LARP IR Cryogenics: Sector 4-5 Heat Load Study for the $10^{35}/cm^2$-s LHC Luminosity Upgrade

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Introduction

The goal of the LHC Accelerator Research Program (LARP) is to contribute to the LHC luminosity upgrade from $10^{34}/cm^2$-s to $10^{35}/cm^2$-s. This upgrade will likely occur in a number of phases [1]. One contribution LARP is focusing on is the interaction region (IR) upgrades. The increased heat loads resulting from the luminosity upgrade will affect not only the thermal design of the IR's, but also the LHC cryogenics system as a whole. This document attempts to address this question by scaling the cryogenics system heat loads and determining the significance of the IR heat loads relative to the system heat loads.

Sector 4-5 (a high-load sector) is analyzed in this document. Only the heat loads to 1.9 K and 4.6-20 K are considered because they are the temperature levels most relevant to the inner triplet.

Analysis

LHC Luminosity Upgrade Options

Two of the LHC luminosity upgrades being considered are the short bunch and long bunch options. The short bunch option has twice as many total particles as ultimate luminosity with twice as many bunches but half the bunch length. The long bunch option has about 15% more total particles than ultimate luminosity but only one-third the number of bunches and a bunch length twice as long. The parameters listed in Table 1 are relevant for estimating the system heat load for the two luminosity upgrade scenarios.

Table 1 Parameters for LHC upgrade options [2, except for the next to last row].

Parameter	Nominal luminosity	Ultimate luminosity	Short bunch luminosity upgrade	Long bunch luminosity upgrade
Beam current, I_{beam} [A]	0.58	0.86	1.72	1.0
No. of bunches, n_{bunch}	2808	2808	5616	936
Bunch length (r.m.s.), σ_z [cm]	7.55	7.55	3.78	14.4
Luminosity, L $[10^{34}/cm^2\text{-s}]$	1.0	2.3	9.2	8.9
Bunch current, I_{bunch} [mA]	0.21	0.31	0.31	1.07
Long. Profile	Gaussian	Gaussian	Gaussian	Flat

The bunch current, or bunch intensity, is calculated by Equation 1.

$$I_{bunch} = \frac{I_{beam}}{n_{bunch}} \tag{1}$$

Heat Load Scaling

The scaling laws of Table 2 can be used to estimate cryogenic system heat loads for each of the luminosity upgrade scenarios based on the parameters in Table 1. For the upgrade scenarios considered here, the relevant parameters are bunch current I_{bunch}, number of bunches n_{bunch}, bunch length σ_z, and luminosity L.

Table 2 Scaling laws of beam-induced loads [3].

Beam parameter	Energy E	Bunch current I_{bunch}	Bunch number n_{bunch}	Bunch length σ_z [r.m.s.]	Luminosity L
Resistive heating	E^2	-	-	-	-
Synchrotron radiation	E^4	I_{bunch}	n_{bunch}	-	-
Image current	-	I_{bunch}^2	n_{bunch}	$\sigma_z^{-3/2}$	-
Photo-electron cloud	-	I_{bunch}^3	n_{bunch}	-	-
Beam gas scattering	-	I_{bunch}	n_{bunch}	-	-
Random particle loss	-	I_{bunch}	n_{bunch}	-	-
Secondaries	E	-	-	-	L
RF losses	-	I_{bunch}^2	n_{bunch}	-	-

At nominal luminosity, the latest photo-electron cloud numbers are reduced by 2/3 from those in the LHC Design Report. At ultimate luminosity, these numbers are reduced by slightly more than 2/3. The electron cloud heat load varies with bunch intensity by a third-power law but there is often a weaker dependence, especially at higher bunch intensities. Also, a decrease in heat load becomes noticeable from about twice the nominal bunch length. Long, flat bunches or super-bunches generate less heat load per proton than at the nominal LHC conditions [4]. Therefore, the photo-electron heat load for the long bunch upgrade is assumed to be equal to that at ultimate luminosity due to the high bunch intensity and the long, flat bunch profile.

Table 3 Distributed steady-state beam-induced loads in an LHC cell [mW/m] [5; 6 (photo-electron cloud numbers)]

	Nominal luminosity		Ultimate luminosity	
Temperature	4.6-20 K	1.9 K	4.6-20 K	1.9 K
Synchrotron radiation	330	1	500	1
Image current	360	1	820	2
Photo-electron cloud	600	6	900	9
Beam-gas scattering	0.4	48	0.4	48
Random particle loss	0-0.1	0-32	0-0.3	0-48
Total beam-induced	1290	56-88	2220	60-108
	Short bunch upgrade		Long bunch upgrade	
Temperature	4.6-20 K	1.9 K	4.6-20 K	1.9 K
Synchrotron radiation	1000	2	575	1
Image current	4629	11	1236	3
Photo-electron cloud	1800	18	900	9
Beam-gas scattering	0.8	96	0.5	55
Random particle loss	0-0.6	0-96	0-0.3	0-55
Total beam-induced	7430	127-223	2712	68-123

Sector Heat Load Calculations

The heat load estimates of Table 3 can be applied to estimate the heat load for a given sector of the LHC. This document presents calculated results for sector 4-5, a high-load sector. Table A-1 in the Appendix summarizes the sector 4-5 heat load calculations for nominal luminosity, ultimate luminosity, short bunch upgrade, and long bunch upgrade operation, respectively. The calculations are detailed in Tables A-2 through A-5 of the Appendix.

With the exception of the photo-electron heat loads, the nominal and ultimate heat loads are taken from the LHC Design Report as indicated. Heat loads for the short bunch and long bunch upgrades are then calculated using the scaling laws of Table 2. The dispersion suppressor heat loads are assumed to scale similarly to the arc heat loads. The 4.6-20 K inner triplet heat load is assumed to be dominated by the photo-electron effect and is scaled accordingly. The 1.9 K inner triplet heat load is assumed to be dominated by the secondary particles as calculated by N. Mokhov (FNAL).

Table 4 Installed refrigeration capacity in the LHC sectors [7].

Temperature level		High-load sector	Low-load sector
50-75 K	[W]	33000	31000
4.6-20 K	[W]	7700	7600
4.5 K	[W]	300	150
1.9 K LHe	[W]	2400	2100
4 K VLP	[W]	430	380
20-280 K	[g/s]	41	27

Figure 1 summarizes the calculated 4.6-20 K heat loads. Based on current estimates, the installed refrigeration capacity is slightly below the ultimate luminosity heat load. Both the short and long bunch upgrades would require system upgrades, with the short bunch upgrade requiring a significantly more extensive upgrade due to the photo-electron effect.

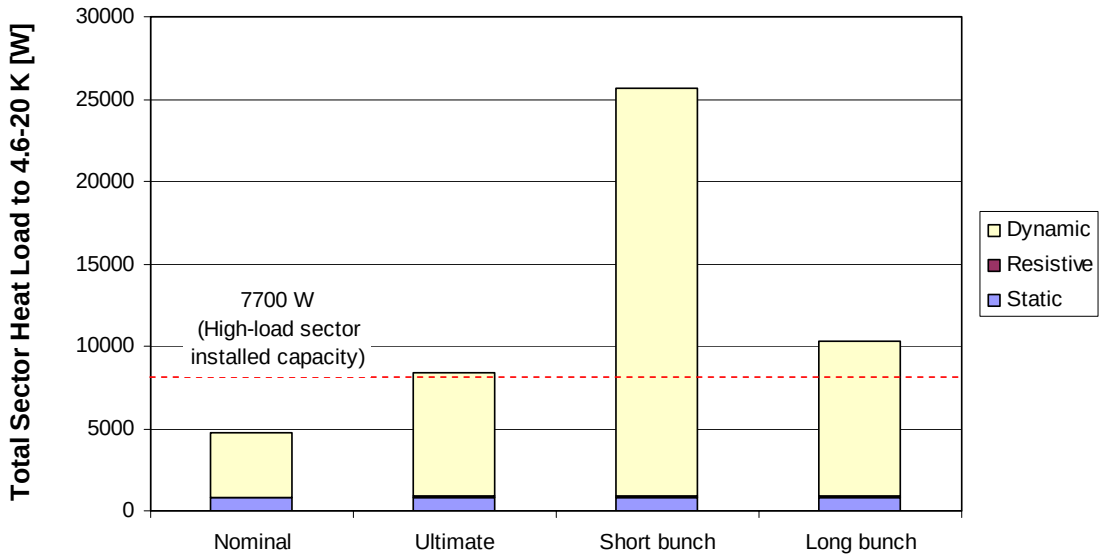

Figure 1 Calculated 4.6-20 K heat loads for sector 4-5 at nominal, ultimate, short bunch upgrade, and long bunch upgrade luminosities.

Similarly, Figure 2 shows the calculated 1.9 K heat loads. The installed capacity is estimated to be sufficient for nominal and ultimate luminosity operations. The installed capacity is exceeded by the heat loads of both the short bunch and long bunch upgrades. The inner triplet dynamic heat load to 1.9 K is indicated for each luminosity, and for both upgrade scenarios it is a significant fraction of the total sector heat load.

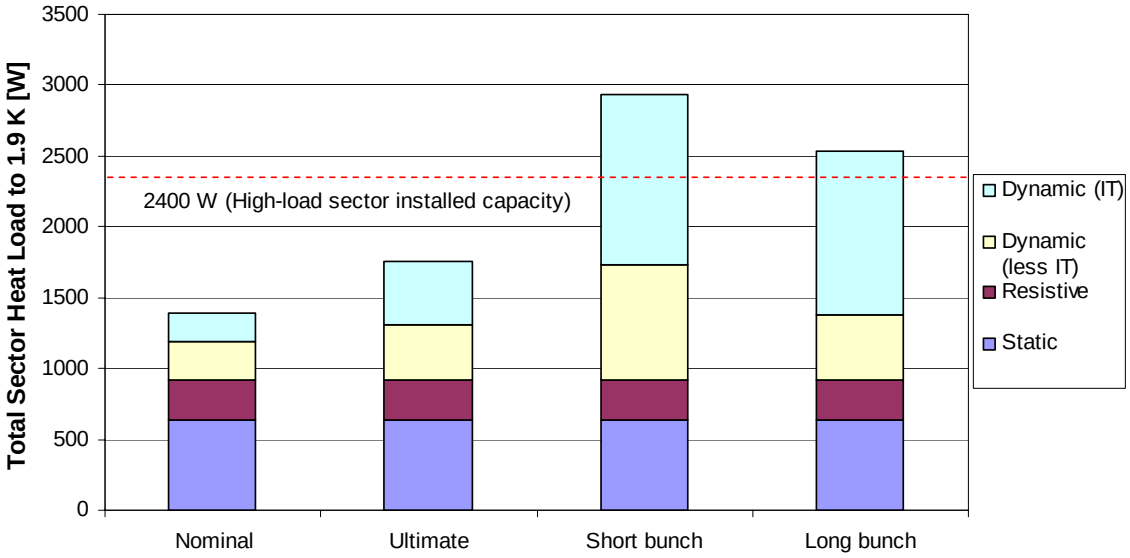

Figure 2 Calculated 1.9 K heat loads for sector 4-5 at nominal, ultimate, short bunch upgrade, and long bunch upgrade luminosities.

Conclusions

Both luminosity upgrade scenarios will require cryogenic upgrades to the 4.6-20 K system. A much more extensive cryogenic upgrade will be required if the short bunch luminosity upgrade is chosen.

The installed 1.9 K capacity is not sufficient for either luminosity upgrade scenario. The inner triplet heat load is significant for both luminosity upgrade scenarios.

A number of possible cryogenic system upgrades can be envisioned and have been discussed elsewhere [8]. Among the possibilities are:

- Upgrade the 4.6-20 K and 1.9 K systems to meet the heat loads of Figure 1 and 2.
- Intercept a sizable fraction of the inner triplet 1.9 K heat load at a higher temperature (e.g., using 4.6-20 K absorbers). This would minimize or even eliminate a 1.9 K capacity upgrade while requiring a larger 4.6-20 K capacity upgrade.
- Upgrade the 4.6-20 K system to meet the heat loads of Figure 1 while adding 1.9 K plants dedicated to cooling the inner triplets.

References

[1] F. Ruggiero, "LHC Upgrade Scenarios and Interaction Region Design," LHC IR Upgrades Workshop, St. Charles, IL, October 3-4, 2005.
[2] Ibid
[3] LHC Design Report Volume 1, Chap. 8, Table 11.7, p. 316. (http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html)
[4] F. Zimmerman, private communication, February 2006.

[5] LHC Design Report Volume 1, Chap. 8, Table 11.8, p. 316. (http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html)
[6] F. Zimmerman, "LHC electron-cloud update," p.10, LHC MAC 10, June 2005. (http://mgt-lhc-machine-advisory-committee.web.cern.ch/mgt-lhc-machine-advisory-committee/lhcmac17/ClosedSession/Zimmermann.pdf)
[7] LHC Design Report Volume 1, Chap. 8, Table 11.11, p. 328. (http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html)
[8] F. Ruggiero, et al., "LHC Luminosity and Energy Upgrade: A Feasibility Study," LHC Project Report 626, December 2002.

Appendix

Table A-1 Sector 4-5 heat load summary.

	Luminosity/Upgrade			
Heat Load [W]	Nominal	Ultimate	Short bunch	Long bunch
4.6-20 K				
Static				
Arc	323	323	323	323
DS 4 + DS 5 (half insertions)	56	56	56	56
LSS 5 (half insertion)	15	15	15	15
LSS 4 (half insertion)	5	5	5	5
QRL	247	247	247	247
Other distribution elements	198	198	198	198
Total Static [W]	**844**	**844**	**844**	**844**
Resistive heating				
Arc	7	19	19	19
DS 4 + DS 5 (half insertions)	2	6	6	6
Total Resistive [W]	**9**	**25**	**25**	**25**
Beam-induced				
Arc	3169	5454	18250	6742
Synchrotron radiation	810	1228	2456	1428
Image current	884	2014	11370	3101
Photo-electron cloud	1474	2210	4421	2210
Beam-gas scattering	1.0	1.0	2.0	1.1
Random particle loss	0.2	0.7	1.5	0.9
DS 4 + DS 5 (half insertions)	638	1829	6120	2261
LSS 5 (half insertion)	45	118	236	118
LSS 4 (half insertion)	31	87	174	353
Total Dynamic [W]	**3883**	**7488**	**24780**	**9473**
TOTAL [W]	**4736**	**8357**	**25649**	**10342**
1.9 K				
Static				
Arc	470	470	470	470
DS 4 + DS 5 (half insertions)	68	68	68	68
LSS 5 (half insertion)	33	33	33	33
LSS 4 (half insertion)	11	11	11	11
QRL	50	50	50	50
Other distribution elements	0	0	0	0
Total Static [W]	**632**	**632**	**632**	**632**
Resistive heating				
Arc	248	251	251	251
DS 4 + DS 5 (half insertions)	38	40	40	40
Total Resistive [W]	**286**	**291**	**291**	**291**
Beam-induced				
Arc	216	265	548	307
Synchrotron radiation	2.5	2.5	4.9	2.9
Image current	2.5	4.9	28	7.6
Photo-electron cloud	15	22	44	22
Beam-gas scattering	118	118	236	137
Random particle loss	79	118	236	137
DS 4 + DS 5 (half insertions)	59	125	258	145
LSS 5 (half insertion)	193	440	1200	1161
LSS 4 (half insertion)	2	2	2	2
Total Dynamic [W]	**470**	**832**	**2009**	**1614**
TOTAL [W]	**1388**	**1755**	**2932**	**2537**

Table A-2 Nominal luminosity sector 4-5 heat load summary.

NOMINAL LUMINOSITY			
Parameters			
Beam current, I_{beam} [A]		0.58	
Number of bunches, n_{bunch}		2808	
Bunch length, L_{bunch} [cm]		7.55	
Luminosity, L [1/cm^2-s]		1E+34	
Bunch current, I_{bunch} [A] = I_{beam}/n_{bunch}		2.07E-04	
4.6-20 K			
System		**Static Heat Load [W]**	**LHC Design Report Reference**
Arc		323	Table 11.2
Dispersion suppressors, DS 4 + DS 5 (half insertions)		56	Table 11.2
Long straight section, LSS 5 (half insertion)		15	Table 11.2
Radio frequency, LSS 4 (half insertion)		5	Table 11.2
Cryogenic distribution line, QRL		247	Table 11.3
Other distribution elements		198	Table 11.3
System		**Resistive Heating [W]**	**LHC Design Report Reference**
Arc		7	Table 11.6
Dispersion suppressor, DS 4 + DS 5 (half insertions)		2	Table 11.6
System		**Dynamic Heat Load [W]**	**LHC Design Report Reference**
Arc		3169	
Synchrotron radiation	810		Table 11.8
Image current	884		Table 11.8
Photo-electron cloud	1474		
Beam-gas scattering	0.98		Table 11.8
Random particle loss	0.25		Table 11.8
Dispersion suppressor, DS 4 + DS 5 (half insertions)		638	Table 11.9
Long straight section, LSS 5 (half insertion)		45	Table 11.9
Radio frequency, LSS 4 (half insertion)		31	Table 11.9
Total 4.6-20 K heat load [W]		**4736**	
1.9 K			
System		**Static Heat Load [W]**	**LHC Design Report Reference**
Arc		470	Table 11.2
Dispersion suppressor, DS 4 + DS 5 (half insertions)		68	Table 11.2
Long straight section, LSS 5 (half insertion)		33	Table 11.2
Radio frequency, LSS 4 (half insertion)		11	Table 11.2
Cryogenic distribution line, QRL		50	Table 11.3
Other distribution elements		0	Table 11.3
System		**Resistive Heating [W]**	**LHC Design Report Reference**
Arc		248	Table 11.6
Dispersion suppressor, DS 4 + DS 5 (half insertions)		38	Table 11.6
System		**Dynamic Heat Load [W]**	**LHC Design Report Reference**
Arc		216	
Synchrotron radiation	2.5		Table 11.8
Image current	2.5		Table 11.8
Photo-electron cloud	15		
Beam-gas scattering	118		Table 11.8
Random particle loss	79		Table 11.8
Dispersion suppressor, DS 4 + DS 5 (half insertions)		59	Table 11.9
Long straight section, LSS 5 (half insertion)		193	Table 11.9
Radio frequency, LSS 4 (half insertion)		2	Table 11.9
Total 1.9 K heat load [W]		**1388**	

Table A-3 Ultimate luminosity sector 4-5 heat load summary.

ULTIMATE LUMINOSITY			
Parameters			
Beam current, I_{beam} [A]		0.86	
Number of bunches, n_{bunch}		2808	
Bunch length, L_{bunch} [cm]		7.55	
Luminosity, L [1/cm^2-s]		2.30E+34	
Bunch current, I_{bunch} [A] = I_{beam}/n_{bunch}		3.06E-04	
4.6-20 K			
System		**Static Heat Load [W]**	**LHC Design Report Reference**
Arc		323	Table 11.2
Dispersion suppressors, DS 4 + DS 5 (half insertions)		56	Table 11.2
Long straight section, LSS 5 (half insertion)		15	Table 11.2
Radio frequency, LSS 4 (half insertion)		5	Table 11.2
Cryogenic distribution line, QRL		247	Table 11.3
Other distribution elements		198	Table 11.3
System		**Resistive Heating [W]**	**LHC Design Report Reference**
Arc		19	Table 11.6
Dispersion suppressor, DS 4 + DS 5 (half insertions)		6	Table 11.6
System		**Dynamic Heat Load [W]**	**LHC Design Report Reference**
Arc		5454	
Synchrotron radiation	1228		Table 11.8
Image current	2014		Table 11.8
Photo-electron cloud	2210		
Beam-gas scattering	0.98		Table 11.8
Random particle loss	0.74		Table 11.8
Dispersion suppressor, DS 4 + DS 5 (half insertions)		1829	Table 11.9
Long straight section, LSS 5 (half insertion)		118	Table 11.9
Radio frequency, LSS 4 (half insertion)		87	Table 11.9
Total 4.6-20 K heat load [W]		**8357**	
1.9 K			
System		**Static Heat Load [W]**	**LHC Design Report Reference**
Arc		470	Table 11.2
Dispersion suppressor, DS 4 + DS 5 (half insertions)		68	Table 11.2
Long straight section, LSS 5 (half insertion)		33	Table 11.2
Radio frequency, LSS 4 (half insertion)		11	Table 11.2
Cryogenic distribution line, QRL		50	Table 11.3
Other distribution elements		0	Table 11.3
System		**Resistive Heating [W]**	**LHC Design Report Reference**
Arc		251	Table 11.6
Dispersion suppressor, DS 4 + DS 5 (half insertions)		40	Table 11.6
System		**Dynamic Heat Load [W]**	**LHC Design Report Reference**
Arc		265	
Synchrotron radiation	2.5		Table 11.8
Image current	4.9		Table 11.8
Photo-electron cloud	22		
Beam-gas scattering	118		Table 11.8
Random particle loss	118		Table 11.8
Dispersion suppressor, DS 4 + DS 5 (half insertions)		125	Table 11.9
Long straight section, LSS 5 (half insertion)		440	Table 11.9
Radio frequency, LSS 4 (half insertion)		2	Table 11.9
Total 1.9 K heat load [W]		**1755**	

Table A-4 Short bunch luminosity upgrade sector 4-5 heat load summary.

SHORT BUNCH UPGRADE			
Parameters			
Beam current, I_{beam} [A]		1.72	
Number of bunches, n_{bunch}		5616	
Bunch length, L_{bunch} [cm]		3.78	
Luminosity, L [1/cm^2-s]		9.20E+34	
Bunch current, I_{bunch} [A] = I_{beam}/n_{bunch}		3.06E-04	
4.6-20 K			
System		**Static Heat Load [W]**	**LHC Design Report Reference**
Arc		323	Table 11.2
Dispersion suppressors, DS 4 + DS 5 (half insertions)		56	Table 11.2
Long straight section, LSS 5 (half insertion)		15	Table 11.2
Radio frequency, LSS 4 (half insertion)		5	Table 11.3
Cryogenic distribution line, QRL		247	Table 11.3
Other distribution elements		198	Table 11.3
System		**Resistive Heating [W]**	
Arc		19	Table 11.6
Dispersion suppressor, DS 4 + DS 5 (half insertions)		6	Table 11.6
System		**Dynamic Heat Load [W]**	
Arc		18250	
Synchrotron radiation	2456		
Image current	11370		
Photo-electron cloud	4421		
Beam-gas scattering	1.96		
Random particle loss	1.47		
Dispersion suppressor, DS 4 + DS 5 (half insertions)		6120	
Long straight section, LSS 5 (half insertion)		236	
Radio frequency, LSS 4 (half insertion)		174	
Total 4.6-20 K heat load [W]		**25649**	
1.9 K			
System		**Static Heat Load [W]**	**LHC Design Report Reference**
Arc		470	Table 11.2
Dispersion suppressor, DS 4 + DS 5 (half insertions)		68	Table 11.2
Long straight section, LSS 5 (half insertion)		33	Table 11.2
Radio frequency, LSS 4 (half insertion)		11	Table 11.2
Cryogenic distribution line, QRL		50	Table 11.3
Other distribution elements		0	Table 11.3
System		**Resistive Heating [W]**	
Arc		251	Table 11.6
Dispersion suppressor, DS 4 + DS 5 (half insertions)		40	Table 11.6
System		**Dynamic Heat Load [W]**	
Arc		548	
Synchrotron radiation	4.9		
Image current	27.7		
Photo-electron cloud	44		
Beam-gas scattering	236		
Random particle loss	236		
Dispersion suppressor, DS 4 + DS 5 (half insertions)		258	
Long straight section, LSS 5 (half insertion)		1200	
Radio frequency, LSS 4 (half insertion)		2	
Total 1.9 K heat load [W]		**2932**	

Table A-5 Long bunch luminosity upgrade sector 4-5 heat load summary.

LONG BUNCH UPGRADE			
Parameters			
Beam current, I_{beam} [A]		1	
Number of bunches, n_{bunch}		936	
Bunch length, L_{bunch} [cm]		14.4	
Luminosity, L [1/cm^2-s]		8.90E+34	
Bunch current, I_{bunch} [A] = I_{beam}/n_{bunch}		1.07E-03	
4.6-20 K			
System		**Static Heat Load [W]**	**LHC Design Report Reference**
Arc		323	Table 11.2
Dispersion suppressors, DS 4 + DS 5 (half insertions)		56	Table 11.2
Long straight section, LSS 5 (half insertion)		15	Table 11.2
Radio frequency, LSS 4 (half insertion)		5	Table 11.2
Cryogenic distribution line, QRL		247	Table 11.3
Other distribution elements		198	Table 11.3
System		**Resistive Heating [W]**	
Arc		19	Table 11.6
Dispersion suppressor, DS 4 + DS 5 (half insertions)		6	Table 11.6
System		**Dynamic Heat Load [W]**	
Arc		6742	
Synchrotron radiation	1428		
Image current	3101		
Photo-electron cloud	2210		
Beam-gas scattering	1.14		
Random particle loss	0.86		
Dispersion suppressor, DS 4 + DS 5 (half insertions)		2261	
Long straight section, LSS 5 (half insertion)		118	
Radio frequency, LSS 4 (half insertion)		353	
Total 4.6-20 K heat load [W]		**10342**	
1.9 K			
System		**Static Heat Load [W]**	**LHC Design Report Reference**
Arc		470	Table 11.2
Dispersion suppressor, DS 4 + DS 5 (half insertions)		68	Table 11.2
Long straight section, LSS 5 (half insertion)		33	Table 11.2
Radio frequency, LSS 4 (half insertion)		11	Table 11.2
Cryogenic distribution line, QRL		50	Table 11.3
Other distribution elements		0	Table 11.3
System		**Resistive Heating [W]**	
Arc		251	Table 11.6
Dispersion suppressor, DS 4 + DS 5 (half insertions)		40	Table 11.6
System		**Dynamic Heat Load [W]**	
Arc		307	
Synchrotron radiation	2.9		
Image current	7.6		
Photo-electron cloud	22		
Beam-gas scattering	137		
Random particle loss	137		
Dispersion suppressor, DS 4 + DS 5 (half insertions)		145	
Long straight section, LSS 5 (half insertion)		1161	
Radio frequency, LSS 4 (half insertion)		2	
Total 1.9 K heat load [W]		**2537**	