COMMENTS ON THE 5-CM-BORE DIPOLES PROPOSED BY KEK
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INTRODUCTION

In this note I compare several features of the dipoles proposed by KEK-Furukawa for the SSC with the current design under study by the CDG. (I refer to these as simply KEK and CDG.)

The KEK magnets use cable conforming to the same specifications as the CDG except that the keystone angle and packing factor are greater, resulting in a thinner cable edge at the inside surface of each layer. For the 50-mm-bore proposed by KEK the keystoning is sufficient to allow the sides of the conductors to lie on radial lines ("fully keystoned"), and there are no wedges.

The ways in which the KEK differs from the CDG are:

Smaller insulation thickness (perhaps unintentional),
Bore diameter 50 mm rather than 40 mm,
Smaller thin-edge cable thickness; a result of the greater keystone angle, but a separate effect,
Greater keystone angle; no wedges required or used for the 50 mm bore.

Rather than try to compare the two designs as they stand, it seems appropriate to consider the above effects separately.

CONCLUSIONS

Additional keystoning certainly offers advantages. And it is no surprise that the larger bore reduces the field multipoles. However even for the 50-mm bore, the field quality is not within tolerance. (The addition of one wedge would probably bring it within tolerance, but that was not investigated.)

RESULTS

INSULATION THICKNESS

KEK uses a cable double insulation thickness of 0.21 mm, whereas the CDG is based on 0.169 mm for the inner layer and 0.175 mm for the outer layer. The CDG is based on Garry Morgan's use of the observed thickness after compression; the KEK might be based on the raw specs. To make a fair comparison I use 0.175 mm throughout.

BORE DIAMETER

Model for Comparison. Each layer is treated as a thick cylindrical sector with current density uniform in azimuth and
varying inversely with radius, extending from the horizontal midplane up to some limiting angle. The limiting angles are adjusted continuously to make the sextupole and decapole exactly zero. This implies a non-integer number of turns, but that’s O.K.; there are reasons why an integer-turn constraint might not be appropriate for the study. The layer thickness is 10 mm throughout. There is no insulation at the midplane, between the coil layers, or on the inside or outside of the collars. The iron has infinite permeability. The current density at the inner edges of the outer layers is 1.21 times that of the inner. I use three ground rules for placing the inner radius of the yoke: no yoke at all (or infinite radius); constant 15 mm distance between the coil and yoke; and one in which that distance increases with increasing bore radius in such a way as to maintain constant stresses in the collars, approximately. The last of the three is the more valid one; the other two are for comparison.

As the bore is increased the upper-edge angles increase, and for the same bore the angles depend on the position of the iron. Table X shows the angles.

Conductor Quantity. The effect of bore radius on conductor quantity is shown in Fig. 1. Note that the conductor quantity required is almost proportional to the bore diameter, as one might have guessed. But it isn’t all that simple. Certainly the conductor required for the inner layer is proportional to the bore diameter if the upper-edge angle is fixed. But, increasing the bore radius by 25% increases the inside radius of the outer layer, and hence the number of turns, by only 17%. But the upper-edge angles increase too, so the net result is about a 25% increase in conductor quantity.

Transfer Function. With a thin coil, changing the coil radius has no effect on the transfer function, provided the conductor size is fixed and the ratio of coil radius to yoke inside radius is unchanged. With a thick coil, two factors enter that increase the transfer function as the bore radius increases. The number of turns in a layer is proportional to the layer inside radius whereas the field is proportional to some average radius. As the bore radius increases, the ratio of inside radius to average radius of each layer increased, and so does the transfer function. There is a further gain in the number of turns resulting from the increase in upper-edge angles. The net result is shown in Fig. 2. The 6% increase in transfer function resulting from increasing the bore diameter from 40 to 50 mm translates into an increase in critical field of 2%, for the constant-collar-stress condition.

Field Quality. The multipoles are presented in Table 1, along with the tolerances.

The KEK design, as presented by KEK, does not have zero sextupole and decapole components. I readjusted the conductor thicknesses very slightly to make them exactly zero, and also added midplane insulation, which KEK omitted. The multipoles are almost the same as those in the table for the 50 mm bore model with non-integer turns described above. All of the multipoles decrease with increasing bore diameter, of course, but even for the 50-mm bore
diameter the multipoles are not within tolerance.

**Coil Stresses.** The circumferential prestress must increase roughly in proportion to the average coil radius, some 17% for the 50-mm bore.

**THICKNESS OF THIN EDGE OF CABLE**

The ratio of thin-edge thicknesses, CDG to KEK, for the bare inner-layer conductor is 1.326 mm / 1.361 mm or 1.167. Upon the addition of a double insulation thickness of 0.175 mm to both, the ratio drops to 1.145. Use of the KEK cable in place of the CDG cable would therefore increase the transfer function by 14.5%. When folded in with the critical curve of the conductor, this would increase the critical field of the magnet by 14.5/3 or 4.8%. Were it not for the degradation resulting from the additional compaction. (The division by 3 is explained in another note.)

In another note I show that current degradation appears to be primarily a function of the cable thin-edge thickness along with the relationship between the two, derived from the Furukawa data. The data for the "old" fine-filament material does not include such severe compaction as required for KEK, but an eye-ball extrapolation indicates a degradation of the order of 7 to 10%. This, folded in with the conductor critical curve by dividing by 3, results in a loss of critical field of 2 to 3%, wiping out much of the gain from the greater load-line slope. For the "new" coarse-filament conductor the additional degradation, from CDG to KEK, is only 2%, resulting in a decrease in critical field of about 0.7%, for a net critical-field increase of 4.1%. This increase is at the expense of a 14.5% increase in the amount of superconductor, a fair deal in this business. This increase, of course, is independent of bore diameter.

**KEYSTONE ANGLE**

For the 50-mm bore, the elimination of the wedges allowed by the greater keystoning has advantages. Costs would be reduced: the cost of the wedges is eliminated, and winding labor costs are reduced. For the 40 mm bore diameter, however, no reasonable amount of keystoning can eliminate the wedges, from a mechanical point of view. And they are also needed for field-quality control. But more severely keystoned conductor still offers advantages. The conductor edges lie more nearly radial, giving a more true Roman-arch effect and less tendency for the conductors to squirt inward. However, the main advantage is the reduction of the inner-edge thickness of the conductor, giving more turns per layer and hence a greater transfer function as described above.
TABLE 1. FIELD MULTIPOLES

Values in table are $1 \times 10^{-4}$ of the dipole field.

<table>
<thead>
<tr>
<th>Order</th>
<th>Constant collar stress</th>
<th>Tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bore diam., mm</td>
<td>KEK[1]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CDR[2]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With lattice mod.[3]</td>
</tr>
<tr>
<td>14-pole, bs</td>
<td>+1.42  +0.60  +0.27</td>
<td>+0.27</td>
</tr>
<tr>
<td></td>
<td>40  45  50</td>
<td>0.04</td>
</tr>
<tr>
<td>18-pole, bs</td>
<td>-0.53  -0.22  -0.095</td>
<td>-0.106</td>
</tr>
<tr>
<td></td>
<td>40  45  50</td>
<td>0.088</td>
</tr>
<tr>
<td>22-pole, b10</td>
<td>+0.096  +0.033  +0.012</td>
<td>+0.013</td>
</tr>
<tr>
<td></td>
<td>40  45  50</td>
<td>0.29</td>
</tr>
</tbody>
</table>

[1] KEK 50-mm-bore design with conductor thickness corrected to eliminate sextupole and decapole.

Figure 1. Effect of bore diameter on quantity of conductor required.
Figure 2. Effect of bore diameter on transfer function.