EFFECT OF HIGH SOLENOIDAL MAGNETIC FIELDS ON BREAKDOWN VOLTAGES OF HIGH VACUUM 805 MHz CAVITIES

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Abstract

There is an on going international collaboration studying the feasibility and cost of building a muon collider or neutrino factory [1,2]. An important aspect of this study is the full understanding of ionization cooling of muons by many orders of magnitude for the collider case. An important muon ionization cooling experiment, MICE [3], has been proposed to demonstrate and validate the technology that could be used for cooling. Ionization cooling is accomplished by passing a high-emittance muon beam alternately through regions of low Z material, such as liquid hydrogen, and very high accelerating RF Cavities within a multi-Tesla solenoidal field. To determine the effect of very large solenoidal magnetic fields on the generation of dark current, x-rays and on the breakdown voltage gradients of vacuum RF cavities, a test facility has been established at Fermilab in Lab G. This facility consists of a 12 MW 805 MHz RF station and a large warm bore 5 T solenoidal superconducting magnet containing a pill box type cavity with thin removable window apertures. This system allowes dark current and breakdown studies of different window configurations and materials. The results of this study will be presented. The study has shown that the peak achievable accelerating gradient is reduced by a factor greater than 2 when solenoidal field of greater than 2 T are applied to the cavity.

INTRODUCTION

The concept of a Muon Collider has been under study internationally for a number of years. High intensity muons are produced from a high-energy high-intensity proton beam hitting a high Z material. Pions are captured and subsequently decay into muons. The capture section consists of a high Z target surrounded by a very high solenoidal capture field of several T. This produces a muon beam of very large 6-D phase space. In order to produce muon beams of high enough quality to be used for a collider, this large phase space must be cooled several orders of magnitude and done quickly, because of the short life time of the muon. Ionization cooling can accomplish the task of cooling the muon beam many orders of magnitude. Ionization cooling consists of passing a high-emittance muon beam alternately through regions of low Z material, such as liquid hydrogen, and very high accelerating RF Cavities within a multi-Tesla solenoidal focusing channel. As the particles pass through the low Z material, they lose momentum in 3-D phase space. The longitudinal component (accelerating frame) is then restored by the RF cavities. This is repeated many times to produce a beam of the quality required for a collider. Although not necessarily required, muon ionization cooling can be used to improve the performance of a neutrino factory.

A key element of the feasibility study is the demonstration of ionization cooling. The Muon Ionization Cooling Experiment, MICE [3], has been proposed and is being planned to demonstrate 10 % cooling which will be enough to validate the technology. This experiment is an international collaborative effort with the US, Europe and Japan as the principle partners. This experiment is planned to take place at Rutherford Appelton Laboratory in England.

Important to any demonstration of muon ionization cooling is the accelerating cavity technology. For the past three years, studies of the limitations of very high electric field gradients in linac type vacuum RF cavities have been taking place in a test facility in Lab G at Fermilab. The purpose of the facility is to determine the effect of very large solenoidal magnetic fields on the generation of dark current and x-rays and its effect on the breakdown voltage gradients of vacuum RF cavities. This facility allows us to test methods and materials to increase the breakdown limit and reduce dark current emissions. Increasing the achievable accelerating gradient would reduce one of the major cost drivers of a future collider or neutrino factory.

THE LAB G TEST FACILITY

The Lab G facility consists of a Fermilab upgrade Linac modulator and controls, a 12 MW pulsed klystron and its waveguide system, a 5 T superconducting magnet with a large warm bore for cavity insertion, cooling water and high vacuum systems for the test cavity and a radiation shielded interlocked test cave. Figure 1 shows a picture of the 5 T superconducting solenoid with the first test cavity (an open cell cavity) being tested in the facility [4]. At its ends are shown thin 125 μm Ti vacuum windows for dark current and x-ray measurements. The facility permits research and development on methods and materials to increase the breakdown limit and reduce dark current emissions. It also allows us to test RF components and qualify RF technology for a future muon collider, neutrino factory or MICE .

The arrangement for the second set of measurements on the LBL Pill box cavity is shown in Figure 2. The single cell LBL cavity is shown in the center of figure 2, [5,6]. It has been designed with removable vacuum end pieces. This arrangement was chosen so that a variety of window configurations and materials could be tested rapidly for

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their breakdown limit and dark current emission. There is a thin 125 µm Ti thick window at the downstream end of the cavity for dark current measurements. [Note: the solenoid has two separate coils. They can be powered to add field (solenoid mode), in opposition (gradient mode), or one coil alone (single coil mode).]

EXPERIMENTAL RESULTS ON THE LBL SINGLE CELL CAVITY

The chart, Figure 3, presents the breakdown limit versus magnetic field results from about a 2 year period of study. The graph shows the limit above which surface damaging sparks occur during a relatively short RF commissioning period of time. Spending long periods, hours, above this limit results in a very large permanent increase in dark current and x-ray emissions. The graph shows the safe gradient operating limit in a magnetic field. Operating near this or at this limit results in little increase in dark current and x-ray emissions over time. The data were taken with the three magnetic field configurations as parameters and are plotted as a function of the field level at the window. This shows that the breakdown limit is strongly correlated with the value of the magnetic field at the site of the window. It also shows a reduction in the breakdown limit of greater than a factor of two above 2 T.

Examination of the damage by SEM and optical microscope showed molten copper disks 100 to 125 µm in diameter scattered over the Be window surface, Figure 4. There was no spark damage observed in the Be or in the TiN coating of the window. Spark damage was only observed in the copper parts of the cavity. The SEM analysis of the molten copper spots indicate they were mainly composed of copper with just a small trace of other elements. Other studies with copper windows inserts were observed to behave in a similar manner. This demonstrates that copper is the weak link in reaching high gradient in large magnetic fields and that Be has a greater intrinsic breakdown limit. It would be impractical and extremely expensive to build the accelerating cavity entirely out of Be. A major portion of the cavity still needs to be made of copper. A research effort is being planned to find a coating that can protect and therefore greatly enhance the breakdown limit of copper.

Figure 5, shows typical x-ray level measurements as a function of gradient without magnetic field over a period of one month. Time starts with the top curve and ends 30 days later at the bottom curve. This demonstrates an observation of a curing effect. As the RF commissioning time goes on, the x-ray levels go down as long as the breakdown limit is not exceeded. However, as soon as a damaging spark occurs, the x-ray emission greatly increases and never recovers to the previous low background level even with continuing RF commissioning. It should be observed that the curves end just below the breakdown limit. This seems to demonstrate that breakdown is determined by the dark current emission near or at breakdown and no matter at what level it starts out ii reaches the same limit point.

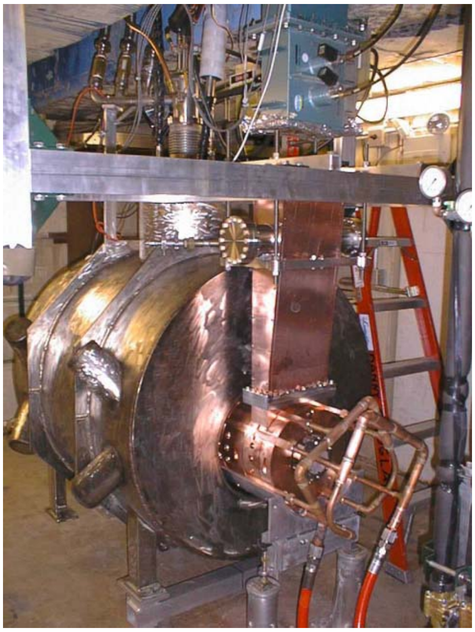

Figure 1: Picture of the open cell test cavity in the Solenoid.

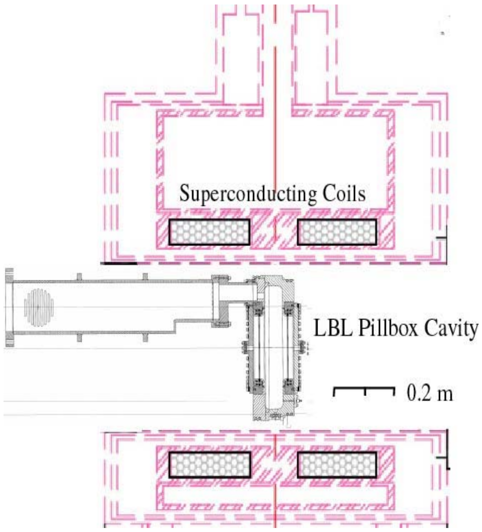

Figure 2: The single cell cavity in the superconducting 5 T solenoid.

Figure 6, shows typical x-ray level measurements as a function of gradient with the magnetic field as a parameter for three field levels. The magnetic field levels increase from bottom to top. This demonstrates a large increase in x-ray levels with increasing magnetic field at lower gradient levels. The x-ray background levels are also higher than without magnetic field because of the focusing effect of the magnet. As the RF commissioning time goes on, the x-ray levels go down as long as the breakdown limit is not exceeded. However, as soon as a damaging spark occurs, the x-ray emission greatly increases and never recovers to the previous low, even after long RF commissioning runs.

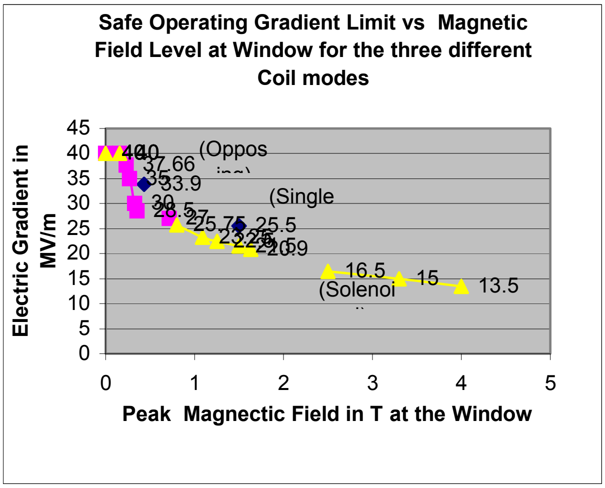

Figure 3: Safe operating electric gradient for the three different coils excitations. Operating above these limits produced damaging sparks that produce large increases in x-ray levels which never fully recover.

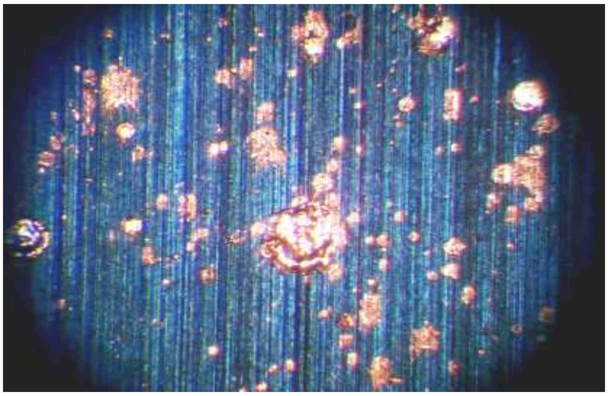

Figure 4: Copper Splatter on Be Window

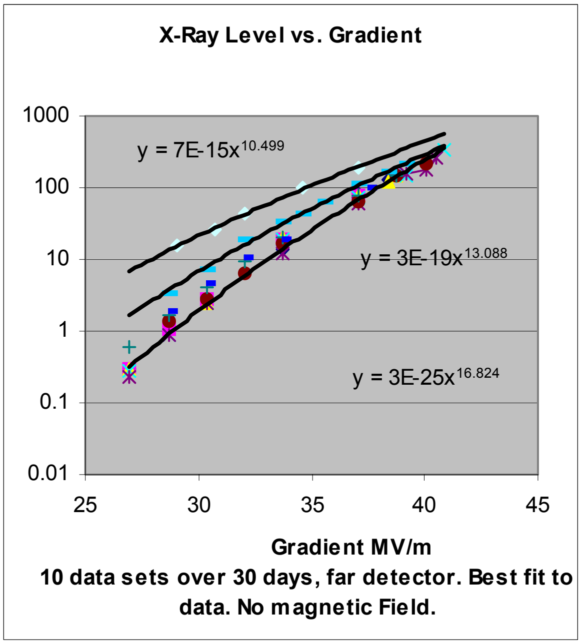

Figure 5: X-ray level in far detector 3 m away from the cavity [vertical scale mrem/hr].

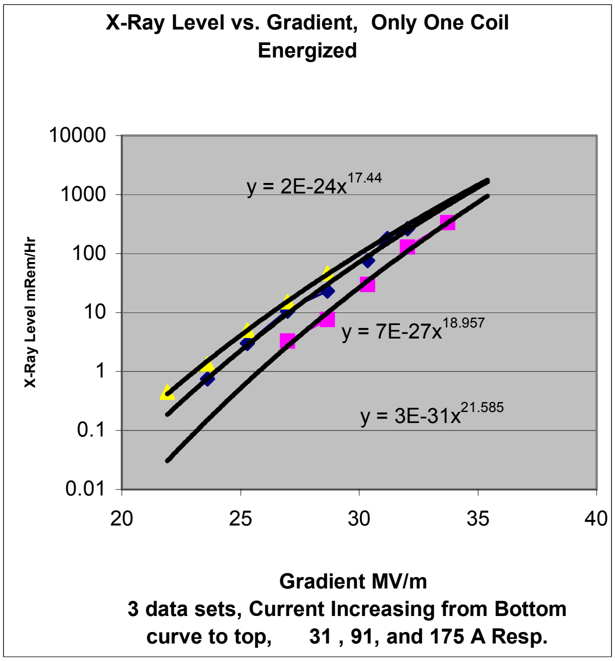

Figure 6: X-ray level in far detector 3 m away from the cavity with magnetic field levels of 0.3 T, 0.91 T and 1.7 T respectively.

SUMMARY AND FUTURE PLANS

A two year study of the breakdown limit of the LBL single cell cavity with large applied solenoidal fields has been completed. The early studies were conducted with copper window inserts and the later studies were done with thin Be windows coated with TiN to suppress multipactoring. In general the breakdown limit is much lower when a solenoidal magnetic field is applied. In addition the dark current and x-ray emissions are much larger after the occurrence of sparking at very high electric and magnetic field levels (above the safe limit curve shown in Figure 3). Even after long RF commissioning runs, the cavity does not return to the previous recorded low background level. The Lab G facility has been recently shut down and the equipment is being moved to the new Fermilab MuCool Test Area (MTA) Figure 7, [7]. Figure 8 shows the high power 805 MHz and 201 MHz transmission lines at top of linac shielding being installed to the MTA.

A modification of the cavity which will allow for the insertion of small button size sample pieces has been designed and is under construction. This will allow for more rapid testing of various materials and coating processes. Materials under consideration for study are chromium, tungsten, and molybdenum [8].

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Figure 7: Picture of the MTA at the south end of the Fermilab linac.

Figure 8: Picture of the high power 805 MHz and 201 MHz transmission lines at top of linac shielding being installed to the MTA.