Cryogenic Systems for the Low Field RLHC Study Cases

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ABSTRACT

Three study cryogenic systems for the low-field approach to an RLHC are outlined, goals are set for the average performance of thermal insulation and refrigeration plant nominal power is worked out for each. All three cases are found to be feasible, and some of the most obvious issues arising from the studies are discussed. Particularly attractive is the system cooling between 4.5 and 6.5 K with sensible heat. Significant savings of system complexity and operating cost over the 4.5 K, latent heat system is found.

I. INTRODUCTION

High-field and cold-iron magnet and cryostat technology has been extensively developed for HERA, RHIC [1], SSC [2] and LHC [3]. In contrast, the low-field, warm-iron system proposed as a candidate for the RLHC [4][5] is in the earliest stages of engineering development. Thus the study cases that follow have a different character from those of the high-field colliders, and the two are not to be compared except in the most general way.

From the cryogenic point of view, the low-field collider consists of two objects – both superconducting DC transmission lines, each carrying 70 kA, and requiring to be kept at a low temperature. In the particular magnet design choice made here, one of the conductors is placed in a two-gap iron magnet, and the other is placed at a distance and acts only as a current return. An important feature of this arrangement, particularly for the cryogenics, is that due to symmetry and to distance, these conductors feel only small net forces from the magnetic environment, making possible simple, low heat leak thermal isolation. It is natural, therefore, to enclose one of the transmission lines in its own compact cryostat within the magnet, and place the other in a larger cryogen-carrying pipe in a parallel insulated cryogenic transfer line which carries the main circulation of the coolant.

II. MAGNET TRANSMISSION LINE

The space provided in the magnet iron for the transmission line cryostat is 3 inches diameter, and the superconducting bus, in the NbTi or Nb_3Sn non-cryostable versions, has a cross-sectional area of about 5 sq-cm including electrical insulation. This insulated bus is enclosed in a cryogen-carrying pipe 2 inches outside diameter by 1.875 inside. The OD is constrained by the requirement of space for the multilayer insulation package

The conductor inside the magnet is at a point of unstable equilibrium in the horizontal direction, and feels a force gradient of about G = 2 MN/sq-m or 275 lb. per inch of conductor per inch of displacement from the center of the magnet iron. If the cold pipe is supported at intervals, the field gradient gives rise to an instability in which the current-carrying pipe bends into a sinuous curve with a period twice the support distance. Surprisingly, this problem is one that can be solved exactly. The elastic curve of the pipe is actually a sinusoid, and the unstable support interval, L, is given by:

$$L^4 = \pi^4 \cdot E \cdot J/G$$

Here E is the modulus of elasticity and J is the moment of area of the section of the pipe. Putting likely values into this formula gives L = 0.845 m. This is feasible, but because of the fourth root, any substantial increase in this spacing is not possible

We take as an example, therefore, a cold line supported at 0.75 m intervals by posts made of Ultem 2100, a filled plastic material made by GE and developed by BNL for the posts of the RHIC cryostat. Assuming that the conductor can be kept within 0.5 mm of the neutral line, the post needs to be able to support 750 N. At 35 MPa maximum stress, 0.214 sq-cm cross section is required. The thermal conductivity integral of this material at 300 K is 0.5 W/cm, so a conduction heat load of 0.14 W/m is to be expected for posts 1 cm long.

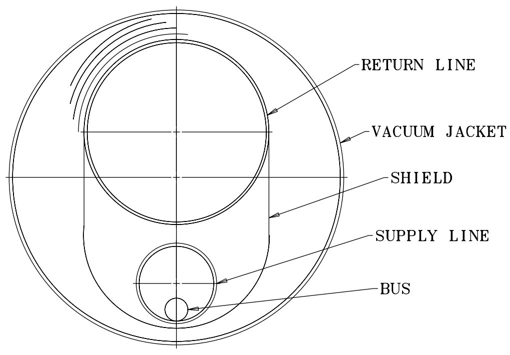
A dimpled mylar multilayer insulation system has been used in a number of large systems and is commercially available [6]. It is reported as performing at the level of 0.3 W/sq-m for 40 layers in a 1 cm thickness. Such performance would produce a radiation heat load of 0.06 W/m to give a total to be expected for this example of 0.2 W/m.

Much opportunity remains for design development with the goal of reduced heat load. For the purposes of cryogenic system study, therefore, it does not seem unreasonable to set this goal at the level of 0.1 W/m with the recognition that this may not be achieved, or if achieved, may not be cost-optimum for the system as a whole.

III. CRYOGENIC SUPPLY AND RETURN PIPING

We consider two thermally isolated pipelines in a single vacuum jacket. One of these contains the transmission line return bus and carries the supply flow of cryogen from the refrigeration station. The other line carries the return flow of cryogen back to the refrigeration station. In contact with this pipe is a thermal shield surrounding the supply line. Thus almost all of the heat leak into the pair of lines is taken as sensible heat in the flow of the return line.

These lines will fit into a 10 - 12 inch vacuum jacket, so the circumference of the cold boundary is somewhat less than 1 meter. If the same dimpled insulation system is used here, one could expect a radiative heat load of about 0.3 W/m. There is more room for the supports in this cryostat than in the magnet transmission line, and although the weight to be supported is greater, the magnetic forces are smaller. Two Ultem posts per meter, each one sq-cm in area and ten cm long, give a heat load of 0.1 W/m for a total heat leak for the cryostat of 0.4 W/m.



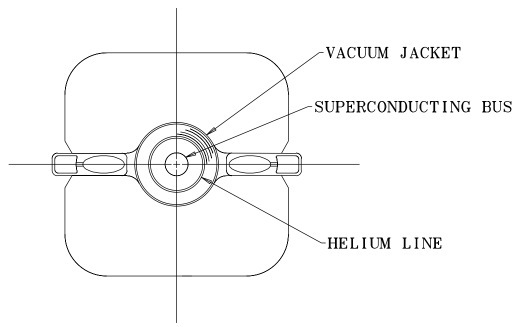


Figure I: Cross-section of magnet and piping cryostats

In the same spirit as that adopted above, the development goal of 0.21 W/m can be set for the cryogenic piping package, 0.2 W/m going into the return line and the remainder, 0.01 W/m, into the shielded supply line. It should be noted that the thermal design problem of the magnet transmission line lies primarily in the support of the line in the magnetic environment, whereas the radiation heat load dominates in the piping cryostat.

Figure I illustrates the relative sizes and relationship of the magnet with its internal transmission line bus and the cryogenic supply and return cryostat. The transmission line return bus is shown inside of the supply pipe which is thermally shielded by the return pipe. The scale if this illustration is given by the vacuum jacket which is 12 inches outside.

IV. CRYOGENIC SYSTEM LAYOUT

The cryogenic system for any of the RLHC cases consists of refrigeration stations distributed around the circumference of the collider. Connected to each of these stations are two “strings” of magnets connected end-to-end which constitute the system to be cooled. An important trade-off in a collider of fixed circumference is the balance between the cost of the stations, which have many economies of scale associated with them, and the costs of dealing with longer strings. These include the costs of larger piping, cost of underground real estate and installation, the logistics of underground work, the larger heat load and cryogen inventory associated with a unit length of the larger piping, and string voltage and quench protection issues. This is not just an economic calculation, because the costs of surface stations are likely to be political as well as economic.

For the low-field RLHC only the first stage of identifying the issues in optimizations of this kind has been reached. Following the work at the Mini-Symposium [5] which has shown that a string length of about 40 km is feasible from a cryogenic and electrical point of view, we divide this RLHC into 16 strings of 38,220 m, each of which consists of 91 cells of 420 m each. These 16 strings are serviced by 8 sector stations each with a refrigeration plant. We add a ninth station to service the insertions.

V. SYSTEM OPERATING REGIMES

Three operating cases are considered. In the first of these a NbTi conductor is employed, and the maximum operating temperature of this conductor is required to be 5 K. The second case supposes a Nb_3Sn conductor that can operate at 6.5 K, and the third imagines a HTc conductor that can operate at 25 K.

A. 4.5 - 5 K Case

For this case a cryogenic system similar to that of SSC is appropriate. Helium at 4.5 K and 3 bar pressure is supplied through the supply line. Each string requires 300 g/s of flow. Of this, 40 g/s is carried all the way to the end of the string and then brought back in the magnet transmission line to the refrigeration plant. As this flow passes along the string the heat load is picked up as sensible heat, the temperature rising from 4.55 K to 5 K in two cells length. Every two cells there is a recooler in this stream in which heat is exchanged with boiling helium at 4.5 K and the temperature lowered again to 4.55 K. There are 45 such recoolers in the string. Saturated helium is supplied to the recoolers by expansion through valves from the supply line, and the saturated gas is returned to the refrigeration plant in the return line.

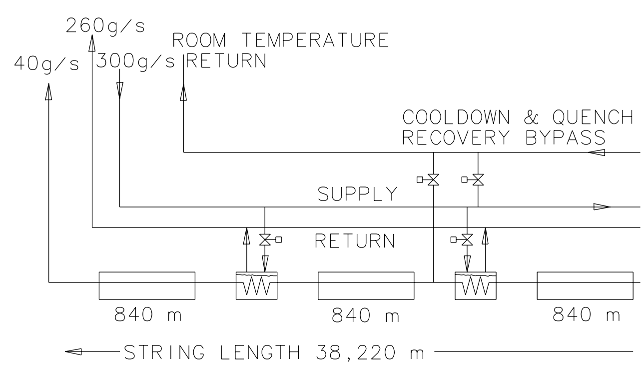


Figure II: String Flow Diagram of the 4.5 - 5 K Case

The heat load on the return line warms up this stream from saturated conditions to 9.7 K and the pressure drops from 1.3 bar to 1 bar as it goes. Thus heat transport down the length of the string operates by means of the latent heat.

Figure II illustrates the layout of the magnet string for this case.

Table I

RLHC Low-Field Case: 4.5 - 5 K Conductor (NbTi)

Parameters				
Number of Sector Stations				8
Number of Strings				16
String Length	m			38,220
Cell length	m			420
Number of Cells/String				91
Number of Recoolers/string				47
String Heat Load				
Heat Loads, Saturated				
Magnet line	W/m	0.1	38,220	3822
Connections	W/cell	1.0	45	45
Recooler	W	8.0	46	368
Cryo-Supply	W/m	0.01	38,220	382
Connections	W/cell	0.1	90	9
Recooler	W	8.0	1	8
Splices	W	1.0	185	185
Subtotal Saturated Load W				4,819
Flow Required, g/s @ 18.52 J/g latent				260
Heat Loads, Unsaturated				
Cryo-Return	W/m	0.2	38,220	7,644
Connections	W/cell	5.0	90	450
Subtotal Unsaturated Load W				8,094
Exit enthalpy J/g @ 260 g/s		61.74		
Sector Heat Load and Ideal Power				
Heat Load, Saturated, 4.5 - 5 K				
Two Strings	W			9,638
Station Piping & Boxes	W			1,400
Sub Total Saturated	W			11,038
Flow Required, g/s @ 18.52 J/g				596
Ideal Power, Saturated	MW		0.725	
Heat Loads, Unsaturated				
Two Strings	W			16,188
Station Piping & Boxes	W			3,700
Sub Total Saturated	W			19,888
Exit enthalpy J/g @ 596 g/s				63.98
Subtotal Ideal Power	MW			1.060
Ideal Power, Cold Comp.	MW			.043
Ideal Power, Unsaturated	MW			1.103
Current Lead Requirement: 25 g/s @ 15 K, 1.3 bar				
Ideal Power	MW			0.085
Total Sector Ideal Power MW				**1.913**
Total Ideal Power, 9 Stations, MW				**17.217**
Nominal Electric Load MW				**66**

It is an advantage to transport the pipeline heat leak as sensible heat. The return line need not be kept at the lowest temperature, but the supply line, which contains a superconducting bus, must be. The flow required in the string with this arrangement is only what is needed to take up by latent heat the load on the bus. The heat load of the return line does not require flow in addition to this. Minimizing in this way the flow required reduces the line sizes needed and the total system heat toad.

Table I gives an outline of cryogenic system parameters for the 4.5 - 5 K case, and Table III includes an estimate of the piping sizes and helium inventory required. There are 45 recoolers in the string of 91 cells and one recooler in the supply line at about the 75th cell. This is needed to maintain the temperature of the bus in this line for the whole length of the string. Included in the ideal power calculation in Table I is a cold compressor in the return to boost the pressure to 1.3 bar.

Table II

Low-Field Case: 4.5-6.5 K Conductor (Nb_3Sn)

Parameters: Same as for the 4.5 - 5 K Case				
String Heat Load				
Heat Loads, 4.5 - 6.5				
Magnet line	W/m	0.1	38,220	3822
Connections	W/cell	1.0	90	90
Recooler	W	8.0		0
Cryo-Supply	W/m	0.01	38,220	382
Connections	W/cell	0.1	90	9
Recooler	W	8.0	0	0
Splices	W	1.0	185	185
Subtotal 6.5 K Load W				4,488
Flow Required, g/s @ 29.2 J/g			154	
Heat Loads, T > 6.5 K				
Cryo-Return	W/m	0.2	38,220	7,644
Connections	W/cell	5.0	90	450
Subtotal Load W				8,094
Exit enthalpy J/g @ 154 g/s		93.85		
Sector Heat Load and Ideal Power				
Heat Load, 4.5 - 6.5 K				
Two Strings	W			8,976
Station Piping & Boxes	W			1,400
Sub Total	W			10,376
Flow Required, g/s @ 29.2 J/g				355
Ideal Power 4.5-6.5 K	MW			0.597
Heat Loads, T > 6.5 K				
Two Strings	W			16,188
Station Piping & Boxes	W			3,700
Sub Total T>6.5 K	W			19,888
Exit enthalpy J/g @ 355 g/s				97.31
Ideal Power	MW			0.684
Current Lead Requirement: 25 g/s @ 15 K, 1.3 bar				
Ideal Power	MW			0.085
Total Sector Ideal Power MW				**1.366**
Total Ideal Power, 9 Stations, MW				**12.294**
Nominal Electric Load MW				**47**

The principal controls for the system are the supply valves which act to maintain the level of liquid helium in the recoolers. The transit time of the transmission line stream between recoolers is 1 hour giving a reasonably rapid quench recovery.

Transient operation such as system cool-down and recovery from upsets are not dealt with here. A quick check shows that 50 g/s is sufficient to cool a string down in about ten days, but in order to operate this process it is probably necessary to have a warm return line parallel to the string with bypasses at intervals.

To put some of the results into this table into perspective we note that the total ideal power proposed for LHC is 10 MW in 4 stations and that the current estimate for the LHC inventory is about 800,000 lHe. The cryogenic system of this case, therefore, is about twice the size planned for LHC with four times the helium inventory. This seems a requirement for the RLHC.

B. 4.5 - 6.5 K Case

This system is presented in Table II above. Here use is made of the large heat capacity of helium in the critical region to provide heat transport and cooling entirely through the sensible heat of the flowing stream. The coolant flows through the magnet transmission line in four parallel streams of about 38 g/s and each takes up 1,110 W in rising in temperature from 4.5 to 6.5 K. As in the 4.5 - 5 K case, these streams are delivered along the strings through the supply line and returned to the refrigeration plant through the return line at pressures between 4 and 1.3 bar.

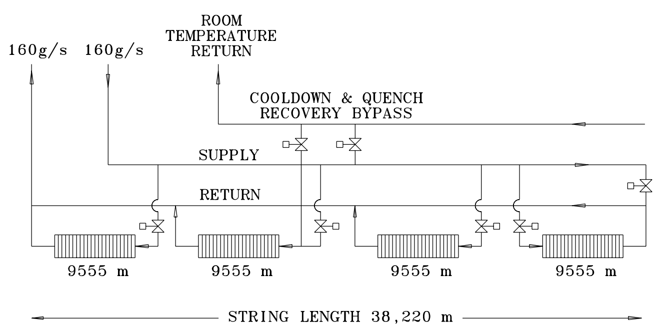


Figure III: String Flow Diagram of the 4.5 - 6.5 K Case

Controls in this case are four parallel flow controllers for the streams in the individual length of the transmission line. A disadvantage of this system is the long transit time of 5 hours for the flow to pass through the transmission line. This can be reduced by including one or more sets of bypass valves in each circuit.

The ideal power estimated here is only 0.7 of the 4.5 - 5 K case, a saving of 20 MW. Refrigeration at 4.5 K has a Carnot efficiency of 66 W/W. Refrigeration at 4.5 - 6.5 K requires 57 W/W. But refrigeration at 6.5 - 16 K requires only 34 W/W. The saving of taking as much as possible of the heat load at the higher temperature is significant. If the conductor in this case could operate at 8.5 K rather than 6.5 K, the required refrigeration plant power instead of being 47 MW would fall to 38 MW.

Note that these electric power numbers represent an estimate of the power requirement of the main compressors of the refrigeration plant at its nominal operating point. Auxiliary system power is not included.

Table III: Line sizing, three cases

Line Sizing		4.5-5 case	4.5-6.5 case	20-25 case
Magnet transmission line				
Length	km	38.22	9.56	9.56
Parallel paths		1	4	4
OD	in	2.0	2.0	2.0
ID	in	1.875	1.875	1.875
Inlet State				
Temp.	K	4.5	4.5	20
Press.	bar	3.2	2.6	18
Flow	g/s	40	38.5	38.5
Outlet State				
Temp.	K	4.5	6.5	25
Press.	bar	2.6	2.3	17.4
Flow	g/s	40	38.5	38.5
Inventory	klHe	50	35	13
Cryo-Supply				
Length	km	38.22	38.22	38.22
OD	in	3.0	2.875	4.0
ID	in	2.875	2.709	3.834
Inlet State				
Temp.	K	4.5	4.5	20
Press.	bar	4.0	4.0	19.5
Flow	g/s	300	160	160
Outlet State				
Temp.	K	4.5	4.5	20
Press.	bar	3.2	3.4	19
Inventory	klHe	141	123	50
Cryo-Return				
Length	km	38.22	38.22	38.22
OD	in	6.625	4.0	4.0
ID	in	6.407	3.834	3.834
Inlet State				
Temp.	K	4.5	6.5	25
Press.	bar	1.3	2.3	17.4
Outlet State				
Temp.	K	12	16	36.9
Press.	bar	1.0	1.3	16.4
Flow	g/s	260	121.5	121.5
Inventory	klHe	33	18	50
Total Inventory for 16 strings				
	klHe	3,584	2,816	1,808

C. 20 - 25 K Case

Table IV presents details of this system which is arranged and operates in the same way as in the 4.5 - 6 K case, but the circulation is at the higher temperature and at the higher pressure of 19.5 - 16 bar. The near-ideal gas at 20 - 25 K takes 29.4 J/g, almost exactly the same as for the 4.5 - 6.5 K case, and the densities are nearly the same also. Thus the high-pressure 20 K gas operates at the same flow rates in the same line sizes. The refrigeration power required, however, is much less for the 20 - 25 K case. In the context of an RLHC, the operating cost suggested for this case, less than 20 MW, is no longer a driving cost item. Thus the pressure is not strong to raise the temperature above 25 K at the sacrifice of even a little superconductor performance.

Table IV: 20 - 25 K Conductor (HTc)

Parameters & Heat Load	Same as for the 4.5 - 6 K case	
Sector Heat Load and Ideal Power		
Heat Load, 20 - 25 K		
Two Strings	W	8,976
Station Piping & Boxes	W	1,400
Sub Total 20-25 K	W	10,376
Flow Required, g/s @ 29.8 J/g		350
Ideal Power	MW	0.148
Heat Loads, T > 25 K		
2 Sectors	W	16,188
Station Piping & Boxes	W	3,700
Sub Total T>25 K	W	19,888
Exit enthalpy J/g @ 350 g/s		197.5
Ideal Power	MW	0.194
Current Lead Requirement: 25 g/s @ 35 K, 16 bar		
Ideal Power	MW	0.073
Total Sector Ideal Power MW		**0.415**
Total Ideal Power, 9 Stations, MW		**3.735**
Nominal Electric Load MW		**14**

Management of the smaller, but still large inventory in this case presents some particular difficulties. Storage as a liquid is cheapest and most convenient, but the refrigeration cycle in this case does not extend to the liquid region. Storage as a gas requires a tank farm of 75 room temperature tanks of the 30,000 gal size at each refrigeration station to hold the gas at 18 bar. This has not only the disadvantage of cost and size of installation, but the gas as well as the collider has to be cooled down in order to bring the facility into operation. This sets requirements for the refrigeration plant whichever way is chosen to deal with the problem.

VI. DISCUSSION

The cases presented here are generally feasible. It is important, however, to make certain that these systems remain feasible if the heat loads are twice what has been assumed in the studies. In the 4.5 - 5 K system, doubling the heat load and the number of recoolers leaves the magnet transmission line cooling scheme unchanged. Also either the number of refrigeration stations would have to be doubled leaving the piping sizes alone, or the size of the individual plants would be doubled and the size of the piping increased by something like a factor of 1.4. Because the plants for this case are already rather large, it seems most reasonable to double the number of stations. These arguments also apply to the 4.5 - 6.5 and the 20 - 25 K cases. In these cases, the number of parallel streams in the magnet transmission line is doubled rather than recoolers. In the 4.5 - 6.5 K case it also probably makes sense to double the number of stations. In the 20 - 25 K case, doubling the size of the plants is practical and the piping sizes can also be increased. All of these increases are feasible, but very undesirable.

There is no need to tolerate these effects of higher heat loads, however, even if it proves impractical to meet the design goals suggested above. Instead it is likely that a more economical compromise is putting gas-cooled radiation shields in the supply and return line cryostat and gas-cooled supports in the transmission line, taking more of the heat load at higher temperature and reducing the refrigeration required to maintain the conductor temperature. This is a natural extension to another temperature level of the sensible heat cooling scheme previously discussed. The goal is to keep the flow rates as low as possible. This huge collider presents a cryogenic problem dominated by refrigeration transport. This is best dealt with in general by using low flow rates and large ΔT.

VII. REFERENCES

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