MICE Note 336

What do we do, if some of the MICE magnets can’t be kept cold using the two-stage coolers?

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Abstract

Tests of the spectrometer solenoids have not been encouraging in terms of keeping the magnets cold using three 1.5 W (at 4.2 K) coolers. The spectrometer solenoids are being rebuilt with additional cooling capacity at 4.2 K. It is hoped that there will be sufficient 4.2 K cooling to keep the magnets cold. The spectrometer solenoids can be kept cold using liquid helium (up to a boil-off of 20 liters per day). This option does not apply for the other magnets in the MICE cooling channel, because there is not enough liquid helium storage within the magnet cold mass. It is important that the MICE collaboration ask the question, “How do we keep the MICE cooling channel magnets cold, if there isn’t sufficient cooling from the 4.2 K coolers?” This report discusses the cooling requirements at both 40 K and 4.2 K for all three types of MICE cooling channel magnets. This report discusses the steps that must be taken in the magnet fabrication to permit the magnets to be cooled using a small (20 to 40 W) external 4.2 K Claude cycle refrigerator. One must also ask the question as to whether there is enough excess capacity in the decay solenoid refrigerator to cool some of the MICE magnets. A plan for cooling the magnets using a Linde 1400 series refrigerator is presented. A plan for increasing the 4.4 K refrigeration from the existing decay solenoid refrigerator is also presented.

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Introduction

The MICE was based on the muon ionization cooling for the level II study done about ten years ago [1], [2]. The original cooling concept envisioned for MICE was to be similar to the cooling system proposed in the level II study. The original MICE magnet and absorber cooling system was to use a central refrigerator that provided cooling in two temperature ranges [3]. In 2004, the author of this report was asked to look at using small coolers to cool the MICE cooling channel magnets and absorbers in place of a central refrigerator [4], [5]. The decision to use small coolers in place of a central refrigerator was made in 2004. The first advantage of using small coolers was the potential for a lower cost for the magnet and absorber cooling. The second advantage, from the RAL perspective, was the fact that the cooling cost would be spread among those providing the magnets. As a result, the design of the MICE cooling channel magnets is based on using small 1.5 W 4.2 K coolers that also provide 40 to 50 W of cooling in the temperature range from 40 to 50 K. This is an important consideration when it comes to designing a system that uses a small Claude cycle refrigerator to supplement the cooling being provided by the 4.2 K coolers.

We have learned a lot from the spectrometer solenoid tests [6], [7], [8]. During the magnet 1 tests, we found that the heat load at the coolers first stages was ~1.5 times what was expected [9]. The heat loads to the cooler first stages was far worse for magnet 2A (about three times what was expected). Magnet 2B was better because we eliminated one of the major sources of the extra heat due to the copper leads going from 300 K to the first stage of the coolers [10]. In addition, we provided and extra 150 W of cooling to the copper plate that connects all of the coolers together and the coolers to the tops of the HTS leads. During the magnet 2B test the copper plate operated in the correct temperature range despite the increased heat load from the shield and the cold mass supports. We can only account for part of the increased heat leak in the magnet 2A and 2B tests as compared to the magnet 1 test. In all three tests the heat flow to the shield is excessive compared to the calculations. Can one reasonably expect the coupling magnet or the focusing magnets to perform better? If anything, these magnets must have a lower first-stage and HTS lead temperature than does the spectrometer solenoid, because there is a magnetic field at the tops of the HTS leads [11].

The second stage heat load was higher than expected as well. Estimates of the 4.2 K heat leak were made for all three spectrometer magnet tests. This author doesn't believe the heat leak estimates for the magnet 1 test or the magnet 2A test. The measured data either doesn't exist or measurements were not properly made. Three methods were used to measure the excess heat load into magnet 2B. There was general agreement between the three methods. In general the measured heat leak into the magnet at 4.2 K was about double what was estimated. The range of the excess heat leak in magnet 2B was from 0.9 to 1.6 W [9]. From these measurements, one would argue that the number of 4.2 K coolers should be increased from three to five. In addition, one must reduce the heat leak to the cold mass from the shield. Can one expect the coupling magnet and the focusing magnet to perform any better than spectrometer solenoid? The design margin for the coupling magnet is larger than for the spectrometer solenoid, so adding one more cooler may be enough. The design margin for the focusing magnet is quite similar to that of the spectrometer solenoid. Because of space limits, adding one-more cooler does not appear to be an option for the focusing magnet.

Since the coolers provide cooling at two temperature ranges, both temperatures ranges must be considered when one look at augmenting the magnet cooling with a small refrigerator. One does not have the option of cooling the HTS leads or the shields with liquid nitrogen, because the temperatures required at the tops of the HTS leads are much lower than 77 K. The actual design temperature at the tops of the HTS leads depends on the magnetic field as well as the temperature margin needed to prevent the leads from burning out. As a result, the coolers remain part of the magnet cooling. This will be discussed further as far as each of the magnet types is concerned.

The cooling at 4.2 K is dependent on a number of factors. These factors include the heat load at 4.2 K and the connection of the coolers to the load. The connection of the coolers to the load is particularly important when the magnet is being cooled by helium in tubes using a thermal siphon circuit. The heat load at 4.2 K is very difficult to predict. Even when one uses a thermal model to do the prediction, the thermal model may not account for all of the sources of heat, some of which are totally unexpected. The heat flow at 4.2 K is also a function of the temperature of the cooler first stages, the tops of the HTS leads, the cold mass intercepts and the shield. With the 4.2 K heat load the devil is often in the details. Before doing anything else, the pressure in the magnet cryostat should be increased to 1.4 atm see whether the coolers will hold the load at 4.6 K.

Why can't the magnet coolers be replaced by a central refrigerator?

The PT-415 coolers provide cooling in the temperature range from 30 to 50 K as well as in the temperature range around 4.2 K. Most of the two stage coolers must be present in order to provide cooling for the HTS leads, the piping and instrumentation lead intercepts, the cold mass intercepts and the magnet shield. The MICE magnets are not designed to cool the leads and intercepts using liquid nitrogen or cooling from a 45-K source of gas. Because the MICE cooling channel magnets were designed to be cooled using two stage coolers, most of these coolers must be retained in order for the tops of the HTS leads to be kept at the proper temperature.

The temperature of the tops of the HTS leads is the primary driver for determining the required first-stage temperature of the coolers. The temperatures of the magnet shields and intercepts are a secondary factor in determining the cooler first stage temperature. The cooler first stage temperature also affects the operating temperature for the cooler second stage for a given heat load into the cooler second stage.

An important factor is the temperature margin of the HTS leads in the event of a power failure that causes the coolers to stop running. The inductance of the MICE magnet is quite high. It takes a long time for the magnets to discharge when the power fails. One must keep the leads cold while the magnet is discharging [12]. A rapid discharge circuit that doesn't fire the quench protection diodes during the discharge has been proposed for all three MICE magnet types [13]. Because the magnet uses diodes and resistors as an integral part of the quench protection system, quenching the magnet has a number of implications not foreseen [14], [15]

The design operating temperature for the HTS leads depends on the temperature margin for the lead at zero induction, the magnetic induction seen by the top of the HTS leads and the orientation of the field with respect to the flat face of the superconductor within the HTS leads. All of the MICE magnets will use multi-filamentary BSSCO tape leads built HTS-110, a New Zealand company [16].

The favorable field orientations are parallel to the direction of the current and parallel to the flat face of the conductor. The orientated HTS materials are designed for magnet applications, and as a result they carry higher currents at fields in the range from 1 T to 4 T. Figure 1 shows the relative lead critical current in an oriented BSCCO lead as a function of magnetic induction and temperature in parallel and perpendicular directions (favorable and unfavorable directions) relative to the flat face of the BSSCO conductor [16]. Note: a relative current of one applies at B = 0 and T = 64 K. Figure 2 shows the favorable and unfavorable magnetic field orientations for the HTS-110 leads.

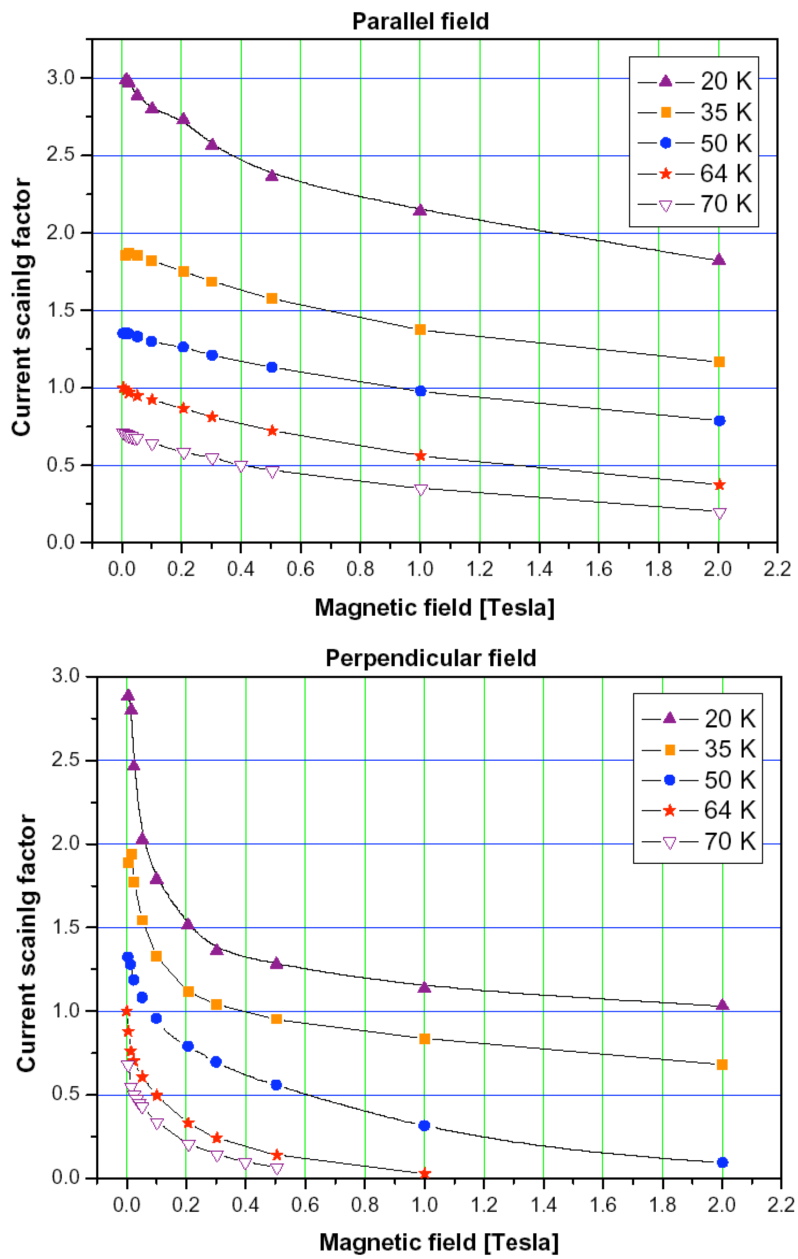

Figure 1. The Relative Critical Current carried a BSCCO HTS Lead in the Favorable Field Orientation (parallel) and the Unfavorable Field Orientation (perpendicular) (with permission from HTS-110 Inc.)

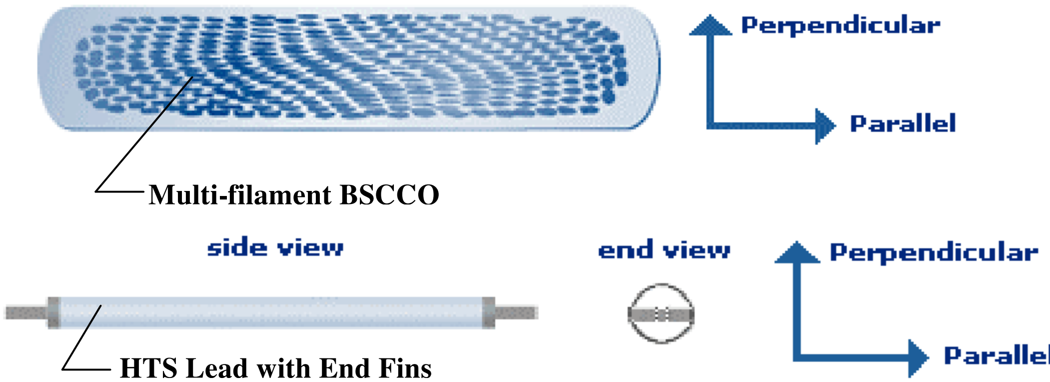

Figure 2. Examples of Favorable Field Orientation (parallel to the flat faces of the conductor) and unfavorable field orientations (perpendicular to the conductor flat face) for leads made for oriented BSSCO tape type HTS superconductor. The lead end fins indicate the conductor flat face direction. (With permission from HTS-110 Inc.)

Since the HTS-110 leads have two of the three field orientations as favorable, in a solenoid magnet without iron it is possible to ensure that the field on the flat face of the HTS leads is always favorable. All one has to do is orient the leads so that the conductor flat face is on a radial line (r direction) and parallel to the magnet axis in the z direction. In all three magnet-types the unfavorable field component should be less than 0.04 T.

The HTS and copper lead requirements for the three types of MICE cooling channel magnets are as follows:

1) The six high current leads for the spectrometer solenoid are designed to operate at 500-A at 64 K with B = 0. The two low current leads for the spectrometer solenoid are designed operate at 100 A at 64 K with B = 0. The high current leads operate at 275 A, and the low current leads operate at 25 to 45 A. The magnetic field at the top of the HTS leads is expected to be less than 0.07 T. At B = 0.07 T, magnetic field orientation is not a large factor. The maximum allowable lead temperature is ~75 K. The temperature of the top of the HTS lead should be as low a possible so there is adequate temperature margin for a power failure at RAL. The heat load to the first stages of the coolers through the copper current leads from room temperature is from 85 to 115 W.

2) The coupling magnets will use two leads that are the same HTS-110 leads as the high current leads for the spectrometer solenoid. At the maximum design current (at p = 240 MeV/c and β = 42 mm in the flip mode) for the coupling coil copper and HTS leads is about 210 A. The magnetic induction at the top of the leads is expected to be about 0.35 T. The maximum allowable temperature is ~69 K. At this magnetic induction, the magnetic field orientation on the leads must be favorable. The temperature of the top of the HTS lead should be as low a possible so there is adequate temperature margin for a power failure at RAL. The heat load to the first stages of the coolers through the copper current leads from room temperature is from 20 to 27 W.

3) The focusing magnets will use four leads that are the same HTS-110 leads as the high current leads for the spectrometer solenoid. At the maximum design current (at p = 240 MeV/c and β = 42 mm in the flip mode) for the coupling coil copper and HTS leads is about 250 A. The magnetic induction at the top of the leads is expected to be about 0.4 T (in the flip mode). At this magnetic induction, the magnetic field orientation on the leads must be favorable. The maximum allowable temperature is ~67 K. The temperature of the top of the HTS lead should be as low a possible so there is adequate temperature margin for a power failure at RAL. The heat load to the first stages of the coolers through the copper current leads from room temperature is from 48 to 65 W.

If the leads for the spectrometer solenoid are improperly installed so that the field direction is unfavorable, the maximum allowable lead temperature drops to ~65 K. If the leads in the coupling magnet installed incorrectly so that the field direction is unfavorable, the maximum allowable lead temperature drops to ~56 K. If the leads in the focusing magnet are installed incorrectly so that the field direction is unfavorable, the maximum allowable lead temperature drops to ~53 K. The importance of installing the leads correctly can't be overstated. The importance of having adequate temperature margin for the leads can't be overstates either.

Figure 3 shows the operating diagram for a PT-415 cooler as measured by Florida State University [17]. From the diagram shown in Figure 3, the ideal cooler first-stage temperature should be in the range from 38 to 45 K. When the first-stage temperature is above 40 K, the second-stage temperature will go up for a given amount of cooling that is taken up by the cooler on the second-stage.

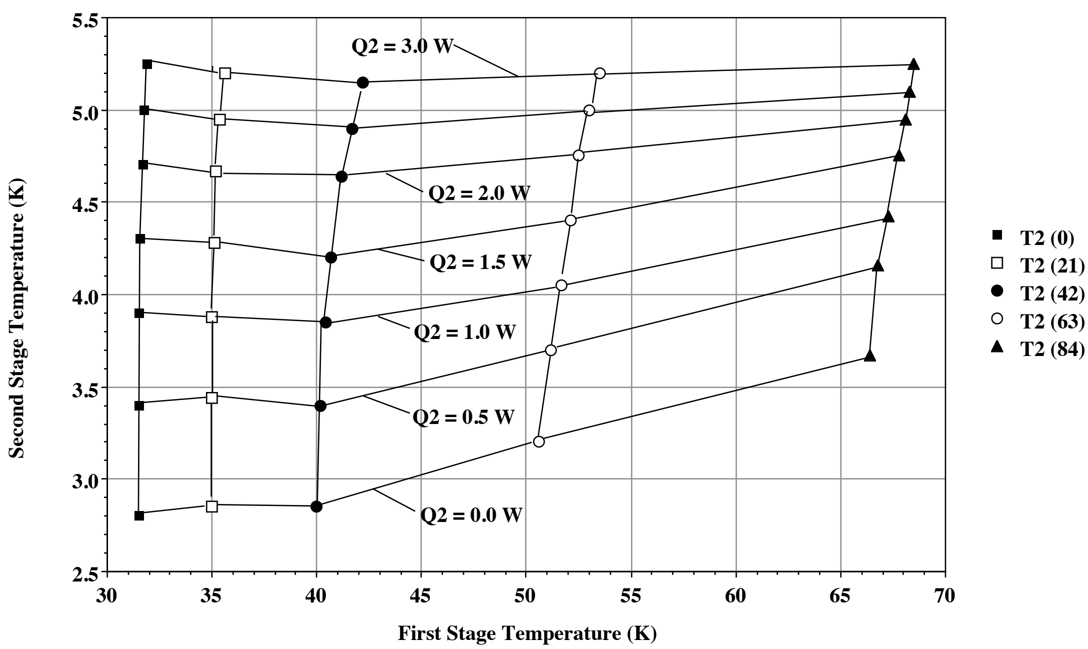

Figure 3. Operating temperature diagram for the first-stage temperature T1 and the second-stage temperature T2 of a PT415 pulse tube cooler as a function of the first-stage heat load Q1 and the second-stage heat load Q2. (Data taken by Florida State University.)

Table 1 compares the calculated heat loads with the available refrigeration at both stages for the three MICE magnet types. The three cases are as follows:

1) The spectrometer solenoid case used is magnet 2 system as it was designed. This case had three PT-415 two-stage coolers. The final version may have as many as five PT-415 coolers plus a single stage GM cooler.

2) The coupling magnet case used in Table 1 is the original coupling coil design with two PT-415 coolers. The final version of the coupling coil design calls for three PT-415 coolers instead of two.

3) The focusing magnet case is the design case that has been calculated by the author. The vendor estimate is lower especially at the second-stage of the cooler. In this case, there is only room for two PT-415 coolers.

Table 1. A comparison of the Calculated Heat Loads for Both Stages of the Coolers when used in the Spectrometer Magnet, the Coupling Magnet, and the Focusing Magnet

Parameter	Spectrometer	Coupling	Focusing
Number of PT-415 Coolers	3	2	2
Total Lead Current (Lead Number)	1770 A (8)	420 A (2)	1000 A (4)
Cold Mass Design Force	500 kN	500 kN	700 kN
Magnet Shield Area	~15 m^2	~8 m^2	~7 m^2
Number of Pipes to cold Mass	4	4	4
Number of Wires to the Shield	147	92	115
Number of Wires to the Cold Mass	84	68	72
Calculated Heat Loads to the Cooler First Stages (T = 40 to 50 K)			
Lead Conduction + i^2 R Heating (W)	85 to 115^	20 to 27^	47 to 65^
Cold Mass Support heat Load (W)	~9	~9	~13
MLI Heat Load (W)	15^^	8^^	7^^
Pipe and Sleeve Heat Load (W)	~12	~10	~4
Instrumentation Wires (W)	~2	~2	~2
Total Design Heat Load (W)	123 to 153	49 to 56	73 to 91*
Heat Load per Cooler 1st Stage (W)	41 to 51	24 to 28	36 to 45*
Calculated Heat Loads to the Cooler Second Stages (T = 4.2 to 4.5 K)			
Lead Conduction + i^2 R Heating (W)	~0.49**	~0.16**	~0.31**
Cold Mass Support heat Load (W)	~0.41	~0.41	~0.62
MLI Heat Load (W)	~1.5^^	~0.8^^	~0.7^^
Pipe and Sleeve Heat Load (W)	~1.2	~0.9	~0.43
Instrumentation Wires (W)	~0.17	~0.14	~0.15
Total Design Heat Load (W)	~3.77	~2.41	~2.21*
Heat Load per Cooler 2nd Stage (W)	~1.26	~1.21	~1.11*

^ The expected range for the copper leads carrying the design currents of the magnet.
^^ The MLI heat leak is 1 W m^{-2} of on the shield and at 4 K the heat leak is 0.1 W m^{-2}.
* The heat leak estimated by the vendor is lower.
** Most of this heat load is HTS lead heat leak with the tops of the leads at 64 K.

Table 1 shows the estimated heat loads on the shield and the cold mass for the three MICE magnet types. The estimated heat loads for the spectrometer solenoid are based on the vendor estimate. The estimated heat loads for the coupling magnet are based on the original estimates by ICST in Harbin. The estimated heat loads for the focusing magnet are based on the spectrometer and coupling magnet heat load estimates. The vendor heat load estimate for the focusing magnet is somewhat lower than the numbers in Table 1.

When one looks at the second stage heat loads, the heat leak through the MLI appears to be the single most unreliable heat leak estimate. The MLI heat leak can be up to 200 percent higher, especially if the shield and cold mass support intercept temperatures are too high. This is serious because the MLI heat leak represents about one third of the total heat load to the cooler second stages.

Errors in the insulation between the cryostat vacuum vessel and the shield will be reflected as higher second-stage heat loads to the coolers. Many of the other heat loads into the coolers second-stages are a function of the shield and intercept temperature squared. The heat leak due to the cold mass supports, the leads, and the pipes and sleeves can be estimated within ~20 percent. The uncertainty in the instrument wire heat leak is quite high, because one doesn't know exactly how the heat from the wires will be intercepted to the cooler first-stages. Fortunately, the instrumentation heat load estimate is represents only 4 to 6 percent of the total heat load to the cooler second stages

The actual heat leaks into the first stages of the coolers measured in the spectrometer solenoid is over a factor of two larger than the numbers shown in Table 1. The reasons for this disparity are not understood. Magnet 2 has a much higher heat load into the cooler first stages than does magnet 1. The difference between the two magnets is not well understood. There doesn't appear to be any one source for the extra heat load into the cooler first stages. It is disturbing that there aren't one or two larges sources for the added heat leak to the magnet shield. The heat load into the cooler second-stages in the spectrometer solenoid appears to about fifty percent higher than the estimated value shown in Table 1. As a result, the spectrometer solenoid will have five two-stage coolers and one single-stage GM cooler capable of generating 185 W at 55 K.

It would be naive to think that similar disparities won't occur in the coupling and focusing magnets. The redesigned coupling magnet cryostat will have an added two-stage cooler. In addition, there are features in the new design that will reduce heat load from the values shown in Table 1. With three coolers, the calculated contingency for first stage is in the range from 125 to 160 percent for the coupling magnet. For the second stage the contingency is close to 90 percent with three coolers. Because of the high magnetic field around the coupling magnet, an added single stage GM cooler is not an option for providing added cooling to the tops of the HTS leads and the shield.

The author's greatest concern is the focusing magnet. The focusing magnets were not designed to use a third cooler. With two coolers, the contingency for first stage is small (from 0 to 15 percent). For the second stage, the margin with two coolers is about 35 percent. If the vendor of the focusing magnet makes errors in the magnet assembly (particularly the MLI), it is quite possible that the shield and HTS lead temperatures will be too high and worse yet, there won't be enough cooling at the second stages to keep the magnet at liquid helium temperature. Because of the high magnetic field around the focusing magnet (particularly in the flip mode), an added single stage GM cooler is not an option for providing added cooling to the tops of the HTS leads and the shield.

How much cooling must be provided by a 4.5 K refrigerator?

It is difficult to estimate whether a magnet will require additional cooling above and beyond what is provided by the coolers that are mounted on the magnet. If all of the magnets operate with the coolers as designed, there is no problem. If even one magnet can't be kept cold using the two-stage coolers, the MICE experiment will not operate as designed. The author of this note feels that it would be foolish not to consider the option of providing added refrigeration at 4.5 K to ensure that MICE will do the physics that it was designed to do. MICE is physics experiment not a cryogenic experiment.

The spectrometer solenoids are different from the other two types of magnets in that there is about 190 liters of helium in the magnet cold mass. The spectrometer solenoid can be filled with liquid helium from a dewar, if the cooling shortfall is less than 1 liter per hour of boil-off at 4.22 K (0.7 W). With this cooling shortfall, the spectrometer magnet may operate at a higher temperature without boiling liquid helium. An occasional helium fill of the magnet cryostat can be done, provided the transfer line is well cooled before the helium is added to the tank and provided the liquid helium is delivered to the top of the helium vessel that is part of the cold mass.

The coupling and focusing magnets have 40 liters or less of liquid helium in contact with the cold mass. These magnets probably can't run with helium from an external dewar. Even if one were able to top off the magnet cryostats with liquid helium, the shields and the leads require cooling from the first-stages of the coolers. One can't reduce the heat load into the cooler first-stages without disassembling the magnet to either reduce the first-stage heat load or to intercept the heat coming down the copper leads from room temperature using liquid nitrogen.

This author proposes that at Claude cycle refrigerator provide 4 K cooling to the magnets that need extra cooling. When on operates the magnet system on a central refrigerator, the operating temperature of the magnet will be in the temperature range from 4.4 K to 4.6 K. The operating temperature of the central refrigerator-liquefier is set by the suction pressure of the compressors and the pressure drop through the low-pressure side of the refrigerator heat exchanger.

The magnets that are most likely to need additional cooling are the spectrometer magnets or the focusing magnets. The third cooler in the coupling magnet will increase the cooling margin for both stages of this magnet by more than 80 percent. The two added coolers on the spectrometer solenoids will increase the cooling margin on the first stage by ~84 W. Depending on how the reassembly of these magnets goes, adding two coolers should increase the margin at 4.2 K to about 25 percent. It appears that it is unlikely that a third cooler can be added to the focusing magnet. The author considered this magnet to have the largest risk of not being able to operate on its two coolers.

Given the experience with the spectrometer solenoid, it is likely that the shortfall in cooling at 4.2 K for a given magnet is 1.5 W or less. If all seven magnets require 1.5 W of added cooling, the needed added cooling would be as large as 10.5 W. The added cooling needed by the magnets is dwarfed by the transfer line losses. A transfer line that delivers cooling to the MICE all and down the length of the magnet string would require an added amount of cooling (about 0.3 W per meter if the line is unshielded). It is likely that the transfer line to deliver helium cooling to the hall and the 12-meter long magnet string would be about 20 meters long each way. The primary feed line would require about 12 W of cooling. Lines that carry helium carry helium to and from the primary lines would require an added 2 to 3 watts per magnet (including bayonet joints). If a valve distribution box is used, the heat load goes up further. The minimum amount of cooling (for one magnet) that would have to be supplied a refrigerator might be ~20 W. If all seven magnets need cooling from a central refrigerator, the added refrigeration could be as high as 45 to 50 W. The truth is somewhere in between.

The best way to reduce the heat loads to the transfer lines is to put the cooled magnets in series. The flow to the magnets is two-phase flow and the flow between magnets is also two-phase flow with more gas entrained within the liquid. The two-phase helium quality (the gas fraction) increases as one goes down the magnet string. A liquid helium vessel with a heat exchanger between the cold box and the transfer lines to the magnets is used to reduce the helium gas fraction of the two-phase helium entering the system. Ideally sub-cooled liquid helium enters the transfer line that goes to the magnet string. Having two-phase helium that is on the liquid side of the two-phase dome reduces the system pressure drop by at least a factor of three. Two-phase helium is returned to the control cryostat (control dewar) where the final phase separation occurs. A two-phase flow system with a low pressure-drop is illustrated in Figure 4.

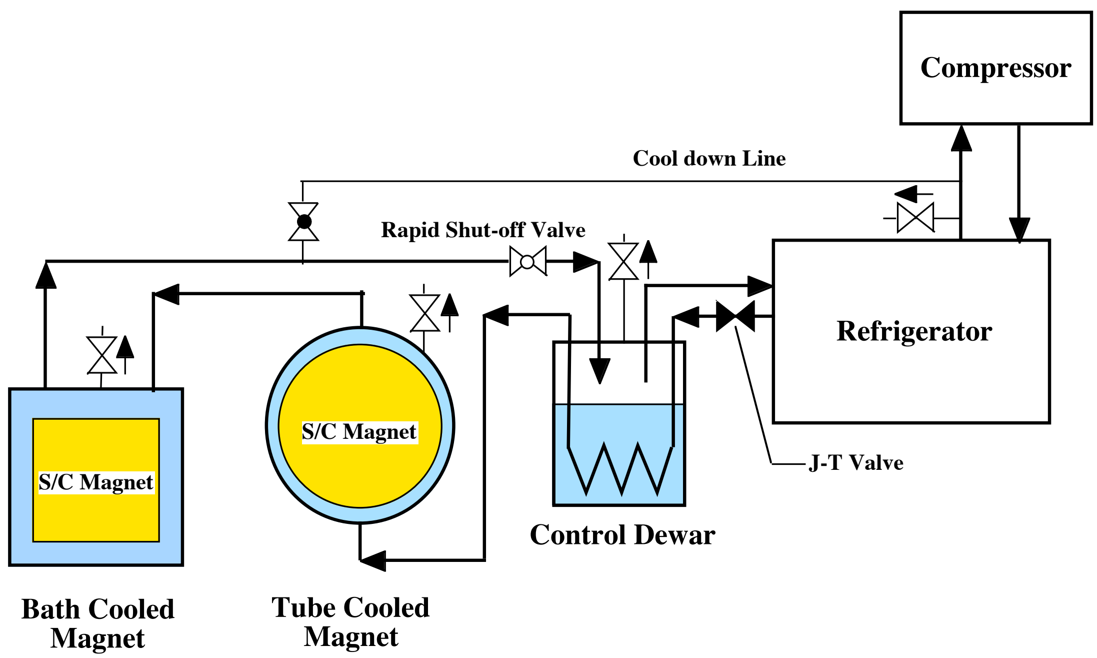

Figure 4. A Schematic of a Two-phase Cooling Circuit with a Refrigerator, a Control Dewar for reducing the Gas Fraction of the Helium, a Tube Cooled Magnet, and a Bath Cooled Magnet. (Using this circuit the magnets can be cooled down using the refrigerator. Note: A rapid shut off valve between the control dear and the refrigerator is not shown)

The type of two-phase cooling system shown in Figure 4 is commonly used to cool large detector magnets [18]. A variation of this flow system was used on the g-2 experiment at Brookhaven [19]. The circuit shown in Figure 4 can be used to cool down the magnets. Valve boxes and parallel circuits in and out of valves boxes increase the heat load to the two-phase helium being circulated to the magnets that need the extra cooling. Valve boxes and parallel circuits should be avoided if possible.

Before discussing the central refrigerator needed to provide cooling for magnets with inadequate cooling, it is useful to discuss what is needed on the MICE magnets so that added cooling can be provided. First, there must be a port where cold two-phase helium can be injected into the magnet. Since the magnet is already cold, the two-phase helium from the transfer line can be injected into the cool-down line that goes to the bottom of the magnet. Second there must be a transfer line that takes the two-phase helium from the top of the magnet to the next magnet. The helium leaving the magnet must be taken off the top of the magnet. In short there must be an entrance port and an exit port for the helium from the refrigeration system. These ports must be part of the cooling system that is built into the magnets in the first place. It is important that the magnets be built to accommodate the ability to keep them cold using an external refrigerator.

In magnets with a helium tank, one may feed the two-phase helium at the top of the tank and take the two-phase helium away at the top of the tank. The transfer line taking helium away from the tank must be separated from the line entering the tank, so that phase separation occurs. The transfer line leaving the tank must be at lower level in the tank than the line entering the tank. The exit line determines the tank helium level.

There is at least one method of cooling both the coupling and spectrometer magnets using a central refrigerator. Both the spectrometer solenoid and the coupling magnet can also be cooled down using a central refrigerator, if needed. It is not clear that the focusing magnet design will allow these magnets to be connected to a central refrigerator. If one is going to allow the option of cooling magnets with a central refrigerator, all of the MICE cooling channel magnets should be designed with this in mind.

Refrigeration Options for Operating the MICE Cooling Channel

There are two options for providing refrigeration to MICE cooling channel magnets that need the extra cooling. The options are: 1) Use a separate piston expander 1400 Claude cycle machine to provide the added cooling to the cooling channel magnets that need the extra cooling. 2) Use the existing RAL machine that is in the MICE hall to provide the added 4 K cooling to the cooling channel magnets that need extra cooling.

A) Use a 1400 Series Refrigerator to Provide Added Cooling to Magnets

Claude cycle refrigerators of the 1400 series have been made since the early 1970's. The first machines were made in 1970 by the 500 Incorporated Division of Arthur D. Little in Cambridge MA in the USA. Over the years, various companies have made these machines. Linde in Tulsa Oklahoma in the USA is still manufacturing these machines. There have been hundreds of these machines installed around the world. Many of these machines are still running. The 1400 machines use two piston expanders and oil lubricated screw compressors. With periodic maintenance, these machines can be quite reliable. For twenty years, the vacuum system for the Bevatron (the synchrotron part of Bevalac heavy ion system) at LBL was cooled to 12 K using four 1400 machines. The primary maintenance required for these machines was changing the oil absorber canisters every three to six months. The newer machines are more reliable than the older machines. The newer machines have better instrumentation than the older machines.

There may be some advantages in using a piston machine over a turbine expander machine in the size range that is required for added cooling for the MICE magnets. A refrigerator with piston expanders is insensitive to the temperature of the lower heat exchangers in the machine. Gas-bearing turbines of the type used by Linde will shut down when the heat exchanger gets to cold. This prevents changes in the direction of the thrust in the turbine thrust bearings found in some turbines. This also prevents damage to the turbine expander blades due to cavitation from helium droplets that may be entrained in the expanding gas as it leaves the turbine.

When a piston expander machine, such as the 1400, is used, the flow circuit shown in Figure 4 can be used to supply 4.5 K cooling to cooling channel magnets that need it. The rapid shut-off valve between the magnets and the control dewar and the magnets can be eliminated, if one wants to recover some of the sensible refrigeration from the magnet quench gasses. Some of the cold gas from a quench can be taken through the heat exchanger and be vented at the intake of the compressor. As a result, some of the sensible refrigeration from the quench ends up in the cold box heat exchangers.

The basic Parameters for the 1410 (helium liquefiers with purifiers) and 1430 (4.6 K helium refrigerators) Linde machines is shown in Table 2 [20], [21].

Table 2. The Basic Parameters for the Linde 1410 and 1430 Helium Liquefiers and Refrigerators as a Function of Line Frequency with and without Liquid Nitrogen Cooling. (The data comes from Linde Cryogenics a Division of Linde Process Plants Inc., 1600 South Yale, Suite 1200, Tulsa OK 74136, USA.)

Model L1410 Liquefaction Performance (Liters/Hour)

50Hz	60Hz	50Hz	60Hz	
Without LN_2 precooling	Without LN_2 precooling	With LN_2 precooling	With LN_2 precooling	Compressor
8	10	16	20	RSS
17	17	39	47	RS
-	-	47	-	RSX

Model 1430 - 4.6K Refrigeration (Watts)

50Hz	60Hz	50Hz	60Hz	
Without LN_2 precooling	Without LN_2 precooling	With LN_2 precooling	With LN_2 precooling	Compressor
30	41	40	51	RSS
64	64	100	114	RS
-	-	114	-	RSX

Model 1410/1430 Main Dimensions

Description	L x W x H (m)	Weight (kg)
Model L1410 Helium Liquefier	1.270 x 1.067 x 1.700	818
Model LR1430 Helium Refrigerator	1.270 x 1.067 x 1.700	818
Compressor - RSS	1.450 x 1.250 x 1.420	1100
Compressor - RS & RSX	1.450 x 1.350 x 1.480	1135

According to Linde, the machine is no longer available with the RSS compressor. The Linde compressor data sheet for the RS compressor shows that the compressor compresses helium from 0.1013 MPa to 1.823 MPa at a rate of about 18 g s^{-1} at 60 Hz and about 15 g s^{-1} at 50 Hz. At 60 Hz the power requirements are 95 kW of three-phase power. At 50 Hz, the power requirements go down to 80 kW. The cooling requirements at 50 Hz are 57 L/min at 24 C maximum temperature at an input pressure 310 kPa.

The mass flow through the J-T circuit at 60 Hz will be ~10 g s^{-1} with pre-cooling. The mass flow through the J-T circuit goes down to ~8.5 g s^{-1} at 50 Hz with pre-cooling. Without pre-cooling the J-T circuit mass flow is about ~7.5 g s^{-1} at either frequency. When the gas entering the gas bearing turbines is at higher temperatures, the mass flow through the J-T circuit is lower. From the experience of the author, the J-T mass flow may be as lower by as much as 2.5 g s^{-1} when there is no pre-cooling.

Piston expanders can be used to expand helium into the two-phase dome. This was first demonstrated by Collins in 1967 using an expander that was similar to the expanders used in a 1400 refrigerator. Piston expanders in place of a J-T valve can boost the 4 K refrigeration performance of a Claude cycle machine by as much as fifty percent. There are a number of machines around the world that use piston expanders in place of the J-T valve. In addition there are no negative consequences in taking 4.2 K gas back through the heat exchanger in a 1400. Theoretically the refrigeration stored in the heat exchanger can be used to speed up a magnet cool down, but this is probably not a factor in MICE.

The operating parameters given in Table 2 apply for a new machine. Older machines may be different depending on the compressors that are attached to those machines. There may be used machines that might become available. These machines appear on surplus lists from time to time. When they appear, they should be snatched up, because the machine is very versatile for general laboratory applications. If an older machine becomes available, the author would suggest that the machine be acquired. There are 1400 machines that have operated for more than 35 years. The factory can refurbish an old machine at a much lower cost than the cost of buying a new machine. The maintenance schedule for a 1400 probably matches that of MICE. These machines do not require operators, but they do require some routine maintenance.

The cost of a new 1400 cold box (100 W at 4.6 K or 39 L hr^{-1} with LN_2 pre-cooling, 50 Hz power), compressor, and spare parts is 546.6 k$ plus installation [22]. The problem at RAL is where to install the new machine and the cost of getting power and cooling to the compressors. The installation costs can be more than the purchase price of the machine and its compressor, assuming that one can find a place to put the compressor, the compressor cooling and the cold box. If the cold box is not MICE hall the added heat loads to the transfer lines will eat up some of the 4.6 K 1400 refrigeration.

B) Use the Existing RAL Central Refrigerator to provide Added Magnet Cooling

There is a Linde refrigerator that is used to cool-down and provides 4.6 K cooling to the 5-meter long pion-decay solenoid for MICE. Ideally, this refrigerator has excess capacity that can be used to cool the magnets that need added refrigeration. There is at least part of the transfer line system needed for cooling the magnets that is already in place. As a result, the excess capacity needed to cool these magnets could be less than 20 W even if a majority of the magnets need added cooling at 4 K.

The control dewar and magnets that are shown in Figure 4 should be connected in series with the decay solenoid heat transfer tank at the down stream end of the flow circuit. The gas leaving the decay solenoid is not supercritical, so it is unlikely that further expansion of the helium through a J-T valve or wet expander is necessary. As shown in Figure 4, the control dewar will ensure that the two-phase helium entering the magnets will have a minimum gas fraction. Reducing the helium gas fraction reduces the pressure drop in the flow circuit. Since the helium coming from the control dewar at a mass flow set by the upstream J-T valve, flow instabilities are eliminated in the two-phase flow circuit downstream from the pion decay solenoid.

The Linde machine that is in place at RAL has gas-bearing turbine expanders. These expanders are sensitive to the temperature in the lower part of the refrigerator heat exchanger. As a result, one cannot pass cold gas from a magnet quench through the heat exchanger of the cold box as one can with a refrigerator with piston expanders. An added rapid shut-off valve is required to keep cold gas from the control dewar from entering the low side of the refrigerator heat exchanger. In addition, the refrigerator J-T valve should be closed when a magnet quenches.

It is not clear that the existing Linde refrigerator as is can be used to provide excess cooling to cooling channel magnets. If there is excess capacity, the option to use the existing Linde plant to cool channel magnets that need the extra cooling should be considered seriously because it is likely to less costly in terms of money and time. If the existing system doesn't have very much excess capacity, one must consider other options in order to increase the available refrigeration in the range of 4.4 K to 4.6 K.

The actual flow circuit for the refrigerator and the 5-meter long decay solenoid is shown in Figure 5. Figure 5 shows the actual temperatures and pressures for the refrigerator and the decay solenoid as it was running on 2 May 2011. The temperature of the helium in the tube connected to the magnet thermal is from 67.6 to 76.1 K. The temperature and pressure of the gas entering the first turbine are 72.2 K and 12.77 bars respectively. The turbine entry temperature is lower than the temperature leaving the shield. This indicates that the flow through the shield tube is only a portion of the flow that is going through the turbines. The gas pressure enters the second turbine 6.36 bars. The temperature of the gas leaving the second turbine is 9.2 K goes up the low-pressure side of the heat exchanger cooling the upper heat exchangers. The temperature and pressure of the gas entering the low-pressure side of the J-T heat exchangers is shown as being 7.23 K and 1.213 bars. The temperature sensor at this point is either defective or there is a large heat leak in the line between the decay solenoid and cold box. The temperature of the gas entering the lower heat exchanger should be around 4.6 K, if the heat leaks are low. None of the mass flows of any of the circuits is given in Figure 5.

Figure 6 shows a preliminary T-S diagram for the decay solenoid refrigerator [23]. The shield was operating over a temperature range from 59.84 K to 61.44 K, which is different from the temperature range shown in Figure 5. The heat load into the shield is shown as 146.1 W. The available refrigeration at 4.41 K is shown as being 44.85 W. According to Figure 5, the temperature drops across the first turbine from 61.4 to 50.0 K. According to Figure 5, the temperature drop across the second turbine is from 12.4 K to 8.2 K. The operating points in the T-S diagram appear to be quite different from the operating points shown in Figure 5. In Figure 5 the turbine circuit flow is 17.96 g s^{-1}. The J-T circuit flow is 3.16 g s^{-1} of which about 0.23 g s^{-1} goes up the gas-cooled leads.

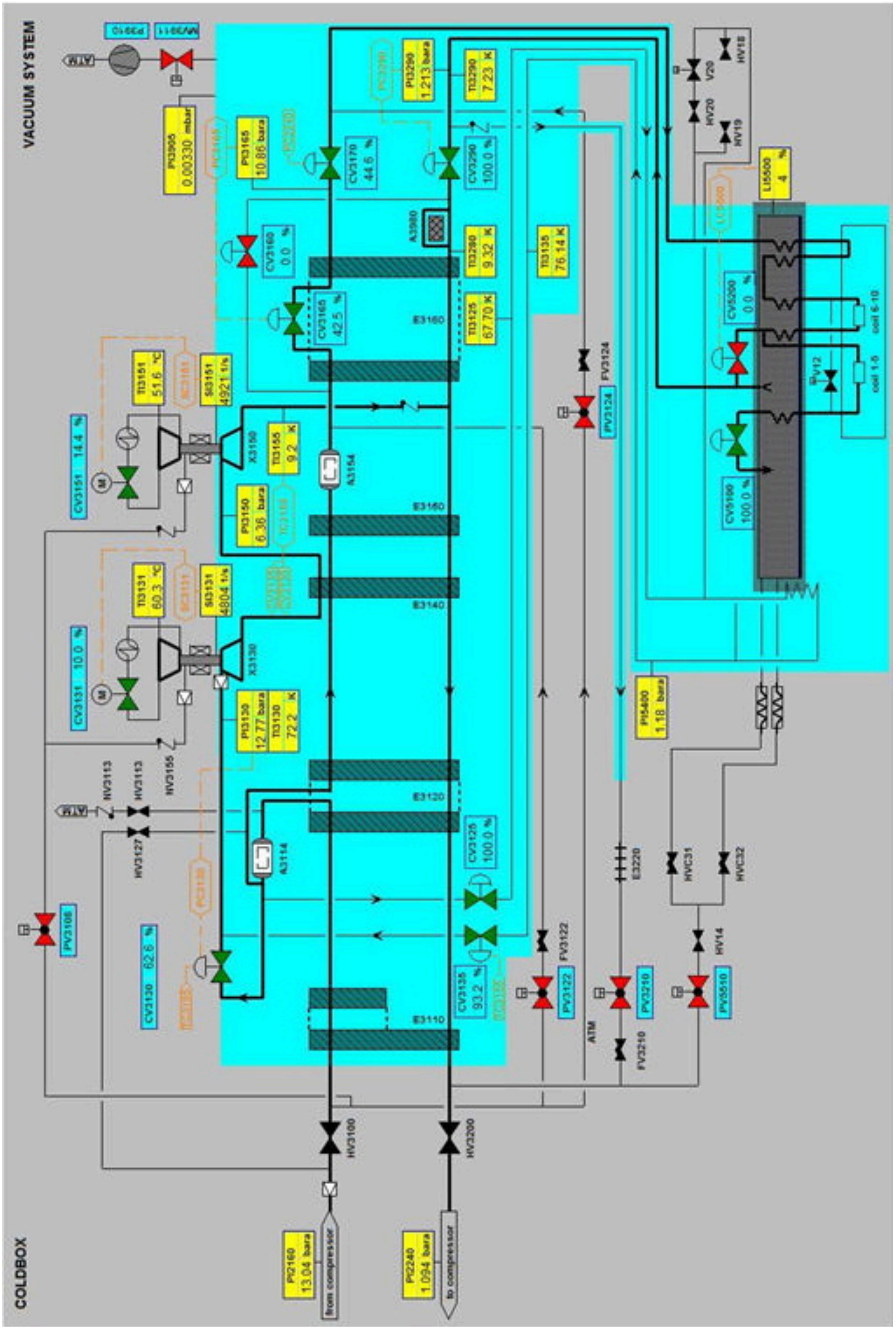

Figure 5. The flow diagram for the Linde Refrigerator connected to the Decay Solenoid. The refrigerator provides supercritical helium at 12.8 bars and 67.6 K. The supercritical helium returns at 76.1 K. The helium leaving the decay solenoid heat exchanger tank to go back to the refrigerator leaves at a pressure of 1.213 bar and about 4.4 K. (Note: the actual pressure and temperature are different from Figure. 6.)

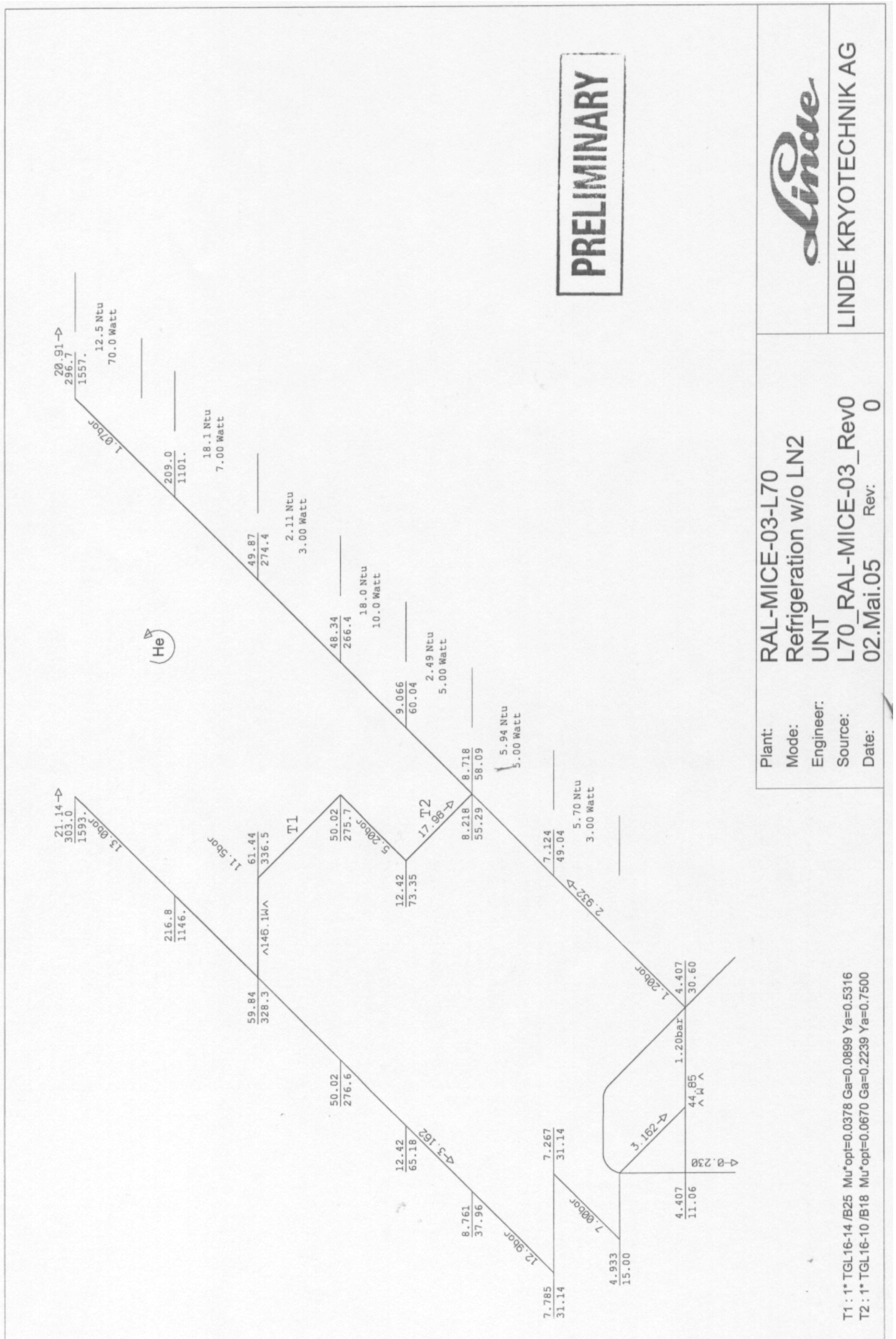

Figure 6. The Design Temperature Entropy Diagram for the Refrigerator and the Decay Solenoid. According to this diagram, the shield transfers 146.1 W to the helium stream that feeds the gas bearing turbine expanders. The shield temperature range is from 59.8 K to 61.4 K. The 4.4 heat load is 44.8 W.

Before doing anything with the Linde refrigerator, one should try to get the magnets to hold on their coolers at a higher temperature than 4.2 K. If the magnet cryostats can be pressurized to 1.4 atmospheres, the equilibrium temperature in the cryostat will go up to about 4.6 K. At 4.6 K each cooler will generate 1.8 to 1.9 W of cooling instead of 1.5 W (at 4.2 K). This means that leaky relief devices have to be replaced with devices that don't leak in order to set the cryostat pressure higher. If increasing the cryostat pressure does not work, the magnet has to be connected to a refrigerator (either the existing RAL refrigerator or another refrigerator).

There are at least four things that should be considered to increase the available refrigeration from the existing Linde plant to supply added 4.5 K cooling to the MICE magnets that need the cooling. These four things in order of difficulty are: 1) Decrease the heat load at 4.5 K in the decay solenoid. 2) Cool the shield of the decay solenoid with liquid nitrogen instead of 70 K gas from the refrigerator. 3) Use nitrogen pre-cooling on the refrigerator. 4) Replace the final J-T valve between 10 bars and 1.25 bars with a wet expansion engine expanding into the decay solenoid heat exchange tank. Steps 1 and 2 should be done together, because both are relatively easy to do. Steps 3 and 4 are more complex. They should be considered after steps 1 and 2 have been implemented.

1) Reduce the Decay Solenoid Heat Leak

The heat leak into the decay solenoid had to be reduced in order for the magnet to operate at its design field. The decay solenoid has a cold bore. Heat streaming into the magnet from room temperature at the ends added many watts of additional heat at 4.2 K. Covering the ends of the bore tube with MLI reduced the heat leak into the decay solenoid enough for it to operate at its design current.

The author of this note suspects that the heat flow into the decay solenoid bore can be reduced further. One can reduce the heat further by attaching a foil made from annealed pure aluminum across the bore and connected to the shield. This should be done at both ends of the magnet. Additional MLI layers should be installed outside of the aluminum foil bore tube shield. The down side of this approach is that added material is put in the pion beam (upstream) and the muon beam (downstream). Is the added mass of the MLI going to be any worse than the absorber windows and the MLI on the absorbers? The author doesn't think so, because the added material is upstream from the diffuser that sets the beam emittance going into the experiment. There may be other changes made to reduce the heat flow to the 4 K region of the decay solenoid. Every watt saved at 4.2 K in the decay solenoid is a watt of refrigeration available for keeping channel magnet cold should that become necessary. One should trim the lead gas flow as much as possible. If the lead flow is reduced by 0.1 g $^{-1}$, the available refrigeration increases by 10 to 12 W.

2) Cool the Decay Solenoid Shield with Liquid Nitrogen instead of the Refrigerator

The Linde refrigerator produces 146 W of cooling at 60 to 70 K. This cooling is taken from the helium stream going to the turbine expanders. If the 146 W is put into liquid nitrogen, thus boiling 3.3 liters per hour of liquid nitrogen, the gas entering the turbine expanders is colder. As a result the flow in the gas stream to the expanders can be reduced. The amount of gas not expanded through the turbines can then go into the stream that goes through the decay solenoid heat transfer tank and the J-T valve. The removal of 146 W of cooling at 60 to 70 K results in an increase in cooling at 4.2 K by about 10 W, because the J-T stream mass flow increases by about 0.5 g s^{-1}.

3) Add Liquid Nitrogen Pre-cooling to the Refrigerator

Liquid nitrogen pre-cooling can increase the refrigeration at 4 K by as much as a factor of two depending on the cycle and other details in the machine design. The increase in performance in machines with gas turbines is usually not large as a factor of two, when liquid nitrogen pre-cooling is used in the cycle. Liquid nitrogen pre-cooling decreases the entry temperature to the turbines and as a result, the mass flow in the helium stream going through the gas-bearing turbines can be decreased. Helium gas not going through the turbines can go through the J-T heat exchanger to provide added cooling at 4.5 K. Standard machines built by Linde and Air Liquide often offer nitrogen pre-cooling as an option. From what the author knows about RAL machine liquid nitrogen pre-cooling was not included.

It appears that retrofitting the existing machine with an additional three-pass heat exchanger (high pressure helium, low pressure helium and liquid nitrogen) would be costly. The gain in refrigeration delivered at 4.5 K could be from 18 to 24 W, if the extra heat exchanger can be installed between the compressors and the cold box.

4) Use a Wet Expander in Place of the Final J-T Valve

According to the T-S diagram shown in Figure 6, the amount of refrigeration produced at 4.4 K is about 45 W. The final expansion from 10 atm to 1.2 atm is through an isenthalpic expander (the J-T valve). If the expansion is closer to isentropic (through and expander that take work out of the gas stream) a forty to sixty percent increase in the refrigeration at 4.4 K will occur. The increase in the refrigeration is from 18 to 27 W.

A number of refrigerators have been built with wet expanders, so the gain in refrigeration at 4.4 K is proven. LBNL has a Cryogenic Consultants refrigerator that develops 250 W with a J-T and about 450 W with a Gardner piston expander in place of the J-T. I would expect this kind of performance increase with the RAL refrigerator.

Adding a wet expander is a solution that is hard to implement because the expansion occurs into the heat exchanger tank of the decay solenoid. At the very least the decay solenoid vacuum vessel would have to be opened up so the lines that connect to the J-T valve can be brought out to an external wet expander. The author knows that piston expander can operate with two-phase helium, but he is not sure that there is an available helium turbine that allows two-phase expansion. This option should be put on the table in the event the previous three solutions don't provide the required added cooling from the existing Linde plant at RAL.

C) RAL Central Refrigerator Connection to the Decay Solenoid and Other Magnets

If one can increase the available refrigeration from the existing RAL refrigerator by 20 W or more, one can use the existing RAL refrigerator to provide cooling to the pion decay solenoid and any of the MICE cooling channel magnets that need extra cooling. The author proposes putting the decay solenoid in series with the forced two-phase cooling circuit used to cool the cooling channel magnets that need extra cooling at 4.5 K. The decay solenoid would still have its supercritical cooling system using helium at about 10 bars. Just as is shown in Figure 5, the helium is expanded to two-phase helium in the decay solenoid heat exchanger tank.

Instead of going back to the low pressure return side of the RAL cold box, the two-phase helium would go to control-dewar where it would flow through a copper-tube heat exchanger that is in liquid helium within a control-dewar. The boiling liquid helium on the outside of the copper tube heat exchanger is used to reduce the gas content of the two-phase helium flowing through the copper tube. The helium within the copper-tube heat exchanger leaves the control-dewar as a liquid. This helium goes out to the cooling channel magnets that need extra cooling. The cooling channel magnets that need extra cooling are connected in series with the control-dewar. The two-phase helium returning from the last magnet in the string comes back to the tank side of the control-dewar where helium phase-separation occurs. The liquid helium, which is at lower temperature than the two-phase helium flowing through the copper-tube heat exchanger, is evaporated to reduce the gas content of the two-phase helium within the copper tube heat exchanger. The boil-off gas from the control-dewar goes to the low-pressure return flow side of the RAL refrigerator. The proposed cooling circuit is shown in Figure 7.

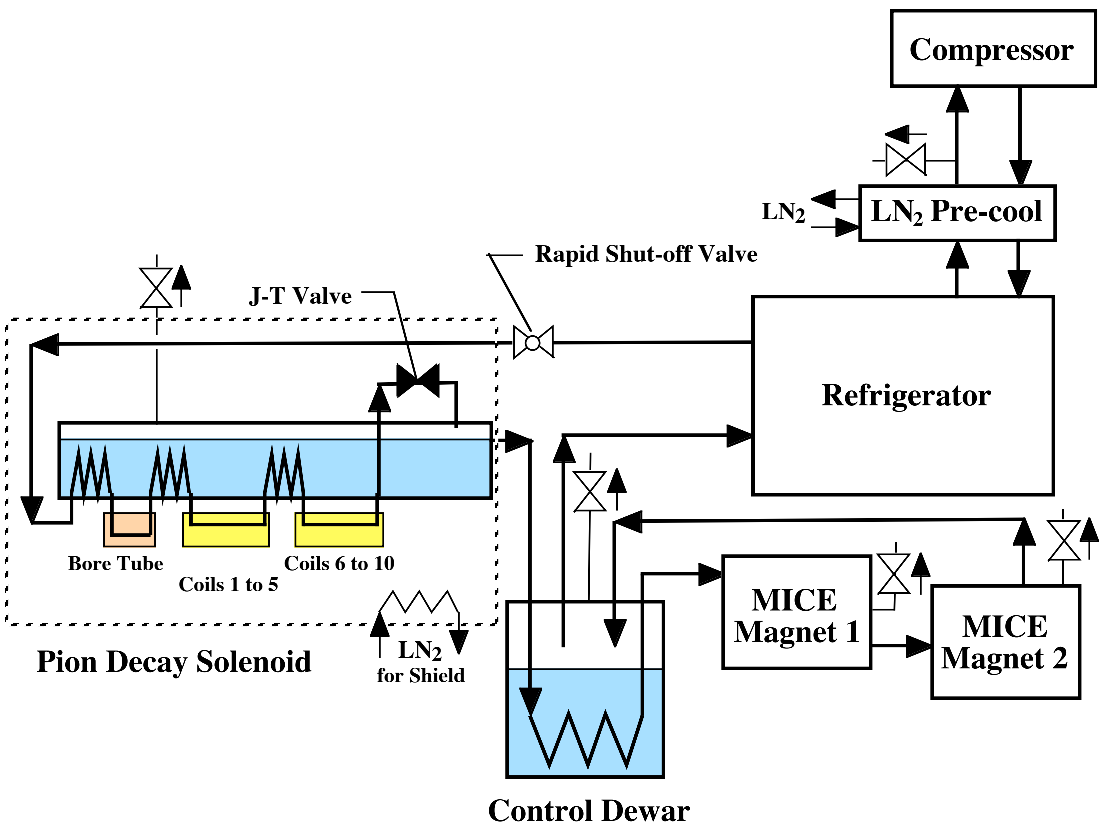

Figure 7. The Cooling Circuit for the Decay Solenoid and Other MICE Cooling Channel Magnets that need Extra Cooling at 4.6 K. (Note: the cooling system that is downstream from the decay solenoid heat exchange liquid helium reservoir should have as low a pressure drop as possible.)

Figure 7 shows the pion decay solenoid and two other magnets being cooled using a series helium cooling circuit. Figure 7 assumes that the decay solenoid shield is cooled using liquid nitrogen. It goes without saying that the heat load into the decay solenoid has been minimized. Figure 7 shows a liquid nitrogen pre-cooling heat exchanger between the compressor and the existing RAL cold box. The J-T valve that is shown in Figure 7 potentially could be replaced with a wet expander.

The helium coming back from the control dewar goes back to the low side of the refrigerator heat exchanger. The author's experience with turbine expander refrigerators suggests that the circuit shown in Figure 7 will not tolerate liquid helium going into the low-pressure side of the heat exchanger. An added rapid shut-off valve may be needed in the line between the control dewar and the low-pressure side of the refrigerator heat exchanger. When a magnet quenches, the rapid shut-off valves must be closed to protect the refrigerator, the control dewar, and magnet cryostats.

One can control the liquid level in the control dewar by using a heater in the control dewar. One can potentially the liquid level in the control dewar by adjusting the opening of the J-T valve that feeds helium to the decay solenoid heat exchanger cryostat. The author doesn't know how the RAL refrigerator is controlled when it operates on the decay solenoid.

The down side of the cooling circuit shown in Figure 7 is the fact that there is an added pressure drop between the decay solenoid heat exchanger tank and the cold low pressure side of the RAL refrigerator. The temperature of the decay solenoid coils can be no colder than the liquid helium in the heat exchanger tank of the decay solenoid. The forced two-phase flow circuit down stream from the decay solenoid helium tank can have a pressure drop from 0.1 to 0.2 bars. As a result, the temperature of the decay solenoid is increased by 0.1 to 0.2 degrees K. This decreases the operating temperature margin for the decay solenoid.

Concluding Comments

This report makes a case for looking at the consequences of not being able to keep the MICE cooling channel magnets cold using the two-stage pulse tube coolers. Tests on the spectrometer solenoids have not demonstrated that these magnets can be kept cold using the two-stage coolers. As a result the design of the spectrometer solenoids and the coupling solenoids has been changed to provide more cooling on the shield and leads as well as at 4.2 K. Such changes have not been made on the focusing magnet.

Since the coolers provide cooling at 40 to 45 K as well as 4.2 K, the coolers can't be replaced with a single central refrigerator. The magnets are designed to be cooled using the two-stage coolers, and the magnets can't be changed easily to allow them to be cooled using a refrigerator alone. Most of the coolers must remain in place to provide cooling to the shields, the leads and the thermal intercepts. If added cooling is to be provided to a magnet, it must be provided only at temperatures in the range from 4.4 to 4.6 K.

The three types of cooling channel magnets are compared in Table 1. The comparison was done for the number of coolers set by the original design. Each magnet is different in that there are different numbers of leads, different shield areas, and different design forces for the cold mass supports. In addition the leads for the three magnets operate at different stray magnetic fields. The level of the field is a function of the channel operating mode and the beam momentum. The spectrometer solenoid HTS lead tops operate at the lowest magnetic field <0.1 T, whereas the coupling and focusing solenoid HTS lead tops must operate in fields of 0.3 to 0.35 T depending on the case. The higher magnetic field at the tops of the HTS leads means that the lead temperature must be lower. This in turn is reflected in the cooler first stage temperature. The heat load per cooler on both stages is presented in the table. The spectrometer solenoid and the focusing solenoids have the highest first stage heat loads whereas the coupling magnet has a much lower first stage heat load. The design heat load per cooler second-stage is nearly the same for the three magnets.

The experience with the spectrometer solenoid has caused LBL to add more coolers to both the spectrometer solenoid and the coupling solenoid. In the spectrometer solenoid, the number of two stage coolers was increased from three to five. The spectrometer solenoid is retaining the single stage GM cooler used in the last test. In the coupling solenoid, the number of coolers is increased from two to three. As far as the author knows, the number of coolers in the focusing magnet remains at two. It appears that the cooling margin for the focusing magnet may be the lowest of the three MICE cooling channel magnet types. Before doing anything else with a magnet that has inadequate cooling at 4.2 K, one should increase the pressure in the cryostat to something of the order of 1.4 bars. This increased the temperature at the second stage from 4.2 to 4.6 K. At 4.6 K each cooler will develop 0.3 to 0.4 W of cooling. In some cases this may be sufficient. The temperature margin of the magnet will go down by 0.4 K, which may mean that the experiment can't operate at higher momentums. Increasing the cryostat pressure means that the relief devices must be leak tight at the higher pressure.

Given the experience on the spectrometer solenoid, the likely refrigeration shortfall for one of the magnet is from 0.5 to 2 W, which was the argument for adding more two-stage coolers. If all seven magnets need added cooling at 4 K, the amount of added cooling is quite modest ~10 W. Unfortunately, one must transport the cooling from the refrigerator to where it is needed in the cooling channel. The transfer line losses are larger than the added refrigeration needed for the magnets. Since the cooling of the shields, leads, and intercepts is taken up by the cooler first-stages, the refrigerator need only produce cooling in the temperature range from 4.4 to 4.6 K. Since there are no gas cooled leads on any of the magnets, there is no need for helium liquefaction.

The spectrometer solenoid has a helium tank that holds 180 liters of liquid helium. Low heat leaks into the spectrometer solenoid that produces a boil off of one liter per hour or less may be made up for by adding liquid helium to the system. The transfer system must be designed so that the lines can be cooled down to 4 K before helium is injected into the magnet cryostat. The coupling and focusing magnets have a stored helium volume that is less than 45 liters. It is unlikely that refrigeration can be supplied to the magnets by adding liquid to the tanks on a periodic basis.

This report suggests that a small ~60 W central refrigerator be used to provide excess cooling at 4.4 to 4.6 K. It is proposed that the refrigeration be delivered as two-phase cooling to the magnets. Most of the refrigeration produced by the refrigerator keeps the transfer lines cold. There are two potential sources for refrigeration to the magnets. These are using the excess refrigeration from and existing refrigerator that provides cooling to the pion decay solenoid. If there is not enough excess refrigeration an additional refrigerator must be acquired. This report looks at using a refrigerator of the 1400 series to provide the extra refrigeration. Machines of this type do appear on surplus lists from time to time. These machines are still available from Linde in the United States. This kind of machine could be used to cool down the entire string of MICE cooling channel magnets. The problem with using a 1400 refrigerator is the cost of buying the machine and installing it at RAL. The installation cost is likely to be more than the purchase price of the machine and its compressor.

Given the high cost of buying and installing a 1400 refrigerator, the best option is to use the Linde refrigerator that cools the decay solenoid. The control dewar for force two-phase cooling on MICE channel magnets can be in series with liquid tank in the decay solenoid. The gas and liquid helium from the decay solenoid tank would go into the two-phase cooling line that goes out to the channel magnets that need extra cooling. A mixture of liquid and gas would return to the control dewar to keep the heat exchanger cold that moves the two phase flow from mostly helium gas to mostly liquid helium. As a result, the pressure drop through the flow system is reduced. The final phase separation occurs within the control dewar. The gas phase returns to the refrigerator.

The amount of excess refrigeration available from the refrigerator that cools the decay solenoid is not known. There are at least four ways that one can increase the amount of excess refrigeration from the decay solenoid refrigerator. 1) One should reduce the decay solenoid heat load and reduce the amount of gas used to cool the leads. This means more insulation for the decay solenoid magnet and it mean a better control system for the lead gas flow from the decay solenoid. 2) One should use liquid nitrogen to cool the decay solenoid shield instead of 60 to 70 K helium gas from the refrigerator. As a result, there is more flow in the refrigerator J-T circuit and from that more 4.5 K refrigeration produced. The excess refrigeration can cool channel magnets. 3) Adding a liquid nitrogen pre-cooling heat exchanger can increase the 4.5 K refrigeration by 40 to 50 percent. 4) If one replaces the final J-T valve in the decay solenoid vacuum vessel with a wet expander the refrigeration produced is increased by 40 to 60 percent. A combination of these steps should permit one to produce enough excess refrigeration to provide cooling for one or more of the MICE cooling channel magnets.

Having adequate cooling for all of the magnets in MICE is essential for the experiment to operate as designed. The author hopes that the coolers on all of the MICE magnets can keep them cold. It some point, the collaboration must consider providing cooling to magnets that need it, in order to run the experiment as designed. The best way of doing this is to use the existing RAL Linde refrigerator to provide the added cooling needed to keep all of the MICE magnets cold.

. A key issue not dressed in this report is how to cool down the MICE cooling channel magnets in a timely way. The proposed solution of using liquid nitrogen and liquid helium to cool down the magnets is time consuming and expensive (particularly liquid helium). Perhaps the collaboration should deal with this problem as well.

Acknowledgment

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