SSCL-365

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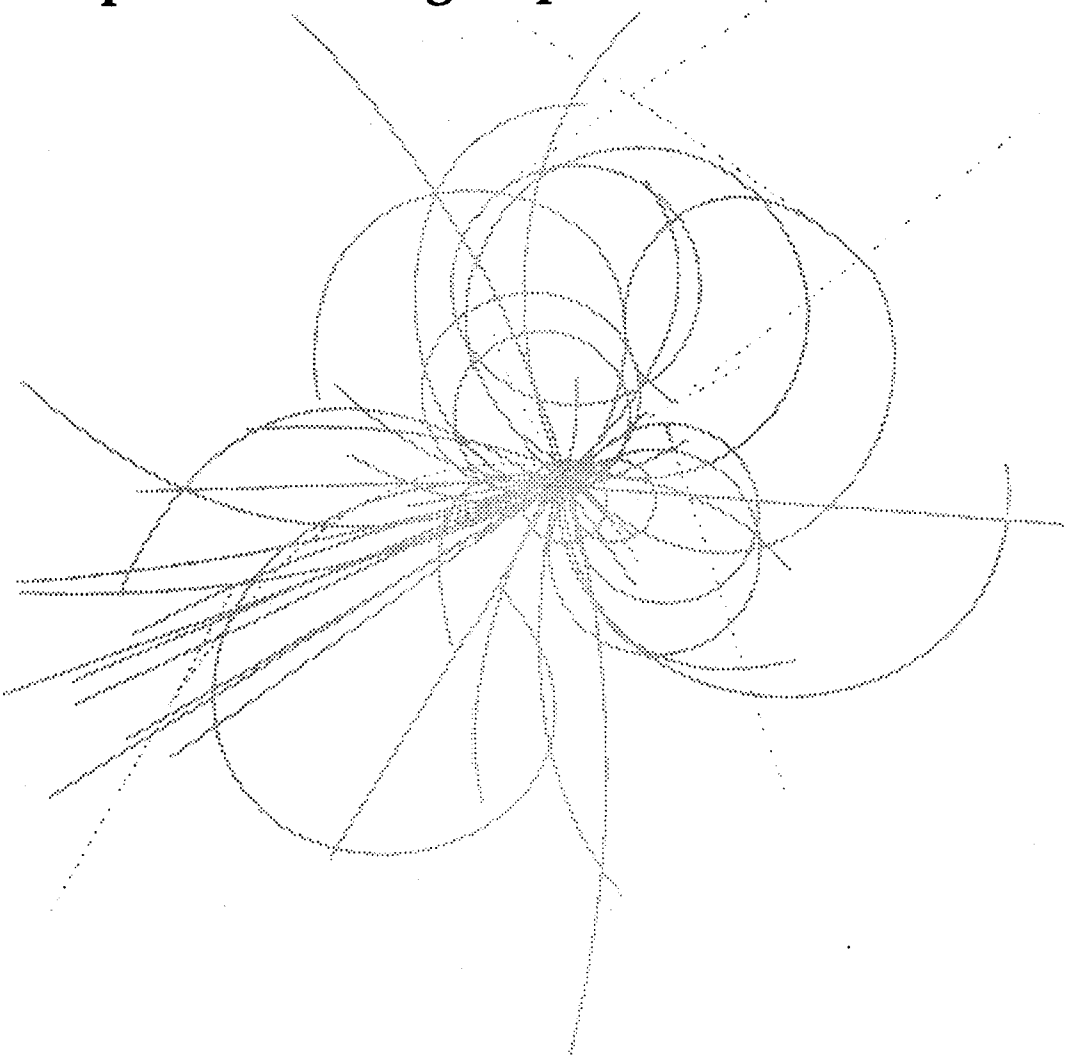
Superconducting Super Collider Laboratory



# Issues and Results in the Development of 2.5 Micron Filament Strand for the HEB

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# ISSUES AND RESULTS IN THE DEVELOPMENT OF 2.5 MICRON FILAMENT STRAND FOR THE HEB

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## INTRODUCTION

The High Energy Booster (HEB) ring which injects protons into the Superconducting Super Collider (SSC) will be ramped with a cycle time on the order of 8 minutes. The current magnet design incorporates a strand with 2.5 μm filaments to reduce the AC loss heating component due to the magnetization hysteresis. The reduced magnetization also makes the correction of the sextupole moment easier. Past experience has shown that Nb-Ti filaments in a copper matrix should have a spacing-to-diameter ratio (s/d) of 0.15 for good fabricability.[1] For 2.5 μm filaments, this results in a spacing on the order of 0.4 μm at final wire size. A Cu-Mn alloy has replaced the copper between the filaments in prototype conductors to effectively eliminate proximity coupling between 2.5 μm filaments which would otherwise occur with copper at this spacing. The resistivity of the material between the filaments is limited by the mean free path being equal to the filament spacing; therefore, cryogenic stability has not been compromised.

This paper discusses design and process parameters in the development of 2.5 μm filament conductor production. Data from current 2.5 μm work from several vendors, some of which are on FFP-type contracts sponsored by the SSCL, are included to demonstrate how close industry is to meeting 2.5 μm conductor needs. If the SSCL were unable to bring 2.5 μm conductor into production within about two years' time, a fall-back HEB design with 6 μm filament conductor would be utilized. Therefore, a strong emphasis on manufacturability is reflected in the key issues. The sole purpose of this paper is to establish a common level of understanding of fine filament needs of the SSC; therefore, the data will be purposely presented without vendor affiliation. The authors have paid careful attention to details to avoid the release of proprietary information in this paper.

## ULTRA-FINE FILAMENT CONDUCTOR PRODUCTION ISSUES

Production processing of 2.5 μm conductor in a minimum of 3000 m lengths with satisfactory superconducting and mechanical properties will require extending our current technology. In the design and processing of 2.5 μm filament conductor, the following issues must be addressed and are receiving emphasis in the present 2.5 μm conductor development program at the SSCL:

1. Reduction of proximity effect coupling between filaments at final wire size.
2. Reduction or elimination of compound formation during the thermo-mechanical processing operations associated with very-fine filament conductors through suitable barrier construction and heat-treatment schedules.
3. Reduction or elimination of filament distortion during all phases of processing.
4. Understanding of the mechanical properties of the matrix material as filament spacing approaches submicron dimensions.
5. Control of mechanical properties of final strand through composite design or strand processing details.
6. Development of adequate critical current density (i.e., attempt to meet or exceed specifications.) while at the same time ensuring suitable mechanical properties in the conductor, especially piece-length.
7. Demonstration of adequate mechanical performance to ensure satisfactory cabling performance and a minimum of cabling degradation.

SSC specifications for 2.5 μm conductor (SSC-M30-000160 for Inner and SSC-M30-000161 for Outer) are essentially the same as those for 6 μm conductor with several modifications. Obviously, the filament size is specified to be nominally 2.5 μm and the spacing between filaments is approximately 0.4 μm to maintain a similar s/d ratio as in 6 μm filament conductor. The critical current specification for 2.5 μm material, which is the same as for the current 6 μm conductor, incorporates additional conductor margin. While it appears that this current level is obtainable, not enough material has been processed to date to evaluate manufacturability.

The total number of filaments is fixed by the copper-to-superconductor ratio (nominally 42,000 for Inner conductor and 24,000 for Outer conductor). In the case of a double multifilament extrusion design, considerable flexibility exists in the number of filaments in the first stacking and the geometric design of the final multifilament stack. The SSC will require that a single billet design be used for all Inner conductor and an equivalent design for all Outer conductor. Vendors must choose a billet design and diameter which offers the best manufacturability, performance, and cost.

A small amount of manganese (~0.5 weight %) has been added to the copper between adjacent filaments (i.e., the copper in the monofilament) in previous 2.5 μm material. This effectively diminishes proximity effect coupling, which would produce an effective filament diameter larger than the actual diameter. The exact amount of manganese and the spacing between filaments (i.e., design of the filament array) for optimal coupling-free superconducting properties are not known; nor are the mechanical properties for producing high-quality cable. Because of the limited amount of time available for development, 2.5 μm conductor production probably will not deviate far from the 0.5 wt.% addition.

Current 6 μm filament diffusion barrier design must be modified for 2.5 μm filaments. The option of using single wrap or multiple wrap barriers still exists; however, all Nb must be procured to the SSC specification for Nb sheet, SSC-MAG-M-4001. As a guide to billet design, the SSC expects that the nominal barrier thickness for 2.5 μm material should have a thickness at the last heat treatment size equivalent to that of the 6 μm filament material with a 4% barrier, i.e., on the order of 9%. The barrier thickness required is dependent on the uniformity in the thickness of the barrier at heat treatment sizes. The goal here is to establish

sufficient process margin by determining an optimal barrier thickness, and to ensure a combination of good piece length and adequate critical current density performance.

The thermo-mechanical optimization of 2.5 μm conductor is likely to be different from 6 μm conductor. It is important to use sufficient material during the thermo-mechanical optimization to obtain some information on piece length and on critical current vs. field properties. It is anticipated that a minimum of 5 kg for each heat treatment is required to accomplish this task. It is important to obtain adequate, but not excessive, $I_c$ from this material. But it is more important that mechanical properties and piece length are not compromised.

The mechanical properties characterized primarily by the sharp bend and spring back tests are as important as the superconducting properties in the production of useful conductor. Dramatic changes in mechanical properties of metal composites can occur when the filament separation is less than 1 $\mu m^2$. Part of final development work on 2.5 μm conductor is to understand any potential for deleterious work hardening. This knowledge should ensure that processing can be developed to avoid excessive filament distortion while maintaining satisfactory mechanical properties for good cabling performance and a minimum of cable degradation.

## RESULTS IN ONGOING 2.5 MICRON DEVELOPMENT

We have evaluated prototype conductor from several vendors. All material surveyed used Nb barriers and a triple extrusion process. The billet designs are considered proprietary and are not disclosed here. A brief description of the image analysis is given here. A plot of the frequency vs. gray level is made from the stored image during the image analysis. A typical plot is shown in Figure 1, where two distinct peaks are shown: one for the filaments and one for the matrix. A gray level is chosen at the minimum between the two peaks to define the boundary between the filaments (shaded) and the matrix. A binary image is then created with all pixels with gray level below the boundary set to be black to represent the filaments. All remaining pixels are set to white to define the matrix. A representative binary image is shown in Figure 2. Note that in order to ensure clear journal reproduction, there are fewer filaments in this image than are seen in a typical analysis. A variety of statistical analyses are then performed on the filaments and the pixel statistics are reported here.

Table 1 contains a list of key parameters of some of this material. The Ic, filament uniformity (mean and standard deviation of the filament size measured on SEM images[3], spring back value, and sharp bend results are tabulated to give some perspective on the current level of manufacturability. The $I_c$ values are quoted from the vendor. The reader is referred to the work of Suzuki et al.[4] and Kanithi et al.[5] for additional 2.5 μm results.

## DISCUSSION

Gregory et al.[6] have shown that Cu-Mn alloy between filaments effectively eliminates proximity coupling until the filament size is well below 1 μm. Therefore it is expected that the proximity coupling is not a major problem. Recent results from Iwaki et al.[4] demonstrate that no proximity coupling exists at any significant magnetic fields in final size 2.5 μm filament conductor.

The barrier thickness in the conductors that come close to or exceed current density specifications appears to be satisfactory for preventing intermetallic formation. Conductors with greatly reduced $I_c$ have shown some intermetallic formation on filaments. However, it is also clear that intermetallic formation is not the sole source of filament non-uniformity. Conductor made by a triple extrusion process can have local filament distortions, especially

for filaments near the outside edge of the sub-elements. The copper between the sub-elements is typically several filament diameters wide. Therefore, in this region the s/d ratio is much larger than for the bulk of the filaments. Under certain processing conditions, the un-mechanically supported filaments can distort into a ribbon-like shape. Images in Figure 3 demonstrate varying degrees of this problem. This filament distortion does not affect the standard deviation of the filament cross-section ($\sigma$) until the distortion is severe. The $\sigma$ is about 13–15% for the current 2.5 μm conductor. This compares to a typical value of 8% for current production 6 μm conductor. It is possible that a three-extrusion process will inherently produce filaments with broader distributions than a two-extrusion process used for 6 μm conductor. It is not yet clear what parameters in the thermo-mechanical processes of conductor processing most affect filament uniformity, given the present case where intermetallic formation has been effectively eliminated with the proper barrier design.

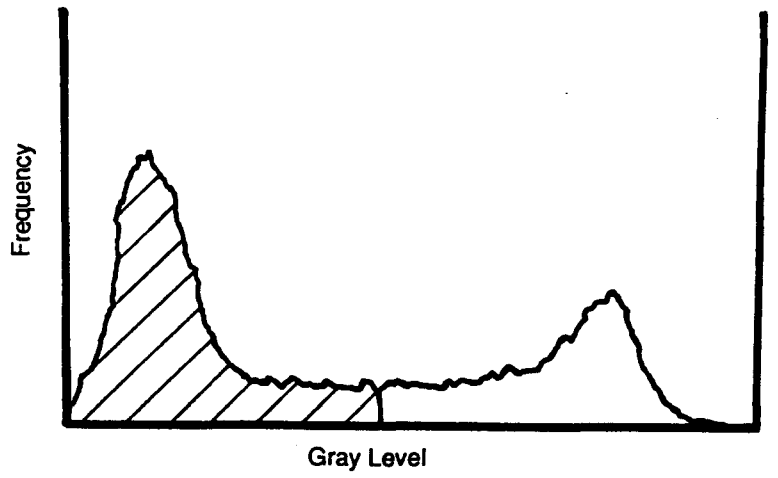


Figure 1. A Plot of Frequency vs. Gray Level from a Stored Image. The minimum in the curve defines the border between the filaments (shaded) and the matrix.

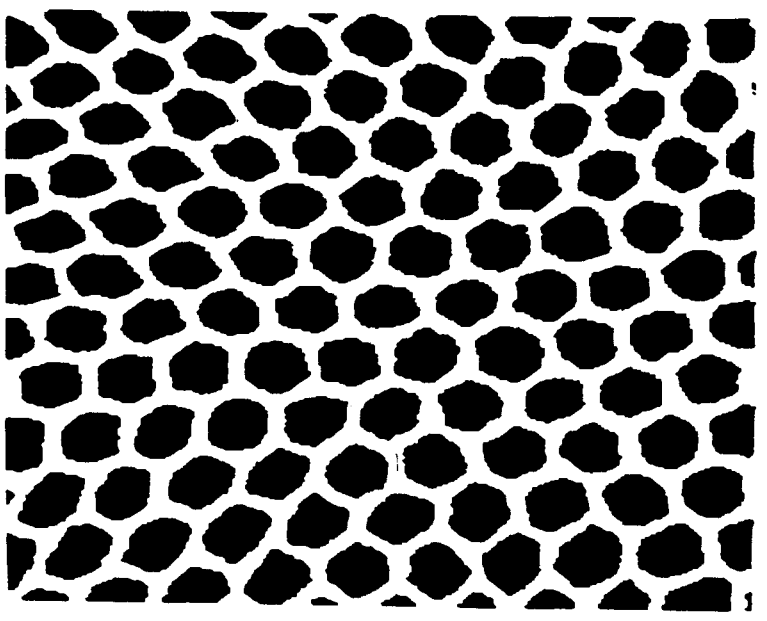

Figure 2. Binary Image Made from the Defined Distribution in Figure 1. Fewer filaments are shown than the number in a typical analysis.

Table 1. 2.5 μm Conductor Data.

| Vendor | Inner/Outer | $I_c$ (amps) | Mean Filament Area (sq. μm) | Filament Std. Dev. (%) | Springback (degrees) | Sharp Bend C or NC/%** |
|---|---|---|---|---|---|---|
| | | | | | | |
| SSCL spec. | Inner<br>Outer | >339<br>>286 | 4.9<br>4.9 | | <980<br><1090 | NC/<1<br>NC/<1 |
| | | | | | | |
| Green | Inner<br>Outer | 337<br>287 | 5.1<br>5.1 | 14<br>15 | 840<br>904 | NC/0<br>NC/0 |
| | | | | | | |
| Blue | Inner<br>Outer | *<br>* | 3.6<br># | 28<br># | 1050<br>1092 | C/70<br>C/70 |
| | | | | | | |
| Red | Inner<br>Outer | 328<br># | 4.7<br># | 15<br># | 768<br># | C/70<br># |
| | | | | | | |
| Black | Inner<br>Outer | 345<br>281 | 4.2<br>4.8 | 13<br>14 | 730<br>925 | NC/0<br>NC/1 |
| | | | | | | |
| Orange | Inner<br>Outer | 200<br>264 | 4.8<br>3.9 | 18<br>15 | 813<br>883 | C/90<br>C/20 |

* Only non-heat treated wire could be drawn to final size.
\# Data not available.
** C = cracked, NC = not cracked; % = percent of broken filaments.

Figure 3. Filament distortion between sub-elements in 2.5 μm conductor made by triple extrusion processes: (left) little distortion, (middle) some distortion, (right) severe distortion. The mechanical properties of these composites degrade as the filament distortion increases.

## ACKNOWLEDGEMENTS

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