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The Superconducting Super Collider

Calculation of Desired Vertical Ovality of SSC Collars

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If the collar material has a larger coefficient of thermal contraction than the yoke and the yoke is split on the horizontal mid-plane, it may be difficult to use the yoke to provide horizontal support to the collared coil. To be inserted easily into the yoke at room temperature the collared coil must be no larger in horizontal diameter than the yoke. When the magnet is cooled to liquid helium temperature the collars will contract more than the yoke and a gap may develop between the collars and the yoke at the horizontal mid-plane. If, however, the collared coil is oversize in the vertical direction, clamping it in the yoke will tend to make its horizontal diameter grow enough to contact the yoke. Thus it may be desirable to design the collars to generate a "vertical ovality."

In this note I discuss a method to calculate the desired ovality of the collared coil at room temperature and the (undeflected) collar shape needed to achieve this. I then calculate the skin stress required to push the collared coil into shape. In both calculations I show the range of values resulting from plausible variations in the calculation parameters and in the coil prestress.

The calculation is based on two requirements: 1) The horizontal radius of the collared coil must be less than or equal to the horizontal radius of the yoke at room temperature and 2) The vertical radius of the collared coil must be sufficiently larger than that of the yoke so that if the yoke mid-plane gap is closed, the horizontal radius of the collared coil is at least as large as that of the yoke. To calculate the required (undeflected) collar shape we start with the desired conditions at 4 K and work backwards. That is, we start with the collared coil, clamped in the yoke, having vertical and horizontal radii equal to the yoke. If the yoke were removed (still at 4 K), the collared coil would grow vertically and shrink horizontally. Condition (1) above requires that at 4 K, the horizontal radius of a free-standing collared coil must be smaller than the yoke by

enough that when warmed to room temperature the yoke and collar radii are equal. The horizontal radius of the collared coil changes due to the thermal expansion of the collar material and due to the change in coil prestress. Horizontal radius of the free-standing collared coil at 4 K must be :

$$\Delta\tilde{r}_h = \tilde{r}_h - \tilde{R}_h = r\ (\ \epsilon_c^c - \epsilon_c^y\ ) + \Delta\sigma\ (\ dr_h/d\sigma\ )$$

where

$\tilde{r}_h$	is the horizontal outer radius of the collared coil at 4 K,
$\tilde{R}_h$	is the horizontal inner radius of the yoke at 4 K,
r	is the nominal outer radius of the collars and inner radius of the yoke,
$\epsilon_c^{c(y)}$	is the fractional length change of the collar (yoke) material from 300 K to 4 K,
$\Delta\sigma$	is the preload change (for a free-standing collared coil) from 300 K to 4 K and
$dr_h/d\sigma$	is the rate of change of horizontal radius with preload.

(In all cases the preload σ refers to the average of inner and outer preloads.)

The vertical radius of the free-standing collared coil at 4 K will be larger than that of the yoke by an amount

$$\Delta\tilde{r}_v = \tilde{r}_v - \tilde{R}_v = \Delta\tilde{r}_h\ (dr_v/dr_h)$$

where

$\tilde{r}_v$	is the vertical outer radius of the collared coil
$\tilde{R}_v$	is the vertical inner radius of the yoke
dr_v/dr_h	is the change in collar vertical divided by horizontal radius for a vertically applied load.

We now imaging warming the free-standing collared coil to room temperature. The vertical and horizontal radii will change due to thermal expansion and to the preload change:

$$\Delta r_v' = \Delta\tilde{r}_v - r\ (\ \epsilon_c^c - \epsilon_c^y\ ) - \Delta\sigma\ (\ dr_v/d\sigma\ )$$

$$\Delta r'_h = \Delta \tilde{r}_h - r\ (\ \epsilon^c_c - \epsilon^y_c\ ) - \Delta\sigma\ (\ dr_h/d\sigma\ ) = 0$$

where

$\Delta r'_{v(h)} = r'_{v(h)} - R_{v(h)}$

and

$r'_{v(h)}$ is the vertical (horizontal) outer radius of the collared coil at 300 K and

$R_{v(h)}$ is the vertical (horizontal) inner radius of the yoke at 300 K.

The equation $\Delta r'_h = 0$ is an expression of condition (1).

If the coil is then removed from the collars, the horizontal and vertical radii of the undeflected collars are given by:

$$\Delta r_{v(h)} = r_{v(h)} - R_{v(h)} = \Delta r'_{v(h)} - \sigma\ (\ dr_{v(h)}/d\sigma\ )$$

where

$r_{v(h)}$ is the vertical (horizontal) outer radius of the undeflected collar and

σ is the room temperature coil preload (average of inner and outer coils.)

The parameters used in this calculation are the ratio of horizontal to vertical collar radius change for a vertically applied force (dr_h/dr_v), the rate of change of vertical and horizontal radii with change in coil preload ($dr_v/d\sigma$ and $dr_h/d\sigma$), the room temperature preload (σ) and the preload change with cooldown ($\Delta\sigma$). For simplicity the preload used is the average of the inner and outer preloads. dr_h/dr_v is taken from finite element calculations[1] in which the vertical force is applied by the yoke. $dr_v/d\sigma$ is taken from measurements of free-standing collared coils.[2] $dr_h/d\sigma$ and an alternate value for $dr_v/d\sigma$ can be obtained from finite element calculations[1] for free-standing collared coils. The room temperature preloads will vary from magnet to magnet so a range of values is used. The cooldown prestress loss is taken from data on magnets with free-standing Nitronic 40 collared coils. A discussion of the values used is in the Appendix.[3]

Table I summarizes the calculations of the desired undeflected collar radii Δr_v and Δr_h for several values of each of the parameters. The vertical radius of the collared coil $\Delta r'_v$ is also displayed; the horizontal radius $\Delta r'_v$ is not displayed because it is zero by definition. The first row represents "standard" conditions: the best values of the calculation parameters and a desirable average prestress. The next three cases vary the magnet prestress and cooldown prestress loss, parameters which will vary from magnet to magnet. The next three cases vary calculation parameters derived from finite element calculations. (See the discussion in the Appendix.[3]) In each case only one parameter is changed relative to the "standard" values and this entry is underlined. The last line contains the combination of "plausible" parameters that generates the largest Δr_v.

The desired vertical ovality of the collared coil varies between about 11 and 13 mils on the diameter. The horizontal radius of the undeflected collar is about 0.5 mils "oversize" while the undeflected vertical radius varies about ±2 mils relative to the yoke. The variation in desired vertical radius depends mostly on the variation in room temperature preload. To guarantee that the collared coil will fit into the yoke at room temperature (condition 1) we must choose the smallest value of Δr; to guarantee that the smallest collared coil will contact the yoke at the horizontal mid-plane at 4 K (condition 2) we must choose the largest value of Δr_v. Values of $\Delta r_h = 0$ and $\Delta r_v = 2$ or 3 mils are indicated.

To check the size of the possible mid-plane gap at 4 K that may result for the largest coils or the possible horizontal separation of the collars from the yoke for the smallest coils, we take several trial values of Δr_v and work "forwards." The coil is put inside the collars, cooled to 4 K and then inserted in the yoke and skin. The rate of change of vertical radius with skin tension $dr_v/d\sigma_s$, obtained from finite element calculations,[1] is approximately bi-linear with a larger slope before the collar contacts the yoke at the horizontal mid-plane. For $\Delta\tilde{r}_h \leq 0$ $dr_v/d\sigma_s = -0.16$ mils/kpsi; for $\Delta\tilde{r}_v \geq 0$ $dr_v d\sigma_s = -0.05$ mils/kpsi. Tables IIa, b and c tabulate the results for three trial collar sizes $\Delta r_v = 3$, 2 and 0 mils respectively for several values of the parameters. Displayed are the vertical radius at which the collars first contact the yoke horizontally (if they do), the gap at the horizontal mid-plane when $\Delta\tilde{r}_v = 0$, the value of $\Delta\tilde{r}_v$ for skin tension

σ_s = 45 kpsi (the expected value at 4 K), the skin tension required to bring the collars and yoke into horizontal contact and to close the mid-plane gap. The mid-plane gap between the two yoke halves at 4 K and zero excitation is twice $\Delta\tilde{r}_v$ at σ_s = 45 kpsi. As in Table I, the first row represents "standard" conditions, the next three vary the magnet parameters, the next five vary calculation parameters and the last two represent the "plausible" values that generate the largest and smallest collared coils. For Δr_v = 3 mils the collars and yoke make horizontal contact under all conditions while a mid-plane gap between 0 and 5 mils is expected. For Δr_v = 2 mils the yoke and collars still make horizontal contact unless all parameters are pushed simultaneously to the "small" limit. The largest mid-plane gap is about 3 mils. The case $\Delta r_v = 0$, $\Delta r_h = 0$ corresponds to the "line-to-line fit" collars assembled without inelastic deformations resulting from the insertion of tapered keys. In this case a radial gap of up to 2 mils exists at the horizontal mid-plane and the yoke mid-plane gap is always closed. The case Δr_v = 2 mils, $\Delta r_h = 0$ seems to offer the best compromise between allowing the collars and yoke to lose horizontal contact and allowing a non-zero mid-plane gap in the yoke.

References

1. J. Cortella, private communication.
2. J. Strait, "Notes on collared coil mechanics and sextupole moment," minutes of the MSIM 11-12 July, 1989.
3. The Appendix has not been written yet.

Table I

dr_h/dr_v	$dr_v/d\sigma$ (mils/kpsi)	$dr_h/d\sigma$ (mils/kpsi)	σ (kpsi)	$\Delta\sigma$ (kpsi)	$\Delta r'_v$ (mils)	Δr_h (mils)	Δr_v (mils)
-0.88	0.56	-0.05	10	-2.25	5.8	0.5	0.2
-0.88	0.56	-0.05	13	-2.25	5.8	0.7	-1.5
-0.88	0.56	-0.05	7	-2.25	5.8	0.4	1.9
-0.88	0.56	-0.05	10	-3.25	6.3	0.5	0.7
-0.88	0.44	-0.05	10	-2.25	5.5	0.5	1.1
-0.88	0.56	0.00	10	-2.25	5.9	0.0	0.3
-0.72	0.56	-0.05	10	-2.25	6.3	0.5	0.7
-0.88	0.44	0.00	7	-3.25	6.5	0.0	2.6

Table IIa

$\Delta r_v = 3.0$ mils
$\Delta r_h = 0.0$ mils

dr_h/dr_v	$dr_v/d\sigma$ (mils/kpsi)	$dr_h/d\sigma$ (mils/kpsi)	$\Delta\sigma$ (kpsi)	σ (kpsi)	$dr_v/d\sigma_s$ $\tilde{r}_h \le \tilde{R}_h$ (mils/kpsi)	$dr_v/d\sigma_s$ $\tilde{r}_h \ge \tilde{R}_h$ (mils/kpsi)	$\Delta\tilde{r}_h=0$ $\Delta\tilde{r}_v$ (mils)	$\Delta\tilde{r}_v=0$ $\Delta\tilde{r}_h$ (mils)	$\sigma_s=45$ $\Delta\tilde{r}_v$ (mils)	$\Delta\tilde{r}_h=0$ σ_s (kpsi)	$\Delta\tilde{r}_v=0$ σ_s (kpsi)
-0.88	0.56	-0.05	10	-2.25	-0.16	-0.05	2.2	0.0	0.9	18	63
-0.88	0.56	-0.05	13	-2.25	-0.16	-0.05	3.7	0.0	2.5	19	94
-0.88	0.56	-0.05	7	-2.25	-0.16	-0.05	0.7	0.0	0.0	17	32
-0.88	0.56	-0.05	10	-3.25	-0.16	-0.05	1.7	0.0	0.4	18	53
-0.88	0.44	-0.05	10	-2.25	-0.16	-0.05	1.3	0.0	0.0	18	44
-0.88	0.56	0.00	10	-2.25	-0.16	-0.05	2.7	0.0	1.2	16	69
-0.72	0.56	-0.05	10	-2.25	-0.16	-0.05	1.6	0.0	0.5	22	54
-0.88	0.56	-0.05	10	-2.25	-0.20	-0.05	2.2	0.0	0.7	15	59
-0.88	0.56	-0.05	10	-2.25	-0.16	-0.07	2.2	0.0	0.4	18	50
-0.88	0.56	0.00	13	-2.25	-0.16	-0.05	4.4	0.0	2.9	16	103
-0.88	0.44	-0.05	7	-3.25	-0.20	-0.07	-	-0.2	0.0	-	13

Table IIb

$\Delta r_v = 2.0$ mils
$\Delta r_h = 0.0$ mils

dr_h/dr_v	$dr_v/d\sigma$ (mils/kpsi)	$dr_h/d\sigma$ (mils/kpsi)	$\Delta\sigma$ (kpsi)	σ (kpsi)	$dr_v/d\sigma_s$ $\tilde{r}_h \le \tilde{R}_h$ (mils/kpsi)	$dr_v/d\sigma_s$ $\tilde{r}_h \ge \tilde{R}_h$ (mils/kpsi)	$\Delta\tilde{r}_h=0$ $\Delta\tilde{r}_v$ (mils)	$\Delta\tilde{r}_v=0$ $\Delta\tilde{r}_h$ (mils)	$\sigma_s=45$ $\Delta\tilde{r}_v$ (mils)	$\Delta\tilde{r}_h=0$ σ_s (kpsi)	$\Delta\tilde{r}_v=0$ σ_s (kpsi)
-0.88	0.56	-0.05	10	-2.25	-0.16	-0.05	1.2	0.0	0.0	18	43
-0.88	0.56	-0.05	13	-2.25	-0.16	-0.05	2.7	0.0	1.5	19	74
-0.88	0.56	-0.05	7	-2.25	-0.16	-0.05	-	-0.2	0.0	-	12
-0.88	0.56	-0.05	10	-3.25	-0.16	-0.05	0.7	0.0	0.0	18	33
-0.88	0.44	-0.05	10	-2.25	-0.16	-0.05	0.3	0.0	0.0	18	24
-0.88	0.56	0.00	10	-2.25	-0.16	-0.05	1.7	0.0	0.2	16	49
-0.72	0.56	-0.05	10	-2.25	-0.16	-0.05	0.6	0.0	0.0	22	34
-0.88	0.56	-0.05	10	-2.25	-0.20	-0.05	1.2	0.0	0.0	15	39
-0.88	0.56	-0.05	10	-2.25	-0.16	-0.07	1.2	0.0	0.0	18	36
-0.88	0.56	0.00	13	-2.25	-0.16	-0.05	3.4	0.0	1.9	16	83
-0.88	0.44	-0.05	7	-3.25	-0.20	-0.07	-	-1.1	0.0	-	8

Table IIc

$\Delta r_v = 0.0$ mils
$\Delta r_h = 0.0$ mils

dr_h/dr_v	$dr_v/d\sigma$ (mils/kpsi)	$dr_h/d\sigma$ (mils/kpsi)	$\Delta\sigma$ (kpsi)	σ (kpsi)	$dr_v/d\sigma_s$ $\tilde{r}_h \le \tilde{R}_h$ (mils/kpsi)	$dr_v/d\sigma_s$ $\tilde{r}_h \ge \tilde{R}_h$ (mils/kpsi)	$\Delta\tilde{r}_h=0$ $\Delta\tilde{r}_v$ (mils)	$\Delta\tilde{r}_v=0$ $\Delta\tilde{r}_h$ (mils)	$\sigma_s=45$ $\Delta\tilde{r}_v$ (mils)	$\Delta\tilde{r}_h=0$ σ_s (kpsi)	$\Delta\tilde{r}_v=0$ σ_s (kpsi)
-0.88	0.56	-0.05	10	-2.25	-0.16	-0.05	-	-0.7	0.0	-	14
-0.88	0.56	-0.05	13	-2.25	-0.16	-0.05	0.7	0.0	0.0	19	34
-0.88	0.56	-0.05	7	-2.25	-0.16	-0.05	-	-2.0	0.0	-	3
-0.88	0.56	-0.05	10	-3.25	-0.16	-0.05	-	-1.1	0.0	-	10
-0.88	0.44	-0.05	10	-2.25	-0.16	-0.05	-	-1.5	0.0	-	8
-0.88	0.56	0.00	10	-2.25	-0.16	-0.05	-	-0.3	0.0	-	14
-0.72	0.56	-0.05	10	-2.25	-0.16	-0.05	-	-1.0	0.0	-	14
-0.88	0.56	-0.05	10	-2.25	-0.20	-0.05	-	-0.7	0.0	-	11
-0.88	0.56	-0.05	10	-2.25	-0.16	-0.07	-	-0.7	0.0	-	11
-0.88	0.56	0.00	13	-2.25	-0.16	-0.05	1.4	0.0	0.0	16	43
-0.88	0.44	-0.05	7	-3.25	-0.20	-0.07	-	-2.4	0.0	-	0

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8/11/89

To: Rodger Bossert, John Carson, Paul Mantsch
From: Jim Strait
Subject: Calculation of Desired Vertical Ovality of SSC Collars

I have finally come to a conclusion about how much vertical "ovality" it is desirable to build into the collars if a horizontally split yoke is to be used. I attach a note discussing (in too much detail, no doubt) the calculations I have done. To save you from having to wade through it I will quote the results. The undeflected collar should have a vertical radius that is 2 mils larger than the yoke and a horizontal radius equal to the yoke at room temperature. This can be accomplished by using collars with a radius equal to the yoke and with the keys positioned so that the center is displaced 2 mils toward the yoke. After the skin has been used to force the collars to conform to the yoke, not only will the yoke and collars be in contact all the way around but the coil will be close to its nominal position.

Note that this is the optimal collar design only if inelastic deformation of the collars does not occur during insertion of the tapered keys. Tapered key coils made by BNL have an additional vertical ovality of up to 4 mils on the radius due to inelastic effects. If we use the collar specified here and have similar deformations in assembling our magnets, mid-plane yoke gaps as large as 10 mils may occur.