

# A MODULAR CAVITY FOR MUON IONIZATION COOLING R&D\*

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## Abstract

A goal of the Muon Accelerator Program (MAP) is the development of an ionization cooling channel for muon beams. Ionization cooling channel designs call for the operation of high-gradient, normal-conducting RF cavities in multi-Tesla solenoidal magnetic fields. However, strong magnetic fields have been shown in some cases to limit the maximum achievable gradient in RF cavities. This gradient limit is characterized by RF breakdown and damage to the cavity surface. To study this issue, we have developed an experimental program based on a modular pillbox cavity operating at 805 MHz. The modular cavity design allows for the evaluation of different cavity geometries and materials – such as beryllium – which may ameliorate or circumvent RF breakdown triggers. Modular cavity components may furthermore be prepared with different surface treatments, such as high-temperature annealing or chemical polishing. This poster presents the design and fabrication status of the modular cavity, as well as plans for the experimental program.

## INTRODUCTION

The short lifetime of a muon ( $\tau = 2.2 \mu\text{s}$ ) poses interesting problems for the design of a muon accelerator. Muon beams must be accelerated quickly before they decay. Transverse cooling must then occur in some fraction of a muon's lifetime, which rules out traditional methods such as stochastic and electron beam cooling [1, 2, 3].

Ionization cooling is the preferred method for quickly achieving the required transverse emittance [4]. In an ionization cooling channel, low-Z absorber sections isotropically attenuate beam momentum, and normal-conducting RF cavities replace only the longitudinal momentum. The RF cavities are placed in multi-Tesla magnetic fields for beam confinement and radial focusing.

Interestingly, copper cavities in strong magnetic fields exhibit increased RF breakdown rates [5, 6]. As shown in Figure 1, the maximum achievable surface electric field decreases as the solenoidal field strength increases from 0 to 4.5 Tesla. RF breakdown events at all field strengths

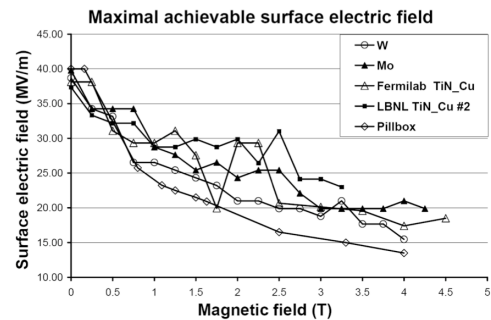


Figure 1: Strong magnetic fields limit cavity gradients via increased breakdown rates, for various cathode materials [5].

cause arc damage on inner cavity surfaces, which may further limit the gradient even in zero magnetic field [7].

The physics of RF breakdown in strong magnetic fields is not well understood. An extensive R&D effort is in progress to develop methods of suppressing or circumventing the problem. This includes testing various vacuum RF cavity designs as well as testing high-pressure gas-filled cavities [8]. We have developed an 805 MHz pillbox cavity that will serve as a testbed for the vacuum R&D program. The cavity has a modular design, which enables relatively quick and easy evaluation of breakdown behavior for different cavity materials, surface treatments, stored energy (by varying gap length), and applied solenoidal field strengths.

Several theories have been proposed to explain the mechanism underlying RF breakdown in strong magnetic fields. Stratakis *et al.* have suggested that field-emitted electrons may be focused by the applied magnetic fields into energetic beamlets that, over several RF periods, repeatedly impact a cavity wall and cause pulsed heating damage through cyclic fatigue [9]. In that case, materials with long radiation lengths and high melting points – such as Be – may absorb less beamlet energy. Similarly, pulsed heating damage may be avoided by using materials such as W, Mo, and various Cu alloys shown to be robust against cyclic fatigue in RF cavities [10].

This paper presents the RF and mechanical designs of a modular cavity for cooling channel R&D, as well as its fabrication status and future plans. The cavity will be tested in Fermilab's MuCool Test Area (MTA).

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### CAVITY DESIGN

The overall goal of this R&D effort is to arrive at a cavity design capable of operating with the pulse lengths, rep rates, and magnetic fields required for an ionization cooling channel in a muon accelerator. An 805 MHz pillbox cavity with demountable end walls can accommodate different materials and surface treatments, as discussed above. Furthermore, this modular design allows for the evaluation of stored energy effects by changing only the central cavity body – the end walls, waveguides, instrumentation, and mechanical supports may all be reused. Damage incurred during RF breakdown may be easily inspected and repaired, or the affected part may be more cheaply replaced. Finally, the modular design allows for duplicate cavity bodies to be fabricated at lower costs, allowing for the accumulation of statistics.

However, a modular design by itself is not sufficient. The cavity should incorporate as many design elements as possible of a “real” ionization cooling channel and should also integrate easily into the MTA. The design must then include: magnetic (aperture) RF coupling at the cavity equator<sup>1</sup>; a geometry that fits inside the 44 cm diameter warm bore of the MTA’s superconducting solenoid; and compatibility with the MTA’s RF, vacuum, and mechanical infrastructure. These various design elements are described below.

#### Simulation

ACE3P, SLAC’s parallel, finite-element simulation suite, was used extensively in the design of this cavity [13]. The basic geometry and RF fields are shown in Figure 2. An 805 MHz pillbox cavity is magnetically coupled through the equator to a narrow, 56-cm-long transition waveguide. This section is necessarily narrow in order to fit within the 44-cm-diameter warm bore of the MTA’s solenoid. Once outside the magnet, the waveguide joins to a 13 cm-long section of standard WR-975 waveguide. This segment houses the vacuum couplings and RF window. Simulated RF parameters are summarized in Table 1.

Of particular interest here is the ratio of peak surface electric field strength on the longitudinal axis to that anywhere else in the cavity. Previous cavities have exhibited breakdown in the region of the RF couplers. This may be due to local field enhancement from high-curvature coupler surfaces. In order to ensure that RF breakdown occurs on the longitudinal axis, and to avoid additional complication in the interpretation of breakdown data, it is important to keep this field ratio as high as possible. The current design features a field ratio of 5.4, an order of magnitude improvement over previous geometries [6].

Multipacting (MP) considerations further complicate the design of the coupling iris. ACE3P’s particle tracking code,

<sup>1</sup>Several R&D cavities introduce RF power through a side wall, parallel to the longitudinal axis [6, 11, 12]. This coupling strategy may introduce strong surface electric fields well away from the longitudinal axis, complicating the interpretation of RF breakdown data.

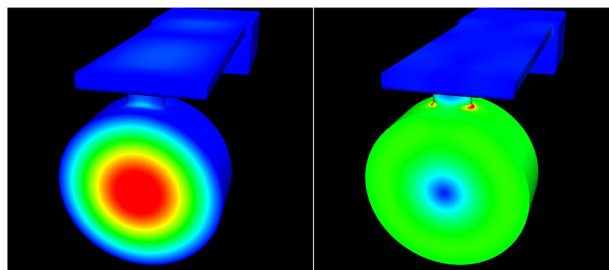


Figure 2: Simulation of electric fields (left) and magnetic fields (right) in the modular cavity, using ACE3P’s eigensolver program, Omega3P.

Table 1: RF parameters for the modular cavity. “Field ratio” denotes the ratio of peak surface electric field on the longitudinal axis to that anywhere else in the cavity. Past MTA experience indicates that achieving critical coupling ( $\beta = 0$ ) requires a design  $\beta \approx 1.3$  in order to allow for clamping losses.

Parameter	Value	Units
Frequency	805.0	MHz
Radius	142.25	mm
Length	104.4	mm
$Q_0$	20500	
$Q_{ext}$	15600	
Coupling coefficient, $\beta$	1.3	
Field ratio	5.4	

Track3P, was used to optimize the coupler geometry for minimal MP in fields between 0 and 3 T. (Future tests will evaluate breakdown behavior in solenoidal fields up to 5 T.) The final coupling iris design is shown in Figure 3, along with the locations of possible resonant MP trajectories at  $B = 0$  T and  $B = 3$  T. Select surfaces will be coated with TiN films in order to suppress secondary electron emission.

As discussed above, the flat end plates of the modular cavity are interchangeable. We intend to test the cavity with Cu and with Be end plates in order to evaluate various theories of RF breakdown in strong magnetic fields. Damaged Be (especially Be dust) presents a respiratory hazard. To minimize the strain on Be components, thermal and me-

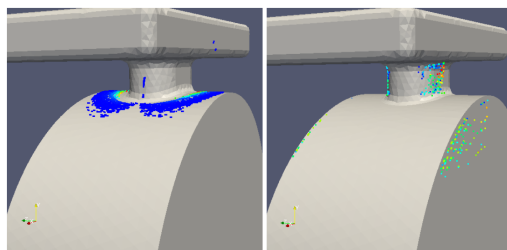


Figure 3: Possible resonant MP trajectory locations shown for  $B = 0$  T (left) and  $B = 3$  T (right). Simulations performed using Track3P.

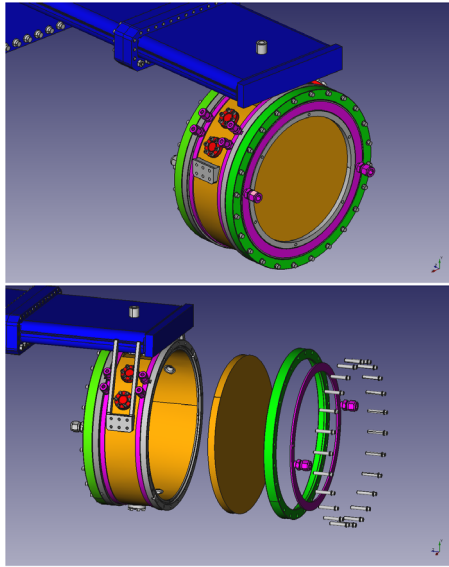


Figure 4: (Above) Color-coded schematic of the cavity and waveguide system. (Below) Exploded view of same, showing how a sample plate is mounted to the cavity body.

chanical strain simulations were performed with TEM3P, ACE3P's multiphysics simulation code. These simulations were used to determine the placement of coolant lines at various points around the cavity, as shown below. The final design limits the temperature rise across Be components to  $\Delta T \approx 4$  K, ensuring that thermal strain is well within safety limits.

The use of beryllium as a cavity component allows measurements of dark current before and during breakdown events. The Be cavity walls are designed with a 1 mm thin "window" in their centers, on the longitudinal axis, through which dark current may pass with minimal scattering. Multiple scattering was studied and the dark current window geometry was evaluated using G4beamline, a particle tracking toolkit developed by Muons, Inc. [14].

### Mechanical Design

Figure 4 is a color-coded illustration of the various mechanical design aspects of the modular cavity. Be or Cu sample plates are bolted to a central Cu cavity body (copper-colored) using a stainless steel retaining ring (green). The cavity body and Cu sample plates are solid OFHC copper. Cooling water lines (magenta) run around the equator and across the face of the sample plates. Six "mini" ConFlat instrumentation ports (red) are designed to accommodate either RF pickups or optical inspection feedthroughs. Waveguide components, shown in blue, are copper-plated 304L stainless steel. RF/vacuum seals are not shown.

The cavity and waveguide system is supported by a non-magnetic stainless steel frame that may be inserted into the MTA solenoid on a set of rails. The entire assembly is shown in Figure 5.

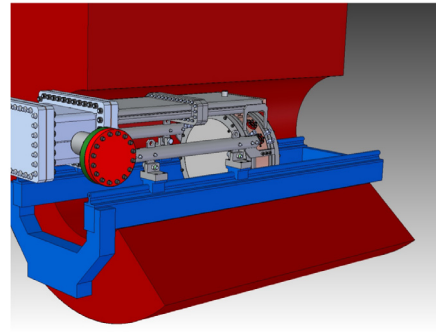


Figure 5: Assembly of the modular cavity system, with cut-away of the solenoid in red. When installed in the magnet the cavity rests on a transfer frame, shown in blue.

## FABRICATION

Fabrication and assembly is in progress at SLAC. We anticipate doing the cold testing and final assembly in August, at which point the cavity will be shipped to FNAL for commissioning and high-power testing.

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