Actualizing the Abstract – How the Cryo-Industry Takes Ideas and Provides Proven Technology for Diverse Applications

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ABSTRACT

Over the past 55 years, Cryomech has been a leading supplier of low-temperature cryogenic solutions for industrial and laboratory applications. Many of these solutions begin with a paper concept to fulfill the needs of a diverse application challenge. Involvement in this industry has provided a unique window into some of the world's most cutting-edge cryogenic applications. In this paper, we explore three of these diverse and scientifically challenging applications of cryogenic cooling. In particular, applications in ground-based telescopes, helium recovery solutions for MEG cryostats, and superconducting technology. Specific examples in each of these areas will describe both the application and the cryogenic technology used to support the application.

INTRODUCTION

Cryomech was founded in 1963 by William E. Gifford during the early years of his career at Syracuse University as a professor of Mechanical Engineering. Since its inception, Cryomech has operated with a special focus and a unique culture of saying yes to challenges that have continuously empowered us to partner with innovators across diverse fields of applications. Many of Cryomech's products have matured from early prototypes that were developed to solve specific heat removal needs. Cryomech now boasts over 30 standard cryocooler models, covering a temperature range from 2.8K to 120K. Despite the wide selection of standard cryocoolers, Cryomech still maintains the ability to further customize per application, including a diverse selection of liquefiers and reliquefiers. With this experience, Cryomech is distinctly positioned to collaborate with thought leaders in pioneering unique solutions for the next generation of cryocooling needs.

CRYOCOOLER APPLICATIONS IN GROUND-BASED TELESCOPES

Introduction of Ground-Based Telescopes

Ground-based telescopes enable the study of the visible and invisible regions of the universe from Earth. Despite the challenges presented by Earth's atmosphere, the ever-expanding technology of ground-based telescopes is an extensive research field, especially when compared to their space-based counterparts. The development and deployment costs of ground-based telescopes are significantly less than space telescopes, and they provide the versatility to simultaneously conduct interdisciplinary studies at a relatively high pace. Perhaps the most beneficial factors are the ease of physical access, ease of repair, and ability to

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readily upgrade. Generally, these telescopes are found in remote regions of the world, at high altitudes with dry climate conditions and predictably harsh environments, demanding the need for proven and reliable cryocooler technology.

Ground-based telescopes are used in diverse fields of research that span from cosmic background radiation from the Big Bang and gravitational wave studies, to currently observable details of the formation and demolition of stars and galaxies, to dark matter and dark energy.

General Background of Cryogenics in Ground-Based Telescopes

The progression of utilizing cryogenics in ground-based telescopes is generalized in four phases: liquid cryogens, early cryocoolers, 2-stage cryocoolers, and milli-Kelvin technologies. Liquid cryogens, such as liquid nitrogen and liquid helium, were used in the initial phases of deployment to remove heat from instrumentation and detectors at 77 K and 4.2 K, respectively. While efficient in addressing the heat lift problem, transporting liquid cryogens to remote sites was challenging, and posed safety concerns associated with handling liquid cryogens in confined spaces.

The next phase of improvements included the introduction of early cryocoolers. Gifford–McMahon (GM) type cryocoolers were used to mitigate the need for liquid cryogens. These coolers had relatively low heat lift capabilities but were able to conductively cool the mating parts and assemblies. The inherent challenges with operating these included high levels of vibration, which were detrimental to operating sensitive detectors, short mean time between maintenance (MTBM) intervals that required attention from a specialist, and limited power availability to operate these systems at remote and desolate locations.

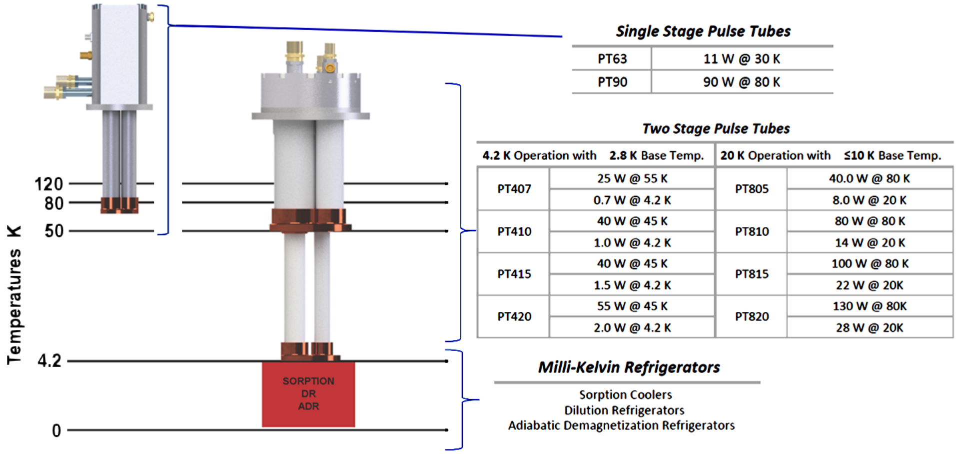
Advancements in cryocooler technology led to the introduction of 2-stage cryocoolers to ground-based telescope applications. At this time, 2-stage cryocoolers were semi-commercially available products that were generally developed and supported by universities or independent research groups. The MTBM was improved, and the vibration levels associated with operating these systems became more manageable when compared to early cryocoolers. Early 2-stage cryocoolers were capable of simultaneously removing heat at approximately 70 K and 20 K on the 1st stage and 2nd stage, respectively. As cryocooler technologies evolved, lower temperatures were achieved with increased heat lift. Before the introduction of milli-Kelvin technologies, 2-stage cryocoolers were successfully operating between 55 K to 65 K on the 1st stage and 4.2 K to 20 K on the 2nd stage.

Presently, ground-based telescopes are installing milli-Kelvin technologies to utilize advanced detectors to the full extent of their capabilities. Milli-Kelvin technologies consist of 2-stage cryocoolers coupled with sorption coolers, dilution refrigerators, or adiabatic demagnetization refrigerators. These commercially available products were integrated and supported by national and international focus groups. Continuously improving heat lift capacities of cryocoolers and extensive focus on vibration reduction are allowing researchers and developers to introduce more complex and highly sophisticated detectors.

Cryocooler Integration and Technical Challenges

Cryomech offers two distinct design envelopes: Single-stage and 2-stage Pulse Tube cryocoolers utilized in ground-based telescopes. Single Stage Pulse Tube cryocoolers cover the 30 K to 80 K temperature range with heat lift capacities of 11W to 90W, respectively. The 2-Stage Pulse Tube cryocoolers operating in the range of 4.2K to 20K with varying heat lift capacities depending on the model. Figure 1 shows specific cryocooler models with their associated performance specifications. Milli-Kelvin coolers, such as sorption coolers, dilution refrigerators, and adiabatic Demagnetization refrigerators, typically use 2-Stage Pulse Tubes as precoolers. The 1st stage of the cryocooler is mainly used for thermal shielding and precooling in the range of 50 K, while the 2nd stage is normally used to provide heat lift between 3 K to 4 K.

There are several technical challenges associated with integrating the above-mentioned Pulse Tube cryocoolers. The two most notable challenges are vibration isolation and serviceability. Sensitive detectors require low levels of vibration to operate effectively. GM cryocoolers inherently have a high level of vibration due to their internal moving displacer/regenerator. Pulse Tube technology significantly reduces vibration concerns. However, depending on the application, additional measures must be taken to achieve acceptable vibration levels for sensitive devices. Bellows assemblies and thermal braids, as shown in Figure 2, are two vibration mitigation techniques that are used in conjunction with Pulse Tube cryocoolers. A bellows assembly is mounted between the cryocooler's room temperature flange and the cryostat housing to dampen the



Single Stage Pulse Tubes

PT63	11 W @ 30 K
PT90	90 W @ 80 K

Two Stage Pulse Tubes

4.2 K Operation with	2.8 K Base Temp.	20 K Operation with	≤10 K Base Temp.
PT407	25 W @ 55 K	PT805	40.0 W @ 80 K
	0.7 W @ 4.2 K		8.0 W @ 20 K
PT410	40 W @ 45 K	PT810	80 W @ 80 K
	1.0 W @ 4.2 K		14 W @ 20 K
PT415	40 W @ 45 K	PT815	100 W @ 80 K
	1.5 W @ 4.2 K		22 W @ 20K
PT420	55 W @ 45 K	PT820	130 W @ 80K
	2.0 W @ 4.2 K		28 W @ 20K

Milli-Kelvin Refrigerators

Sorption Coolers
Dilution Refrigerators
Adiabatic Demagnetization Refrigerators

Figure 1. Pulse Tube Cryocooler Models and their associated cooling capacities.

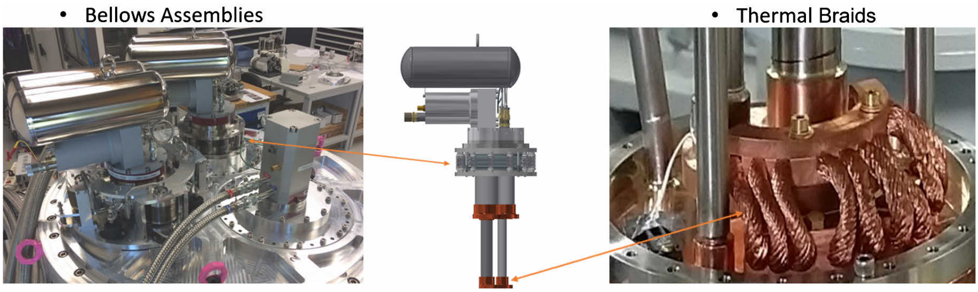


Figure 2. Photos of cryocooler fitted with bellows assembly and thermal braids for vibration isolation [1].

dynamic displacement introduced by the warm end of the cryocooler. Thermal braids are used in combination with the bellows assembly to further decouple the displacement observed at the heat exchanger.

The second major technical challenge presents itself during the cryocooler's service interval. For regularly planned cryocooler service intervals, the goal is to minimize downtime and reduce the risk of critical errors associated with removing and reinstalling the cryocooler into the cryostat. To address these challenges, Cryomech has developed an Ultra High Vacuum (UHV) compatible sleeve that serves as a permanent thermal connection to the cryostat. As shown in Figure 3, when installed in the sleeve, a conductive connection is made between the heat exchangers of the cryocooler and the sleeve. The sleeve isolates the cryocooler from the cryostat's mating assemblies and allows for the removal and reinstallation of the cryocooler without breaching the cryostat's vacuum space. The sleeve is equipped with a port to evacuate the cryocooler interface space, an electrical feedthrough for instrumentation, and an independent pressure relief valve as a safety precaution.

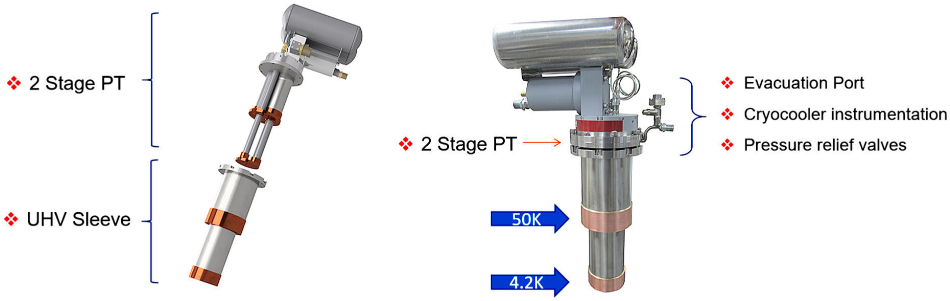


Figure 3. UHV sleeve to cryocooler interface.

HELIUM RECOVERY SOLUTIONS FOR MEG CRYOSTATS

Introduction of a Conventional Magnetoencephalography (MEG) Cryostat

Magnetoencephalography (MEG) is a functional neuroimaging technique for mapping brain activity by recording magnetic fields produced by electrical currents occurring naturally in the brain. Commercial MEG systems presently use superconducting detection coils inductively coupled to superconducting quantum interference devices (SQUIDs) to measure MEG signals. SQUIDs are extremely sensitive detectors of magnetic flux. They utilize a Josephson junction to detect MEG signals from the human brain varying between 10^{-11} and 10^{-14} Tesla.

MEG systems operate at the temperature of liquid helium (LHe), requiring LHe as the coolant. In many MEG facilities, the evaporated helium gas is released from the MEG cryostat into the atmosphere. Regular manual transfer of LHe is required. This mode of operation is quite costly since the supply of LHe is scarce, expensive, and sometimes unreliable, and regular helium transfers require a significant amount of trained technician labor. The large expense of helium maintenance has limited the widespread use of this technology for measuring human brain functions.

Design Challenges for a Closed-Cycle Helium Reliquefier in an Innovative MEG Cryostat

In order to eliminate the manual transfer of LHe, closed-cycle helium reliquefiers are being utilized in many applications. For MEG cryostats there are two main design approaches. In one approach, the reliquefier is placed above MEG sensors within a single cryostat in order to reduce the heat loss from the reliquefier to the MEG cryostat. The reliquefier, however, must be turned off during MEG measurements. In the second approach, the reliquefier is placed outside the MEG cryostat to reduce the noise transmitted to the MEG sensors. A notable challenge to this approach is minimizing the LHe losses as it flows through the transfer tube from the reliquefier to the MEG cryostat.

Therefore, the design challenges of closed-cycle helium reliquefiers for MEG applications are: 1) Continuous, uninterrupted operation during MEG measurements; 2) Ultra-low vibration and noise level requirements; 3) Reduction of LHe loss in the transfer tube from the reliquefier to the MEG cryostat.

Solutions for Ultra-Low Vibration, Uninterrupted, and Maintenance-Free Operation

Cryomech has developed efficient, closed-cycle helium reliquefiers for MEG that are compact and simple in design without requiring a storage gas tank or a gas purifier, with very low vibration noise for uninterrupted operation of the reliquefier during MEG measurements [2]. These reliquefiers use a 2-Stage 4K Pulse Tube cryocooler developed at Cryomech.

One of these systems has been installed in a MEG facility at Boston Children's Hospital (BCH) established for basic and clinical human brain development research [2]. A 2-Stage Pulse Tube cryocooler, Cryomech model PT415-RM, utilizing a remote motor configuration, was used in their reliquefier application. Figure 4 shows the closed cycle helium reliquefier installed in a pediatric MEG system at BCH.

Figure 4. Photos of the closed cycle helium reliquefier installed in a pediatric MEG system at BCH.

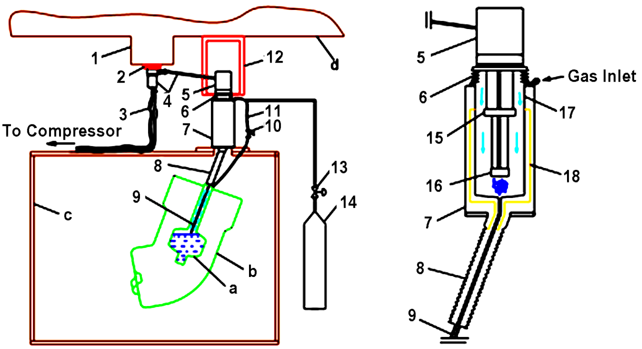


Figure 5. Design of helium reliquefier installed in a pediatric MEG system at BCH.

Figure 5 shows the design of the helium reliquefier. The high-pressure helium gas from the compressor is delivered to the rotary valve-motor assembly (4) via a pair of long flexible hoses (3). The motor assembly is detached from the cryocooler (5) to reduce vibration of the reliquefier body (7). It is mounted on a sliding carriage (2). The rotary valve-motor assembly feeds compressed gas to the cryocooler (5) via a flexible hose (4). A bellows (6) is inserted between the cryocooler and the reliquefier body to reduce vibration transmission. A support structure (12) mounted on the ceiling (d) holds the cryocooler firmly. The reliquefied liquid helium drips down through the flexible transfer tube (8) and an insertion tube (9) into the inner belly (a) of the MEG cryostat (b). The evaporating helium vapor returns to the reliquefier via two paths: (1) through the transfer tube which allows for LHe to drip down and helium gas to rise up to the reliquefier chamber through a single tube without vapor trap; and (2) through a stainless steel, flexible vapor line (11).

Vibrations from the helium reliquefier must be sufficiently low to provide facile noise cancellation in real time during MEG measurements. Vibration levels were significantly reduced by: 1) using a Pulse Tube cryocooler with no solid, moving displacers (compared to a GM cryocooler), which greatly reduces vibration from the cryocooler; 2) using a remote motor assembly detached from the Pulse Tube cryocooler via a flexible hose to minimize vibration transmission to the cryocooler ; 3) mounting the remote motor assembly on a sliding carriage to allow free movement of the assembly to reduce any forces exerted on the reliquefier assembly; 4) use a flexible transfer tube connecting the reliquefier to the fill port of the MEG cryostat to reduced the transmission of vibration from the cryocooler to the MEG system, and 5) using a bellows assembly installed between the cryocooler and the reliquefier body to minimize vibration transmission.

The magnetic noise produced by the helium reliquefier was evaluated after it was installed at the MEG facility at BCH. Figure 6 (a) shows the amplitude spectral density of the output of one of the magnetometers of the inner layer of the MEG system with the cryocooler ON and OFF. The reliquefier noise can be further eliminated using signal space projection (SSP) and synthetic gradiometer (SG), shown in Figure 6 (b).

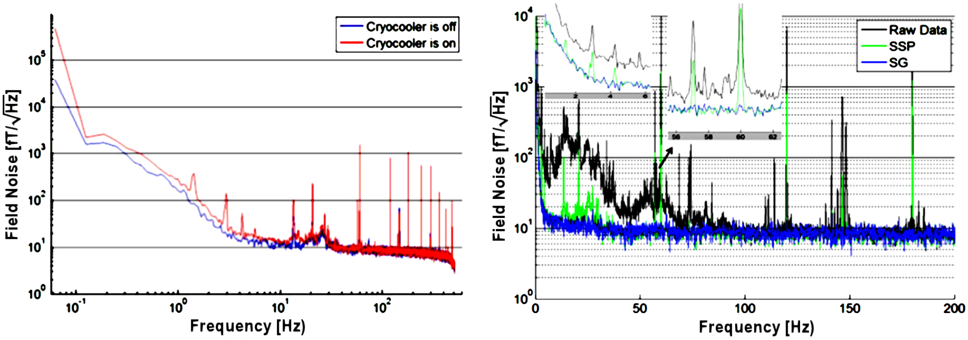


Figure 6. Magnetic noise comparison when the helium reliquefier is on and off: (a) Raw output of a magnetometer channel in the inner layer of the sensor array with and without the reliquefier on. (b) Elimination of the reliquefier noise with SSP and SG.

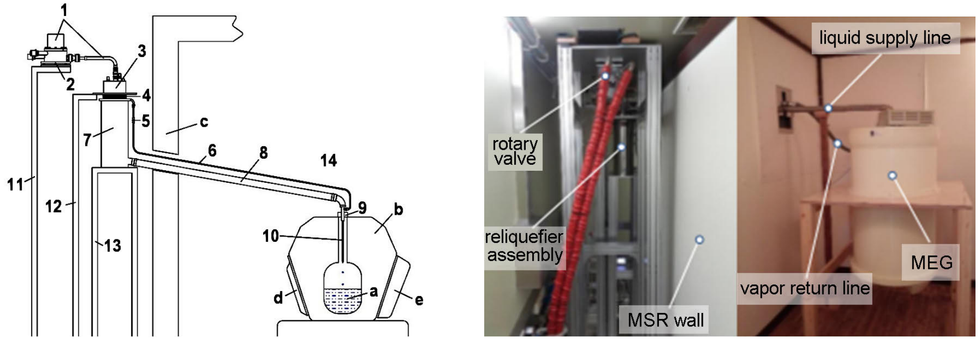


Figure 7. Schematic and photo of the helium reliquefier installed in the MEG facility of KRISS

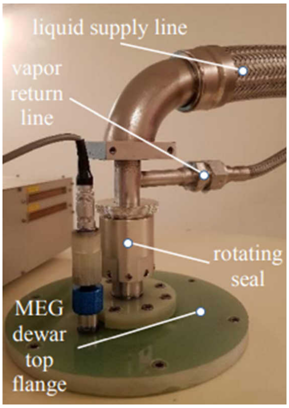


Figure 8. Photo of rotating seal and liquid supply line mounted to the MEG.

Another helium reliquefier has been installed in the MEG facility of the Korea Research Institute of Standards and Science (KRISS) [3], shown in Figure 7. They are developing a dual-helmet MEG (b) which can be used for both adult and pediatric patients. The adult helmet (e) contains 192 gradiometers and the pediatric helmet (d) houses 144 gradiometers.

A 2-Stage Pulse Tube cryocooler (3), Cryomech model PT420-RM, was mounted in the reliquefier (7). Vibrations were significantly reduced by employing the same techniques used on the BCH system. Unlike the reliquefier at BCH, this reliquefier design required a 1.5 m long, flexible, horizontal liquid supply line (8) due to space restrictions above the magnetically shielded room (MSR). The dual-helmet MEG design requires the entire MEG assembly to rotate 180° horizontally to switch between the adult and pediatric helmets. The liquid supply line incorporated a rotating seal (9) that allows the MEG to rotate axially about the insertion tube (10). Shown in Figure 8, this rotating seal, developed specifically for this project, creates a helium-tight enclosure for both stationary and dynamic conditions when mounted to the top of the MEG helmet.

The magnetic noise produced by the helium reliquefier was evaluated after installation in the MEG facility of KRISS [4]. Figure 9 shows a comparison of the noise with and without the helium reliquefier on. The test results show that the difference in noise levels, with the reliquefier on and off, is very minimal.

SUPERCONDUCTING MAGNET APPLICATIONS

Introduction to Superconductivity

Superconductivity is a material state in which electricity flows without resistance. Though Heike Kamerlingh Onnes first observed this phenomenon in 1911 while experimenting with Mercury in liquid helium, most materials become superconducting at sufficiently low temperatures. Superconductivity was

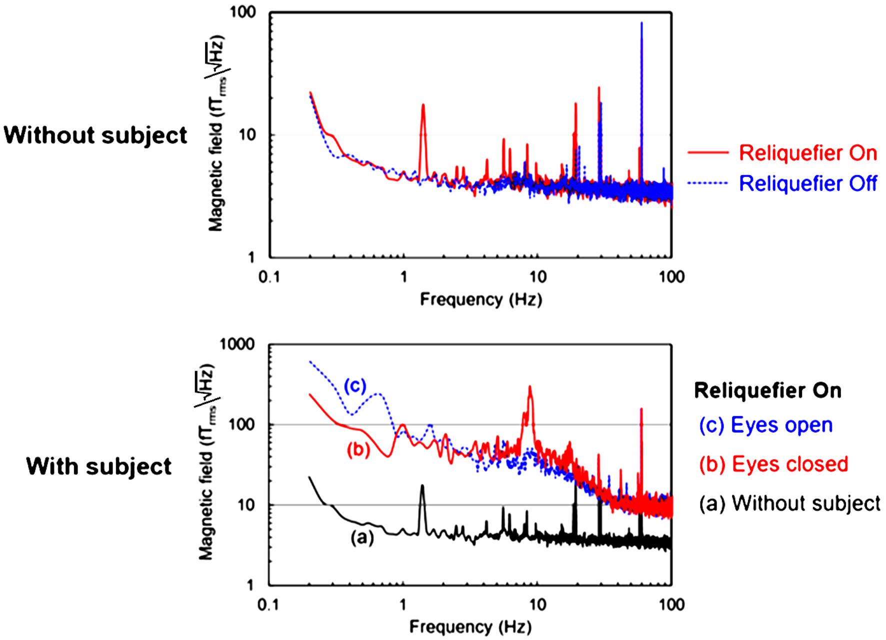


Figure 9. Comparison of noise with and without the helium reliquefier ON.

observed in several more materials after this initial discovery, but it wasn't until 1957 that a widely accepted theory of superconductivity was proposed by Bardeen, Cooper and Schrieffer.

The so-called BCS theory proposed that superconductivity was a result of electron-phonon interactions in a material which causes electrons to form pairs known as Cooper pairs. Phonons are the quantized description of lattice energy, which is typically dominated by thermal energy. At sufficiently low temperatures, phonons can be influenced by an electron and create a ripple in the lattice of the material due to an electrostatic interaction, as depicted in Figure 10. This ripple creates an area of higher positive charge behind the electron, which attracts a second electron, creating the Cooper pair. Since this theory was proposed, superconductivity has been observed in some materials at higher temperatures. This discovery has created two classes of superconductors known as low temperature and high temperature superconductors (LTS and HTS). The BCS theory does not offer a complete explanation for HTS materials because they become superconducting at temperatures where thermal energy still governs phonons.

Superconducting materials have been used to create technology for a wide range of applications. One of the most notable uses has been in creating large electromagnetics that generate strong magnetic fields which would otherwise be much more costly and technologically difficult to produce. The largest commercial application for superconducting magnet technology is magnetic resonance imaging (MRI). There has also been significant development in electromechanical technology such as superconducting motors and generators. Superconducting magnets are utilized in the research market in particle accelerators and mass spectrometers for material research.

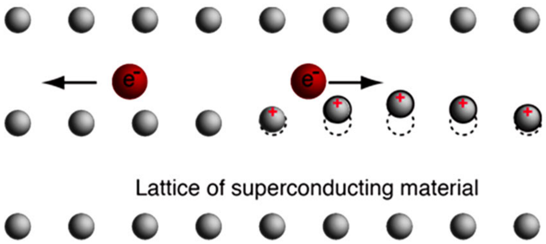


Figure 10. Electron-Phonon interaction in superconducting materials [5]

Though HTS materials were discovered more than 35 years ago, the technology is only now becoming commercially available. Recent advancements in manufacturing materials such as Rare-Earth Barium Copper Oxides (REBCO) and Magnesium Diboride (MgB2) have begun to make HTS technology a viable solution to many of the aforementioned applications. Including the obvious benefit of operating at a higher temperature than traditional LTS, HTS magnets can produce a higher magnetic field as the temperature decreases. This allows manufacturers to produce stronger magnets in a smaller package.

Neutron Electric Dipole Moment Experiment at SNS

The application discussed here is the Neutron Electric Dipole Moment (nEDM) Experiment, which will be conducted at the Spallation Neutron Source (SNS) at Oak Ridge National Labs (ORNL). The intent of this experiment is to answer a very fundamental question – why does matter exist? At the beginning of the universe, the Big Bang created matter and antimatter in equal amounts. Shortly after, most of the matter was annihilated in matter /antimatter collisions. Modern estimates suggest that only one billionth of the original matter remained. All prevailing theories for why all matter wasn't annihilated point to the neutron having a nonzero electric dipole moment (EDM).

$$\sigma \sim \frac{1}{E\tau\sqrt{N}} \tag{1}$$

The EDM is a measure of polarity or a nonuniform distribution of charge in a particle. The EDM of a neutron has been measured previously, but this newly designed experiment is intended to improve on this measurement by two orders of magnitude, to the order of 10^{-28} e-cm. The statistical sensitivity of an EDM experiment is described by Eq. 1 where *E* is the electric field, ô is the neutron storage time, and *N* is the number of neutrons [6]. The experiment utilizes properties of superfluid helium to significantly increase these three values and thus greatly improve the sensitivity of the experiment.

Figure 11 shows a rendering of the entire experimental apparatus as well as the measurement cell. The measurement cell is immersed in super fluid helium, which allows for the in-situ creation of ultra-cold neutrons, significantly increasing the storage time in the measurement cell. A high electric field of 75 kV is generated within the measurement cell and a highly uniform magnetic field of 30 mG is created with the magnetic coil package constructed from superconducting lead. The uniformity of the magnetic field is critical for such precise measurements. The experiment requires a uniformity of ~1 ppm/cm and < 1 pT magnetic fluctuations. Figure 12 shows the inner magnet vessel. The inner magnet vessel is constructed entirely of aluminum to eliminate any magnetic interference. Due to the strict magnetic field requirements, the cooling system for the magnet must be located outside of a magnetic shield. The vessel is designed with a heat exchanger consisting of 45m of D-tube wrapped around the outside of the vessel. The remote cooling system circulates cryogenic helium gas through the heat exchanger to maintain a temperature of ≤5.5K.

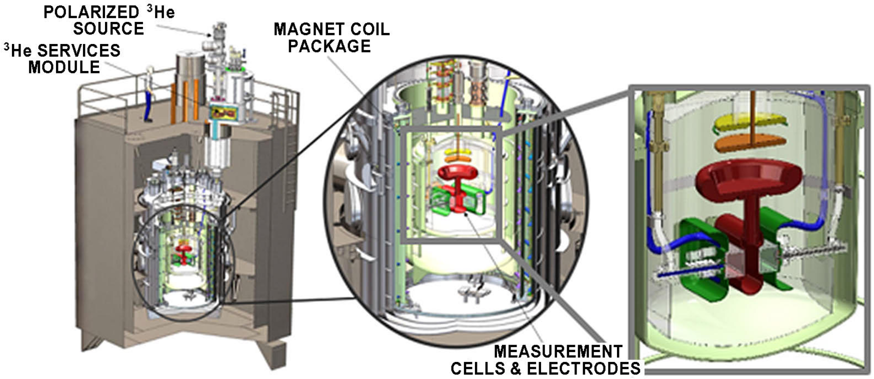


Figure 11. Rendering of the experimental apparatus for the nEDM Experiment [7]

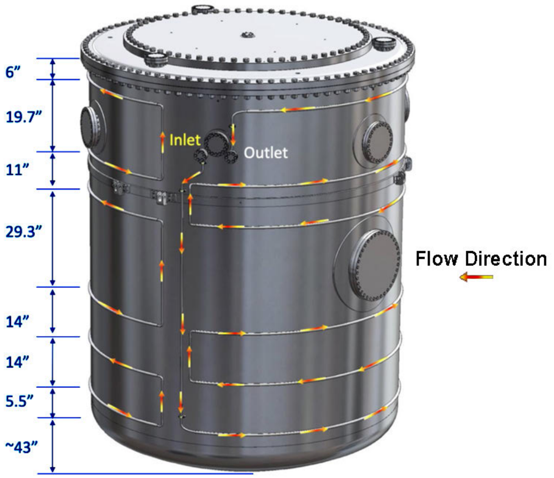


Figure 12. Inner Magnet Vessel and heat exchanger flow direction

Cold Helium Circulation System Development

The remote cooling system developed by Cryomech is known as a cold helium circulation system (CHCS) and is based on two 4 K Pulse Tube cryocoolers, Cryomech model PT420. Figure 13 shows a schematic and a digital rendering of the CHCS described here. Gas is circulated by a room temperature helium compressor, Cryomech model CP103. Room temperature helium gas flows into the 1^{st} recuperator and then to a heat exchanger coupled to the 1^{st} stage of each cryocooler and is cooled to ~30K. Gas then flows through a 2^{nd} recuperator and through a heat exchanger coupled to the 2^{nd} stage of each cryocooler and is cooled to 5.2 K. Helium gas flows to the magnet heat exchanger through a flexible, vacuum jacketed transfer line that is 0.94 m long. Warmer return gas flows back to the cooling system through a 2^{nd} vacuum-jacketed transfer line and cools the incoming gas through each recuperator. The design includes an additional port to easily install a third PT420 cryocooler for future expansion and increased cooling capacity.

The performance requirements for the system were to provide 4W of cooling at 5.5K at the outlet of the magnet heat exchanger. Performance tests were conducted at Cryomech using a compact heat exchanger. An artificial heat load was applied to the heat exchanger using electric heaters. Temperature measurements

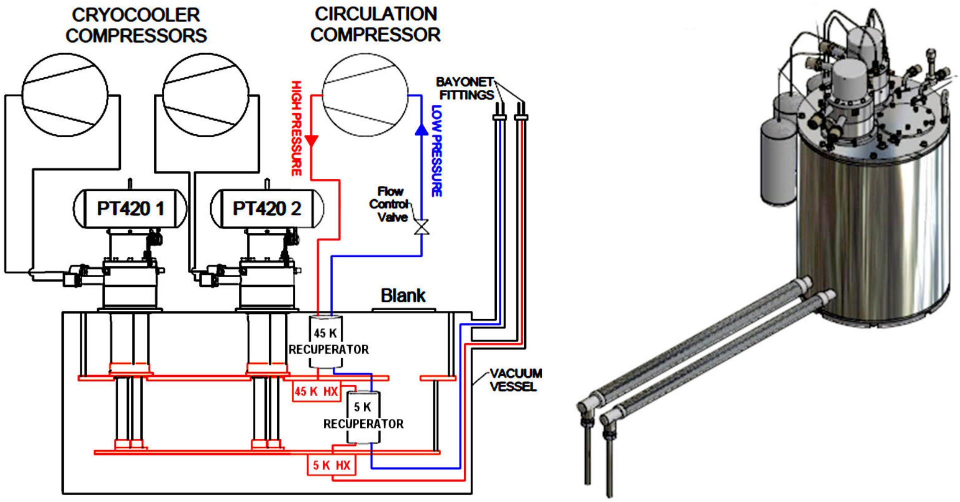


Figure 13. Schematic and digital rendering of the Cold Helium Circulation System.

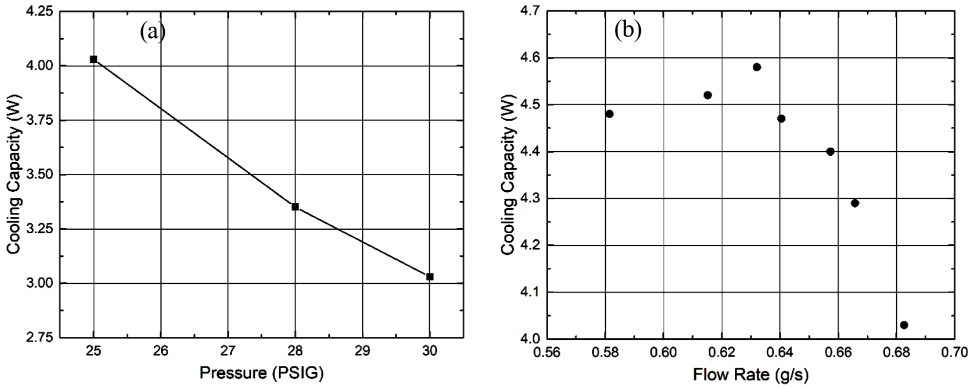


Figure 14. (a) Cooling capacity vs helium pressure at a constant flow rate of 0.68 g/s and (b) cooling capacity vs helium flow rate at a constant pressure of 25 PSIG.

were taken at the inlet, outlet, and on the heat exchanger using three Lakeshore DT670-CU-1.4L calibrated silicon diode temperature sensors. Due to the temperature requirement, the operating pressure was chosen to be very close to the critical point of helium. The specific heat of helium increases significantly as the critical point is approached, thus reducing the temperature rise across the magnet heat exchanger.

Figure 14a shows the measured cooling capacity with respect to operating pressure at 5.5K. As the pressure decreases from 30 PSIG to 25 PSIG, the cooling capacity increases from 3.03W to 4.03W. Below 25 PSIG, the temperature became unstable due to cyclic phase changes within the system. The cooling capacity was then measured at different flow rates while maintaining a constant pressure of 25 PSIG, as shown in Figure 14b. The cooling capacity increased from 4.03W to 4.58W at 5.5K as the flow rate decreased from 0.68 g/s to 0.63 g/s. The cooling capacity begins to decrease below 0.63 g/s. It is critical that the cooling system remain stable in the case of a short period of increased heat load.

A heat impulse test was also run in which a 10W heat load was applied for 60 seconds and then removed. The inlet and outlet temperatures increased and returned to the expected operating temperature in ~45 minutes.

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