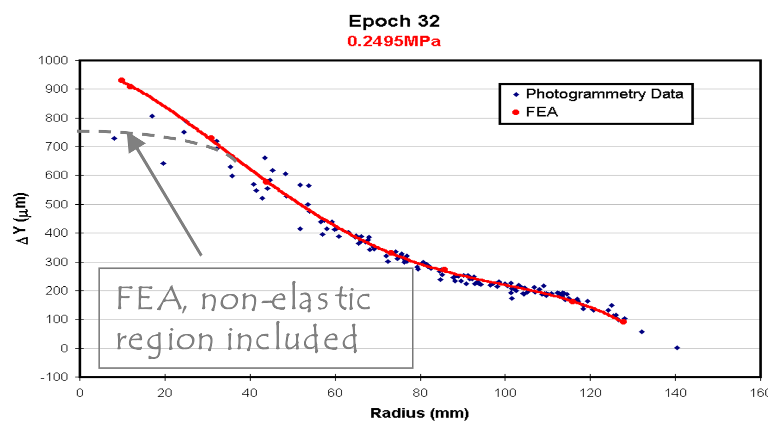
# Absorber R&D (MUCOOL)

- Developing strong, thin windows (IIT, NIU, Oxford, U-Miss.) is a primary focus of absorber work
  - destruction tested windows at NIU (with satisfactory results)
    - 340 μm windows break at 120 psi (8 atm)
    - new window shape is stronger and can be even thinner



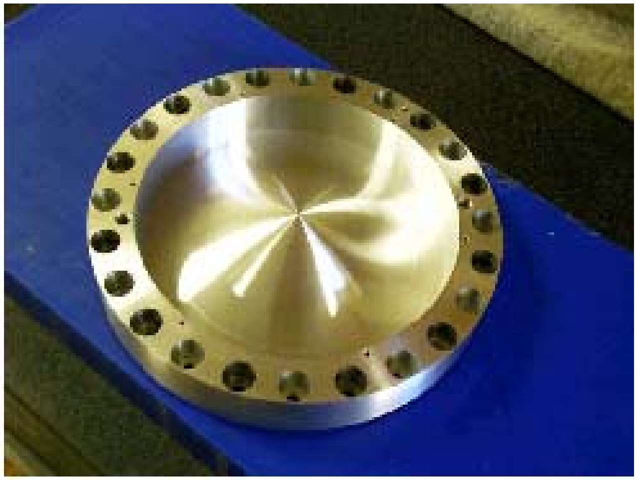

  - use photogrammetry to characterize window behavior and verify FEA calculations ($LH_2$ safety requirement)

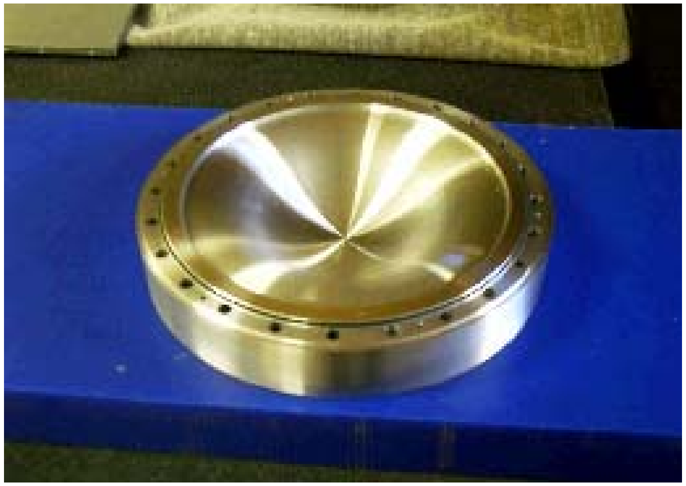




# Absorber R&D (MUCOOL)

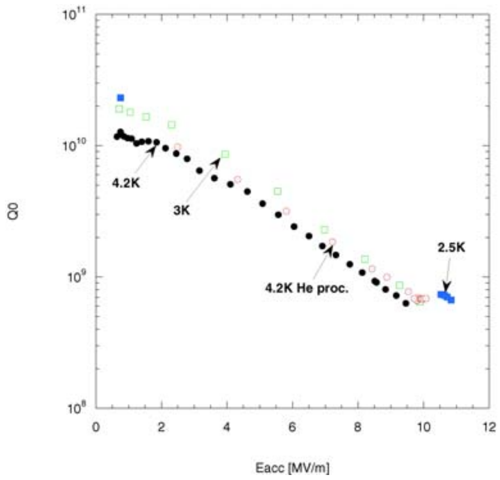
- Stronger, thinner "inflected" windows built (at U.-Miss.) and tested successfully at Fermilab
  - 125 μm window is 3x stronger than original design
    - burst at 140 psi





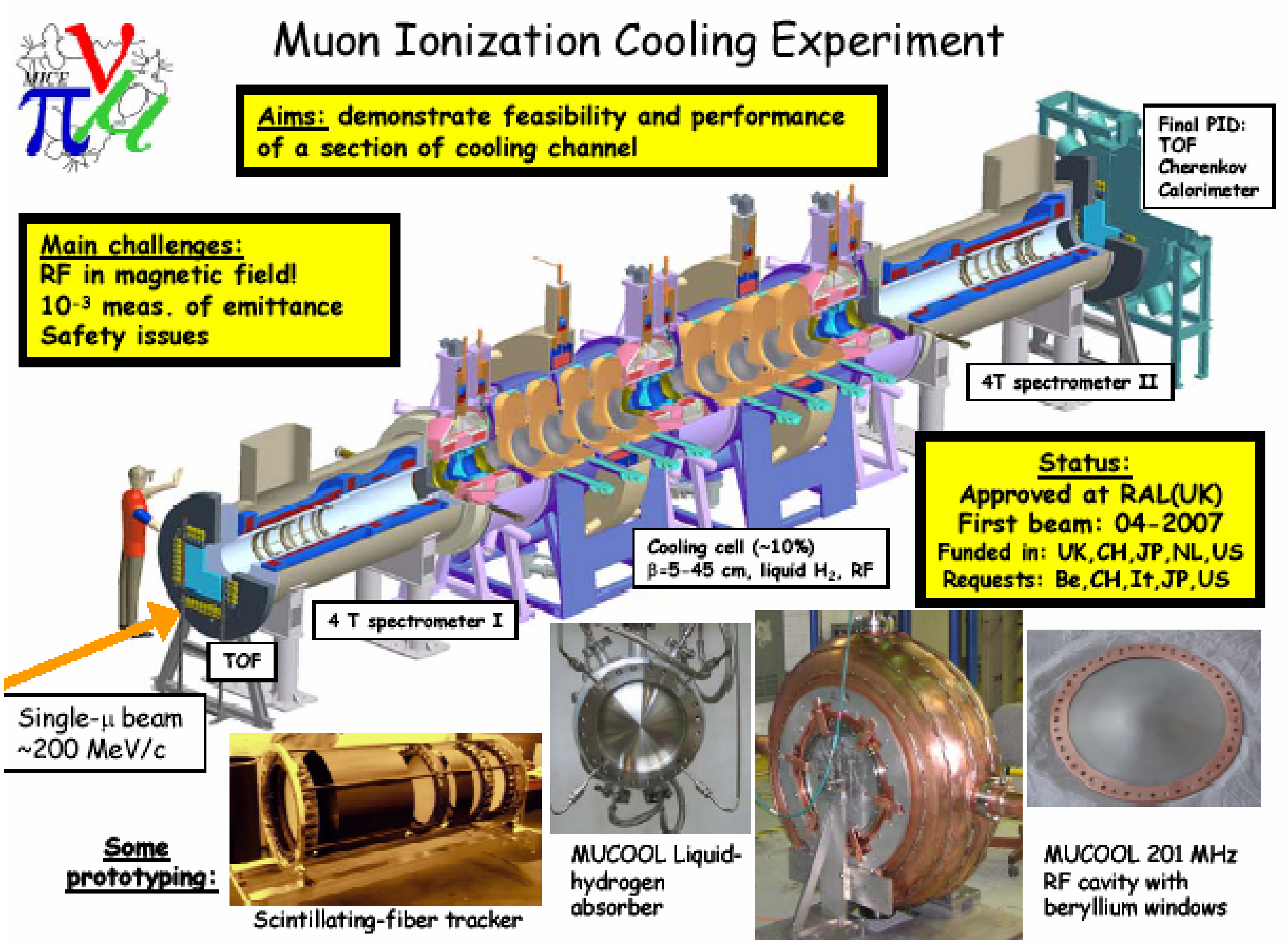
# SCRF R&D

- Initial test of 201-MHz scrf cavity at Cornell gave 11 MV/m
  - *Q* slope unacceptably large
- Work on 201 MHz scrf for acceleration system has shifted gears (but funding uncertain)
  - now trying to understand *Q* slope in terms of impurities and Nb coating properties




- Building 500 MHz cavity to study Nb sputtering techniques
  - can study phenomena more cost-effectively with smaller cavity

# MICE


Muon Ionization Cooling Experiment
Aims: demonstrate feasibility and performance of a section of cooling channel
Main challenges:
RF in magnetic field!
10-3 meas. of emittance
Safety issues
Final PID:
TOF
Cherenkov
Calorimeter
4T spectrometer II
Status:
Approved at RAL(UK)
First beam: 04-2007
Funded in: UK,CH,JP,NL,US
Requests: Be,CH,It,JP,US
Cooling cell (~10%)
β=5-45 cm, liquid H2, RF
4 T spectrometer I
TOF
Single-μ beam
~200 MeV/c
Some prototyping:
Scintillating-fiber tracker
MUCOOL Liquid-hydrogen absorber
MUCOOL 201 MHz RF cavity with beryllium windows

# MICE

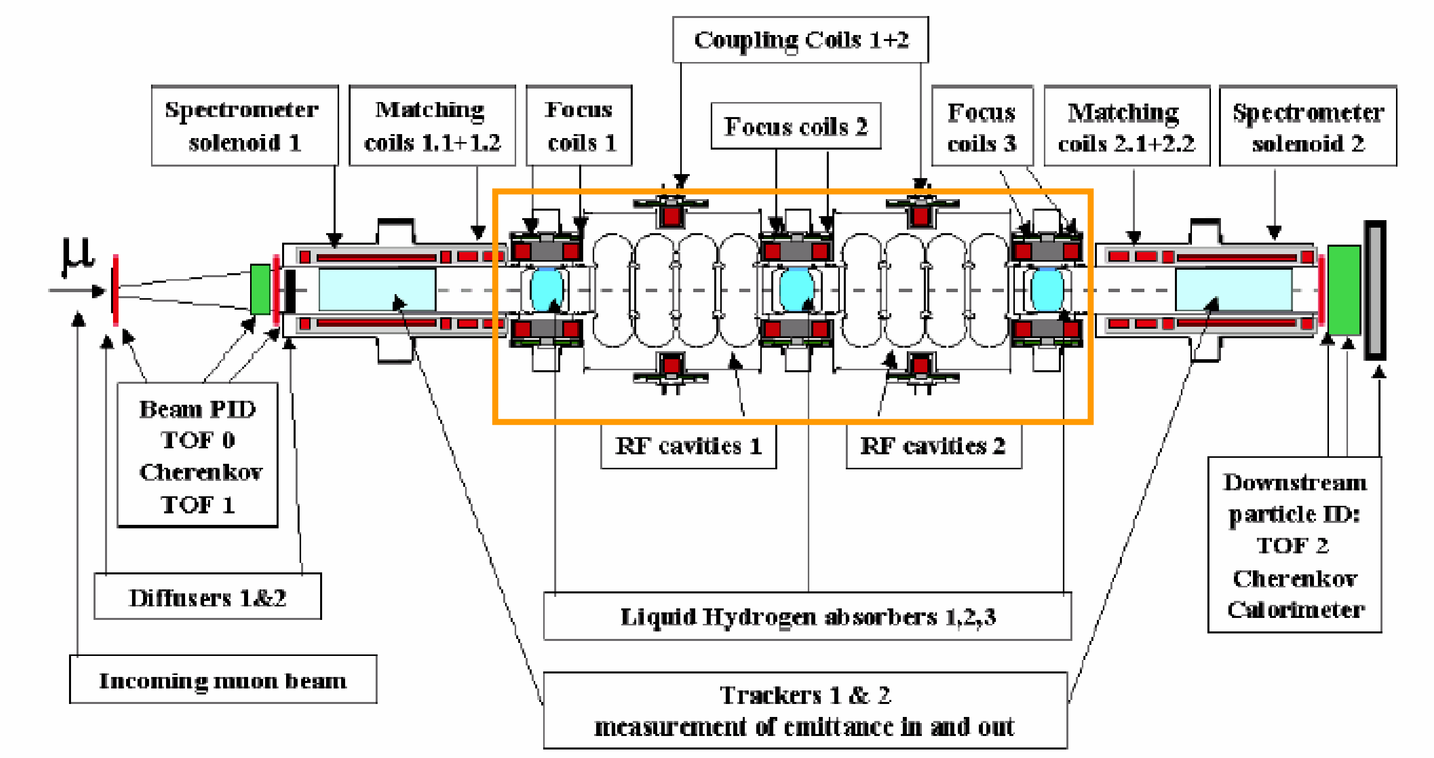
- Motivation for MICE
  - muon-based Neutrino Factory is most effective tool to probe neutrino sector and hopefully observe CP violation in lepton sector
    - results will test theories of neutrino masses and oscillation parameters, of importance for particle physics and cosmology
  - a high-performance Neutrino Factory (≈4 x $10^{20}$ $\nu_e$ 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

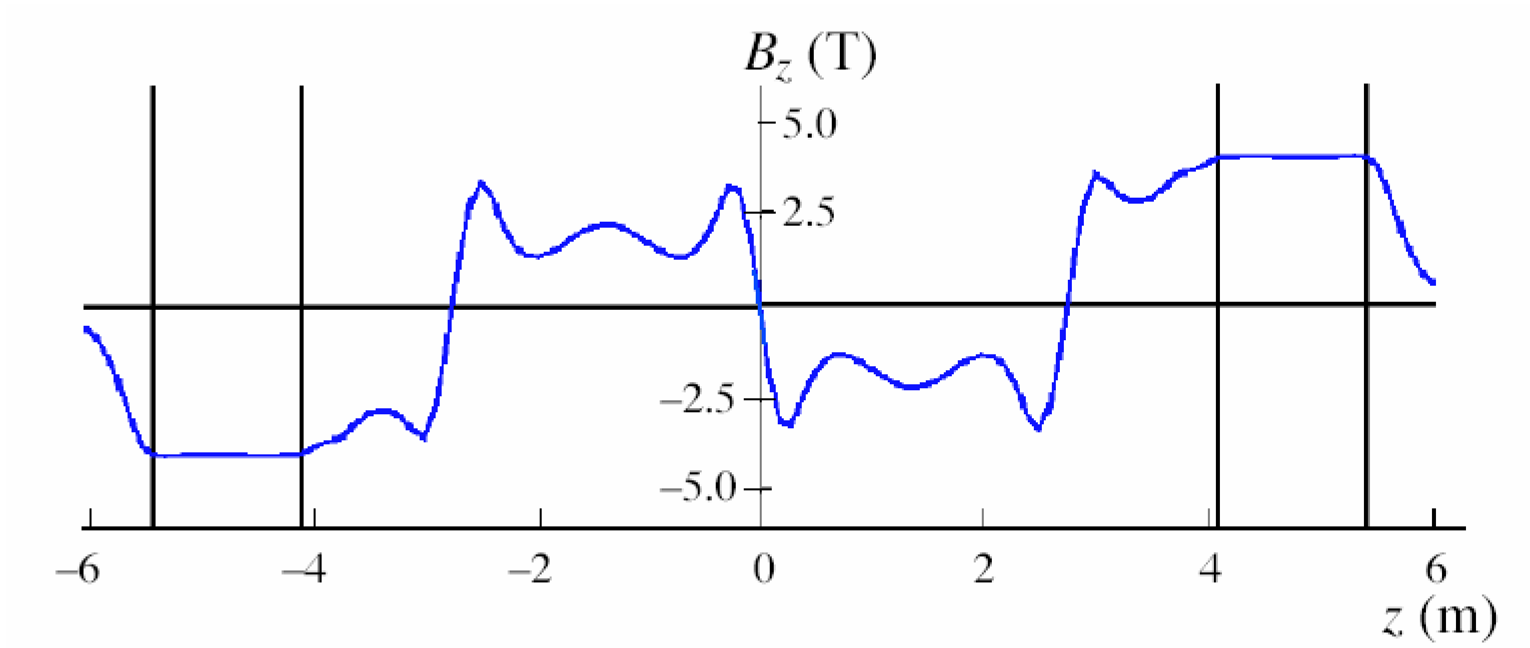
# MICE

- 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

# MICE

- 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



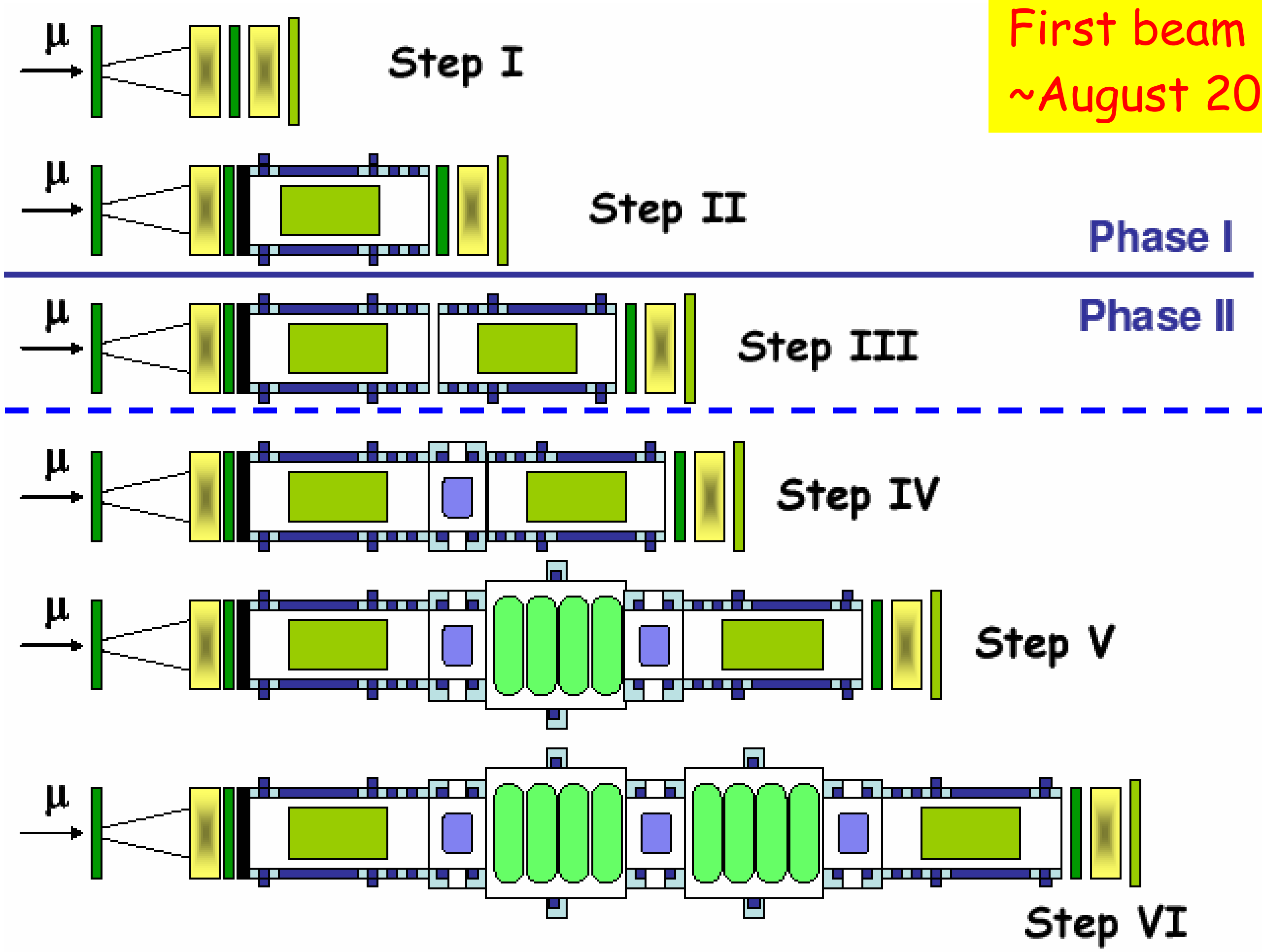



- **An alternative magnetic configuration with no field flip will also be tested**

# MICE

- **MICE cooling channel will be built up in stages to ensure complete understanding and control of systematic errors**

First beam
~August 2007



# MICE

- 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)
    - most of this is now in hand
- In U.S., MUTAC + MCOG have strongly recommended MICE
  - experiment considered "crucially important demonstration"
- U.S. funding obtained from both DOE and NSF
  - partial funding obtained; remainder from NFMCC annual budget
  - Phase I hardware fabrication well under way

# MICE

- **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

**Asia**
KEK
Osaka
ICST-Harbin

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

# Future Plans

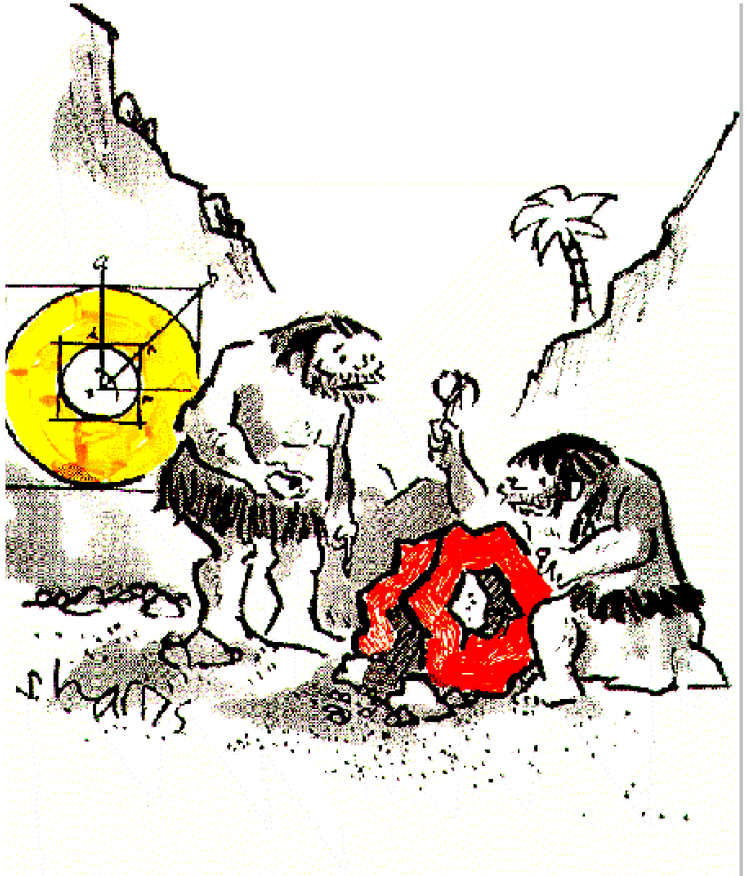
- Targetry
  - complete MERIT experiment and publish results
- Cooling/MICE
  - complete testing of 805 MHz and 201 MHz high-gradient cavities
  - complete MICE experiment and publish results
- Acceleration
  - study *Q* disease and develop mitigation techniques
  - participate in EMMA test program
- Simulations
  - continue developing cost-optimized front-end for Neutrino Factory
  - participate in International Design Study (follow-on to ISS)
  - continue collider studies with aim of completing feasibility study
    - collaborate on MCTF test program

# Summary

- International community has made excellent progress in identifying and studying the R&D topics relevant to design of muon-based NF and collider
  - both driven by strong science case
- Close collaboration among groups in Asia, Europe and the U.S. serves to minimize duplication of effort and maximize R&D effectiveness
  - examples: MICE, MERIT, ISS, NuFact workshops
- Muon Collider R&D effort reinvigorated by creation of MCTF at Fermilab
  - developing plans for 6D cooling experiment (MANX)
- NFMCC R&D program fosters close collaboration between accelerator and particle physicists, including training of students and post-docs
- We welcome additional collaborators to this challenging endeavor

# Summary

We must continue to build and test hardware!



*"I guess there'll always be a gap between science and technology."*