

VACUUM RF BREAKDOWN OF ACCELERATING CAVITIES IN MULTI-TESLA MAGNETIC FIELDS*

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Abstract

Ionization cooling of intense muon beams requires the operation of high-gradient, normal-conducting RF structures within multi-Tesla magnetic fields. The application of strong magnetic fields has been shown to lead to an increase in vacuum RF breakdown. This phenomenon imposes operational (i.e. gradient) limitations on cavities in ionization cooling channels, and has a bearing on the design and operation of other RF structures as well, such as photocathodes and klystrons. We present recent results from Fermilab's MuCool Test Area (MTA), in which 201 and 805 MHz cavities were operated at high power both with and without the presence of multi-Tesla magnetic fields.

INTRODUCTION

Bright muon beams occupy a relatively large volume in phase space when first created, and these beams must be cooled quickly due to the short lifetime of the muon (2.2 μ s at rest). Ionization cooling is the preferred approach to this problem [1]. This approach requires the operation of high-gradient RF structures in the presence of multi-tesla solenoidal magnetic fields, and such fields have been shown to have an effect on the rate and extent of RF breakdown in copper cavities [2].

RF Breakdown Model

We have a conceptual model of breakdown that may explain the impact of magnetic fields [3]. Surface irregularities such as asperities are a source of field emission during high-power operation. Normally, field emitted electrons have a phase-dependent trajectory. However, in the presence of a strong solenoidal magnetic field, these electrons are focused into "beamlets" with current densities between 10^3 and 10^5 A/m². Over multiple RF cycles, these beamlets may cause pulsed heating and cyclic fatigue of cavity surfaces, making them more susceptible to breakdown.

In the context of accelerating cavities, RF breakdown is characterized by an abrupt electrical arc, shorting the cavity and dissipating its stored energy. This event is often accompanied by a flash of visible light, transient spikes in cavity vacuum pressure and x-ray intensity, and damage on the cavity surface.

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The MuCool Test Area

The MuCool Test Area (MTA), located at the south end of the Fermilab Linac, is an experimental hall optimized for R&D related to muon ionization cooling: RF power is available in the hall at 201 MHz (4.5 MW) and at 805 MHz (12 MW); cavities may operate within the 44 cm warm bore (or fringe field) of a 5 T superconducting solenoid; a 400 MeV H⁻ beamline is aligned with the magnet axis; and a class-100 portable clean room is available for assembly, inspection, and servicing of sensitive components.

The cavities described in this paper are all copper standing-wave structures, operated at the MTA in the TM₀₁₀ mode and designed to address specific problems related to ionization cooling and RF breakdown. We have also built and operated cavities that are loaded with high-pressure gas, which gas suppresses RF breakdown and can serve as a cooling medium in a pressurized muon ionization cooling channel. This high-pressure RF (HPRF) technology has been successfully shown to mitigate the problem of RF breakdown and represents a possible path toward ionization cooling [4]. HPRF cavities are discussed elsewhere in these proceedings [5, 6]. The term "vacuum cavity" will be used here to differentiate between conventional, evacuated RF cavities and HPRF technology.

SURVEY OF MTA VACUUM CAVITIES

805 MHz Pillbox Cavity

The 805 MHz pillbox cavity has a gap length of 8.1 cm. RF power is coupled through an end wall via a curved coupling iris and a transition waveguide. See Figure 1. The cavity has been run recently with windows composed of grids of aluminum tubes, 1 cm in diameter and spaced 3.2 cm apart [7].

Cavities in cooling channels might be built with apertures that are closed by beryllium foils, allowing muons to pass while preserving high shunt impedance. Grid windows offer improved strength and longer average radiation length compared with beryllium. Cavity wall materials with large radiation lengths may also help to circumvent some problems associated with RF breakdown, as discussed below.

With one grid and one Cu wall, the 805 MHz pillbox has a frequency of 805.3 MHz and an unloaded $Q_0 = 1.48 \times 10^4$. With two grid walls, the frequency shifts to 801.0 MHz and $Q_0 = 1.44 \times 10^4$.

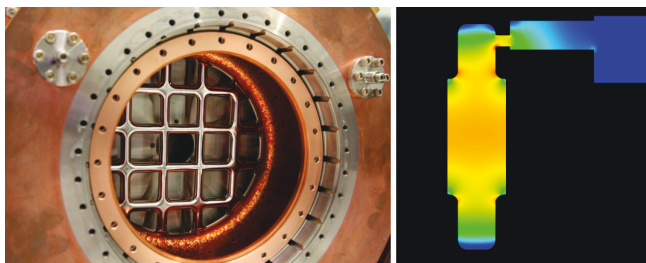


Figure 1: 805 MHz pillbox cavity with one window removed and one grid window visible (left), and simulated electric field distribution via SLAC's ACE3P code suite (right) [8].

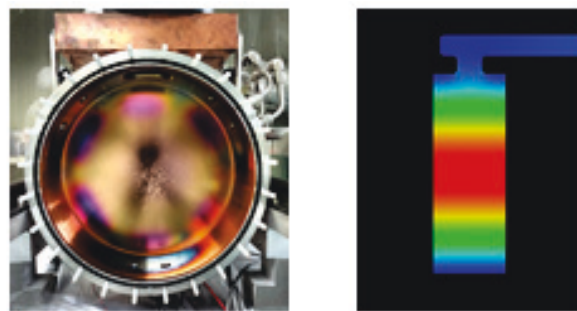


Figure 3: Modular cavity interior (left) and simulated electric field distribution via SLAC's ACE3P code suite (right).

All-Seasons Cavity

Muons, Inc. has designed a cavity to operate either under vacuum or loaded with high-pressure gas – “a cavity for all seasons” [9]. The vacuum-mode operation of the All-Seasons cavity (ASC) is discussed here.

The ASC has a gap length of 14.5 cm, a fundamental mode frequency of 810.4 MHz, and an unloaded $Q_0 = 2.8 \times 10^4$. RF power is coupled through an end wall via a coaxial transmission line. The cavity geometry and electric field distribution are shown in Figure 2. The ASC walls are stainless steel, plated with 25 μm of copper.

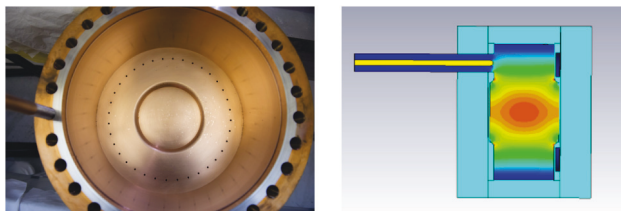


Figure 2: All-Seasons cavity interior (left) and simulated electric field distribution via CST Microwave Studio (right).

Modular Cavity

An 805 MHz pillbox was built with easily-removable end walls, in order to facilitate rapid inspection between high-power runs and to evaluate the effect of different wall materials on cavity breakdown probability. The removable walls (and other design choices) allow duplicate cavity bodies with, e.g., varying gap lengths to be fabricated relatively inexpensively. The so-called “modular cavity” is shown in Figure 3 and described in depth elsewhere in these proceedings [10].

The modular cavity has a gap length of 10.4 cm, a frequency of 804.5 MHz and an unloaded $Q_0 = 2.2 \times 10^4$. Power is coupled through an iris at the cavity equator, via a narrow waveguide. This coupling approach ensures that the on-axis surface electric field is the highest field anywhere on the cavity interior, thus minimizing the likelihood of breakdown and damage at the coupling iris (or other high-curvature regions of surface field enhancement). The cavity body and end walls are constructed with solid OFHC copper.

201 MHz MICE Cavity

The 201 MHz MICE cavity is a prototype cavity for the Muon Ionization Cooling Experiment and is discussed in depth elsewhere in these proceedings [11]. Relevant RF parameters are shown in Table 1. The large beam irises are closed with curved beryllium windows, 0.38 mm thin. The cavity walls were electropolished in order to suppress field emission and multipacting [12].

Table 1: 201 MHz MICE cavity parameters

| Parameter | Value |
|--------------------|--------------------|
| Frequency | 201.25 MHz |
| Inner diameter | 121.7 cm |
| Beam iris diameter | 42.0 cm |
| Gap length | 42.0 cm |
| Q_0 | 5.35×10^4 |

CAVITY OPERATION

Figure 4 summarizes the performance of these various cavities. Several cavity configurations – the ASC and the pillbox with ≥ 1 grid windows – fit the conceptual model of breakdown quite well for $B > 0$. The achievement of relatively constant gradients in strong magnetic fields is an important demonstration that vacuum cavities can operate stably in muon ionization cooling channels.

Two cavities demonstrate maximum achievable gradients for $B > 0$ that are considerably lower than the model predicts – the modular cavity and the 805 MHz pillbox with copper (i.e. without grid) walls. Following the model outlined in [3], the solid Cu walls in these cavities may be more susceptible to pulsed heating effects, compared with Cu-plated steel (ASC) or the grid windows. Furthermore, those cavities' shorter gap lengths relative to the ASC suggests $\sim 10 - 20\%$ greater impact energy of dark current electrons for a given accelerating voltage, exacerbating pulsed heating effects. Ongoing work in the MTA (see below) will help to resolve some of these questions.

The MICE cavity is somewhat of a special case. Its status as a prototype cavity means that no attempt was made to

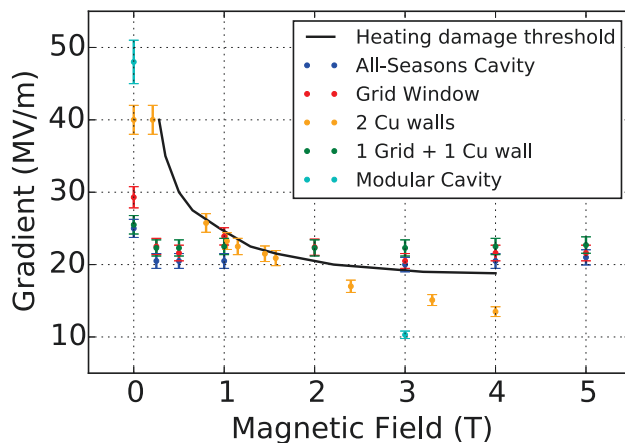


Figure 4: Gradients achieved by various vacuum cavities in the MTA, as a function of applied magnetic field. Several configurations of the 805 MHz pillbox are shown: two flat Cu walls (“2 Cu walls”), one flat Cu wall and one grid window (“1 Grid + 1 Cu wall”), and two grid windows (“Grid Window”). The black line indicates the threshold for damage due to pulsed heating and cyclic fatigue from beamlets, per [3].

determine the maximum achievable gradient during operation. Perhaps because of its intensive surface treatment, this cavity conditioned to its design gradient in zero magnetic field with no sparks. Furthermore, this cavity operated in the fringe field of the MTA solenoid ($0.1 < B < 0.3$ T, very similar to the MICE configuration) with a spark rate below 10^{-6} .

ONGOING WORK

We have fabricated beryllium end walls for the modular cavity. These walls are, at the time of writing, being coated with TiN to suppress secondary electron emission. The plates are 1.2 cm thick, with a 1 mm “window” at the center, allowing field emission beamlets to escape the cavity with minimal scattering. When these Be walls are installed on the cavity, we will be able to observe field emission beamlets directly with a Faraday cup and/or photographic plates, as described in Reference [13].

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