Lab G RF Test Cell Construction, Operation, Safety, and First Results

R. E. Hartline, R. P. Johnson

Muons, Inc., Batavia, IL 60510

C. M. Ankenbrandt, M. Kuchnir, A. Moretti, M. Popovic

Fermi National Accelerator Lab., Batavia, IL 60510

M. Alsharo'a, E. L. Black, K. Cassel, D. M. Kaplan, A. V. Obabko

Illinois Institute of Technology, Chicago, IL 60616

Abstract

This document describes the RF Test Cell (TC) used at Lab G for the study of high voltage breakdown of dense gases. This investigation is the first phase of a DOE STTR grant[1] to develop RF cavities that work at high gradient by virtue of being filled with a dense gas to suppress RF breakdown. These cavities are to accelerate muons to be used in a Neutrino Factory, Muon Collider, or Intense Muon Source. The operational requirements to achieve the goals of the study are listed in chapter 1. Then a TC consistent with this list is described in chapter 2. The construction choices and their safety ramifications for this prototype RF cavity are discussed. The plans for operating this TC in the Lab G environment are described and operational safety issues are discussed in the next three chapters containing the formal documents submitted to the Fermilab safety panel. Chapter 3 is the Engineering Note used for the pressure vessel analysis, chapter 4 is the Flammable Gas Analysis, and chapter 5 is the ODH Risk Analysis. Chapter 6 contains the first RF measurements of the TC. First breakdown measurements and subsequent physical examination indicated problems with a loose electrode. Chapter 7 contains the first ever measurements of Paschen data for helium and hydrogen gases near 805 MHz. These data are at the highest gas densities ever achieved at any frequency for these gases, where maximum stable gradients of 28 MV/m for helium and 50 MV/m for hydrogen were measured at liquid nitrogen temperature.

[1]The proposal can be seen at http://www-mucool.fnal.gov/mcnotes/public/ps/muc0247/muc0247.ps.gz

Table of Contents

Abstract 1
Introduction 3
Chapter 1. Test Cell Operational Requirements 6
RF Requirements 6
Pressure Requirements 6
Thermal Requirements 6
Magnetic Requirements 6
Instrumentation Requirements 6
Lab G Compatibility Requirements 6
Chapter 2. Test Cell Design 7
Overview 7
RF/Pressure Seal Development Program 8
Coaxial Line and Coupling Loop 9
Quarter-Wave Coaxial Pressure Feedthrough 9
TC Instrumentation 10
Location 10
Switchover 11
TC Cool-Down and Warm-up 11
Experimental Layout 12
Chapter 3. Pressure Vessel Engineering Note 13
Chapter 4. Flammable Gas Risk Analysis for the High-Pressure RF Test Cell 14
Chapter 5. Oxygen Deficiency Hazard Risk Analysis for the High-Pressure RF Test Cell 15
Chapter 6. First Test Cell Measurements 16
TC resonant frequency versus P for He and N2 at 71°F 16
TC resonant frequency versus T and P for helium 17
TC resonant frequency correction 17
First Breakdown measurements 17
Chapter 7. Latest TC Measurements 21
Helium Data 21
Hydrogen Data 22

Introduction

Neutrino Factories[2] using accelerated muon beams are generally deemed too expensive, where the detailed studies at Fermilab[3] and Brookhaven[4] each show construction costs around $2 billion. Muon Colliders[5] are generally not even considered feasible, partly because there is no credible design that could be considered an existence proof. Nevertheless, these machines can be the future of Fermilab.

The MUCOOL program is to develop technology for these new machines. The liquid hydrogen energy absorbers that are under development by the ICAR[6] and other universities and the Fermilab and LBL RF cavity programs at Lab G have been underway for some years. More recently a new initiative to study an alternate path to these new machines has started, with a rather unconventional funding source. Muons, Inc is a new small business which has been funded by a Small Business Innovation Technology Transfer (SBIR/STTR) grant to study the idea of using gaseous instead of liquid hydrogen for energy absorber and to see if the dense hydrogen gas will suppress breakdown in RF cavities.

Muons, Inc. is dedicated to the idea that a dense gaseous energy absorber enables an entirely new technology to generate high accelerating gradients for muons by using the high-

---

[2] *Neutrino beams from muon storage rings: Characteristics and physics potential,* S. Geer, PRD 57, 6989 (1998);

Prospective study of muon storage rings at CERN, B. Autin, A. Blondel and J. Ellis eds, CERN yellow report CERN 99-02, ECFA 99-197;

Current Activities for a Neutrino Factory at CERN, R. Garoby, CERN-PS-2001- 007-RF NuFact Note 74, available from http://muonstoragerings.web.cern.ch/muonstoragerings ;

The Study of a European Neutrino Factory Complex, B. Autin et al., *NuFact* Note 103 (Dec, '01)

A Feasibility Study of A Neutrino Factory in Japan, Y. Kuno ed., available from http://www-prism.kek.jp/nufactj/index.html

[3] *Feasibility Study on a Neutrino Source Based on a Muon Storage Ring*, D. Finley and N. Holtkamp ed., March 2000 http://www.fnal.gov/projects/muon_collider/nu-factory/fermi_study_after_april1st/

[4] *Feasibility Study II of a muon based neutrino source*, S. Ozaki et al., available from http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

[5] *Status of muon collider research and development and future plans,* C. M. Ankenbrandt et al., Phys. Rev. ST Accel. Beams 2, 081001 (1999)

[6] Illinois Consortium for Accelerator Research. http://www.iit.edu/~bcps/hep/icar.html

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 only possible for muons because they do not scatter as do strongly interacting protons or shower as do less-massive electrons. Multiple scattering is important, though, and a long scattering length is beneficial. In this application, hydrogen gas is twice as effective as helium, the next best gas. Additionally, use of a gaseous absorber presents other practical advantages that make it a simpler and more effective cooling method compared to liquid hydrogen flasks in the conventional designs used in the Fermilab and Brookhaven Neutrino Factory studies mentioned above.

Dense hydrogen gas should suppress RF breakdown quite effectively as old measurements suggest and ongoing measurements by Muons, Inc. and IIT at Fermilab should confirm. Provided one can supply the required RF power, much more gradient can be available than is needed to overcome the energy loss in the absorber.

A perfect vision of the use of pressurized high gradient RF cavities for a Neutrino Factory starts after the muon decay region with a momentum-time phase space rotation, followed by transverse cooling, then 6-d cooling, and then acceleration into a storage ring. These four steps would all be done with pressurized RF cavities having superimposed magnetic fields as required. Thus the muon beam would be accelerated to high energy in the shortest possible time using the highest possible gradients. The only material the beams would pass through besides the gaseous hydrogen would be the thin beryllium grids between the RF cavities (to make them each independent closed cells with good voltage profiles) and two pressure windows, one just after the pion decay channel and one near the storage ring.

The path to an affordable Neutrino Factory and a credible design of a Muon Collider has four essential projects that Muons, Inc is pursuing with SBIR/STTR proposals:

1) The development of Pressurized **High Gradient RF Cavities** is the subject of an STTR grant with IIT (Prof. Daniel Kaplan, Subcontract PI), which was begun in July 2002. Phase 1 of this project is to build an 805MHz test cell and use it to measure the breakdown voltages of gases at Fermilab. Phase 2, if approved, is to extend the measurements at Fermilab's Lab G and the Muon Test Facility to include effects of strong magnetic fields and ionizing radiation at 805 and 200MHz.

2) The development of **High Power RF Sources** for muon acceleration, using the low resistivity and high Q of cold copper or using pulse-compression techniques similar to those used to increase SLAC's energy, is the subject of a grant proposal in collaboration with Fermilab (Dr. David Finley, Subcontract PI). This project will allow cooling systems to operate up to the limits of RF breakdown shown in project 1). For example, if sufficient voltages can be developed, it may be possible to have an effective time-momentum phase-rotation using the pressurized RF cavities immediately after the muon decay region.

3) The development of a realistic **Transverse Ionization-Cooling** channel using gaseous absorber and high-gradient RF is the subject of another proposal. Collaborating with Fermilab's Technical Division (Dr. David Finley, Subcontract PI), Muons, Inc. will develop the engineering

design with simulations and prototypes of an experiment at the Rutherford Appleton Laboratory (RAL) to demonstrate transverse ionization cooling.

4) The fourth project is to develop a realistic design for **Six-Dimensional Cooling** using gaseous absorber and pressurized high-gradient RF in a snake-like configuration. This technique is similar to those of ring-coolers in concept, but has several technical advantages such as simple injection/extraction and the ability to modify the parameters of the channel as the beam gets cooled. The high gradient RF makes the snake section so short that a ring design has little cost advantage. This proposal is with Thomas Jefferson National Accelerator Facility (Dr. Yaroslav Derbenev, subcontract PI).

Below we describe the first steps of this program. The pressing need is to demonstrate that RF cavities filled with high-density hydrogen act as Paschen's Law predicts. The next steps are to show that there are no unexpected problems from magnetic fields or ionizing radiation. These things require a test cell that can easily be opened up for examination and modifications and yet is safe enough for rather extreme and unusual conditions for an RF cavity. The first measurements must be done rather quickly as the phase 2 proposal is due April 23, and the likelihood of continued funding would be greater if real data from the Test Cell in Lab G could be included.

Chapter 1. Test Cell Operational Requirements

RF Requirements

The Test Cell quality factor, Q, must be relatively high and reproducible after reassembly. The TC resonant frequency, f_0, must be matched to the 805-MHz klystron. The TC resonant frequency will shift due to changes in the dielectric constant from variable gas density and to changes in physical dimensions from thermal and pressure expansion or contraction. Thus f_0 must be chosen such that the klystron bandwidth will allow sufficient power to the TC for frequencies off the initial TC resonance. An impedance-matched coaxial pressure feedthrough is required between the klystron wave-guide and the TC. Electrodes inside the TC with a constant and well-known gap must define the breakdown point. Assembly and disassembly should allow quick and easy access to the inside of the Test Cell for electrode examination and replacement.

Pressure Requirements

Pressures from under 1 atmosphere up to 50 atmospheres should be possible for any non-corrosive gas. The pressure/RF Seals must be gas-tight at the required pressures and temperatures. The design of the TC must be very robust from the point of view not only of high-pressure safety but also of convincing containment of flammable gases.

Thermal Requirements

The TC must operate at liquid nitrogen (LN2) and room temperatures, and there must be good thermal conductivity between the gas in the TC and the LN2 bath. The coaxial feedthrough must stay near room temperature to guarantee the structural safety of the epoxy dielectric. This implies that the heat transfer along the coaxial line from Test Cell to Feedthrough must be restricted and there should be a means for active temperature control of the feedthrough.

Magnetic Requirements

In 2003, in phase 2 of the proposal, the TC will be operated in the Lab G LBL solenoid. Although magnetic components cannot be used in phase 2, they are permissible in phase 1, if required.

Instrumentation Requirements

Signals from forward and reverse couplers in the transmission line from the klystron will indicate RF breakdown. A pickup loop in the cavity will allow required RF calibrations. A platinum resistor will be inserted into the cavity to measure the gas temperature. Gas pressure transducers in the gas distribution manifold should be read out by computer. A fiber optic cable leading into the cavity is being investigated as a means to detect sparks and corona.

Lab G Compatibility Requirements

Access to the Lab G facilities will be shared with other users of the facility. It is therefore important to be able to switch to and from TC operation quickly. The wave-guide changeover should be simple and not require specialized technicians. The TC should occupy a small, unobtrusive footprint in the cave so that it can stay in place while other experiments are underway. The TC should be easily removable from the cave so that it can be opened for examination or modification while other experiments take their turn.

Chapter 2. Test Cell Design

Overview

Figure 2-1 shows a cross section schematic of the prototype TC to be used for the initial tests at Lab G. The top and bottom discs of the pillbox design are standard 12" stainless steel (SS) Conflat[7] blanks commonly used for vacuum applications. These are strong, relatively inexpensive, and come with 32 holes drilled (top) or tapped (bottom). These were initially chosen in order to try using Conflat seals with a replaceable copper gasket in this high-pressure application.

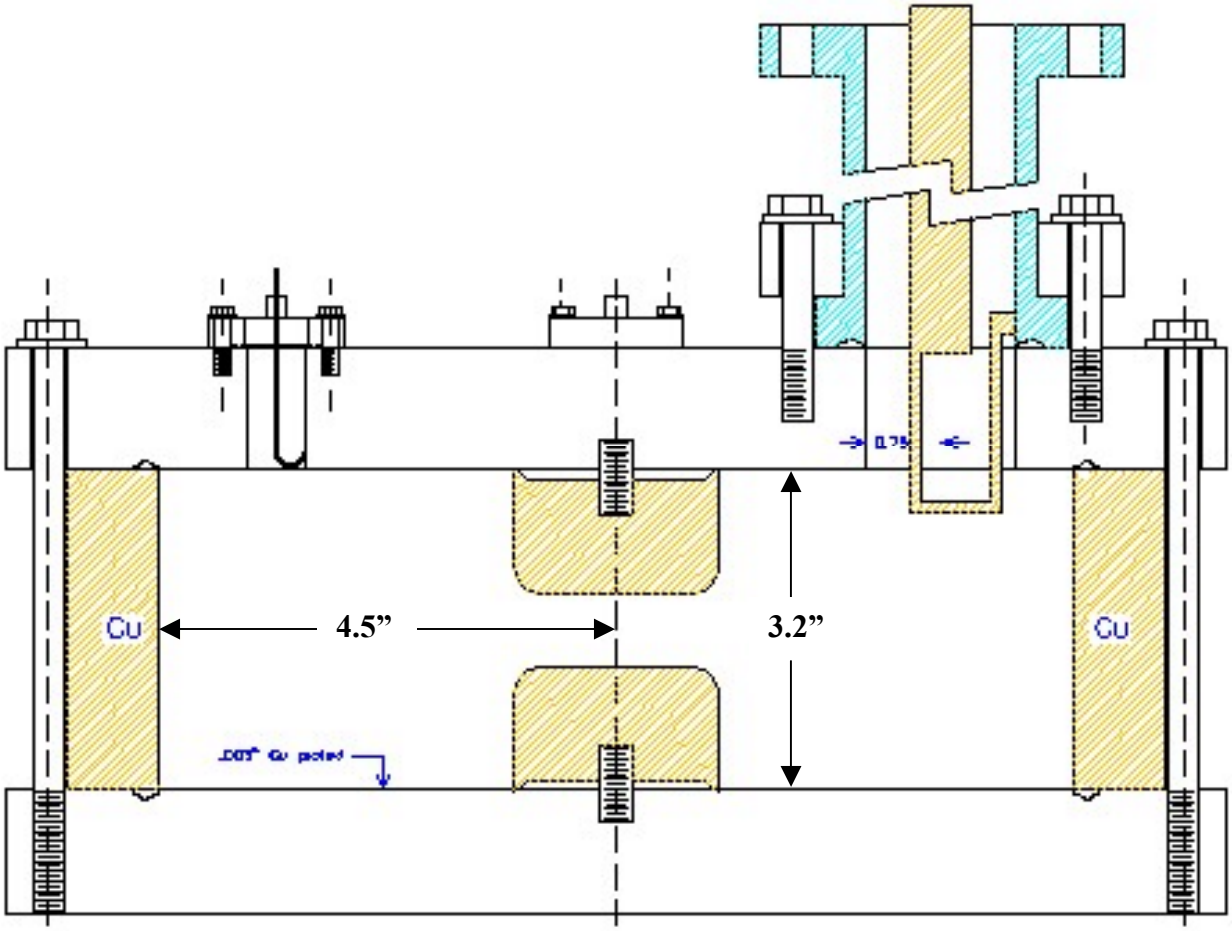


Figure 2-1. Test Cell Schematic

The cylindrical wall of the pillbox is made of copper to ensure good thermal conductivity between the contained gas and the LN2 bath. 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.

[7] Conflat® is a registered trademark of the Varian Corporation. Descriptions of components can be seen, for example, at http://ancorp.com/html/products/p-Conflat.html

Figure 2.2 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 spherical 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. More component pictures are shown in chapter 3.

Figure 2-2 TC components

The next major section of this report contains the materials and components to be used in the TC construction. The results of stress and deflection calculations and measurements are also presented there.

RF/Pressure Seal Development Program

The problem of a high-pressure seal with the requirements as described in the first section of this document is a new one. An experimental development program[8] was started in July 2002 to address this problem. Using 6" diameter Conflat blanks and hydrostatic testing, it was discovered that the standard vacuum techniques based on SS knife-edges and copper gaskets leaked at a few tens of atmospheres pressure. This is probably because pressure-induced deflections pulled the knife-edges out of the copper.

Indium seals were thought to have a better chance of working and there is some body of knowledge at Fermilab with published specifications of the seal seating groove shapes and

[8] See the HP RF development status report by R. Johnson at the LBL MUCOOL meeting for pictures of the hydrostatic and pneumatic test apparatus in action at http://www.fnal.gov/projects/muon_collider/cool/meetings/lbnl1002/lbnl_1002_agenda.html

dimensions. Unfortunately, Indium is relatively expensive and a simple TC reassembly could require about $600 of the material. This would stress our STTR phase 1 budget and be even more of a problem for larger, 200 MHz cavities to be investigated in phase 2.

The development program has had considerable success with 1/8" diameter 60-40% **lead-tin solder** as a replacement for the Indium. The solder forms what is anticipated to be an excellent RF interface by virtue of its electrical conductivity and is sufficiently flexible to provide a good gas-tight seal under the required pressure and temperature changes. The solder is formed into a ring by joining the heated and melting ends of a loop such that they are effectively self-soldered together. Examination of the solder seal after it has been used shows the solder adhering to the groove so strongly that it can only be removed by melting the solder.

Hydrostatic tests with 6" diameter Conflat blanks using the solder seal show a good seal up to the 3500PSI limit of our pump. In these tests, the SS-Copper-SS interface to be used in the TC was simulated and it was determined that tinning the copper surface improved the adhesion of the seal, although the non-tinned seal interface also worked to the 3400PSI pump limit. **Pneumatic tests** of the lead-tin solder seal on the 6" Conflat assembly were successful up to the 1800PSI limit of the helium gas bottle pressure. The seal was also tested pneumatically to 1800 PSI at low temperature by submerging the assembly in liquid nitrogen. The seal successfully survived 3 temperature cycles with cool-down to LN2 temperature and warm-up to room temperature at 1800PSI. Early hydrostatic tests were done on a 12" Conflat with a lead-solder seal without the benefit of a torque wrench, yet a pressure of 1400PSI was reached before a leak developed.

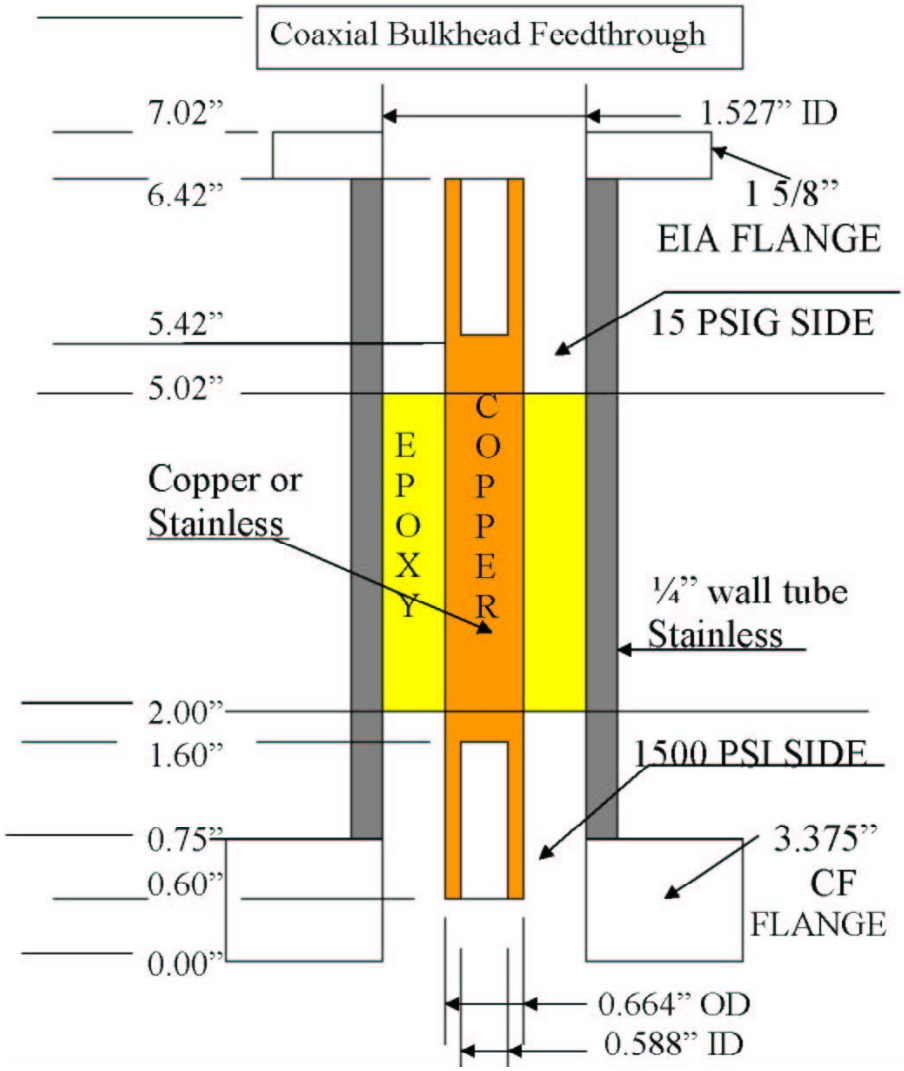
Coaxial Line and Coupling Loop

The ¼"-thick copper-plated stainless steel pipe shown securely bolted to the upper disk of the assembly in Figure 1 has four functions. First, as a coaxial transmission line, it carries the 805 MHz power into the cavity using a SS internal conductor with an RF coupling loop at the end. Second, by using SS materials and Teflon disks as standoffs, it restricts heat flow from the TC body immersed in LN2 to the epoxy filled pressure feedthrough. The inside of the tube and the center conductor may be plated with a thin layer of copper to reduce RF heating and power loss. Teflon standoffs supporting the center conductor can provide a gas baffle to help stratify the gas in the coaxial line so that the temperature in the main body of the TC will be better defined by the liquid nitrogen bath. Third, by virtue of a robust connection to the TC upper plate it provides a solid support structure. The TC assembly will be suspended by the pipe, which will be clamped to unistrut on the blockhouse wall, such that the liquid nitrogen cryostat can be raised to envelop the body of the TC. Fourth, the pipe and the attached RF coupling loop can be rotated by loosening the bolts to allow the coupling factor to be adjusted for the different quality factors expected at different temperatures. Of course, to make this adjustment the TC body will have to be supported and gas pressure removed.

Quarter-Wave Coaxial Pressure Feedthrough

The RF feedthrough is the interface between the klystron wave-guide and the TC. It must transfer RF power through the 50-atmosphere pressure boundary without significant electrical reflections or power loss. Epoxy and ceramic dielectrics have been investigated for this application and a successful epoxy solution has been found. The length of the epoxy dielectric is chosen to be ¼-wave at 805MHz to provide impedance matching. Initial tests on the first

prototype indicate acceptable matching behavior. The epoxy provides the needed pressure barrier. Figure 2-3 shows a schematic of the feedthrough.



TC Instrumentation

Two Ceramaseal high-pressure cryogenic feedthroughs, rated at 3000PSI from room temperature to below 80K, will be bolted to the upper SS plate of the TC over small holes leading to the inner chamber. One will have an antenna or pickup loop for RF measurements and the other will have a platinum resistor to measure the temperature of the TC gas.

Location

The TC location in the Lab G concrete blockhouse is shown[9] on Figure 5 along with the waveguides connecting to the 805MHz klystron. The TC will be secured to the unistrut on the wall of the blockhouse by means of two clamps on the 3 foot-long 2" diameter SS coaxial line that is bolted to the top plate of the TC. Thus the TC will be suspended by this pipe so that a

[9] Drawing number 2130-000-ME-391217

cryostat containing liquid nitrogen can be easily placed under it and raised to immerse the TC for cool-down.

The TC, weighing about 150 pounds, can be rolled into place supported by a moveable table until the clamps are secured. Then the upper coaxial waveguide and gas line can be connected. The coaxial line between the existing waveguide and the TC is secured to the concrete ceiling of the blockhouse so that it allows complete freedom of movement within the room and is high enough to not be a head-bumping hazard.

The high-pressure gas manifold is on the outside of the east blockhouse wall, such that a ¼" SS line of less than 15' length can be fed through the gap in the concrete blocks to the TC.

Switchover

The TC experimentation will alternate with the ongoing measurements of the LBL single cell cavity, which operates in the LBL solenoid (this is shown as "experiment 2" on the Fermilab drawings). It is anticipated that the solenoid will not be magnetically energized during the TC operation, although it may remain cold in a stand-by state. Of course, the LBL cavity will not operate at the same time as the TC since the klystron will feed only one experiment at a time.

Only one 90-degree waveguide section needs to be removed from the "Experiment 2" configuration to allow the TC to be connected to the klystron. As shown on Figure 5, this 90-degree section is replaced by a waveguide-to-3"diameter coaxial converter which points upward. From there a 3" 90-degree coax elbow feeds a 3" bi-directional coupler to a 3" to 1.5" converter followed by a 1.5" bi-directional coupler and a 1.5" 90-degree elbow which connects to the high-pressure epoxy feedthrough on the TC.

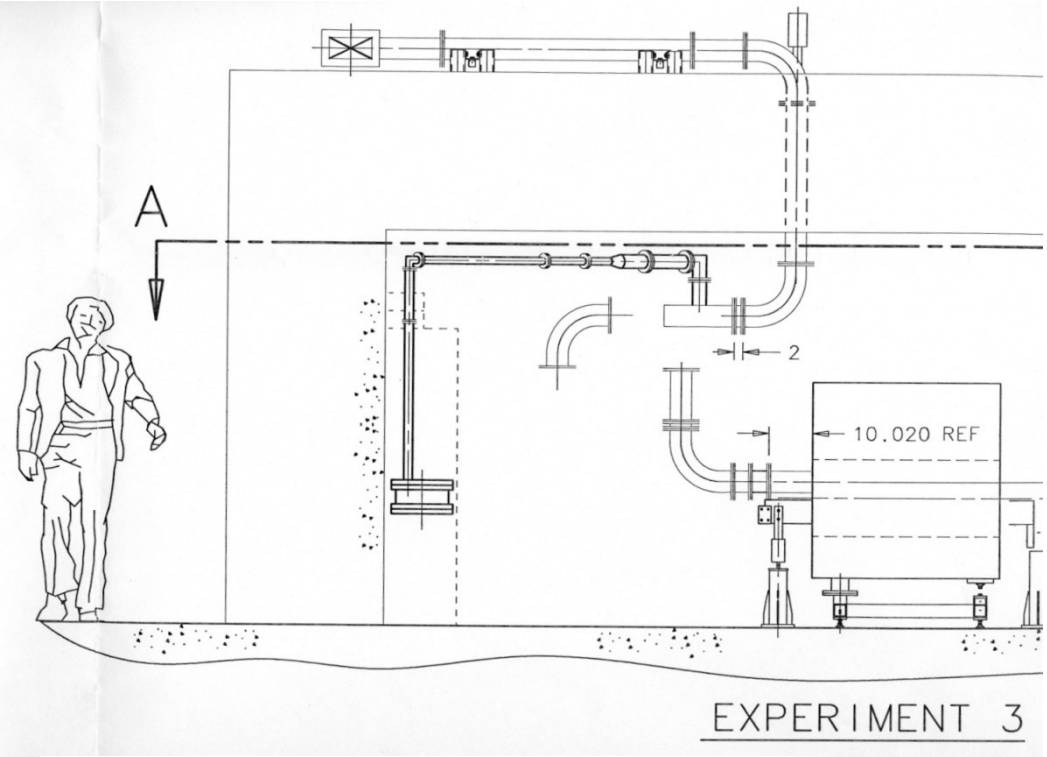
Procedures for installing and removing the TC are shown in appendices 2 and 3.

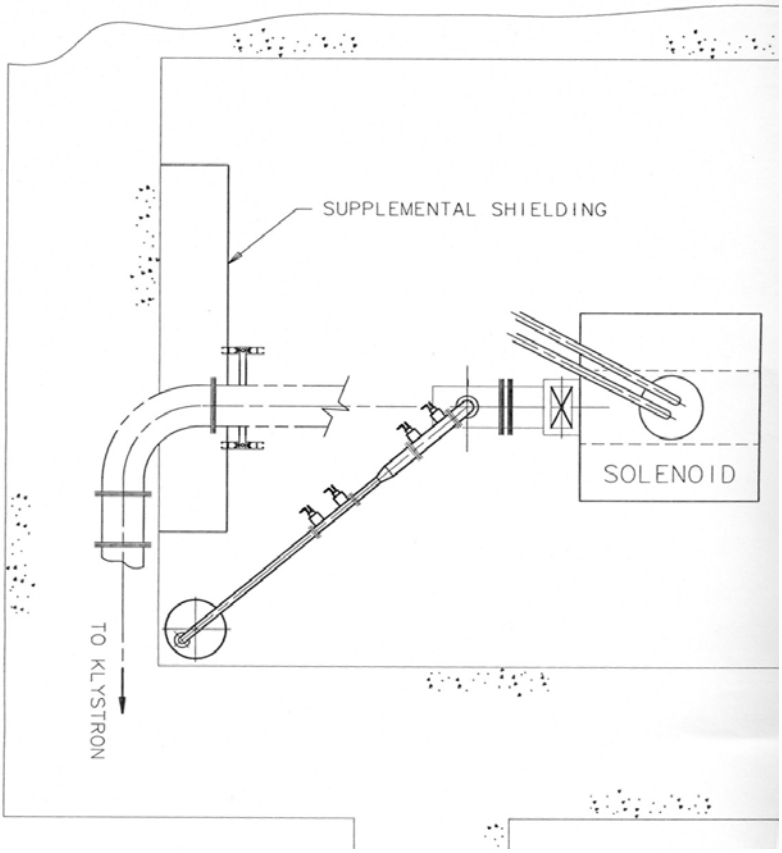
TC Cool-Down and Warm-up

Most of the operation of the TC will be at room temperature. Only when all measurement procedures have been done many times will cryogenic operation start. Assuming that there are no surprises in the TC behavior, cold operation should be relatively rare, perhaps 10 to 20% of operating hours.

The procedure for operating the TC at liquid nitrogen temperature assumes that experimental runs will be of short-enough duration that manual filling of the cryostat will be adequate. An insulated container normally used to keep beer kegs cold will act as a cryostat. It will be placed under the TC and raised onto a support so that the TC is near the bottom of the cryostat. Liquid nitrogen will be poured over the TC body until it is cooled and the liquid nitrogen stops boiling. To warm the TC, the cryostat will be removed and the TC left with a bucket under it to collect melting ice water.

Experimental Layout





Chapter 3. PRESSURE VESSEL ENGINERING NOTE PER CHAPTER 5031

Chapters 3 and 4 are available on the web at
http://members.aol.com/roljohn/chapters34.pdf

Chapter 4. Flammable Gas Analysis for the High-Pressure RF Test Cell Setup at Lab G

Chapters 3 and 4 are available on the web at
http://members.aol.com/roljohn/chapters34.pdf

Chapter 5. ODH Analysis for the High-Pressure RF Test Cell Setup at Lab G

This chapter can be seen at
http://members.aol.com/roljohn/chapter_5_ODH.pdf

Chapter 6. First Test Cell Measurements

TC resonant frequency versus P for He and N2 at 71°F

After getting the Beams Division okay to pressurize the TC, on Feb 12 and 13 we measured the resonant frequency of the TC and a function of nitrogen gas pressure at room temperature (71 degrees F) and with helium gas at room temperature and at liquid nitrogen temperature.

Figure 6.1 shows the circuit analyzer frequency measurements as a function of pressure. The pressure change affects the frequency in three ways: 1) the outward deformation of the plates causes the electrodes to separate, which causes the frequency to rise because the capacitance decreases, 2) the deformation increases the cavity volume, which lowers the frequency, and 3) the density of the gas increases, which lowers the frequency because of the increased dielectric constant. We expect hydrogen to behave more like the nitrogen curve because of its high dielectric constant.

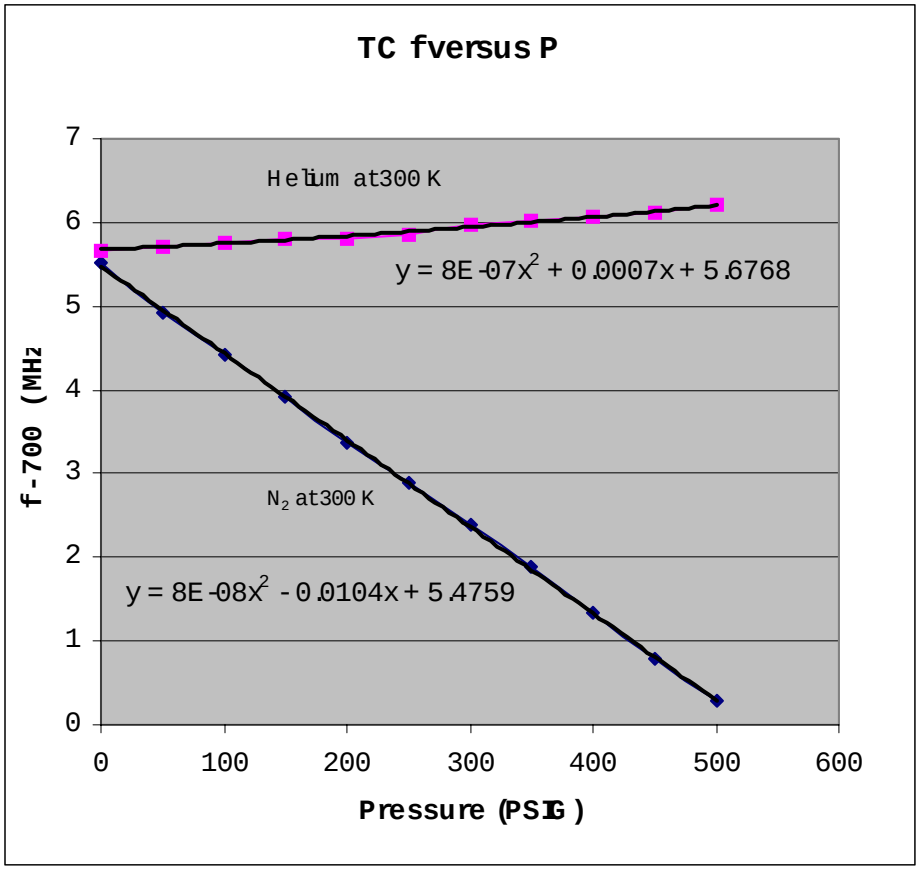


Figure 6.1 Frequency measurements for the TC at room temperature for helium and nitrogen.

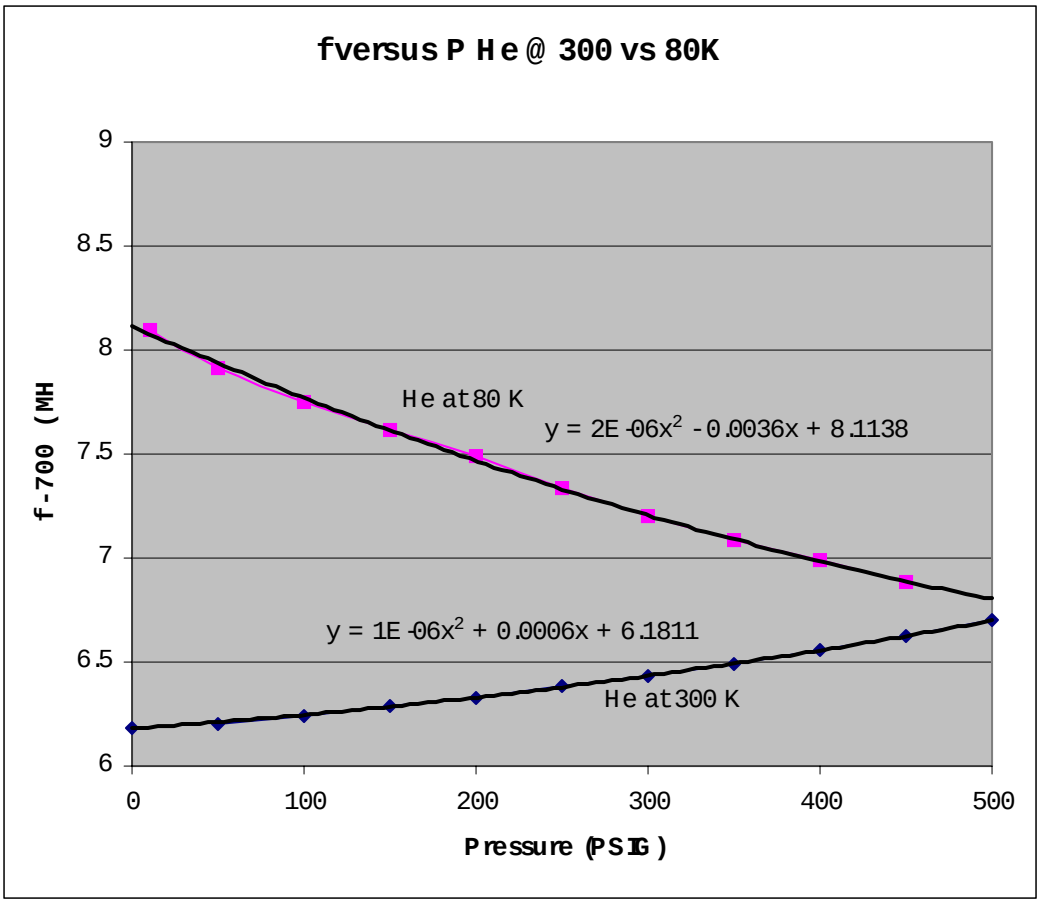


Figure 6.2 TC resonant frequency versus T and P for helium

TC resonant frequency versus T and P for helium

The results for helium at room and liquid nitrogen temperatures are shown in figure 6.2.

TC resonant frequency correction

The radius of the electrode edges was changed from 0.25" to 0.94", which changed the measured room temperature resonant frequency from 706.2 MHz as in the plot above to 806.02 MHz. This means all of the expected helium frequencies should be within the bandwidth of the 805 MHz klystron.

Design Changes

For the measurements described below, the loop power coupler has been replaced by a capacitive coupler. That is, the central conductor of the coaxial line protrudes slightly into the cavity and is not connected to anything in the cavity. The pickup is also without a loop.

First Breakdown measurements

Our first opportunity to attach the TC to the klystron came with a break in the LBL closed cell testing of the beryllium windows on March 8. Measurements with nitrogen and helium at room temperature were taken on March 10. The results are shown on the figure 6.3 as points labeled

N2 3/10 and He 3/10. The nitrogen data (blue points) seem to show some continuity at least, while the helium breakdown voltage data (red points) have no obvious relation to pressure.

The breakdown voltages are determined by first adjusting the klystron frequency to minimize the reflected power, then by raising the RF amplitude until the pick-up on the TC indicates a spark. The pick-up calibration according to Al is such that 4 volts on the pickup corresponds to 5.5MV/m surface gradient on the electrodes and about 15 percent lower than that for accelerating gradient. The estimated surface gradient numbers are plotted.

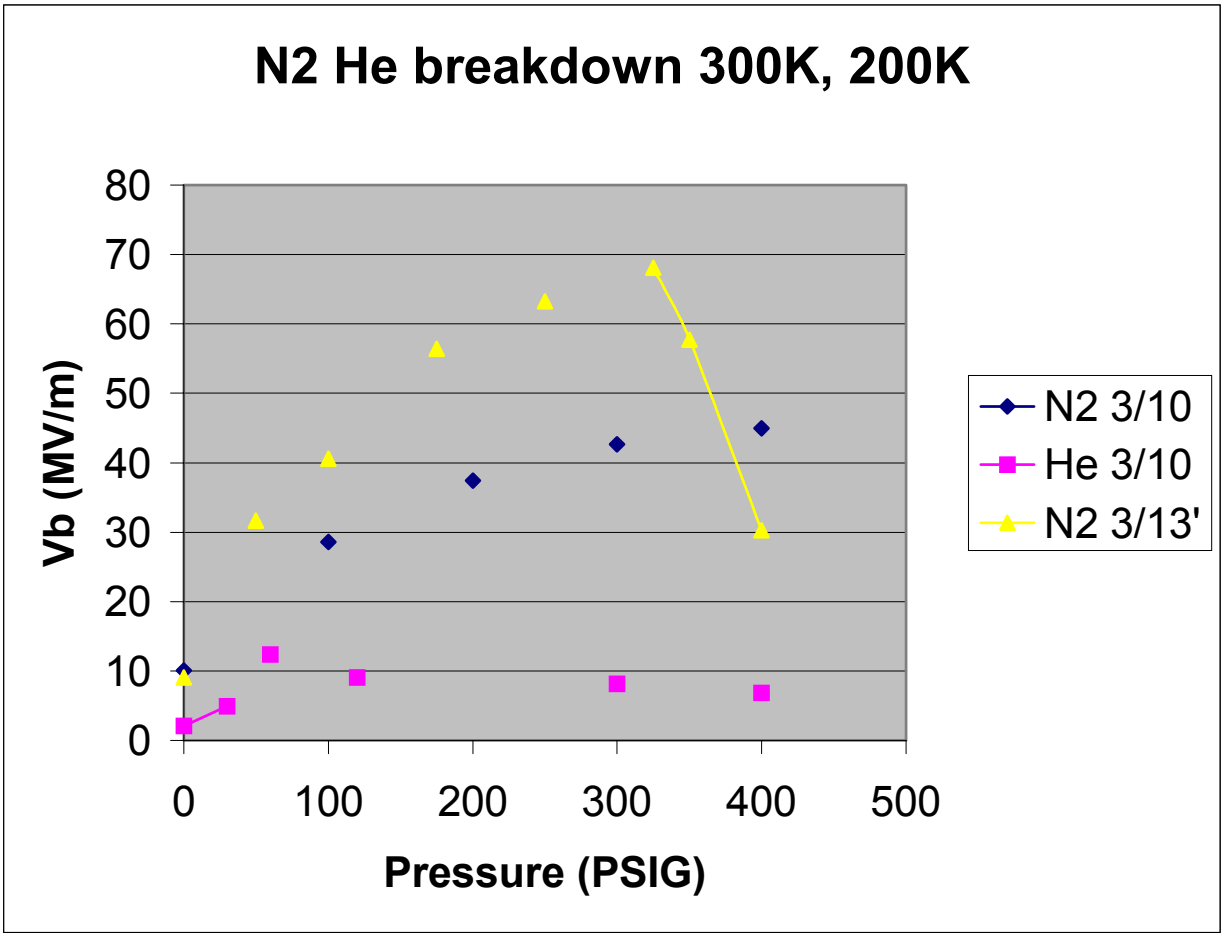


Figure 6.3 Breakdown gradients versus pressure for helium and nitrogen at room temperature measured on 3/10 and for nitrogen on 3/13 at some ice-covered temperature.

Later on March 10 the TC was cooled to 80K and the points marked Vb 3/10 on figure 6.3 were taken. Breakdown occurred at low gradients and as a complicated function of pressure.

Changing the pressure causes the frequency to change because of the change of density (and the corresponding change in the dielectric constant) and also by the changing cavity dimensions and volume. There was also some indication that the breakdown levels could be improved by conditioning, again indicating that the phenomena were from the surface and that we were not seeing the gas properties. It is possible that some multipactoring could have such behavior. Some klystron running on the morning of March 11 was done before the TC had some leaks fixed. The TC had been at 0 PSI helium overnight. When the small blank covering a hole in the

top plate was removed to replace a gasket, there was a strong ozone odor, indicating the air had leaked into the TC.

On March 12, a very careful study of the helium at 80K was done. The TC was bathed in LN2 and pressurized to 500 PSI. The gas was allowed to sit for a half an hour to be sure everything was at thermal equilibrium. All subsequent measurements were done by releasing helium so that no gas temperature change was possible. The resonant frequency was measured for each point to ensure that the pressure was what the gauge said. The breakdown voltage was read from the pickup amplitude on an oscilloscope. These data are shown on figure 6.3 as the blue and red points. The breakdown voltages were slightly below the data taken two days before, but had the same general variation with pressure. The TC was then refilled with helium and the yellow points labeled Vb3/12' were taken. These breakdown data were higher that those taken a few hours earlier but had the same general variations as a function of pressure. The better behavior may have been due to the conditioning that the first measurements afforded or possibly the new charge of helium.

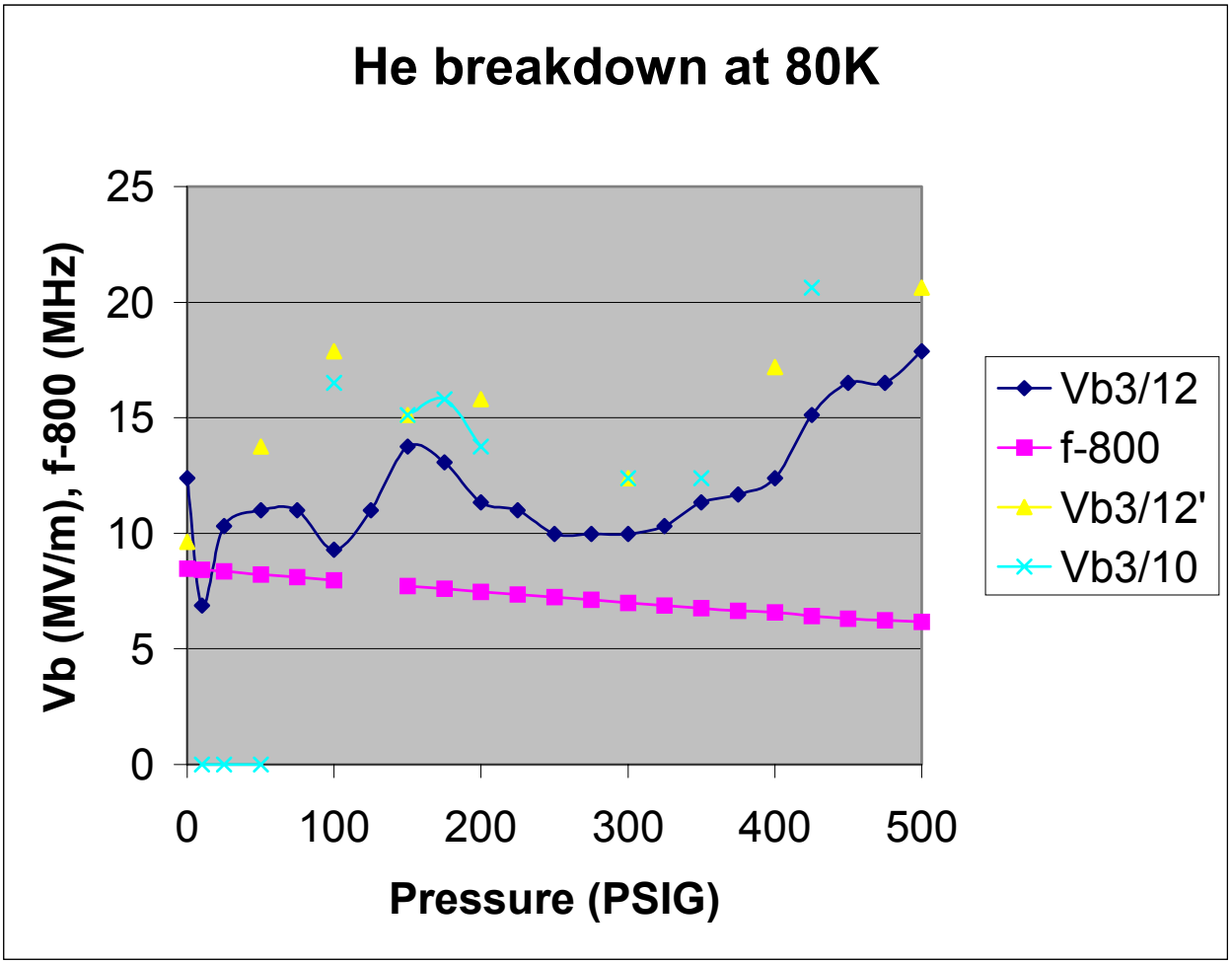


Figure 6.4 Breakdown voltages for helium at 80K as a function of pressure measured at three different times. The TC frequency is measured by minimizing reflected power.

Before opening the TC to do an autopsy and to allow the LBL cavity tests to continue, we decided to redo the breakdown curve for nitrogen at room temperature to see if anything had changed. Although the TC had no LN2 bath for several hours, it was still pretty cold and encased in ice. The yellow points on figure 6.3 show the breakdown voltages for this condition as a function of pressure. At 350 and 400 PSI the cavity breaks down at lower voltages than at lower pressures. So even nitrogen shows behavior unlike that expected for a Paschen curve. Further, after conditioning for a couple of hours, the breakdown voltage increased from 30 to 69 MV/m at 400 PSI.

We conclude that we sensitive to the characteristics of the metal surfaces. These properties seem to be influenced heavily by helium. The variation of breakdown voltage as a function of pressure seems puzzling. Perhaps the induced resonant frequency changes from the pressure changes have an influence on breakdown due to mutipacting.

If gas purity is an issue, we should go to a vacuum purge. The long coaxial pipe and the closed, hollow central electrode may not allow fast purging by gas exchanges.

Results of examination of the inside of the TC

Bob discovered that the top electrode was very difficult to remove, but bottom one much less so. He was also able to observe discolored spots as evidence of sparking on the surfaces of the electrodes at the expected regions at the tips and also at unexpected places. The spots were only visible and not apparent to the human finger (what other kind could he use?).

Evidence of sparking was seen on the copper plated stainless steel next to the base of the lower electrode. There was also evidence inside the electrode assembly of sparking around the region of the threaded rod that holds the lower electrode to the plate. At this location there was some black powder that we can only guess is some remnant of machining oil left in the threads.

Thus, we know that currents were flowing along the threaded rod as could only happen if the electrical conductivity between the edge of the copper electrode and the copper plated stainless steel plate were bad. Spark evidence on the bottom plate near the base of the electrode supports this view as well. This could explain our strange helium data, where pressure changes affected the breakdown voltages in mysterious ways. That is, the flexing of the plates caused by pressure changes could affect the connection of the electrodes.

Since there seemed to be no anomalous sparking evidence around the upper electrode, we can believe that it is possible to have the electrodes tight enough for good electrical conductivity. For our next run we will take extra precautions to clean all components and to make sure the doorknob electrodes are well secured. We will also investigate the effects of conditioning on our geometry, with nitrogen and helium.

Chapter 7. Latest TC Measurements

For the measurements taken below, the TC was modified before reassembly as follows. The electrodes were sanded with 1500 grit wet/dry sandpaper to remove the small tip left from the 4 mil radius change and to make the surface smooth. The copper plating within 0.5" of the bottom electrode screw hole was removed by sanding, and the threads were recessed 3/8" by drilling a 1/2" diameter hole. The electrodes were made as tight as possible with a strap wrench.

The TC had a measured Q_o of 25,300 at 77 K and 13,600 at room temperature. The calculated room temperature Qo for the TC was 19,200. The measured room temperature Q 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 EB welded together and with only a few small ports.

The Q 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 Qo improvement factor of 2.82 for highly purified copper since Q is inversely proportional to the square root of the resistively.

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. A commercial vendor performed the plating on the end plates as a normal business operation. It takes special plating baths and solutions to produce very high purity copper plating. The plating was not specified to be very high purity because there was enough RF power reserve to over come the expected lower Q produced by the standard commercial plating. 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.

Helium Data

Figure 7.1 shows the breakdown voltages for the test cell with helium gas at liquid nitrogen temperature as a function of pressure. The black data points 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 red curve is 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.

The RF capacitive probe as shown on the TC schematic was used to determine the TC frequency and gradient. One could easily determine the TC frequency by maximizing the amplitude of the signal from the probe as a function of the klystron pulse generator frequency. The probe was calibrated by measuring its response for a given input power and using a MAFIA model to relate that to gradient.

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

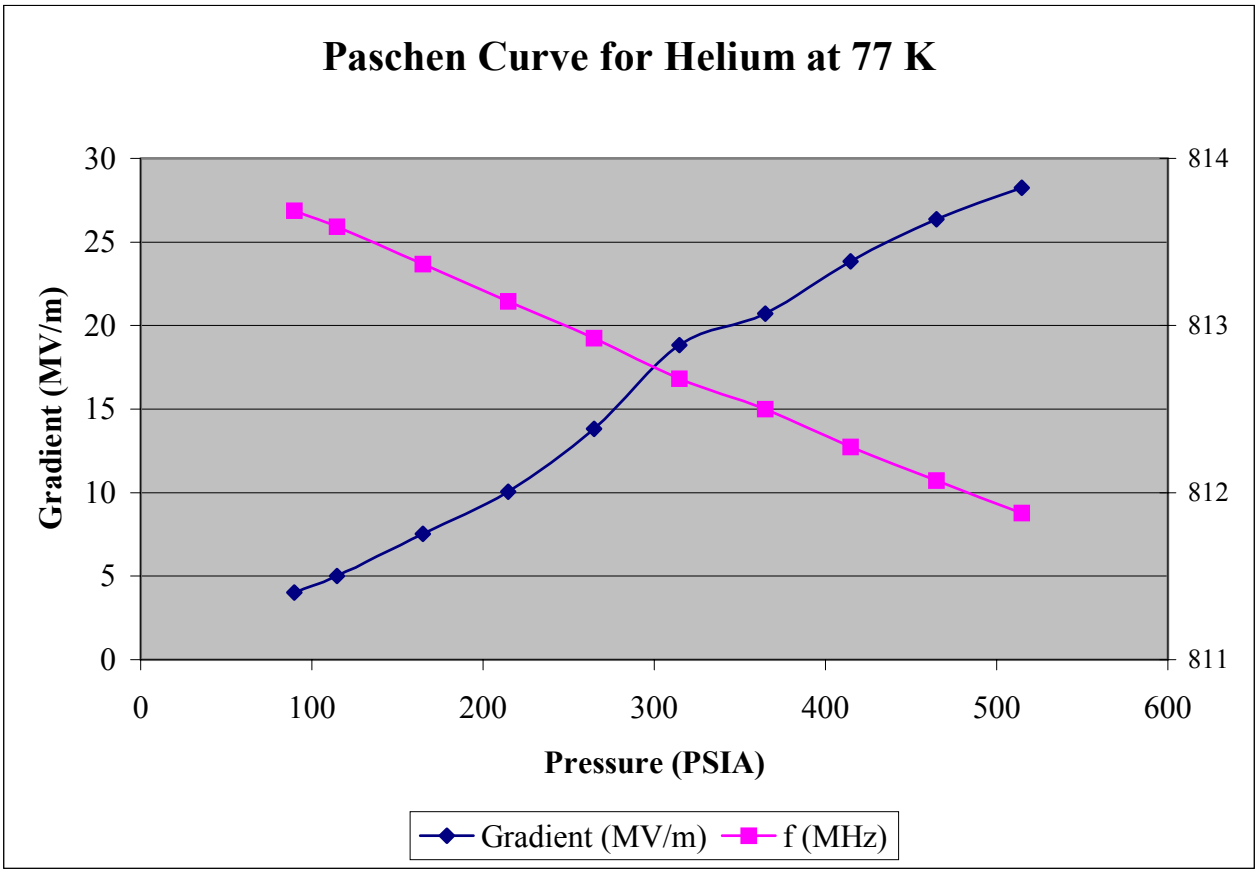


Figure 7.1. Maximum stable RF gradient for helium gas at liquid nitrogen temperature as a function of pressure. This curve was the proof of principle goal of the STTR phase I project.

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 black points in figure 7.2 were obtained:

These new data show the same Paschen Law behavior as the helium data, where the maximum stable gradient increases almost linearly with pressure. In the hydrogen case, however, the rate of increase of the maximum gradient diminishes at 170 PSIA where the gradient reaches 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.

We do not understand this behavior yet, although we have some ideas. RF breakdown in the pressurized test cell requires the same sort of RF conditioning that is usual for evacuated cavities. That is, the application of many breakdown events allows higher and higher voltages to be attained. Thus the breakdown is dominated by gradient at the surface of the electrodes and the qualities of the electrodes rather than the gas itself. The next efforts of the test cell development will be to improve the electrode surface qualities (e.g. geometry, polishing, metal choice) to the

point where the properties of the gas are dominant in the breakdown process. We believe that the 50 MV/m limit represents breakdown at the copper electrode surface, much as expected from Townsend's second coefficient being dominant. One possibility is that the power in the discharges is sufficient to cause damage to the electrodes rather than the polishing action seen in most RF conditioning. Examination of the TC electrodes after this run 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.

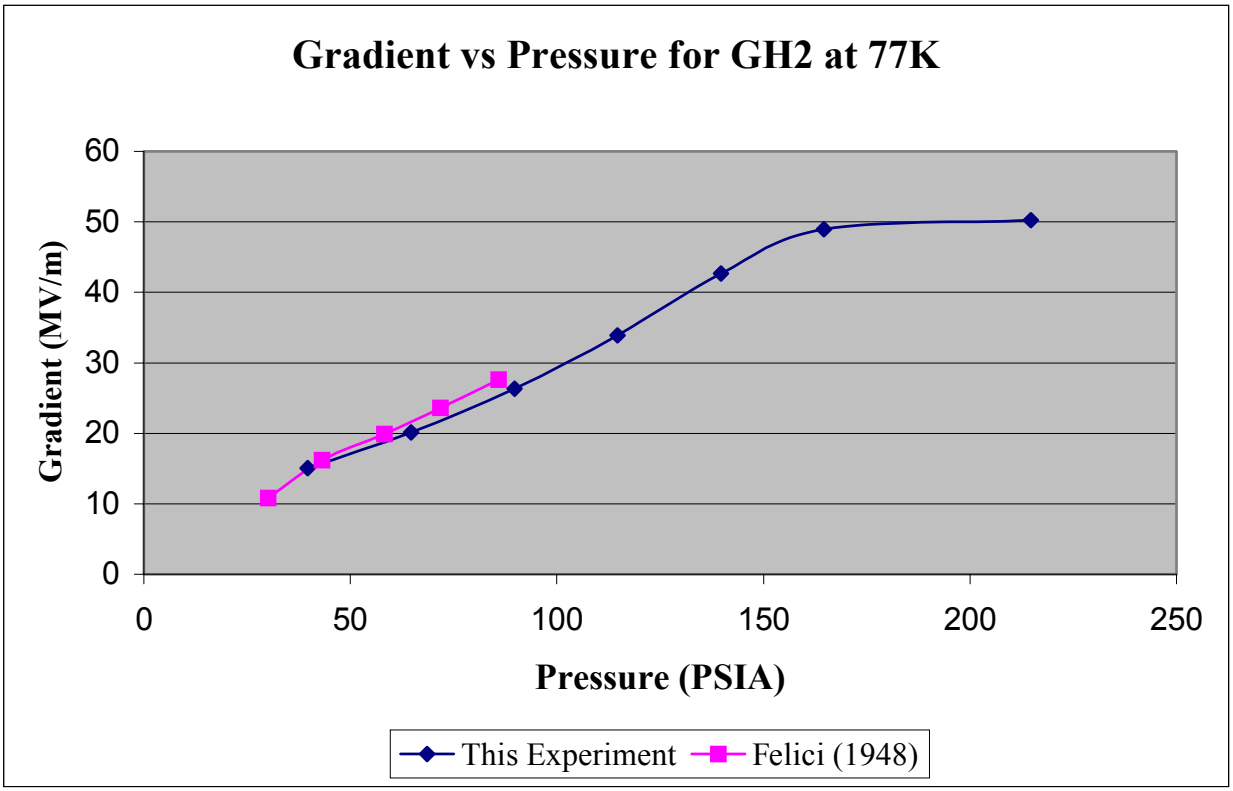


Figure 7.2. Maximum stable RF gradients for hydrogen gas at liquid nitrogen temperature as a function of pressure compared to the breakdown gradients of Felici and Marchal (1948). After raising the voltage until breakdown occurs, the black points are obtained by then slowly lowering the power until the RF runs stably, with no sparking. The red points are the breakdown gradients shown on figure 2 from 1948 scaled to a pressure of the equivalent gas density.

Most important in this measurement is the fact that we have extended the range of possibilities for muon cooling. We have made measurements of high-gradient RF in dense gas, where 805MHz is a viable frequency for muon ionization cooling. We have used a cryogenic technique to achieve high gas density.

We have also measured hydrogen breakdown and stability levels above those ever made before. The highest density data measured in 1948 and shown in figures 2 and 4 correspond to 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 maximum stable gradient 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.