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Gas propagation following a sudden loss of vacuum in a pipe cooled by He I and He II.

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Abstract. Many cryogenic systems around the world are concerned with the sudden catastrophic loss of vacuum for cost, preventative damage, safety or other reasons. The experiments in this paper were designed to simulate the sudden vacuum break in the beam-line pipe of a liquid helium cooled superconducting particle accelerator. This paper expands previous research conducted at the National High Magnetic Field Laboratory and evaluates the differences between normal helium (He I) and superfluid helium (He II). For the experiments, a straight pipe and was evacuated and immersed in liquid helium at 4.2 K and below 2.17 K. Vacuum loss was simulated by opening a solenoid valve on a buffer tank filled nitrogen gas. Gas front arrival was observed by a temperature rise of the tube. Preliminary results suggested that the speed of the gas front through the experiment decreased exponentially along the tube for both normal liquid helium and super-fluid helium. The system was modified to a helical pipe system to increase propagation length. Testing and analysis on these two systems revealed there was minor difference between He I and He II despite the difference between the two distinct helium phases heat transfer mechanisms: convection vs thermal counterflow. Furthermore, the results indicated that the temperature of the tube wall above the LHe bath also plays a significant role in the initial front propagation. More systematic measurements are planned in with the helical tube system to further verify the results.

1. Introduction

Cryogenic systems throughout the world are used in a variety of applications from space launch vehicle fuel storage to magnet cooling in MRIs, NMRs and particle accelerators. One major safety concern of a cryogenic system which stores a liquid cryogen such as nitrogen, hydrogen or helium is the sudden loss of vacuum. Loss of vacuum introduces a huge heat load on the liquid cryogen which causes it to boil rapidly and can cause a dangerous build in system pressure. This is one of the major reasons cryogenic systems are designed with many safety mechanisms [1-2].

Particle accelerator systems such as the European X-Ray Free Electron Laser at Deutsches Elektronen-Synchrotron (DESY) Germany or the proposed Linear Collider in Japan are cryogenic systems which use Superconducting Radio Frequency (SRF) technology to generate an accelerating electromagnetic field. These systems are composed of multiple segments called cryomodules which contain SRF niobium cavities, baths of liquid helium (LHe), sensors and other machinery. Cryomodules contain two vacuum spaces. The first vacuum space is the insulation space for the helium bath which immerses the niobium cavity. The second vacuum space is in the center niobium beam tube where the accelerated particles travel. The first vacuum shield space is frequently, but not always, isolated to a cryomodule. If the cryomodules are isolated then only a single module would be affected in the case of a vacuum insulation shield failure. The second vacuum space is an interconnected void between all cryomodules of the system. If there is a sudden rupture of this second vacuum space, there is potential that the entire system could become affected [3-7].

Vacuum loss in the particle accelerator beam-lines has the potential to cause considerable damage of the systems. These safety concerns have lead several SRF accelerator laboratories to conduct many simulations and tests in the development stage. For example, tests performed at Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab in the US to ensure pressure relief and safety devices were appropriately sized to handle the pressure build up from rapid boiling of helium due the heat load [8]. There are two aspects to consider when investigating loss of vacuum in the beam-line tubes. First is the heat load introduced on a cryomodule by the entering air. This causes pressure buildup in a cryomodule. The second is the scope of the failure or how many cryomodules will become contaminated due to a rupture. The scope of the failure is determined by the propagation speed of air in the vacuum space or how far the gas will travel in a given time interval. Safety devices installed along the beam tube can limit the scope of failure by isolating cryomodules ahead of the propagating gas front.

Previous research at NHMFL Cryogenics Lab attempted to quantify and model the propagation of the gas front in a beam tube using a pipe immersed in LHe. It was observed from experimentation that the propagating gas front speed decreases exponentially along the length of a tube in normal helium (He I). This paper expands on that research looking at the difference between normal helium and super fluid helium (He II).

2. Experiment

2.1. Design simplification

This experiment worked from a simplified model of a cryomodule. The SRF niobium cavities in the cryomodule are complex shape of a series of elliptical shaped cells and short interconnecting center pipes. To simplify the shape for both analysis and fabrication, a straight pipe was used. This allows a constant cross section over the measured length. Oxygen free high conductivity (OFHC) copper pipe was used instead of niobium due niobium's nonstandard sizes, difficulty in procurement and high cost. In addition, copper can be silver-brazed or welded to stainless steel making it easier to use in fabrication. Fabrication using niobium involves nickel plating before welding which is a costly process.

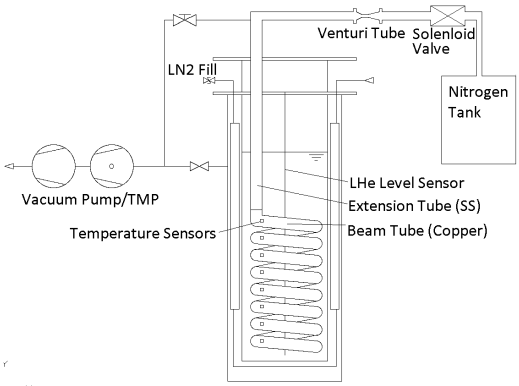
In an actual loss of vacuum situation air will rush into the beam tube and condense or freeze. Air is a mixture of several different elements and compounds, which is complex to analyze. Dry air is a mixture of two major components 21% oxygen and 78% nitrogen by volume. To simplify the experiment and control possible variation in results, pure nitrogen gas was used.

2.2. Experimental systems

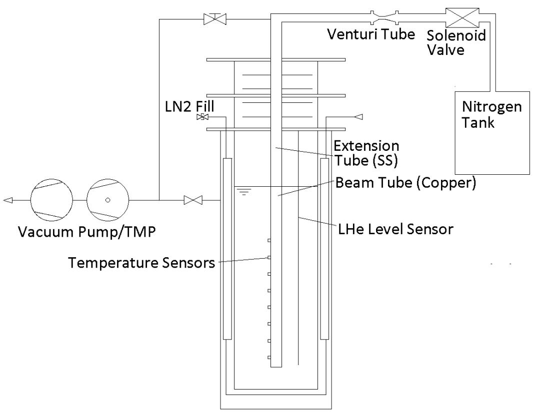
Initial experiments to study the gas propagation were conducted in a straight tube immersed in LHe [6-7]. It was desired to change the system and look at longer propagation lengths while allowing tests to use less helium. The system also needed to allow new coils to be switched and resolve an issue with data noise. A new system was proposed and fabricated incorporating a helical tube design instead of a straight tube design. A diagram of the original straight tube experimental setup is shown in figure 1a and the improved helical tube diagram is shown in figure 1b. Figure 2 shows a picture of the helical tube structure after fabrication. Nitrogen reservoir for the straight tube setup was 86 L and is 757 L for the helical tube system. The reservoir for the helical system was changed to minimize the pressure drop of the reservoir for the duration of the experiment thereby maintaining a near constant mass flow rate. The nitrogen tank reservoir is connected to a fast-acting solenoid valve with an opening time <25 ms. Exit of the solenoid valve is connected to a miniature venturi tube for flow regulation. The venturi tube is attached to a 32 mm 304 stainless steel (SS) extension tube. The extension tube penetrates through and is supported by an aluminium top plate flange. On the other side of the aluminium flange is a tube union allowing the copper coil segment to be detached and replaced for future experiments. The extension tube continues from the union then is silver brazed to an oxygen free high conductivity (OFHC) copper pipe. The copper pipe functioned as a simplified beam tube for the experiment. Table 1 shows a comparison of the geometries of the old and new system.

Table 1. Oxygen free high conductivity copper pipe dimensions.

	Straight tube system	Helical tube system
Pipe length (m)	1.5	5.75
Inner pipe diameter (mm)	32.1	25.4
Wall thickness (mm)	3	1.25
Coil diameter (mm)	-	229



(a)



(b)

Figure 1. System diagram of the straight beam tube (a) and the helical beam tube (b).

Figure 2. Internal assembly of helical tube system.

2.3. *Instrumentation and Safety*

To measure gas propagation in the copper tube eight Lake Shore Cernox^{TM} thermometers were encapsulated in 2850 FT Stycast® epoxy to provide insulation from the bulk LHe [9]. The copper tube was thin walled unlike the straight tube system so it was deformed slightly and polished to create a flat surface for the sensor to mount. Each sensor was installed with indium foil and Apiezon® N thermal grease to ensure good thermal contact on the outer surface at regular intervals of 12.7 cm for the straight tube and 71.9 cm for the helical system. The sensor was secured to the tube by twisting stainless steel wire and varnish from Lake Shore. Figure 3 shows the installation of one sensor on the helical tube system. Previous research conducted at NHMFL showed temperature monitoring of the tube surface more responsive to the gas front arrival than pressure sensors so this method was continued for the helical tube system [6]. Data from the temperature sensors was routed into four Data Translation, Inc. DT9824 USB data acquisition modules and recorded with National Instruments LabView^{TM} at a frequency of 4800 Hz.

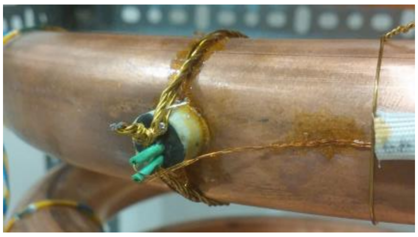


Figure 3. Stycast® epoxy encapsulated temperature sensor mounting on surface of helical tube system.

A superconducting liquid helium level sensor was attached to the side of the beam tube to accurately measure the liquid level. For the helical tube system, the 45.7 cm calibration hole was aligned with the start of the copper pipe after the elbow.

A cold cathode gauge (range of 10-3 to 10-7 torr) was attached to the beam tube to measure the vacuum pressure prior to cooling down and running the experiments. Pressure in the nitrogen gas reservoir was measured with a 1000 Torr vacuum gauge.

Liquid helium boils off rapidly following a large heat load in a system. Two large diameter 5 psi safety valves were placed on the system to ensure minimal pressure build-up while venting as much helium as possible into the helium recovery line. Following the experiment, the system was allowed to warm to room temperature to remove all frozen gases and prepare for subsequent experiments. To prevent pressure build up inside the beam tube during warming, another safety relief valve for the internal beam tube space was added.

During transfer of liquid cryogens standard procedures were taken when dealing with cryogenic liquids: safety goggles, long insulated gloves, and long clothing.

2.4. *Experimental procedure*

To begin an experiment, the beam tube and vacuum shield were fully evacuated below 10^{-5} Torr with an turbo-molecular pump system. Once the system was fully evacuated, liquid nitrogen (LN_2) was filled into the LN_2 shield on the cryostat and the inner LHe bath for precooling. After LN_2 was left in the system for at least ten hours, LN_2 in the inner bath was drained back into a Dewar by pressurizing the inner bath with He gas. After the LN_2 was removed, the system was allowed to warm to 90 K to ensure all the liquid nitrogen was gone from the LHe bath space. During the 90 K warmup phase the nitrogen gas buffer tank was purged with ultra high purity nitrogen gas three times then left at 760 Torr for the experiments. Following the warmup, the LN_2 shield was refilled and then LHe was slowly transferred into the system over several hours. For the He II run, the cryostat was slowly filled to a maximum level of 83.8 cm on the liquid level sensor. After the bath was full, the helium recovery line was closed, and the bath was opened to a large facility vacuum pumping system. The facility vacuum pump pumped on the bath until it reached under 1.9 K. For He I experiment, the bath was not pumped on. He I was filled to the same level that the He II was pumped down to which ended up being 45.7 cm liquid level measurement or the copper-stainless pipe transition. When the sensors read the appropriate temperature, the liquid level indicated a level over the sensors, all vacuum valves were closed isolating the pumping systems from the beam tube and the helium bath in the He II experiment. The liquid level was recorded and the gas pressure in the buffer tank was verified then data acquisition was started. When the acquisition system had been recording for at least one second, a signal current was supplied to the solenoid valve to open between the buffer tank and the evacuated tube. The solenoid valve was left open for at least 8 seconds allowing nitrogen gas to flow then the valve was shut. Following the experiment, the data was then processed via Matlab.

3. Results

3.1. Preliminary data processing

In the straight tube system, the data output from the sensors had a significant amount of harmonic noise. To solve the issue, a moving average was used to smooth out the data and then determine the rise time [6-7]. The smoothed-out curve was then used to find the threshold temperature that was three times the standard deviation (σ) of the sensor with the maximum noise over the average bath temperature (μ). The effect of taking the moving average is shown in figure 4. Time equal to 0 is when the solenoid valve opened on the system. This method of data smoothing was also used in the helical tube system even though the data was cleaner. Figure 5a shows all the temperature data without smoothing for the straight tube system and figure 5b shows the temperature data without smoothing for the helical system. Comparing the two graphs, it can be seen the worst sensor has a ±0.25 K temperature swing. In the new helical system, the noise issue was mitigated but not eliminated and less than ±0.05 K swing was observed.

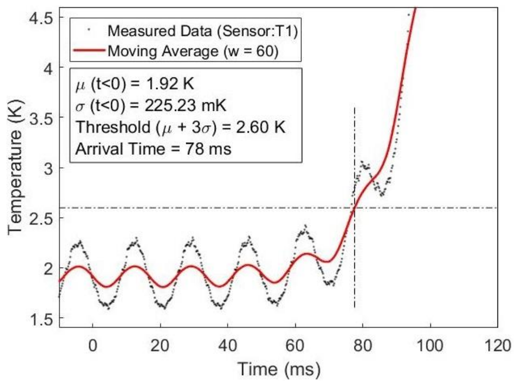
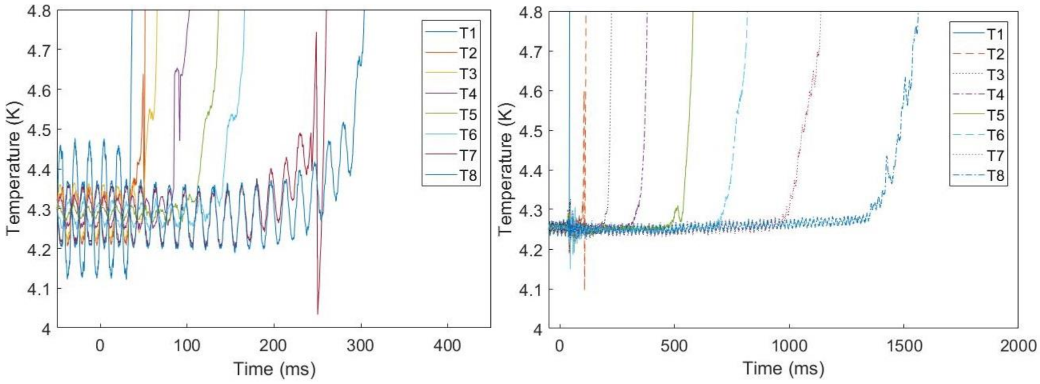


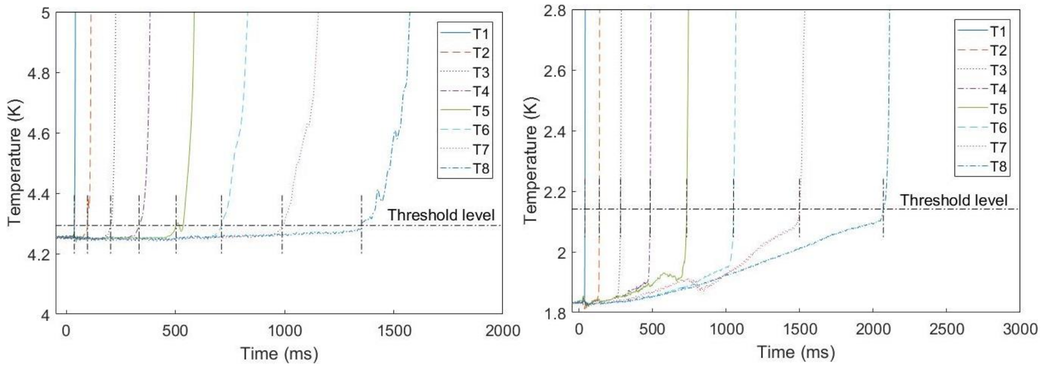
Figure 4. Effect of smoothing out harmonic data noise seen in the temperature data.

For the new helical tube setup, there was an observed gradual rise in all the sensor data for He II run starting as soon as the first temperature sensor rises as seen in figure 6b. This was perhaps due to the sensors close proximity (51 mm spacing from pitch) to each other and the highly efficient thermal counterflow of He II. The threshold temperature could not be set to three times the sensor deviation as it was for the He I run and previous straight tube analysis. A value of 2.15 K bath temperature was chosen for analysis purposes because it was in the near vertical slop region of the graph for all the sensors and just below the 2.17 K He II phase transition temperature. Figure 6 shows the threshold temperature across all eight temperature sensors after a 60 point average smoothing for both He I and He II test. At time 0 the solenoid valve opened on the system.



(a) (b)

Figure 5. Shows the non-smoothed data noise in all temperature sensors for the straight tube system (a) and improved noise level in new helical system (b) for a He I run.



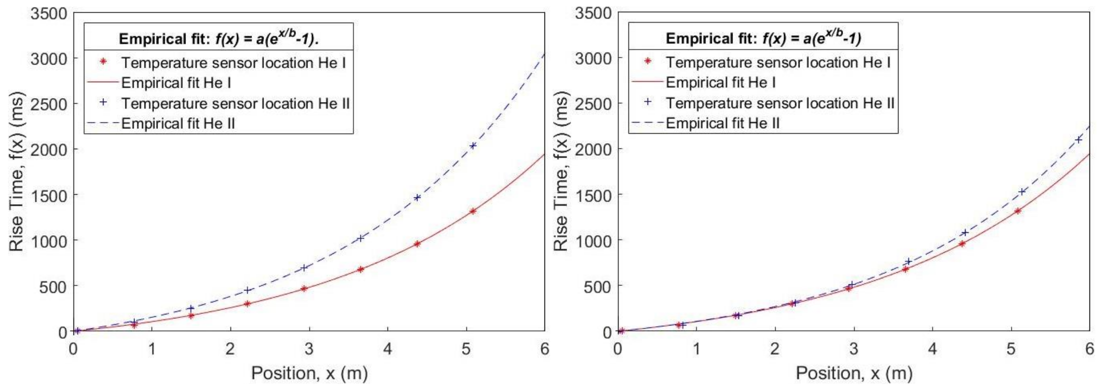
(a) (b)

Figure 6. Threshold temperature and corresponding rise time for all temperature data in the helical system after 60 point moving average smoothing for He I (a) and He II (b).

3.2. Gas front propagation modelling.

After rise times were acquired, a model of gas propagation can start to be formed. Following the previous model proposed by R Dhuley et.al. [7], an exponential curve was fit using $f(x) = a(e^{x/b}-1)$ where $f(x)$ is the arrival time at the location x and $x = 0$ is the liquid level and the entrance to the tube. The coefficients a and b are obtained by non-linear least squares regression. Converting the arrival time- location curve to propagation velocity yields the equation $v = v_o\, e^{-x/b}$. In the equation, the v_o term is the velocity at the tube entrance and is $v_o = b/a$. It is assumed that start of condensation section of the tube occurs at this first temperature sensor which is immersed in liquid helium. Figure 7a shows the rise time as a function of position and the curve fit to the model for both He I and He II. Table 2 shows the a and b coefficients, the calculated initial velocity v_o with the helical system, as well as the previously obtained values for He I in the straight tube system and a nitrogen reservoir pressure at 760 Torr. It can be seen that the He II run slows faster than the He I run which can be expected because of the high heat transfer rate of He II via thermal counterflow. Looking at the coefficients, there are some significant discrepancies between the values previously proposed and the values calculated from the same method. From those calculated coefficients, inlet velocities are different: the previously calculated value of 20.32 m/s versus this time a calculated value of 11.42 m/s and 7.91 m/s. Looking at only He I, coefficients for the helical tube and the previously obtained values also under He I the differences could be explained by the different tube diameters, different wall thicknesses, and different tube length. The previous model doesn't take these physical aspects into account.

Looking at just the helical tube data, there should be trivial difference in the entrance velocity of the tube between the He I and He II since they were conducted in the same system under the same experimental parameters: same liquid level and same reservoir tank pressure. The previously proposed model assumes that most all condensation and deposition start below the LHe bath level. Removing this assumption, the analysis was redone such that the temperature sensor location was based on the maximum fill level of the liquid helium not the actual level of the liquid helium. For He I data, the analysis point stayed the same but for He II, the analysis point was 38 cm higher so the position data shifted. This was done because the upper portion of the tube is still cold from the fill and evacuation process. In addition, He II will creep up the surface of the pipe to some extent so there will be a film of He II higher up which also has some additional cooling effect. The new analysis with shifted He II position is shown in figure 7b and the coefficients are listed in table 3. From the graphed and tabled analysis, one can now see that the inlet velocities match closely for both He I (11.42 m/s) and He II (11.40 m/s). This indicates there is a significant amount of condensation and deposition in the tube section above the bath. Looking again at figure 7 and the coefficient data in table 3, it also can be seen that He II shows a slightly higher velocity decay rate, but the rate difference is significantly smaller than the initial analysis. The shifted data again also shows very different results when compared to the previously obtained values which still could be explained by different physical aspects of the straight pipe system versus the helical pipe system.



(a) (b)

Figure 7. Graphs of rise time as a function of position. Graph (a) was analysed based on actual LHe level and (b) was shifted and analysed based on maximum LHe fill level before vacuum pumping.

Table 2. Calculated coefficients and inlet velocity based on actual liquid level height at 760 Torr.

	a (s)	b (m)	$v_o = b/a$ (m/s)
Helical tube He I	0.236	2.70	11.42
Helical tube He II	0.323	2.56	7.91
Published straight tube He I [5]	0.031	0.63	20.32

Table 3. Calculated coefficients and inlet velocity based on maximum filled level.

	a (s)	b (m)	$v_o = b/a$ (m/s)
Helical tube He I	0.236	2.70	11.42
Helical tube He II	0.216	2.46	11.40

4. Conclusion

Sudden vacuum loss is important in many cryogenic systems. Vacuum loss can be dangerous to those in the vicinity of the system, and it can cause significant expensive equipment damage. Particle accelerators have two vacuum chambers which could lose vacuum. The first is the insulation, and the second is the vacuum tube which the particles travel in. In an effort to better understand and model how gas propagates following a catastrophic failure in the second tube space, the NHMFL Cryogenics Lab has been conducting experiments in breaking vacuum in tubes surrounded by liquid helium.

The first system was a straight tube system which was used to propose an exponential model for determining the arrival time and velocity decay rate in the tube. To improve the system and further develop the model, the system was changed to a helical tube based system. This new system allows for easy switching of different tubes and longer tube lengths while using less liquid helium. In addition, the noise seen in the straight tube system was mitigated.

The difference between He I and He II was tested in the helical system. The data was first analysed by the method previously developed at NHMFL. He I data had inconsistent results between the straight tube and the helical tube. This could be because of different physical tube parameters between the experiments. Initial analysis of the He II data showed a faster decay rate or higher slowing rate, but there were inconsistencies in the inlet velocities between He I and He II. The inlet velocities should be approximately the same because they were conducted under the same gas reservoir pressure in the same system yet were significantly different. In an attempt to solve the discrepancy, He II data was reprocessed removing the assumption that the condensation or deposition region is only in the LHe bath and assuming that it also happens much higher in the tube. Changing the assumption shifted the origin up by 38 cm to the location which is the maximum fill level of the LHe before vacuum pumping and converting it to He II. The result of the shifted analysis was the inlet velocities matched indicating there is likely significant condensation and deposition happening above the LHe bath level.

In future, we plan to conduct further investigations and refine the propagation model. Better understanding about what happens above the liquid level is needed so the inlet velocities should correspond to each other. In addition, it is planned to look at the different physical aspects of a tube and how these factors play into the propagation.

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