U.S. Muon Accelerator Program
Activity Description

The Study of high-gradient RF cavities in strong magnetic field utilizing the MuCool Test Area (MTA) at Fermilab

I. Introduction

This document describes a research plan put forth in response to the recommendations of the P5 subpanel report and as directed by OHEP. Recommendation 25 of the P5 report states that OHEP should:

- Reassess the Muon Accelerator Program (MAP). Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D….

In addition recommendation 26 of the P5 subpanel report states:

- Pursue accelerator R&D with high priority at levels consistent with budget constraints. Align the present R&D program with the P5 priorities and long term vision, with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long-term efforts. Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators.

The MuCool Test Area is an accelerator component test facility unique in the world in that it offers users the capability to test and evaluate the performance of 201 and 805 MHz RF cavities in the presence of high magnetic field and with an intense beam of protons. It is also safety rated for operating components requiring either high-pressure hydrogen gas or liquid hydrogen. These accelerator components have applicability in the production of ultra-intense muon sources that can be used in advanced neutrino sources and could vastly improve the sensitivity of experiments that study the possibility for lepton flavor changing reactions.

An in-depth understanding of rf breakdown, in general, requires studying breakdown in as many different conditions as possible. The MTA capabilities enable such studies under conditions not available anywhere else. Much has already been learned at the MTA, but several questions remain open. For instance, the dependence of vacuum breakdown on surface materials and magnetic fields is an important area of study. In addition there is indication from recent MTA experimental results that ceramic-loaded gas-filled cavities could have application in compact, high-gradient accelerating structures.

The program has 5 functional areas; three of which form the basis of the scientific effort:

1. Operations and experiment support
2. Beam line upgrades
3. MICE RF cavity support
4. Vacuum RF studies
5. High-pressure H_2 gas-filled cavity studies

II. MICE RF Cavity support

The present MTA 201-MHz program is based on the first MICE production cavity that was produced at LBNL and installed in a single-cavity vacuum vessel. This Single Cavity Test System (SCTS) will be used to gain experience with all aspects of the RF system that is to be used in MICE: mechanical assembly, tuner system, RF power couplers, vacuum system and instrumentation. The knowledge gained will feed into the final fabrication, assembly, testing and commissioning plan for the MICE Step V RFCC module required for its ionization cooling demonstration.

II.1 Test plans and schedule

Initial commissioning of the cavity will be done with thick flat Cu windows. These will be replaced by thin curved Be windows after the first run. After commissioning to the MICE operational gradient (8 MV/m) with no magnetic field, the vessel will be moved up against the MTA solenoid to place the cavity in its fringe field (on-axis field at cavity window ~ 0.5T).

The cavity requires about 1 MW of peak power at the design gradient of 8 MV/m. The Linac test station at Fermilab can provide up to 4 MW, but access to high power tubes depends on the conditioning schedule and the availability of spares for Linac operations. After establishing the operational baseline for MICE, demonstration of higher gradient will be pursued as permitted by the schedule.

The following tests are envisioned, each taking about a month with 1-2 months in between tests in order to mesh with the rest of the MTA program and the Linac schedule. The estimated total time is 16-20 months with testing beginning in August of 2014:

1. Coupler conditioning to full power and instrumentation shakedown
2. Cavity commissioning to 8 MV/m at B=0 with Cu windows, inspection, installation of Be windows
3. Cavity commissioning to 8 MV/m at B=0
4. Cavity inspection, vacuum system modification
5. Commissioning to 8 MV/m at B>0, inspection
6. Commissioning to 12 MV/m at B=0
7. Commissioning to 12 MV/m at B>0, inspection
8. Commissioning to 16 MV/m at B=0
9. Tune to Linac reference frequency, beam test (without and with B field), inspection
10. Coupler testing in different orientations

Collaborators from the UK are expected to participate in testing at the MTA to gain experience in cavity operations and become familiar with available signals and instrumentation.

The fringe field from the MTA solenoid at the position of the cavity and RF power couplers is somewhat different from what they would see in the MICE channel. It is possible to move the vessel in order to increase the B-field on the RF power couplers to a level that will be seen in MICE. The MICE prototype 201 MHz cavity which was tested in the MTA (reaching 21 MV/m, B=0) only showed damage in the RF power couplers when operating in magnetic field. A conceptual design is also available for a compact structure that would enable more detailed RF power coupler conditioning and testing in different magnetic field configurations using the MTA solenoid.

Finally, if time permits, the 201 MHz cavity will be tested with beam. This would be the first time that a pillbox cavity with thin Be windows would be operating at high-gradient with an intense beam. The cavity would be tuned to the Fermilab Linac frequency using custom spacer rings and phase locked to the beam to study beam-induced effects.

III. Vacuum RF experimental program

III.1 Overview

The goal of the vacuum RF program is to characterize and better understand the phenomenon of vacuum RF breakdown in the presence of strong magnetic fields. This phenomenon presents challenges to the development of muon ionization cooling channels. A better understanding of vacuum RF breakdown in strong magnetic fields is relevant to many other fields, however, including the conditioning of fusion reactors, the design and optimization of RF photocathode guns, the generation of high-frequency electrical power, and RF breakdown of normal conducting cavities without strong magnetic fields.

Figure 1 shows the test vehicle that will be used in this program. It is an 805 MHz pillbox cavity that is modular in design (can easily be reconfigured) and allows for careful control over sources of systematic error in studies of RF vacuum breakdown in strong magnetic fields. Furthermore, it provides a method to directly compare the RF performance of different materials and different surface treatment methods under these conditions.

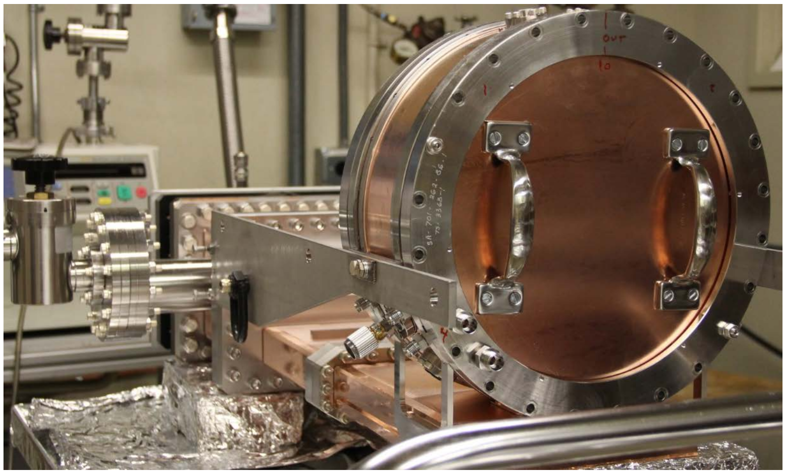

Figure 1. 805 MHz Modular RF cavity.

III.2 Experimental questions

The modular cavity experimental program aims to study RF breakdown in strong magnetic fields with precise control over systematic errors. The priorities of this program are set according to these questions:

1. What is a realistic accelerating gradient on which to base designs for ionization cooling channels using vacuum RF cavities?
2. How does the high-power conditioning sequence influence breakdown behavior in strong magnetic fields?
3. How is breakdown dependent on material properties?
4. What is the “RF lifetime” of a clean copper surface? Of a beryllium surface?

The above questions may be addressed over approximately two years of operations in the MTA. The following section is a brief outline of the prioritized vacuum RF work in the MTA.

III.3 Detailed explanation of planned activities

III.3.1: High-power RF characterization and initial testing

The common goal of MTA-based breakdown studies is a direct comparison between the maximum gradient achievable at B = 0 T and that achievable at B > 0 T. The extent to which prior high-power RF processing history affects future performance is unclear, especially if the external magnetic field strength varies during the conditioning and run history. Field emitter density, fatigue history, and surface cleanliness all begin to change during the first RF cycles during high-power operations. The amount of change to these parameters and their resultant effects on maximum achievable gradient are not yet sufficiently understood.

Separate measurements on two quantifiably similar sets of end plates will characterize variations in maximum achievable gradient due to the order of measurements. One set of plates is commissioned and measured first at B = 3 T and then at B = 0 T. Another identically prepared set of plates is commissioned and measured first at B = 0 T and then at B = 3 T. The difference in initial states between plate sets can be quantitatively characterized through the use of witness samples during fabrication and assembly.

III.3.2: High-power test with Be end plates

High-power testing of the modular cavity with beryllium walls is a critical experimental step for several reasons. First, a model of RF breakdown in strong magnetic field predicts that beryllium may be more resistant to damage and performance degradation. Moreover, the relative transparency of beryllium to dark current allows for instrumentation (such as Faraday cups) that would provide characterization of various breakdown phenomena that are very relevant to the design and operation of an ionization-cooling channel.

III.3.3: Surface lifetime studies

We expect cavity surface characteristics (roughness, field emitter density, hardness, crystallinity) to change over time. In particular, pulsed RF heating has been shown to result in cyclic fatigue and deformation of cavity surfaces. The 805 MHz modular cavity is unique in its ability to provide a statistical assessment of the “breakdown lifetime” of Cu and Be surfaces. We will re-finish end plate surfaces, finely polish them using SRF-type surface treatment techniques, and then run at high power and with B > 0, tracking the variation in the maximum achievable RF gradient with respect to the number of RF pulses.

III.3.4: Construction of a 15 cm cavity body

The 805 MHz modular cavity gap length is 10.44 cm. This length gives a $\pi/2$ phase advance at 805 MHz for particles with $\beta = 0.87$. Our calculations show that the impact energy for a field-emitted electron is maximized for gap lengths between 10 and 11 cm. A 15 cm gap length will minimize the impact energy of these electrons, potentially reducing the damage sustained to the cavity during breakdown. If resources permit, we will build a 15 cm long cavity body so that we could determine if the breakdown rates differ significantly between a 10.44 cm and a 15 cm cavity. If this is the case, we will have learned important information about the influence of electron impact energy on breakdown rates.

IV. High-pressure H2 gas-filled RF (HPRF) cavity studies

A new type of RF cavity has been developed for ionization cooling; a dense hydrogen gas-filled RF cavity. Gaseous hydrogen in a RF cavity has two functions: It suppresses dark current, and it serves as the low-Z ionization cooling material. We have already demonstrated in the MTA that an 800 MHz RF test cell filled with high-pressure hydrogen gas can be operated at gradients up to 50 MV/m (with copper electrodes) under multi-Tesla magnetic fields, without exhibiting any RF breakdown problems. Furthermore, we demonstrated that introducing small amounts of O_2 controlled the residual gas plasma induced by an intense proton beam exposure of the cavity. These results, when projected to the beam intensities required for high energy physics operation, indicate that this type of cavity can meet the necessary specifications for a high brightness muon source.

HPRF cavity technology is attractive for applications beyond ionization cooling. A hadron flux monitor near a MW-target has a critical radiation issue. The flux can be measured accurately by observing the amount of ionization plasma in a gas-filled RF resonator. The system is very simple and robust to radiation damage. In addition, a dielectric loaded HPRF cell has the potential to be used for a compact RF energy storage cell for intense beam accelerators.

The challenge that we will address in this proposal is how to incorporate a gas-filled RF cavity into a compact magnet. Loading an RF cavity with dielectric material allows for a reduction in the cavity diameter without a concomitant increase in the fundamental frequency. A proof-of-principle test has been done at the MTA. Dense gas in the cavity suppressed RF breakdown on the surface of a loaded ceramic. The maximum RF gradient that was observed corresponded to the dielectric strength of the ceramic in the cavity.

The experimental program over the next 18 to 24 months will focus on an evaluation of dielectric materials, the relevant criteria being high dielectric strength (≥ 15 MV/m) and low loss tangent ($\leq 10^{-4}$). Low-power RF tests are in progress to measure the dielectric constants and loss tangents of various samples in the low-power RF test cell shown in Figure 2. In addition, an existing 805 MHz high-power test cell will be loaded with a new dielectric insert so that we can test its functionality with an intense beam and multi-Tesla fields. A schematic of this new test configuration is shown in Figure 3. The experimental program we envision is given below:

1. Low power RF sample test
2. High power RF test in the MTA
   i. Measure available accelerating gradient under multi-Tesla fields
3. Beam test in the MTA with high-power test cell
   i. Determine the maximum accelerating gradient in the presence of intense charged beam and in multi-Tesla fields
   ii. Demonstrate how to control plasma loading

Successful completion of this series of tests will validate much of the required engineering for gas-filled RF cavity applications.

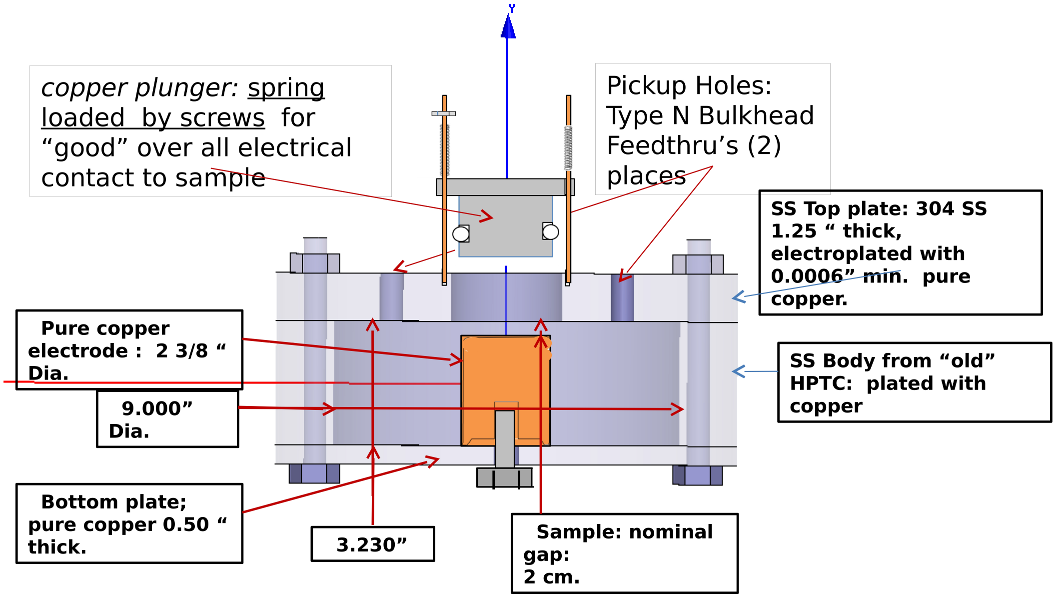

Figure 2. Layout of the low-power test cell. Each sample will be mounted between the top of the copper electrode (orange) and the copper plunger (grey).

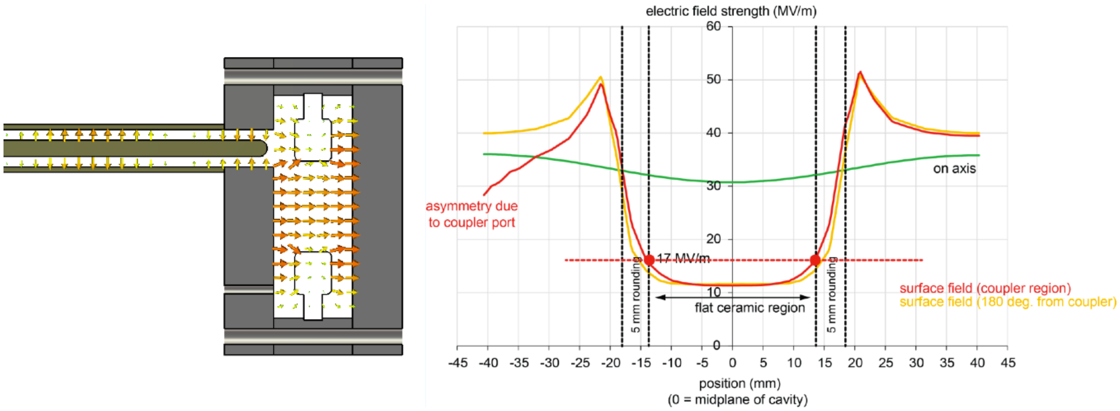

Figure 3. (Left) Layout of the high-power test cell and power coupler, and (Right) E-field on the RF axis (green), at power coupler (red) and at the inner surface of ceramic ring (orange) in the test cell.

IV. MAP supported personnel in the MTA program and MTA run schedule

Table 1 below gives the MAP-funded personnel involved with the MTA RF work and Figure 5 gives a block diagram of the MTA schedule over roughly 18 months starting in FY15. The effort includes 10.7 costed FTEs in FY15 with 8.3 of those being based at Fermilab.

Table 1. MAP-funded personnel on MTA RF

Institution	Personnel	Position
FNAL	A. Moretti D. Bowring K. Yonehara M. Leonova D. Peterson M. Popovic R. Pasquinelli R. Schultz Mech. design (0.5 FTE) Technician pool (2.7 FTE)	Engineer Scientist Scientist Postdoc Engineer Scientist Engineer Engineer Designer Technician
IIT	Y. Torun B. Freemire	Faculty Postdoc
University of Chicago	A. Kochemirovskiy	Graduate student

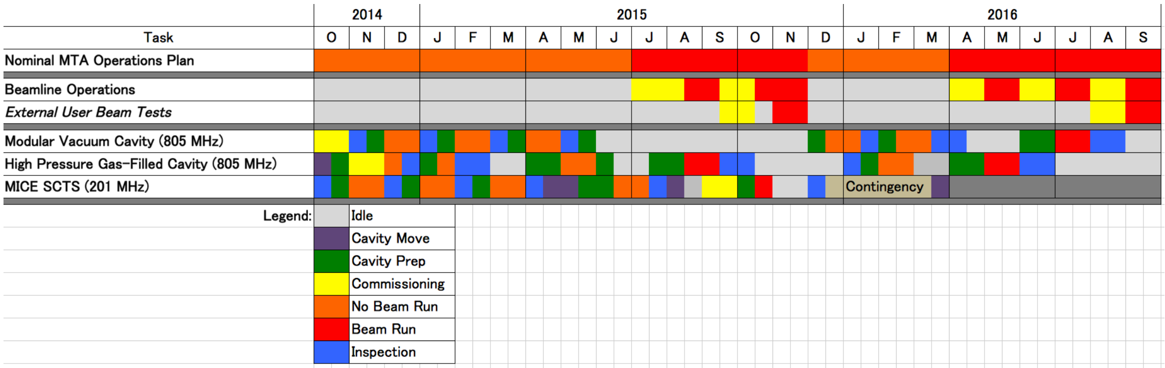

Figure 4. MTA run schedule.