MuCool Overview

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Illinois Institute of Technology

MAP Meeting
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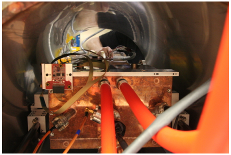
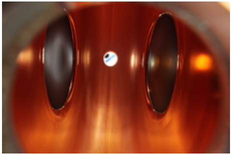
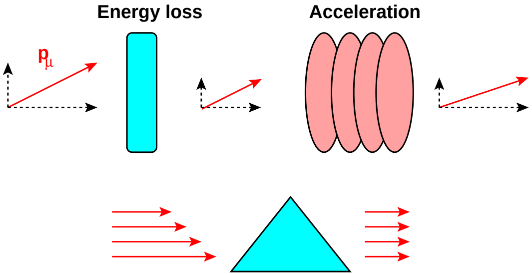




Ionization Cooling

The only muon cooling scheme that appears practical within the muon lifetime (2.2μs).



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

Ionization Cooling

Normalized transverse emittance ε of muon beam in solenoidal channel

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

ε_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

- tight packing to minimize decay losses
- low muon momentum
- emittance exchange for 6D cooling (or twisted field – Guggenheim, HCC, snake)

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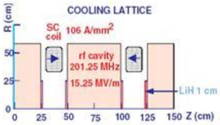

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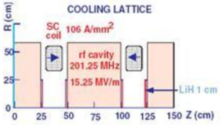

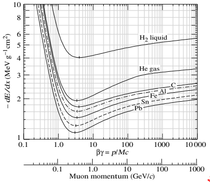

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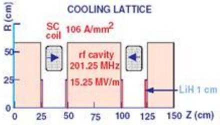
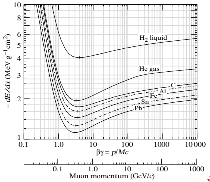




Field emission

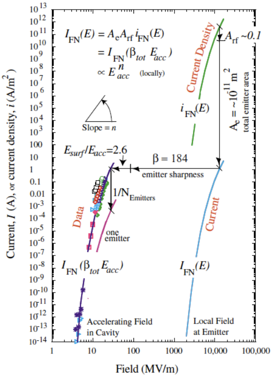
- Electrons tunneling through work function ϕ at metal surface due to the rf electric field E
- Enhanced by sharp features on the surface: $E_s = \beta_s E$

- Described by the Fowler-Nordheim current density j

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

- Steep dependence in E

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



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 $\vec{B}_{ext} \parallel \vec{E}_{rf}$, electrons can ride magnetic field lines between the accelerating gap and cause damage due to the focused current density
- When $\vec{B}_{ext} \perp \vec{E}_{rf}$, electrons can be deflected into grazing angles to the surface before being accelerated
- Must develop understanding to mitigate problem in cooling channel designs
- Need experimental data with $\vec{B}_{ext} \perp \vec{E}_{rf}$
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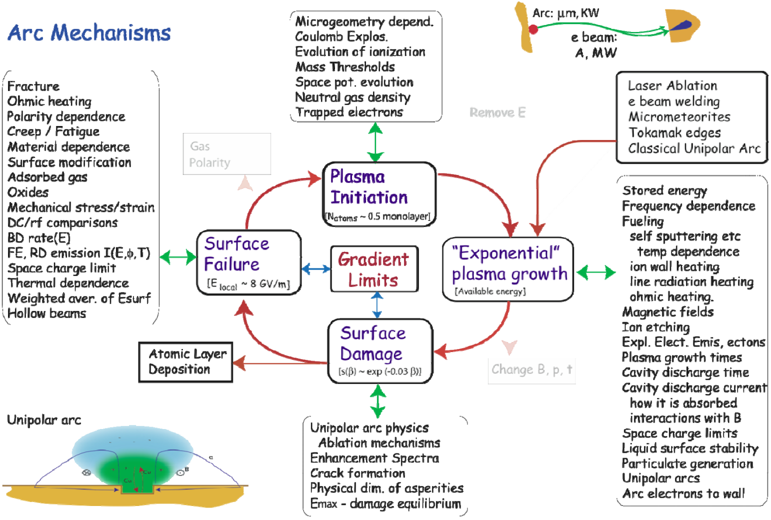
The breakdown story (Norem)



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)
- Magnetic shielding: at cavity locations (Rogers)

reduced cooling performance

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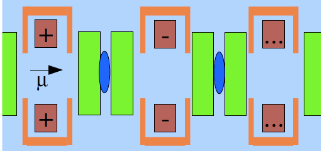

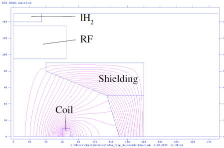

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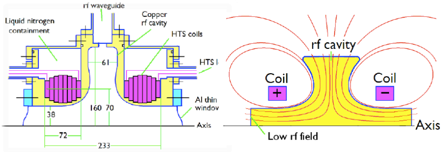

Loss of x 2 gradient advantage in pillbox geometry

- High-pressure gas: suppress breakdown by moderating electrons (Muons Inc.) – need beam test

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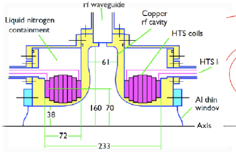

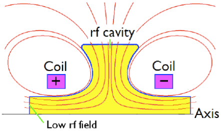

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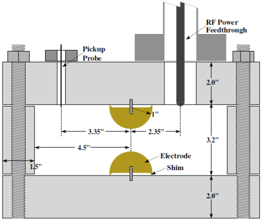

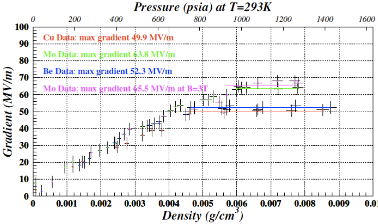

MuCool R&D Project at Fermilab

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.

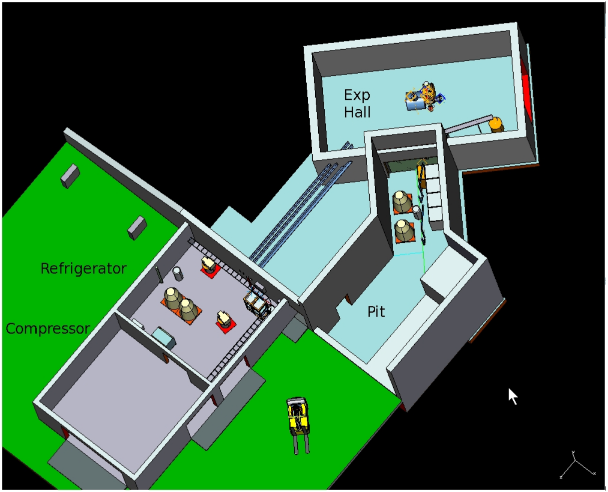
MuCool Test Area (MTA) – http://mice.iit.edu/mta/

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
- Cryogenic plant
- 400 MeV p beamline

MuCool Test Area (MTA)



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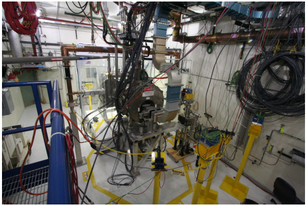
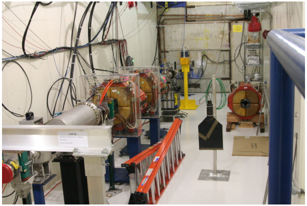
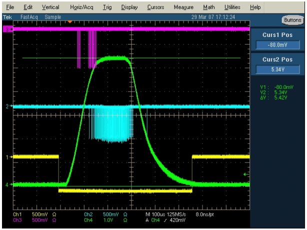
Experimental Hall



Beamline



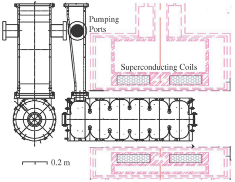


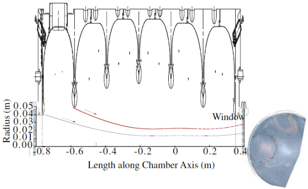
X-rays at high gradient

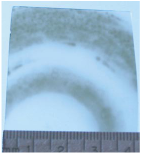
Compressor Room

MTA RF R&D Program

- Initial studies with 6-cell 805 MHz cavity hinted at limits of Cu surface and effect of magnetic field
  - 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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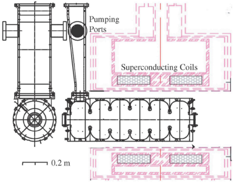

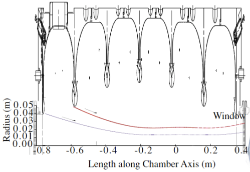

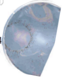

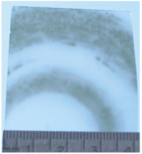

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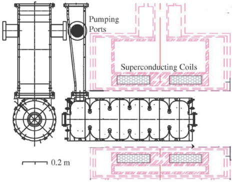
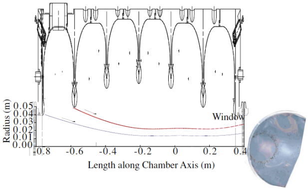
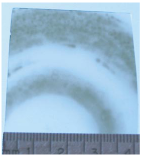
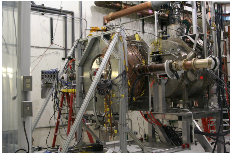
  - strong dark current soaking up all rf power beyond 55 MV/m surface field
  - field emission beamlets focused by magnetic field (enough to drill holes in windows)








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
- Evidence for sparking in the coupler (Norem's comet?)

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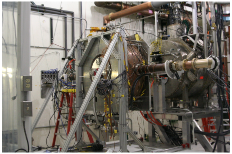

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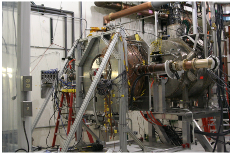

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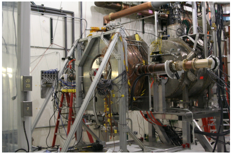

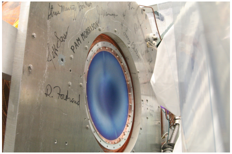

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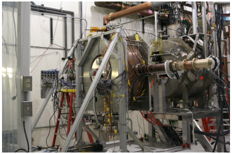

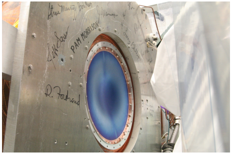

MTA RF R&D Program

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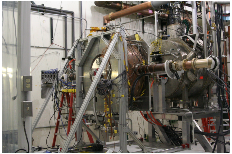

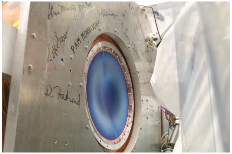

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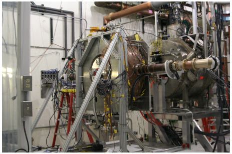

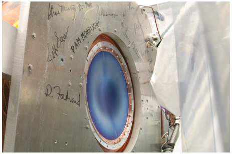

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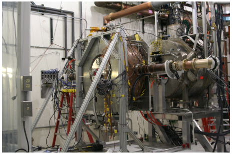

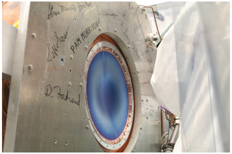

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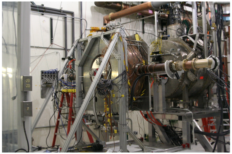

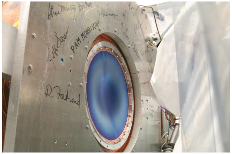

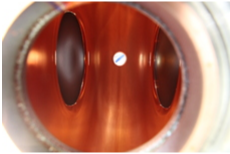

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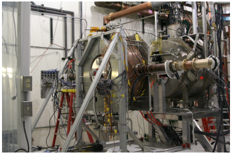
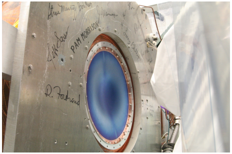
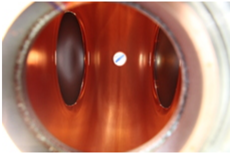




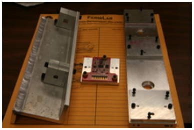
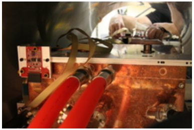
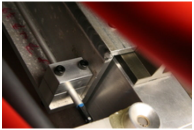
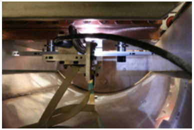


Not covered in this talk

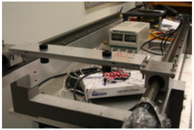
- 805-MHz pillbox cavity (M. Jana talk)
- E$\perp$B rectangular box cavity (A. Moretti talk)
- 805-MHz HPRF cavity (K. Yonehara talk)
- 201-MHz single cavity module, MICE cavities (A. DeMello, D. Li talks)
- Modeling, breakdown physics (D. Li, J. Norem, A. Tollestrup talks)
- Muons Inc 805-MHz "4-season" pillbox cavity (could run under both vacuum and pressure)

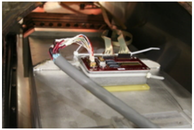
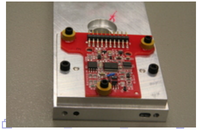
Magnetic Field Mapping

- Magnetic insulation depends strongly on angle
- MTA solenoid field never mapped in detail before
- Expect good alignment of magnetic axis with bore based on manufacturing tolerances but wanted to confirm

- Fiducial holes drilled during cavity fabrication
- Machined blocks to mount NIKHEF sensors
- Used cavity as mounting fixture – data taken at corners
- Gaussmeter fixed in bore for normalization
- Bore to be mapped next with cart on rails



Summary of experimental program

- trying to demonstrate a working solution to RF cavity operation in high external magnetic field for muon cooling
- major MAP milestone
- big impact on cooling channel design and future system tests
- multipronged approach to cover maximum ground with available resources

Cavity		Outstanding issues	Proposed resolution	Experimental tests
Vacuum	pillbox	Breakdown and damage	Better materials	Mo, W, Be buttons Be-walled 805-MHz cavity
			Surface processing	Electropolished buttons 201-MHz pillbox in B-field
			Coatings	ALD-coated buttons ALD-coated cavity
	rectangular open-iris		Magnetic insulation	E⊥B box cavity E‖B box cavity Modified cavity-coil geometry
Pressurized		B-field/pressure effects	Materials tests	805-MHz 4-season cavity
		Beam-induced ionization	Measure ionization lifetime	805-MHz cavity in beam
		Frequency dependence	Test at different frequency	Pressurized 201-MHz cavity

Beam in the Hall!

Good news (A. Bross)

- First beam pulse to "emittance absorber" (beam stop 2) Monday PM (C. Johnstone)
- Intensity about 1.8×10^{12} protons/pulse at 1 pulse/min
- Tuning continued Tuesday, efficiency about 80%
- Activation in hall low: 10 mrem/hr at 1 ft from absorber after 100-150 pulses with no cooldown
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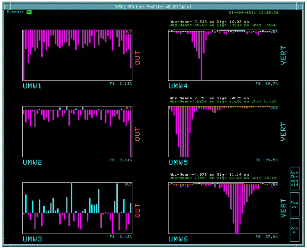

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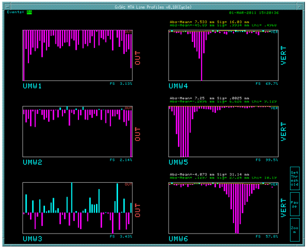

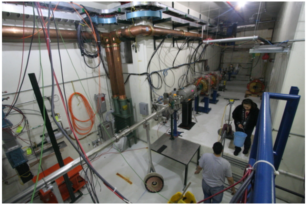

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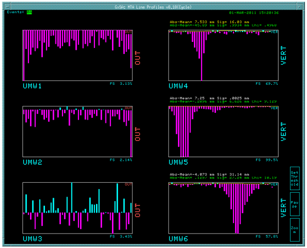

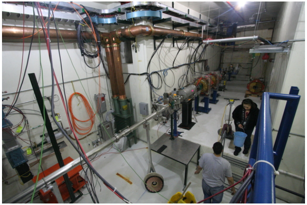

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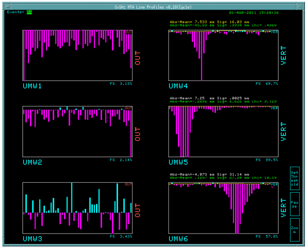

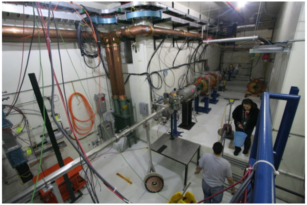

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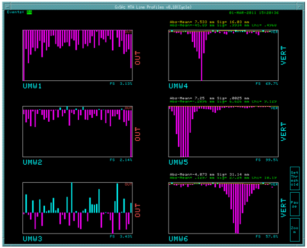

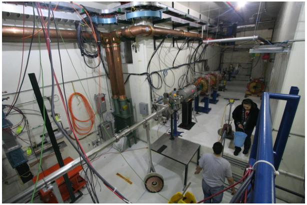

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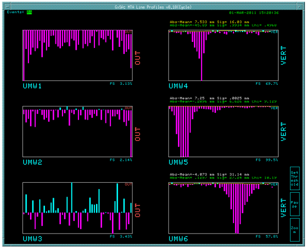

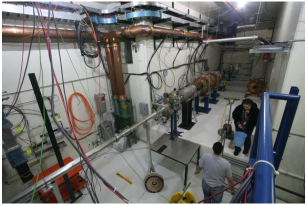

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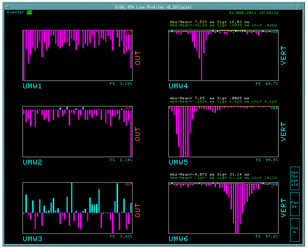

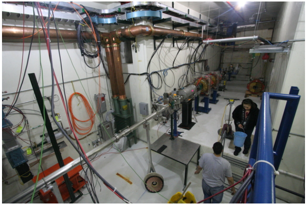

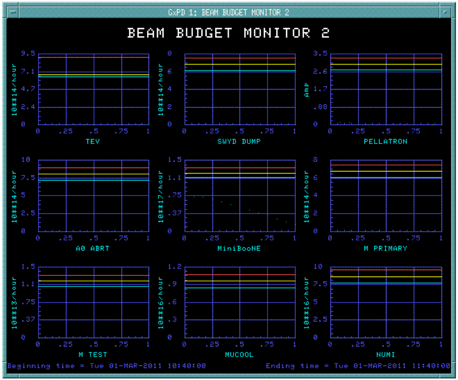

- Activation issues after beam operations
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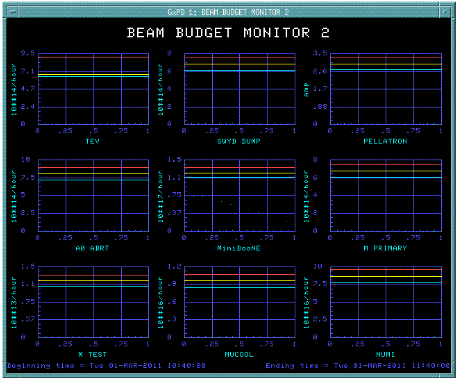
- Beamline also built as diagnostic station for Linac (emittance measurement)
- Scheduling will be more complicated

On the MAP at Fermilab



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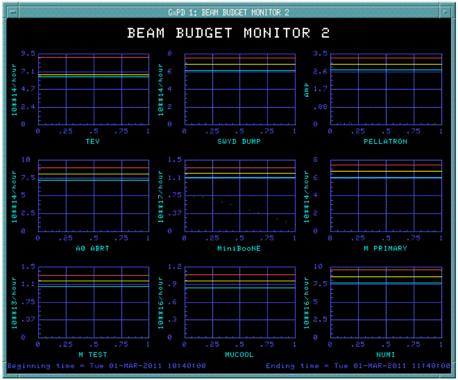

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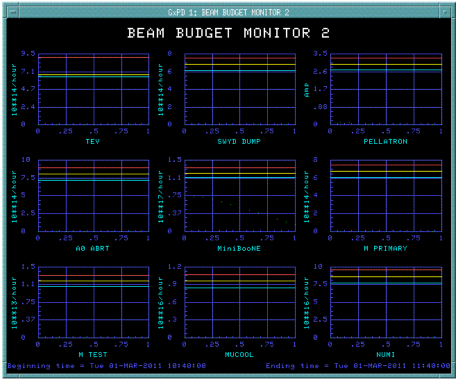

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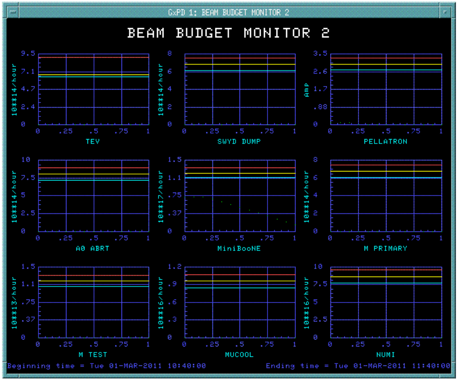

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MTA Infrastructure – Recent Updates

- Cryogenic plant
  - stable operation
  - 2nd compressor tested
  - need 2-3 week downtime to reconfigure exhaust line and minimize condensation in hall
- 805 MHz RF: 2nd station installed in hall
  - new switch and waveguide
  - cavity stand
  - cables and patch panel in hall
- Beamline
  - beampipe extension
  - vacuum instrumentation
  - gate valve
  - cables

Infrastructure

- Controls: components purchased for environmental monitoring
  - air flow and quality, temperature, humidity, water on floor
  - local network extension
- Experimental diagnostics
  - Scintillator+PMT counters (for X-rays) retested
  - Fiber+PMT system for light from cavity sparks
  - HPRF cavity diagnostic stand
- Linac Gallery "control room"
  - Added rack to controls area
  - Cooling fans on racks
  - Patch panels for 2nd RF station
  - Updated 805-MHz LabView RF control with external trigger
  - CAMAC DAQ for experiment signals revamped
- Planning for coupling coil and 201-MHz single-cavity vessel installation (major effort)

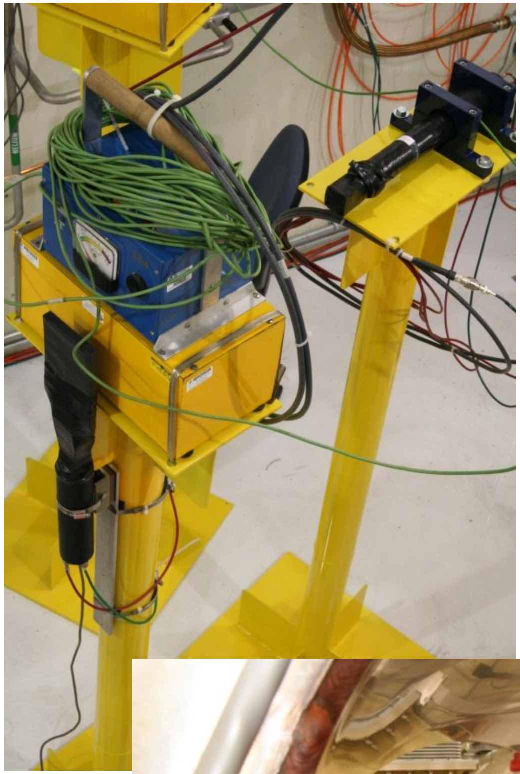
MTA Instrumentation

Ben Freemire – IIT

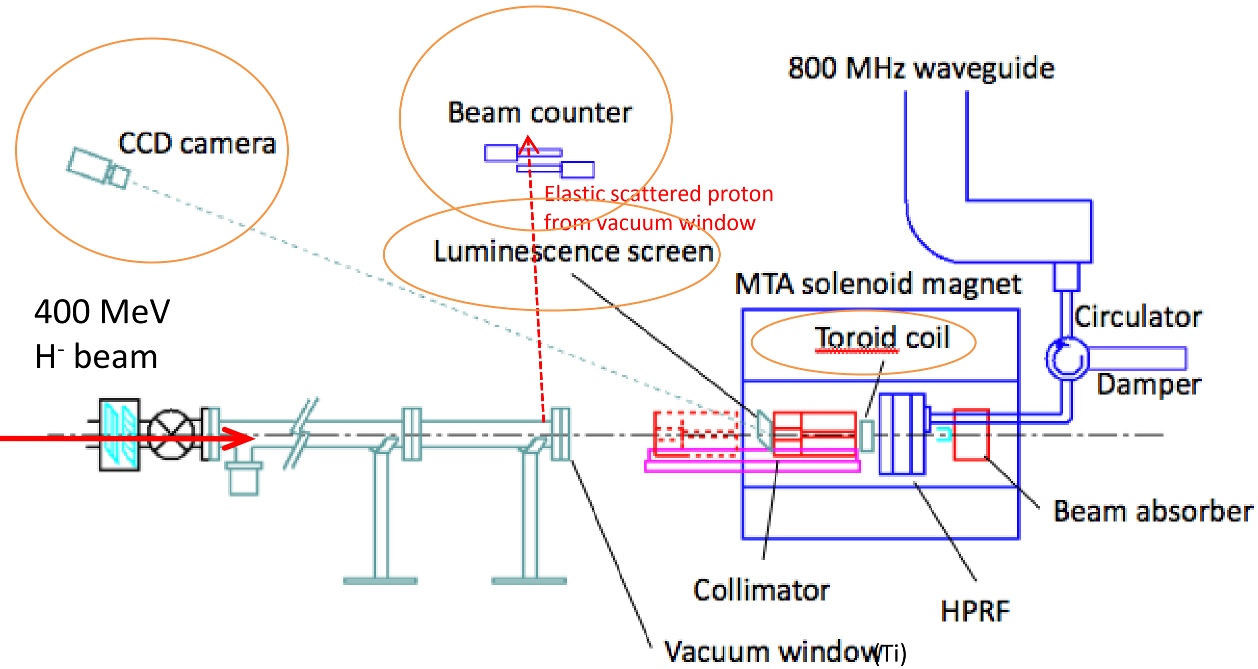
Detectors / Signals

- Electric and magnetic pickup signals
- Directional couplers
- Scintillator & PMT counters for X-rays
- NaI crystal
- Fiber & PMT for cavity spark light
- Chipmunks (ionization chambers)
- Acoustic pickup

- CCD camera and luminescence screen
- BPM, Multiwire chambers
- Toroidal coil
- Fibers & SiPMs



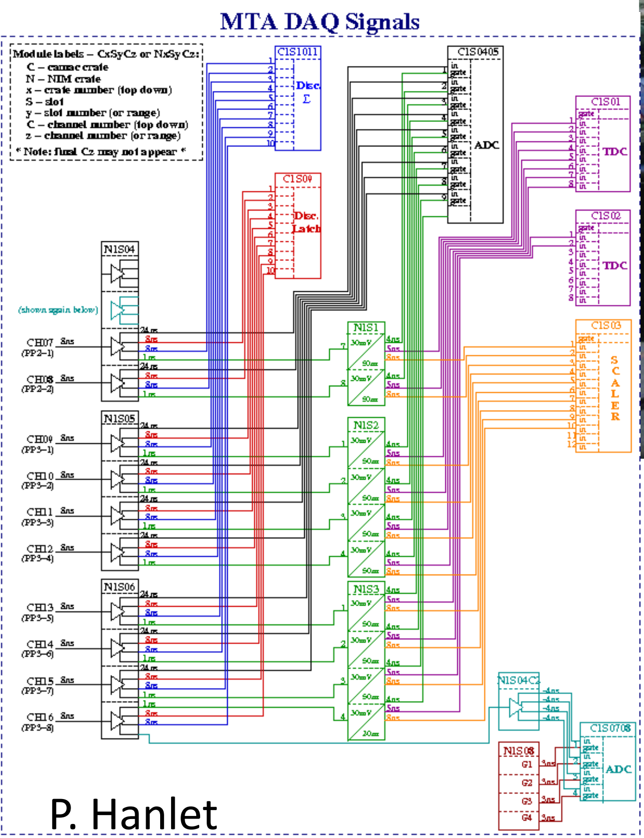
HPRF Detector system



K. Yonehara

Name	Diagnostic signal	ADC input
SiPM/PMT1	Top plate Light trig.	Fast Osc1
SiPM/PMT2	Top plate Spectroscopic	Fast Osc1
SiPM/PMT3	Topl plate TPB/spare	
SiPM/PMT4	Side wall Light trig.	
SiPM/PMT5	Side wall Spectroscopic	
SiPM/PMT6	Side wall TPB/spare	
RF Pickup1	Electric signal	Fast Osc1
RF Pickup2	Magnetic signal	Slow Osc
RF Forward1	Upstream of Circulator	
RF Return1	Upstream of Circulator	Slow Osc
RF Forward2	Between Circulator&cavity	
RF Return2	Between Circulator&cavity	Slow Osc
Toroid1	In front of cavity	Fast Osc1
Toroid2	MTA beamline	Fast Osc2
Beam counter	Telescope	Fast Osc2
RF Klystron	TTL From MCR	Fast Osc2

Controls



P. Hanlet

FrankenDAQ

Analog scope

Chair

Function generator

Pickup signal patch panels

Fast scope

Spark PMT power supply

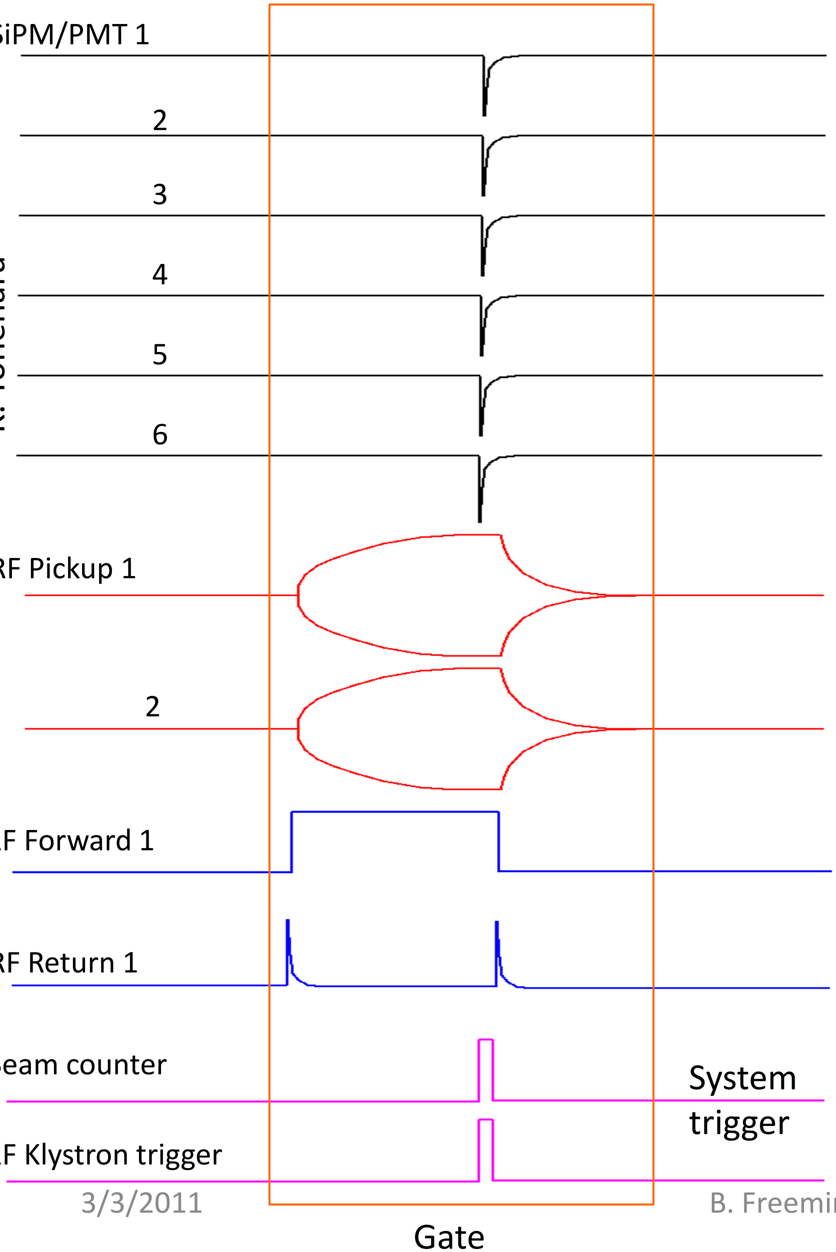
ACNET monitoring

Yagmur's PC

LabVIEW DAQ PC

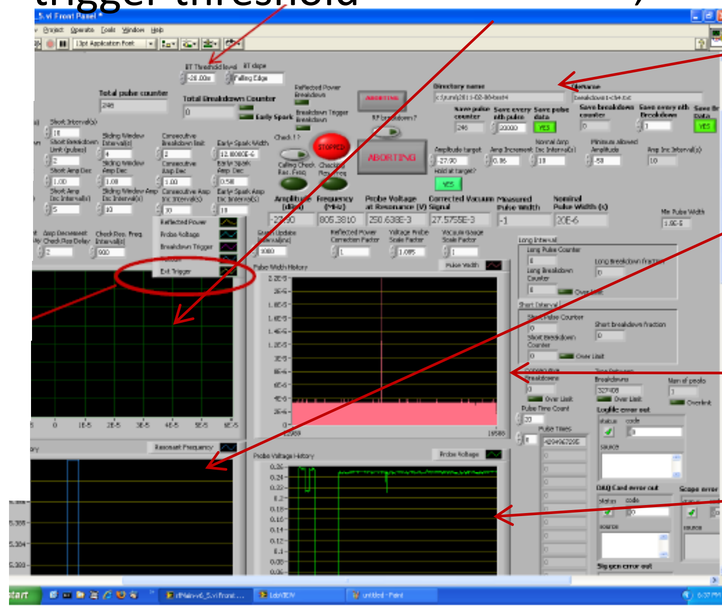
DAQ

K. Yonehara



PMT breakdown trigger threshold

Reflected power, probe voltage, breakdown trigger, vacuum, external trigger



Run filename and directory

Frequency history

Pulse width history

Pickup probe voltage history

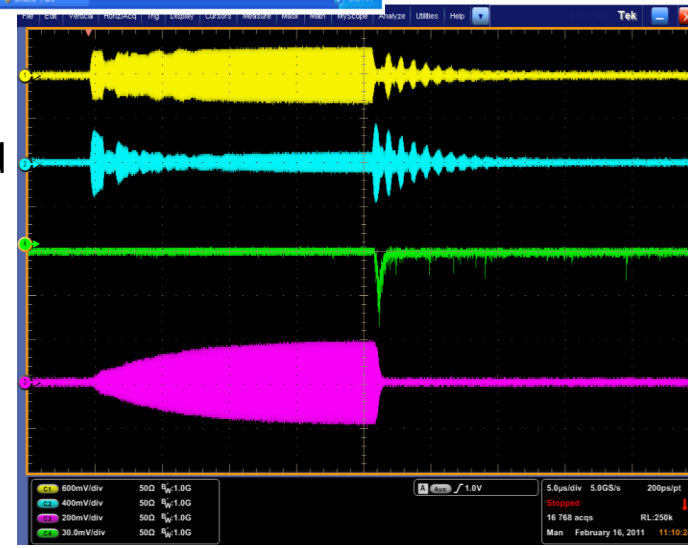
Breakdown pictured

Yellow – Forward RF Power

Blue – Reflected RF Power

Green – PMT signal

Magenta – RF signal



Schedule

- Initial 805 MHz pillbox test with flat Cu plates complete
- cryo upgrade soon
- beam commissioning
- HPRF cavity in beam
- magnet field mapping
- other items in various stages of readiness
  - other buttons in 805 pillbox
  - 201 MHz cavity coupler repair and operation
  - 2nd HPRF beam test as needed
  - rectangular box cavity with B $\parallel$ E
  - 2nd rectangular box cavity with B $\perp$ E
  - 4-season cavity
  - ALD cavity

Manpower

New additions since summer:

- Mukti Jana (FNAL)
- Moses Chung (back from Korea for long visit)
- Pierrick Hanlet (IIT) large fraction of time now on MTA
- Ben Freemire (IIT): grad student
- Timofey Zolkin (U. Chicago): grad student
- Last Feremenga (U. Chicago): undergrad
- Anastasia Belozertseva (U. Chicago): undergrad
- Muons Inc. personnel in training
- Team stronger than ever before

Outlook

- $B \perp E$ box cavity data analysis under way
- Pillbox cavity experiment in progress
- Major effort in HPRF cavity experimental setup and theoretical background
- Facility busier than ever, now with beam