# Effect of cable and strand twist-pitch coincidence on the critical current of flat, coreless superconductor cables[a]

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(Received 15 July 1991; accepted for publication 11 August 1991)

Data are presented which indicate that a very simple technique for enhancing the critical current in flat, coreless superconductor cables is to match the cable twist pitch with the strand twist pitch in such a way that the same group of filaments within each strand is degraded at each successive bend at the cable edges. This coincidence condition minimizes current transfer among filaments, enhances the slope of the voltage-current characteristic, consistently improves the critical current by about 10% in these tests, and is easy to apply.

This letter presents a very simple method to enhance the transport critical current density $J_c$ in flat, coreless superconductor cables, such as the "Rutherford" cables utilized in construction of the Superconducting Super Collider (SSC) accelerator magnets. The technique recognizes and compensates for the fact that the superconductor filaments within each strand are periodically degraded where the strands are bent at the cable edges.[1,2] The degradation in $J_c$ is not uniform across the strand where it is bent, but affects the filaments on the outside of the bend (where the tensile strain is greatest) significantly more than the filaments on the inside of the bend.

When the degraded filaments within a strand at one bend do not match up with the *same* degraded filaments at the next bend, current transfer across the strand matrix material is required to redistribute the current among the filaments and optimize the total current that can be carried by the strand. This produces voltages within the strand as the current redistributes across the normal matrix material, degrading the overall critical current of the cable (especially when measured at sensitive electric-field detection levels).[3]

This situation presents the opportunity for a conceptually very simple method to minimize the bend degradation in flat, coreless cables. The techniques is to *match the cable twist pitch with the strand twist pitch such that the same group of filaments within each strand are degraded at each successive bend* (see Fig. 1). With this technique current transfer among the filaments within the strand is minimized, current-transfer voltages are minimized, and the $J_c$ is not degraded as much by the edge bending. The technique requires only that the cabling twist pitch coincides with an *integral* multiple of the strand twist pitch.

To test this technique, we studied a series of NbTi strands that are candidate superconductors for the construction of the SSC dipole magnets (0.65 mm diam, filament twist pitch of 1.27 cm). The conductors were wound on flattened mandrels in such a manner that the spacing between bends at the mandrel edges occurred at either integral or half integral multiples of the strand twist pitch (see Fig. 1). The thickness of the mandrel and the finite length of strand wrapped around the mandrel edge were taken into account in calculating the width of the mandrel needed to match the bend spacing with the strand twist pitch.

The sample-mandrel assembly was then placed in the bore of a high-field solenoidal magnet such that the winding axis of the sample was concentric with the central axis of the bore of the test magnet. The voltage taps were counterwound along the superconductor in order to minimize the loop area for inductive pickup in the high field test magnet. The samples were held in place with varnish, which in most cases was sufficient to support the Lorentz forces experienced by the strand during testing. $J_c$ data were obtained with transport current applied along the strand in both directions and the results averaged to make a first-order correction for the self-field effect. Precision of the $J_c$ measurements is about $\pm 2\%$.

Figure 2 presents a logarithmic plot of a set of voltage-current ($V$-$I$) characteristics obtained on sample 1 when the strand bends are spaced by 1.5 and 2 strand twist pitches. Focusing on the data for a bend-spacing: strand-twitch pitch ratio, $R$, of 1.5, we see that the slope of the $V$-$I$ curve is relatively low at high electric field. In contrast, for the other set of data where the ratio, $R$, is 2, the slope of the $V$-$I$ characteristic is significantly higher at high electric fields and the critical current remains considerably higher, especially at electric fields below $10^{-7}$ V/cm. Furthermore, when the test is repeated at a smaller ratio of 1, the $J_c$ and slope recover to higher values. Thus, the degradation in these quantities occurs only when the bend spacing is not an integer multiple of strand twist pitches.

This is seen more clearly in Fig. 3 where $J_c$ has been determined at an electric field criterion of $10^{-7}$ V/cm and plotted as a function of the bend spacing (expressed as the bend-spacing strand-pitch ratio, $R$) imposed on the strand for magnetic fields ranging from 3 to 8 T. Figure 3 also shows the results for several other NbTi strands having different local copper-to-superconductor area ratios (that is, the ratio in the immediate vicinity of each filament, not the overall ratio) and diffusion barrier materials. As seen in Fig. 3, the $J_c$ for all samples periodically increases and decreases as the bend spacing alternately matches up with an integral or half-integral number of strand twist pitches. That is, an integral ratio of bend-spacing: strand-twist-pitch ratio consistently produced a $\sim 10\%$ $J_c$ improvement

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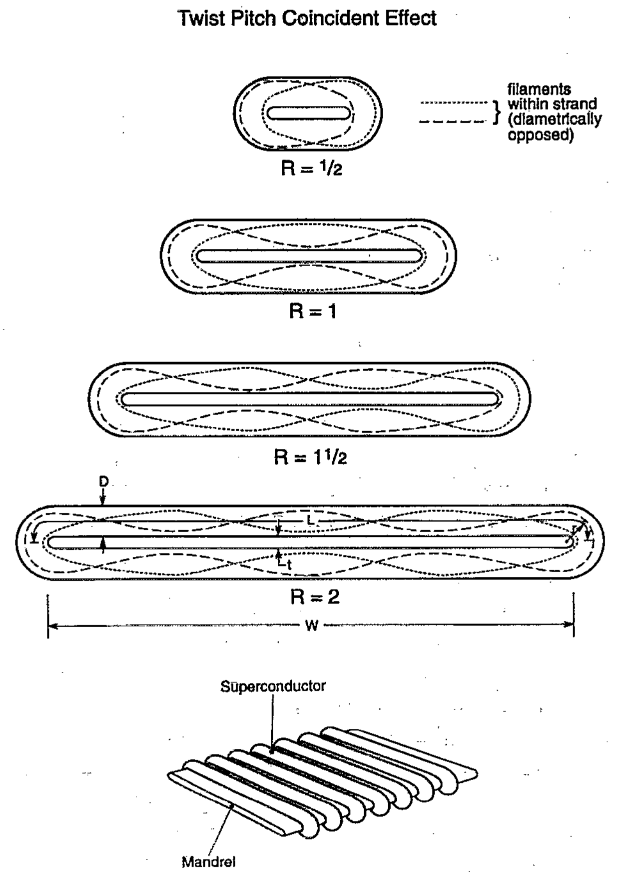


FIG. 1. Test geometry, showing bend-to-bend separations that are an integral or half-integral multiple ($R$) of the strand twist pitch.

in this test (corresponding to about a factor of 10 difference in voltage, as seen from Fig. 2) under widely varying conditions of magnetic field, local area ratio, and diffusion barrier material.

Similar results were obtained for the logarithmic slope of the $V$-$I$ curves. The slope of the $V$-$I$ curve can be represented by $n$,[3–5] defined as

$$n = d \ln V / d \ln I. \quad (1)$$

Plots of $n$ versus the bend spacing are presented in Fig. 4. This figure shows that $n$ periodically increases and decreases with the bend spacing, in direct correspondence to the variation in $J_c$. The highest values of the slope, $n$, are obtained when the bend spacing coincides with an integer number of strand twist pitches. The difference in $n$ can be more than 60%.

The logarithmic slope, $n$, of the $V$-$I$ curve is an index of the amount of inhomogeneity in $J_c$ along the filaments within a strand.[6] As discussed in Ref. 6, however, $n$ is affected only by inhomogeneities along a given filament, and not by differences between different filaments. The data presented here illustrate this point. For the half-integer case, many filaments within the strand experience alternate high and low bend degradation at the points of bending. This forces considerable current transfer to occur among the filaments in order to redistribute the current

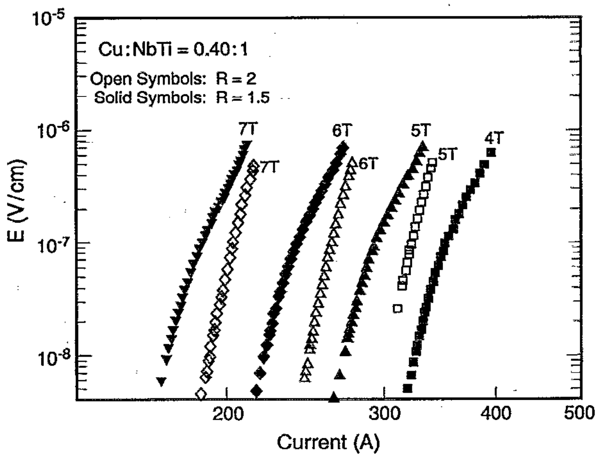


FIG. 2. Logarithmic plot of the voltage-current characteristics of a NbTi strand showing significant degradation in $J_c$ and $n$ when bends are spaced apart by 1.5 twist pitches, in contrast to 2 twist pitches.

among the filaments between bends in order to optimize the total current carried by the strand.

However, when the bend spacing is matched to the strand twist pitch, it is always the same group of filaments that are most severely degraded at each bend, and a large redistribution of current among the filaments is not needed to optimize the total current carried by the strand. Slight mismatches in the bend-spacing: strand-pitch ratio are not important, as long as the affected group of filaments changes slowly over many twist lengths so that a long

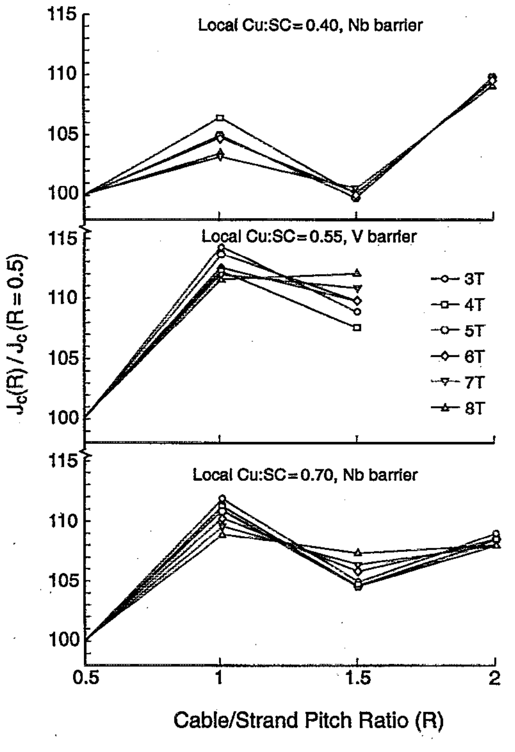


FIG. 3. Critical current of three NbTi strands having different copper-to-superconductor local area ratios as a function of the bend-spacing: strand-twist pitch ratio, $R$. The data show a significant improvement in critical current for integral values of $R$.

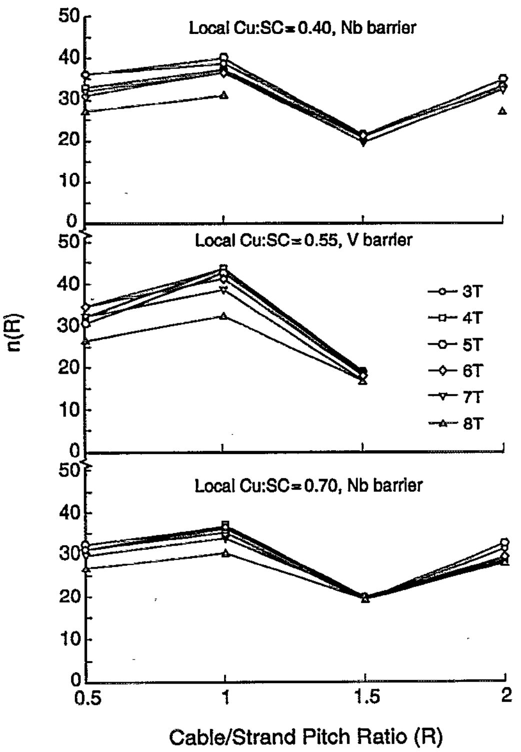


FIG. 4. Logarithmic slope $n$ of the voltage-current characteristics of the same three NbTi strands as in Fig. 3, showing a similar improvement in $n$ for integral values of $R$.

length of strand is available for current to transfer from the degraded group of filaments to the less degraded group of filaments.

The strand length, $x$, needed to accommodate the transfer of current among the filaments is given by[3]

$$x=(0.1/n)^{1/2}(\rho_m/\rho^*)^{1/2}\,D \qquad (2)$$

where $D$ is the strand diameter, $\rho_m$ is the resistivity of the matrix material, and $\rho^*$ is the resistivity criterion. Substituting values for these NbTi samples, we find that the current transfer length $x$ becomes greater than the strand twist pitch at a strand resistivity $\rho^*$ of about $1.4\times10^{-3}$ Ω cm (an electric field of $10^{-8}$ V/cm at 6 T), which explains the degraded $J_c$ seen *at low electric field levels* in Fig. 2 for half integral values of $R$. However, the transfer length $x$ is less than one tenth the strand twist pitch at a high electric field of $10^{-6}$ V/cm, for example, corresponding to $\rho^*=1.4\times10^{-11}$ Ω cm at 6 T. In this regime, the current can redistribute between successive bends and there is little effect, as seen in Fig. 2 *at high electric fields.* From a practical standpoint, however, strand resistivities for magnet applications should be less than $10^{-14}$ Ω cm, so this coincidence twist effect is expected to make a significant difference in such applications.

These experiments were performed on strands wound around a mandrel with a very small cable twist pitch to have a significant number of bends within the small test volume of a research magnet. The method, however, can be simply adapted to the practical Rutherford cable configuration where the strand progresses along the cable with a

TABLE. I. Optimum cable twist pitches for SSC superconductor cables.

| Ratio, $R$ | Inner cable | Outer cable |
|---|---|---|
| 2 | 44.4 mm (1.75 in.) | 45.1 mm (1.78 in.) |
| 3 | 72.1 mm (2.84 in.) | 72.5 mm (2.86 in.) |
| 4 | 98.6mm (3.88 in.) | 98.9 mm (3.89 in.) |
| 5 | 124.6 mm (4.90 in.) | 124.8 mm 4.91 in.) |

reasonable cable pitch. The strand length between bends $L$ is then given approximately by:

$$L=[(P/2)^2+W^2]^{1/2}=R\,S \qquad (3)$$

where $P$ is the cable twist pitch, $W$ is the overall cable width. (If we make the reasonable assumption that the extra small length at the strand's neutral axis needed to round the corner at the cable edge is approximately equal to twice the strand width, then this equation holds exactly.) As before, we desire that $L$ be an integral number of strand twist pitches $S$ (that is, the ratio $L/S\equiv R$ is an integer).

In the case of SSC cables, the strand twist pitch $S$ is typically 12.7 mm (not compensating for back twist). The overall cable width is 12.3 mm for the inner cable and 11.7 mm for the outer cable. Substituting these values into Eq. (3) results in the coincident cable pitches given in Table I. These data thus suggest that setting the cable twist pitch to, for example, 72.1 mm for the inner cable, or 98.9 mm for the outer cable may be a simple way to improve the overall $J_c$ in these cables. Cables with different strand twist pitches or cable widths are readily determined using Eq. (3). (Compensation for back twist can be similarly calculated.) Thus, this coincident-twist method presents the possibility of enhancing the overall critical current simply and with little additional cost, only an adjustment in twist pitch during cabling.

The author is grateful to G. A. Reinacker, N. F. Bergren, and C. C. Clickner for assistance with the measurements; N. F. Bergren, S. L. Bray, and R. Gerrans for help in preparing the cross-sectional photomicrograph; R. Goldfarb and R. M. Scanlan for helpful discussions. The wire used in this study was manufactured by Intermagnetics General Advanced Superconductors, Inc. under DOE-SBIR contract. This work was supported by the U. S. Dept. of Energy Division of High Energy Physics and the NIST superconductor program.

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