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# DESIGN STUDY ON FUTURE ACCELERATOR MAGNETS USING LARGELY KEYSTONED CABLES

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## Abstract

In the near future, superconducting magnets with a small beam aperture will be required for high energy proton colliders. When coils are designed to be self arched over a small beam pipe, it simplifies the magnet construction both in the winding procedure and in the field quality control. Fabrication of these coils requires cables with large keystone angles. A new structure of "braid-in-strands" is devised to produce these cables. Two types of magnet coils are studied for use of these cables. The straight section of a magnet has been fabricated as a preliminary test. Strand positions have all been measured on the cross section of the coil. Magnetic field analysis is made on the basis of the position data of the strands.

## Introduction

Dipole magnets with two-layer coils have been developed for TEVATRON at Fermilab.[1,2] The Rutherford type cables of keystoned shape were wound into the coils. They were self arched over the magnet aperture without containing any wedges in the winding. This indicates that the keystone angle of the cable fitted the magnet aperture (full keystone cable). In the magnet cross section, all cables were vertically directed to the center of the magnet aperture. This is a special feature of self-arched coils. The structure of these coils was useful to simplify both the winding procedure and the field quality control. The basic simplicity of the structure made it possible to produce a great number of magnets which had an acceptable field quality.[1,2]

A high energy proton accelerator in the energy region of 10 to 20 TeV will be built in the near future.[3,4] The proton beam size decreases generally by increasing the diameter of an accelerator ring. The future high energy accelerator then has a magnet aperture of a smaller size than in the case of TEVATRON. A dipole magnet has been designed for the Superconducting Super Collider (SSC).[5,6] The magnet possesses two-layer coils. In comparison to TEVATRON, this magnet have the following characteristics. The diameter of the coil aperture is reduced by about half. The cable width is increased by about 20 %. The keystone angle of the cable is smaller by 20 % (outer coil) to 40 % (inner coil). When the cable with the smaller keystone angle is wound into a magnet coil without use of any wedges, the resultant coil aperture becomes much larger than the design value. This is because the keystone angle is too small for the winding to fit the design aperture (partial keystone cable).

Many wedges were required in this design. They were inserted into the coils to compensate the original curvature of the windings. Both the size and the position of the wedges were chosen carefully to achieve a good field quality.[6] The use of these wedges arched the coils as a whole. Unlike that of TEVATRON, therefore, this arch was not made in a completely self-arched manner. All cables were not vertically directed to the magnet center. Thus, the adoption of the partial keystone cable brought about complexity in the winding procedure and in the field quality control.

It is desirable that the magnet for the future accelerator will have the structure of the self-arched coils. A preliminary study[7,8] has been made by a KEK group to apply this structure to the magnet for the future accelerator. The magnet requires the cables with the larger keystone angle (full keystone cable) that fits the smaller coil aperture. It has been difficult to fabricate such cables. This is because the excess cable deformation causes their critical current to be degradated during the cable forming procedure. New technology has been developed in Japan to fabricate these cables. They are now available in a mass-production scale. We will present the development of the cable with the larger keystone angle. Both the design and the experimental studies will be described for the dipole magnet with the self-arched coils.

## Full keystone cable

The full keystone cable has been developed by a Japanese company, Furukawa Industry. The cable is principally a Rutherford type, but contains a superconducting or pure aluminum braid inside the usual strands ("braid-in-strands" structure). The structure of the cable is illustrated in Fig. 1. The picture is shown in Fig. 2. The braid is put closely to one edge of the cable, so that it raises the cable thickness mainly on this side. The braid thus has an important

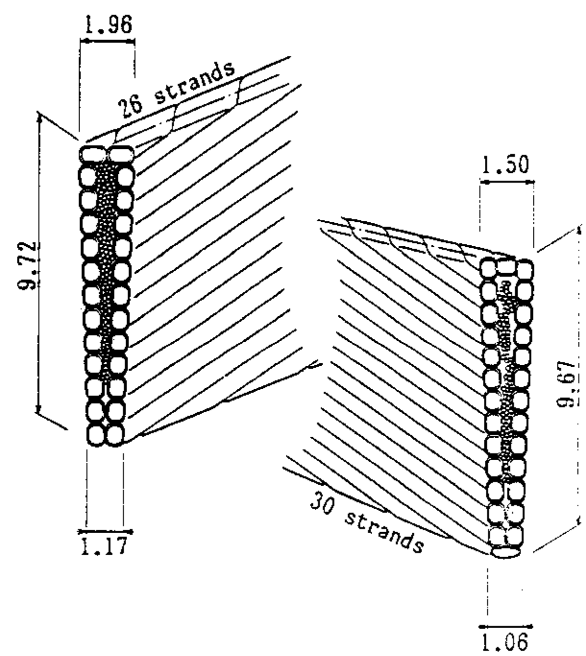



Figure 1. Largely keystoned cable. The Rutherford type stranded cable contains an inner braid therein. The width is expressed in units of mm.

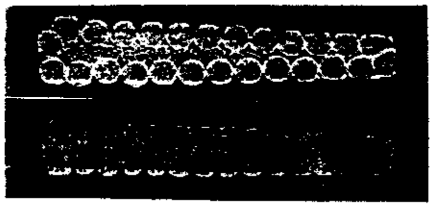


Figure 2. Picture of the cross section of largely keystoned cables. The upper and lower photographs indicate the cables with 23 and 30 strands, respectively.

Table I. Specifications of the braid-in-strands cable.

| | Inner layer | Outer layer |
|---|---|---|
| Number of strands | 26 | 30 |
| Width (bare) (mm) | 9.67 | 9.67 |
| Thickness (bare) (mm) | 1.17-1.96 | 1.06-1.50 |
| Keystone angle (deg) | 4.64 | 2.61 |
| Transposition pitch (mm) | 72 | 75 |
| Strand diameter | 0.748 | 0.648 |
| Filament diameter ($\mu$m) | 6 | 5 |
| Cu:SC ratio | 1.71 | 1.69 |
| No. of strands in braid | 75 | 75 |

role in the increase in the keystone angle. The keystone angles are 4.64 and 2.61 degrees for the inner and outer coils, respectively. The angles for the corresponding coils are 1.61 and 1.21 degrees in the SSC magnet.[6] The present values are about twice as large as that for the SSC magnet.

The specifications of the cables are shown in Table I. In a typical design described in the next section, the nominal current is 6.37 kA for the central field of 6.5 T. The filament diameter is 5~6 $\mu$m. The cables have different copper-to-superconductor ratios for the inner and outer coils. At 6.5 T, the overall current density is 370 and 450 A/mm$^2$ for the inner and outer coils, respectively. The average cross sectional dimension of the cable is 10.0 $\times$ 1.72 mm for the inner coil and 10.0 $\times$ 1.42 mm for the outer. These values include the thickness of insulation layers, and they stand for the dimensions after collaring. The values in the table show the dimension of bare cables. The cable is insulated by Kapton tape (thickness 2 $\times$ 0.025 mm) with half overlapping. B stage epoxy resin impregnated glass tape (thickness 0.10 mm) wraps the cable with a gap space of 1 mm.

The braid in the cable is made of a number of thin superconducting or pure aluminum wires of 0.1 mm diameter. It will be studied experimentally whether or not the coupling current through the braid produces an anomalous effect on the magnet performance. If the effect is considerably large, surface insulated pure aluminum wires should be used instead of the superconducting braid.

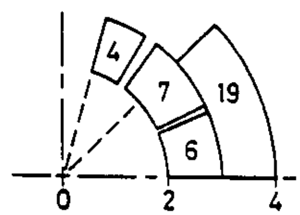
## Design of the magnet with self-arched coils

The magnet with the self-arched coils has the following characteristics.

(1) On a plane of the magnet cross section, all cables are vertically directed to the magnet center. Hence, mechanical properties of the coil such as elastic modulus are basically the same in the radial direction. This also applies to the azimuthal direction. The cables are expected to be wound, cured and collared in a more uniform manner.

Table II. Specifications of the magnet having circular aperture coils with two wedges per quadrant. The cross section of the coils is illustrated in the figure below the table.

| | Inner layer | Outer layer |
|---|---|---|
| Radius (mm) | 20.0-30.0 | 30.2-40.2 |
| No. of turns (half) | 6+7+4 | 19 |
| Maximum angle (deg) | 74.0 | 44.0 |
| Wedge angle (deg) | 23.9-25.9<br>53.5-58.2 | none |
| Iron inner radius (mm) | 55.7 | |
| Transfer function (G/A) at 2kA | 10.4 | |
| Current (kA) for 6T | 5.8 | |
| Harmonics ($10^{-4}$ @1cm) at 2kA | | |
| Sextupoles($b_2$) | 0.0 | |
| Decapoles ($b_4$) | 0.0 | |
| 14 poles ($b_6$) | 0.0 | |
| 18 poles ($b_8$) | 0.0 | |
| 22 poles ($b_{10}$) | -0.1 | |
| 26 poles ($b_{12}$) | 0.03 | |




The abscissa is scaled in units of cm. Figures in the coils stand for the number of turns.

(2) There is less probability for locational errors of the cables for the reason in item (1). Better reproducibility of multipole characteristics may be expected for field homogeneity.

(3) All radial dimensions of coils are fixed to certain values. The multipole characteristics are simply determined by the angular configuration of coils. The control of the field quality is easier because less parameters determine the field distribution.

(4) Insertion of less wedges may achieve a good field homogeneity more readily. The use of less wedges simplified the winding procedure.

## Circular aperture coils

A diameter of 4 cm is taken as the magnet coil aperture. The inner diameter of iron yoke is 5.56 cm. The magnet specifications are listed in Table II. Two wedges are used for a quadrant. The transfer function and the field homogeneity shown in Table II are similar to that of the SSC magnet. Characteristics of the magnet design are summarized in Table III in the case of use of less wedges. During the calculation, coil radii and current density are kept basically the same as in Table II.

When no wedge is used, the magnet design leads to considerably less number of turns in the outer coil. The design produces the larger values of both 14 and 18 poles: $b_6$=-1.4 and $b_8$=0.5 in the usual units of $10^{-4}$ at 1 cm. The transfer function decreases to an appreciable extent. In contrast, the TEVATRON dipole magnet having no wedge showed a negligible magnitude of 14 poles.[1] Whereas the coil aperture in the present design is about half of that in the TEVATRON magnet, the cable width is larger by a quarter in this design. Hence, the present magnet has a larger ratio of cable width to its coil aperture than the TEVATRON magnet, and accordingly does relatively thicker shell coils for its coil aperture. While the inner coil largely contributes to production of the 14 pole component, the outer coil does to a slight degree. This is the

Table III. Characteristics of circular aperture magnets in the case of fewer wedges. Values for the magnetic field are shown at a current around 2 kA.

| | Wedges for a quadrant | |
|---|---|---|
| | None | One wedge |
| Number of turns (half) | | |
| Inner coil | 18 | 13+5 |
| Outer coil | 18 | 18 |
| Maximum angle (deg) | | |
| Inner coil | 72.4 | 73.7 |
| Outer coil | 36.5 | 41.0 |
| Wedge angle (deg) | | |
| Inner coil | – | 51.2-53.7 |
| Transfer function (G/A) | 10.0 | 10.5 |
| Harmonics ($10^{-4}$ @1cm) | | |
| Sextupoles($b_2$) | 0.0 | 0.0 |
| Decapoles ($b_4$) | 0.0 | 0.0 |
| 14 poles ($b_6$) | -1.4 | 0.0 |
| 18 poles ($b_8$) | 0.5 | 0.4 |
| 22 poles ($b_{10}$) | -0.08 | -0.1 |
| 26 poles ($b_{12}$) | 0.01 | 0.02 |

reason for the appearance of 14 poles in the case of no wedge design.

For use of one wedge, adjustment of the coil configuration leads to a negligible size of 14 poles, but the value of 18 poles still remains to be slightly larger i.e. $b_8$=0.4. When another wedge is added, the values of both 14 and 18 poles become negligibly small by choosing a suitable coil configuration. Two wedge design thus produces the best field homogeneity. The SSC magnet was designed by partial keystone cables, and has four wedges[6] for a quadrant; half of them mainly serve to compensate the inadequate coil arch which is ascribed to the partial keystone cables.

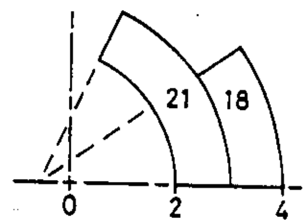
Eccentric circular coils

As mentioned above, at least a single wedge is required to reduce the 14 pole component in the circular aperture design. This may suggest to us that the coil in the high angle region should contribute less to the total field. When the coil at the high angle moves apart from the magnet center, one may achieve a condition that produces the good field homogeneity. There are two types of configuration that achieve this principle. The one is circular coils on an eccentric circle. The deviation of the coil center from the magnet center becomes a parameter to adjust the field homogeneity. The other is those coils that have an elliptic aperture with a form elongated along the vertical axis. This elongation is adjustable for field quality control in this case. It has been found that both kinds of configuration produce a good field homogeneity in nearly the same manner.

One can see that the coils in the elliptic configuration incompletely form the circular arch: The curvature of the coils varies with their angle from the horizontal plane. Then, adoption of the elliptic coils does not lead to the self-arched winding. The eccentric configuration is, therefore, chosen for the reason described above. The design example of the eccentric circular coils are shown in Table IV. No wedge is used in this design. The 14 pole component is adjusted to zero. The value of 18 poles still remains, but it is a very small amount. One can not make this value zero without use of thin wedges. The design of elliptic aperture coils produces basically the same results.

Table IV. Specifications of the magnet with eccentric coils. The cross section of the coils is illustrated in the figure below the table.

| | Inner layer | Outer layer |
|---|---|---|
| Center deviation (mm) | 5.23 | 5.23 |
| Radius (mm) | 25.23-35.23 | 35.43-45.43 |
| No. of turns (half) | 21 | 18 |
| Maximum angle (deg) | 65.61 | 35.49 |
| Iron inner radius (mm) | 55.7 | |
| Trans. function (G/A) at 2kA | 11.6 | |
| Current (kA) for 6T | 5.16 | |
| Harmonics ($10^{-4}$ @1cm) at 2kA | | |
| Sextupoles($b_2$) | 0.0 | |
| Decapoles ($b_4$) | 0.0 | |
| 14 poles ($b_6$) | 0.03 | |
| 18 poles ($b_8$) | 0.14 | |
| 22 poles ($b_{10}$) | 0.02 | |




The abscissa is scaled in units of cm. Figures in the coils stand for the number of turns.

Fabrication of the straight section

For producing the magnet of good field quality, it is most important to settle the cables correctly into the design position. The coils are influenced on their cable position by such factors as winding accuracy, curing pressure, collaring pressure and collar deformation. The careful choice and control of these factors should lead to the successful construction of high quality magnets. Therefore, checking the cable positions is useful to find an adequate method of the magnet construction.

The magnet having circular aperture coils with two wedges per quadrant was chosen for fabrication. The straight section was constructed to obtain information on the actual cable positions. The length of this section was as short as 15 cm. The short section was

Figure 3. The straight section as assembled.

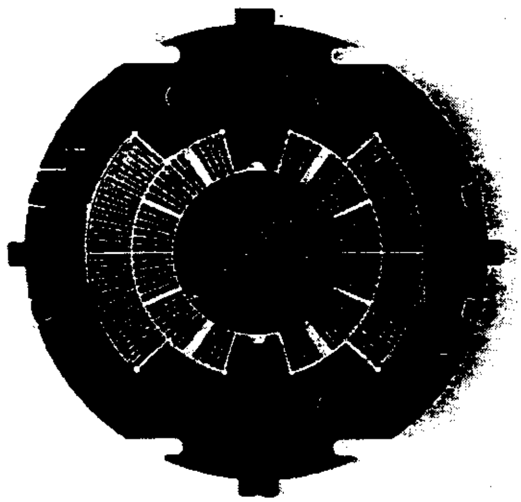


Figure 4. Cross section of the magnet with self-arched coils. There are two wedges for a quadrant.

made under the same condition as in the actual magnet construction. Fig. 3 shows the picture of the assembled straight section.

### Field analysis based on the strand location

The straight section of the magnet was vacuum-impregnated with a low-viscosity epoxy resin. This sample was cut out with a metal saw into a piece 13 cm long. The length is approximately twice the transposition pitch of the cable. The cross section of the piece is shown in Fig. 4. The measurement of the strand location was made on both sides of this short piece. The apparatus of measuring the cable location was an industrial television camera. This camera was installed on the head that was capable of moving three dimensionally. The center of every strand was searched by using a monitor television, and its position data were taken by a personal computer. It was found experimentally that the position of the strand center was reproducible within an accuracy of 20 $\mu m$.

The field calculation based on the positions of every strand[8] should reproduce the magnetic field, which would appear in the magnet constituted by this conductor configuration. The computed results are valid very well, specially for a current around 2 kA. This is because neither the magnetization of superconductor nor the saturation of iron yoke appears significantly in this current region. Furthermore, deformation of coils is still negligibly small at this current. Fabrication of this short straight section and its subsequent analysis serve to construct the high quality magnets in a controlled manner.

The harmonics values deduced from the strand positions are listed in Table V. The two sides of the straight section are designated as A and B. In this calculation, the field was expanded exactly at the center of mass of all strands. The quadrupole component then remains in this table. This component is ascribed to a slight anomalous asymmetry in the cable location. While the sextupole value is in the middle of the $10^{-4}$ order, the component with poles higher than six are negligible in size. These results are considered to be acceptable when it is taken into account that they were obtained for the first test.

Table V. Harmonics calculated from the experimental results. The values are listed in units of $10^{-4}$ $B_o^{-1}$ $cm^{-n}$.

| Pole No. | Side A | | Side B | |
|---|---|---|---|---|
| n | $b_n$ | $a_n$ | $b_n$ | $a_n$ |
| 1 | 1.30 | 0.32 | 3.35 | -1.02 |
| 2 | 3.79 | 0.40 | 3.90 | -0.38 |
| 3 | 0.23 | -0.28 | 0.31 | 0.22 |
| 4 | 0.18 | -0.038 | 0.15 | 0.003 |
| 5 | -0.020 | -0.060 | -0.092 | 0.054 |
| 6 | 0.070 | -0.006 | 0.084 | -0.011 |
| 7 | -0.011 | 0.018 | -0.007 | -0.001 |
| 8 | -0.015 | 0.003 | -0.075 | -0.012 |
| 9 | 0.002 | 0.003 | 0.003 | 0.002 |
| 10 | -0.093 | -0.000 | -0.091 | -0.001 |
| Trans.func.(G/A) | 10.410 | | 10.408 | |

### Conclusion

The magnet with the self-arched coils is desired for the future high energy accelerator. The magnet requires the cables with large keystone angle for them to make the self-arched coils. The new idea of "braid-in-strands" structure enabled us to successfully fabricate the special keystone cables. Two types of self-arched coils were found to produce the good field homogeneity. Prior to construction of a whole magnet, the straight section of the circular aperture magnet was fabricated to obtain the detailed information on the cable position.


### Acknowlegements

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