ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOAD2

RF BREAKDOWN OF 805 MHz CAVITIES IN STRONG MAGNETIC FIELDS*

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Abstract

Ionization cooling of intense muon beams requires the operation of high-gradient, normal-conducting RF structures in the presence of strong magnetic fields. We have measured the breakdown rate in several RF cavities operating at several frequencies. Cavities operating within solenoidal magnetic fields $B > 0.25$ T show an increased RF breakdown rate at lower gradients compared with similar operation when $B = 0$ T. Ultimately, this breakdown behavior limits the maximum safe operating gradient of the cavity. Beyond ionization cooling, this issue affects the design of photoinjectors and klystrons, among other applications. We have built an 805 MHz pillbox-type RF cavity to serve as an experimental testbed for this phenomenon. This cavity is designed to study the problem of RF breakdown in strong magnetic fields using various cavity materials and surface treatments, and with precise control over sources of systematic error. We present results from tests in which the cavity was run with all copper surfaces in a variety of magnetic fields.

INTRODUCTION

Strong, external magnetic fields have been shown to have an effect on the rate and extent of RF breakdown in normal-conducting cavities [1, 2]. The impetus for these studies was the design of ionization cooling channels for a future muon accelerator. Muons must be cooled quickly due to their relatively short lifetime. Ionization cooling – the only cooling method viable on muon-appropriate timescales – requires the operation of copper cavities in multi-Tesla external, solenoidal magnetic fields [3].

A model has been proposed to explain the effect of strong magnetic fields on RF breakdown rates [4]. In this model, field emission current from asperities (or other irregularities) on a cavity's surface is focused by the external solenoidal magnetic field into "beamlets" with current densities between 10^3 and 10^5 A/m^2 depending on field strengths, cavity geometry, etc. These beamlets may persist over multiple RF periods, causing cyclic fatigue and damage on cavity walls and contributing to an increased breakdown probability. Increases in solenoid field strength beyond some threshold value ($B \approx 0.5$ T in this context) produce negligible changes in beamlet current density due to space charge effects.

Breakdown probabilities may therefore be reduced by careful surface preparation, which reduces the number of defects causing surface electric field enhancement. Note also that the problem is mitigated by using cavity materials with long radiation lengths, such as beryllium. Low-Z materials should allow beamlets to exit the cavity without depositing energy in cavity walls and contributing to material fatigue and damage.

Breakdown behavior consistent with this model has been observed in several RF cavities. The relevant methodology and results are described here.

EXPERIMENTAL SETUP AND RF MEASUREMENTS

Work was performed at the MuCool Test Area (MTA) at the south end of the Fermilab Linac. The MTA is an experimental hall optimized for R&D related to muon ionization cooling [5]. RF power is available in the hall at 201 MHz (4.5 MW) and at 805 MHz (12 MW). RF structures can be operated at high power inside the 44 cm diameter bore of a 5 Tesla superconducting solenoid. A data acquisition system (DAQ) automates the collection of data from six oscilloscopes and a wide array of instrumentation [6]. The DAQ also detects breakdown sparks in real time by examining (a) the time derivative of a cavity pickup probe voltage signal; (b) the time derivative of power reflected from the cavity; and (c) light from a spark, transmitted through an optical fiber and detected by a photomultiplier tube. Cavities are prepared and inspected inside a class-100 portable clean room.

A spark rate of 1 in 10^5 RF pulses defines the maximum "safe" operating gradient of a cavity. Higher breakdown probabilities lead to lower cooling channel efficiencies.

The All-Seasons Cavity

RF breakdown may be suppressed by pressurizing cavities with gas, which gas can also serve as an ionization cooling medium [7]. Furthermore, for "traditional" evacuated cavities, there is some interest in studying the dependence of breakdown probabilities on cavity materials and surface preparations [4, 8]. Muons, Inc. has designed, built, and tested a cavity suitable for R&D on these various ideas – "a cavity for all seasons" [9]. The so-called All-Seasons cavity (ASC) is shown in Fig. 1. It has replaceable walls, can be pressurized up to 100 atm or evacuated to 3×10^{-8} Torr, and is fed with a coaxial power coupler.

* Work supported by Fermilab Research Alliance, LLC under Contract No. DE-AC02-07CH11359.

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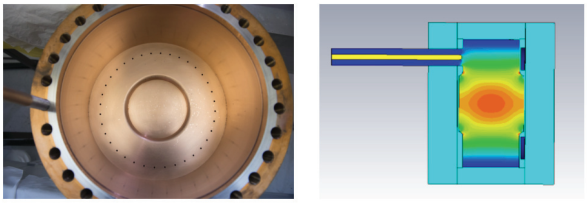

Figure 1: All-Seasons cavity interior (left) and electric field of the TM_{010} mode (right), simulated using CST Microwave Studio. Note the bolts and RF seal region in the left-hand photo.

A Pillbox Cavity with Grid Windows

As discussed above, lowering the density of material in the path of dark current and/or breakdown arcs may reduce breakdown probabilities. An implementation of this idea is to replace solid cavity walls with windows made of metal grids [10]. Figure 2 is an illustration of this concept. Water could circulate in the tubes that compose the gridded window, further reducing pulsed heating effects.

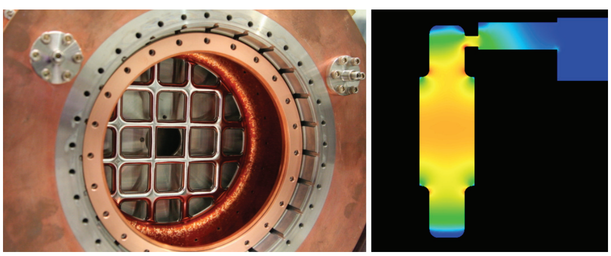

Figure 2: An 805 Mhz pillbox cavity with windows composed of a grid of tubes (left) and electric field of the TM_{010} mode (right), simulated using SLAC's ACE3P RF code suite.

This cavity design was tested in three configurations: (a) two grid windows, one on either side of the cavity; (b) one grid window opposite one solid copper cavity wall; and (c) two solid copper walls.

Results from these various cavity runs are summarized in Fig. 3. RF parameters for these cavities are listed in Table 1.

Table 1: RF parameters for the All-Seasons Cavity (ASC), the pillbox with grid windows (GW), the same pillbox with one grid window and one flat Cu wall (GWCU), and the modular cavity (MC). The modular cavity will be addressed in more detail below.

Parameter	**ASC**	**GW**	**GWCU**	**MC**
Frequency (MHz)	810.4	801.0	805.3	804.4
$Q_0/10^4$	2.8	1.44	1.48	2.2
Gap length (cm)	14.5	8.1	8.1	10.4
R/Q (Ω)	220	259	289	233

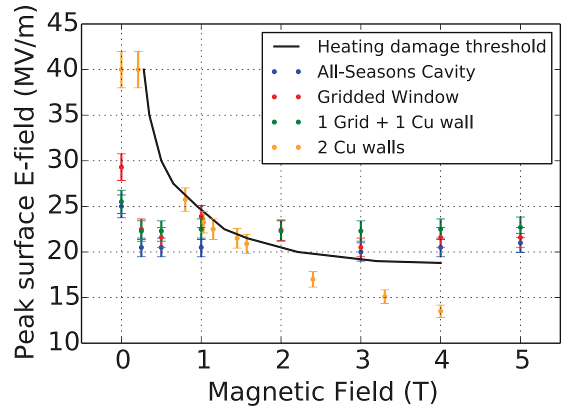

Figure 3: Peak surface electric field vs. external, applied B-field for cavity configurations described above. The black line indicates the threshold for surface fracture from beamlet heating, as discussed in [4].

ONGOING R&D

Figure 3 shows rough agreement between experimental results and the model described in [4]. Deviation from theory may be explained by (a) breakdown rates dominated by high surface E-fields in the coupler region (see Fig. 4); (b) variable conditioning histories of cavity surfaces between tests; or (c) a surplus of field emitter sites on unpolished, machined copper surfaces.

A new cavity was designed and built with the goal of greater experimental flexibility and improved control over these systematic error sources. The flat walls of the cavity are clamped into place and RF contact is made via a Cu gasket. This allows the walls to be easily removed for inspection or reconditioning of cavity surfaces. The wall material can also be changed, allowing for direct comparisons between cavity wall materials (e.g. Cu vs Be). Accordingly, this structure is referred to as the "modular cavity". RF properties of this cavity are listed in Table 1. The cavity walls have been chemically polished to reduce the density of field emitter sites. Preliminary measurements on a 201 MHz cavity in the MTA indicate that SRF-style surface preparation best practices facilitate rapid commissioning with few or no sparks [11].

Surface electric fields in the coupler region are ≥ 5 times smaller than the on-axis field of the TM_{010} mode, with the goal of reducing breakdown probability in the coupler region. Figure 4 compares this design with the couplers of the other two cavities discussed in this paper. The coupler shape was optimized to minimize resonant electron trajectories across a range of magnetic fields, as shown in Fig. 5. This design and optimization work was performed using the ACE3P RF simulation code suite [12].

In addition to conventional cavity instrumentation (vacuum gauges, thermometry, etc.) the cavity is equipped with: optical fibers to transmit light from breakdown events and their precursors for spark detection and spectroscopy; NaI crystal detectors, scintillators, and a Faraday cup to monitor

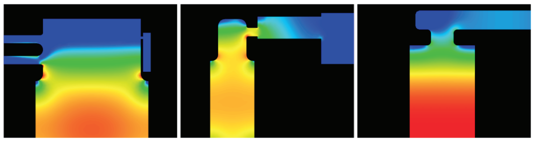

Figure 4: Simulated log-scale electric field distribution (ACE3P) for ASC (left), GW (center), and MC (right) with emphasis on the coupler region.

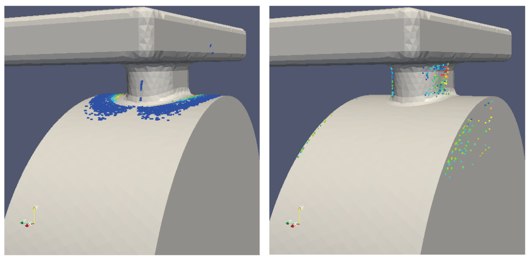

Figure 5: Resonant electron trajectories for $B = 0$ (left) and $B = 3$ Tesla (right) near the coupler of the modular cavity.

x-ray emission and darkk current; and piezoelectric transducers for the acoustic localization of breakdown arcs [13].

The modular cavity has been commissioned to 30 MV/m, accumulating almost two million pulses with a rep rate of 5 Hz and a pulse length of 30 μs. The maximum safe operating gradient has not yet been established for $B = 0$ due to anomalous saturation of the klystron's output power at 1.8 MW. Maintenance is ongoing and the modular cavity will resume running as soon as possible. Typical pulse behavior is shown in Fig. 6.

FUTURE PLANS

The influence of conditioning history can be determined using the modular cavity; its flat walls can be resurfaced and polished between runs so that direct comparisons may be made between performance at $B = 0$ and at $B > 0$.

The cavity will be run with beryllium walls in order to investigate breakdown probability dependence on materials.

At the maximum safe operating gradient for a given B-field, breakdown rates will be measured over many millions of pulses in order to better understand the time-dependence of breakdown rates in strong magnetic fields.

With beryllium walls it is possible to send beam through the modular cavity, allowing us to study its effect on breakdown rates over time.

ACKNOWLEDGEMENTS

This research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

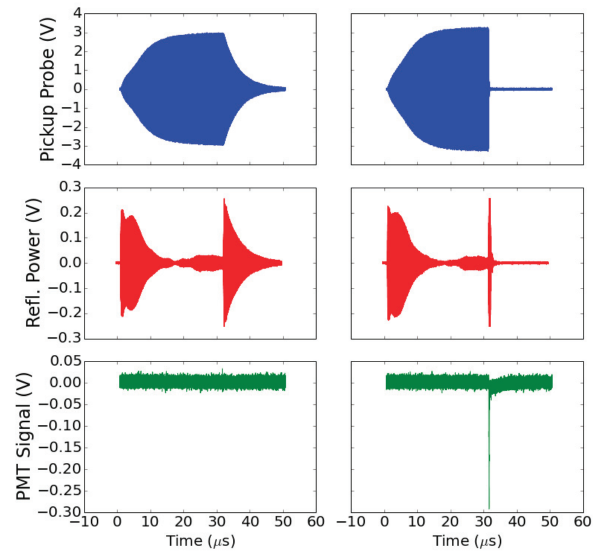

Figure 6: Waveforms recorded for the modular cavity: pickup probe voltage (blue), reflected power from directional coupler (red), and visible light via optical fiber and PMT (green). The left column shows a normal pulse, while the right column shows a pulse during RF breakdown, captured by the DAQ.

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