Normal-Conducting RF Cavity R&D at the MuCool Test Area

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1 Introduction

Over the last 9 years, a rich program on RF cavity operation in magnetic field has been carried out at the MuCool Test Area (MTA) at Fermilab with the goal to establish RF component technology for advanced muon and neutrino sources and contribute to fundamental studies on breakdown physics. Driven by the need for acceleration in strong external magnetic field, a basic requirement for ionization cooling, we have developed

- high-gradient, robust normal conducting RF cavities that condition with minimal breakdown,
- an understanding of vacuum RF cavity performance in magnetic field,
- high-pressure RF (HPRF) cavities that are not affected by magnetic field,
- a theory of plasma loading in HPRF cavities validated by beam tests.

Looking forward, we envision a 2.5-3 year effort to bring key elements of this R&D program to a successful conclusion.

For the past 3 years, tremendous R&D progress has been made, supported by the Muon Accelerator Program (MAP). Earlier this year, the Particle Physics Project Prioritization Panel (P5) recommended that DOE-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 August 2014, DOE-OHEP convened a review of the MAP effort. The committee endorsed a 3-year ramp-down of the MAP effort focused on completion of the MICE (Muon Ionization Cooling Experiment) cooling demonstration. Furthermore, the committee report recommended:

> Aspects of MAP beneficial to future neutrino sources should be transferred into GARD, directly competitive with other GARD objectives.

In September 2014, DOE-OHEP approved a 3-year budget profile for the conclusion of MAP and MICE. Within this budget profile, funds are available to support 1.5 years of MTA operation – the timescale required for characterization of the MICE RF system.

In light of these recommendations, we are proposing to complete critical elements of the MTA program as part of a balanced portfolio for medium- and long-term general accelerator R&D. GARD funding for 1-1.5 years after the conclusion of MAP funding for the MTA would allow us to fully exploit the scientific potential of this promising program. This work would include

- continued studies of vacuum and high-pressure RF cavities at 201 and 805 MHz utilizing the MTA's extensive instrumentation taking advantage of the existing infrastructure,
- tests in external magnetic field and high intensity beam, and
- studies on a range of materials and surface finishes.

The MTA provides an excellent environment for a better understanding of RF cavity performance using a wide range of variables with good control over systematics by exploiting the unique combination of capabilities at a single facility.

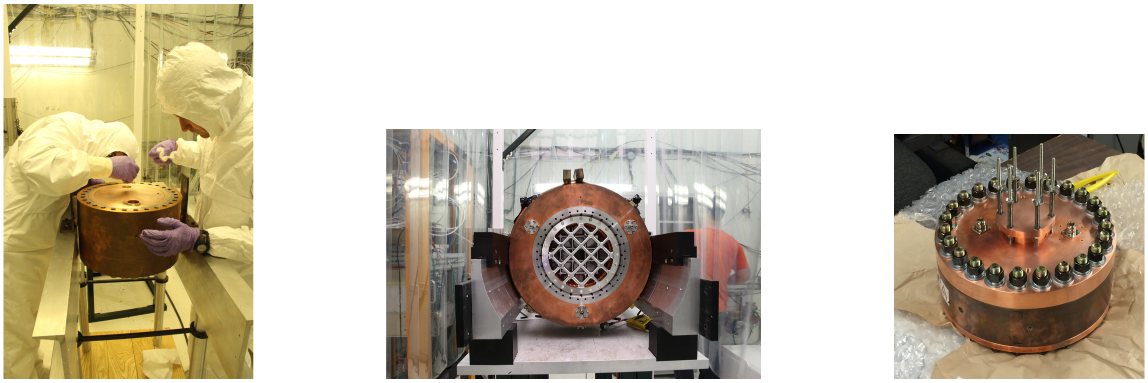

Figure 1: Cavity configurations recently tested in the MTA:
(a) Long pillbox ("all-season") cavity (b) Pillbox with gridded-tube windows (c) Dielectric sample test

1.1 Recent Accomplishments and Potential Impact

A 201-MHz cavity (MICE prototype) is currently operating and is instrumented with a wide array of detectors to study its performance. The interior surface of this cavity was electropolished and its assembly was done in a clean room. This new way of preparing Cu cavities using techniques developed for superconducting RF (SRF) has resulted in remarkable performance: the cavity was commissioned to design gradient in 3 days and did not have a single breakdown in 2 months of operation. An earlier 201-MHz prototype cavity was also electropolished and exhibited similar behavior: very fast conditioning and a maximum achievable gradient of > 20 MV/m that was only limited by available RF power. This reinforces some recent work done by SLAC and KEK, in which a 14.2-GHz cavity underwent SRF-style surface preparation and consequently conditioned much faster than an equivalent conventional cavity. The results from our 201-MHz and SLAC's 14.2-GHz structures (structures that differ by almost 2 orders of magnitude in frequency/size and 3 orders of magnitude in stored energy) confirm the benefits of this kind of surface treatment and clean-room assembly. Such techniques pay clear dividends in terms of initial commissioning, cavity protection, and overall performance.

A linear accelerator made of cavities that require little or no conditioning can provide an enormous benefit to any facility. Specifically, such well-behaved cavities reduce the risk of delays to machine startups and to associated physics programs. Note also that economies of scale help to control any extra costs stemming from these surface treatment and assembly techniques. These tests have established a basic building block of future high intensity muon and neutrino sources: low-frequency pillbox cavities with thin, low-Z windows to accommodate large muon beams. A test of the MICE cavity with intense beam is planned and would complete demonstration of the concept.

A long (0.35 wavelength) 805-MHz pillbox cavity (shown in Fig. 1a) was operated in an external magnetic field of up to 5 T at over 20 MV/m. Another 805-MHz pillbox cavity (Fig. 1b) with gridded tubes (a window option developed by a former MTA grad student for his mechanical engineering Ph.D.) was successfully tested in up to 5 T field at $>$20 MV/m surface gradient. The performance of these cavities is consistent with predictions from our model of breakdown in strong magnetic fields.

A new 805-MHz "modular" cavity has been built to support breakdown studies with well-controlled systematics. The cavity is being prepared for commissioning and a detailed test plan is in place to answer important questions about normal-conducting RF performance in strong magnetic fields. This cavity program will enable detailed and well-controlled systematic studies, spanning different materials and surface preparation techniques that are potentially useful in building better performing copper RF structures.

An 805-MHz cavity pressurized with up to 100 atm of H_2 gas was tested with a high intensity 400-MeV proton beam at up to 50 MV/m to measure beam-induced plasma loading and with an external magnetic field of 3 T. Furthermore, control of the plasma loading effect through the addition of a small amount of electronegative dopant species (O_2) was demonstrated in this test. The observed loading was modeled as a cold plasma oscillation and the implementation was built into a particle-in-cell (PIC) code using the measured parameters. Combined collective effects such as space charge and plasma coherent motion were investigated in the code. The same cavity was also operated with a sample of dielectric material to confirm suppression of breakdown with high pressure gas. Several material samples were measured in another test cavity (Fig. 1c) as candidates for dielectric loading of the HPRF cavity and full-size dielectric inserts will be tested at high power and with beam to provide a proof-of-principle demonstration of cavity size reduction for use in compact HPRF accelerating structures which are immune to the magnetic field effect. These cavity tests have demonstrated a viable path to muon ionization cooling channels.

Recent MTA results indicate significant potential advances in RF cavity technology. Such advances may benefit other areas beyond intense, cold muon beams. The MTA offers unique opportunities for detailed studies of these new directions in normal conducting RF R&D.

1.2 The Facility

The MTA is an accelerator component test facility with the following capabilities:

- high peak power pulsed RF at two frequencies (12 MW at 805 MHz and 4 MW at 201 MHz) with variable rep rate up to 15 Hz,
- infrastructure for RF cavity instrumentation signals with automated monitoring and control software for cavity operation,
- a superconducting solenoid with a pair of Helmholtz coils that can be powered individually to create a uniform solenoidal field (up to 5 T) or a gradient field configuration, with a warm bore large enough to fit 805-MHz cavities,
- a cryogenic plant that provides liquid He and N_2 used for operating the solenoid with spare capacity,
- a class-100 portable clean room in the experimental hall near the test stations used for cavity assembly, reconfiguration and inspection,
- a beamline that brings the 400-MeV high-intensity H^-/p beam from the Fermilab Linac with beam position, profile and intensity diagnostics,
- extensive diagnostics for cavity characterization including X-ray rates and spectra, radiation dose rates around cavities, light intensity and spectrum inside cavities, and
- safety infrastructure for hydrogen gas and liquid.

This infrastructure represents a unique resource for the field of RF research.

1.3 Participation

The MTA program has supported a steady stream of student projects: 29 students (16 undergraduate and 13 graduate) since 2006, 8 over the past year. There are currently three Ph.D. students: one working on using acoustic sensors for detecting the position of breakdown events; one on the analysis of the modular cavity for R&D on breakdown in strong magnetic fields; and one on modeling of beam-induced plasma in HPRF cavities. The first Ph.D., on plasma loading of the HPRF cavity using data from the beam test, was completed in 2013. A M.Sc. project on tuning system tests of the MICE cavity was completed earlier this year. Several undergraduate student projects are launched every summer. In addition, undergraduate mechanical engineering students from the Fermilab co-op student program have been contributing to infrastructure upgrades and experimental apparatus. Ten postdoctoral researchers have participated in the MTA experimental activities and data analysis so far. We intend to continue student involvement in the MTA program at the graduate and undergraduate levels in physics as well as electrical and mechanical engineering. The facility provides abundant opportunities to train future scientists and engineers in a broad range of accelerator science and technology through hands-on experience with real hardware.

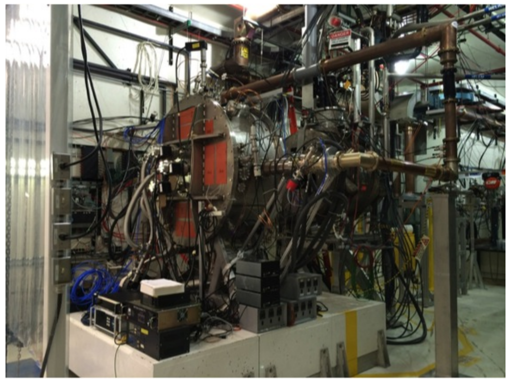

Figure 2: MICE Single Cavity Test System

The MTA program has been steered by a partnership between Fermilab and collaborators from universities, other national labs and industry. The program has always had strong international participation and support and six of the students who participated in MTA projects were from institutions outside the US.

2 Program Details

As previously noted, the MTA program will be supported by MAP through mid-FY16. This will enable completion of the 201-MHz MICE cavity test program. It will also provide support for the general RF in magnetic field research effort. We believe there is tremendous benefit to completing this effort. This would be possible with roughly a year of GARD funding starting in mid-FY16.

2.1 MICE Cavity Testing

A MICE 201-MHz cavity was electropolished and installed in a vacuum vessel for the first time last year. This Single Cavity Test System (SCTS), shown in Fig. 2, serves as the prototype for the MICE RF module and forms the basis for the 201 MHz MTA program. The SCTS is being used to gain critical experience with all aspects of the MICE RF system: mechanical assembly, tuner system, RF power couplers, vacuum system, and instrumentation. Work planned in the UK at the MICE experimental hall relies heavily on the operational experience gained in the MTA with the successful operation and characterization of the SCTS. The system uses MICE-style RF input couplers and mechanical tuners, and will be operated with thin curved Be windows in an external magnetic field.

Current Status and Significance

Commissioning of the cavity to the original MICE baseline gradient (8 MV/m) with no magnetic field was completed without a single observed breakdown event. Testing at higher gradients ($\geq$ 11 MV/m) is in progress with thick flat Cu windows. After the current commissioning run, these windows will be replaced by MICE-style thin, curved Be windows and the cavity will be tested in an external magnetic field. The latest MICE configuration calls for 2 MW per cavity. The test station at Fermilab can provide up to 4 MW.

In the present MAP plan, the cavity will be operated at high gradient and the input couplers exposed to strong magnetic fields in order to validate their performance. Additionally, we will carry out a beam test in which the cavity will be phase locked to the beam to study beam-induced effects. This will be the first time that a pillbox cavity with thin Be windows operates at high-gradient with an intense beam. This large pillbox cavity operates with very high stored energy, so exploring its performance envelope will provide useful insight into vacuum breakdown.

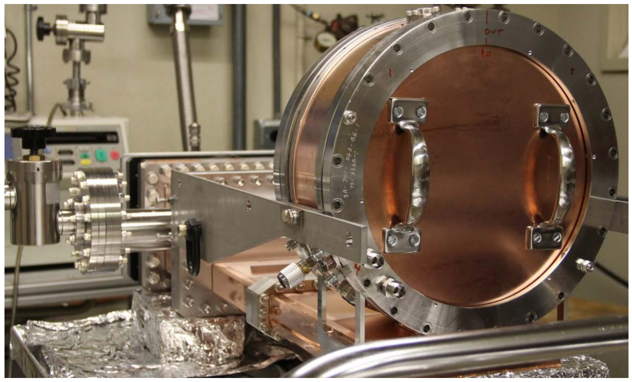

Figure 3: 805 MHz Modular RF cavity

2.2 Vacuum RF Experimental Program

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 3 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.

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:

- What is a realistic accelerating gradient on which to base designs for ionization cooling channels using vacuum RF cavities?
- How does the high-power conditioning sequence influence breakdown behavior in strong magnetic fields?
- How is breakdown dependent on material properties and surface preparation?
- 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 is a brief outline of the proposed 805-MHz vacuum RF work in the MTA:

1. High-power RF characterization with an all-Cu cavity body. The goal here is to commission the cavity and establish a maximum safe operating gradient in a range of magnetic fields.
2. High-power test with Be end plates. Past experimental evidence and theoretical guidance suggest that a cavity with Be walls is more resistant to RF breakdown and damage.
3. Surface lifetime studies. Operate the cavity with clean Cu end-plates for a large number of pulses to monitor the change in breakdown rate over time.

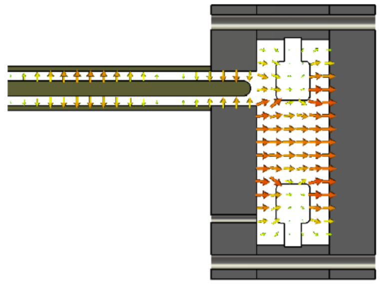

Figure 4: High-power test cell with dielectric insert and power coupler

2.3 High-Pressure Gas-Filled RF (HPRF) Cavity Studies

We are exploring a potentially transformational RF technology for ionization cooling – an RF cavity filled with high-pressure gas. High-pressure gas in a RF cavity has two functions: it suppresses dark current and can serve as a cooling medium. Measurements at the MTA have demonstrated operation of HPRF cavities without breakdown at high gradient in multi-Tesla magnetic fields. A beam traversing such a cavity ionizes the gas, creating a plasma which loads the cavity, referred to as plasma loading. This effect can be mitigated by addition of an electronegative dopant to the gas to capture free electrons. A theory of plasma loading has been developed and validated with measurements made at the MTA. The experimental results obtained with H_2 gas and an electronegative dopant indicate that these cavities can operate in magnetic fields at the beam intensities required for high energy physics applications. A complete understanding of the impact of this environment on the beam can only be obtained by detailed modeling of the beam-plasma interaction and associated collective effects. Tools are being developed for self-consistent simulation of plasma production and its interaction with particle beams and external fields. Additional beam testing is required to obtain the plasma parameters needed to confirm the model and validate the simulation tools.

Loading an RF cavity with dielectric material allows for a reduction in cavity size without a concomitant increase in the fundamental frequency leading to compact channels. Another potential benefit of HPRF technology is that it can enable high-gradient operation of dielectric-loaded cavities. This is not viable for conventional vacuum cavities due to breakdown at dielectric surfaces. In order to demonstrate this capability, the existing 805-MHz high-power test cell will be loaded with a new dielectric insert and operated with an intense beam and a strong external magnetic field.

A schematic of the HPRF test configuration with a dielectric insert is shown in Figure 4. This configuration will be used in the experimental program described below:

1. Perform low level RF measurements of the cavity with four alumina ring inserts of varying purity in order to determine the dielectric constant and loss tangent of each.

2. Operate the cavity at high power, without beam, with and without magnetic field up to 5 T, to qualify the dielectric inserts and establish a baseline cavity behavior.

3. Operate the cavity at high power, with beam, with and without magnetic field up to 5 T. to study the interaction of the beam and plasma with the dielectric material. This includes doping the gas in order to control plasma loading.

4. Operate the cavity at high power with inserts to determine the dielectric strength of each.

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

HPRF cavity technology is attractive for applications beyond neutrino factories and muon colliders. Some examples follow.

- Existing technology for hadron flux monitors is not robust in the high-radiation environment in the vicinity of MW-class targets. Gas-filled RF resonators offer a simple and robust solution in this environment. In these devices, the beam flux can be measured accurately by observing the amount of plasma loading.

- Another potential application is a dielectric loaded HPRF structure which can serve as a compact RF energy storage cell for high-intensity accelerators.

- Finally, an HPRF-based cooling channel combined with a high-intensity muon source could greatly increase the sensitivity of the Mu2e experiment as well as other experiments that benefit from higher brightness muon beams.

3 Resources

The MTA is a facility supported by the Fermilab Accelerator Division. The program currently involves about 10 FTE's of effort, most of it based at Fermilab. The majority of the hardware required for carrying out the proposed program over the next 2-3 years is already in place, so the M&S requirements are modest. For a 1-year extension of the MTA effort by the GARD program, funding of roughly $1M/year would be required in FY16 and FY17, corresponding to approximately 5 FTE-yrs of effort in each fiscal year.

4 Conclusion

Muon accelerator capabilities will likely be key to intense cold muon sources, precise and accurate neutrino sector measurements and ultimately efficient exploration at high energy for the long-term future of particle physics. Acceleration in strong focusing external magnetic fields is a necessary feature for practical muon-based machines. Great strides have been made over the past few years within the MTA program toward understanding and enhancing the performance of RF cavities in strong magnetic fields. The MTA program is also poised to contribute to the fundamental understanding of breakdown in normal conducting RF structures which may offer advancements at a wide range of accelerator facilities. The facility has a unique combination of capabilities built over the past decade that are essentially irreplaceable. We propose leveraging the investment in this facility by continuing support of key experimental efforts at the present modest level to allow completion of critical R&D in the next 2.5-3 years.