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TEMPERATURE RISE IN THE SSC DIPOLE COILS UNDER SYNCHROTRON RADIATION HEATING
Preliminary analysis

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Abstract

We analize the heat transfer modes that determine the temperature rise of the SSC dipole coils under the nominal synchrotron radiation heat load of 0.142 W/m, namely: conduction across the dipole cross section, helium longitudinal convection in the annular passage between the beam tube and the coils, and helium transverse natural convection at lamination gaps.
It appears that the temperature rise is likely to exceed the desired value of 0.05 K. The main reasons are the high thermal resistance of the insulation (Kapton layers), the relatively small helium mass flow rate in the annular passage, and the apparently small effect of transverse natural convection (mixing) at lamination gaps. It is difficult to predict how much the temperature rise will be without experimental input, although values as high as 0.18 K could be expected according to our estimations.
It is important to emphasize that our conclusions are subject to experimental verification, particularly because the Kapton thermal conductivity at low temperature is not a well defined quantity, and because our analysis of the natural convection was based on crude models. This is a complex problem, and the most reliable way to predict which is going to be the temperature rise is by measuring a full-scale dipole with a heat source that simulates the synchrotron radiation heat load. The main purpose of this note is not to predict the temperature rise, but to show that it is likely to be higher than the desired value of 0.05 K and to help in the design of an experiment to measure it by showing critical areas and by presenting some sensitivity analysis.
We also explore the possibility of increasing the mass flow rate in the annular passage. It appears that solving the problem this way would require a significant (and expensive) increase in the annular passage gap (from 0.14 cm to about 0.65 cm). With such an increase, bore liners become feasible and should be considered because they are probably a better option to intercept the synchrotron heat.

Introduction

At 20 TeV, the 73 mA proton beam in the SSC emits approximately 0.142 W/m of synchrotron radiation[1]. Once this energy has been dumped as heat at the inner wall of the beam tube, it will flow through the beam tube and its associated wrapping to the helium in a 0.14 cm annular passage between the beam tube and the coils inner surface. In the present dipole design, the longitudinal helium convection in this passage is not enough to "shield" the coils from the heat , the helium in the annular passage reaches thermal equilibrium after a certain length and consequently all the synchrotron heat must flow to the bulk of the helium coolant which flows in four passages in the iron yoke. As a result, there is going to be a temperature rise of the dipole coils under synchrotron radiation heat load. This temperature rise depends on the effective thermal resistance between the coil and the yoke coolant channels. The thermal resistance depends not only on the thermal resistance of the different materials and interfaces, but also on convective heat transport by transverse helium natural convection within magnet passages (for example, in gaps between collar packs).

An early estimation of the temperature rise[1] predicted a value of 0.055 K . The first numerical calculation was made by General Dynamics (GD) using a lumped-parameter thermal model[2]. The result was 0.167 K, a value considerably larger than the earlier estimation. In both cases, transverse convective heat transfer was not taken into account. It has been pointed out before[3] that the origin of this difference lies in a factor of ten lower value for the Kapton thermal conductivity that is used in the GD model. It turns out that the Kapton thermal conductivity is not a very well defined quantity at low temperatures; it can vary by a factor of ten at temperatures below 10 K depending on the degree of crystallinity[4]. The lower value of the Kapton conductivity used in GD model seems to be in principle justified because of its consistency with measurements on Kapton film[5], but further investigation of this matter and perhaps measurements needs to be undertaken if we need a more accurate prediction of the temperature rise.

In an SSC note[6], M. McAshan and P. VanderArend observe that the large thermal resistance predicted by GD, if it were observed, would create significant problems in the temperature control of the superconductor for the system as a whole, it would increase capital and operating costs of the refrigeration, and it would be a very undesirable limitation to the flexibility to increase the heat loading in machine upgrade. They suggest to establish a design requirement to *limit the temperature rise to 0.05 K under the synchrotron radiation heat load, and they* propose as a first step simple modeling of the natural convection process to determine what is needed in a design in order to meet the requirement. The natural convection of the helium had been neglected in the previous predictions of temperature rise, and therefore it could be possible that when this additional heat transport process is considered the effective thermal resistance results low enough to satisfy the proposed design requirement without any profound effect on the basic collar designs or significant changes in costs.

GD recently delivered a report[7] in which for the first time a simple modeling of the natural convection process under the synchrotron radiation heat load in the SSC dipoles is published. Their conclusion is that natural convection heat transport reduce the temperature rise from the previously estimated 0.167 K to 0.1 K; and that by increasing the gap between collars packs to ~ 1/8" or by doubling the amount of the already existent 1/16" gaps it will be possible to reduce the temperature rise to within 0.05K. In our opinion, the GD model of the natural convection effect on the temperature rise is not appropriate, and their conclusions may be too optimistic and should be taken with care. The reasons for our disagreement and for our more pessimistic position about natural convection effects in the SSC dipoles can be found in this note.

In this note, we analyze the heat transfer mechanisms that determine the temperature rise in the SSC dipoles under synchrotron radiation heat load: conduction across the dipole cross section, longitudinal convection in the annular passage, and transverse natural convection between lamination gaps. We found the prediction of the temperature rise to be a very complex problem, much more difficult than previously estimated. However, all indications so far are that with the present dipole design the temperature rise will most likely exceed the desired value of 0.05 K under synchrotron radiation heat load, and that some aspects of the SSC dipole design will have to be reconsidered if we want to keep the temperature rise below 0.05 K. Experimental input is needed at this point in order to have a more accurate prediction, and hopefully this note might provide some points of discussion for planning an experiment.

Synchrotron radiation heat flux distribution

J.D. Jackson already calculated the synchrotron radiation heat flux distribution into the helium in the annular passage for a 2 mil copper plating and RRR (Residual Resistivity Ratio) ~ 50 on the inner surface of the beam tube[8]. Here we use his analytical solution to investigate the effects of copper plating thickness and conductivity on the heat flux distribution. We found that Jackson's assumptions that the curvature can be neglected and the problem analyzed locally in terms of flat slabs of copper, steel, and wrapping[8] is not appropriate for large copper conductivities and/or large copper plating thickness. However, the solution in this case case can be found with little error by superposition of n "slab" solutions with heat inputs at $\pm n2\pi r$, where n = 0, 1, 2, ...; and r is the beam tube radius (1.63 cm). Jackson's assumptions are reasonable for the values he used, which were design values.

The present copper plating thickness specification is 3 ± 1 mil, and the RRR specification without magnetic field is 200 < RRR < 1000[9]. With magnetic field, the RRR decreases. According to measurements, the data fit the following formula for thin copper layers (~ 4 mil)[9]:

$$\mathrm{RRR(B)} = \frac{0.0014\mathrm{B} + 1}{0.0014\mathrm{B} + \frac{1}{\mathrm{RRR(0)}}} \quad (\mathrm{B\ in\ T}) \tag{1}$$

The factor 0.0014 is new data, yet to be confirmed (by comparison, for bulk copper the factor is 0.0032). From (1), at 6.6 T the RRR limits are 70 < RRR (6.6T) < 100. For this analysis, the direction of the magnetic field was not taken into account. This could change the results for RRR in the beam tube copper plating under a magnetic field, and introduce an angular dependence. This matter needs further investigation.

There is a relationship in the thermal conductivity of copper and its RRR at low temperatures. For example,

$$k\,(4\ \mathrm{K}, \mathrm{RRR}=50) \quad \sim 3\ \mathrm{W/cm\text{-}K}$$
$$k\,(4\ \mathrm{K}, \mathrm{RRR}=1000) \sim 60\ \mathrm{W/cm\text{-}K}$$

The following figure is a summary plot of the results obtained for different copper RRRs and thickness. In all cases, the 0.14 2W/m heat input[1] is deposited in a very narrow stripe (1 mm) on the "away from center" side of the inner surface of the beam tube. Fig. 1 shows the "output" heat flux distribution into the helium in the annular passage. For details, see ref. 8.

We see that the expected curve from design parameters has a significant angular dependence, and that we cannot assume that the heat flux into the helium has a uniform angular distribution. Increasing the copper plating thickness to 4 mil doesn't help much either. It is for an RRR of about 1000 that it is possible to assume an (almost) uniform angular distribution, but an RRR of 1000 corresponds to a high-purity copper without magnetic field present. However, the heat flux distribution shown in Fig. 1 it is not necessarily equal to the heat flux distribution that goes into the coils because the helium in the annular passage could convect circumferentially, and this heat transport by helium convection would change the heat flux distribution that goes into the coils, making it more uniform (we assume that helium in the annular passage is in thermal equilibrium). At the present moment is difficult to estimate this effect, and therefore, as a worst case, we will take the heat flux distribution into the helium in the annular passage as equal to the heat flux distribution into the coils.

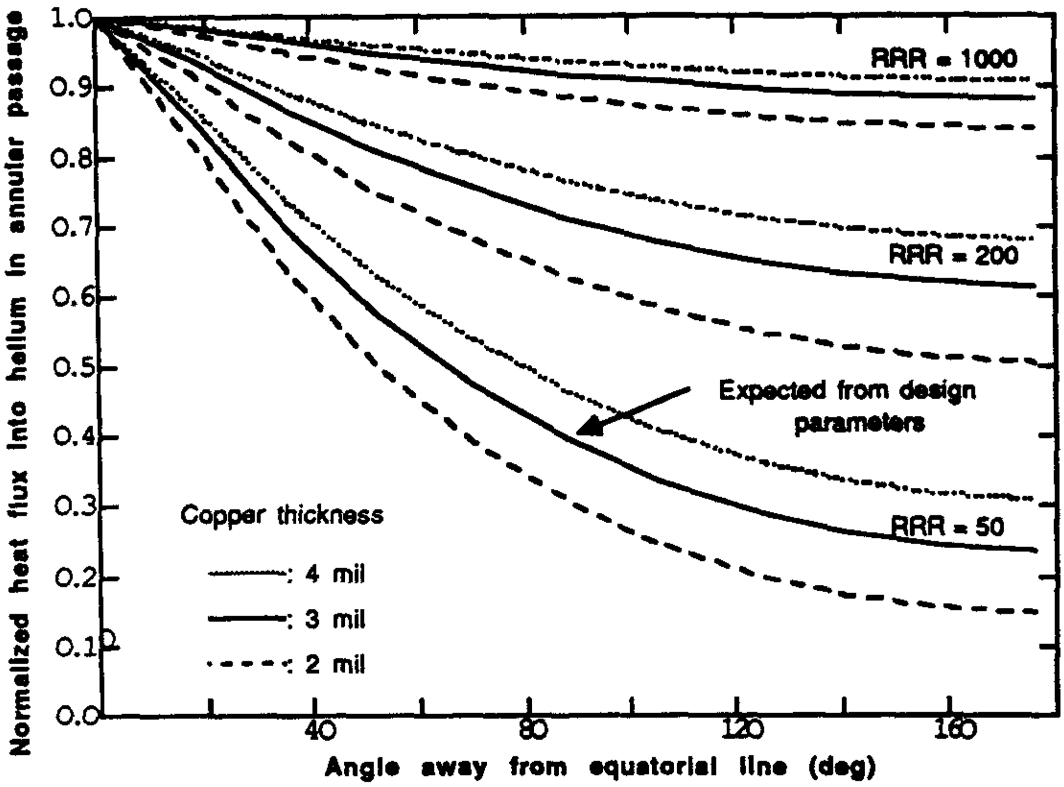


Fig. 1: Normalized synchrotron radiation heat flux angular distribution into the helium in the annular passage as a function of copper plating thickness and residual resistivity ratio (RRR).

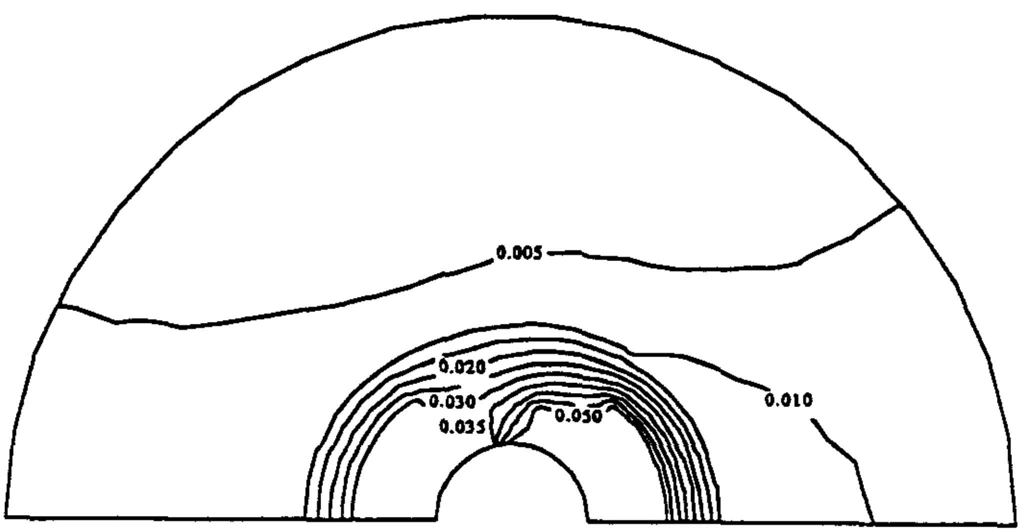
Conduction across the dipole cross section

In this section we present a simplified finite element calculation of the temperature rise distribution in the dipole cross section due to conduction of synchrotron radiation heat. We have ignored convective heat transport in this analysis, and therefore <u>results should be interpreted with caution</u>. We will consider convective heat transport in the next sections.

The purpose of this calculation is to verify the GD temperature rise result[2] of 0.167 K, to find out how uniform is this temperature rise within the coil, and to define a "solid" effective thermal conductance between the beam tube annular passage and the yoke coolant channels. We will then use this effective thermal conductance to estimate the effect on the temperature rise of the longitudinal helium convection in the annular passage (next section).

The heat flux distribution into the coils used in the model was calculated in the previous section and corresponds to a copper plating thickness of 3 mil and an RRR of 50 (see Fig. 1). The total heat input is 0.0014 2W/cm[1].

We used the program MacPoisson[10] to find the temperature rise distribution in the yoke, collar, and coils. MacPoisson cannot model contact thermal resistances, so in order to include the very important effect of Kapton layers we solved first the problem without Kapton layers, and then we estimated the Kapton layers effect by adding to the MacPoisson results the temperature rise across an equivalent layer of Kapton. The thickness of this equivalent layer is the sum of all the layer's thickness. Fig. 2 shows MacPoisson's result and input properties.



Yoke conductivity (Iron) = 0.0249 W/cm-K
Collars conductivity (304 S.S.) = 0.00259 W/cm-K
Coils conductivity (Avg. Cu, NbTi) = 2 W/cm-K

Kapton, Teflon, glue, and contact thermal resistances not included.

WARNING: this result should be interpreted as a lower limit. It has been shown that Kapton layers could add a significant thermal resistance.

Fig. 2: Temperature rise under synchrotron radiation heat load (due to solid conduction alone)

In summary, we have:

$$\Delta T^{\text{no kapton}}_{\text{coil away from center}} \sim 0.05\text{ K} \qquad \Delta T^{\text{no kapton}}_{\text{coil closer to center}} \sim 0.035\text{ K}$$

Although the input heat flux has an angular dependence, the temperature rise in each coil is almost uniform. The reason is the high effective thermal conductivity of the coil with respect to the collar. If Kapton layers were present in the model, the temperature rise within the coils would also be almost uniform for the same reason.

The temperature rise across the equivalent Kapton layer can be estimated from:

$$\Delta T_{\text{kapton}} \sim \frac{q''\Delta l}{K} \tag{2}$$

where: q'': normal heat per unit area at the "away from center" coil/collar interface. From program output ~ 0.0777 mW/cm^2

Δl: equivalent Kapton layer's thickness ~ 0.033 in = 0.084 cm

K: Kapton thermal conductivity[5] ~ 0.05 mW/cm-K

Replacing in (2):

$$\Delta T_{\text{kapton}} \sim 0.13\text{ K.}$$

Adding the temperature rise across Kapton layers to the temperature rise obtained without Kapton in the "away from center" coil, the total temperature rise results:

$$\Delta T^{\text{total}}_{\text{coil away from center}} \sim 0.18\text{ K}$$

This result is close to the GD result[2] of 0.167 K . Our higher temperature rise results from considering a non-uniform heat flux angular distribution.

The validity of the material properties used in our model have been discussed before[3], and in principle they seem reasonable with the thermal conductivity of Kapton being the main uncertainty for the reasons already mentioned in the introduction. Since Kapton has a dominant thermal resistance in the dipole cross section, it follows that further investigation of its conductivity and most likely measurements needs to be undertaken for a more accurate prediction of the temperature rise. We used a Kapton thermal conductivity value of 0.05 mW/cm-K obtained by Raudebaugh et. al.[5] in measurements made on Kapton brand film (type unspecified) of 5 mil thickness and previously heated to 423 K. This is the same value used by GD in their model[2].

Note that for this estimation of the temperature rise we haven't considered the following: the effect of helium circumferential convection in the annular gap on the angular heat flux distribution; the effect of contact thermal resistances; and the effect of heat transport by longitudinal and transverse helium convection. Therefore, our result of a temperature rise of 0.18 K shouldn't be interpreted as a prediction of the actual temperature rise that will happen under synchrotron radiation, but as a quantity that allow us to define an approximate "solid" effective thermal conductance between the annular gap and the yoke channels. We define this conductance U' as:

$$U' = \frac{q'}{\Delta T} = \frac{0.00142 \, W/cm}{0.18 \, K} \sim 0.008 \, W/cm\text{-}K \qquad (3)$$

The effective thermal conductance is defined with respect to the maximum temperature rise (the temperature rise of the away from center coil).
In the next sections we use this solid thermal conductance to estimate helium convection effects on the temperature rise.

Longitudinal helium convection in the annular passage

According to previous estimates[1-2], there is about 1 g/s of helium flowing in the 0.14 cm beam tube annular passage, between the beam tube and the inner coil surface. An energy balance of the helium flowing in this channel gives:

$$m' C_p \frac{dT}{dX} = q' - U'(T - T_0) \tag{4}$$

where: m' = mass flow rate ~ 1g/s
C_p = helium specific heat = 3.803 J/g-K at 4 atm and 4.35 K
T = local helium temperature in the annular space
T_0 = helium temperature in the yoke channels (taken as constant)
q' = synchrotron radiation heat rate per unit length = 0.00142 W/cm
U' = effective thermal conductance per unit length between the annular space and the yoke channels ~ 0.008 W/cm-K (see previous section)
X = coordinate along the axis

For constant coefficients and an entrance temperature $T(X=0) = T_0$, the solution of (4) is:

$$T(X) - T_0 = \frac{q'}{U'}[1 - \exp(-\frac{U'X}{m'C_p})] \tag{5}$$

From (5), we see that at a characteristic length $L = m'C_p/U'$ ~ 475 cm the helium (and coil) temperature rise reaches 63.2% of the maximum temperature rise q'/U' ~ 0.18 K.

Therefore, the longitudinal convection in the annular space is not enough to shield the coils from the synchrotron radiation heat load along all the dipole length (1,600 cm); after a certain length the helium reaches thermal equilibrium and this heat has to be carried to the yoke coolant channels, creating a temperature rise q'/U' in the coils (the possibility of transverse natural convection is considered in the next section).

We now explore the possibility of increasing the mass flow rate m' in the annular passage. From (5), the mass flow rate needed in the annular passage in order to satisfy the proposed requirement of a maximum temperature rise[6] of 0.05 K is given by:

$$m' = \frac{-U'Dl}{C_p \ln(1 - \frac{0.05}{q'/U'})} \tag{6}$$

where Dl is the dipole length. If we accept the predicted value for U', then replacing in (6);

$$m' \sim 10 \text{ g/s}$$

Therefore, the mass flow rate in the annular gap needs to be increased by an order of magnitude from its present estimated value of 1 g/s.

In order to increase this mass flow rate, it is necessary to increase the annular passage gap. Assuming that the pressure drop along the dipole remains the same, then, from pressure drop relations[11]:

$$\frac{f_1}{D_{h1}}\frac{m_1'^2}{A_1^2} = \frac{f_2}{D_{h2}}\frac{m_2'^2}{A_2^2} \tag{7}$$

where: f = friction factor
D_h = hydraulic diameter = 4A/P
P = wetted perimeter = $2\pi\,(2r_i + G)$
A = flow area = $\pi\,G(2r_i + G)$
G = annular passage gap
r_i = annular passage inner radius ~ 2 cm

In general, the friction factor depends on the Reynolds number to some power, depending on whether the flow is laminar, transitional or turbulent and depending on the roughness of the walls. In the annular passage, the flow is turbulent, the walls are very rough, and in addition there are obstacles such as the G-10 bumpers. Therefore, we expect the friction factor to depend very weakly on the Reynolds number. In other words, we can neglect the f dependence with mass flow rate in the annular passage and write:

$$f_1 \sim f_2 \tag{8}$$

Writing (7) in terms of annular passage inner radius and gap and using (8), we have:

$$\frac{m_1'^2}{G_1^3(2r_i + G_1)^2} \sim \frac{m_2'^2}{G_2^3(2r_i + G_2)^2} \tag{9}$$

If $G \ll 2r_i$, then $(2r_i + G_1) \sim (2r_i + G_2)$, and we have now from (9):

$$\frac{G_2}{G_1} \sim \left(\frac{m'_2}{m'_1}\right)^{2/3} \tag{10}$$

Therefore, if we want to increase the mass flow rate one order of magnitude, we will have to increase the gap size 4.64 times according to (10). In consequence, in order to have a mass flow rate of 10 g/s in the annular space we need to have a gap of about 4.64x0.14 = 0.65 cm.

It is interesting to note that if the flow were laminar, and the walls were smooth, the gap size would have to increase just $10^{1/3} \sim 2.15$ times due to the decrease of the friction factor with mass flow rate increase ($f = 64/Re$ in this case).

In summary, with an annular passage gap of 0.65 cm, the longitudinal helium convection in the beam tube region appears to be enough to limit the maximum coil temperature rise to 0.05 K under a synchrotron radiation heat load of 0.0014 2W/cm and an effective thermal conductance between the annular gap and the yoke channels of 0.008 W/cm-K.

It is not the purpose of this note to suggest a change in the dipole cross section design to accommodate a larger annular passage between the beam tube and the coil. We realize that this is an important and expensive change (particularly due to the required increase in gap size), and that many factors should be taken into account for such a decision. Moreover, the predicted ~~high~~ effective thermal conductance between the annular gap and the yoke channels have not been experimentally confirmed yet, and the contribution of natural convection heat transport has not been in our opinion realistically estimated so far. In addition, the mass flow rate in the annular passage of 1 g/s with the present design hasn't been experimentally confirmed. In addition, with an annular passage gap of about half a centimeter other probably better options to intercept the synchrotron heat become feasible. One example is bore liners[14], in which for instance the synchrotron radiation heat is carried away by helium gas at 20 K flowing in a small passage (line) attached to the bore tube. There are vacuum and structural problems associated with bore liners, but is an important option to consider if there is a decision to increase the annular gap because it can result in lower operating costs of the machine and in an important margin for overload and machine upgrade[14].

Transverse helium natural convection

There is an additional heat transport path to consider, and that is by helium natural convection between lamination gaps. Liquid helium has a relatively large specific heat (C_p ~ 3.8 J/g-K), a relatively large coefficient of thermal expansion (β ~ 0.11 K^{-1}), a relatively low viscosity (μ ~ 0.0038 cp)*, and therefore heat transport by buoyant effects could be present even with small temperature differences. Therefore, we should consider the possibility of heat transport by helium natural convection under synchrotron radiation heat load.

The most likely path for this mode of heat transport is in gaps between collars packs. For this analysis, we consider 6" long collar packs separated by a 1/16" gap. This gap is filled with liquid helium. The helium in the gap is in contact with the helium flowing in the beam tube annular passage through a relatively small top and bottom open spaces (apertures) between the inner coils. At every gap we can imagine a process by which part of the warm helium in the annular passage, heated while flowing along the collar pack, exits through the top aperture due to buoyancy effects; and cold helium from the bottom of the gap enters the annular passage through the bottom aperture. This mixing at gap locations reduces the temperature of the helium flowing in the annular passage , and if the temperature reduction is large enough it is possible to imagine an equilibrium state in which the combined effect of longitudinal helium convection along the collar pack and of transverse natural convection (mixing) at gaps between collars packs maintain the maximum temperature rise below 0.05 K, even for the low solid thermal conductance estimated previously. Warm helium from the gap could cooldown while flowing through small passages at the collars/yoke interface, and mixing could be possible at gaps between yoke laminations. Thus, part of the synchrotron radiation heat could be transported and dumped near the collars/yoke interface without flowing through the coils.

This rather complicated scenario is the one that needs to be analyzed to determine wether natural convection at lamination gaps will help in reducing the temperature rise under synchrotron radiation heat load or not.

From (4), the equilibrium temperature drop at gaps of the helium flowing in the annular passage required to maintain a temperature rise below 0.05 K is:

$$\Delta T_{gaps} = (0.05 - \frac{q'}{U'}) \left(1 - \exp(\frac{U'L}{m'C_p})\right) \qquad (11)$$

L is the collar packs length (15.24 cm). Fig. 3 shows ΔT_{gaps} as a function of m' for the predicted thermal conductance of 0.008 W/cm-K. A lower helium mass flow rate means faster heating in collar packs, and therefore the temperature drop at the gaps required to maintain a temperature rise below 0.05 K increases with decreasing mass flow rate. For the expected mass flow rate of the present design, m' ~ 1 g/s, the required temperature drop at gaps is ~ 5 mK.

Fig. 4 shows the helium temperature rise in the annular passage as a function of distance along the dipole for two cases: no temperature drop at gaps, and a temperature drop at gaps at equilibrium of 5 mK. We see that a temperature drop of 5 mK at the gaps makes a significant difference in the maximum temperature rise.

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* For comparison, water at 20 C has C_p ~ 4.18 J/g-K, β ~ 0.0002 K^{-1} , and μ ~ 1 cp.

Eqn. (11) and Figs. 3 and 4 are requirements, not predictions of natural convection effects. Now we are going to see if we can expect the natural convection effects to meet the requirements, mainly by analyzing which are the possibilities of transverse flow (mixing) at the gaps.

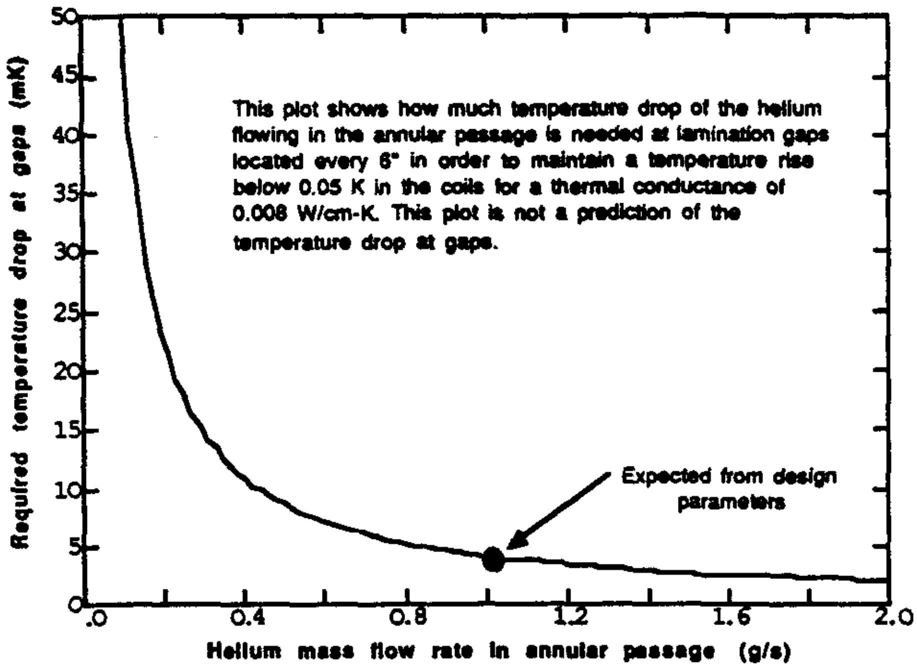

Fig. 3: Required temperature drop at gaps in order to maintain a temperature rise below 0.05 K as a function of helium mass flow rate in the annular passage

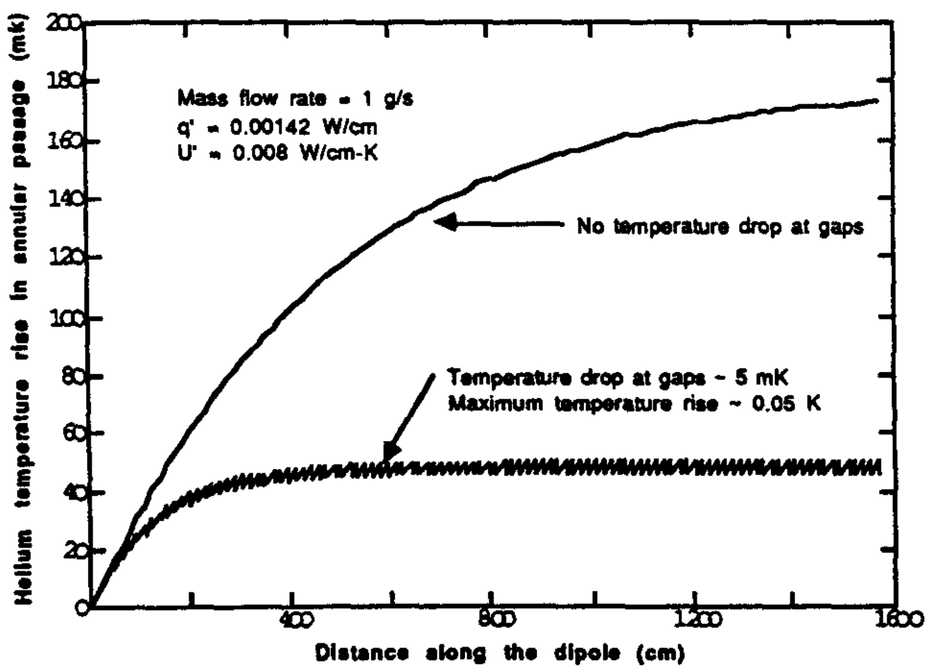

Fig. 4: Helium temperature rise in the annular passage as a function of the distance along the dipole for two cases: no temperature drop at gaps, and 5 mK of temperature drop at gaps

A starting point for the analysis is to estimate which forces are dominant in the helium flowing through the annular passage while crossing a gap between collars packs. There are two competing forces: a longitudinal inertia force (or "impact" force) due to the fact that the helium is flowing with a certain velocity and therefore carrying momentum, and a vertical buoyant force due to the fact that the helium flowing in the annular space, being warmer than the helium in the gap, has a lower density. If, for example, inertia forces result much larger than buoyant forces, then we can expect almost no mixing at collars gaps (no transverse flow), and we can anticipate a very limited contribution of natural convection heat transport in reducing the temperature rise under synchrotron radiation. Thus:

$$\text{Inertia force: } F_i = A\left(\frac{1}{2}\rho v^2\right)$$
$$\text{Buoyant force: } F_b = (AL_g\rho)g\beta\Delta T \tag{11}$$

where: A: annular space cross section (long. flow area) ~ 1.594 cm^2
L_g: gap width ~ 0.16 cm
ρ: helium density = 0.1364 g/cm^3 at 4 atm, 4.35 K
v: helium longitudinal velocity $= \dfrac{m'}{\rho A} \sim 4.6$ cm/seg ($m' \sim 1$g/s)
g: acceleration of gravity = 980 cm^2/seg
β: coefficient of thermal expansion = 0.11 K^{-1} at 4 atm, 4.35 K
ΔT: temperature difference = 0.05 K

replacing in (11)

$$F_i \sim 2.3 \text{ dynas}$$
$$F_b \sim 0.19 \text{ dynas}$$

$$\frac{F_i}{F_b} \sim 12 \tag{12}$$

Thus, inertia forces are about one order of magnitude larger than buoyant forces and therefore inertia forces are expected to be dominant. However, the ratio (12) is not so large as to allow us to conclude that we have no mixing at the gaps, although we can expect a relatively small transverse flow compared to the longitudinal flow.

It is possible to argue that a global analysis such as the previous one is not valid to describe the local situation at the top aperture, where helium is expected to exit. For a local analysis, I will follow now the method of Humprey and To[12]. Humprey and To analyzed the case of free and mixed convection in a cavity with an imposed external flow. They conclude that when the ratio of inertia to buoyant forces at the vicinity of the aperture plane, characterized by Re^2/Gr (Re: Reynolds number, Gr: Grashoff number), is less than 0.4, the flow field is dominated by buoyant forces, and when this ratio is larger than 21, the flow field is determined by inertial forces and loses any tendency to be redirected by buoyancy forces. For a ratio between 0.4 and 21, inertia forces compete with buoyant forces and the flow field becomes complicated, but for $Re^2/Gr > 2$, the flow is dominated by inertial forces.

The Re and Gr numbers are defined as:

$$Re = \frac{vL_g}{\upsilon}$$
$$Gr = \frac{g\beta\Delta T L_g^3}{\upsilon^2} \tag{12}$$

where: L_g = characteristic length = gap width ~ 1/16" = 0.16 cm
v = characteristic velocity ~ 4.6 cm/s
ΔT = characteristic temperature difference = 0.05 K
$\upsilon = 0.278\times10^{-3}$ cm^2/s at 4 atm and 4.35 K

Replacing in (12);

$$Re \sim 2{,}650$$
$$Gr \sim 286{,}000$$

$$\frac{Re^2}{Gr} \sim 25 \tag{13}$$

Thus, following the Humprey and To criteria to determine which forces are dominant at the aperture plane, we arrived at the same conclusion than with the previous global analysis: inertia forces are expected to be dominant. For a ratio of 25, Humprey and To predict that the flow loses any tendency to be redirected by buoyant forces, and it presents all the characteristics typical of a shear-driven cavity flow. Fig. 5 shows a schematic of a typical shear-driven cavity flow[13]. We can think of the externally imposed flow as the helium flowing through the annular passage, and the cavity as the gap between collars packs. As illustrated in the figure, the flow regime can be divided into three zones: Zone 1-external boundary layer, Zone 2-mixing region or shear layer, and zone 3-rotating core. Zone 3 corresponds to a shear-driven cavity flow. In the case of relatively deep cavities, the flow structure can present additional (secondary) vortexes. In the mixing region there is a highly turbulent shear layer, and measurements show [13] that the temperature gradient is relatively very large across the shear zone, thus revealing it to be a transfer-rate controlling layer. In the rotating core, the temperature remains uniform, presenting little or no resistance through it. For deeper cavities, the temperature increases again for locations deeper than y/b ~ 1, thus indicating presence of slower-moving secondary vortexes.

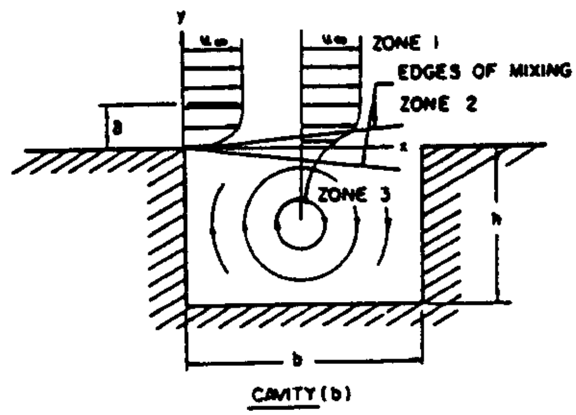

Fig. 5: Schematic of a shear-driven cavity flow as a result of an externally imposed flow

In summary, all indications so far are that the transverse flow is small (and perhaps negligible) compared to the longitudinal flow. Inertia forces of the helium flowing in the annular passage are dominant and seem to prevent the redirection of flow due to buoyant forces. If we reduce the mass flow rate to reduce inertia forces, then the required temperature drop (and therefore, the required transverse flow) at gaps increases because of faster heating in collar packs (see Fig. 3). However, our analysis is based on crude models. Better models would require considerable computational efforts, and the complex nature of the boundary conditions would be a serious limitation for a reliable result. In conclusion, we think that it is important to experimentally confirm the results obtained with our crude models.

Conclusions

The temperature rise under synchrotron radiation heating is difficult to predict. However, all the indications so far are that the temperature rise will most likely exceed the desired value of 0.05 K and could reach values as high as 0.18 K. The main reasons are the high thermal resistance of Kapton layers, and the relatively small helium mass flow rate in the annular passage between the beam tube and the coils. Transverse natural convection and mixing at lamination gaps doesn't appear to be of much help in reducing the temperature rise, mainly because longitudinal inertia forces of the helium flowing in the annular passage seems to be high enough to prevent the redirection of flow due to buoyant forces. This needs to be experimentally confirmed.

The most reliable way to predict which is going to be the temperature rise is by measuring a full-scale dipole with a heat source that simulates the synchrotron radiation heat load. With a carefully planned experiment, it should be possible to determine whether natural convection effects contribute to the heat transfer or not. Measurements of the kapton film thermal conductivity at low temperatures and under SSC-like crystallinity and mechanical conditions are also needed to properly analyze the experimental results, which should include longitudinal and transverse temperature rise measurements as a function of helium mass flow rate in the annular passage and as a function of heat load.

With the present design, and from the thermal point of view, the annular passage is useless because under synchrotron radiation the helium flowing in the passage reaches thermal equilibrium after a certain length and consequently all the synchrotron heat has to be transported to the yoke coolant channels with the resultant temperature rise in the coils. We could, for example, increase the passage gap to increase the helium mass flow rate; or we could use the annular passage to smooth the angular dependence of the synchrotron radiation heat flux. This could be done, for example, by forcing the helium to flow in an helicoidal way; and, as an additional benefit, the reduced helium velocity (due to the higher pressure drop in the annular passage) could increase the chances of natural convection transverse flow at the gaps.

We have explored the possibility of increasing the mass flow rate in the annular passage in order to "shield" the coils from the synchrotron radiation heat for a longer length. We found that the annular passage gap has to be increased from its present 0.14 cm to about 0.65 cm to allow a required helium flow of ~ 10 g/s to maintain the coils below 0.05 K. This result should be taken with care, because it is based on several estimations. However, it appears that solving the problem this way would require a significant (and expensive) change in the dipole cross section design. In addition, with an annular passage gap of about half a centimenter bore liners become feasible and should be considered because they are probably a better option to intercept the syncrotron heat.

At this point, experimental input is essential to continue with the analysis and prediction of the dipole temperature rise under synchrotron radiation heating. Based on the estimations made so far, it is likely that some aspects of the SSC dipole design will have to be reconsidered if we want to keep the coils' temperature rise below 0.05 K.

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