STUDY OF RF BREAKDOWN IN 805 MHz PILLBOX MODULAR CAVITY IN STRONG MAGNETIC FIELD

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Abstract

RF breakdown has a negative impact on a cavity's performance, especially with the presence of strong magnetic fields. This issue can arise in designs of muon ionization cooling channel, RF guns, klystrons and in many other applications. The MuCool Test Area at Fermilab is the facility that allows us to study the effects of static magnetic field on RF cavity operation. As a part of this research program, we have tested an 805 MHz pillbox "modular" cavity in strong external magnetic fields. The design of the cavity allowed for a better control over sources of systematic error. "Modular" structure of the cavity enables easy dismounting of the endplates to perform inspection of inner surfaces after each run as well as swapping endplates to study the effects of various materials on breakdown phenomenon. Coupler design ensures maximum electric field enhancement on cavity axis, thus reducing breakdown probability in the coupler region. The results and analysis from high-power runs with zero and non-zero external magnetic fields will be presented.

INTRODUCTION

Muon ionization cooling channel designs require RF cavities to be operated in strong external multi-tesla magnetic fields [1, 2]. Among other factors RF cavity performance is limited by breakdown: current discharge across a cavity accompanied by an abrupt drop in stored energy, bursts of light and x-ray emission, and a transient increase in vacuum pressure. It has been experimentally shown that breakdown rates increase to unacceptable levels in the presense of strong magnetic fields [3].

A model has been proposed which explains the role of strong magnetic fields during breakdown [4]. In the presence of a solenoidal magnetic field $\gtrsim 1$ T, field-emitted electrons are focused into "beamlets" with current densities of 10^3 - 10^5 A/m^2 at impact site. Space charge effects prevent further increase in beamlet current density above 0.5T. These beamlets persist over multiple RF cycles and, through their impact on cavity surfaces, cause pulsed heating, cyclic material fatigue, and eventual breakdown. Following this model, materials with higher radiation length might be less prone to cyclic fatigue and may therefore exhibit lower breakdown rates.

Cavity Design

The "modular cavity" (MC) was designed to investigate the effect of strong external magnetic fields on RF breakdown with low systematic error. The term "modular" here indicates that the flat end walls of the pillbox cavity can be un-mounted easily, making the process of cavity inspection simplified compared to standard cavities with single body-brazed construction. This is illustrated in Figure 1.

The cavity was designed with two 14 mm-thick copper detachable end plates. Flat copper gaskets are used to make RF contact. RF power is delivered via a flat waveguide, allowing the cavity to fit in a 44 cm diameter magnet bore. Power is inductively coupled to the cavity via an aperture that minimizes electric field enhancement. This helps to ensure that the surface electric field is highest on the cavity's longitudinal axis, thus reducing the likelihood of breakdown in the coupler region [5]. The RF properties of the modular cavity are summarized in Table 1. Error bars on resonant frequency and quality factors reflect range of measured calibration values performed on the cavity after assembly-disassebly iterations between runs.

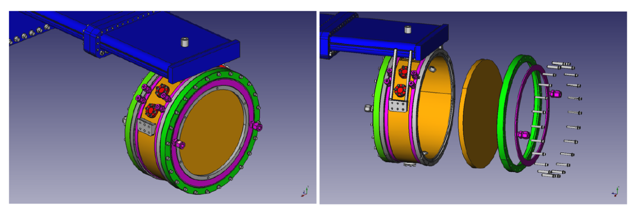

Figure 1: 3D model (left) and exploded view (right) of modular cavity.

Table 1: RF Properties of the Cavity

Parameter	Value
Frequency	804.5 ± 0.2 MHz
Q_0, Q_L	23000 ± 1000, 11000 ± 500
Coupling constant, β	0.9
Gap lenth	10.44 cm
Base vacuum pressure	3x10^{-8} Torr
Pulse length	30 µs
Stored energy at 20 MV/m	6 Joules
Typical rep rate	10 Hz

The features of the 805 MHz modular cavity allow for careful control over breakdown conditions in strong magnetic fields, as the cavity could be disassembled and inspected after each run. The goal of the modular cavity program is to build a coherent picture of the breakdown process with good statistics, low systematic error, and under conditions resembling those in an ionization cooling channel.

Instrumentation and Data Acquisition

Several oscilloscopes with sampling rate up to 20 Gs/s, providing 24 data points per RF cycle, were used to record time-sensitive signals coming from the cavity. The following "fast" data is continually recorded during operation: two pickup probes; light ports coupled to optical fibers, looking into the cavity body; scintillators and NaI detector registering X-ray radiation; and two directional couplers measuring forward and reflected RF power. Other signals monitored include vacuum pressure in the cavity; temperature of the flat walls, cooling fluid, etc.; and integrated radiation levels in the hall using ionization chambers. Additionally, the cavity was also instrumented with an array of acoustic transducers for localization of breakdown events [6].

Figure 2 shows an example of two waveforms, illustrating a normal pulse and a breakdown event. The spark detection system used to detect breakdown events implements the logical "OR" between the time derivative of the pickup probe signal (threshold value of 1 µs), an early spike in reflected power, and the presence of a strong PMT signal indicating light in the cavity.

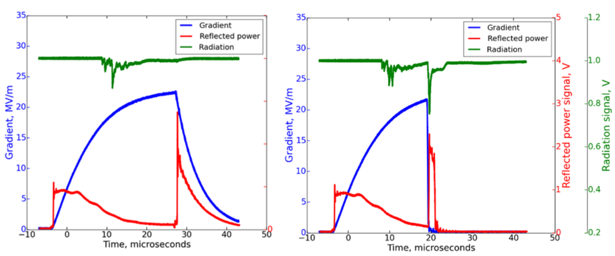

Figure 2: Envelope of pickup signal (blue), NaI radiation detector (green), reflected power (red) for normal event (left) and breakdown event (right).

Damage Inspection Process

A portable inspection system, designed for use in clean room conditions, was used to characterize breakdown damage on cavity surfaces. It consists of a flatbed scanner with maximum resolution of 10^5 pixels per mm^2 and a digital VHX-100K microscope with 200x optical zoom and 3D imaging capabilities.

The modular cavity walls are chemically polished and prepared using best practices from SRF. Additionally, the endplates are coated with a ~20 nm layer of TiN to supress secondary electron emission. Thorough inspection of inner surface of modular cavity was performed after each higpower run. Results of those inspections will be discussed below.

RF Measurements

Initial evaluations of ionization cooling channel efficiencies give the maximum allowable spark rate as one spark in 10^5 RF pulses. In this paper, the "maximum safe operating gradient" is the maximum average on-axis gradient at which the breakdown rate is smaller than 1 spark in 10^5 RF pulses. To measure the peak surface electric field, the cavity is equipped with two RF pickup loops. After each inspection RF parameters of the cavity were measured and field calibration coefficienty adjusted accordingly. The quality factor and resonant frequency measurement were consistent throughout high-power runs as shown in Table 1.

HIGH-POWER TEST RESULTS

First $B = 0T$ High-power Run

During the first high-power run in zero external magnetic field a maximum gradient of 45±5 MV/m was achieved. After the run, the flat endplates were removed and inspected. Figure 3 shows the picture of endplates on which the inspection is performed.

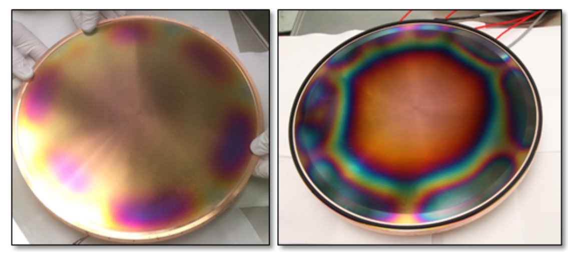

Figure 3: Interior surface of endplates. The variation in coloring is due to difference in TiN coating thickness.

Damage discovered after the first high-power run is shown in Figure 4. The damage is sub-mm in scale and appears to have very little variation in depth (less than 10 µm). No damage was observed in the input coupler region. The cause of this damage is unclear, but may have resulted from breakdown, field emission, or simply the removal of subsurface impurities during conditioning.

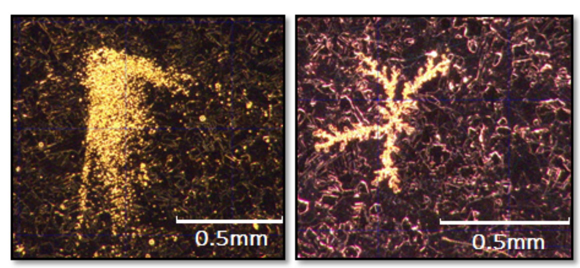

Figure 4: Typical cavity damage observed after high-power B=0T run.

First $B = 3T$ High-power Run

After establishing the baseline performance in zero external magnetic field, the cavity was tested in 3 T external field. The cavity could not reach gradients above 12 MV/m without exceeding the 10^5-pulse breakdown limit. The run was stopped for the inspection after 55 detected spark events.

168 new breakdown damage sites were observed on each flat cavity wall. Digital micrographs of typical breakdown damage sites are shown in Figure 5. All these new pits had

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round shape and diameter between 1 and 2 mm. Some of the pits have a core of burnished, apparently melted and solidified copper at their centers.

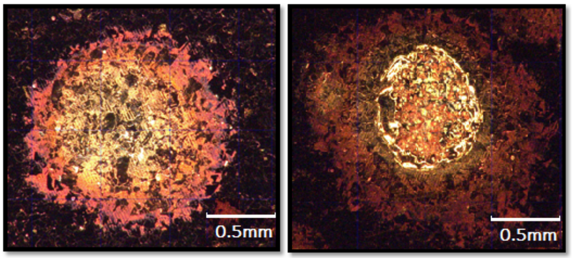

Figure 5: Microscopic images of typical breakdown "pits" with and without melted core present.

The cavity walls were scanned at 1800 dpi resolution and the coordinates of the breakdown sites were recorded. The endplates show a near-perfect mirror image of damage accumulated during this run, as shown in Figure 6. Due to our sequence of inspections we can state that all the "pits" occured during operation at $B = 3$ T. Most of breakdowns happened at gradients between 10 and 12 MV/m.

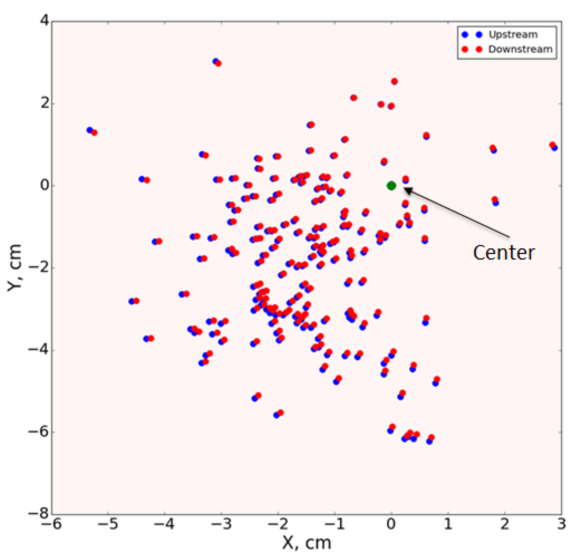

Figure 6: Map of breakdown damage from a reference point of downstream endplate, upstream coordinate are flipped in X. Red and blue dots correspond to pits on the opposing flat walls.

$B = 0T$ Conditioning Run

Inspection after the B=3 T run showed significant damage on the surface of edplates. It is likely that surface damage from previous runs caused breakdown to occur at gradients significantly lower than the first $B = 0$ run. Previous experience operating similar cavities indicates that conditioning in 0 T may help to process through defects on the surace created during high field operation and subsequently improve the performance in 3 T [7] The cavity was conditioned up to 22 MV/m after running for 7 million RF pulses and detecting approximately 450 sparks. After this run, another inspection was performed. No new damage traces were observed. Some copper spots (likely solidified splashes of liquid metal) seems to have disappeared, as shown in Figure 7.

After conditioning run, cavity was again tested in B=3T field. Safe operating gradient was esablished to be 10.2 ± 0.5MV/m.

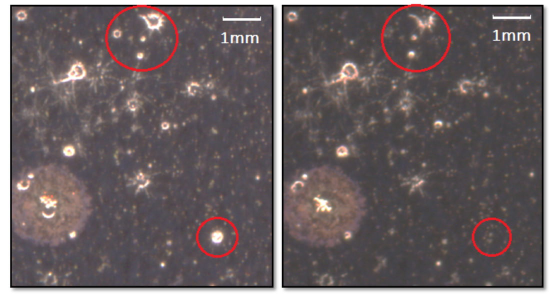

Figure 7: Copper "splashes" observed after B=3 T run (left) and the same region (right) after the subsequent B=0 T conditioning run. Disappearance of spots is highlighted.

CONCLUSION

We presented results of high-power test of pillbox Modular cavity. We demonstrated the deterioration of maximum safe operating gradient in 3T field compared to baseline zero field performance. Several inspections were performed after each run to track the correlation between damage forming processes and run conditions. Observed variance in damage characteristics between B=0T and B=3T runs indicates different energy deposition mechanisms: presence of strong external magnetic field produces more "violent" damage that prevents stable operation at high gradients. Observed perfect one-to-one correspondence between the pits on the opposing flat endplates after 3 tesla run supports the model of breakdown being induced by focused dark current beamlets inside the cavity. It is not clear why we have factor of 3 mismatch between the number of breakdown events detected and pits observed. Possible explanation may both include limitations of instrumentation used and physics involved in pit formation, analysis is ongoing.

The next steps in Modular Cavity experimental program will involve operation with Beryllium endplates instead of copper. We will test the hypothesis that Beryllium, material with smaller radiation length than copper, will ameliorate the gradient performance of the cavity in strong magnetic field. Additionally, dark current electrons passing through thin (1mm) 1-inch-diameter Beryllium window will enable us to directly measure field emission current and track surface evolution.

ACKNOWLEDGEMENT

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