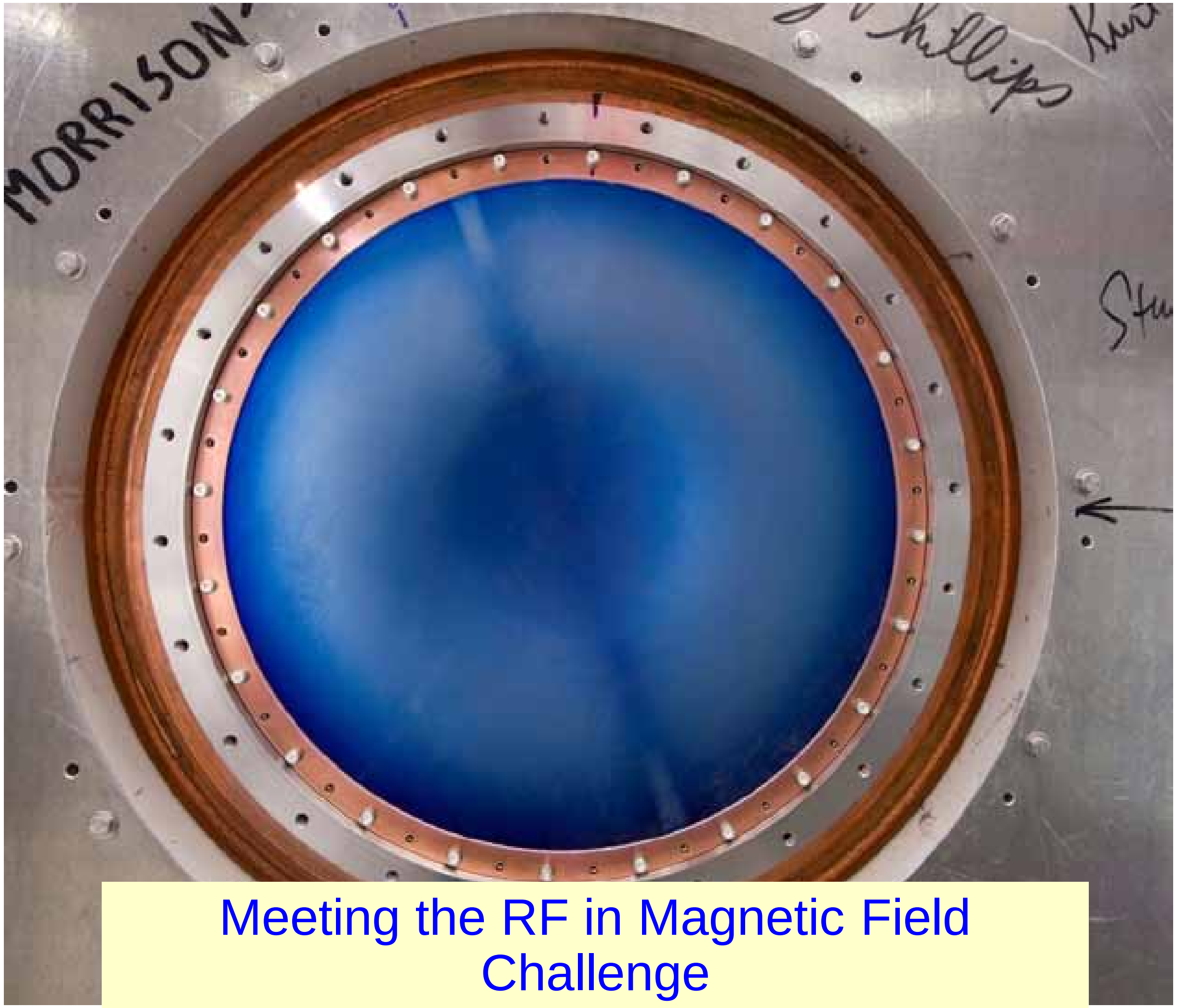
RF Strategy & the MuCool Test Area



Meeting the RF in Magnetic Field Challenge

- Outline
  - The “RF Challenge”
  - Science of RF Breakdowns
  - Current Program (Where we are)
    - Derun Li’s talk (next) will discuss where we are going
    - As will Katsuya Yonehara
  - The MuCool Test Area
  - Summary

Goals of This Talk

- We have a well defined and measured experimental program
- There are extensive scientific underpinnings for the program
- The experimental effort is supported by detailed simulation work which is predictive

Just to Review

Remember, from Long Ago – *(Yesterday)*

Normal Conducting RF

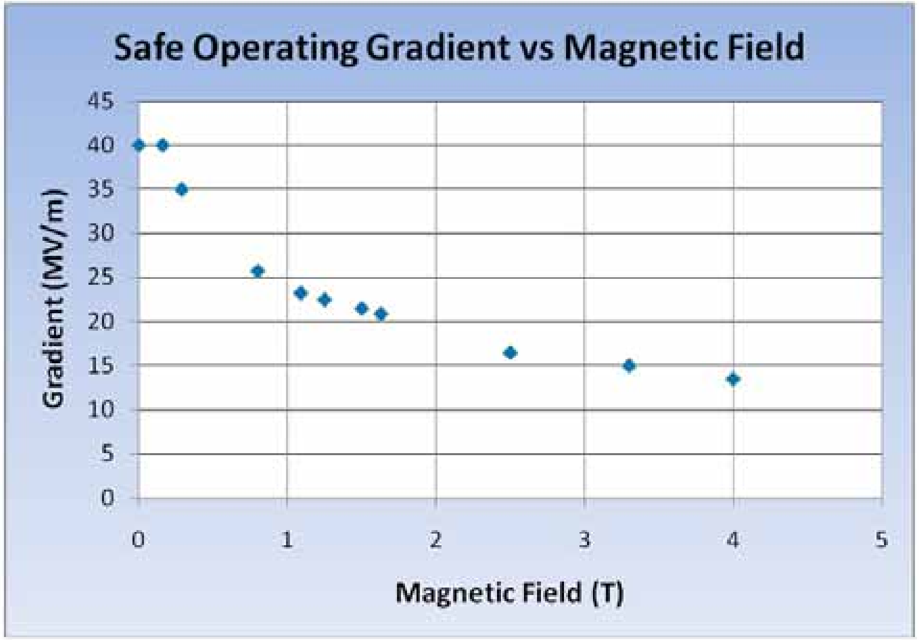
R&D Issues and Present Status

- Muon bunching, phase rotation and cooling requires Normal Conducting RF (NCRF) that can operate at high gradient within a magnetic field strength of up to approximately 6T
  - Required gradients (15-18MV/m) easily obtainable in absence of magnetic field

But

The RF *Challenge*

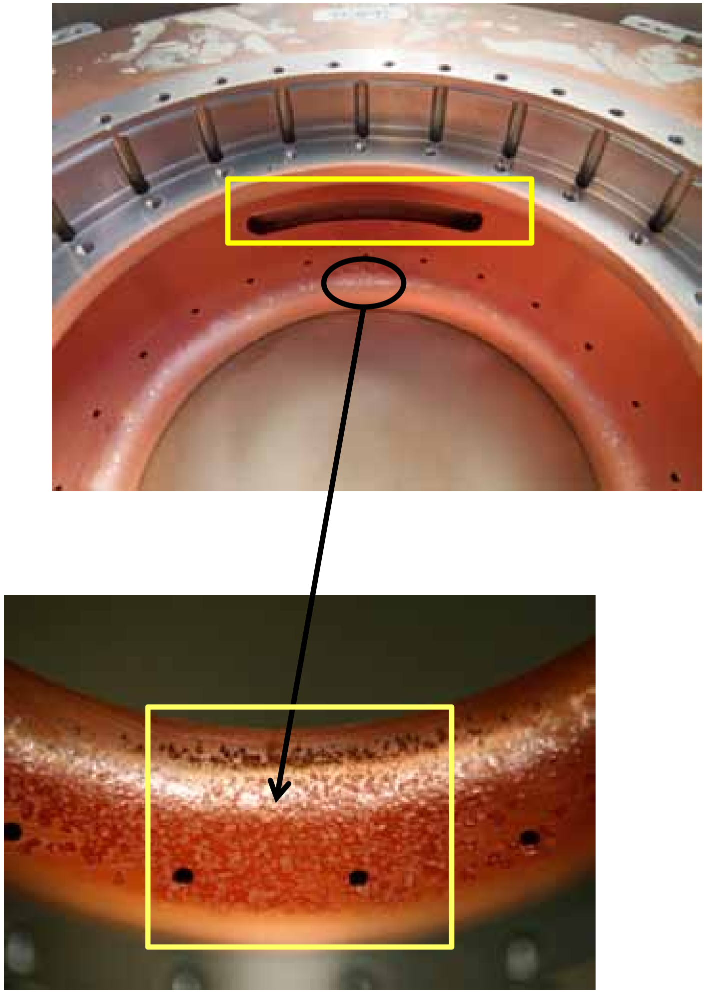
- Significant degradation in maximum stable operating gradient with applied B field

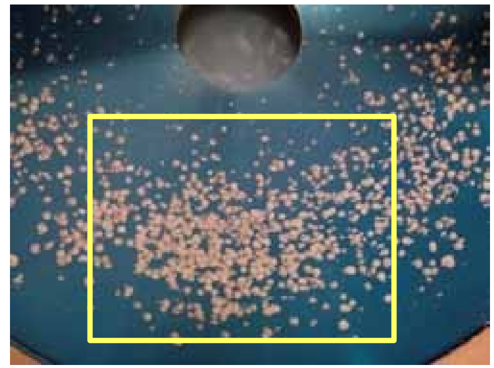


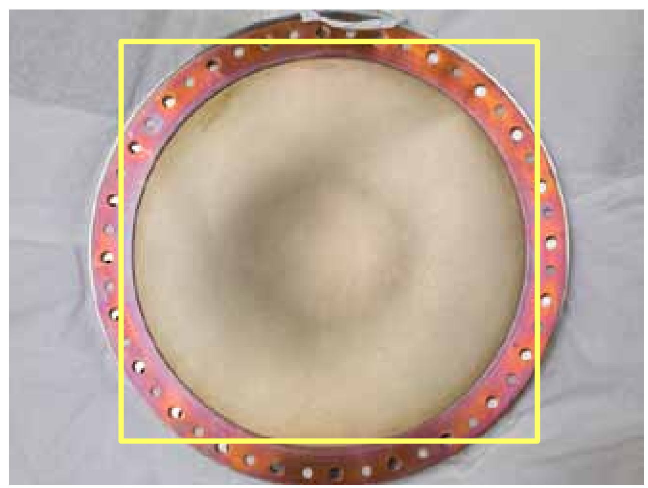
- 805 MHz RF Pillbox data
  - Curved Be windows
  - E parallel B
  - Electron current/arcs focused by B
- Degradation also observed with 201 MHz cavity
  - Qualitatively, quite different

805 Pillbox

Post-Mortem





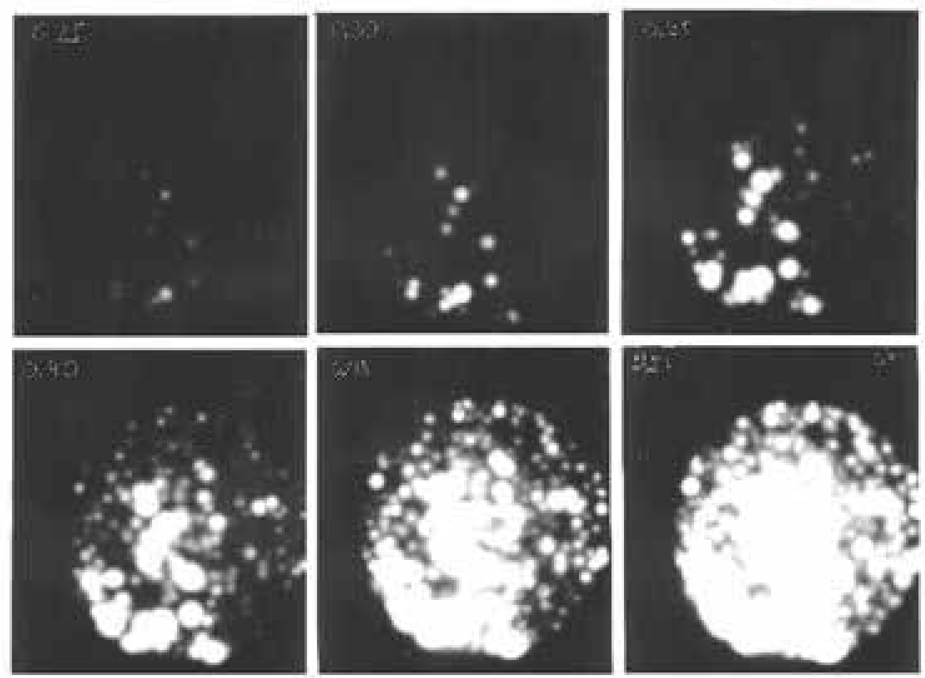


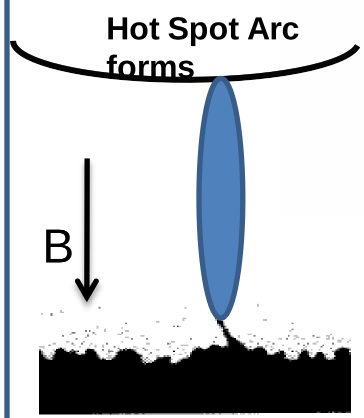
- Significant damage observed
  - Iris
  - RF coupler
  - Button holder
- However
  - No damage to Be window

805 MHz Imaging

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

8.8 - 17.6 MV/m





Cavity Energy
W=1/2 CV^2
» 1-5 joule
All goes into melting Cu

Surface Field Enhancement
Initiates the event & B focuses the e^- current which causes damage

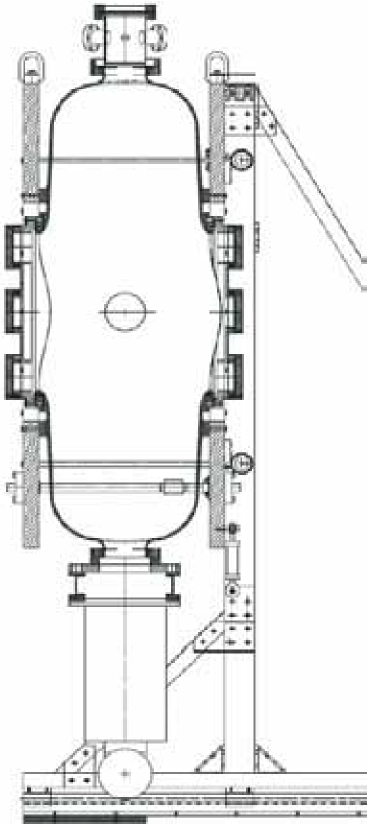
201 MHz Cavity Test

Treating NCRF cavities with SCRF processes

- The 201 MHz Cavity – *Achieved 21 MV/m*
  - Design gradient – 16MV/m
  - At 0.75T reached 10-12 MV/m

However, No observed damage!

201 MHz Prototype



Note: Stored energy available to sparks » 100J

RF Breakdowns

- Are not all equal
  - – NCRF conditioning (B=0), process allows for higher gradient operation *("conditioning")*
  - – NCRF (B ^{1} 0), process can cause damage and require re-conditioning at lower gradient in order to reach the same gradient attainable before breakdown

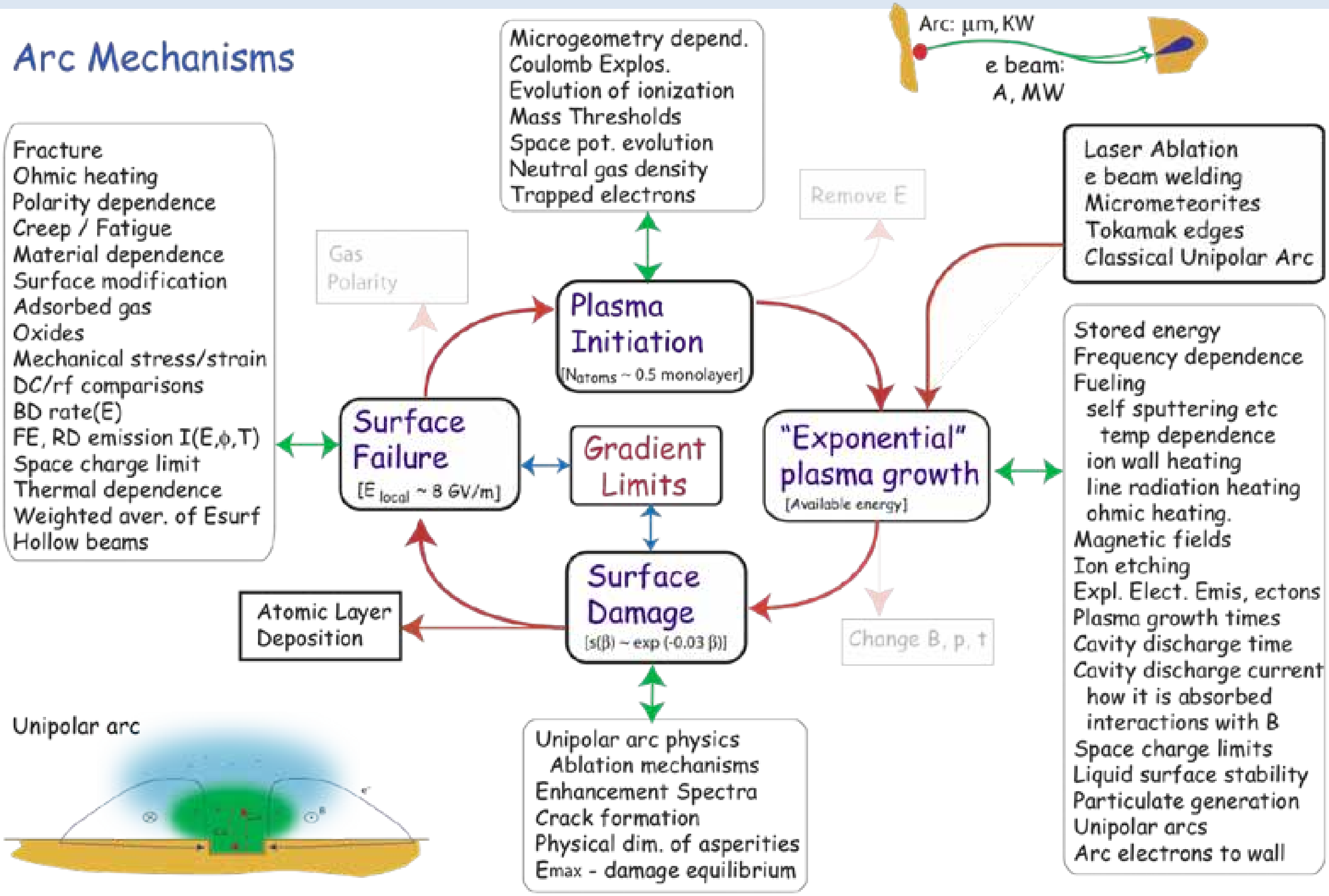
The Science of RF Breakdown

Vacuum

- In recent years, we have learned a great deal about the Science of RF Breakdown
  - Vacuum Arcs
    - An explanation of the formation of high b asperities
      - Surface Field Enhancements
    - Predictions of very high surface fields in arcs, consistent with measurements.
    - An explanation of the microstructure in arc pits
    - Preliminary results of arcs in static B fields.
    - Comparison with studies of unipolar arcs.
    - Calculations of sputtering and erosion rates.
  - Effects due to magnetically focused Field Emission
    - Including studies with SCRF

The Science of RF Breakdown II

Vacuum



Norem *et al.*, 2001-2010

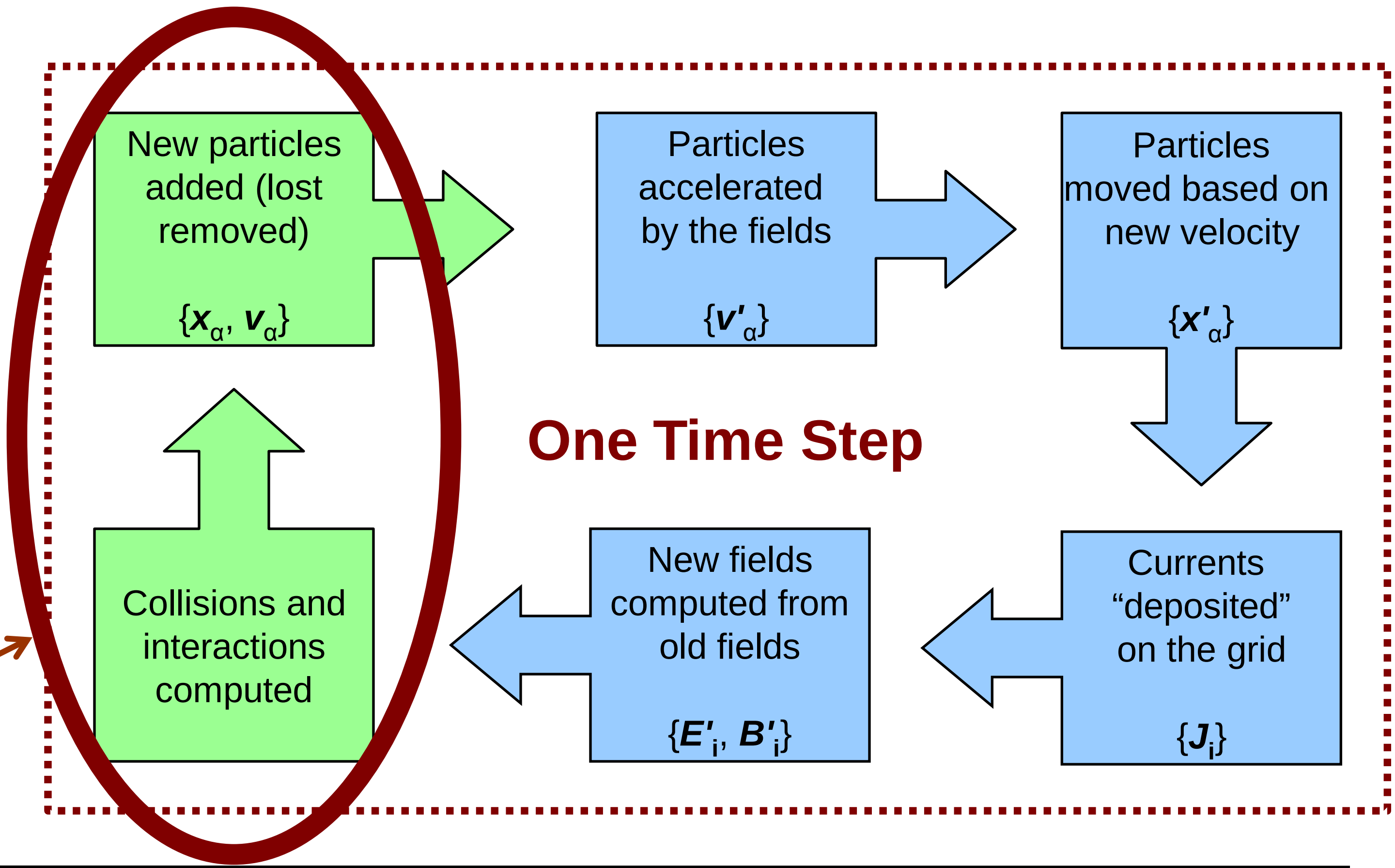
Workshop on Uni-polar Arcs, ANL, Jan. 2010
Breakdown Physics Workshop, CERN May 2010

The Science of RF Breakdown III

Vacuum

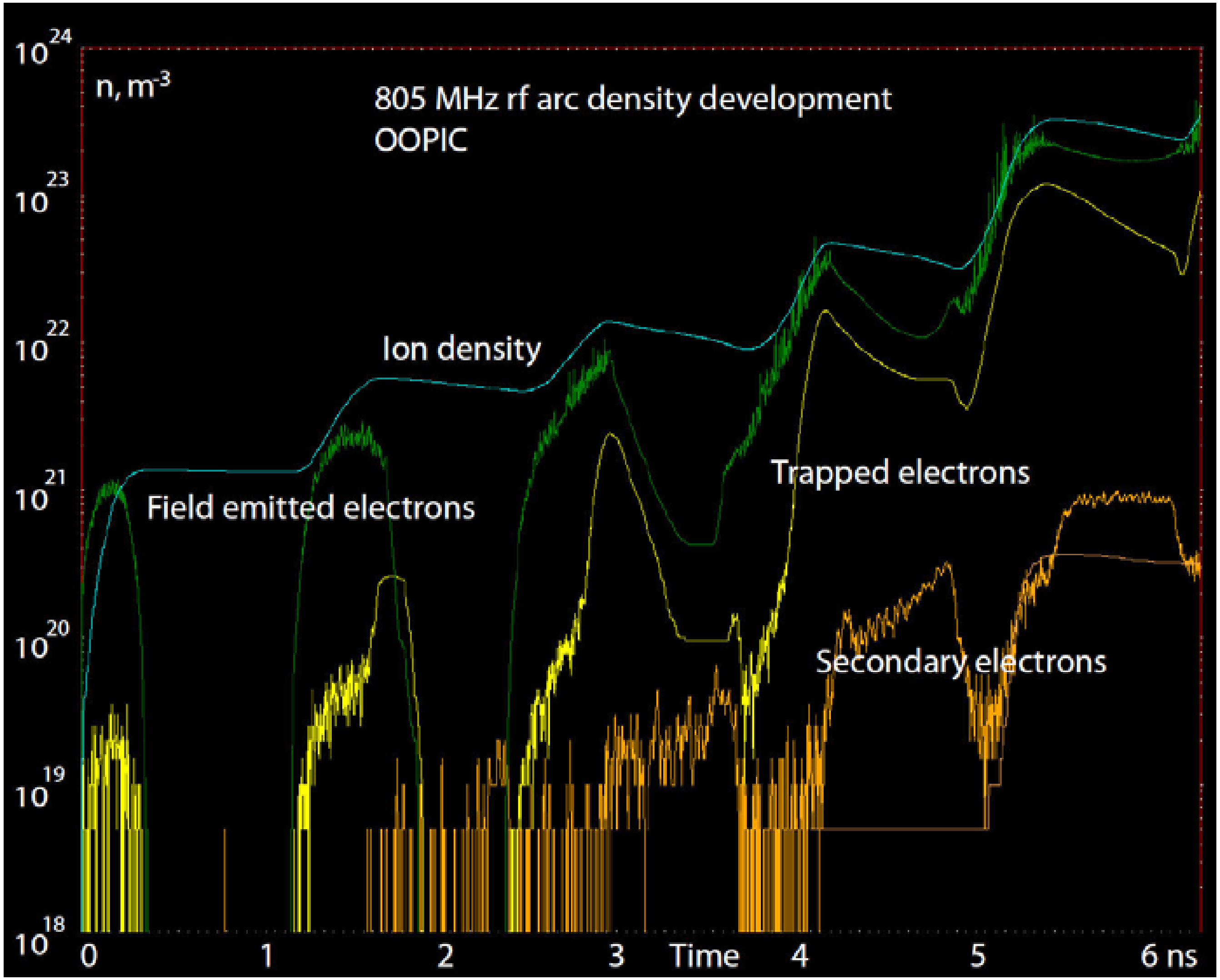
- Advanced Simulation Code
  - OOPIC & VORPAL: Kevin Paul, Tech-X

This is where all the interesting physics for RF breakdown takes place!!!



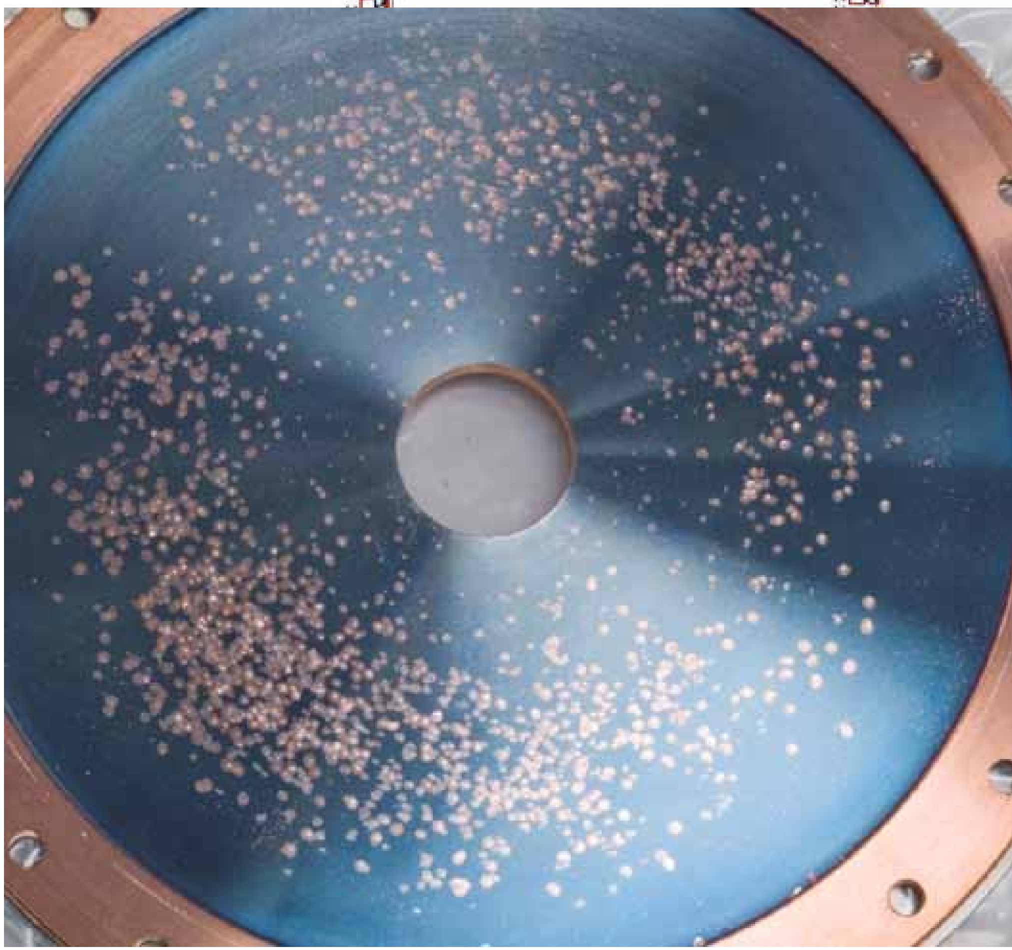
The Science of RF Breakdown IV

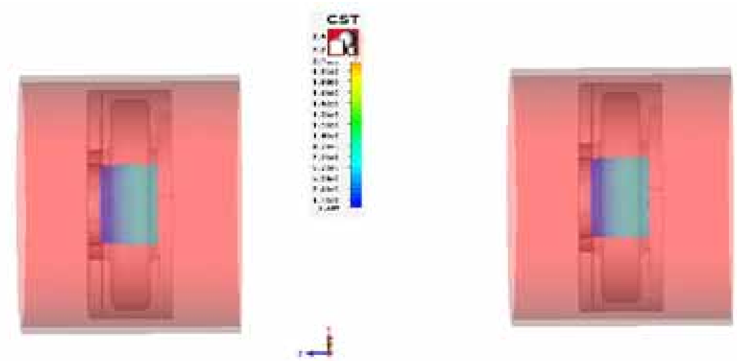
Vacuum



The Science of RF Breakdown V

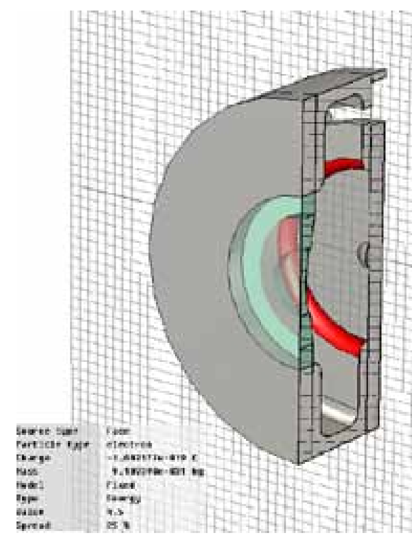
Vacuum





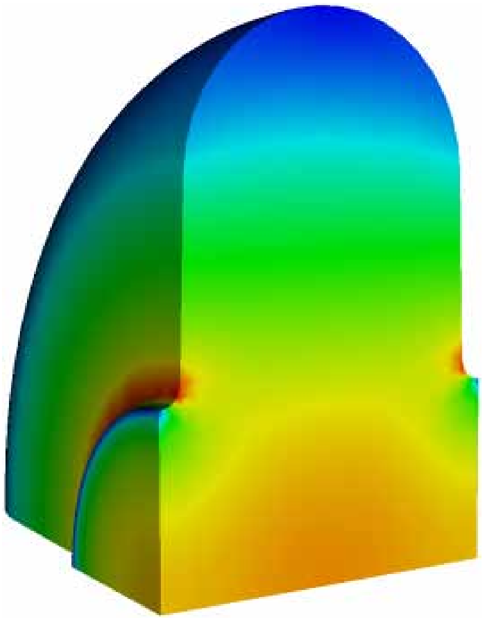
0.25 T **0.5 T**

ulation

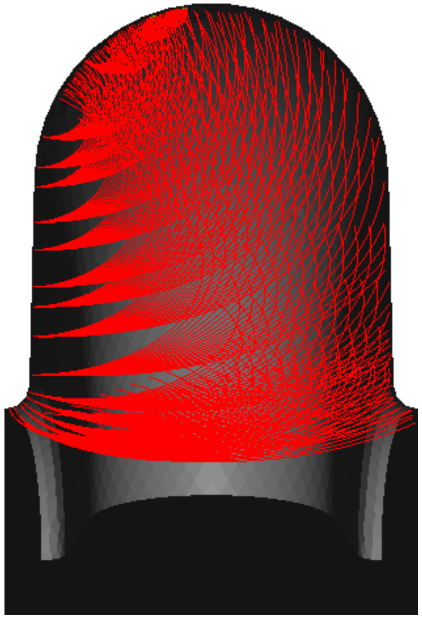


The Science of RF Breakdown VI
Vacuum

- Numerical studies at BNL and SLAC (in collaboration) using Omega-3P and Track-3P codes,
  - Cavity with flat windows: 5 MV/m on axis; 2-T uniform external magnetic field; scan of a few points from one cavity side



E field contour



Trajectories without external B field

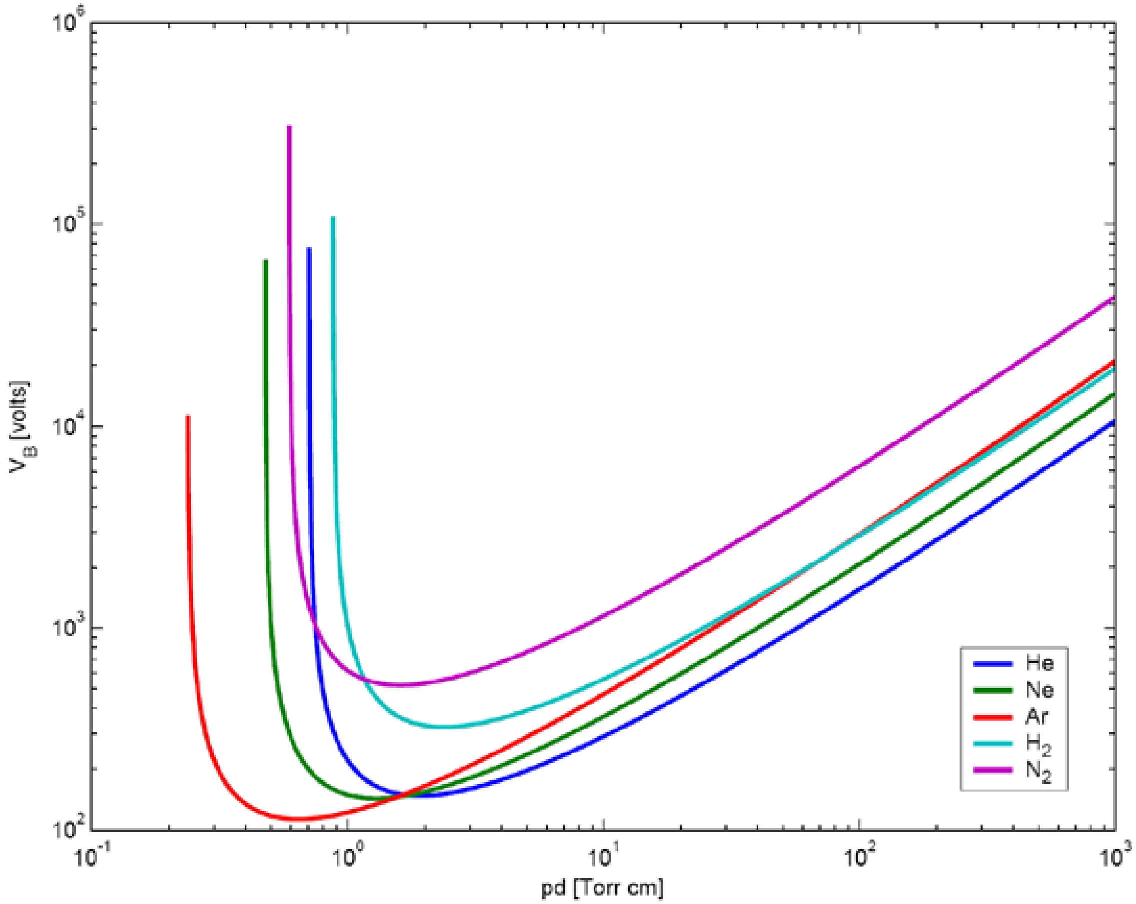
Trajectories with external B = 2-T field

The Science of RF Breakdown

Gas

- RF cavities filled with High-Pressure H_2
  - Paschen's Law

$$V_{bd} = \frac{a(pd)}{\ln(pd) + b}$$



Rolland Johnson
Shelter Island 2002

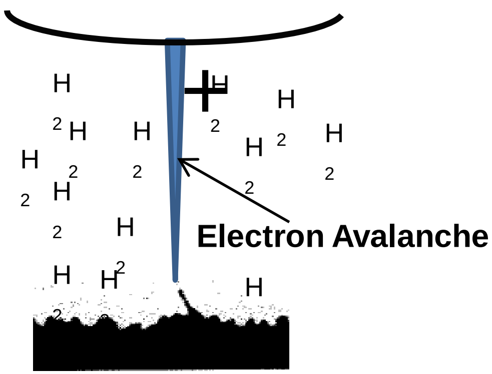
The Science of RF Breakdown II

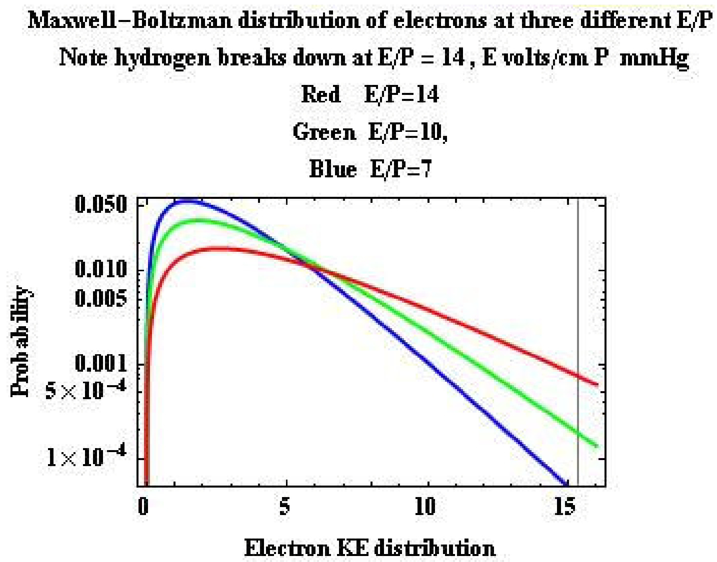
Gas

Gas Filled Cavities

No focusing of electron avalanche

$V_{rf} = V_o \, Sin[wt]$





Cavity Energy
$W=1/2\ C\ V^2$
» 1 joule ® Heats gas

Note: 40MV/m & 100 Atm
E/p » 5

Collision frequency >> cyclotron frequency
B has no effect !

Done?

The Science of RF Breakdown III

Gas

- However we want to operate with up to 10^{13} muons/pulse
  - – Beam-impact ionization + Ionization by secondary e^-

m+ H_2 à m+ H_2^+ + e^- $\qquad\qquad$ $e^- + H_2$ à $H_2^+ + 2e^-$

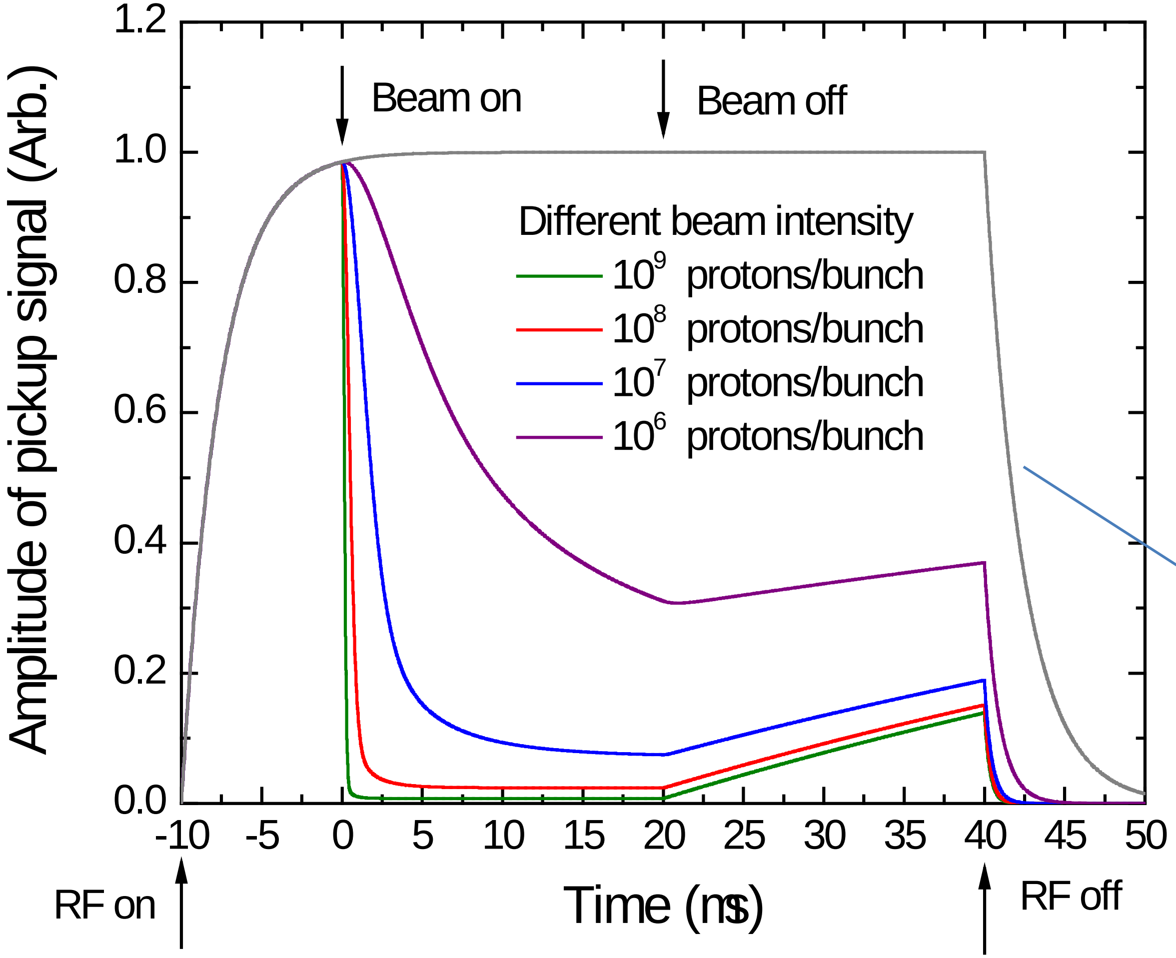
$$\frac{Dn_e}{1\ \text{muon}} » \frac{r\,(dE/dx)Ds}{W_i(» 35\ \text{eV})} ´ \frac{1}{(pr_b^2 Ds)} \sim 1000/\text{cm}^3$$

Most electrons (>90%) are quickly thermalized inside the cavity by elastic and inelastic collisions, and drift with RF until annihilated by recombination or attachment

The Science of RF Breakdown IV

Gas

see K. Yonehara's talk



1. Rapid decay of pickup signal according to the ionization rate

2. Saturation level and recovery rate determined by the recombination rate

Gray line: normal signal without beam

Solution:?
Electron "getter"
Electro-neg. Gas

Science of RF Breakdown

Summary

- Although the study of breakdown in RF cavities is an active (& continuing) field of research, and academic study of RF breakdown is not MAP's mission
- We know:
  - Without surface field enhancements, there is no field emission
  - Without field emission, the events that lead to the damaging breakdowns (B ¹ 0 will not occur)
- So:
  - Eliminate (ameliorate) the surface field enhancements
  - Or mitigate the damaging effects to the cavity from the resulting events

NCRF Program
R&D Strategy

Fermilab

- *Technology Assessment (continuation of existing multi-pronged program)*
  - Surface Processing
    - Reduce (eliminate?) surface field enhancements, field emission
      - SCRF processing techniques
        - » Electro-polishing (smooth by removing) + HP H_2O rinse
      - More advanced techniques (Atomic-Layer-Deposition (ALD))
        - » Smooth by adding to surface (conformal coating @ molecular level)

Vacuum

  - Materials studies: Use base materials that are more robust to the focusing effects of the magnetic field
    - Cavity bodies made from Be or possibly Mo
  - Magnetic Insulation
    - Inhibit focusing due to applied B
  - High-Pressure Gas-filled (H_2) cavities

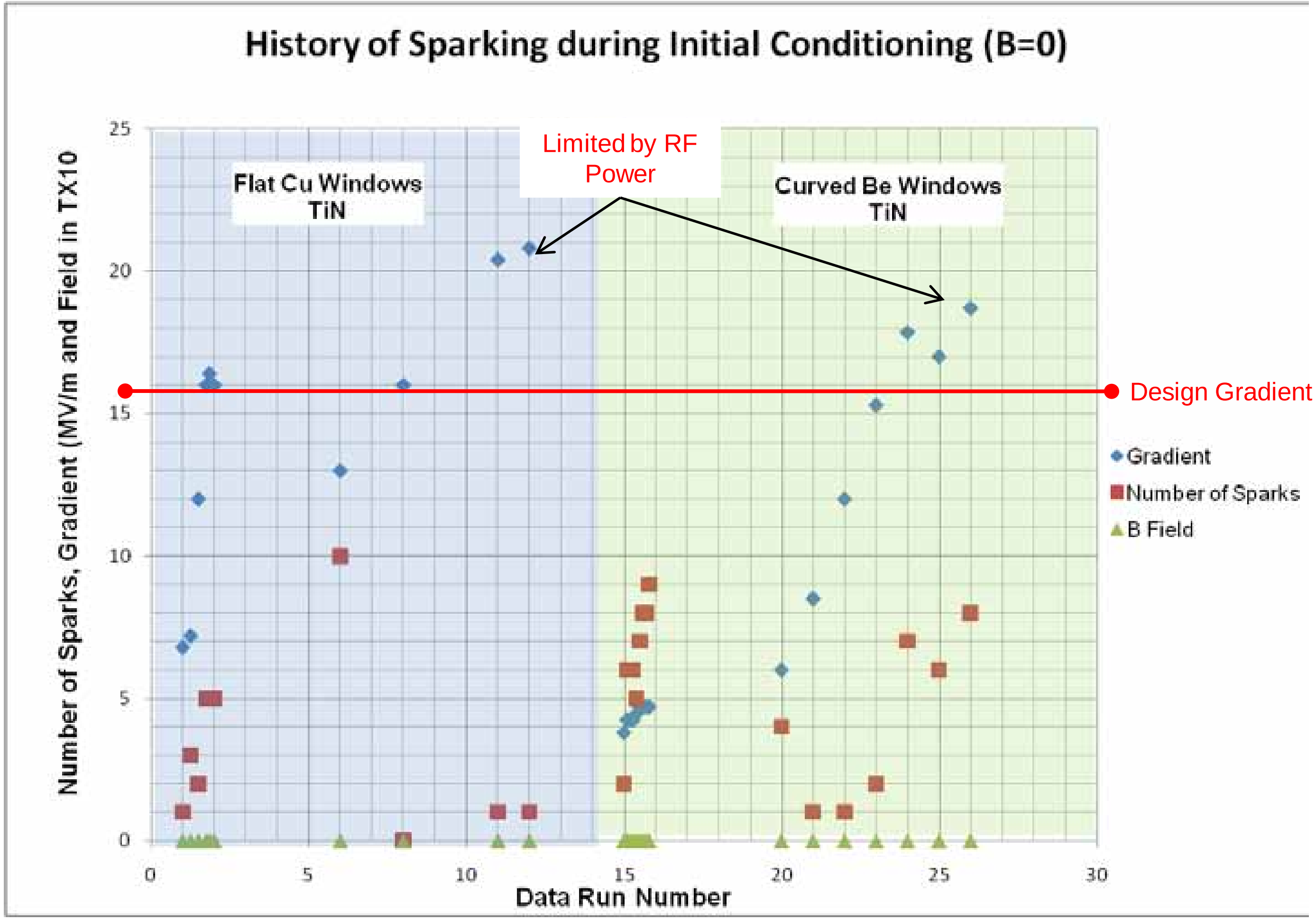
201 MHz Cavity Test

Treating NCRF cavities with SCRF processes

- ***21 MV/m*** *Gradient Achieved* (Design – 16MV/m)
  - *Limited by available RF power (4.5 MW)*

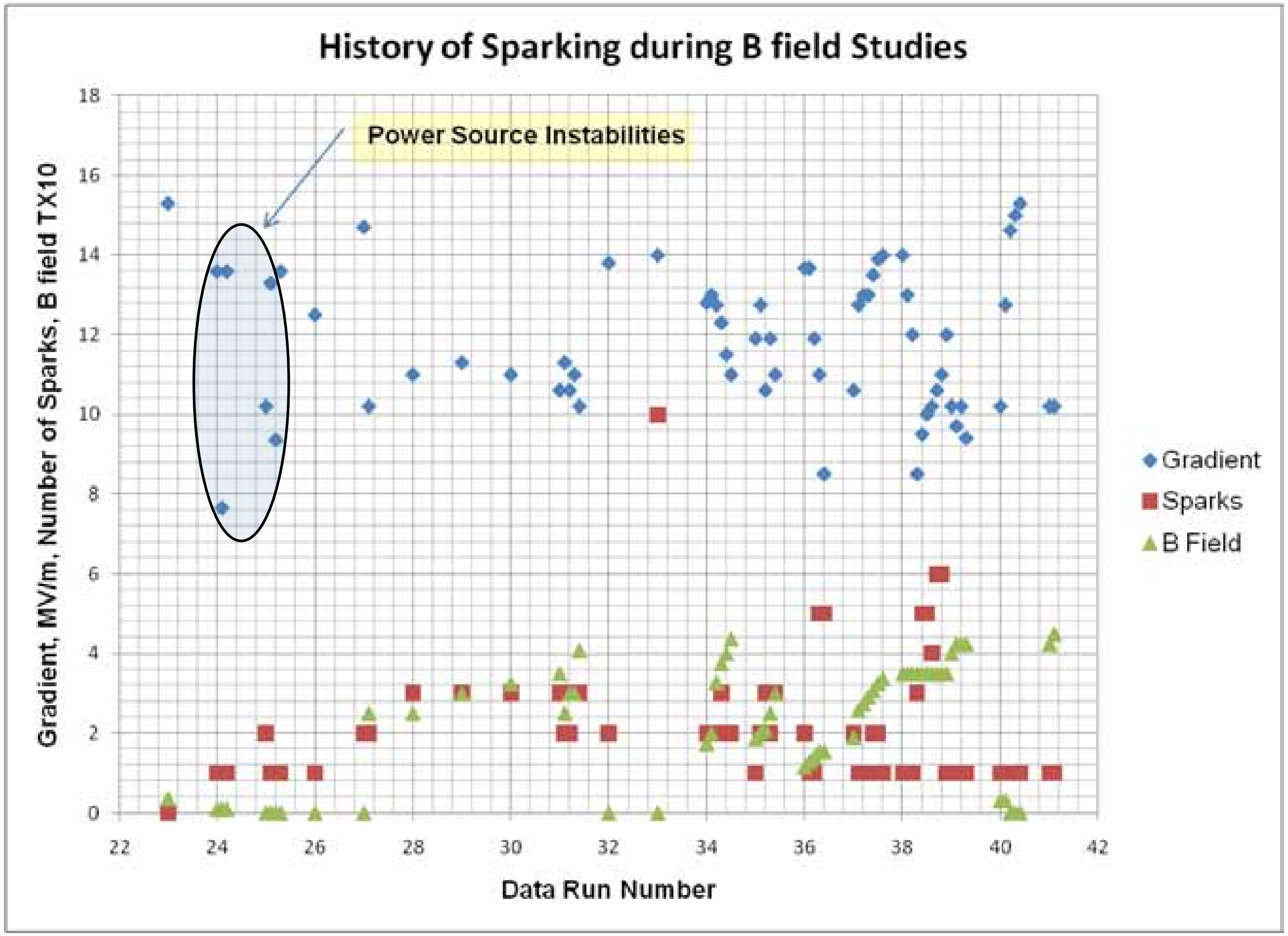
201 MHz Cavity Running

Summary I (B=0)



201 MHz Cavity Running

Summary II (B>0)

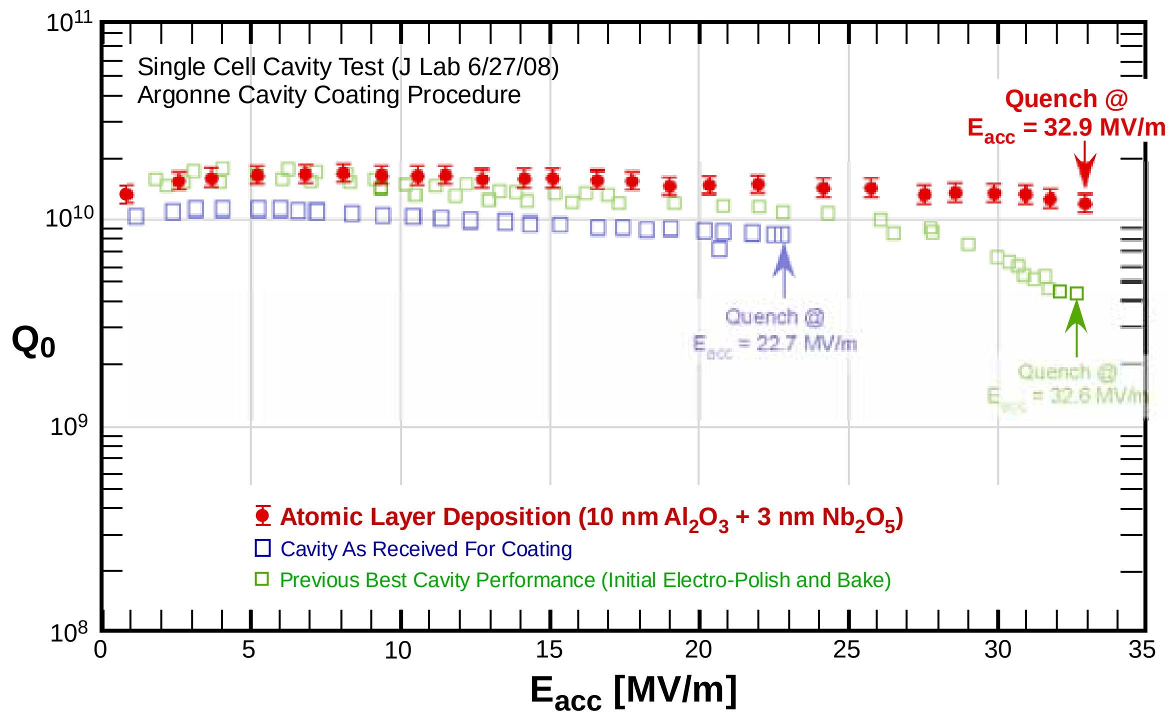


201 MHz Cavity B Field Tests
Summary

- Sparking @ B=0 did condition the 201 cavity
- Sparking @ B ¹ 0 causes damage (B relatively low)
- Although we "broke" the 201, it did re-condition @ B=0.
- But upon inspection of the cavity
  - No observed damage
    - SCRF processing techniques help

Advanced Processing Concept
Atomic Layer Deposition (ALD)

- Field enhancements in RF cavities root cause of surface breakdown
  - Due to high local electric fields that exist at surface asperities (field enhancements)
  - Cover asperities with a conformal coatings applied with Atomic Layer Deposition (ALD)
  - Has been applied to SCFR



1 example of ALD processing of 1.3GHz SCRF cell

NCRF R&D Program

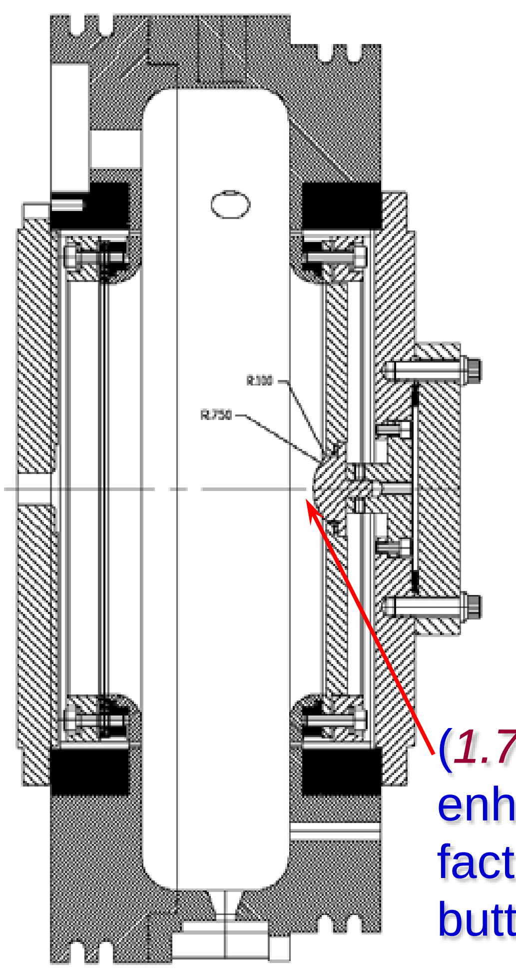
- Potential paths towards a solution: *Phase I: Technology Assessment* (continuation of existing program) Multi-pronged approach:
  - Surface Processing
    - Reduce (eliminate?) surface field enhancements, dark current
      - SCRF processing techniques
        - Electro-polishing (smooth by removing) + HP H_2O rinse
      - More advanced techniques (Atomic-Layer-Deposition (ALD))
        - Smooth by adding to surface (conformal coating @ molecular level)
  - Materials studies: Use base materials that are more robust to the focusing effects of the magnetic field
    - Cavity bodies made from Be or possibly Mo
  - Magnetic Insulation
  - High-Pressure Gas-filled (H_2) cavities

Vacuum

Material Studies

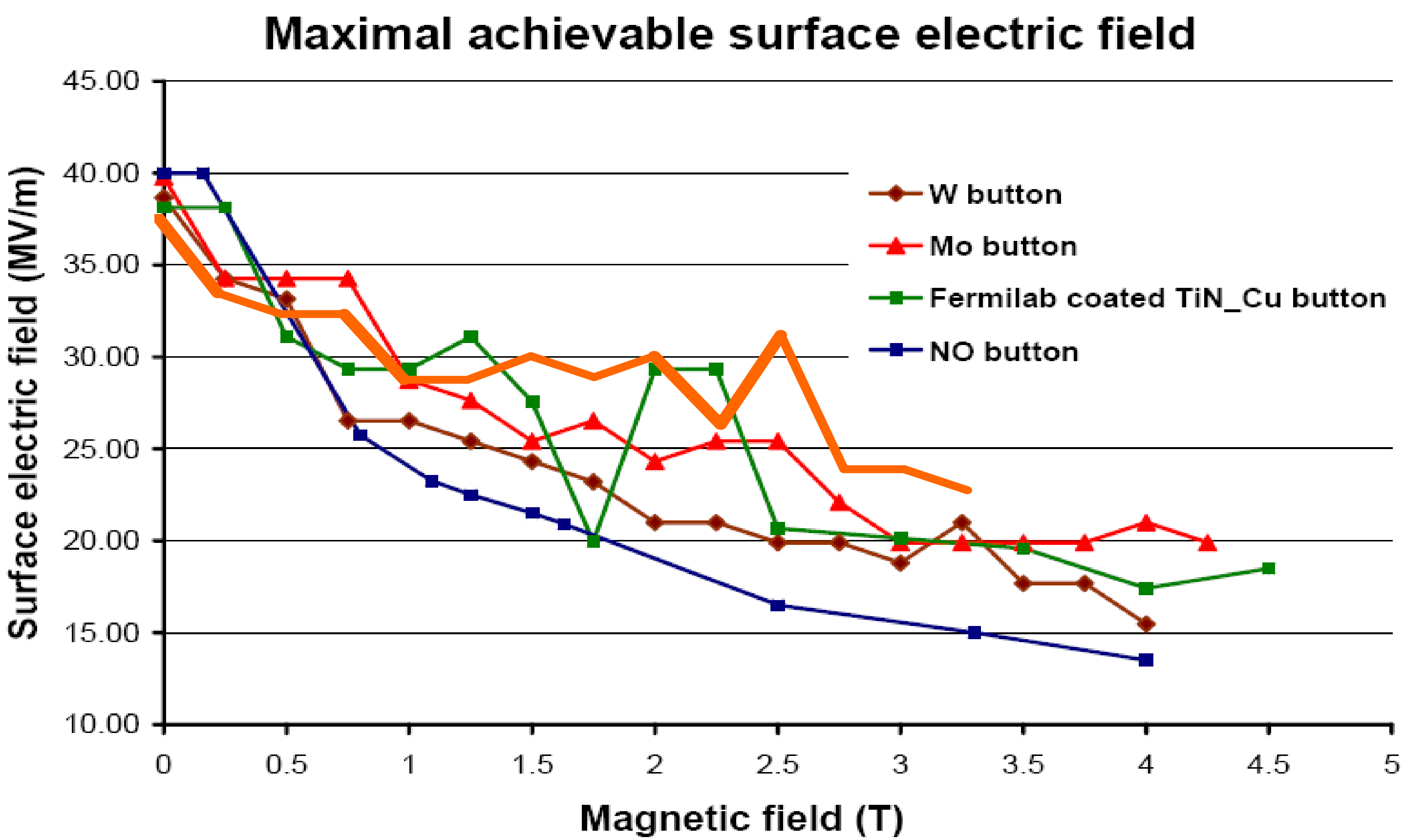
- “Button” system in pillbox cavity designed for easy replacement of test materials
  - Tested so far: TiN-coated Cu & Mo, bare Mo and W
  - Results to date indicate that Mo can improve performance at a given B field by somewhat more than 50%
  - 16.5MV/m ® 26MV/m

Molybdenum buttons



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

Button RF Cell Data
Summary



NCRF R&D Program

Ø Potential paths towards a solution: *Phase I: Technology Assessment* (continuation of existing program) Multi-pronged approach:

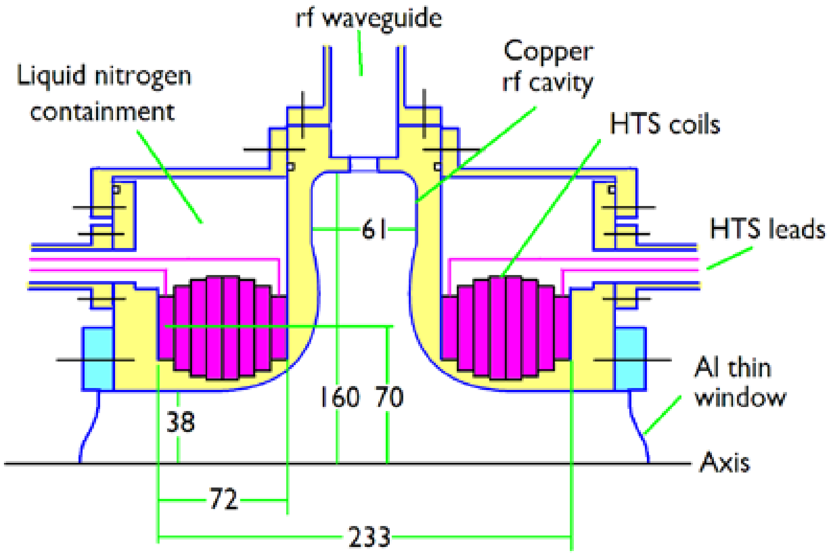
- Materials studies: Use base materials that are more robust to the focusing effects of the magnetic field
  - Cavity bodies made from Be or possibly Mo
- Surface Processing
  - Reduce (eliminate?) surface field enhancements, dark current
    - SCRF processing techniques
      - » Electro-polishing (smooth by removing) + HP H_2O rinse
    - More advanced techniques (Atomic-Layer-Deposition (ALD))
      - » Smooth by adding to surface (conformal coating @ molecular level)
- Magnetic Insulation
- High-Pressure Gas-filled (H_2) cavities

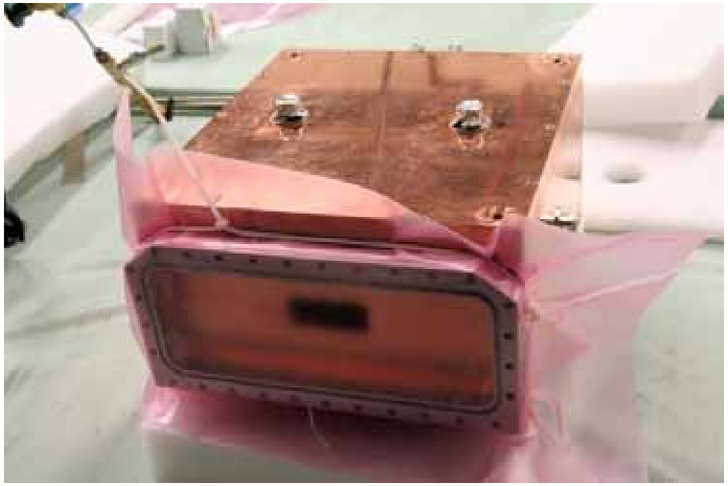
Vacuum

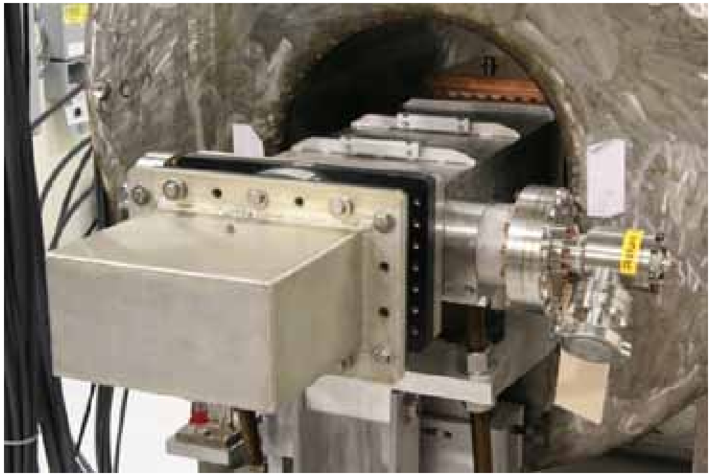
Fermilab

Magnetic Insulation

Conceptual Design



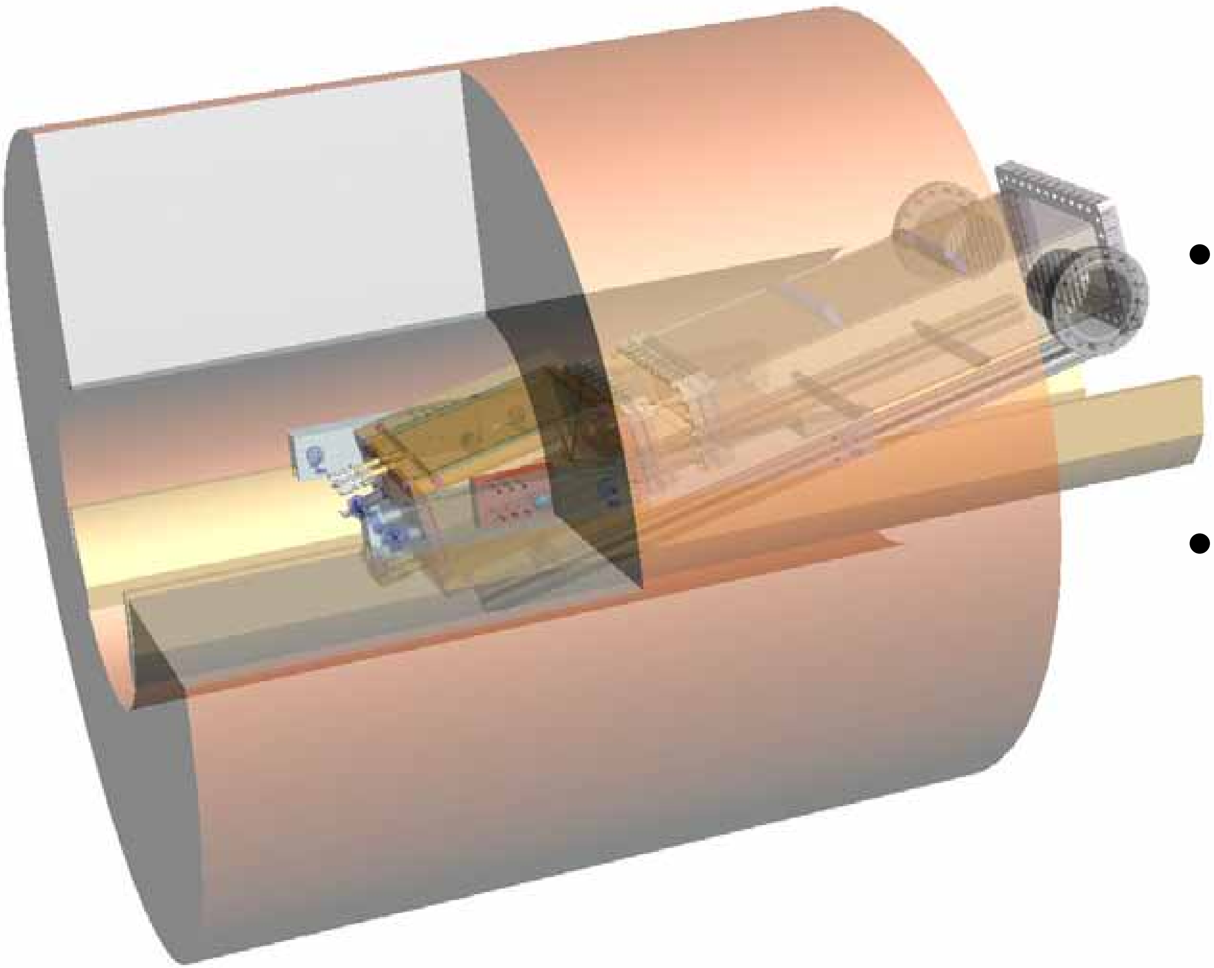




- Although lattices that employ magnetic insulation have drawbacks with respect to the required RF power, we are studying the concept using a newly completed 805 MHz box cavity

Fermilab

Box Cavity in Solenoid



- Max angle w/r to horizontal » 12^0
  - E at 78º w/r to B
- Max Gradient (B=0)
  - 40MV/m

Fermilab

NCRF R&D Program

Muon Accelerator Program

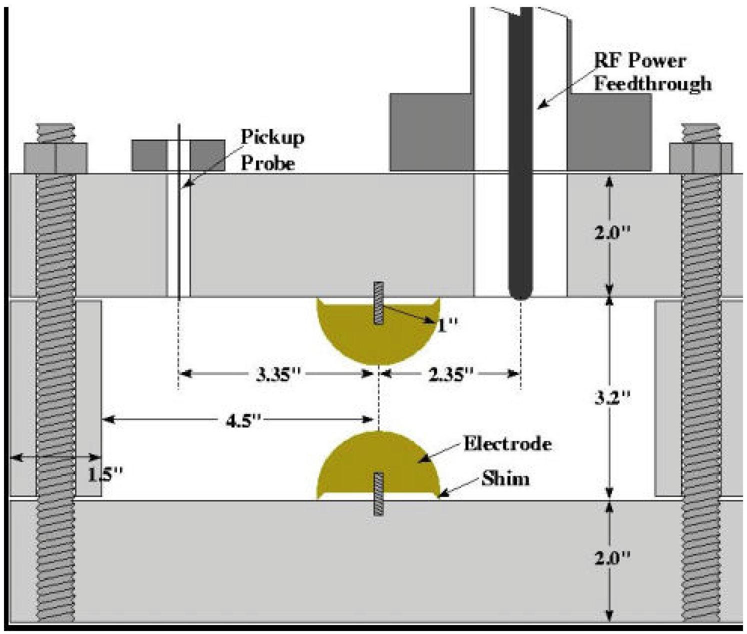
- Potential paths towards a solution: *Phase I: Technology Assessment* (continuation of existing program) Multi-pronged approach:
  - Materials studies: Use base materials that are more robust to the focusing effects of the magnetic field
    - Cavity bodies made from Be or possibly Mo
  - Surface Processing
    - Reduce (eliminate?) surface field enhancements, dark current
      - SCRF processing techniques
        - » Electro-polishing (smooth by removing) + HP H_2O rinse
      - More advanced techniques (Atomic-Layer-Deposition (ALD))
        - » Smooth by adding to surface (conformal coating @ molecular level)
  - Magnetic Insulation
  - High-Pressure Gas-filled (H_2) cavities

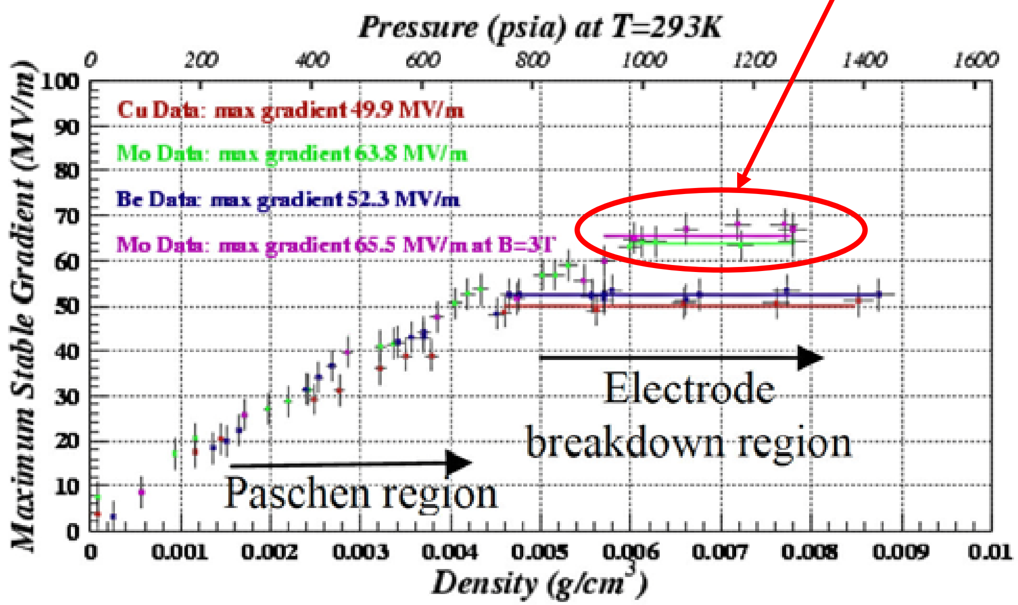
Vacuum

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**

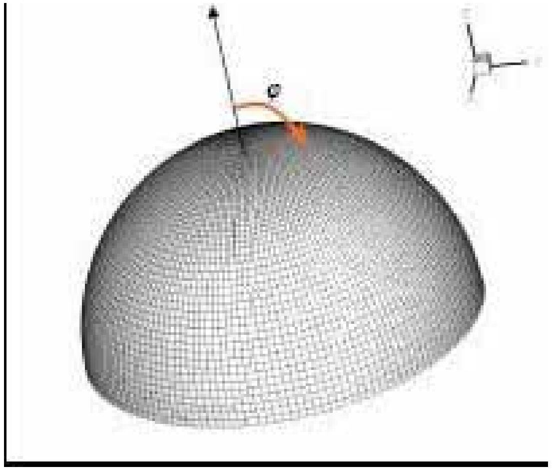
No Difference B=0 & B=3T

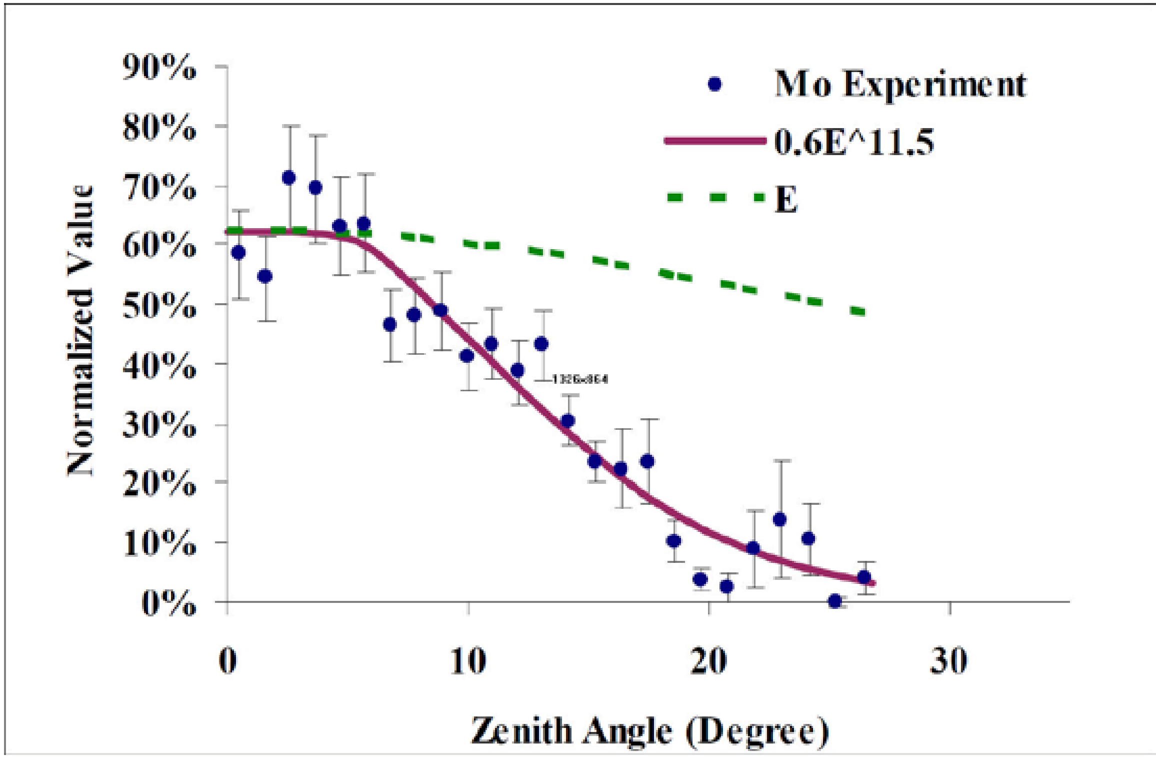




Well beyond gradient requirement for HCC

High Pressure H_2 Filled Cavity Results
In Surface Breakdown Regime

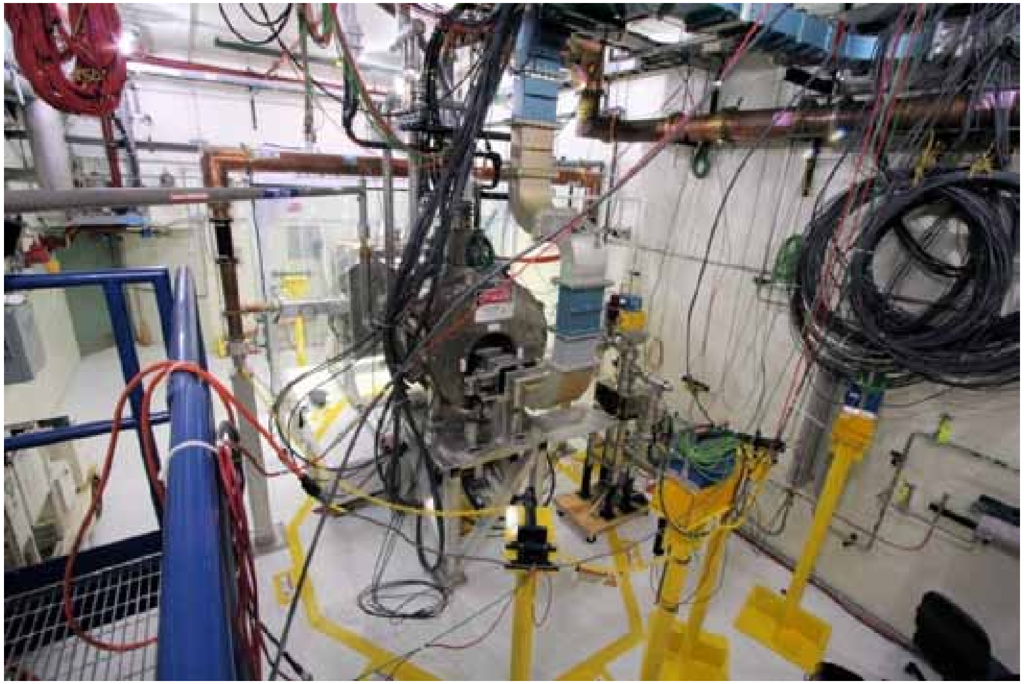




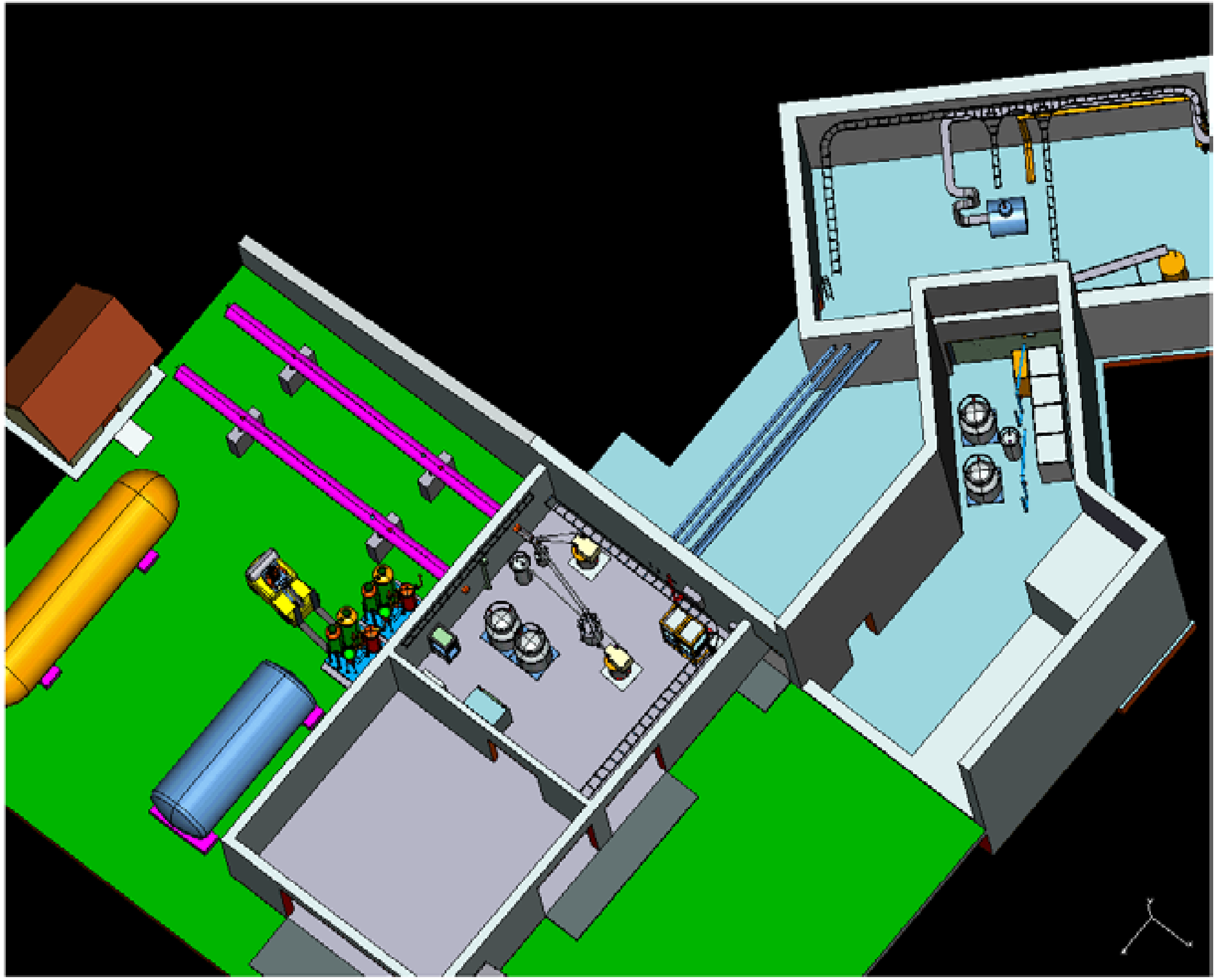
Pit distribution fit to E_{max} (ANSYS)
» Fowler-Nordheim

RF Test Facility

- MuCool Test Area (MTA)
  - RF power
    - 201 MHz (5MW)
    - 805 MHz (12 MW)
  - Class 100 clean room
  - 4T SC solenoid
    - 250W LHe cryo-plant
  - Instrumentation
    - Ion counters, scintillation counters, optical signal, spectrophotometer
  - 400 MeV p beam line



MTA Layout



MTA RF

MTA Cryo

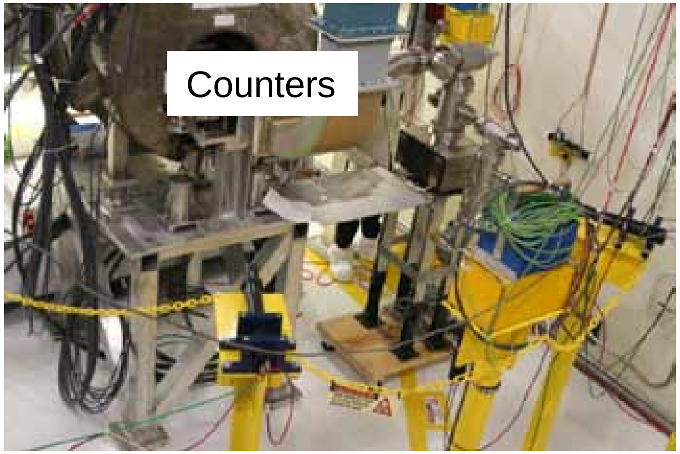
Valve Box & Transfer Line

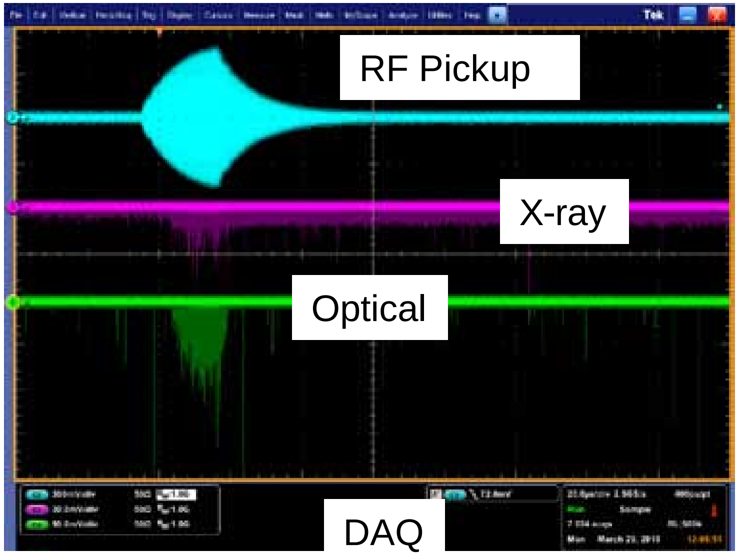
MTA Hall – Clean Room

MTA Hall – Clean Room II

- Goal for Clean room : Class 100
  - Achieved better than Class 10
    - Even with 3 people inside: Class 40
- Goal for Hall: Class 1000
  - Achieved Class 500

MTA Instrumentation



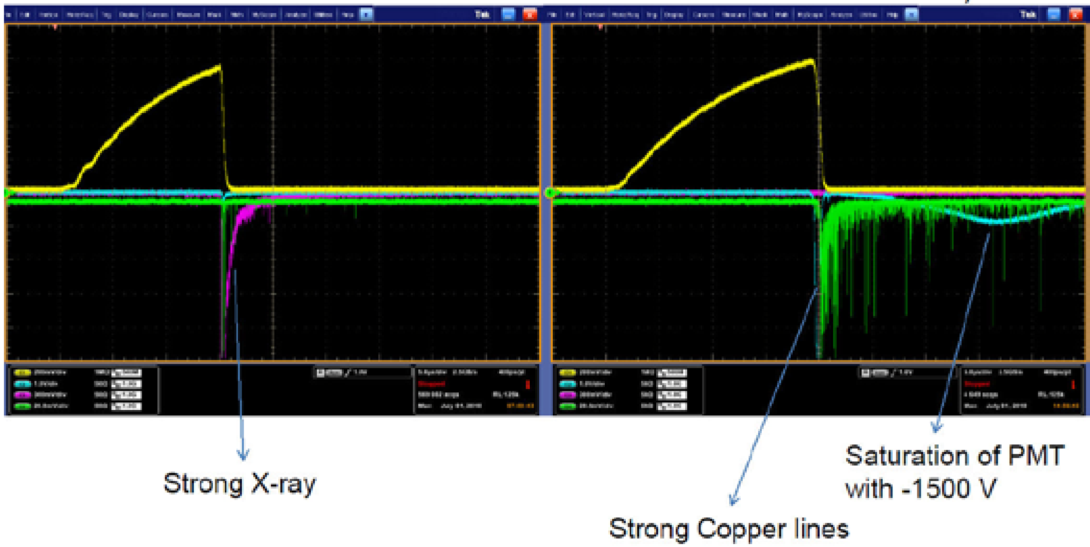


Optical Diagnostics

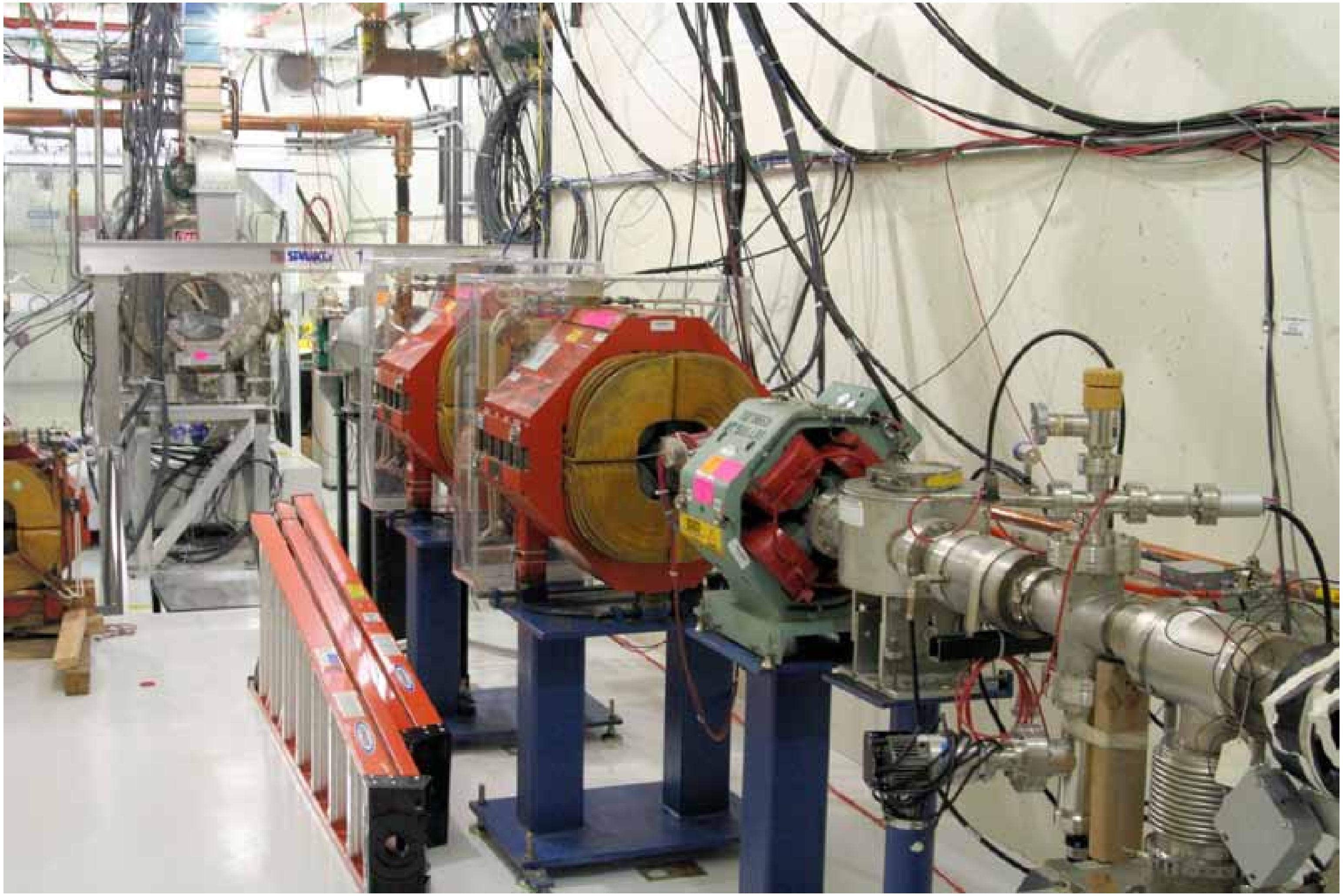
Yellow: Electric Pick Up
Cyan: Trigger PMT (-1500 V)
Magenta: X-ray (Channel 7)
Green: Spectrometer (515. 3 nm Copper line)

Data of 6/30: 0 T

Data of 7/01: 3 T, 0°

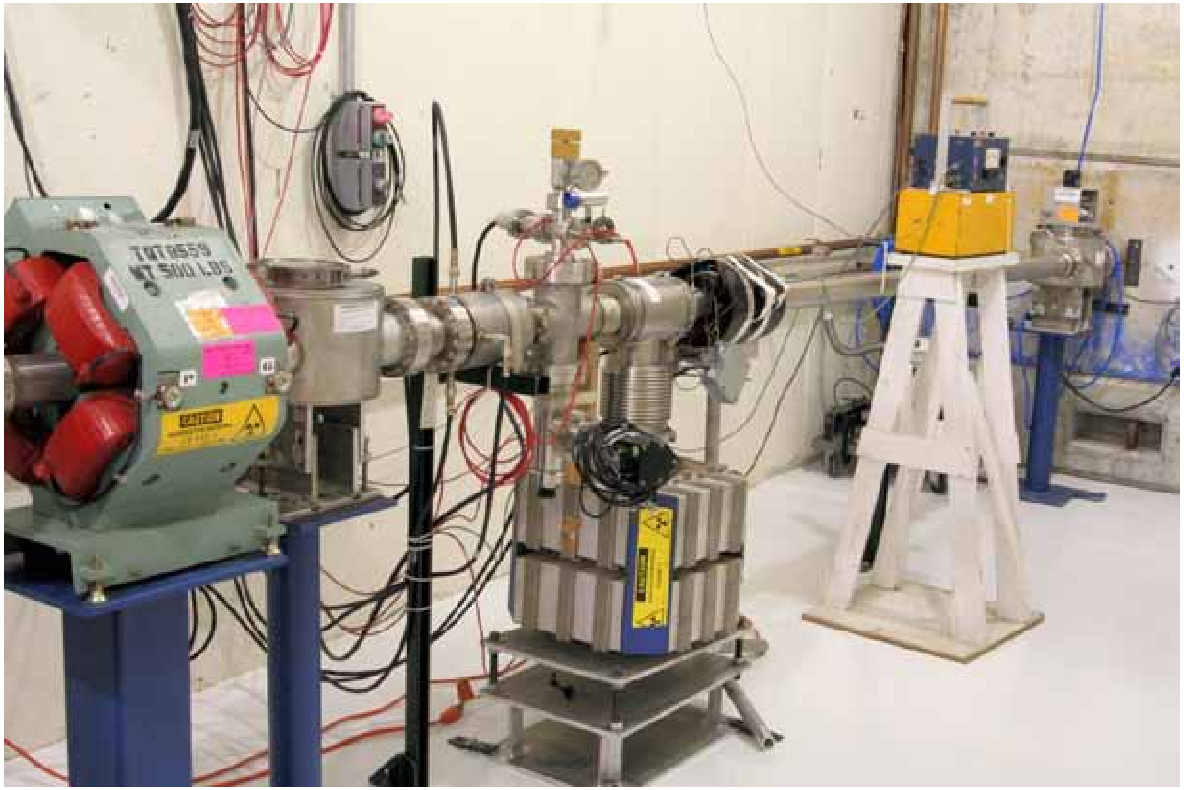


Current MTA Beam Line



MTA Beam Line Status

- Beam Line Installation
  - Complete
- Beam Line commissioning to first beam stop.
  - Complete
- First pass @ Radiation assessment review
  - Complete
- First beam experiments by the end of the year



The MTA is a World-Class Facility (& Unique):
High-Power RF; High-Intensity Beam; H_2 handling, SC Magnet

Phase I RF Program (2 year)

D. Li, Next Talk

- Complete tests on Magnetic Insulation
  - Second box test series with E ^ B
  - Box with orientation E || B
- Be materials tests
  - Button cavity test
  - Be wall cavity
- ALD coated button test
  - And with purpose RF cavity
- Beam tests of high pressure H_2 filled cavity
- 201 MHz tests in higher B field
  - Need new SC magnet - FY2012

RF Strategy

Down Selecting

- Down selection of RF cavities will be based on the outcome of the experimental studies. The successful cavity technology must work at an acceptable RF gradient (requirements are, of course, dependent on the position along the channel, i.e., phase rotation, bunching, initial cooling, final cooling, etc.) in a multi-tesla magnetic field. Engineering, fabrication, integration, and cost of the cavity and RF power must also be considered

Summary

- We have a comprehensive program aimed at developing a solution to the *"RF Challenge"*
- The experimental program is robust and scope-appropriate, is coupled with mature simulation efforts and is backed by a good understanding of the physics of breakdown/arcs in RF structures
- This multi-pronged approach gives us confidence that we can meet this challenge and minimize the risk to a future Muon Collider

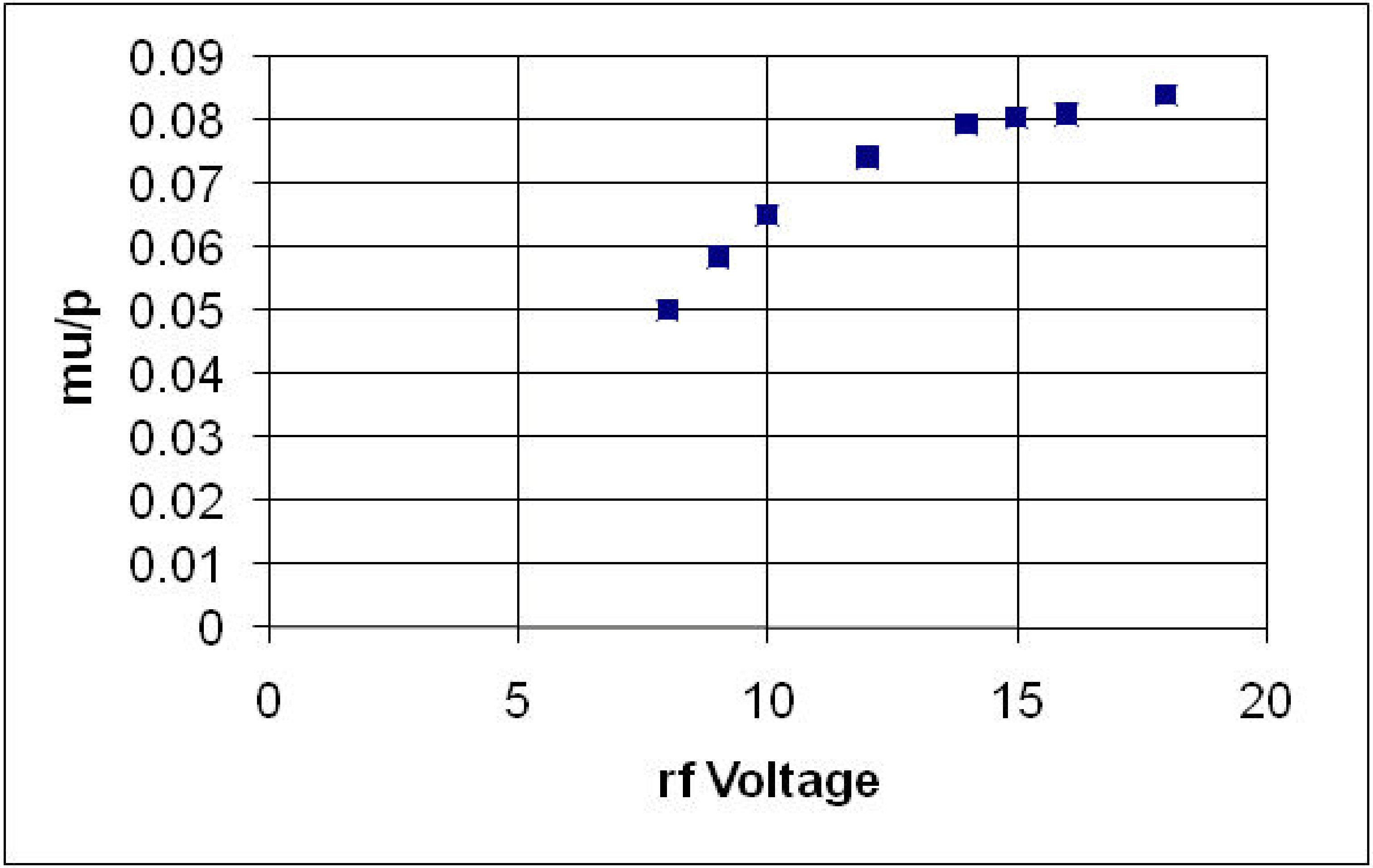
Acknowledgments

The ongoing effort on NCRF has a long list of contributors who have contributed to this presentation. I thank them all (in no particular order):

Bob Palmer Jim Norem Alvin Tollestrup Moses Chung
Bob Rimmer Derun Li Al Moretti Pierrick Hanlet Zubao Qian
Dazhang Huang Katsuya Yonehara Yagmur Torun Milorad Popovic
Diktys Stratakis Kevin Paul Steve Virostek Thomas Prolier

END

But it is not a Cliff



m/p after initial (4D cooling)