STUDIES OF RF BREAKDOWN OF METALS IN DENSE GASES*

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Abstract

A study of RF breakdown of metals in gases has begun as part of a program to develop RF cavities filled with dense hydrogen gas to be used for muon ionization cooling. A pressurized 805 MHz test cell is being used at Fermilab to compare the conditioning and breakdown behavior of copper, molybdenum, chromium, and beryllium electrodes as functions of hydrogen and helium gas densities. These results will be compared to the predicted or known RF breakdown behavior of these metals in vacuum.

INTRODUCTION

Muons provide clear advantages to electrons and hadrons in a collider. As compared to an electron collider, their rest mass, $m_\mu=207m_e$, provides more center of mass energy for particle production. Furthermore, their mass greatly reduces the synchrotron radiation, thereby reducing the energy loss in accelerating the beam. The advantage in using muons over hadrons in a collider is the greatly reduced background due to the lack of spectator partons which partake in the collisions.

The disadvantage, of course, is the finite lifetime of muons, $\tau_\mu=2.2\mu s$. This drawback, though not insurmountable with time dilation, creates technical challenges which include the simultaneous rapid cooling and rapid acceleration of the beam. Cooling is required because muons are most copiously generated from hadroproduction of pions and kaons which subsequently decay to muons. This process results in a muon beam which is generated with an inherently large emittance. A bright beam therefore requires significant cooling to reduce the requisite number of protons, as well as to reduce the emittance of the beam to match the acceptance of an affordable machine. Due to the short lifetime of the muon, the only suitable method for this is ionization cooling [1].

The second technical challenge is the rapid longitudinal acceleration of the muon beam by increasing the gradient in the RF cavities. A novel idea being tested by Muons, Inc, is to take advantage of Paschen's Law to increase the gradient in the cavities by use of dense gas.

Present activities of Muons, Inc are to demonstrate both the physics and the engineering feasibility of the special components required in the construction of a muon collider. Much of the work to study the physics is performed by simulations, and can be viewed in these proceedings. This paper discusses one of the components, the experimental studies of high pressure RF cavities.

* Work supported by the U.S. DOE STTR grant DE-FG02-02ER86145.
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HIGH PRESSURE RF CAVITIES

In 1889, F. Paschen [2] published the results of his work on suppression of breakdown of gases in high electric fields. What later became known as Paschen's Law states that the breakdown voltage is a function of gap length, d, and gas density, ρ, such that $V=V(d,\rho)$. Paschen's Law predicts that for a given geometry, gases will break down above a particular voltage for a particular gas density; this implies that each gas has its own Paschen curve.

In air, the Paschen curve is shown in Figure 1 [3], where the maximum voltage is shown to rise in a vacuum, where RF cavities are normally run. One can also see that breakdown is also suppressed at higher gas densities. It is in this regime that Muons Inc proposes to test its RF cavities.

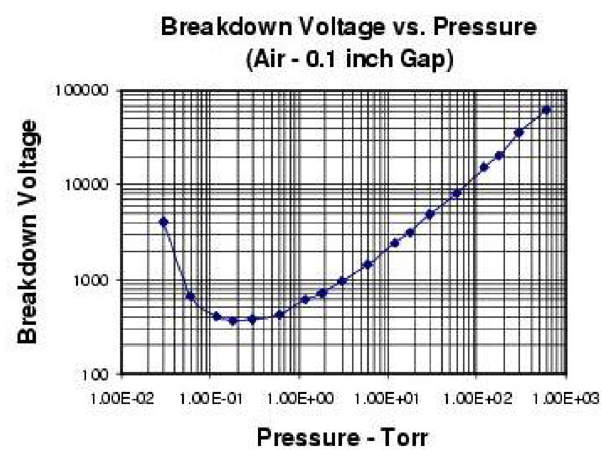

Figure 1: Paschen Curve for air.

There are three advantages for operating RF cavities with dense gas: (1) suppression of gas breakdown allows the cavities to be run at higher gradients, (2) the dense gas serves as an absorber for cooling the muon beam, and (3) the gas itself can be flowed and used as a refrigerant to remove the heat dissipated in the cavities. Note that high pressure RF cavities are only viable for muons, since hadrons would interact strongly with the gas.

A series of three tests are planned to be performed a the **M**uCool **T**est **A**rea, or MTA, at Fermilab: (1) material test to determine the highest achievable gradients, (2) operational tests inside the field of a solenoid magnet, and (3) operational tests in the presence of ionizing radiation.

The first of the tests is described in this paper. Paschen's Law only applies to the breakdown of gas, so it remains necessary to test for the optimal material from which to make or plate the cavities. For both H_2 and *He*, we will test electrodes of copper, beryllium, molybdenum, and plated chromium. These materials are selected as candidates for RF cavities based on work of P. Wilson [4]. A diagram of the expectations is shown in Figure 2.

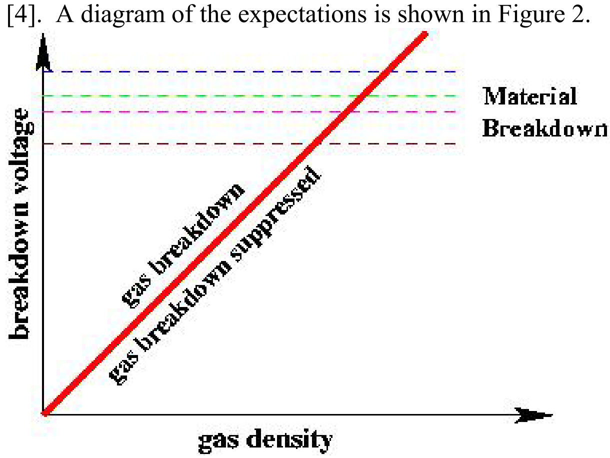

Figure 2: Expected results for material testing of RF cavities. The solid line represents the Paschen curve for a single gas. The dashed lines represent the different materials to be tested.

EXPERIMENTAL APPARATUS

The experiment at the MTA is performed with a simple pillbox cavity as shown in Figure 3. The cavity is a *9 in* diameter by *3.2 in* copper plated, stainless steel pressure vessel, with *1 in* radius hemispherical electrodes along the cylindrical axis.

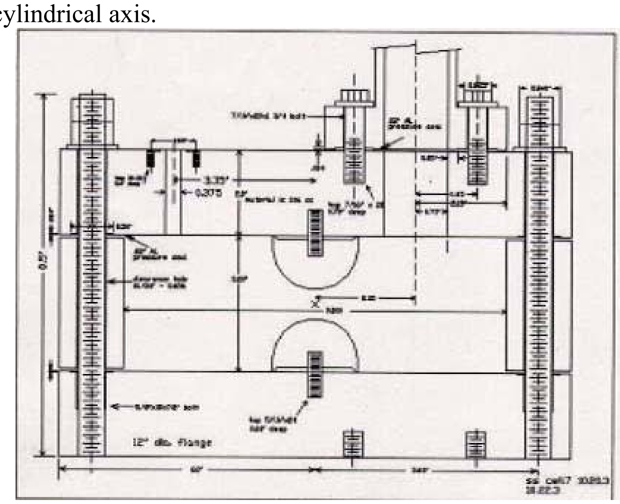

Figure 3: Cross sectional drawing of Muons Inc test cell.

An *805 MHz* klystron in the Fermilab LINAC gallery provides power to the test cell via a *320 ft* waveguide transitioning to *3 in* then *1.5 in* coaxial lines. Directional couplers at the klystron and each end of the coax lines are used to measure the power transmission, and a pickup probe directly measures the magnitude of the RF signal in the cavity.

The vessel is first purged by cycling pressurizing and venting of the test cell with *He* and then H_2, to get the *99.995%* gas purity required for the measurements. The pressure, and hence density, of the gas is then set to the desired value, and the frequency is then tuned to maximize power into the cell. This is required since changing the density changes the dielectric constant, which in turn changes the resonance frequency of the cavity. Recent measurements of the frequency vs. pressure for both H_2 and *He* are shown in Figure 4. Here, the horizontal bars show resonances that occur in the interface with the waveguide. In order to perform the experiment, we choose pressures, and thus frequencies which lie in between these waveguide resonances.

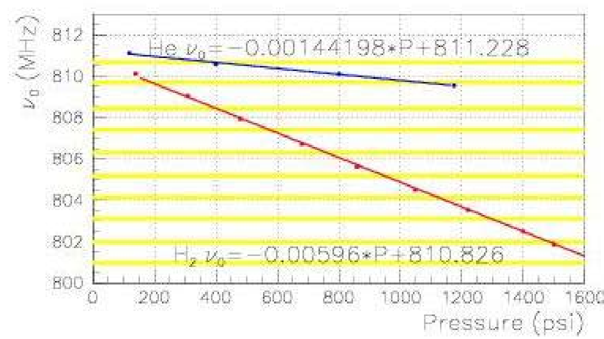

Figure 4: Initial measurements of cavity resonant frequency vs. pressure in the test cell. Horizontal bars indicate resonances in the waveguide. The upper points are *He* data and lower points are the H_2 data.

With the cavity under pressure, conditioning can be completed in a matter of hours rather than days. Once conditioning is complete, the measurements are made by first adjusting the pressure, then ramping the power from the klystron until breakdown occurs. At this point, the power is reduced until no further breakdown occurs. For each electrode, these data points are recorded as a function of gas pressure in the test cell. The Paschen curve is expected to be the same for the same gas for each electrode, until the point where breakdown is in the material, rather than the gas, as in Figure 2. This fact will further simplify normalization of the data since we expect the Paschen curve to be identical for each electrode.

Previous measurements taken with the same test cell at Lab G at Fermilab are shown in Figure 5 [5]. The data here were taken with both *He* gas (lower curve, squares) and H_2 gas (upper curve, diamonds) at liquid nitrogen temperatures, *T=77K*. The star represents the maximum stable gradient point of *79.9 MV/m* taken at *P=265 psi* with molybdenum electrodes. These data were taken with *20μs* pulses from an *805 MHz* klystron. Conditioning of the cavity was completed after three hours at the maximum gradient. The dip at *190 psia* in the H_2 data curve is believed to be due to a resonance in the waveguide at which breakdown occurred in the waveguide, rather than in the test cell.

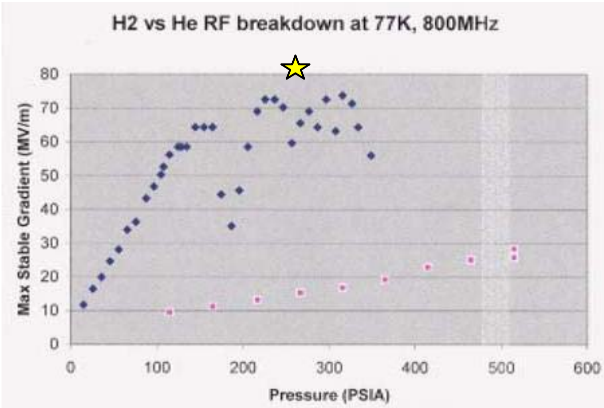

Figure 5: Previous Paschen curve measurements taken at Fermilab's Lab G.

CONCLUSION

A muon collider, would be a powerful new facility for answering many questions of particle physics today [6], both because of the potential center of mass energy and the fact that the probes are leptons. Demonstrations of the physics and engineering of an ionization cooling requires tests of individual components prior to tests of a full fledged cooling channel. One such test is the feasibility and optimization of high pressure RF cavities being performed at Fermilab by Muons, Inc. We expect to have results on the optimization of materials for high pressure RF cavities in the late spring 2005.

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[6] The most recent thoughts from a variety of authors are available from the plenary sessions of NuFact04, http://www-kuno.phys.sci.osaka-u.ac.jp/~nufact04/agenda.html
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C. Quigg, http://arxiv.org/abs/hep-ph/9803326

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