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Studies of High Voltage Breakdown in Superfluid Helium and SQUID Noise: a R&D Effort to Support the Neutron Electric Dipole Moment Experiment at SNS

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Studies of High Voltage Breakdown in Superfluid Helium and SQUID Noise: a R&D
Effort to Support the Neutron Electric Dipole Moment Experiment at SNS
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I. Abstract:

An experiment to measure the electric dipole moment of the neutron (nEDM) is under construction at the Spallation Neutron Source (SNS) in Tennessee. It has the potential to improve the sensitivity of the current experimental limit by two orders of magnitude. [2] In order to assist this experiment, our group at Indiana University Cyclotron Facility (IUCF) is investigating the high voltage breakdown in normal state liquid and superfluid helium. In addition, the properties of Superconducting Quantum Interference Devices (SQUID), which will be used to monitor the variation of the ambient magnetic field and the precession of the helium-3 co-magnetometers, are being characterized in the high voltage environments. The dielectric strength of the normal state and superfluid helium has been found to be dependent on the pressure and temperature. Details of the experimental design and results as well as the observed abnormal hysteresis in the high voltage breakdowns will be discussed in this report.

II. Introduction:

The neutron Electric Dipole Moment (nEDM) collaboration will be performing a measurement of the nEDM at the Spallation Neutron Source at Oak Ridge National Laboratory. The neutron is made of fundamental particles with positive and negative charge, namely two down quarks with charge -1/3e and one up quark with charge +2/3e, where e is the charge of the proton. Although electrically neutral, a separation in the positive and negative charges would result in an electric dipole moment of the neutron. If

a nEDM exists it has to lie along the axis of the spin (and thus along the magnetic dipole axis). If placed in an external magnetic field a magnetic dipole will experience a torque (eq. (1)). This will cause the dipole to precess about the direction of the magnetic field. Similarly an electric dipole moment will precess under the influence of an external electric field. The rate of this spin precession is governed by the combined Larmor precession frequency (eq. (2)).

(1) $$\tau_B = \mu \times B, \tau_E = \delta \times E$$

(2) $$\omega = \mu \cdot B \pm \delta \cdot E$$

Many previous experiments applied the technique of nuclear magnetic resonance (NMR) to extract the size of the EDM. The current best limit of the nEDM (δ_e), given by an experiment using ultracold neutrons (UCN), has provided a limit of $\delta_e < 1 \times 10^{-26}$ e-cm[2]. The SNS-nEDM measurement expects a value as low as $\delta_e < 10^{-28}$ e-cm. [2]

In order to perform this measurement, the collaboration will pass a beam of polarized neutrons into a helium bath thereby producing polarized UCNs by the down scattering process.[2] The UCNs are then trapped in a material cell under the presence of both an electric and magnetic field. The information of neutron spin precession can be extracted with the addition of polarized helium-3 atoms as co-magnetometers. Flipping the direction of the electric field will change the precession frequency by twice the value of the electric field strength multiplied by the electric dipole moment. Consequently, in order to enhance the measured observable, it is essential to maximize the applied electric field. Furthermore, the stability of the field is important for a variety of reasons. In particular, the sensitive electronics (SQUID sensors) inside the HV volume could be damaged by the fluctuations associated with an unstable field. It is possible that the

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intense electric fields produced during a spark could induce excessive amount of current through the delicate Josephson Junctions of the SQUID thus destroying it. Consequently, it is very important that the applied electric field is stable and that no sparks are present in the system during the experiment.

The required stability of the electric field comes also from concerns of the mechanical structure of the electrodes. A breakdown, which is characteristic of an unstable electric field, results in a current discharge between electrodes, mostly initiated from the negatively charged electrode (cathode) to the positively charged electrode (anode). This discharge is accelerated in the electric field and begins an ion shower. At the point of impact the energy from this shower can pit the surface of the positively charged electrode. This phenomenon can result in sharp discontinuities on the surface of the electrodes which leads to localized regions of high electric field strength. These discontinuities can act as a catalyst for future breakdowns. Since this creates a localized region of increased electric field it decreases the voltage that can be applied throughout the entire HV volume for subsequent measurements after the initial pitting.

In the experiment, polarized He-3 atoms will be used for two main reasons. First, He-3 acts as a co-magnetometer. He-3 atoms sample the magnetic field in the same volume occupied by UCNs. It can provide information of magnetic field fluctuations. The He-3 density of liquid helium is much higher than that of neutrons and consequently the precession of the He-3 will produce a larger signal, which will make it feasible to measure using SQUID magnetometry. Second, the He-3 can be used to analyze the spin of UCNs. When the spin of the He-3 is anti-aligned with that of the neutrons the following reaction: $n + He^3 \rightarrow H^3 + p$ will occur at the maximum rate. The final

products of the reaction then ionize the He^4 molecules and create UV scintillation light. This scintillation light is then frequency-shifted on the surface of the cell and transported to photomultiplier tubes using light guides. By using the measurement of the He-3 precession rate and the modulation frequency of the scintillation light, one can determine the precession rate of the neutrons using a simple beat frequency relation.

Our HV measurement was motivated by the results of work done at Los Alamos. This series of tests characterized the breakdown properties of a large system of superfluid helium. Their design uses a voltage amplification system to increase the applied field in the HV volume. The following schematic shows the amplification design:
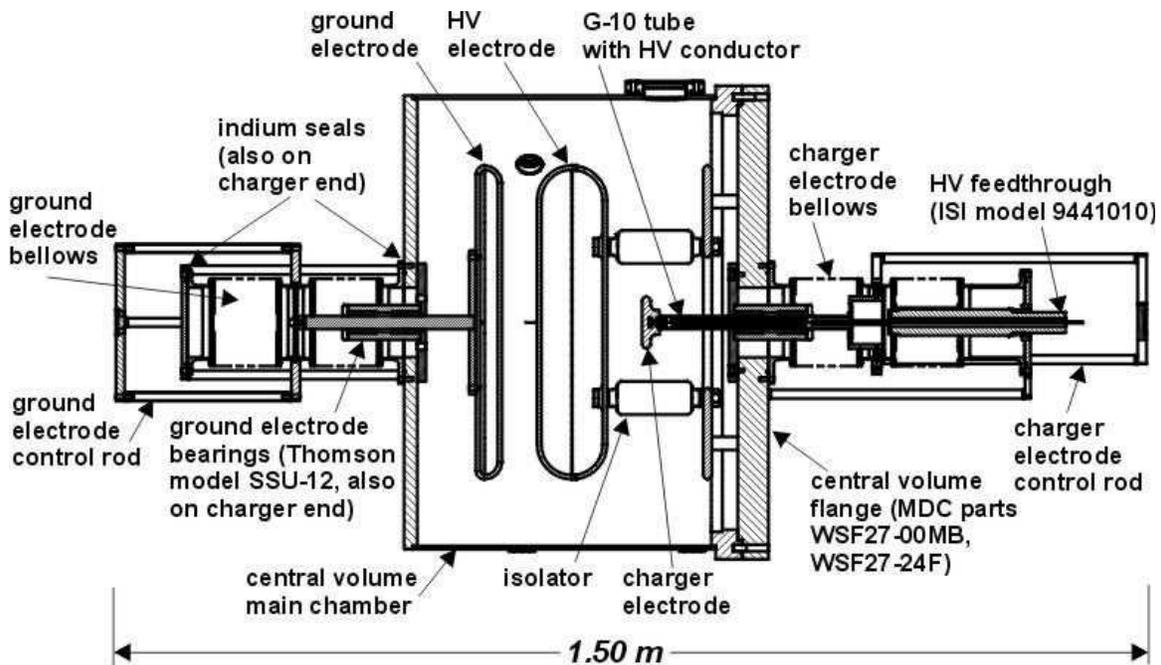
Figure 1: Cross sectional view of the HV volume and amplification system used in the HV tests at Los Alamos. [3, Figure 2]

The amplification systems works by charging the electrodes, disconnecting the circuit while the electrodes are charged, and then physically pulling back the ground

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electrode. This causes the energy and electric field inside the electrodes to increase to the desired field strength.

The results of the test showed that the maximum applicable voltages in LHe before and after the lambda transition are comparable at and below pressures of 100 torr. Their experiment also showed a pressure dependence on the breakdown in normal state liquid helium. [3] The system at Los Alamos was unable to reach the high electric field (50 kV/cm) required to perform the EDM experiment. Their tests did show, however, that pressurization has promising results for meeting these goals, although further testing is required.

These results were the main motivation for our effort to characterize the breakdown strength's dependence on pressure. It is noteworthy, however, that our experiment has sacrificed size in order to decrease the cool down time and thereby the cost and time obligation that the larger system at Los Alamos has. The small size of our apparatus allows us to do a test and modify the probe as frequently as twice in one day as apposed to the two weeks that it takes the larger experiment at Los Alamos. Consequently our cryostat is being used to make quick measurements of a variety of effects including electrode material, electrode spacing, pressurization path on the phase diagram, and the effects of perturbing the fluid, to name a few. The information gathered in this process has been presented to the nEDM collaboration as a series of recommendations, which may be applicable to the full scale system. These results will later be verified and tested in the full scale system where bulk properties of the fluid might be more important.

In summary the R&D effort at IUCF has produced preliminary data related to two parts of this process. First, to determine the characteristics that maximize the stable applicable electric field in normal state liquid Helium and superfluid Helium. Second, characterizing the noise of SQUID sensors in a high voltage (HV) field as well as developing effective ways to shield the SQUID from effects of the HV field that might increase the noise of the SQUID detectors.
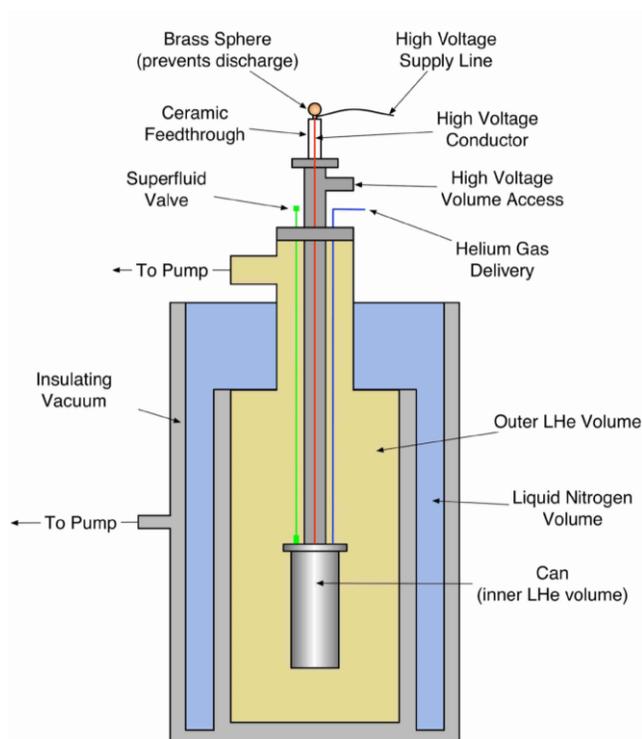
III. Design of the High Voltage test setup:

a. Cryostat:

In designing the cryostat, there were multiple goals that needed to be taken into account. These goals and their subsequent solutions will be described in the following sections. The basic goal of the cryostat design was to be able measure the effects of pressure and temperature independently on the breakdown strength of superfluid He. To perform this measurement the system needed to be able to produce superfluid He and cool it to 1.5 K.

Since the temperature of the system is controlled by pumping on the vapor pressure of a LHe bath, two independent volumes are required if measurements are to be made with pressurized superfluid. The outer LHe volume is connected to the pumping systems and is used to control the temperature of the system. An inner LHe volume, which will be referred to as the HV volume throughout this paper, is immersed in the outer LHe volume. While the HV volume is in thermal contact with the outer LHe volume it is physically separated, so that it can be pressurized independently. A system

had to be designed to deliver HV to the cryogenic HV environment. Throughout all of the tests it was important to be able to monitor the temperature continuously, therefore temperature sensors needed to be implemented in the system. LHe level sensors were also required in order to verify that the electrodes were fully immersed in LHe during HV testing.

For the SQUID characterization, RF and magnetic shielding (using superconducting Pb) needed to be implemented in order to decrease the background noise. Furthermore, the ability to simulate RF interference using a wire loop was desired in order to test the effects of noise of different frequencies on the SQUID. Finally it was important to maximize the size of the HV volume in order to accommodate electrodes of reasonable size, yet still leave enough room to avoid large fields on the boundaries. At the same time it was important to minimize the mass of the probe in order to decrease the cool down time as well as the amount of helium expended in the cool down process.

b. Mechanical structure of the probe:

The cryostat is top loaded into the helium dewar. The top flange of the cryostat connects with a vacuum o-ring seal to the dewar. A series of

Figure 2: Diagram of cryostat and dewar system.
Drawing by Maciej Karcz

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tubes and a rod, which are 20" long, run from the top flange to the HV flange. The rod is a control rod for the superfluid needle valve that separates the dewar's outer LHe volume and the HV volume. There are then two 1/8" SS tubes that each house three threaded wire pairs. Finally there is a 1/8" hollow SS tube that is used to pressurize the HV volume, which will be described in further detail below, and a HV tube. The HV tube houses the HV conductor in a vacuum environment and is concentric to both the top and HV flange. A cylindrical can is bolted into place at the bottom of the HV flange. The HV volume is made vacuum tight by compressing a Mylar o-ring between a v-grove on the HV flange and the can. There are a series of radiation baffles on the tubing run in order to provide a radiation barrier between the 300 K and 2 K environments.

The can acts as a barrier between the inner HV volume and the outer LHe volume. This allows the probe to be cooled by pumping on the outer LHe volume without affecting the pressure in the HV volume. The physical separation of these two volumes is what makes the cryostat capable of measuring the breakdown strength of normal state and superfluid helium as a function of pressure and temperature independently. A superfluid needle valve was implemented in the system to allow the HV volume to be filled at the same time as the outer LHe volume.


c. Electrical: High Voltage (HV)

The HV system, as was described briefly above, needs to deliver HV to the cryogenic HV volume. Since the breakdown strength of He vapor is very low the HV line needed to be physically separated from the outer LHe volume of the dewar. In order

to isolate the HV conductor it was placed in a vacuum. This prevents condensation on the 4K end of the HV line, which then might act as a channel for breakdown. Our final design is depicted in a schematic in Figure 2. The HV line houses the HV conductor and consists of a ¾" ss tube with a HV feedthrough welded on the HV volume end. The other end of the tube terminates with a KF-25 flange. A tee on the tube above the top flange is terminated with a KF-25 flange that allows the HV flange to be connected to a pump and evacuated. The HV line was inserted through holes in the top and bottom flange and then welded in place. On the top end of the HV line a fitting has been constructed that consists of a KF-25 flange welded to a HV feedthrough. By connecting this fitting to the top of the HV line it is possible to isolate the HV line from the other environments.

Two Teflon tubes have been inserted into the HV line. This increases the dielectric strength of the piping and thereby decreases the chance of a breakdown in the HV line. The Teflon also decreases the difficulty of assembling the
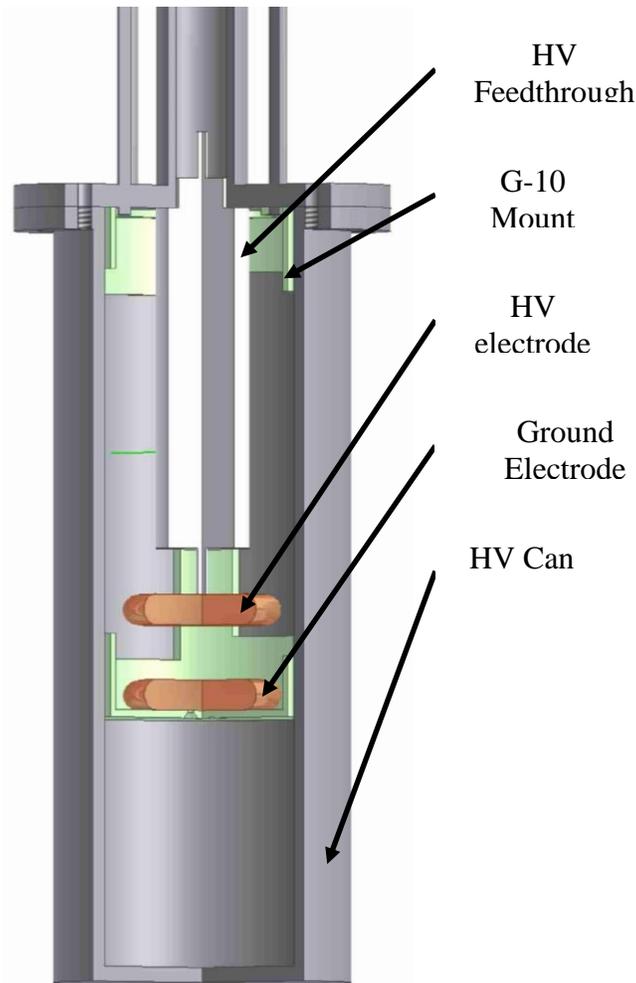
Figure 3: Cross sectional view of the HV volume.

system by acting as a guide for the SS tube that joins the central conductor of the two HV feedthroughs. This small SS conducting tube fits snuggly over the central conductors of the two feedthroughs.

d. Electrode Material and Spacing

A mounting system had to be designed in order to be able to change the electrode material, geometry, and spacing. This mount needed to be either adjustable or multiple mounts of different length had to exist so that the electrode spacing could be easily changed. Another important property of the mounting system was that it had a good dielectric strength in order to minimize the leakage current.

Since the HV volume needed to be superfluid tight, a vacuum tight HV feedthrough was required for the HV line. To simplify the design of the mounting system a commercial HV feedthrough (Lesker, Part # EFT2011091, 20 kV rating) was purchased that had a screw on connection on the end. By making an electrode that was threaded and screwing it onto the HV feedthrough it was possible to hold the HV electrode in place. The HV feedthrough is designed to electrically isolate the rest of the cryostat by using quality ceramic dielectric. This simplified the mounting system of the ground electrode. Since the HV feedthrough established the cryostat as ground, this meant that the ground electrode only had to be connected to the surface of the cryostat to ensure that it was grounded.

Having the electrodes already electrically isolated increased the freedom of the mount design for the ground electrode. It was now possible to move away from designs

that were centered around minimizing the leakage current. Materials that were more easily assembled, less expensive, and easier to machine were then considered. Decreasing the cross sectional area of the mount in order to decrease the conducting area became less important as well. The final design consisted of a G-10 tube with slots cut out of the sides to make assembly easier. A G-10 cap was glued to the top of the G-10 tube. The G-10 cap had through holes allowing the ground electrodes to be bolted to the G-10 mount. A ring of G-10 was produced that fit snuggly into the end of the G-10 cylinder. The ID of the ring was sufficient that it could slide over the HV electrodes and there were through holes in the ring that allowed it to be screwed to HV flange of the cryostat. The G-10 ring was then glued to the G-10 cylinder using Stycast 2850, which is a glue with good cryogenic and high vacuum properties as well as having a similar thermal expansion coefficient to G-10 [5]. The gap between the electrodes was adjusted by adding or removing shims between the G-10 ring and the HV flange. The length of the G-10 tube was sufficiently short that no tests would be required for electrodes spacing less than the spacing when no spacers were inserted, however if there was a desire to move the electrodes closer spacers could be inserted behind the ground electrode.

The dielectric properties of the G-10 mount were also used in order to shield the wires in the HV environment from the HV field. By running any wires that we installed in the system on the outside of the G-10 mount we were able to ensure that they would not be in the HV environment. The G-10 mount would also decrease the field that the wires experienced because of the shielding properties of the dielectric. Finally taping the wires to the G-10 mount guaranteed that they would not vibrate in the system and thereby decrease the noise associated with their induced electromagnetic fields.

e. Pressurization:

In order to be able to fill and separate the HV volume and the outer LHe volume a superfluid leak tight valve was implemented on the top of the HV flange. A control rod ran from the pin in the needle valve to a rotary feedthrough on the top flange. This allowed the two volumes to be connected or disconnected as desired. Separating the two volumes allowed the system to be cooled by pumping on the outer LHe volume without decreasing the pressure in the HV volume.

The system also needed a method for pressurizing the HV volume. The original idea was to attach a bellows to the bottom of the HV volume. While the LHe was filled into the HV volume the bellows would be partially compressed against the bottom of the helium dewar. After closing the needle valve and pumping on the system the pressure inside the HV volume would remain at roughly atmospheric pressure. We could then increase the pressure by further compressing the bellows or reduce the pressure by allowing them to expand. The expansion of the bellows could be controlled by implementing another bellow at the room temperature end of the cryostat above the vacuum seal. Adding or removing weight on the top bellows would compress both the top and bottom bellows. We also considered designs where the top bellows were connected to a set of threaded rods that would allow the height of the cryostat to be adjusted directly.

After presenting this idea to the nEDM collaboration it was brought to our attention by George Sidel that an alternative method of pressurization could be easily

implemented into our system. This method was to attach the HV volume to a regulated

helium gas bottle at room temperature. By using this method it was possible to monitor

the pressure inside the HV volume with pressure gauges at room temperature. The

pressure in the HV volume could also be easily controlled by using a pressure regulator

connected to the helium gas bottle. In order to implement this idea it was necessary to

add another stainless steel tube (1/8" OD), which I will refer to as the pressurization line.

The pressurization line runs from the HV volume to the top flange. The top of the tube is

then connected to the helium bottle through a gas manifold. The description of the gas

manifold is discussed in the following section.

f. Gas manifold:

A gas manifold system services both the pressurization line and the HV line. It

was designed to connect a helium bottle to the pressurization line, connect or disconnect

pressure gauges from the HV volume, purge the system with helium gas, and evacuate

the HV line. Figure 4 is a schematic of the gas manifold.
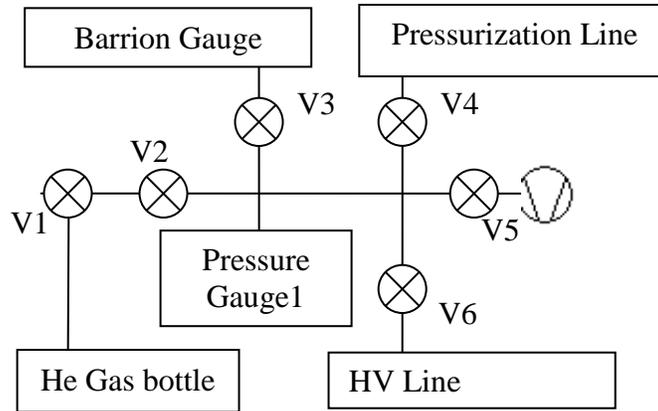
Figure 4: Schematic of gas manifold. The valves are labeled one through six and will be referred to as Vn where in is the number of the valve.

Instead of describing the train of thought that led to the plumbing design I will go through the capabilities and advantages of our final design. To give a summary of what is to come the general design goal was to create a system that would minimize the connections that had to be made during a data run. During this process it will be assumed that all valves are closed unless otherwise mentioned. I will also assume that the linear valve, V1, is always open since it is not a shut off valve, and therefore doesn't control the overall gas flow but instead just controls conductivity.

I mentioned above that the HV line needs to be evacuated before a cool down. In order to do this valves V4 and V6 are opened. This allows the HV line to be connected with the HV volume and the pumping system that is used to cool the outer LHe volume. It is also worth noting that this allowed the HV line to be purged at the same time as the HV volume and outer LHe volume.

The gas manifold allows the system to be purged with helium gas before LHe is transferred, a process consisting of two steps. First valves V3, V4, V6 and the needle valve are opened and the system is evacuated. When the pressure goes off scale on our

barrion gauge (roughly .001 torr) the valve to the pump is closed and V2 is opened

thereby filling the volume with helium gas. When the system has been pressurized to

atmospheric pressure the process is repeated. On the final purging cycle, while the

system is in vacuum, valve V4 is closed before the rest of the system is filled with He

gas. This leaves the HV line in vacuum as is desired during a data run.

The gas manifold also allows the second pressure gauge to be closed off from the

rest of the system. This is a safety measure to protect the barrion gauge by closing it off

from the system if the pressure rises above 800 torr.

V5 allows a pump to be connected the HV line should it be necessary to pump on

the HV volume while the two LHe volumes remain separated. This also gives the ability

to vent the system if for some reason the needle valve becomes inoperable due to a clog

or another unforeseen event.

g. Mounting Structure for SQUID Sensors:

Another goal of the original cryostat was to characterize the properties of a

SQUID in a HV environment. The ability to simulate radio frequency (RF) interference

and monitor the SQUID's response was also desired. In order to achieve both of these

requirements another piece was implemented in the system. A macor piece was attached

to the back of the G-10 mount. The macor piece was a cylinder of radius 1" and

thickness ¾". Two grooves were lathed out of the sides of the macor piece. These

allowed us to wrap a wire around the macor piece which we then connected to a function

generator using wire runs inside our auxiliary wire tube. By running the function

generator it was then possible to produce simulated RF interference. The macor piece also had four through-holes corresponding to the holes in the ground electrode. To secure the macor piece screws were inserted through the macor piece, G-10 mount, and finally into the ground electrode. The SQUID was then stuck to the back of the macor piece using Blue Tac or tape. The SQUID requires six wires which were run through a dedicated SQUID wire tube (1/8" SS) for RF shielding.

h. LHe Level Sensor (American Magnetics, 18" length, 17" active length, ¼" OD)

It is important to be able to ensure that the LHe level is sufficiently high to cover the region of HV during a data run. Consequently, two LHe level sensors were installed in the LHe volume of the dewar. The first was inserted through an auxiliary tube that was used as a vent. The second, a calibrated sensor, can accurately measure the level of superfluid Helium. It was inserted into the access tube used for LHe transfer after the system was filled with LHe.

III. Experimental Procedure and Methods:

a. HV Measurement Preparation

All of the HV measurements began with a similar procedure, which will be described throughout this section. Each step of this process was preformed in order to prepare for a measurement; consequently they will not be mentioned again.

First a set of tests was preformed on a wooden table outside of the dewar and was used to verify that the cryostat was breaking down between the two electrodes. The voltage was ramped up while the electrodes were being visually inspected. During the breakdown a spark in the electrode gap indicated that the cryostat was working correctly, however if the breakdown was not visible or not in the electrode gap an investigation of the mode of breakdown had to be preformed. Assuming that the breakdown was in the gap, the can was installed on the system and a second test was done in air.

The second test was designed to verify that applying the can did not affect the breakdown strength. Therefore the voltage of breakdown with the can on was compared with the voltage without the can. If these two values were similar then the next step was to insert the probe into the system. If the breakdown voltage was significantly lower with the can on this would indicate that something moved when the can was installed or that the electrodes were discharging to the can. The breakdown voltages were also compared with an expected value, which depended on the electrode materials, spacing, and the breakdown strength of air (6kV/1.3mm).

The cryostat is then top-loaded into the dewar. The insulating vacuums on the helium transfer line and the dewar were pumped on at this time. The system was then purged with gas while the dewar and transfer line were being evacuated. The evacuation process was described in the section Gas Manifold. The whole system was purged three times. If the HV volume will be pressurized during the data run an additional test is performed. The HV volume is pressurized while the needle valve is closed and the outer LHe volume is evacuated. The pressure is increased to roughly 800 torr and the system is monitored for pressure changes in the outer LHe volume. An increase in pressure in the

outer LHe volume is a sign that the Mylar o-ring seal between the can and the HV flange

fails to be vacuum tight. This is important because a leak in the Mylar o-ring will prevent

the system from being pressurized. By troubleshooting this problem before the cool

down it is possible to waste less helium.

After purging the system and testing the Mylar o-ring the pump on the insulating

vacuum and LHe transfer line are shut off. The nitrogen volume (cold shield) of the

cryostat is then filled. The liquid nitrogen shields the outer LHe volume from the 300K

environment by providing an intermediary temperature. The cold surfaces of the nitrogen

volume cryopump the insulating vacuum during the cool down process thereby further

decreasing the heat load on the LHe volume. After the nitrogen volume has been filled

the needle valve is open and the LHe transfer is preformed. When the HV volume and

outer LHe volume are filled with LHe the transfer line is removed and the second LHe

level sensor is inserted into the LHe fill port. Finally the connection on the LHe level

sensor is sealed and the system is ready to begin a measurement.

b. First Generation HV Measurement Goals:

Initially the goal of the HV system was to measure the breakdown strength of

LHe. The tests were focused around an attempt to verify that the system was behaving as

designed and in particular that the breakdown was happening between the two electrodes.

These tests used SS steel electrodes of planer geometry. The planer geometry was

selected because of its similarity to the HV system at Los Alamos. The majority of the

first generation tests consisted of comparing the breakdown voltage before and after

removing a component from the system, changing the background gas, or modifying the system in some other way. The evacuation rate of the outer LHe volume was also measured to provide a point of reference for future tests. A large deviation from this rate might suggest that a leak had formed in the system. We found that it takes roughly thirty five minutes to pump from 750 torr to ~37 torr, the pressure at which the superfluid transition takes place (Fig. 6).

Due to a chronic issue with leaky Mylar o-ring seals and the inconsistency of the results the decision was made to upgrade the probe. The first set of SQUID performance data was taken while the system was being upgraded.
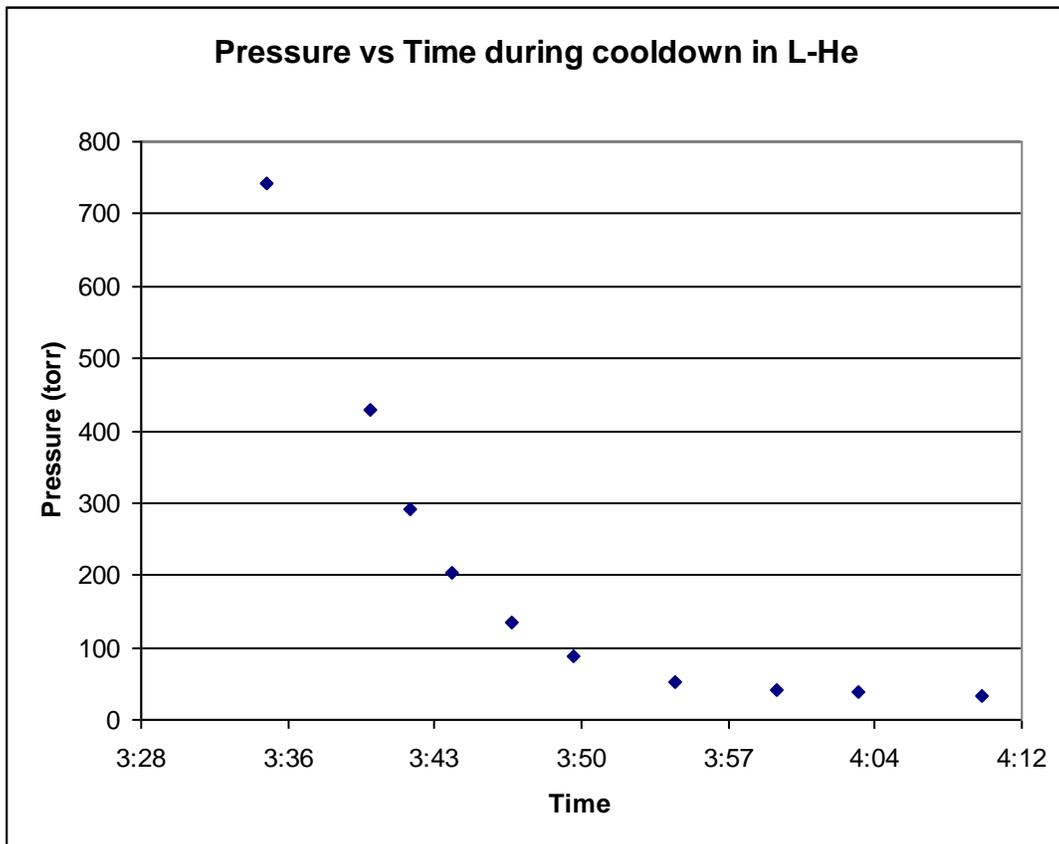
Figure 5: Graph of the pressure as a function of time. The pumps are evacuating the Outer LHe volume that is filled with LHe.

c. First Generation Probe Modifications:

    i. Temperature Sensors:

       Two temperature sensors were implemented into the system. These served two main purposes. First and foremost the sensors gave an alternative and more reliable was of determining the temperature in the HV volume than the vapor-pressure curve and the pressure of the outer LHe volume. They also gave an indirect method of measuring the LHe level in the HV volume. The main heat sources of the system come from above and consequently as the LHe level in the can decreases the top of the can begins to increase in temperature. Furthermore, the increased temperature migrates down the volume as the level continues to drop. Therefore by having two temperature sensors in the volume, at different heights, it is possible to infer if the electrode gap is exposed to helium vapor. The temperature sensor, a Ruthenium Oxide resistor, works by measuring the resistance and current across the resister. By comparing the resistance with a calibration table provided by Lakeshore, it is possible to determine the temperature in the gap. The first temperature sensors were secured to the macor piece using dental floss. This ensured that the temperature sensor was close to the HV gap. The second was positioned on the inside of the G-10 mount below the pressurization line. The temperature sensors can be operated in two ways. Connecting one lead to each side of the sensor allows a measurement of the resistance of the resistor and wire run; this is the less accurate method of measuring the temperature because the resistance of the wire run has to be accounted for. The other alternative is to attach two leads to each side of the resistor.

This allows measuring of both the resistance and current across the temperature sensor and consequently gives a higher accuracy measurement of the temperature.

In general the four lead system is preferred, however there were cases in which, due to the limited number of wires running to the HV volume it was necessary to use the two leads measurement. Once both of the temperature sensors were installed in the system the lower one was run with 4 leads and the upper with only 2. The resistance of the thermometer was typically 1.00 k Ohm at room temperature and 1.24 k Ohm at 4 K.

d. Second Generation HV Procedure:

The second generation HV tests were prepared in the usual manner. Two HV data points were taken with LHe at atmospheric pressure before cooling the system. A data point consists of ramping up the HV power source until a spark discharges in the system as was described earlier in the paper. This is determined by a quick drop in voltage on the HV power source, which is accompanied by an increase in current through the HV power source. After a spark occurs the voltage at which there was a breakdown is recorded as well as the pressure inside the HV volume and outer LHe volume; resistance of the thermometer; and LHe level

The cool down of the system begins by opening the valve to the pumps. Data points could be taken during the cool down, however, after the first few data runs breakdown measurements were not taken during the cool down process because of the repeatability of earlier results. At roughly 50 torr more HV data points were taken. These points were taken to investigate the HV breakdown's reaction in the region around

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the lambda point transition (~30 torr) into superfluid. More data points were taken in superfluid helium before pressurization.

The second stage of the measurement is pressurization. The needle valve is closed. V2, V3, and V4 are opened letting He gas into the HV volume. The pressure regulator is set adjusted to control the pressure in the HV volume. Generally the pressure was set to 800 torr. The helium gas coming from room temperature is a heat source for the system and consequently both the outer LHe volume and the HV volume heats up momentarily. The system is left to equilibrate and eventually the pumps bring the temperature back across the lambda transition. During this process we can take data points of superfluid helium under controlled pressure as desired.

The final stage of the data run is the warm up. The helium bottle is turned off and the pumps are turned off allowing the system to warm up. During this process measurements can be taken as necessary. The system is left alone until the pressure reaches roughly 800 torr at which point a valve is opened to allow gas to escape from the system. For safety measures, if at any point the pressure in the HV volume increases over 800 torr the needle valve is opened or the HV volume is vented through V5.

e. Second Generation HV results:

The early data runs showed that as the pressure of the LHe increased so did the breakdown voltage. This was the expected result and verified the results measured in the larger system at Los Alamos. The breakdown strength decreased in superfluid helium. A promising result of the preliminary tests was that pressurizing the normal state helium

increased the breakdown voltage (Fig. 6), however, the system could not easily

accommodate tests on pressurized superfluid.
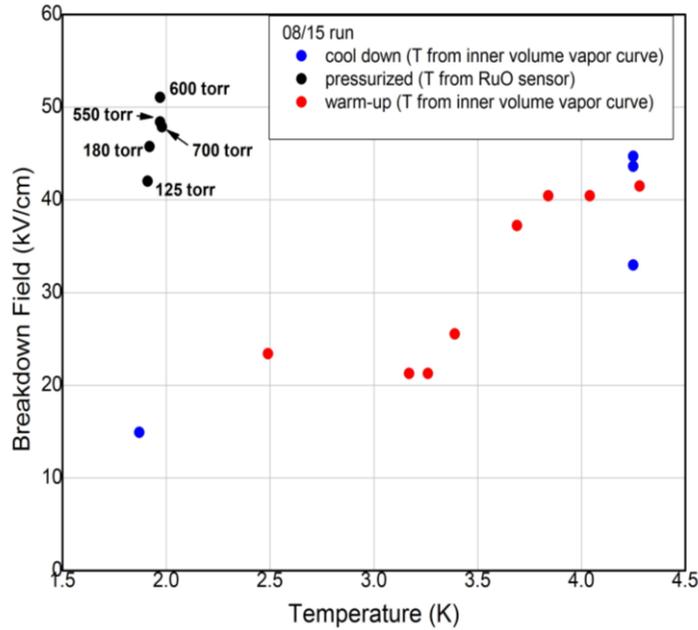
Figure 6: This is a plot of the breakdown field strength as a function of temperature.

These results prompted further testing of this phenomenon. Our tests at IUCF led

to the discovery of a hysteretic effect involving the pressurization cycle. As is shown in

Figure 7, the cool down and pressurization phases of both data runs had similar results,

however during depressurization the plot on the right shows improvement in the

breakdown strength. After the pressurization is completed valve V2 is closed and the

system is allowed to equilibrate. The outer LHe volume pulls heat out of the HV volume

thereby causing the gas in the line to condense until the pressure in the HV volume

matches that of the outer LHe volume. The minimum pressure achieved after

pressurization was generally lower than what was achieved when simply pumping on the

system originally. This is possibly due to the longer duration of cooling and because

most of the thermal mass has been sufficiently cooled. Performing a breakdown test after

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preparing the system in this way shows that the breakdown voltage remains high. This

suggests that it would be possible to pressurize the volume briefly, turn off the pressure,

and perform the nEDM measurement at the saturated vapor pressure and desired
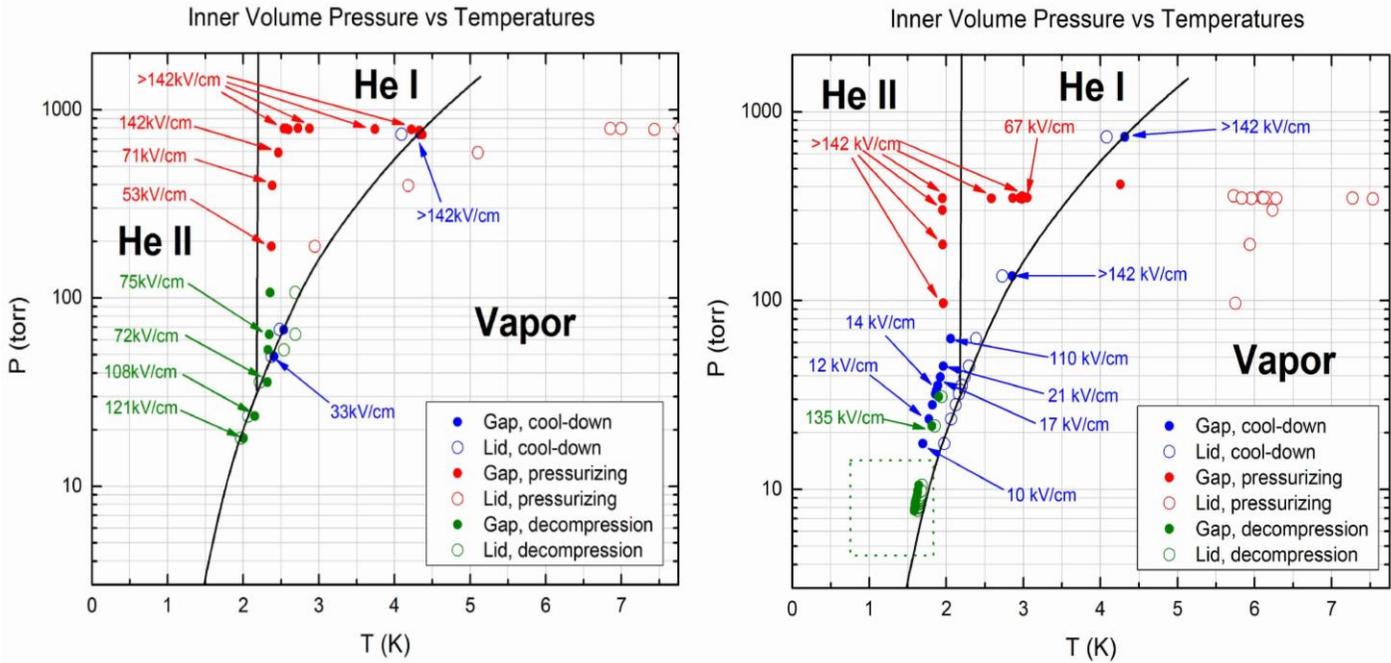
Figure 7: Graphs of breakdown strength as a function of temperature and pressure plotted on the phase diagram. This data was taken on Jan 28th 2008 (left) and Feb 4th 2008 (right).

temperature (sub-Kelvin). This has the added benefit that the helium gas bottle can be

turned off removing that heat source from the system

f.   Second Generation HV Discussion:

This hysteretic effect is a very intriguing effect, that has the potential of greatly

simplifying the process of doing the measurement because it allows the measurement to

be done in a non-pressurized system with all of the benefits of the pressurization. It was

suggested that this hysteretic effect is caused by a suppression of quantum vortices in the

superfluid helium, which are described in some detail in the paper by Milliken, Schwarz, and Smith [4]. The hypothesis was that these vortex quanta act like channels for electrical breakdown in the superfluid thereby decreasing the breakdown strength. Furthermore, our group proposed that by pressurizing the system we were suppressing these vortices. In order to test this hypothesis it is necessary to affect the number of active vortices in the HV volume and view the effect on the breakdown voltage. The lambda transition is a turbulent phase transition and this is when the vortices are created [4]. In this paper the measure the time constant on the dissipation of these to be on the order of an hour [4]. Therefore by taking a breakdown voltage data point after crossing the lambda transition and then a couple of hours later you could in theory test the effect of the number of vortices on the breakdown voltage. Due to the size of the dewar's outer LHe volume this is not possible because after a couple of hours it would not be possible to ensure that the gap between the electrodes was completely submerged in LHe. Another method of testing this phenomenon is described in the following section.

g. PZT Goals, Design, and Results:

A Piezoelectric Transducer (PZT) is a crystal which, when a change in mechanical stress is applied to a certain axis of a crystal, a current is induced through the crystal [5]. The converse piezoelectric effect, as the name suggests, consists of a voltage being applied across the crystal resulting in a deformation of the crystal. By applying an alternating voltage across the PZT an oscillation in the mechanical structure is produced in the crystal. A system was constructed, for our cryostat, to allow a PZT to be mounted

in view of the electrode gap. A sinusoidal alternating voltage would then be applied to the PZT to perturb the system. A critical speed over 10 m/s is required to induce vortices in superfluid LHe, therefore by oscillating the PZT, turbulence would be induced in the system and possibly additional vortices. These induced vortices together with the remnant vortices from the superfluid transition may produce a higher density of vortices thereby enhancing the effect on the breakdown strength.

In order to expose the perturbed superfluid helium to the electrode gap it is necessary for the PZT to be in view of and in close proximity to the electrodes. To do this a PZT mount was designed that screwed to the inside of the G-10 mount. The PZT mount consisted of a G-10 rod with a slit cut into the end into which the PZT could be inserted. The PZT was held in place with a set screw that was screwed in from the outside. The PZT was slightly wider than the OD of the mount allowing some of the conducting surface to be exposed at the base of the PZT. Wires from the auxiliary wire tube were soldered to each side of the PZT. These wires where then connected to a function generator. The PZT and function generator system were connected to the circuit shown in Figure 8, which could be used to measure the mechanical resonance of the PZT by monitoring the voltage output during the PZT operation.
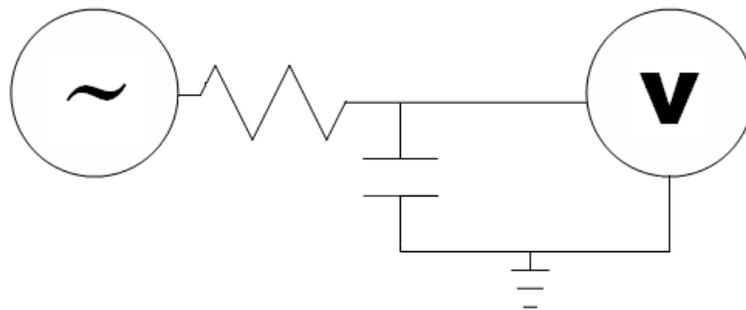
Figure 8: Circuit Diagram of the PZT control circuit. The capacitive load is the PZT.

Experimentation with the function generator output showed that the largest amplitude of oscillation occurred at the lowest frequency resonance. We found that we were unable to measure the amplitude of oscillation when the frequency was much above 1 kHz. Without the ability to measure the amplitude of oscillation at higher frequencies it was not possible to verify that the largest electrical resonance results in the largest linear speed. In order to overcome this shortcoming the PZT was run at multiple resonances during the PZT tests. This ensured that the largest electrical resonance was achieved, which is believed to correspond to the largest mechanical resonance. The PZT was also run off resonance as a control data set to measure the effects of the time dependent field on the breakdown strength.

The PZT measurement procedure was the same as the second generation HV test procedure until the end of the pressurization stage. After pressurization the system was allowed to equilibrate with valve V2 closed. After equilibration the PZT was turned on at a particular frequency for an allotted amount of time, generally a few minutes. After the system had been exposed to the perturbation a breakdown voltage test was preformed. Depending on the results of the breakdown voltage test another breakdown voltage measurement or PZT cycle would follow. It is worth noting that the signal of vortices being created and acting as breakdown channels would be a decreased breakdown voltage followed by a exponential decay toward the breakdown voltage measured before the PZT cycle. This would suggest that the vortices were created, affected the breakdown voltage, and the effect decayed as the vortices dissipated. In an attempt to ensure that the PZT ran at the highest linear speed possible tests were preformed, during the run, where the

frequency of the PZT was scanned from a couple Hz to 50 kHz. There were also tests in

which the PZT was left on during the HV breakdown measurement in order to verify that

any induced vortices did not have sufficient time to dissipate between the time the PZT

was turned off and the HV breakdown measurement. This also allowed observations of

the effect an applied AC field on the HV breakdown behavior.

h.   PZT Results:

A series of tests have been preformed to determine the effect of perturbing the

LHe in the HV volume using a PZT. Initial results suggested a response to the PZT cycle,

however the correlation remained unclear. The data taken on 2/4/2008 (Fig. 9) shows

breakdown measurements in which running the PZT on resonance appears to decrease the

breakdown strength as well as measurements with the opposite result. Although the

results were inconsistent they were sufficient to motivate further testing.
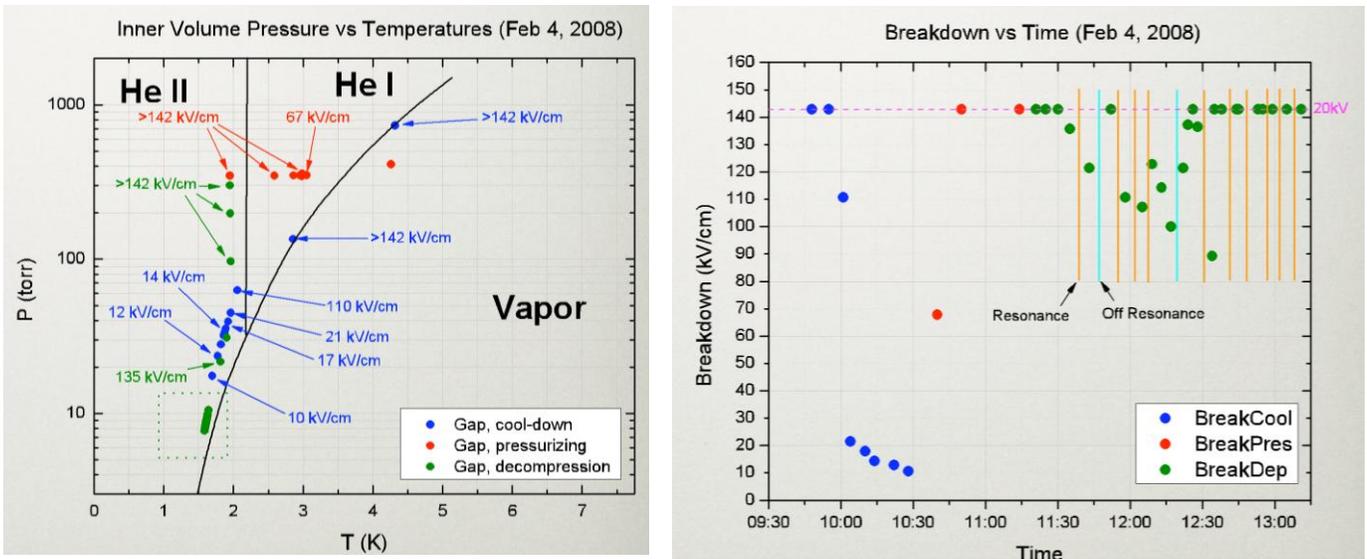
Figure 9: (left) Graph of the breakdown voltages plotted on the phase diagram. This data was taken on the first PZT data run. (right) Graph of the breakdown voltage as a function of time. The vertical lines correspond to runs of the PZT.

In the second PZT data set (Fig.10) the results remain inconsistent. The improved resolution of the time dependence after a PZT cycle shows that there seems to be no effective detriment to the breakdown strength. The hashed region in Fig. 10 shows a measurement where the PZT was left running during the breakdown measurement. This test was preformed to verify that the time constant of vortex dissipation wasn't sufficiently short that the signal was immeasurable after the time it would take to do a breakdown measurement. The final conclusion of these data runs was that the PZT had no repeatable effect. It is possible that the linear speed was not high enough to induce vortices since it was not possible to verify that the linear speed of the PZT was greater than 10 m/s.
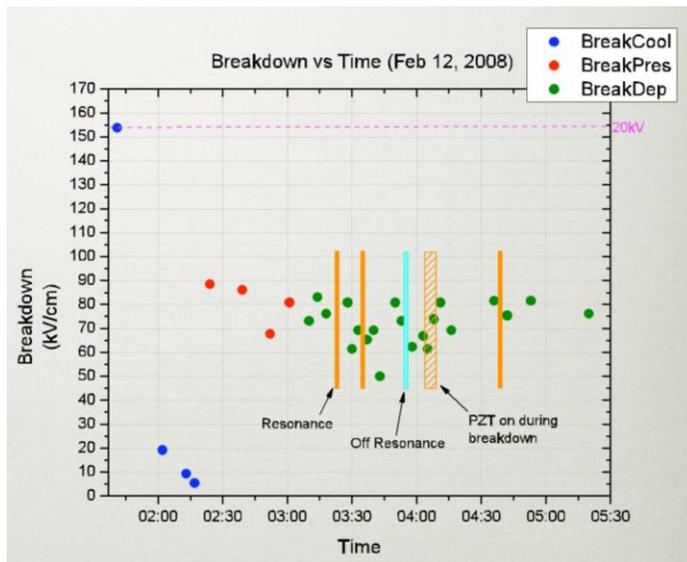
Figure 10: Graph of the breakdown voltage throughout a data run. The vertical lines correspond to PZT runs.

An attempt to coat a PZT with gold plating in order to improve its conductivity was preformed; however the PZT shattered during the sputtering process. Due to time constraints a further investigation of the PZT and the effect of vortices on the breakdown voltage was postponed. Second generation PZT measurements may be performed, however nut until investigations on the electrode surface smoothness are completed. A further effort might be put into measuring the amplitude of the PZT

oscillation as well as increasing the linear speed to improve the probability of vortex formation.

i.   Polarity Test:

Previously published results have shown that the polarity of the sphere-plate capacitor system, like the one at IUCF, greatly affects the breakdown strength [4]. This was tested by taking more data after the polarity of the HV source was reversed thereby making the spherical electrode the anode and the plate electrode the cathode.(Fig. 10)**.** The results of this test showed that the breakdown strength decreased after the polarization was reversed. This can be seen by comparing Fig. 10 with the first generation HV measurements.
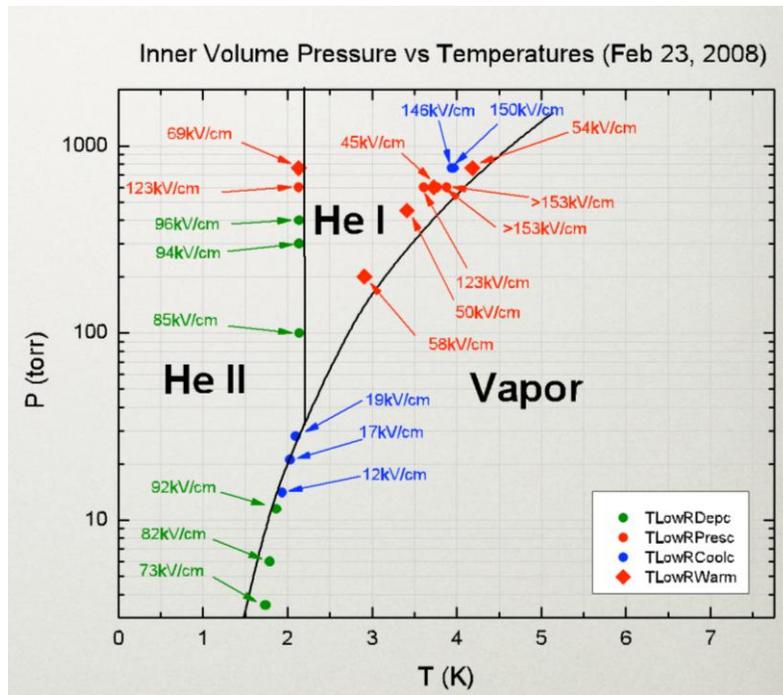
Figure 11: Graph of HV data plotted on the He phase diagram. Polarity of the ss ball electrode is positive.

IV. Conclusion:

The HV R&D carried out by our group at IUCF has produced significant results directly applicable to the nEDM experiment. The group has experimentally demonstrated the improved breakdown strength in superfluid He under pressurization. Furthermore, a hysteretic effect has been observed, which suggests that even after removing the applied pressure the breakdown remains elevated. This effect has been hypothesized to be a suppression of the quantum vortexes in the superfluid. Since the quantum vortices might act as excessive conducting paths for the electrons, a reduction in the vortex density could result in improved breakdown strength. The tests to verify the effects of quantum vortices using PZT actuators have been, however, inconclusive. Another theory has been suggested that the hysteretic effect is actually a manifestation of a change in the surface wetting characteristics after a pressurization cycle. This hypothesis could be studied using electrodes with surfaces of extreme smoothness, such as float glass or silicon wafers.

Reversing the polarity of the HV source, and therefore electrodes has shown that the polarity of the system has a strong effect on the breakdown strength. This is thought to be caused by the differences in the geometry of the two electrodes. Since the breakdown initiates on the cathode the surface roughness, surface area, and bubble formation properties of the cathode have a larger effect on the breakdown strength than those same properties of the anode.

The group is currently still measuring the effects of various phenomena and their impact on the breakdown voltage. An effort is underway to coat a dielectric electrode with a conducting surface. This is expected to decrease the noise for the SQUID reading in the system by decreasing the conducting materials, which may induce eddy currents if the field in the volume is changing. These eddy currents will be measured by the SQUID and thereby increase the background noise of the reading.

One further test relevant to the nEDM experiment is the optical detection of breakdown or micro-discharged caused by the HV environment in superfluid helium. The nEDM experiment relies on the detection of scintillation lights to decode the spin precession frequency of neutrons, and therefore any sources that could cause scintillations should be well understood. An optic fiber system is being designed in order to measure any background light that might result from the HV field. The general design is that a wavelength shifting optic fiber will be wrapped on the inside of the G-10 mount. This optic fiber will then couple with a clear fiber that runs through the auxiliary wire tube, through the Stycast glue seal, and into the BNC box at the top of the line. This will then be coupled to another fiber which will run to a photomultiplier tube (PMT) that will be located at room temperature. The wavelength shifting fiber will be selected to down scatter ultraviolet light into green or blue light in order to take advantage of visible light's increased attenuation length.

V.   References:

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