GASEOUS HYDROGEN FOR MUON BEAM COOLING[1]

R. P. Johnson, R. E. Hartline, Muons, Inc., Batavia, IL 60510
C. M. Ankenbrandt, M. Kuchnir, A. Moretti, M. Popovic, Fermilab, Batavia, IL 60510
M. Alsharo'a, E. L. Black, D. M. Kaplan, Illinois Institute of Technology, Chicago, IL 60616

Abstract

Muons, despite their short lifetime, have an advantage in that they can be accelerated through matter without suffering appreciable scattering as do strongly interacting protons or electromagnetic showering as do less massive electrons. Thus RF cavities filled with dense gas to suppress electrical breakdown can provide high gradients for relatively short muon ionization-cooling channels for Neutrino Factories and Muon Colliders. Hydrogen gas, with large dE/dx, radiation length, and heat capacity, also acts as the perfect energy absorber having several engineering advantages. The progress of a DOE STTR grant project to develop high-pressure high-gradient RF cavities is described. First measurements of RF breakdown curves are reported, where stable operation was achieved with surface gradients of 50 MV/m for hydrogen and 28 MV/m for helium.

INTRODUCTION

The development of liquid hydrogen energy absorbers and RF cavities for ionization cooling of muon beams has been underway for some years by members of the Neutrino Factory and Muon Collider Collaboration, NFMCC [2]. These efforts will lead to a Muon Ionization Cooling demonstration Experiment, MICE [3]. Last year a new initiative started to study an alternative to the NFMCC-MICE technique for ionization cooling [4]. Muons, Inc, in partnership with IIT, has been funded by a Small Business Technology Transfer (STTR) grant to develop high gradient RF cavities that are filled with a dense gaseous energy absorber that also suppresses RF breakdown as described by Paschen's Law [5].

A dense gaseous energy absorber enables an entirely new technology to generate high accelerating gradients for muons by using the high-pressure region of the Paschen curve. Electrical breakdown is suppressed in this case because the mean free path for an ion in a dense gas is so short that collisions prevent acceleration to high-enough energy to create an avalanche. This idea of filling RF cavities with gas is new for particle accelerators and is possible only for muons because they do not scatter as do strongly interacting protons or shower as do less-massive electrons. Multiple Coulomb scattering is important, though, so a long scattering length is beneficial.

In this application, hydrogen gas is twice as effective as helium, the next best gas [4]. The use of a gaseous absorber presents other practical advantages [6] that make it a simpler and more effective cooling method compared to the liquid hydrogen flasks used in the NFMCC and MICE designs. Also, a new idea for six-dimensional cooling using gaseous hydrogen has been proposed [7].

LAB G TEST CELL

Phase I of the STTR grant was to build an 805 MHz RF test cell (TC) and to use it at Lab G at Fermilab to measure breakdown characteristics of helium gas at high pressure and at liquid nitrogen temperature. Figure 1 shows a cross section schematic of the prototype TC used for the initial tests at Lab G. The top and bottom discs of the pillbox design are standard 12" diameter stainless steel (SS) Conflat blanks commonly used for vacuum applications. These are strong and relatively inexpensive, with replaceable copper gaskets that did not work in this high-pressure application. Instead, the gaskets were replaced with rings of lead-tin solder in special grooves.

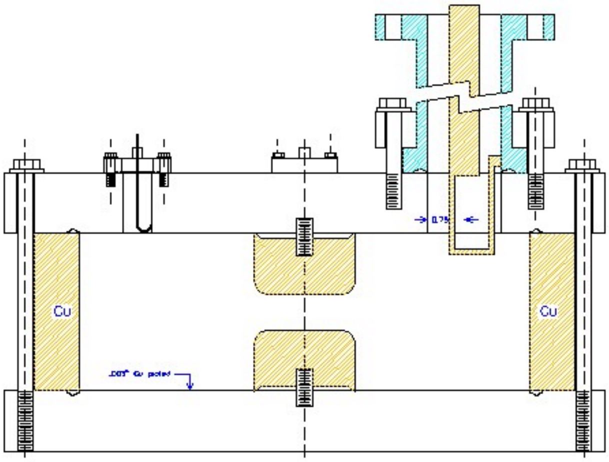

Figure 1. Test Cell Schematic. The ID is 9 inches, the internal height 3.2 inches, and the electrode gap is 2 cm.

The cylindrical wall of the pillbox is made of copper to ensure good thermal conductivity between the contained gas and a liquid nitrogen bath surrounding the TC. Stainless steel bolts hold the copper cylinder between the two SS disks. Stainless steel and copper are used in this application because they have almost identical coefficients of thermal expansion. This feature reduces the design complications, making the interfaces effectively static problems and the bolt tensions almost independent of temperature.

The 30-inch long SS coaxial RF feed shown in figure 1 allowed the pressure barrier to be well above the LN2 bath where it did not suffer thermal variations. This allowed a simple barrier design where the central conductor was epoxied in place. The power feed and probe used for the measurements described below were

0-7803-7739-9

not loop-couplers as shown in the schematic, but capacitive stubs.

A network analyzer was used to measure the Qo and calibrate the pickup probe at room temperature and at liquid nitrogen temperature. Calibrated directional couplers were used to measure the forward and reflected RF power. The program SuperFish was used to calculate the ideal Qo and shunt impedance of the cavity from which the power for a given gradient was calculated. One could easily determine the TC resonant frequency by maximizing the amplitude of the signal from the probe as a function of the klystron pulse generator frequency.

The TC had a measured Q_o of 25,300 at 77 K and 13,600 at room temperature. The calculated room temperature Q_o for the TC was 19,200. The measured room temperature Q_o is about 30 % lower than calculated. This, however, is within the expected normal range for cavities that are bolted together. One normally comes within 5 % of calculation with high purity copper cavity brazed or electron-beam welded together and with only a few small ports.

The Q_o improved a factor of 1.86 at 77 K compared to room temperature. The resistance ratio for pure copper over this temperature range is 8. This corresponds to an expected Q_o improvement factor of 2.82 for highly purified copper since Q is inversely proportional to the square root of the resistivity. However, the TC was not constructed solely of high purity copper. The outside cylinder of the TC was made of high purity copper but the end plates were made of copper plated stainless steel. The lead-tin solder seal between the copper plated disks and the copper cylinder may have had a larger effect on the Q than the plating material, however, but remains to be investigated.

Figure 2. Twelve-inch-diameter Copper-plated stainless-steel Conflat disk and electrode.

Figure 2 shows a picture of the bottom disk and one doorknob electrode just before the TC was assembled to measure hydrogen breakdown for the first time. The shape of the electrode was made more hemispherical than shown in the schematic to match the TC frequency to that of the klystron. All internal SS surfaces were plated with copper to improve the cavity quality factor and reduce RF heating. At 800 MHz, the skin depth is 2.7 microns so that any plating of at least 10 microns is sufficient.

Because of the use of high-pressure hydrogen, safety issues were a major concern. The Test Cell Document [8] prepared for the Fermilab Liquid Hydrogen Target Safety Panel contains the required engineering note, flammable gas analysis, and oxygen deficiency analysis.

HELIUM DATA

Figure 3 shows the breakdown voltages for the test cell with helium gas at liquid nitrogen temperature as a function of pressure. The dark diamonds were obtained by first raising the klystron power until breakdown occurred, then slowly lowering the power until the pulses were clean, with no breakdown over a few minute period. The light squares show the resonant frequency of the cavity (MHz). The RF frequency is a sensitive measure of the pressure. A close examination of the frequency point at 315 PSIG shows the pressure is set incorrectly and the actual pressure was 345 PSIG, which explains why that gradient point seems high.

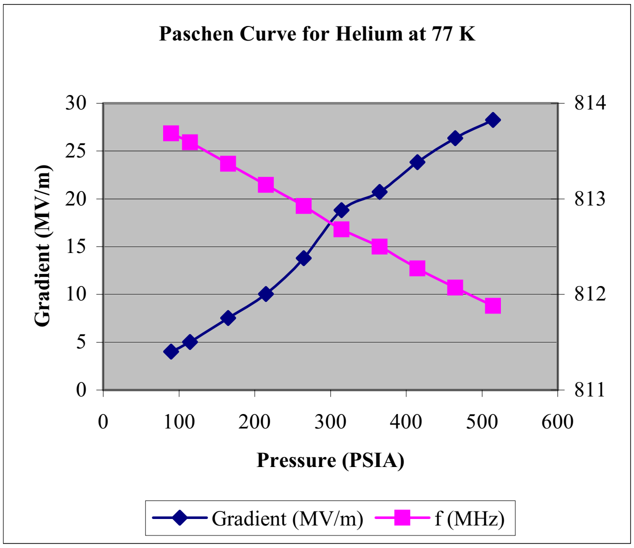

Figure 3. Maximum stable RF gradient (dark) for helium at liquid nitrogen temperature and cavity frequency (light) as a function of pressure. The dark Paschen curve was the proof of principle goal of the STTR phase I project.

The data seem to follow the linear increase with gradient expected by Paschen’s Law up to a value useful for muon cooling applications.

HYDROGEN DATA

On April 11, the use of hydrogen gas in the Lab G environment was authorized. After 3 hours of conditioning at 450 PSIG at 77 K the maximum gradient increased from 35 MV/m to over 55 MV/m. Another 5 hours of conditioning did not improve the maximum gradient and may have made it worse. At that point the dark points in figure 4 were taken. After raising the voltage until breakdown occurred, the dark colored diamonds were obtained by then slowly lowering the power until the RF ran stably, without sparking.

The previous data measured in 1948 [9], shown in figure 4 as light colored squares, have a maximum of 28 MV/m at 23 atmospheres at room temperature and DC conditions. In figure 4 the pressures of these data have been scaled to 77 K for comparison.

The new data show the same Paschen's Law behavior as the helium data, where the maximum stable gradient increases almost linearly with pressure, up to 170 PSIA. In the hydrogen case, however, the rate of increase of the maximum gradient diminishes once the gradient reaches 50 MV/m, presumably due to breakdown at the electrode surface.

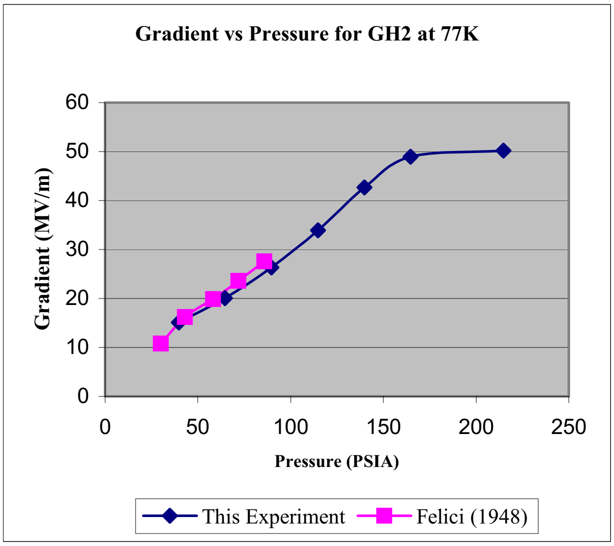

Figure 4. Measured maximum stable RF gradients for hydrogen gas at LN2 temperature compared to the DC breakdown gradients of Felici and Marchal (1948).

The pressurized test cell required RF conditioning that is usual for evacuated cavities. That is, the application of many breakdown discharges usually allows higher and higher voltages to be attained. The breakdown above 170 PSIA in figure 4 is dominated by gradient at the surface of the electrodes and the qualities of the electrodes rather than the gas itself. One possibility is that above 50 MV/m the power in the discharges is sufficient to cause damage to the electrodes rather than the polishing action seen in most RF conditioning. Examination after this run of the TC electrodes, initially prepared with 1500 grit sandpaper and cleaned with alcohol, showed no visible surface imperfections. However, it may be difficult to see the difference between a surface that holds off 55 MV/m and one that holds off 50 MV/m. In the future we will examine the detailed behavior of the breakdown above 170 PSIA, where the maximum gradient seemed to deteriorate with conditioning time rather than improve.

CONCLUSIONS

This study has extended the range of possibilities for muon cooling. Measurements have been made of high-gradient RF in dense gases near 805MHz, a viable frequency for muon ionization cooling. A cryogenic technique has been used to achieve high gas density.

RF breakdown and stability levels for hydrogen gas have been measured at the highest density to date. The maximum stable gradients of 50 MV/m for hydrogen and 28 MV/m for helium are high enough to be very interesting for cooling channels with these continuous gaseous absorber materials.

REFERENCES

[1] This work is supported in part by US DOE grant DE-AC02-ER86145 and by the Illinois HECA grant to the Illinois Consortium for Accelerator Research.

[2] M. Alsharo'a et al., Status of Neutrino Factory and Muon Collider Research and Development and Future Plans, submitted to Phys. Rev. ST Accel. Beams, e-Print Archive: hep-ex/0207031 (2002).

[3] Proposal to the Rutherford Appleton Lab: An International Muon Ionization Cooling Experiment (MICE), The MICE Collaboration. January, 2003 http://hep04.phys.iit.edu/cooldemo/micenotes/public/pdf/MICE0021/MICE0021.pdf

[4] R. P. Johnson et al., Gaseous Hydrogen and Muon Accelerators, in International Workshop on Hydrogen in Materials and Vacuum Systems, Edited by G. Myneni and S. Chattopadhyay, AIP Conference Proceedings 671, Melville, New York, 2003.

[5] Sanborn C. Brown, Basic Data of Plasma Physics, The Fundamental Data on Electrical Discharges in Gases, American Vacuum Society Classics, AIP Press, 1993, p 149.

[6] R. P. Johnson and D. M. Kaplan, A Gaseous Energy Absorber for Ionization Cooling of Muon Beams.MUC/NOTE/COOL_EXP/PUBLIC/195 March, 2001.

[7] Ya. Derbenev and R. P. Johnson, Six-dimensional muon beam cooling in a continuous, homogeneous, gaseous hydrogen absorber, COOL03, May 2003, RIKEN, Japan. To be published in NIMA.

[8] R. E. Hartline et al., Lab G RF Test Cell Construction, Operation, Safety, and First Results, munote-001 5/06/03. http://members.aol.com/muonsinc/TC.pdf

[9] Meek and Craggs, "Electrical Breakdown in Gases", John Wiley & Sons, 1978, p. 557.