STUDIES AND CONSTRUCTION OF SUPERCONDUCTING MAGNETS APPLIED TO SYNCHROTRONS OF MORE THAN 1000 GeV

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(presented by G. Bronca)

Abstract

The main characteristics of superconducting magnets are investigated in connection with their use in a synchrotron of more than 1 000 GeV.

1. Introduction

The possible use of superconducting magnets to build synchrotrons has been investigated for many years, first by trying to understand both theoretically and experimentally the behavior of superconducting materials in pulsed conditions and then in studying the new problems arising when one wants to build and use superconducting magnets for this special purpose.

The work reported in this paper shows how a synchrotron dipole would look like and why new concepts should be incorporated in the design.

The main characteristics of the accelerator (stored energy, losses, etc...) have been estimated as a function of the aperture, the central flux density, and the cycle duration. From the results, one would like to emphasize some particularly striking points.

For all these studies the dipole coils are assumed to be made of sectorial blocks with a constant overall current density Jo. Jo is taken in such a way that Jo =90000/Bo (Bo central flux density in Tesla, Jo in A/m2) in the range 4 T $<$Bo$<$6 T. Two cases are considered according to the location of the iron shielding, inside or outside the cryostat.

2. The aperture

2.1 Shape of the aperture

For superconducting dipoles the shape of the aperture has to be reconsidered compared to the shape of conventional dipoles.

In the case of high energy injection (100 or 200 GeV) the good field aperture has to be increased by the space needed for ejection. This space is added horizontally for a conventional synchrotron and then the horizontal size to the vertical size ratio is close to 2.5 to 1. One could also add this space vertically for vertical ejection, the aspect ratio is then about 0.5 to 1.

The curves of fig.1 show for a dipole without iron the ampere-turns and the stored energy as a function of the aspect ratio, the area of the useful aperture being kept constant (as an example). In this con-

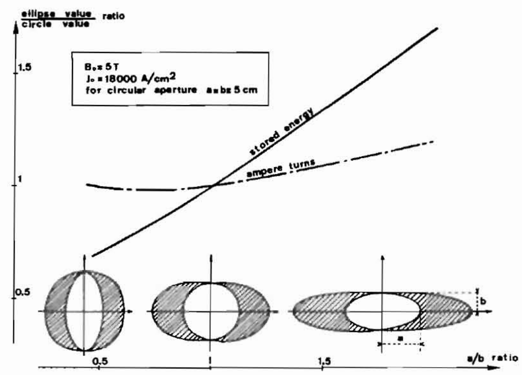

FIG.I- Influence of the shape of the aperture.

sidered case, if the ampere-turns are almost the same, the stored energy decreases by a factor 2.8 as the aspect ratio goes from 2.5 to 0.5.

Though this factor might be smaller if an iron shielding is taken into account and in using higher current density the advantage should be kept and contrarily to conventional dipoles the useful aperture should be a vertical ellipse in superconducting dipoles.

2.2 Size of the aperture

For superconducting synchrotron it seems, as one will see later, that it is more interesting to have a long cycle. The average beam intensity can be kept constant in using multiturn injection. Different types of multiturn injection can be used. One will consider storage in azimutal space and in synchrotron phase space.

2.2.1 Storage in azimuthal space: For the present design with the P.S. as injector the radius ratio is 11. Assuming the P.S. can supply 10^{13} protons per cycle with one cycle per second it should be possible to store 10^{14} protons in 11 turns. This method is not being used for the conventional 300 GeV machine because of its corresponding too long cycle duration, but for many reasons in high energy superconducting synchrotrons long cycle duration will probably have to be accepted. It has to be noticed that this method of injection does not require any extra aperture of the vacuum chamber.

2.2.2 Storage in synchrotron phase space : This method is interesting in the case of a new synchrotron, when injection is made at 100 or 200 GeV from the

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conventional machine. This injection scheme requires an extra radial space of 2.5 mm per turn.

In taking into account a closed orbit deviation of ± 10 mm the space for the beam is ± 20 mm horizontally and ± 16 mm vertically. The beam emittance and the energy spread values correspond to 200 GeV [1] . To these values have to be added ±2.5 mm per turn horizontally for injection and ± 20 mm vertically for ejection when assuming vertical ejection.

Then the good field half aperture should be, in using 4 turns injection as an example, ± 36 mm vertically and ± 30 mm horizontally.

2.3 Remark

These aperture figures concern a machine whose β max is 110 m. It is obvious that with a different structure of the lattice leading to a smaller β a reduction of the aperture would be obtained. Roughly the aperture varies as $\sqrt{\beta}$. Under these conditions to a half aperture of 60 mm for a β of 110m (case of the 300 GeV conventional machine and of the 1300 GeV superconducting machine) corresponds a half aperture of 29 mm for a β of 26 m (case of the 100 GeV cold magnet synchrotron [2])

2.4 The "bad field" margin

It is the space which has to be added to the useful aperture in such a way that the manufacture errors do not affect this good field aperture. The distinction has to be made between systematic deviation (the same for all dipoles) and random deviation (the same within a dipole but different from one to another).

Analysis of error made at SACLAY [3] shows that the angular error coming from the setting of the upper coil on the lower coil is the most severe. It gives a quadrupolar field error (fig.2).

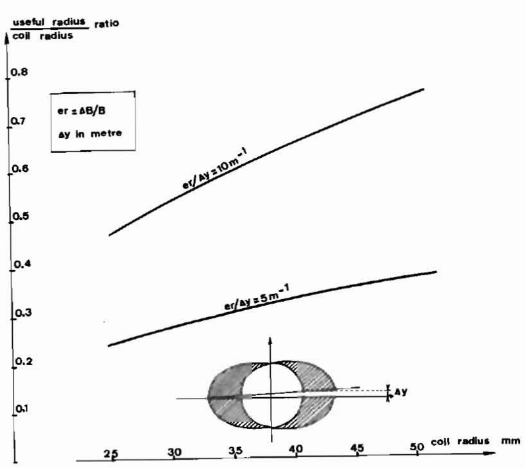

FIG.2- "Bad field" margin coming from the quadrupolar error.

In taking into account this errors alone, if we use a 50 mm coil radius dipole and if we let the geometrical setting deviation be 0.2 mm the good field radius with $\Delta B/B < 2.10^{-3}$ is 38 mm which means the bad field margin would be 12 mm in this case. This $\Delta B/B < 2.10^{-3}$ corresponds to the tolerances of the random quadripolar error for a machine whose radius is 1100 m, ν = 27.75 and involving 864 dipoles.

2.5 Correction of the errors

A self correcting system is beeing experimented at SACLAY[4] . It is made up of short circuited windings whose symmetry is that of the error which has to be corrected. These windings are located between the main coil and the useful area. Fig.3 shows a photograph of such a device designed to cut down sextupolar error. The main difficulties arise from the accuracy needed to manufacture and locate this winding, but the experiment is going on in a satisfactory way.

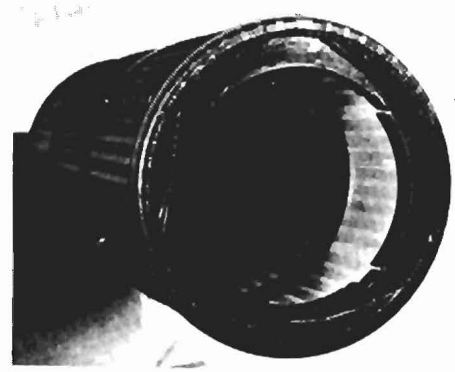

FIG.3- Sextupole correcting winding.

3. The central flux density B_o

With Niobium-Titanium superconducting material the sensible limit of maximum field is a little above 6 T. Most of the experts choose Bo between 4 T and 6 T. It is our opinion at SACLAY that one has to use the maximum gain allowed by superconductor and to aim Bo to be close to 6 T. This is particularly true in the present projects where one does not have to design a completely new machine with all its parameters, but rather to transform existing conventional machines in which the radius of the tunnel is given. The only criterion is then to get the maximum energy. For the present CERN project, 6 T would allow to reach 1300 GeV while 4 T would give only 870 GeV. Furthermore it has to be noticed, as the total magnetic length would probably be less with the superconducting design than with the 300 GeV conventional machine, that the above mentioned energy must be considered as optimistic.

When the central flux density Bo increases one can draw the following conclusions, in taking as basis a given aperture

(10 cm) and in comparing solutions with warm and cold iron. These two solutions are different in the following way :

- Cold iron: The iron is located inside the cryostat and is used to hold the internal magnetic forces. It is then located very close to the coil and helps very much in saving ampere-turns and stored energy, but iron hysterectic losses increase the total low temperature losses.

- Warm iron : The iron shielding is located outside the cryostat. The forces have to be contained by some other non magnetic holders which take space and the iron is far away from the coil compared with the first case. The saving in ampere-turns and stored energy is much less important but iron losses are not to be taken into account.

The thickness of the non magnetic holder is proportional to the magnetic forces and the average flux density within the iron shielding is 2 T. Other details of the calculation have been published elsewere [5]

- Stored energy : The cold iron solution allows to reduce by about 30% the stored energy compared with the far warm iron solution. The stored energy increases faster than Bo^2 even in the cold iron solution where it grows from 86 kJ/m at 4 T to 285 kJ/m at 6 T (roughly as Bo^3). This is due to the increase of the coil width related to the field increase.

- Iron weight : It is roughly the same for the two solutions. It grows a little faster than Bo^2, namely from 0.75 t/m at 4 T to 2 t/m at 6 T, the average flux density within the iron shielding beeing 2 T.

- Overall diameter of the magnet : Also about the same for the two solutions, it grows from 46 cm at 4 T to 75 cm at 6 T.

- Losses : In taking into account only the magnetization losses in the superconductor for 4 μ filament diameter and the hysteretic losses in the iron for the cold iron solution (5.10^{-2} J/c.kg for the 3.75% silicon steel), the total losses are about twice bigger in the cold iron solution than in the warm iron solution. These losses grow faster than Bo^2. They increase from 50 J/c.m at 4 T to 150 J/c.m at 6 T for the cold iron solution.

Do not forget that all the above results assume a coil aperture of 10 cm diameter. For a given aperture the comparison between 4 T and 6 T of all the above items, shows a smaller difference as Jo increases, while for a given Jo it shows a greater difference as the aperture decreases.

Fig. 4 gives the stored energy as a function of the aperture for different Bo in the two solutions cold and warm iron.

As a conclusion it has to be noticed that higher flux density is costly, but it is also the only way, with a given tunnel radius to have higher energy of particles.

In addition if the increase of Bo increases the capital cost of the magnet, the

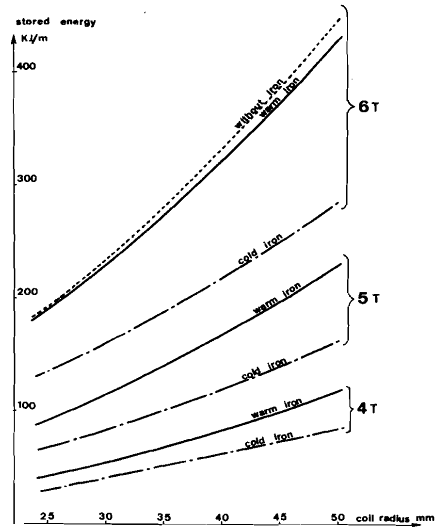

FIG.4- Stored energy as a function of the aperture.

corresponding increase in stored energy and low temperature losses can be minimized by using long cycle duration.

4. Advantage of long cycle duration

The table below gives the characteristics of machines using synchrotron phase space multiturn injection in the case of 1, 5 and 10 injected turns. For the different cases the cycle duration is chosen in such a way that the average beam intensity be the same as well as the duty factor. Bo is 6 T corresponding to 1300 GeV.

Number of turns		1	5	10
Half beam aperture	mm	20	32.5	45
Safety margin	mm	15	15	15
Half coil aperture	mm	35	47.5	60
Rise time	s	3.3	16.5	33
Cycle duration	s	8.2	41	82
Stored energy	kJ/m	190	265	350
Peak power	kVA/m	114	32	21
Losses at Helium temperature (W/m)	warm iron	9.2	5	4.4
	cold iron	17.1	7	5.7

The static losses of the cryostat are included : 3.5 W/m.

From these figures it is very interesting to point out that, although the aperture is increased in using multiturn injection, the peak power and the losses decrease very much.

For the 1300 GeV superconducting machine using 10 turns injection, the total low temperature losses in the cold iron solution would be 26 kW while the peak power would be 98 MVA which is less than the peak power of the 300 GeV conventional machine presently designed.

In addition the comparison between single and multiturn injections is pessimistic because it is not taking into account that the aperture is partly determined by ejection. For example even for one turn injection a 20 mm half aperture would not be large enough.

Figure 5 shows that the gain on losses value which is very important up to cycle duration of about 60 s becomes negligible afterwards. It is also to be noticed for long cycle duration that, due to static losses, no more appreciable difference can be found between the two solutions warm and cold iron.

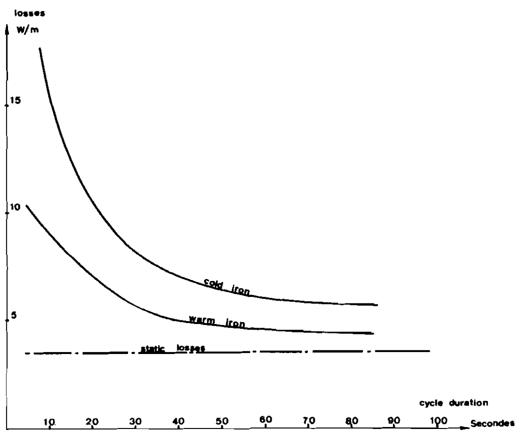

FIG.5- Helium temperature losses as a function of the cycle duration.

5. Behavior of superconducting materials

The work undertaken in the past, as well theoretically as experimentally has shown clearly that losses decreased with filaments size. Futhermore correctly cooled coils made up of transposed composites with small twist pitch, exhibited little degradation (Ib/Ic $\geqslant$ 90%) and mesured to calculated losses ratios were found to be between 1 and 2.

As far as the theory is concerned, two more effects were estimated and added into the calculations :

- First, the twisting results in differences of areas between filaments located at the edge and filaments located in the center of the composite. The correct Jc value computed from short sample test leads to computed losses which can be up to 10 % bigger than the old values.
- Second, filaments located at the edge of the composite after twisting are no more perpendicular to the external field giving also a change of Jc and this last effect increases the computed losses by a few per cent.

In addition the distribution of the electric field is modified and so are the losses which are by now being computed numerically. Finally the interaction of the self field, whose effect was found to be less important than expected, with the external field leads to a non uniform distribution of the current within the different layers of filaments and to high peak losses power when current is close to reach the critical current.

This effect is now being investigated.

Experimentally, short sample tests show that the assembling of composites into cable or braid results in big degradation (up to 30%). The reason has not been found yet.

The best cooling method of the coils remains helium channels but the research of a more compact winding leads to use heat drains which have, to be efficient, to protrude a few mm from the coil into the helium bath. However for high pulse frequency (2 s) they might prove to be not good enough with the present level of losses corresponding to 10 μ filaments.

The increase of losses when cooling is not efficient enough shows that the growth of temperature has a complicated action because a decrease of losses as Jc decreases could be expected.

6. Pulsed dipole modele "MOBY"

A pulsed dipole model has been under construction for a few months at SACLAY.

Its main features are gathered in the following table.

Coil aperture (circular)	100 mm
Central flux density	6 T
Overall current density	15 000 A/cm2
Magnetic length	50 cm
Stored energy	285 KJ/m
Total ampere-turns	1.2 10^6 At
Current	1 500 A
Copper to superc.ratio	1 to 1
Filaments diameter	10 μm
Nb of fil. per composite	1 000
Composite diameter	0.44 mm
Twist pitch	2 mm
Nb of composites in a cable	24
Dimension of the cable	4 x 2 mm2
Hysterectic losses :	
- in superc.	133 J/cycle/m
- in iron (3.75 % Si)	100 J/cycle/m

The cold iron solution has been chosen for this dipole, the main reason being to hold the big internal forces. This allows, among other simplifications, to use a simple metallic cryostat at least for its outer wall. The inner wall is also metallic but made of a very thin corrugated tube of stainless steel. Corrugations along the beam axis cut down eddy currents up to negligible level The cooling is obtained by interlaying insulated copper heat drains between all layers of the coil which is epoxy impregnated. The heat drains protrude from the coil into the helium bath.

As one thinks the real future of superconducting is low pulse frequency, the cycle time at which the coil is expected to work without degradation is about 20 s, nevertheless the power supply will allow experiments as low as a six-second period. The coil is wound according to the so called constant turn length in each layer technique. This technique enables to build very compact coils without any joint within each pole cable length and with no protruding coil ends. Many copper models have been wound that way. Figure 6 shows a hard copper model and figure 7 shows the tridimensional winding machine. On figure 8 a layer of heat drains can be seen under a layer of conductor which is being set up. It has to be noticed that the drains can be set very easily as well in the ends as in the straight parts of the coil.

This model is scheduled to be tested beginning of 1972. The iron shielding, the coil holders and the cryostat are under construction.

The superconducting cable, supplied by IMI, is being compacted by now and the length for the first pole (800 m) will be delivered in october.

A more realistic dipole as long as 2 meters will be initiated during 1972 and will be considered as a real prototype of a synchrotron dipole.

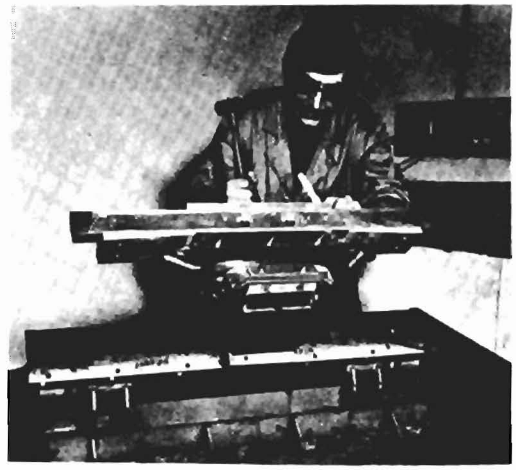

FIG.7- Winding machine for a dipole

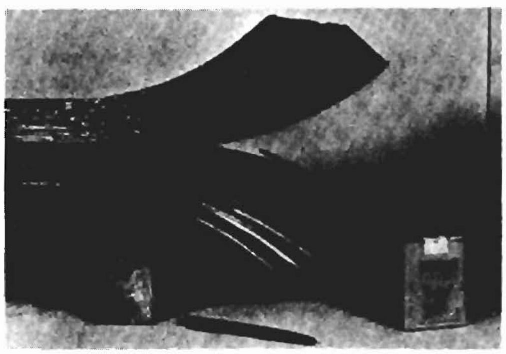

FIG.6- Hard copper dipole prototype

FIG.8- Heat drain cooling system

References

[1] "A design of the european 300 GeV research facilities"- MC 60 - 2/12/1970

[2] "Cold magnet synchrotron" - BNL 15 430

[3] F. KIRCHER - "Erreurs dues au mauvais positionnement de bobines dipolaires blindées". - GATS/71-38 du 19.04.1971

[4] A. DAEL & F. KIRCHER - "Correction d'un champ dipolaire par enroulements supraconducteurs." - GATS/71-06 du 15.1.1971

[5] J. PEROT - "Caractéristiques de dipôles supraconducteurs dans la gamme 4 T à 6 T." - GATS/71-82 du 9.08.1971

DISCUSSION

H. BRECHNA: Stored energy per unit length in dipole and quadrupoles, and magnetic field enhancement due to iron, are functions of the coil and iron dimensions. What are the dimensions of the coil and iron shield, which have been assumed to calculate the curves in Figure 4?

G. BRONCA: The width of the coil does not depend on the aperture. It is 3.8 cm, 4.8 cm and 5.8 cm for 4T, 5T and 6T field, respectively. The dimensions of the iron depend on both the aperture and the field. It is assumed to have an average of 2T field in the median plane of the yoke.

G. BRIANTI: Is the saving in stored energy, by adopting an aperture bigger vertically than horizontally, independent of the current configuration (intersecting ellipses or cos θ)?

G. BRONCA: The calculations have been made in the case of intersecting ellipses. We believe that we would get about the same results for any other configuration giving uniform field.

E.G. KOMAR: What is your opinion about accelerators with magnets that are moving during the cycle?

G. BRONCA: I know that this scheme was proposed by the Leningrad group and discussed at the Russian national conference last November. I have no opinion; we did not study this scheme.

N. MARSHALL KING: Regarding the aperture aspect ratios you have quoted, I believe that your argument is correct for the dipoles near to a D quadrupole in a vertical ejection scheme, for a FODO lattice. Similarly, the opposite kind of aspect ratio is found in the dipoles near an F quad. for horizontal ejection from a FODO. However, the other dipoles have a more nearly circular aperture occupation.

Also the argument does not apply to a triplet-type lattice. One of the reasons we were attracted originally to the SC_1 lattice was the near-circular beam occupation.

Finally, the argument is affected by details such as the location of the S_1 septum. In the latest CERN lattice, S_1 is downstream from an F quadrupole, and leads to horizontal-ejection aperture requirements not unlike those for vertical ejection.

G. BRONCA: In the case of apertures adapted in each magnet to the β function requirements, the gain will apply to part of the magnet dipoles.

It would be useful to try to apply the advantage of vertical elliptical aperture in the design of the lattice.

R. WIDERØE: Do the figures given for the maximum energy with 4T and 6T correspond to the design of the CERN 300 GeV machine?

G. BRONCA: Yes, the energies of 870 GeV and 1300 GeV corresponding to 4T and 6T field are calculated for the present magnetic length of the 300 to 400 GeV machine as described in the MC/60 report (about 4600 m).

A. ASNER: Your indicated current density is rather conservative. What would your stored energy and peak power be for twice this current density?

G. BRONCA: Going from 15 kA/cm^2 to 30 kA/cm^2 the stored energy would be reduced by a factor of 1.8 for a 25 mm radius aperture and by a factor of 1.4 for a 50 mm radius aperture.