MuCool and Neutrino Factory R&D

Fermilab Accelerator LRP Open Session
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Introduction

• Neutrino Oscillation Physics has created a revolution in HEP in recent years
• Quite possibly the ultimate tool for studying neutrino oscillations (and neutrino interactions in general) is the so-called Neutrino Factory (see S.Geer's talk)
• The Fermilab community is actively involved in the international Neutrino Factory R&D effort
  ◆ Physics studies
  ◆ Accelerator design and simulation
  ◆ Accelerator component design, construction, and test
• The MuCool Collaboration is focusing on R&D on components for a particular implementation of a Neutrino Factory
  ◆ Muon Ionization Cooling
Muon Ionization Cooling

- Although the concept of muon ionization cooling is relatively straightforward (transverse, at least)
  - Muons pass through material losing energy
  - They are then accelerated regaining only longitudinal momentum

- However, theory is sometimes much simpler than reality
Muon Ionization Cooling

- There are both linear and ring implementations proposed for muon ionization cooling ...

**Note**: Rings provide 6D cooling and therefore present some differences in implementation.
Muon Ionization Cooling

• ... They all require high-gradient Normal-Conducting RF, some sort of absorber, and high field magnets

• The theory, and now detailed and quite extensive simulations show that ionization cooling can work
  ◆ Still some problems to be solved with 6D cooling
    ▲ Injection and extraction

• However, engineering a real system is a daunting task
  ◆ Performance criteria in design/simulation – quite aggressive
  ◆ Many of the specifications push state-of-the-art
  ◆ System integration problems are formidable
  ◆ Operational safety concerns are an issue

• Before building a complete cooling channel an extensive R&D program is required in order to
  ◆ Demonstrate there are no unforeseen problems
  ◆ Verify performance criteria are met
    ▲ With high-intensity beam in many cases
  ◆ Demonstrate cooling in a test channel

• Note
  ◆ For Neutrino Factories and Muon Colliders these same statements can be made regarding: Proton Driver, Targetry, Acceleration
    ▲ No off-the-self items!
The MuCool Collaboration

- **MuCool Mission**
  - Design, prototype and test all components of a muon ionization cooling channel
  - Perform high beam-power engineering test of cooling section
  - Support MICE (cooling demonstration experiment)
    - Successful MuCool + MICE programs will provide key technical input to decision on Neutrino Factory

- Consists of 70 scientists from 18 institutions from the US, Europe, and Japan
- Primary Support for MuCool comes from non-base program funds
  - Accelerator R&D through broader Muon Collaboration
- Fermilab staff are involved in essentially all aspects of the R&D program
- Fermilab staff key members of the Neutrino Factory Design Effort (Muon Collaboration)
The Details - SFOFO Cooling Lattice

**Basic Components**
- Absorbers – Most likely LH$_2$
- 201 MHz RF
- Superconducting Solenoids (On-axis fields up to $\approx 3-4T$)

This shows lattice to be tested in MICE
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
    - kW for ring cooler designs
- 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?
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
    - Phase I
      - Open Cell cavity reached 54 MV/m surface field (25 MV/m on axis)
        - Large dark currents increased with B field - tested to 2.5T

Lab G RF Cave showing 5T SC Magnet
44 cm bore
Lab G Tests Phase II
- Closed Cell (pillbox) - $E_{acc}/E_{surf} = 0.99$
- Reached 34MV/m with little sparking and low background
  - Thick Cu windows
  - B=0
RF Cavity Prototype Tests
805 MHz Pillbox

- With Solenoidal field
  - Thin (0.015”) Cu windows
    - Dark currents much larger, damage seen
      - Pitting
    - Dark currents reduced via conditioning
    - Conditioned to 20 MV/m
  - Be windows (0.010”)
    - TiN coated
    - 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 R&D - 201 MHz Cavity Design

- Design Complete
  - Electrical, Mechanical, and thermal analyses have been done
    - $E_{pk, \text{surf}} = 26.5$ MV/m
  - Fabrication has started
  - Goal is to have a 201 MHz cavity under test at Fermilab 04

201.25 MHz cavity conceptual design

Exploded views showing foil and grid mounting hardware
Absorber R and D

FNAL/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:** \( M = L_R \frac{dE_\mu}{ds} \) 
  
\( M^2 \) (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>
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<tr>
<td>GH(_2)</td>
<td>4.103</td>
<td>61.28</td>
<td>1.03</td>
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<tr>
<td>LH(_2)</td>
<td>4.034</td>
<td>61.28</td>
<td>1</td>
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<tr>
<td>He</td>
<td>1.937</td>
<td>94.32</td>
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<td>LiH</td>
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<td>1.639</td>
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<td>0.30</td>
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<tr>
<td>CH(_4)</td>
<td>2.417</td>
<td>46.22</td>
<td>0.20</td>
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<tr>
<td>Be</td>
<td>1.594</td>
<td>65.19</td>
<td>0.18</td>
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**H\(_2\)** is clearly Best - 
Neglecting Engineering Issues 
Windows, Safety
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 LH$_2$ (or gaseous H$_2$)**
    - Window design paramount
      - H$_2$ containment
    - Proximity to RF adds constraints (ignition source)
  - **Window material must be low Z and relatively thin in order to maintain cooling performance**

$H_2$ implies engineering complexity
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

Forced-Flow with external cooling loop
• 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
Gaseous Absorber – Muon’s Inc

- Work on Phase I STTR
  - 805 MHz test cell
    ▲ Tested at Lab G
  - Cell conditioned at 450 psig @ 80K
  - Max stable gradient
    ▲ 47 MV/m
  - Data agree well with Pashen Law up to ≈ 170 psig
  - From 170-500 psig no increase in max gradient
    ▲ Surface breakdown
      - Improve electrode surface qualities
  - Data extrapolate to almost 240 MV/m at 80K & 100 atm
MuCool Test Area
MuCool Test Area (MTA)

- Facility to test all components of cooling channel (not a test of ionization cooling)
  - RF power from Linac (201 and 805 MHz test stands)
    - Waveguides pipe power to MTA
  - LHe refrigeration plant for tests of LH$_2$ absorbers and for superconducting magnets
  - Hydrogen gas facility
MuCool Test Area (MTA)

- First Experiment in MTA is now setting up
  ▲ LH$_2$ Convectiv-flow absorber (KEK)
- We eventually wish to bring Linac Beam out the area
  ▲ Designed to accommodate full Linac Beam
  ▲ 1.6 X 10$^{13}$ p/pulse @15 Hz
    - 2.4 X 10$^{14}$ p/s
    - ≈ 600 W into 35 cm LH$_2$ absorber @ 400 MeV
- This will allow us to test cooling components at high beam current
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
    - Has Now Received Scientific Approval from the UK!
- MuCool Collaboration interface to MICE
  - Design Optimization/develop of Study II cooling channel
    - Simulations
  - Detailed engineering
    - Full component design
    - Systems integration
    - Safety
  - RF, Absorber - development, fabrication, and test
  - Development of beam line instrumentation
  - MuCool will prototype and test cooling hardware including MICE pieces which the collaboration is responsible
- High-intensity Beam Tests are ultimately the responsibility of MuCool and are, of course, fully complementary to MICE
MuCool Plans

- **Continue 805 MHz RF studies in Lab G**
  - Window and grid tests
  - Surface treatment/materials tests
    ▲ Effect on dark current and breakdown
- **Continue development of thin windows for absorbers**
  - Already within the material budget of Study II even with the extra windows
- **MuCool Test Area (MTA)**
  - First work in MTA has started - fill of LH₂ absorber (convective)
- **In FY04**
  - Provide 201 & 805 MHz capability for MTA
  - Provide as much of the cryo infrastructure as funding allows
  - Fabricate first 201 MHz cavity and bring to MTA for test
  - Possibly move Lab G magnet to MTA for test with cavity
  - Initiate Full beam-line design and complete shielding assessment
    ▲ Dependent on availability of Laboratory resources
- **In FY05**
  - Complete MTA cryo (if needed)
  - Fabricate coupling-coil prototype (funding driven - Lab help)
  - Begin installation of 400 MeV beam line from Linac
    ▲ Dependent on availability of Laboratory resources
- **In FY06**
  - Bring high intensity beam to MTA (again dependent on Lab resources)
    ▲ Test complete set of cooling components in high intensity beam
Conclusions

- Excellent progress has been made on the design and engineering of ionization cooling components
  - On-going 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
      - This work is of general interest to HEP Accelerator R&D
  - Design of LH₂ absorbers and windows has matured
    ▲ "Thin" window required spec appears to have been met
  - Detailed engineering of components has matured
  - MuCool Test Area is complete and first experiment is being setup
- Speed of progress in FY04+ will depend on funding
  - Beam to the MTA will have to be addressed by the laboratory
- MuCool is a thriving International Collaboration
  - Absorbers - Japan
  - Absorber/Window design - UK
  - Closely coupled to and working with the MICE collaboration