

Rapid cycling superconducting magnets

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The paper deals with the general problematic related to the development of fast cycled superconducting magnets for application in particle accelerator machines. Starting from the requirements of SIS300 synchrotron under design at GSI and an envisaged future Super-SPS injector at CERN, it is shown which developments are mandatory in the superconducting wire technology and in the magnet design field.

1. INTRODUCTION

The next future high intensity accelerator machines will require bending magnets which are able to generate relatively intense fields (from 5 to 6 T) at charging rates of 1 - 1.5 T/s [1,2]. There are in particular two projects, which since now are asking for advanced dipoles and quadrupoles rapidly cycled: the SIS300 of the GSI and the Super-SPS at CERN.

The GSI is planning a complex of accelerators (FAIR) widely based on the superconducting magnet technology [3]. In particular the synchrotron SIS300 (the name comes to it from the demanded value of 300 Tm for the magnetic rigidity) will have to accelerate heavy ions (es. U 92+) until to an energy of 34 GeV/u. This synchrotron requires 120 dipoles superconductors of length 2.7 m, aperture 100 mm, field 6 T and ramp rate of 1 T/s. The synchrotron also includes 180 superconducting quadrupoles for generating a gradient of 90 T/m.

Since some times the CERN is studying possible systems in order to increase the LHC luminosity. In particular the possibility of upgrading PS and SPS is being investigated. A Super-PS would have to inject until 100 GeV in a Super-PS that injects into LHC at

1 TeV. The Super-PS shall be made by dipole magnets giving 3 T ramped at 2 T/s. The Super-SPS requires superconducting magnets for a field of 4-5 T ramped at 1.5 T/s, to have a cycle with a repetition rate of 10 s.

With relation to the SIS300, the GSI has planned a relevant R&D activity because the construction of superconducting dipoles, able to generate a high magnetic field (6T) while pulsed at 1T/s, has been never attempted. The basic problem is due to the high level of ac dissipation strongly limiting the magnet operation: the dissipation may be so high to quench the magnet or enough high to require a high cost for the thermal loads to the cooling system.

Same problematic is found in the Super-SPS. It has been calculated that using the technology currently available the level of ac dissipation during a cycle would be 35 W/m (with a peak value of 70 W/m). The total dissipations of the machine would be as high as 140 kW, an unacceptable value equivalent to the installed cooling power for all LHC.

An acceptable dissipation stays at a level of 15 kW in total, equivalents to 3.75 W/m in the dipole. The main consideration leading to fix this limit is based on the existence of unavoidable beam losses,

that reasonably will be of the order of $10^{12} \text{p} \times 1000 \text{GeV}/10\text{s} = 15 \text{ kW}$. Since the refrigeration system will have, any way, to take charge of this dissipation, the maximum value that can be accepted for the ac dissipations in magnets must be of the same order.

In this paper the main sources of ac dissipations in fast cycled superconducting dipoles are reviewed and the aims of possible R&D activities are discussed.

2. AC LOSSES IN S/C WIRES

The mechanisms leading to ac losses in superconducting wires come from two main mechanisms [4].

There is a basic effect related to the viscous motion of fluxoids (the quantum of magnetic flux) in the superconductor, causing an irreversible magnetization. The second main source is related to the presence of dynamic shielding currents coupling the filaments in a wire and the strands in a cable. In the following sections these effects are discussed with details.

2.1 Magnetic hysteretic losses in superconducting filaments

The superconductors involved in practical superconducting wires are of II type, i.e. these materials having the best electrical transport capabilities: nevertheless the high critical current density causes a strongly irreversible magnetization and consequently a high loss. This characteristic is tied to the existence of an interaction that pins the fluxoids to the irregularity of the lattice (voids, dislocations, impurities, non-superconducting phases), normally referred as pinning centers.

The penetration of the magnetic flux is opposed by stationary shielding currents composed of the sum of the microscopic currents of the single fluxoids. These currents interact with the magnetic field according to the Lorentz force, pushing the fluxoids to move into the sc material. The existence of a force (pinning force) opposed to the Lorentz force allows from one side the conduction without dissipation of very high transport currents ($3 \cdot 10^9 \text{ A/m}^2$ for NbTi at

$T=4.5 \text{ K}$ and $B=5\text{T}$), but, at the same time, it is the reason of the hysteresis in the magnetization. The energy dissipated in a field cycle is given by the integral over a field cycle of the magnetization M according:

$$W = \oint_{\text{cycle}} M dH \quad (1)$$

For a wire of diameter $2a$ placed in a transverse magnetic field B cycling from 0 to B_m , the loss, per unit volume of superconductor, in one cycle is:

$$Q = \frac{8}{3\pi} J_c a B_m, \quad (2)$$

where J_c is the critical current density. As Eq. 2 shows, the higher the critical current density the higher the losses. The dissipation is also directly proportional to the physical dimensions of filaments. This is one of the reasons for which the superconducting wires (Figure 1) are constituted by several filaments of diameter up to $100 \mu\text{m}$, embedded in a copper matrix acting as stabilizer.

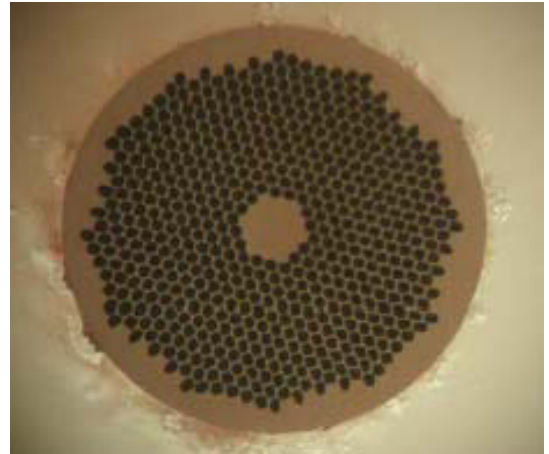


Figure 1. Multi-filamentary structure of a typical superconducting wire. Hundreds of fine NbTi filaments are embedded in a copper matrix. (This wire composes the cable used for the winding of CMS coil)

Even in stationary regime, the wire composing the winding of a magnet must have thin filaments ($< 100 \mu\text{m}$) to avoid that the heat generated from accidental penetrations of the magnetic flux causes chain of effects (flux jump) leading to the transition of the superconductor in the normal state (intrinsic stability criterion).

How thin can be made the filaments? In order to answer to this question we have to consider the constructive processes of the wires through extrusion operations, cold drawings and heat treatments. These steps allow starting from a cylindrical billet of typical diameter of 100–300 mm to arrive after subsequent reductions to the final wire with a diameter of approximately 1 mm, the so-called strand. Several strands may be assembled in the typical cable for accelerator magnets i.e. the flat Rutherford cable (Fig.2).

To the aim of having an acceptable mechanical stability during the drawing processes, the ratio between filament to filament spacing and their diameter must be not smaller than 0.15 [5].



Figure 2. Several strands are assembled through a cabling process to give the flat Rutherford cable (Case of CMS conductor made from 36 strands)

Unfortunately there is a lower limit to the filament spacing, determined by the filament coupling for proximity effect, causing a dramatic increase of the magnetization (and therefore of the losses) at low fields. This limit for a pure metal like copper (the wire stabilizer) is around $0.5 \mu\text{m}$ [6]. Consequently the minimum filament diameter is in the order of $3.5 \mu\text{m}$. One way to obviate to this

problem is to include in the copper of the matrix some manganese impurities, which not only suppress the proximity effect, but also increase the matrix resistivity, so reducing the losses, as shown in next section. This technique can lead to filament as fine as $2 \mu\text{m}$. However the resistivity of the matrix can not be increased too much, because this leads to a reduction of stability.

2.2 Coupling currents between superconducting filaments

The superconducting filaments composing a strand are electrically connected through the metallic matrix. When a time variable magnetic field is applied normally to the strand (typical situation in the windings of any magnet), the field variation induces currents that circulate around the filaments and close through the matrix. These currents decay

with a time constant $\tau = \frac{\mu_0}{2\rho_{\text{et}}} \left(\frac{l}{2\pi} \right)^2$, where l is

twice the length along which the currents cross between filaments (in principle for parallel filaments $l/2$ may be as long as the wire length), and ρ_{et} is the transverse resistivity of the wire. In order to avoid that the time constant is so large that the induced currents are higher than the critical current, the wire is twisted (Figure 3) forcing the induced coupling currents to close in many loops of length correspondent to half the twist pitch l_p (in the time constant formula the length l is replaced by the twist pitch length).

In the case in which the coupling currents decay constant is much lower than the ramp time T of the magnetic field (varying from 0 to $B_{\text{e peak}}$), the dissipation per unit wire volume in a cycle can be written as:

$$Q_e = \frac{B_{\text{e peak}}^2}{2\mu_0} \frac{8\tau}{T} \quad (3)$$

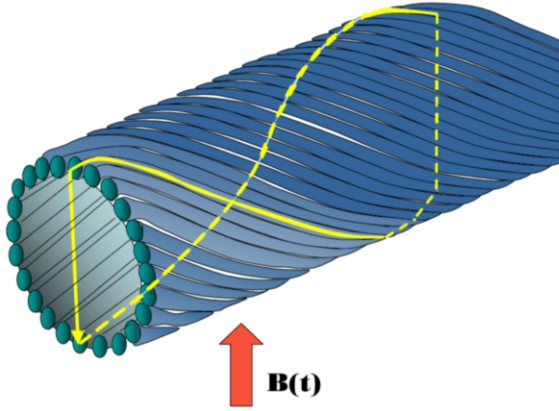


Figure 3. Twisted filamentary structure of a superconducting wire. The coupling currents partially flow inside the filaments and then close through the matrix.

This dissipation is directly proportional to the twist pitch which therefore must be as small as possible. Practically the minimum ratio between the twist pitch and the diameter of the wire is around 4-5, under this ratio, mechanical deformations can occur causing a severe degradation of electrical transport properties. The other important parameter, to be controlled for reducing the losses, is the transverse resistivity, dominated by the resistivity of the matrix. At a temperature of 4.2 K and a field of 1 T the copper has a resistivity of $1.81 \cdot 10^{-10} \Omega\text{m}$. The resistivity of copper doped with manganese at 0.5-0.6 wt% is 3 times higher, reducing therefore this type of dissipations by the same factor [7].

2.3 Coupling currents between strands of a Rutherford cable

A time variable magnetic field, applied normally to the wide face of a Rutherford cable, causes coupling currents between the strands with the same mechanisms occurring between filaments of a single wire. Given the particular structure of the Rutherford cable there are two mechanisms of couplings (Figure 4): those that take place between the strands opposing on the two faces (cross-over) and those between two adjacent strands. AC dissipations in a cycle are proportional to $Q_c \propto \frac{B_{c\text{peak}}^2}{R} \frac{l_{p\text{Ruth.}}}{T}$, where

$l_{p\text{Ruth}}$ is the twist pitch of the cable and R is the transverse resistance (in a twist pitch). For the losses due to cross-over $R=R_c$, for the losses due to adjacent coupling $R=R_a$. As for the strands, the parameters to minimize are the twist pitch and the coupling resistances. In particular it is important to keep R_c , as low as possible because, due to the large cross section it influences in determining way the whole losses. An effective way to reduce R_c [8] consists in interposing between the two faces of the Rutherford a 20-30 μm thick stainless steel core, which, blocking the transverse currents, eliminates almost completely this contribution to losses (Figure 5).

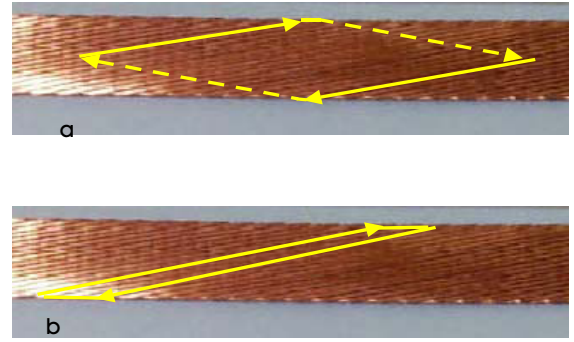


Figure 4. Coupling currents in a Rutherford cable due to a time variable magnetic field normal to the wide face. Case a) Coupling between opposite strands, b) Coupling between adjacent strands.

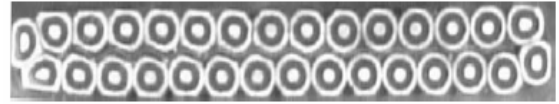


Figure 5. By inserting a thin stainless steel core between the two layers of a Rutherford cable, the coupling resistance R_c is so high to prevent this coupling mechanism, with a high benefit for the ac losses.

3. ACTIVITIES TOWARDS A DEVELOPMENT OF A LOW LOSS CABLE

Table 1 reports the characteristics of a present and a future conductor, showing the potential reduction of losses coming from dedicated developments. When computing the AC losses in a Rutherford cable, it appears that the main contribution would come from the coupling currents between opposite strand in the Rutherford.

Once this contribution has been suppressed by blocking the cross-over currents as explained in the previous section, the main source is given by the hysteretic losses in the superconducting filament (60%).

One of the main tasks of a R&D activity should be devoted to develop a superconducting wire with fine filaments and good transport properties. The experience acquired in the last years seems to show that the two requirements act in opposite way since the achievement of finer than 3 μm filaments has a detrimental effect on J_c , due to filament distortion.

The constructive processes shall be optimized. For obtaining 2.5 μm filament, a wire of 0.87 mm diameter needs 43500 filaments. The only way for getting this result is to either use the double stacking method or the so-called hexagonal-cell approach, which is a single stacking method, where a relatively small number of starting elements are first stacked

into thin hexagonal tubes, which are then stacked into the billet, with initial dimensions 250 mm [9]

The second main source of losses (20%) is due to the coupling currents inside the wire. The reduction of this contribution depends on both the possibility to obtain a very small twist pitch (few mm) and on the use of copper matrix doped with manganese and/or including CuNi barrier.

Of course, once a satisfactory set of solutions has been found for the wire, the critical current degradation due to the cabling shall be investigated.

Furthermore, once a cable has been developed the winding methods shall be tested to check the winding technology involving a conductor potentially more rigid with respect a Rutherford made of copper stabilized wire with no stainless steel sheet. This can be done through the construction of winding models (length 1 m). This activity is also important in view of cold tests aimed to the understanding of the real operating temperature and the effective operating margins. Independently from the minimization of the heat generation during the field variation, the problem of the heat removal shall be solved in a reliable way. It is important to optimize the heat transfer from conductor to the coolant so to limit the temperature rise [8].

Table 1

Actual and future characteristics of superconducting wire for fast cycled magnets (A wire around 1 mm diameter has been considered for this comparison)

Parameter	Actual (LHC dipole type)	Low Losses wire	
		Target	Factor of reduction
Filament Diameter (μm)	6	2	3
Wire twist pitch (mm)	25	4	40
Transverse resistivity ($\text{n}\Omega\text{m}$)	0.214	0.650	3
Cable twist pitch (mm)	100	100	1
Crossover Resistance R_c ($\text{m}\Omega$)	0.04	20	500
Adjacent Resistance R_a ($\mu\Omega$)	64.0	200	3

4. CONCLUSIONS

The possibility to operate accelerator machines at high energy and high intensity is strictly connected with the technological developments of low losses superconducting dipole and quadrupole magnets for field as high as 6 T. The maximum of efforts shall be devoted to the superconducting wire and cable developments aimed to obtain wires with 2 μm filaments, embedded in a Copper-Manganese matrix, involving in case Nickel barriers. The main technological problem is related to the achievement of acceptable electrical transport properties. Once a satisfactory cable has been developed, the winding technology needs to be tested through the construction of short models (1 m) and prototypes (full scale), which, once cold tested, may allow to validate our hypotheses on the losses (in terms of temperature margin) and on the real performances of the conductor in operative conditions (i.e. R_a and R_c resistances and behavior of the conductor under mechanical cycles). Finally, life tests are essential for this kind of magnets, to check the mechanical structure and the materials choice, and to validate as well the maintenance of the mechanical properties for long time cycling operations: actually, this kind of study has never been attempted.

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