Development of Scaling Rules for Rutherford Type Superconducting Cables

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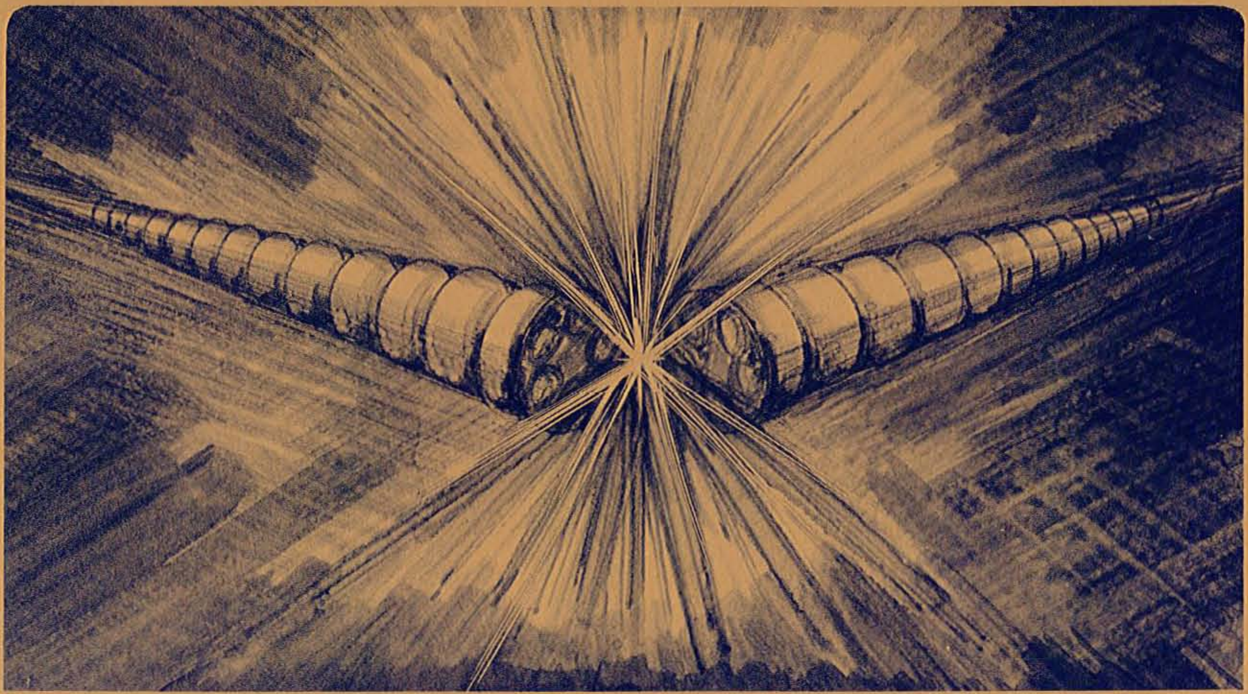

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Abstract

During the R&D phase of the Superconducting Supercollider (SSC) program, LBL was responsible for establishing the parameters for cables used in SSC dipole and quadrupole magnets. In addition, LBL has collaborated with Fermi National Accelerator Laboratory on the design and fabrication of a new cable for use in the Low Beta Quadrupoles. As a result of the development work on these and other cables, we have arrived a set of scaling rules which provide guidelines for choosing the parameters for a wide range of superconducting cables. These parameters include strand size, strand number, keystone angle, percent compaction, cable pitch and compacted cable dimensions. In addition, we have defined the tolerance ranges for the key cable manufacturing parameters such as mandrel size and shape, strand tension, and Turkshead temperature control. In this paper, we present the results on cables ranging from 8 strands to 36 strands of 0.65mm wire and from 8 strands to 30 strands of 0.8mm wire. We use these results to demonstrate the application of the scaling rules for Rutherford-type cable.

Introduction

Rutherford-type superconducting cables are made of an association of strands organized into two layers. The result is a rectangular or trapezoidal cross section cable with a much larger width than the thickness. This basic type of cable is the design which has been used for the Tevatron, HERA, and SSC projects.

The design of a cable for a dipole magnet requires a dialog between the magnet designer, who is concerned with questions of field homogeneity, structural integrity, coil fabrication, etc. and the cable designer, who is concerned with questions of cable manufacturability, critical current degradation, and dimensional tolerances. An example of this dialog is the choice of keystone angle. For reasons of simplicity and magnet structural integrity, the magnet designer may propose an ideal Roman-arch structure. However, because of other considerations such as field homogeneity and excessive cable degradation, a partially keystoned cable is often chosen. In order to make these trade-off decisions in a clear and logical way, we have developed a series of guidelines which can be used in designing new cables. These guidelines will now be described, with reference to the recently completed design of the new wide cables for the 50 mm bore SSC dipole magnet[1].

Cable Design Guidelines

The wire parameters for the new wide SSC cables were kept identical to those developed for the earlier 23 and 30 strand cables. The reasons are: (1) wire processing parameters are set, (2) significant quantity of wire is in the "pipeline", so the delay associated with the change over is minimized, (3) these wire sizes resulted in reasonable values for the number of strands required. More general guidelines which can be used to select the wire size are:

1. A smaller strand diameter will produce a more flexible cable.
2. A small strand diameter will allow a large cold work range after extrusion and this should result in a high J_c[2]
3. However, fabrication costs increase and wire breakage may increase as wire size decreases.
4. The wire size must be chosen so that the required current capacity is achieved within the strand number limit. (The number of strands may be limited by availability of machinery or by tendency for cables to collapse).

The keystone angle and cable compaction are interrelated parameters. The minor edge compaction must be limited in order to minimize the degradation in critical current (I_c) due to cabling, as in shown in Fig. 1. A series of 28-strand cables were made with wire from the same source and the narrow edge packing factor (PF1) was increased, where

$$PF1 \equiv \frac{\text{wire area}}{1/2 \cdot \text{cable thickness} \cdot \text{wire diameter}}.$$

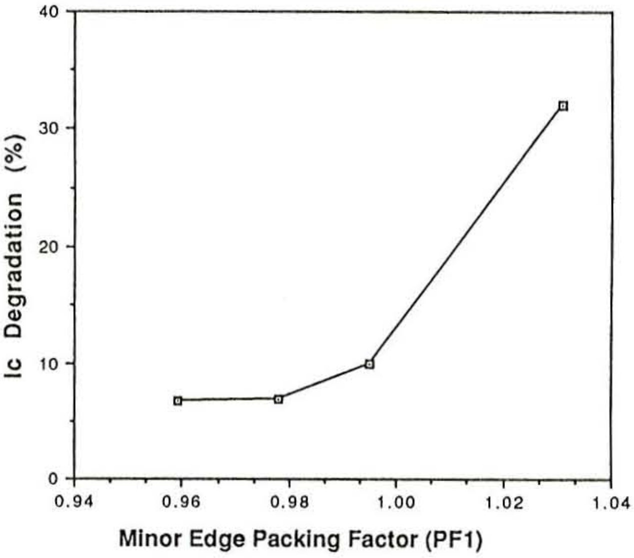

Figure 1. Relationship between critical current degradation and minor edge packing factor for cables made with wire from the same source.

These cables were then measured at Brookhaven National Lab in their cable test facility, in the orientation which yields the critical current of the cable minor edge[3]. As the figure indicates, the amount of I_c degradation increases as the packing factor increases above about 98%. Thus, we limit the narrow edge compaction to about 95% in the initial cable design.

The major, or wide edge thickness should be chosen such that the upper and lower strands are in contact (i.e. 2x strand diameter). This helps maintain cable integrity and uniform dimensions, although the effective cable modulus still varies from minor to major edge. These guidelines meant that the 50 mm bore SSC dipole required a partially keystoned cable instead of a fully keystoned (large angle) cable.

The lay pitch of the cable is chosen as an optimization of the following parameters, where a shorter pitch produces

(1) a less stable cable
(2) a cable which is easier to bend at the ends of the magnet
(3) a more severe deformation of the wire at the edge of the cable
(4) a wider cable, or, if the width is maintained constant, a more highly compacted cable.

The cable width is generally specified by the magnet designer in order to provide the current necessary to achieve the design field value. However, there are several guidelines which the cable designer uses in setting the width specification:

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(1) The cable width is determined very precisely in the cabling operation by the width of the Turkshead rolls. However, the width increase due to the elasticity of the strands so that the dimension measured by the cable measuring machine, with a lateral pressure of only approximately 0.7 MPa, is increased. Also, the actual width dimension of the inner cable in the dipole magnet is probably larger, since the cable is not constrained at the bore of the dipole, thus the cable width tolerance is set at -0.00 mm, + .05 mm.

(2) The cable I_c degradation is even more sensitive to overcompression from the side rolls than from the top and bottom rolls, so compaction from the side rolls must be minimized.

Cable Manufacturing Guidelines

The importance of uniform tension on the strands between the spools and the Turkshead has long been appreciated and controlled[4]. Recently, however, we discovered that the absolute value of the strand tension can play a role in cable I_c degradation. A statistical study first indicated that there was a relationship between I_c degradation and the strand size, with degradation being more severe for the smaller strand diameter. After the other possible causes were eliminated, we concluded that the primary factor responsible for the increased I_c degradation with small strands was the wire tension. The relationship for wire stress, taking into account the wire area and the composite nature of the wire is

$$T = \frac{\Delta}{1+\rho}\tau + \frac{\Delta \cdot \rho}{1+\rho} \cdot \mu \tag{1}$$

where T = wire tension
ρ = copper to superconductor ratio
Δ = wire cross sectional area
τ = yield strength of the superconductors
μ = yield strength of the copper

using $\tau = 107\text{-}110$ MPa and $u = 38\text{-}40$ MPa, we calculate, for a strain in the superconductor of 1%, the maximum allowable tension is 3.4 to 3.6 Kg for a 0.8mm diameter strand with a Cu to superconductor ratio of 1.3/1 and 1.4-1.6 Kg for the 0.53 mm wire with a Cu to superconductor ratio of 1.5/1. When these values were used, the large difference in the I_c degradation between cables made with large or small strands is greatly reduced. The remaining difference can be explained as an artifact due to the fact that no self-field correction is made to the wire I_c values which are used to calculate the cable I_c degradation[3].

A final optimization which is performed during cable manufacturing is the degree of residual twist in the cable. This parameter is important from the standpoint of coil winding and coil behavior after the epoxy curing operation. If the residual twist is in the "wrong" direction, the cable tends to collapse when it is transferred from the storage spool to the coil form[5]. If the residual twist is excessive in either direction, the coil tends to twist when it is removed from the epoxy curing fixture, and subsequent assembly steps are difficult[5]. This cable residual twist is caused by a release of stored elastic energy in the twisted strands as they are deformed in the Turkshead. This effect can be counteracted by applying a back-twist to the wire during the cabling operation. However, care must be taken not to remove so much twist that circulating currents are induced in the strands during magnet ramping[6].

Conclusions

The scaling rules which are discussed in this paper have been used to develop three new cables: the 36-strand Low Beta Quadrupole cable[7], and the wide inner and outer cables for the new 50 mm bore SSC dipole[1]. In the absence of these scaling rules, the time required for optimization of the original 23-strand inner and 30-strand outer SSC cables was several years. In contrast, the new cables mentioned above were optimized over a period of several months.

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