Final report

Participation in Muon Collider/Neutrino Factory Research and Development

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1. Introduction

Muon accelerators hold great promise for the future of high energy physics and their construction can be staged to support a broad physics program from a low-energy cooled muon source for lepton flavor violation experiments through a Neutrino Factory for neutrino mixing experiments to an energy frontier Muon Collider [1,2]. Design work and technology R&D for muon accelerator facilities have been carried out over the past decade by the international Neutrino Factory and Muon Collider Collaboration [3,4, 5], augmented more recently by the Fermilab Muon Collider Task Force. The US effort on muon accelerator R&D has recently been reorganized into a national Muon Accelerator Program (MAP) [5].

Assoc. Prof. Yagmur Torun and Prof. Daniel M. Kaplan have been working on muon cooling with support from DOE and the IIT group has been on the forefront of experimental ionization cooling R&D for many years. Prof. Torun has served as Deputy Spokesperson for MuCool, led the software and analysis groups in MICE and served as MICE Collaboration Board Chair. Prof. Kaplan has served as US spokesperson, deputy spokesperson, Collaboration Board Chair and Editorial Board Chair for MICE. In the new MAP organization, Prof. Kaplan is the Level-1 manager for Systems Tests and has also served as the Level-2 manager for MICE while Prof. Torun holds the Level-2 post of MTA Coordinator. Sr. Research Associate Dazhang Huang worked on the experimental study of RF cavities and X-ray backgrounds at the Fermilab MuCool Test Area (MTA) for the MuCool and MICE projects, carried out simulations of breakdown in RF cavities and explored collective effects in ionization cooling through simulation and analytical studies. Sr. Research Associate Pierrick Hanlet has worked on data acquisition and controls in the MTA program and led the controls and monitoring effort in MICE. Sr. Research Associate Durga Rajaram has worked on simulation, reconstruction and calibration software for MICE detectors. Graduate student Ben Freemire has worked on acquisition and analysis of data on beam induced plasma loading of cavities filled with high-pressure hydrogen gas and this will be his Ph. D. thesis.

In this report, we provide recent highlights from the MuCool RF cavity R&D program [6,7,8].

2. MuCool RF Experimental program

The MuCool RF program has recently been focused on exploring the solution space for RF cavity operation in strong external magnetic field, as quickly and efficiently as possible, within the available resources. This work was organized along 4 branches:

A. Search for better materials

805-MHz pillbox button cavity: This is a cylindrical pillbox-shaped Cu cavity with provision for replaceable end plates including thin Be windows and removable electrode inserts (Figure 2.1). The pillbox geometry has the advantage of a low ratio for peak surface field to accelerating gradient (about 1). In an ionization cooling channel, the cavity would be terminated using thin windows of low-Z material for minimum impact on the muon beam. This cavity was used early on in the program to study several aspects of RF in muon cooling channels: the magnetic field dependence of gradient; feasibility of thin windows (Cu and Be); potential cavity materials (tested as electrodes) that are more robust with respect to breakdown damage [9,10,11]. Initial tests showed a factor of 2.5 drop in achievable maximum stable gradient in an external magnetic field of 3T compared to no-field operation (16 vs 40 MV/m). Thin pre-stressed curved Be windows were successfully used at high power and established feasibility of the pillbox concept for muon cooling. An alternative termination of the ends in a pillbox geometry considered originally was grids of thin-walled tubes and such grids had been built for testing. A test of grid windows in this cavity will be performed if allowed by the schedule. Electrodes made of several different materials (Cu, Mo, W, Be) were tested to study their response in a high-gradient environment [12,13,14]. The electrodes were shaped to enhance the electric field on their surface by compared to the on-axis gradient.

Figure 2.1: 805-MHz cavity (left) with the iris, end plate and button visible inside. Thin Be window (right).

Recently, Be and Cu buttons were tested in a new geometry which included: symmetric configuration with buttons on both sides of the cavity; lower field (factor of 3 instead of 1.7) on cavity surfaces (including the coupler) for the same field on the button. The maximum gradient (on the button surface) at low sparking rate was somewhat better for Be (40 MV/m at $B=0T$, 33 MV/m at $B=1.5$ and $3T$) compared to Cu (35 MV/m at $B=0T$, 30 MV/m at $B=1.5T$, 28 MV/m at $B=3T$). The interior of the cavity was inspected after the runs and showed additional deposits on the endplates, small (micron) scale damage spots on the Be buttons and larger (millimeter) scale damage sites on the Cu buttons (Figure 2.2). Analysis of button surfaces is ongoing. However, given the accumulated damage on the surface of this cavity, especially around the coupler area, a new test device is needed in order to reach reliable conclusions about performance including a comparison of Be vs Cu walls. A new 805-MHz modular pillbox cavity was designed by SLAC and LBNL, is currently under fabrication and will be used to continue systematic studies of pillbox cavity performance for muon cooling.

Figure 2.2: Cu (left) and Be (right) buttons after testing in the 805-MHz pillbox cavity.

A new 805-MHz modular pillbox cavity was designed by SLAC and LBNL, is currently under fabrication and will be used to continue systematic studies of pillbox cavity performance for muon cooling (Figure 2.3)

Figure 2.3: New 805-MHz pillbox design with modular geometry.

- b. **805-MHz "all-season" pillbox cavity:** Another 805-MHz pillbox cavity built by Muons Inc. under contract with LANL was also installed and operated in the MTA [15,16]. This cavity has a true pillbox shape (no buttons) and was designed for both vacuum and high pressure operation. It also has a longer gap (about twice that of the button cavity). The cavity was installed and tested in the solenoid bore and the performance was essentially the same (25 MV/m) with 0 and 3T magnetic field. This cavity (shown in Fig 2.4) has no built-in diagnostic ports and the accuracy of the gradient measurement was limited without a probe antenna inside. Later, the gas input port was be used to install an RF pickup antenna to sample the field during operation in addition to signals from directional couplers. The cavity also has no provisions for cooling and its thick stainless steel body limits heat transfer to air. Further high-power testing of this cavity with the additional diagnostics is expected to be complete soon. It will be followed by partial disassembly and inspection to look for signs of breakdown damage.

Figure 2.4: 805-MHz all-season cavity installed outside (left) and inside the solenoid (right).

B. Surface Processing

- a. **201-MHz MICE cavity:** A 201-MHz prototype MICE cavity was built using superconducting RF techniques (electro-polishing, high-pressure water rinsing) and was tested in the MTA [17,18]. It was operated above its design gradient of 16 MV/m and the X-ray flux around the cavity was measured to make estimates of the background MICE tracking detectors would be subject to. Large (~40cm diameter) thin Be windows were also used in this cavity successfully. Inspection of the interior surface revealed no signs of damage in the Cu body or the Be windows. This cavity was also operated in the fringe field of the MTA solenoid and some reduction in performance was observed.
- b. **MICE single-cavity module:** A vacuum vessel designed to hold one 201-MHz cavity was fabricated by an outside vendor (Fig 2.5). One of the MICE cavities will be installed in this vessel and operated in the MTA hall. When the MuCool “coupling coil” is installed in the MTA, this single-cavity module will be tested with a large magnetic field over its entire volume.
- c. An ALD-coated (Atomic Layer Deposition) cavity experiment at the MTA is under consideration.

Figure 2.5: 201-MHz single-cavity module drawing (left); vacuum vessel at Fermilab (right).

C. Magnetic insulation: box cavity

The main component of the magnetic field in a muon cooling channel is along the beam axis for focusing. If breakdown is caused mainly by field emitted electrons “riding” magnetic field lines across the accelerating gap, another possible solution is to devise a coil and cavity geometry in which the external magnetic field (B) lines are parallel to the cavity surface and therefore perpendicular to the RF electric field (E). This is sometimes referred to as magnetic insulation. Such a configuration suffers from integration challenges (as the coils need to be pushed close to the cavity iris) and gives up the efficiency advantage of the pillbox. A rectangular box cavity was designed at Fermilab and built using electropolished Cu plates and an experiment at the MTA was set up to test operation of the cavity with B perpendicular to E and a rotatable support system to adjust the relative angle (Figure 2.6)[19]. The cavity was operated at up to 50 MV/m with $B=0$. The achievable gradient in $B=3T$ was about 33 MV/m with the field perpendicular to E withing a degree and dropped to 25 MV/m at 3-4 degrees. Although the technique appears to work for a small range of angles, it was eliminated from consideration as impractical for muon cooling channels.

Figure 2.6: Box cavity model (left); cavity on a rotating pivot being installed in the MTA solenoid (right).

D. High-pressure hydrogen gas filled (HPRF) cavity

Another approach is to moderate the electrons using a high-pressure low-Z gas instead of vacuum inside the cavity volume, originally proposed by Prof. Kaplan and R. Johnson [20]. In this case, the reduced mean free path means electrons cannot traverse the gap with enough energy to cause damage and breakdown. In addition to absorbing the dark current, the dense H₂ gas can also serve as an ionization cooling medium. This effect has been experimentally confirmed using a high-pressure RF (HPRF) cavity for which the breakdown gradient varied linearly with gas pressure following Paschen's Law [21] and was unaffected by the magnetic field [22]. The achievable gradient is about 1 MV/m per atm of H₂ gas up to the surface breakdown limit of the cavity material. However, the response of such a cavity to an intense beam was initially unknown. Ionization from a beam pulse will create a plasma, and unless the free electrons are eliminated by recombination before the next beam pulse arrives, the electrons will “short out” the cavity. The neutralization process can be accelerated by the addition of an electronegative gas as dopant. The lifetime of ionization electrons depends on the interactions of various ions and is not easily calculable from known properties. Two beam tests of the 805-MHz HPRF cavity was performed in 2011 and 2012 [23,24,25,26,27,28] and a wide range of parameters explored including RF gradient (5-50 MV/m), H₂ gas pressure (20-100 atm), beam intensity and dopant concentration. The beam intensity was dialed down to as low as 1/30 of the peak to study the onset of beam-induced loading. Dry air was tested as a dopant in addition to SF₆ in a wide range of concentrations in H₂ to measure the effect of oxygen as the electronegative species. Other combinations explored included dry air in He and N₂ as well as D₂ (deuterium) to explore the ion dynamics. Some data was taken at 3T magnetic field as well. The experimental configuration is shown in Figure 2.7.

Figure 2.7: Upstream views of beam tuning configuration showing toroid and collimator (left), scintillating screen and pre-collimator (middle) installed in solenoid. Downstream view (right) of HPRF cavity (background) with RF power feed and beam absorber (foreground).

A new high-speed oscilloscope and upgraded data acquisition system allowed saving the signals from the cavity in better resolution. Figure 2.8 shows the cavity pickup signal. When the beam goes through the cavity filled with hydrogen gas, a large number of electron-ion pairs are formed due to energy loss by the beam protons. As these free charges oscillate following the alternating electric field, a large fraction of the input RF power is consumed by the plasma leading to a fast drop in the gradient. The dependence of power dissipation by the electron swarm on pressure and electric field has been calculated (Figure 2.9) and

matches the data showing that the contribution from the ions is much smaller. As electrons get absorbed by recombination with the positive ions, an equilibrium RF field amplitude is reached in the cavity. When the beam is removed, the RF field recovers.

Figure 2.8: Electric field inside the HPRF cavity for 1470psi H2 without (black) and with (red) beam, and with 1% dry air doping (blue).

Figure 2.9: Energy absorbed by electrons from RF field in good agreement with predictions (preliminary).

Doping by electronegative gas can quickly remove electrons and the ions then contribute significantly to RF power dissipation. For the same concentration of dry air (and hence O₂), the energy loss dw is smaller for D₂ than H₂ as expected. So far, the results are in quantitative agreement with the theory and extrapolation of the model to possible Neutrino Factory or Muon Collider cooling channel beam parameters (much higher beam intensity) imply that HPRF could in principle work for muon cooling.

3. Outlook

Muon accelerator R&D has recently transformed into one of the main options for the future of high energy physics facilities. Through our DOE supported work, we have made great progress at IIT toward solving one of the main challenges for muon accelerators: ionization cooling technology. The Muon Accelerator Program should answer the question of feasibility for muon accelerators within the next decade and we intend to continue and strengthen our participation in this effort.

Representative Publications:

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- [2] From Neutrino Factory to Muon Collider, D. M. Kaplan, AIP Conf. Proc. 1382 (2011) 64.
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- [5] Accelerator design concept for future neutrino facilities, M. Apollonio *et al.* (the ISS Accelerator Working Group), JINST 4 (2009) P07001.
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- [9] Muon Cooling: MuCool and MICE, Y. Torun, Nucl. Phys. B (Proc. Sup.) 155 (2006) 381.
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- [16] G. Kazakevich *et al.*, Conditioning and Future Plans for a Multi-purpose 805 MHz Pillbox Cavity for Muon Acceleration, submitted to Proceedings of the 2012 International Particle Accelerator Conference (IPAC12), New Orleans, LA, May 20-25, 2012.
- [17] MUCOOL/MICE RF cavity R&D programs, D. Li *et al.*, AIP Conf. Proc. 981 (2008) 299.
- [18] 201 MHz Cavity R&D for MUCOOL and MICE, D. Li *et al.*, Proceedings of the 2006 European Particle Accelerator Conference (EPAC06), p1367.
- [19] Rectangular Box Cavity Tests in Magnetic Field for Muon Cooling, Y. Torun *et al.*, proceedings of IPAC10 (2010 International Particle Accelerator Conference), May 23-28, 2010, Kyoto.
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- [21] Studies of RF Breakdown of Metals in Dense Gases, P. Hanlet *et al.*, Proceedings of PAC05, p. 3259.
- [22] High Pressure RF Cavities in Magnetic Fields, P. Hanlet *et al.*, Proceedings of EPAC06, p. 1364.

- [23] Influence of Intense Beam in High Pressure Hydrogen Gas Filled RF Cavities, K. Yonehara *et al.*, submitted to Proceedings of the 2012 International Particle Accelerator Conference (IPAC12), New Orleans, LA, May 20-25, 2012.
- [24] Electron Recombination in a Dense Hydrogen Plasma, B. Freemire *et al.*, submitted to Proceedings of the 2012 International Particle Accelerator Conference (IPAC12), New Orleans, LA, May 20-25, 2012.
- [25] Study of Electronegative Gas Effect in Beam-Induced Plasma, B. Freemire *et al.*, submitted to Proceedings of the 2012 International Particle Accelerator Conference (IPAC12), New Orleans, LA, May 20-25, 2012.
- [26] Beam Profile Measurement in MTA Beam Line for High Pressure RF Cavity Beam Test, M. Jana *et al.*, submitted to Proceedings of the 2012 International Particle Accelerator Conference (IPAC12), New Orleans, LA, May 20-25, 2012.
- [27] Beam Tests of a High Pressure Gas-Filled Cavity for a Muon Collider, T. Schwarz *et al.*, submitted to Proceedings of the 2012 International Particle Accelerator Conference (IPAC12), New Orleans, LA, May 20-25, 2012.
- [28] High Pressure RF Cavity Test at Fermilab, B. T. Freemire *et al.*, Proceedings of PAC11 (2011 Particle Accelerator Conference), Mar 28-Apr 1, 2011, New York.