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Thermal Behavior of RHIC BPM Cryogenic Signal Cables

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Introduction

The thermal behavior of the Beam Position Monitor Cryogenic Signal Cables is a function of cable length and materials, the method of thermal anchoring, and resistive heating of the cables by the beam induced signal current. Interest in this thermal behavior is motivated by the possibility that temperature rise in the cables might become a limit to beam intensity in RHIC. The thermal and electrical properties of the cables exhibit strong dependence on temperature and on bunch length and shape. An examination of the applicability of available software led to the decision to write a custom program to model this problem. Progressive refinement of this model has led to comparisons of cable heating and beampipe heating limits to beam intensity in RHIC.

Design Requirements and Cable Construction

The design requirements for BPM Cryogenic Signal Cables[1] typically include conductor materials which minimize both heat leak to cryogenic temperatures and heat generation by beam signal currents, radiation resistance requirements which preclude the use of teflon, phase matching within a few picoseconds, and insertion loss matching within about 0.01 dB in a structure with gradients from room to cryogenic temperatures. These requirements remove the cables from the category of catalog items, and their procurement can be viewed as a development project[2,3]. Table 1 shows the materials originally specified in the cable RFP, and alternate configurations proposed, on the basis of materials availability, by the vendors who responded to the bid solicitation.

Table 1: Cable Materials

Item	Original Specification	Alt Configuration 1	Alt Configuration 2
inner conductor	silver plated beryllium copper	silver plated copper	silver plated copper
outer conductor	stainless steel with copper plating on the inside diameter	stainless steel	stainless steel with copper plating on the inside diameter
dielectric	tefzel, polyethylene, or SiO_2	tefzel	SiO_2

The Thermal Analysis

The initial thermal analysis[4] of the cable did not take resistive heating of the cable by the signal current into consideration. The heat load situation was subsequently affected by a cost and materials availability driven design change (elimination of copper plating of the interior of the stainless steel outer conductor) which reduced static heat leak at the expense of increased resistive heating in that conductor[5]. The impact of that change was compounded by the possibility of beam intensities[6] and bunch lengths[7] which differ from the originally specified Design Manual parameters. The problem in that configuration was first analyzed[8] using an analytical solution to the heat conduction equation with approximations for the spectral content of the beam and the temperature dependent thermal and electrical conductivities of the cable. Those results indicated the possibility of excessive temperature rise, and motivated the development of a more sophisticated model.

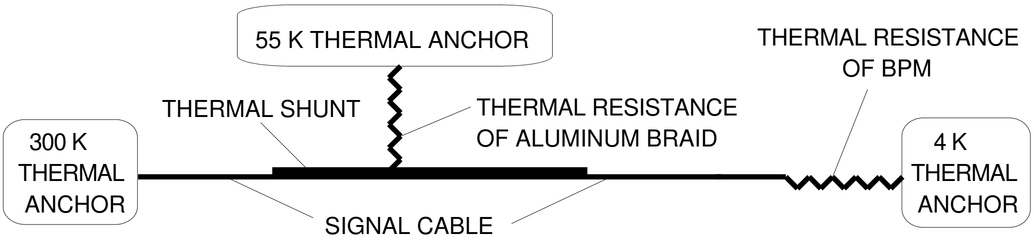

Figure 1. Signal Cable Thermal Circuit

The thermal circuit under consideration is shown in Figure 1. The 1.22 m long signal cable is attached to the room temperature feedthru (300 K thermal anchor) at one end, and to the BPM at the other end. The cable sees the 4 K thermal anchor thru the thermal resistance of the BPM, and the 55 K thermal anchor thru the thermal resistance of the aluminum heatsink braid. The thermal shunt is 0.6 m long for the cable with the bare stainless steel outer conductor and 0.4 m long for the cable with the copper plated outer conductor, with a cross sectional area of 1.2 cm^2, and is fabricated from aluminum alloy stock sections. The heat source, resistive heating by the signal current, is distributed along the length of the cable. This circuit was analyzed using a finite difference equation method called the relaxation method. The program analyzes heat flow in 1 cm steps along the length of the cable. Heat flow occurs because of the thermal conductance of the cable and RF heating from the signal current. The analysis uses a variable gaussian bunch length excitation modified by the response of the BPM to determine the intensity and spectral content of the signal in the cable. Frequency and temperature dependent skin depths and electrical resistivities, and temperature dependent thermal conductivities of the cable and the thermal anchors, are determined at each iteration of the calculation. The method is discussed in greater detail elsewhere[9].

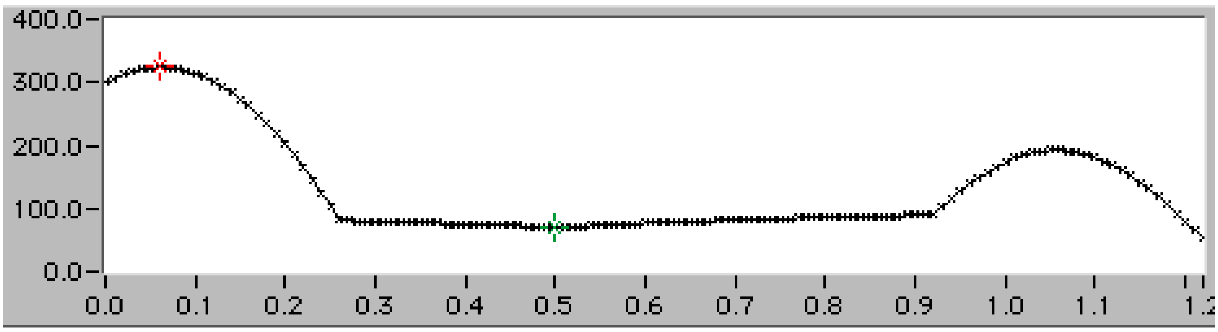

Figure 2. Typical Temperature [K] Profile along the length [m] of the Signal Cable

Figure 2 shows a typical plot of the calculated temperature profile along the length of the cable with the bare stainless steel outer conductor. Input parameters for this plot include a beam intensity of 3 x 10^{11} charges per bunch and 114 bunches in the machine (hereafter referred to as 'RHIC upgrade intensity'), with a rms bunch length of 15 cm and the beam displaced 1 cm from the reference orbit (displacing the beam results in higher currents in the cable attached to the nearer stripline). The peak at left is around 320 K. The plateau along the length of the shunt is higher than 55 K because of the thermal resistance of the braid between the shunt and the 55 K thermal anchor. Likewise, the right end is higher than 4 K because of the thermal resistance of the BPM between the cable and the 4 K thermal anchor. The magnitudes of the temperature peaks near each end are inversely proportional to the thermal conductivity of the cable. The unavailability of the silver plated beryllium copper center conductor, and the substitution of silver plated copper, was a fortuitous circumstance. Given the physical constraints of the cable installation in the CQS cryostat, it would have been much more difficult to arrive at a solution without the presence of the thermal conductivity of the copper center conductor. This illustrates the evolution of our approach to the problem, from an effort to maximize thermal isolation to an effort to minimize thermal isolation without inflicting an unacceptable heat load on the cryogenic system.

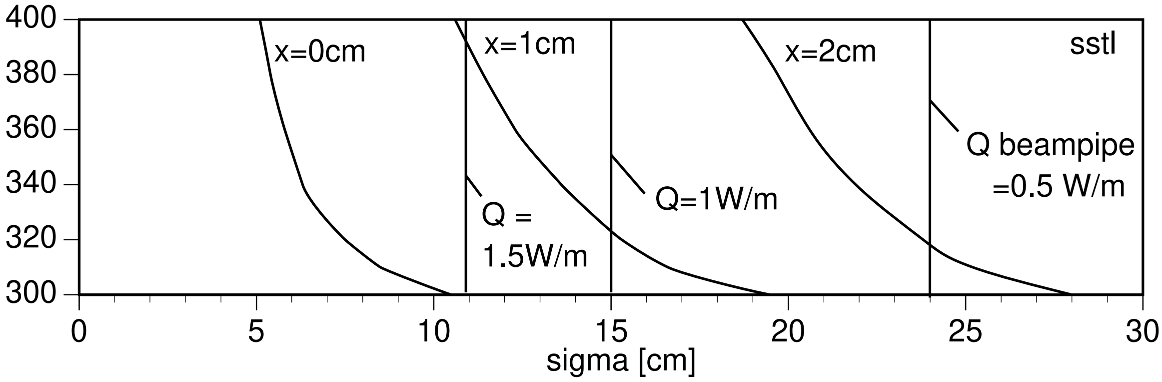

Figure 3. Temperature[K] vs Bunch Length for Bare Stainless Steel Cable

The maximum temperature in the cable with the bare stainless steel outer conductor as a function of bunch length is shown in Figure 3. All curves are for RHIC upgrade beam intensity. Curves are shown for beam offsets of 0, 1, and 2 cm. The maximum permissible operating temperature for the tefzel dielectric, bare stainless steel outer conductor cables is around 400 K. At higher temperatures deformation of the dielectric can result in variations in impedance and insertion loss, and the thermal expansion of the tefzel has the possibility to rupture the outer conductor. The vertical lines represent beampipe heating by the image current at the given bunch length.

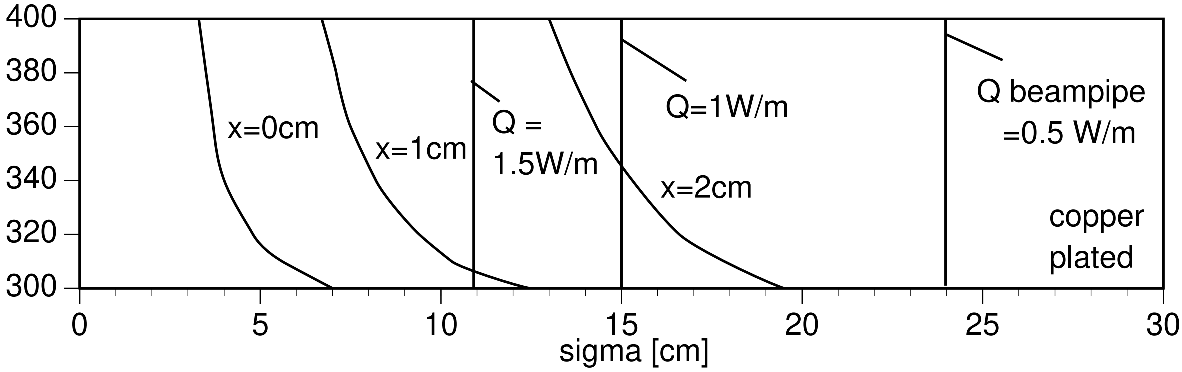

Figure 4. Temperature[K] vs Bunch Length for Copper Plated Cable

The maximum temperature in the cable with the copper plated outer conductor as a function of bunch length is shown in Figure 4. All other conditions are as in Figure 3. The maximum operating temperature for the silicon dioxide dielectric cables (the manufacturer who offers this dielectric is the only one who offers the copper plated outer conductor) is much higher, around 700 K. For purposes of comparison all of the calculations in this paper will assume a maximum operating temperature of 400 K for the copper plated cable, although higher temperatures are tolerable.

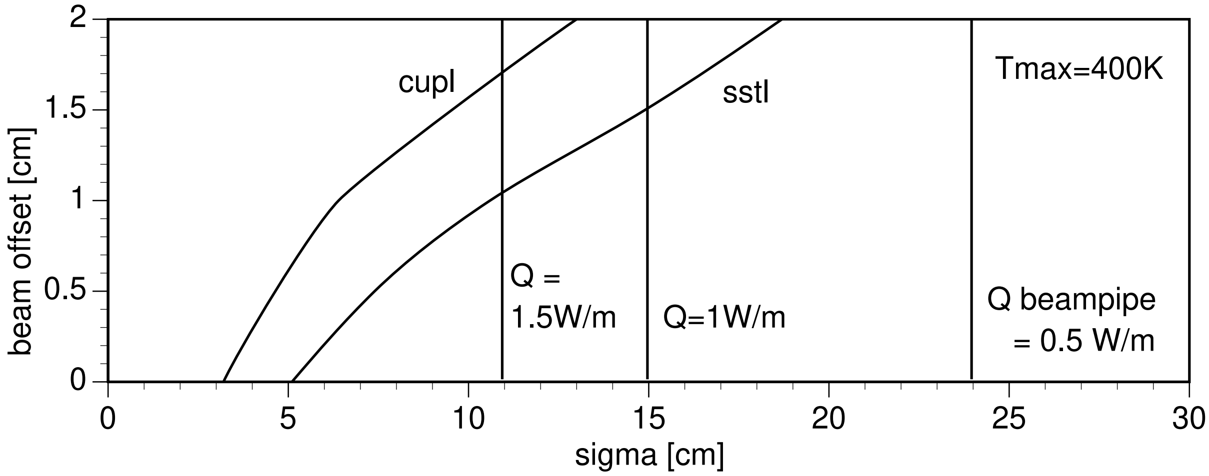

Figure 5. Operating Curves Based on 400 K Maximum Temperature

Figure 5 plots the combinations of bunch length and beam offset which result in a 400 K operating temperature. Operation in the region to the left of the 'operating curve' for the tefzel dielectric cable (stainless steel outer conductor) should be considered forbidden by the possibility of damaging the BPM signal cables. Again, the vertical lines represent beampipe heating by the image current at the given bunch length.

The Magnet Quench Limit

There is some sense in which magnet quench can be considered a non-destructive fuse for the BPM signal cables. The desired condition is that the resistive heating of the beampipe by the beam image current in RHIC causes the magnets to quench before the signal cables get hot enough to be damaged. Quench temperature[10] at the design operating field of 3.45 T is about 6 K. Steady state operation of the cryogenic system with circulating stream temperatures approaching 6 K has not been investigated in detail. A brief discussion of that operating condition is presented in the Appendix.

The conclusion drawn there is that operation at 1 W/m of beampipe heating is probably possible with the present cryogenic design, although local helium temperatures will slightly exceed the 4.8 K maximum stipulated in the design manual. Given a favorable outcome of efforts to tweak the refrigerator and recooler performance, it is conceivable that RHIC could be operated with image current heating approaching 1.5 W/m.

Transient Effects

The thermal time constant of the temperature rise in the magnet coil (resulting primarily from the heat capacity of the helium in the annular space between the beampipe and the coil) is about 60 times greater than that of the signal cables for the bare stainless steel cable and about 20 times greater for the copper plated cable. In other words, a beam instability whose high frequency content raises the magnet coil temperature one degree K (about the amount required to quench) will raise the bare stainless cable temperature 60 K. If the possibility of transient effects is taken into consideration it seems prudent to limit the maximum continuous operating temperature of the bare stainless signal cable to around 340 K.

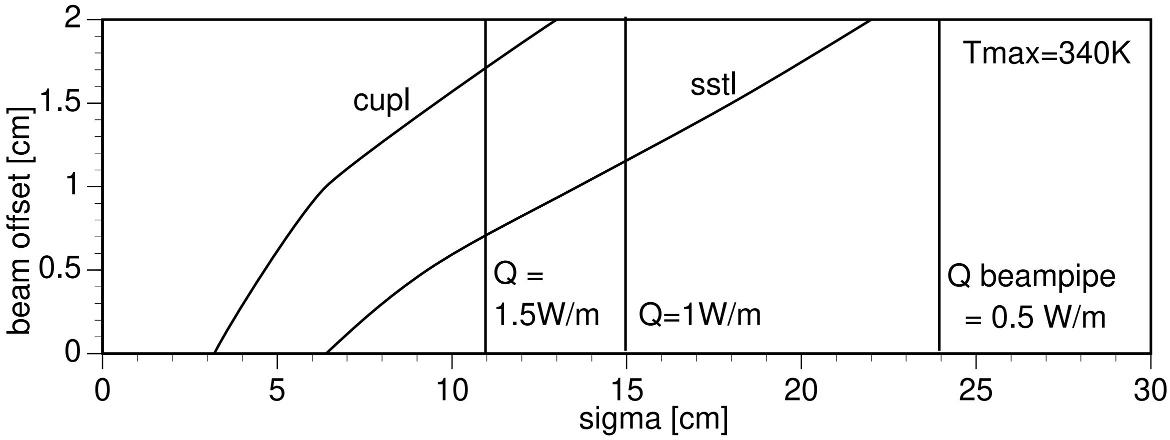

Figure 6. Operating Curves Based on 340 K Maximum Temperature

Figure 6 duplicates the plot of Figure 5 with this transient effect taken into consideration, plotting the combinations of bunch length and beam offset which result in this 340 K operating temperature for the bare stainless steel cable. The operating curve for the silicon dioxide dielectric, copper plated cable corresponds to a maximum temperature of 400 K, although higher temperatures are tolerable.

The vertical lines in Figure 6 represent beampipe heating by the image current at the given bunch length. At any operating point of the cryo system, there will be such a vertical line that represents the amount of beampipe heating that will cause a magnet to quench. When the operating curves lie to the left of the magnet quench line, the magnets will quench before the signal cables are damaged. Figure 6 indicates that in the presence of transients the bare stainless steel cable is subject to damage with beam offsets of slightly greater than 1 cm if the cryo system can hold off magnet quench at 1 W/m. If heat loads approaching 1.5 W/m eventually become acceptable, beam offsets of slightly more than 0.6 cm in the presence of transients could result in cable damage. It is more difficult to imagine operating conditions which would result in damage to the copper plated cables.

The Effect of More Bunches

It has recently been proposed[11] to change the frequency of the RF system to eliminate the previous limitation to 114 bunches in RHIC. With this design change it will be possible to operate RHIC with a large range of numbers of bunches, up to a maximum of 360. This change will reduce the amount of heating seen by the signal cables relative to the beampipe. For a given total heat load on the beampipe, as the number of bunches increase, the length of the bunches must also increase. For short bunches, the signal on the cable is a pulse of the length and shape of the bunch, followed shortly by a pulse of the opposite polarity. The second pulse is the reflection from the shorted end of the stripline. As the bunch length approaches the stripline length (the effective electrical length is about 23 cm) these two pulses start to destructively interfere. The result is that signal cable heating relative to beampipe heating is reduced for longer bunches, offering more protection to the cables by the magnet quench limit.

Measurement Results

Our confidence in the validity of our calculations is bolstered by three circumstances. First, the results calculated with the most recent version of the program are in reasonable agreement with earlier versions and with the original hand calculations. Second, when our program is slightly modified to calculate beam image current heating of the vacuum pipe, our results agree with independent calculations[5]. And finally, we are collaborating with LHC[3], where there is a similar problem, to cross check each other's results. Despite this, it seemed wise to go ahead and actually make some measurements to validate the calculations (an added benefit being the slightly less direct validation of the beampipe heating calculations).

A bare stainless steel, tefzel dielectric signal cable was installed in vacuum in a dewar. The cable was thermally anchored to liquid nitrogen pots at two points separated by a distance of 0.36 m. One end of the cable was driven by an RF source supplying 10 W at 300 MHz, and the other end was terminated in a 50 ohm load. The temperature was measured at the thermal anchors and midway between the anchors.

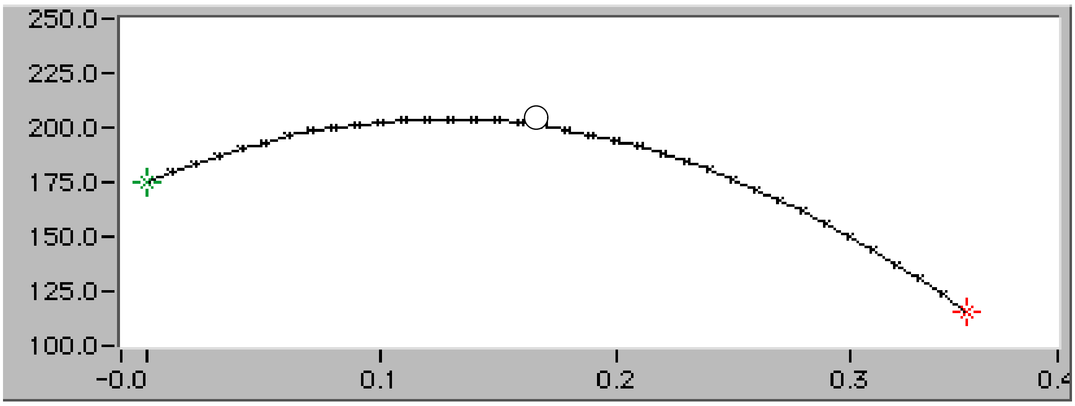

Figure 7. Temperature [K] Profile along the length [m] of the Signal Cable

The result of this measurement is shown, along with a curve which represents the temperature profile in the cable as calculated by the program. Input data to the program was the length between thermal anchors, the input power and frequency, and the measured temperatures at the thermal anchors. The measured temperature at the middle of the cable was 208 K, and is represented by the circle located 0.17 m from the end. The calculated temperature at this location is 204 K.

Conclusion

Under normal upgrade intensity operating conditions, with the beam centered between the BPM electrodes, the BPM signal cables cannot be damaged by resistive heating of the cables by the beam induced signal current. The magnets quench due to resistive heating of the beampipe by the beam image current before the cables are damaged. As the beam is moved off center the nearer electrode gathers more power from the beam, and the margin of protection provided by magnet quench is reduced. An extreme scenario, with the cryogenic system optimized to permit heat loads on the beampipe approaching 1.5 W/m, would require operation off-momentum, with beam offsets in excess of 1 cm, to damage the signal cables. When the effect of transients (greater high frequency content due to beam instabilities being one possibility) is taken into consideration, this offset is reduced to about 0.6 cm. It is possible to instrument a subset of the signal cables to provide a beam abort temperature interlock for this extreme scenario.

REFERENCES

1. P.R. Cameron, Specification for Cryogenic Signal Cables, Spec. No.: RHIC-CR-E-1811-0061. see also the appropriate sections of the RHIC Design Manual.
2. our efforts in this procurement process were paralleled and often preceded by Don Martin (private communication), who shared information regarding SSC BPM signal cable procurement.
3. J.P. Papis and L. Vos, LHC Project: BPM Short Cables, CERN SL/Tech Spec 92-16, 1992.
4. BPM signal cable heat leak to 55K and 4K was calculated by John Koehler and documented in two memos, dated 3/31/92 and 7/6/92.
5. This evolution parallels that of the RHIC beampipe, wherein the copper inner coating was eventually abandoned because of problems with cost and availability. See
   H. Hahn, RHIC Performance Limitations Due to Beam Heating of Vacuum Chamber, RHIC Tech Note 31, December, 1987, and
   A.G. Ruggerio and S. Peggs, Vacuum Pipe Heating in RHIC, RHIC/AP/46, November, 1994.
6. M.A. Harrison, High Luminosity p-p Operation at RHIC, RHIC/AP/8, August, 1993.
7. A.G. Ruggerio and S. Peggs, Vacuum Pipe Heating in RHIC, RHIC/AP/46, November, 1994.
8. P.R. Cameron, Thermal Anchoring of BPM Signal Cable, RHIC Beam Instrumentation Section Internal Report, September, 1994.
9. The program, and a description of its operation, are available at the RHIC Beam Instrumentation Section Web Site, http://iguana.rhic.bnl.gov/.
10. W. Sampson, private communication.
11. J.M. Brennan, private communication.
12. Thanks to M. Rehak and K.C. Wu for tutorials on the magnets and the cryogenic system.
13. K.C. Wu, Process Performance and Carnot Efficency for RHIC Refrigerator, AD/RHIC/RD-74, August 1994.

Appendix: High Beam Intensity and Magnet Quench

The purpose of the following discussion[12] is to develop an estimate of the maximum tolerable beampipe image current heating before magnet quench. The intent is to develop an estimate which results in a reasonably conservative BPM signal cable design. Such an estimate will necessarily explore non-conservative projections of the operating conditions of the magnets and cryogenic system. This discussion is not meant to assert that such conditions will be achieved, but merely to suggest that they are possible.

The 4 K heat load at the cryogenic system design operating point (no beam heating and including 20% contingency) is about 10.3 KW. The 4 K refrigerator capacity is about 24 KW. A possible operating condition would have 6.7 KW of the surplus cooling power applied to the 6700 m of cryogenic beampipe, absorbing a resistive heating of the beampipe of 1 W/m. At 100 g/s helium flow and 1 W/m beampipe heating the 90 m of cryogenic beampipe between recoolers would absorb 90 W of beampipe heat, and the enthalpy change would be 0.9 J/g. If this heat were absorbed at about 4.5 K, the helium temperature rise between recoolers due to beam heating would be about 0.23 K. In the recooler this 90 W of beampipe heat will require the vaporization of about 4.5 g/s of liquid, in addition to the 2.5 g/s required for the static heat load, for a total of about 7 g/s. In the high refrigeration case[13], the design recooler cooling stream mass flow rate is about 9 g/s.

Within each individual dipole the situation is complicated by the fact that the 100 g/s circulating flow is split between the flow path concentric to the beampipe and the parallel bypass holes through the magnet iron. Of the 100 g/s circulating flow, only about 3 g/s flows along the beampipe. At 3 g/s helium flow and 1 W/m beampipe heating the 10 m of cryogenic beampipe within the dipole would absorb 10 W, the enthalpy change would be 3.3 J/g and the helium temperature rise from one end of the beampipe to the other would be about 0.8 K if all 10 W were to fall on the flow path concentric to the beampipe. This temperature rise is reduced by transverse conduction of heat through the magnet iron to the bypass flow. This transverse conduction is enhanced by longitudinal conduction in the magnet coil and iron. The resulting temperature rise from one end of the beampipe to the other is about 0.5 K. Helium entering the annular space between the beampipe and the magnet iron at one end of the magnet at 4.5 K would exit the opposite end at about 5.0 K. Mixing of the two helium flows occurs in the magnet end volumes, so that the temperature of helium on the beampipe at the entrance to the dipole is always the bulk temperature of the 100 g/s flow at that location in the string.

The conclusion drawn here is that operation at 1 W/m of beampipe heating is probably possible with the present cryogenic design, although local helium temperatures will slightly exceed the 4.8 K maximum stipulated in the design manual. Given a favorable outcome of efforts to tweak the refrigerator and recooler performance, it is conceivable that RHIC could be operated with image current heating approaching 1.5 W/m.