



Neutrino Factory and Muon Collider Collaboration R&D Program

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CENTER FOR BEAM PHYSICS

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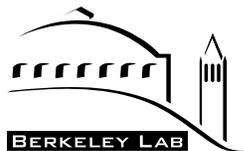
Advanced Accelerator R&D Subpanel Meeting—Fermilab
February 16, 2006



Outline



- **Organization**
- **Process**
- **History**
- **Physics context**
- **International perspective**
- **R&D overview**
- **R&D accomplishments**
- **Future plans**
- **Summary and outlook**



Organization



- U.S. Neutrino Factory and Muon Collider Collaboration broadly based
 - 135 scientists and engineers from 37 institutions

US Labs (6)

ANL
BNL*
FNAL*
LBNL*
ORNL
TJNAF

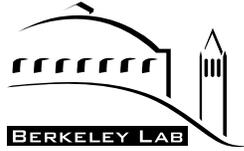
U.S. Institutions (17)

Columbia Univ.
Cornell Univ.
IIT
Indiana Univ.
Michigan State Univ.
Muons, Inc.
NIU
Princeton Univ.
Tech-X Corp.
UC-Berkeley
UC-Davis
UCLA
UC - Riverside
U. Illinois, Urbana-Champaign
Univ. of Iowa
Univ. Mississippi
Univ. Wisconsin

Foreign Institutions (14)

BINP
CERN
DESY
INFN-LNF
JINR, Dubna
Karlsruhe
KEK
Kernfysisch Versneller Inst.
Osaka Univ.
Oxford Univ.
Pohang Univ.
RAL
Tel Aviv Univ.
TRIUMF

*Sponsoring Lab



Organization



- **Some U.S. support has come from non-DOE sources**

ICAR Institutions (5)

IIT (absorbers, **MICE**, Study IIa)
NIU (absorbers)
Northwestern U. (diagnostics)
U. Illinois Urbana-Champaign
(absorber instrum., cooling ring, Study IIa)
U. Chicago (cooling theory, diagnostics)

NSF Institutions "University Consortium" (9)

Cornell (SCRF)
Columbia (HARP, NuFact03)
IIT (**MICE**)
NIU (absorbers)
U. Illinois Urbana-Champaign (absorber DAQ)
U. Chicago (cooling theory)
Michigan State U. (radiation damage)
UC-Riverside (cooling ring)
(U. Mississippi (absorber windows, acceleration))

Funding eliminated Summer '04

UC program funding ended last year

NSF MICE funding (\$100K/yr for 3 years)
granted to IIT starting FY05; MRI for MICE
tracker electronics (\$750K) awarded FY06

- **We also greatly benefit from collaborators in Europe and Japan**
- **Lack of ICAR and NSF funds hampers training function of NFMCC**



Organization



- **Neutrino Factory and Muon Collider Collaboration goals**
 - **NFMCC** governed by Charter* defining its goals and organization

“The goal of this organization (referred to hereinafter as the Muon Collaboration) is to study and develop the theoretical tools, the software simulation tools, and to carry out R&D on the hardware that is unique to the design of neutrino factories and muon colliders. An important part of the program will be an extensive experimental program to verify the theoretical and simulation predictions and to gather the necessary data for a future facility.”

*see http://www.cap.bnl.gov/mumu/info/MC_Charter_Final_020903.pdf

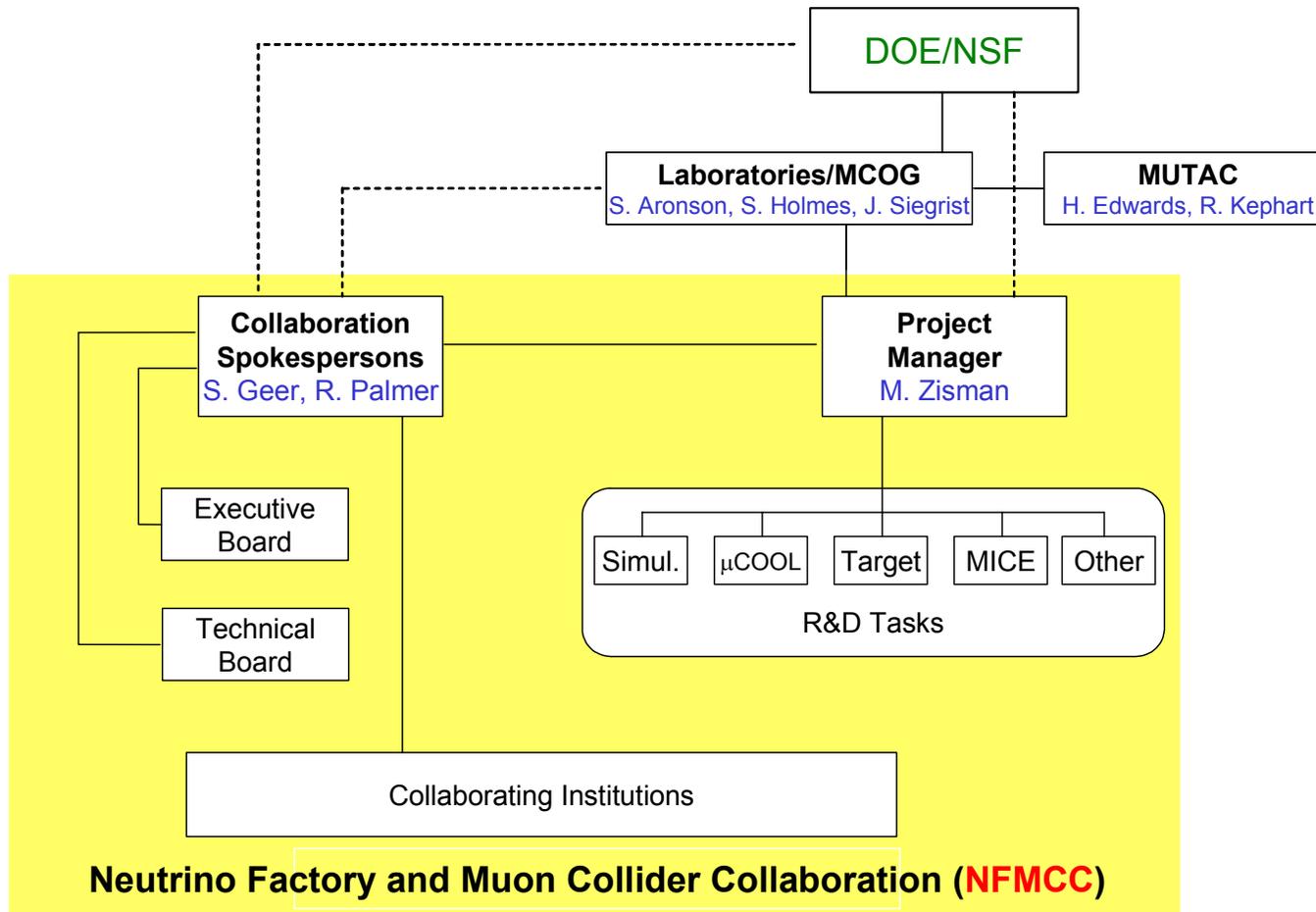
Shortened form of name no longer used;
MC → NFMCC

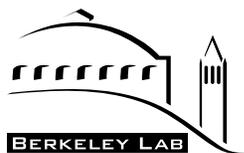


Organization



- **NFMCC** organization chart





Organization



- Organization details
(see http://www.cap.bnl.gov/mumu/mu_home_page.html)

Muon Collaboration Oversight Group (MCOG)

S. Aronson	BNL
S. Holmes	FNAL (contact)
J. Siegrist	LBNL

Muon Technical Advisory Committee (MUTAC)

H. Edwards	FNAL (Outgoing Chair)
R. Kephart	FNAL (Incoming Chair)
C. Adolphsen	SLAC
M. Breidenbach	SLAC
G. Dugan	Cornell
R. Garoby	CERN
M. Harrison	BNL
J. Hastings	SLAC
S. Henderson	ORNL
M. Lindner	TU-Munich
K. Yokoya	KEK

NFMCC Management

S. Geer (FNAL), Co-spokesperson
 R. Palmer (BNL), Co-spokesperson
 M. Zisman (LBNL), Project Manager

Next MUTAC review: March 16-17,
2006 at Fermilab



Organization



- Membership in MC Executive and Technical Boards
(see http://www.cap.bnl.gov/mumu/mu_home_page.html)

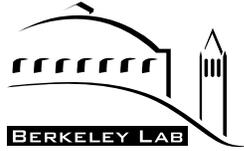
Executive Board

S. Geer	(FNAL)	Co-Spokesperson
R. Palmer	(BNL)	Co-Spokesperson
A. Sessler	(LBNL)	Associate Spokesperson
M. Tigner	(Cornell)	Associate Spokesperson
D. Cline	(UCLA)	
D. Errede	(UIUC)	
G. Hanson	(UC-Riverside)	
D. Kaplan	(IIT)	
K. McDonald	(Princeton)	
A. Skrinsky	(BINP-Novosibirsk)	
D. Summers	(U.-Mississippi)	
A. Tollestrup	(FNAL)	
W. Weng	(BNL)	
J. Wurtele	(UC-Berkeley)	
M. Zisman	(LBNL)	Project Manager
J. Gallardo	(BNL)	Secretary

Technical Board

S. Geer	(FNAL)	Co-Spokesperson
R. Palmer	(BNL)	Co-Spokesperson
A. Bross	(FNAL)	MUCOOL
M. Green	(LBNL)	
D. Hartill	(Cornell)	
H. Kirk	(BNL)	
D. Kaplan	(IIT)	MICE
K. McDonald	(Princeton)	Targetry
J. Norem	(ANL)	
R. Fernow	(BNL)	Simulations
R. Rimmer	(Jlab)	
M. Zisman	(LBNL)	Project Manager

- **NFMCC** is a mix of accelerator and particle physicists
 - from both National Labs and Universities



Process



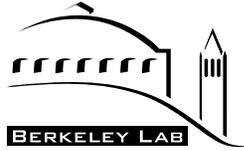
- Each year, R&D groups propose an annual program to the Technical Board, based on **NFMCC** budget guidance from DOE
- PM prepares budget based on this input
 - subsequently approved by Technical Board, Executive Board, and Co-Spokespersons
 - budgets determined by R&D program, not by “institutional commitments”
- After budget finalized, PM negotiates milestones with each institution based on the R&D plan
 - milestones specify dates and deliverables
 - a “report card” is generated at year’s end to audit performance
- PM summarizes annual spending and accomplishments in a detailed report for MCOG and DOE at the end of each year
 - report also includes non-DOE information insofar as it is available



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)
- **NFMCC** became formal entity at Orcas Island meeting (≈ 100 scientists and engineers) in May 1997 and requested funding from DOE
- Initial focus of intensive activity:
 - theory and design simulation
 - targetry R&D
 - cooling channel R&D
- **NFMCC** oversight/review structure initiated by DOE and Lab Directors
 - first significant funding came in Spring '98
- By Summer 1999, **NFMCC** had investigated
 - Higgs Factory (Phys. Rev. STAB 2 081001 (1999))
 - High-energy Muon Collider (Snowmass report)
 - Neutrino Factory



History



- First MUTAC review recommended that **NFMCC** focus on one of these and conduct **end-to-end technical study**
 - **choice was Neutrino Factory** (viewed as technically simpler)
- In 1999-2000, Fermilab director sponsored **Feasibility Study I**
 - required ~\$1M engineering effort
 - conclusions (see http://www.fnal.gov/projects/muon_collider/nu-factory/nu-factory.html)
 - **Neutrino Factory is feasible**
 - intensity goal was not met
 - facility would be **expensive** (~\$2B)



History



- In 2000-2001, BNL director + **NFMCC** co-sponsored **Feasibility Study II**
 - again required ~\$1M engineering effort
 - conclusions (see <http://www.cap.bnl.gov/mumu/studyii/FS2-report.html>)
 - intensity goal met (5x Study I)
 - facility still expensive



History



- HEPAP Subpanel report in 2002 supportive of **NFMCC** effort
 - comment on accelerator R&D

*“We give such **high priority** to accelerator R&D because it is **absolutely critical** to the future of our field. ... As particle physics becomes increasingly international, it is **imperative that the United States participates broadly in the global R&D program.**”*

- recommendation on **NFMCC** R&D program

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

This recommendation has not been honored to date



History



- **Community support**

6 January, 2003

To: John O'Fallon

From: J. Conrad
W. Louis
D. Michael
M. Shaevitz
S. Wojcicki

Dear John,

We would like to encourage you to increase support for Neutrino Factory R&D in FY04.

Neutrino oscillation physics has entered a very exciting period. In the not-too-distant future we expect that results from MiniBooNE and MINOS will add to the excitement. No matter what the results are from these experiments it is already clear that more ambitious long-baseline experiments will be needed in the future. It also seems increasingly likely that we will ultimately need the full power of a Neutrino Factory to unambiguously determine all of the parameters that describe neutrino oscillations. This will be particularly true if the LMA solution to the solar neutrino problem is confirmed (which initial KamLAND results suggest is the case), or if MiniBooNE and/or MINOS make discoveries that indicate there is more going on than just three-flavor mixing.

The HEPAP subpanel recommended a funding level for Neutrino Factory R&D at the FY01 level of 8M\$ per year. We understand that since that recommendation support for the all important R&D has been significantly reduced. We believe it is important to maintain an investment in the long-term future. Since the HEPAP subpanel presentations the R&D seems to have made good progress, and the physics case for an eventual Neutrino Factory has, if anything, grown stronger. We would therefore like to encourage a restoration of the support for Neutrino Factory R&D to the level that the subpanel recommended.

cc: Steve Geer
Bob Palmer



Physics Context

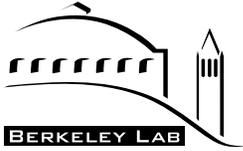


- **NFMCC** focus on Neutrino Factory driven by physics
 - in particular
 - 1) exciting evidence for **neutrino oscillations**, with parameters that are within reach of future accelerator experiments
 - 2) an **understanding of the accelerator-based experiments** needed to fully exploit the initial discovery
- Beam properties

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

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

- **decay kinematics well known** (minimal systematic uncertainties in spectrum, flux, and comparison of μ^+ and μ^- results)
- $\nu_e \rightarrow \nu_\mu$ **oscillations give easily detectable “wrong-sign” muons**
- Unique capabilities for $\sin^2 2\theta_{13} \leq 0.01$

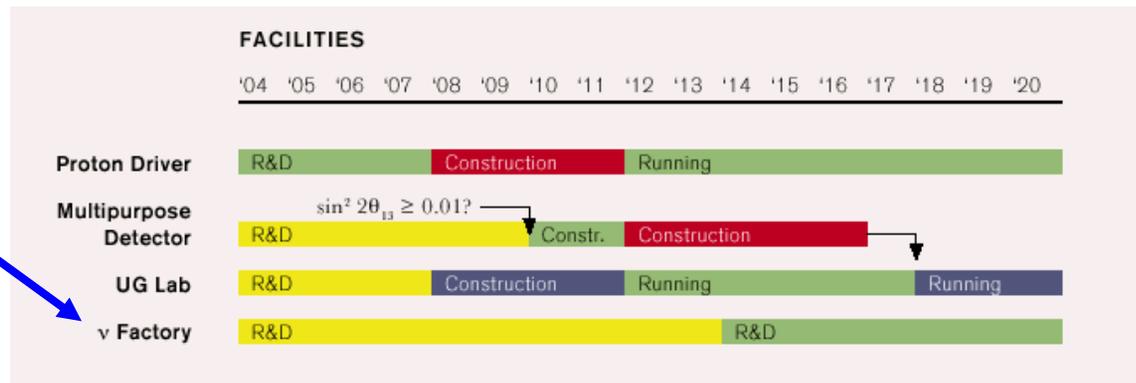


Physics Context



- APS Neutrino Physics Study assumes that our program is ongoing
 - *Research and development to assure the practical and timely realization of accelerator and detector technologies critical to the recommended program. Of particular importance are R&D efforts aimed toward development of a high-intensity proton driver, a neutrino factory, a very large neutrino detector, and techniques for detection of ultra-high-energy neutrinos.*

— **MC R&D** program is explicitly called out in timeline



◦ here, **yellow** is <\$10M/yr and **green** is \$10-40M/yr



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

7th International Workshop on Neutrino Factories and Superbeams

NuFact 05

June 21-26, 2005
Laboratori Nazionali dell' INFN
Frascati (Rome), Italy

International Advisory Committee

R. Aleksan (Marseille)	R. Klanner (DESY)
R. Aymar (CERN)	Y. Kuno (Osaka)
S. Bertolucci (INFN)	S. Myers (CERN)
M. Calvetti (INFN)	S. Nagamiya (KEK)
S. Chattopadhyay (Jlab)	W. Namkung (Pohang U.)
H. Chen (IHEP)	M. Napolitano (INFN)
E. Coccia (INFN)	P. Oddone (LBL)
P. Dorman (Imperial College)	K. Peach (RAL)
B. D'Ettorre Piazzoli (INFN)	R. Petronzio (INFN)
U. Dosselli (INFN)	A. Sessler (LBNL)
R. Eichler (PSI)	M. Shaevitz (Columbia U.)
T. Engelen (CERN)	A. Skrinsky (BINP)
G. Fortuna (INFN)	H. Sugawara (Hawaii)
B. Foster (Oxford U.)	M. Tigner (Cornell U.)
S. Holmes (Fermilab)	Y. Totsuka (KEK)
B. Kayser (Fermilab)	M. Witherell (Fermilab)
S. Katsanevas (IN2P3)	S. Wojcicki (Stanford U.)
T. Kirk (BNL)	C. Wynn (CERN)

Scientific Program Committee

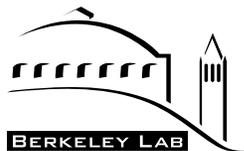
A. Blondel (Geneva U.)	K. Long (Imperial College)
J. Bouchez (Saclay)	Y. Kuno (Osaka)
D. Casper (Irvine)	F. Meot (Saclay)
Y. Declais (Lyon U.)	M. Mezzetto (INFN)
A. de Rujula (CERN)	Y. Mori (KEK)
R. Edgecock (RAL)	K. Nakamura (KEK)
E. Fernandez (IFAE Barcelona)	V. Palladino (INFN)
G. Fogli (INFN)	F. Ronga (INFN)
S. Geer (Fermilab)	A. Rubbia (ETH Zurich)
D. Harris (Fermilab)	T. A. Shibata (Tokyo Tech)
D. Hartill (Cornell U.)	P. Strolin (INFN)
H. Haseroth (CERN)	G. Tzanakos (Athens)
P. Hernandez (Valencia)	O. Yasuda (Tokyo Met U.)
M. Lindner (TU Muenchen)	M. Zisman (LBNL)
M. Lindroos (CERN)	

Local Organizing Committee

S. Buontempo (INFN, Napoli)	
M. C. D'Amato (INFN, LNF)	
G. De Lellis (INFN, Napoli, Scientific Secretary)	
P. Migliozi (INFN, Napoli, Scientific Secretary)	
V. Palladino (INFN, Napoli, Chair Person)	
L. Palumbo (Roma1 U.)	
A. Paoloni (INFN, LNF)	
L. Sabatini (INFN, LNF)	
F. Terranova (INFN, LNF, Scientific Secretary)	
C. Vaccarezza (INFN, LNF)	
L. Volano (INFN, LNF)	

For Further Information
Please Contact:
nufact05@inf.infn.it
<http://www.inf.infn.it/conference/nufact05>

Logos: fact, TUV, INFN, HAMAMATSU, PHOTONICS, MICOS, CAEN, ST, etc.



International Perspective



- **Activities in Europe**

- **European Feasibility Study completed in 2002**

The Study of a European Neutrino Factory Complex, P. Gruber *et al.*,
CERN/PS/2002-080 (PP), CERN-NUFACT 122, December, 2002;
<http://slap.web.cern.ch/slap/NuFact/NuFact/nf122.pdf>

- **ECFA report encouraged R&D effort; EMCOG set up (Spring 2002)**

- **Beams for European Neutrino Experiments launched in 2004 (Chair: Vittorio Palladino)**

- **MICE** given UK funding approval in 2004

- **MERIT** experiment at CERN given final approval in 2005

- **International Scoping Study (ISS) of Future Neutrino Factory and Superbeam Facility launched at NuFact05**

- hosted by RAL; sponsored by BENE, **NFMCC**, NuFact-J, UKNF

- **NFMCC is a major participant in MICE, MERIT and ISS**



International Perspective



- European "MCOG": **EMCOG**

CERN: **Carlo Wyss (Chair)**, John Ellis, Helmut Haseroth

CEA: Pascal Debu, François Pierre

IN2P3: Jean-Eric Compagne, Jacques Dumarchez, Stavros Katzanevas

INFN: Marco Napolitano (Napoli), Andrea Pisent (Legnaro)

GSI: Oliver Boine-Frankenheim, Ingo Hofmann

Geneva: Alain Blondel (Secretary)

PPARC: Ken Long

PSI: Albin Wrulich

RAL: Rob Edgecock, Ken Peach

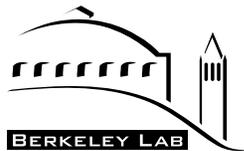
- comment on **MICE**

"Cooling is on the critical path for a neutrino factory; there is a consensus that a cooling experiment is a necessity."

- comments on **MERIT**

"Locating this experiment at CERN would certainly encourage participation from European collaborators."

The experiment seems able to achieve its very important goal, and is therefore highly recommendable. Several clever solutions are envisaged."



International Perspective



- **Recent European recommendations**

SPSC (October, 2004): *“CERN should arrange a budget and personnel to enhance its participation in further developing the physics case and the technologies necessary for the realization of such [neutrino] facilities. This would allow CERN to play a significant role in such projects wherever they are sited.”*

SPC to CERN Council (December, 2004): *“Future neutrino facilities offer great promise for fundamental discoveries. CERN should join the world effort in developing technologies for new facilities: Beta beams, Neutrino Factory...wherever they are sited.*

Focus now on enabling CERN to do the best choice by 2010 on future physics programme.”

- **CERN Council set up Strategy Group on future plans in Europe**
 - **report due in May 2006**



International Perspective



- Activities in Japan (KEK, Kyoto, Osaka)
 - Japanese Neutrino Factory group has also done a Feasibility Study

A Feasibility Study of
A Neutrino Factory in Japan

Version 1.0

NufactJ Working Group

May 24, 2001

- contributing to **NFMCC** effort (MUCOOL absorbers and FFAG acceleration studies)
- also **MICE** (absorbers, tracker components), **MERIT**, and **ISS**



R&D Overview



- Since FY03, the **NFMCC** DOE budget has been nearly flat-flat
 - with Subpanel's help, hope to restore funding to FY01-FY02 level

Year	DOE-base (\$M)	DOE- NFMCC (\$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	2.2	1.8 ^{a)}	4.0
FY05	1.9	1.7	3.6
FY06	1.8	1.8	3.6

^{a)} Includes \$0.4M supplemental funds

- Helped by NSF funding for **MICE**
 - operating level is \$100K per year for FY05-07, plus FY06 MRI grant (\$750K) for tracker detector electronics and spectrometer
- By juggling projects across fiscal year boundaries and careful prioritization, we continue to make progress...
 - ⇒ international experiments have **only schedule (not cost) contingency**



R&D Overview



- FY06 **NFMCC** budget (only DOE-**NFMCC** funds)[†]

Institution	COOLING /MICE	TARGETRY	ACCEL./ COLLIDER	EFFORT ^a	RESERVE	TOTAL (\$K)
BNL		405				405
FNAL	45					45
LBNL ^b	680				70	750
ANL				150		150
IIT				85		85
Mississippi	20	25		20		65
Princeton		105				105
UCLA	25		45			70
UC-Riverside			20			20
ORNL		95				95
Jlab	5		5			10
TOTAL (\$K)	775	630	70	255	70	1800

^aIncludes beam simulation and diagnostics effort.

^bIncludes MICE funding of \$620K.

[†]Also: salary support from BNL, FNAL, LBNL; support from NSF of \$0.1M + \$0.75M MRI grant

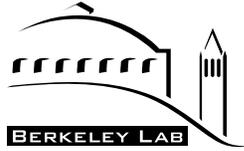


R&D Overview



- Supplemental request submitted to DOE in January 2006 (priority order)
 - priorities decided in discussions between Spokespersons and PM

<u>Item</u>	<u>Request (\$K)</u>
1) Coupling coil design and construction	975
2) MICE design, commissioning, operation, analysis	350
3) ISS travel support	50
TOTAL	1375



R&D Overview



- **Comments from April '04 MUTAC report**

*“The **Muon Collaboration continues to make significant progress**, but with very constrained M&S funding. As last year, 1M\$ more would make a significant impact. This is especially true in light of the questionable ICAR funds, and the opportunity to do the CERN target experiment.”*

*“...**US support on MICE is important for the international preparation to proceed**. Approval of the US MICE proposal would have significant positive impact on the Muon Collaboration and its ability to develop hardware.”*

*“The Committee notes the **significant progress achieved in establishing a worldwide collaboration and the integration of the various R&D programs**. In particular Japanese participation has increased in many areas such as MuCool, MICE, targetry, FFAG and NuFact workshops. The **MICE proposal is an example of the effective operation of this larger collaboration**.”*



R&D Overview



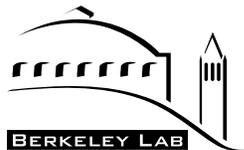
- **Comments from April '05 MUTAC report**

“The activities pursued today are clearly focused on the most important subjects determining the feasibility of a neutrino factory, relying on—and contributing to—the MICE experiment at RAL (UK) and the nTOF11 experiment at CERN.”

“There is the potential that the Muon Collaboration efforts would enable significant physics opportunities. Readiness to exploit these opportunities requires completion of a variety of proof of concept R&D tasks. MC is focused to carry out these tasks.”

“We note that muon accelerators (factories or colliders) are one of the very few HEP future accelerator ideas on the horizon, that R&D to develop these ideas and provide proof of principle takes years of consistent effort and support, and that major collaborative efforts and international commitments must have consistent support.”

“The MC has been exemplary in its drawing of collaborators from a wide diversity of HE physicists in the muon acceleration futuristic concepts.”



R&D Overview



- MCOG FY04 comments

“MUTAC and MCOG note the continuing successes in the muon R&D work accomplished during the past year, especially the technical creativity shown in Neutrino Factory conceptual designs utilizing FFAG machine concepts for accelerating muons, as well as the significant progress in establishing worldwide collaboration in the study of important technical R&D topics. We are particularly pleased with the continuing progress by university-based groups in advancing some of the important machine R&D topics associated with cooling and the Muons, Inc. conceptual work on high-pressure, cold hydrogen gas forming an absorber mass inside a normal rf cavity to provide an integrated muon cooling environment. This progress has occurred in spite of four successive years of severe budget decreases that have strongly restricted the scope of experimental R&D work able to be carried out by the Muon Collaboration.”

“...MCOG accepts and endorses the MUTAC Report attached here and urges the DOE to seek ways of supplementing R&D funding for the Muon Collaboration. An additional amount of \$1M or more, per year, would provide important relief to the program and improve the rate of advance in the technical areas of study. We urge the DOE to consider such an increase in funding as they prepare future budgets for the muon R&D program.”



R&D Overview



- **MCOG FY05 comments**

“MCOG recommends that the U.S. continue its active participation in the MICE collaboration: this is the most ambitious program for demonstrating a practical implementation of muon cooling in a full experimental context.”

“MCOG strongly supports the NFMCC efforts to carry out the high intensity target tests on a liquid mercury target currently approved at CERN.”

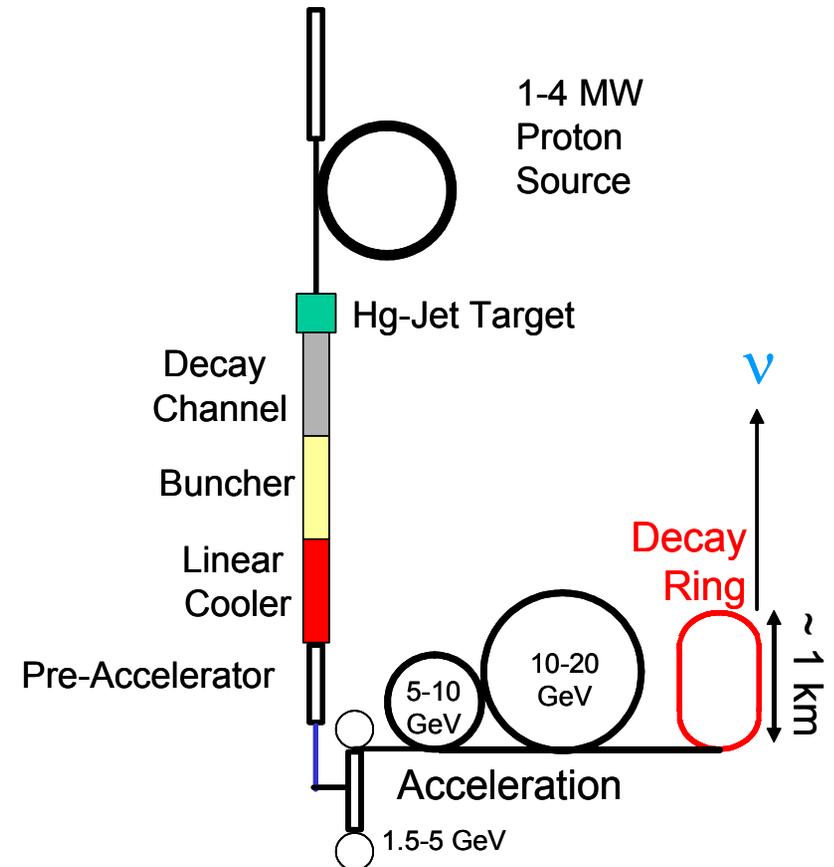
“MCOG recommends strong participation of the NFMCC within the World Design Study, which represents the next iteration of the “Feasibility Study” series conducted within the U.S. over the last several years.”

“MCOG recommends that DOE consider providing additional funding, at a level of \$0.4M or more per year, to provide important flexibility within the program and increased confidence that technical milestones can be met on a reasonable time scale.”

“World Design Study” morphed into International Scoping Study

- Neutrino Factory comprises these sections (**NFMCC** doing R&D 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)
⇒ Muon Ionization Cooling Experiment
- **Acceleration**
(130 MeV \rightarrow 20-50 GeV with RLAs or FFAGs)
- **Decay Ring**
(store muon beam for \approx 500 turns; optimize yield with long straight section aimed in desired direction)



U.S. Study IIa design

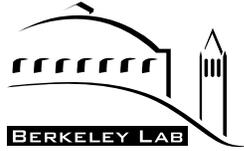
- Not an easy project, but no fundamental problems found



R&D Overview



- Challenges of a muon-based Neutrino Factory
 - muons have **short lifetime** ($2.2 \mu\text{s}$ at rest)
 - puts premium on rapid beam manipulations
 - requires **high-gradient NCRF** (in magnetic field) for cooling
 - requires presently untested **ionization cooling** technique
 - requires **fast acceleration** system
 - muons are **created as tertiary beam** ($p \rightarrow \pi \rightarrow \mu$)
 - low production rate \Rightarrow
 - **target that can handle multi-MW beam**
 - large muon beam transverse phase space and energy spread \Rightarrow
 - **ionization cooling**
 - **high-acceptance** acceleration system and decay ring
- These challenges go well beyond those of standard beams, so **need substantial R&D effort**



R&D Overview



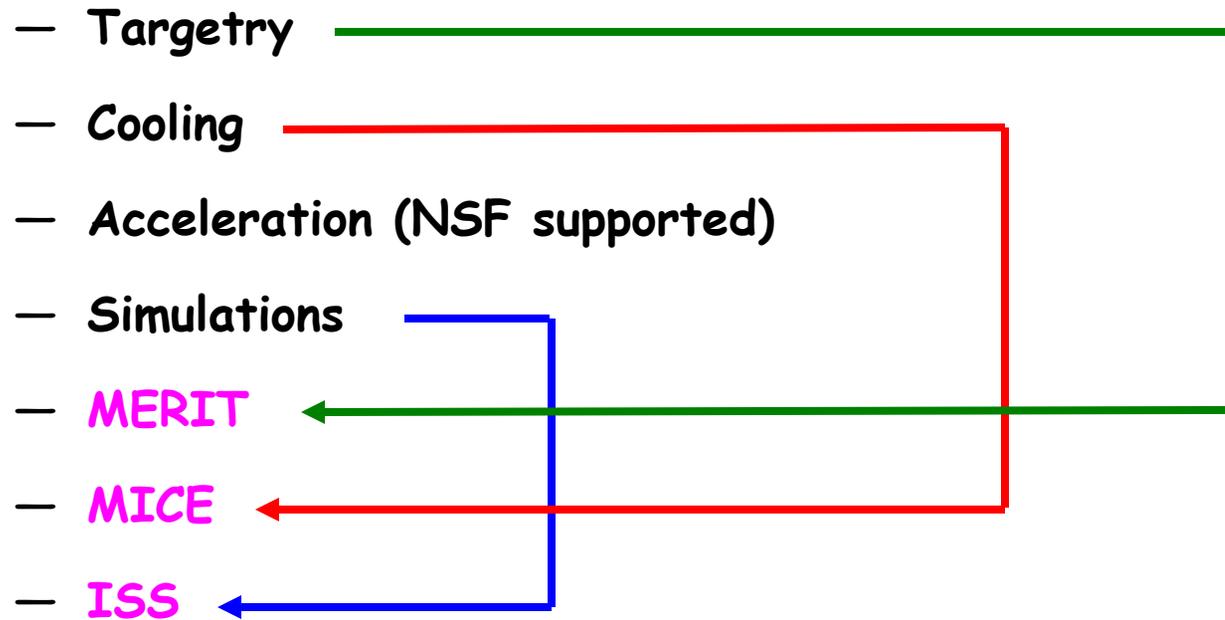
- **NFMCC** R&D program has the following components:
 - hardware development of cooling channel components (**MUCOOL**)
 - development of high-power target technology (**Targetry**)
 - **simulation and theory** effort in support of Neutrino Factory and Muon Collider design
- **NFMCC** also participates in three international endeavors:
 - **MICE** (ionization cooling demonstration)
 - **MERIT** (high-power Hg-jet target)
 - **ISS** (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
 - a substantial part of the working group report based on this work



R&D Accomplishments

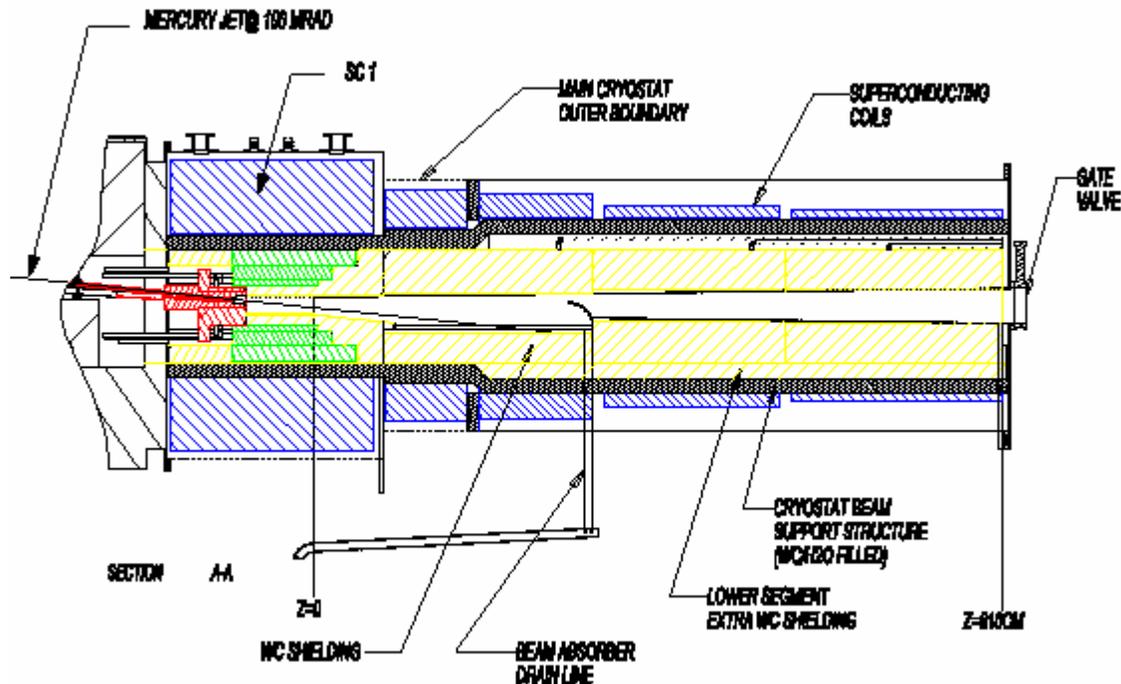


- R&D progress has been made on all fronts:



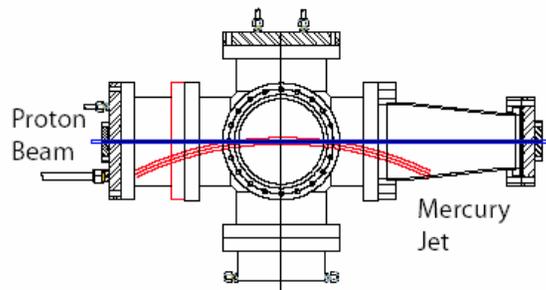
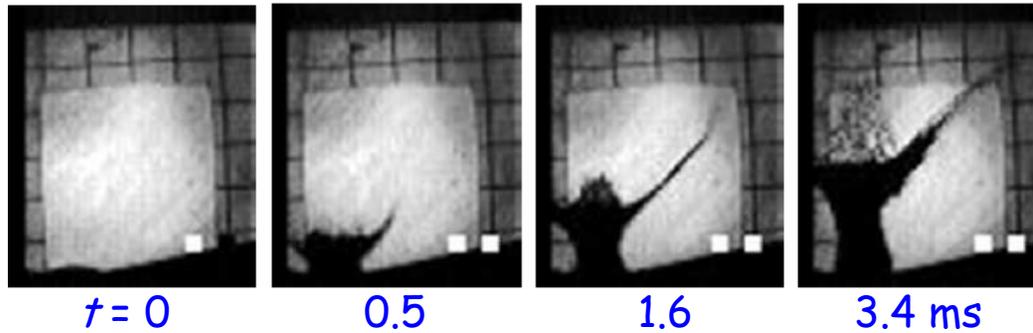
R&D Accomplishments

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

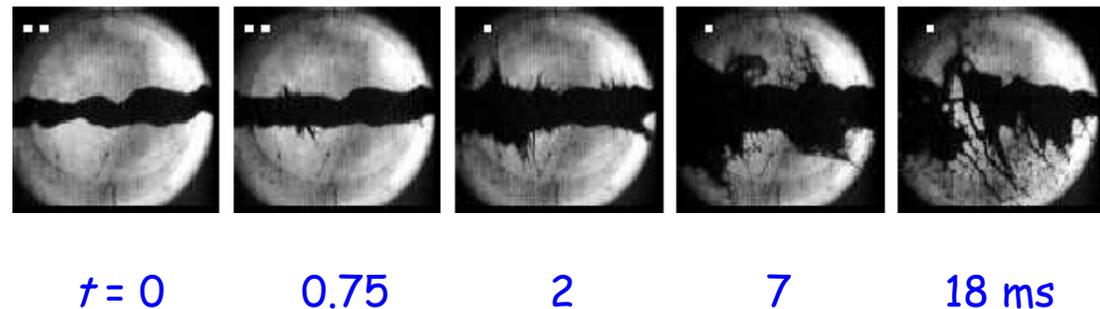


- Targetry effort focused mainly on validating efficacy of Hg-jet target
 - **E951 experiment** looked at both stationary and moving Hg

Hg thimble

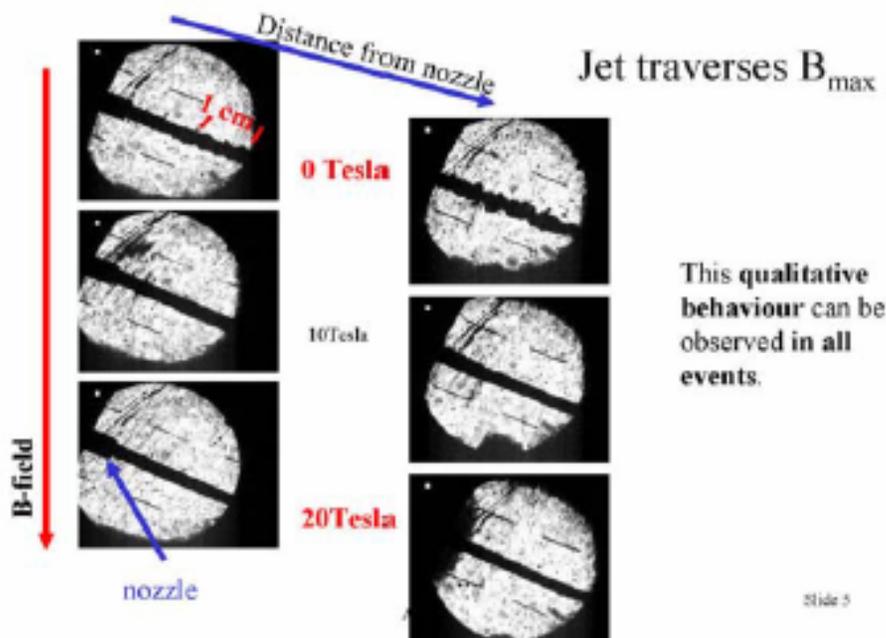


Hg jet

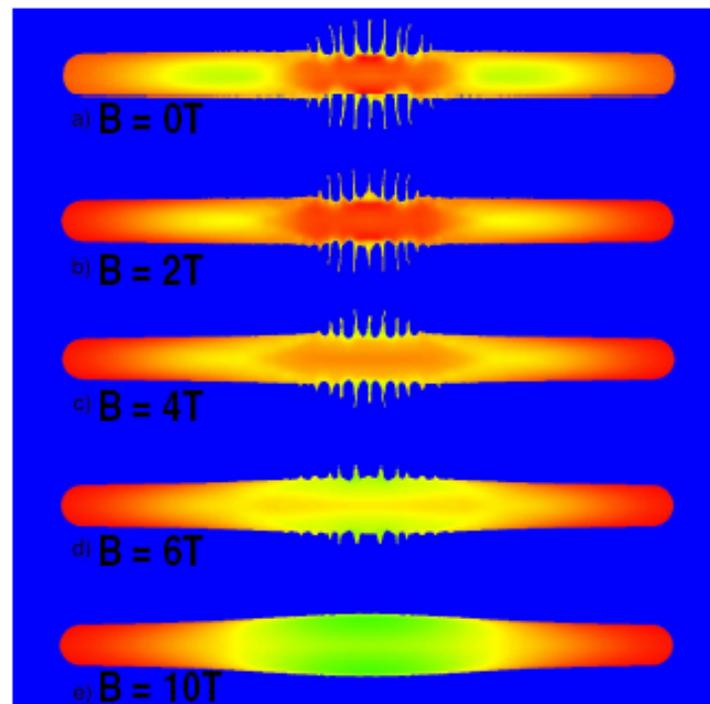


- Without magnetic field, Hg jet looks workable

- With magnetic field, surface instabilities are stabilized

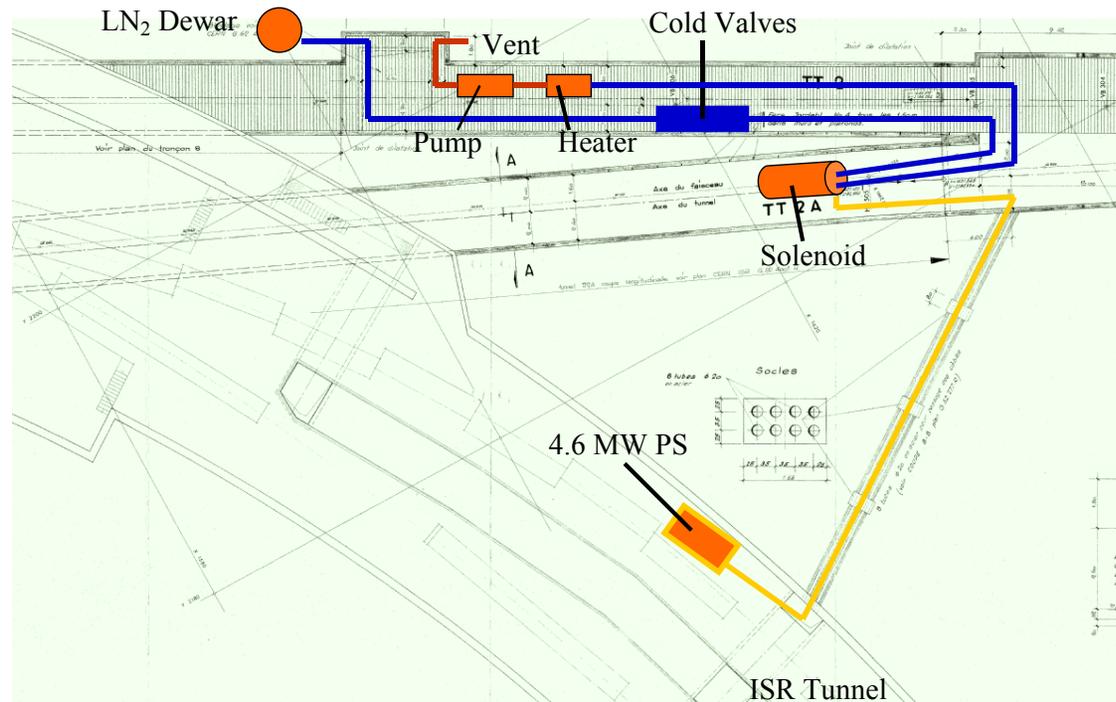


Experiment (Fabich)



MHD simulation (Samulyak)

- To do beam test of Hg jet with magnetic field, **MERIT** proposal submitted to CERN April, 2004 (approved April 2005)
 - first beam ~April, 2007
 - venue change necessitated by elimination of continued A3 line running at BNL



- Fabrication of 15 T magnet completed
 - operates at 80 K (cryogenic but not superconducting)
 - 8 MVA CERN power supply being refurbished to operate magnet
 - repetition rate ~ 0.001 Hz (20 minute cycle)

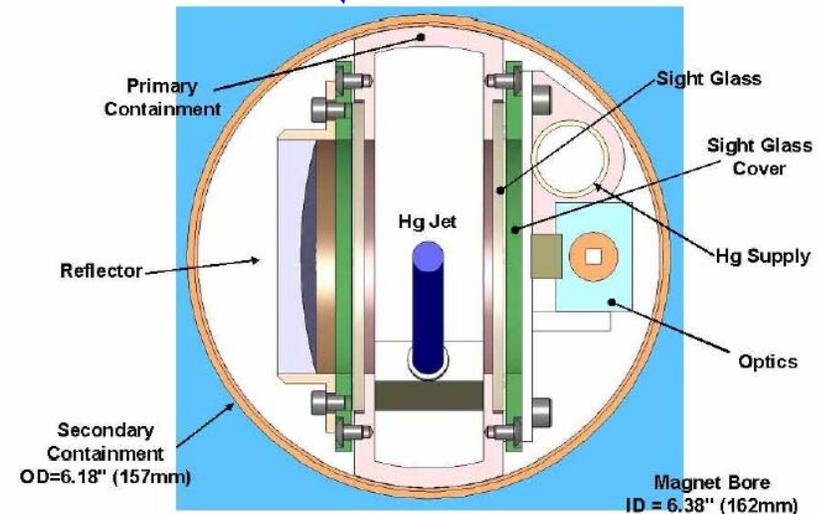
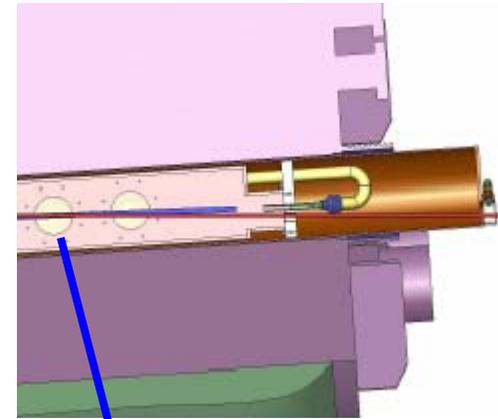
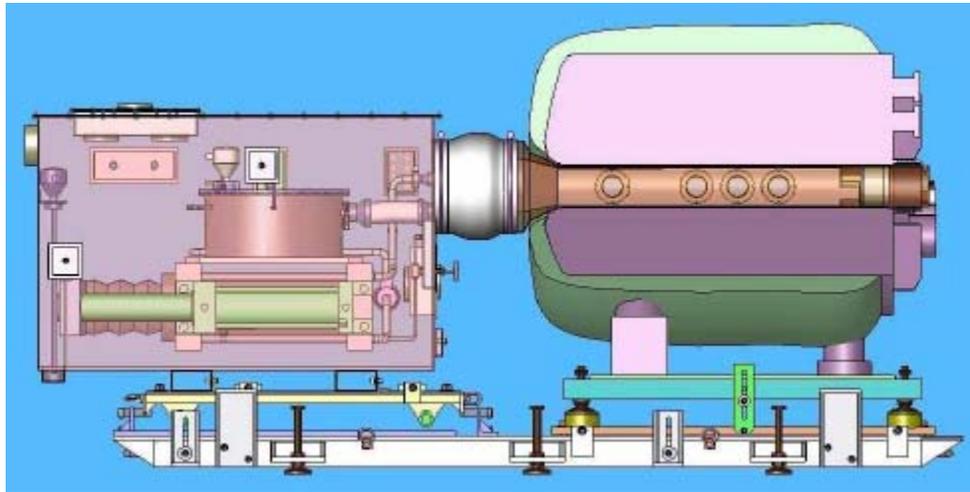
15-T solenoid in test location at MIT



8 MVA power supply at CERN



- Components for Hg jet system for CERN target test experiment are being developed in collaboration with ORNL

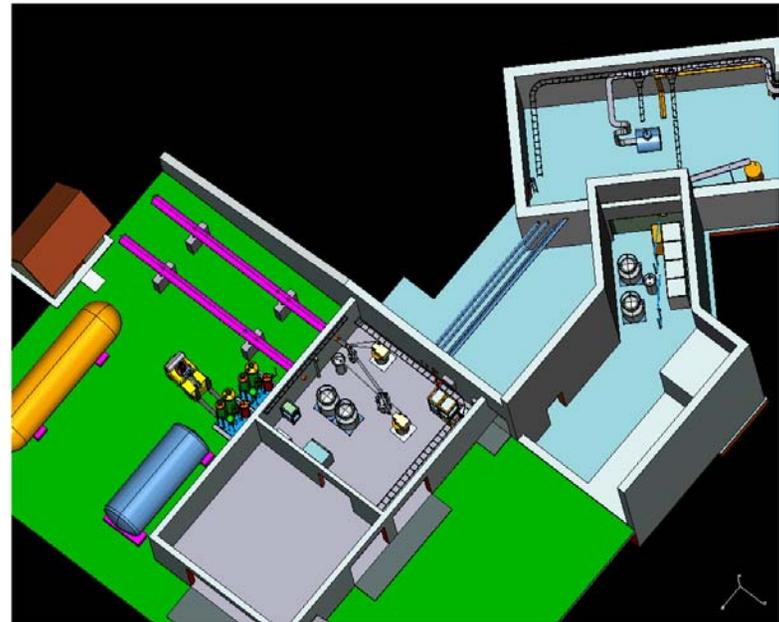




R&D Accomplishments



- Cooling component tests (rf cavities and absorbers) carried out in newly constructed area at Fermilab
 - MUCOOL Test Area (MTA, provided by NFMCC)
 - located at end of 400 MeV linac; will ultimately be used for beam tests (“blast” tests)

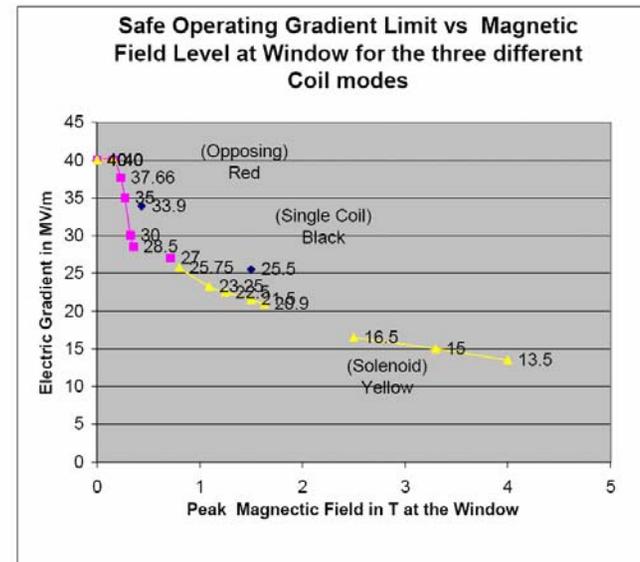


- Motivation for test program: degradation in performance observed when strong magnetic field is applied

201 MHz cavity



5-T solenoid +
805-MHz cavity

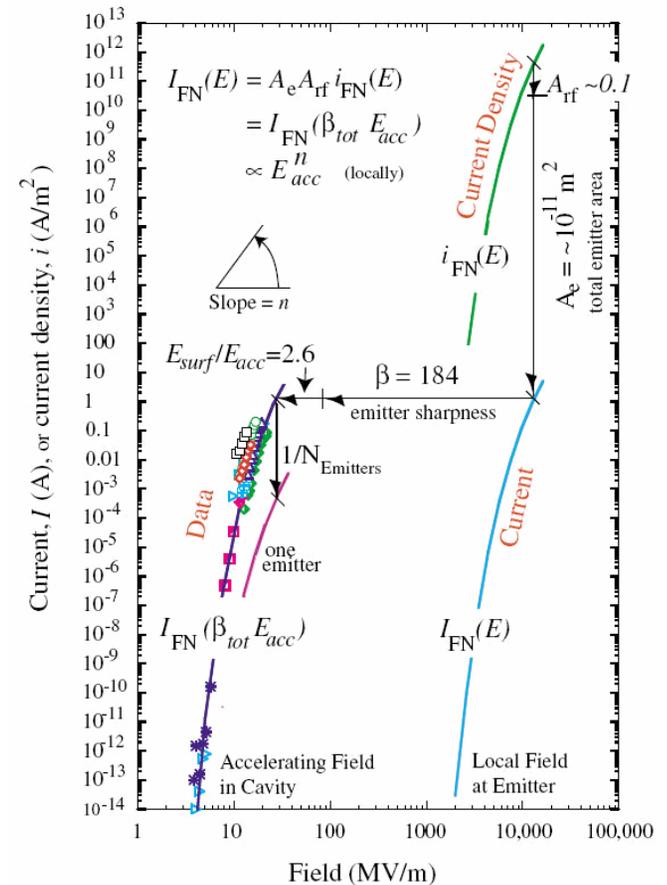


- Working to develop insights into mechanism(s) of cavity breakdown
 - model (**Norem**) assumes that breakdown results when surface field exceeds tensile strength of cavity material ($E_{surf} = \leq \sqrt{(2T/\epsilon_0)/\beta_{eq}}$)
 - explains many aspects of high-field cavity operation

breakdown rates as function of E and pulse length
 dependence on gas pressure
 dependence on solenoidal field
 dependence of E_{max} on pulse length and frequency
 "spitfests"
 conditioning process

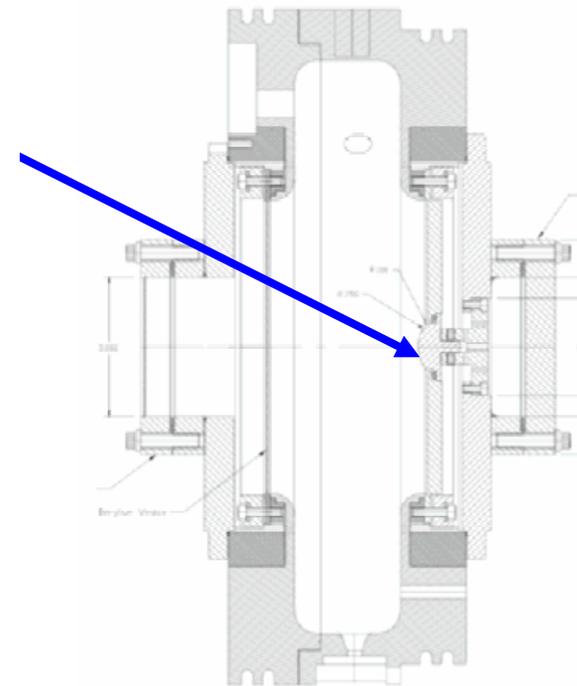
— publication in preparation

- Model is relevant to other machines, e.g., linear colliders

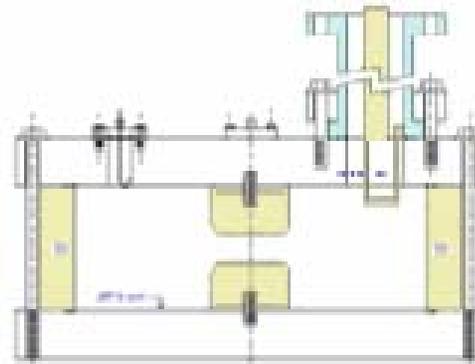


- Tests will use 805-MHz pillbox cavity with replaceable windows or “buttons”
 - cavity fits in bore of MTA solenoid
 - generate field enhancement at buttons to test performance of materials and/or coatings

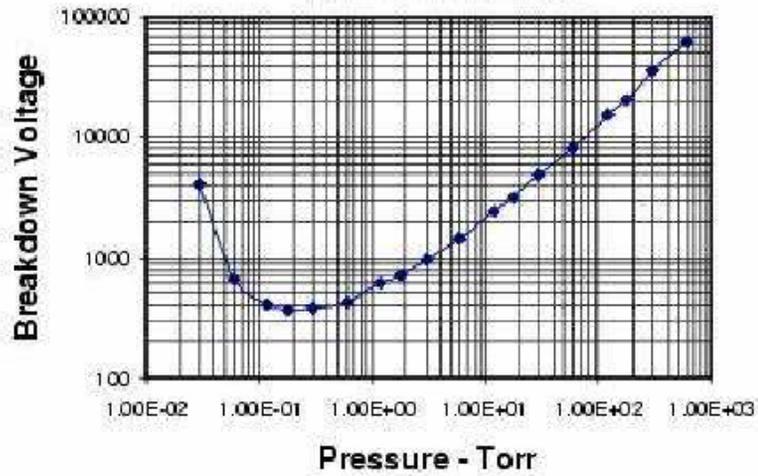
“Button” for materials tests



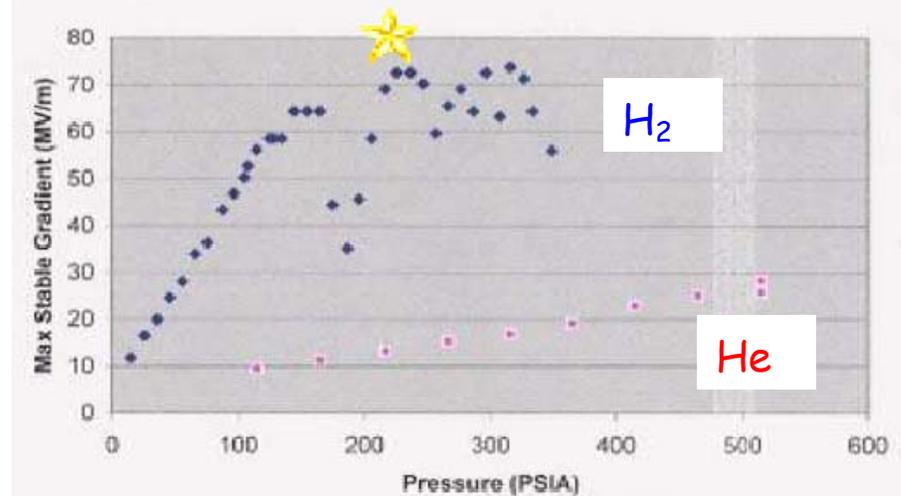
- Tested pressurized version of button cavity (Muons, Inc.)
 - use high pressure H_2 gas to limit breakdown



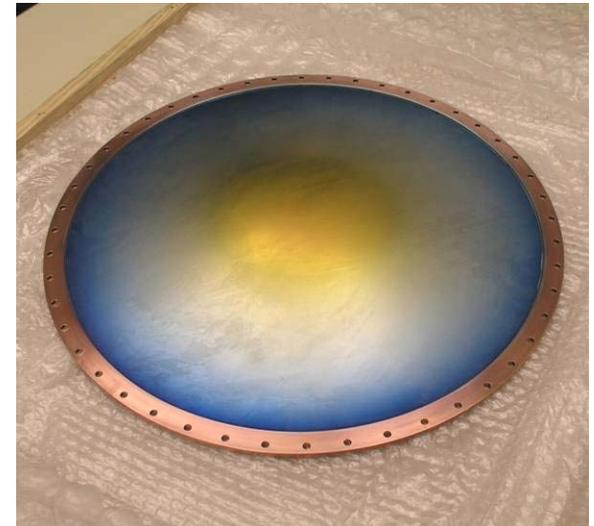
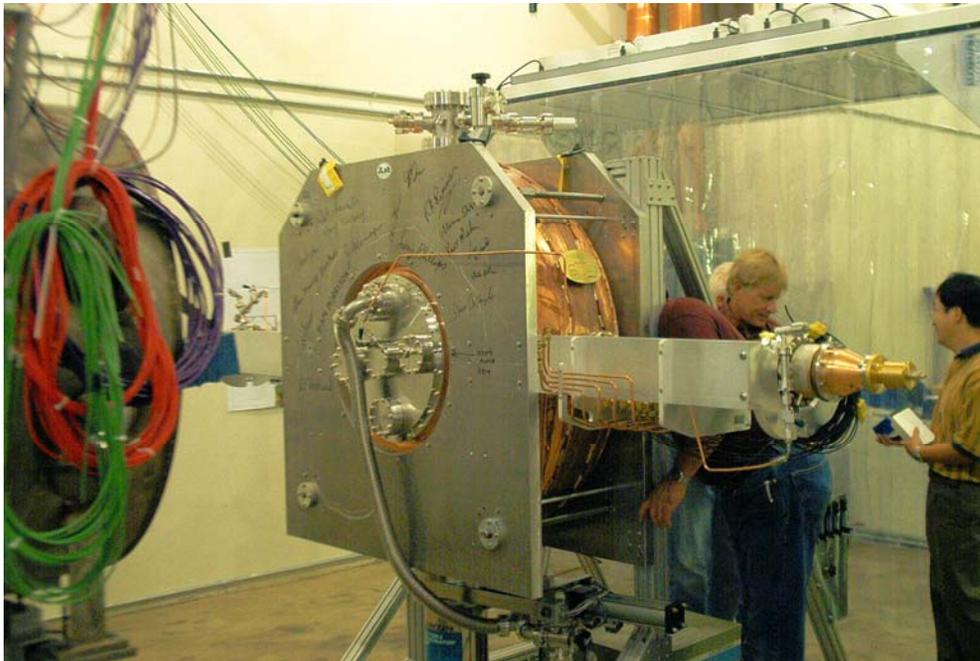
Breakdown Voltage vs. Pressure
(Air - 0.1 inch Gap)



H_2 vs He RF breakdown at 77K, 800MHz

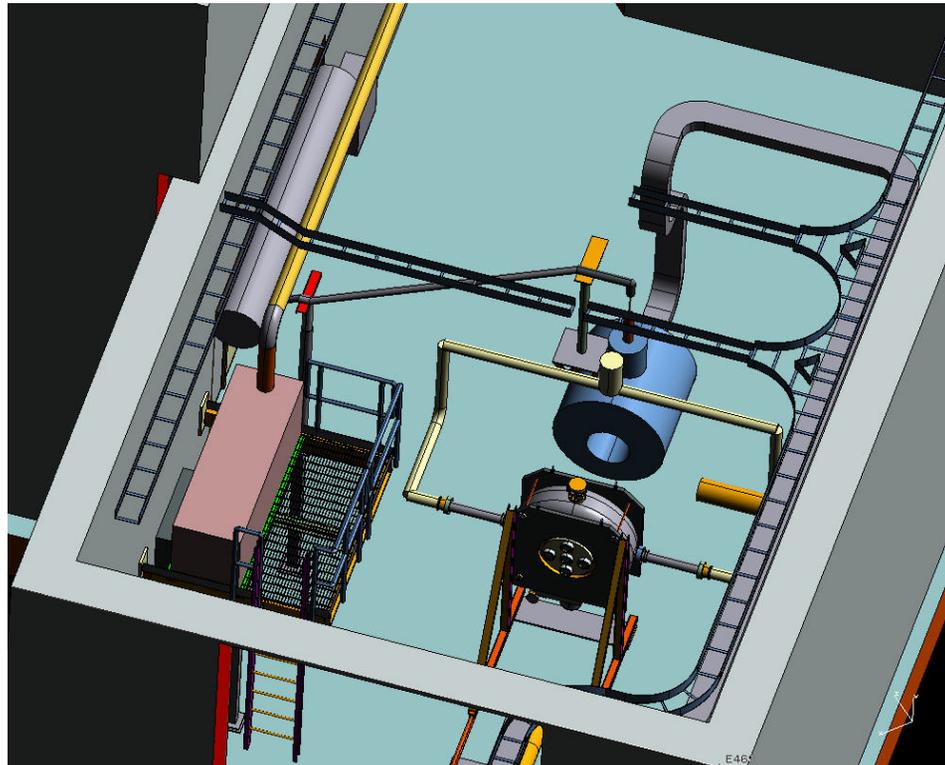


- Initial tests of 201 MHz cavity will commence
 - LBNL, Jlab, and U-Miss collaborated on cavity fabrication
 - cavity installed at MTA and awaiting power connection



42-cm curved Be window

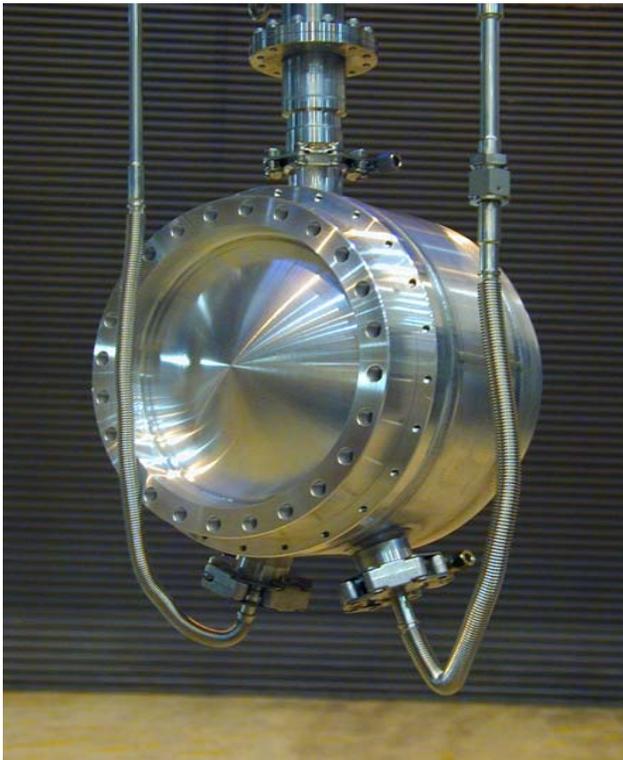
- 201-MHz cavity can be tested in close proximity to 5-T solenoid to provide some magnetic field
 - more realistic field configuration requires large diameter coupling coil (awaiting sufficient funding to acquire this)



- Absorber group has developed strong, thin windows
 - new stronger (\Rightarrow thinner) design built (at U.-Miss.) and tested successfully at Fermilab
 - 125 μm window is 3x stronger than original design
 - burst at 140 psi



- Initial absorber LH₂ filling tests carried out at MTA last summer
 - convection-cooled absorber prototype fabricated at KEK
 - plan to also test Fermilab forced-flow absorber design here

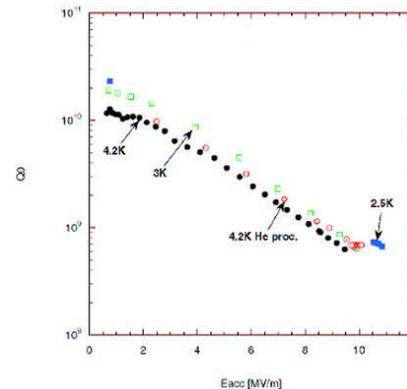


Prototype LH₂ absorber



Test cryostat at MTA

- 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 (and lost funding traction as well!)
 - 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



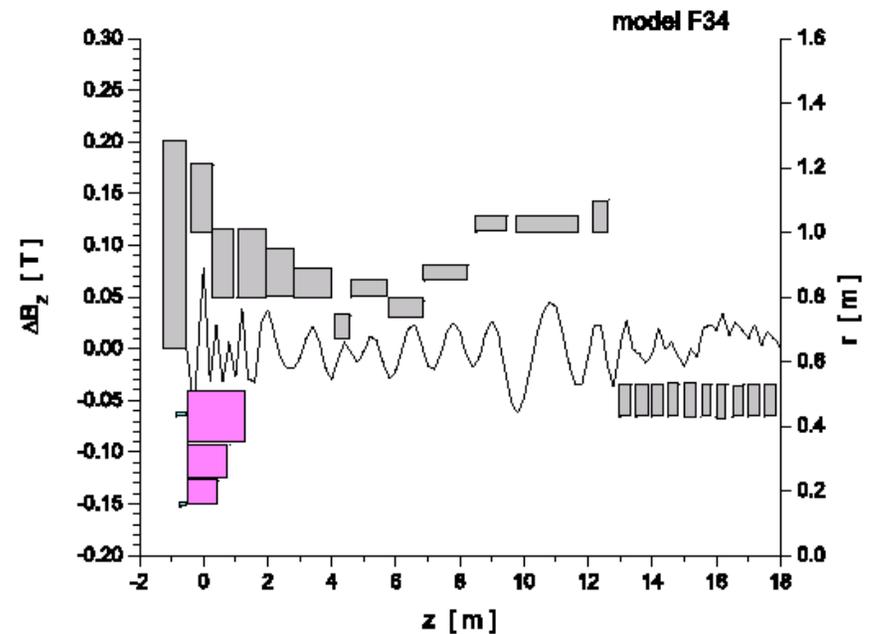
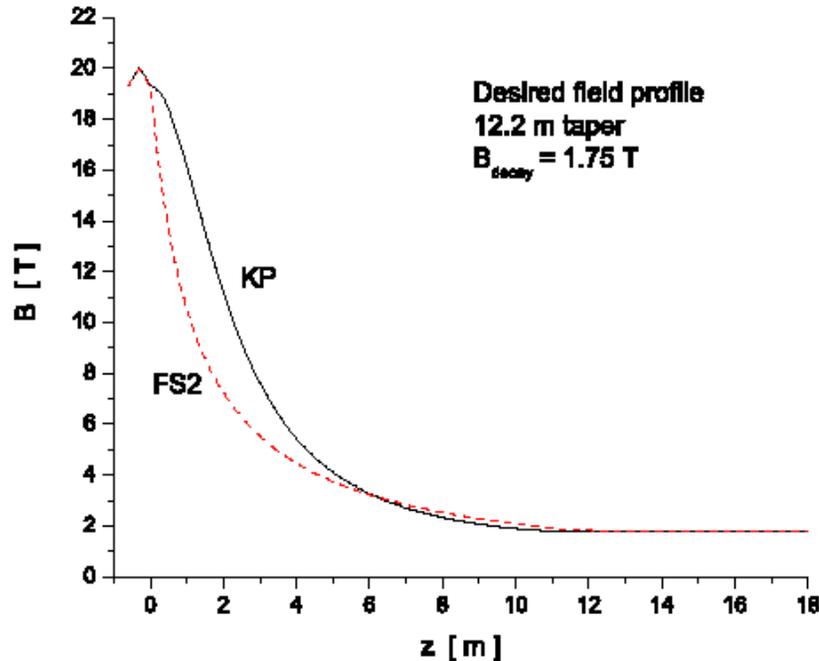
R&D Accomplishments



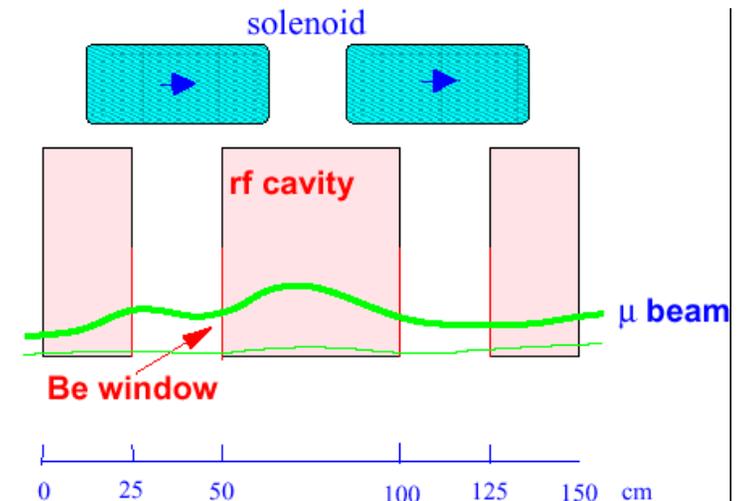
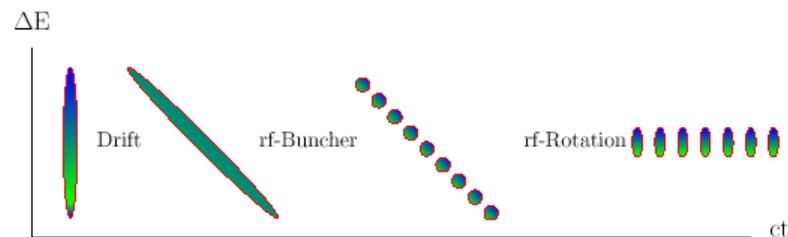
- Simulations

- main focus was to participate in APS Multi-Divisional Neutrino Study (<http://www.aps.org/neutrino/>)
 - detailed report written by “Neutrino Factory and Beta Beams Experiments and Development Working Group”
 - <http://www.aps.org/neutrino/loader.cfm?url=/commonspot/security/getfile.cfm&PageID=58766>
 - considerable progress made in simplifying front-end systems while maintaining performance
 - developed RF bunching and phase rotation scheme
 - simplified cooling channel
 - adopted FFAG scheme for final acceleration stages
 - preceded by linac and dogbone RLA
- ⇒ something for everyone!

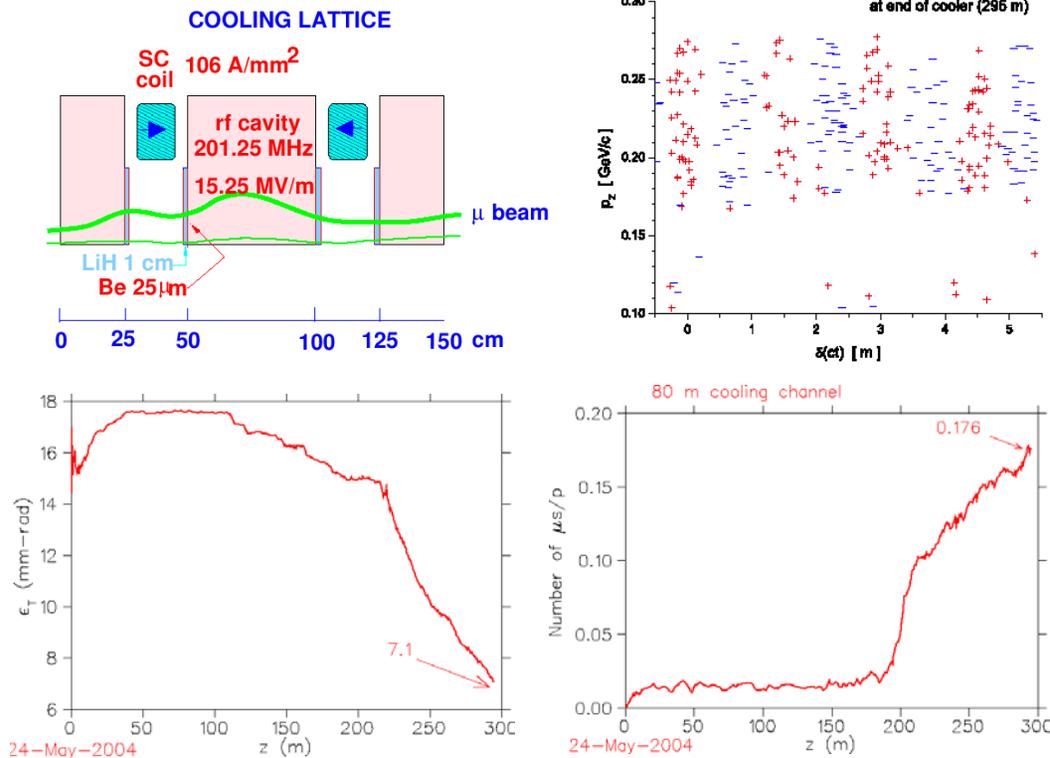
- Reoptimized capture section field profile
 - not much different, but 10% intensity gain
 - field tapers to 1.75 T (vs. 1.25 T in FS2)



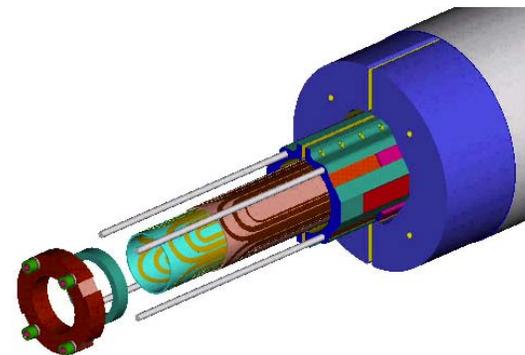
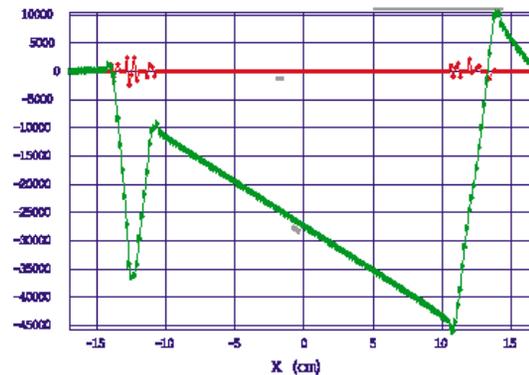
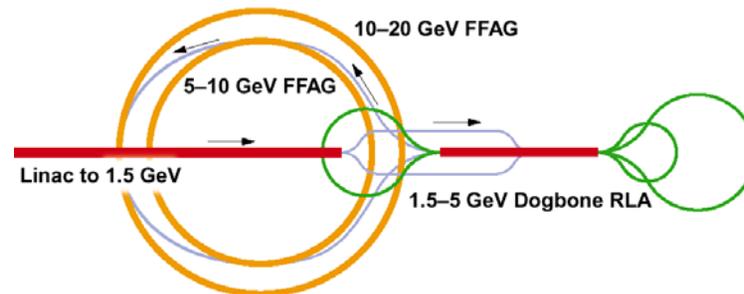
- Use RF to bunch, then to phase rotate
 - performance acceptable and less expensive than induction linacs
 - uses “standard” cooling channel components
 - keeps both μ^+ and μ^-
 - RF frequencies vary along the beam channel

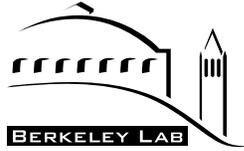


- Use simplified cooling channel
 - shorter, fewer magnets and cavities, simpler absorbers (replace LH_2 with LiH)
 - performs acceptably for both μ^+ and μ^- (with larger downstream acceptance)



- Looked at FFAG scheme for cost-effective acceleration
 - below 5 GeV, linac + RLA scheme looks more cost effective
 - required combined-function dipoles appear feasible and affordable
 - discussion of building an electron model of FFAG continues





R&D Accomplishments



- Goals of **MICE**
 - 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
- 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
- Both **simulations** and **apparatus tested** must be **as realistic as possible**
 - incorporate full engineering details of all components into simulation

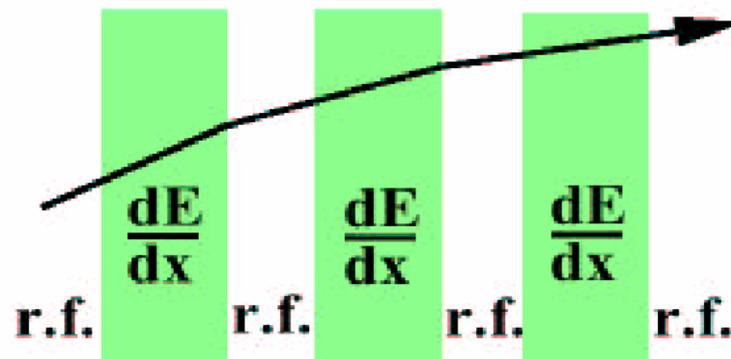


R&D Accomplishments



- Main challenges of **MICE**
 - operating high-gradient **RF cavities in solenoidal field** and with field terminations (windows)
 - operating **LH₂ absorbers with very thin windows** and consistent with safety regulations
 - integration of cooling channel components while **maintaining operational functionality**
- Another challenge
 - for cost reasons, we use only a single cell of a cooling channel
 - ⇒ emittance reduction will be small in absolute terms ($\mathcal{O}(10\%)$)
 - wish to measure emittance reduction at level of 10^{-3}
- Technical solutions build upon component R&D activities already under way outside of **MICE**

- Ionization cooling 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



- 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

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

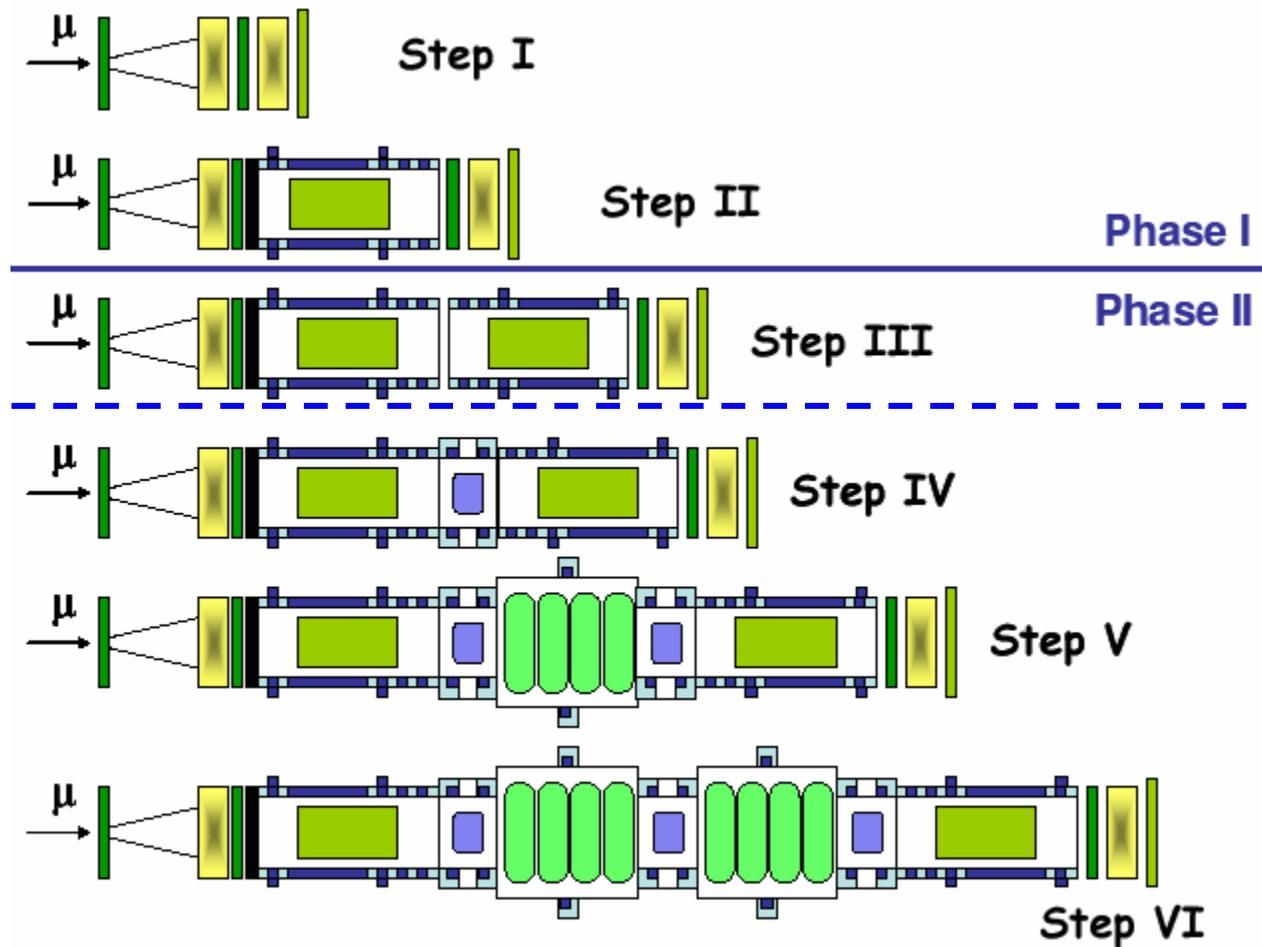
cooling

heating

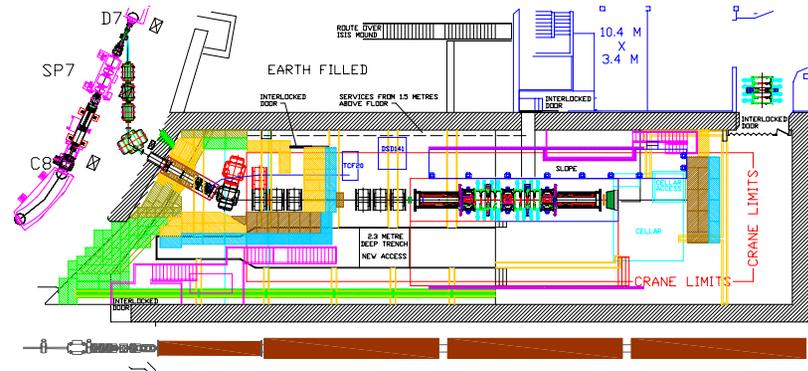
$$\varepsilon_{x,N, \text{equil.}} = \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta m_\mu X_0 \left| \frac{dE_\mu}{ds} \right|}$$

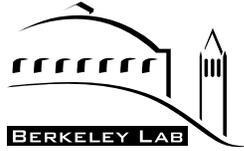
- prefer low β_\perp (\Rightarrow strong focusing), large X_0 and dE/ds (\Rightarrow H₂ is best)

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



- 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**...on purpose for a change





R&D Accomplishments



- **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
 - R&D system (1st article) released for fabrication November, 2005
 - passed Gateway 2-3 review in December 2004
 - Phase I UK funds (£9.7M) now in hand
 - other Phase I contributions (Japan, U.S., Switzerland) also available now
 - spokesperson: **A. Blondel** (Geneva)
 - first beam April, 2007



Future Plans



- **Targetry**
 - continue design and fabrication of **MERIT** components
 - continue support of magnetohydrodynamics simulations
- **Cooling**
 - test 201 MHz high-gradient cavity (17 MV/m)
 - test 805 MHz cavity with curved window, grid, and “buttons”
- **Acceleration**
 - study **Q disease** and develop mitigation techniques
- **Simulations**
 - continue developing **cost-optimized front-end** for Neutrino Factory
 - identify **Proton Driver requirements** from Neutrino Factory application
 - participate in upcoming **World Design Study** (follow-on to **ISS**)



Future Plans



- **MICE**
 - complete fabrication of spectrometer solenoids and tracker electronics
 - begin fabrication of other U.S.-supplied components (RFCC module)

NOTE: NFMCC is an R&D organization, *not* a project team
When a Neutrino Factory project is launched, a Lab (or Labs) will run it



Summary and Outlook



- **NFMCC** has made **excellent progress** in identifying and studying the R&D topics relevant to design of **Neutrino Factory** based on **high-intensity muon storage ring**
 - and developing concepts for a future **Muon Collider**
- **Solid R&D management and planning processes** are in place to ensure that activities are well-focused and effective
 - internal audits by PM; external audits by MUTAC/MCOG
- **Close interactions with** corresponding groups in **Europe and Japan** serve to minimize duplication of effort and maximize R&D effectiveness
 - examples: **MICE**, **MERIT**, **ISS**, NuFact workshops
- Fosters **close collaboration between accelerator and particle physicists**
- **NFMCC** program **integral to the “big picture”** laid out in *The Neutrino Matrix* report (APS Multi-Divisional Study)
 - **strong endorsement of NFMCC R&D program will greatly help in securing additional funds to accomplish goals in a timely manner**

Final Thought

