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SSC MAGNET COOLING, RECONSIDERED

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a refrigerator compressor pressure increase will increase coil cooling mass flow as well as total mass flow, but very inefficiently.)

One could operate the refrigerator at a lower temperature than is now planned and thus not decrease the stability of the warmest magnet in a given cell (but note that c_p decreases with temperature). In that case the temperature along a dipole as well as along a cell varies more for increased heat loads, and one would have to examine first the effect on magnet field quality due to an accompanying greater variation of superconductor magnetization.

Finally, we wish to point out that the originally intended cooling scheme for the SSC magnets made use of "parallel" helium flow through the coil cooling passage. One orifice was to be placed at the helium inlet end of the upper bypass through the yoke, and another at the outlet of the lower one. Thus a pressure difference is developed between lower and upper bypasses. As still in use, the yoke and collars are assembled as 6″ sections, with a gap of 1/32 to 1/16″ between them. Therefore helium will actually pass upward. By blocking off alternating paths in gaps between yoke sections and between yoke and collars, a large number of parallel cooling paths for the coils can be created. For instance, one-half of the mass flow entering the bottom bypass could be forced upward past the coils. With the mass flow entering the top bypass amounting to about half of the entering bottom flow, it follows that one third of the total magnet mass flow is transferred from bottom to top bypasses, and thus past the coils. For a total flow of 100 g/sec, this would amount to a 33 g/sec coil cooling flow, compared to the present 1 g/sec.

With the just described method we calculated helium temperature increases of 0.01 to 0.03 K. These increases, as well as very small main coil temperature increases, were essentially independent of the Kapton heat conductivity. Trim coil temperature increases were about 0.02 K and do depend on Kapton heat conductivity. But the trim coils are designed with a fair margin.

Synchrotron radiation heat increases will still result in warmer helium, and warmer coils, as before, requiring increased total mass flow or more recoolers if deemed necessary.

This cooling method was eliminated when it was felt that heat diffusion from coils to bypasses would be adequate for the given parameters and operating conditions, and, indeed they still are, although somewhat marginally for $k_p = 6 \times 10^{-5}$ W/cmK, if verified. Certainly, the heat diffusion method results in somewhat simpler magnet assembly than the original method.

If desired, the original method could be "revived" by means of calculations making use of the latest required input data.

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Summary and Conclusions.

Previous calculations concerning SSC magnet cooling had shown that the present design would be very adequate under proposed operating conditions and for the predominant material parameters. For a heat load due to synchrotron radiation of 2 W per dipole, a maximum temperature increase along the trim coil of 0.09 K and along the inner main coil 0.06 K was found. Although the mass flow through the coil cooling passage was only 1 g/sec, heat diffusion radially between inner coil and bypasses was sufficient to obtain these small temperature increases. A question has been raised recently whether eventual upgrading of the beam intensity in the SSC could be accommodated. An increase by a factor of 5, leading to synchrotron radiation heat of 10 W, would result in temperature increases to 0.43 K for the trim coil and 0.29 K for the main coil which may not be acceptable.

Recently it has been reported that a measurement of the Kapton insulation heat conductivity at magnet operating temperature has resulted in a value that amounts to only about one-tenth of that of other insulators. In that case, for radiation heat of 2 W, acceptable temperature increases of 0.29 K are found for the trim coil and of 0.16 K for the main coil, respectively, but for 10 W one obtains 1.44 K and 0.76 K, respectively.

Various, perhaps simple, changes are considered in this Note to obtain the possibility for some later upgrading: one can try to minimize the amount of Kapton insulation, or replace the stainless steel collars with a better heat-conducting material, or omit them (?), or one can try to increase the mass flow in the coil cooling passage. To accomplish the latter, one might increase the helium pressure drop that the refrigerator can produce, which is inefficient ($M \sim \Delta p^{1/2}$) and expensive in operation. Or one might increase the radial width of the cooling passage by either increasing the diameter of the main coils and yoke (very expensive and time-consuming), or by reducing the size of beam tube and trim coil by, say, 0.1 to 0.15 radially (requires redesign of trim coil, field measuring equipment, and beam tube with copper plating).

Existence of the especially low Kapton heat conductivity should be verified as soon as possible. If indeed verified, the magnets most probably could still be cooled for a 2 W heat load due to synchrotron radiation, but not so if the heat load were increased substantially. Design changes would then be required. A compromise, making use of some of the above-mentioned steps (see Table 7) would then allow a radiation heat load of 5 W.

Of course, design changes could be avoided by decreasing the machine energy when beam intensity is to be increased. For a five-fold intensity increase, beam energy would then have to be 13 TeV instead of twenty in order to obtain the present 2 W heat load. This would most probably not be desirable.

Unless the total helium mass flow is increased, for a substantial increase of heat load, the temperature of the helium will rise considerably as it passes through eleven magnet cells, unless the capacity or number of the recoolers is increased. Adding recoolers may still be feasible at reasonable cost, but not after the machine is built. (As mentioned,

The previous calculations concerning SSC magnet cooling can be found in SSC Technical Note No. 26 (1985). In order to avoid difficulties with the vacuum in the beam tube, the possibility of removing heat due to synchrotron radiation by means of small projections into the tube, was considered there. Tests have shown that the projections will not be required, and thus, at 20 TeV operating energy, it is expected that heat amounting to 2 Watt per dipole will be deposited uniformly along the tube wall.

Because of the small gap between beam tube /trim coil assembly and main coil inner diameter, only about 1 g/sec of supercritical helium can pass through this coil cooling passage, with the end-to-end pressure difference that will be available. A total of 100 g/sec will pass through the magnets, most of it through bypasses through the magnet yokes. A mass flow of only 1 g/sec will not be capable of removing the synchrotron radiation heat without heating trim coil and main coil inadmissibly; temperatures along the dipoles would increase by 0.5 K in the helium, about 0.6 K in the trim coil, and 0.45 K in the main coil. These temperature increases are essentially inversely proportional to the mass flow.

For the present design, depending on dimensions and heat conductivities, heat is also removed by radial diffusion through various (thin) layers of electrical insulation, through stainless steel collars, possible layers of stagnant helium, and through the yoke to the mentioned bypasses where heat can be exchanged effectively to a large helium mass flow. Such a model was used in the mentioned Tech. Note, and it was found that the magnet coils can be cooled very adequately under anticipated operating conditions. More recently, it has appeared that one of the main insulating materials in the magnets may have, for plastics, an unusually low heat conductivity at magnet operating temperatures. A reduction by an order of magnitude is mentioned. One must therefore expect that less heat will diffuse radially, and the coils will remain warmer. This effect is to be calculated in this Note. We will find that the coil can still be cooled adequately, but probably somewhat marginally. If, in addition, the beam intensity, and therefore the synchrotron radiation heat, were increased substantially, any acceptable margin would soon be eliminated. Small gains could be made by minimizing the thickness of Kapton layers. It should also be pointed out that the stainless steel collars substantially reduce the amount of heat that can diffuse radially. (An increase of synchrotron radiation heat would, of course, require increased refrigeration capacity, possibly including increased pressure difference Δp for a given magnet design. Δp would be approximately proportional to the square of the mass flow.)

Some modifications were made in the equations used in the previous Tech. Note. We shall therefore restate them here, but without derivations. First, we give definitions and input data:

T_t: temperature along trim coil.

T_o: helium temperature along coil cooling passage.

T: temperature along main coils.

T_a: temperature along yoke (and along helium in bypasses because of excellent heat exchange).

$H_1 = 5.4 \times 10^{-5}$ Q (W/cm) = total heat reaching dipole per unit length.

resulting in

$$h_1 = (d/k_p + 1/h'_1)^{-1}$$

for turbulent flow heat exchange from trim coil assembly to helium and

$$h_{11} = (d_1/k_p + 1/h'_1)^{-1}$$

for exchange from helium to inner main coil. For stagnant helium:

$$h_1 = (d/k_p + r_h/k_h)^{-1}$$
$$h_{11} = (d_1/k_p + r_h/k_h)^{-1}$$

In this case it is not necessary to solve for m (eq. 4), but one can set m to an arbitrary very small value ($\neq 0$, so that the computer program will not diverge).

We will now have to solve the following set of differential equations:

$$\frac{du_t}{dz} = [-H'_2(z) + h_1 A_0(T_t - T_o)]/k_{tcu}a_{tcu} \tag{7}$$

$$\frac{dT_t}{dz} = u_t \tag{8}$$

$$\frac{du}{dz} = [-H_3 + h_{11}A_o(T - T_o) + s_c(T - T_a)]/k_{cu}a_{cu} \tag{9}$$

$$\frac{dT}{dz} = u \tag{10}$$

$$\frac{dT_a}{dt} = [H_1 - H_2 - H_3 + s_c(T - T_a)]/(M - m)c_p \tag{11}$$

A sixth first-order equation for T_0 can be added. However, this would make the computer program redundant. It is possible to integrate this equation, obtaining

$$T_0 = (k_{tcu}a_{tcu}u_t + k_{cu}a_{cu}u - Mc_p(T_a - T_{in}) + mc_pT_a + \int_o^z H(z)dz)/mc_p \tag{12}$$

$$H(z) = H'_2(z) + H_1 - H_2$$

$T_{in} = 4.4$ K is the average helium temperature at the entrance to a dipole.

Boundary conditions are

$$z = O: \quad T_a = T_{in}$$
$$u_t = u = O$$
$$z = \ell: \quad u_t = u = O$$

Equations 7 to 10 take into account heat diffusion along the copper in trim coil and main coils, which tends to level the temperature distributions, thus reducing maximum temperatures.

The necessary computer program was assembled and operated by K. Jellett. Results of calculations for some relevant cases follow in Tables I to VII. Our "standard parameters", as used for previous calculations, are

M $= 50 =$ probable total helium mass flow during field measuring procedure.

d_c $= 0.13$ cm $=$ radial gap between trim coil and inner coil assembly.

d $= 0.04$ cm $=$ insulation thickness in and around trim coil.

d_1 $= 0.02$ cm $=$ insulation thickness at inside of inner main coil.

c_p $= 4$ (J/gK) $=$ helium heat capacity at or near operating temperature.

μ $= 3.5 \times 10^{-5}$ (g/cm sec) $=$ helium viscosity.

ρ $= 0.136$ (g/cm^3) $=$ helium density.

c_p, μ, ρ, and k_h are here assumed to be constant, since large temperature deviations from operating temperature T_{in} are not allowed in any case. NBS temperature functions for these quantities could be incorporated into the computer program but would require considerably more computer time.

f_i $= f_c = 1.5 =$ wall roughness factors in coil passage and bypasses.

Next, determine coil passage mass flow m:

$$K_i = 10^{-6}[(0.0014 + 0.125/R_1^{0.32})f_i\ell/R_h + 1]/2\rho A^2 \tag{2}$$

$$k_c = 10^{-6}[(0.0014 + 0.125/R_2^{0.32})f_c\ell/r_h + 1]/2\rho a^2 \tag{3}$$

Solve for

$$m = MK_i^{1/2}/(k_c^{1/2} + K_i^{1/2}) \tag{4}$$

A $= \pi D^2$ (total for 4 bypass holes).

R_h $=$ D/4.

R_1 $= 4R_h(M - m)/\mu A$.

a $= A_o d_c$.

r_h $= d_c/2$.

R_2 $= 4r_h m/\mu a$. (this "Reynold's number" must be $>\sim 2000$, otherwise the flow becomes laminar, in which case m becomes so small that, for heat exchange, we can assume that the helium is practically stagnant, or, where possible, flows only slowly around the trim coil assembly since synchrotron radiation impinges on the "outer" side of the beam tube, and the heat is not really uniformly distributed around it by the copper plating inside the tube. Of course, eventual total blockage of the helium flow in the coil passage is also conceivable since it is rather narrow to begin with).

For the pressure drop across 17 cells, each containing 10 dipoles and 2 quadrupoles, we obtain

$$\Delta p = 187K_i(M - m)^2(atm) \tag{5}$$

Equations 2 and 3 also take into account the velocity heads at the magnet ends.

For heat exchange to helium in the coil passage we use

$$h_1' = 0.023k_h R_2^{0.8}(\frac{\mu c_p}{k_h})^{0.4}/4r_h(W/cm^2K) \tag{6}$$

Q = 33 (W) = total heat per cell (equivalent to about 11 dipoles), or 3 W per dipole. Q = 121 W if synchrotron radiation heat is 10 W, = 231 W for 20 W.

H_2 = wH_1 (W/cm) = average synchrotron radiation heat per unit length.

w:

Q	33	121	231
w	0.67	0.91	0.95

ℓ = 1680 (cm) = physical length of magnet.

H_3: heat that may be generated in coil (here set to $H_3 = 0$).

$H_2'(z)$: synchrotron radiation heat distribution along axis z. Here $H_2'(z) = H_2$ = const. (See mentioned Tech. Note if $\neq$ const.)

$$s_c = \left(\frac{d_p}{21.2k_p} + \frac{d_s}{28.3k_s} + \frac{d_h}{34.6k_h} + \frac{d_i}{36.7k_i} + 1\right)^{-1} \tag{1}$$

is the conductance for heat flow from inner main coil to bypasses, combining:

d_p = 0.13 cm = total of thicknesses of insulation in and around main coils (mostly Kapton). d_p might be reducible to 0.065 cm.

d_s = 1.8 = average radial thickness of stainless steel collars.

d_h = 0 or 0.05 = radial width of helium-filled gap between collars and yoke.

d_i = 10 (or 12) average heat flow path length in yoke.

k_p = 6 x 10^{-4} W/cm K = heat conductivity of Kapton at magnet operating temperature, or

$k_p \leq 6 \times 10^{-5}$, a very low value which has been reported recently.

k_s = 3 x 10^{-4} = heat conductivity of stainless steel in collars.

k_h = 2.2 x 10^{-4} = heat conductivity of helium under operating conditions.

k_i = 0.04 = heat conductivity of yoke iron.

The numerical factors in s_c are determined by the average heat flow cross sections. The fifth term, the number "one", is the (approximate) small contribution due to the heat exchange in the bypasses.

A_0 = 9.6 cm^2/cm = average heat exchange area in coil cooling passage per unit length.

a_{cu} = 9.3 cm^2 = copper cross section in coil.

a_{tcu} = 0.1 cm^2 = copper cross section in trim coil.

k_{cu} = 4 (W/cm K) = average heat conductivity of coil copper.

k_{tcu} = 2.5 = average heat conductivity of trim coil copper ($< k_{cu}$ because of exposure to higher magnetic field).

D = 2.9 = diameter of the four bypasses through yoke.

M = 100 (g/sec) = total helium mass flow per dipole during operation, or

Q (W)	w	d_p (cm)	d_s (cm)	d_h (cm)	d_i (cm)	d_c (cm)	k_p (W/cmK)	M (g/sec)	T_{in} (K)
33	0.67	0.13	1.8	0.05	10	0.13	6×10^{-4}	100	4.4

With every Table, deviations from these standards are given. Temperatures are given as differences from average dipole inlet temperature T_{in}; $\Delta T_{\nu max} = T_{\nu max} - T_{in}$. If S is the synchrotron radiation heat and additional heat load is ~1 W, then

$$Q = 11(S + 1)$$

Thus, for $S = 2$, $Q = 33$, etc.

Table 1: Standard parameters. Q, S varied. **Main Coil**

Q (W)	S (W)	m (g/sec)	Δp_{tot} (atm)	ΔT_{imax} (K)	ΔT_{omax} (K)	ΔT_{max} (K)	ΔT_{amax} (K)
33	2	0.92	0.135	0.089	0.073	0.061	0.007
121	10			0.433	0.353	0.294	0.024
231	20			0.862	0.701	0.583	0.046

Table 2: Kapton heat conductivity $k_p = 6 \times 10^{-5}$ W/cmK

Q (W)	S (W)	m (g/sec)	Δp_{tot} (atm)	ΔT_{imax} (K)	ΔT_{omax} (K)	ΔT_{max} (K)	ΔT_{amax} (K)
33	2	0.92	0.135	0.291	0.200	0.155	0.006
121	10			1.443	0.991	0.763	0.019
231	20			2.874	1.974	1.520	0.035

Table 3: $k_p = 6 \times 10^{-5}$, vary d_p and d_c.
(For $d_c = 0.065$ cm, helium in coil cooling passage is practically stagnant.)

d_p	d_c	Q	S	m	Δp_{tot}	ΔT_{imax}	ΔT_{omax}	ΔT_{max}	ΔT_{amax}
0.13	0.13	33	2	0.92	0.135	0.291	0.200	0.155	0.006
0.13	0.065			-	0.137	0.331	0.230	0.170	0.007
0.065	0.13			0.92	0.135	0.243	0.153	0.105	0.006
0.13	0.13	121	121	0.92	0.135	1.443	0.991	0.763	0.019
0.13	0.065			-	0.137	1.642	1.137	0.840	0.024
0.065	0.13			0.92	0.135	1.205	0.753	0.515	0.021

Table 4: $k_p = 6 \times 10^{-5}$, vary d_c. Main Coil

d_c	Q	S	m	Δp_{tot}	ΔT_{tmax}	ΔT_{omax}	ΔT_{max}	ΔT_{amax}
0.13	33	2	0.92	0.135	0.291	0.200	0.155	0.006
0.26			2.96	0.130	0.207	0.118	0.091	0.004
0.39			5.72	0.123	0.161	0.072	0.056	0.004
0.52			8.95	0.116	0.137	0.050	0.039	0.003
0.13	121	10	0.92	0.135	1.443	0.991	0.763	0.019
0.26			2.96	0.130	1.027	0.584	0.449	0.010
0.39			5.72	0.123	0.798	0.359	0.276	0.007
0.52			8.95	0.116	0.688	0.246	0.189	0.006

Table 5: $k_p = 6 \times 10^{-5}$, no collars: $d_s = 0$, $d_i = 12$, $d_h = 0$.

Q	S	m	Δp_{tot}	ΔT_{tmax}	ΔT_{omax}	ΔT_{max}	ΔT_{amax}
33	2	0.92	0.135	0.267	0.177	0.130	0.006
121	10			1.325	0.874	0.640	0.020
231	20			2.640	1.740	1.274	0.037

Table 6: M = 50 g/cm. Vary k_p. (Measuring procedure).

k_p	Q	S	m	Δp_{tot}	ΔT_{tmax}	ΔT_{omax}	ΔT_{max}	ΔT_{amax}
6×10^{-4}	121	10	0.441	0.038	0.522	0.411	0.321	0.052
	231	20			1.037	0.815	0.635	0.098
6×10^{-5}	121	10	0.441	0.038	1.606	1.123	0.850	0.045
	231	20			3.197	2.235	1.689	0.086

Table 7: A compromise, if $k_p = 6 \times 10^{-5}$.

d_p	d_h	d_c	d_s	M	Q	S	ΔT_{tmax}	ΔT_{omax}	ΔT_{max}	ΔT_{amax}
0.065	0	0.26	1.8	100	66	5	0.469	0.249	0.167	0.008
0.065	0	0.26	0	100	66	5	0.448	0.228	0.139	0.008

In Table 1, total heat load Q is varied. One sees that ΔT_{tmax} for the trim coil and ΔT_{max} for the inner main coil are approximately proportional to Q. For $Q = 33$ W ($S =$ 2W), temperature increases are fully acceptable, but for $Q = 121$ ($S = 10$ W) they are most likely not acceptable. It is reported that the trim coils are designed with a large margin, and for the main coil $\Delta T_{max} = 0.1$ to 0.15 K may be admissible. Therefore $S =$ 5 W would be possible.

In Table 2 the Kapton heat conductivity k_p is decreased by an order of magnitude. Now "normal" operation $Q = 33$ ($S = 2$ W) is still acceptable, but for $Q = 121$, ΔT_{max} = 0.76 K and $\Delta T_{tmax} = 1.44$ K !

It may be possible to reduce the amount of low conductivity Kapton. In Table 3, $k_p = 6 \times 10^{-5}$, and d_p is reduced from 0.13 cm to 0.065. This is shown in the 3rd row.

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Comparing with the first row, ΔT_{tmax} does not change very much, but ΔT_{max} has decreased substantially. In the second row only the cooling gap d_c has been reduced from 0.13 to 0.065, which increases the temperature differences since the helium now becomes almost stagnant. For increased heat load, $Q = 121$ ($S = 10$ W), the temperature differences remain unacceptably high, although the reduction of ΔT_{max} is substantial. Reduction of d_p, if feasible, might be combined with other measures.

If one could easily increase the gap d_c between trim and main coils, mass flow, and therefore heat exchange, could be increased. Table 4 gives results for $k_p = 6 \times 10^{-5}$. For $Q = 33$, an increase from $d = 0.13$ cm ($\sim 0.05''$) to $d_c = 0.52$ cm ($\sim 0.2''$) would give reductions of ΔT_{tmax} from 0.29 to 0.14 K and of ΔT_{max} from 0.16 to 0.04 K. For $Q = 121$ we obtain reductions to 0.68 and 0.19 K, respectively, which might be barely acceptable. Probably gap d_c would have to be increased to 0.65 cm or 0.78 ($5/16''$), unquestionably at great monetary expense.

In Table 5, the stainless steel collars have been eliminated ($d_s = 0$), whose heat conductivity is rather small. Then also the collar-to-yoke gap $d_h = 0$. For $k_p = 6 \times 10^{-5}$ one finds useful, but insufficient temperature reductions.

In presently available magnet measuring set-ups a mass flow M $\approx$ 50 g/sec only is available. Table 6 shows that this might still be barely adequate for $k_p = 6 \times 10^{-4}$ and $Q = 121$ ($S = 10$ W), but not for $k_p = 6 \times 10^{-5}$.

A possible compromise is considered in Table 7. Here we assume that insulation thickness d_p indeed can be reduced to 0.065 cm, that coil cooling gap d_c can be increased to 0.26 cm ($0.1''$) by (a) minimizing the trim coil insulation, (b) possibly decreasing the beam tube wall thickness by a small amount, and (c) by decreasing the beam tube radius by 0.1 cm or so. (Occasionally it was indicated that this may be allowable from the point of view of accelerator physics.) We have chosen $S = 5$ W, a factor of 2.5 in beam intensity, and obtain $\Delta T_{max} = 0.17$ K with collars, or $\Delta T_{max} = 0.14$ K without. $\Delta T_{tmax} \approx 0.45$ K.

Ultimately, for $k_p = 6 \times 10^{-5}$, a substantial increase in beam intensity may have to be accompanied by a reduction in beam energy E. Synchrotron radiation heat is proportional to BE^3 where $= B$ magnetic field. For a given accelerator diameter, B is approximately $\sim E$. Still, for $S = 10$ (factor of five increase in beam intensity), E would have to be reduced substantially, from 20 to 13 TeV.

If one wanted to consider eventual upgrading of the SSC to higher intensities (which certainly has been accomplished for accelerators built in the past), a new measurement of k_p would appear very necessary and urgent in order to verify its small value at operating temperature. This would most likely require very much less effort and funding than what would be required for R&D, and possibly construction cost, if changes from the present magnet design were decided upon without prior verification of the value of k_p. $S = 5$ W would be acceptable for $k_p = 6 \times 10^{-4}$.