NCRF R&D Plan

Derun Li
Center for Beam Physics
Accelerator and Fusion Research Division
Lawrence Berkeley National Laboratory

Muon Accelerator Program Review
Fermilab, August 24 - 26, 2010

Outline

- Introduction and Goals
  - Brief review of NCRF programs
- RF R&D Plan
  - Experimental Studies at 805-MHz
    - RF gradients (pillbox cavity with and without RF buttons) in multi-Tesla magnetic fields
    - Cavity with magnetic insulation to study ExB effect
    - High pressure RF cavity + Beam test at the MTA
    - Atomic layer deposition (ALD) cavity
    - RF breakdown studies
  - MuCool 201-MHz cavity tests
    - Baseline design for MICE
  - RF cavities for MICE
    - Status
- Milestones
- Cavity down selection
- Summary

Introduction I

- **Muon capture, bunching, phase rotation and ionization cooling require**
  - **Low frequency normal conducting RF cavities**
  - **High RF gradient operation in up to 6 T magnetic fields**

Parameter	Value	Unit
Buncher cavity frequency range	233.6 – 319.6	MHz
Maximum buncher cavity gradient	8.0	MV/m
Phase rotation cavity frequency range	202.3 – 230.2	MHz
Maximum phase rotation cavity gradient	12.0	MV/m
Initial cooling channel cavity frequency	201.25	MHz
Initial cooling channel cavity gradient	15.25	MV/m

Introduction II

- **We have learned a great deal about the NCRF for muon acceleration**
  - **Cavity design, engineering and construction**
    - **805-MHz open-cell cavity**
    - **805-MHz pillbox cavity**
    - **Be windows for 805-MHz and 201-MHz cavities**
    - **Pillbox cavity with RF buttons**
    - **805-MHz HP RF cavity (Muons Inc.)**
    - **Two 805-MHz box cavities**
    - **201-MHz cavity with Be windows for MuCool (baseline for MICE)**
    - **Ten 201-MHz cavities with Be windows for MICE (two spares)**

Introduction III

- High power RF tests with/without magnetic field
  - 805-MHz open cell cavity
  - Pillbox cavity + Be windows + RF button
  - 805-MHz HP RF cavity (Muons Inc.)
  - One box cavity
  - 201-MHz cavity with Be windows for MuCool
- What we have learned from the high power tests so far
  - Achievable accelerating gradients degrade due to external magnetic fields (by approximately a factor of 2 at 3-Tesla magnetic field)
  - External magnetic fields in association with RF fields cause damage on cavity surfaces
- Operation of RF cavity in strong B field is a challenge

Goal: Find a workable solution through targeted R&D

Goals

Develop a workable solution for high gradient NCRF operating in B fields between approximately 3 and 6 T.

Support sub-assembly prototyping for the 6D cooling bench test.

1. Guggenheim
2. FOFO Snake
3. HCC

Multi-Institute Collaboration

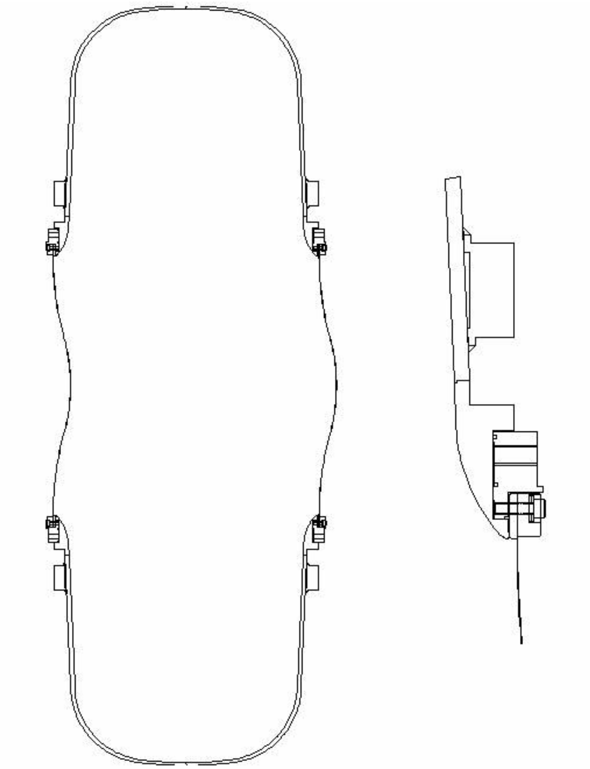
- **RF R&D has been a successfully operating collaborative effort:**
  - Fermi National Accelerator Laboratory
  - Lawrence Berkeley National Laboratory
  - Brookhaven National Laboratory
  - Jefferson Laboratory
  - Illinois Institute of Technology
  - Argonne National Laboratory
  - University of Mississippi
  - SLAC National Accelerator Laboratory
  - Muons Inc.
  - Tech-X Corp.
- **RF test facility, MTA at Fermilab**

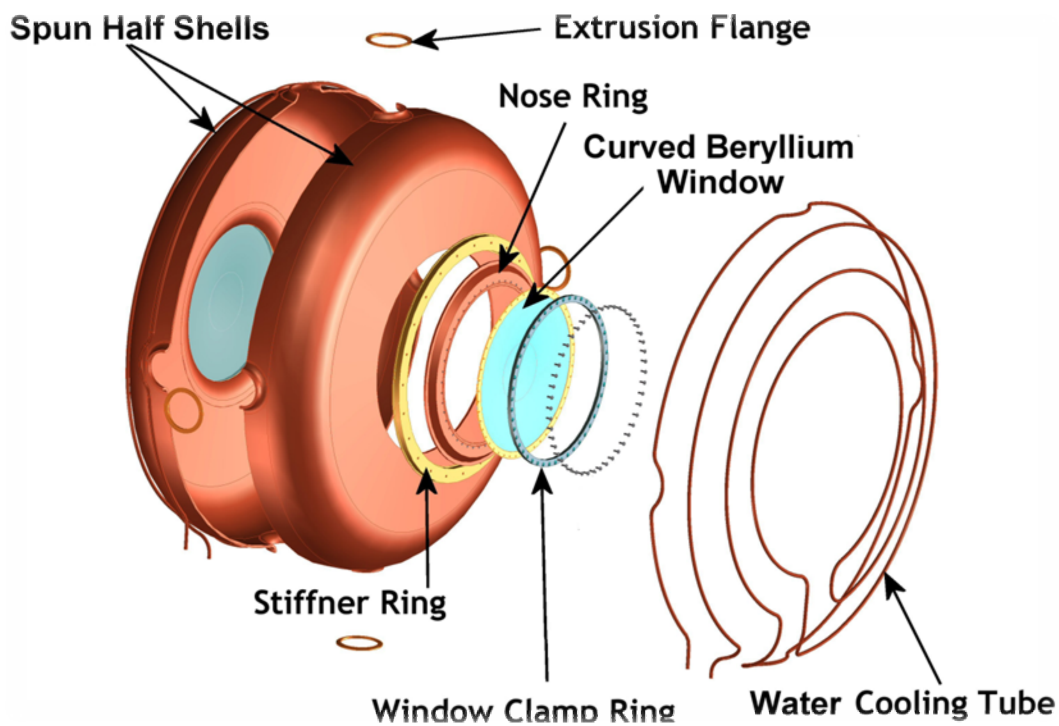
NCRF Cavity for Muon Beams

- **RF cavity options, why and how we got here:**
  - **Muon beams are born with large emittance and decay and must be confined by strong magnetic field**
  - **Must use NCRF**
    - **Pillbox-like cavity with beam irises terminated by thin Be windows (muons can penetrate)**
      - **High RF electric field between two “parallel” planes**
      - **TiN coating at high electric field region**
      - **A factor of 2 higher cavity shunt impedance**
      - **Two times less RF power for a given gradient**
      - **Independent cavity phase control**
    - **RF heating on thin Be windows could detune the cavity**

Two double-curvature windows pointing in the same direction

NCRF Cavity for Muons





- **Cavity has been tested successfully without magnetic fields**
- **Be windows can withstand high RF power in strong magnetic field without damage**

RF Cavity Design Parameters

- The cavity design parameters
  - Frequency: 201.25 MHz
  - $\beta = 0.87$
  - Shunt impedance (VT^2/P): ~ 22 MΩ/m
  - Quality factor (Q_0): ~ 53,500
  - Be window diameter and thickness: 42-cm and 0.38-mm
- Nominal parameters for MICE and (cooling channels) in a neutrino factory or muon collider
  - 8 MV/m (~16 MV/m) peak accelerating field
  - Peak input RF power: 1 MW (~4.6 MW) per cavity
  - Average power dissipation per cavity: 1 kW (~8.4 kW)
  - Average power dissipation per Be window: 12 watts (~100 watts)

NCRF Cavity with External B Field

- **RF challenge**
  - **Achievable RF gradient decreased by more than a factor of 2 at 4 T**
- **An efficient front-end system of a neutrino factory or muon collider requires high gradient NCRF cavity operation in a multi-tesla magnetic field**
- **Targeted R&D programs to understand the RF breakdown problems in magnetic fields → a workable solution**
  - **Physics models and numerical simulations,**
  - **Experimental programs and new techniques:**

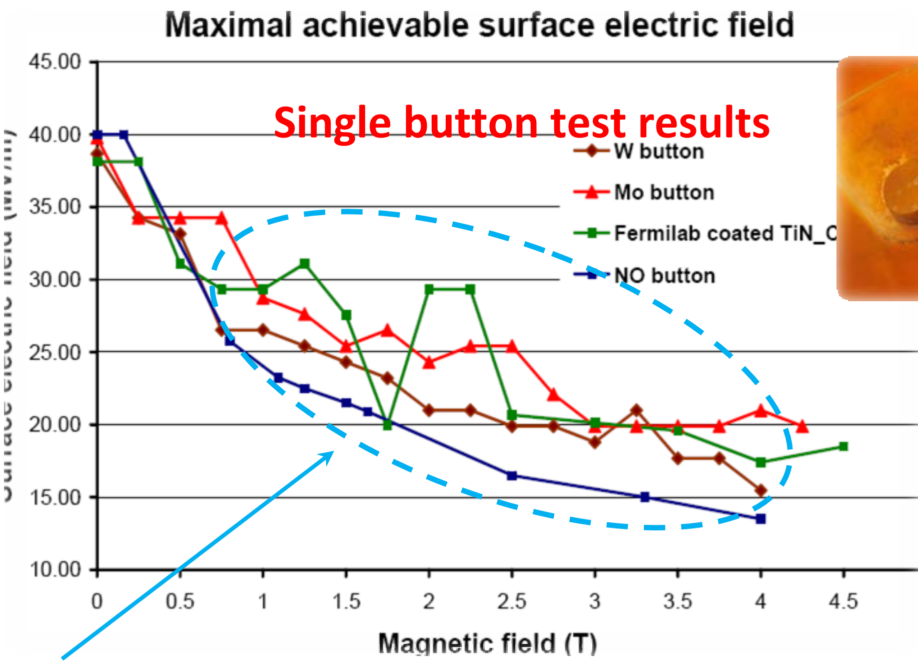
❑ **The 805-MHz with RF buttons**
❑ **High pressure cavity**
❑ **ALD to eliminate field emission**
❑ **Be wall cavity**
❑ **Box cavity to study E x B effects**
❑ **Magnetic field insulated cavity**
❑ **Physics model to understand RF breakdown in magnetic fields**

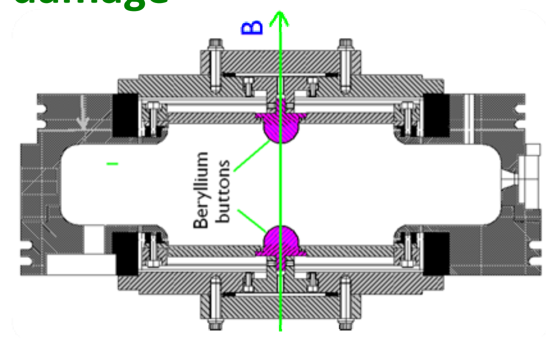
Overview of R&D Plans

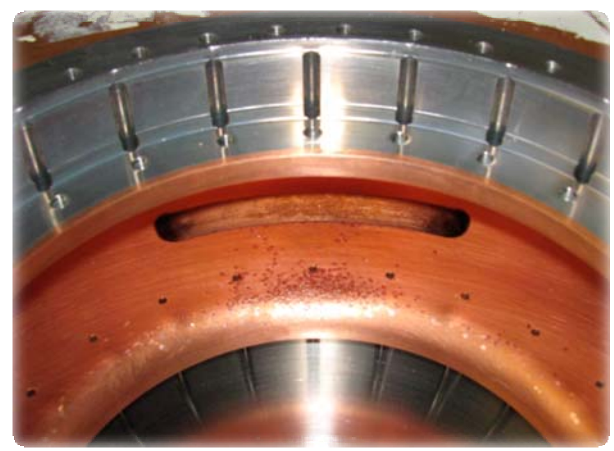
- **Continue experimental RF breakdown studies at 805-MHz**
  - The 805-MHz pillbox cavity has been refurbished and is ready for more button tests for RF breakdown studies
  - New high pressure cavity and test with beam at MTA
  - Magnetic insulation
    - Box cavities to study E x B effects
  - High pressure cavity at different frequencies
  - Beryllium wall cavity
  - Atomic layer deposition (ALD) cavity
  - Physics model to understand RF breakdown in magnetic fields
- **201-MHz cavity program**
  - Test of 201-MHz MuCool cavity with magnetic fields
  - RF cavities for MICE
  - Superconducting coupling coil required for MuCool RF breakdown studies at MTA, Fermilab

RF Button Tests at 805-MHz

- **Continue experimental studies using RF button cavity at 805-MHz**
- **The cavity has been refurbished at Jlab and ready for Be-Be button test**
  - **Enhanced button design with 3 times higher peak fields**
  - **Be-Be button configuration: higher fields w/o surface damage**



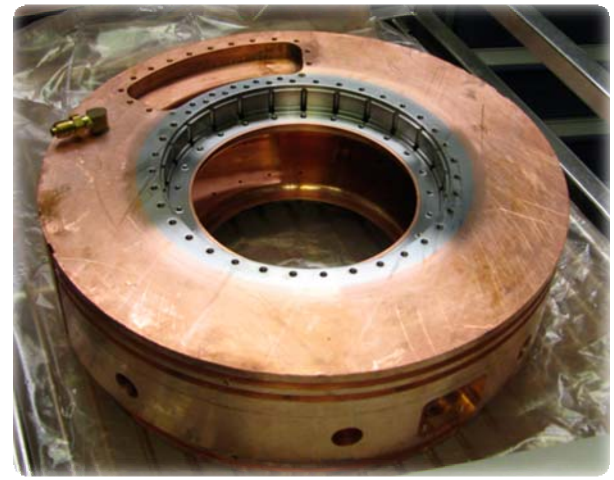




Scatter in data may be due to surface damage on the iris and the coupling slot

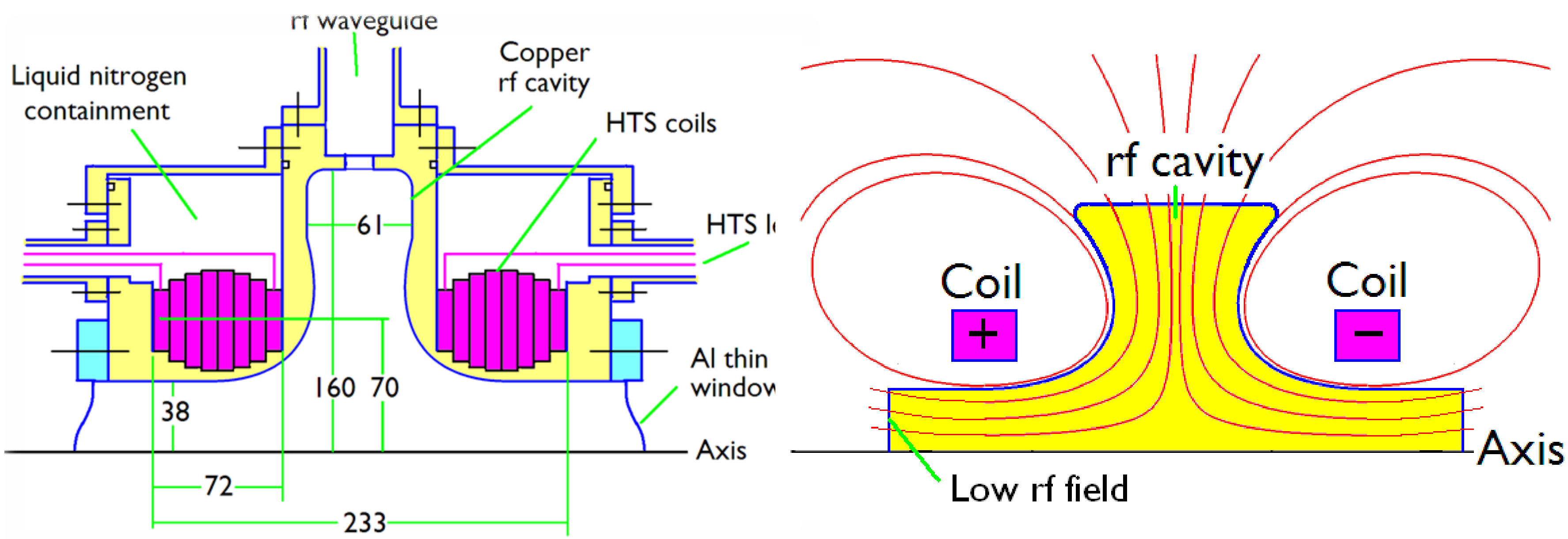
RF Button Tests at 805-MHz

- **The pillbox cavity has been refurbished at Jlab and is ready for RF button tests**



Magnetically Insulated RF Cavity

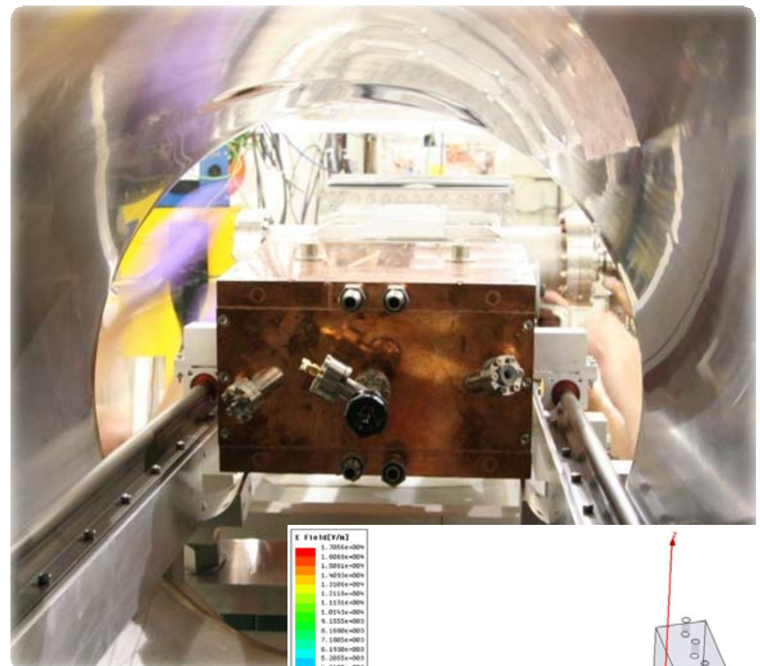
- **Cooling channel concept with magnetic field insulated RF cavity**

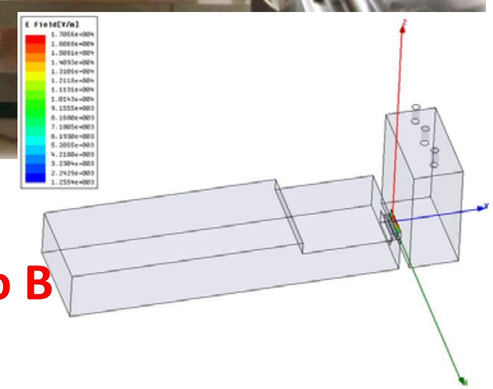


- **Understanding of RF breakdown in magnetic field**
- **Box cavity test at MTA under way now and will be continued**
  - **Note: Magnetically shielded cavity is not as efficient in RF power usage as the pillbox**

Box Cavity Tests at 805-MHz

- **Continue experimental studies of magnetic insulation at 805-MHz**
- **Box cavity has been tested at 0 (E perpendicular to B) to 4 degrees at 3 T**

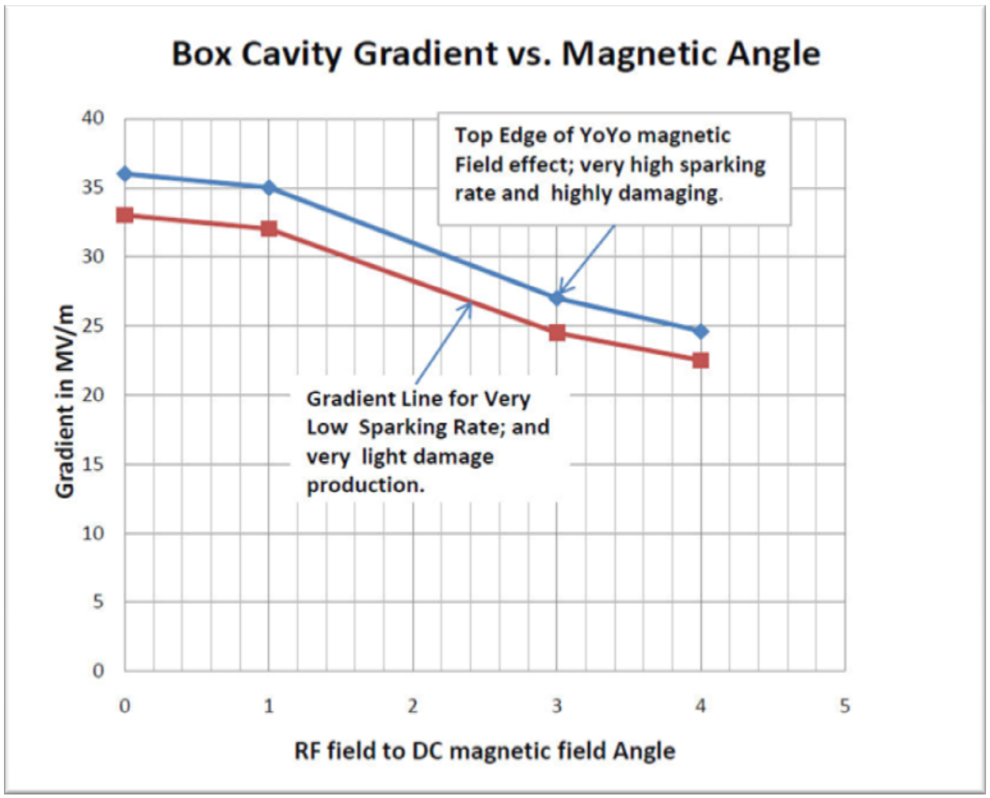


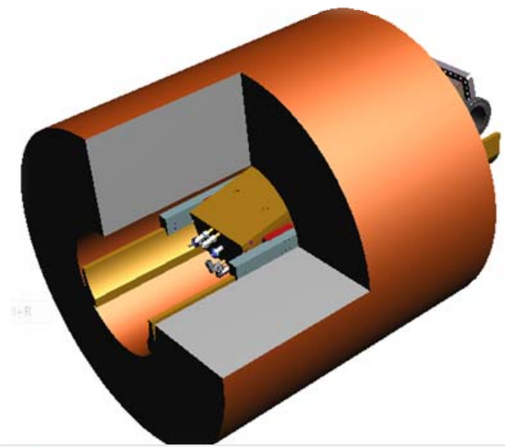


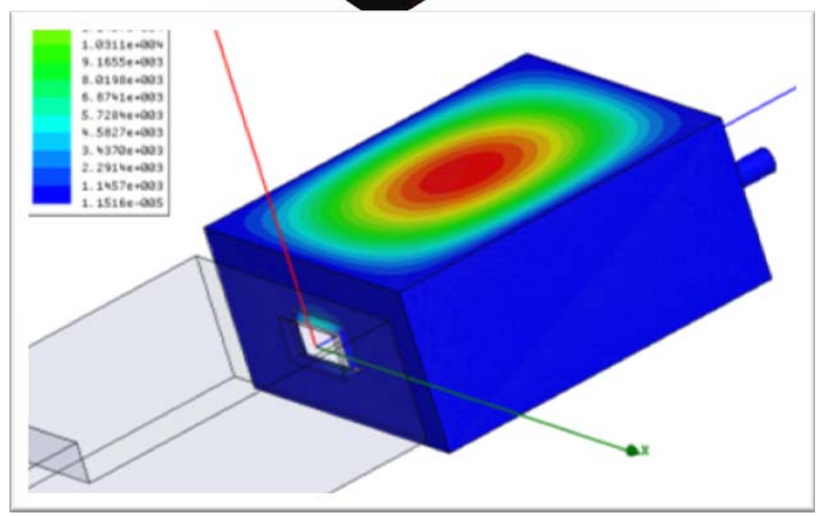
- **Cavity inspection did not show any surface damage**
- **Continue tests using the second cavity with E parallel to B**
- **Preliminary data, analysis is under way**

Box Cavity Tests at 805-MHz

- **Increase gradient gradually to the blue curve (sparking rate < 1/20,000)**
- **Reduce to lower gradient and increase again**
- **Repeat several times until the gradient stays at the red curve (sparking rate < 1/200,000)**

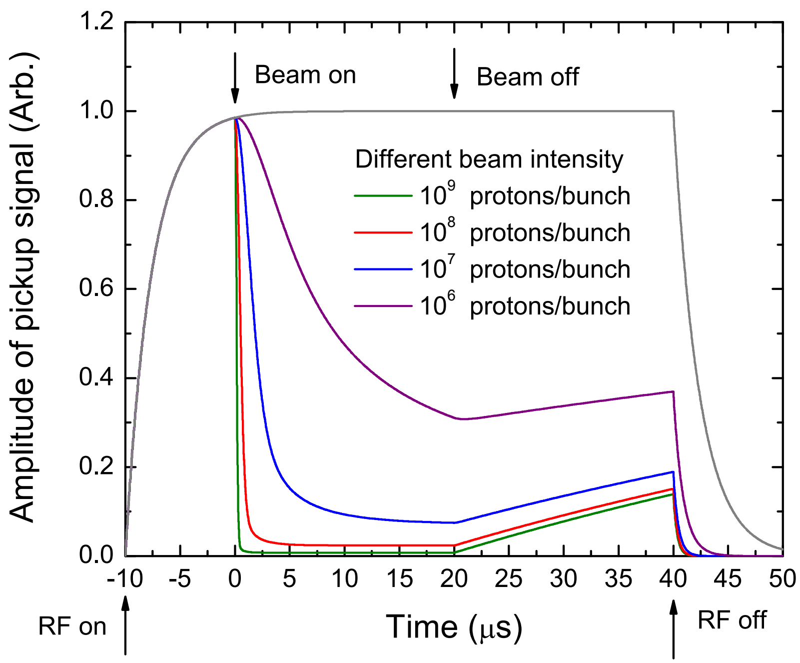


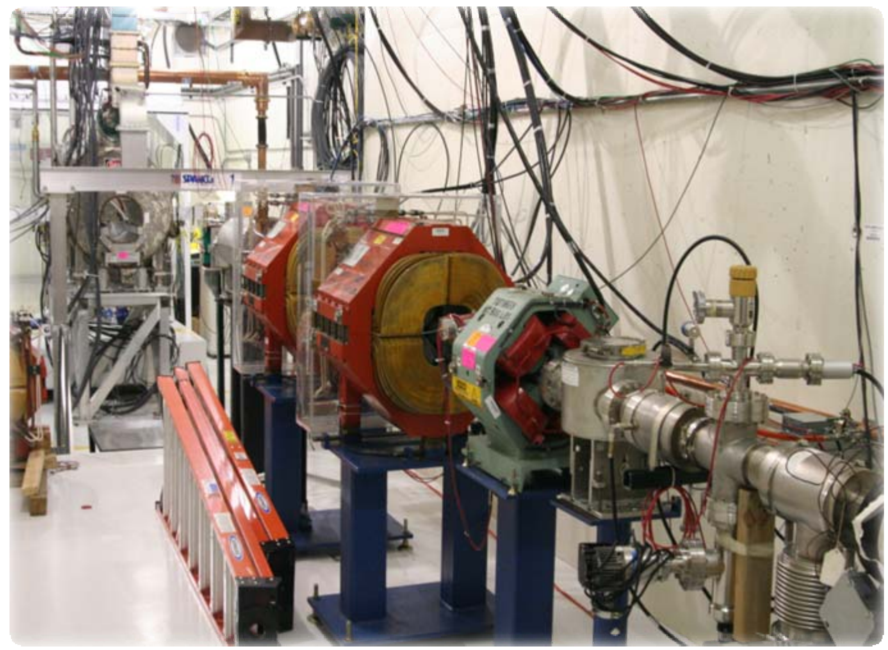




HP Cavity Tests at 805-MHz

- **Continue experimental studies of HP RF cavity at 805-MHz (Yonehara's talk)**
- **RF gradient not affected by external B field**



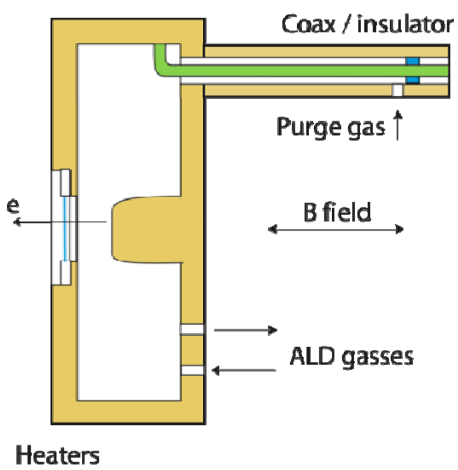


- **New test cell being designed, built to test with 400 MeV proton beam**
- **Verify theoretical predictions**

ALD to Eliminate Field Emission?

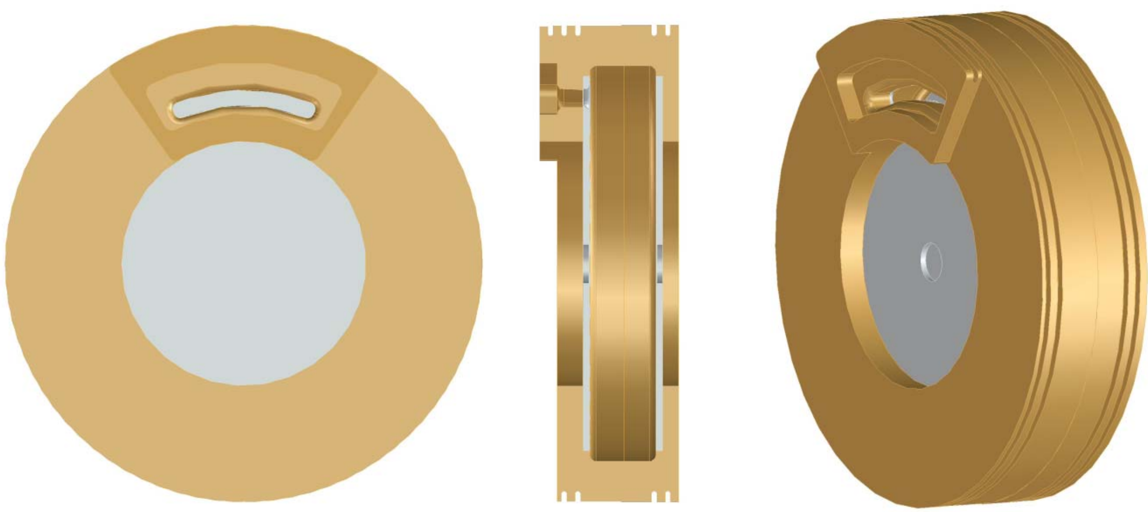
- **Single-cell SC cavity ALD coated at ANL**
  - **Alumina barrier layer plus niobium oxide coating**
- **Cavity prepared and tested at JLab**
  - **Result equaled best previous performance with no field emission**
- **Encouraging results and the coating process is conformal, can coat compounds (e.g. NbN, and multi-layer Gurevich structure)**

- **Design and test of a cavity that is "RF breakdown-proof"**
- **ALD can conformally coat emitters & breakdown sites during operation,**
  - **Increasing local radii**
  - **Reducing the local field, $E_l \sim 1/r$**
  - **Field emission, $\sim E_l^{\sim 14}$**
  - **Breakdown rate $\sim E_l^{\sim 30}$**
- **The experiment will be conducted in the Fermilab MTA**
- **Continue exploring the ALD technique on NCRF cavity**
- **Field emission can be monitored during the process**



Beryllium Wall RF Cavity

- Based on the physics model, Beryllium is the ideal material for the cavity surface
- Operation at low temperature
- Aluminum is significantly better than Copper



Conceptual cavity design and Engineering design are under way

- **Common characteristics**
  - Two bolted halves w/RF and vacuum seal
  - Main body is Cu plated Hastelloy or solid Cu
  - Cavity inner side walls are beryllium (TiN coated)
  - Slotted coupling port in side wall
- **Beryllium side wall options**
  1) Thin Be foil (~500 mm) brazed to side walls
  2) Thick Be plates (~ 6 mm) brazed to side walls
  3) Solid Be side walls (no brazing)

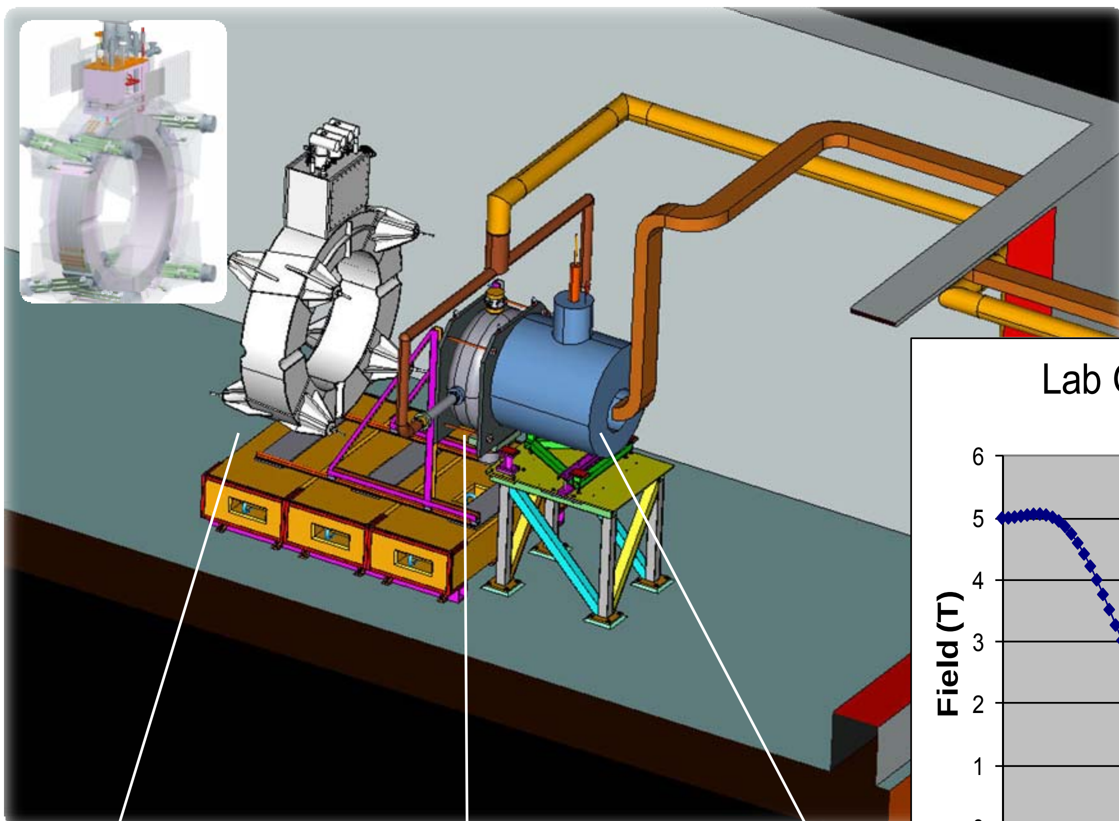
Tests of 201-MHz RF Cavity I

- **SRF cavity post-processing techniques help NCRF**
- **No surface damage found in recent inspection of the 201-MHz MuCool cavity**

- **Tests will resume using the fringe fields of Lab G magnet**
  - **More realistic and systematic studies require Coupling Coil magnet (will be available by 2011)**

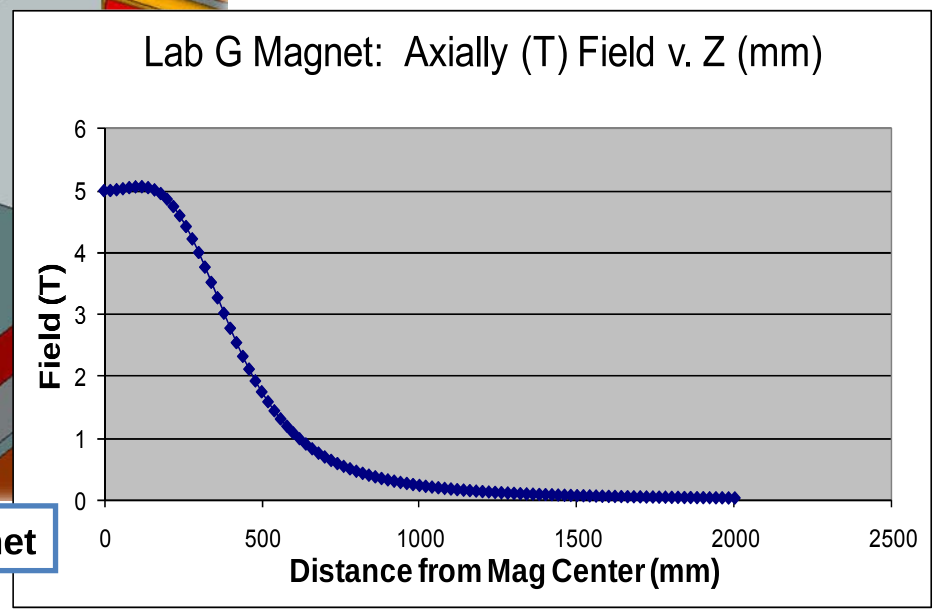
Tests of 201-MHz RF Cavity II

- **Tests of the 201-MHz cavity with magnetic fields**



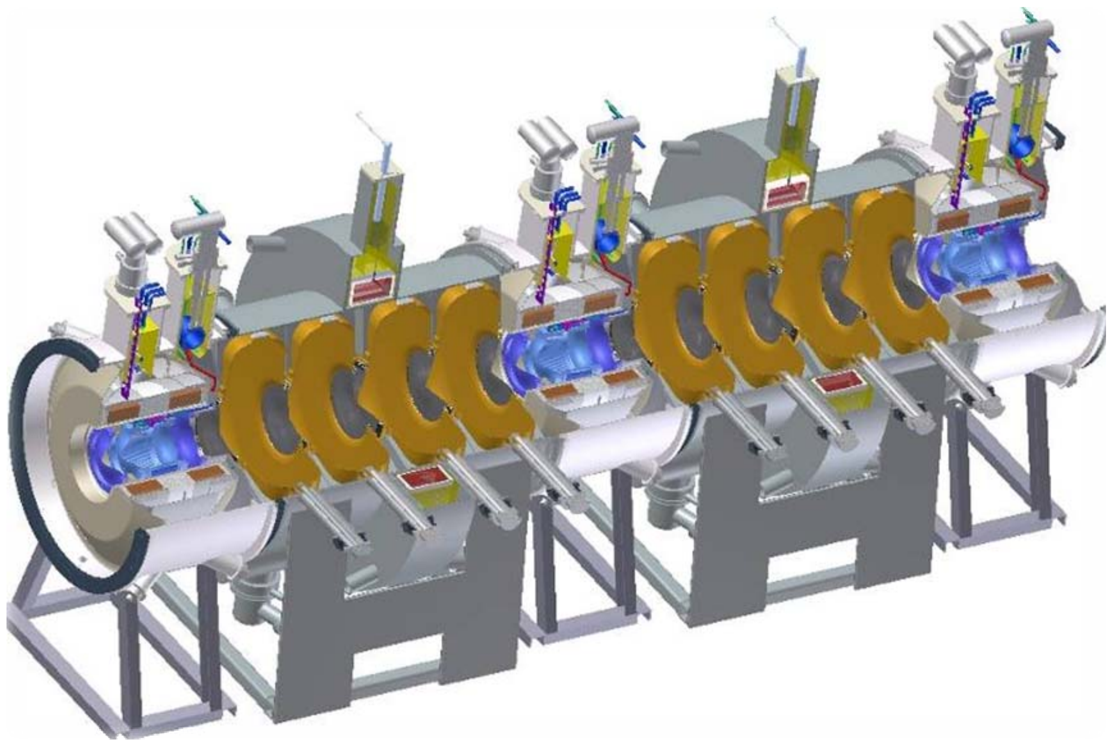
SC CC magnet | 201-MHz Cavity | Lab G Magnet

- **Initial 201 MHz operation in B Field**
  - **Limited to a few hundred Gauss**
- **SC CC magnet available by end of 2011**



RF Cavities for MICE I

Eight 201-MHz cavities in the MICE cooling channel



- First five cavities arrived at LBNL last year and have been measured
- Second batch of five cavities will be complete by Oct. 2010

RF cavities for MICE II

- The first five MICE cavities have been measured in three different window configurations using Be windows #1 and #2 (reference windows)

Cavity #	1	2	3	4	5 (spare)*
Freq. (MHz)	201.084	200.888	201.247	200.740	201.707

*no water cooling tube brazed to the cavity body

RF cavities for MICE III

- Production of the second batch of five MICE cavities going well at Applied Fusion Company in California
  - Nose rings
  - Port extruding and flanges
  - Brazing water cooling tubes
- Modified extruding technique
  - Experimented using the test cavity
  - Need argon gas purge to prevent oxidation of cavity surface
  - Measure oxidation layer thickness

Milestones I

FY10 Complete engineering design for Be-wall RF cavity
Complete initial HPRF cavity beam test
Test magnetically insulated "box" cavity
Complete Be-wall cavity design

- **Demonstrate experimentally that RF breakdown in a multi-tesla magnetic field can be mitigated at 805 MHz**
  - **~ 30 MV/m surface gradient**
- **Test HPRF cavity with 400 MeV proton beam at the MTA**
  - **New test cavity design, fabrication and installation + beam test**
  - **Understanding physics of beam-gas-RF interaction in HPRF cavity**
- **Understand RF breakdown physics in magnetic field insulated cavity**
  - **Complete box cavity tests of E x B studies**

Milestones II

FY11 Fabricate Be-wall RF cavity

- Use base materials that are more robust to the heating caused by focused beamlets in the magnetic field
- Cavity bodies made from Be or possibly Mo
  - Design, engineering and fabrication of Be-wall cavity

FY12 Test new HPRF cavity at 805 MHz

Complete Be-wall RF cavity tests at 805 MHz

Test 201-MHz cavity with coupling coil in MTA

Cavity down-selection

- Systematic experimental studies of RF breakdown physics in vacuum and HP gases at 805 MHz
  - RF breakdown at material surface
  - Physics of beam, gas and RF interaction

Milestones III

FY12 Test new HPRF cavity at 805 MHz

Complete Be-wall RF cavity tests at 805 MHz

Test 201-MHz cavity with coupling coil in MTA

Cavity down selection

- **SC Coupling Coil magnet available by end of 2011**
- **Demonstrate the required RF gradient at 201 MHz in a more realistic magnetic field**
- **RF breakdown scaling**
  - **Stored energy**
  - **Electron energy**
  - **Frequency**
- **Verify conditioning and operation at 201 MHz in a multi-tesla magnetic field**

Milestones IV

Down-selection of RF cavities will be based on

- Outcome of these experimental studies
- The cavity must work at an acceptable RF gradient in a multi-tesla magnetic field
  - Phase rotation
  - Bunching
  - Initial cooling
  - Final cooling
- Engineering, fabrication and integration
- Cost of the cavity
- Cost of RF power

Milestones V

FY14 Prepare RF test cavity with ALD coating

Potentially reduces or eliminates surface field emission

- Proven technology for nano-fabrication of materials
- Succeeded in a SC RF cavity test in increasing FE limit and *Q* at high field
- Can apply almost any ALD deposited metal
- Design and test of a cavity that is "RF breakdown-proof"
- A DOE supplemental funding award for FY10 should allow us to move this milestone forward significantly

Summary

- Muon front-end system requires normal conducting RF cavity operating at high gradient in a few Tesla magnetic field
  - Remains a challenge
  - R&D plans developed to find a workable solution
- Plans for RF breakdown studies
  - Vacuum cavities
  - High pressure RF cavity tests with beam at the MTA
- 201-MHz RF cavities for MICE progressing well

We believe our targeted R&D programs will lead to a workable RF cavity solution in magnetic field!