ii. Heat Load of Magnets and Refrigeration Distribution System

One of the most important factors in the design of the cryogenic system is to properly identify every part of the load imposed upon the system. Wherever possible this load should be as low as is consistent with good design and fabrication practice in order to minimize the operating costs of the accelerator. The aggregate design load, of course, should be kept low enough that a sufficient margin can be maintained between the actual load and the capacity of the existing refrigerator to permit short cooldown times and high reliability.

A heat load budget for the entire RHIC system was maintained throughout the conceptual design period of the project and was periodically updated. The current budget is given in Table 3-1. No refrigeration has been allowed for any item which does not appear in this table. Table 3-2 shows the details of the heat load budget for a 9.7 m Arc Dipole Magnet. Table 3-3 gives the details for an Arc CQS (Corrector-Quad-Sextupole) Magnet. It has been assumed that all dipoles have equal heat loads and that all quadrupoles have the same heat load as an Arc CQS.

Table 3-4 supports the values given in Table 3-1 for the Magnet Power Lead lines of that table. The power bus for the magnets is carried cold (superconducting) in the helium piping which crosses the Intersection Regions (IR). These leads are distributed as shown in Table 3-5. Except at 4 o'clock and 10 o'clock, only two high amperage leads, for the dump resistor, are required per ring per IR. Other leads of lesser amperage also exit at a typical sextant. These leads introduce a conductive load of about 30 W into the magnet helium flow. The penetrations for these leads are incorporated into the design of the valve box. Only one valve box per ring is located at each IR. The remainder of the lead requirements can be handled by low amperage leads (50 A) which are, for convenience, bundled into groups for the gas-cooled penetration. These low amperage leads are located one in each arc CQS assembly and in insertion quadrupoles around the ring.

Table 3-1. Cryogenic System Heat Load Allowance

			Primary Load W @ 4 K			Secondary Load W @ 55 K		
Magnet System:								
Dipoles - 8 cm Aperture	360	ea	@2.51	902		@24.7	8906	
Dipoles - 13 cm (D0)	24	ea	@5.01	120		@49.5	1188	
Dipoles - 20 cm (DX)	12	ea	@7.52	90		@74.2	891	
CQS Assemblies & Insert. Quads	492	ea	@1.78	877		@16.4	8066	
Insertion Magnet Connecting Pipe	1183	m	@0.25	296		@ 1.3	1479	
Corr, Trim, Heater, Volt Tap Leads	492	ea	@3.75	1846		@ 0	0	
Beam Vacuum Pump Connects	48	ea	@1.50	72		@ 5.3	254	
Beam Pipe Warm/Cold Trans	92	ea	@0.50	46		@ 0.2	18	
Magnet System Load Sub-Total					4249			20802
Magnet Power Leads in Lead Pots:								
Main Coils				1282			0	
By-Pass Leads				1189			0	
Magnet Power Leads Sub-Total					2471			0
Cryogenic Distribution System:								
Refrigerator/ Ring Connection Piping	350	m	@0.57	200		@ 2.3	800	
Ring Piping	2400	m	@0.50	1200		@ 2.1	5000	
Valves - 4 K	221	ea		210			1272	
Filters	120	ea		115			974	
Valves - 55 K	47	ea	0	0		@ 3.7	174	
Valve Box with Leads & Recooler	12	ea	@22.0	264		@162.0	1944	
Cryo. Distrib. System Sub-Total					1989			10164
Liquid Helium for Detectors (proposed)					0			0
Sum of Steady-State Individual Component Allowances Above:					8708			30966
Load Contingency and Off-Design Performance Allowance (20%)					1742			6193
Cryogenic System Design Operating Point:					10449			37159
Refrigerator Capacity				24800			55000	
Capacity to Operating Point Ratio:				2.4			1.5	

Table 3-2. Heat Load Allowance per 9.7 m Arc Dipole

Item	Primary W @ 4.6 K	Secondary W @ 55 K
Total Support System	0.30	3.24
Insulation - Radiation & Cond.	1.69	12.70
Interconnect Insulation	0.22	6.80
Other	0.30	2.00
Total for Dipole	2.51	24.74

Table 3-3. Heat Load Allowance for Arc CQS Assembly

Item	Primary W @ 4.6 K	Secondary W @ 55 K
Total Support System	0.20	2.16
Insulation - Rad. & Cond.	0.56	4.23
Interconnect Insulation	0.22	6.80
Beam Position Monitor	0.40	1.20
Other	0.40	2.00
Total for CQS	1.78	16.39

Table 3-4. Magnet Power Leads for RHIC 92 Lattice

LEAD FUNCTION	# of Gas-Cooled Lead Assemblies by current rating				
	12x50A	12x150A	1600A	6300A	TOTAL
Dipole, Main				8	
Quad, Main				8	
DX & D0 Bypasses			44		
Insertion Quad and Dipole Trim and Bypass Circuits		60			
Corrector Coils	492				
TOTAL NUMBER	492	60	44	16	615
LOSS RATE (per kA) USED:					
0.06 g/s + 1.2 W			x	x	
0.085 g/s + 1.7 W		x			
0.08 g/s + 0.3 W	x				
ESTIMATED FLOW (g/s)	20.66	9.2	4.22	3.0	37.6
Equiv. W @ 100 W/(g/s)	2066	920	422	300	3760
ESTIMATED CONDUCTION (W)	89	187	85	60	427
TOTAL LOSS - Equiv. W	2155	1107	507	360	4129
OFF-DESIGN RESERVE (6%)	129	44	23	73	269
MAXIMUM EXPECTED LOAD	2284	1151	530	433	4398

Table 3-5. Distribution of Magnet Power Leads for RHIC 92 Lattice
Cold Bus Across Intersection Region

LEAD LOCATION	# of Gas-Cooled Lead Assemblies by current rating					
	12x50A	12×150A	1600A	6300A	TOTAL	Load (W)
2:00 Yellow Valve Box	0	5	4	0	9	
2:00 Blue Valve Box	0	5	6	0	11	
4:00 Yellow Valve Box	0	5	2	4	11	
4:00 Blue Valve Box	0	5	4	4	13	
6:00 Yellow Valve Box	0	5	2	0	7	
6:00 Blue Valve Box	0	5	4	0	9	
8:00 Yellow Valve Box	0	5	2	0	7	
8:00 Blue Valve Box	0	5	4	0	9	
10:00 Yellow Valve Box	0	5	4	4	13	
10:00 Blue Valve Box	0	5	6	4	15	
12:00 Yellow Valve Box	0	5	2	0	7	
12:00 Blue Valve Box	0	5	4	0	9	
TOTAL ABOVE	0	60	44	16	120	1974
Dist. in IR Magnets	204			204	893	
Dist. in Arc Magnets	288			288	1262	
RHIC TOTAL	49260	44	16	612	4129	

Heaters built into the magnets are powered during warm-up. One pair of leads at every CQS is required for these heaters. These leads have been designed into the "bundle" which includes the 12X50 A leads for the correction coils.

Table 3-6 is a listing of each equipment item in a typical sextant (1 and 12 o'clock regions are shown) with its budgeted heat load and the temperature profile which results. This table has been calculated using the baseline load as a model. The baseline flow of 100 g/s is used in this calculation and, as shown, all magnets are below the design maximum temperature of 4.6 K. A similar table has been developed (but is not shown here) for a high heat load model in which each component has twice its baseline heat load. The helium flow rate is increased to 150 g/s and with that change, it is still possible to hold the maximum magnet temperature under 4.6 K.

The parameters used for the calculations in Table 3-6 are as follows:

Recooler Heat Exchanger Effectivity:

Quad = 0.75

Inlet = 0.95

(The Recooler Overall Effectivity Used Includes the Effect of By-Pass Flow)

He Bath Temp = 4.300 K

Magnet Pressure = 4.5 bar

Magnet Temperature = 4.5 K

C_P = 3.956 J/g□K

Flow = 100 g/s

Dipole Heat Load = 2.505 W

Quad Heat Load = 1.782 W

Beam Tube Pump = 1.500 W

Table 3-6. RHIC Temperature & Heat Load Profile by Element for Typical Sextant of One Ring with Six Recoolers

Element No.	Element Description	Estimated Heat Load (W)	Cumulative for Recool (W)	Gas Temp Out (K)
BI12---	Carryover Prev.	70.6	70.6	4.473
BI12-VJX	Cross-Insert VJP	40.0	110.6	4.575
BI12-VBX	Valve Box	12.5	123.1	4.606
BI12-VBX	Valves	75.0	198.1	4.796
BI12-PL1	Magnet Leads 1	30.0	228.1	4.872
BI12-RCX	Recooler1*Feed	-216.9	11.3	4.328
BI12-VJIN	VJ Line fr Valve Box	10.0	21.3	4.354
BI12-WCX1	Warm/Cold Trans.	0.5	21.8	4.355
BI12-DX	Common Magnet	7.5	29.3	4.374
BI12-WCX2	Warm/Cold Trans.	0.5	29.8	4.375
BI12-WC0	Warm/Cold Trans.	2.5	32.3	4.382
BI12-D0	Dipole	5.0	37.3	4.394
BI12-Q1	Insertion Quad	2.7	39.9	4.401
BI12-PL1	12×50 Corr. #1	2.0	41.9	4.406
BI12-Q2	Insertion Quad	2.7	44.6	4.413
BI12-PL2	12×50 Corr. #2	2.0	46.6	4.418
BI12-Q3	Insert. Quad+WC	2.7	49.3	4.425
BI12-PL3	12×50 Corr. #3	2.0	51.3	4.430
BI12-WC3	Warm/Cold Trans.	0.5	51.8	4.431
BI12-VJ3	Q3 Straight	7.8	59.6	4.451
BI12-WC4	Warm/Cold Trans.	0.5	60.1	4.452
BI12-Q4	Insertion Quad+WC	2.7	62.8	4.459
BI12-PL4	12×50 Corr. #4	2.0	64.8	4.464
BI12-Q5	Insertion Quad+PL	1.8	66.5	4.468
BI12-PL5	12×50 Corr. #5	2.0	68.5	4.473
BI12-D5	Dipole	2.5	71.0	4.480
BI12-RC6	Recooler 2*Quad	-53.3	17.8	4.345
BI12-Q6	Insertion Quad+PL+RC	1.8	19.5	4.349
BI12-PL6	12×50 Corr. #6	2.0	21.5	4.354
BI12-D6	Dipole	2.5	24.0	4.361
BI12-Q7	Insertion Quad	1.8	25.8	4.365
BI12-PL7	12×50 Corr. #7	2.0	27.8	4.370
BI12-Q8	Insertion Quad+PL	1.8	29.6	4.375
BI12-PL8	12×50 Corr. #8	2.0	31.6	4.380

Element No.	Element Description	Estimated Heat Load (W)	Cumulative for Recool (W)	Gas Temp Out (K)
BI12-VJ8	Q8 Straight	1.5	33.1	4.384
BI12-D8	Dipole	2.5	35.6	4.390
BI12-VJ9	Q9 Straight	1.5	37.1	4.394
BI12-Q9	QF+S+C	1.8	38.9	4.398
BI12-PL9	12×50 Corr #9	2.0	40.9	4.403
BI12-D9	Dipole Cell 1	2.5	43.4	4.410
BI12-Q10	QD+S+C+PL	1.8	45.2	4.414
BI12-PL10	12×50 Corr. #10	2.0	47.2	4.419
BI12-D10	Dipole Cell 1	2.5	49.7	4.426
BI12-Q11	QF+S+C+PL	1.8	51.5	4.430
BI12-PL11	12×50 Corr. #11	2.0	53.5	4.435
BI12-D11	Dipole Cell 2	2.5	56.0	4.441
BI12-Q12	QD+S+C	1.8	57.8	4.446
BI12-PL12	12×50 Corr. #12	2.0	59.8	4.451
BI12-D12	Dipole Cell 2	2.5	62.3	4.457
BI12-Q13	QF+S+C	1.8	64.0	4.462
BI12-PL13	12×50 Corr. #13	2.0	66.0	4.467
BI12-D13	Dipole Cell 3	2.5	68.6	4.473
BI12-RC14	Recooler 3*Quad	-51.4	17.1	4.343
BI12-Q14	QD+S+C+RC	1.8	18.9	4.348
BI12-PL14	12×50 Corr. #14	2.0	20.9	4.353
BI12-VP14	Beam Tube Pump	1.5	22.4	4.357
BI12-D14	Dipole Cell 3	2.5	24.9	4.363
BI12-Q15	QF+S+C	1.8	26.7	4.368
BI12-PL15	12×50 Corr. #15	2.0	28.7	4.373
BI12-D15	Dipole Cell 4	2.5	31.2	4.379
BI12-Q16	QD+S+C+PL	1.8	33.0	4.383
BI12-PL16	12×50 Corr. #16	2.0	35.0	4.388
BI12-D16	Dipole Cell 4	2.5	37.5	4.395
BI12-Q17	QF+S+C	1.8	39.3	4.399
BI12-PL17	12×50 Corr. #17	2.0	41.3	4.404
BI12-D17	Dipole Cell 5	2.5	43.8	4.411
BI12-Q18	QD+S+C	1.8	45.6	4.415
BI12-PL18	12×50 Corr. #18	2.0	47.6	4.420

Element No.	Element Description	Estimated Heat Load (W)	Cumulative for Recool (W)	Gas Temp Out (K)
BI12-D18	Dipole Cell 5	2.5	50.1	4.427
BI12-Q19	QF+S+C	1.8	51.9	4.431
BI12-PL19	12×50 Corr. #19	2.0	53.9	4.436
BI12-VP19	Beam Tube Pump	1.5	55.4	4.440
BI12-D19	Dipole Cell 6	2.5	57.9	4.446
BI12-Q20	QD+S+C	1.8	59.6	4.451
BI12-PL20	12×50 Corr. #20	2.0	61.6	4.456
BI12-D20	Dipole Cell 6	2.5	64.1	4.462
BI12-RC21	Recooler 4*Quad	-48.1	16.0	4.341
BI12-Q21	QF+S+C+RC+L	1.8	17.8	4.345
BI12-PL21	12×50 Corr. #21	2.0	19.8	4.350
BI1-D20	Dipole Cell 7	2.5	22.3	4.356
BI1-Q20	QD+S+C	1.8	24.1	4.361
BI1-PL20	12×50 Corr. #22	2.0	26.1	4.366
BI1-VP19	Beam Tube Pump	1.5	27.6	4.370
BI1-D19	Dipole Cell 7	2.5	30.1	4.376
BI1-Q19	QF+S+C	1.8	31.9	4.381
BI1-PL19	12×50 Corr. #23	2.0	33.9	4.386
BI1-D18	Dipole Cell 8	2.5	36.4	4.392
BI1-Q18	QD+S+C	1.8	38.2	4.397
BI1-PL18	12×50 Corr. #24	2.0	40.2	4.402
BI1-D17	Dipole Cell 8	2.5	42.7	4.408
BI1-Q17	QF+S+C	1.8	44.5	4.412
BI1-PL17	12×50 Corr. #25	2.0	46.5	4.417
BI1-D16	Dipole Cell 9	2.5	49.0	4.424
BI1-Q16	QD+S+C+PL	1.8	50.8	4.428
BI1-PL16	12×50 Corr. #26	2.0	52.8	4.433
BI1-D15	Dipole Cell 9	2.5	55.3	4.440
BI1-Q15	QF+S+C	1.8	57.0	4.444
BI1-PL15	12×50 Corr. #27	2.0	59.0	4.449
BI1-D14	Dipole Cell 10	2.5	61.5	4.456
BI1-RC14	Recooler 5*Quad	-46.2	15.4	4.339
BI1-Q14	QD+S+C+RC	1.8	17.2	4.343
BI1-PL14	12×50 Corr. #28	2.0	19.2	4.348

Element No.	Element Description	Estimated Heat Load (W)	Cumulative for Recool (W)	Gas Temp Out (K)
BI1-VP14	Beam Tube Pump	1.5	20.7	4.352
BI1-D13	Dipole Cell 10	2.5	23.2	4.359
BI1-Q13	QF+S+C	1.8	25.0	4.363
BI1-PL13	12×50 Corr. #29	2.0	27.0	4.368
BI1-D12	Dipole Cell 11	2.5	29.5	4.374
BI1-Q12	QD+S+C	1.8	31.2	4.379
BI1-PL12	12×50 Corr. #30	2.0	33.2	4.384
BI1-D11	Dipole Cell 11	2.5	35.7	4.390
BI1-Q11	QF+S+C+PL	1.8	37.5	4.395
BI1-PL11	12×50 Corr. #31	2.0	39.5	4.400
BI1-D10	Dipole Cell 12	2.5	42.0	4.406
BI1-Q10	QD+S+C+PL+PL	1.8	43.8	4.411
BI1-PL10	12×50 Corr. #32	2.0	45.8	4.416
BI1-D9	Dipole Cell 12	2.5	48.3	4.422
BI1-Q9	QF+S+C+WC	1.8	50.1	4.427
BI1-PL9	12×50 Corr. #33	2.0	52.1	4.432
BI1-D8	Dipole	2.5	54.6	4.438
BI1-VJ8	Q8 Straight	3.0	57.6	4.446
BI1-WC8	Warm/Cold Trans.	0.5	58.1	4.447
BI1-Q8	Insert Quad+PL+WC	1.8	59.9	4.451
BI1-PL8	12×50 Corr. #34	2.0	61.9	4.456
BI1-Q7	Insertion Quad	1.8	63.7	4.461
BI1-PL7	12×50 Corr. #35	2.0	65.7	4.466
BI1-D6	Dipole	2.5	68.2	4.472
BI1-RC6	Recooler 6*Quad	-51.1	17.0	4.343
BI1-Q6	Insertion Quad+PL+RC	1.8	18.8	4.348
BI1-PL6	12×50A Lead #36	2.0	20.8	4.353
BI1-D5	Dipole	2.5	23.3	4.359
BI1-Q5	Insertion Quad	1.8	25.1	4.363
BI1-PL5	12×50A Lead #37	2.0	27.1	4.369
BI1-Q4	Insertion Quad + WC	2.7	29.8	4.375
BI1-PL4	12×50A Lead #38	2.0	31.8	4.380
BI1-WC4	Warm/Cold Trans.	0.5	32.3	4.382
BI1-VJ3	Q3 Straight	7.8	40.1	4.401

Element No.	Element Description	Estimated Heat Load (W)	Cumulative for Recool (W)	Gas Temp Out (K)
BI1-WC3	Warm/Cold Trans.	0.5	40.6	4.403
BI1-PL2	12×50A Lead #39	2.0	42.6	4.408
BI1-Q3	Insertion Quad + WC	2.7	45.3	4.414
BI1-PL2	12×50A Lead #40	2.0	47.3	4.419
BI1-Q2	Insertion Quad	2.7	49.9	4.426
BI1-PL1	12×50A Lead #41	2.0	51.9	4.431
BI1-Q1	Insertion Quad	2.7	54.6	4.433
BI1-D0	Dipole	5.0	59.6	4.446
BI1-WC0	Warm/Cold Trans.	2.5	62.1	4.452
BI1-WCX1	Warm/Cold Trans.	0.5	62.6	4.453
BI1-DX	Common Dipole	7.5	70.1	4.472
BI1-WCX2	Warm/Cold Trans.	0.5	70.6	4.473
	Total Sextant Load	467.0		
	Total Recooler Load	-467.0		

The actual RHIC heat load is varies between 11.4 and 12 kW, depending on whether the accelerator is powered to full current. Of this, the conduction and radiation load is approximately 8.4 KW, and the total lead flows vary between 30 and 35 grams/second. All leads are not powered to maximum current at the same time.

The heat load is not evenly distributed throughout a sextant. The first recooler, located at the Q6 magnet, typically sees the highest load, as it sees long transfer lines and triplet magnets. Recoolers in mid arc have lower loads. This pattern is repeated throughout the sextants, as indicated in figure 3-1, which shows the actual measured heat load distribution in the Blue ring.

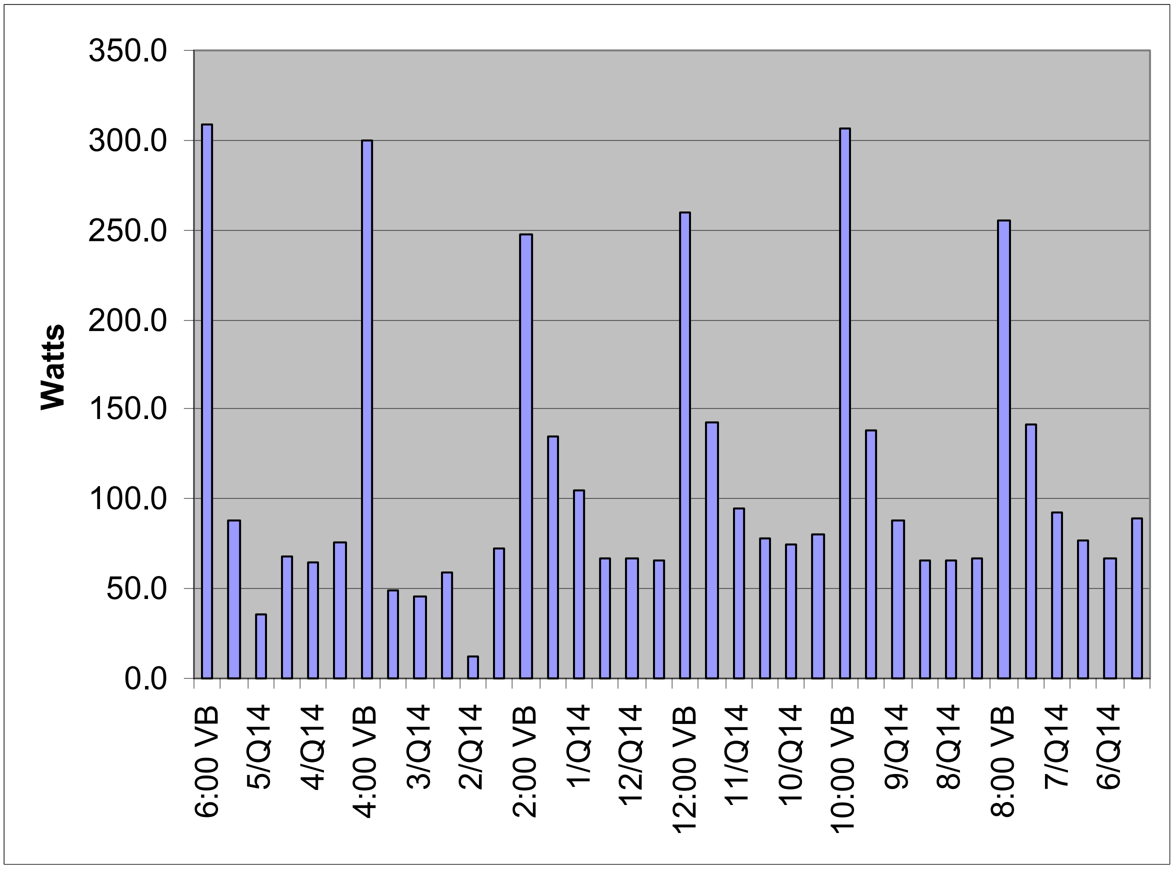

Figure 3-1 .Actual Heat Load Distribution in Blue Ring