

**MANUFACTURE OF KEYSTONED FLAT SUPERCONDUCTING
CABLES FOR USE IN SSC DIPOLES***

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Abstract

The superconducting magnets used in the construction of particle accelerators are mostly built from flat, multistrand cables with rectangular or keystone cross sections.

In this paper we will emphasize the differences between the techniques for cabling conventional wires for cabling superconducting wires. Concepts for the tooling will be introduced.

The effects of cabling parameters on critical current degradation are being evaluated in collaboration with NBS-Boulder. The results of these studies are presented in papers MH-6 and MH-8 at this conference.^{1,2}

Introduction

The Superconducting Super Collider project involves the largest amount of superconducting cable ever envisaged for a single machine. Furthermore, the design calls for exceptional accuracy and improved characteristics of the cable. A part of the SSC research and development program is focused on these important questions.

Superconducting Strands

The wires used for manufacturing these cables are made of superconducting filaments of niobium-titanium embedded in an O.F.H.C. copper matrix. The wire was obtained from several manufacturers, and are described in Refs. 3-5.

The superconducting material is a composite with highly anisotropic properties. The NbTi filaments exhibit a much higher yield strength than the copper matrix, and also respond differently to the heat treatment steps. Any annealing operation at the end of the production must be performed at a temperature low enough not to interfere with the ultimate cold working sequence which is applied to the material in order to produce high current densities. The copper matrix yield strength can vary from roughly 6 kpsi to 50 kpsi, depending on the annealing condition.

The composite strands are twisted around their own axis during the manufacturing process before reaching their final diameter. The purpose of this partial transposition is to improve the electrical behavior of the conductor in rapidly changing fields; however, for the low pulse frequencies applied in accelerator magnets, the required twist period is relatively long (one to four twists per inch).

The twisted nature of the filaments has an important effect on cabling. The superconducting wires show an important "memory effect". Even after the final anneal, any further attempt to change the dimensions or the strand shape causes a counter twist of varying amounts. This particular behavior is very important and will be addressed later.

In order to produce the magnetic field homogeneity required in the accelerator magnets, the cable dimensions must be accurate to ± 0.001 " in

width and ± 0.0002 " in thickness. The cables are made of 20-30 wires, so the accuracy of their diameters must be equal or better than 0.0001".

General Principles of Cabling

Making a cable consists of organizing several strands in a compact manner with an overall stable shape. This means that the product will come back to its original shape after any mechanical attempt to disturb it.

In order to achieve this condition, the gyration radius of each strand's cross section must be minimum (minimal inertia). This is naturally obtained with round cables made of a hexagonal array of wires around a central core:

- If the wires are parallel to the cable axis, we have a compact cable, but the stability is only obtained in straight lengths and under tension.
- If the wires are cabled when their ends are not free to rotate around their own axis ("solid cabler"), the resulting cable contains an elastic torque, but each strand is not twisted with respect to its own reference system. It is twisted with respect to the cable reference system (Fig. 1A).
- If the wires are cabled and twisted at the same time in the opposite direction with respect to the cable reference system at the ratio of one twist for one turn of the cabler's barrel, we obtain a stable cable which does not show an elastic torque. When we try to uncable any one of the strands, with the ends fixed, we do not observe any twist because the planetary motion has already changed the reference system (Fig. 1B).

This second process is the usual one currently applied in the cabling industry.

These general principles are used as guidelines in order to make cables from twisted strands which will lie flat. However, in order to manufacture flat or keystone cables, we must modify somewhat these general principles.

The rectangular or keystone cross section made of two strand layers is far from the minimal inertia condition; furthermore, there is no core to support the strand's radial pressure, and the primary tendency of such a cable is to collapse under the tension needed to produce the cable.

Cable collapse can be avoided if the flattening in the turkshead is large enough to reshape the strands into a polygonal cross section which increases the wire to wire friction and locking effect on the cable edge. This stops the strand's radial motion toward the cable axis. However, this flattening must not cause degradation of the superconductor by filament breakage.

Wire tension is generated at several locations in the strand path: (1) a brake on the wire spool to avoid free wheeling, (2) a brake on the wire itself to provide a constant straight path up to the mandrel tip and finally, (3) pulling effort to shape the cable in the turkshead rollers.

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There are several things which can be done to reduce the cable tension; a highly polished mandrel (on which the strands' spirals are preformed immediately before flattening in the turkshead) can help. An adequate lubrication on the mandrel is essential; however, excessive lubrication can cause the cable to slip on the pulling capstan.

During a cabling operation performed in the "solid cabler" mode, we can observe a twist pattern on the superconducting wires between the spools and the turkshead. A common but incorrect impression is that the rotation of the cabler drum generates this twist. In fact, it is due to the memory release phenomena associated with the strand twist which was mentioned earlier. This explains why a cable made of previously twisted strands, as is generally the case, has to be cabled in the opposite direction from the original wire twist. Sometimes, the memory release effect exceeds the necessary planetary twist; we have mentioned earlier that a light over-twist gives more compact round cables. This is not true for flat or keystone cables due to the lack of solid core on which the external strands could exert pressure. If this happens, the cable shows a general residual twist.

The choice of the correct planetary ratio could be confusing for some observers because, if we need to remove more than 1 twist per drum turn, the planetary twist looks to be in the wrong direction versus the usual one.

There are many factors involved in the determination of the optimal over or under twist:

- Number and size of the NbTi filaments
- Value of the Cu/SC ratio
- Level of annealing of the copper matrix
- Degree of compaction in the turkshead

The torque stress configuration, natural or that resulting from the planetary, is periodic along the wire due to the fact that the cold work in the turksheading operation is mostly generated on the thinner edge of the cable. The half pitch length of wire between the interlocking points on the edges is much less cold worked, and the upstream twist torque is partially kept in these segments of wire through the turkshead. It takes several tens of feet operation to obtain a constant upstream torque, and this torque is obviously more uniform for all the wires if their path is equal in length.

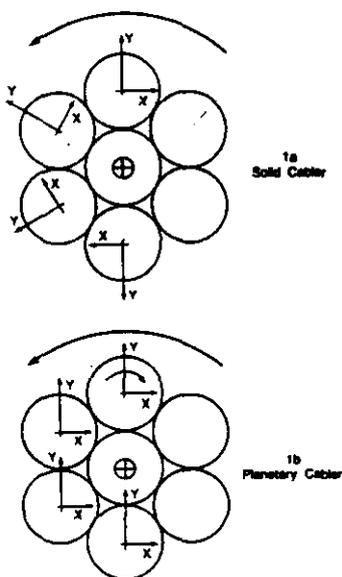


Fig. 1. Two Cable Modes

Design of a Cabling Machine

According to the principles listed above, the design of a good cabler should obey some simple rules:

- o The wire paths, from the spool to the turkshead should be of the same length.
- o A spool planetary drive with several reduction ratios should be available.
- o The wire tensioners should be able to induce a constant tension for each strand from the beginning to the end of the spool.
- o A mechanical transmission should connect the main rotation drive and the pulling device.
- o The pulling device (capstan or caterpillar) should not allow any cable slippage.
- o An accurate positioning device should give a true measure of the distance between the mandrel tip and turkshead center plane.

Mandrel Design and Positioning

The mandrel is one of the forming tools for the cable; the two wire layers are contained externally by the turkshead aperture and internally by the mandrel. The mandrel is a transition positioning tool between the conical surface of the wire array to the straight or keystone cross section of the cable. The position accuracy of the mandrel is a very critical parameter in the cabling process; the strands should never have enough freedom to cross over each other. The mathematical definition of the surface containing the strands is an hyperbolic conoid, the strands being one of the generative family.

In order to avoid additional pulling force due to friction of the strands on the mandrel, it should be:

- made of hard material
- carefully polished
- lubricated
- shaped as close as possible to the internal tangential surface of the wires

Consequently, the mandrel should look like a conical blade, the edges of which are converging to the width of the turkshead's aperture and the faces converging to the center plane of the cable; the tip of the mandrel being the last tangential contact point with the strands. Due to the capstan effect, any discontinuity in the wire back tension is dangerously amplified proportionally with the friction on the mandrel.

An alternate mandrel design (constant perimeter design) was proposed several years ago. The perimeter of the mandrel was calculated to be equal to the internal perimeter of the tube strands in close contact. However, this design has the following disadvantages:

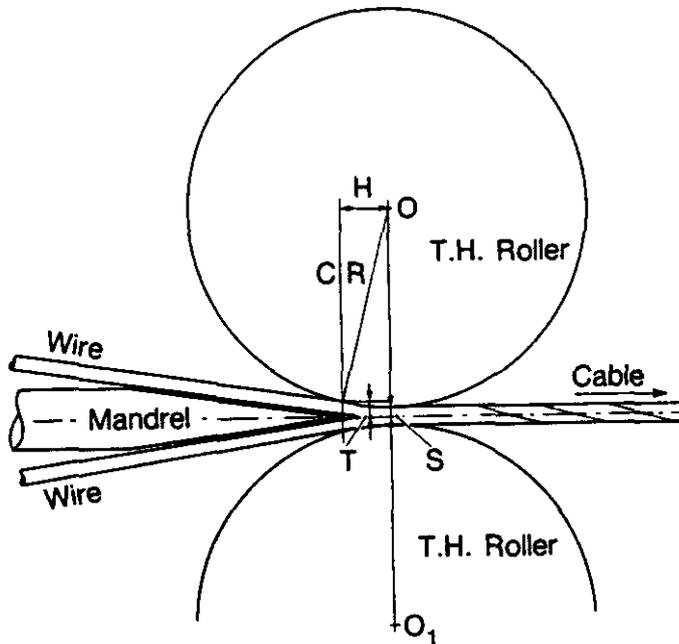
- The friction of the strands is increased due to the length of the contact.
- The shape transition makes compulsory the tip's enlargement; consequently, more drag is generated.
- The core of the mandrel is small in diameter due to the size of the wires usually cabled. This produces an unwelcome flexibility of the tool.

The theoretical positions of the mechanical elements involved in the turksheading operation are given in Fig. 2. and is the minimum distance between mandrel tip and turkshead center. We can also use this formula to evaluate the maximum distance which will be obtained with a "T" value incorporating one additional wire diameter; this corresponds to a possible crossover accident in the cable.

In the case of a keystone cable, we obtain two values for "S", one for the minor side, one for the

major, and two values for "H". In this way, we can evaluate how the mandrel tip must be wedged to obtain an equal guidance across the cable width.

The only lubrication point in the cabling process is at the part of the mandrel in contact with the wires. After the cable exits the turkshead, any oil is undesirable because it could interfere with the pulling device operation by causing slippage on drums or belts. An air wipe installation on the cable after the turkshead is probably the best solution. We have used successfully a solution of synthetic oil in a solvent such as Freon which evaporates in a short time.



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- T = 1/2 mandrel tip thickness + 1 wire O.D. + play + Tolerances
- R = Turkshead roller radius
- C = 1/2 cord at H distance from center
- S = 1/2 cable thickness

$$H = \sqrt{R^2 - C^2} \quad C = R + S - T$$

$$H = \sqrt{R^2 - (R+S-T)^2}$$

H = minimum distance between mandrel tip and turkshead center

H = maximum when T = 1/2 mandrel tip + 2 wires O.D. + play + tol.



Fig. 2. Mandrel Position

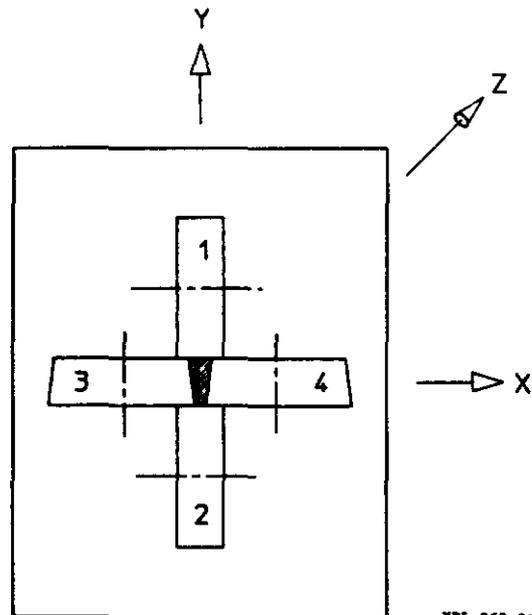
Turkshead

The turkshead is the sizing machine in the flat cabling process. Most of the forming performed in the industry this way is a rectangular cross section. The standard setting of the machine gives an infinity of dimensions from zero to the width of the rollers.

For the keystone cables we need at least one roller ground to the keystone angle. Two rollers ground to the half angle is more symmetrical; four ground rollers give symmetry and wear resistance.

However, there are lateral forces applied on two of the rollers and these forces, added to the variability of the assembly, can change the angle by as much as 25% for a used machine not carefully assembled. Such variations are incompatible with the accuracy needed for the cable dimensions.

Another way to configure the turkshead is to grind two rollers at the cable width and at half the keystone angle. The other two rollers are kept flat and apply a symmetrical pressure on the sides of the keystone rollers. This design (Fig. 3) gives a far more constant dimension of the product; however, we need a set of two rollers for each cable shape, the only flexibility being the average thickness of the cable.



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Fig. 3. Turkshead Settings

Pulling Device (Capstan or Caterpillar)

Capstan and caterpillar are the main two types of pulling devices. Both of them should be perfectly synchronized with the rotating drum of the cabler in order to obtain a constant cable pitch and avoid an accidental overwrap of the mandrel with wires. The caterpillar system is self-tailing which means that a sample of the cable can be taken without loss of tension or excessive waste of material.

A capstan does not have the same possibility because it must be followed by a take-up which provides the tension needed for a no-slip operation.

At present, we feel that a caterpillar or belt-wrap capstan is preferable for the R and D cabler; a drum capstan may prove more reliable for a production machine.

Cable of Cables

The use of small cables e.g., 6 around 1 wire, as sub-elements of a larger cable was already proposed several years ago.^{6,7} The main advantage of such a design is to obtain a more flexible cable and smaller superconducting filaments.

We have made some samples of such cables; from the cabling point of view, the main difference is that the sub-element shows a different type of memory effect, no longer initiated by the pretwisting of the elementary wires. The solid core of the sub-element absorbs the radial pressure generated at the time of the sub-element cabling.

The cabling of such a material is more difficult than the cabling of a solid wire: cable collapsing occurs for a much smaller tension of the cable; the locking effect at the cable's edge level is less efficient.

If we define a dimensional ratio $\alpha = 2/n$ with n = number of strands, the cable of cables will lose stability for values of α larger than for solid strand cables.

Estimated values for α :

solid strand cables	$\alpha >$	$\frac{1}{20}$
cable of cables	$\alpha >$	$\frac{1}{13}$

Another weak point for a cable of cables is a lower elastic modulus, mainly due to a larger void ratio. If we try to reduce this void ratio by compaction, we observe a larger degradation than for solid strand cables; however, we may gain stability improvement in magnets through a better helium environment.

Conclusions

We have built at LBL an experimental cabler which incorporates all the recommendations discussed earlier. This machine was made from a large gap lathe which was equipped with a variable frequency drive. (See Fig. 4.)

We have already made over sixty thousand feet of experimental cable and have verified the design philosophy discussed above.

The various cables manufactured with our experimental cabler show good dimensional accuracy. This accuracy results mostly from the use of the "symmetrical setting" of the turkshead.

Cable compaction is a very sensitive parameter for the cable quality; we need a high elasticity modulus with the lowest possible degradation. These two parameters vary in opposite directions as a function of compaction. A compromise has to be found in order to impose cable specifications leading to the best possible magnet.

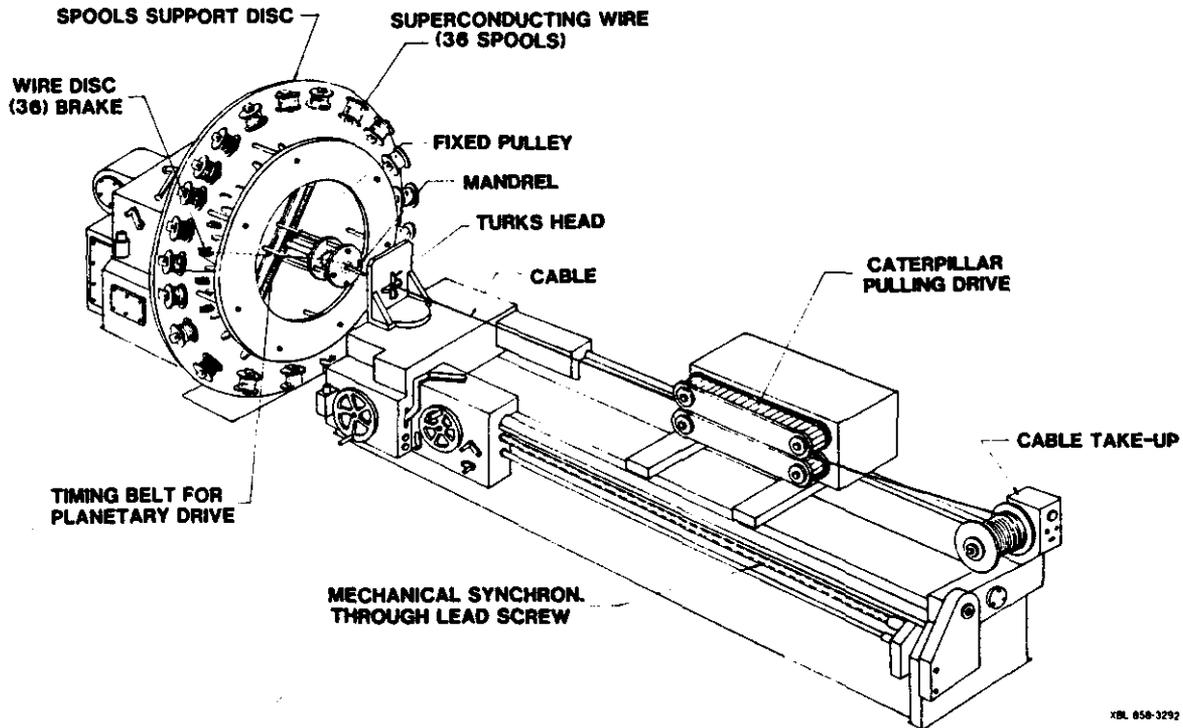


FIG. 4. Experimental Cabling Machine

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