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Composite superconducting wires for fast ramped magnets

G. Iannone [a, *], F. Quero [a], U. Gambardella [a], P. Fabbricatore [b], S. Farinon [b], G. Volpini [c]

[a] INFN-Sezione di Napoli, Complesso Universitario Monte, S. Angelo, via Cintia, 80126, Napoli, Italy
[b] INFN-Sezione di Genova, via Dodecaneso 33, 16146, Genova, Italy
[c] INFN-Sezione di Milano, Laboratorio LASA, Via F.lli Cervi, 201, 20090, Segrate, Milano, Italy

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Recently the need for fast ramped superconducting magnets in new particle accelerator pushed the development of a new class of NbTi wires able to operate at magnetic ramp rates in the 1T/s range with ac losses that can be handled by ordinary cryogenic systems, *e.g.* few W/m in long dipoles. During the last decade INFN, in the framework of an international cooperation for the developments of fast ramped superconducting dipoles, launched a wire development program which stepped in three phases of wire design and industrial production. The aim of the program was to develop superconducting wires to be used in the construction of a full size superconducting fast ramped magnet (namely a dipole). This paper describes the main steps towards the development of a low loss superconducting multi filament wire. Three main ideas were the pillars of the development activities: the reduction of the geometrical filament size down to 2 μm, the use of CuMn resistive barriers to reduce the inter filament coupling currents, and the reduction to the minimum allowable value of the twist pitch.

1. Introduction

The superconducting cables presently involved in bending and focusing magnets for particle accelerators have, as basic element, a multifilamentary superconducting wire. The main superconducting applications in accelerators till now are involving NbTi wires (*e.g.* HERA at Desy, Tevatron at Fermilab, Large Hadron Collider at CERN), which have a critical temperature of $T_C = 9.2$ K (at $B = 0$ T) and a critical field of $H_{c2} = 14$ T (at $T = 0$ K). Typical critical current density for this material is as high as $J_c = 3$ kA/mm^2 at $B = 5$T, $T = 4.2$ K. The use of a superconducting material is just a part of the problem in making a superconducting cable able to carry such high current values.

A superconducting wire suitable for application in accelerators actually is a composite made of finely divided different materials, i.e. thin filaments of superconducting material, a normal conducting matrix and possibly thin barriers or additional different materials included in the matrix [1,2]. Several wires are twisted together in order to reach the required current value in a magnet. In addition to ensure structural support and electrical insulation for the cable winding, special composite laminates are used in superconducting magnets [3,4].

In order to work properly, the wire must be cooled down to liquid helium temperature. Due to the high cost of the refrigeration systems it is crucial the minimization of the thermal losses at low temperature, which, in addition to increasing operational costs, may also bring to a decrease of the superconducting transport proprieties. Although for a superconductor the electrical resistance is near zero, several dissipation mechanisms may appear in a superconducting wire, as it will be described in Section 2.

In addition to gain thermal efficiency, the use of new superconducting materials is envisaged since 1989 with the discovery of high temperature superconducting materials (HTS) [5]. However, additional difficulties have been introduced in the structure of a superconducting wire based on these new materials, which make them not yet ready to be used in high reliability devices.

Despite the large number of superconducting materials used in manufacturing superconducting wires or tapes, *e.g.* NbTi, Nb_3Sn, MgB_2, and 1G and 2G HTS tapes, based on high Tc superconductors BiSCCO and REBCO, respectively, the most used one in practical application is still the niobium based alloy NbTi. This is due both to its unsurpassed metallurgical features and to its low cost and wide availability. Nowadays, improved technology on this kind of superconducting wire has made it reliable in several fields ranging from accelerator magnets to sophisticated and stable Magnetic Resonance Imaging (MRI) solenoids.

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[*] Corresponding author. Tel.: +39 089 968271.
E-mail address: iannone@sa.infn.it (G. Iannone).

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Our application, the fast ramped superconducting magnets, covers highly dissipative working conditions for a superconducting wire at cryogenic temperature, which causes high power demand at room temperatures, *i.e.* large operational costs. For this reason it is of fundamental importance to develop superconducting wires able to minimize the dissipated power at low temperature both for maximizing the magnet stability and for reducing the cost of refrigeration.

In the past, a similar superconducting wire was developed within the R&D efforts for the SSC accelerator project [6]. Despite some good results, the developed process did not appear easily reproducible, and industrial scale production cannot be guaranteed. The Italian Institute for Nuclear Physics (INFN) and GSI Institute of Nuclear Physics in Darmstadt (Germany), in the framework of DISCORAP (Dipoli SuperCOnduttori RApidamente Pulsati) project, besides the realization of a fast ramped SIS300 dipole prototype [7,8], also carried out a wire development program to manufacture a low loss wire for this application [9–12] to get a maximum dissipated power of 5 W/meter on the final dipole. The development program was performed in three steps: i) the first layout of the wire, which was used in the winding of the DISCORAP prototype dipole, was made of 3 μm thin NbTi filament with CuMn interfilament matrix resistive barriers, manufactured at Luvata Pori; ii) a second generation wire, also manufactured at Luvata Pori (Finland), had different CuMn barrier layout, which has been later used in the winding of a second dipole developed under the CRISP (Cluster of Research Infrastructures for Synergies in Physics) European project; iii) a third generation wire had a reduced filament size, 2 μm, and has been manufactured by EAS Bruker (Germany).

In this paper we summarize the main transport and magnetic properties measured on the three generations so to evaluate the main contribution of the wire losses to the total dipole dissipations. In Section 2 we briefly resume the main mechanisms of power dissipation in superconducting wires while the fabrication process of the superconducting composite is described in Section 3. In Section 4 the improvement in wire design is described through different wire generations, while experimental results for hysteretic losses are presented in Section 5. In Section 6 the electromagnetic *ac* coupling is analyzed by means of both ac susceptibility measurements and numerical simulations. Conclusions are drawn in Section 7.

2. Stability and dissipations in a composite superconducting wire

Despite its key feature, *i.e.* the zero resistance state, a superconducting wire has its own intrinsic dissipation mechanisms, related to the fact of being able to transport current. In fact, the transport of current in technological superconductors, called Type II superconductors, occurs for a mechanism where the magnetic field is able to penetrate the superconductor, in form of fluxons (quantized magnetic flux) which enter into the superconductor as the external field rises or the current increases [13]. The fluxon motion by the Lorentz force generated by the bias current is intrinsically dissipative. In fact the varying magnetic flux gives rise to voltages across the material, and consequently generates heat that may cause a local temperature increase. Usually fluxons are pinned to structural defects or impurities, called pinning center, always present or artificially induced in superconducting material. The more the pinning is strong, the larger is the critical current.

Under certain conditions, the so called “flux jumping” dissipation effect arises in high current density superconductors, due to a sudden motion of a bundle of fluxons inside the material [1].

The most successful remedies against flux jumping consist in reducing the flux motion (adiabatic stability) or removing the heat generated (dynamic stability). Both remedies involve a thin subdivision of the superconductor. In fact, concerning the adiabatic stability criteria it is possible to define a stability parameter β for a superconducting wire [1]:

$$\beta = \frac{\mu_0 J_C^2 a^2}{\gamma C (T - T_C)} \tag{1}$$

where a is the filament radius, J_C is the critical current density, γ the material density, C is the heat capacity and T_C the critical temperature. To ensure the adiabatic stability a value of $\beta < 3$ is required, thus, for a NbTi wire, the filament radius have to be kept <<100 μm.

Consequently, in order to deal with reasonable current levels, a superconducting wire must be composed by several superconducting thin filaments. Commercial superconducting wires are therefore manufactured in the form of multifilamentary composite, consisting in several filaments subset, called bundles, embedded in a matrix of normal metal. Copper is usually chosen for its good electrical and thermal conductivity, and also for its ductility, which is very helpful in the fabrication process. The use of copper also promotes both dynamic stability against flux jumping and protects the conductor from burn out in the case of quench (*i.e.* a sudden transition to normal conducting state somewhere in the wire), as it offers alternative path to the flowing current. The dynamic stability in a multifilamentary wire is defined through Eq. (2) expressing the characteristic distance d_{st} in which the heat is driven away from the filaments faster than it is being generated [9].

$$d_{st} = \sqrt{\frac{k(T_C - T)(1 - \lambda)}{\lambda J_C^2 \rho}} \tag{2}$$

where κ is the estimated thermal conductivity for the overall sub-element, actually mainly affected by the copper, and λ is the local value for the filling factor of NbTi in the local copper matrix. For round filaments, a runaway instability can occur when the (round) sub-element diameter $d_r > 4\sqrt{2} d_{st}$.

The dissipative nature of the flux motion can be observed directly through a hysteretic behavior of magnetization with respect to the applied external magnetic field, similar to what happens in ferromagnetic material. This dissipation mechanism have been deeply analyzed in the scientific literature in the framework of the Bean's critical state model [14,15]. The hysteretic volume losses depend on the filament size and its critical current density.

The subdivision of superconductor in thin filaments is the only way to obtain a thermally stable wire but it introduces a new dissipation mechanism, as it gives rise to the coupling of filaments in time varying fields [1]. This mechanism is due to induced eddy currents which flow among filaments through the resistive matrix. The twisting of the thin filaments, shown in Fig. 1, just limits these currents partially flowing in superconducting filaments and partially through the matrix. An important parameter is the transverse resistivity ρ_{et} of the wire. The higher ρ_{et} the lower the coupling currents strength. When required, specific large values of ρ_{et} can be achieved by using a more resistive alloy in the matrix, such as CuMn or CuNi, replacing pure copper. Unfortunately the transverse resistivity cannot be increased indefinitely because increasing ρ_{et} decreases the thermal conductivity of the matrix, and consequently the dynamical stability.

3. Wire fabrication process

In this section we briefly summarize the fabrication process of NbTi based multifilamentary composite. Fig. 2 shows a schematic