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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

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

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

- Energy absorbers with large $\Delta E$ per radiation length (LH2: 29MeV/m x 8.9m; LiH: 151MeV)
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Of MICE & MuCool

MICE
Experiment at RAL to demonstrate and measure cooling

MuCool
R&D program at Fermilab to develop ionization cooling components
Of MICE & MuCool

MICE

Experiment at RAL to demonstrate and measure cooling aims of the International Muon Ionization Cooling Experiment are:

- to show that it is possible to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory

- to place it in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of cooling

MuCool

R&D program at Fermilab to develop ionization cooling components
Of MICE & MuCool

MICE
Experiment at RAL to demonstrate and measure cooling

MuCool
R&D program at Fermilab to develop ionization cooling components

mission:

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

1. Better materials: more robust against breakdown (melting point, energy loss, skin depth, thermal diffusion length, etc.)
2. Surface processing: suppress field emission (superconducting RF techniques, coatings, atomic layer deposition)
3. Shielding: iron (Rogers), bucking coils (Alekou, WG3)
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Loss of x 2 gradient advantage in pillbox geometry

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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
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
- big impact on cooling channel design and future system tests
- multipronged approach to cover maximum ground with available resources

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- quantify magnetic field dependence of gradient
- establish feasibility of thin windows
- test buttons with different materials/coatings

- Back after rebuild at JLab, tested again
- Poor performance (10 MV/m at 3T)
- To be tested with Be buttons soon
- Reprocessing afterwards (Bowring)

**Safe Operating Gradient vs Magnetic Field**

![Graph showing gradient vs magnetic field](image)

Yağmur Torun
MICE & MuCool – NuFact11 – 8/4/11
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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
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
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
- No surface damage seen on cavity interior
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Evidence for some sparking in the coupler

SEM images of 201 MHz coupler.

Unipolar arc?
modular pillbox with replacable end walls
- designed for both vacuum and high-pressure
- tested under vacuum to 16 MV/m in the MTA
- coupler failure (now replaced)
- to be operated again at higher power and in magnet
- looking into Be walls
- G. Kazakevich et al., PAC11
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- First beam experiment at MTA
- Started running on Jul 12
- HPRF previously shown to work in high B at the MTA (P. Hanlet et al., EPAC06)
- Goal: evaluate cavity loading from beam-induced ionization (M. Chung et al., IPAC10)
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500 psi N2
500, 800 and 950 psi H2
8µs beam, 2 intensities
dopant test (N2, SF6) next week
analysis in progress
First beam pulse to "emittance absorber" (beam stop 2) Feb 28
Intensity about $1.8 \times 10^{12}$ protons/pulse at 1 pulse/min
Phosphor screen upstream of collimator to measure beam spot
Beamline and instrumentation upgraded
$O(10^{11})$ protons through collimators
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$O(10^{11})$ protons through collimators
Students at the MTA (past year)

- Anastasia Belozertseva (U. Chicago) – magnetic field mapping
- Last Feremenga (U. Chicago) – magnetic field mapping
- Ben Freemire (IIT) – HPRF beam test (thesis), everything else
- Giulia Collura (Torino) – HPRF beam test
- Timofey Zolkin (U. Chicago) – dark current instrumentation
- Peter Lane (IIT) – acoustic sensors for detecting cavity sparks
- Raul Campos (NC State) – beamline magnet support
- Ivan Orlov (Moscow State) – HPRF beam test simulation
- Tom Mclaughlin (Valparaiso) – magnetic field mapping
MTA Schedule and Outlook

- **Experimental program**
  - HPRF cavity in beam – first test to be finished next week
  - 805 MHz pillbox cavity with Be buttons – Aug 2011
  - 201 MHz cavity coupler repair and operation in large B
  - further HPRF beam tests as needed – by Mar 2012
  - rectangular box cavity with $\mathbf{B} \parallel \mathbf{E}$
  - more $\mathbf{B} \perp \mathbf{E}$ rectangular box cavity tests?
  - 4-season cavity – Aug 2011
  - ALD cavity – under discussion

- **Infrastructure**
  - beam commissioning complete
  - cryo upgrade in progress
  - magnet field mapping soon
  - 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
Ionization cooling has many challenges in practice
Need demonstration with real hardware to establish
  components can be engineered
  performance can be accurately predicted
MICE concept

- Beamline to deliver 140-240 MeV/c muons
- Track one $\mu$ at a time through one cell of cooling lattice (FSII)
- Momentum measurement before and after the cooling hardware
- Particle ID to remove decays and beam contamination
- Form muon "bunch" in software

Requires

- High purity muon beam, low-mass trackers + PID detectors
MICE accelerator hardware

- 3 absorber + focus coil (AFC) modules expected delivery this year
- 2 rf cavity + coupling coil (RFCC) modules cavities to be completed this year, CC under construction (Zisman, WG3)
- 2 spectrometer modules for trackers and matching (under repair)
- G. Hanson (WG3)
2 SciFi trackers ready
3 TOF walls commissioned in Step I, upgraded afterward
2 aerogel CKOVs commissioned
KL commissioned, EMR partially installed
Phase space from TOF (Rayner)
Phase space from TOF (Rayner)
MICE SCHEDULE -- update July 2011

STEP I
completed -> Aug2010

STEP IV
Q3 2012

STEP V
Q2 2014 *)

STEP VI

*) target date, necessary to run step V before long ISIS shut-down Aug.2014-Feb.2015
Next steps

- Step IV: emittance measurement with trackers
  - Step V: cooling measurement with RF
  - Step VI: full period of cooling lattice
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- Step IV: emittance measurement with trackers
- Step V: cooling measurement with RF
- Step VI: full period of cooling lattice
Next steps

- Step IV: emittance measurement with trackers
- Step V: cooling measurement with RF
- Step VI: full period of cooling lattice
Step I complete
Beamline magnets, target and instrumentation operational
Magnets and absorbers under construction
Tracking detectors ready
PID detectors mostly commissioned (EMR in progress)
Online and offline software developed
Schedule under control
5 Ph. D.’s so far, 6 more expected this year
Demonstrate ionization cooling within 3 years
MICE and MuCool making steady progress
On track for establishing practical ionization cooling technology in the next few years