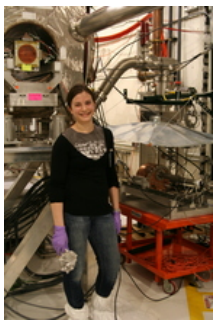
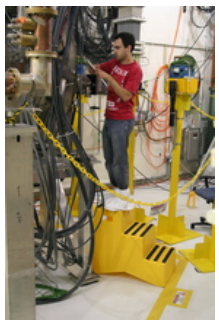
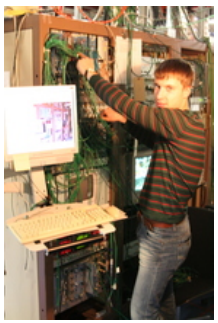
Recent MTA Results

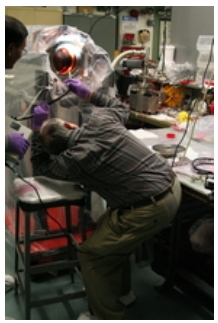
Yağmur Torun

Illinois Institute of Technology/Fermilab

Muon Collider 2011
June 29, 2011 – Telluride

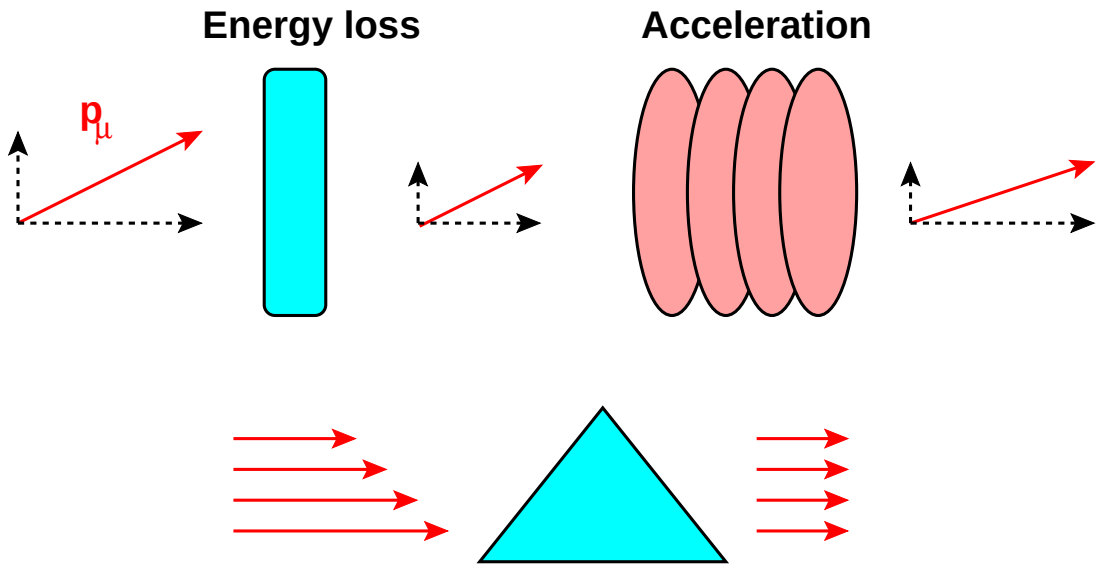





Ionization Cooling

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
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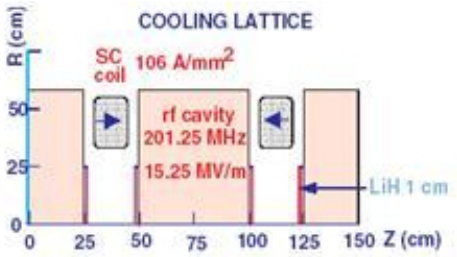

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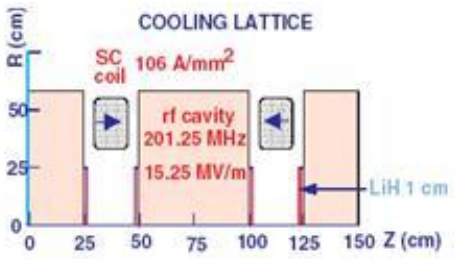

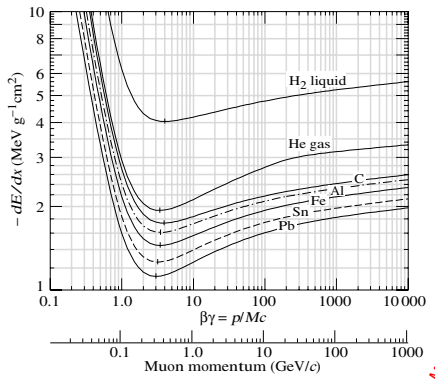

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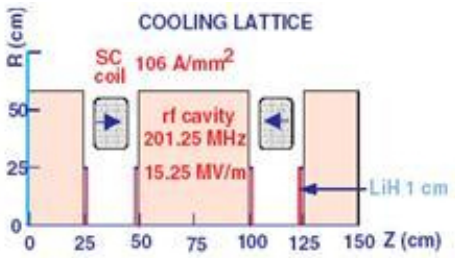
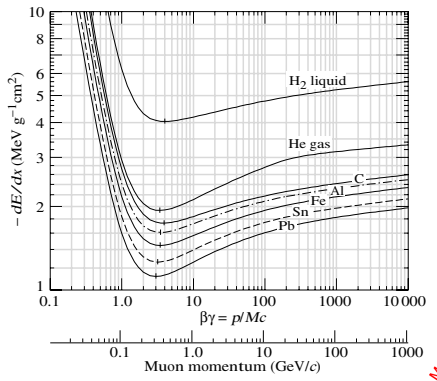




Field emission

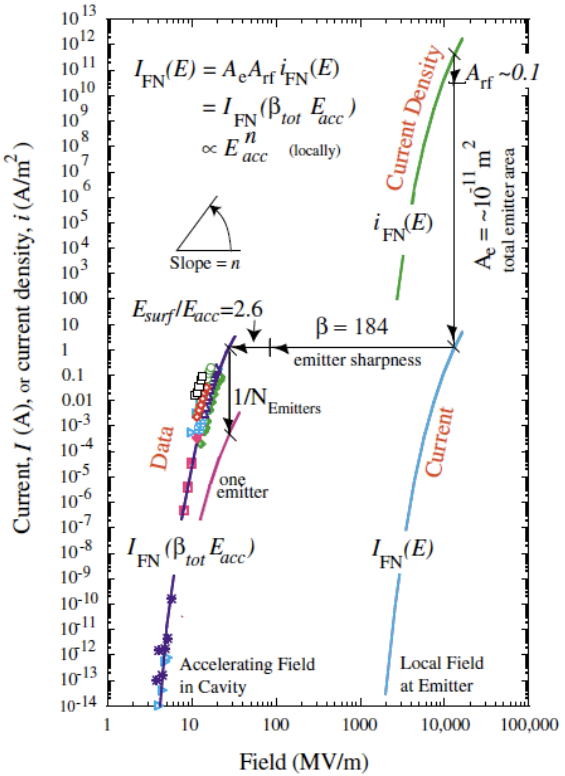
- Electrons tunneling through work function ϕ at metal surface due to the rf electric field E
- Enhanced by sharp features on the surface: $E_s = \beta_s E$

- 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 (where normally $\vec{B}_{ext} \sim\parallel \vec{E}_{rf}$)
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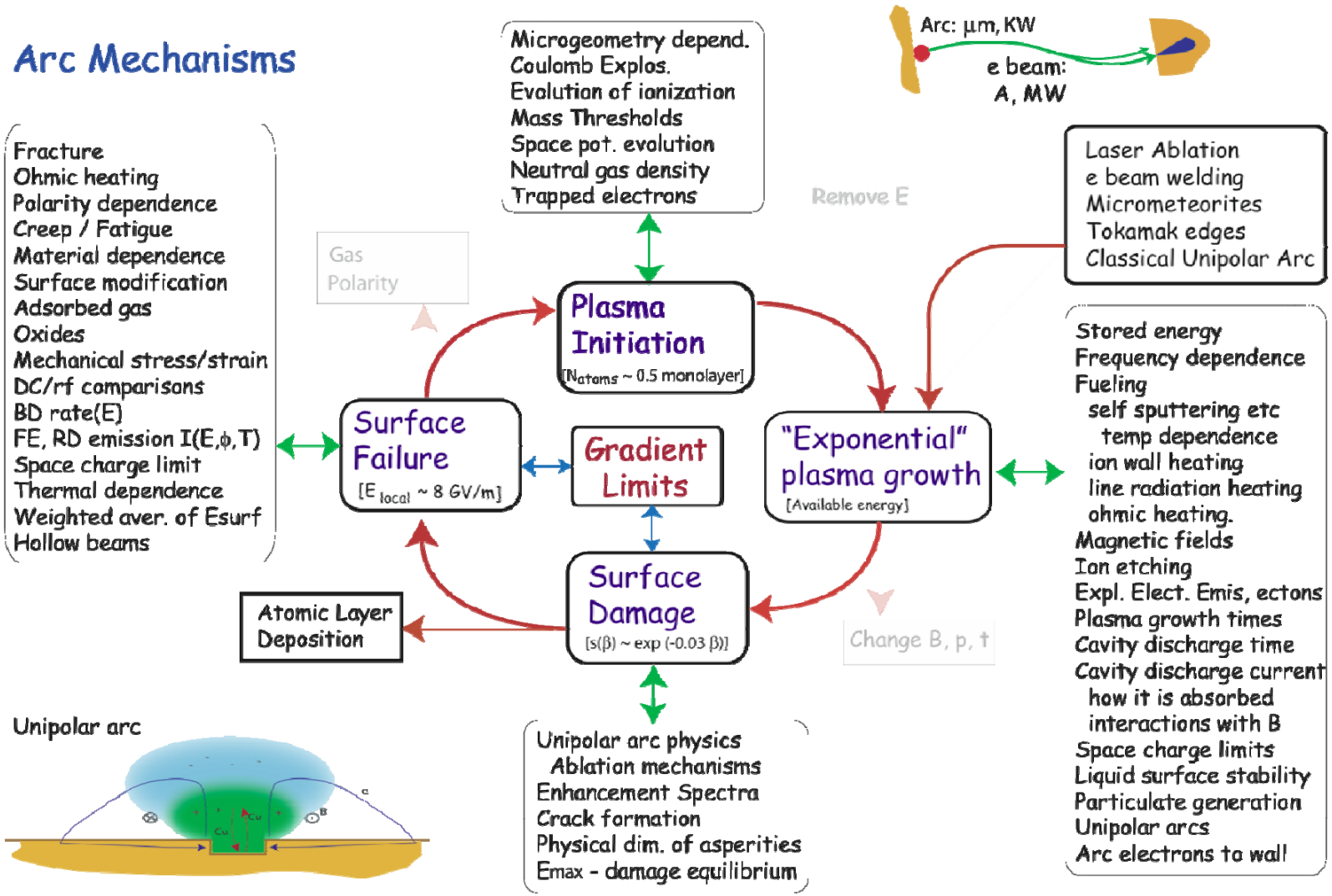
One way to look at it (Norem)



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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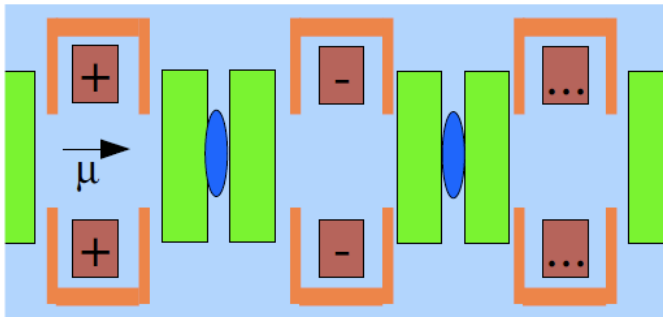

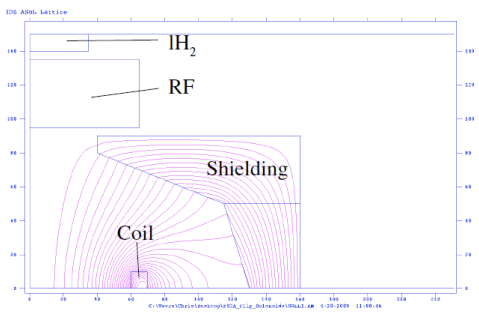

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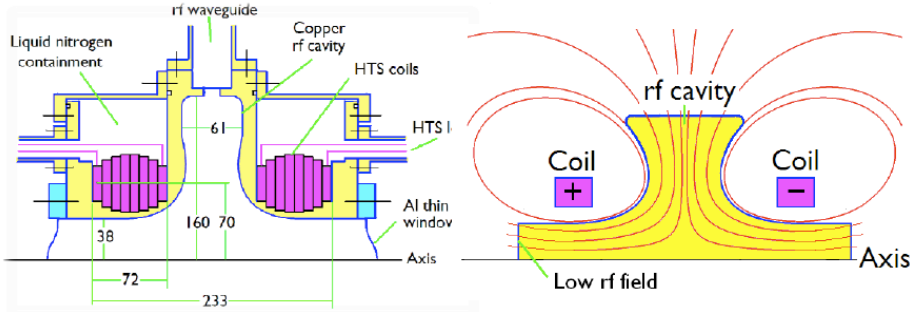

Loss of x 2 gradient advantage in pillbox geometry

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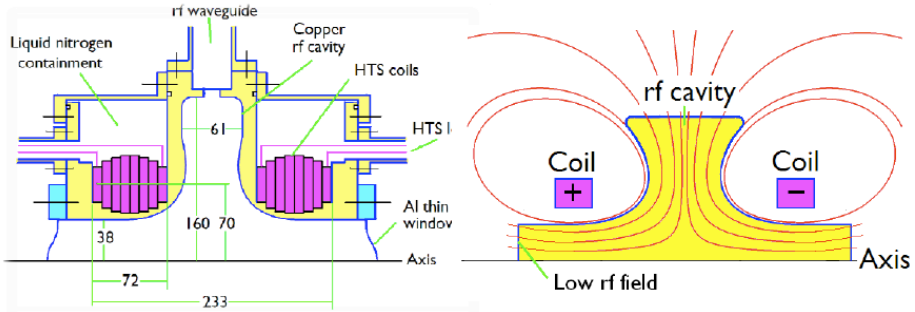

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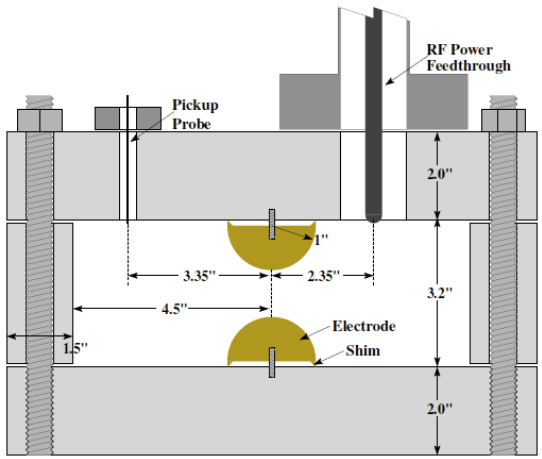

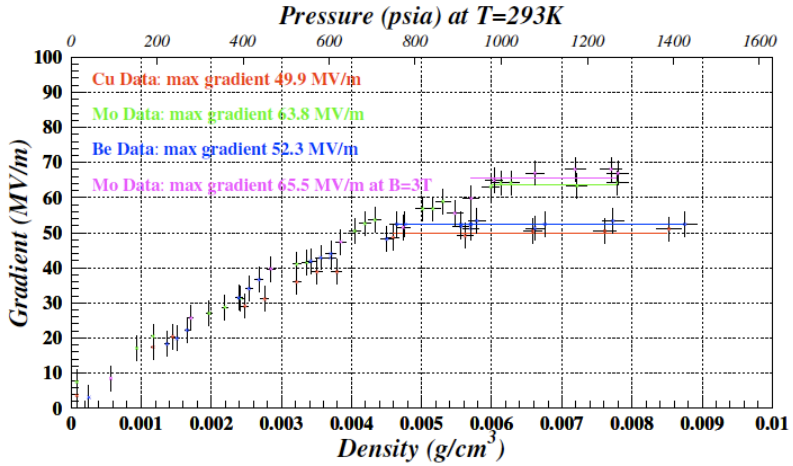

MuCool R&D Project at Fermilab

Mission

- design, prototype and test components for ionization cooling
  - Energy absorbers
  - RF cavities
  - Magnets
  - Diagnostics
- including associated simulation and theoretical studies
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Current focus is on RF in magnetic field.

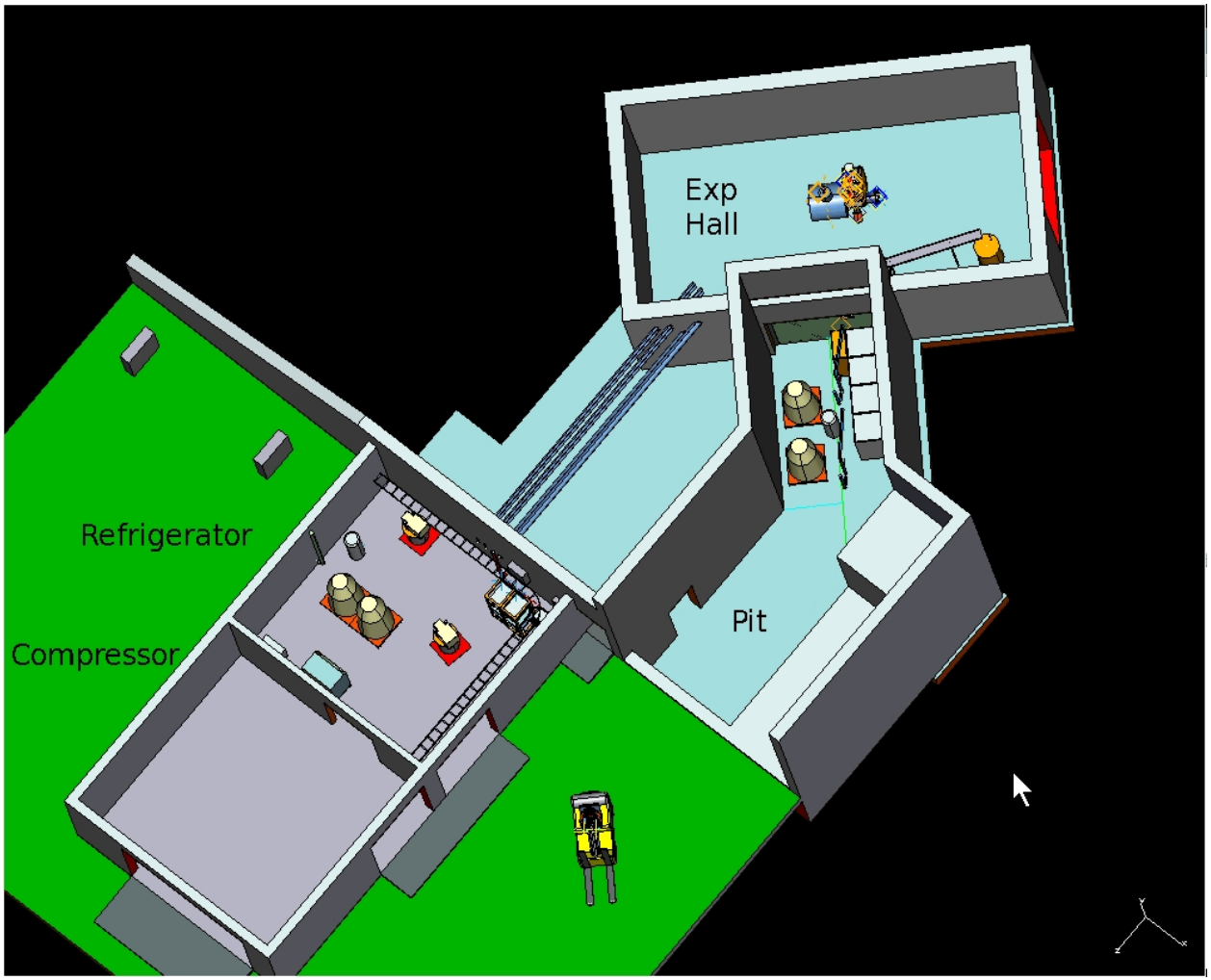
MuCool Test Area (MTA) – http://mice.iit.edu/mta/

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



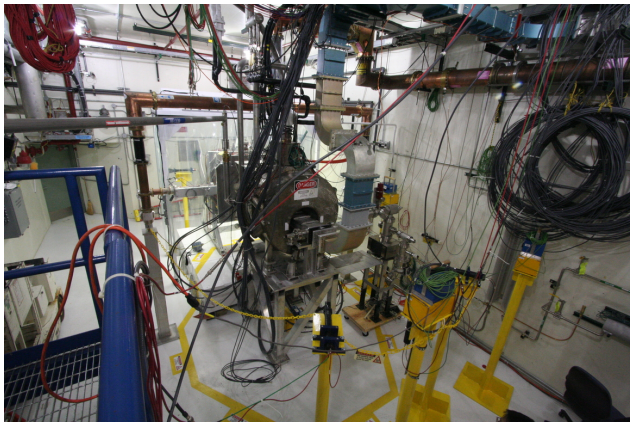
- RF power (13 MW at 805 MHz, 4.5 MW at 201 MHz)
- Superconducting magnet (5 T solenoid)
- Large coupling coil under construction
- 805 and 201 MHz cavities
- Radiation detectors
- Cryogenic plant
- 400 MeV p beamline

MuCool Test Area (MTA)

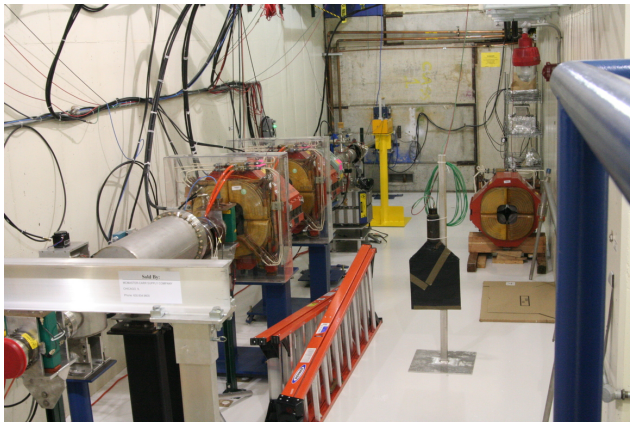


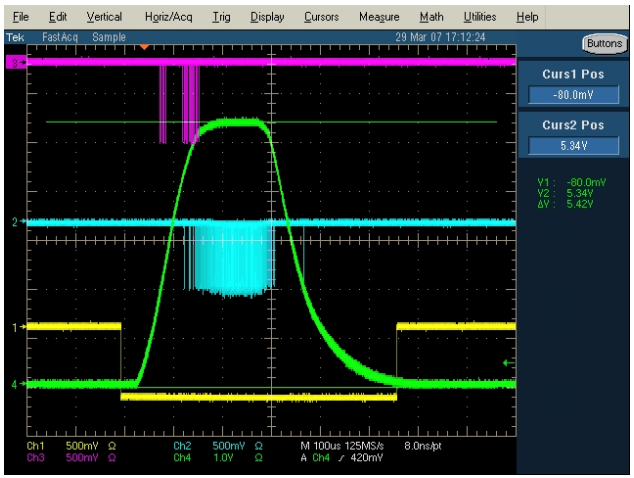
MuCool Test Area (MTA)

Experimental Hall



Beamline



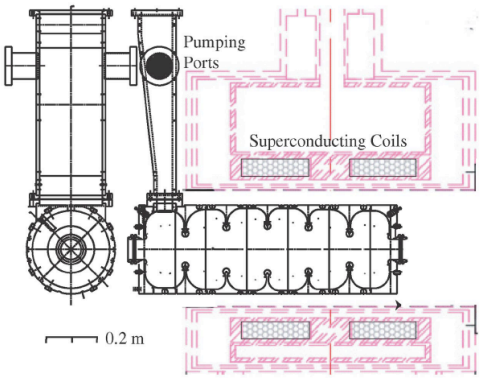


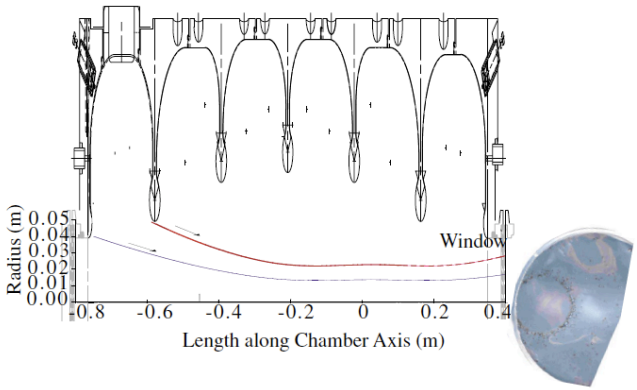
X-rays at high gradient

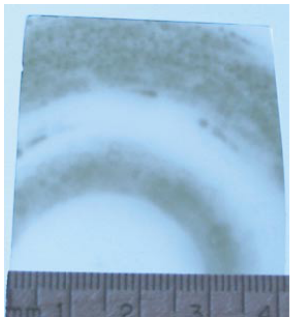
Compressor Room

It all started with ..

- 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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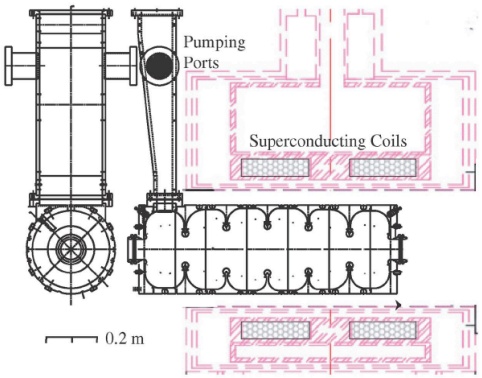

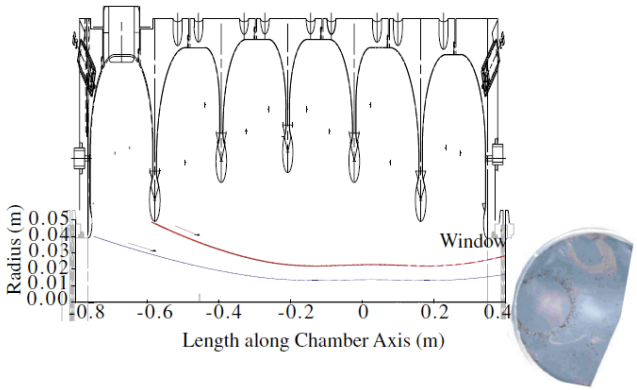

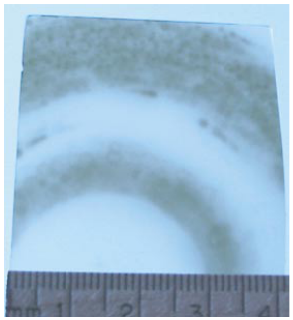

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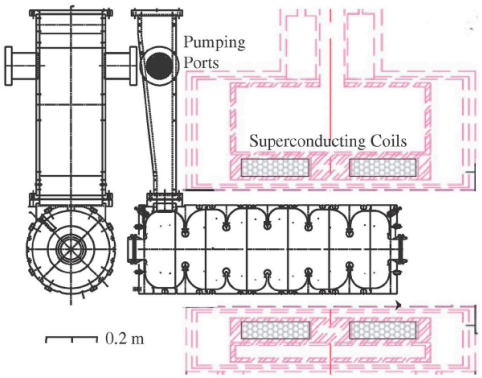

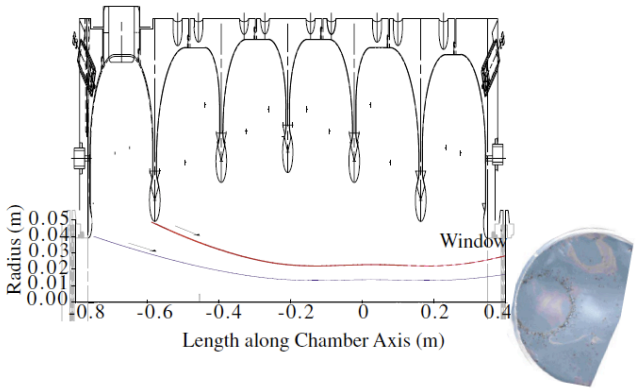

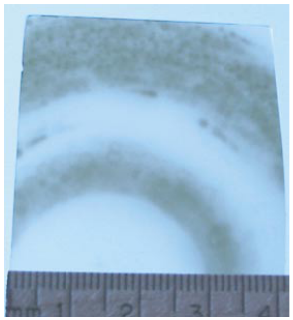

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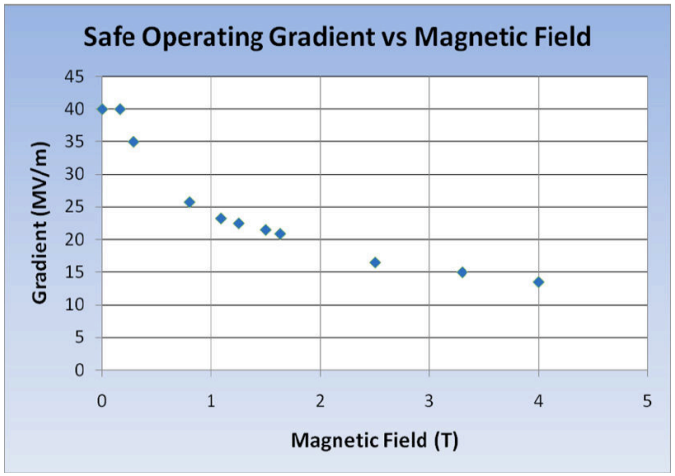

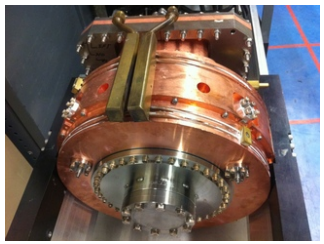

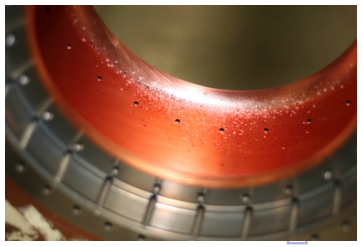

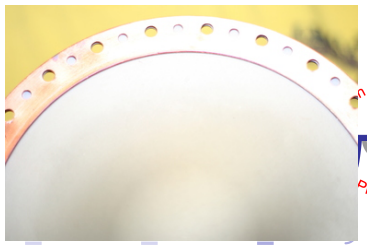

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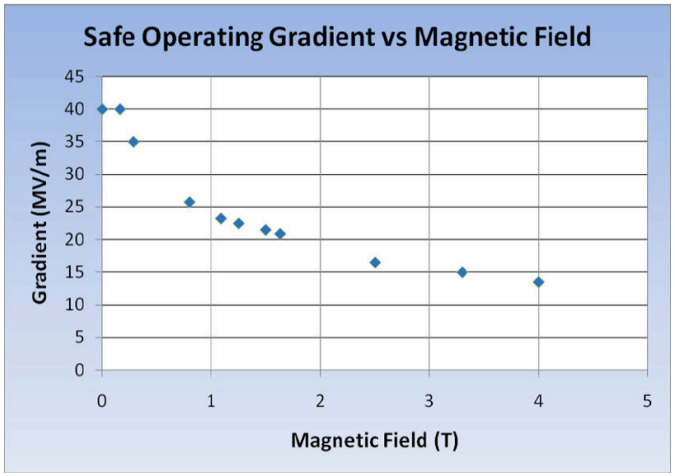

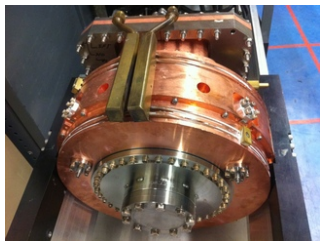

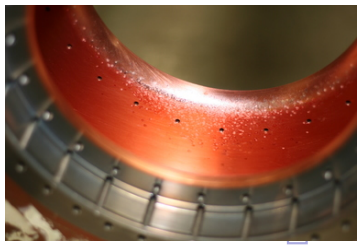

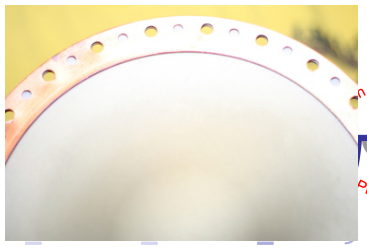

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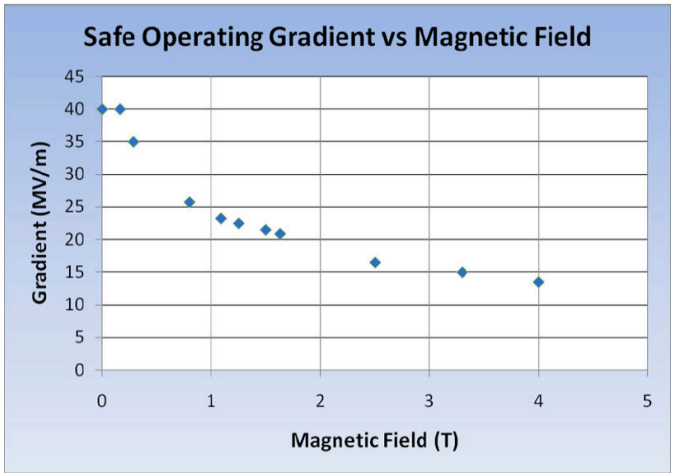

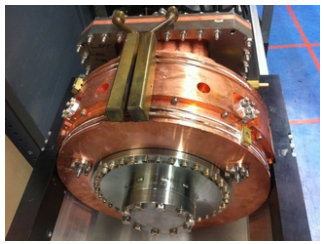

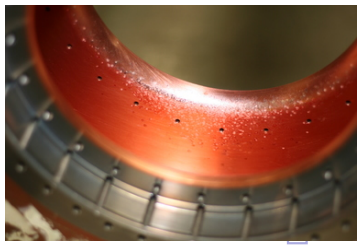

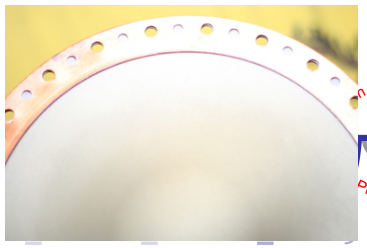

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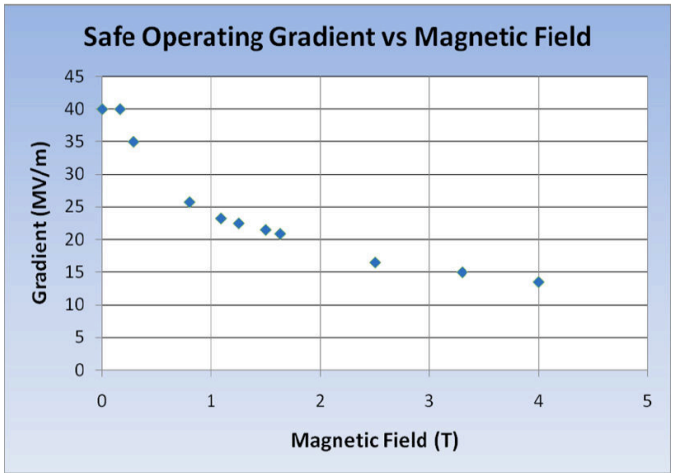

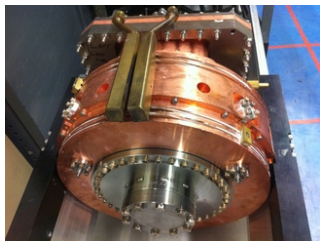

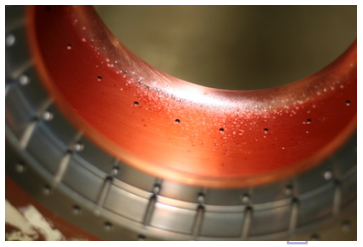

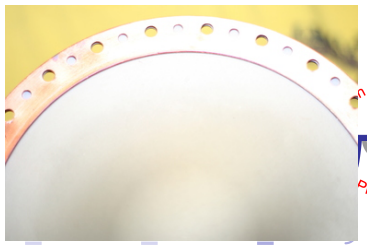

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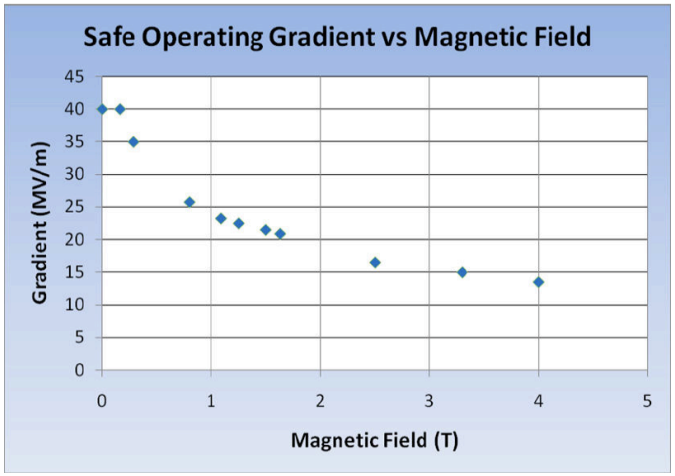

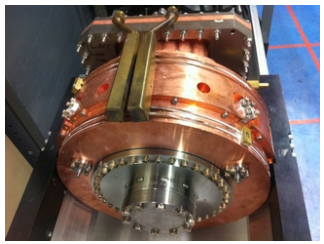

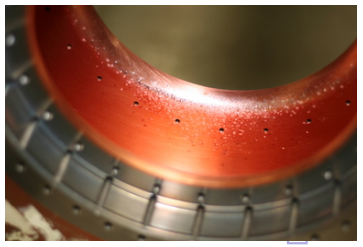

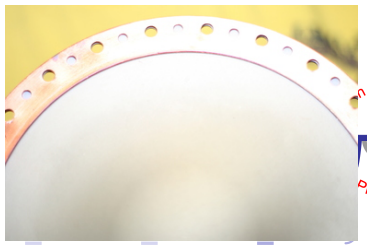

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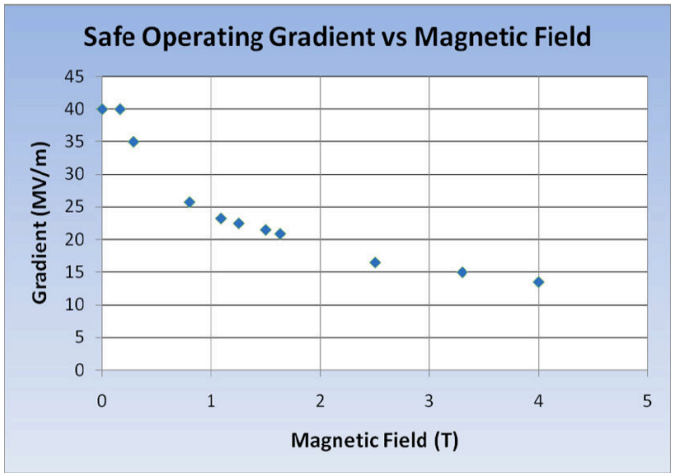

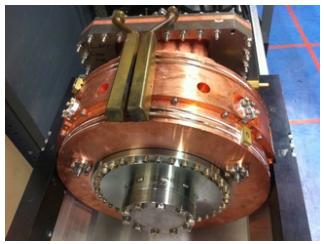

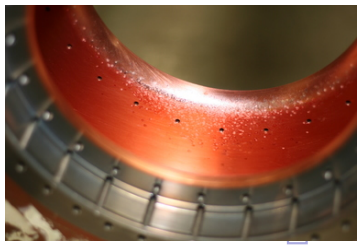

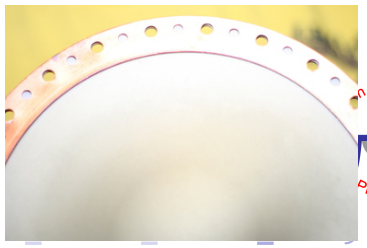

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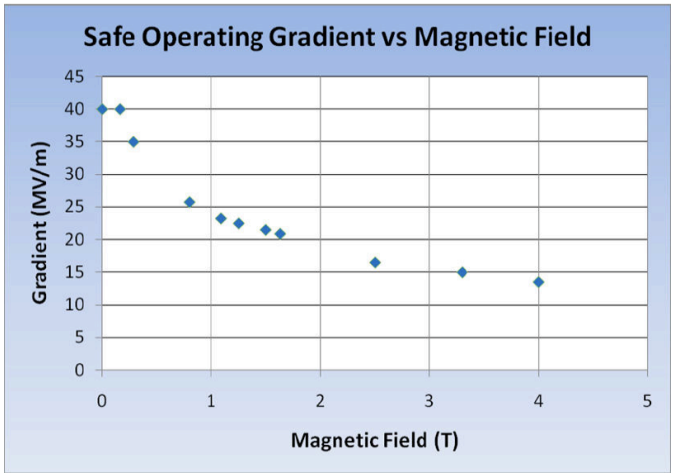

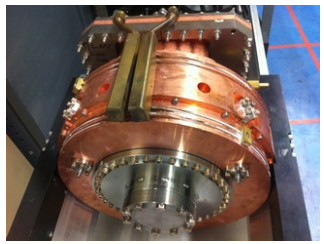

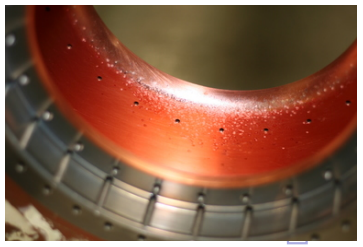

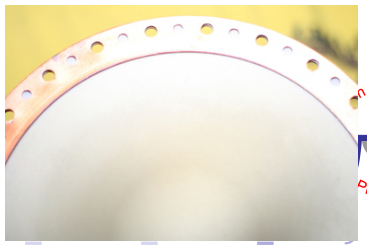

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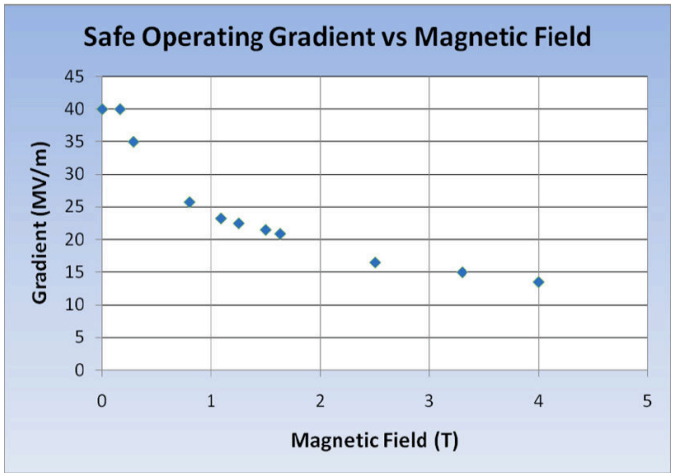

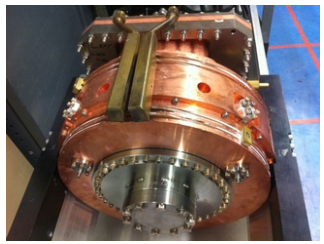

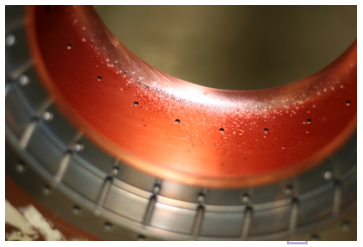

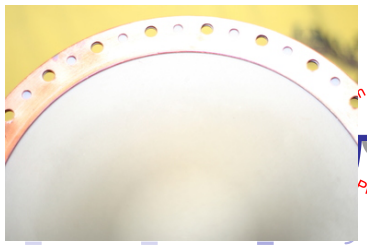

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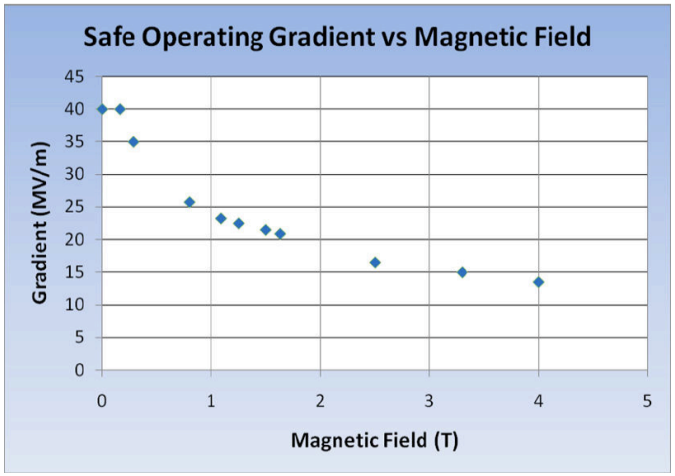

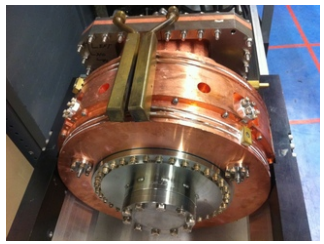

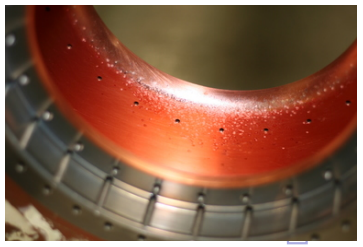

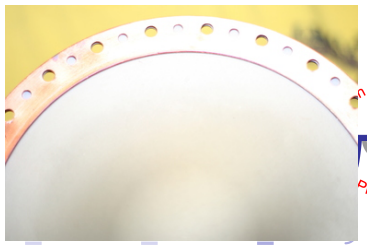

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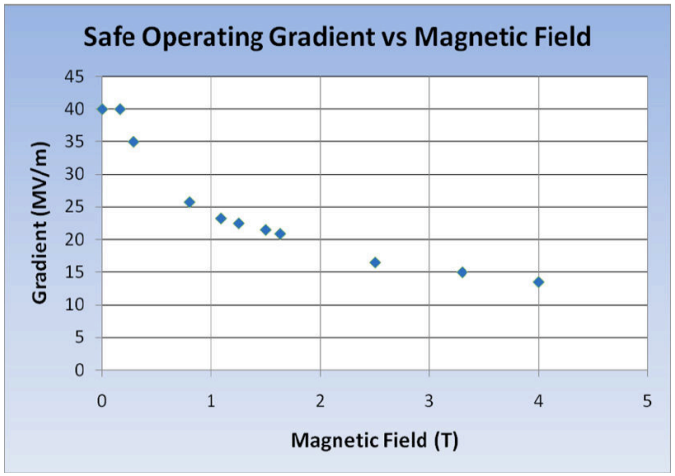
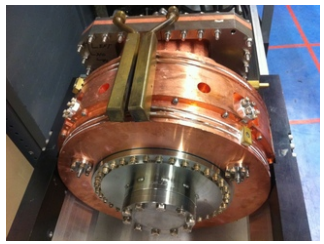
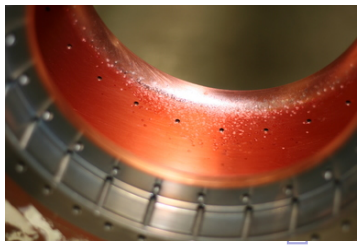
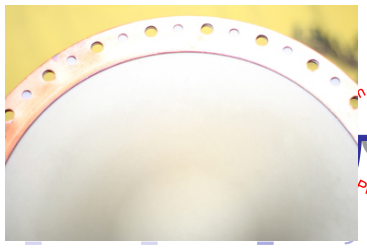


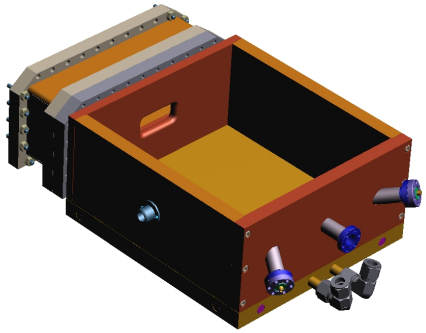


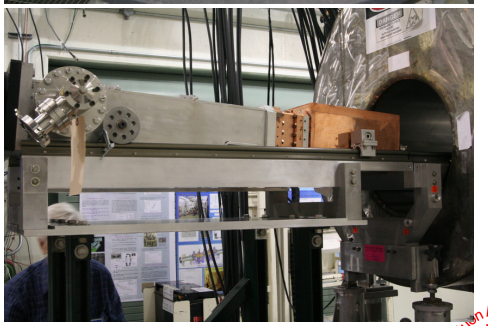




Box Cavity (Moretti)

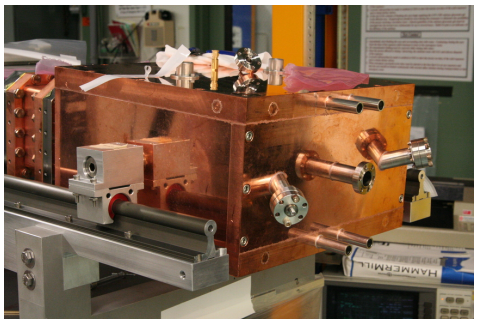
- Rectangular geometry chosen for test cavity to allow fast fabrication and simplify analysis
- Interior dimensions: 276.5 x 250 x 123.8 mm
- Made of 101 OFE copper plates
- Attached in two hydrogen brazing cycles
- Support system designed to rotate cavity pivoting around magnet center by up to 12^o
- 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

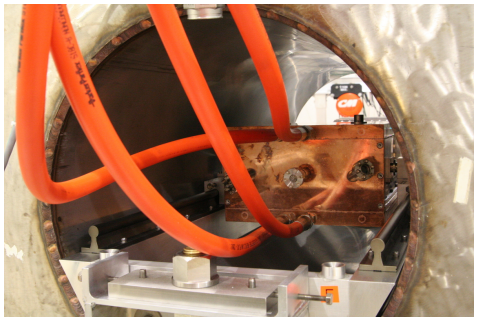


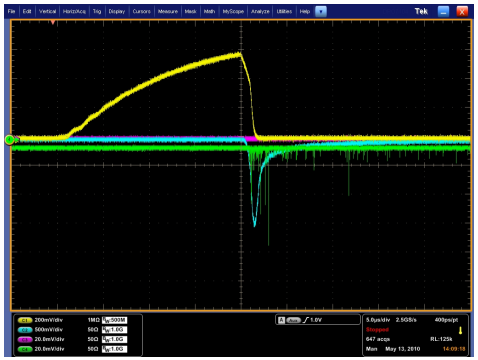


Box Cavity

- Operated in the MTA magnet Mar-Sep 2010
- Automated control program, optical diagnostics
- Commissioned to 49MV/m at B=0
- Took data at 0, ± 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 obvious damage
- RF, optical and X-ray signals during sparks saved for analysis

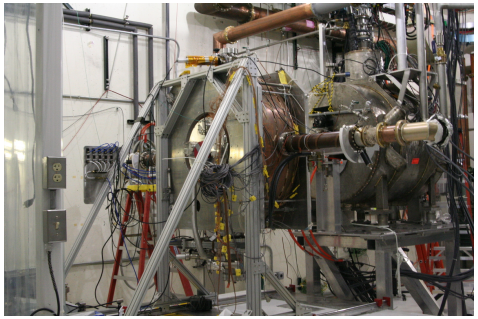






201 pillbox

201 MHz MICE prototype cavity



- SRF-like processing (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
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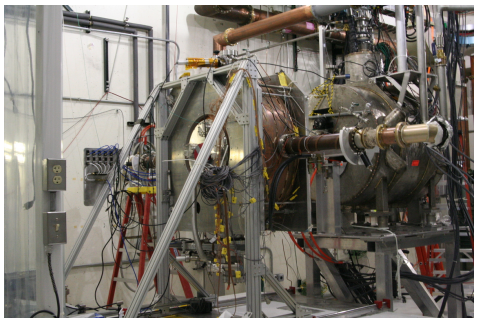

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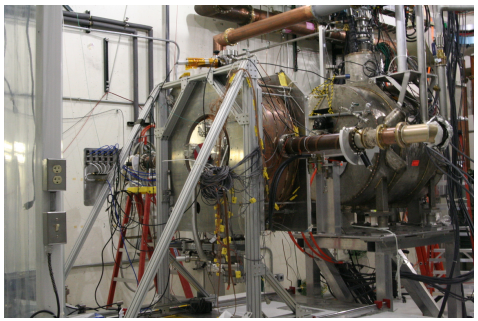

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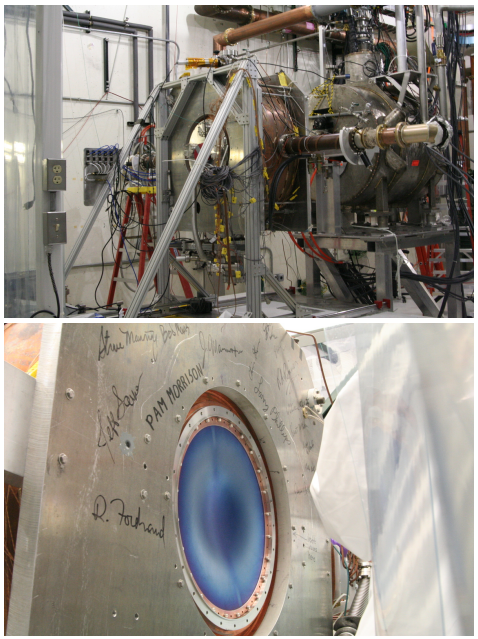

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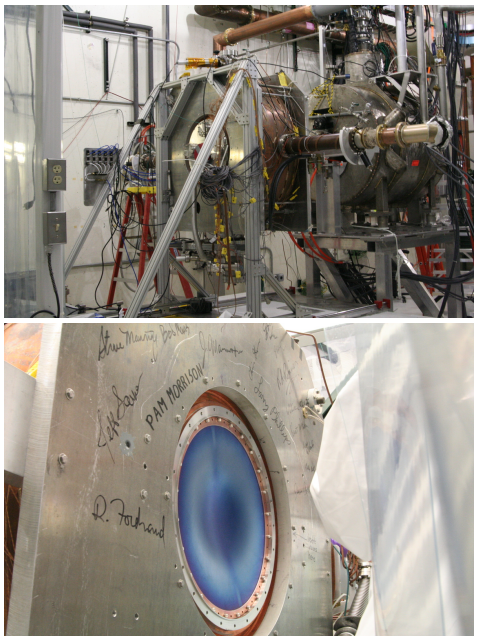

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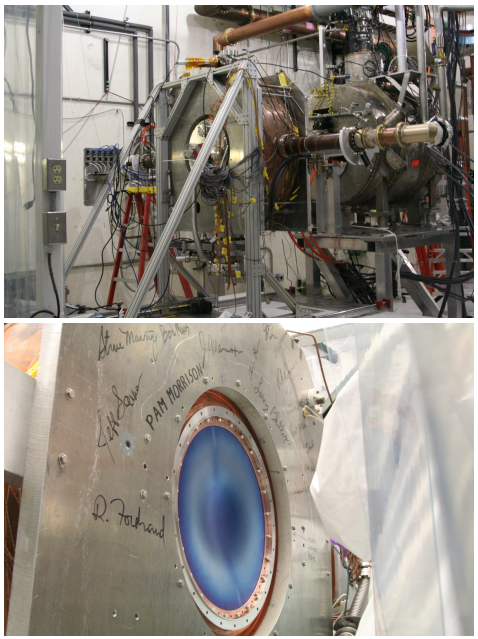

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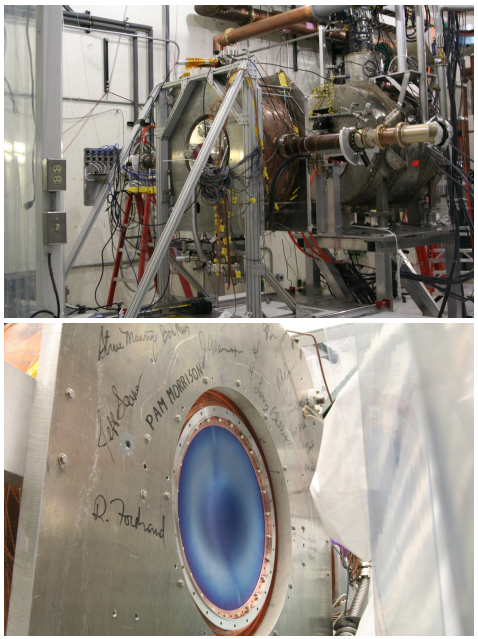

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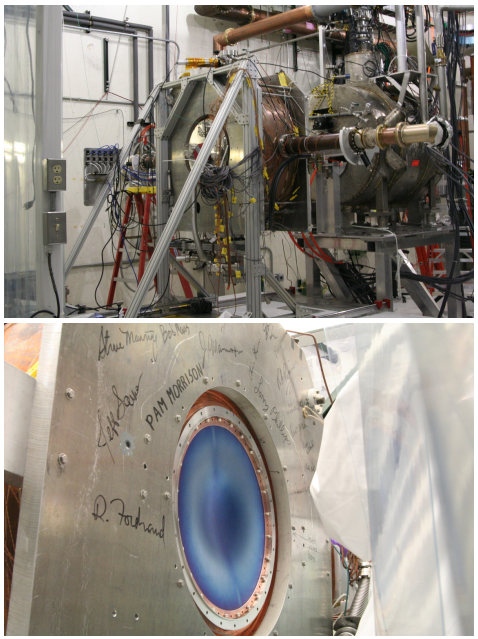

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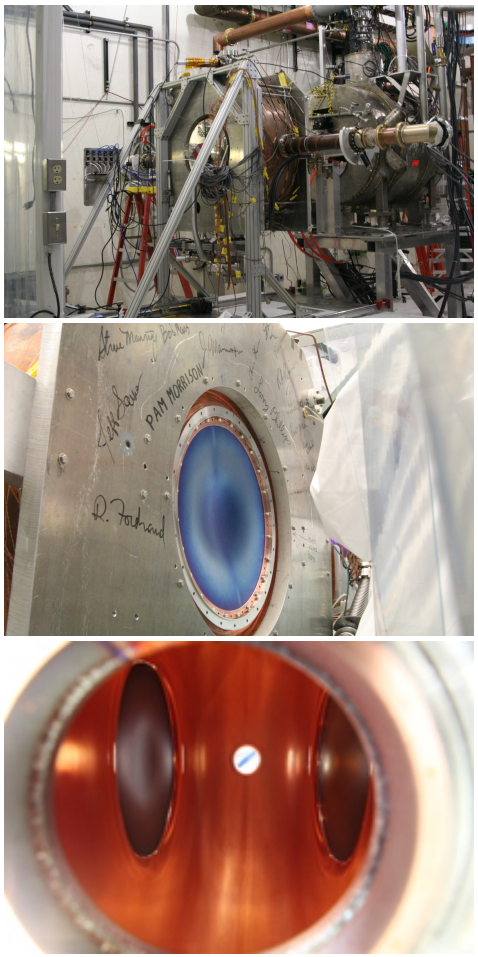
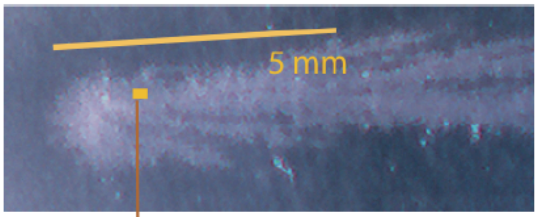
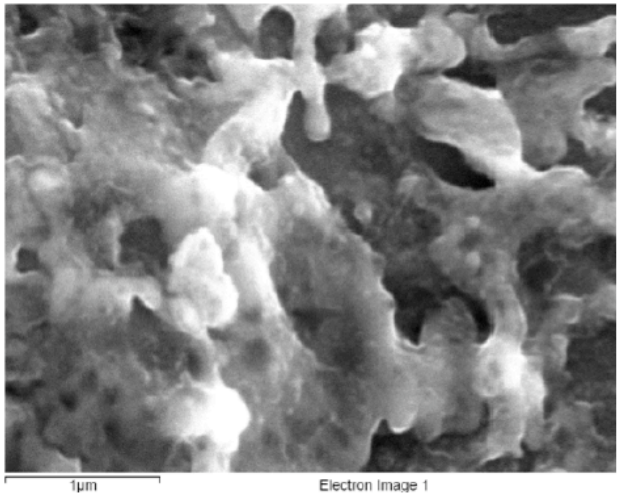


201 pillbox

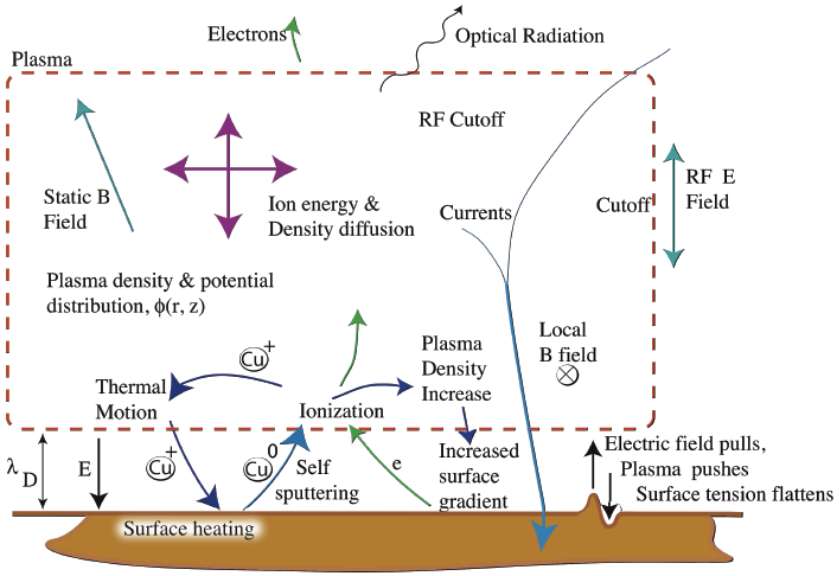
Evidence for some sparking in the coupler



SEM images of 201 MHz coupler.



Unipolar arc?



4-Season cavity (Muons Inc., LANL)

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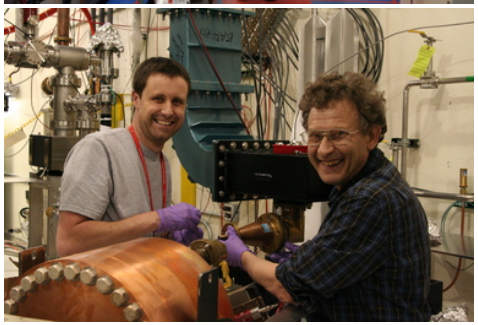

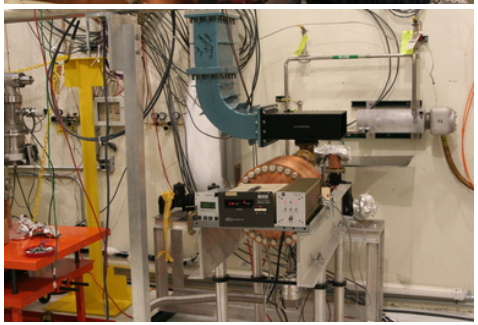

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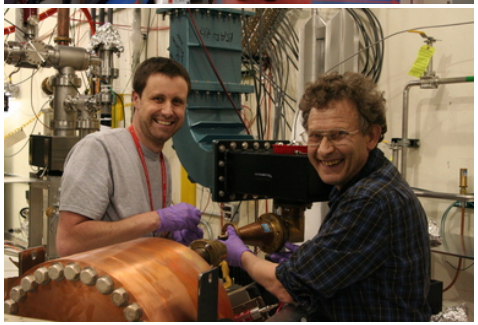

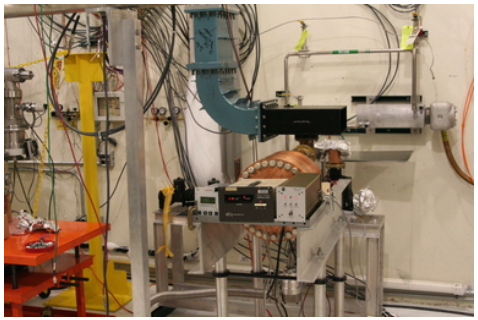

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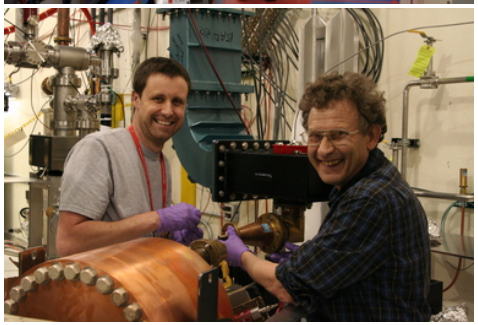

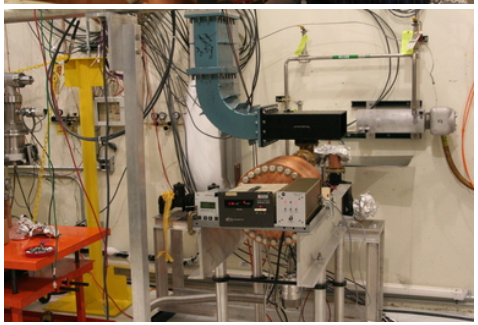

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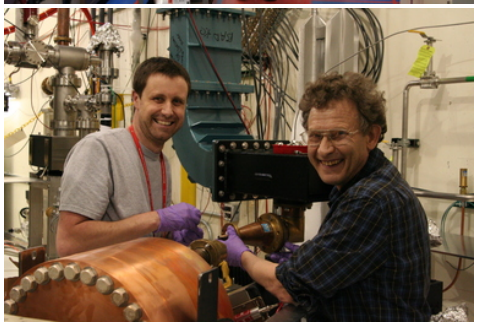

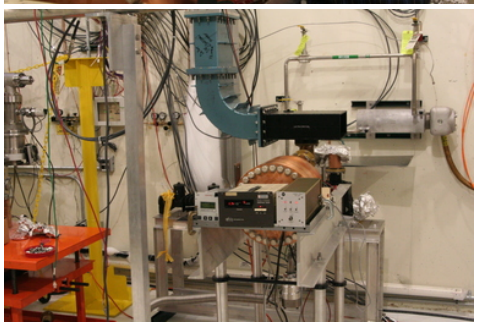

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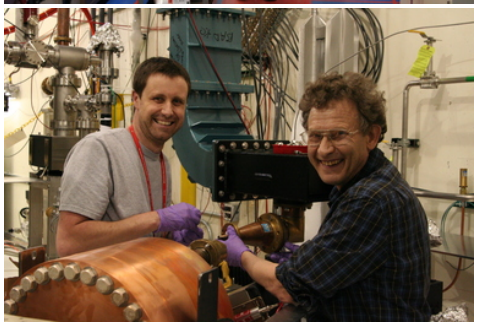

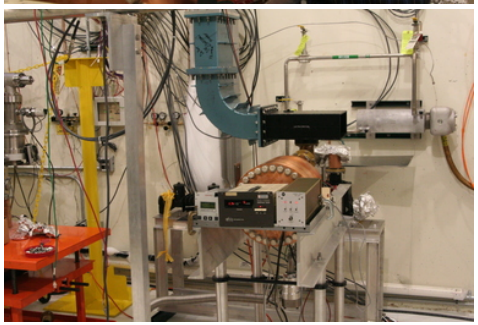

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HPRF cavity beam test (Yonehara)

- First beam experiment at MTA
- Currently our highest priority
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- Goal: evaluate loading due to beam induced ionization
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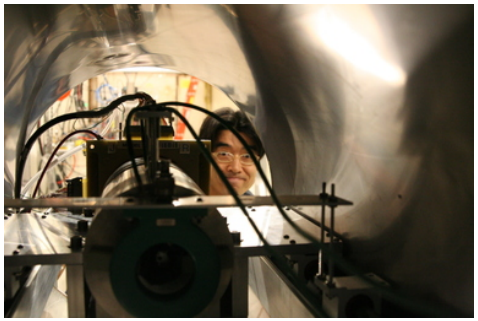

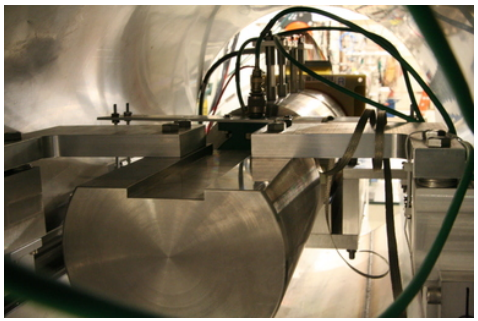

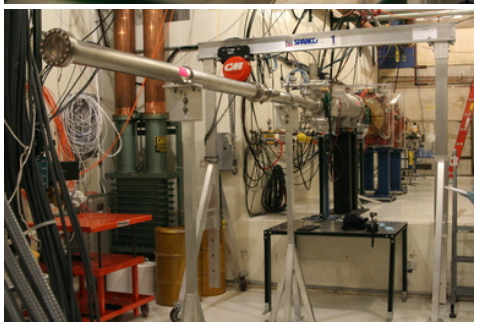

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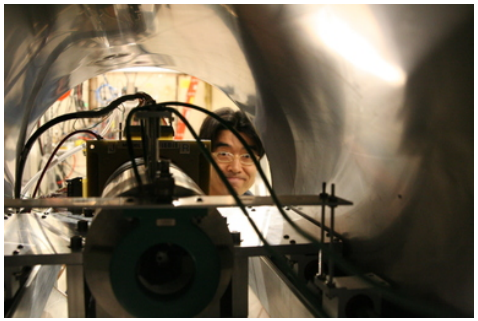

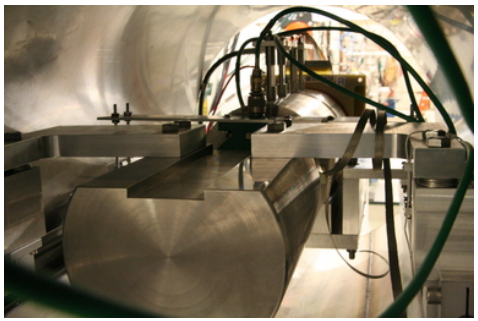

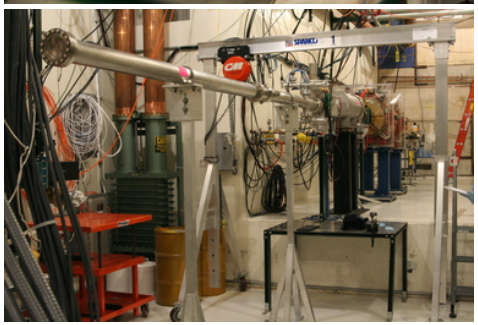

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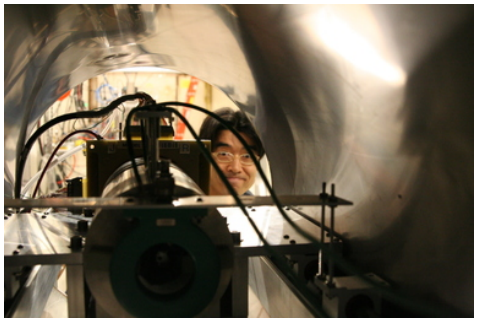

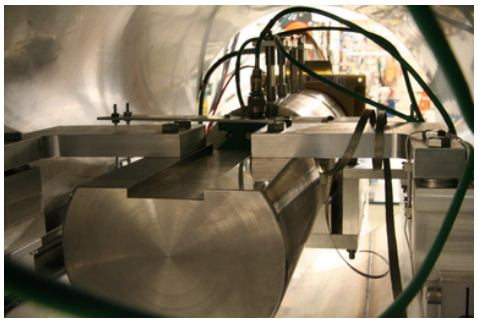

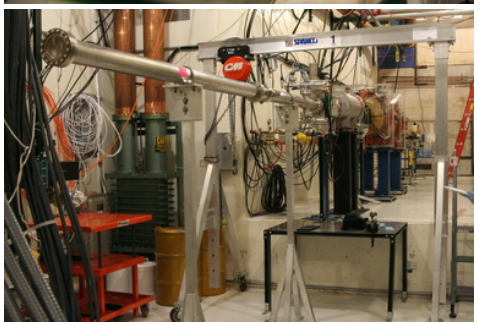

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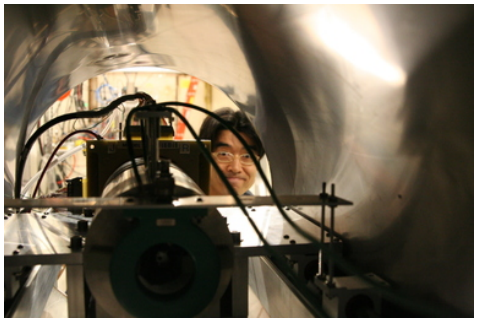

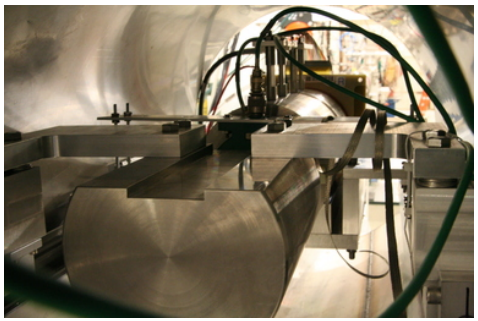

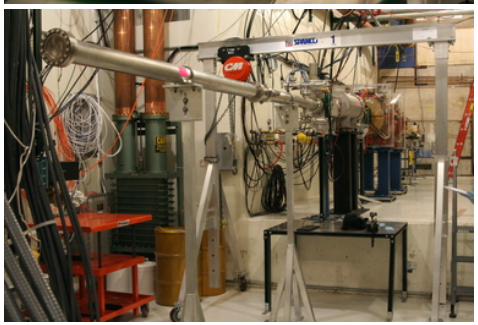

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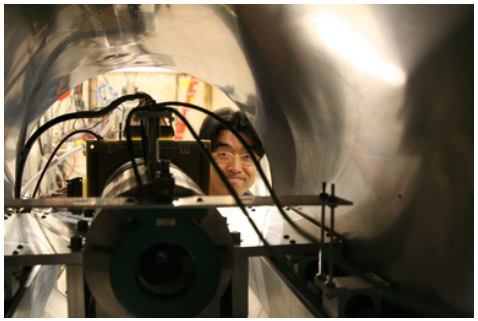

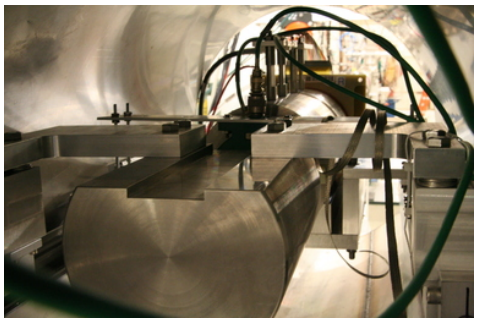

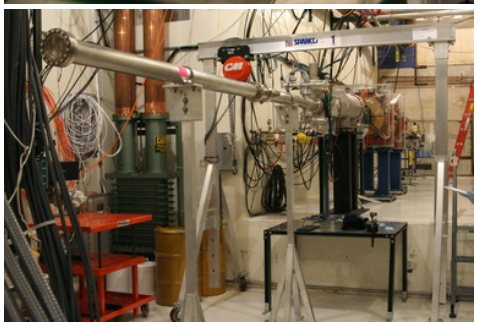

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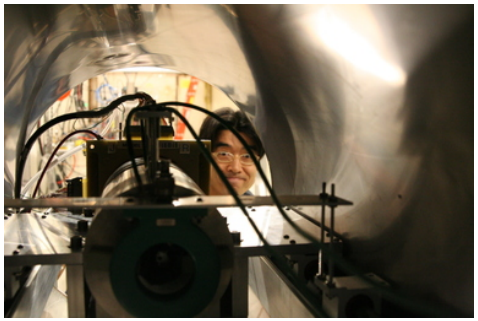

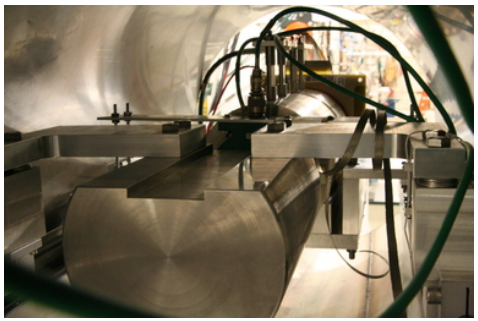

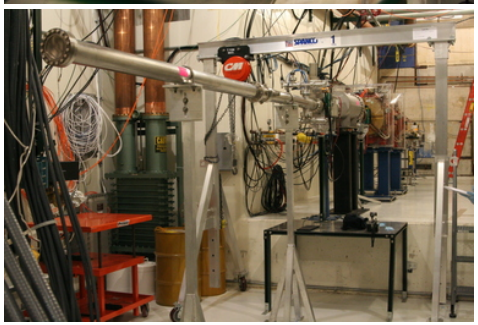

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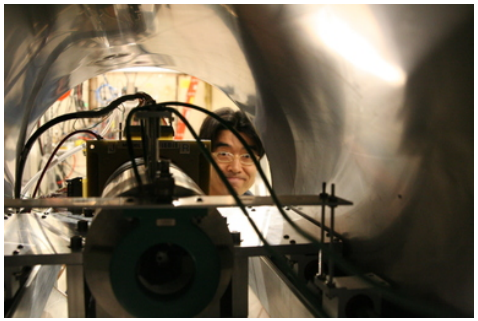

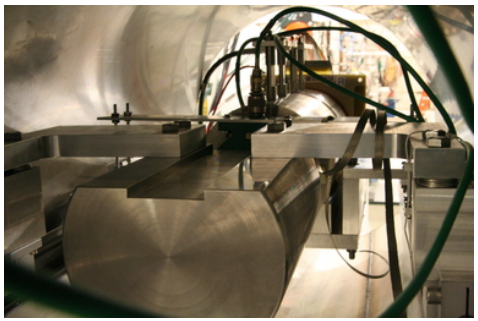

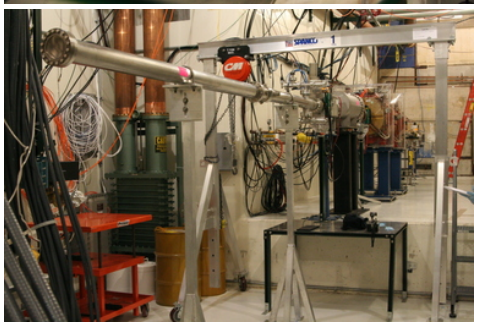

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HPRF cavity beam test (Yonehara)

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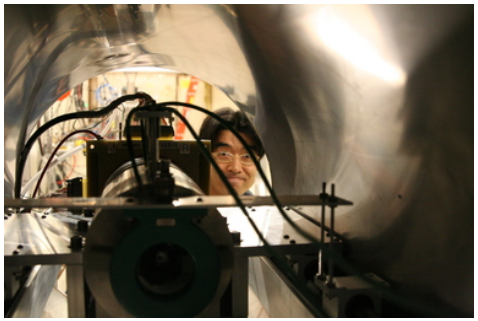

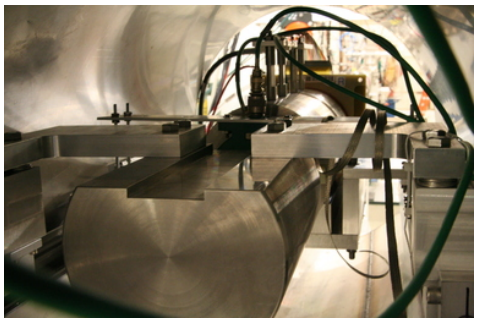

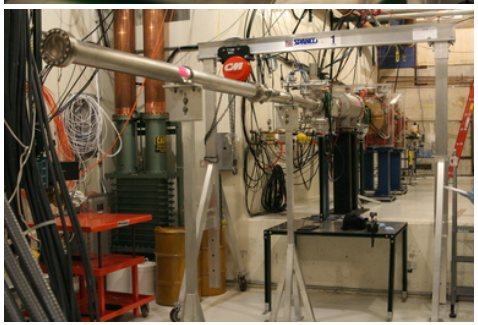

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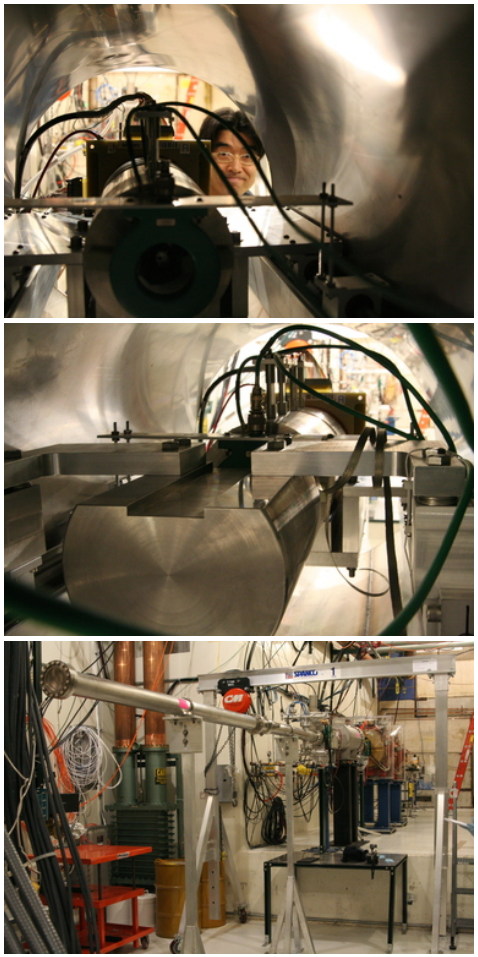

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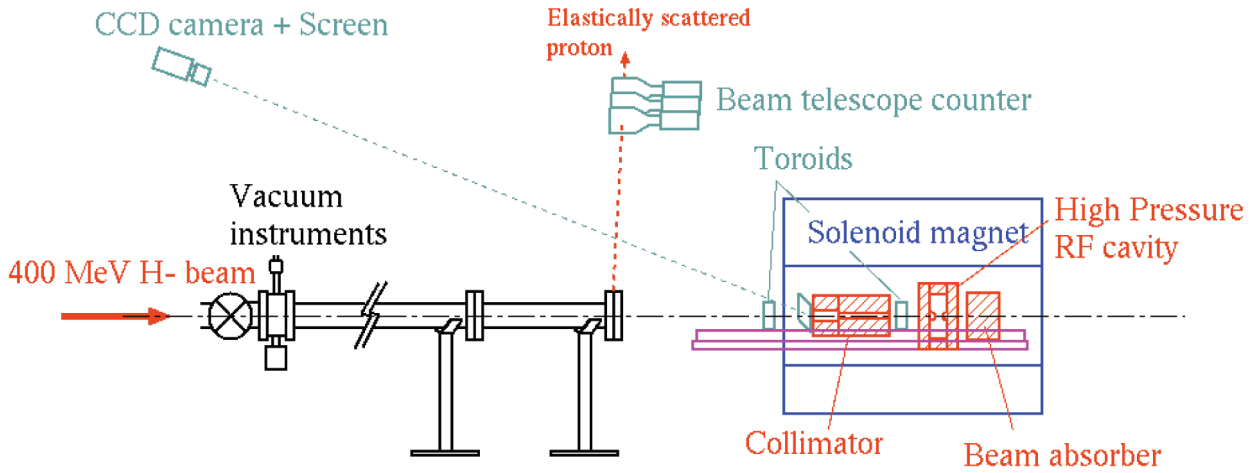

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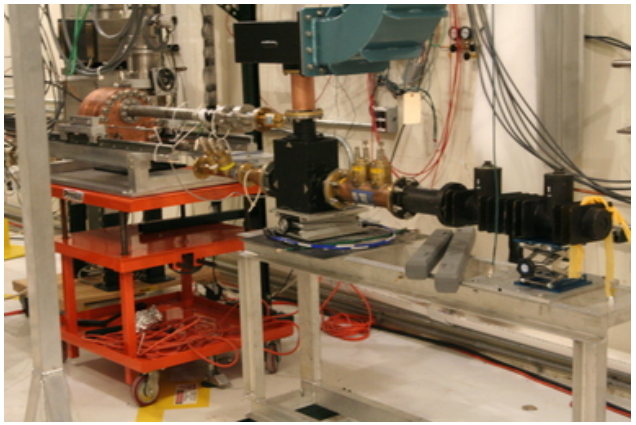

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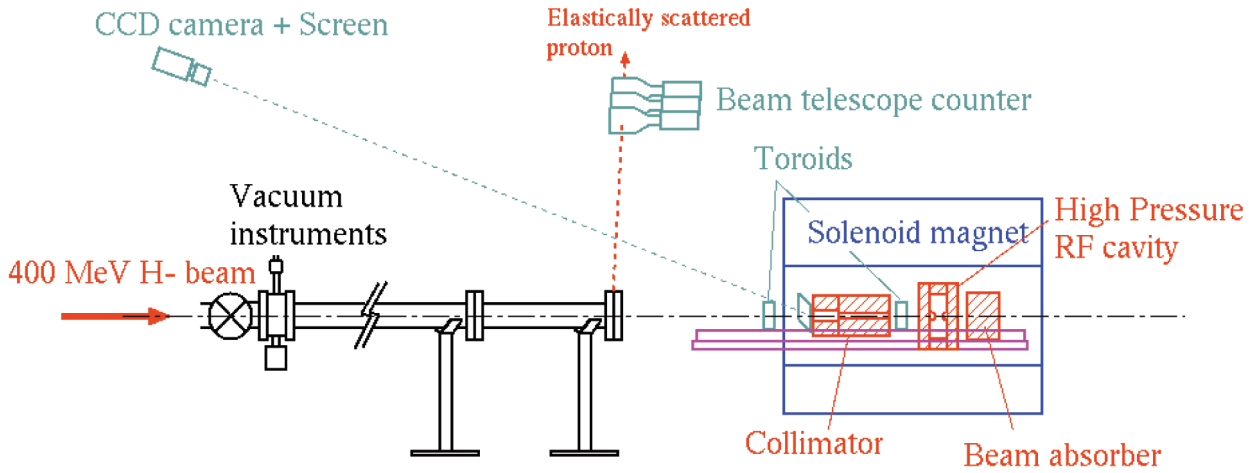

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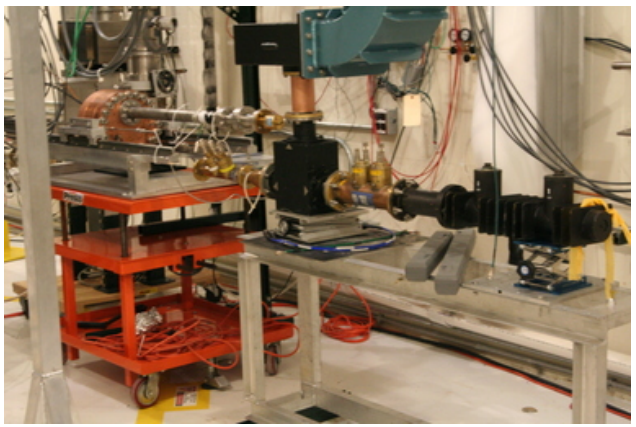

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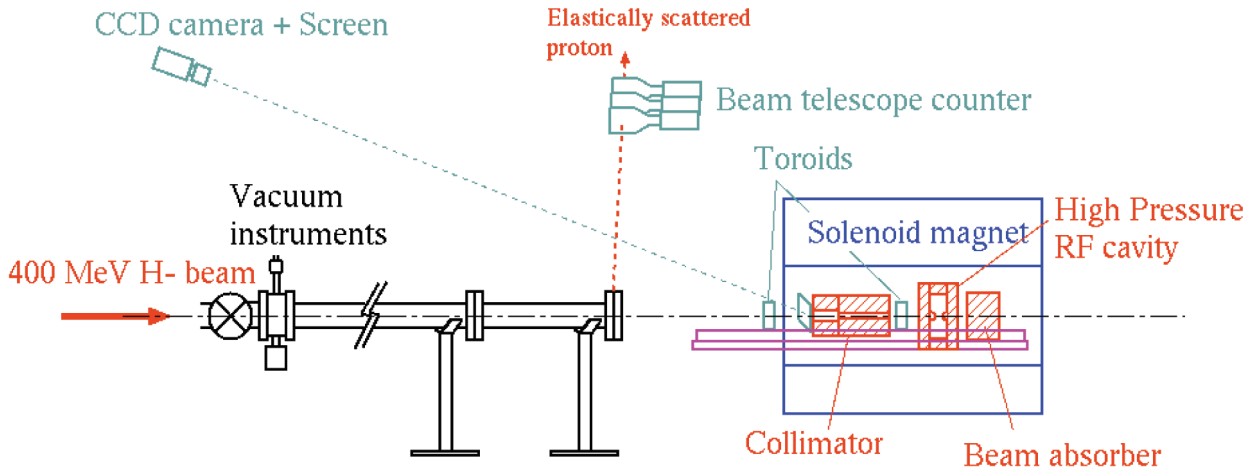

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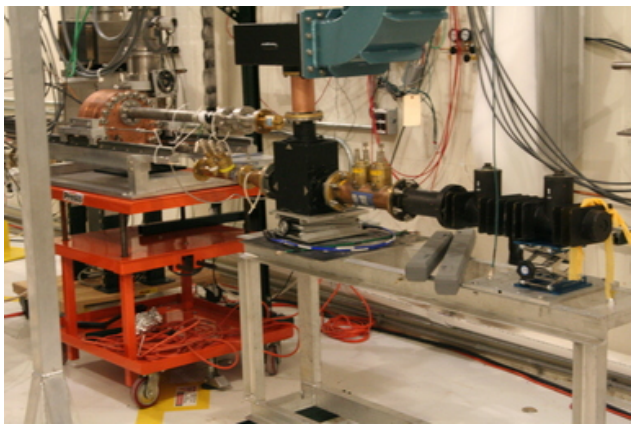

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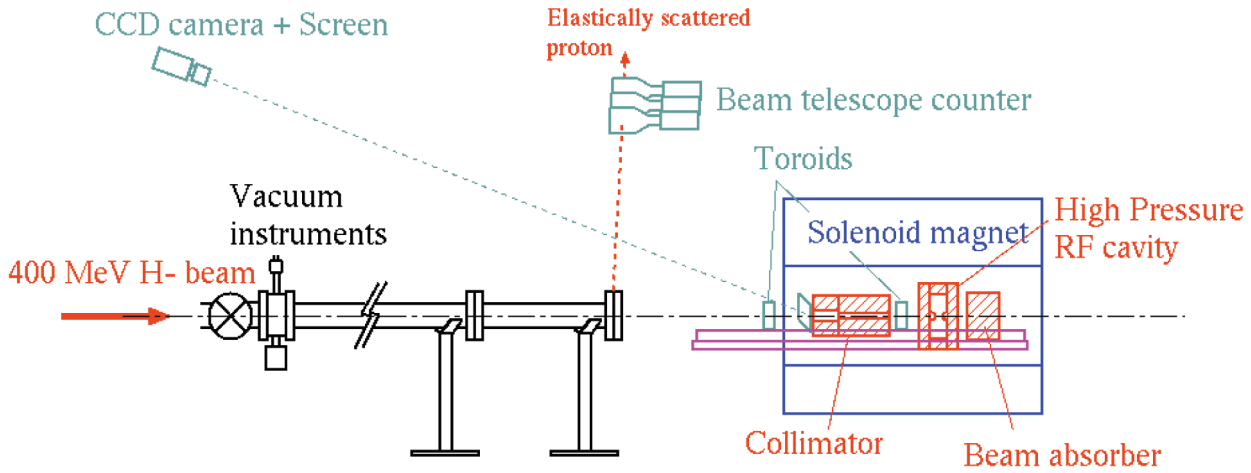

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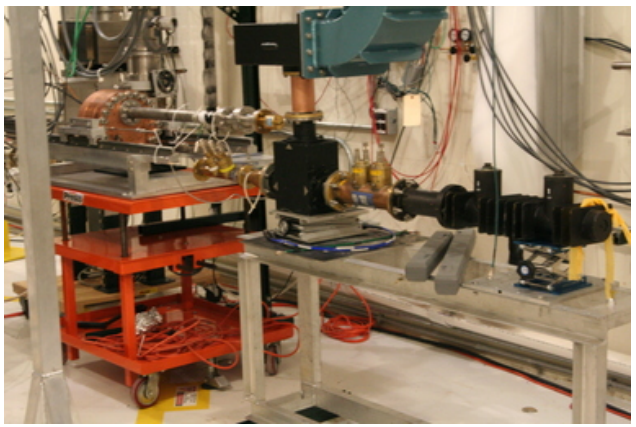

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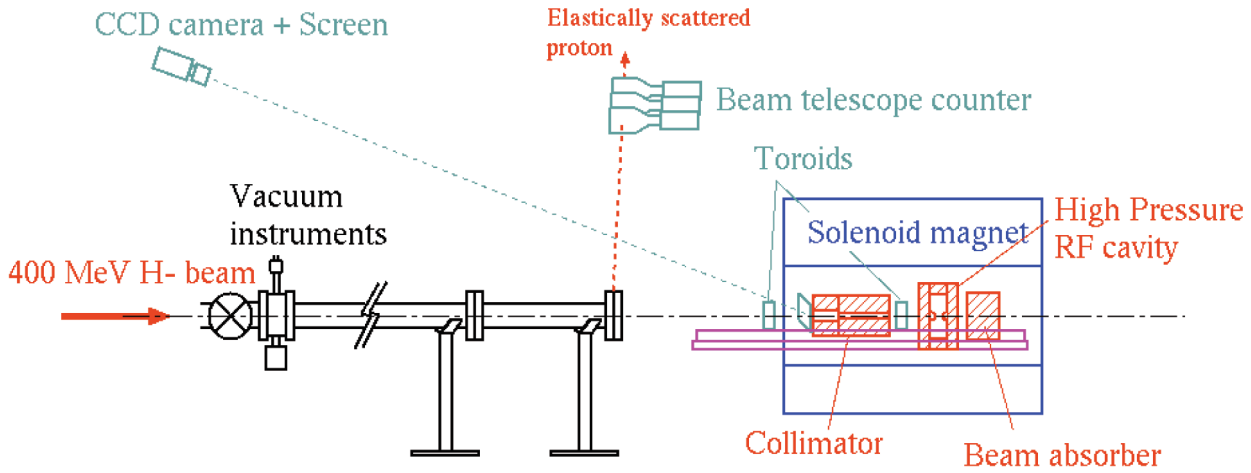

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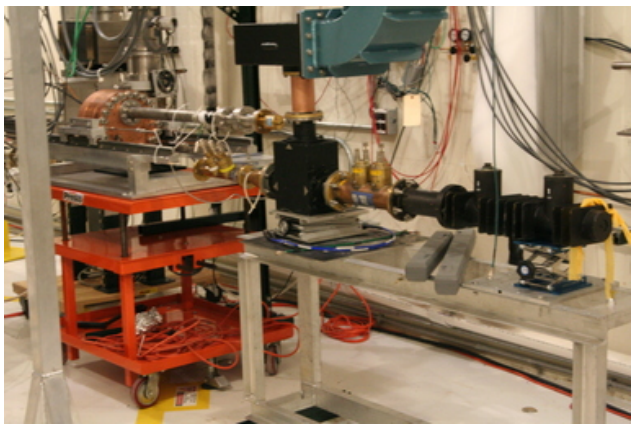

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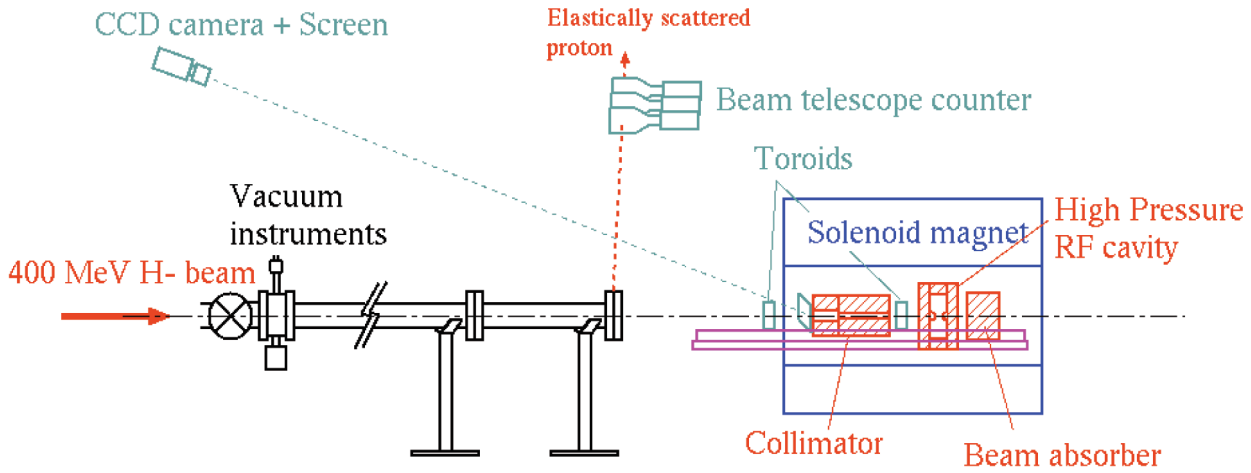

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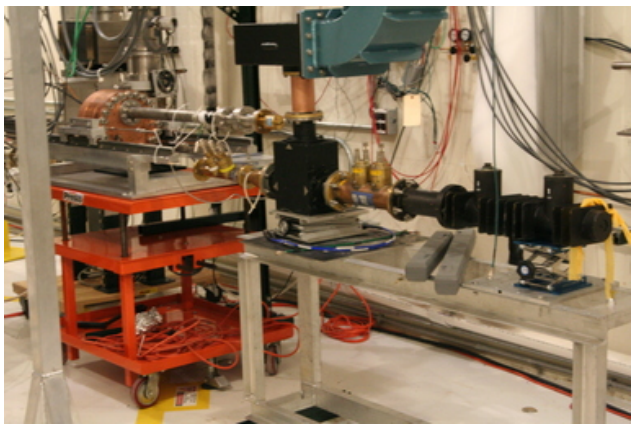

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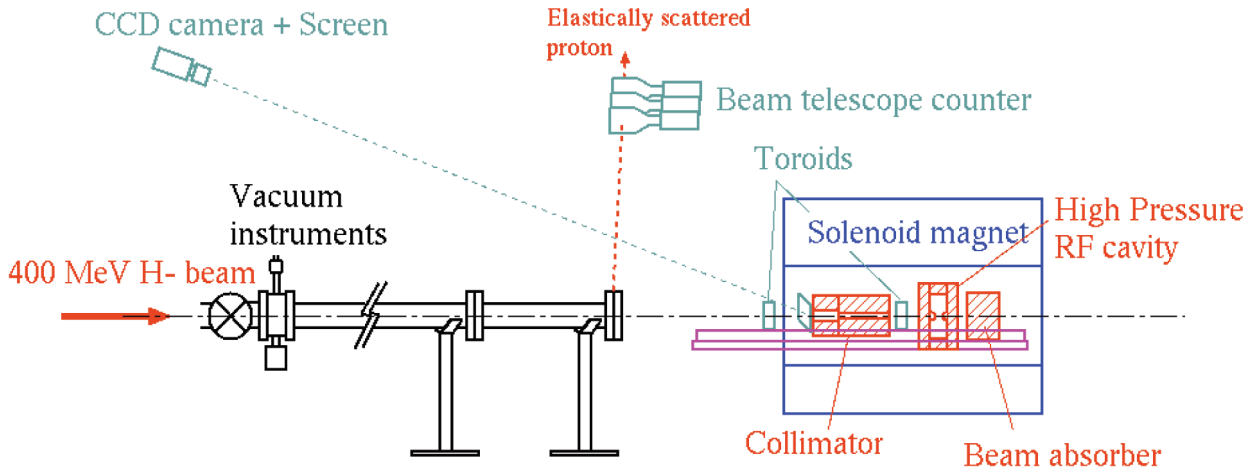

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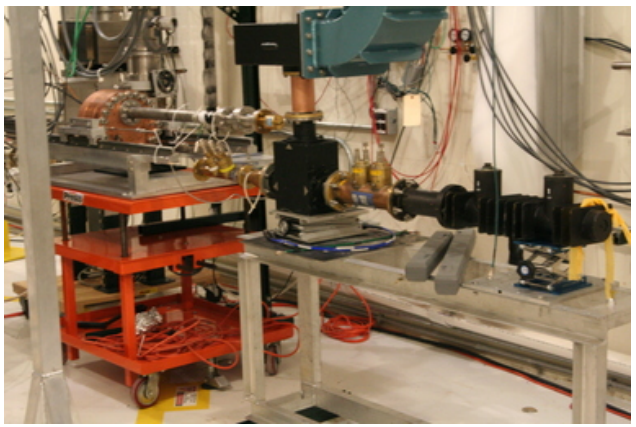

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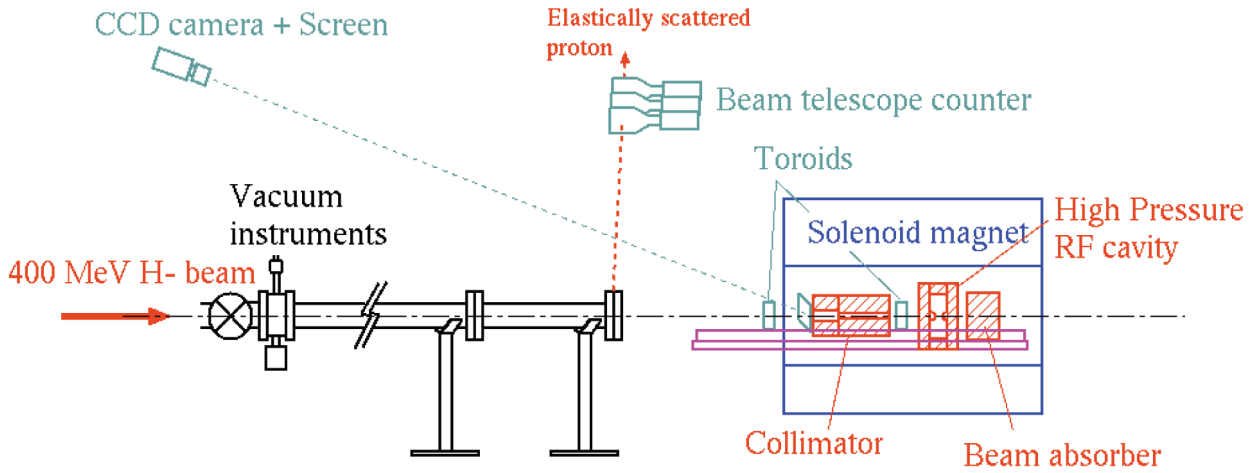

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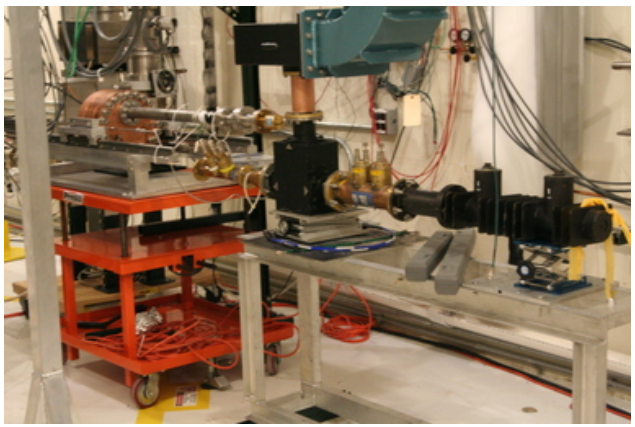

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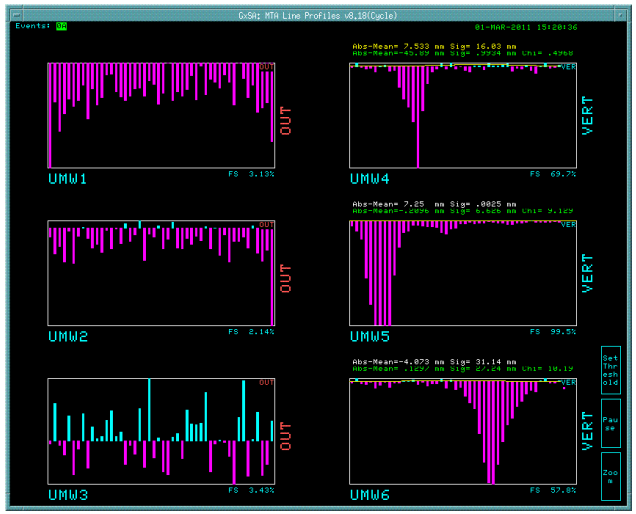

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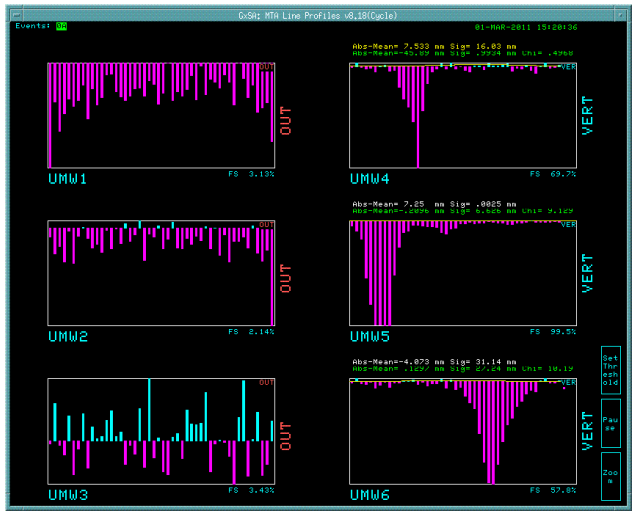

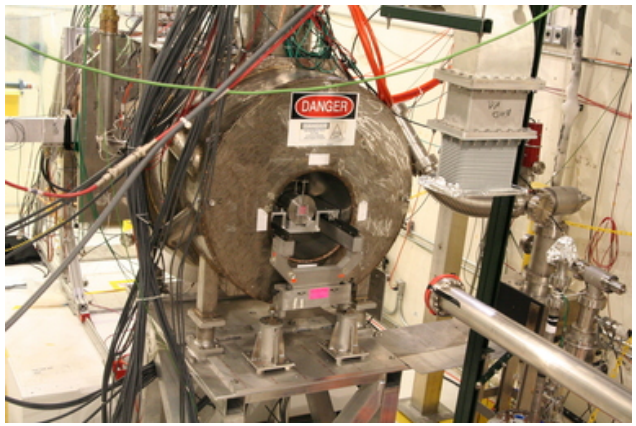

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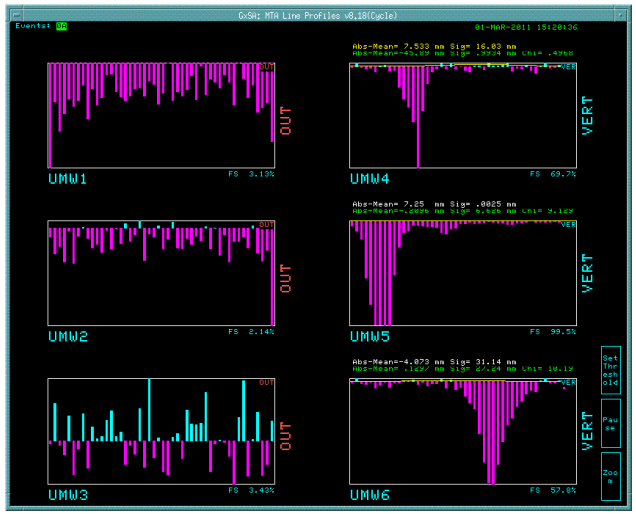

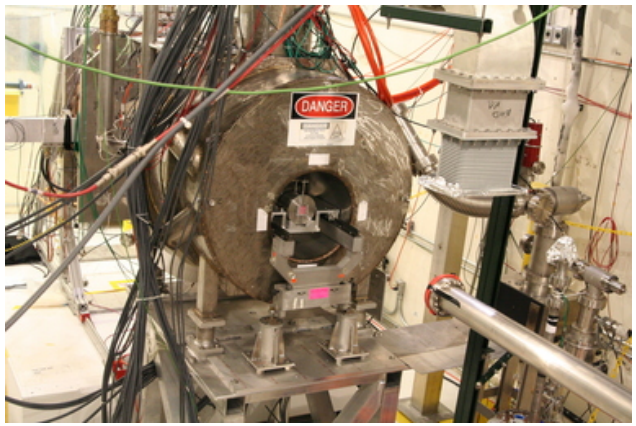

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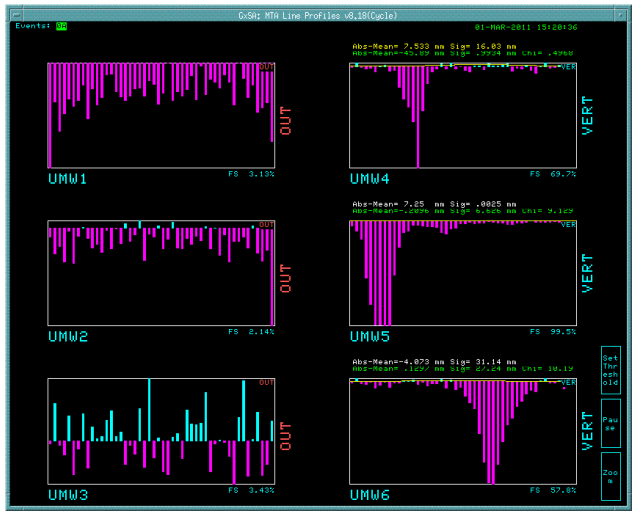

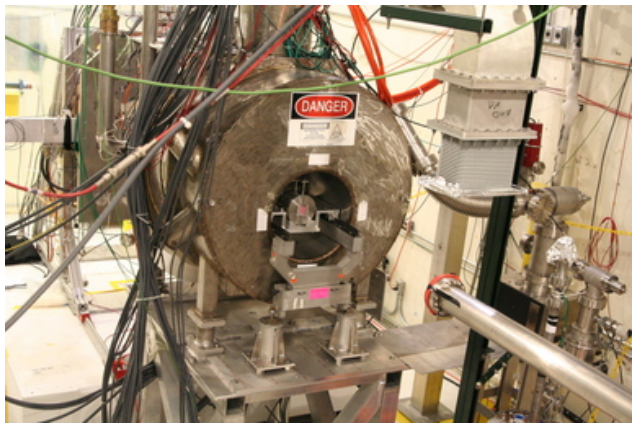

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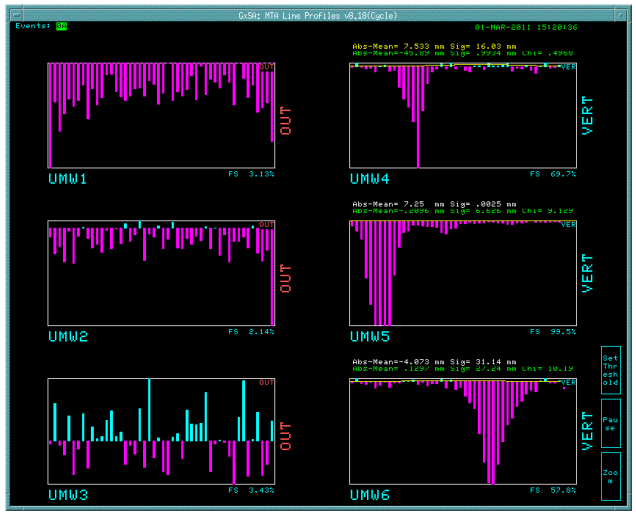

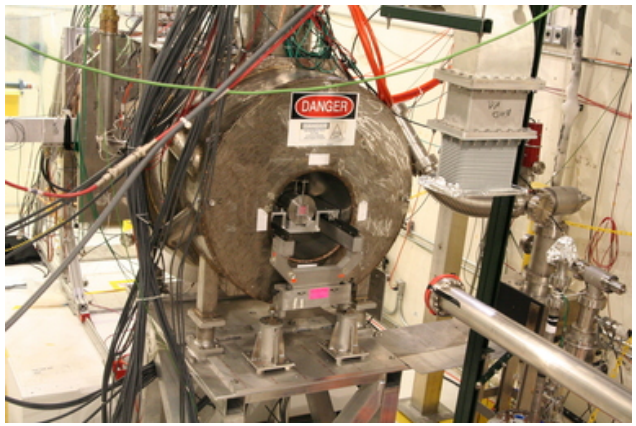

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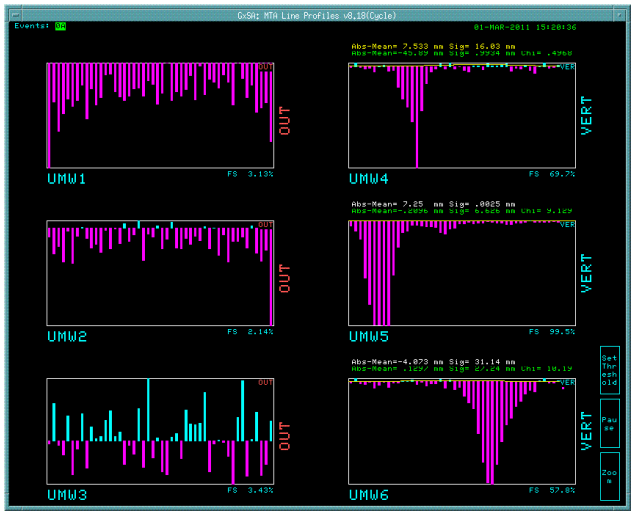

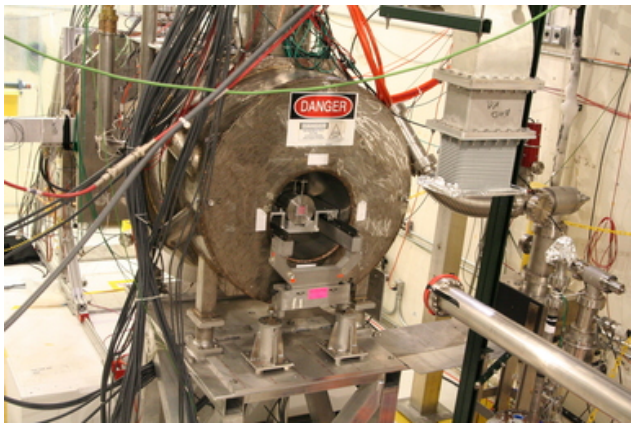

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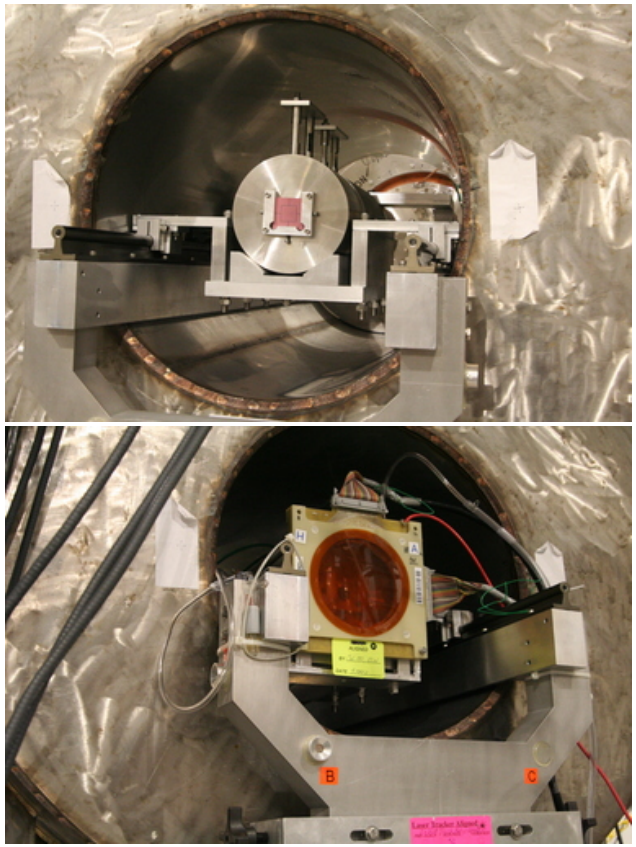

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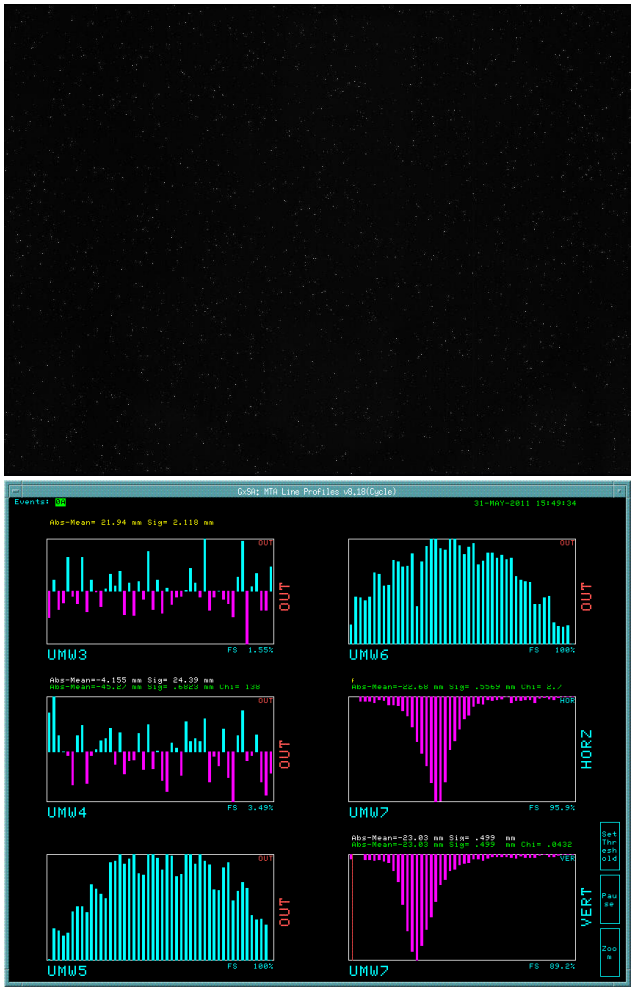

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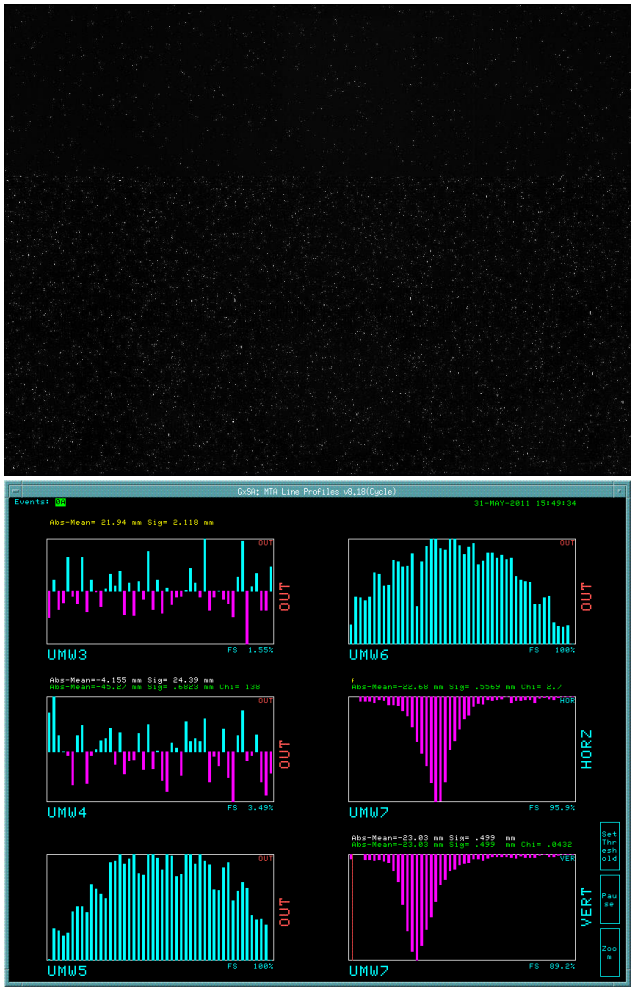

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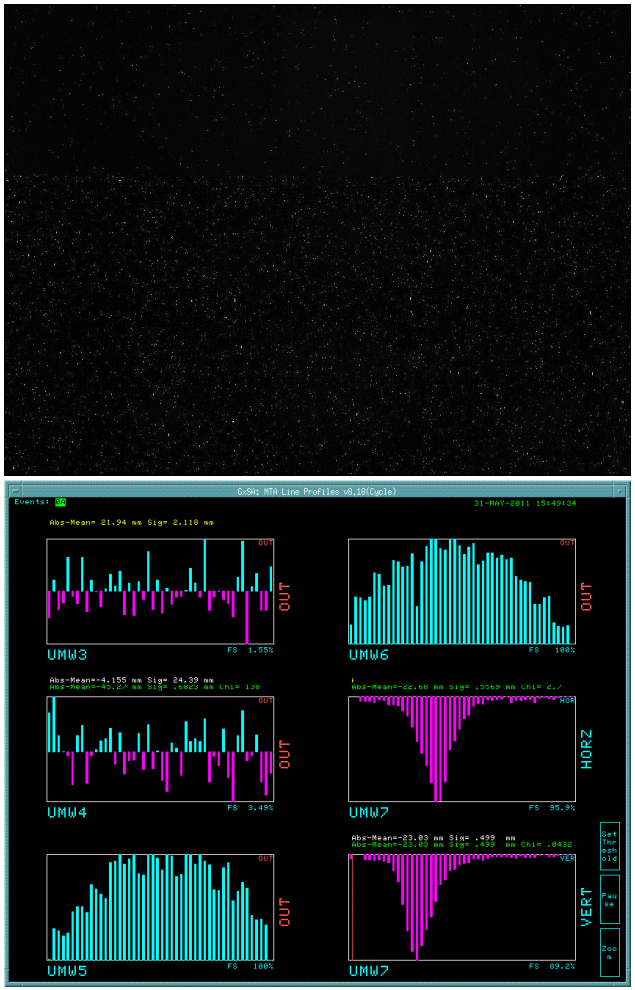

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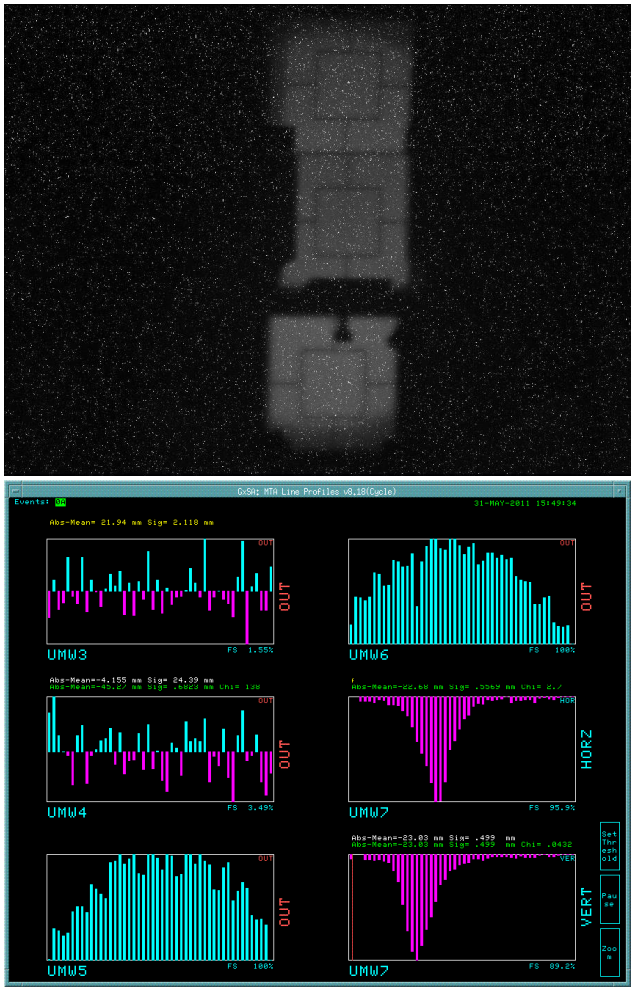

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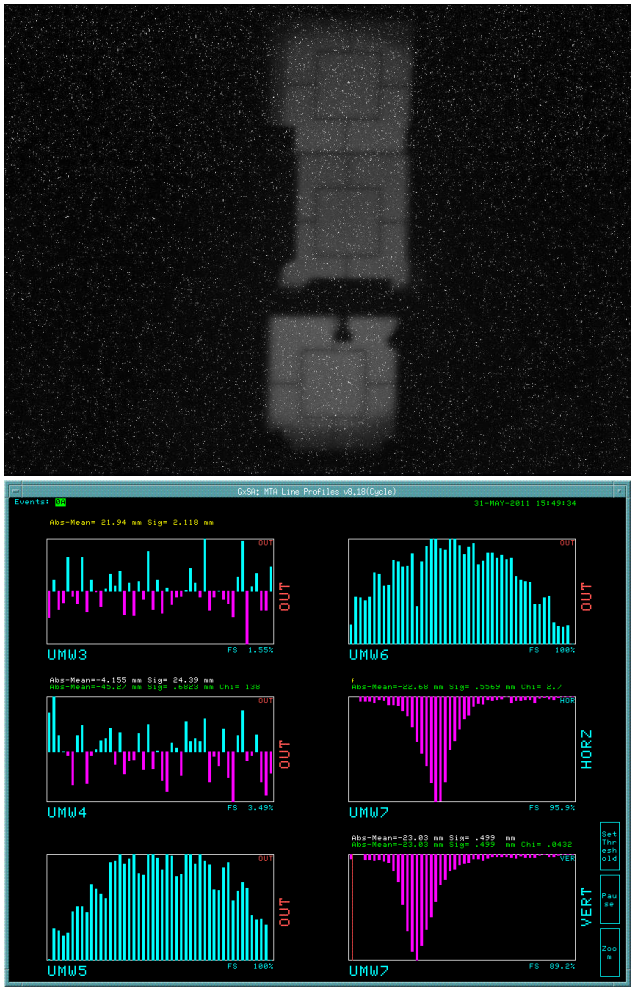

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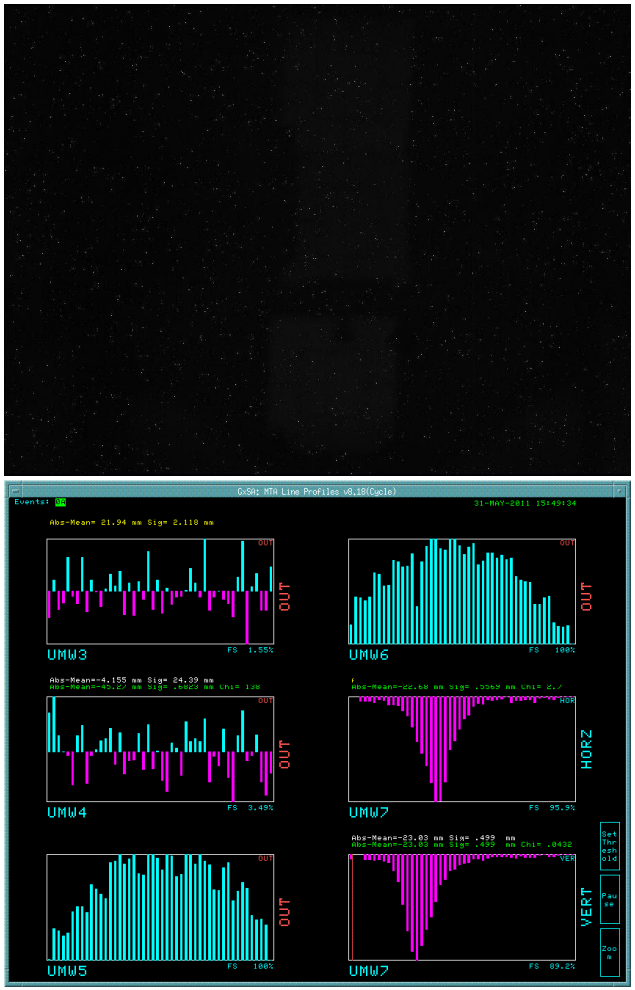

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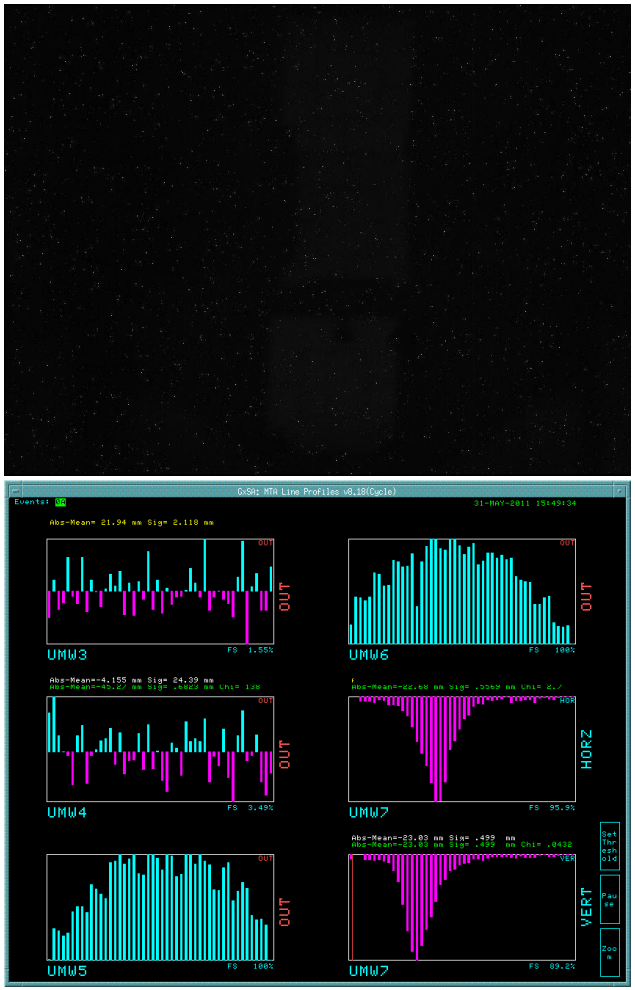

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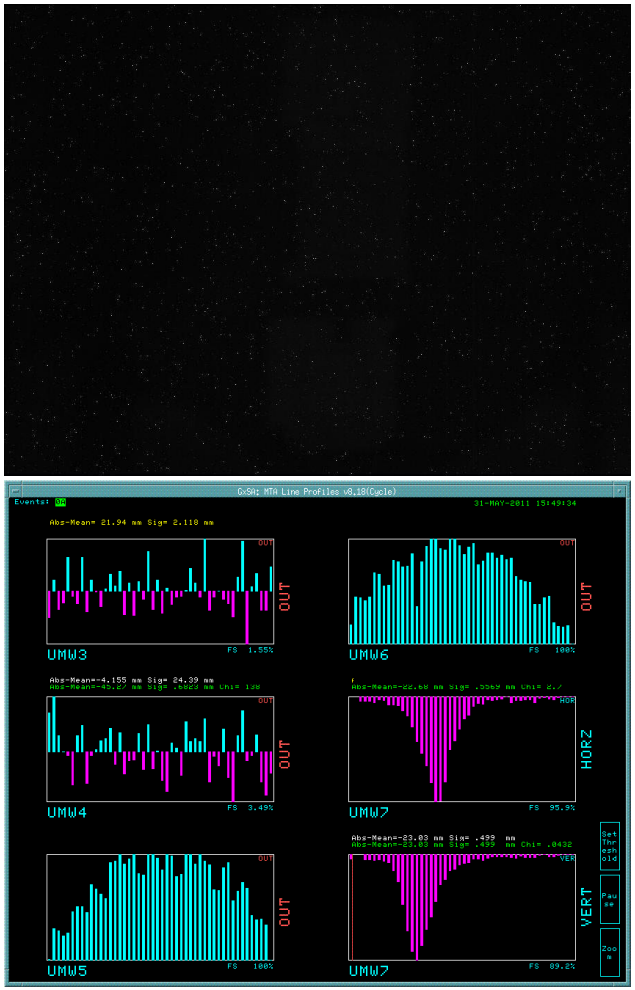

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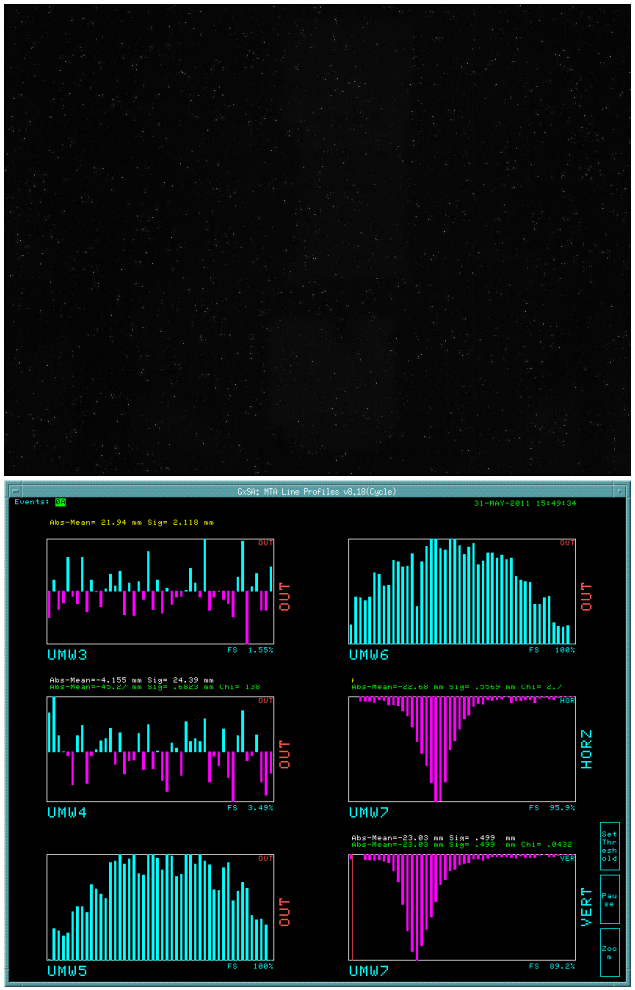

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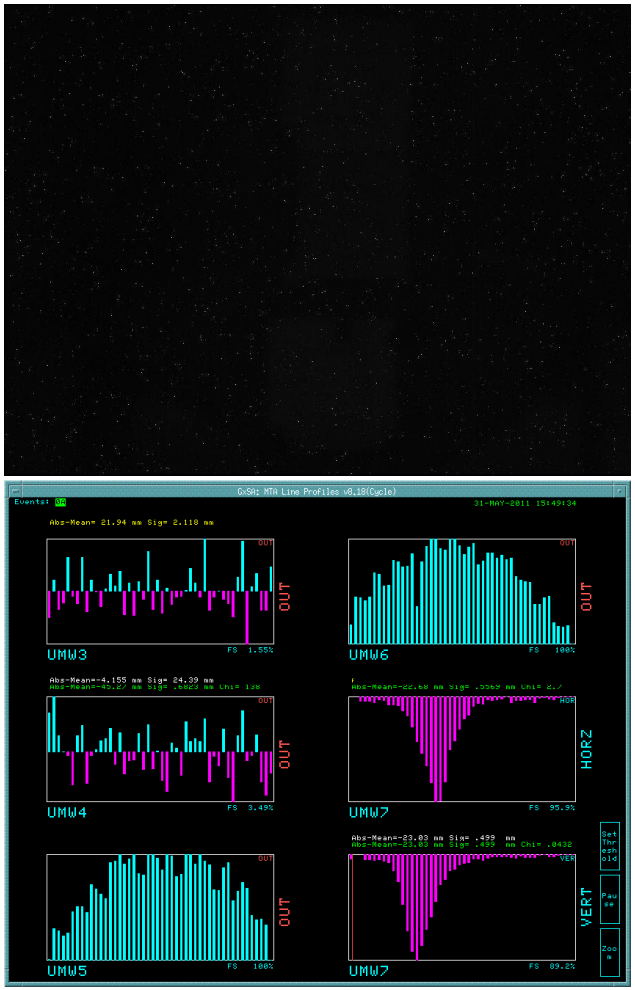

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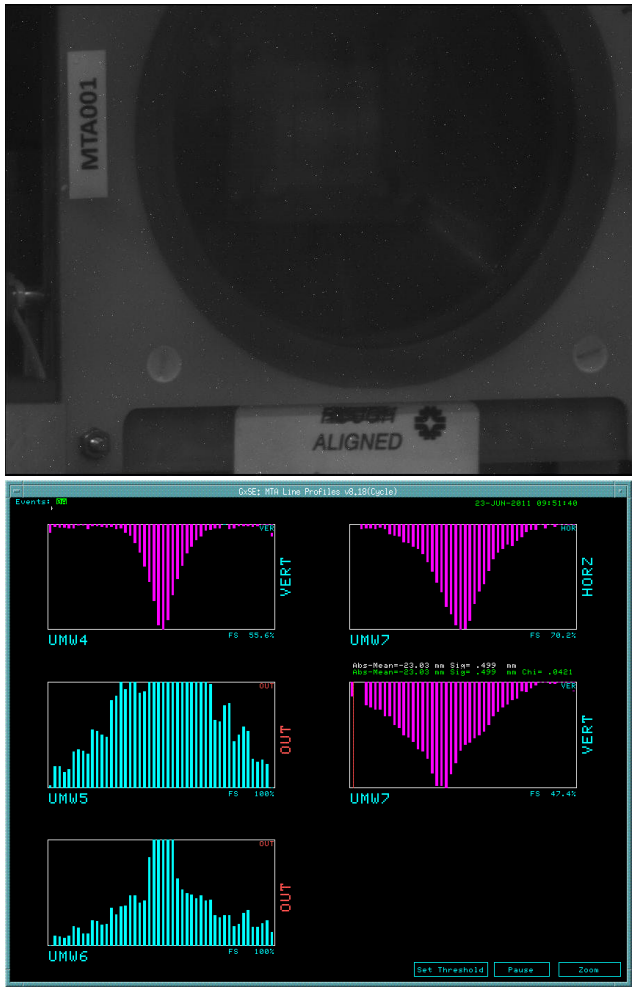

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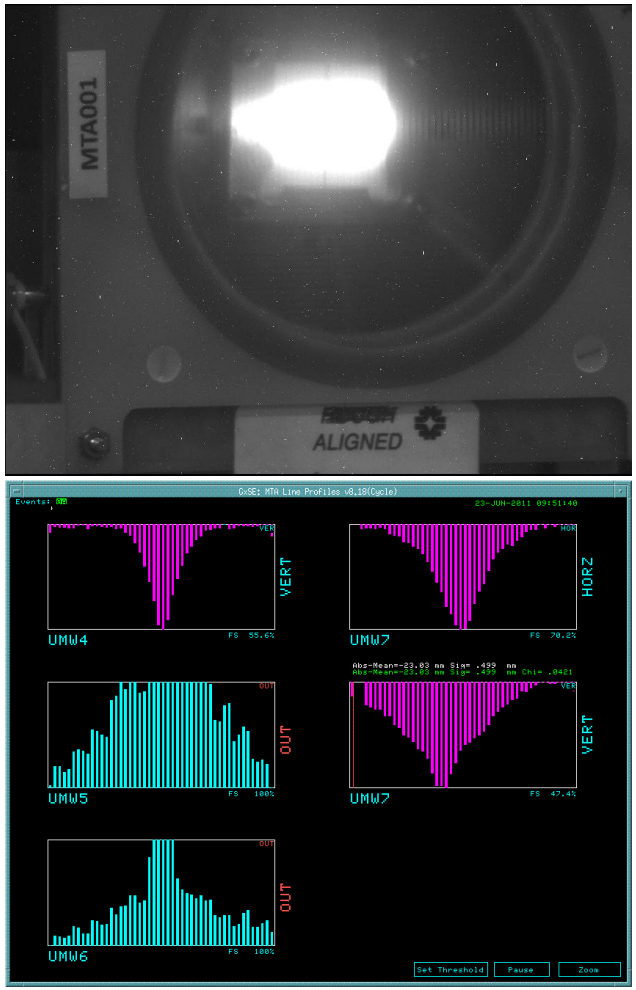

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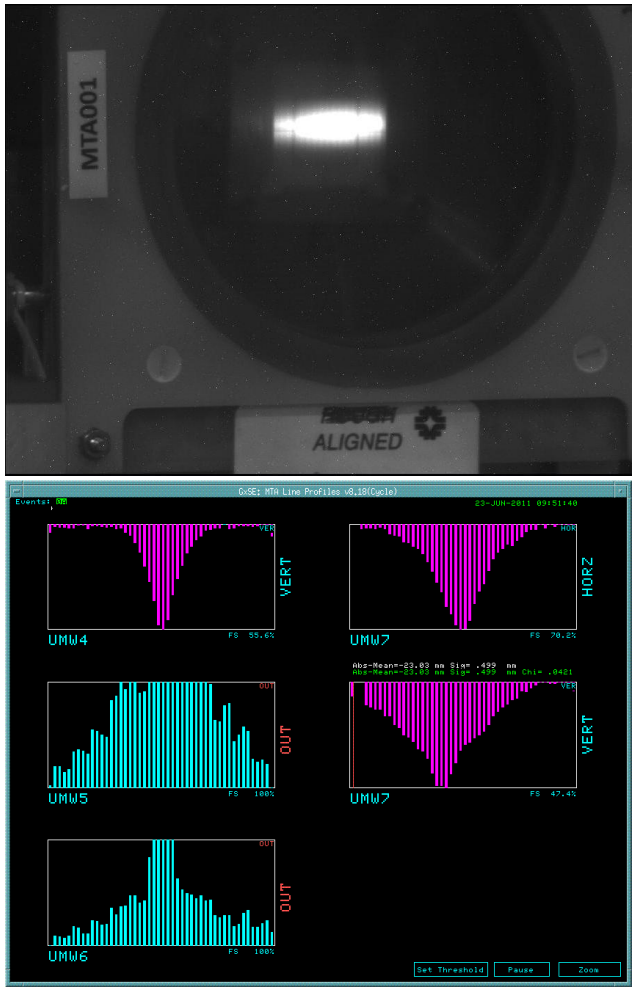

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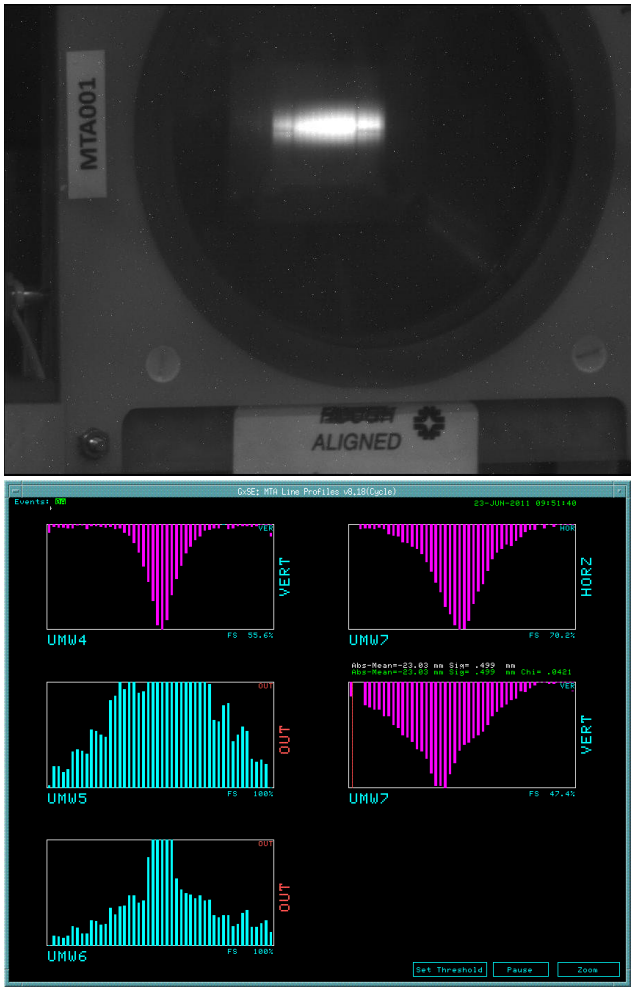

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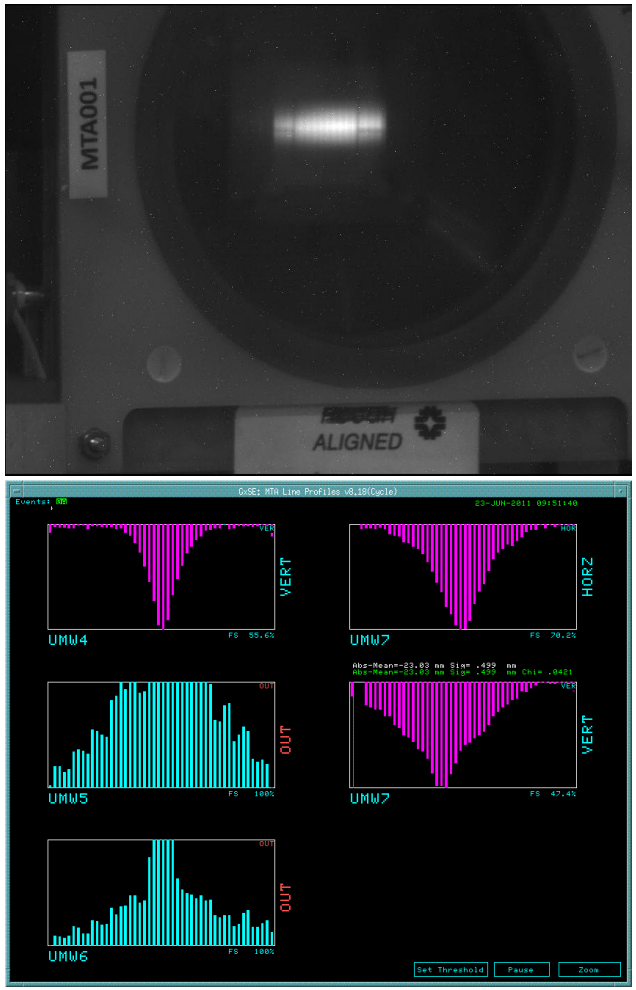

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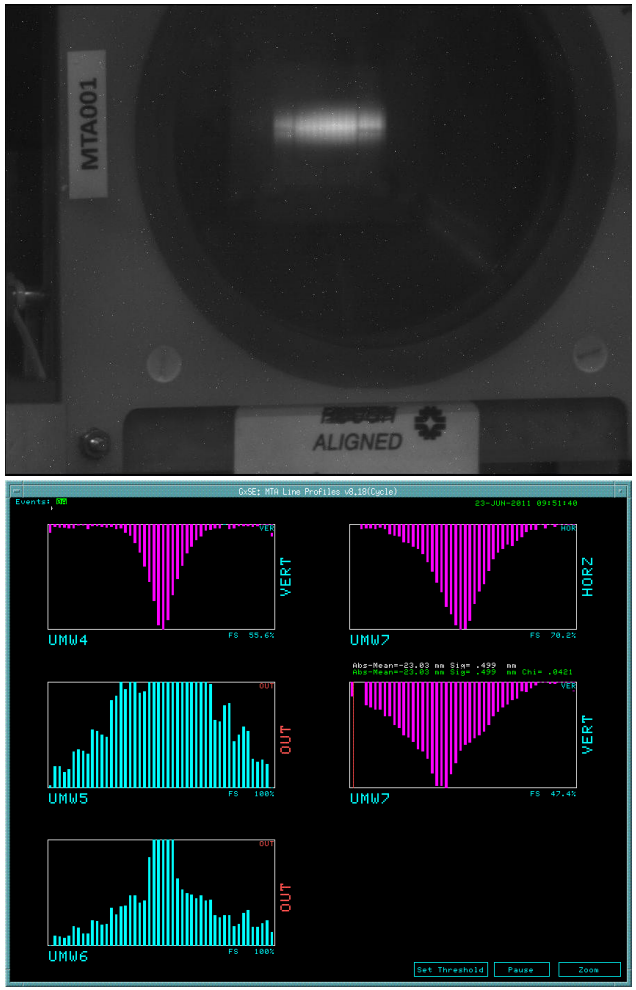

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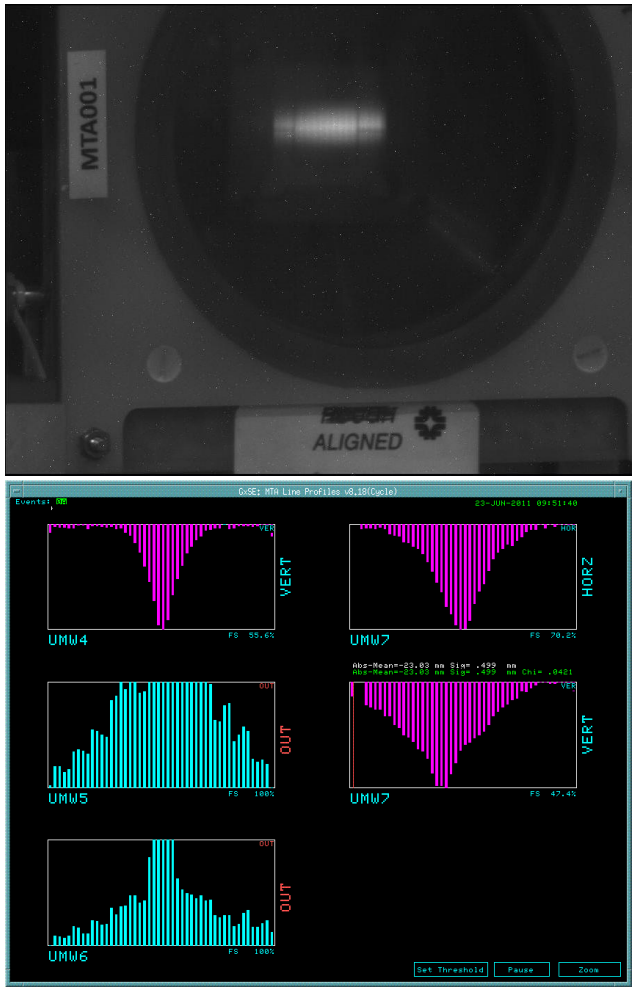

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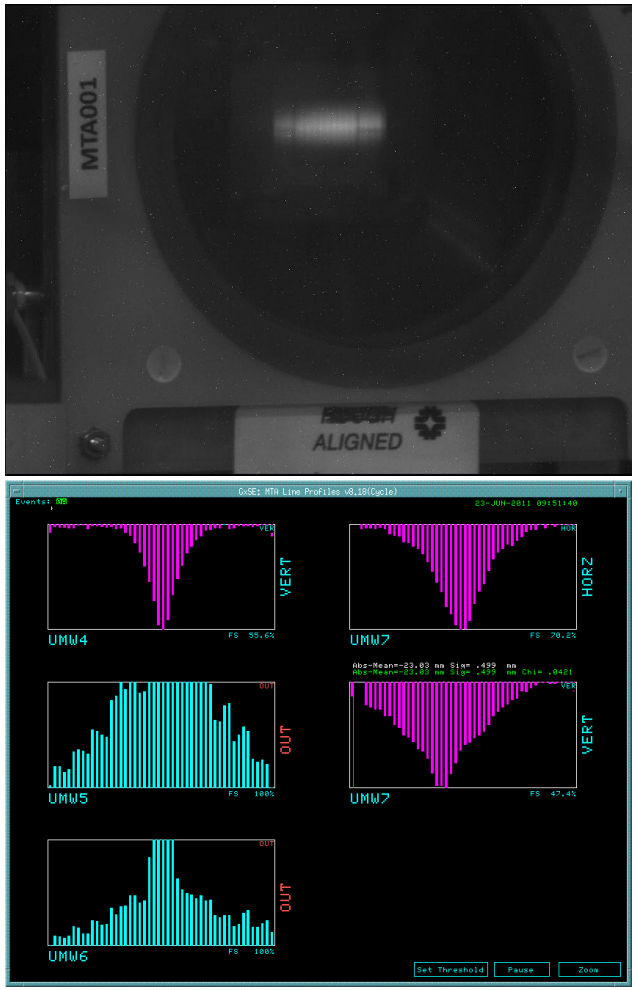

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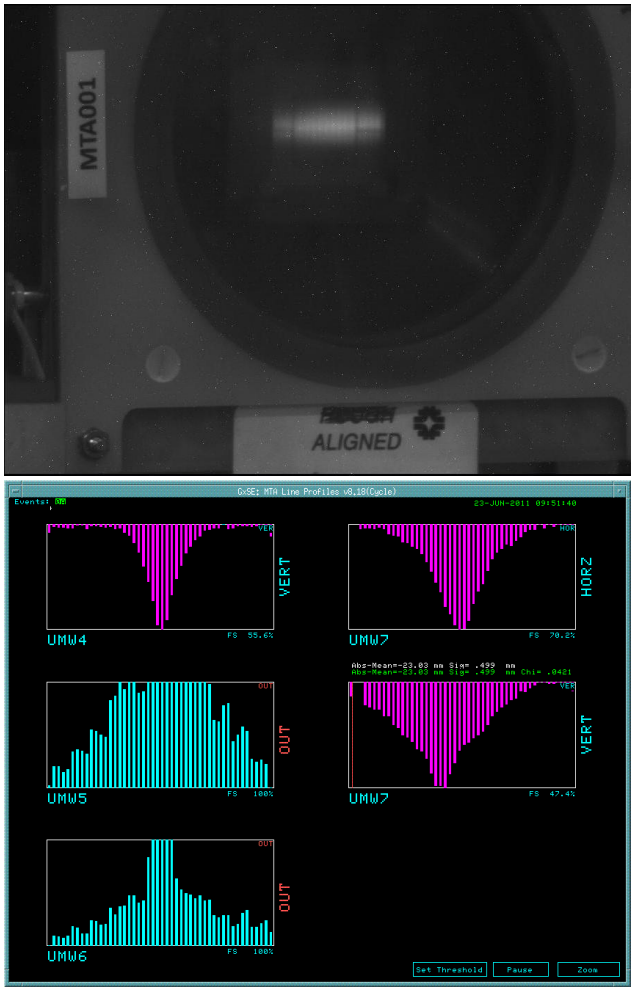

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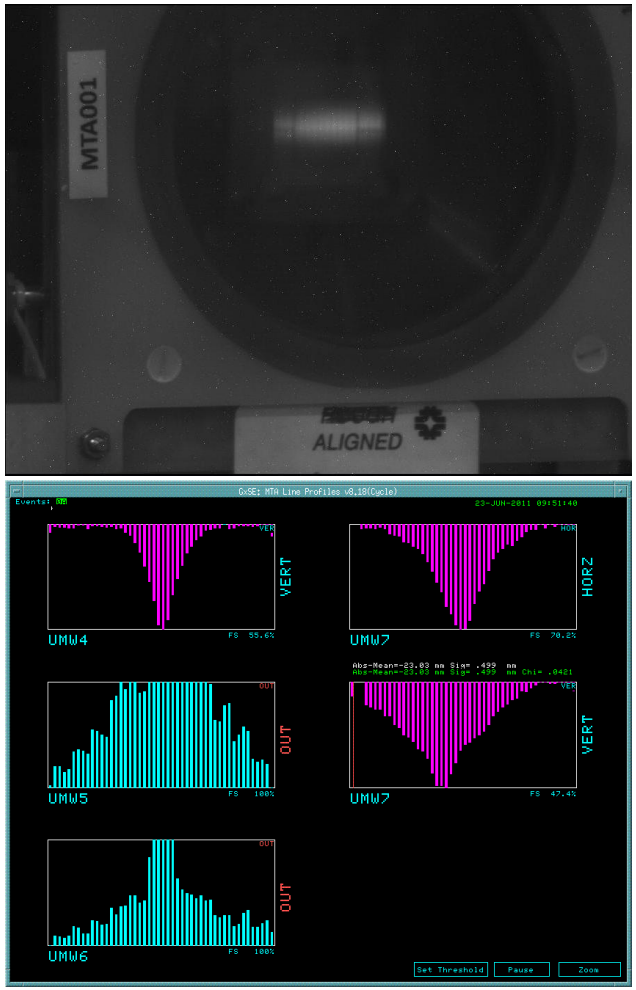

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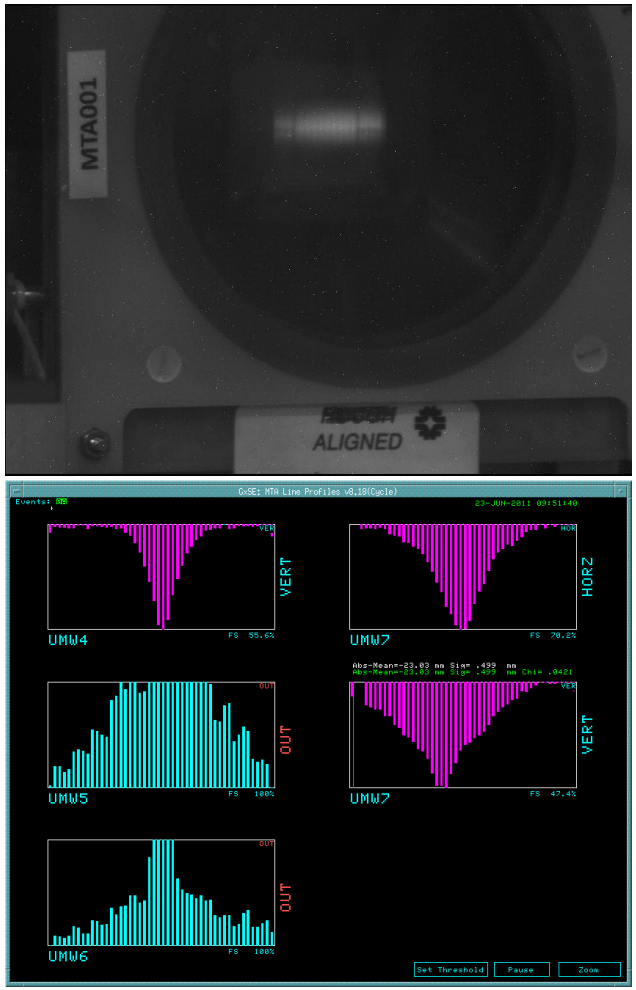

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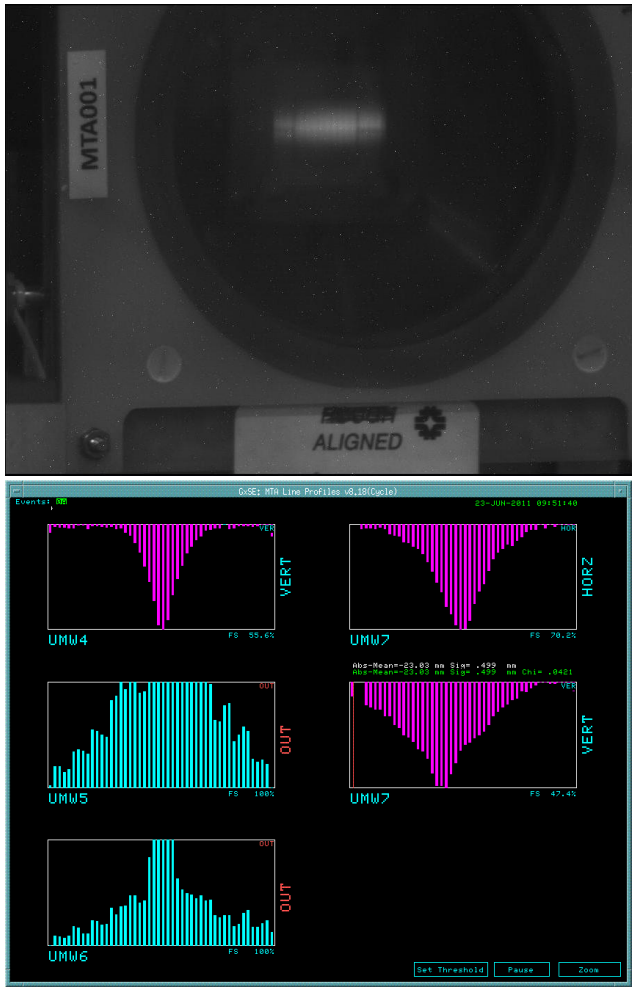
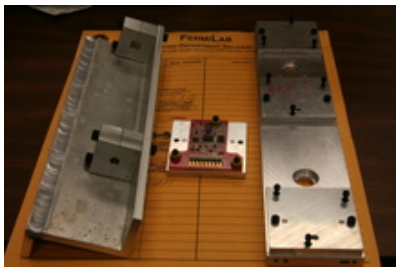
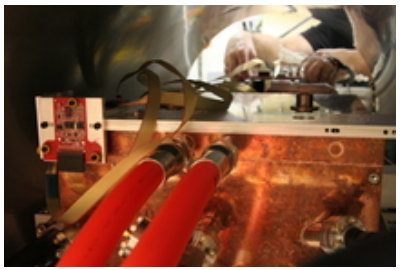
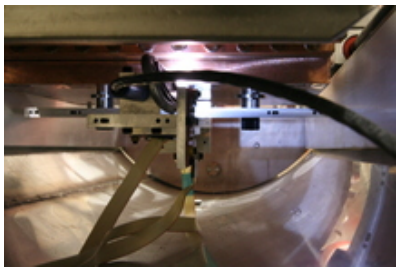


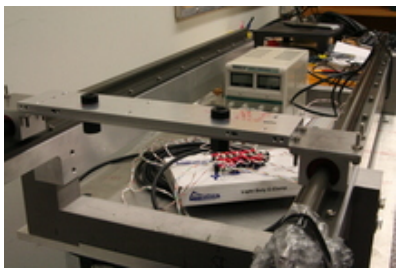
Magnetic Field Mapping

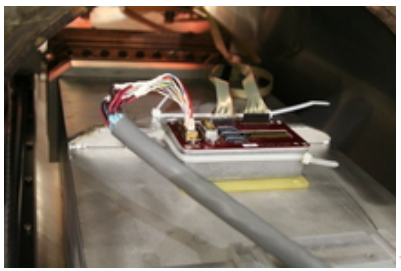
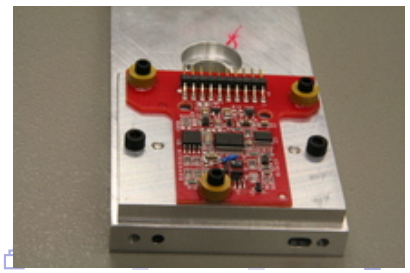
- Magnetic insulation depends strongly on angle
- MTA solenoid field never mapped in detail before
- Expect good alignment of magnetic axis with bore based on manufacturing tolerances but wanted to confirm



- 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



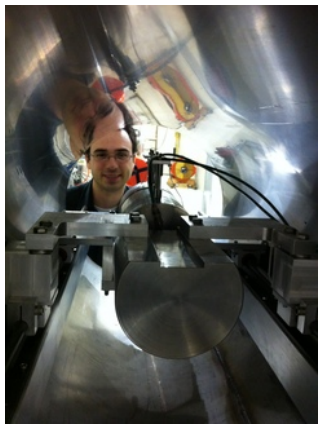
Summary of experimental program

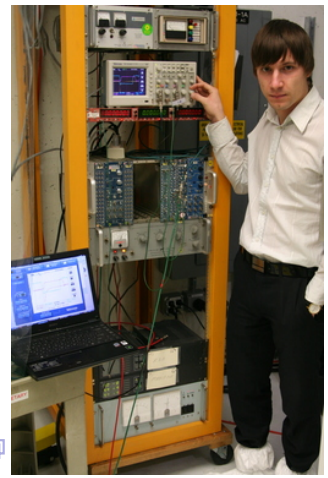
- trying to demonstrate a working solution to RF cavity operation in high external magnetic field for muon cooling
- major MAP milestone
- big impact on cooling channel design and future system tests
- multipronged approach to cover maximum ground with available resources

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

Students

- Anastasia Belozertseva (U. Chicago) – magnetic field mapping
- Last Feremenga (U. Chicago) – magnetic field mapping
- Ben Freemire (IIT) – HPRF beam test, everything else [poster]
- Giulia Collura (Torino) – HPRF beam test [poster]
- Timofey Zolkin (U. Chicago) – dark current instrumentation, pillbox data [poster]
- Peter Lane (IIT) – acoustic sensors for detecting cavity sparks
- Raul Campos – beamline magnet mechanical support
- Ivan Orlov – GEANT4 simulation of experimental setup



MTA Schedule and Outlook

- Experimental program
  - HPRF cavity in beam – almost there
  - 805 MHz pillbox cavity with Be and other buttons
  - 201 MHz cavity coupler repair and operation in large B
  - further HPRF beam tests as needed
  - rectangular box cavity with B $\parallel$ E
  - more $\perp$ E rectangular box cavity tests
  - 4-season cavity
  - ALD cavity
- Infrastructure
  - beam commissioning close to completion
  - cryo upgrade in progress
  - magnet field mapping at next opportunity
  - RF circulator/switch to be installed in Linac
  - coupling coil and single-cavity module in Hall
- Expect to demonstrate a working solution to RF cavity operation in high magnetic field within the next 2 years