RF STUDIES AT FERMILAB MUCOOL TEST AREA

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Abstract

The accelerating gradient in a RF cavity is limited by many factors such as the surface material properties, RF frequency, the external magnetic field and the gas pressure inside the cavity. In the MuCool Program, RF cavities are studied to understand these basic mechanisms with the aim of improving the maximum stable accelerating gradient of RF cavities in magnetic field. These cavities are being developed for muon ionization cooling channels for a Neutrino Factory or Muon Collider. We report studies using 805 MHz and 201 MHz RF pillbox cavities in the MuCool Test Area (MTA) at Fermilab. New results include data from buttons of different materials mounted in the 805 MHz cavity, a study of the accelerating gradient in the 201 MHz cavity and X-ray background radiation rates from the cavities due to Bremsstrahlung. The 201 MHz cavity has been shown to be stable at 21 MV/m at zero magnetic field, well in excess of its 16 MV/m design gradient. We also discuss results from the 201 MHz cavity operation in magnetic field and introduce the test of E × B effects with the 805 MHz box cavity.

INTRODUCTION

The experimental work in the MuCool Test Area (MTA) at Fermilab has been underway since 2001. The effort includes button material tests on the 805 MHz cavity with the magnetic field provided by a 5 Tesla solenoid; and 201 MHz cavity tests with 2 curved Be windows with and without magnetic field. A number of buttons made of various materials have been tested, and new results including the maximal achievable surface gradient and X-ray background as a function of magnetic field were obtained.

The orientations of E and B field play an important role in breakdown. In order to study the relationship between field emission and the orientations of the E and B field, an E × B experiment based on a new 805 MHz box cavity is planned and initial design work has been done.

805 MHz CAVITY MATERIAL TEST

The cavity material test program began in May, 2007. The goal of this program is to find materials and coatings that can withstand high surface electric field in strong magnetic field. For easy replacement of the test material in the cavity, the test materials are made into small buttons.

805 MHz Button Cavity

The 805 MHz button cavity is located inside the superconducting solenoid magnet. The magnet is designed to provide a field of up to 5 Tesla. The 805 MHz button cavity is sketched in Fig. 1, where the test button is attached on a copper flange coated with TiN.

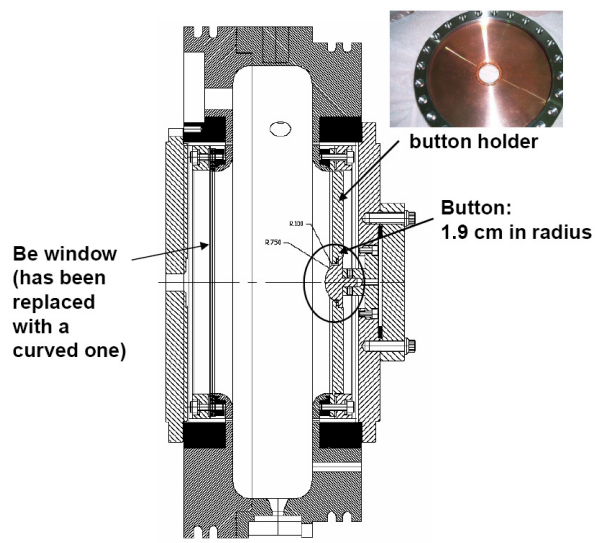

Figure 1: (Color) Layout of the 805 MHz button cavity. There is a 1.7× field enhancement factor on the button surface.

In the experiment, we observed that with thin flat Be windows, the cavity resonant frequency at high cavity fields varied from pulse to pulse by +/-30 kHz. This instability was due to the electromagnetic impulse and instantaneous RF heating and subsequent movement and oscillation of the window. Therefore, we replaced the flat Be windows with thinner (0.38mm) curved Be windows designed by W. Lau and S. Yang of Oxford University, UK to eliminate the detuning of the resonant frequency. In this configuration, the resonant frequency of the 805 MHz button system stabilized around 810 MHz, which is very close to the simulation result (~ 811 MHz).

Achievements

Since May, 2007, the button materials that have been tested so far are: a Cu button with TiN coated at Fermilab; a bare Mo button; a bare W button and two Cu buttons with TiN coated at LBNL marked as #1 and #2.

During the test in 2007, we found the Fermilab coated Cu button with TiN coating was seriously damaged with magnetic field up to 4 Tesla and electric field on the order of 30 MV/m [1]. Therefore, the test results may not be

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accurate. We then obtained two new Cu buttons with TiN coated at LBNL, and two different techniques were applied on these buttons in order to make the coating harder and smoother.

Figure 2 shows the maximal achievable surface electric gradient for various materials as a function of magnetic field. For each test, careful conditioning was done and all the data points are stable for a long period and repeatable. The curve labelled "Pillbox" refers to results with the cavity terminated by a thick Cu plate instead of the button assembly. On the plot, we can see there is a large fluctuation for the Cu button with TiN coated at Fermilab, which is assumed to be due to the loss of the TiN coating. We can also see the Mo curve is generally above the W curve, which implies Mo is able to withstand higher electric field than W, and this is consistent with the theoretical expectation.

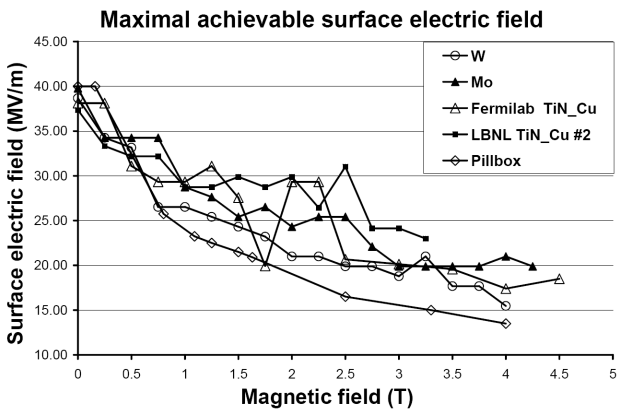

Figure 2: maximal achievable surface electric field on buttons made of various materials as a function of external magnetic field.

Another encouraging result which can be seen in Fig. 2 is that the LBNL coated Cu button #2 behaves better than all the other curves, particularly at high magnetic field, which indicates that the TiN coating can help materials to withstand higher surface electric field.

Field emission is an important issue in MICE (Muon Ionization Cooling Experiment) operation; it creates X-ray radiation from the cavity which can cause backgrounds in the tracking detectors [2]. Figure 3 shows the X-ray output from the 805 MHz button cavity detected by the MTA X-ray detector RD46 "chipmunk" (an ionization chamber), as a function of accelerating field on axis at various external magnetic field values. The log-log scale plot shows power-law growth, i.e., $\sim E^{13}$, which is consistent with the Fowler-Nordheim field emission law.

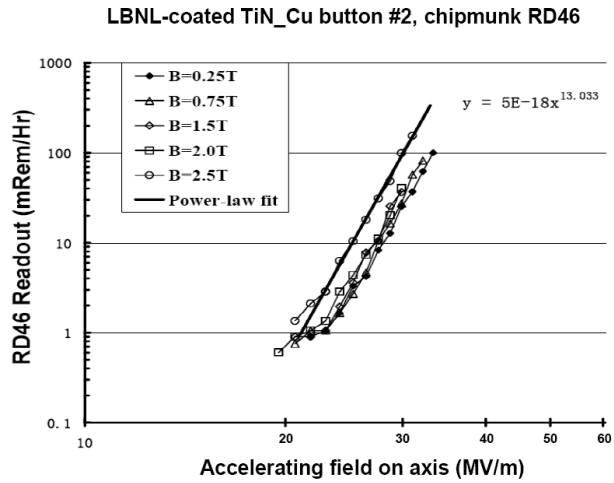

Figure 3: X-ray radiation background of the 805 MHz button cavity, detected by RD 46 "chipmunk". Readings are averaged over 20 seconds' period.

In the beginning of the muon cooling channel, a muon beam of radius on the order of ten centimeters must be accommodated; and the cooling system must run stably in a strong magnetic field. A 201 MHz cavity has been tested for this application for years. In past operations, the cavity reached 21 MV/m stable accelerating gradient on axis at zero magnetic field. More details can be found in [1]. Recently, tests in non-zero magnetic field have been carried out and are described below.

201 MHz Cavity Test in Magnetic Field

In MICE, all the accelerating cavities are placed in a magnetic field to obtain good focusing of the muon beam. In the previous tests of the 201 MHz cavity, the cavity was always placed far from the solenoid and the magnetic field there is only on the order of 10^{-3} Tesla. A large diameter coupling coil is under construction in Harbin [3] that will be used to test the 201 MHz cavity in high magnetic field. In order to test cavity behavior in magnetic field before the coupling coil arrives, we moved the 201 MHz cavity into the fringe field of the magnet. This configuration is shown in Fig. 4.

The primary goal of this test was to confirm whether the 201 MHz cavity could run stably at the design gradient of 16 MV/m in a magnetic field of a few Tesla. Other specifications to be tested/confirmed are [4]: peak input RF power ~4.6 MW per cavity; average power dissipation per cavity ~8.4 kW; average power dissipation per Be window ~100 W. With the cavity moved close to the magnet, the maximal magnetic field at the Be window near the solenoid would be 1.5 Tesla if the peak magnetic field on axis inside the solenoid is 5 Tesla. However, the magnetic field in the solenoid was limited to less than 4.2 Tesla due to quench issues.

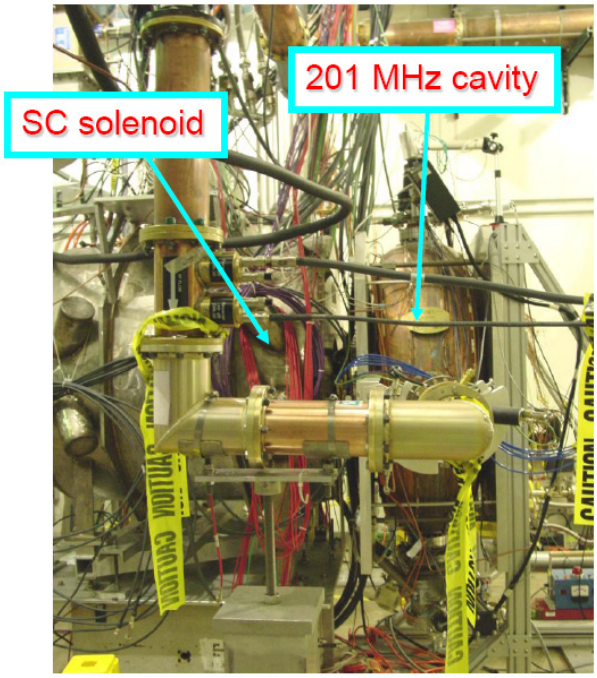

Figure 4: (Color) The 201 MHz cavity inside the fringe field of the solenoid.

Results

We achieved 14 MV/m accelerating gradient at 0.37 Tesla in the center of the 201 cavity. Figure 5 shows the X-ray background from the 201 cavity, which can be used to estimate the MICE X-ray background.

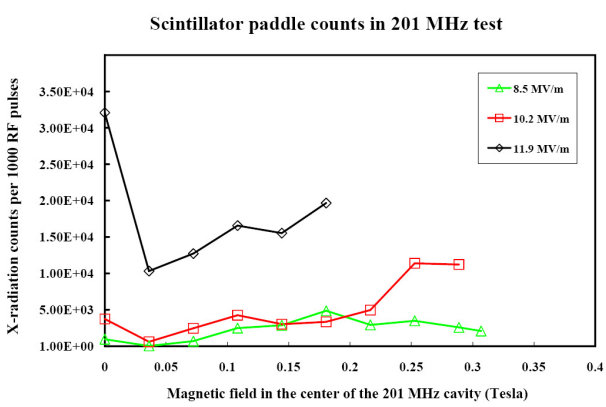

Figure 5: (Color) X-ray background of the 201 MHz cavity, detected by a scintillator paddle detector, which is about 5 meters from the center of the cavity. The high rates at low magnetic field are due to strong multipacting.

E × B EXPERIMENT

In one breakdown model [4] (Fig. 6), the surface electric field introduces a field emission current, and when there is an angle between the current and the magnetic field, there will be a torque acting on the field emitter. At high gradients, this torque can be strong enough to break the field emitter and produces plasma under bombardment of field emission electrons. The plasma can be the trigger of breakdown. Therefore, the relative orientation of the electric and magnetic fields play a critical role in RF breakdown. In order to explore this effect in a controlled setting, a separate E × B experiment is planned.

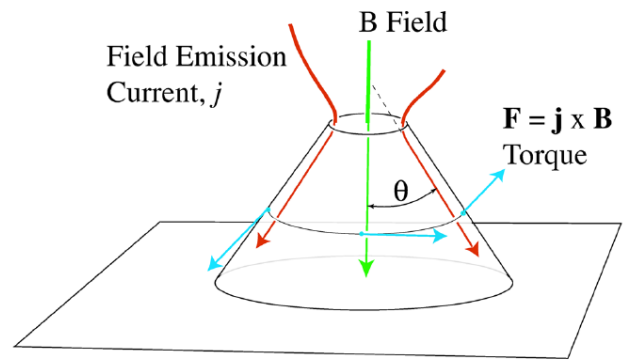

Figure 6: (Color) Torque on the field emitter due to angle between E and B field.

A new rectangular 805 MHz "box" cavity was designed to do this study; the orientation of the cavity (and therefore the electric field in the cavity) can be varied with respect to the external magnetic field to study the effect on cavity gradient. Figure 7 is the schematic of this configuration. The range of the angle between accelerating and magnetic field is 90±15 degrees.

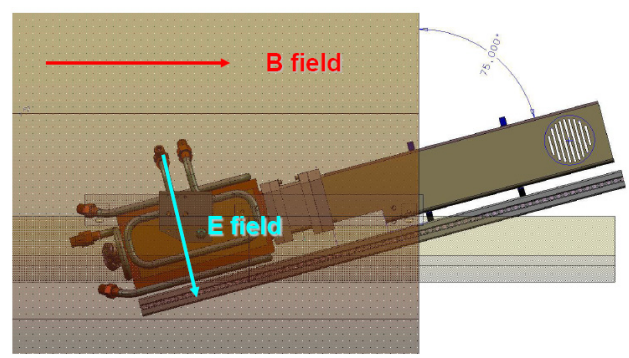

Figure 7: (Color) Schematic of E × B study layout with the new 805 MHz rectangular box cavity.

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