# Cryogenic Systems for the High Field RLHC Study Cases

M. McAshan and P. O. Mazur
*Fermi National Accelerator Laboratory, Batavia, IL 60510*

## ABSTRACT

Cryogenic system requirements are discussed for three different choices of superconductor and consequent operating temperature for the high-field RLHC. All three cases appear to be feasible. Cryogenic system parameters are determined, including power requirements. We are able to study the case using a magnet based on NbTi superconductor with particular confidence because it is a straightforward scaling of LHC technology.

## I. INTRODUCTION

The two basic high-field designs for the 50 TeV RLHC are referred to in the summary paper [1] as being either of known or of new technology. The known technology is that of the NbTi cos-theta type that has been extensively developed for use in the Tevatron, HERA, and SSC [2] and most recently for LHC [3]. New technology includes $Nb_3Sn$, High Tc, and hybrid magnets which are to be developed in the future. Thus for the purposes of the studies undertaken here, we are able to build upon the known technology to examine the cryogenic requirements and some possible solutions for an "LHC-style" magnet fabricated with NbTi conductor, $Nb_3Sn$ conductor, or HTc conductor. From a cryogenic viewpoint, these magnets differ principally in their required operating temperature. There are some additional differences which arise, such as synchrotron radiation interception, beam tube vacuum considerations and cryogen inventory control which we also discuss.

## II. HIGH-FIELD, KNOWN TECHNOLOGY CASE

In developing a cryogenic system concept for this case, one has the benefit of having the very large amount of development and system design that has gone into the LHC. The dipole for the 50 TeV collider is assumed to be of the LHC design, operating at 1.9 K, and the system like that of LHC. A few comparison numbers important in determining cryogenic system requirements can be drawn from the parameter list of the RLHC Summary and are given in Table I below.

Table I: Parameter ratios
High-field, Known Technology RLHC to LHC

| Parameter | Ratio |
|---|---|
| Total Circumference | 5.18 |
| Total Length of Bend | 6.30 |
| Synchrotron Radiation Power | |
| per unit length | 6.30 |
| Beam current | ≈ 0.10 |
| Stored Beam Energy | |
| per unit Length | .68 |

With the additional assumptions that the RLHC dipole and cryostat are 10% larger in diameter and 20% heavier than those for LHC and the magnet current is 10% higher, the heat load budget for the LHC dipole can be scaled to obtain an estimate for the heat loads in the RLHC dipole. This is done in Table II.

The only significant difference revealed by this exercise is at the 4.5 - 20 K temperature level, and extending this larger load to the LHC system as a whole, the result is an approximately doubled total load at this level. Although this much added load needs to be taken into account in budgeting refrigeration plant capacity, no qualitative change in the LHC cryogenic system seems to be required. In fact, the currently proposed piping sizes appear to be adequate for this additional load. It seems possible, therefore, to develop a technically feasible estimate for a RLHC cryogenic system by a high-level scaling of the LHC system.

This can be done by scaling the number of dipoles by the 6.3 mentioned in the table above, taking into account the loads tabulated and multiplying the number of sectors by 5, the ratio of the ring circumferences. In this process the number of refrigeration plants, power supplies, dumps, and so forth goes from 4 to 20, the length of the tunnel transfer line scales by 5, and the length of the magnet strings remains about the same requiring no changes in line sizing, voltage rating, cooldown times, and the like. The number of insertions remains the same but their length increases as required by the higher energy.

Table II: Heat load budget, RLHC Dipole

| Heat Load | Temperature level, K 50-75 W | 4.5-20 W | 1.9 W |
|---|---|---|---|
| Posts | 15.8 | 1.23 | 0.14 |
| Shield | 48.1 | | |
| Radiative | | 0.04 | 1.85 |
| Instrumentation | 0.4 | | 0.26 |
| Conduction, beam screen | | | 0.23 |
| Subtotal | 64.3 | 1.27 | 2.48 |
| Splices | | | |
| Cold mass (9) | | | 1.24 |
| Interconnect (6) | | | 0.58 |
| Subtotal | | | 1.82 |
| Beam-Induced | | | |
| Synchrotron Radiation | | 36.9 | |
| Image Current | | 0.3 | |
| Longitudinal Impedance | | 0.2 | |
| Beam-gas | | | 0.74 |
| Subtotal | | 37.4 | 0.74 |
| **Grand Total RLHC** | **64.3** | **38.7** | **5.04** |
| Total (Yellow Book) LHC | 58.6 | 12.2 | 4.71 |

Not accurately dealt with in this way are things scaling with the number of cells. The cell length in the RLHC will be longer than in the LHC, at a ratio something like 10/3 rather than the 6.3/5 used here, so the number of quads and short straights with their transfer line interconnections will be fewer in the RLHC relative to dipoles than the scaling assumes.

The procedure outlined above scales to the RLHC the three most important items in determining the requirements of the LHC cryogenic system, namely the dipole load, the tunnel transfer line load and cost, and the number of refrigeration plants and their connection boxes. It overestimates by something like a factor of two the number of half-cells, and so overestimates somewhat the total heat loads.

Applying this scaling to determine RLHC heat load and refrigeration station size gives the result shown in Table III. It is reasonable to take this ideal power requirement as the nominal operating point for the RLHC. The LHC refrigeration station has two cold boxes each rated at 18 kW at 4.5 K, equivalent to an ideal power of 1.2 MW. The total size of an LHC station, therefore, is 2.4 MW, just more than the 2.26 MW required by the RLHC. Because a plant cannot operate with satisfactory availability under real conditions at its absolute maximum capacity, plants for the RHLC will have to be somewhat larger than those planned for LHC.

Table III: Total Heat Loads of the RLHC by Scaling from the LHC

| Temperature Level | Load kW (g/s) | Ideal Power MW |
|---|---|---|
| 50 - 75 K | 1644.0 | 6.36 |
| 4.5 - 20 K | 413.2 | 15.37 |
| 1.9 K | 115.1 | 21.95 |
| 50 - 300 K liquefaction | 919.6 g/s | 1.44 |
| Total Ideal Power | | 45.12 |
| Ideal Power per Station (20 Stations) | | 2.26 |

The LHC cryogenic system remains feasible with the higher synchrotron radiation heat load of the RLHC. This does not mean that it remains optimum as well, and the rather large ideal power shown in Table III for the 4.5 - 20 K level suggests that a temperature increase in this intermediate level might produce a worth while saving in operating cost.

Using the full-load power requirement estimated for the LHC plants, the nominal operating electric power for the RLHC cryogenic system is estimated in Table IV at 180 MW. The nameplate total includes all redundant and intermittently operating machinery and other electric power connected in the refrigeration station.

Likewise, the LHC cryogenic system cost estimate can be scaled to give an estimate for the RLHC system. This can be seen in Table V. The information on LHC costs is taken from the DOE assessment of LHC published in June 1996 [4]. All of the categories in this estimate scale by the factor 5 in the procedure described above. An adjustment has been made for the LEP equipment already installed which is to be used by LHC. The adjustment for refrigeration plant capacity has been mentioned above as needed to meet the somewhat larger capacity requirement of RLHC. Note that there is a contingency of about 10% in the LHC cost estimate that has been preserved in this scaling.

Table IV: Nominal Operating Electric Power for RLHC Cryogenics by Scaling from the LHC

| | Nominal Operating MW | Nameplate Total MW |
|---|---|---|
| 2.26 MW Ideal (@ 26.5% average) | 8.5 | 12.0 |
| Auxiliaries | 0.5 | 1.5 |
| Total per Station | 9.0 | 13.5 |
| Total for RLHC System 20 Stations | 180.0 | 270.0 |

Table V: Capital Cost of RLHC Cryogenic System by Scaling from the LHC

| | Estimated Cost MCHF |
|---|---|
| Refrigeration Equipment | 135 |
| Arc Cryoline | 108 |
| Other Transfer Lines | 27 |
| Interface Boxes | 36 |
| Contingency | 31 |
| Total LHC Estimate | 337 |
| Adjustments | |
| LEP equipment & infrastructure | 40 |
| Refrigeration Capacity | 35 |
| Adjusted Scaling Basis | 412 |
| Scaled RLHC Cryogenic system Cost | |
| MCHF | 2,060 |
| M$ | 1,650 |

A cryogenic system of the size and complexity of the one contemplated here presents unprecedented operational, control, and availability problems. Concerns of this kind are certainly reasonable, and reservations about the practicability of such an enterprise as this are justified. In defense of the relevance of the estimate made above, it should be recognized that the LHC cryogenic system plan is in an advanced state of development and optimization with only a few improvements left to be made. The most important and costly system choice, the use of a tunnel transfer line, has been adopted; and from the point of view of an RLHC there is much virtue to be made from this necessity. The tunnel transfer line is a backbone which can provide for tunnel system segmentation and the transfer of cryogens and refrigeration from station to station. Further, the LHC plan and costs include using multiple cold boxes, compressor plant, and cold compressors at each station. Thus provisions are included in the scaled system for quite deep redundancy which strongly supports high availability in the RLHC.

## III. HIGH-FIELD, NEW TECHNOLOGY CASES

### A. $Nb_3Sn$ Case, 4.5-5 K Operation

These cases of new technology magnets are clearly much less well defined than the 1.9 K NbTi collider considered above. Making the assumption that an LHC-style two-in-one arrangement is the practical choice for $Nb_3Sn$ conductor, we will assume that the high-field dipole will be a package twice the diameter and four times the weight of the LHC magnet. This allows at least an educated guess as to what the heat load budget for the dipole would be. This is shown in Table VI together with an extension of this budget to the RLHC system as a whole.

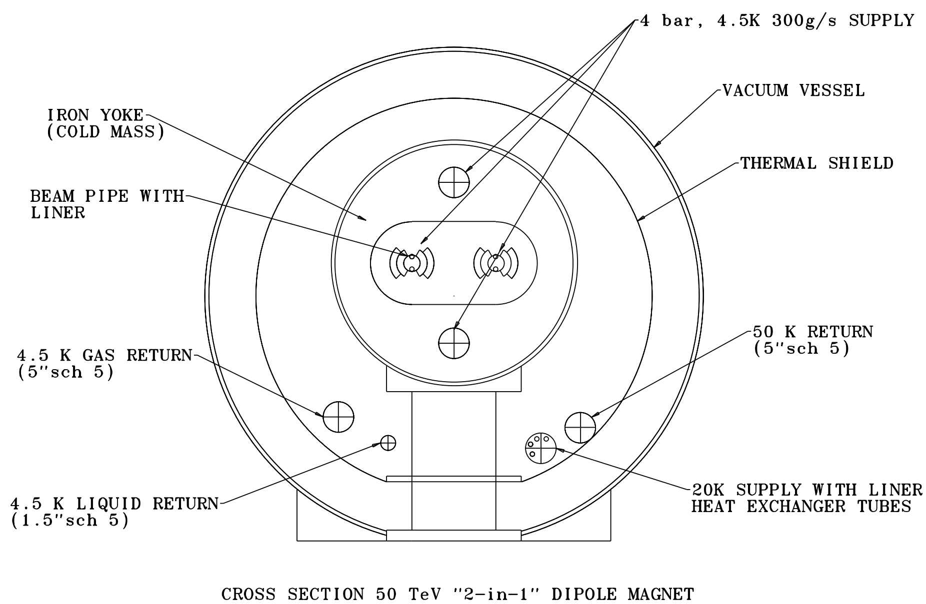


Figure I: Cross-section of 50 TeV Magnet Cryostat, 4.5 - 5 K Case

A model on which a cryogenic system can be based in this case is the SSC, but the result will not be as reliable as the scaling done from the LHC. Because the heat load due to the synchrotron radiation is fairly high, it is reasonable to choose a layout with slightly shorter strings than the SSC. Thus we divide this ring into 16 sectors. There will be 32 strings of 18 half-cells each. Each half-cell will be 180 m long and contain 10 dipoles each 14.44 m magnetic length together with a short straight containing the superconducting quadrupole and correctors. The string length in this arrangement is 3240 m to compare with the SSC length of 4250 m.

The cryogenic system that is assumed in this case is of the simplest kind. Like the SSC, the 4.5 K level operates with a 100 g/s 4 bar, 4.5 K stream passing down the length of the string inside the cold mass and returning in a pipeline. A recooler placed in each cell keeps this stream below 5 K. Each recooler is fed through an expansion valve from the returning 4 bar stream, and the saturated gas is returned to the refrigeration station in a second pipeline.

A third pipeline carries a stream of 240 g/s at 4 bar and 20 K from the refrigeration plant to the end of the string where it is returned in a fourth pipeline in contact with the radiation shields of the magnet cryostats. All four of these lines are carried within the magnet cryostat in the general arrangement shown in Figure I.

Also indicated in the figure is a system for removing the synchrotron heat load from the beam tube liners. Following the LHC design, there are two cooling tubes on each liner each carrying a stream of 0.5 g/s at 20 bar. In addition there are 4 more streams of 0.5 g/s, each in a separate tube, that travel inside the 20 K supply pipe in the cryostat. Thus in any one magnet, 4 of these tubes are carried in the 20 K line and 4 are attached to the beam screens of the two bores of the magnet. At each magnet interconnect, the sets of tubes exchange places. The streams heated inside the bore tubes are placed in thermal contact with the 20 K helium stream, and the cooled streams redirected to flow along the screens of the next magnet to be warmed again by the synchrotron radiation heat. The result of this arrangement is that the heat load of the synchrotron radiation on the bore liner is transferred to the 20 K stream.

In the particular case dealt with here, the temperature rise of the streams traveling down one dipole is about 6.4 K and the stream in the third pipe rises from 20 to 30 K traveling down the string. The approach temperature of the heat exchanger in pipe 3 is 1 K, so the maximum temperature of the beam screen at the end of the string is 37 K. The stream returning in pipe 4 enters at 30 K and exits at 50 K picking up 25 kW from the shield of the cryostat of each string.

The 1 MW ideal power per plant shown in Table VI is close to the size of one of the LHC 18 kW cold boxes. Again identifying the ideal power requirement with the nominal operation level, an estimate for the nominal operating electric power is included in the table.

It is clear in the breakdown by load of the ideal power given in the table that there is a somewhat disproportionate amount at the 30 - 50 K level. One can expect to find a minimum total ideal power by raising the shield temperature and taking some extra heat leak at 4.5 K. Another temperature level can be added by returning the 30 K flow to the refrigeration plant using it only to station the supports. An additional stream at some higher temperature, say 60 or 80 K, can be supplied to the shield or the shield can be cooled with nitrogen. This will reduce the operating power of the refrigeration system at the cost of adding two more pipes to the cryostat. This is a familiar trade-off and one that involves a host of issues that are part of the detailed design.

Table VI: RLHC High-Field, $Nb_3Sn$ Case
4.5 - 5 K Conductor Temperature

| Heat Load | | Temperature level, K | | |
|---|---|---|---|---|
| | 50-300 | 30-50 | 20-30 | 4.5 |
| | g/s | W | W | W |
| **Dipole Cryostat (14.44 m length)** | | | | |
| Posts | | 28.8 | | 1.25 |
| Shield & Connections | | 86.6 | 1.0 | |
| Radiative | | | 0.1 | 0.49 |
| Instrumentation | | 0.4 | | 0.26 |
| Conduction, beam screen | | | | 1.00 |
| Subtotal | | 115.8 | 1.1 | 2.24 |
| Splices | | | | |
| Cold mass (9) | | | | 1.50 |
| Interconnect (6) | | | | 0.64 |
| Subtotal | | | | 2.14 |
| Beam-Induced | | | | |
| Synchrotron Radiation | | | 65.7 | |
| Image Current | | | 0.3 | |
| Longitudinal Impedance | | | 0.2 | |
| Beam-gas | | | | 2.40 |
| Subtotal | | | 66.2 | 2.40 |
| **Total Dipole** | | **115.8** | **67.3** | **6.78** |
| Total Half-Cell (10 dipoles plus straight) | | 1,390 | 673 | 81.4 |
| Total String, kW (18 half-cells plus leads) | 18 | 25.0 | 12.1 | 1.47 |
| **Total Sector, kW** (Two strings plus transfer lines) | **40** | **60.0** | **25.0** | **3.6** |
| Each Insertion (2) | 150 | 60.0 | 10.0 | 4.0 |
| **Total RLHC, kW** | **940** | **1080** | **420** | **65.6** |
| **Ideal Power by Load, MW** | **1.85** | **7.19** | **4.69** | **4.31** |
| **Total Ideal Power, 18 Stations, MW** | | | | **18.04** |
| **Ideal Power per Ref. Station, MW** | | | | **1.00** |
| **Nominal Operating Electric Load MW** | | | | **72** |

It should be pointed out that if the superconductor can be operated at a temperature as high as 5.5 K, the recoolers and the saturated gas return line can be eliminated from the plan, and the magnet cooled by the sensible heat of the 100 g/s stream between 4.5 and 5.5 K. This trade-off involves the cost and current density of the superconductor, and so is a complicated issue also.

## B. HTc Case, 25 K Operation

This case assumes a magnet using high-temperature superconductor that can operate at 30 K. It is further assumed that this magnet and cryostat will be like that for the $Nb_3Sn$ case above, that is, twice the size of the LHC. In this case, though, this is not the pessimistic assumption about the size but the optimistic one.

The cryogenic system too is very similar to the $Nb_3Sn$ case. This time, the synchrotron radiation is taken on the magnet bore tube which is maintained between 20 and 30 K by a longitudinal flow of helium gas.

Table VII: RLHC High-Field, HTc Case
20 - 30 K Conductor Temperature

| Heat Load | | Temperature level, K | | |
|---|---|---|---|---|
| | 50-300 | 50-75 | 20-30 | 4.5 |
| | g/s | W | W | W |
| **Dipole Cryostat (14.44 m length)** | | | | |
| Posts | | 28.8 | 2.5 | |
| Shield & Connections | | 86.6 | 1.5 | |
| Radiative | | | 3.4 | |
| Instrumentation | | 0.4 | 0.3 | |
| Conduction, beam screen | | | | 1.00 |
| Subtotal | | 115.8 | 6.7 | 1.00 |
| Splices | | | | |
| Cold mass (9) | | | 2.6 | |
| Interconnect (6) | | | 1.1 | |
| Subtotal | | | 3.7 | |
| Beam-Induced | | | | |
| Synchrotron Radiation | | | 65.2 | 0.50 |
| Image Current | | | 0.3 | |
| Longitudinal Impedance | | | 0.2 | |
| Beam-gas | | | 2.4 | |
| Subtotal | | | 68.1 | |
| **Total Dipole** | | **115.8** | **78.5** | **1.50** |
| Total Half-Cell (10 dipoles plus straight) | | 1,390 | 812 | 18.0 |
| Total String, kW (18 half-cells plus leads) | 18 | 25.0 | 14.6 | 0.32 |
| **Total Sector, kW** (Two strings plus transfer lines) | **40** | **60.0** | **35.0** | **0.8** |
| Each Insertion (2) | 150 | 60.0 | 15.0 | 0.8 |
| **Total RLHC, kW** | **940** | **1080** | **590** | **14.4** |
| **Ideal Power by Load, MW** | **1.85** | **4.18** | **6.58** | **0.95** |
| **Total Ideal Power, 18 Stations, MW** | | | | **13.56** |
| **Ideal Power per Ref. Station, MW** | | | | **0.75** |
| **Nominal Operating Electric Load MW** | | | | **52** |

The unsolved technical problem in this kind of machine is the bore-tube vacuum. The 30 K operating temperature is too high for hydrogen adsorption to be effective and too low for non-evaporable gettering. A solution, obviously not the only one, but one that will work, is 4.5 K cryopumping with an adsorbent. In the heat load budget worked out below, it is assumed that the case of the LHC is turned inside out, and that there is a partial beam screen in the bore tube cooled by tubes containing a flow of 4.5 K helium. In this case, the heat load is into the 4.5 K cryopump from the magnet bore tube rather than the other way around. The greatest part of the synchrotron radiation load is taken at 30 K, with only a small part reflected onto the 4.5 K cryopumping surfaces. These are shielded by slotted 30 K surfaces or baffles.

Table VII gives the details for this case. It is somewhat disappointing to see that the ideal power remains at a rather high level which is not the payoff desired from high temperature superconductor. The problem lies in the heat load from synchrotron radiation and heat leak all of which is taken at an average temperatures close to that of the superconductor. We can see this problem clearly if it is assumed that the superconductor operates at 33.3 - 50 K and that the entire load at 20 - 75 K, 1,670 kW, is taken at this level. The efficiency is 6.3 W/W, only 10% of what is required at 4.5 K, but the ideal power required for this large load is 10.5 MW, about the same as what is listed in the table.

The conclusion to be drawn for this system with large and heavy magnets and a large synchrotron radiation load is that we must go to still higher temperatures. In retrospect, it is clear that the case that should have been analyzed has the superconductor at the 33.3 - 50 K level and a bore liner and cryostat shield at 150 K. The vacuum problem could perhaps then be solved by NEG pumps at 150 K. The expectation is that the total ideal power might then be reduced to about 5 MW, giving an electric power requirement for this case of 30 MW. We do not, however, have a reliable and consistent model for the heat loads in this higher temperature situation, and it is difficult to give a clearer assessment at this time.

## IV. DISCUSSION

The cases presented here show the feasibility of cryogenic systems for the high-field option for the RLHC. These systems are, particularly for the 1.9 K system, complicated and costly, with high operating cost. To some extent this is due to the high heat loads in these systems which are a consequence of the size of the magnet systems and the presence of synchrotron radiation heating of the inside of the magnet, very close to the superconductor. For the design of the high-field collider, the synchrotron radiation produces very valuable damping of beam transverse motions which simplifies the design. In the cryogenic systems we are seeing the disadvantages that go with this good feature. These heat loads are most manageable in the 25 K system, but even in this case, these studies show that a careful choice of temperature levels and careful thermal design of the cryostat will be needed to take full advantage of the opportunities offered by the properties of HTc.

The problems of system design that lead to complexity are well represented in the LHC system and are brought into sharp focus by the proposal made here for a large scale-up. It is important to recognize that a cryogenic system for an RLHC in order to do its job must support a large number of operating modes. The equipment and sizes and capacities are determined by the envelope of requirements of these modes, and each required capability has disadvantages in some of the modes as well as the advantages that meet system requirements. This presents a problem of optimization over a large number of dimensions.

We see in the LHC cryogenic system a design that is well along in the process of development. The systems analyzed for the new technology collider cases, in contrast, are only at the beginning of the development process. Therefore, although the new technology cases may appear significantly simpler than the NbTi case, further development of these cases may very well lead to more complex and costly systems. The resulting more complete designs may have less contrast with the NbTi case.

## V. REFERENCES


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