- This presentation is a recap of one we gave to DOE-OHEP in March.
  - Our most recent successes are therefore not included.
- This is a “meta-talk” -- I'm going to switch back and forth between explaining concepts and explaining explanations.
- Very little concrete feedback from DOE. We'll discuss this more at the end of the talk.

Normal Conducting RF R&D Experimental Program:

Utilizing the MTA Beyond MAP…

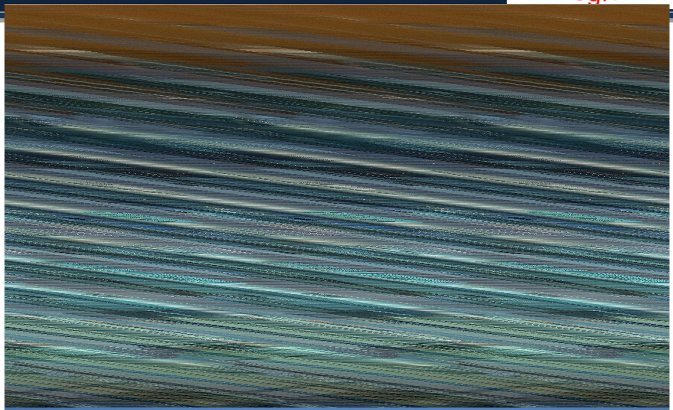
Daniel Bowring, Katsuya Yonehara

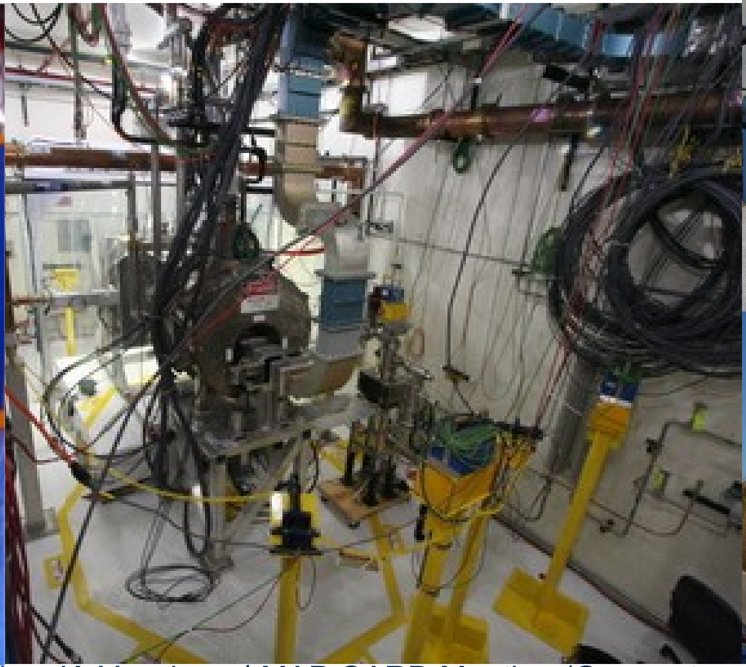
APC, Fermilab

March 30, 2015

MTA Overview I

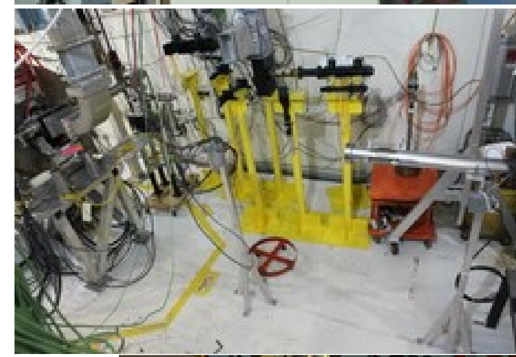
- Facility Includes:
  - Control area in Linac Gallery
  - Underground experimental hall
  - Surface building (cryogenics plant)





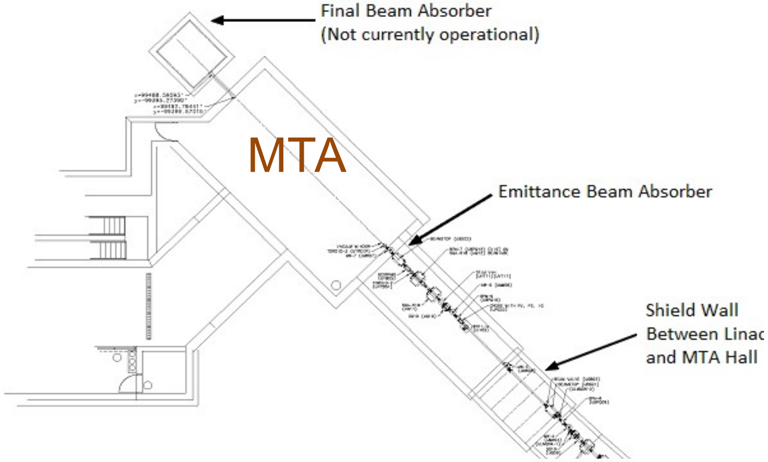
MTA Overview II

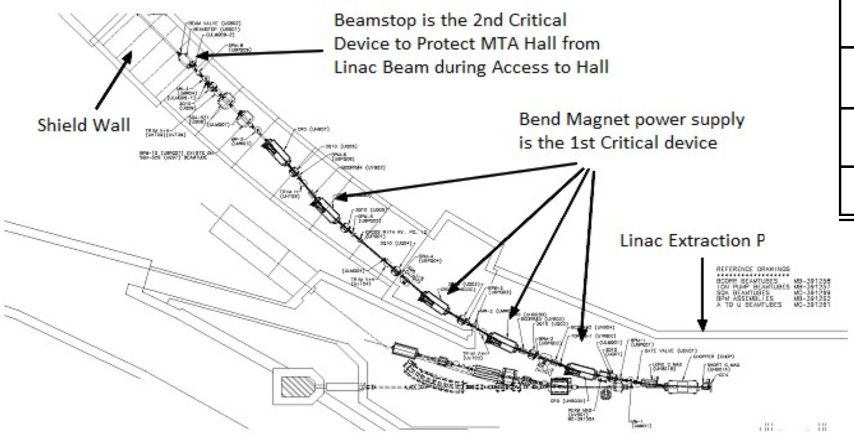
- RF Capability linked to Fermilab Linac
  - 805 MHz
    - 12 MW RF power available
    - RF switch, circulator and loads installed upstream
      - Allows klystron operation/service independent of MTA hall configuration
      - Provides clean RF signals for experimental data
    - RF switch and 2 waveguide branches in hall provide support for 2 independent test stations
  - 201 MHz
    - 4.5 MW RF power available
    - RF switch and load installed upstream
      - Allows amplifier operation independent of the MTA hall configuration
- Extensive diagnostics available for RF cavity characterization



MTA Overview III

- 400-MeV H- beamline and instrumentation
  - Commissioned to multiple locations within hall





Parameter	Value	Unit
Kinetic Energy	400	MeV
Energy Spread Full Width	1.25	MeV
Beam Current	25	mA
RF Structure	201.24	MHz
Bunch Length (95%)	<0.8	ns
Pulse Length	Up to 50	μs
Max Particles/Bunch	7.5×10^{8}	
Max Particles/Pulse	7.5×10^{12}	
Max Beam Power	7.5	kW
Beam Emittance (95%, normalized)	8	pi mm-mrad

RF R&D: Introduction

- High Gradient Normal Conducting RF (NCRF) R&D
  - Program at the MTA focuses on:
    - In-depth understanding of the physics of RF breakdown
    - Design requirements for operating cavities in strong magnetic fields
      - Surface preparation techniques that can significantly benefit overall NCRF performance (with and without B-field)
      - The use of high pressure gas to suppress RF breakdown
        …including studies of the beam interaction with the gaseous medium
      - The development of compact dielectric-loaded RF structures
    - R&D of RF in a magnetic field also benefits
      - Application of RF photocathode guns, etc.
      - Conditioning of fusion reactors
      - Novel detector technologies
  - Program Goals under MAP a NCRF cavities with gradients of:

    25 MV/m @ 805 MHz and 3 T

    16 MV/m @ 201 MHz and 3 T

RF R&D: Key Accomplishments

- Novel high gradient NCRF cavities
  - Development of RF cavities with conventional open beam irises terminated by beryllium windows
    a higher shunt Impedance
    a lower RF power
  - Development of beryllium windows
    - Thin and pre-curved beryllium windows for 805 and 201 MHz cavities

- Design, fabrication and testing of a range of NCRF cavities
  - Vacuum cavities utilizing SCRF surface preparation techniques
    - Able to achieve full power operation with no preliminary processing
  - 805 MHz pillbox cavities
    - Enabling detailed validation of physics models of RF breakdown
  - 201 MHz Cavity Prototype for the International Muon Ionization Cooling Experiment (MICE)
    - Operational testing for the demonstration of ionization cooling
  - HPRF cavities
    - Beam tests to validate beam-induced plasma formation, mitigation and impacts
    - Validation of dielectric-loaded cavity concepts

Why Should This Be Of Interest to OHEP?

Although SCRF has been a major R&D focus of the field…

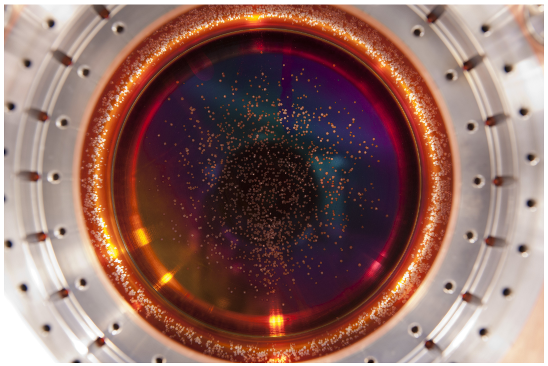
- Normal conducting RF remains a major component of accelerator design
- The accomplishments noted here enhance NCRF capabilities
  - More robust
  - Higher gradient
  - An expanded range of potential applications of these structures

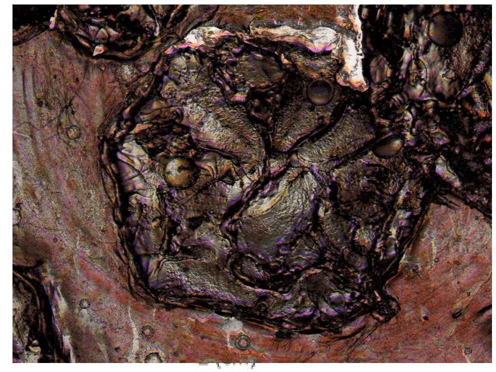
RF R&D: Thrusts Beyond MAP

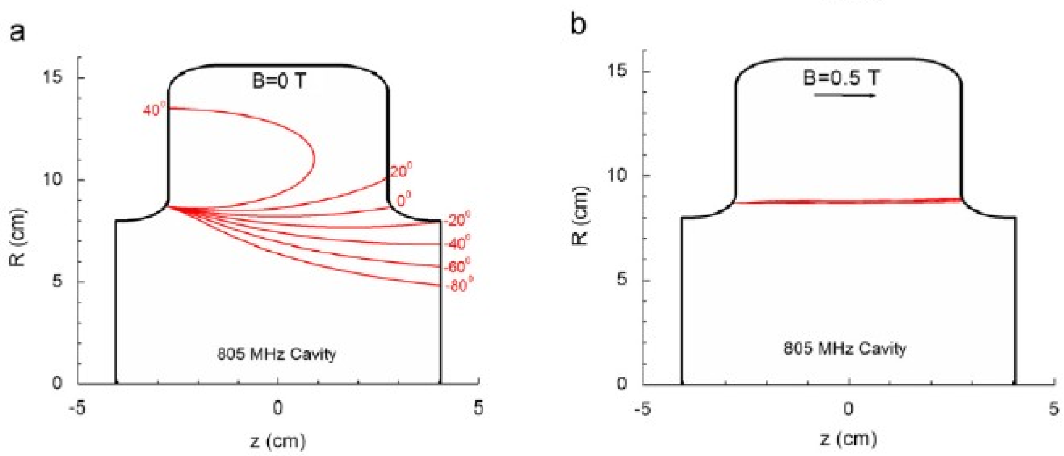
- Two major thrusts of NCRF R&D are proposed for continuation within the GARD portfolio:
  - Vacuum RF Studies using the 805 MHz "Modular" Cavity
    - Understand key features of our model of RF breakdown and damage
    - Synergistic with other high gradient R&D
  - High Pressure RF Studies
    - Novel applications of beam acceleration
    - RF energy storage systems
    - Set the stage for new detector technologies relevant to the neutrino program

RF R&D: Vacuum Cavity Program

Fowler-Nordheim current may be focused by strong *B*-fields into beamlets, leading to cyclic fatigue, breakdown.





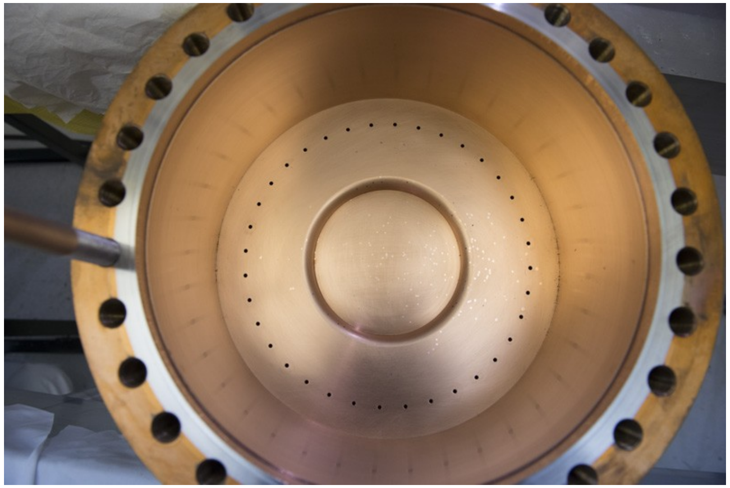


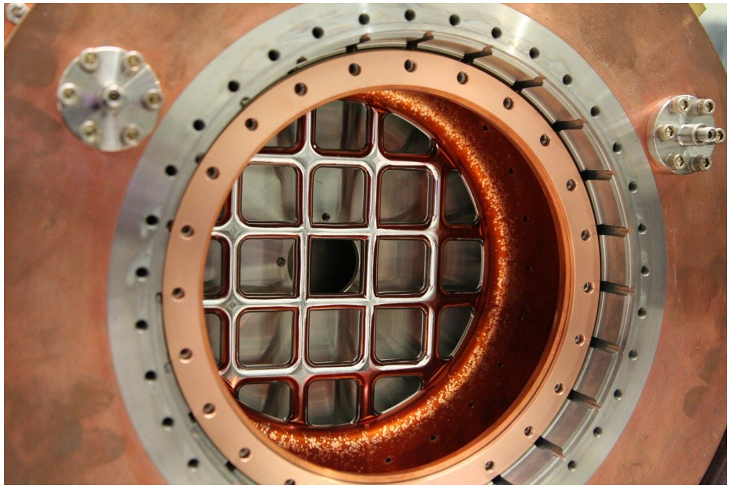
D. Stratakis *et al.* NIMA 620 (2010) 147-154.

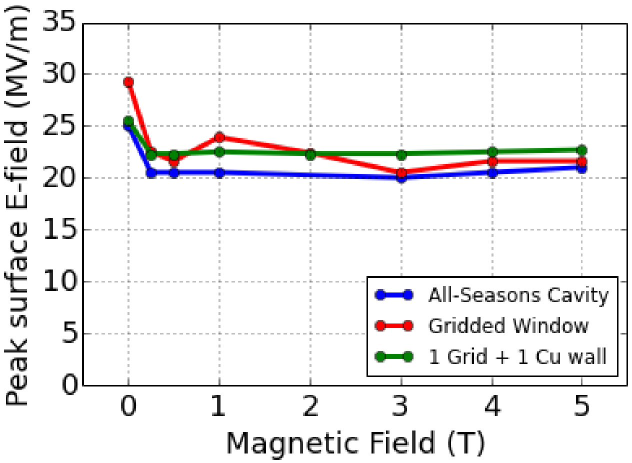
The experimental basis for this model is presented on the following slide.

RF R&D: Vacuum Cavity Program

Observed cavity behavior fits our model of breakdown in strong magnetic fields.



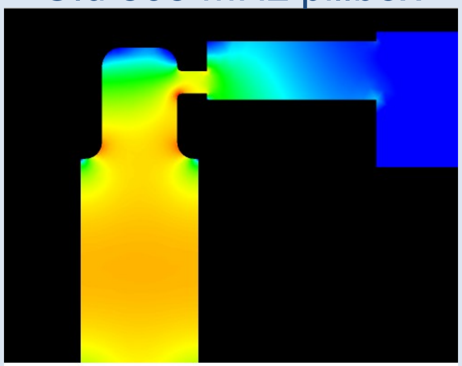


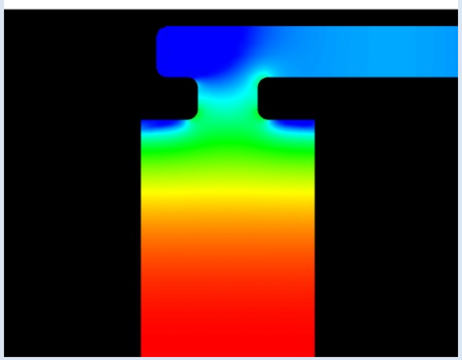


The 805 MHz “Modular Cavity” design addresses these issues directly.

Surface E-field at couplers is 5x lower than at cavity axis.

Old 805 MHz pillbox

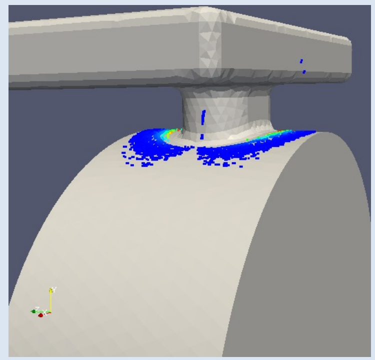


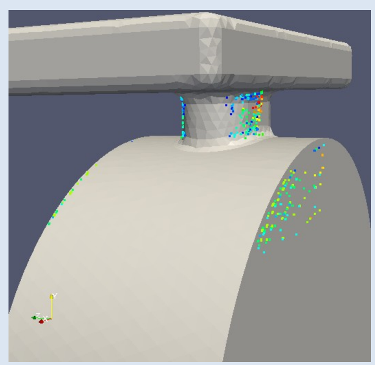


Modular cavity

Multipacting is optimized over a range of *B*-field values.

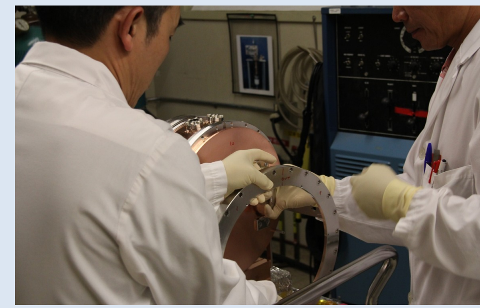
B = 0 Tesla

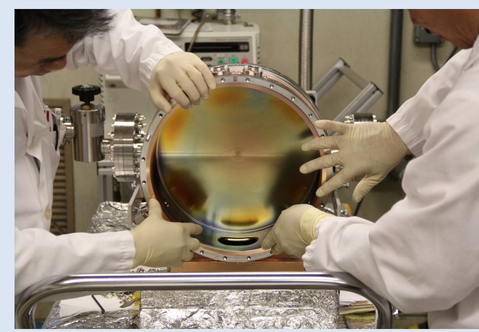




B = 3 Tesla

End walls easily removed for inspection, reconfiguration, materials studies.

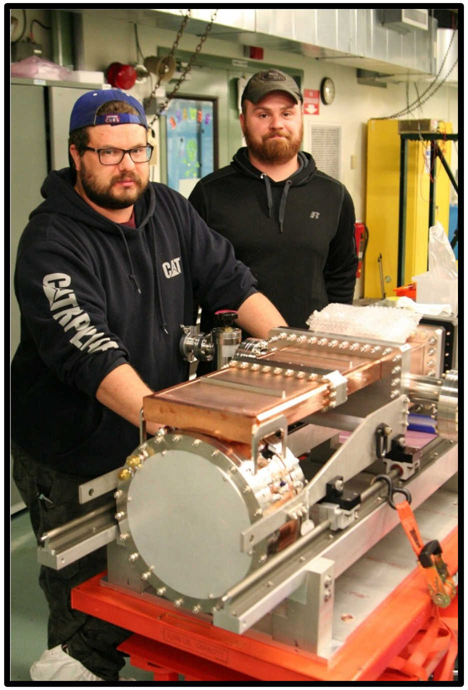


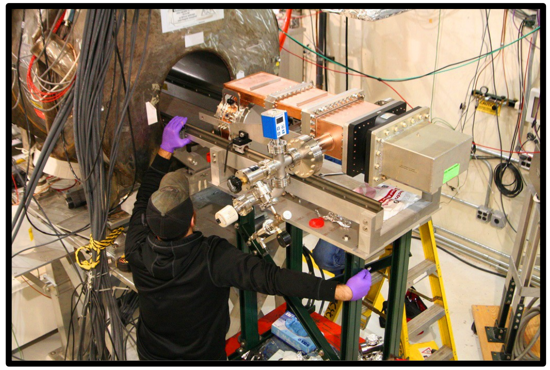


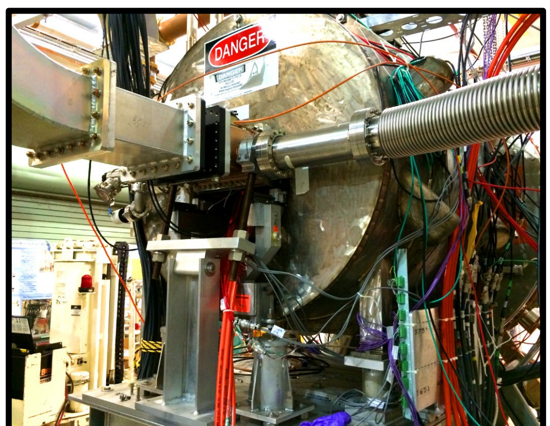
Not shown: Extensive instrumentation (e.g. Faraday cup), cooling circuits. Improved DAQ.

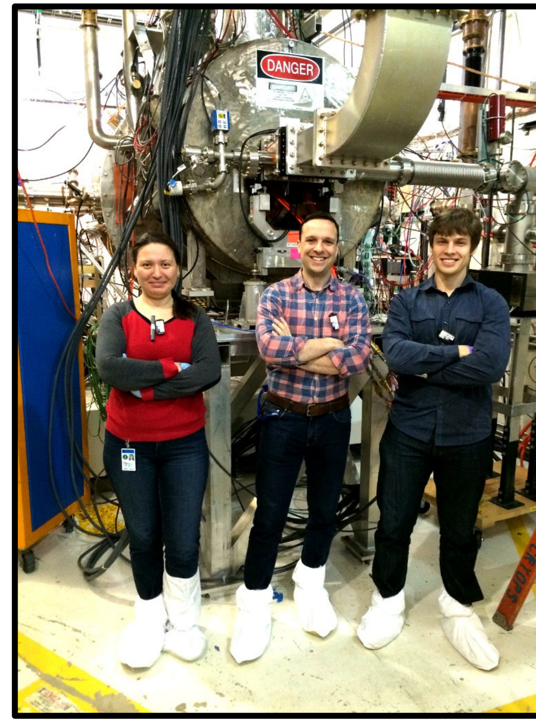
RF R&D: Modular Cavity Program

Verifying this model requires 2-3 years of measurements with the modular cavity, extending ~1-1.5 years beyond end of MAP support.







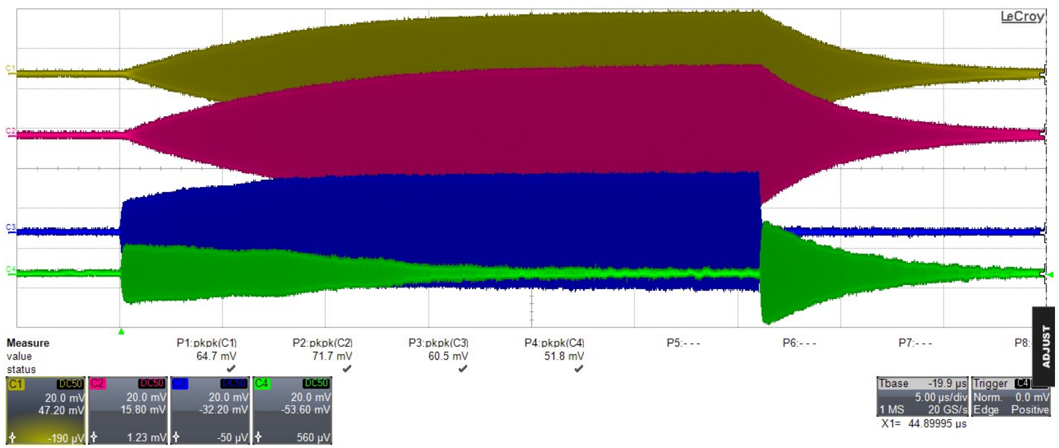


Experimental program underway now!

RF R&D: Modular Cavity Program

Experimental Program and Status

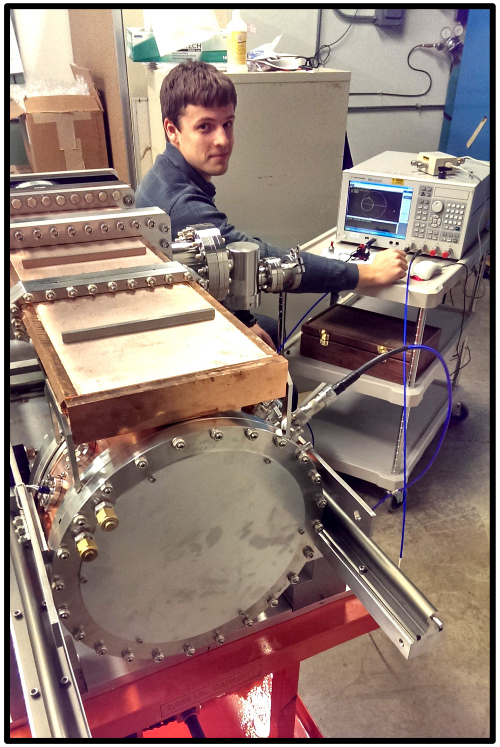
1. Gradient vs. *B* studies with copper end walls
2. Copper surface “lifetime” analysis
3. Gradient vs. *B* studies with beryllium end walls
4. Studies with beam (time permitting)



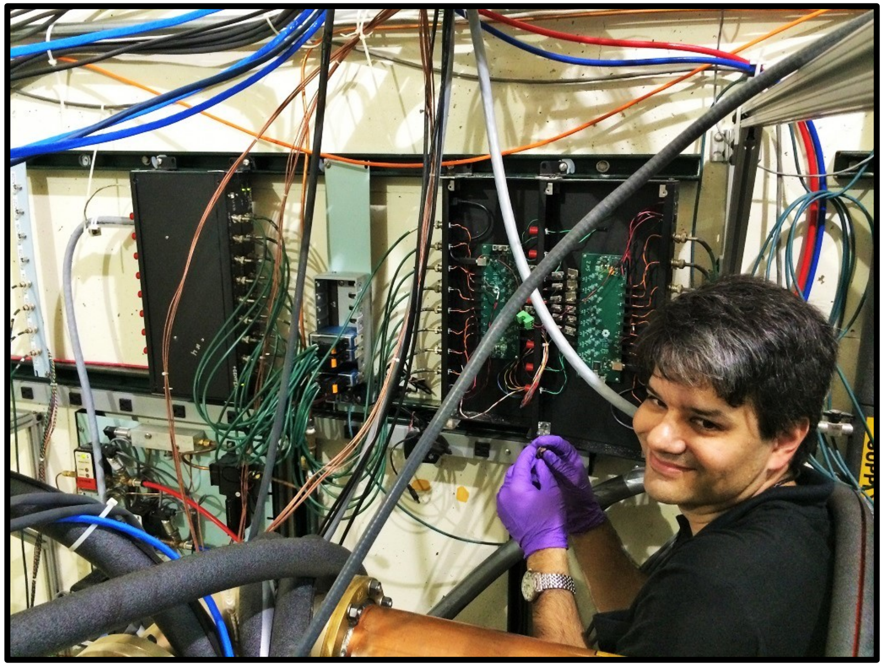
The cavity is running now in the MTA, in parallel with the MICE effort. Preliminary results will be shown at IPAC in a contributed oral presentation.

RF R&D: Modular Cavity Program

The modular cavity program is critical for the successful completion of two PhD theses.



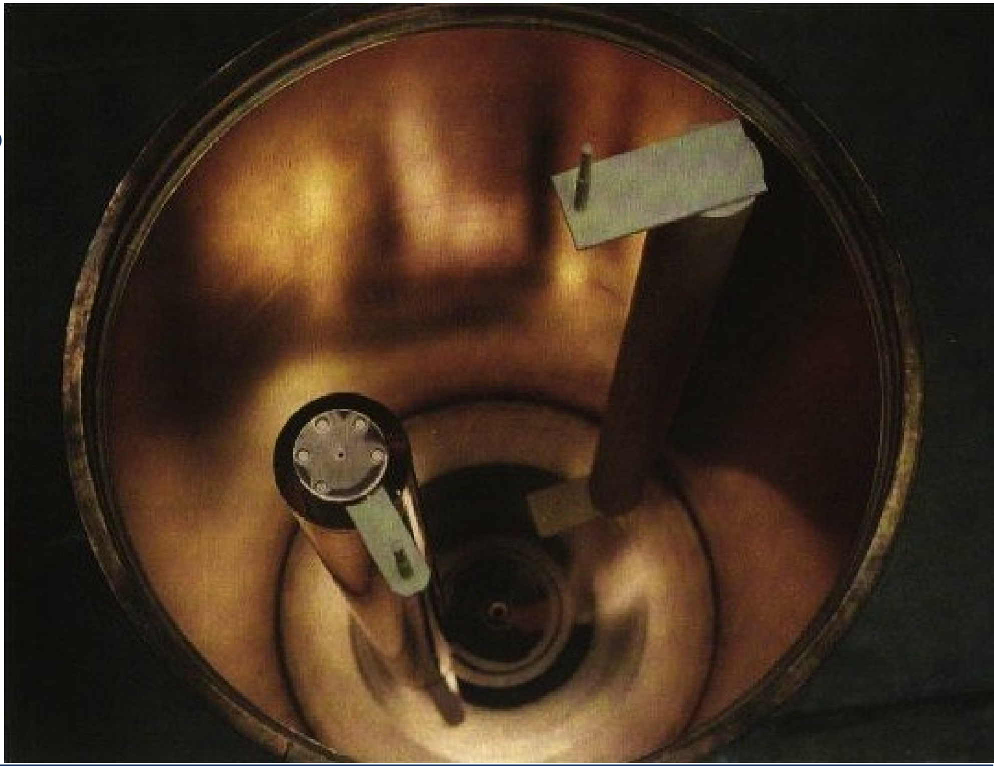
Alexey Kochemirovskiy (U. Chicago) on RF breakdown in strong magnetic fields

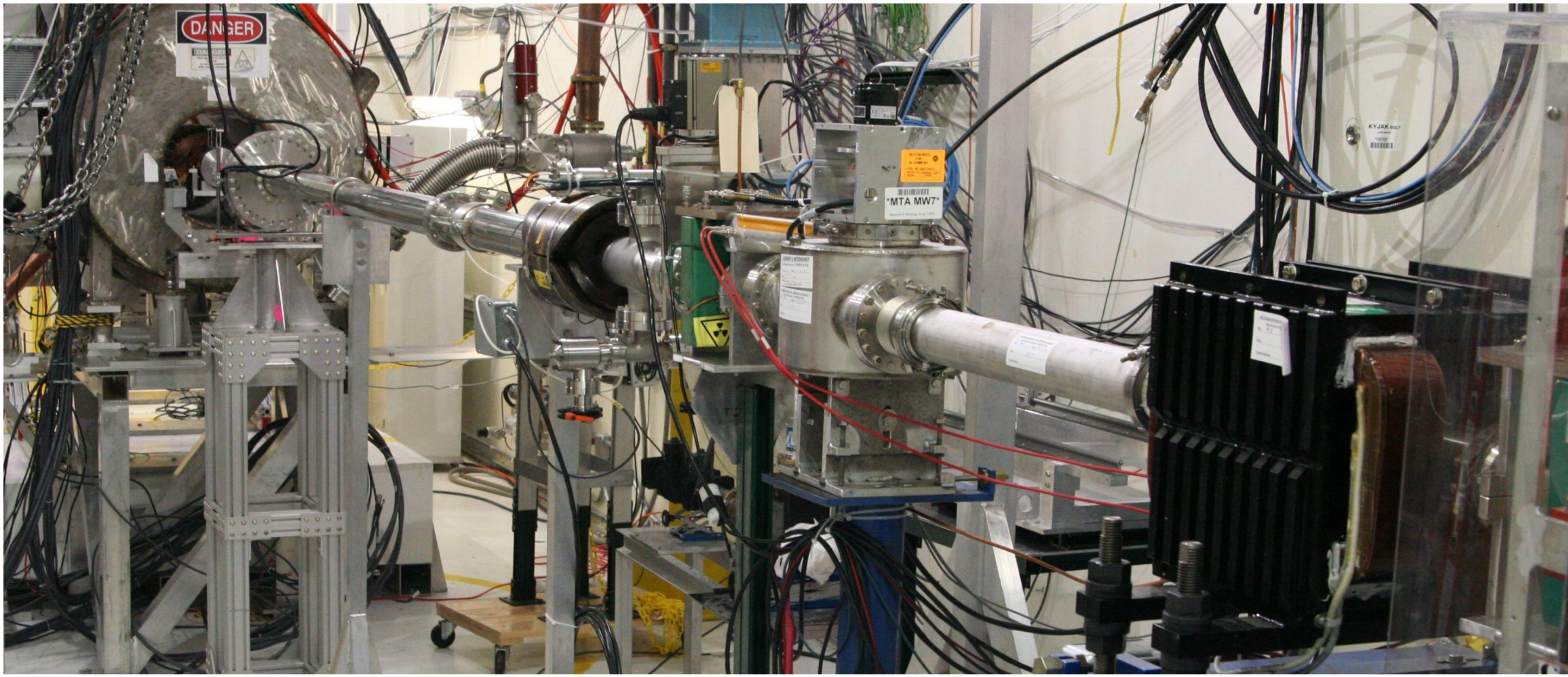


Peter Lane (IIT) on the use of acoustic sensors for spark localization in cavities

RF R&D: Future Thrusts

- Opportunities for ADMX
  – Axion-to-photon conversion detection
  – Cold, normal-conducting RF cavities operating in strong magnetic fields
  – Dialogue with ADMX experiment about potential for collaboration





High-Pressure Gas-Filled RF Cavity Program

RF R&D: Unique Features of Gas-Filled RF Cavities

- High-pressure GH_2 can suppress RF breakdown
  - Eliminates gradient sensitivity to B-field (60 MV/m irrespective of B)
- Fundamental Question:

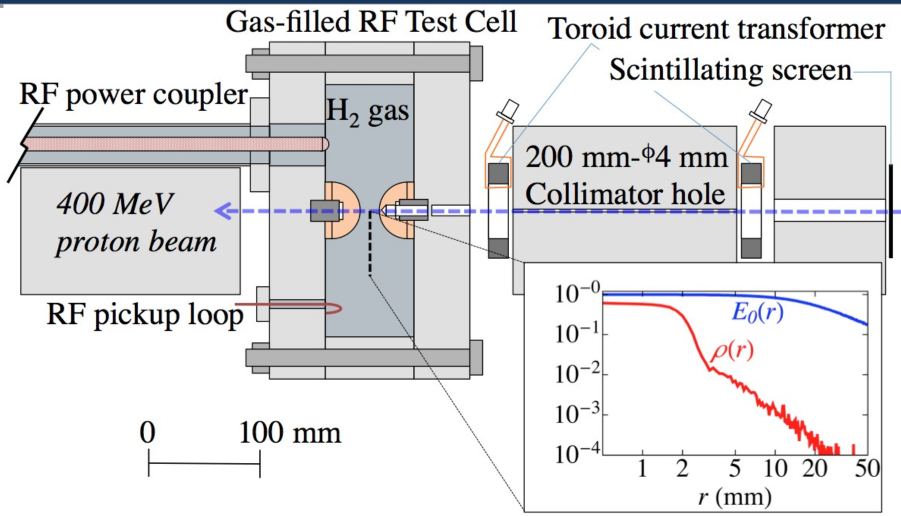
"What happens when an intense beam passes through a gas-filled cavity?"

  - Beam studies at the MTA a beam-induced plasma impact on gradient
    - M. Chung et al., PRL 111, 184802, 2013
    - Quantitative theory validated by measurement of RF energy absorption by plasma using H_2(D_2) gas with an electronegative dopant
  - Current focus a beam-plasma interaction
    - Charge neutralization compensation of beam space charge
  - Compact high-gradient RF cavities
    - Dielectric-loaded cavities enable significant size decrease
    - Breakdown on dielectric surfaces mitigated by high-pressure gas

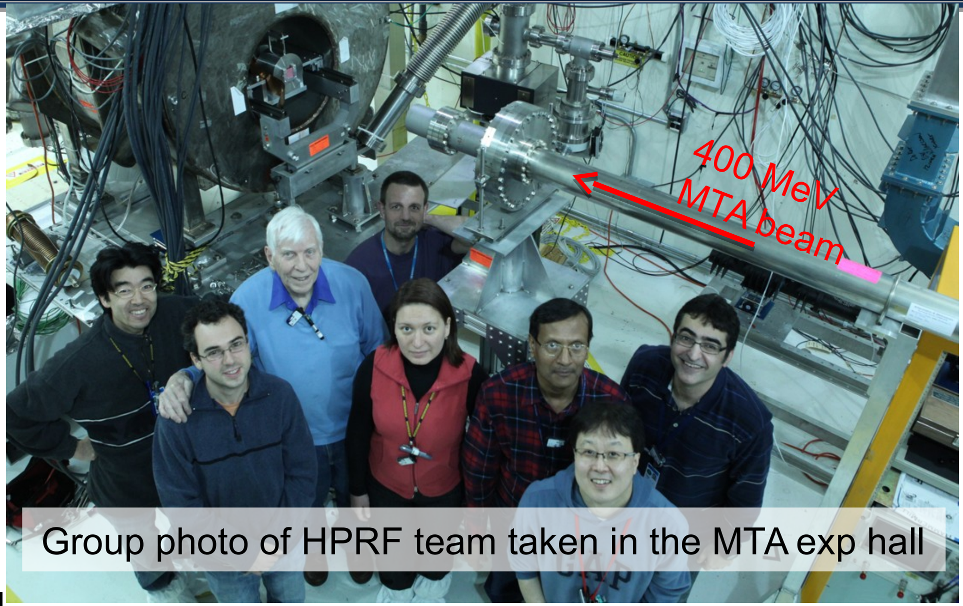
a HPRF technology has significant potential for new applications

RF R&D: High-Pressure Gas-Filled Cavities

How does gas interact with intense beam in RF fields?

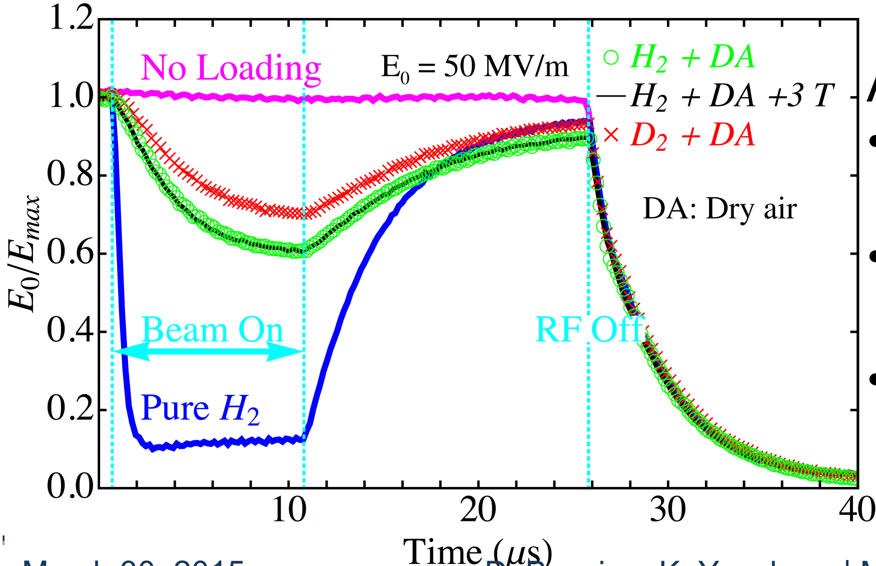


Apparatus of MTA beam test



Group photo of HPRF team taken in the MTA exp hall

Observed RF amplitude in the HPRF test cell

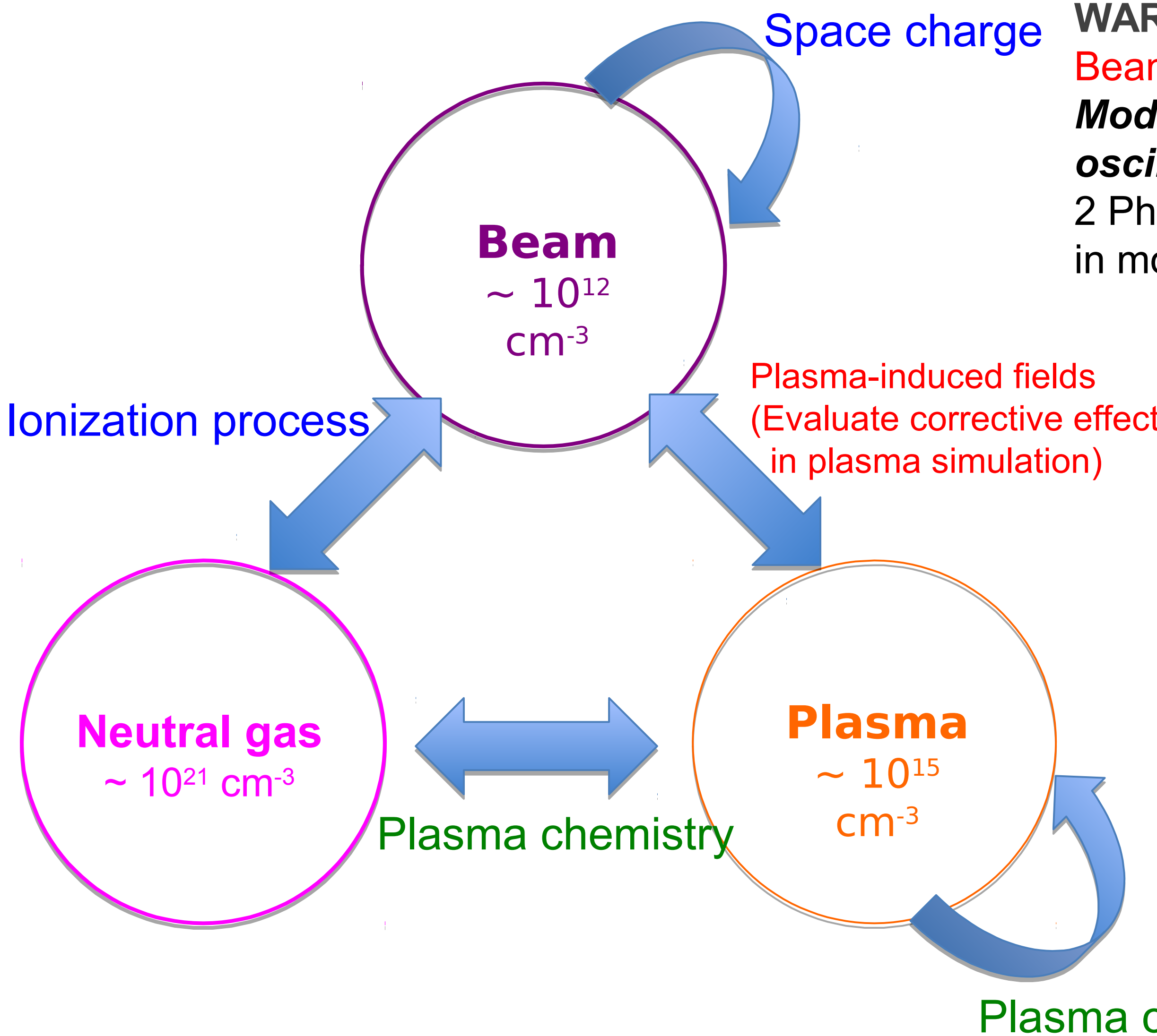


Accomplishments:

- Experimentally verified RF power loading model due to beam-induced plasma
- Demonstrated improvement by addition of an electronegative gas dopant: Dry air (DA) & SF_6
- Results published in:
  *PRL **111**, 184802, 2013*

RF R&D: High-Pressure Gas-Filled Cavities

Physics of Gas-Filled RF cavity a Interactions among three elements



WARP simulation in a gas channel
Beam (red) & Plasma (green);
Model plasma-induced beam oscillation
2 Ph.D students currently participating in modeling effort

[James's movie goes here.]

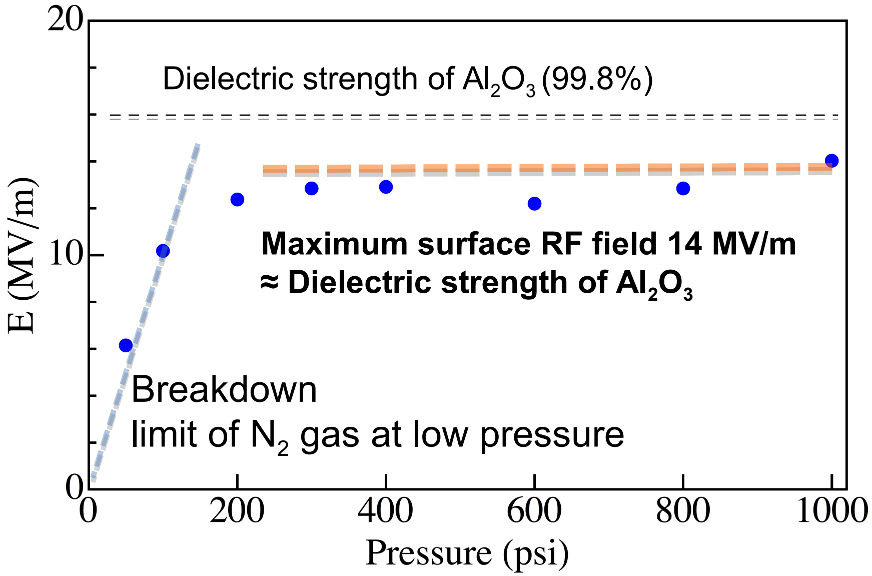
RF R&D: Dielectric-Loaded HPRF Cavities

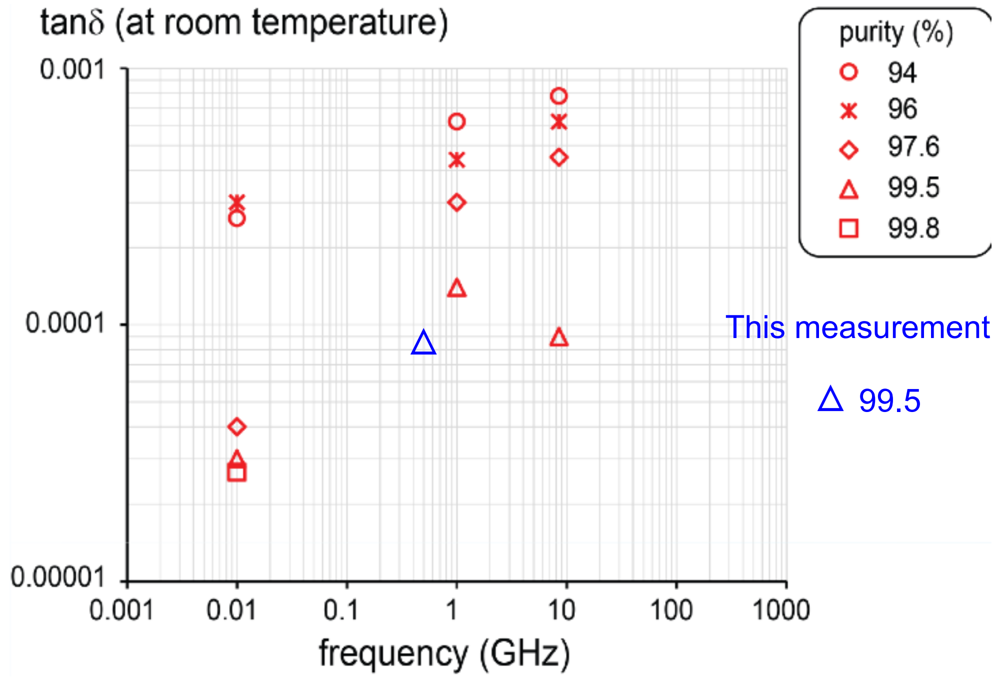
Compact High Gradient RF Cavity

- Insert dielectric material in RF cavities to shrink the radial size
- Surface breakdown is suppressed by inert gas

$$r \propto \frac{1}{f\sqrt{\epsilon}}$$

Measurement of maximum surface gradient in an Al_2O_3 (Alumina) loaded gas-filled RF test cell versus gas (N_2) pressure

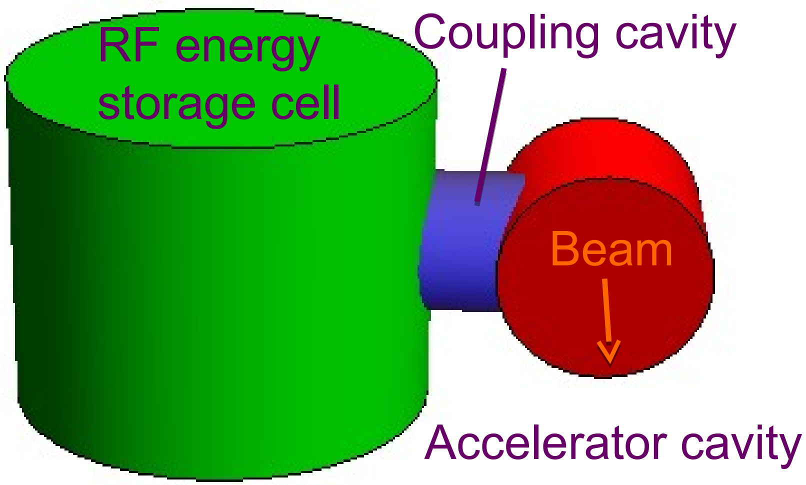




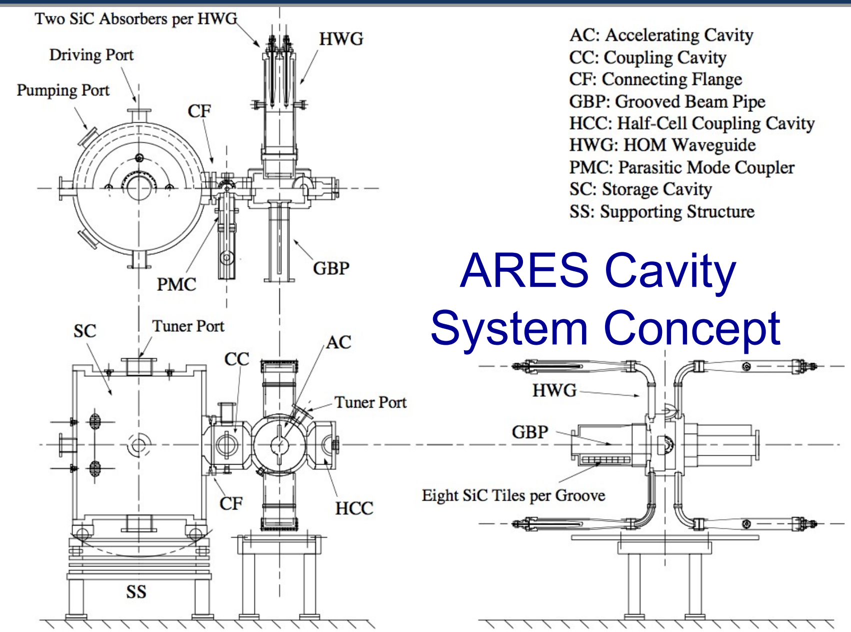
Next step: Beam tests targeted for FY16 & FY17

RF R&D: Future Research Thrusts

- Compact RF energy storage cell (SC)
  - Beam loading compensation for intense beams
  - Dielectric-loaded a high-density energy storage
  - High pressure gas stabilizes against breakdown



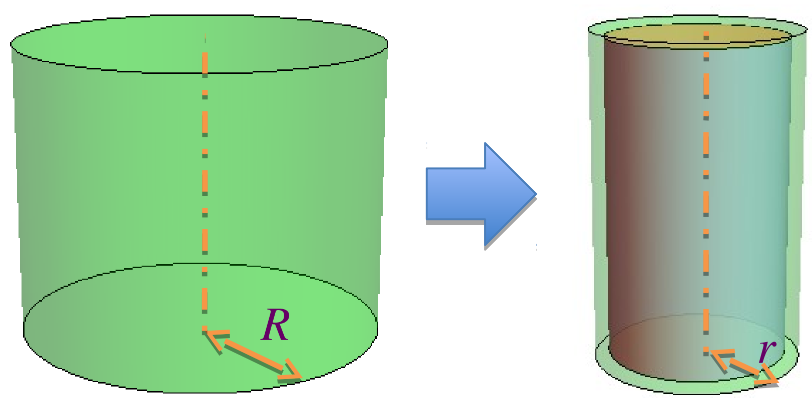
RF Energy Storage Cell Concept



ARES Cavity System Concept

Empty (vacuum) storage cell

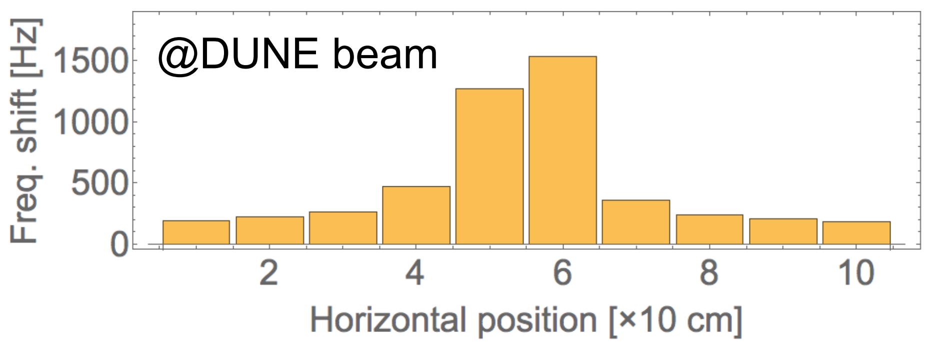
Gas and ceramic filled storage cell

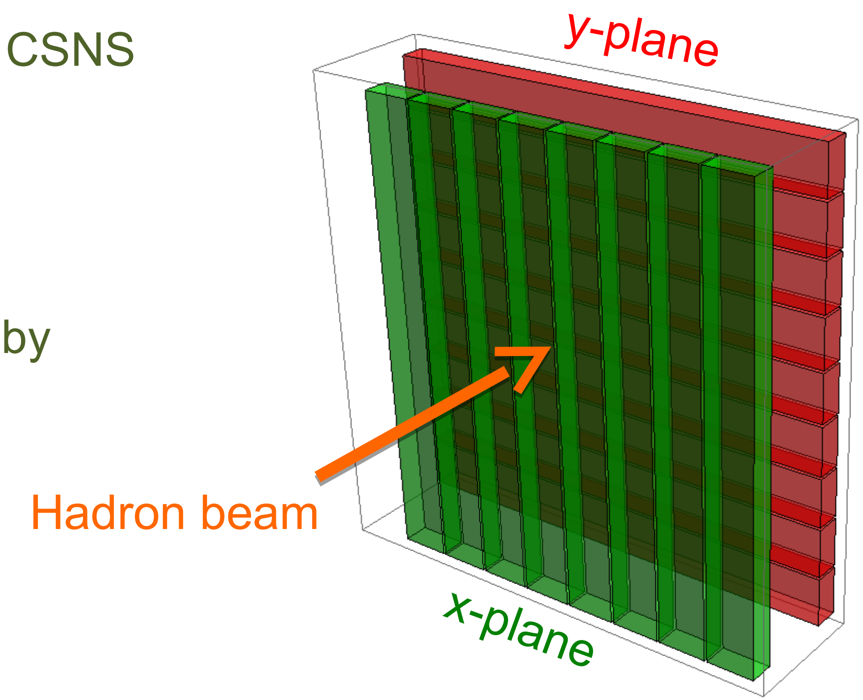


$$r = R/\sqrt{\varepsilon}$$

RF R&D: Future Research Thrusts

- Hadron Monitor Technology
  - MW-Beam facilities: Require beam monitors with improved radiation resistance
    - Neutrino Sources: DUNE, T2K, LBNO
    - Spallation Neutron Sources: SNS, ESS, CSNS
  - Gas-filled RF Resonator Hodoscope
    - Offers radiation robust technology
    - Relative permittivity shift in resonator is proportional to plasma density produced by a hadron beam





Gas-filled RF resonator strip

Summary

- Normal Conducting RF remains an important element of the accelerator R&D portfolio
- The infrastructure in the MuCool Test Area at Fermilab provides unique capabilities for advancing NCRF capabilities
  - Accelerator applications
  - Novel detector applications
- The proposed program offers significant potential gains for a relatively modest investment

That concludes the talk we gave. Now a few parting thoughts:

- Facility support for MTA is included in FNAL Accelerator Division's FWP. This is great news!
- We made a strong case, but times are tough.