MuCool Overview and Plans

Muon Cooling R&D
MUTAC 04
A. Bross
This Review

- MuCool presentations for this afternoon
  - Overview: Bross
  - NCRF: Li
  - RF Studies: Torun
  - LH$_2$ Absorber Windows: Cummings
  - LH$_2$ Absorber Tests: Ishimoto
  - Cooling Channel Instrumentation: Errede
  - Gaseous Cooling: Johnson
The MuCool Collaboration

**Mission**
- Design, prototype and test all cooling channel components
- Perform high beam-power engineering test of cooling section
- Support MICE (cooling demonstration experiment)

**Consists of 18 institutions from the US, Europe, and Japan**

**RF Development**
- ANL
- Fermilab
- IIT
- JLAB
- LBNL
- Univ. of Mississippi

**Absorber R&D**
- Fermilab
- IIT
- KEK
- NIU
- Oxford
- UIUC
- Univ. of Mississippi
- Univ. Osaka

**Cooling Demonstration (MICE)**
- ANL
- BNL
- Fermilab
- Fairfield
- IIT
- Iowa
- JLab
- LBNL
- NIU
- UCLA
- UC Riverside
- UIUC
- Univ. of Chicago
- Univ. of Mississippi

**Beam Diagnostics**
- ANL
- Fermilab
- IIT
- Princeton
- Univ. of Chicago

**Solenoids**
- LBNL
MuCool Management Structure

• Spokesperson and Technical Area Leaders:

  ♦ Spokesperson: Alan Bross
  ♦ Technical Area Leaders:
    ♦ RF: Al Moretti, FNAL
        Derun Li, LBNL
    ♦ RF Diagnostics: Yagmur Torun, IIT
    ♦ Absorbers: Mary Anne Cummings, NIU
    ♦ MuCool Test Area: Milorad Popovic, FNAL
SFOFO Cooling Lattice

- R&D Focus of MuCool
  - Component testing Fermilab
  - High Power
    - Both RF and Beam
  - System test - MICE @ RAL

- High-gradient
Research and Development Challenges

- Can NCRF cavities be built that provide the required accelerating gradients?
  - AND operate in multi-tesla fields!
- Can the heat from $dE/dx$ losses be adequately removed from the absorbers?
  - On the order of 100's W for a neutrino factory
- Can the channel be engineered with an acceptably low thickness of non-absorber material in the aperture?
  - Absorber, RF, & safety windows
- Can the channel be designed & engineered to be cost effective?
MuCool Test Area

The MuCool Collaboration Enters a new Era

“Escape from the Wilderness”
MuCool Test Area

- Facility to test all components of cooling channel (not a test of ionization cooling)
  - At high beam power
    - Designed to accommodate full Linac Beam
    - $1.6 \times 10^{13}$ p/pulse @15 Hz
      - $2.4 \times 10^{14}$ p/s
      - $\approx 600$ W into 35 cm LH$_2$ absorber @ 400 MeV
  - RF power from Linac (201 and 805 MHz test stands)
    - Waveguides pipe power to MTA

Is Now Complete!
The MTA is becoming our focus of Activity

- LH$_2$ Absorber tests
- RF testing (805 and 201 MHz)
- Finish Cryo-Infrastructure
- High pressure H$_2$ gas absorbers
- High Intensity Beam
MTA Tour

Compressor Room
Access Pit
MTA Tour

H₂ Buffer Tank
H₂ Manifold Room
MTA Tour

Access Pit
MTA Tour

MTA Experimental Hall
MTA Tour

KEK LH$_2$ Absorber
MTA Tour

MTA Experimental Hall
From Linac
(Lots of Activity)
MTA Tour

View from Wilson Hall
RF Trench visible
MTA - Near Term Schedule

- **KEF Absorber Cooldown**: Wed 4/20 to Mon 4/27
- **HVAC**: Mon 4/20 to Sun 4/26
- **RF Controls and Instrumentation**: Mon 4/20 to Tue 4/21
- **RF Experimental Program**: Tue 4/20 to Mon 5/3
  - Install/Verify/pipelines from MTA to cavity
  - Al Waffle Grid:
    - Installation: Fri 4/16 to Thu 4/22
    - Data Run: Fri 4/24 to Thu 4/30
  - Curved Be Window Test:
    - Installation: Fri 4/24 to Thu 4/30
    - Data Run: Fri 4/24 to Thu 4/30
  - Button Chamber:
    - Installation: Fri 4/24 to Thu 4/30
    - Data Run: Fri 4/24 to Thu 4/30
  - Muons in C1 Magnet Test:
    - Installation: Fri 4/24 to Thu 4/30
    - Data Run: Fri 4/24 to Thu 4/30
  - 291 MHz Tests:
    - Install New Vacuum System
    - Install Stables
    - Prepare Instrumentation:
      - Prototype Delivery
        - Mon 4/20
        - Mon 4/20
        - RF and Vacuum installation
        - Tue 4/21
        - Mon 4/20
        - Mon 4/20
        - RF and Vacuum installation
        - Tue 4/21
        - Mon 4/20
    - Commissioning and Background Measurements
      - Tue 4/21
      - Mon 4/20
  - **KEK/NERA Test III**: Fri 4/24
    - Setup: Fri 4/24 to Thu 4/30
    - Data Run: Fri 4/24 to Thu 4/30
  - **MTA Cryo-Infrastructure**: Tue 4/18 to Mon 5/1
    - Engineering for Piping
    - Check for Piping Billing
    - Piping Contract
    - Vestigial Installation and Setup
    - Commissioning
Currently plan to operate either RF or LH$_2$/H$_2$ tests, but not both simultaneously. We are discussing with the Laboratory how we can work in both modes simultaneously.
MTA Cryo-Infrastructure

Compressor Room
- Two 400 HP 2-stage oil injected screw compressors

Refrigerator Room
- Tevatron satellite refrigerator to be operated on 5 K mode and 14 K mode (3” DE, 3” WE)
- Helium and nitrogen Dewar

Transfer line connections to experimental hall which includes 5K, 20K, 80K circuits

Heat exchanger

Towards Experimental Hall
MTA High Intensity Beam

- FNAL Study group has been formed to design 400 MeV beamline for the MTA
  - Under Craig Moore
    - External Beams Department
  - Develop Engineering Design
    - Cost
    - Schedule
  - Safety Analysis
    - Linac Area and Beamline
    - Shielding Assessment for MTA
      - Essentially Complete
  - Preliminary thoughts
    - “Spin” beam in order to provide large (30 cm) aperture
      - Instead of large Quads
      - Simpler and therefore Cheaper
  - Timeline still driven by resource availability
MTA Shielding Assessment

- Conclusions from Present Study
  - A credible beam accident at MTA is less severe than normal operation.
  - At normal operation the following classification is suggested (Fermi RCM):
    - Berm above target hall – Controlled Area of minimal occupancy (0.25 – 5 mrem/hr);
    - Access pit – Radiation Area with rigid barriers/locked gates (5 – 100 mrem/hr);
    - Cryo room – Radiation Area with rigid barriers/locked gates (5 – 100 mrem/hr);
    - Compressor room – Controlled Area of minimal occupancy (0.25 – 5 mrem/hr);
    - Parking lot – Normal (not controlled) area (dose rate below 0.05 mrem/hr).
RF Cavity R and D

ANL/FNAL/IIT/LBNL/UMiss
RF Cavity R&D - Prototype Tests

- Work to date has focused on using 805 MHz cavities for test
  - Allows for smaller less expensive testing than at 201 MHz
  - Lab G work at Fermilab
- Unfortunately due to a Klystron failure in the Linac, the Lab G Klystron had to be moved back to the Linac
  - As of December 25, 2003 the Lab G facility ceased operation
- We are now moving as rapidly as possible (with a great deal of support from the Fermilab Beams Division) to bring up 805 and 201 MHz RF test capability to the MTA
  - Moving Vacuum, power, etc systems to MTA
  - Move Magnet to MTA

Lab G RF Test Cave showing 5T SC Magnet
44 cm bore
R.I.P.
RF Cavity R&D – Quick Review

- Open cell cavity reached peak surface field of 54 MV/m (25 on axis)
  - Large dark currents
    - Damage to windows
    - Punctured Ti window in worst case
- Closed Cell (single) cavity
  - B=0, Cu window – Low Bkg.
    - Reached 34MV/m
  - With B field
    - TiN coated Be window (0.01"
    - Initially conditioned to 16MV/m
      - Dark currents then rose
    - However, no damage in evidence to Be
      - Copper contamination
        - From iris/flange surface
    - At 8MV/m dark currents very low
      - Acceptable for MICE
RF Cavity Closed Cell Magnetic Field Studies

- Data seem to follow universal curve
- Sparking limits max gradient
- Copper surfaces the problem
RF R&D - 201 MHz Cavity Design

- Design Complete and Fabrication well under way
  - Expect $E_{\text{surf}}^{\text{pk}} = 19$ MV/m (17 MV/m on axis)
  - Now has curved windows
  - Goal is to have a 201 MHz cavity under test at Fermilab in the Fall
RF R&D – 201 MHz Cavity Design
Tube-Grid Aperture Study

- Finite Element analysis of tube grid design
  - First applied to electromagnetic model of 805 MHz cavity
    - For Lab G test

Grid Model | Electric Field | Magnetic Field
--- | --- | ---
4x4-Connected | 3.60 | |
4x4 -Waffle | 2.30 | 1.80 |
6x6 -Waffle | | 1.64 | 1.40 | 1.39 |
6x6 Middle- Concentrated/Waffle | | | 1.40 | 1.25 | 1.00 |

Maximum Surface Field Enhancement

Thesis work of Mohammad M. Alsharo’a
IIT
Absorber R and D

IIT/KEK/NIU/Osaka/Oxford/UIUC/UMiss
Absorber Design Issues

2D Transverse Cooling

\[
\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2} \frac{dE_\mu}{ds} \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu L_R} 
\]

and

\[
\epsilon_{N,\text{min}} = \frac{\beta_\perp (14 \text{ MeV})^2}{2\beta m_\mu \frac{dE_\mu}{ds} L_R} 
\]

Figure of merit: \( M = L_R dE_\mu / ds \)

\( M^2 \) (4D cooling) for different absorbers

<table>
<thead>
<tr>
<th>Material</th>
<th>( \langle dE/ds \rangle_{\text{min}} ) (MeV g(^{-1}) cm(^2))</th>
<th>( L_R ) (g cm(^{-2}))</th>
<th>Merit</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH(_2)</td>
<td>4.103</td>
<td>61.28</td>
<td>1.03</td>
</tr>
<tr>
<td>LH(_2)</td>
<td>4.034</td>
<td>61.28</td>
<td>1</td>
</tr>
<tr>
<td>He</td>
<td>1.937</td>
<td>94.32</td>
<td>0.55</td>
</tr>
<tr>
<td>LiH</td>
<td>1.94</td>
<td>86.9</td>
<td>0.47</td>
</tr>
<tr>
<td>Li</td>
<td>1.639</td>
<td>82.76</td>
<td>0.30</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>2.417</td>
<td>46.22</td>
<td>0.20</td>
</tr>
<tr>
<td>Be</td>
<td>1.594</td>
<td>65.19</td>
<td>0.18</td>
</tr>
</tbody>
</table>

\( H_2 \) is clearly Best - Neglecting Engineering Issues

Windows, Safety

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A. Bross
Absorber Design Issues

- Design Criteria
  - High Power Handling
    - Study II – few 100 W to 1 KW with “upgraded” (4MW) proton driver
    - 10 KW in ring cooler
      - Must remove heat
  - Safety issues regarding use of LH₂ (or gaseous H₂)
    - Window design paramount
      - H₂ containment
    - Proximity to RF adds constraints (ignition source)
  - Window material must be low Z and relatively thin in order to maintain cooling performance

H₂ implies engineering complexity

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Absorber R&D

- Two LH$_2$ absorber designs are being studied
  - Handle the power load differently

Forced-Convection-cooled. Has internal heat exchanger (LHe) and heater - KEK System

Forced-Flow with external cooling loop

2004
• Convection is driven by beam power and internal heaters
• LHe heat exchanger removes heat from absorber walls
• Two-dimensional Computational Fluid Dynamics calcs
  ◆ Flow essentially transverse
  ◆ Max flow near beam
  ◆ Heaters required to setup convective loops
Forced-Flow Absorber

- Heat removed with external heat exchanger
  - LH$_2$ pumped from absorber to heat exchanger
  - Nozzles in flow path establish turbulent flow
  - Simulation via 2D and 3D FEA
Absorber Windows

- Thin windows are required in all absorber designs
  - Critical design issue
    - Performance
    - Safety
  - First examples made with AL T6061
  - Maybe even thinner with
    - Al-Li alloy - 2195

Design Iteration
HemiSpherical – Inflected
(Now also used for RF)

Containment Windows

Vacuum

Absorber
• Work on STTR Phase II
  ◆ 805 MHz test cell
    • Tested at Lab G
  ◆ Cell conditioned at 450 psig @ 80K
  ◆ Max stable gradient
    • $\approx 80$ MV/m
  ◆ Data agree well with Paschen Law up to $\approx 200$ psig
Beam line Instrumentation

- **CVD Diamond**
  - For beam diagnostics can be very thin
    - Lots of charge - 36 e-h/µm-mip
  - Rad Hard
  - Low-quality (small mfp) might be useable
  - First prototypes have been tested
    - Very Fast (limited by electronics)
    - Large signal
    - Some of the diamond is approx. linear over full intensity range (3 × 10^{11} e-/cm^2)
      - Needs more study

- **MTA Instrumentation**
  - Intrinsically safe solution
    - Temperatures, Magnet currents, BPMs.
    - Local readout (PC) + ACNET
Simulation Work

• Cooling Components as mentioned
  ♦ Absorbers – 2D and 3D Finite Element Analysis (FEA)
    2D Computational Fluid Dynamics (CFD)
  ♦ RF – Electromagnetic modeling of Be windows and grids
    FEA modeling of window deflection/stress
• Quad-focused cooling channel
• Study II cooling channel
  ♦ GEANT4 simulation including latest window design
• MICE
  ♦ GEANT4 framework developed
MuCool and MICE

- **Muon Ionization Cooling Experiment (MICE)**
  - Demonstration of “Study II” cooling channel concept
- **MuCool Collaboration interface to MICE**
  - Design Optimization/develop of Study II cooling channel
    - Simulations
  - Detailed engineering
    - Full component design
    - Systems integration
    - Safety
  - RF cavity development, fabrication, and test
  - Absorber development, fabrication, and test
  - Development of beam line instrumentation
  - MuCool will prototype and test cooling hardware including MICE pieces for which the collaboration is responsible
- **High-intensity Beam Tests are responsibility of MuCool and are, of course, fully complementary to MICE**
MuCool Plans

- **Continue development of thin windows for absorbers**
  - Already within the material budget of Study II even with the extra windows

- **Begin work in the MuCool Test Area (MTA)**
  - KEK LH\textsubscript{2} absorber test first. Phase I complete by mid-May, second set of tests in August
  - Provide 201 & 805 MHz capability for MTA
  - Move Lab G magnet to MTA
  - Continue 805 MHz RF studies in Lab MTA (starting in June)
    - Window and grid tests
    - Surface treatment/materials tests
      - Effect on dark current and breakdown
  - Provide as much of the cryo infrastructure as funding allows
    - Very likely ALL of it
  - Fabricate first 201 MHz cavity and bring to MTA for test
    - On Schedule for delivery in Fall

- **In FY05**
  - Start 201 MHz RF test program in MTA
    - 805 MHz testing likely to continue interleaved with 201 testing
  - Complete MTA cryo (if needed)
  - Fabricate coupling-coil prototype
    - If funding is available
  - Begin installation of 400 MeV beam line from Linac

- **In FY06**
  - Bring high intensity beam to MTA
    - Test complete set of cooling components in high intensity beam
Conclusion

- Excellent progress has been made in the last year
  - MTA is complete
    - On budget and on schedule
      - HVAC is late
    - Absorber testing underway
  - RF test program to begin in June (805 and then 201 in Fall)
    - NCRF R&D has demonstrated High Gradient low dark current operation
    - R&D continues in order to continue to push HG Low DC operation in B field
    - Use of Be RF windows looks promising
  - Design of LH$_2$ absorbers and windows has matured
    - “Thin” window required spec appears to have been met
  - Detailed engineering of components has matured
- MuCool is a thriving International Collaboration
  - Absorbers - Japan
  - Absorber/Window design - UK
  - Addressing many of the needs of MICE