The Fermilab Accelerator Science Program

Muon Acceleration Program Overview and Recent Progress

Alan Bross
Fermilab
December 3, 2008

Fermilab Muon Acceleration Program
Outline

- Introduction
- Organization and Personnel
- Recent Accomplishments

Andreas Jansson will cover:

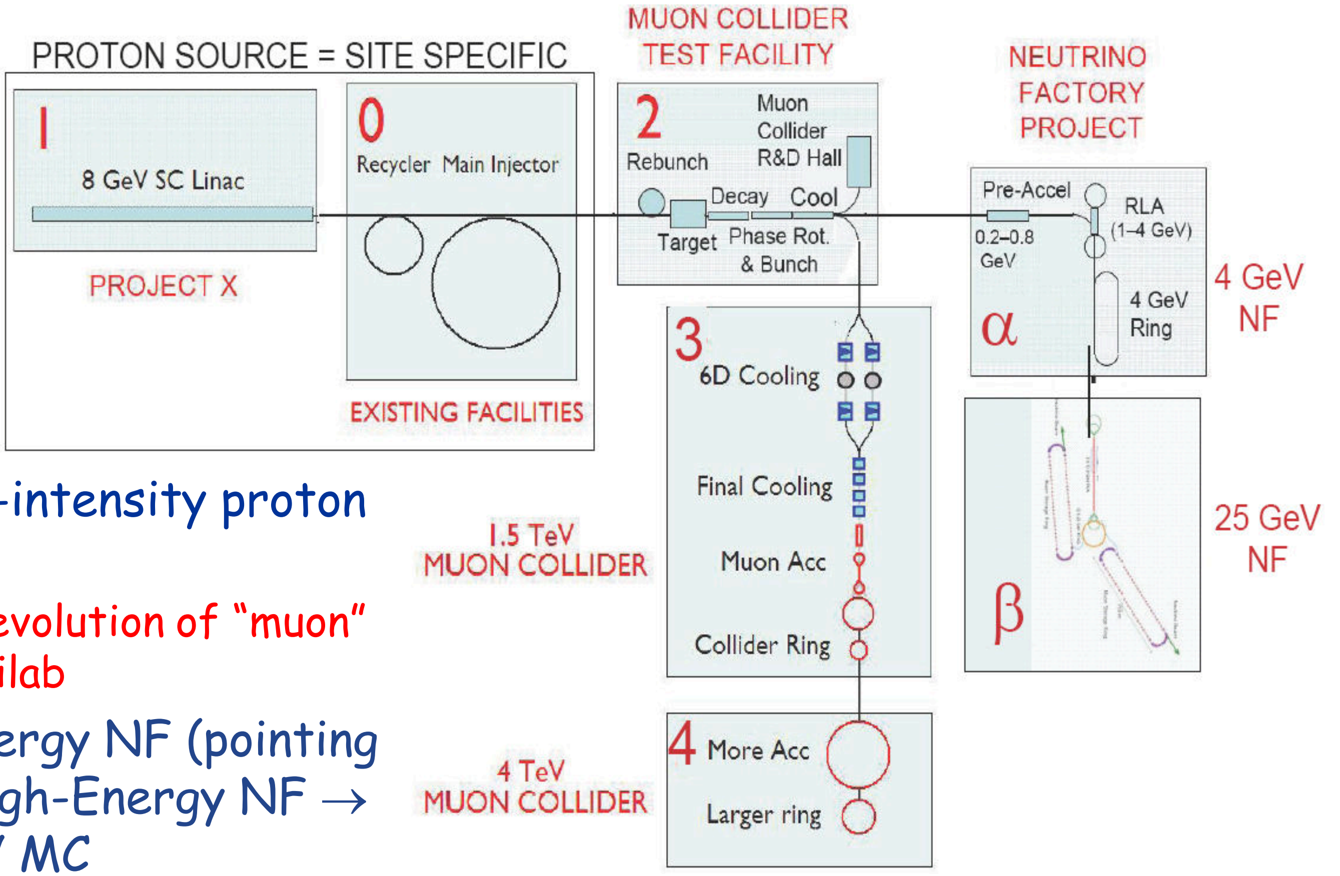
- Proposal Detail for FY2010-2012
- Budget Request

Introduction

Motivation and connection to Future HEP Facilities

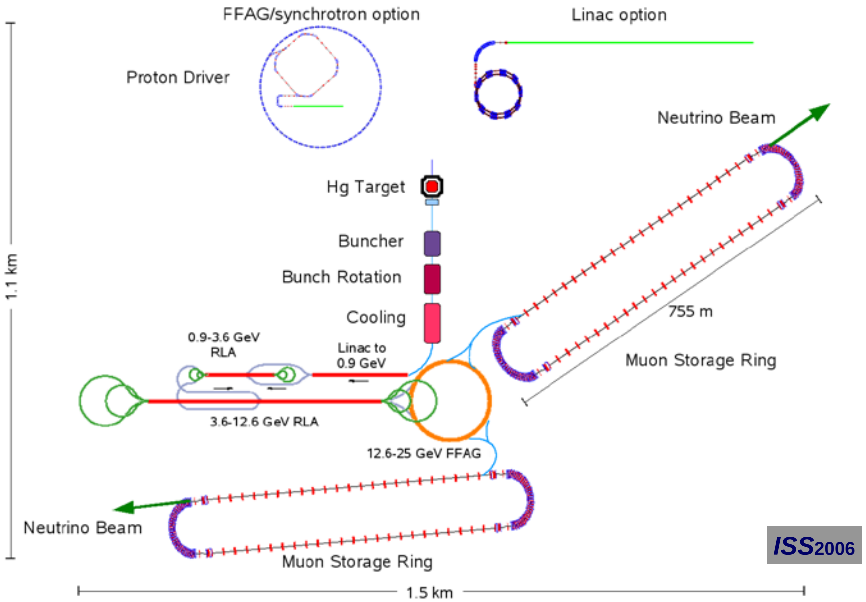
Why Muon Acceleration R&D?

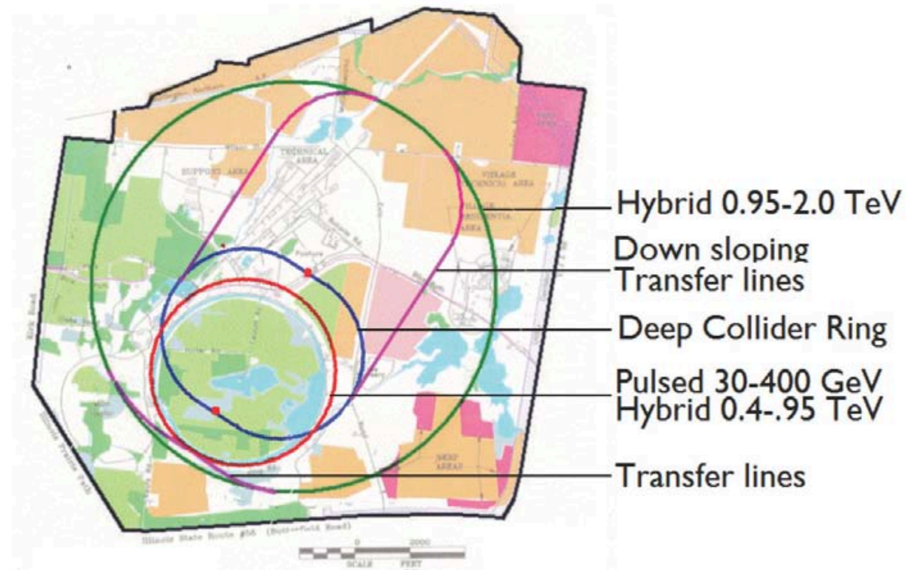
Muon Complex Evolution At Fermilab



- Starting with a high-intensity proton source: Project X
  - We see a natural evolution of "muon" program for Fermilab
- Project X → Low-Energy NF (pointing to Homestake) → High-Energy NF → 1.5 TeV MC → 4 TeV MC

Muon Acceleration and Future HEP Facilities
Neutrino Factory & Muon Collider



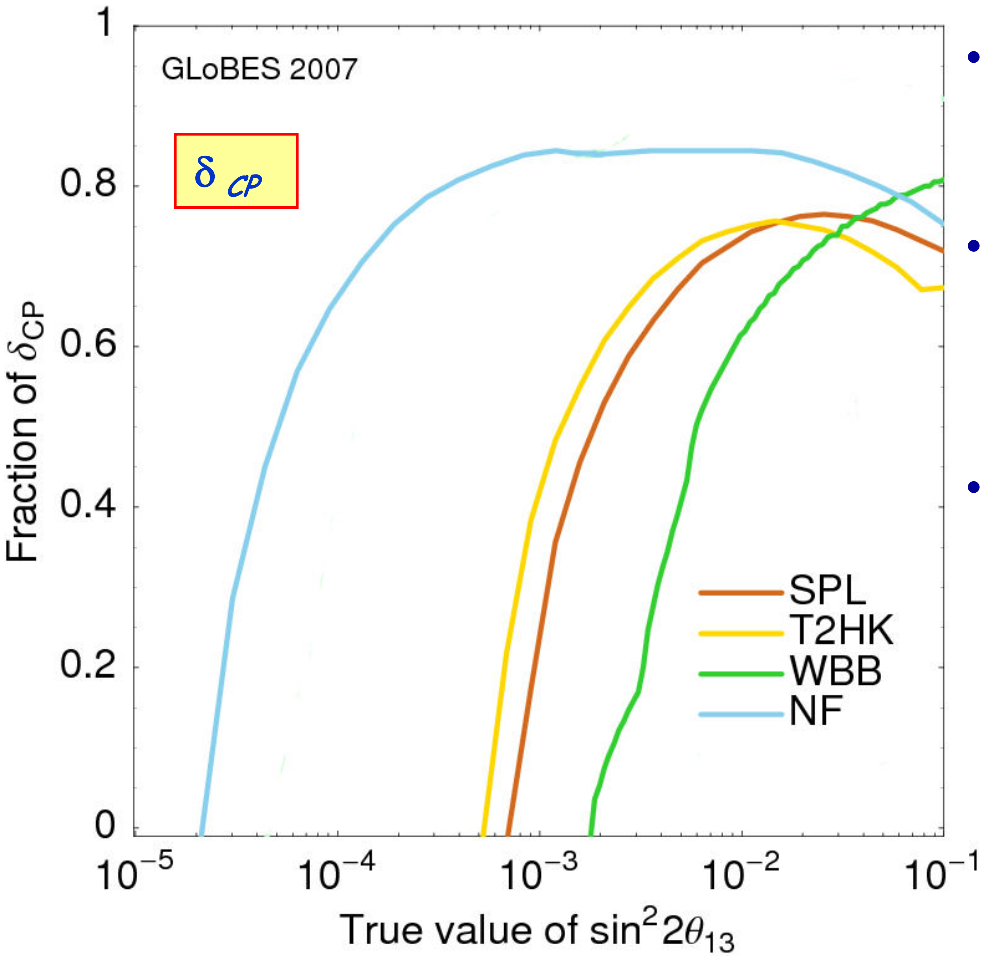


- Neutrino Factory
  - IDS Baseline (FS1, FS2(a)(b), ISS)
    - 25 GeV μ storage ring
    - 4 GeV Option under study

- MC: One Concept
  - 4 TeV Center-of-Mass
    - Rapid-Cycling Synchrotron Acceleration

Common Front-End, SMALL FOOTPRINT

NF Motivation - Physics Reach (ISS)



- The NF gives the best Physics Reach
  - NF ≡ Precision
- Even with $\sin^2 2\theta_{13}$ in the range of 5 X 10^{-4} to 10^{-3}, these very aggressive "conventional" experiments – Run Out of Steam
- Similar arguments can be made for $\sin^2 2\theta_{13}$ discovery reach and determination of the neutrino-mixing mass Hierarchy

SPL: 4MW, 1MT H_2OC, 130 km BL
T2HK: 4 MW, 1MT H_2OC, 295 km BL
ProjX: 2MW, 1MT H_2OC, 1300 km BL

NF: 4MW, 100KT MIND, 4000 & 7500 BL

Muon Collider - Motivation

Reach Multi-TeV Lepton-Lepton Collisions at High Luminosity

Muon Colliders may have special role for precision measurements.
Small ΔE beam spread -
Precise energy scans

Small Footprint -
Could Fit on Existing Laboratory Site

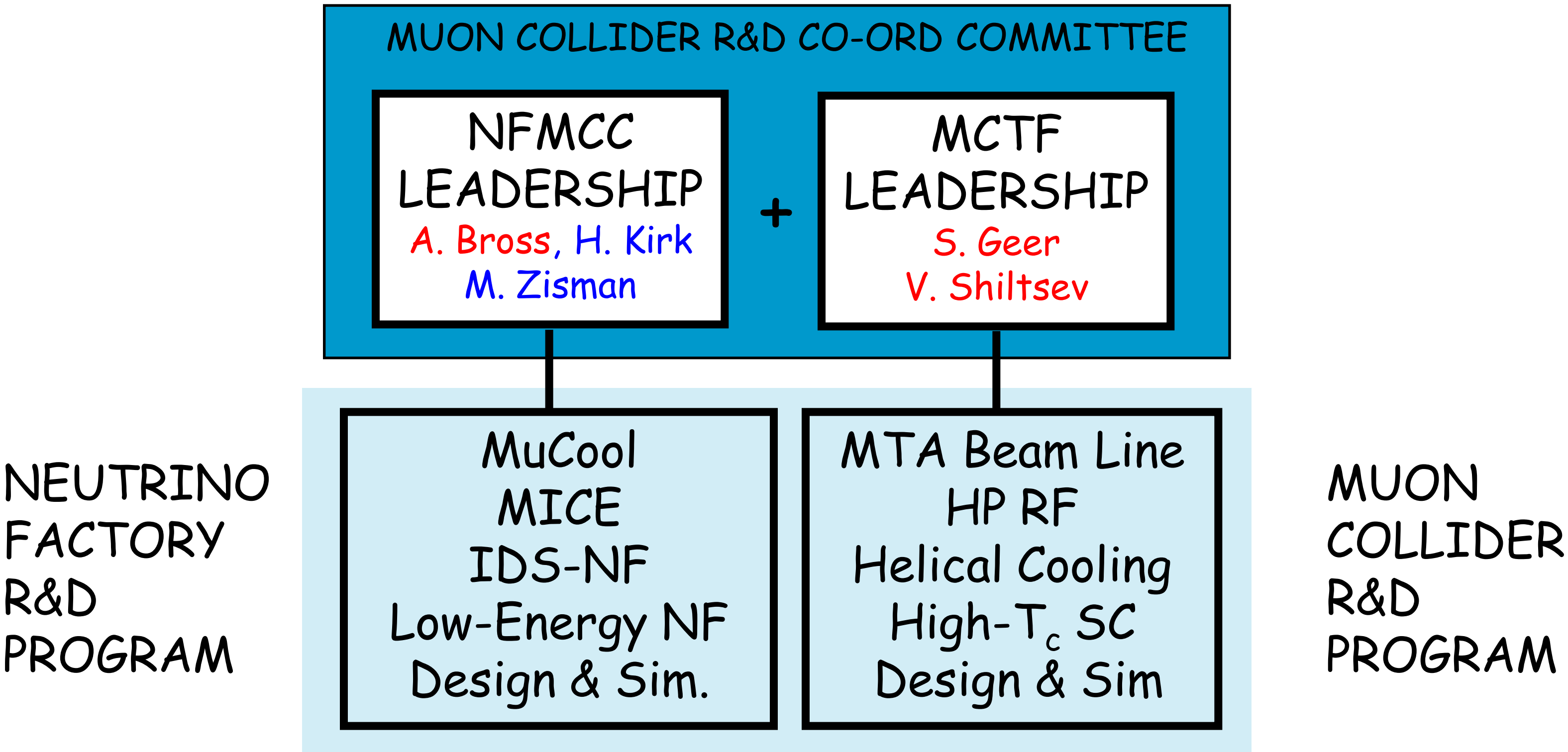
Muon Acceleration R&D
Focus of Fermilab Program

- We are currently focusing a number of the critical R&D questions (In collaboration with our National Lab and University Partners)
  - Operation of High Gradient RF in strong B field
    - MuCool Experimental program @ Fermilab MuCool Test Area
  - Magnet Design for muon cooling channels (Helical & Ultra-high Field)
    - Fermilab Technical Division
  - Muon Ionization Cooling Demonstration
    - Muon Ionization Cooling Experiment
    - Design/simulation/component test of 6D muon cooling
      - 6D muon cooling experiment
  - Design/simulation of acceleration systems
  - Design/simulation of MC storage ring and IP
  - Neutrino Factory RDR
    - With IDS for a NF
      - Physics, Accelerator Facility, Detector
  - MC DFS
    - The Muon Collider Task Force will study essentially all aspects of the MC facility for the DFS
    - Physics and Detector studies
      - Fermilab Theory Group and Particle Physics Department

Organization

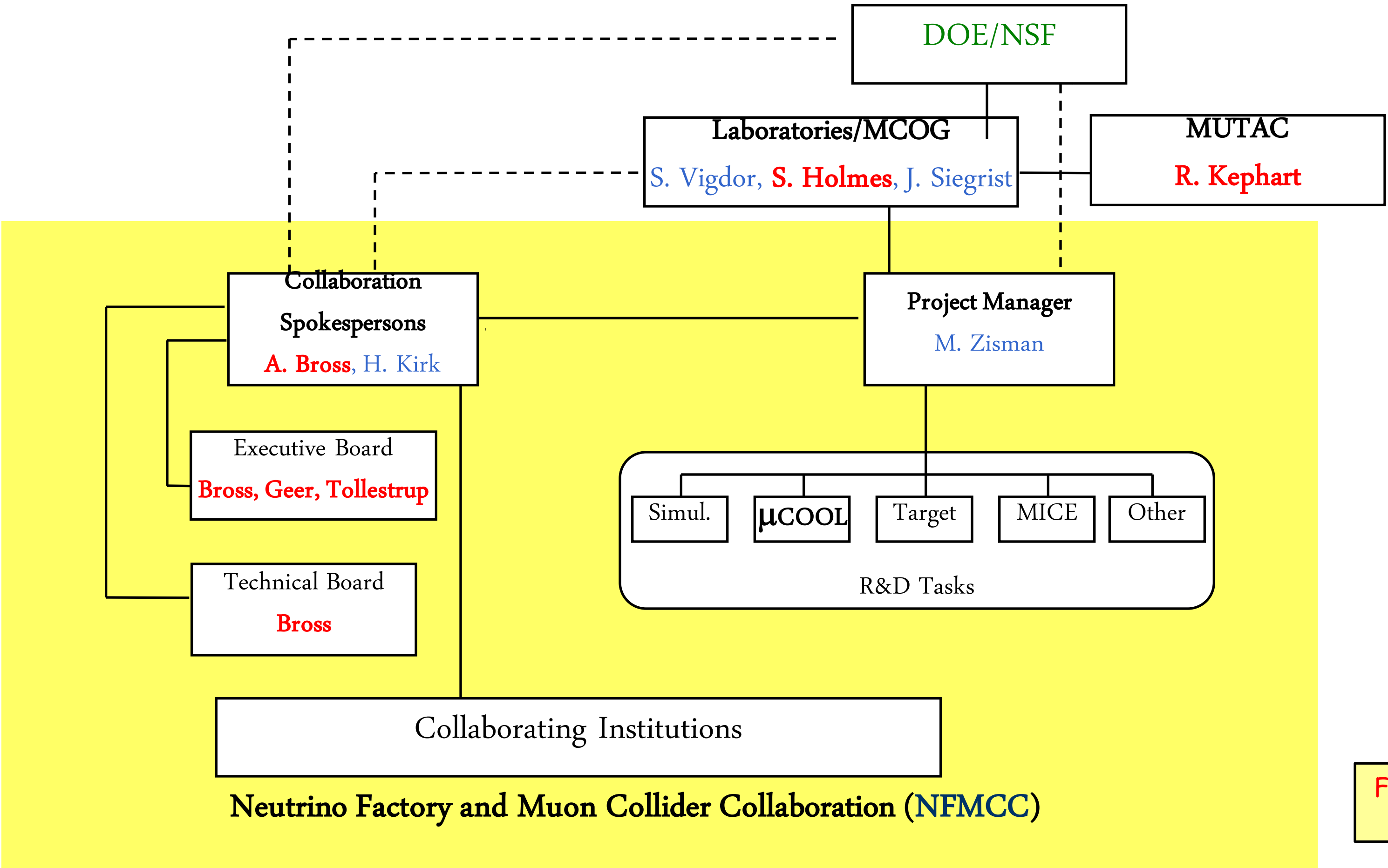
Muon Acceleration R&D Organization

- R&D Program carried out by two groups
  - Neutrino Factory and Muon Collider Collaboration
  - Fermilab Muon Collider Task Force



NFMCC Organization

Fermilab One of the Founding Institutions



Fermilab Assuming Leadership Role

Fermilab Manpower

- Over the past 3-5 years, the Fermilab effort on Muon Acceleration has ramped up to approximately 21 FTEs
  - Accelerator Physics Center 7
    - MuCool, MICE, MERIT, NF:ISS/IDS, Simulation/Design
      - Y. Alexahin, C. Ankenbrandt, V. Balbekov, A. Bross, M. Chung, E. Gianfelice-Wendt, A. Jansson, A. Kurup, N. Mokhov, A. Moretti, D. Neuffer, I. Rakhno, S. Striganov, Y. Torun, K. Yonehara, C. Yoshikawa
  - Accelerator Division 5
    - MuCool Test Area Infrastructure & Beam Line, μ acceleration systems
      - D. Broemmelsiek, F. Garcia, M. Geynisman, M. Hu, C. Johnstone, A. Klebaner, M. Popovic
  - Particle Physics Division 6
    - MICE Detectors and Instrumentation, High T_c superconductor, magnet design
      - R. Flores, R. Rucinski, P. Rubinov, G. Sellberg, A. Tollestrup, M. Utes
  - Technical Division 3
    - Magnet Design
      - E. Barzi, M. Lamm, A. Markarov, Vladimir Kashikhin, Vadim Kashikhin, A. Zlobin

Fermilab μ Acceleration R&D Program

Key Technical Ingredients Common to NF and MC Facilities

- Proton Driver
  - Project X
- Target, Capture, and Decay
  - create π's; decay into μ's
- Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce emittance of the muons
    - Cost-effective for NF
    - Essential for MC
- Acceleration
  - Accelerate the Muons
- Storage Ring
  - store for ~1000 turns

80% Overlap in initial R&D

But there are Key Differences

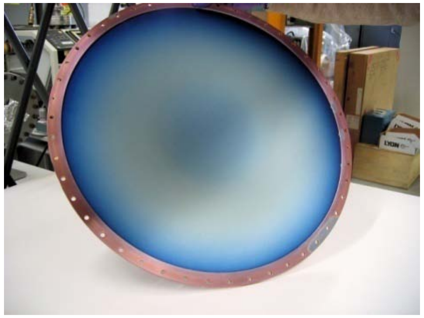
Neutrino Factory	Muon Collider
Cooling ▪ Reduce transverse emittance · $\varepsilon_\perp \sim 7$ mm **Acceleration** ▪ Accelerate to 25 GeV ▪ May be as low as 5-7 GeV **Storage Ring** ▪ No intersecting beams	**Cooling** ▪ Reduce 6D emittance · $\varepsilon_\perp \sim$ 3-25 μm · $\varepsilon_L \sim$ 70 mm **Acceleration** ▪ Accelerate to 1-2 TeV **Storage Ring** ▪ Intersecting beams

Muon Cooling: MuCool and MICE

Component R&D and Cooling Experiment

A. Bross, A. Klebaner, A. Kurup, A. Moretti, M. Geynisman, Y. Torun

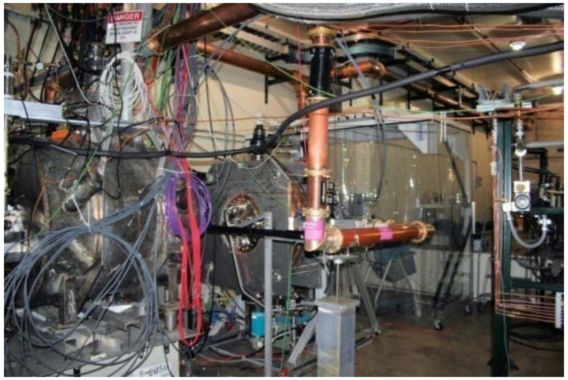
- MuCool
  - Component testing: RF, Absorbers, Solenoids
    - With High-Intensity Proton Beam
  - Uses Facility @Fermilab (MuCool Test Area –MTA)
  - Supports Muon Ionization Cooling Experiment (MICE)
  - 10 institutions from the US, UK and Japan participate



50 cm ∅ Be RF window

MuCool Test Area

MuCool
201 MHz RF Testing



MuCool
LH_2 Absorber Body

RF Test Program

A. Bross, A. Kurup, A. Moretti, Y. Torun

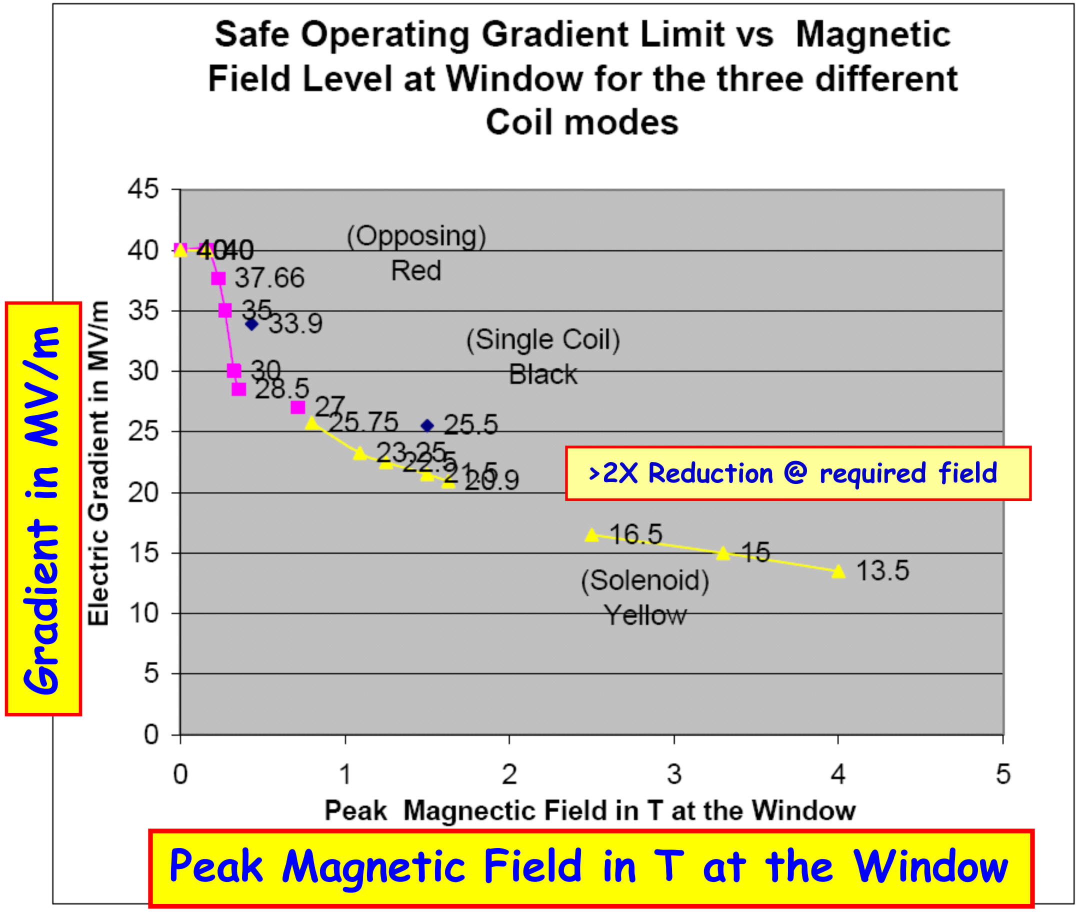
Fermilab has the primary responsibility to carry out the RF Test Program

- Study the limits on Accelerating Gradient in NCRF cavities in magnetic field
- It has been proposed that the behavior of RF systems in general can be accurately described (predicted) by universal curves
  - Electric Tensile Stresses are important in RF Breakdown events
- This applies to all accelerating structures
- Fundamental Importance to both NF and MC
  - Muon capture, bunching, phase rotation
  - Muon Cooling
  - Acceleration

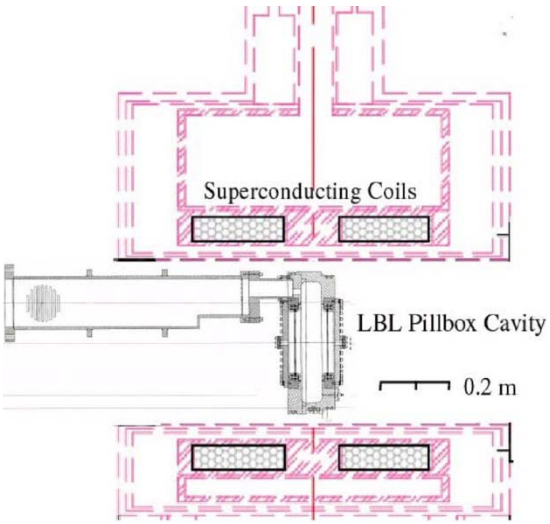
Arguably the single most critical Technical challenge for the NF & MC

The Basic Problem – B Field Effect

805 MHz Studies



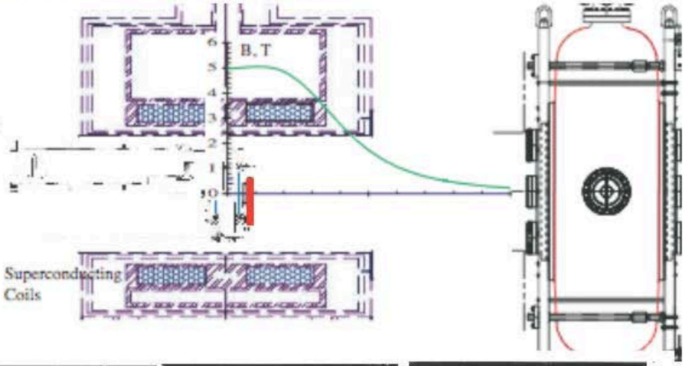
- Data seem to follow universal curve
  - Max stable gradient degrades quickly with B field
- Remeasured
  - Same results



805 MHz Imaging

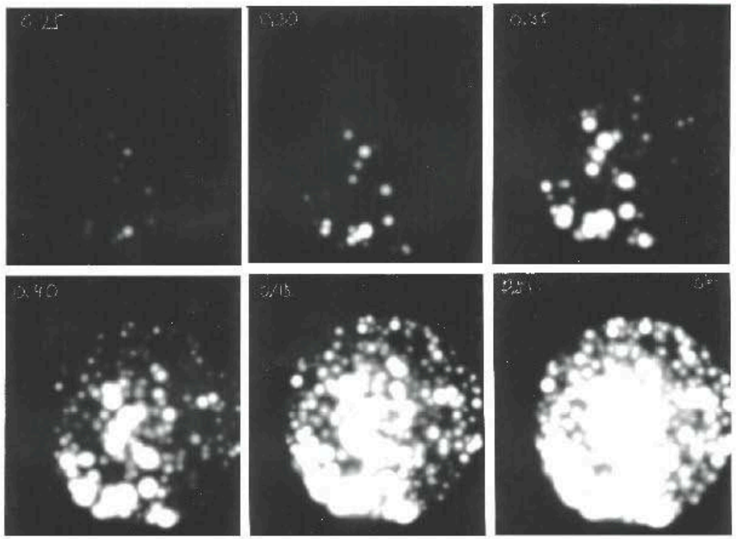
Polaroid Pictures of Field emitters

- Inserting polaroids near the window,



- Gives a picture of how the field emitters change with rf field.

  8.8 - 17.6 MV/m

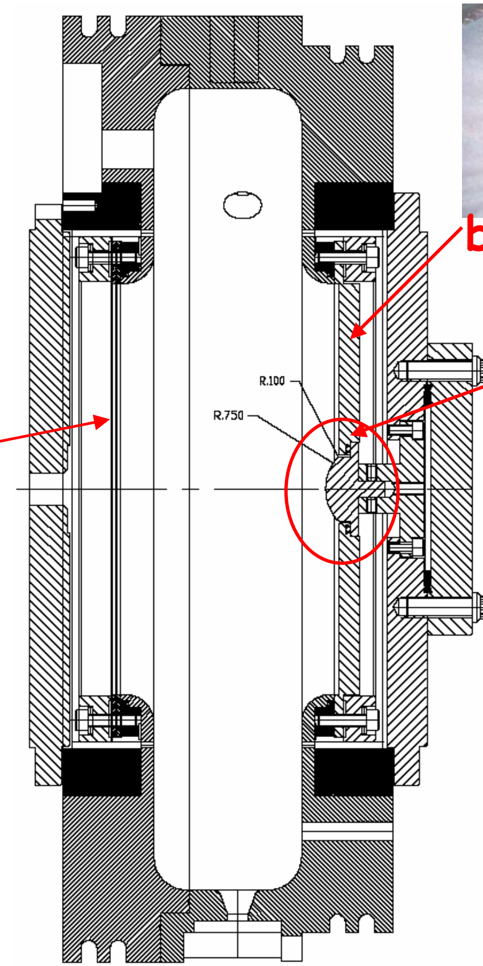


Facing the RF B Field Challenge

- Three Approaches to a Solution
  - Reduce/eliminate field emission
    - Process cavities utilizing SCRF techniques
    - Material Studies
  - RF cavities filled with High-Pressure gas (H_2)
    - Utilize Paschen effect to stop breakdown
  - Magnetic Insulation
    - Eliminate magnetic focusing
      - Not Yet Tested

Cavity material ("Button") test

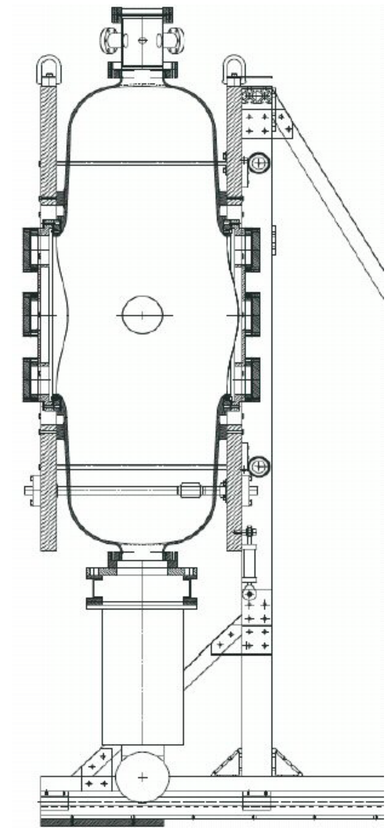
- "Button" system in pillbox cavity designed for easy replacement of test materials
- Tested so far: TiN-coated Cu & Mo, bare Mo and W
- To be tested: Cu (electro-polished & unpolished), Be
- Results to date indicate that TiN can improve performance at a given B field by somewhat more than 50%
  - 16.5MV/m → 26MV/m



(*1.7x* field enhancement factor on button surface)

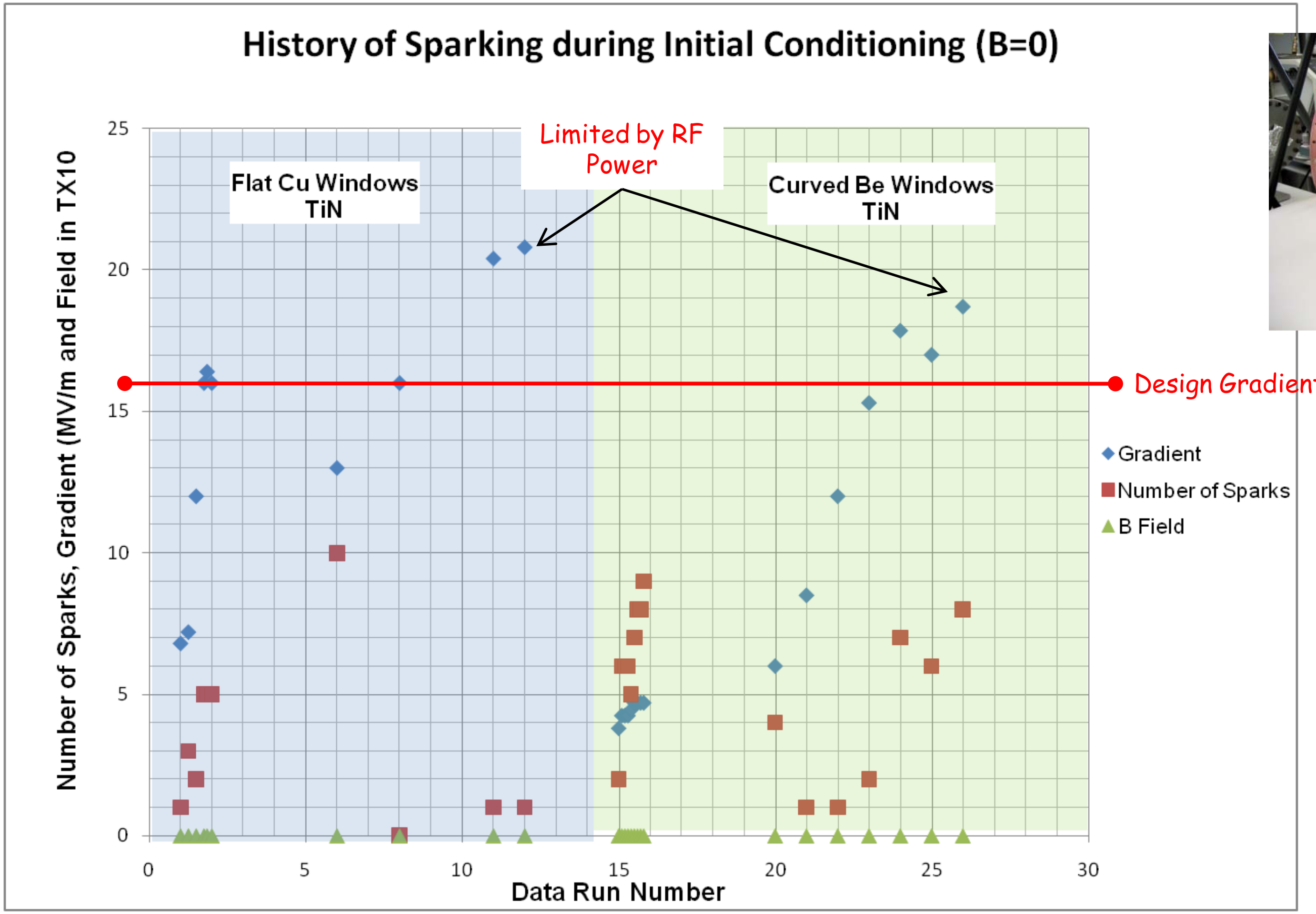
RF R&D – 201 MHz Cavity Test
Treating NCRF cavities with SCRF processes

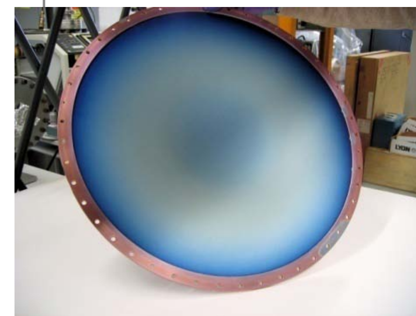
- The 201 MHz Cavity – *21 MV/m Gradient Achieved* (Design – 16MV/m)
  - *Treated at TNJLAB with SCRF processes – Did Not Condition*



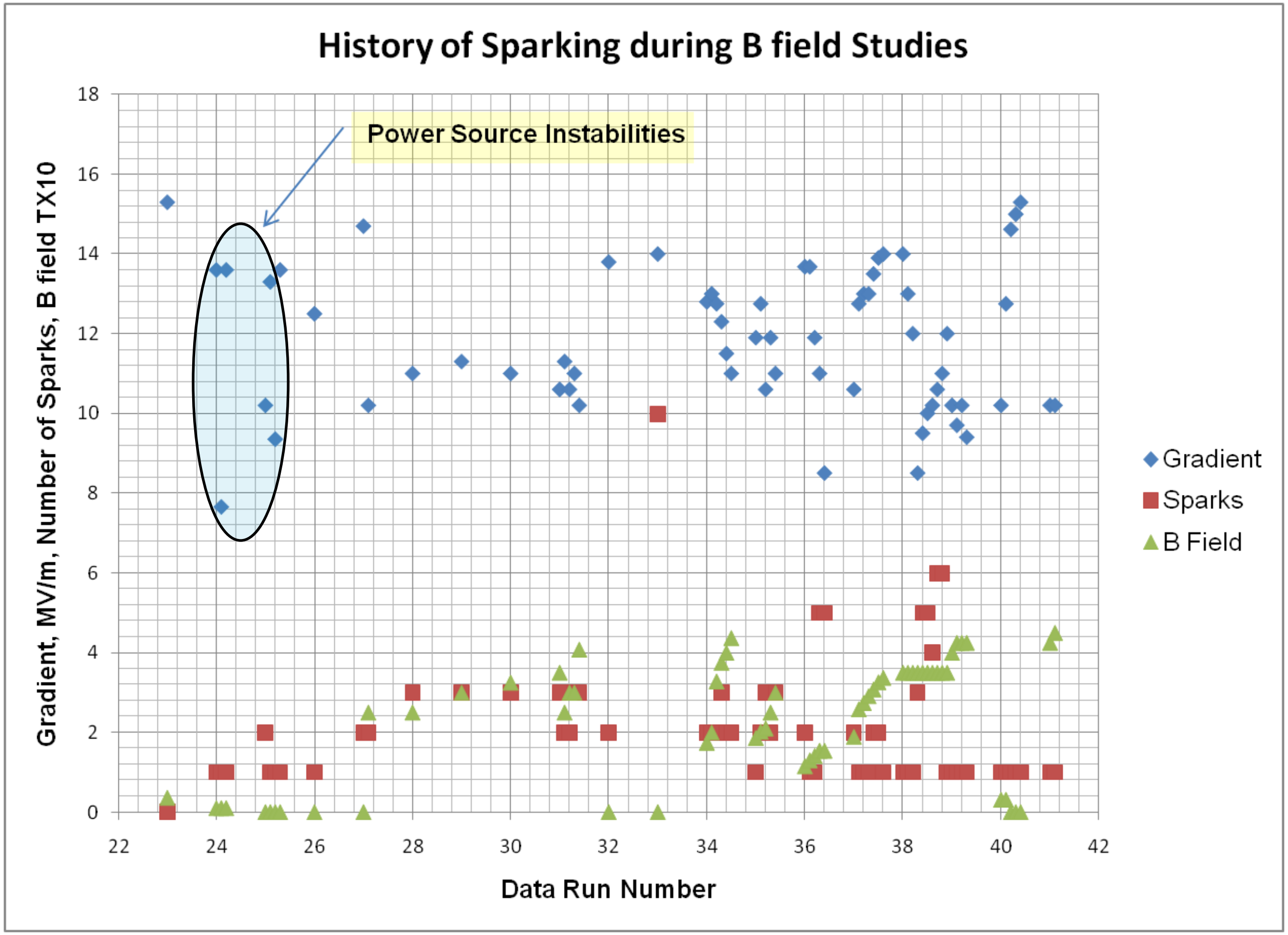
201 MHz Cavity Running

Summary I (B=0)

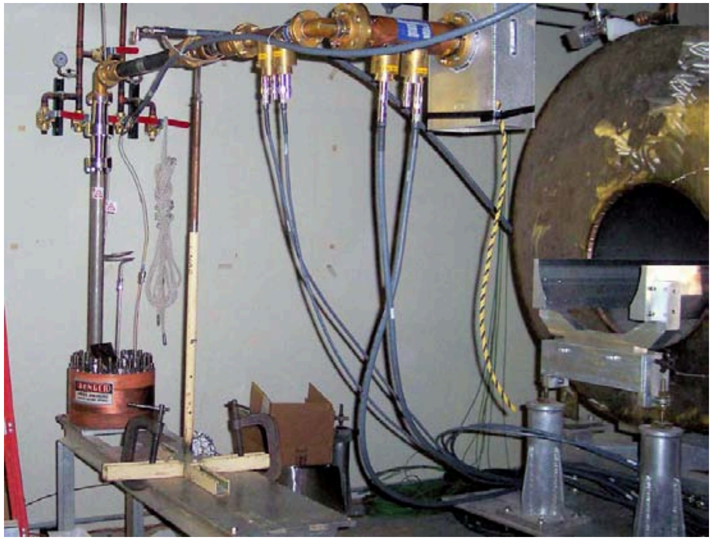


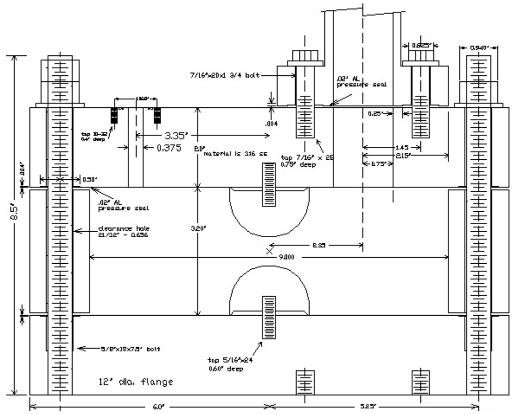


201 MHz Cavity Running
Summary II (B> 0)

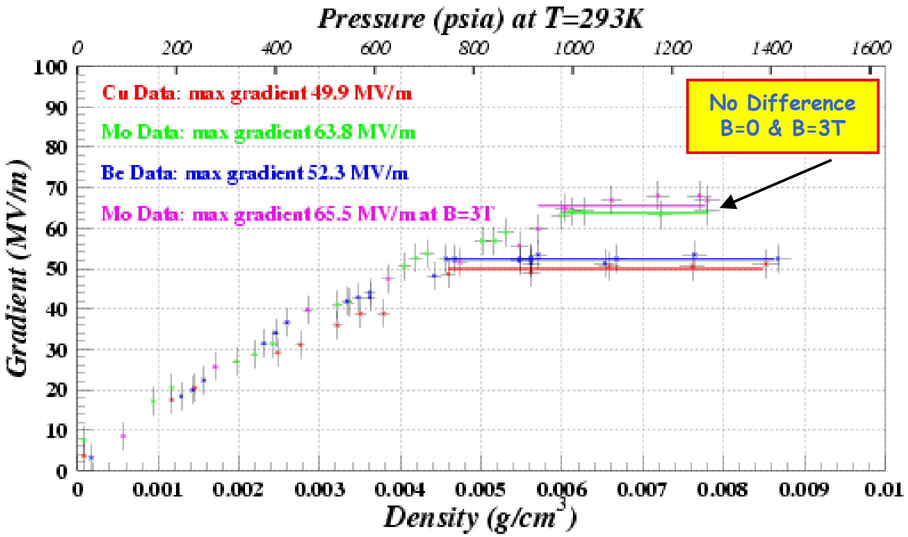


High Pressure H_2 Filled Cavity Work *with Muons Inc.*





- High Pressure Test Cell
- Study breakdown properties of materials in H_2 gas
- Operation in B field
  - No degradation in M.S.O.G. up to ≈ 3.5T
- **Next Test – Repeat with beam**



Facing the RF B Field Challenge

- Promising indications @ a Solution
  - SCRF Processing techniques help
    - Reduce dark current
  - Cavity material properties seem to be important
    - TiN helps
      - Coupled with SCRF processing may reduce FE even more
    - Mo, Be Coatings?
  - Gas-filled cavities show promise
    - Operation with beam **critical** next test
- Concepts for magnetic insulation need to be tested as soon as possible

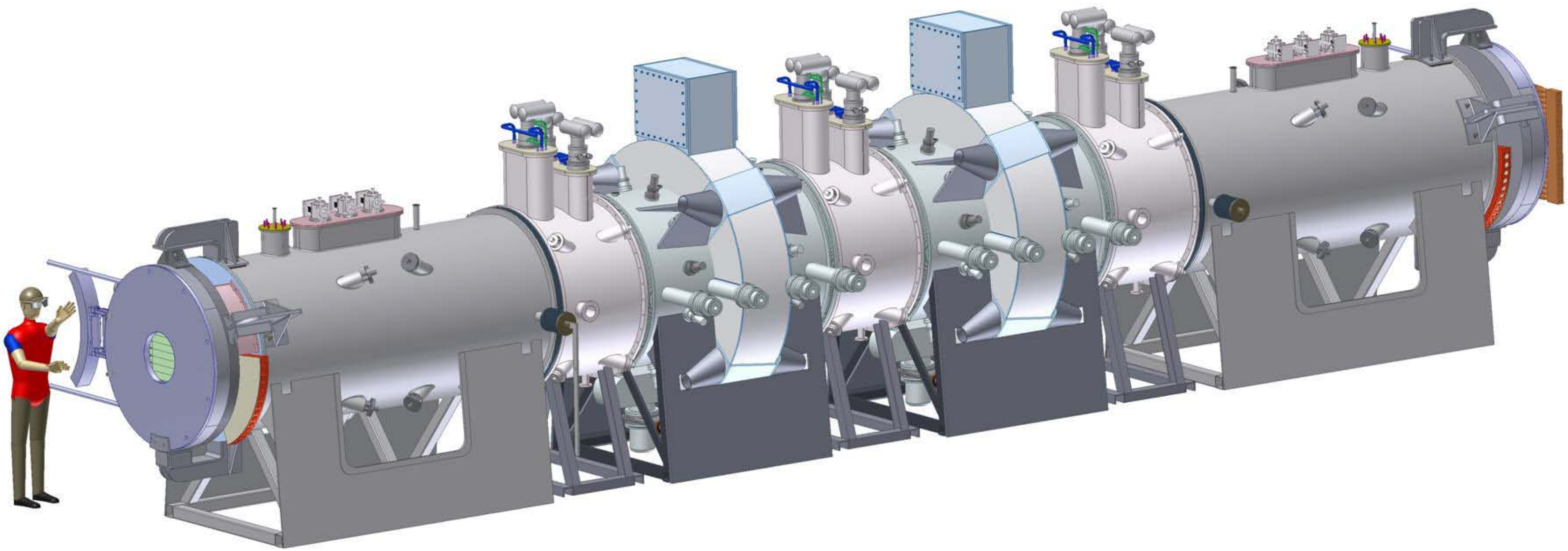
MTA Beam Status/Commissioning

F. Garcia, C. Moore, C. Johnstone, I. Rakhno

- Beam Line Installation
  - Complete
- Beam Line commissioning to first beam stop has started
  - Beam has been successfully transported to BS1
- Still doing radiation shielding assessments
- Will start at low intensity
  - Need Shielding upgrade (over-burden) for high-intensity
    - Full pulse intensity, limited #pulses/min

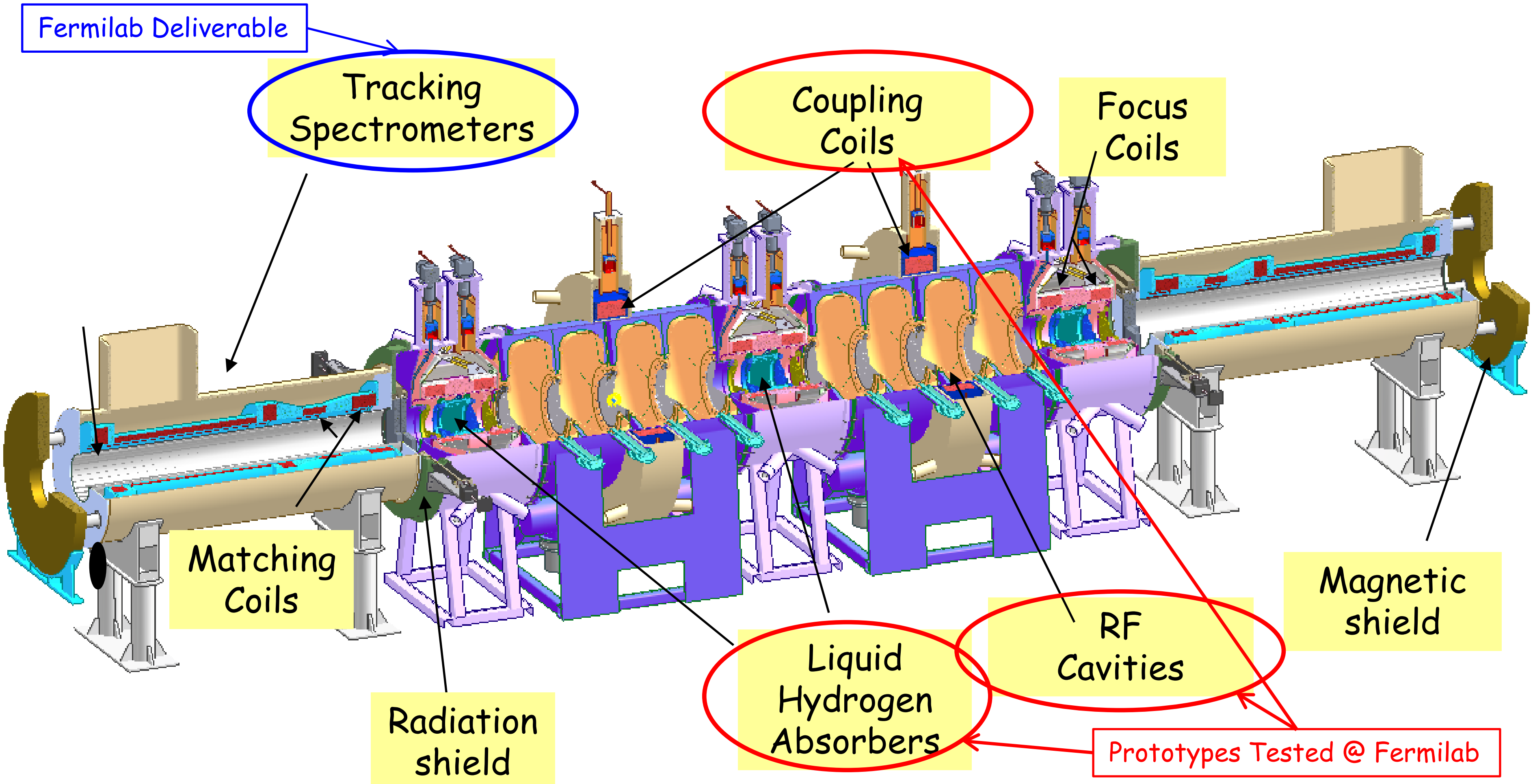
MTA is a Unique Facility in the World
High-Power RF; High-Intensity Beam; LH_2 handling

Muon Ionization Cooling Experiment (MICE)



Muon Ionization Cooling Experiment

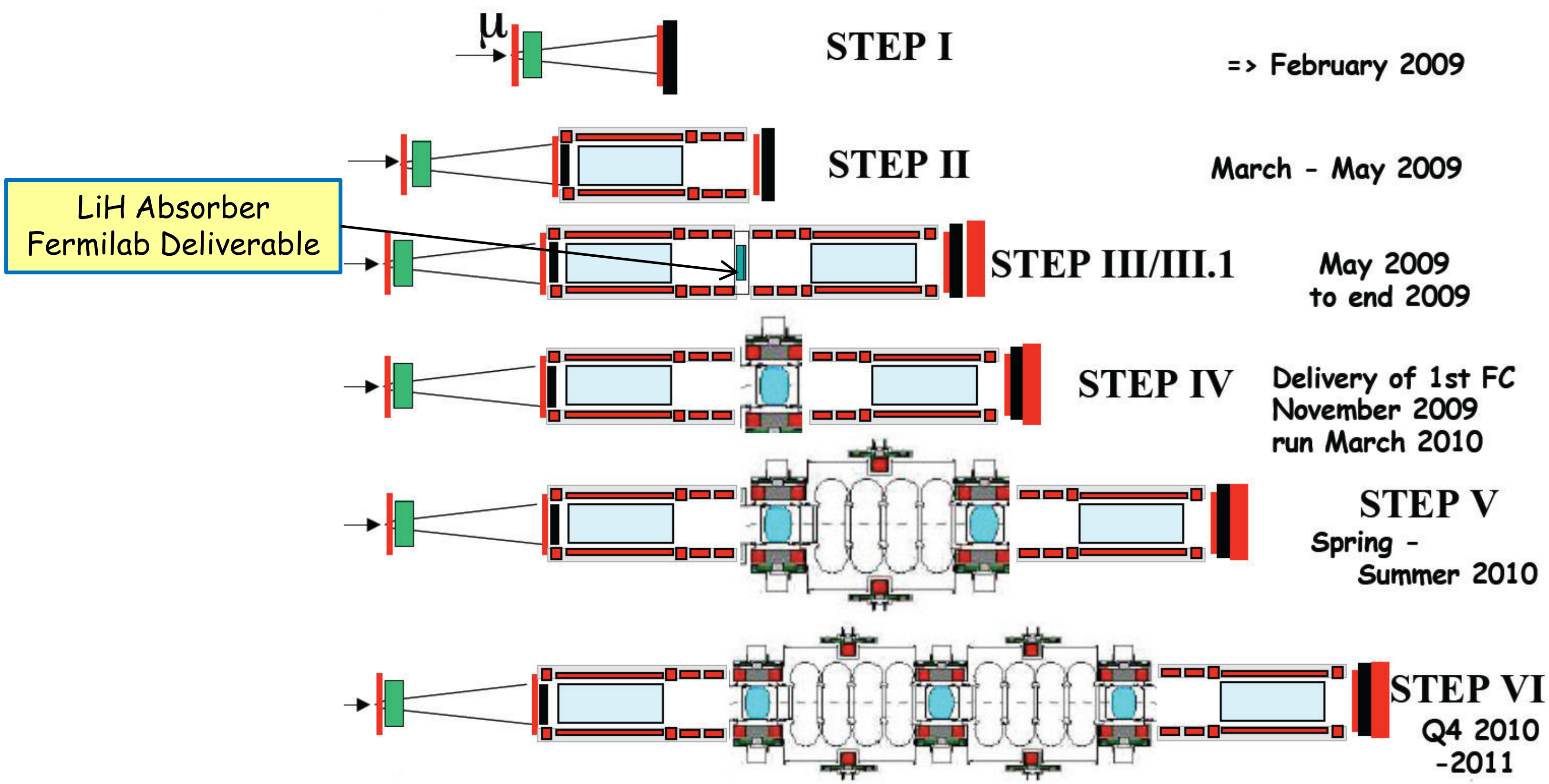
A. Bross, R. Flores, CM. Lei, M. Popovic, R. Rucinski, P. Rubinov,
G. Sellberg, Y. Torun, M. Utes



Muon Ionization Cooling Experiment (MICE)

Measurement of Muon Cooling - Emittance Measurement @ 10^{-3}

Best estimate of MICE Schedule as of October 2008



Progress on MICE

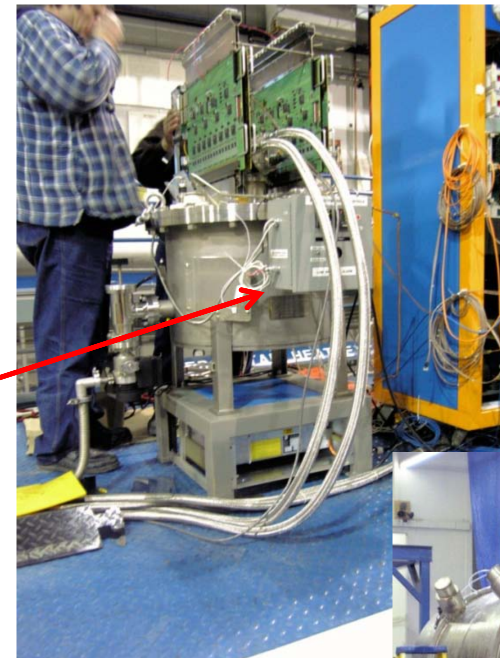
- Beam Line Complete
  - First Beam March 30th!
    - Registered in Fermilab Beam Profile Monitors
- First Spectrometer Winter/Spring 09
  - Fiber Tracker – Fermilab Deliverable

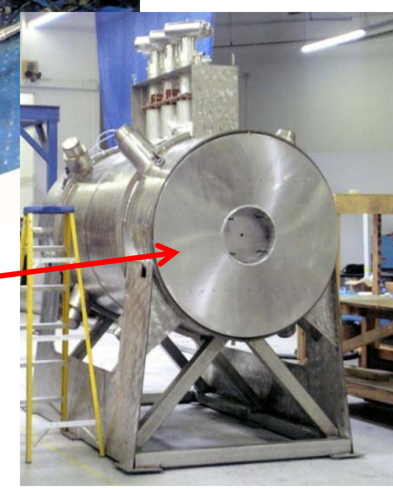
Fiber Tracker

Beam Profile Monitor

Fermilab Responsibilities in MICE

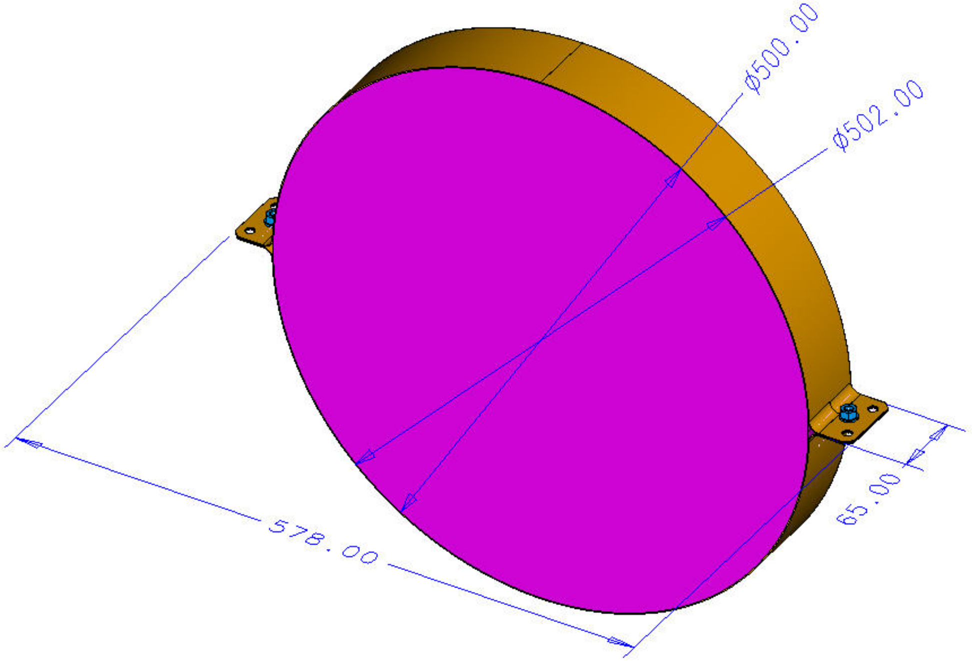
- Beam Line
  - Beam Line monitors
    - Scintillating fiber detectors
      - Beam Profile Monitors
- Spectrometers
  - Fiber ribbons for Fiber Tracker
  - Fiber Readout
    - Photo detector (VLPC) and cryogenics
      - New closed-cycle cryogenics system
        - 9K operation
    - Analog Front-end Board
  - Field mapping of Spectrometer magnets
    - Using upgraded ZipTrack System





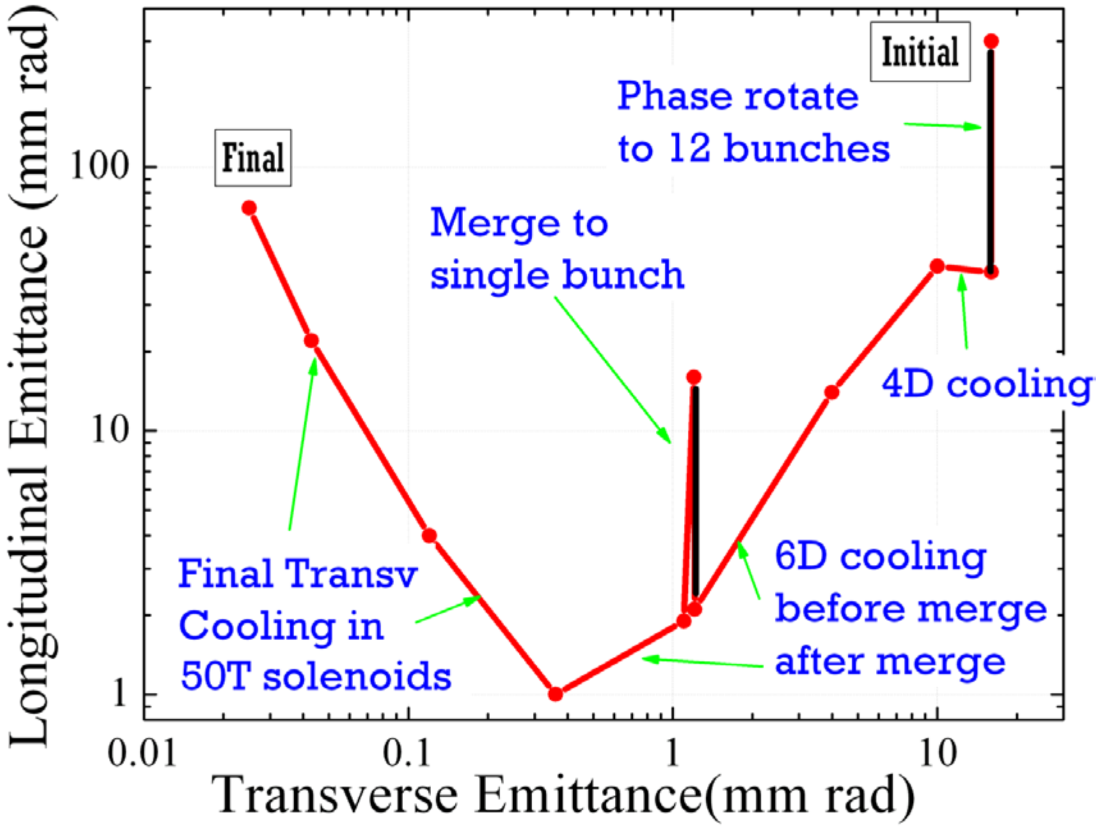
Fermilab Responsibilities in MICE II

- Absorbers
  - Supported testing of prototype (KEK design) LH_2 @MTA
  - Provide LiH disks for step III.1
    - Procure through Y12
    - Perform thermal tests at Fermilab



LiH Absorber Disk with Carbon-fiber support bracket

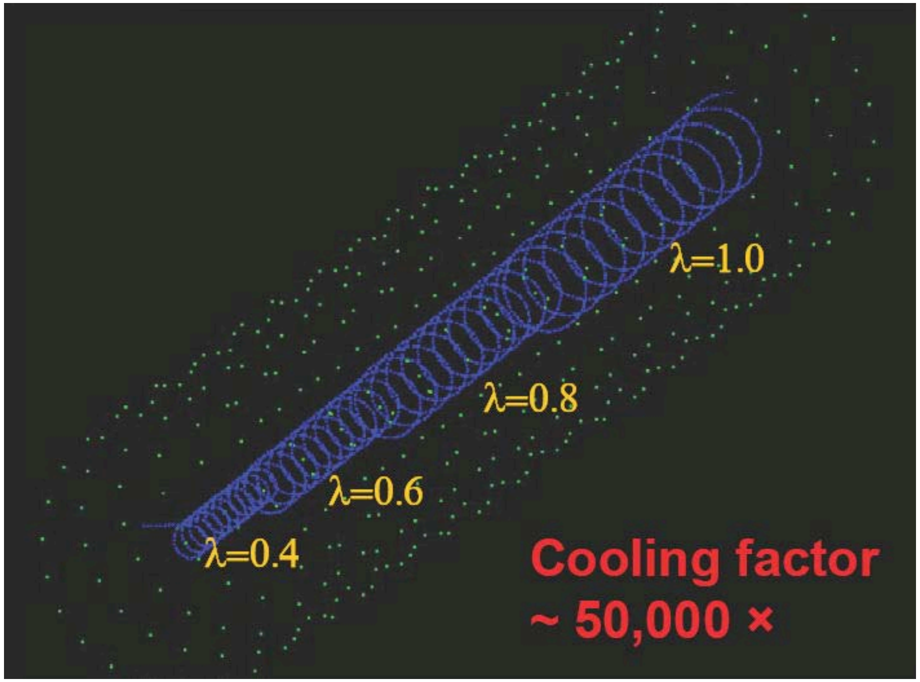
Helical Cooling, Final Cooling and Magnetic R&D

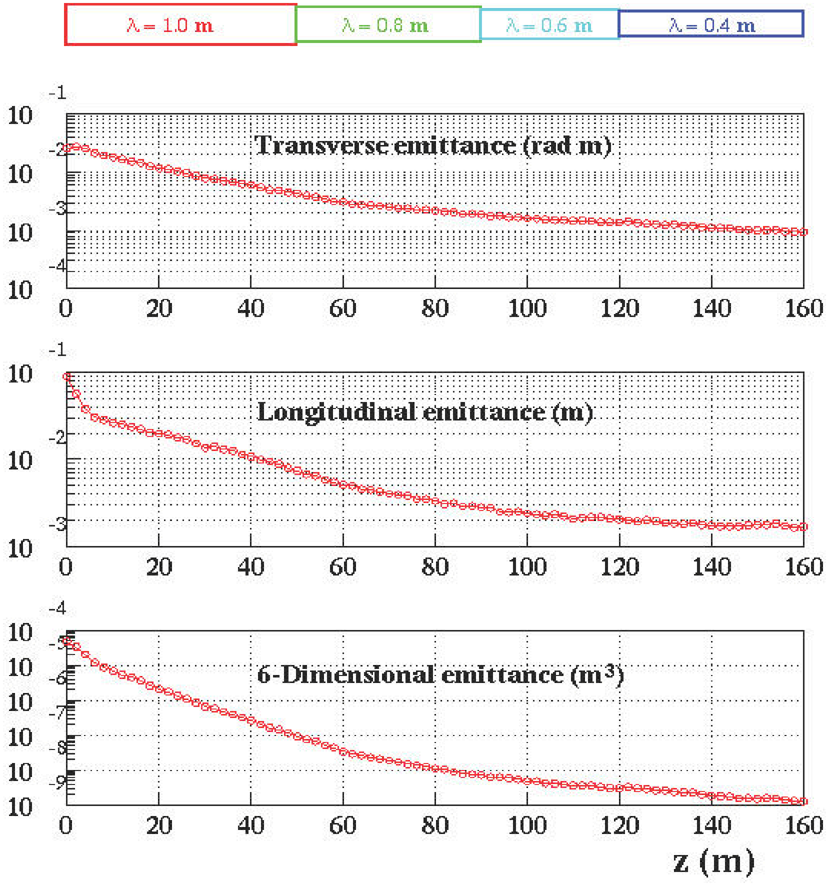


Helical Cooling Channel

V. Balbekov, A. Jansson, K. Yonehara (*with Muons Inc*)

- Magnetic field is solenoid B0+ dipole + quad
- System is filled with H2 gas, includes rf cavities
- Cools 6-D (large E means longer path length)
- **But, incorporating RF is Engineering challenge!**

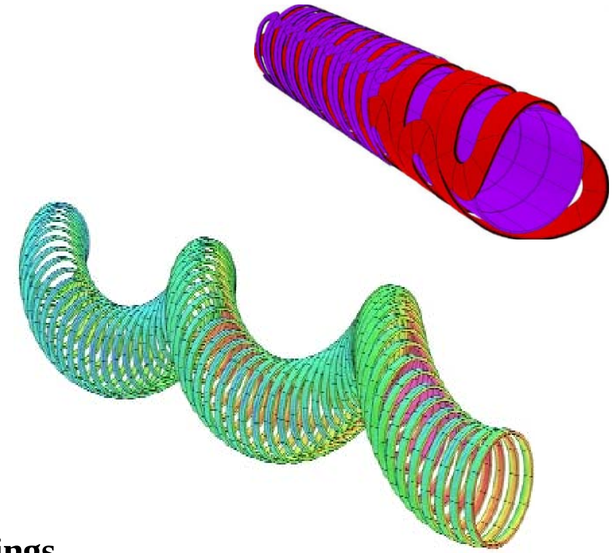


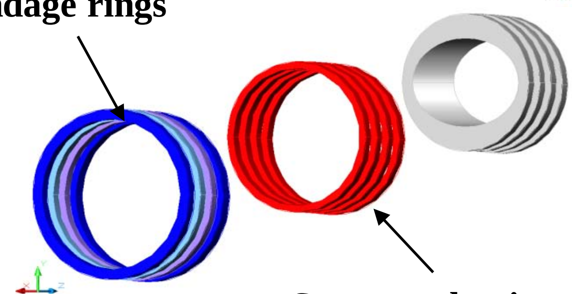


HCC Magnet Design & Prototyping

V. Kashikhin , M. Lamm, A. Makarov

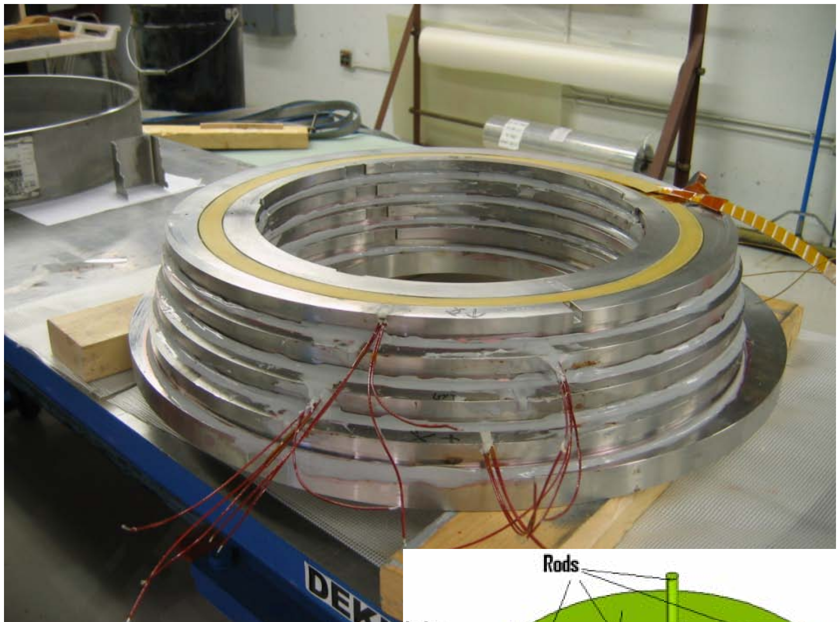
- Helical solenoid (HS): Smaller coils than in a "snake" design
  - Smaller peak field
  - Lower cost
- Field components in HS determined by geometry
  - Over constrained
  - Coil radius is not free parameter
- 4 Coil Demonstration Model
  - Validate mechanical structure and fabrication methods
  - Study quench performance and margins, field quality, quench protection
  - Use SSC conductor

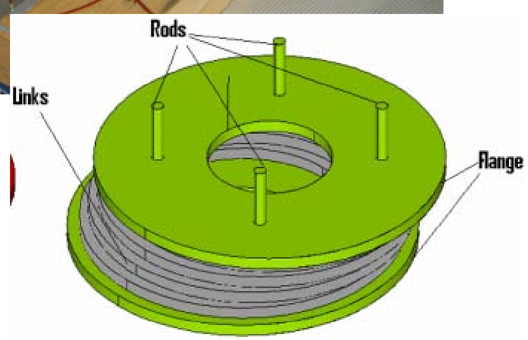




4-coil fabrication status

Photo of magnet during construction





Fabrication Complete !

Instrumentation:

- Voltage taps, strain gauges, quench protection heaters

Model test:

- Room temp. magnet measurements
- Cold test: November 2008 (in progress)

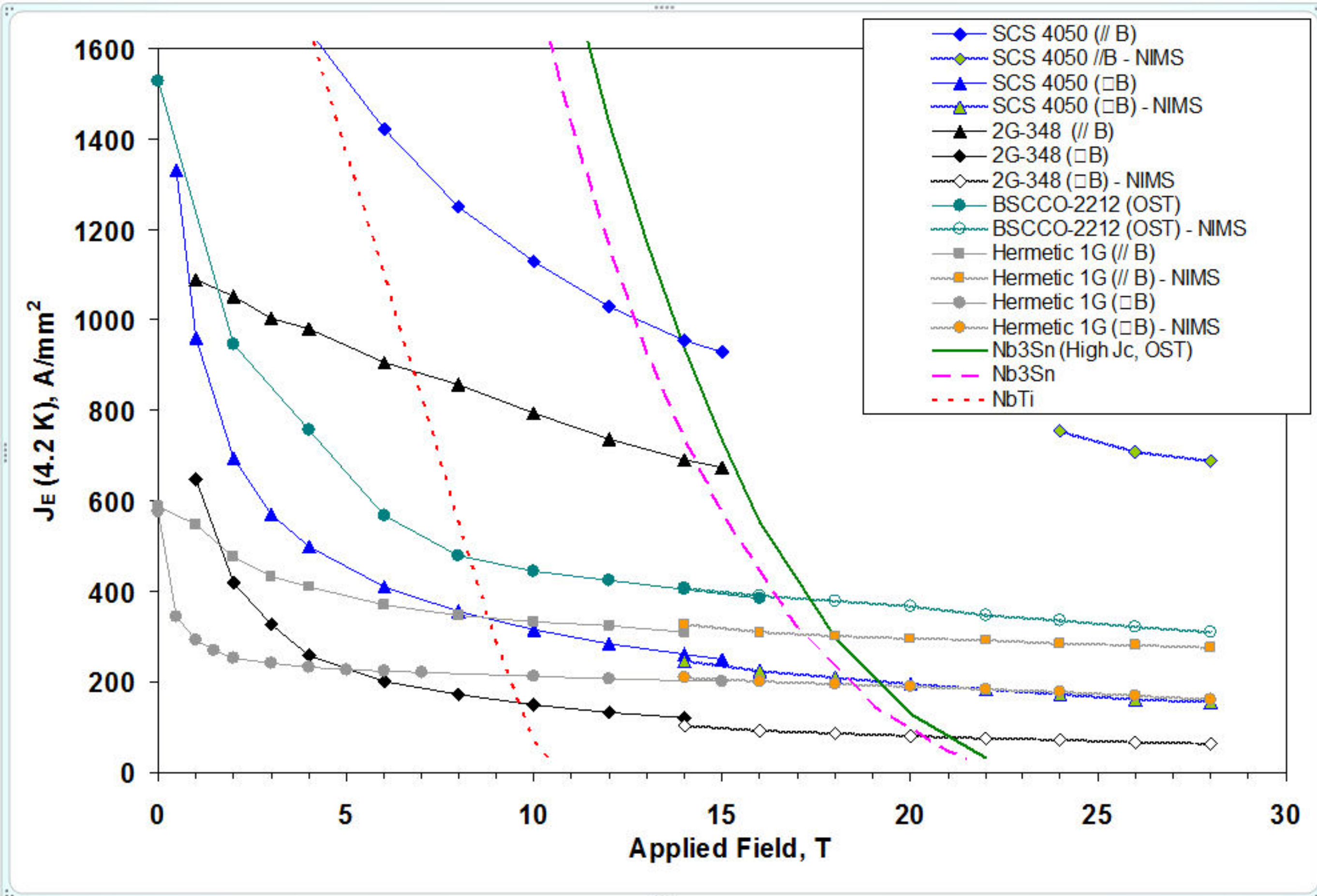
MCTF Conductor Program

Extreme-High-Field Magnets

E. Barzi, M. Lamm, A. Tollestrup

- Several schemes for the final stage(s) of muon cooling for the MC require 30-50T solenoids ⇒ High Temperature Superconductor R&D
- Fermilab is leading the effort to form a National HTS R&D Program
  - Address very-high magnet R&D in general
- Emphasis on HTS strands, tapes and cables
  - Nb3Sn and Nb3Al strand and cable R&D is supported by other programs (DOE, LARP, NIMS/FNAL/KEK, CARE, etc.)
- Fermilab R&D infrastructure
  - Two Oxford Instrument Teslatron stations with 16T and 17T solenoids, and test temperatures from 1.9K to 70K
  - 42-strand cabling machine
  - Probes to measure
    - I_c of HTS strands and tapes as a function of field, temperature, and field orientation
    - Transverse pressure sensitivity of strand I_c in a cable
  - 28 kA SC transformer to test cables at self-field in LHe

HTS Conductor tests for High Field Magnets



- Detailed measurement of I_c angular dependence for HTS tapes at fields up to 15-16 T at FNAL
- High field tests, up to 28T performed at NIMS, Japan
- Input data for High Field HTS Solenoid design studies

Simulation Effort

Simulation Effort - Overview

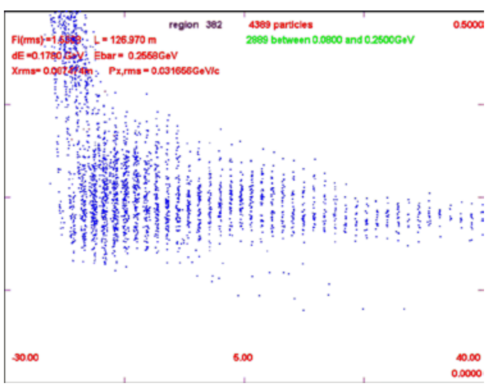
Y. Alexahin, V. Balbekov, E. Gianfelice-Wendt, A. Jansson, C. Johnstone
N. Mokhov, D. Neuffer, S. Striganov, K. Yonehara

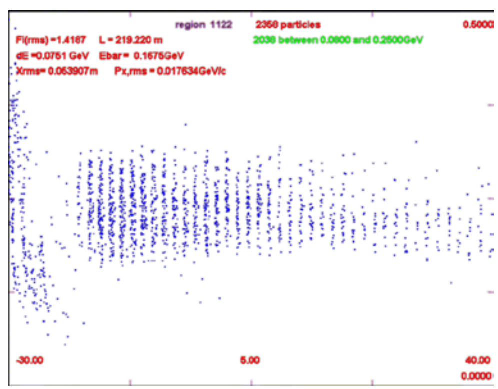
- Proton Driver
  - Extensions to Project X
- Particle production/flux simulations and compare to data (MERIT Experiment)
  - APC – Energy Deposition Group
- Muon Front-End
  - Capture, decay, phase rotation
- Muon Cooling Channels
  - FOFO (MICE)
  - FOFO Snake
  - Helical
- Acceleration
  - FFAG
    - Design/Simulation + participation in the Electron Model Muon Accelerator (EMMA)
- Muon Collider Storage Ring
  - Optimization of ring and IP optics
- Started MC Physics and Detector Study Group
  - E. Eichten & C. Hill (Theory)
  - M. Demarteau (Detector)

Front-End Simulation

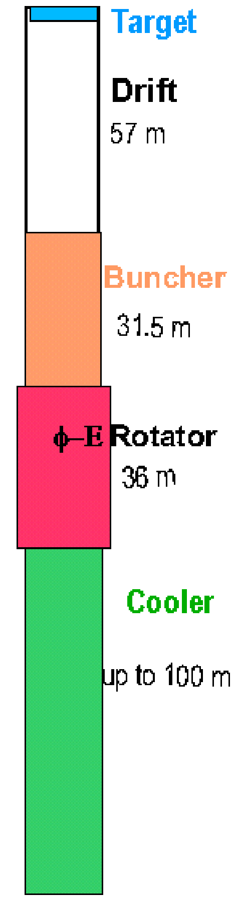
D. Neuffer

- Reduce drift, buncher, rotator to get shorter bunch train:
  - 217m ⇒ **125m**
  - **57m drift, 31.5m buncher, 36m rotator**
  - **Rf voltages up to 15MV/m (×2/3)**
- **Obtains ~0.26 μ/p in ref. acceptance**
  - **Slightly better ?**
    - **~0.24 μ/p for Study 2b baseline**
- **80+ m bunchtrain reduced to < 50m**
  - **Δn: 18 -> 10**





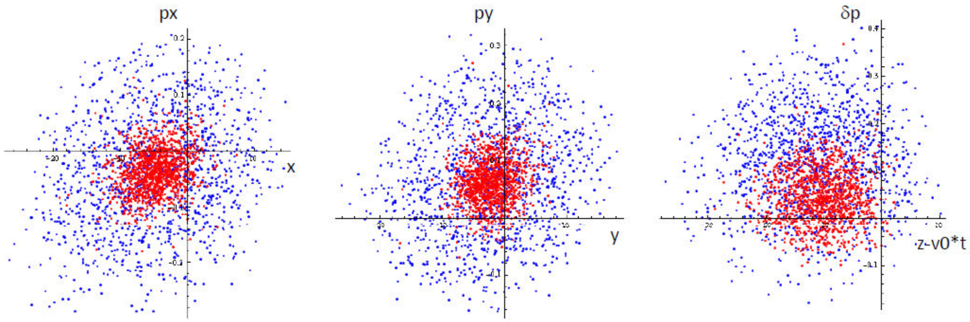
500MeV/c

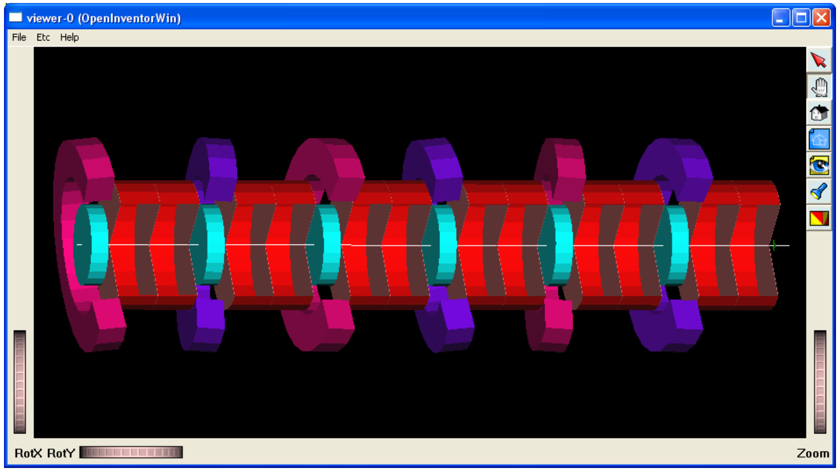


Helical 200MHz FOFO snake (vacuum RF)

Y. Alexahin

- Like FOFO Cooling channel, but with solenoids tilted or displaced
  - 6D
- Cools μ^+ and μ^-



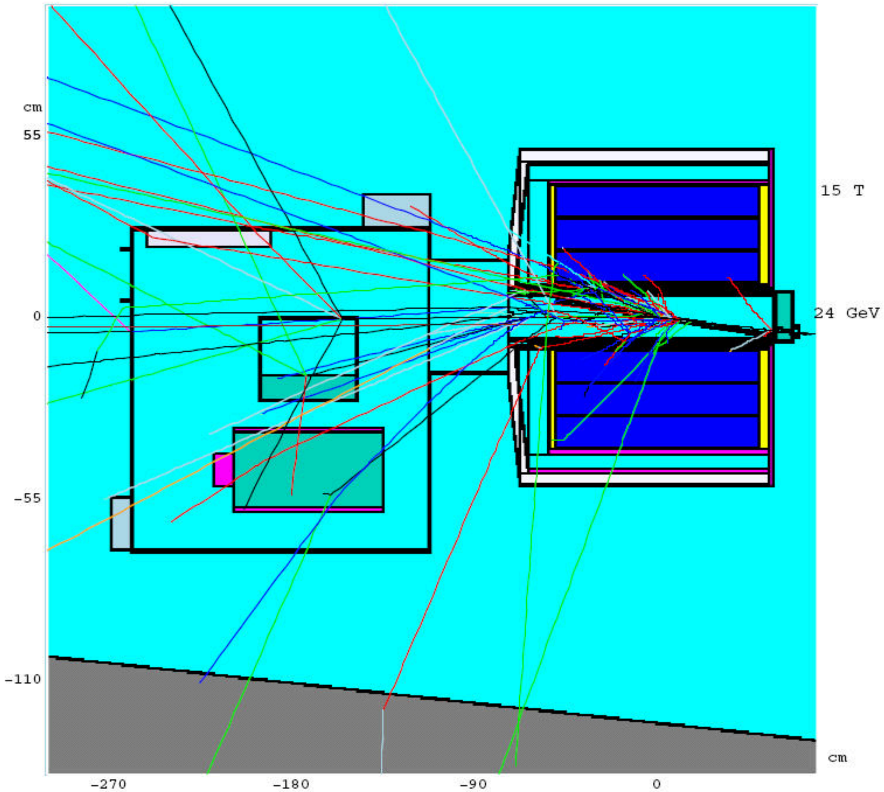


Emittances (cm)	Initial	Final
6D	7.66	0.04
Transverse (av)	1.81	0.25
Longitudinal	3.47	1.36

Fermilab Contribution to MERIT

N. Mokhov, S. Striganov

- Developed Full Mars Simulation
  - Particle fluxes, energy deposition, absorbed dose and residual activity in the experimental hall
  - Absorbed dose and activation of mercury system
  - Secondary particle production
- Study/define diagnostics needed for experiment
  - Radiation load in components
  - Radiation shielding
  - Particle production in secondary beam
- Now comparing particle production rates in data to simulations/predictions



MERIT Has Now Delivered Proof of Principle for 4MW Targetry

Concluding Remarks

R&D Milestones

- Significant progress in a number of key components of the Fermilab Muon Acceleration Program
  - MuCool - 21MV/m @ 201MHz (Design: 16MV/m)
  - MICE – Have completed and delivered most of our hardware responsibilities
    - First Beam
  - Much progress on the design and simulation for a Helical Cooling channel
    - Excellent progress on Helical Magnet Prototype
  - Beginnings of a National program (&collaboration) on High Temperature Superconductor and its application in extreme-high-field magnets
    - Extensive testing on currently available commercial conductor/cable
  - On track for the first beam experiment in the MTA in early 2009
  - Strong participation in the International Scoping Study for a NF
    - IDS-NF has been launched – *Deliver NF RDR in 2012*
  - Developed a plan on how to deliver a design feasibility study (DFS) for a Muon Collider by around 2012 (MCTF)

End Note

Over the last 5 years the μ acceleration Program at Fermilab has:

- Made noteworthy advances in a number of key technical areas
  - High-Gradient NCRF
  - 6D μ cooling channel design, simulation and component prototyping
  - High field magnet design
  - Muon Ionization Cooling Experiment
  - Muon Collider lattice and IP design
- This work has helped put the NF on a solid technical foundation & significantly improved the prospects for the MC
- Provides a unique facility to carry out R&D
  - MuCool Test Area
- Has given the HEP community a better understanding of the physics potential for the NF and for the MC
  - And provided a deeper understanding of the technical promise (and risks) of these facilities