# RF Cavity Operation in Strong Magnetic Fields

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NuFact10
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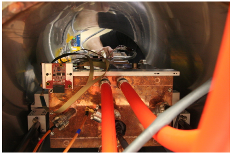
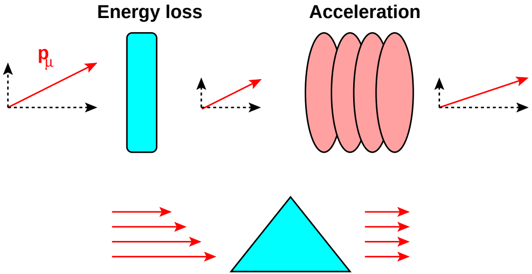


# Ionization Cooling

The only muon cooling scheme that appears practical within the muon lifetime (2.2$\mu$s).




Mainly transverse; longitudinal cooling requires momentum-dependent path-length through the energy absorbers

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Normalized transverse emittance $\varepsilon$ of muon beam in solenoidal channel

$$\frac{d\varepsilon}{ds} \simeq \frac{\left\langle \frac{dE}{ds} \right\rangle}{\beta^2 E} (\varepsilon - \varepsilon_0), \quad \varepsilon_0 \simeq \frac{0.875\text{MeV}}{\left\langle \frac{dE}{ds} \right\rangle X_0} \frac{\beta_\perp}{\beta}$$

$\varepsilon_0$: equilibrium emittance (multiple scattering $\sim$ cooling)

- Energy absorbers with large *dE* per radiation length (LH2: 29MeV/m x 8.9m; LiH: 151MeV)
- Strong focusing (large B-field), $\beta_\perp \sim p/B$
- High-gradient rf cavities to replace longitudinal momentum and for phase focusing

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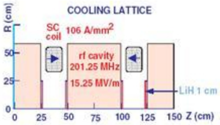

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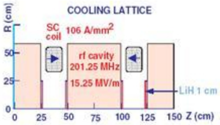


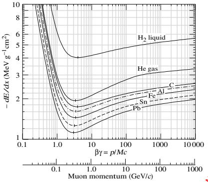

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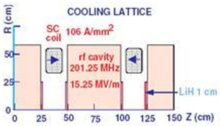
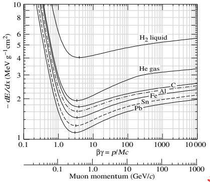


# Field emission

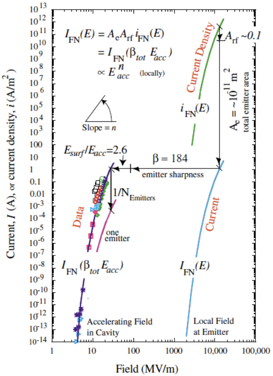
- Electrons tunneling through work function $\phi$ at metal surface due to the rf electric field $E$
- Enhanced by sharp features on the surface

- Described by the Fowler-Nordheim current density $j$

$$j(E) = \frac{A}{\phi}(\beta_s E)^2 \exp\left(-\frac{B\phi^{3/2}}{\beta_s E}\right)$$

- Steep dependence in E

$$j \sim E^m \rightarrow m = \frac{E}{j}\frac{\partial j}{\partial E} \simeq 2 + \frac{67.4 \text{ GV/m}}{\beta_s E}$$



# Effect of Magnetic Field

- External magnetic fields can significantly modify the performance of rf cavities by changing the dynamics of electrons coming off the surface at field emission sites (including any plasma cloud that might form near the surface)
- When $\vec{B}_{\text{ext}} \parallel \vec{E}_{\text{rf}}$, electrons can ride magnetic field lines between the accelerating gap and cause damage due to the focused current density
- When $\vec{B}_{\text{ext}} \perp \vec{E}_{\text{rf}}$, electrons can be deflected into grazing angles to the surface before being accelerated
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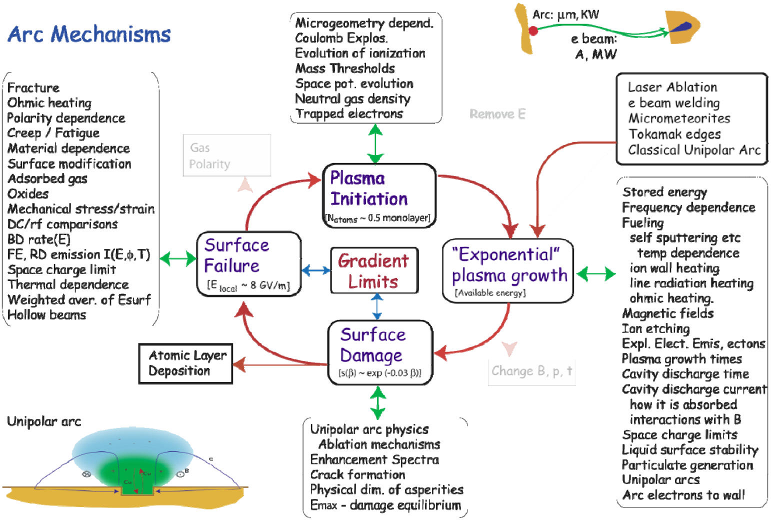

# Potential Solutions

- Better materials: more robust against breakdown (melting point, energy loss, skin depth, thermal diffusion length, etc.)
- Surface processing: suppress field emission (superconducting RF techniques, coatings, atomic layer deposition)
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reduced cooling performance

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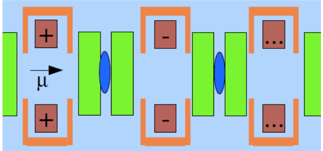


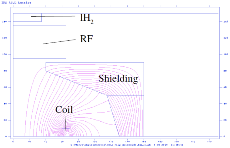


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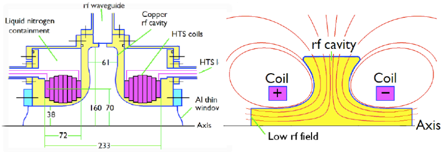
- Magnetic insulation: modified cavity/coil designs to keep B⊥E on cavity surfaces (Palmer)




Loss of x 2 gradient advantage in pillbox geometry

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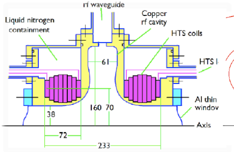


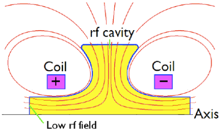


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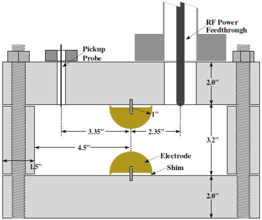


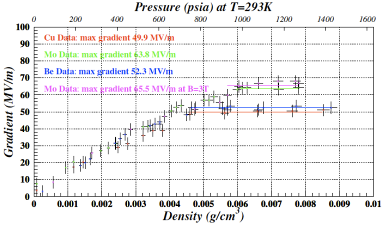

### Mission

- design, prototype and test components for ionization cooling
  - Energy absorbers
  - RF cavities
  - Magnets
  - Diagnostics
- including associated simulation and theoretical studies
- support system tests

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MuCool now folded into Muon Accelerator Program.

# MuCool Test Area (MTA) – http://mice.iit.edu/mta/

Dedicated facility at the end of the Linac built to address MuCool needs

- RF power (13 MW at 805 MHz, 4.5 MW at 201 MHz)
- Superconducting magnet (5 T solenoid)
- Large coupling coil under construction
- 805 and 201 MHz cavities
- Radiation detectors
- Cryo plant (commissioned this year)
- 400 MeV p beamline (commissioned to upstream of hall)

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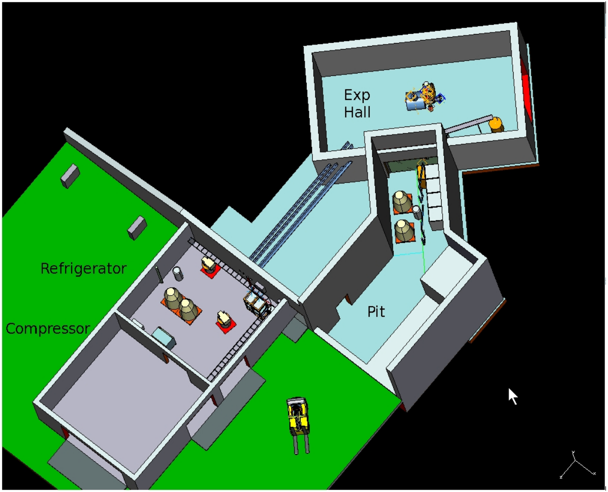

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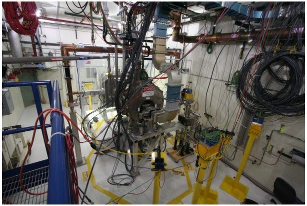
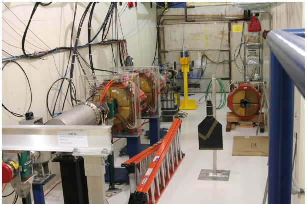
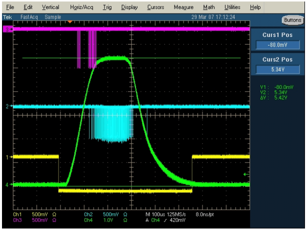
Experimental Hall



Beamline






X-rays at high gradient

Compressor Room

# MTA RF R&D Program

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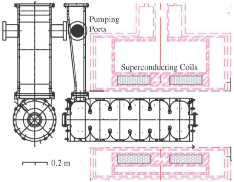
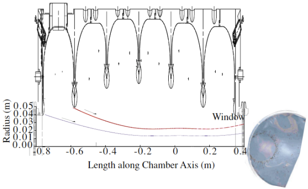
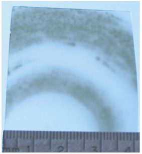
  - strong dark current soaking up all rf power beyond 55 MV/m surface field
  - field emission beamlets focused by magnetic field (enough to drill holes in windows)



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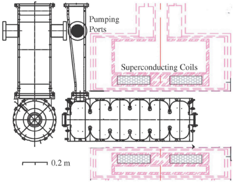


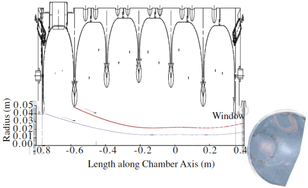


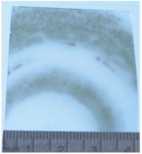

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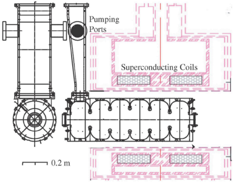


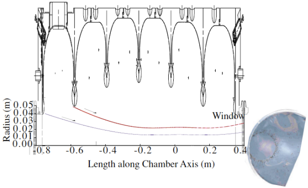


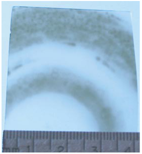

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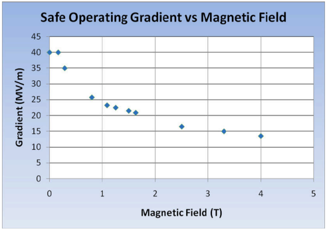


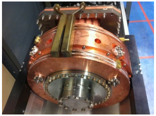

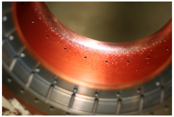

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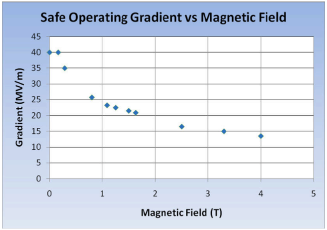


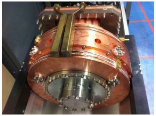

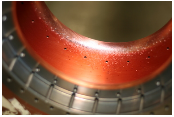

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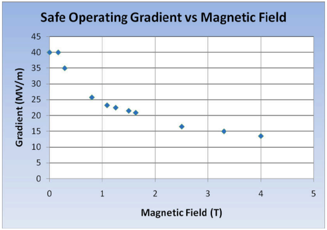


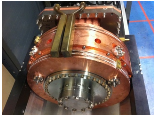

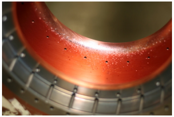

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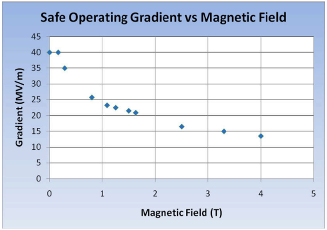


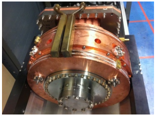

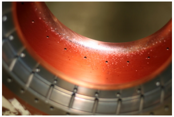

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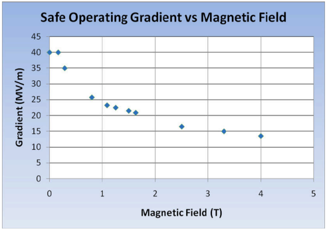


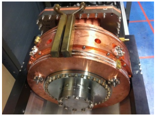

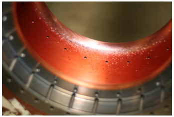

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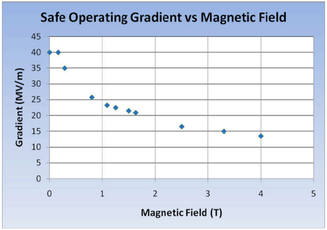


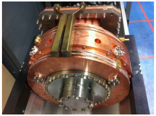

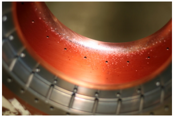

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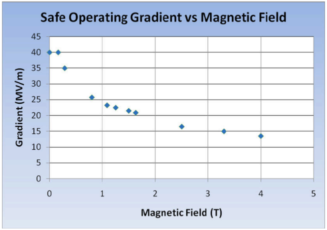
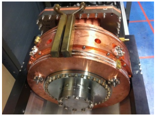
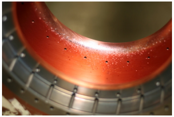
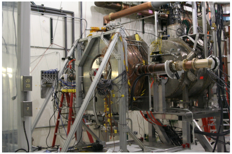




## 201 MHz MICE prototype cavity

- built very clean (electropolished, etc.)
- conditioned to design gradient very quickly
- ran successfully with thin curved Be windows
- operated in stray magnetic field
- radiation output measured (MICE detector backgrounds)
- large diameter coil needed for field configuration closer to MICE
- No surface damage seen in visual inspection



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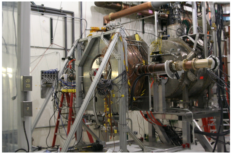

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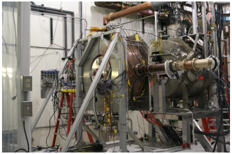

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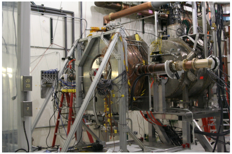

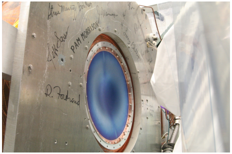

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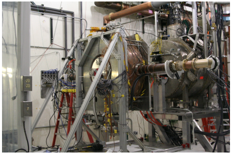

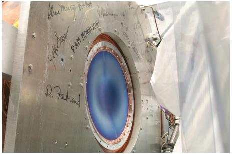


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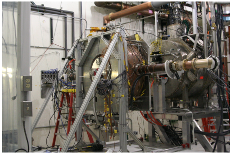

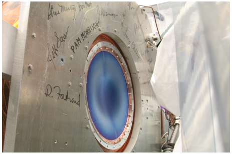

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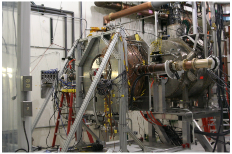

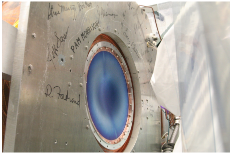

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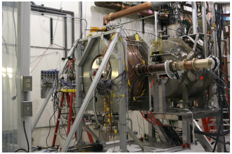

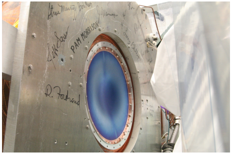

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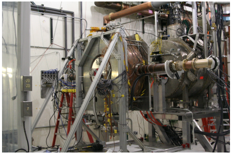
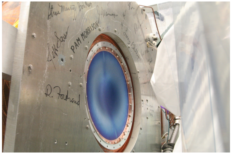
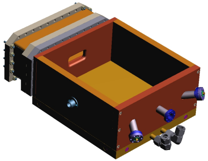
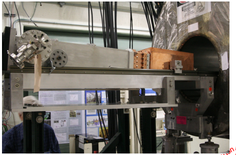




# Box Cavity

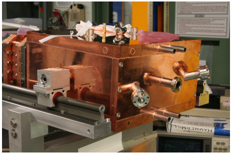
- Rectangular geometry chosen for test cavity to allow fast fabrication and simplify analysis
- Interior dimensions: 276.5 x 250 x 123.8 mm
- Made of 101 OFE copper plates
- Attached in two hydrogen brazing cycles
- Support system designed to rotate cavity pivoting around magnet center by up to $12^o$
- Rectangular coupling aperture with rounded edges and a coupling cell built to match the power coupler to waveguide
- Three CF flange tubes for rf pickups and optical diagnostics
- $f_0 = 805.341$ MHz, $Q_0 = 27.9 \times 10^3$, coupling factor 0.97

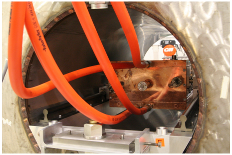




# Box Cavity

- Operating in the MTA magnet since mid-March
- Automated control program, optical diagnostics
- Commissioned to 49MV/m at B=0
- Took data at 0, $\pm$1, 3, 4$^o$ wrt B axis (3T)
- Large effect seen at 3-4$^o$ (stable gradient down to about 25MV/m)
- Some degradation even at 1$^o$
- Visual inspection of interior, no spark damage
- RF, optical and X-ray signals during sparks saved for analysis



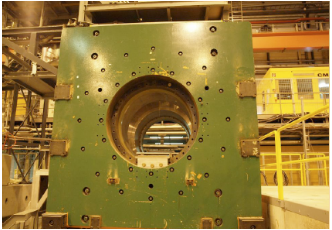


# Experimental roadmap

| Cavity | Outstanding issues | Proposed resolution | Experimental tests |
|---|---|---|---|
| Vacuum: pillbox, rectangular, open-iris | Breakdown and damage | Better materials | Mo, W, Be buttons<br>Be-walled 805-MHz cavity |
| | | Surface processing | Electropolished buttons<br>201-MHz pillbox in B-field |
| | | Coatings | ALD-coated buttons<br>ALD-coated cavity |
| | | Magnetic insulation | $E \perp B$ box cavity<br>$E \parallel B$ box cavity<br>Prototype with modified cavity-coil geometry |
| Pressurized | Beam-induced ionization | Measure ionization lifetime | 805-MHz cavity in beam |
| | Frequency dependence | Test at different frequency | Pressurized 201-MHz cavity |

# New test facility at CERN? (G. Prior)

- M1 magnet (3T, 1.4m bore)
- T2H2 area (floor space, infrastructure, control room)
- Could be used to test MuCool or MICE 201 MHz cavity
- Major effort and coordination with other users required
- Could become another long-term test facility (CERN NuFact Test Area?)



# Outlook

- 805 MHz rectangular box cavity run with B⊥E complete
- Data should provide insight into effect of magnetic field
- Another box cavity with B||E also in the pipeline
- 805 MHz pillbox cavity will be running again to study breakdown resistance of different surfaces using buttons
  - Be
  - ALD coating
- 201 MHz pillbox cavity to be tested again
- High pressure RF tests to continue (with beam when available – late 2010)
- Be-walled cavity being designed
- We hope to demonstrate a viable solution to RF in magnetic field for muon cooling within the next couple of years at the MTA
- RF strategy meeting at Fermilab: Nov 15-16, 2010 (contact A. Bross, D. Li or YT)