MuCool Test Area Progress and Plans

Yağmur Torun
Illinois Institute of Technology/Fermilab

All Experimenters’ Mtg
Aug 6, 2012 – Fermilab
• The only muon cooling scheme that appears practical within the muon lifetime (2.2 μs)
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Ionization Cooling

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- Cooling mainly transverse in a linear channel
- Longitudinal cooling requires momentum-dependent path-length through the energy absorbers
Ionization Cooling

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

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

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

- Energy absorbers with large $\Delta E$ per radiation length (LH$_2$: 29MeV/m x 8.9m; LiH: 151MeV)
- Strong focusing (large B-field), $\beta_{\perp} \approx p/B$
- High-gradient rf cavities to replace longitudinal momentum and for phase focusing
- Tight packing to minimize decay losses
- Low muon momentum exchange for 6D cooling (or twisted field – Guggenheim, HCC, snake)
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MuCool

R&D program at Fermilab to develop ionization cooling components

mission:

- design, prototype and test components for ionization cooling
  - absorbers (LH2, solid LiH)
  - RF cavities
  - magnets
  - diagnostics
- carry out associated simulation and theoretical studies
- support system tests (MICE, future cooling experiments)

Current focus: RF in high external magnetic field
Potential Solutions

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

3. Shielding: iron, bucking coils
4. Magnetic insulation: modified cavity/coil designs to keep $B \perp E$ on cavity surfaces (R. Palmer et al.)

Loss of $x \times 2$ gradient advantage in pillbox geometry → dropped
Potential Solutions

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Loss of $x^2$ gradient advantage in pillbox geometry → dropped

5. High-pressure gas: suppress breakdown by moderating electrons (R. Johnson et al., Muons Inc.)
Dedicated facility at the end of the Linac built to address MuCool needs

- RF power (12 MW at 805 MHz, 5 MW at 201 MHz)
- 5 T superconducting solenoid
- 805 and 201 MHz cavities
- Radiation detectors
- Cryogenic plant
- 400 MeV p beamline
- Class-100 portable clean room
- Hydrogen safety infrastructure
MTA Diagnostics

- RF forward, reflected, pickup signals
- Vacuum pressure
- Scintillator+PMT counters for X-ray rates, spectra
- Ionization chambers for radiation dose rates
- Spectrometer for cavity light analysis
- Thermocouples for cavity temperature
- Acoustic sensors for spark detection (under development)
- Toroids for beam intensity
- BPM, MW and scintillator for beam profile
- Environmental monitoring
Summary of MuCool experimental program

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

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Yağmur Torun
MTA – AEM – 8/6/12
Students at the MTA (past 1.5 year)

- Lisa Nash (U. Chicago) – HPRF
- Adam Sibley (Trinity) – HPRF breakdown study
- Oleg Lysenko (U. Chicago) – HPRF beam test
- Jared Gaynier (Kettering) – circulator installation
- Jessica Cenni (Pisa) – dielectric loaded cavity
- Tom McLaughlin (Valparaiso) – magnet mapping, circulator installation
- Ivan Orlov (Moscow State) – HPRF beam test simulation
- Raul Campos (NC State) – beamline magnet support
- Peter Lane (IIT) – acoustic sensors for spark detection
- Timofey Zolkin (U. Chicago) – dark current instrumentation
- Giulia Collura (Torino) – HPRF beam test
- Ben Freemire (IIT) – HPRF beam test (thesis), +lots more
- Last Feremenga (U. Chicago) – magnetic field mapping
- Anastasia Belozertseva (U. Chicago) – magnetic field mapping
805-MHz pillbox button cavity

- Pillbox geometry with thin curved Be windows
- Button holder for removable electrode inserts
- Used to

Refurbished at JLab
Ran with Be & Cu buttons (similar max gradient)
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![Graph: Safe Operating Gradient vs Magnetic Field](image)

**safe operating gradient vs magnetic field**

- Magnetic Field (T)
- Gradient (MV/m)

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![Graph showing safe operating gradient vs magnetic field](image.jpg)

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805-MHz pillbox button cavity

- Poor performance after refurbishing
- Possibly from coupler area damage
- Tested Be and Cu buttons
- Did somewhat better with Be than Cu
- Conservative conditioning with Be due to safety concerns
- After flat-endplate runs
  - Additional damage to problem areas (iris, coupler)
  - Deposits on endplates
- After button runs
  - More damage on Cu buttons
  - Some features on Be buttons also
  - Deposits on endplates
- Replacement test cavity under design (SLAC)
Two new vacuum cavities were considered for future use:
- a replacement for the beat-up 805-MHz button cavity (SLAC)
- a pillbox Be-wall cavity (LBNL)

preferably with no coupler issues

Arrived at modular design
- replaceable end walls
- coupling and diagnostics on center ring

Dielectric loaded HPRF (Muons Inc.)
modular pillbox with replaceable end walls
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designed for both vacuum and high-pressure
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All-Season cavity (Muons Inc., LANL)

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HPRF previously shown to work in high B at the MTA (P. Hanlet et al., EPAC06)

- Intense muon bunch creates lots of electron-ion pairs potentially shorting the RF cavity mitigated by electronegative dopant gas (K. Yonehara et al., PAC09, IPAC10; Freemire et al. IPAC12)
HPRF Program

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HPRF – 2nd beam test (Spring 2012) – Yonehara

- successfully concluded May 8
  - wealth of physics data starting Apr 18
  - $10^{10}-3 \times 10^{11}$ ppp
  - 300-1520 psi H2
  - SF6 and dry air dopant at many concentrations
  - also, He+air, N2+air, D2
  - 5-50 MV/m (with high-power hybrid coupler & loads)
  - some data with B=3T
  - Yonehara/Leonova/Jana/Freemire, IPAC12
Analysis team hard at work (Freemire, Chung, Yonehara, Tollestrup) – good agreement with theory

1470psi H2 (1% dry air)

PRELIMINARY
First beam pulse to "emittance absorber" Feb 28, 2011
Intensity about $1.8 \times 10^{12}$ protons/pulse at 1 pulse/min
Scintillator screen upstream of collimator to measure beam spot
Stronger dipole installed last year to fix vertical bend at the end
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201 pillbox
201 MHz MICE prototype cavity

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No surface damage seen on cavity interior

radiation output measured (MICE detector backgrounds)

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- configuration closer to MICE
- No surface damage seen on cavity interior
Evidence for some sparking in the coupler

SEM images of 201 MHz coupler.

Unipolar arc? (J. Norem)
201-MHz Single-Cavity Module

Yağmur Torun

MTA – AEM – 8/6/12
201-MHz Single-Cavity Module

Yağmur Torun
MTA – AEM – 8/6/12
201-MHz Single-Cavity Module Workshop

Tuesday 19 June 2012 from 09:00 to 18:00 (US/Central) at Fermilab (WH13SE)

### Schedule

**09:00 - 09:15**
- **Introduction 15’**
  - Speaker: Alan Brosa (Fermilab)
  - Material: Slides

**09:15 - 09:35**
- **Handling and transport at Fermilab 20’**
  - Speaker: Ryan Schultz (Fermilab)

**09:35 - 09:45**
- **Support modifications 10’**
  - Speaker: Ryan Schultz (Fermilab)

**09:45 - 10:00**
- **Cavity status 15’**
  - Speaker: Tianhuan Luo (University of Michigan)
  - Material: Slides

**10:00 - 10:15**
- **Tuners 15’**
  - Speaker: Allan DaMello (Lawrence Berkeley National Laboratory)

**10:15 - 10:30**
- **Tuner Control 15’**
  - Speaker: Pierrick Hanlet (Illinois Institute of Technology/FNAL)
  - Material: Slides

**10:30 - 10:45**
- **Break**

**10:45 - 11:00**
- **Couplers 15’**
  - Speaker: Allan DaMello (Lawrence Berkeley National Laboratory)

**11:00 - 11:15**
- **RF plumbing 15’**
  - Speaker: Alfred Moretti (Fermilab)
  - Material: Slides

**11:15 - 11:30**
- **Diagnostics 15’**
  - Speaker: Yagmur Torun (Illinois Institute of Technology)

**11:30 - 12:15**
- **Assembly procedure 45’**
  - Speakers: Allan DaMello (Lawrence Berkeley National Laboratory), Steve Virostek (Lawrence Berkeley National Lab)

**12:15 - 13:30**
- **Lunch**

**13:30 - 13:45**
- **RF measurements 15’**
  - Speaker: Denan Li (BNL)

**13:45 - 14:00**
- **Alignment and scanning 15’**
  - Speaker: James Volk (Fermilab)

**14:00 - 14:10**
- **Vacuum system 10’**
  - Speaker: Alfred Moretti (Fermilab)
  - Material: Slides

**14:10 - 14:20**
- **Water hookup 10’**

**14:20 - 14:35**
- **Safety issues 15’**
  - Speaker: James Volk (Fermilab)

**14:35 - 14:45**
- **Schedule 10’**
  - Speaker: Yagmur Torun (Illinois Institute of Technology)

**14:45 - 15:00**
- **Future options 15’**
  - Speaker: Yagmur Torun (Illinois Institute of Technology)

**15:00 - 15:15**
- **Break**
Components

- 1st MICE cavity EP’ed at LBNL
- 11 Be windows ready
- 6 tuner forks fabricated
- components for 6 actuators fab; need bellows and assembly
- RF couplers to be built

assembly area at Lab 6

rough plan for handling and transport (R. Schultz, J. Volk)

assembly fixture design in progress (A. DeMello)

vertical assembly similar to (but much easier than) MICE RFCC

schedule will be set by assembly fixture and coupler fabrication
Outlook

- **Experimental program**
  - HPRF cavity in beam – 2nd test finished
  - HPRF breakdown study (no-beam) – finished
  - All-season cavity (true pillbox) run next
  - 805-MHz pillbox cavity with grid windows (Summer)
  - 201-MHz single cavity module (Fall)
  - New 805 MHz modular pillbox with Be/Cu walls
  - ALD cavity – under design
  - Dielectric-loaded cavity for helical cooling
  - beam tests (HPRF and vacuum) after shutdown
  - 201-MHz single-cavity module with CC

- **Infrastructure**
  - beamline upgrade, cryo plant maintenance
  - RF circulator/switch installation/commissioning
  - planning for coupling coil installation
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Useful reading

Serious degradation of RF cavity performance in strong external magnetic fields. Currently main focus of MuCool.

- Magnetic field effect first seen at Fermilab’s Lab-G with a 6-cell 805-MHz cavity

- Studied in more detail at MTA with 805-MHz pillbox cavity

- Various models proposed
Box Cavity

- Rectangular geometry chosen for test cavity to allow fast fabrication and simplify analysis
- Support system designed to rotate cavity pivoting around magnet center by up to $12^\circ$
- 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
- $f_0 = 805.3$ MHz, $Q_0 = 27.9 \times 10^3$, coupling factor 0.97
- YT et al., IPAC10
Box Cavity

- Operated in the MTA magnet Mar-Sep 2010
- Commissioned to 50 MV/m at B=0
- Took data at 0, ±1, 3, 4° wrt B axis (3T)
- Large effect seen at 3-4° (stable gradient down to about 25 MV/m)
- Some degradation even at ≤ 1° (33 MV/m)
- Visual inspection of interior, no obvious damage
- RF, optical and X-ray signals during sparks saved for analysis
- Magnetic insulation seems to work but not well enough to make up for lost shunt impedance
- Dropped from list
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 mapped in detail with cart on rails
- 500 psi N2
- 500, 800 and 950 psi H2
- 8µs beam, 2 intensities
- dopants (N2, SF6)