TEST OF NEW ACCELERATOR SUPERCONDUCTING DIPOLES SUITABLE FOR HIGH PRECISION FIELD

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Abstract

Field homogeneity of superconducting dipoles for accelerators is still difficult to achieve. To reach the required homogeneity level of 10^{-4} the conductors must be located within a few hundreths of mm. At present all the superconducting machines in construction or in project use the most developed technique of the double shell configuration. This technique is very sensitive to conductor size and a great care must be taken to reach the needed field homogeneity. The design proposed in this paper is a current block configuration which uses accuratly punched laminations with slots for conductor location. The design is then much less sensitive to conductor size. Furthermore the tooling needed to build such magnets is much less expensive than the one needed for the shell design. Three short dipoles have been constructed and tested. Very good results in field homogeneity have been obtained directly from the original design.

Introduction

Today, two big accelerators using superconducting magnets are being constructed : the "Doubler" at Fermilab which is nearly completed and "UNK" in Serpukhov which is at an earlier stage of development.

In Europe the DESY Lab in Hamburg is developing models for the HERA project and in Japan some work is also being made for the TRISTAN machine.

All these machines have adopted as main design the two shell coil configuration developed by Fermilab for many years. This technique has many good features, but is very sensitive to size and mechanical properties of conductors, so that the 10^{-4} level in field homogeneity is hard to achieve. Many full size dipoles have been constructed at Fermilab before reaching an acceptable quality and it is not known how many magnets will be needed to reach the same level in other laboratories. Therefore it seems desirable to develop alternative solutions. The design proposed here was partly supported by DESY which is interested at looking at eventual alternative solutions for the HERA project.

Principle of the new design

Although the proposed solution was fully described[1] it may be usefull to shortly recall the basic features, which are very simple. Figure 1 shows the shell configuration compared with the block configuration.

- Let us consider first the shell (on the right of Fig.1).

For this design the coil is first cured in an accurate mold and then clamped into stainless steel collars made of accurate punched laminations. When molded and later clamped, the angular position of the conductors, which is the most important parameter for field homogeneity, is only controlled at the two ends of the coils (top of the upper coil and bottom of the lower coil). Between these two accurate boundaries there are many conductors whose distribution depends on their size, local friction, mechanical properties, etc... The horizontal median plane, boundary between upper and lower coils, is during clamping a "floating" point depending on modulus of elasticity of the two coils. To achieve very high homogeneity of field this design requires not only to have accurate curing mold and collars, but also to have very tight tolerances on conductors and insulating materials (size and modulus of elasticity), and to control frictional behavior during molding and clamping. Another solution may be to build the coil, to make magnetic measurements and after field analysis to shim correctly the coils. This implies to destroy the collars and to reclamp the coils at least one time.

- Let us consider now the block design (on the left of Fig.1).

The principle of punched laminations is kept to get several very accurate grooves in the collars.

This time the collars serve also as curing mold for the conductors which are directly wound into the grooves. Differences in conductor sizes result as before in cumulative errors but now limited within the two accurate boundaries of the grooves. Going from the two shells to a four block configuration increases by a factor of four the number of accurate boundaries in conductor positioning.

From the mechanical point of view, the azimuthal forces acting on each block of conductors are directly taken by the steel fins which separate the grooves and do not apply on the following block of conductors. This results in electromagnetical stresses in azimuthal direction about 4 times smaller than with the shell configuration.

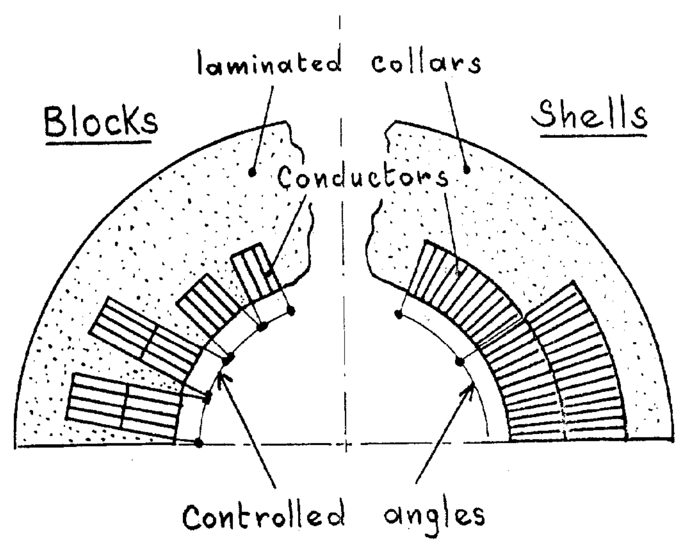

Fig. 1. Block and shell configuration.

Characteristics of the dipoles constructed

Two types of dipoles have been built. They both have a four block configuration and use a rectangular flat cable. In the first type (Fig.2) the cable is located in the grooves with its bigger dimension parallel to the radial direction. We call this type "block I".

In the second type (Fig.3) the cable is located in the grooves with its bigger dimension perpendicular to the radial direction. We call this second type "block II". The nominal central field is 4.4 T (7650 A) for block I

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and 5 T (7840 A) for block II. The coil aperture is 100 mm in diameter. The straight parts have 0.34 m and the overall length 0.64 m. An iron core of 0.240 m of inner diameter is located over the straight parts only (ends not covered). Both types of dipoles use the same flat cable which contains 23 Strands of 1.04 mm in diameter. Each strand has 2046 filaments of NbTi of 13μ, with a copper to superconducting ratio of 1.8/1. Overall dimensions including a 0.1 mm thick Kapton as insulation is 2.12 x12 mm^2. Short sample current is 9600 A at 5 T and 4.2 K. This cable was supplied by MCA.

Three magnets were built, two of the "block I" type and one of the "block II" type.

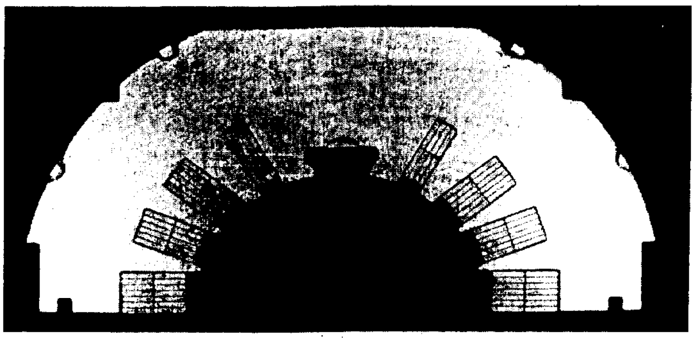

Fig. 2. "Block I" type dipole.

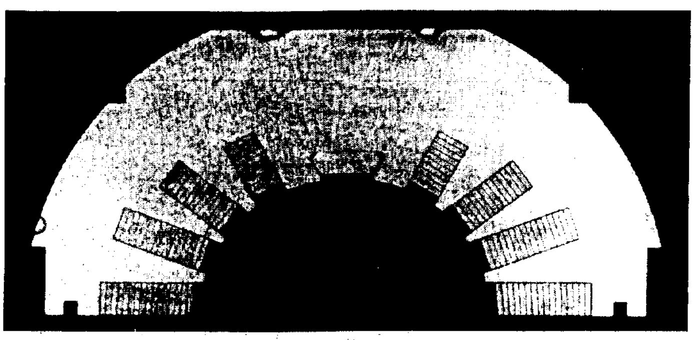

Fig. 3. "Block II" type dipole.

Construction details

The collars with grooves are staked on a length corresponding to the straight parts of the coils. The grooves are insulated to ground by a Kapton sheet 0.125 mm thick. Then the conductors are wound into the grooves some spacers being fixed at the ends to insure winding continuity. The ends of block I are very different from those of block II, the conductor being bent for the first one along its small dimension and for the second along its large dimension.

The conductor is wound with wet epoxy in the straight parts of the coil and molded in the grooves by pressing an inner mandrel during curing. A very light tooling is needed in the ends where a "fast glue" is used to stick the conductors from place to place until the final curing occurs. Just before curing a thin epoxy is also added to the ends where it penetrates by capillarity. The winding time is longer than for the two shell design but after molding the collaring operation is also completed which is not the case for the two shells. In addition, for the block II type, only one curing operation is needed instead of two. This fabrication does not need such toolings as : winding mandrel, curing molds, curing press, collaring press, all used for the shell design, and is therefore much less costly.

Mechanical problems

The main mechanical problem encountered with this new design is the difficulty to presstress the conductor within the grooves. In order to keep the simplicity of the construction the conductors are entered into the grooves with low azimuthal pressure. This leads to a Young modulus of each block of conductors as low as 300 kg/mm^2. Therefore under magnetic pressure the blocks of conductors can move slightly within each groove. Fortunately the split of magnetic forces, as mentioned above, limits the displacements and it can be calculated that the total deformation only leads to an increase of 10^{-4} on $\Delta B/B$ at the limit of the useful aperture (due to sextupole term). However, during the design of these magnets, the consequence of such a low modulus on training behavior was not clear.

Magnet tests

Training

Figure 4 shows the training curves for the three magnets. They behave almost the same. The first quench occurs between 70 and 80% of short sample current which is practically attained after 5 to 7 more quenches.

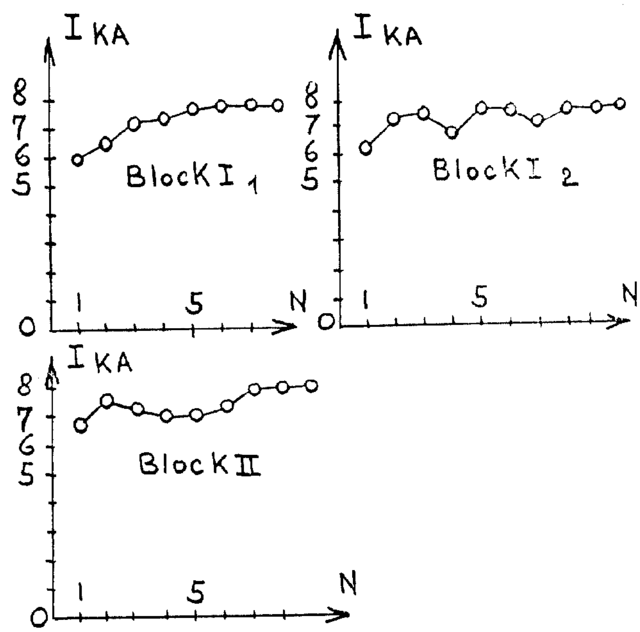

Fig.4. Training curves for the three magnets.

Field homogeneity

The multipole coefficients have been measured in the middle of the straight parts of the magnets using a rotating pick up coil.

These coefficients have the following definition :

$$\frac{\Delta B}{B} = \sum_{n=2}^{n=\infty} Cn\left(\frac{z}{a}\right)^{n-1}$$

a is the inner coil radius.
Z is the complex coordinates in the useful aperture.

The table I gives the $\Delta B/B$ due to each term up to n = 9 at the limit of the useful aperture of HERA (z = 25 mm). As it can be seen, all the coefficients are within the required tolerances of HERA for the two magnet types.

TABLE I

Multipole moments at nominal currents (ΔB/B at 25 mm radius in 10^{-4} units).

n		Block I_1	Block I_2	Block II	Tolerances HERA
2	Normal	1.5	- 0.8	- 1.2	± 2.5
	Squew	- 2.2	- 0.7	- 2.2	± 2.5
3	Normal	4	4.5	2.6	± 6
	Squew	- 0.5	- 0.2	- 0.3	± 2
4	Normal	- 0.3	0.1	- 0.6	± 2
	Squew	- 0.4	0.3	0	± 2
5	Normal	- 0.1	- 0.3	0.4	± 2
	Squew	0.1	0	0.3	± 2
6	Normal	0.2	0	0.3	± 2
	Squew	0	0.4	- 0.6	± 2
7	Normal	0.3	0.2	- 0.1	± 2
	Squew	- 0.2	0.1	0	± 2
8	Normal	0.2	0	- 0.2	± 2
	Squew	0.6	0.1	- 0.2	± 2
9	Normal	0	0	- 0.2	± 2
	Squew	0	0	0	± 2

In a previous paper[2], very shortly after the two first magnets of type I were tested the sextupole moments were shown to be out of tolerances. An increase of the sextupole moment appeared at high field. After better analysis this effect was found to come from a three dimensional iron saturation effect. It was later confirmed by further magnetic measurements without iron. As it has been said before, the ends of the coils are not covered by the iron core and as the magnet is very short the magnetic flux of the end saturates the iron.

Figure 5 gives the sextupole moment of block I_1 at the limit of the useful aperture (Z = 25 mm) with this saturation effect. Also it can be seen that the effect of wire movement is limited to 10^{-4} at maximum field. It has been calculated that the remaining 3.10^{-4} sextupole (which should be zero) comes from the ends of the coil in this very short magnet.

Conclusion

These new types of dipoles are very promising. The three magnets constructed reached the required accuracy for the HERA machine from first design. This is true for the two types of dipole whatever the way the conductors are layed into the grooves (Type I or II). The reproducibility of the two type I magnets is within 10^{-4}.

As expected, precision comes more from the accurate punching of the grooves than from individual conductor location.

The training behavior is satisfying in spite of the low presstress achieved within the grooves. New design which allows presstress is already made for a full length magnet(3), but at present no funding is planned for this new step.

As a conclusion this design seems to be adequate whenever a good field is required. Its construction cost is competitive with that of the shell design for mass production, but, in addition, due to the low cost of the tooling (compared to the shell design its cost should be 2 or 3 times less), this type of magnet should be chosen whenever one or a few units have to be made.

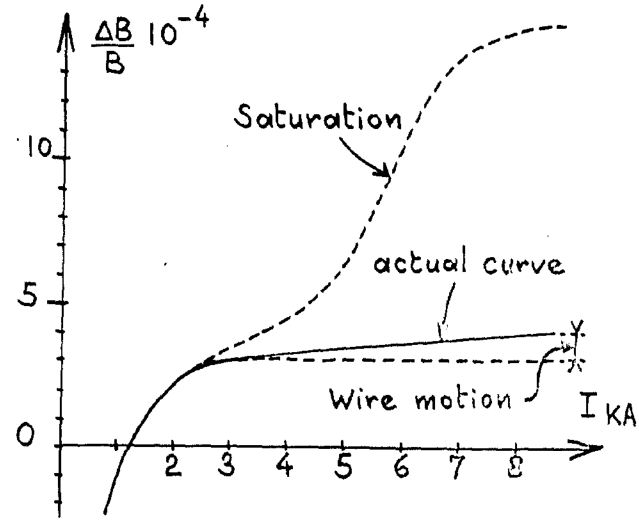

Fig. 5. Sextupole moment as a function of current.

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