LARP IR Cryogenics: Parametric Studies of Heat Transfer in IR Quadrupole Magnets – Beam Pipe to External Heat Exchanger

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Introduction

A design temperature profile for an upgraded LHC interaction region (IR) has been documented [1]. Provided here are results of parametric studies investigating magnet geometry and superfluid helium heat transfer within this design temperature profile.

The heat transfer path discussed here has five segments: beam pipe annulus to collar pole tip, collar pole tip to yoke inner diameter, yoke inner diameter to yoke cooling holes, yoke cooling holes to heat exchanger (HX) crossover pipe, and through the HX crossover pipe. The design temperature profile specifies a temperature drop of 200 mK from the beam pipe to the heat exchanger: 150 mK from the beam pipe annulus to the HX crossover pipe and 50 mK through the HX crossover pipe.

Analysis

Heat Deposition Data

Figure 1 shows heat deposition data [2]. The blue bars represent the quadrupole cold masses. The red bars indicate a corrector magnet. For the quadrupoles, each bar is approximately 0.5 m of length. The quadrupoles have a 90 mm bore. The beam pipe liners are made of W-25 Re with a thickness of 11.5 mm in Q1 and 2.5 mm elsewhere. Luminosity is $10^{35}/cm^2$-s. From this plot it is obvious that the non-IP end of Q1 will be the limiting location in the He II thermal design of the upgraded IR.

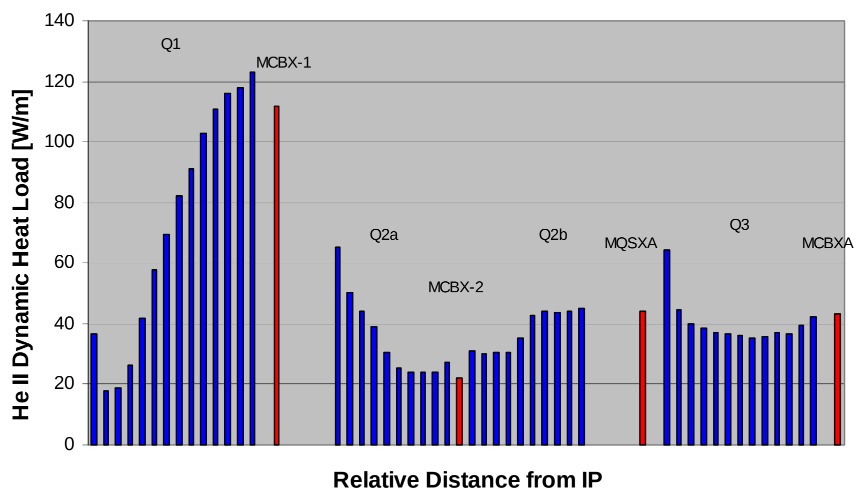


Figure 1 He II dynamic heat load vs. relative distance from the IP for an upgraded LHC IR, 90 mm quadrupoles with W-25 Re liners.

The heat deposition raw data can be found in the Appendix of this document.

Thermal Center and Heat Removal Distribution

The thermal center of each cold mass can be estimated using the data of Figure 1. The thermal center is the point where there is a zero temperature gradient in the cold mass. On one side of the thermal center, all heat flows toward the IP end of the cold mass. On the other side of the thermal center, all heat flows toward the non-IP end of the cold mass. The thermal center, x_{TC}, is located by finding the point where Equation 1 is true.

$$\int_0^{x_{TC}} q^3(x)\,dx = \int_{x_{TC}}^{L} q^3(x)\,dx \qquad (1)$$

The longitudinal heat flow through the cold mass cooling holes is given by q(x). The ends of the cold mass are at positions 0 and L. This equation assumes that the temperature drop from the magnet thermal center to either end of the cold mass is equal. This is not necessarily true, so Equation 1 gives only an approximate location of the thermal center.

The estimated distribution of heat to be transferred from the cold masses to the heat exchanger through the crossover pipes is shown in Figure 2. The values in parentheses are the corrector magnet depositon contributions. Those not in parentheses are the cold mass deposition contributions.

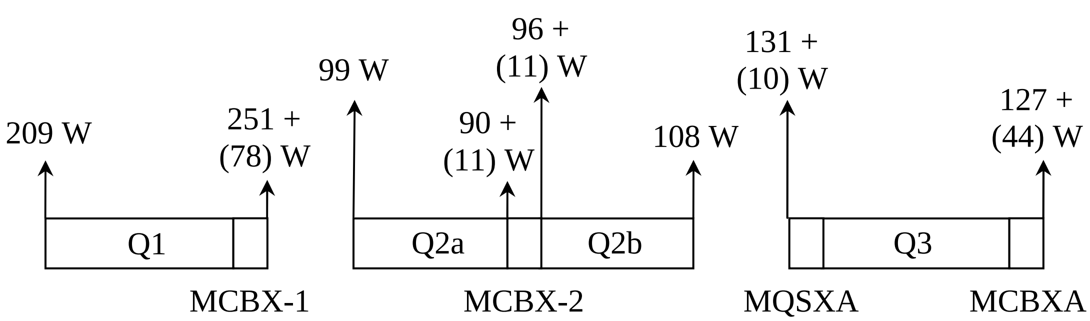


Figure 2 Estimated cold mass heat removal distribution from the upgraded inner triplet.

Crossover Pipes

Crossover pipes carry the heat from the cold masses to the heat exchanger. In the current inner triplet, there are five crossover pipes: one at the IP end of Q1; one per interconnect between Q1 and Q2a, Q2a and Q2b, and Q2b and Q3; and at the non-IP end of Q3. Two additional crossover pipes will likely be required in the upgraded triplet so that there will be a crossover pipe at each end of every cold mass, with the exception of one crossover pipe between Q2a and Q2b. Using more crossover pipes will minimize the He II conduction length and the heat flux in each pipe.

The design temperature profile assigns a 50 mK temperature drop in the crossover pipe, from 2.00 K to 1.95 K. Figure 3 plots the minimum pipe inner diameter as a function of He II conduction length for a range of heat loads. The inner triplet heat loads from Figure 2 are included, and common pipe sizes are indicated on the vertical axis.

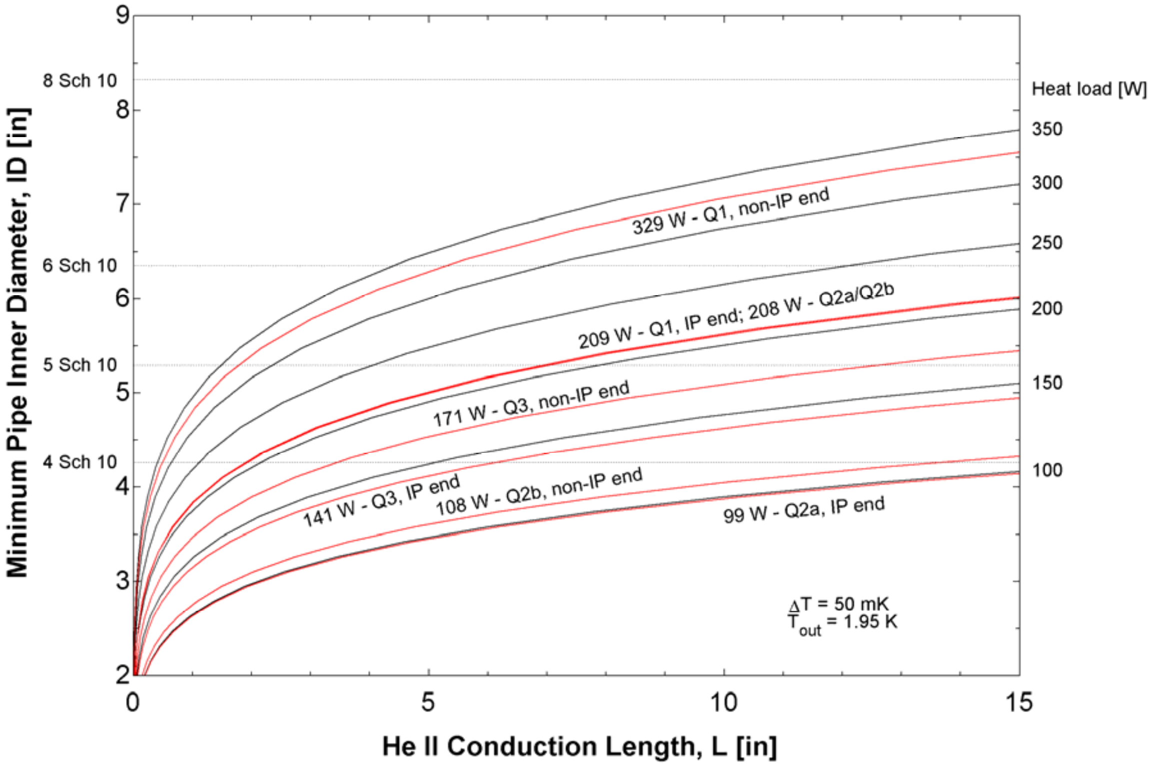
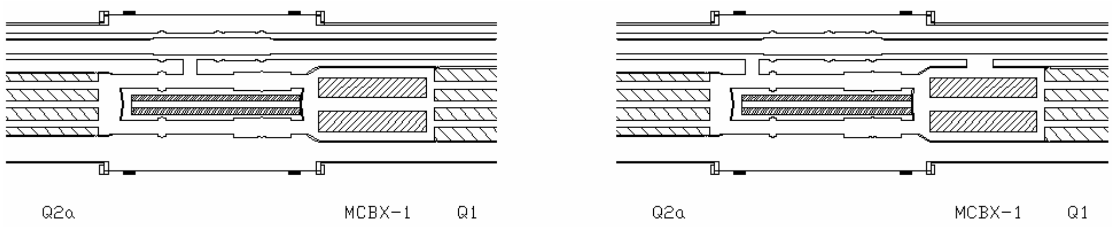


Figure 3 Minimum pipe inner diameter vs. He II conduction length for a range of heat loads.

Based on the existing cryostat cross-section, the largest pipe that could reasonably be placed in the cryostat is six inches (6 IPS).

The non-IP end of Q1 has the greatest heat load. There is also a corrector magnet at this location, so the magnet skin is extended to place the end dome beyond the corrector. This extended skin would be an ideal location for the crossover pipe, as shown in Figure 4.. The crossover would then be much shorter than if it is connected to the end dome. The estimated length is three inches, so from Figure 2 the temperature drop through a six-inch pipe could be kept to less than 50 mK. The significantly lower heat transfer rates for all other crossover pipes indicate that a 50 mK temperature drop should be able to be maintained through all inner triplet crossover pipes.



a) b)

Figure 4 a) Piping arrangement in the current Q1-Q2a interconnect. b) Possible piping arrangement in the upgraded Q1-Q2a interconnect.

Yoke Longitudinal Cooling Channels

The current design of the LHC IR upgrade quadrupole has 400 cm^2 of yoke longitudinal cooling channels [3]. This is compared to 113 cm^2 in the current quadrupole design. With a temperature of 2.00 K at the non-IP end of the Q1 cold mass, the calculated temperature at the thermal center of the Q1 cold mass is 2.012 K.

Yoke Radial Cooling Channels

Yoke radial cooling channels are required to transfer heat from outside the collars to the yoke longitudinal cooling holes. These cooling channels are envisioned as being created by removing a small portion of the full thickness of the yoke lamination at the parting plane, as shown in Figure 5. As the yoke laminations are stacked, the orientation must be periodically alternated so that heat can be transferred to all of the longitudinal cooling holes. The frequency of this orientation change must be specified so that the yoke radial cooling channels match with the collar radial cooling channels, providing the shortest possible He II conduction path.

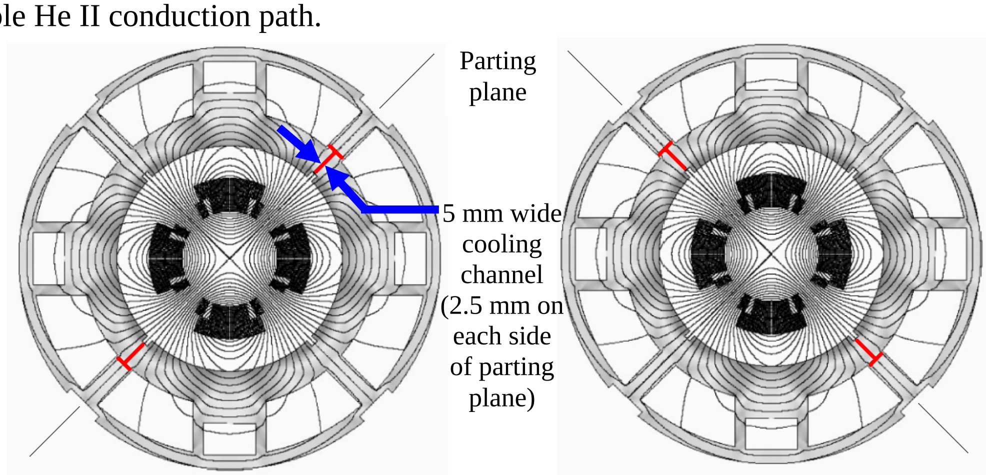


Figure 5 Yoke radial cooling channels (red) created by removing material from the yoke laminations. Periodically changing the orientation of the laminations so that heat is transferred to all of the longitudinal cooling channels is also illustrated. Cooling channel width is the parameter of note.

It is assumed that yoke laminations are about 1.5 mm thick, and a 40 mm He II conduction distance is estimated. Figure 6 shows the calculated Q1 non-IP end temperature profile for various cooling channel widths, where cooling channel width is as shown in Figure 5. In Figure 6, the bottom line is the calculated temperature profile of the longitudinal cooling channels. The other lines are calculated temperature profiles at the outer diameter of the collar for given widths of yoke radial cooling channel. A yoke radial cooling channel width of 5 mm is recommended to keep the temperature drop below 10 mK.

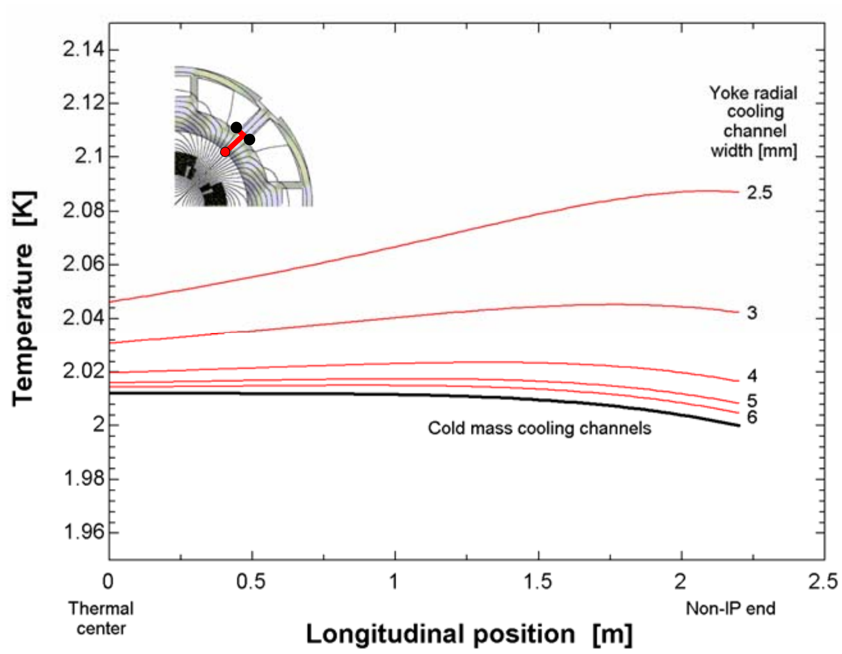


Figure 6 Temperature vs. longitudinal position at the Q1 non-IP end for a range of yoke radial cooling channel widths.

Collar Radial Cooling Channels

Collar radial cooling channels are required to transfer heat from the beam pipe annulus to the iron yoke.

In Figure 7, the bottom line is the calculated temperature profile of the longitudinal cooling channels. The line above is the calculated temperature profile at the iron yoke inner diameter with 5 mm wide cooling channels. The other lines are calculated temperature profiles at the collar inner diameter for various collar radial cooling channel sizes. Collar cooling channel size is expressed as a percentage of the collar pole tip open for He II heat transfer. The inner pole tip is 19.8 mm wide [4] and the path length from the inner pole tip to the outer diameter of the collar laminations is 36 mm [5].

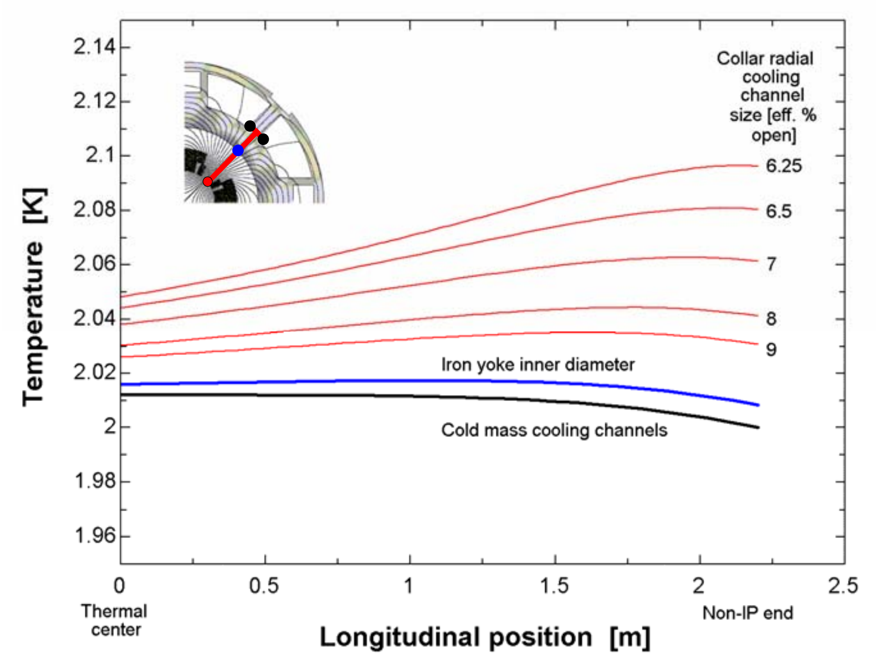


Figure 7 Temperature vs. longitudinal position at the Q1 non-IP end for a range of collar radial cooling channel sizes.

The current LHC Q2 quadrupole magnets have a cooling channel equivalent to 4% of the inner pole tip area, or one missing collar lamination in each quadrant per 1.5 inches of length [6]. With the large heat load increase in the upgraded IR, it will not be possible to maintain this 4% open, at least in the Q1. The required temperature drop through the cold mass would be too great. There is some temperature drop tradeoff with the crossover pipes. This is summarized in Figure 8. Approximately 5% open is the best that can be achieved, and this is only if none of the available 200 mK temperature drop is allocated to the crossover pipe. This pertains only to the Q1 cold mass - 4% open may still be achievable in the Q2 or Q3 due to their lower heat loads.

If the second generation magnets are constructed similarly to the first generation magnets, it is recommended to have collar cooling channel area equivalent to 7% of the pole tip area, or one missing lamination per 0.84 in.

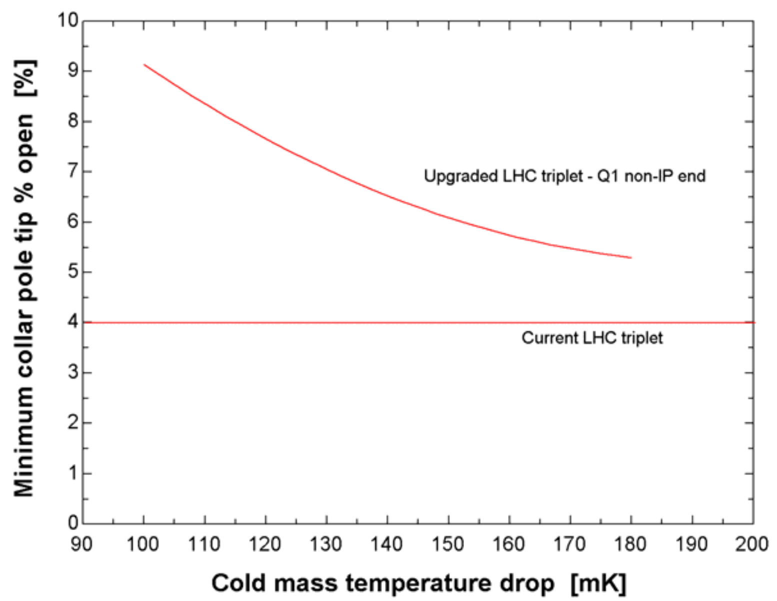


Figure 8 Minimum collar pole tip percent open vs. cold mass temperature drop from the beam pipe annulus to the heat exchanger crossover pipe.

If the second generation magnets use pole pieces instead of lamination pole tips, the cooling channels should be specified in terms of size and number of holes drilled through the pole pieces. In Figure 7, it is important to notice that the collar radial cooling channels are specified in terms of effective percent open. Only half of the holes drilled through the pole pieces should be considered as active cooling channels because of the quantity and orientation of yoke radial cooling channels illustrated in Figure 5. Each pole tip has an area of 0.0198 m^2 for each meter of magnet length. At 14% open (7% effectively open), there must be 4.3 in^2 of cooling channels drilled through each pole piece per meter of magnet length.

Whatever collar radial cooling channel size and frequency are chosen, the yoke laminations should change orientation with the same frequency so that the collar and yoke radial cooling channels line up.

Beam Pipe Annulus

The heat is deposited in the coils, concentrated in the horizontal and vertical planes with the greatest deposition at the coil inner diameter. This heat is transferred to the He II at the coil inner diameter and is conducted circumferentially through the beam pipe annulus to the collar pole tips. The existing inner triplet has a 1 mm annular gap between the beam pipe and the coils. A significant portion of this annular gap can be closed off due to protruding ground wrap insulation that separates the coils from the collars. With the Nb_3Sn coils being considered for the LHC upgrade, the coil ground wrap insulation is formed to the coil shape and would therefore not restrict circumferential heat transfer around the beam pipe.

Figure 9 shows the calculated temperature profile of the Q1 non-IP end. The bottom line is the temperature in the cold mass longitudinal cooling channels. The line above is the temperature at the iron yoke inner diameter. The next line above is the temperature at the collar pole tip. The top line is the temperature in the beam pipe annulus, 45 degrees from the collar pole tip, with a 1 mm annular gap filled with He II.drop. The maximum calculated temperature is 2.09 K. In order to remain in He II, the minimum He II annular gap is 0.85 mm.

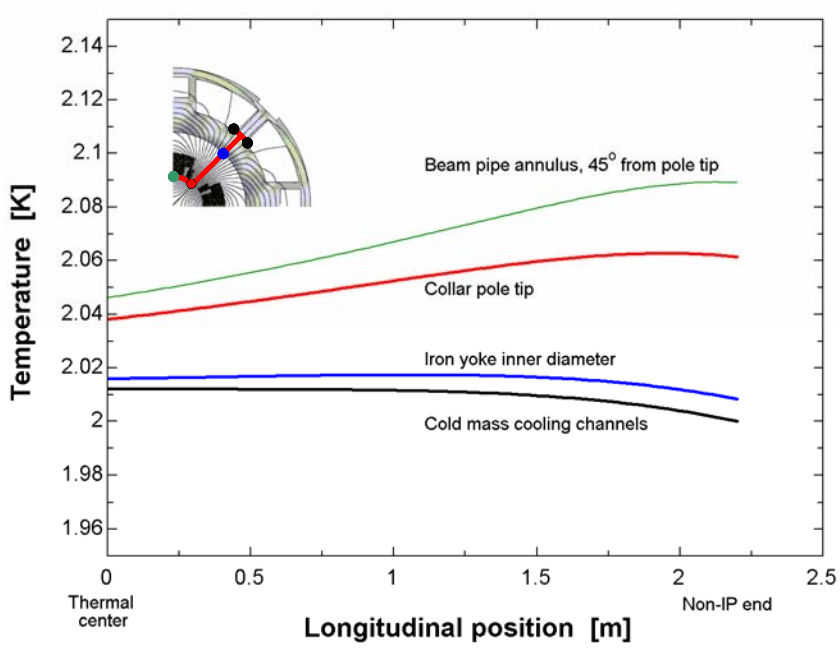


Figure 9 Temperature vs. longitudinal position at the Q1 non-IP end.

Conclusions

Calculations have been presented, providing values for critical parameters in He II cooling of the Nb_3Sn quadrupoles. The recommended values are summarized in Table 1 with the corresponding temperature drop.

Table 1 Comparison of calculated temperatures and design temperatures for the design parameters specified.

Design parameter	**Value**	**Calculated temperature range [K]**	**Design temperature range [K]**
Beam pipe He II annular gap	1 mm	2.089 – 2.061	2.150-2.000
Collar radial cooling channels	7% open (effective)	2.061 – 2.008	
Yoke radial cooling channels	5 mm wide	2.008 – 2.000	
Yoke longitudinal cooling channels	400 cm^2	2.000	
Crossover pipe	6 Sch 10 (6.357 in ID)	2.000 – 1.971	2.000 – 1.950

With these design parameters, the calculated cold mass temperatures remain within the design temperature profile. The warmest location in the cold mass, at the Q1 non-IP end beam pipe annular gap, remains comfortably below the lambda point. An additional 20 mK of temperature drop (relative to the design temperature drop) at the cold end of the Q1 non-IP end crossover pipe is also available.

All of the analyses presented here are for the Q1 non-IP end. These calculations will be repeated, integrating the magnet heat exchanger design, for each end of every cold mass to arrive at a more accurate temperature profile for the inner triplet.

References

[1] R. Rabehl, "LARP IR Cryogenics: Design Temperature Profile," LARP Document 100, December 2005.
[2] I. Rakhno, private communication, January 17, 2006.
[3] A. V. Zlobin, et al., "Conecptual Design Study of Nb_3Sn Low-Beta Quadrupoles for 2nd Generation LHC IRs," Proceedings of the 2002 Applied Superconductivity Conference (ASC 2002), Houston, TX, August 2002..
[4] R. Bossert, et al., "Development of TQC01, a 90 mm Nb_3Sn Model Quadrupole for LHC Upgrade based on SS Collar," Proceedings of the 19th International Conference on Magnet Technology (MT-19), Genova, Italy, September 2005.
[5] Fermilab drawing 5520-ME-411750, "LARP Quadrupole, TQ2a Model, Collar Lamination – Large."
[6] T. Peterson, "Inner Triplet Heat Summary"

Appendix – Inner Triplet Heat Deposition Data for $10^{35}/cm^2$-s Luminosity and W-25 Re Beam Pipe Liners (11.5 mm thick in Q1, 2.5 mm thick elsewhere).

Magnet			Heat	Load	(W/m)	for	Q1	region
		Z (m)		R<R1	R1<R<R2	R2<R	Total	1 sigma
		22.965						
Q1	1	23.31	23.14	21.4	7.15	8.067	36.62	0.172
	2	23.91	23.61	12.85	2.072	3.14	18.06	0.0996
	3	24.21	24.06	13.95	2.077	2.756	18.79	0.126
	4	24.698	24.45	19.89	3.019	3.538	26.45	0.121
	5	25.185	24.94	31.84	4.739	5.277	41.85	0.157
	6	25.672	25.43	44.1	6.597	7.311	58.01	0.202
	7	26.16	25.92	52.76	7.902	8.907	69.57	0.233
	8	26.648	26.4	62.62	9.277	10.37	82.27	0.27
	9	27.135	26.89	69.59	10.26	11.51	91.36	0.292
	10	27.622	27.38	79.13	11.29	12.56	103	0.321
	11	28.11	27.87	85.65	12.05	13.4	111.1	0.345
	12	28.41	28.26	89.79	12.55	13.82	116.2	0.444
	13	28.85	28.63	90.82	12.78	14.22	117.8	0.393
	14	29.335	29.09	95.31	13.01	14.92	123.2	0.403
MCBX-1	1	30.2	29.85	86.75	7.363	17.9	112	0.35
Q2a	1	32.55	32.3	26.8	18.78	19.71	65.29	0.198
	2	33.12	32.84	21.58	15.04	13.53	50.15	0.168
	3	33.42	33.27	18.96	13.24	11.82	44.02	0.208
	4	34.042	33.73	16.39	11.88	10.57	38.84	0.181
	5	34.663	34.35	13.05	9.152	8.232	30.43	0.12
	6	35.285	34.97	11.34	7.577	6.566	25.48	0.103
	7	35.907	35.6	10.86	7.362	5.814	24.04	0.105
	8	36.528	36.22	10.99	7.261	5.541	23.79	0.102
	9	37.15	36.84	10.94	7.426	5.59	23.96	0.126
	10	37.55	37.35	12.73	8.317	6.007	27.05	0.138
MCBX-2	1	38.55	38.05	12.85	3.76	5.602	22.21	0.108
Q2b	1	39.158	38.85	12.97	9.814	8.123	30.91	0.126
	2	39.767	39.46	14.37	8.927	6.829	30.12	0.167
	3	40.375	40.07	14.53	9.113	6.743	30.38	0.137
	4	40.983	40.68	14.64	9.248	6.665	30.56	0.139
	5	41.592	41.29	17.31	10.45	7.317	35.08	0.154
	6	42.2	41.9	21.28	12.92	8.717	42.92	0.173
	7	42.5	42.35	21.7	13.1	9.222	44.03	0.242
	8	43.017	42.76	21.4	13.16	9.053	43.62	0.189
	9	43.533	43.27	22.01	13.12	9.028	44.15	0.191
	10	44.05	43.79	22.49	13.46	9.243	45.19	0.204
MQSXA	1	46.682	46.57	24.23	5.809	14.21	44.25	0.324
Q3	1	47.45	47.21	28.38	20.15	15.91	64.45	0.244
	2	48.2	47.83	21.91	12.92	9.952	44.78	0.171
	3	48.5	48.35	19.75	11.8	8.545	40.09	0.238
	4	48.98	48.74	19.06	11.25	8.053	38.36	0.192
	5	49.467	49.22	18.83	10.7	7.697	37.23	0.191
	6	49.95	49.71	18.65	10.64	7.43	36.73	0.189
	7	50.435	50.19	18.5	10.51	7.331	36.35	0.19
	8	50.917	50.68	18.03	10.14	7.101	35.27	0.194
	9	51.4	51.16	18.31	10.36	6.912	35.58	0.196
	10	51.885	51.64	19	11.07	7.089	37.16	0.202
	11	52.37	52.13	18.75	10.88	7.055	36.69	0.2
	12	52.855	52.61	20.43	11.7	7.347	39.48	0.221
	13	53.335	53.09	21.98	12.47	7.912	42.36	0.231
MCBXA	1	54.882	54.37	23.21	12.7	7.128	43.04	0.213