Muon Accelerator Program

Michael S. Zisman
Center for Beam Physics
Accelerator & Fusion Research Division
Lawrence Berkeley National Laboratory

Muon Collider Meeting—Telluride
June 27, 2011

Introduction (1)

- Muon-based collider would be a powerful tool in the experimentalist's arsenal

- Design and performance evaluations for such a facility have been ongoing for more than 10 years
  - until recently, two entities involved in coordinated program
    - Neutrino Factory and Muon Collider Collaboration (NFMCC)
    - Muon Collider Task Force (MCTF)
  - coordination done by leadership of the two organizations

- Recent interest by Fermilab management has spurred increased effort to understand Muon Collider design
  - DOE has likewise started to consider this option more seriously

Introduction (2)

- At urging of DOE, Fermilab has set up joint organization based on NFMCC and MCTF
  - both organizations brought under common leadership
  - Program Director will report to Fermilab Director
- New organization named Muon Accelerator Program (MAP)
- *Interim* co-directors were designated by Fermilab
  - Geer and Zisman
- Charged with preparing proposal for submission to DOE and organizing its subsequent review
  - review held at Fermilab August 24-26, 2010
    - see http://indico.fnal.gov/conferenceDisplay.py?confId=3474
      - contains links to talks, supporting documents, and close-out slides
  - reviewers judged that program was worth funding

Introduction (3)

- Goal of MAP is to execute multi-year R&D program to
  - complete Design Feasibility Report for MC
  - participate in IDS-NF effort toward NF RDR
  - carry out supporting technology R&D
  - participate in system tests of 4D and 6D cooling
    - MICE and 6D "bench test" (no beam)
- Written Program Management Plan signed off by DOE in March 2011
  - MAP is now an "official" national R&D program

Formal Approval (March 2011)

Department of Energy
Office of Science
Washington, DC 20585

MAR 15 2011

Dr. Pier Oddone
Director
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510-0500

Dear Dr. Oddone:

Attached please find a signed copy of the Muon Accelerator Program Management Plan that has been submitted to the Office of High Energy Physics for approval. With this letter, I am formally approving the MAP program and its organization structure. As you know, starting in Fiscal Year 2011, OHEP has activated a separate B&R code (KA-15-02-03) for research conducted under this program.

I am looking forward to hearing new and exciting research results from this important program.

Sincerely,

Michael Procario
Acting Associate Director of Science
for High Energy Physics

Attachment

cc: Stuart Henderson, Associate Director for Accelerator, Fermilab
Steve Geer, Co-Director for MAP, Fermilab
Michael Zisman, Co-Director for MAP, LBNL

Mission Statement

- **Mission statement approved by Fermilab Director**

"The mission of the Muon Accelerator Program (MAP) is to develop and demonstrate the concepts and critical technologies required to produce, capture, condition, accelerate, and store intense beams of muons for Muon Colliders and Neutrino Factories. The goal of MAP is to deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider and/or a next-generation neutrino beam facility. Coordination with the parallel Muon Collider Physics and Detector Study and with the International Design Study of a Neutrino Factory will ensure MAP responsiveness to physics requirements."

MAP Organization

- Straightforward organizational structure requested by DOE
  - project-like
    - Program Director makes final decisions
      - subject to oversight of Fermilab Director
    - simplified oversight structure
      - MCOG (an NFMCC entity) was eliminated
        - MuTAC reports directly to Fermilab Director

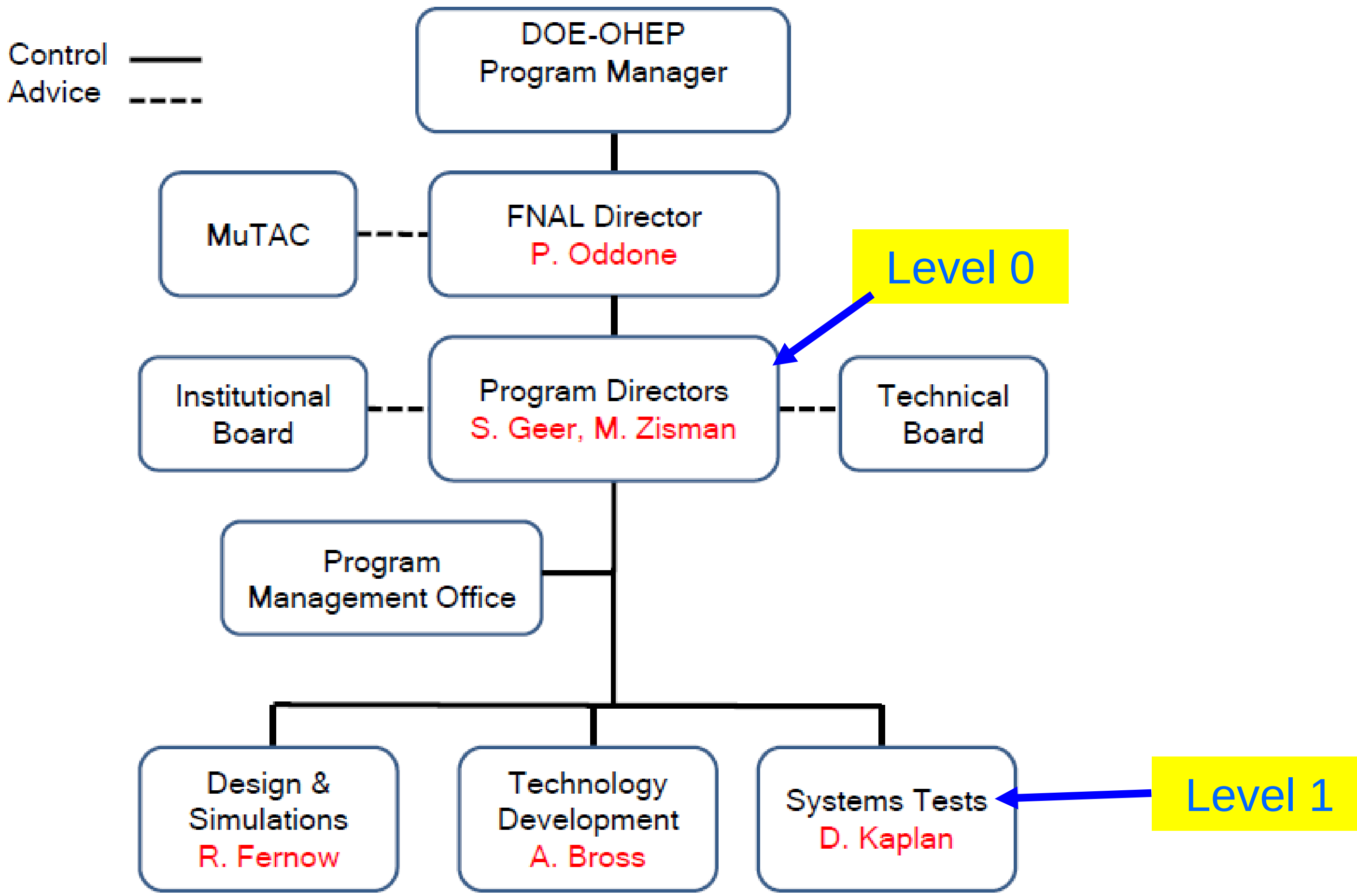
- MAP organization set up and populated
  - funded and operated as "MAP" in FY11

Organizing Principles

- **Create organization that delivers**
  - a coherent, national R&D program
  - a multi-institutional program (Labs, Universities)
  - a streamlined structure with clear reporting lines
- **Key principles**
  - Fermilab provides overall management
  - cooperative effort integrating NFMCC and MCTF
  - maintains existing NFMCC international commitments
  - led by Program Director who controls funding
  - adequate oversight (MuTAC, PMG, DOE)
    - MAP Program Manager at DOE will be designated

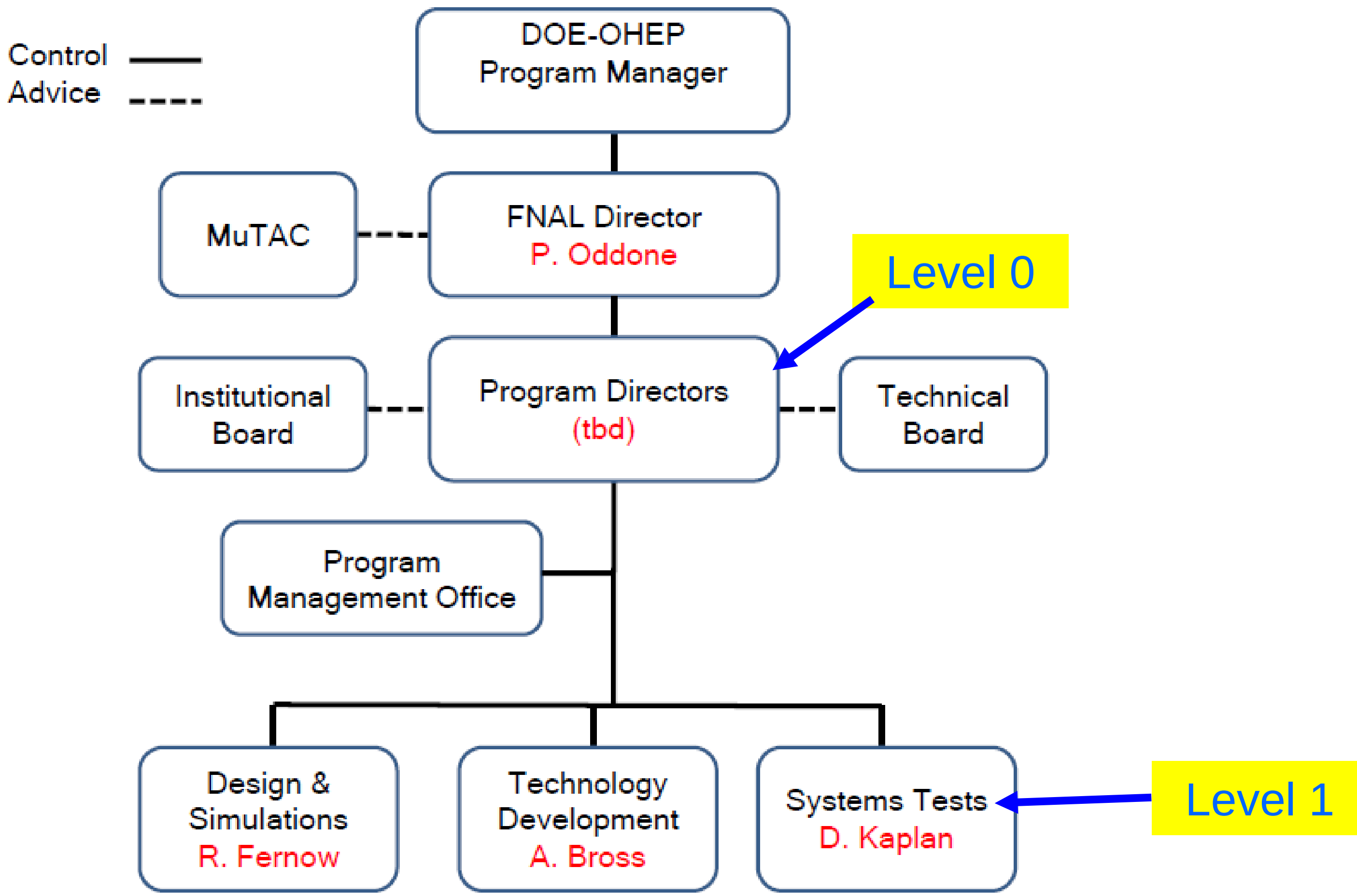
MAP Upper Level Organization

- Organization in place and functioning since review
  - Level 0 names are interim appointments



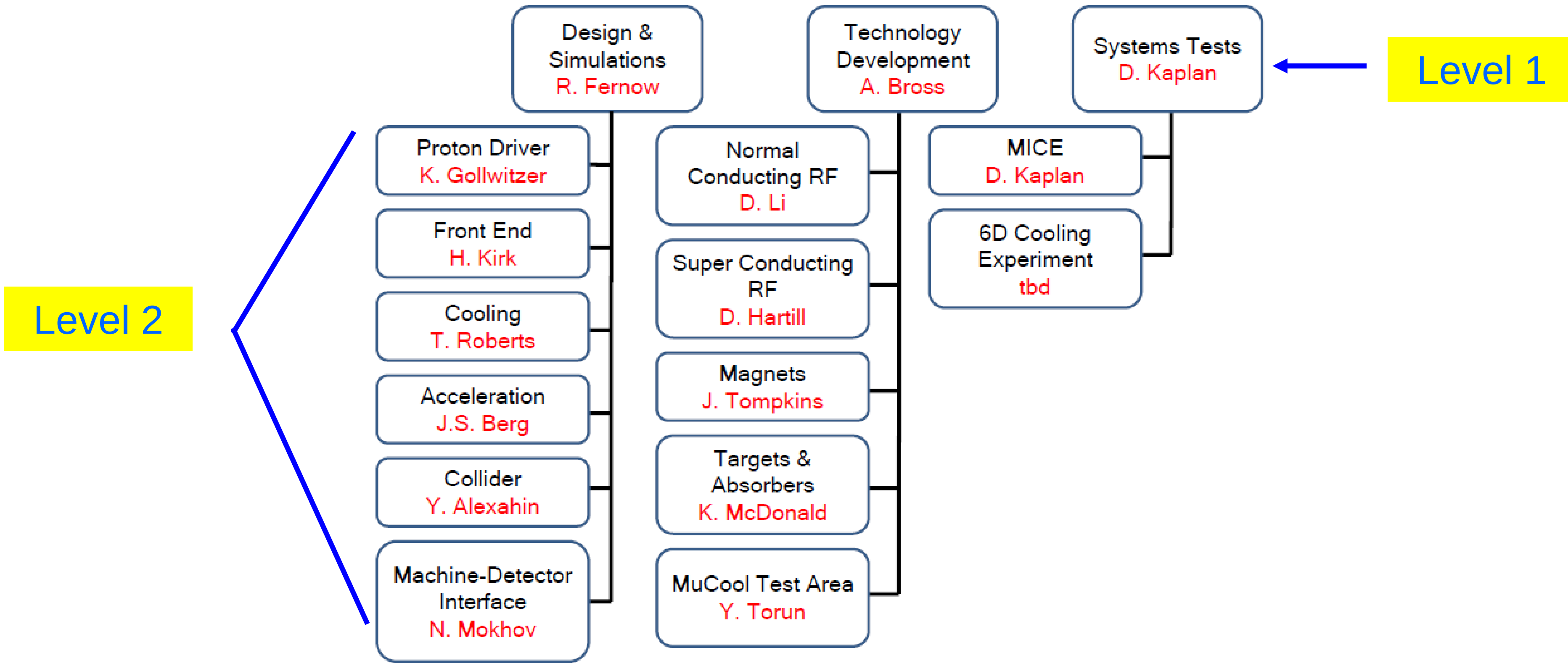
Upper Level Organization-Today

- "Permanent" Director being searched for now



MAP Level 2 Organization

- **Level 2 organization in place and functioning**
  - L2 leaders chosen by L1 leaders
    - approved by Program Co-Directors



Main Deliverables

- **Defined main "deliverables"**
  - **both for nominal and augmented scenarios**
    - **present funding reality below the "nominal" guidance**

MAP deliverables.

Deliverable	Nominal schedule	Augmented schedule
MC DFS		
Interim	FY14	——
Final + cost range	FY16	FY15
MICE hardware completion	FY13	
RF studies (down-select)	FY12	
IDS-NF RDR	FY14	
6D cooling definition	FY12	
6D cooling section component bench test	FY16	FY15
6D demonstration proposal	FY16	FY15

MAP Budget Request

- **Based on guidance, built nominal plan for ~\$15M per year**
  - **also proposed "augmented" plan at peak of ~\$19M**
    - **would permit completion of tasks one year earlier**

- **Requested profiles in FY10 \$M are:**

	Y1	Y2	Y3	Y4	Y5	Y6	Y7
Nominal	10.3	15.4	15.5	15.5	15.5	15.5	14.9
Augmented	10.3	15.4	17.9	19.2	19.5	19.4	—

NOTE: As for FY11 (=Y2), present guidance is that FY12 (=Y3) will again be ~\$10M, not \$15M

Will need to re-baseline plan for lower budget scenario

Oversight (1)

- **Oversight comes from**
  - Fermilab Director
  - DOE Program Manager
  - Program Management Group (PMG)

- **Muon Collider Technical Advisory Committee (MuTAC)**
  - international review group (reports to Fermilab Director)
    - currently chaired by D. Rubin (Cornell)
    - meets ~annually to assess program

- **DOE annual reviews**
  - set up annually by DOE Program Manager
    - original MAP review was first of these

Oversight (2)

- **Program Management Group**
  - comprises resource managers from primary MAP institutions, chaired by S. Henderson
    - resolves resource issues as they arise
      - resource-loaded schedule and WBS are primary tools to assess ongoing needs and impact of program changes
    - fosters inter-institutional communication
  - monitors progress of program monthly
    - definition of goals and strategic approach (evolutionary)
    - progress against plan (technical and resource utilization)
      - resource and schedule implications of configuration change actions
    - major procurements (ensure timely execution)
    - cost accounting

Down-Selection Process (1)

- **Choosing among technical alternatives not easy**
  - **MAP approach: specify "initial design configuration"**
    - **recognize that ideas will change**
      - **provide formal mechanism for this to happen**
  - **in a few cases, initial design configuration not yet specified**
    - **e.g., RF technology or 6D cooling**
  - **we have specified *procedure* to make decision on initial design configuration (or change it later)**
    - **responsibility for down-selection rests with MAP Director**
      - **aided by Level 1 leaders**

Down-Selection Process (2)

- **Procedural steps**
  - in consultation with Mgmt Council, Level 1 leader defines set of technical criteria to judge against
  - after MAP Director's approval, criteria made available to proponents and all MAP members
  - MAP Director will appoint review group to evaluate alternatives and make recommendation
  - MAP Director makes final decision on choice
  - decision communicated formally to PMG
    - PMG can request external review, e.g. MuTAC, if desired

Muon Accelerator Advantages

- **Muon-beam accelerators can address several of the outstanding accelerator-related particle physics questions**
  - **energy frontier**
    - point particle makes full beam energy available for particle production
      - couples strongly to Higgs sector
    - Muon Collider has almost no synchrotron radiation or beamstrahlung
      - narrow energy spread at IP compared with e^+e^- collider
      - uses expensive RF equipment efficiently ($\Rightarrow$ fits on existing Lab sites)
  - **neutrino sector**
    - Neutrino Factory beam properties

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

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

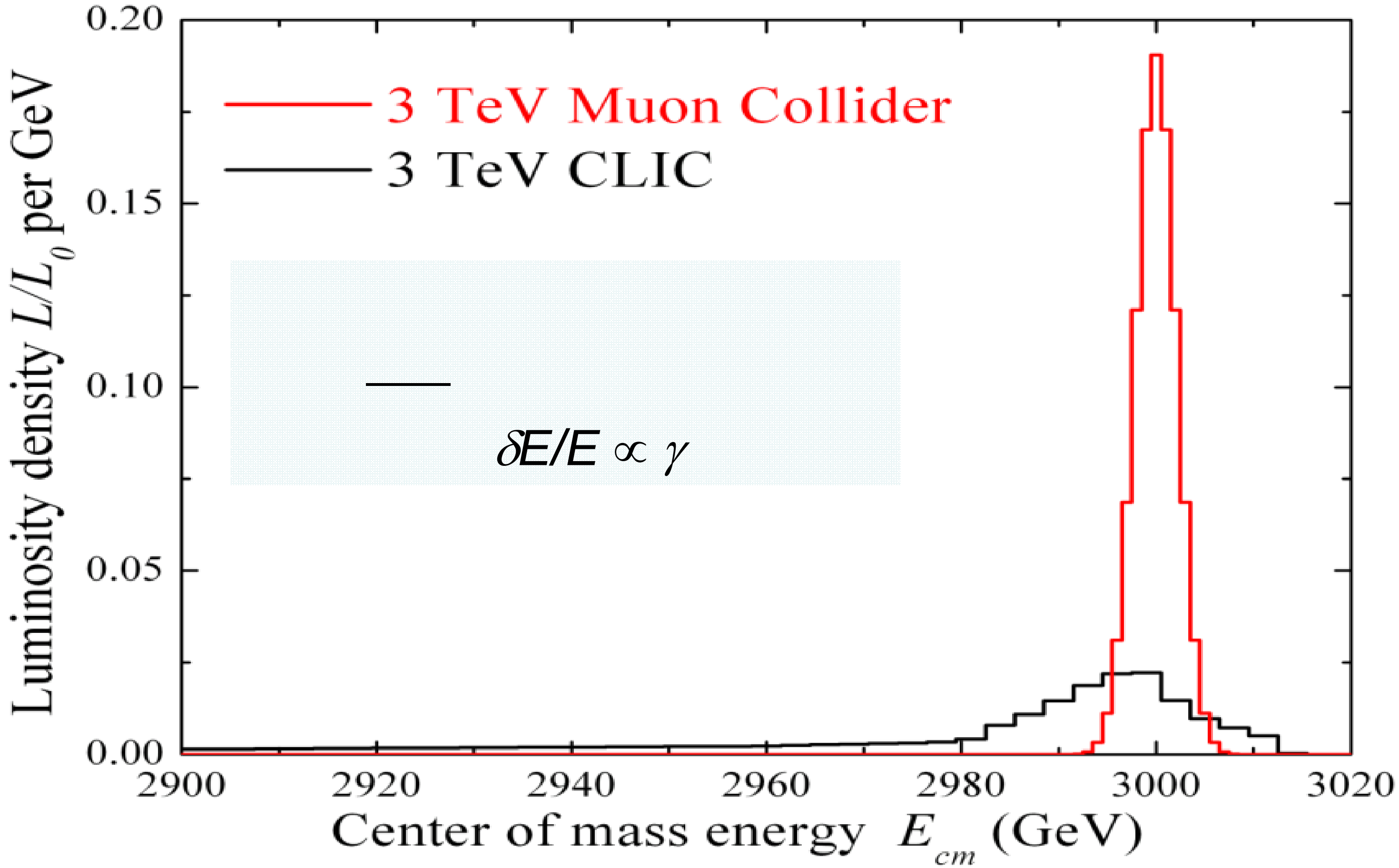
Produces high energy ν_e, above τ threshold

    - decay kinematics well known
      - minimal hadronic uncertainties in the spectrum and flux
    - $\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable "wrong-sign" μ (low background)

Unmatched sensitivity for CP violation, mass hierarchy, and unitarity

Collider Energy Spread

- **High muon mass greatly reduces beamstrahlung**



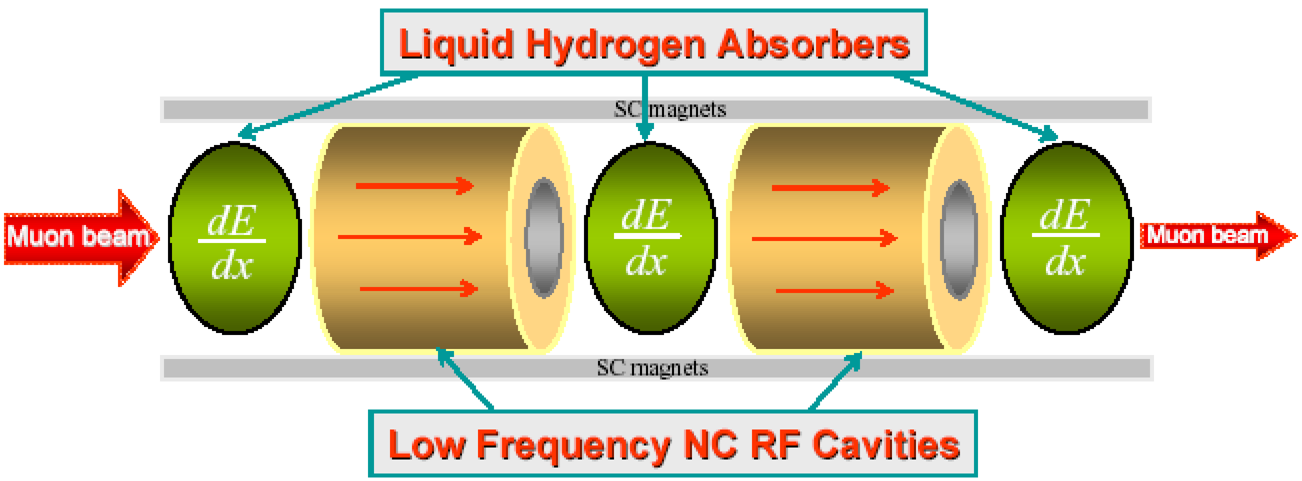
R&D Issues

- **Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)**
  - low production rate
    - need target that can tolerate multi-MW beam
  - large energy spread and transverse phase space
    - need emittance cooling
    - high-acceptance acceleration system and decay ring
- **Muons have short lifetime (2.2 μs at rest)**
  - puts premium on rapid beam manipulations
    - high-gradient RF cavities (in magnetic field for cooling)
    - presently untested ionization cooling technique
    - fast acceleration system

If intense muon beams were easy to produce, we'd already have them!

Ionization Cooling (1)

- **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 $p_{x,y}/p_z$



Ionization Cooling (2)

- There is also a heating term
  - for SR it is quantum excitation
  - for 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 $\beta_\perp$ (strong focusing), large X_0 and *dE/ds* (H_2 is best)

MAP R&D Plan

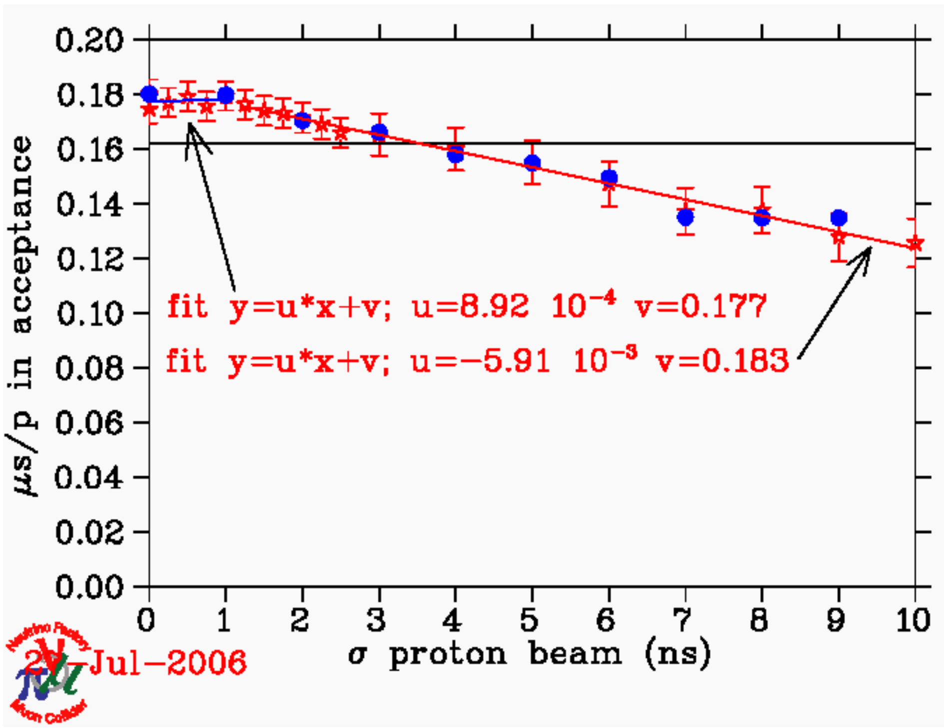
- **Main deliverables**
  - design and simulations
    - MC Design Feasibility Study (DFS)
      - intended to be a "high-end" feasibility study
        - includes associated physics and detector studies
        - engineering and costing not fully detailed
        - defines R&D program (extending beyond initial plan)
    - NF RDR (under IDS-NF auspices)
      - help with engineering and costing (select areas)
      - participate in accelerator design of various subsystems
  - component development and testing
    - demonstration of key technologies
      - sufficient to allow down-selection of cooling channel schemes
        - may not be able to pick unique optimal scheme, but will identify the most promising approaches
  - system tests of 4D and 6D cooling
    - participate in MICE and 6D "bench test" (no beam)

R&D Specifics

- **Main Muon Collider R&D issues include (see WG2 talks):**
  - **simulations**
    - **optimization of subsystem designs**
    - **end-to-end tracking of entire facility**
  - **technology**
    - **operation of normal conducting RF in an axial magnetic field**
    - **development of low-frequency SRF cavities**
    - **development of high-field solenoids for final cooling**
    - **development of fast-ramped magnets for RCS**
    - **decay ring magnets that can withstand the mid-plane heat load from muon decay products**
  - **system tests**
    - **high-power target proof-of-concept [MERIT] ✓**
    - **4D ionization cooling channel proof-of-concept [MICE]**
    - **preparations for future 6D cooling experiment**

Technical Challenges (1)

- **Proton beam parameters**
  - desired proton intensity for MC or NF is 4 MW
    - e.g., 2.5 x 10^{15} p/s at 10 GeV or 2.5 x 10^{14} p/pulse at 10 Hz
  - desired bunch length is 1-3 ns to minimize intensity loss
    - not easily done at high intensity and moderate energy

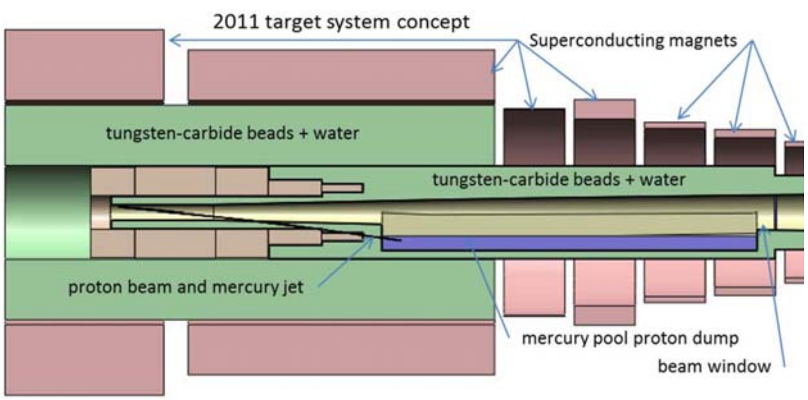


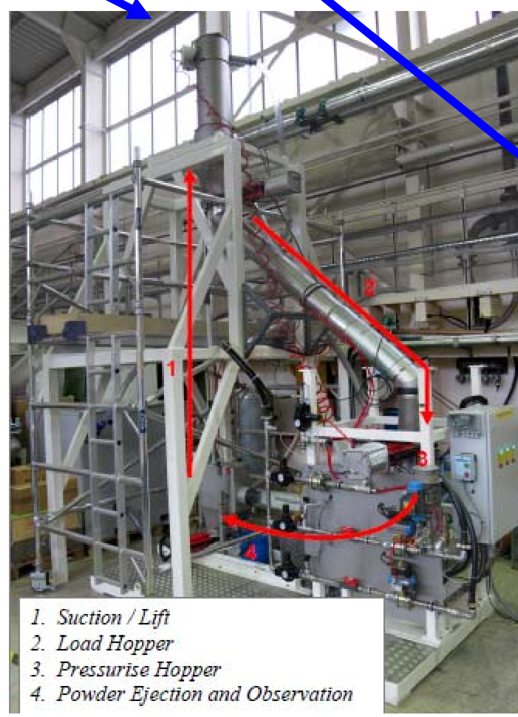
Difficult requirement at low beam energy (5-10 GeV)

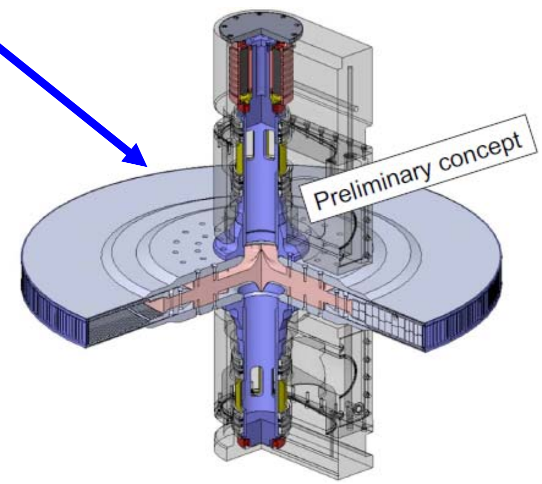
Technical Challenges (2)

- **Target**
  - **favored target concept based on Hg jet in 20-T solenoid**
    - **jet velocity of ~15 m/s establishes "new" target each beam pulse**
      - **magnet shielding is daunting, but appears manageable**
  - **alternative approaches (powder or solid targets) also being pursued via EUROnu**

Hg-jet target
(MERIT)

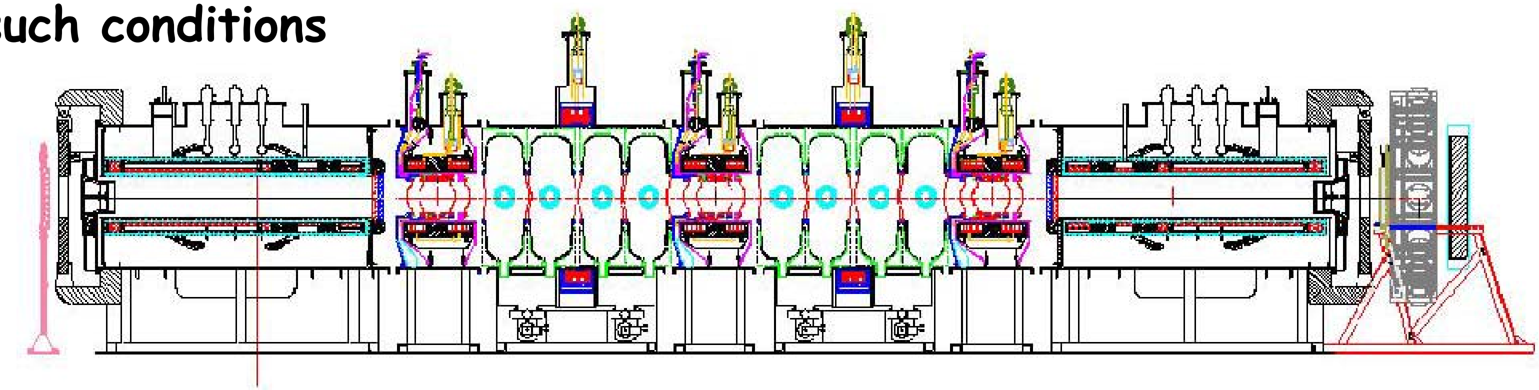


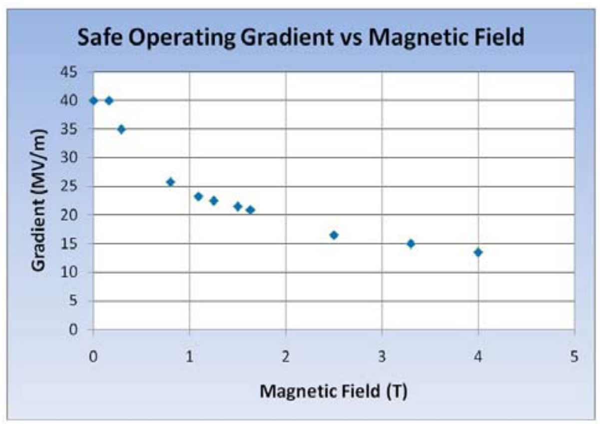




Technical Challenges (3)

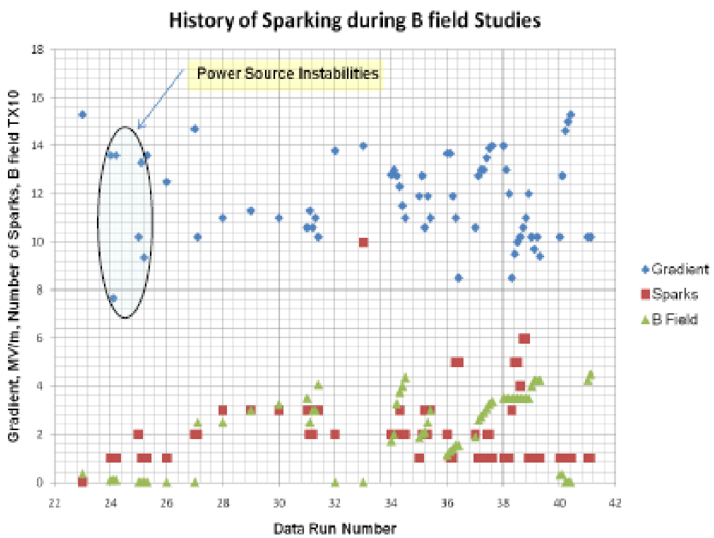
- **Normal conducting RF**
  - *cooling channel requires high-gradient RF immersed in a strong magnetic field*
    - 805-MHz experiments indicate substantial degradation of gradient in such conditions

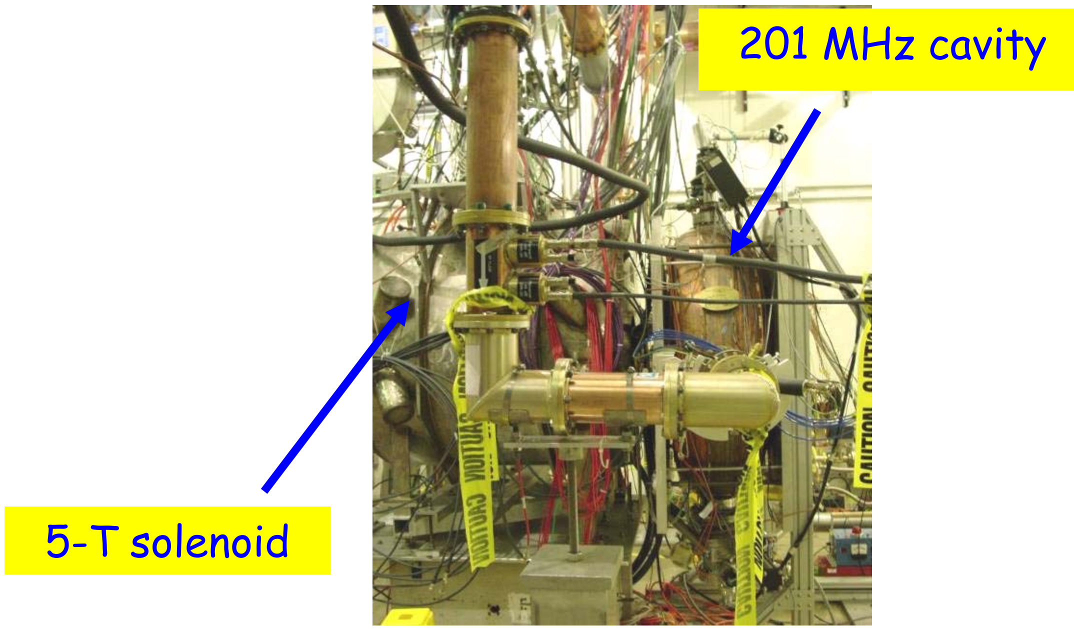




MuCool R&D (1)

- MuCool program does R&D on cooling channel components in MuCool Test Area at Fermilab [Bross talk]
  - RF cavities, absorbers
- Motivation for cavity test program: observed degradation in cavity performance when strong magnetic field present
  - 201 MHz cavity easily reached 21 MV/m without magnetic field
  - initial tests in fringe field of Lab G solenoid show some degradation
    - and lots of scatter

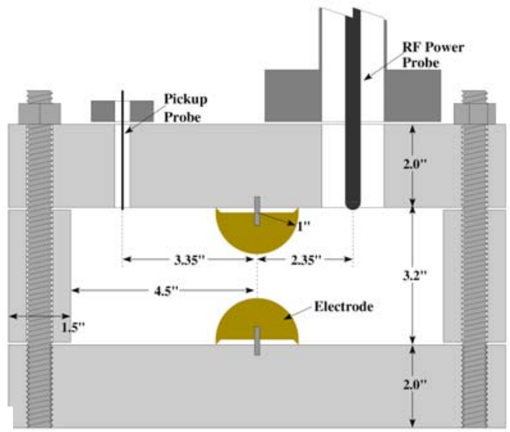


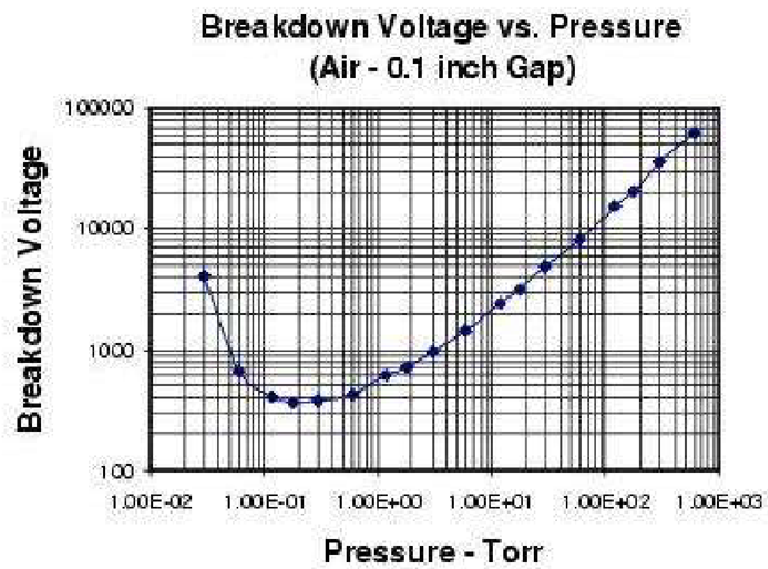


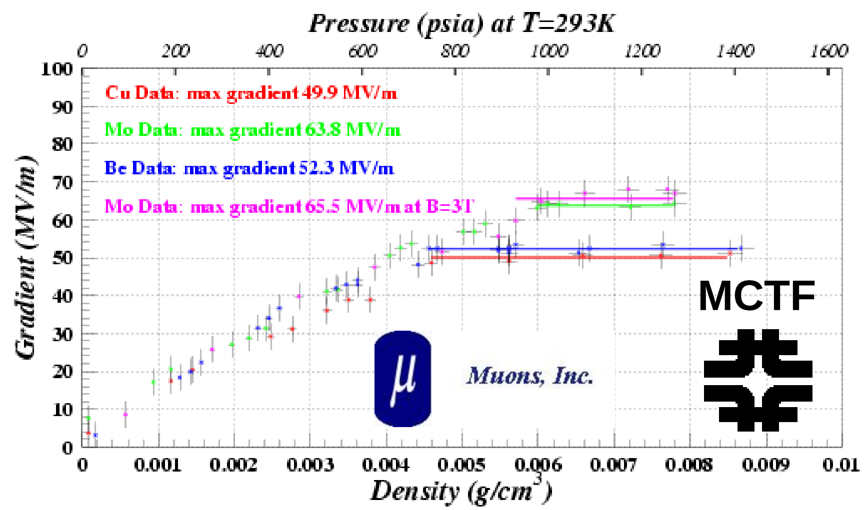
MuCool R&D (2)

- **Tested pressurized button cavity at MTA** FNAL + Muons, Inc.
  - **use high-pressure H_2 gas to limit breakdown ($\Rightarrow$ no magnetic field effect)**

Remaining issue:
What happens when high intensity beam traverses gas?

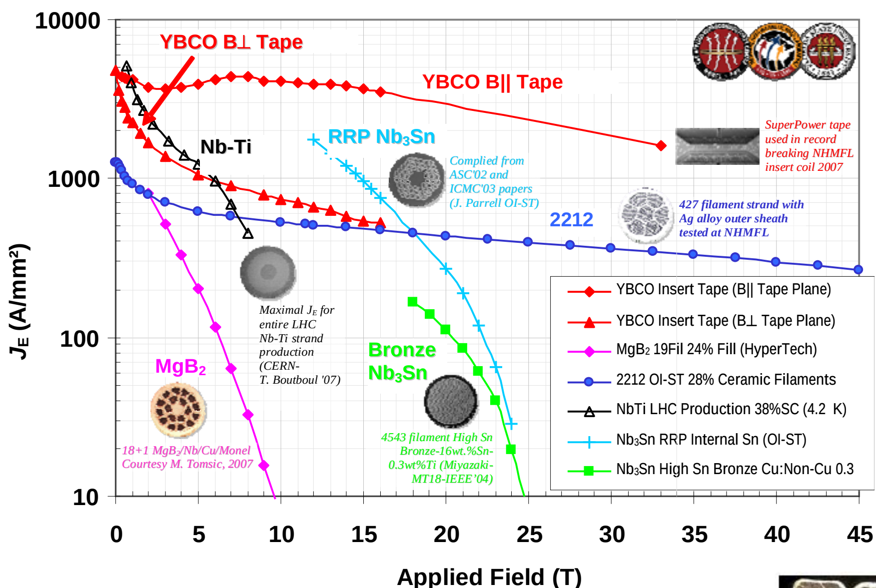




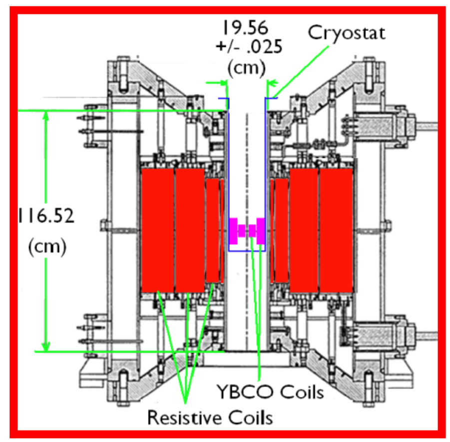


High Field Solenoids

- **End of cooling channel, needs high field solenoids (~30 T)**
  - ongoing national program under way to develop high-field HTS solenoids
    - great promise, but many challenges
      - conductor performance, quench protection, stresses

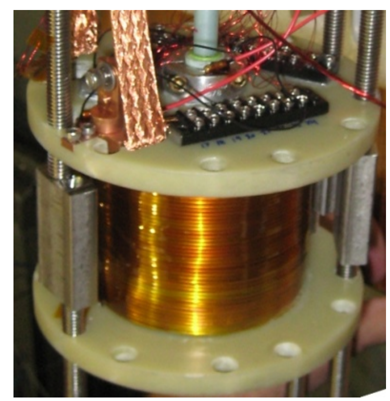


PBL (SBIR) 35T design



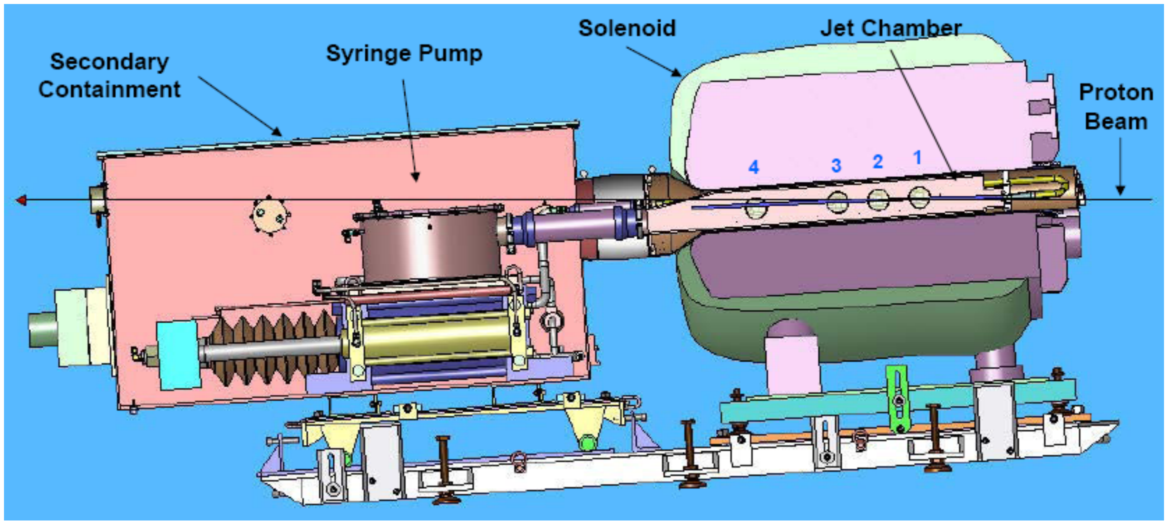
FNAL TD test cable.
Test degradation of J_c
in cabling process

NHMFL YBCO Test Coil (27T – ΔB = 7T)

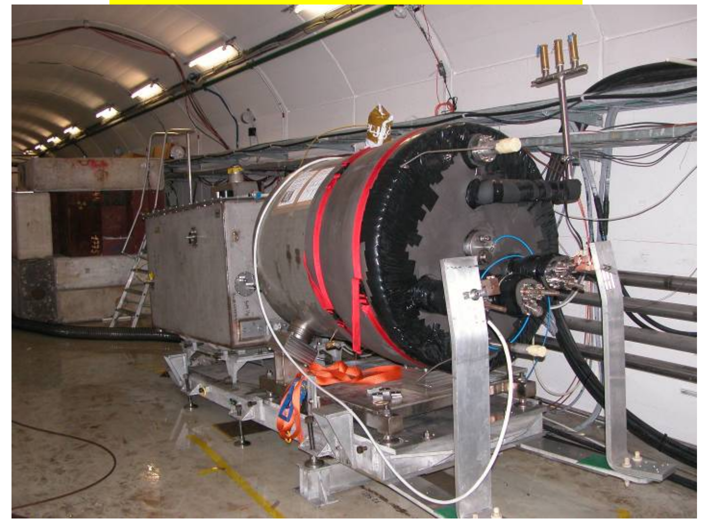


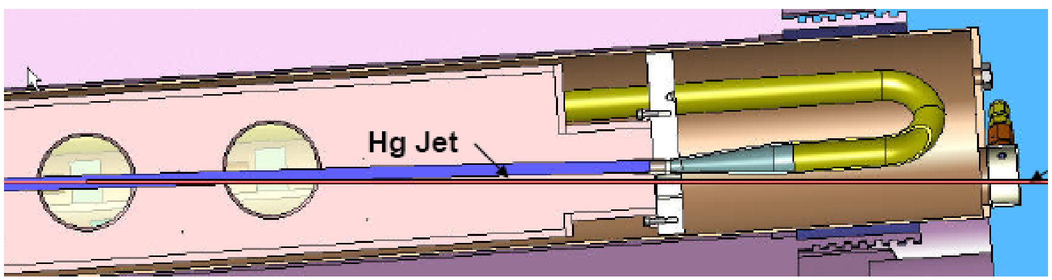
MERIT Experiment

- MERIT completed beam test of Hg-jet target in 15-T magnetic field using CERN PS

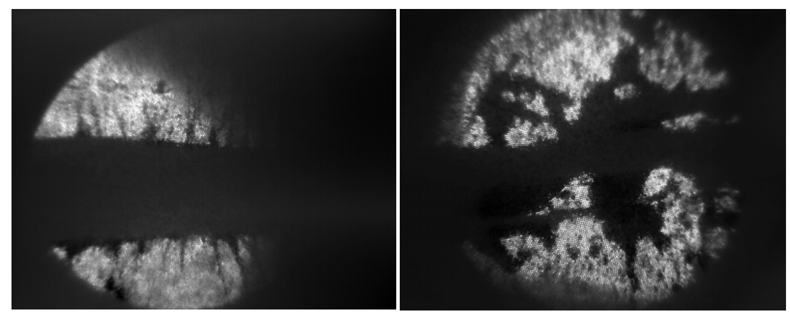


Installation at CERN





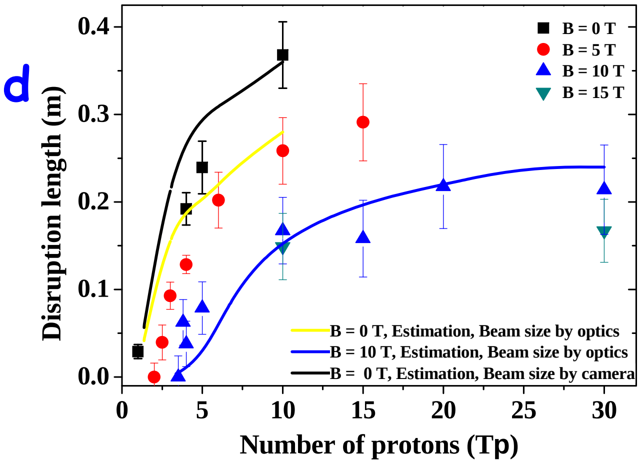
Schematic of MERIT experimental setup



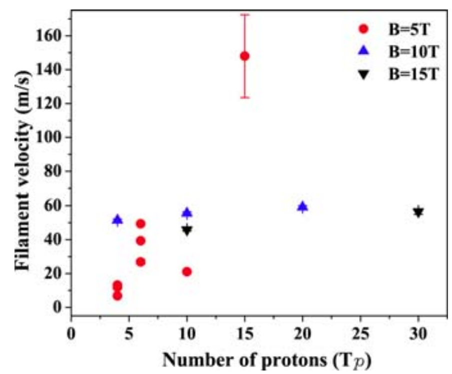
During After
10 Tp

MERIT Results

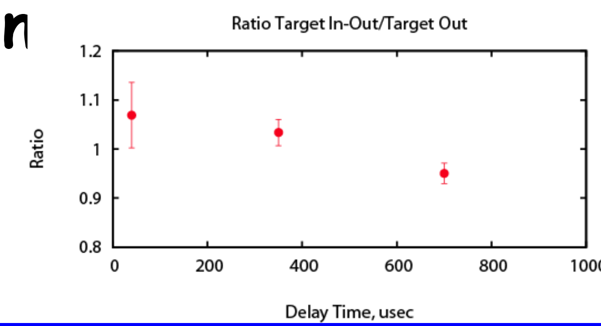
- **Monitored disruption optically with fast camera**
  - no disruption for pulses with <2 Tp
  - disruption length smaller at higher magnetic field



- **Estimated filament velocity**
  - max. value ~60 m/s
    - o suppressed at high B



- **Studied time-dependence of π production**
  - look for degradation due to jet disruption
    - o ~5% loss for long times (>400 μs)



MERIT Conclusions

- Power handling of target is adequate
  - disruption length of ~20 cm ⇒ 70 Hz rep. rate at 15 m/s
  - 115 kJ per pulse x 70 Hz gives 8 MW of beam power
    - 4 MW design value seems "comfortable"

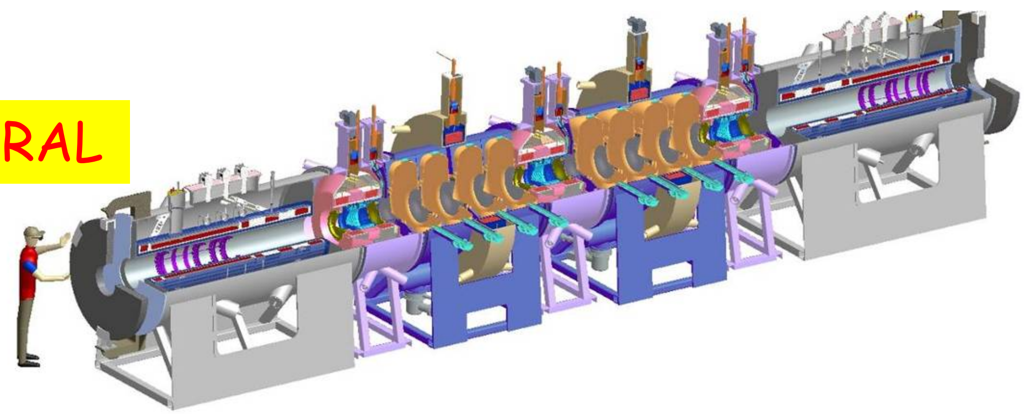
MERIT serves as a satisfactory proof-of-principle of Hg-jet concept

- Issues to pursue (none require beam)
  - look for damage to containment vessel from 60 m/s filaments ✓
  - splash mitigation in Hg beam dump (from both beam and spent jet)
  - system aspects of continuous flow device

MICE Goals

- Cooling demonstration aims to:
  - design, engineer, and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
  - place this apparatus in a muon beam and measure its performance in a variety of modes of operation and beam conditions
- Another key aim:
  - show that design tools (simulation codes) agree with experiment
    - gives confidence that we can optimize design of an actual facility
- Getting the components fabricated and operating properly is teaching us a lot about both the cost and complexity of a muon cooling channel
  - measuring the "expected" cooling will serve as a proof of principle for the ionization cooling technique

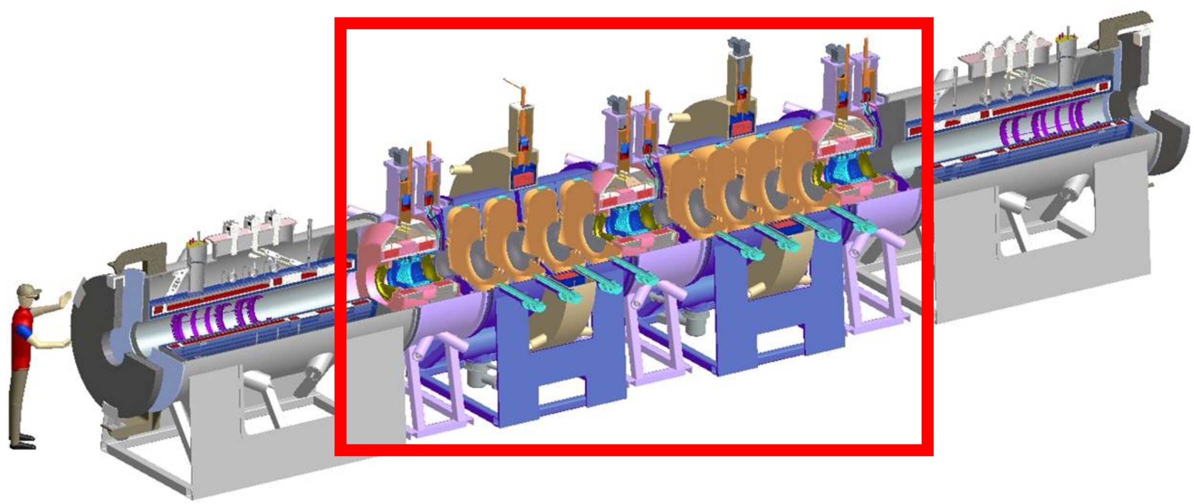
Experiment sited at RAL



System Description

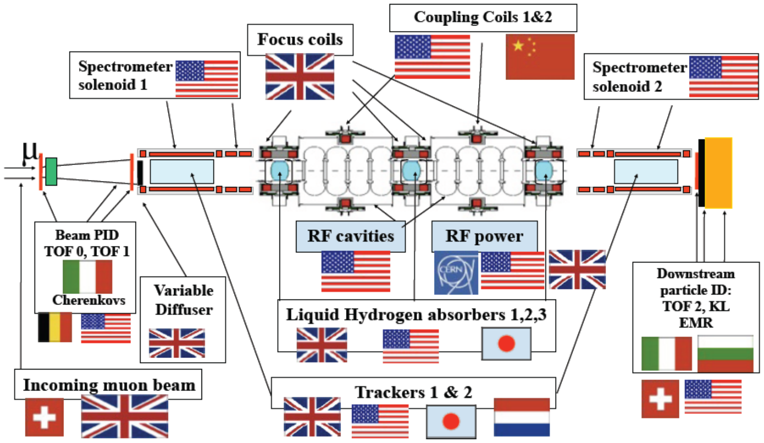
- **MICE includes one cell of the FS2 cooling channel**
  - **three Focus Coil (FC) modules with absorbers (LH_2 or solid)**
  - **two RF-Coupling Coil (RFCC) modules (4 cavities per module)**

- **Along with two Spectrometer Solenoids with scintillating fiber tracking detectors**
  - **plus other detectors for confirming particle ID and timing (determining phase wrt RF and measuring longitudinal emittance)**
    - **TOF, Cherenkov, Calorimeter**



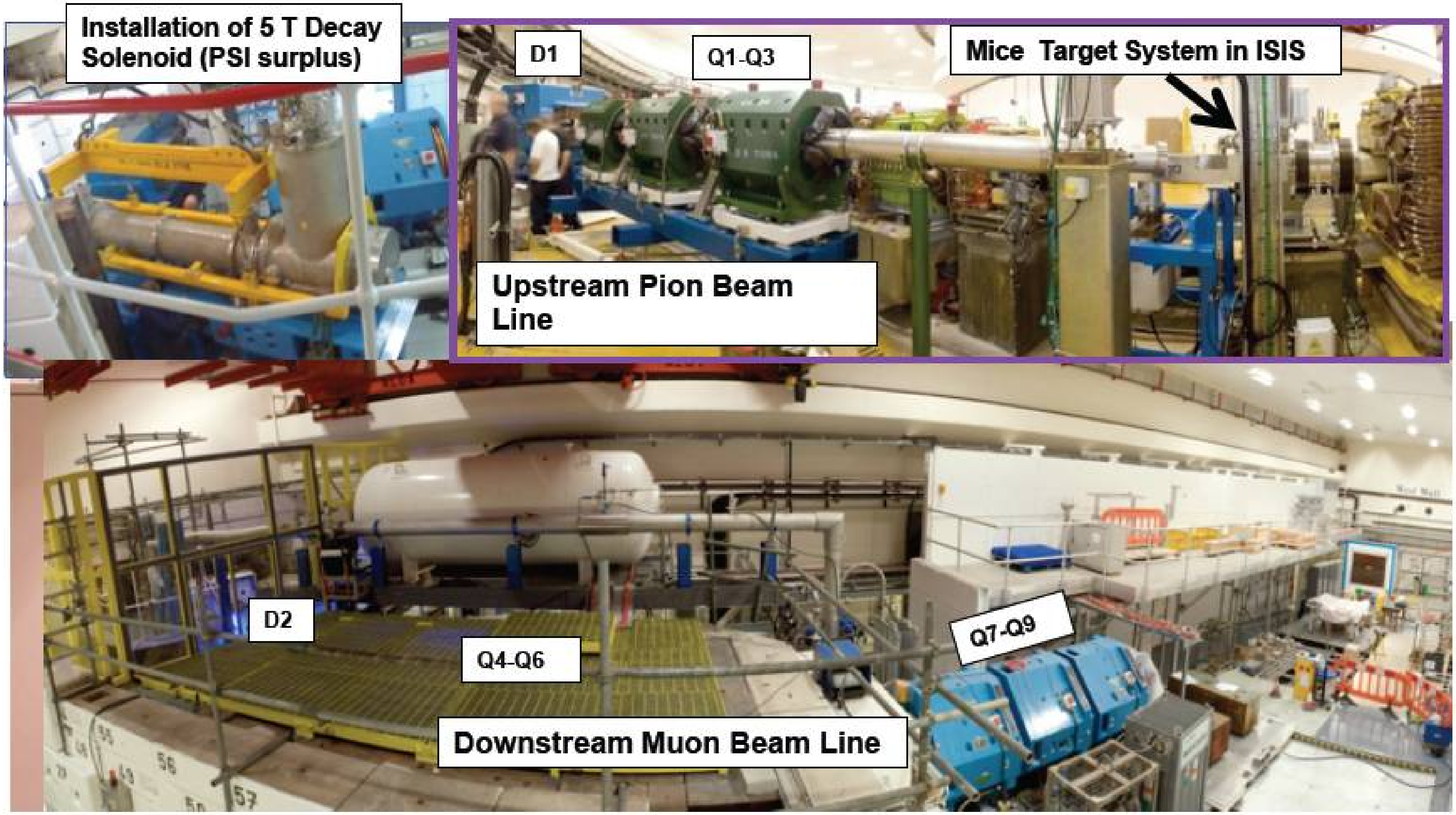
MICE Collaboration

- **International collaboration of ~130 scientists/engineers**
  - *experiment uses secondary beam from 800 MeV ISIS synchrotron at RAL*



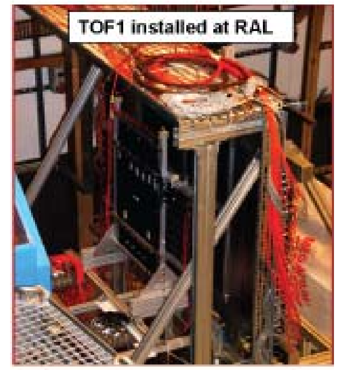
MICE Status (1)

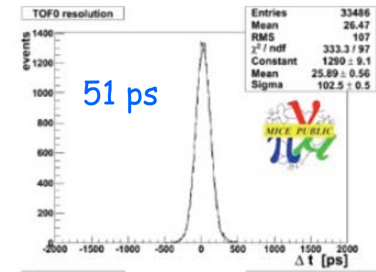
- **Beam line installed and fully operational**

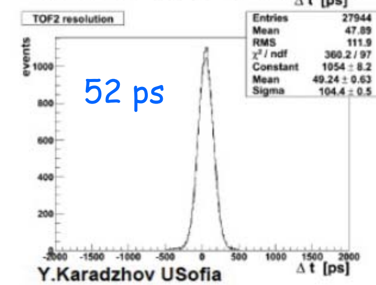


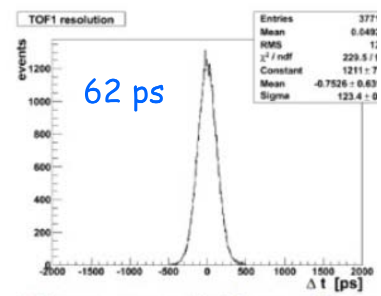
MICE Status (2)

- Particle ID can suppress unwanted particles (pions, protons, decay electrons) to 10^{-3} level
  - use
    - TOF counters (3 sets) ✓
    - Cherenkov counters (2) ✓
    - KL sampling EM calorimeter ✓
    - Electron-muon ranger (under construction)

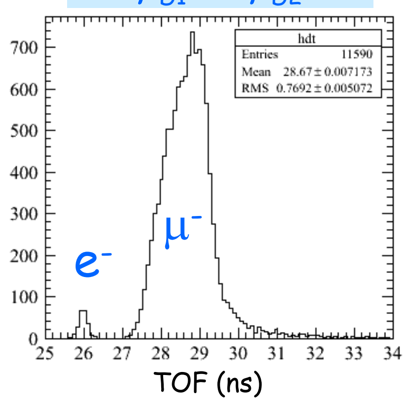




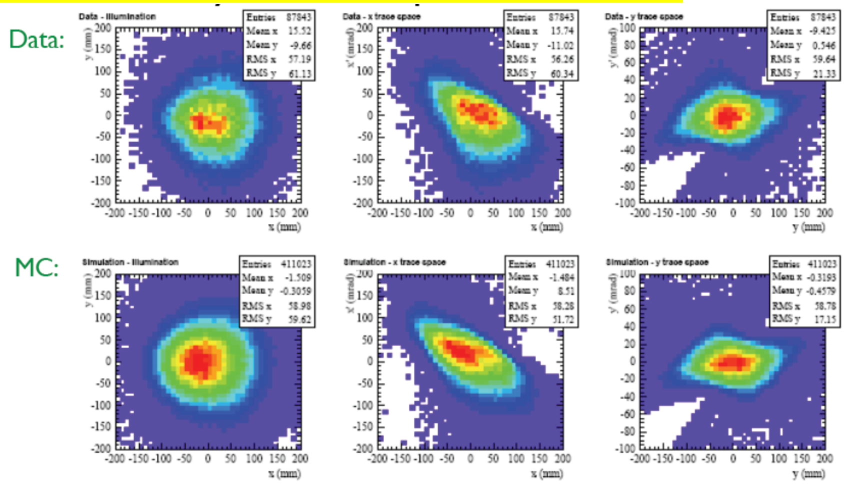




Select muons with two dipoles: $p_{D1} = 2p_{D2}$



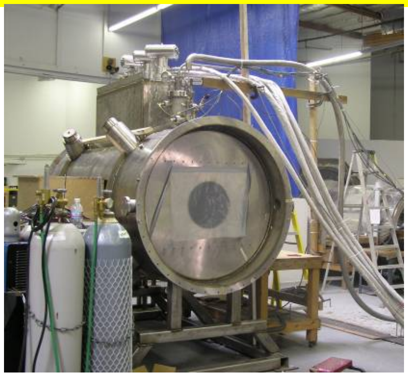
TOF detectors can measure emittance (well reproduced by simulations)



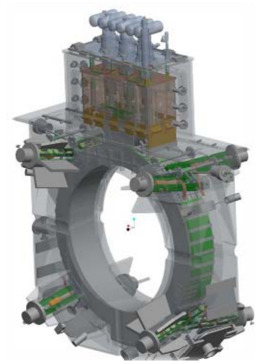
MICE Components

- **All MICE cooling channel components are now in production**

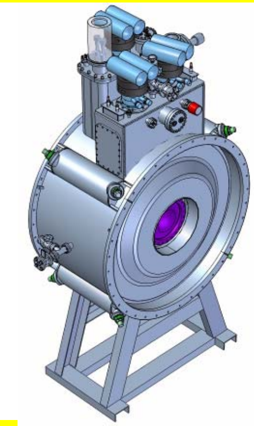
Spectrometer Solenoid (Wang NMR)



CC cryostat (SINAP) & coil (Qi Huan Co.)

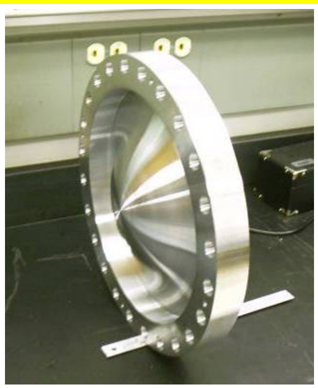


FC (Tesla Eng., Ltd.)



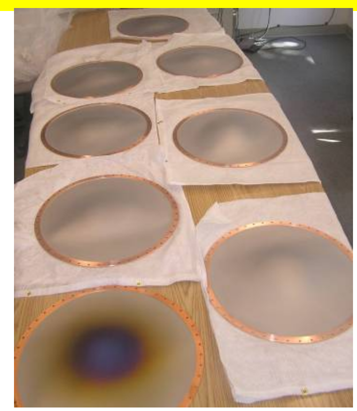
Absorber (KEK/Mirapro)

Absorber window (U-Miss)



Cavities (Applied Fusion)

Be windows (Brush-Wellman)



Summary

- MAP organization is in place and functioning
  - a natural evolution of the NFMCC+MCTF heritage
    - multi-institutional to reflect MAP population
    - NSF has involvement via IB and MuTAC
  - search for new Director under way
- Strong oversight mechanisms in place
  - involvement of resource managers at MAP institutions will be a key to success
- R&D toward a MC making steady progress
  - MERIT established ability of Hg-jet to tolerate >4 MW of protons
  - MICE is progressing (major components all in production)
    - looking forward to first ionization cooling measurements in a few years!
- Development of muon-based accelerator facilities offers great scientific promise and remains a worthy—though challenging—goal to pursue

Backups

Reviewers

- DOE staff
  - Kovar, Procario, Len, Strauss, Crawford
- NSF staff
  - Whitmore
- Technical consultants
  - accelerator systems
    - Peggs, Markiewicz
  - accelerator physics
    - Cai, Cary
  - RF
    - Adolphsen, Jensen
  - magnets
    - McIntyre, Zeller
  - management
    - Womersley

Institutional Board

- **Membership includes**
  - ANL: Harry Weerts
  - BNL: Ilan Ben-Zvi
  - FNAL: Vladimir Shiltsev
  - Jlab: Andrew Hutton
  - LBNL: Steve Gourlay
  - ORNL: Van Graves
  - SLAC: Tor Raubenheimer
  - Cornell: Don Hartill (Chair)
  - IIT: Dan Kaplan (Secretary)
  - Princeton: Kirk McDonald
  - UCB: Jonathan Wurtele
  - UCLA: David Cline
  - UCR: Gail Hanson
  - U-Miss: Don Summers

Technical Advisory Committee

- **MuTAC**
  - John Byrd, LBNL
  - David Finley, FNAL
  - Vladimir Litvinenko, BNL
  - Peter McIntosh, Daresbury Lab
  - Lia Merminga, TRIUMF
  - David Rubin (Chair), Cornell
  - Michael Shaevitz, Columbia
  - Thomas Roser, BNL
  - Susan Smith, Daresbury Lab
  - Mike Syphers, Fermilab $\rightarrow$ MSU
  - Frank Zimmermann, CERN