IOP Conf. Series: Materials Science and Engineering **171** (2017) 012034 doi:10.1088/1757-899X/171/1/012034

Heat Exchanger Can Assembly for Provision of Helium Coolant Streams for Cryomodule Testing below 2K

E N Smith, R Eichhorn, P Quigley, D Sabol, C Shore, D Widger

Cornell Laboratory for Accelerator-Based Sciences and Education, Ithaca, NY 14853-5001, USA

ens5@cornell.edu

Abstract. A series of heat exchanger can (HXC) assemblies have been designed, constructed and built to utilize existing 4.2 K liquefaction and compressor capabilities to provide helium gas coolant streams of 80 K, 4.5 K, and liquid from 1.6 to 2.0 K for operating cryomodules containing from one to six superconducting RF cavities built for an energy recovery linear accelerator. Designs for the largest assemblies required up to 100 W of cooling at 1.8 K with precise temperature control, especially during cool-down, and up to 2000 W at 80 K (with a 40 K temperature rise). A novel feature of these assemblies was the use of relatively inexpensive brazed stainless steel plate heat exchangers intended for room-temperature operation with water or oil, but which in practice worked well at cryogenic temperatures. The choice of operating temperatures/pressures were to provide single-phase helium flow for better control of coolant distribution in the 80 K and 4.5 K streams, to take advantage of locally elevated heat capacity near the critical point for the 4.5 K stream, and in the region below 2 K to get the best possible Q from the niobium cavities under test.

1. Introduction

Over the last several years Cornell has been developing and testing many of the key components for its proposed Energy Recovery Linac (ERL). Realistic testing of the superconducting radio frequency (SRF) cavities, the auxiliary components such as input couplers (IC) and higher-order mode absorbers (HOM) needed to make a complete system, and a prototype cryomodule in which to house them has required provision of cryogenic supply streams of similar characteristics to what has been proposed for the overall project. The SRF cavities have been designed with the intent to run surrounded by superfluid helium at temperatures of either 2.0 K at 32 mbar pressure, or 1.8 K at 16 mbar pressure. In addition, it is planned to provide a stream of helium gas cooling at pressures of 15-20 bar at near 40 K for intercepting heat leakage from radiation and support structures, as well as the much larger heat load from dissipation of RF energy in the HOM and IC loads. Finally, there are thermal intercepts at 5-6 K, to be cooled by helium gas at about 3 bar, slightly above the critical pressure for helium. Many labs using SRF have developed 2 K test systems in recent years, with varying refrigeration requirements and often using some amount of existing equipment. Thus each system is a bit different, as may be seen in some typical references [1-4]. We describe an approach convenient for our facility.

Because the Cornell synchrotron has a large cryogenics plant for operating the accelerator, with significant spare cooling capacity at 4.5 K, and also some extra margin on compressor capacity, it seemed desirable to try to use this existing installation as primary contribution for refrigeration for this testing program. However, it is not designed for operation below atmospheric pressure, and is not equipped to deliver an intermediate temperature stream of helium gas for cooling thermal shields and intermediate temperature loads. As a consequence, several heat exchanger cryomodules (HXC's) have been designed and built to allow testing of assemblies under conditions relevant to their eventual use. The primary change which has been made in the coolant streams has been to substitute an 80 K coolant temperature (easily provided by heat exchange with a lN2 supply) for the eventually intended 40 K. This increases somewhat the heat load on the lower temperature stages, but is adequate to allow the functional testing of all the components.

This paper will focus primarily on the most recently constructed HXC, partly because it is intended for use with the highest heat loads, but mainly because it has made some improvements on both the ease of operation and control and on the cryogenic efficiency of two earlier designs.

The nominal maximum heat loads for which this HXC were designed to handle under steady-state operating conditions were:

- 2000 W going into the 80 K helium gas stream, warming it to 120 K on passage through the test cryostat, a 40 K temperature rise, requiring a mass flow rate of 10 g/s.
- 50 W going into the 5 K thermal intercept system with a 2 K temperature rise upon passing through the test cryostat, requiring a 5 g/s mass flow rate.
- >100 W cooling provided from the 2 K system, requiring up to 10 g/s throughput of sub-cooled liquid helium being provided to the test cryostat

Beyond the requirements for steady-state operating conditions, it is necessary to provide relatively small temperature gradients among the components within the test cryostat during cooldown operations to avoid excessive strains from differential thermal contraction. Because the several tons of thermal mass being cooled in the test cryostat gave rise to long and varied thermal time constants, it was desired to keep the cooling rate below 4 K/h, to ensure that the temperature spread was under 20 K among all of the test cryomodule components during the part of the cooldown above 80 K.

2. Mechanical Construction

As shown in figures 1 and 2, the HXC is contained in a cylindrical stainless steel vacuum vessel with overall length of about 2 m and diameter of approximately 1 m. This vacuum vessel is supported above floor level by three legs of approximately 1 m in length in order to put it at an appropriate level for the beamline and cryogenic input lines incorporated in the cryomodules to be tested. All of the cryogenic input and output lines, feedthroughs for electronics, and extended stems for low-temperature valves are mounted on a lower spool section about 60 cm high, as are the mechanical supports for the heat exchange structures inside. A removable top can and a bottom plate are bolted on to the flanges of this spool, with vacuum seals made with rubber o-rings. Removal of the top can and bottom plate give easy access to the interior for both the initial construction and sensor wiring and for any subsequent modifications that might be desired. The insulation vacuum in the HXC shares a common vacuum space with the cryomodule under test, and with a length of 10-20 m of transfer lines for incoming lN2, lHe, and cold return He gas from the nearest vacuum isolation at a remote valve box connecting to the main laboratory cryogenic system. The supply of the lN2 and the lHe, which may be considered as the primary coolants for the system are regulated by electro-pneumatic valves in the remote valve box, based on the levels in the lN2 and lHe reservoirs in the HXC (as measured by sensors in the HXC), and the gas returning to the cryogenic system, labeled as "cold He gas return" is bypassed in that same remote valve box directly to the compressor warm-gas input during parts of the cooldown procedure when the exiting gas is still too warm to be of benefit to the liquefier system. Most of the valves, pressure regulators, flow meters, gaseous nitrogen exhaust, connection to pump skids for pumping below atmospheric pressure, etc. required for the operation of the system are mounted in the immediate vicinity of the vacuum vessel, although the control electronics is in remotely located electronics racks. Some of the valves that need adjustment only during pre-cooling operations are manually operated, but most are remotely actuated electro-pneumatic valves because during much of

IOP Conf. Series: Materials Science and Engineering **171** (2017) 012034 doi:10.1088/1757-899X/171/1/012034

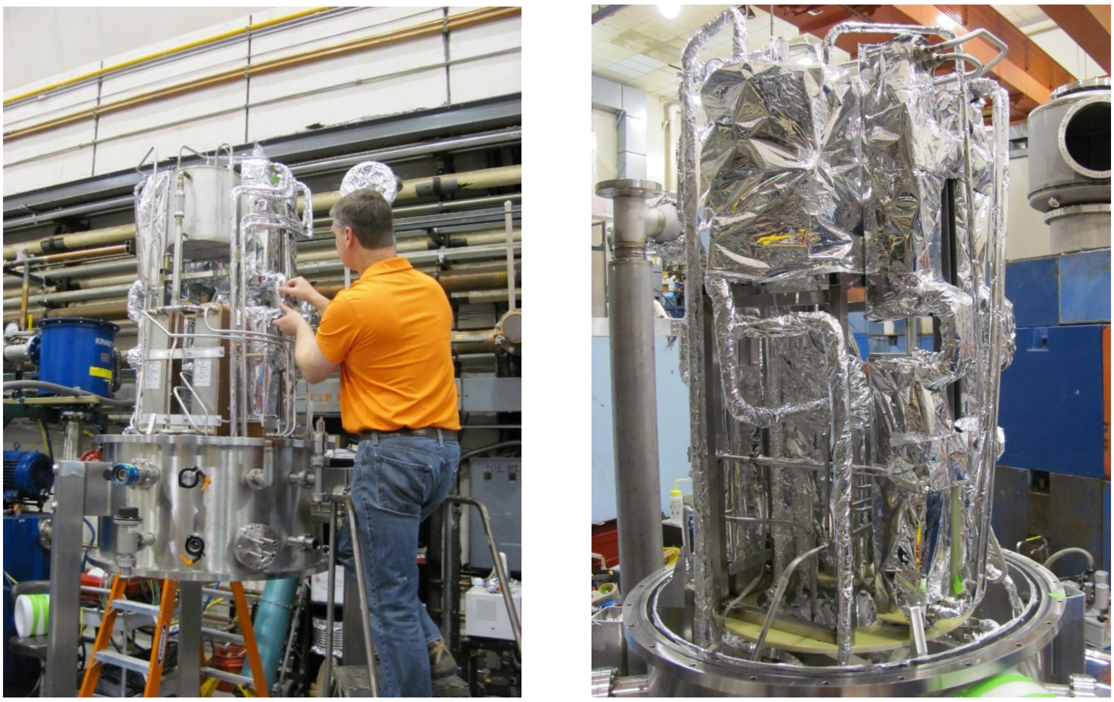
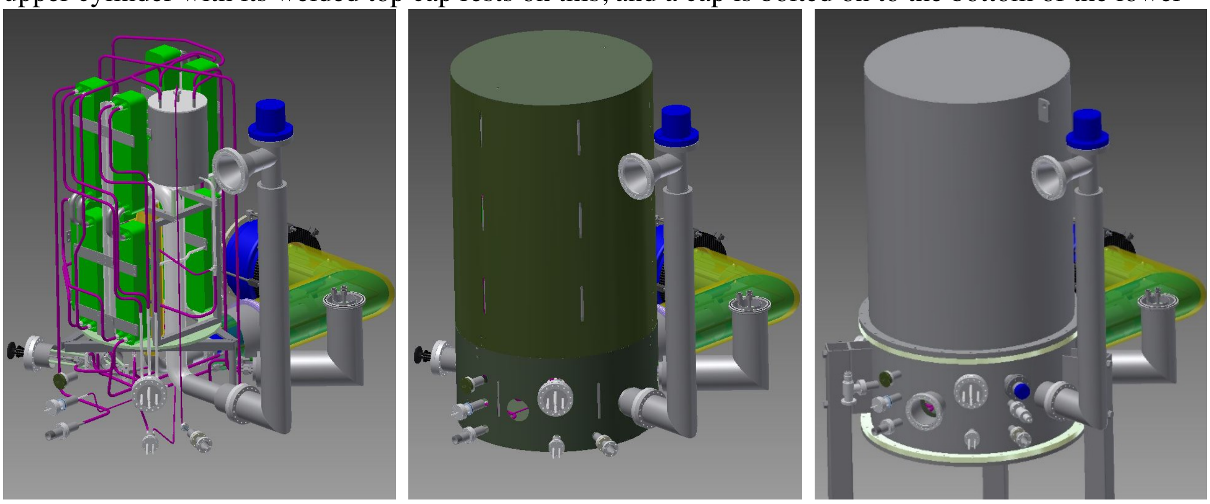


Figure 1. Two views of the partially assembled HXC during construction.

the actual testing procedure the apparatus is in a radiation producing area with personnel excluded.

Cooling for an 80 K shield is provided through a stainless steel tube first fitted with a number of short sections of snugly fitting aluminum tube, then preformed into an appropriate shape to mate to two aluminum cylinders a few cm smaller diameter than the vacuum can. Each cylinder is formed from sheet with pre-cut penetrations, which are then rolled and welded. The short aluminum-clad sections on the six longitudinal straight sections of stainless tubing for each cylinder are then welded into appropriate slots on the aluminum cylinders for thermal contact. The lower cylinder, with all the penetrations for piping and electrical wiring is mechanically fixed to the vacuum can for support, the upper cylinder with its welded top cap rests on this, and a cap is bolted on to the bottom of the lower



(a) (b) (c)

Figure 2. A view of the layout of components of the HXC in panel a, with the 80 K radiation shield added in panel b, and the outer vacuum can added in panel c.

cylinder. Flanging on this stainless steel tubing (which doubles as the fill line for the lN2 bath) allows for easy assembly of the lN2 shield after the interior plumbing, wiring, and insulation are completed. A superinsulation blanket (twenty layers of aluminized Mylar® with woven polyester interlayer spacing), was wrapped outside the solid radiation shield. Superinsulation was also wrapped around the bodies of the various heat exchangers, the interconnecting tubing, and the helium bath. All of the tubing on the lines at atmospheric pressure or higher was ½" with .028" walls (approx. 12.7 mm, .7 mm), while the pumping line was approximately 50 mm in diameter. Shortly outside the vacuum can, the pumping line was increased to 150 mm diameter for the long run to the pumping skid. Almost all of the joining of tubing inside the vacuum space was done with TIG welding, with just a small number of small diameter VCR flanges being used to allow connections to the cryomodule under test, and the remote cryogen delivery lines. To avoid cold ceramic feedthroughs between the cryogen spaces and the vacuum, wiring for the level detectors in the lN2 and lHe baths was run through small diameter tubes leading out to room temperature.

3. Detailed functional description of steady-state operation

First we will consider the operation of the HXC in the conditions of normal operation after both the HXC and the system under test have already been cooled down from room temperature to the normal experimental use conditions. The schematic view in figure 3 shows room temperature helium gas at an elevated pressure of somewhat over 15 bar (1.5 MPa) being admitted to the HXC through pressure regulator PR1 to the first heat exchangers HX1 and HX2, where the gas is cooled by outflowing gas from the cryomodule under test to a temperature somewhat near to 80 K (depends on the heat load on the cryomodule under test, and could be as high as 120 K with the maximum 2 kW load), and then is cooled the rest of the way to 77 K in HX3, by means of thermal exchange with boiling liquid nitrogen provided by a thermo-siphon from the liquid nitrogen bath. The delivery rate of liquid nitrogen on that

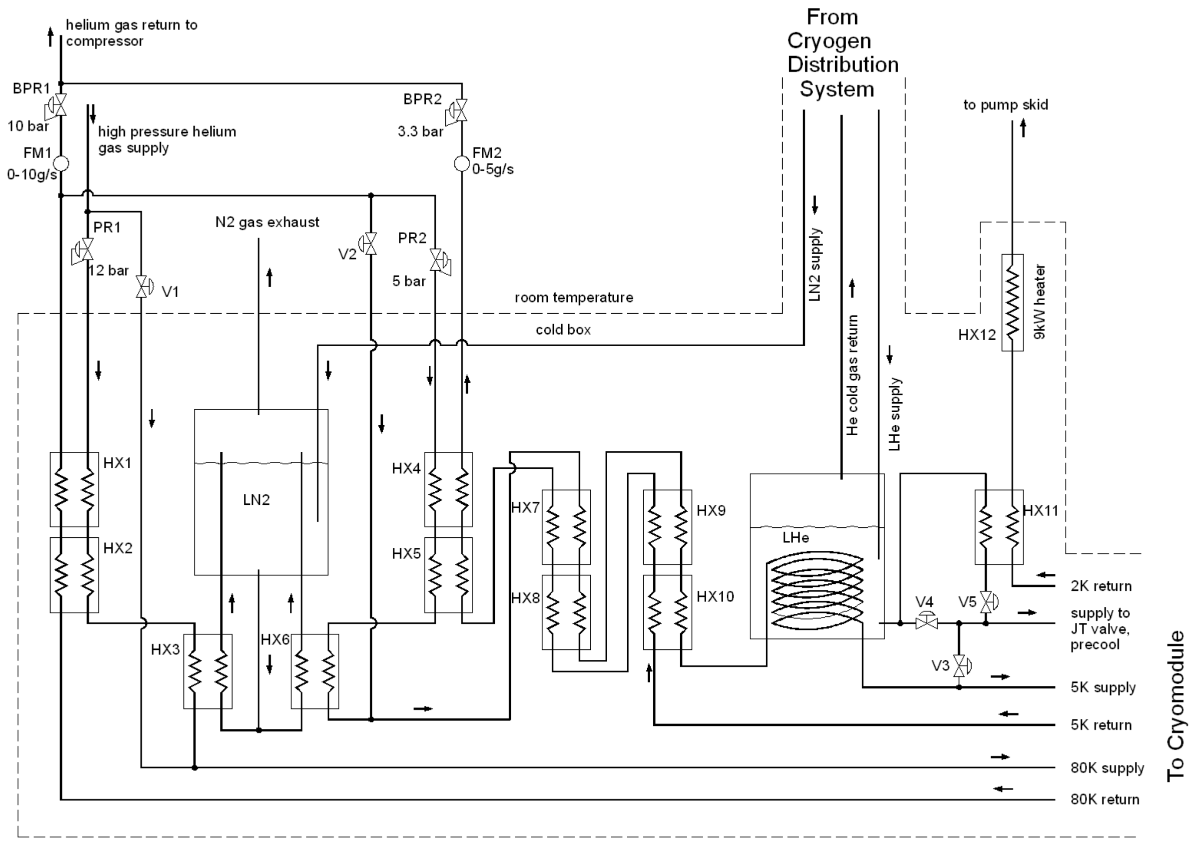


Figure 3. Schematic view of the helium flow through the HXC.

side of the exchanger is self-regulated by the pressure difference caused by the difference in density of the cold liquid in the tube from the bottom of the lN2 bath to the bottom of HX3, and the density of the vapor returning to the space above the lN2 bath from the warmer top of that heat exchanger. The overall level of the liquid surface in the lN2 bath is measured by a capacitive level meter, and maintained constant by feedback to an electro-pneumatic valve located on the remote valve box connecting to the building cryogenic system.

The rate of flow of the 77 K He gas stream to the test cryomodule is regulated by a remote valve in that test cryomodule. That is normally set at a constant value during the testing operations, with the amount of valve opening chosen to make the flow rate measured by FM1 on the output flow stream appropriate to the anticipated heat load expected for the experimental conditions. Up to this point, no attempt has been made to regulate the flow rate under continuous feedback, it has just occasionally been adjusted by the system operator under computer control to conform to the day's experimental plan. As there is rather small pressure drop within the HXC, and with a desire to keep the pressure drops within the test cryomodule in the range intended for the ultimate refrigeration system designed for a string of up to 60 cryomodules, the return pressure is maintained by a back-pressure regulator, BPR1, set at around 1 MPa.

While part of the return gas goes directly back to the input of the building helium compressor system, a portion is used to provide the gas stream for the 5 K cooling loop, since this part of the system is in any case operated at a lower pressure to take some advantage of the elevated heat capacity of helium near the critical point (resulting in a lower temperature rise for a given mass flow at the same heat load). In normal continuous operation, the pressure for the inlet to the 5 K system is set at around 500 kPa, and is initially cooled down to 77 K by the heat exchangers HX4-6 exactly as was done for the 80 K cooling stream. Then, however, it is sent through another series of four heat exchangers HX7-10 being cooled to near the 4.5 K temperature bath by the returning gas from the test cryostat. At this point the incoming gas is run through a 4 m long spiral tube of 12.7 mm diameter copper tubing immersed in the liquid helium bath, and from there at a temperature of 4.5 K on into the test cryostat, with the flow rate being adjusted with a cryogenic valve located within the test cryostat. As with the 80 K system, the outlet pressure is adjusted at room temperature by a back-pressure regulator (BPR2) set for about 350 kPa, and the flow (measured by flow meter FM2) is set to keep the rise in temperature of the gas returning from the test cryostat was at an acceptable temperature.

The input liquid for the "2 K" cooling in the system is withdrawn from the 4.5 K helium bath in the HXC and pre-cooled in HX11 by the exiting evaporated gas from the test cryostat (maintained at a carefully regulated temperature, typically in the range from 1.6 K to 2.0 K depending on the experiment) to produce a sub-cooled liquid typically at a temperature around 3 K upon leaving the HXC via V5 (V3 and V4 closed) to the test cryostat. The sub-cooled 3 K liquid was expanded through a remote JT valve in the test cryostat, with the valve opening adjusted to maintain a constant level in a 2 K bath in that cryostat. The temperature of the system was regulated by adjusting the pumping speed of a remotely located pumping skid by means of a variable-frequency drive, with the pressure being monitored by a capacitance manometer and controlled to within about 0.1 mbar, providing temperature stability of 2-3 mK at 1.8 K. The gas exiting from HX11 was warmed from 4.5 K to room temperature by contact with a 9 kW cartridge heater (HX12) mounted in a sidearm on the main vacuum can. Regulating the heater current to maintain a heater temperature of 100 °C results in the gas flow exiting the vacuum can close to room temperature.

4. Description of individual heat exchangers

All the heat exchangers HX1-HX10 are stainless steel brazed-plate heat exchangers, Bell and Gossett model BP415-40 (http://bellgossett.com/heat-exchangers/brazed-plate-heat-exchanger/), which produce a highly turbulent flow through herringbone patterns stamped into each of the 40 plates, approximately 500 mm long, 100 mm wide, separating the supply and return flows. These exchangers are in fact designed for heat exchange in liquid systems such as water or oil at room temperature, but seem to work well and reliably for these helium gas flows at cryogenic temperatures. We have seen no instances of leakage in these exchangers, either to the vacuum space or between the two directions of flow, with up to about 1.5 MPa pressure in daily use in the gas flow streams, over several years of operation in three different HXC modules of similar design. The heat exchanger bodies have in general been mounted vertically so that the warmer end is higher and the colder end is lower, as suggested by the schematic in figure 3, so as to avoid detrimental convective heat transfer from one end of the exchanger to the other under lower coolant flow velocities. We have found that in the flow path from 300 K to 80 K that the supply and return flow streams through the two series heat exchangers are kept within 5 K of each other under the balanced flow conditions of normal operation, and that the final cooling to 77 K in HX3 is nearly perfect, with the much smaller temperature difference and the boiling interface of the lN2 providing a constant low-temperature sink over a larger fraction of the length.

The same style of exchanger has also worked well going from 77 K-5 K. For example, in one test sequence with a flow rate of about 1.5 g/s, gas entering the test cryostat at 4.7 K and warmed to near 6.6 K under a 5 K heat load of around 25 W (coming from multiple sources), the temperature difference between the supply and return sides of the cold end of HX10 was 0.8 K, with the gas entering the final tubular exchanger at 7.4 K. This has seemed quite satisfactory performance from the four plate exchangers connected in series in this temperature range, with a temperature gradient of 70 K longitudinally along the exchanger, and exchanging over 98% of the available heat between the return and supply streams.

HX11 was a Hampson-type heat exchanger using a spiral of finned copper tubing for the input liquid, constrained between a pair of inner and outer stainless steel tubes which accommodated the low-pressure return gas flow. It was constructed for us by Ability Engineering on a design kindly furnished to us by Tom Peterson from an identical exchanger he had previously built for a cryostat with similar 2 K heat load at Fermilab.

5. Operation during cooldown mode

Because the prototype cryomodule being tested is quite long (10 m) and has a large cryogenic mass (several tons of stainless steel, aluminum, titanium, niobium) with many components requiring very precise relative positioning, it was considered essential to have very uniform cooling to prevent distortions or even structural failure of components from variable rates of thermal contraction. It was determined that for the initial cooldown, we wanted to be able to cool down to 80 K at a maximum rate of 4 K/h, with no more than 20 K difference in temperature between the hottest and coldest points in the interior. Because of a wide variation of thermal masses and degree of contact to points of cooling, it was effectively necessary to maintain flow rates of around 10 g/s of He gas through the 80 K loop, and an additional 5 g/s through a combined 5 K and 2 K system. In an earlier version of the HXC intended for smaller systems, we had tried to maintain a gradually decreasing input temperature by filling the lN2 bath to a shallow level to limit the effectiveness of the thermo-syphon. This proved impossible to do, with alternation between bursts of fast cooling and slow cooling always ensuing. For subsequent versions, we implemented a parallel flow path (through V1 for the 80 K system, through V2 for the 5 K system) which bypassed the first three heat exchangers. By varying the opening of V1 and V2, we could start by directing almost all of the flow straight from 300 K and adding only a small admixture of 77 K gas through the normal path, then gradually shut down V1 and V2 as the test system grew colder. In the 5 K system, at this stage of operations above 80 K, there was of course no lHe admitted to the lHe bath, and hence no further cooling of this gas stream before going to the test cryomodule. Because the mass of the 5 K thermal intercepts in the system being cooled was quite small, and on the contrary the mass of the space eventually going to operate at 2 K was very large, most of the flow was diverted through V3 into the 2 K system, where it was further subdivided by the pre-cool valve and the JT valve of that cryostat to inject cold helium into different parts of that 2 K system. This procedure indeed resulted in a very smooth cooldown of the cryostat, with both the prescribed cooling rate and within the maximally allowed thermal differences we had in advance decided would be acceptable. Figure 4 shows our experience on the first cooldown.

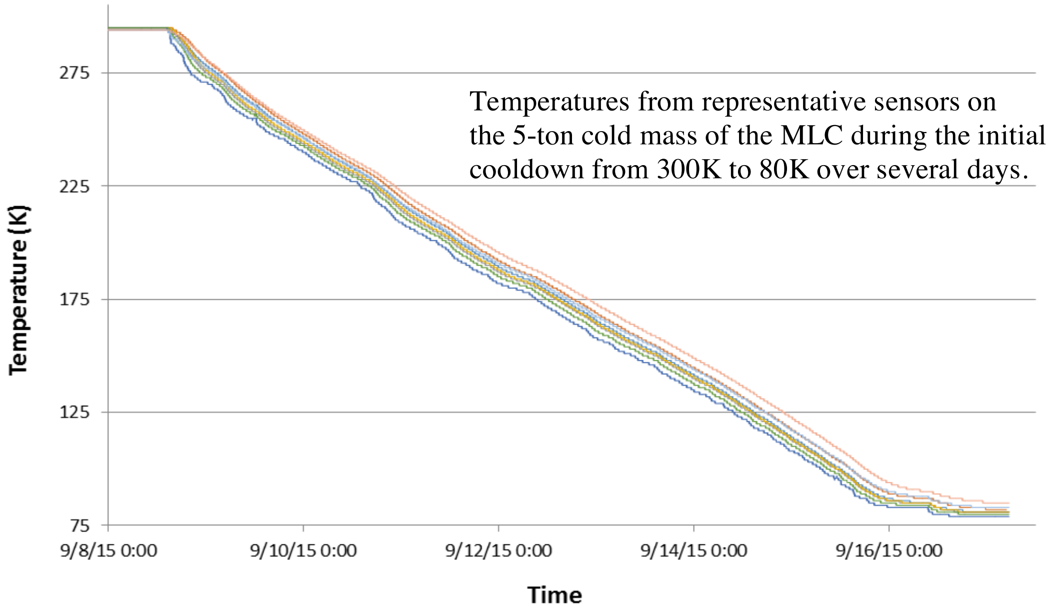


Figure 4. Showing actual slow, controlled cooldown of test cryomodule over several days.

One obvious potential difficulty with this procedure is that the flow through the supply and return sides of the heat exchangers is no longer evenly balanced through much of the pre-cool procedure. In the 80 K loop, for much of the procedure there is much higher mass flow rate of cold gas through the return path than through the supply side of HX1 and HX2. Initially this is not much of a problem because that return gas is not far below room temperature, but for much of the cooldown, the gas exiting from the vacuum insulated part of the system is far below room temperature, and required a combination of external heating tapes and fan cooling to limit ice condensation from the atmosphere for the several days of cooldown. This did not present a problem on the 5 K cooling side, as almost all of the cooled gas was passing out of the cryostat via the 2 K pumping line, so HX4 and HX5 were not so far out of balance, and the exiting gas from the 2 K pumping line was equipped with a 9 kW heater (HX12), since in normal operation it is necessary to restore a large flow rate of cold gas to room temperature before it gets out to the room temperature line to the helium pumping system.

Below 80 K, the thermal expansion is drastically smaller, and we no longer worry about rate of cooldown because of thermal stresses. At this point, V3 is closed, the lHe bath in the HXC is filled, and helium admitted to the test cryostat through V4 (with V5 closed, as during this process we want to avoid heat exchange in HX11 between the cold liquid/gas coming into the cryostat and the still hot gas coming out). The flow rate into the cryostat 2 K system is adjusted by its internal JT and Precool valves, as is the flow to the 5 K system through the cryostat 5 K valve. Because of different speculations about the variation of properties of the superconducting cavities in our test cryostat depending on the rate they are cooled through their superconducting transition near 9 K, cooldowns for this lower part of the temperature range have been carried out many times, ranging from an hour or two to several days. The controls we have had available have been very convenient for this part of the procedure. Once a liquid level has been established in the test cryostat, then V4 is closed, V5 is opened, and the normal operation may be resumed.

6. Earlier version of HXC used for test of Injector Cryomodule

Our first HXC in this style is shown below in figure 5. It used a pair of inlet and outlet valves, rather than pressure regulators to establish flow rate, and a common flow stream for cooling both the 5 K and 80 K loads, using two separate 80 K cooling loops in series to get adequate mass flow. It required both the 5 K and 80 K coolant streams to be near the same pressure, and was harder to cool down from room temperature in a smooth fashion. The JT valve was contained in the HXC, rather than in the test cryomodule. Another HXC of smaller capacity was constructed for testing individual cavity assemblies, and tried out many of the changes made for the HXC described in this paper.

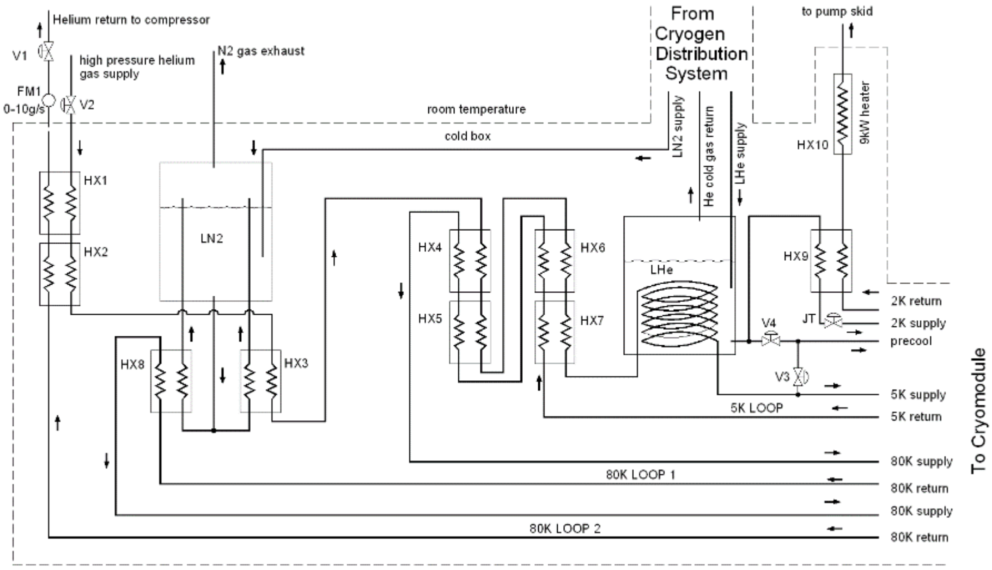


Figure 5. Diagram of earlier HXC design for Injector Cryomodule testing.

7. Operational experience with the HXC

At this time, we have been using the system for several months of testing many aspects of our first prototype Main Linac Cryomodule (MLC) for the ERL. This combination of HXC and MLC are next going to be placed into operation as central components of the CBETA project which will give a more complete test of ERL operation. A similar HXC used for several years of testing of our Injector Cryo Module (ICM) including several cycles of warmups and cooldowns from room temperature has recently been modified to incorporate some of the improvements made on the basis of our earlier experience, and this pair of units will also be incorporated into the CBETA project. While pushing the capacity of our laboratory liquid helium refrigeration system somewhat near to its capacity limits, we feel these HXC systems have been an advantageous way to use existing refrigeration capacity to expand into operation at 2 K at the hundreds of Watts level and to use high-pressure gas cooling for high-load thermal intercepts in testing prototypes to extend our SRF capabilities.

References

[1] Ozelis J et al. , *Joint Accelerator Conference Proceedings,* **PAC2007-WEPMN106**, *http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/WEPMN106.PDF.*

[2] Kaneda S et al., *Joint Accelerator Conference Proceedings,* **EPAC2008-MOPD014**, *http://accelconf.web.cern.ch/AccelConf/e08/papers/mopd014.pdf.*

[3] Than R, Lederle D, Masi L, Orfin P, Porqueddu R, Soria V, Tallerico T, Talty P and Zhang Y , *Joint Accelerator Conference Proceedings,* **PAC2011-TUP223**, *http://accelconf.web.cern.ch/AccelConf/PAC2011/papers/tup223.pdf.*

[4] Kern R, Hermansson L, Gajewski K, Ruber R, Junquera T, Thermeau J and Bujard P, *Joint Accelerator Conference Proceedings,* **SRF2015-TUPB026**, *http://accelconf.web.cern.ch/AccelConf/SRF2015/papers/tupb026.pdf.*

Acknowledgments

Support for this project is from National Science Foundation grants PHY-1002467 and DMR-0807731.