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Phase I Final Report

Reduce Nb_3Sn strand deformation when fabricating high J_c Rutherford cables

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ABSTRACT

During Phase I, our efforts were to reduce subelements deformation when fabricating Nb_3Sn Rutherford cables. Our first focus is on 217-sublement tube type strand. We successfully made a few billets in ¾" OD tube with different Cu spacing between subelements, and supplied the strands to Fermi Lab for cabling. Through the rolling test characterization, these types of strands did not have enough bonding between subelements to withstand the deformation. We saw copper cracking between subelements in the deformed strands. We scaled up the billet from ¾" OD to 1.5" OD, and made two billets. This greatly improves the bonding. There is no copper cracking in the deformed strands when we scaled up the diameter of the billets. Fermi Lab successfully made cables using one of this improved strands. In their cables, no Cu cracking and no filament bridging occurred. We also successfully made a couple of billets with hex OD and round ID subelements for 61-subelement restack. Due to the lack of bonding, we could not judge its cabling property properly. But we know through this experiment, we could keep the Nb round, once we select the proper Cu spacing.

Phase I Results

The primary objective of this Phase I was to develop an improved tube type strand with solid Sn design that can be made into a Rutherford cable without subelement breakage and merging. In this Phase I, first we focused on making ¾" OD standard 217-subelement billets, and we tried to improve their cabling-ability by changing the spacing between subelements. We found out for the ¾" OD starting size there is no enough cold work for good bonding between the subelements. Hence, through rolling tests, we could see the Cu crack between the subelements. We scaled up the billet from ¾" OD to 1.5" OD, and constructed a billet, which shows a much better cabling property. Fermi Lab made a 10 meter long cable using this wire. The details are described in the following tasks.

Task 1. Make a standard 217-subelement restacked strand to reach J_c of 2500 A/mm^2 at 12 T, 4.2 K. This strand is the baseline for future billet design and transport properties improvement.

In this first billet, we used our standard design for making filaments. Figure 1 shows the filament structure. The pure Sn rod was inserted in a 0.58" OD/0.53" ID Cu tube and drawn down to get into the 0.5" OD/0.32" ID Nb7.5%Ta tube. The desired Nb/Sn ratio is 3.1. The whole assembly was inserted into a 0.58" OD/0.53" ID Cu tube and drew down to 1.102 mm, and then hexed through the 0.0382" F-F hexagonal die, to get ready for the 217-subelement restack in ¾" OD customized Cu tube.

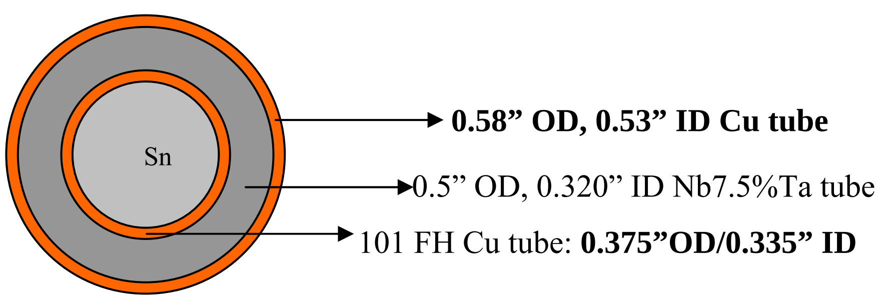


Figure 1. Filament Structure.

Figure 2 shows the restacked structure. The outer Cu tube has a 0.75" OD, and customized internal ID, which is to avoid the subelement distortion in the outer ring. This restack has 192 subelements with 19 filaments in the middle. This billet was drawn down to 0.753 mm, then twisted and overdrawn down to 0.7 mm and even to 0.5 mm. The final strand was denoted as T2075. Figure 3 shows the cross-section of strand after drawing down to 0.7 mm and 0.5 mm.

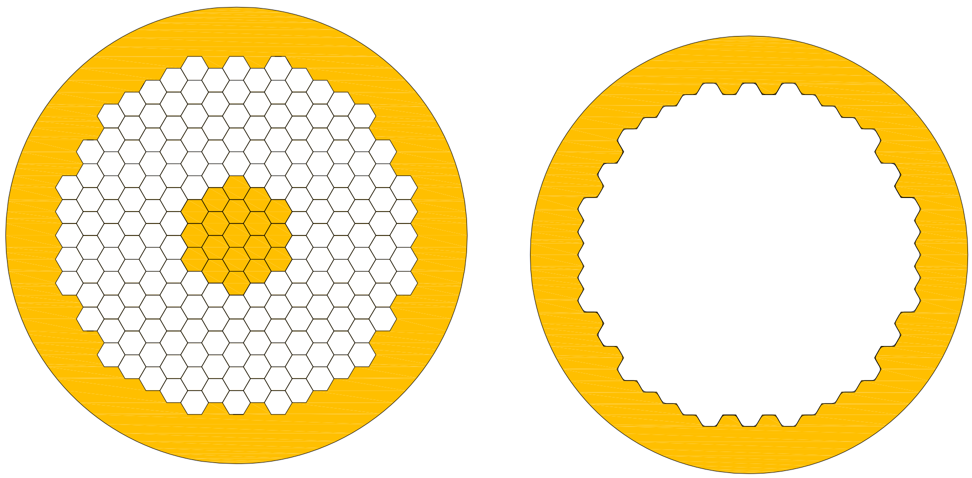


Figure 2. Schematic drawing of 217-subelement restack, customized tube and restack.

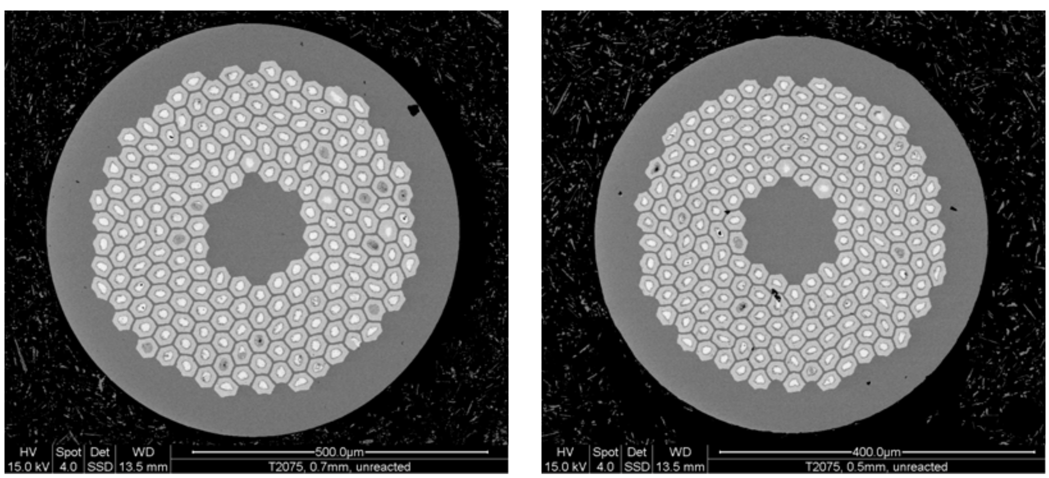


Figure 3. Cross-sections of T2075 at 0.7 mm and 0.5 mm.

This 0.7 mm strand was heat-treated at 625 °C for 200 hours. The strand was characterized at OSU. Figure 4 shows its non-Cu J_c curve with field. The non-Cu J_c at 12 T is about 2440 A/mm^2. This is our standard strand. Through heat-treatment optimization, we should get the J_c over 2500 A/ mm^2.

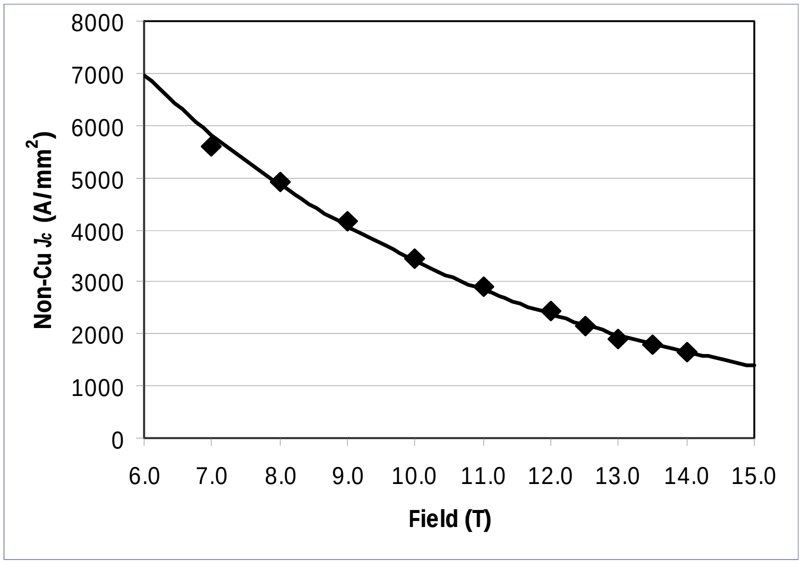


Figure 4. Non-Cu J_c of T2075 at 0.7 mm (625 °C x 200 h).

Task 2: Method one to improve Rutherford cabling: use different Cu levels between subelements, and make a few 217-subelement restacked strands.

The background section of the proposal describes the previous Rutherford cable experiments conducted at Fermi Lab. Fermi Lab indicated that the filament breakage around the edges of the Rutherford cable was similar to what they experienced when they first started to cable SMI PIT Nb_3Sn strands (now being developed by Bruker). This problem was improved by SMI by putting more Cu around the subelements and less Cu around the restack. We used the same initial approach to improve the cabling of the Nb_3Sn Tube Type strands with solid Sn core. In order to create restacked strands with various Cu between subelements, we started making subelements with different thickness of external Cu. In this task, we varied the thickness of the external Cu tube for subelements. Table I shows the plan on the three billets. In Task 1, we made three billets, T2637, T2617 and T2574. T2637 has the same design as T2075 made in Task 1.

TABLE I. Plan on Billets with various Cu ratio between Sublements.

Index	Billet Name	Used Cu Tube dimension (inch)	Cu area % in the subelement
1	T2637	0.58” OD x 0.53” ID	17%
2	T2617	0.60” OD x 0.53” ID	23%
3	T2574	0.62” OD x 0.53” ID	28%

Figure 5 shows the three subelements with different levels of Cu on the outside. Starting from left to right, T2637 used 0.025” thickness Cu tube, T2617 used 0.035” thickness Cu tube and T2574 used 0.045” Cu tube for their subelements. These subelements were chopped, acid cleaned and restacked into the customized ID, ¾” OD Cu tubes for 217-subelement restack. As shown in Figure 2, there were 192 Nb-Sn subelements around 19 Cu filaments in the middle for each restack. Both billets were drawn down, twisted and overdrawn down to final size for characterization.

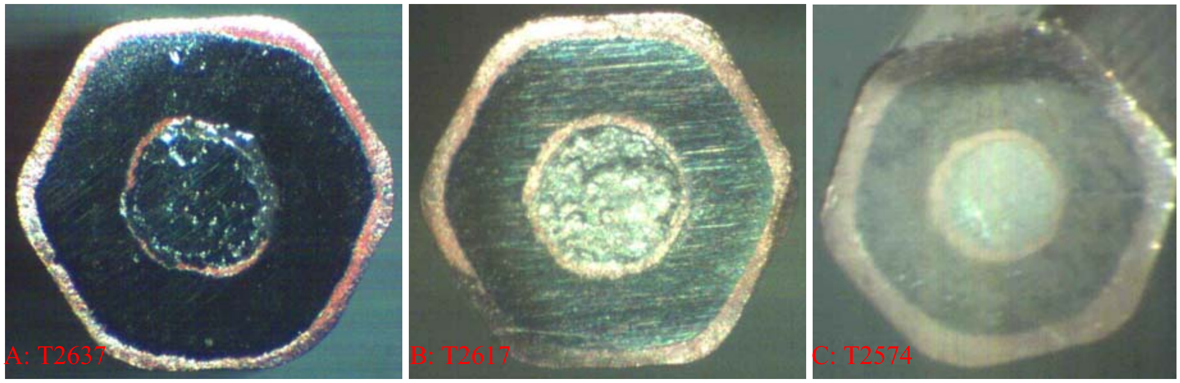


Figure 5. Three subelements with different levels of Cu on the outside.

We used rolling tests to simulate the effects of cabling strands. We selected 1.0 mm and 0.7 mm strands for the testing to show the effect of strand diameter. Figure 6 shows the cross-sections of the round samples at 0.7 mm and 1.0 mm. It is quite obvious to see that the spacing between subelements in T2637 is the narrowest, and that in T2574 is the widest. The spacing between subelements in T2637 is about 10%, that in T2617 is about 15%, and the one in T2574 is about 20%, which are a little different from the designed one since the acid cleaning before restacking removed some Cu.

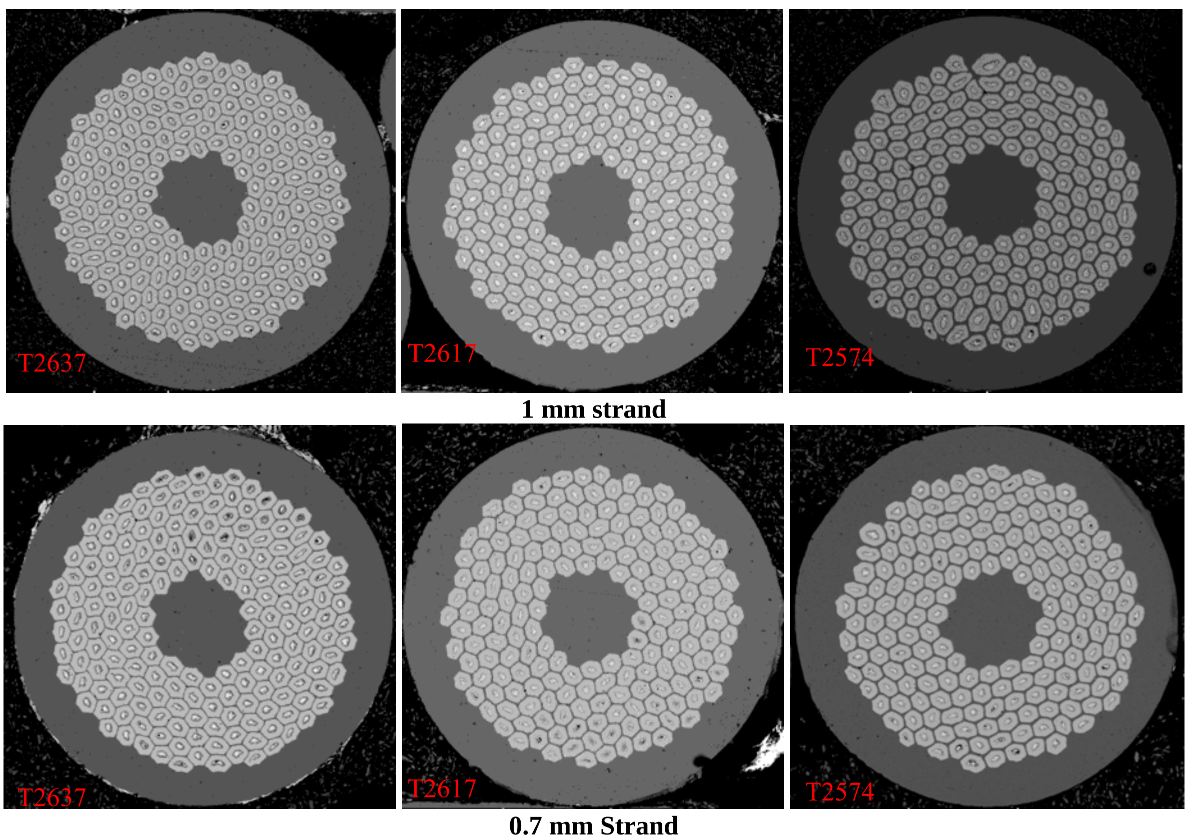
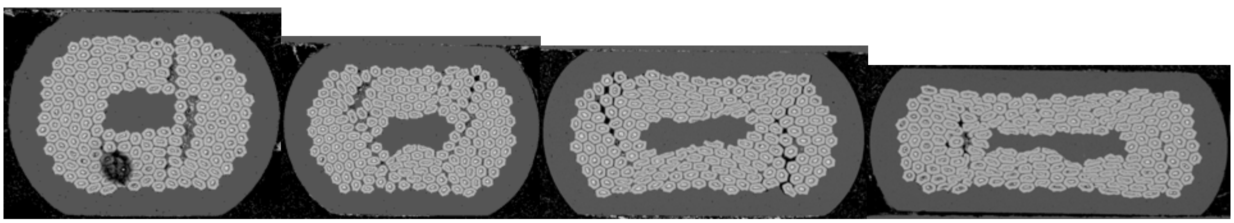


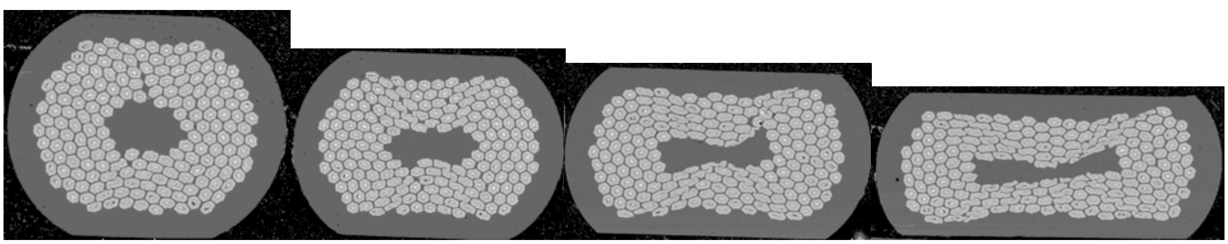
Figure 6. Cross-sections for round wires at diameter of 1 mm and 0.7 mm.

For cabling characterization, firstly, we deformed all the three strands to various levels using a rolling, or flattening, process. We ran each of the strands through a rolling machine, which results in a widened strand with two flat edges. We then measured the resulting strand with a micrometer to confirm the distance between the two flat edges is close to our goal, with an accuracy level of approximately ±0.02 mm. In this study, we looked at four different deformation levels: 14%, 20%, 30%, and 40%. In the case of 1.0 mm, these deformations equated to rolled size of 0.86 mm, 0.80 mm, 0.70 mm and 0.60 mm. In the case of 0.7mm strands, these deformations equated to rolled sizes of 0.60mm, 0.56mm, 0.49mm, and 0.42m. For % reduction we used the formula (OD-RD)/OD, where OD represents the original diameter of the strand, and RD represents the rolled diameter of the strand.

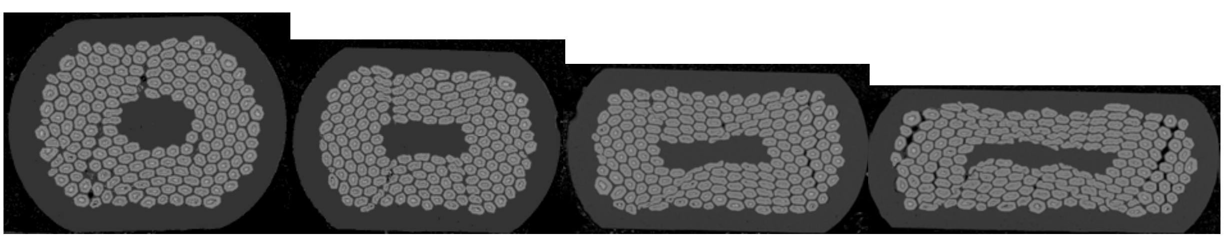
After rolling all the strands, we took the short samples, cold mounted them and polished them to a level of 0.03 microns using a combination of manual and automatic polishing. All the cross-sections were observed under SEM.



(a) T2637 with narrowest spacing (10%) between subelements



(b) T2617 with middle spacing (15%) between subelements



(c) T2574 with widest spacing (20%) between subelements

Figure 7. Cross-sections of the three 1 mm strands with different spacing after different levels of deformation (14%, 20%, 30%, and 40%, starting from left to right).

Figure 7 shows the cross-sections of the 1 mm diameter strands after different levels of deformations. For each strand, starting from left to right, the deformations are 14%, 20%, 30%, and 40%. For all the three strands, we saw cracking of the copper between subelements as shown in Figure 8. We saw breakage and merging of subelements as shown in Figure 8. The cracking of the Cu between subelements is a big issue here which made it hard to judge the other types of breakages. This may be caused by lack of bonding between subelements. T2075 and T2617 0.7 mm wires have been sent to Fermi Lab for cabling. They characterized both wires and show similar results. The details on these two strands were reported in Task 6.

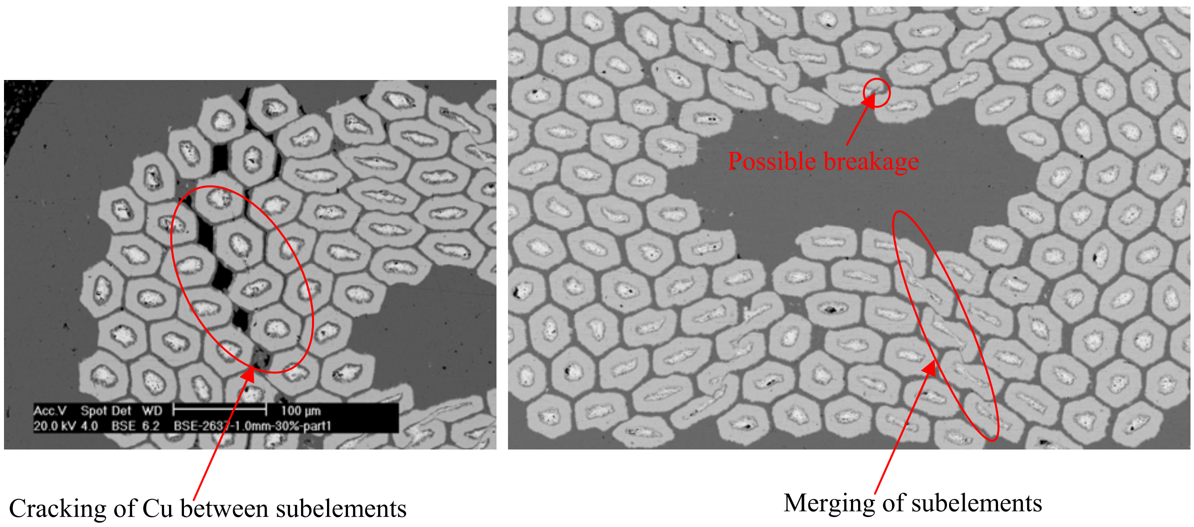
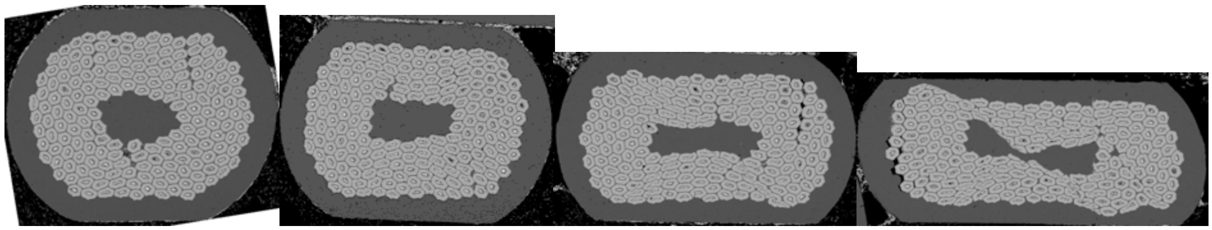


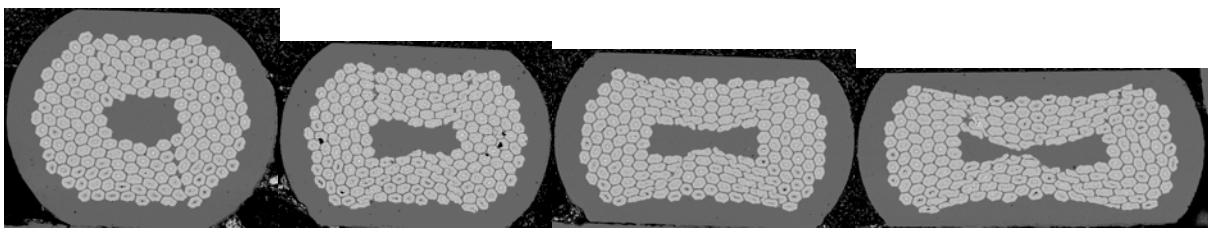
Figure 8. Main issues occurring after rolling.

Figure 9 shows the cross-sections of the 0.7 mm diameter strands after different levels of deformation. For each strand, starting from left to right, the deformations are 14%, 20%, 30% and 40%. For the 0.7 mm strands, we sent T2705 (similar to T2637) and T2617strands to Fermi Lab for characterization. The details will be reported in Task 6. We observed the 0.7 mm strands after different deformation of T2637, T2617 and T2574. For T2637 and T2617 strands, we still saw the cracking of Cu between subelements, the subelement breakage and merging. But in T2574 strand cross-sections, we did not see cracking of Cu between subelements. In 14% and 20% deformation samples, we saw very few subelement breakages for T2574. This indicates that the larger spacing will be helpful for cabling, but the optimal spacing need to be further investigated in Phase II. Cracking of Cu between subelements is a critical issue for these strands which we have to solve. Through observation, the 0.7 mm strands have less Cu breakage than 1.0 mm strands, possibly due to the better bonding in 0.7 mm strand.

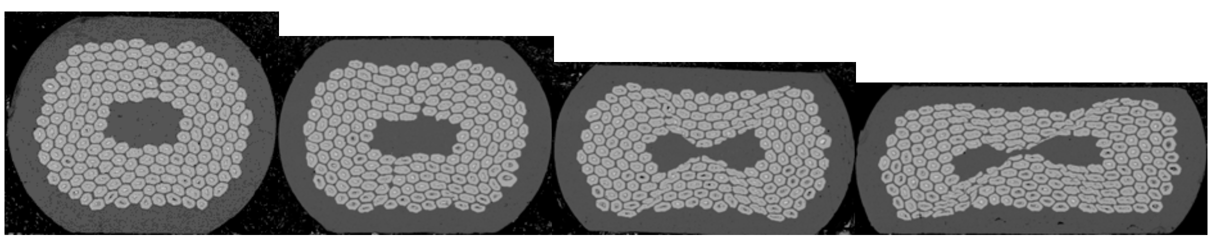
In order to solve this, we scaled up the starting billet size to improve the bonding between subelements in next task. We used 1.5” OD Cu tube for restack instead of ¾” OD.



(a) T2637 with narrowest spacing (10%) between subelements



(b) T2617 with middle spacing (15%) between subelements



(c) T2574 with widest spacing (20%) between subelements

Figure 9. Cross-sections of the three 0.7 mm strands with different spacing after different levels of deformation (14%, 20%, 30%, and 40%, starting from left to right).

Task 3. Method two to improve Rutherford cabling: Vary Cu percentages in the middle and the outer side of the restacked billets.

Based on what we found in Task 1, we have to solve the Cu cracking issue for our ¾” OD billets. We assumed it is due to the lack of bonding between subelements. Hence, in this task, we scaled up the billet size to 1.5” OD. This scale-up results in an increase of the total amount of cold work at the 0.7 mm and 1.0 mm strand sizes. It also results in longer piece lengths from the larger billet. We made the subelement using the 0.58” OD x 0.53” ID Cu tube which is similar to those in T2075 and T2637 strands. The subelement was drawn down to 2.05 mm, and then went through the 0.069” F-F hexagonal die to get ready for restacking in the 1.5” OD, customized ID Cu tube as shown in Figure 10. This 1.5” OD tube is designed for 271-subelement pattern restack, which will hold 234 Nb-Cu-Sn subelements and 19 Cu subelements. This Cu tube has about 40% Cu in area. This restacked strand was denoted as T2508.

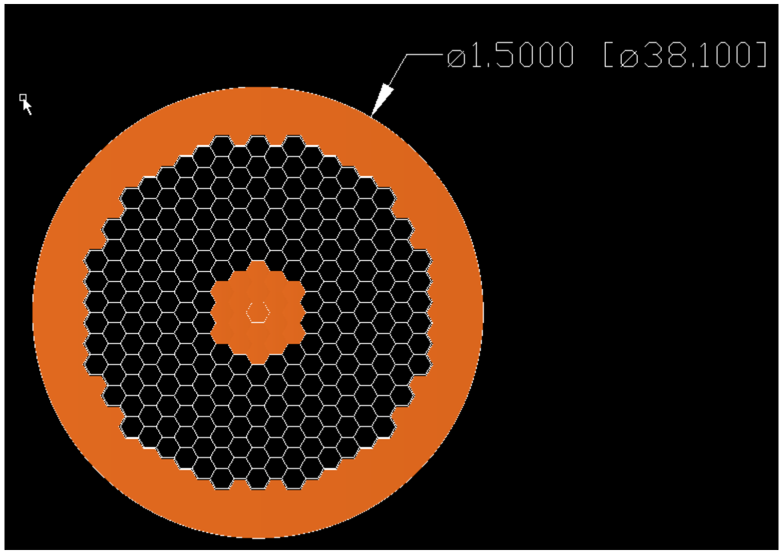
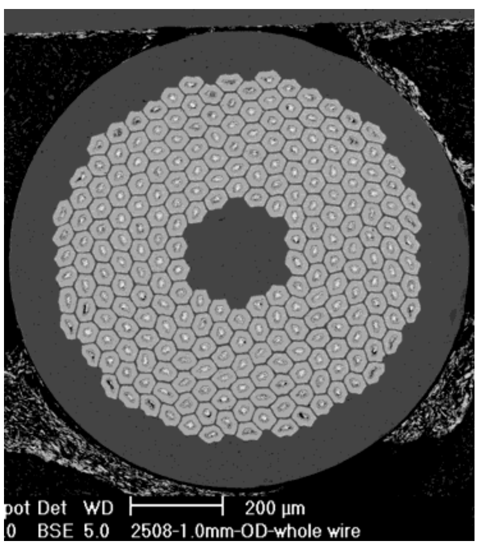


Figure 10. The restacking of (234 subelement + 19 Cu) structure.

The restacked billet was drawn down to different sizes. Figure 11 shows the 1 mm and 0.7 mm wire cross-sections. In the 0.7 mm strand, the subelement diameter is 30 μm. This strand was further drawn down without any problem.



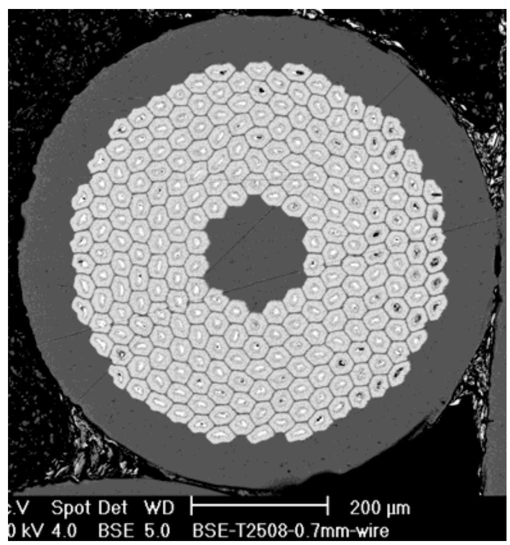
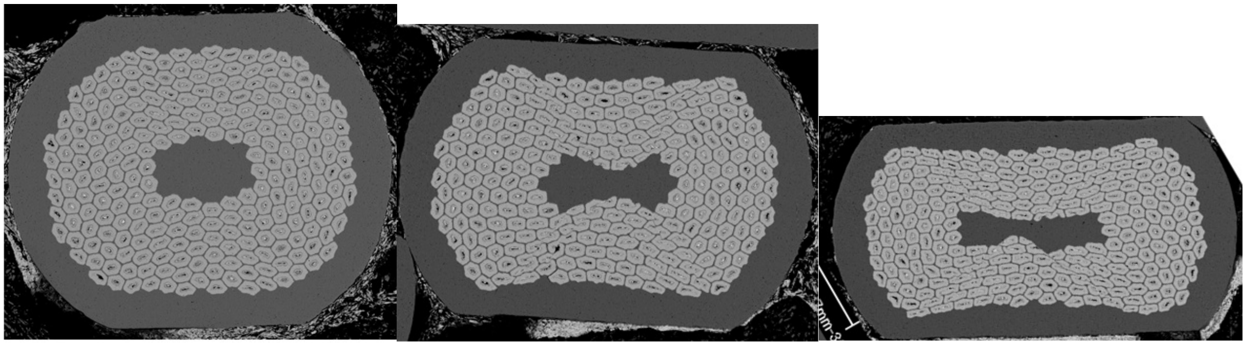


Figure 11. Cross-sections of T2508. **Left:** 1.0 mm strand with subelement size of 43 μm; **Right:** 0.7 mm strand with subelement size of 30 μm.

In order to characterize its cabling property, we did a series of rolling tests on the strand just as in Task 2. We selected the 0.7 mm strand and ran the strand through a rolling machine, and then measured the resulting strand with a micrometer to confirm the distance between the two flat edges is close to our goal, with an accuracy level of approximately ±0.02 mm. In this study, we looked at three different deformation levels of the 0.7 mm strand: 14%, 20%, and 30%. These deformations equated to rolled sizes of 0.60 mm, 0.56 mm, and 0.49 mm, found with the formula (OD-RD)/OD, where OD represents the original diameter of the strand, and RD represents the rolled diameter of the strand. We did not do the 40% deformation since it is not representative of the real cabling process. Figure 12 shows the whole cross-sections of the deformed strands.



(a) 14% (b) 20% (c) 30%

Figure 12. Cross-sections of T2508 0.7 mm strands after different levels of deformation (Deformations are 14%, 20%, and 30%, starting from the left to right).

Through further investigation, in the deformed strand, we could still see subelement breakage and merging defects there, but no Cu cracking was observed, which demonstrated that the bonding between subelements has been improved through scaling up the starting billet to 1.5” diameter. In this Phase II, we will continue to use the 1.5” OD Cu tube, and will use the optimal spacing learned from Task 1.

In this task, we proposed to change the external tube thickness to see its effect on the cabling. We etched our currently used 1.5” OD customized 271-subelement ID Cu tube down to 1.38”, which leaves about 28% Cu in area. We made exactly the same subelements as those in T2508. The subelement was drawn down to 2.05 mm, hexed through the 0.069” F-F distance hexagonal die, and then cut into 5 ft long pieces for restacking. These chopped subelements were restacked into the etched 1.38” Cu tube and then drawn down. This billet was denoted as T2525.

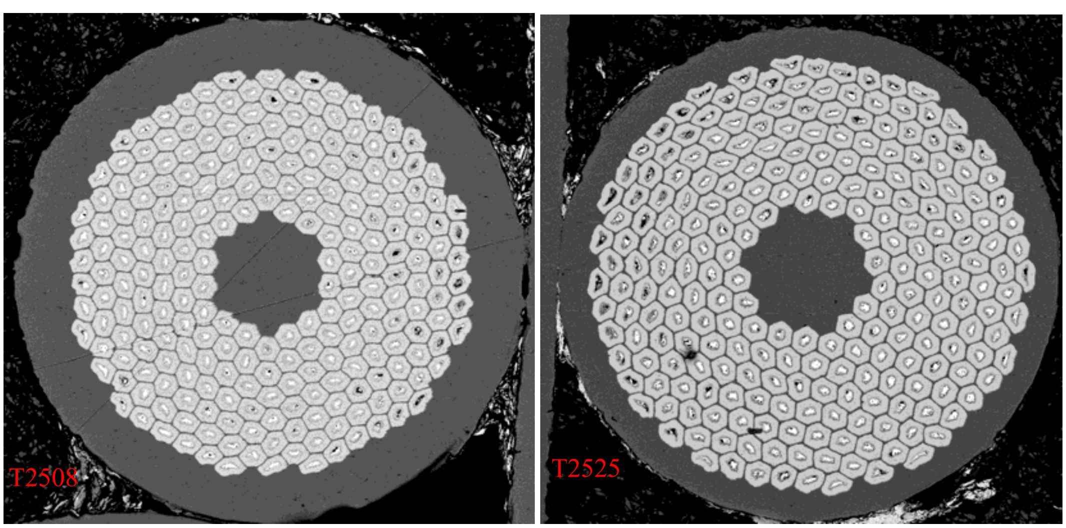
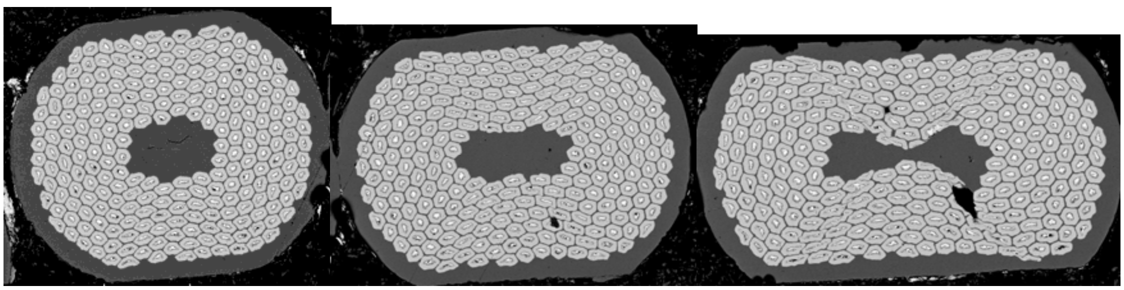


Figure 13. Cross-sections of T2508 and T2525 at 0.7 mm.

Figure 13 shows its cross-sections at 0.7 mm and its comparison with T2508. T2525 has much less Cu on the outside. Its outer ring of subelements distorted more due to the thin jacket of the whole strand, but T2525 was drawn down to 0.7 mm successfully.

We did the rolling tests for the T2525 to characterize its cabling properties, and then measured the resulting strands with a micrometer to confirm the distance between the two flat edges is close to our goal, with an accuracy level of approximately ±0.02 mm. We looked at three different deformation levels of the 0.7 mm strand: 14%, 20%, and 30%. Figure 14 shows the deformed strands after different levels of deformation. Comparing T2525 with T2508 briefly, it is hard to say which is better or worse. In this Phase II, we will continue working on this, and we will do detailed analysis on the deformed strand. In addition, we will increase the Cu ratio in the middle to see if that helps cabling.



(a) 14% (b) 20% (c) 30%

Figure 14. Cross sections of the deformed strands of 0.7 mm T2525.

Task 4. An additional method to improve Rutherford cabling: Make subelments with round Nb and hexagonal Cu. This has the potential to increase the J_c up to 3000 A/mm^2 at 12 T and 4.2 K for the restacked wire.

Dr. Barzi of Fermi Laboratory once pointed out [1] the special subelements with round Nb and hexagonal Cu in the PIT restacked strands improved the Rutherford cabling. We adapted this into our tube-type strands. In this task, we started with ¾" Cu OD tube, and tried to get Cu "tube" with a round ID and a hexagonal OD for subelement. For 217-subelement in ¾" tube, the subelement size is about 1 mm which is too small to get into the tube. Hence, we reduced the restack count to 61-subelement, which requires the subelement size of about 2 mm. Figure 15 is the plot for the 61-subelement restack.

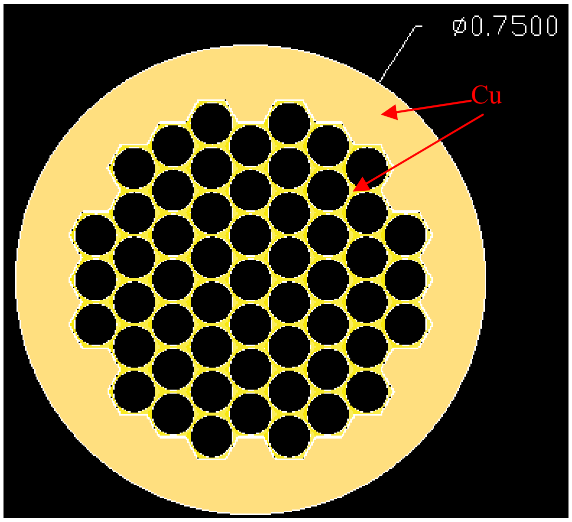


Figure15. Schematic plot of 61-subelement with perfect array.

We purchased the Cu "tube" with a round ID and a hexagonal OD from AT Wall for this experiment. Its dimension is 0.071" F-F OD x 0.046 ID, which is the best we could get in this size tube. The thickness is about 0.0125" which means the S/D is up to 0.5. It is very high. In order to match our standard subelement with 0.58" OD x 0.53" ID, we have to etch the tube. It is hard, but we got it done. Then we made a standard subelement as in Task 1, drew it down to 1.2 mm, and then etched the outer Cu away. The subelement with Nb on the outside surface has been assembled with the Cu tube.

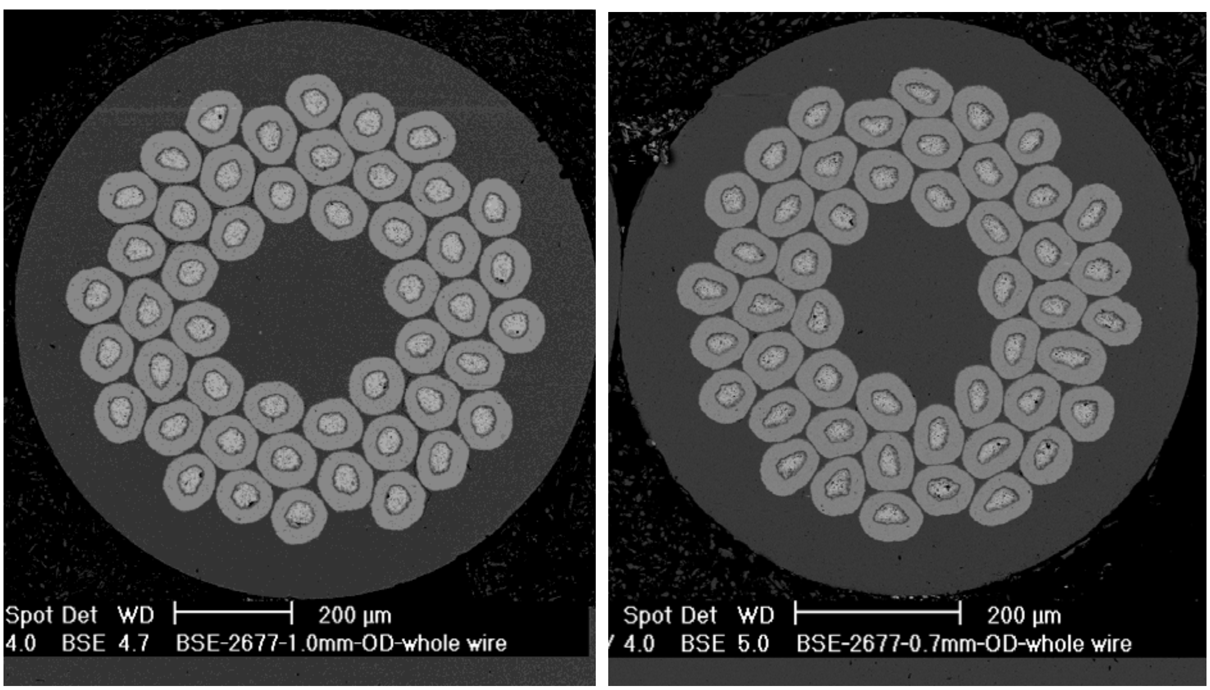


Figure 16. Cross-sections of T2677.

This assembled hexagonal-Cu round-Nb subelement was restacked in the Cu tube, and drawn down. This restacked wire was denoted as T2677. Figure 16 shows the cross-sections of T2677 at 1 mm and 0.7 mm. It is obvious that there is too little Cu between the subelements in this restack. We need to leave more Cu in the subelement. Hence, we did another experiment on using the hex OD round ID Cu tube. We etched the Cu tube to get the S/D of 0.2. We made a standard subelement as in T2677, and drew it down to 1.2 mm, then etch the outer Cu away. The subelement with Nb on the surface has been assembled with the Cu tube. This subelement was assembled in the 61-subelement customized ID Cu tube. This restacked wire was denoted as T2716. The restack was drawn down. Figure 17 shows its cross-sections at 4 mm and 0.7 mm. In the 4 mm cross-section, the subelement shape is pretty decent, but it has more distortion when getting down to 0.7 mm. We are not sure if it is due to the end effect or real distortion in the wire. We will continue to investigate this in Phase II.

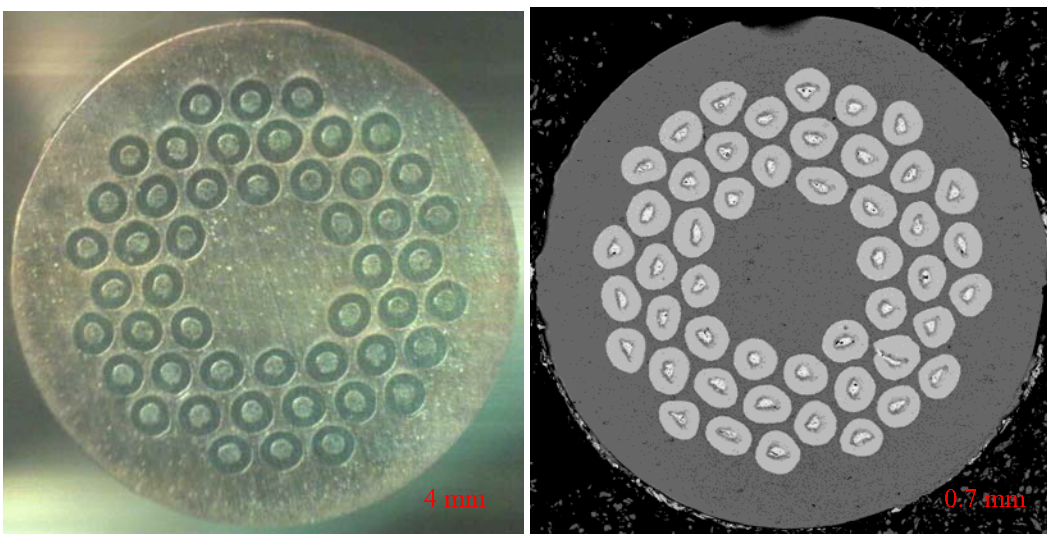


Figure 17. Cross-sections of T2716 at 4 mm and 0.7 mm.

Due to the bonding issue, we just did the light rolling for these two strands. We rolled these two 0.7 mm strands down to 0.6 mm, which is about 14% deformation, see Figure 18. There is cracking of copper between subelements as we would suspect, due to using a ¾" restack. In Phase II, we will scale up the billet to 1.5" OD and make the S/D of the subelement about 0.15, which may reduce the distortion. Figure 18 also shows less cracking when there is more copper between the subelements, most likely due to better bonding. In this Phase II, we will scale up the billet size to 1.5" OD to improve the bonding between subelements.

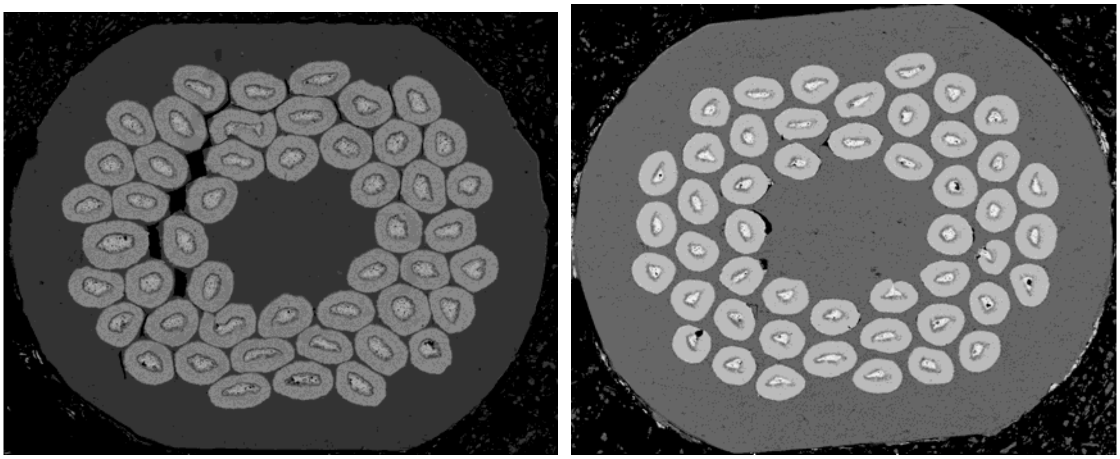


Figure 18. Cross-sections of 0.7 mm T2677 and T2716 after 14% deformation.

Task 5. Characterize the Restacked Strands.

All the test results have been shown in Task 1-4, below we describe the types of tests and how the tests are conducted.

Cabling characterization: We used rolling tests to characterize the cabling capability of various strands. We rolled the strands to get various deformation levels: 14%, 20%, 30%, and 40%. All the strands were evaluated and compared.

OSU focused on materials science investigations of the strands, reaction optimization, and transport properties:

Electro-optical Characterization: OSU investigated the (1) level of reaction completeness, (2) chemistry along the radial direction within the subelement, (3) measurement of the grain size of samples, and BSE SEM, and EDS investigation of the strands.

Superconducting Property Characterization: OSU measured the transport J_c properties of strands. OSU's test stand is capable of 15 T at 4.2 K and 17 T at 2.2 K. Transport current levels of 1800 A are readily and routinely available. The measurement set-up has a fast quench protection circuit, and the measurement probe is 1800 A-capable.

Task 6: Sent strands to Fermi Lab for making Rutherford cables

Three strands have been sent to Fermi Lab to be characterized. Table II shows the strands information. We will describe the results separately.

Table II. Details on the strands supplied to Fermi Lab in Phase I

Strand	Starting billet size	Restack count	Sub size at 0.7 mm	Cu% between Subs	Outer Cu% in restack
T2075	¾"	217	35 μm	10%	35%
T2617	¾"	217	35 μm	15%	35%
T2508	1.5"	271	30 μm	10%	35%

T2075 & T2617: ¾" OD billets with different Cu spacing

We sent the 1st two strands to Fermi Lab for cabling, T2075 & T2617. Both strands have different spacing between the subelements. We selected T2075 and T2617 strands from Task 1, drew them down to 0.75 mm, twisted them in 15 mm pitch length, and then overdrew them down to 0.7 mm. About 1000 ft length of each wire was sent to Fermi Lab for cabling characterization.

Before cabling, Fermi Lab used rolling tests to simulate the effects of cabling strands, and these procedures allowed us to obtain a much more homogenous comparison between different types of strand than would be possible from studying strands only after they are cabled. In these experiments, deformation is systematically imposed and the results are studied microscopically and electrically.

Fermi deformed strands of T2075 and T2617 to various levels using a rolling, or flattening, process. They ran the strands through a rolling machine, which results in a widened strand with two flat edges. In this study, they looked at four different deformation levels: 14%, 20%, 30%, and 40% which is the same as we did in Task 2. The 0.7mm strands were rolled to 0.60mm, 0.56mm, 0.49mm, and 0.42mm, respectively.

About 10 inches of material of each billet and rolled size were taken and cut into 10 one-inch pieces. These pieces were potted in epoxy using various methods to ensure that they remained straight during the potting process. They were then cut on both sides using a low-speed diamond saw, and the remaining samples were polished on both sides to a level of 0.05 microns using a combination of manual and automatic polishing. This procedure resulted in ten samples, each containing twenty cross sections of material. Figure 19 shows a completed sample set.

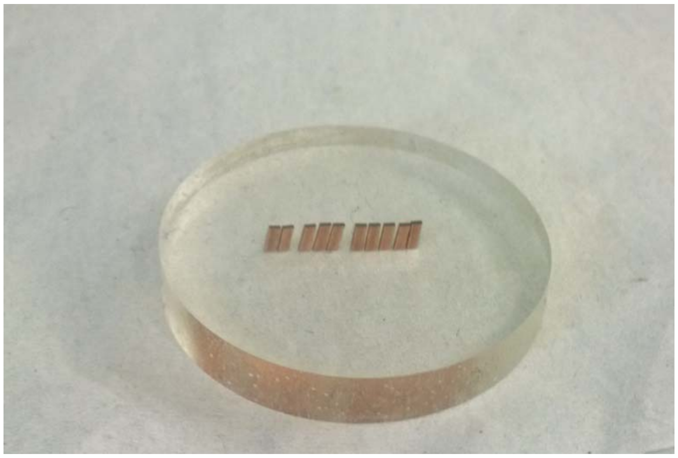


Figure 19. Completed polished sample.

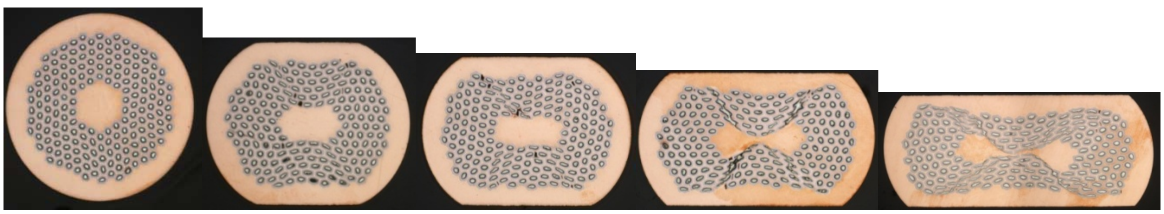


Figure 20. Billet T2075 – 10% Spacing.

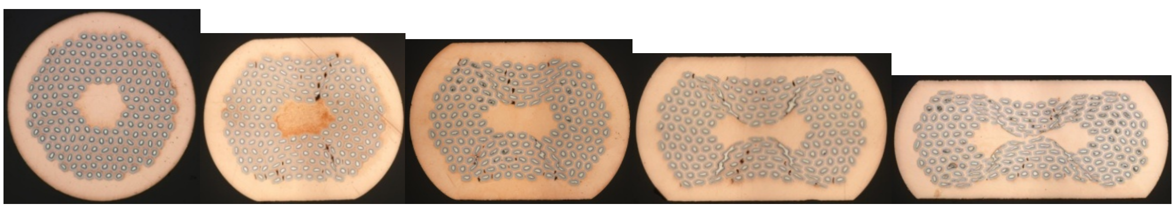


Figure 21. Billet T2617 – 15% Spacing.

One cross section of each sample, as seen under the microscope, is shown in Figures 20-21. Fermi Lab also observed the cracking of the copper along the shear lines between subelements in the rolled strands. These cracks were seen on several cross sections of every rolled size and billet, but never in the undeformed (round) strands. Some small amount of this phenomenon is visible in the pictures above, but a more detailed example is shown in Figure 22. This is due to the lack of bonding between subelements. Once we scaled up the starting billet size from ¾" OD to 1.5" OD, this phenomenon went away since the bonding is greatly improved.

Figure 22. Cracked Copper between subelements.

After noting and documenting this phenomenon, Fermi Lab moved on to their standard analysis procedure to compare the two billets. As is typical, they checked for two types of damage: breakage and merging of subelements. They checked for this damage at magnifications of 20x and 50x (200 times and 500 times naked eye view, respectively). A quick check was done at the 20x level, followed by a more detailed check of any apparent problematic areas at the 50x level. They also created a design-specific map in order to document specific locations of the damage, in case this information is useful for future studies. They took note of all damage to subelements in the round strand and in the first three sets of deformed strands of each billet. The deformations of the samples studied were 0%, 14%, 20%, and 30%, respectively. The 40% deformation level sample was left out due to time constraints and the fact that damage at this level is never observed in cabled strands.

The following is a complete list of the strands checked for damage:

Hyper Tech T2075 (180 Subelements + 19 Cu in the Center, 10% Spacing between Subelements)

- 0% deformation (0.7mm diameter) – 20 cross sections
- 14% deformation (0.6mm diameter) – 20 cross sections
- 20% deformation (0.56mm diameter) – 20 cross sections
- 30% deformation (0.49mm diameter) – 20 cross sections

Hyper Tech T2617 (180 Subelements + 19 Cu in the Center, 15% Spacing between Subelements)

- 0% deformation (0.7mm diameter) – 20 cross sections
- 14% deformation (0.6mm diameter) – 20 cross sections
- 20% deformation (0.56mm diameter) – 20 cross sections

- 30% deformation (0.49mm diameter) – 20 cross sections

Damage was separated into six categories:

- Broken
- Niobium Merged
- Tin Merged
- Possibly Broken
- Niobium Possibly Merged
- Tin Possibly Merged

A subelement was counted as one damaged subelement if it had any of the above types of damage. If the subelement displayed only one of the questionable types of damage indicated in the last three categories, it was assigned a value of 0.5 damaged subelements. These questionable subelements represent the error bars in the chart below (Figures 23-24). All numbers are averages of damaged subelements counted over 20 cross sections.

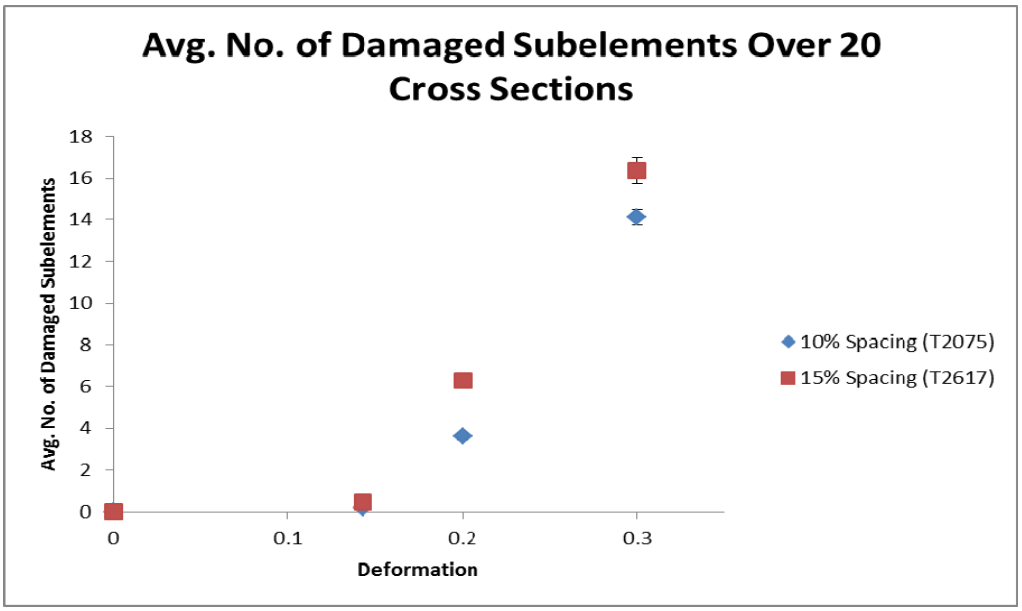


Figure 23. Damaged Subelements Relative to Deformation.

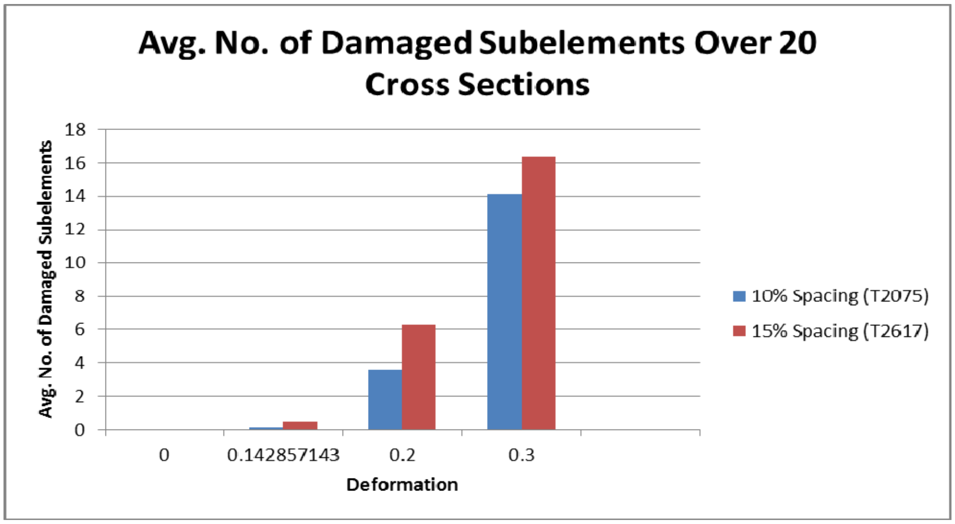


Figure 24. Damaged Subelements Relative to Deformation.

Consistently, over all deformations, more damage was observed in T2617 (with 15% spacing) than in T2075 (with 10% spacing). This conclusion is apparent also in the photos below (Figures 25-27). The bonding between subelements is critical for judging the defects after deformation.

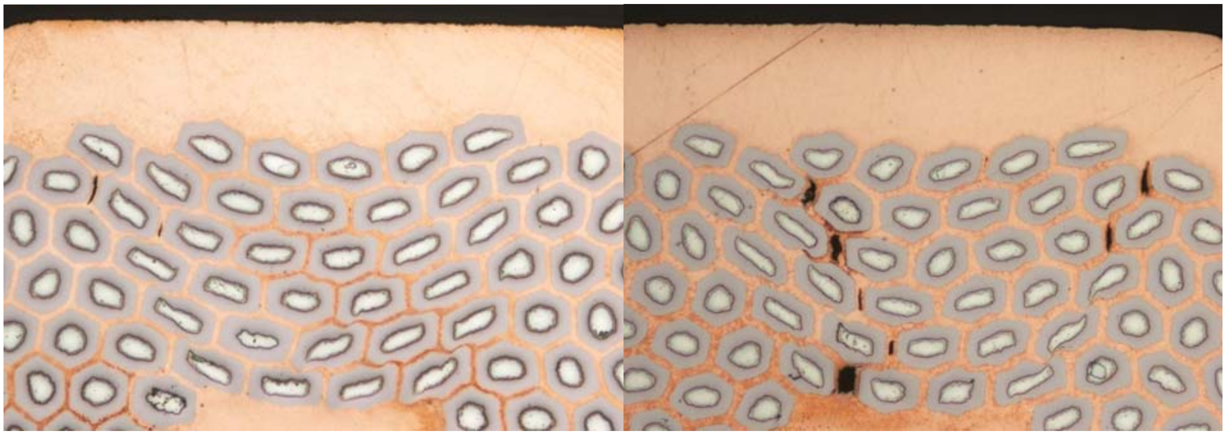


Figure 25. 14% Deformation. 10% spacing left, 15% spacing right.

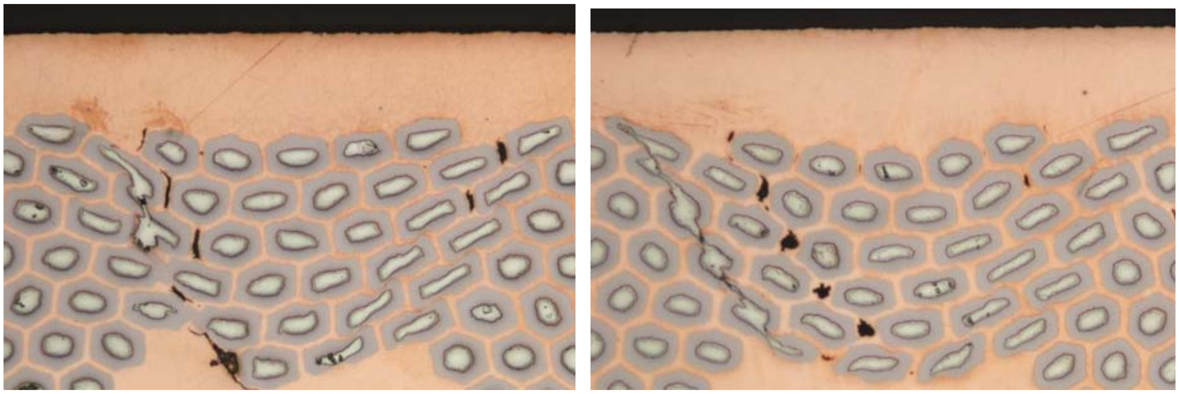


Figure 26. 20% Deformation. 10% spacing left, 15% spacing right.

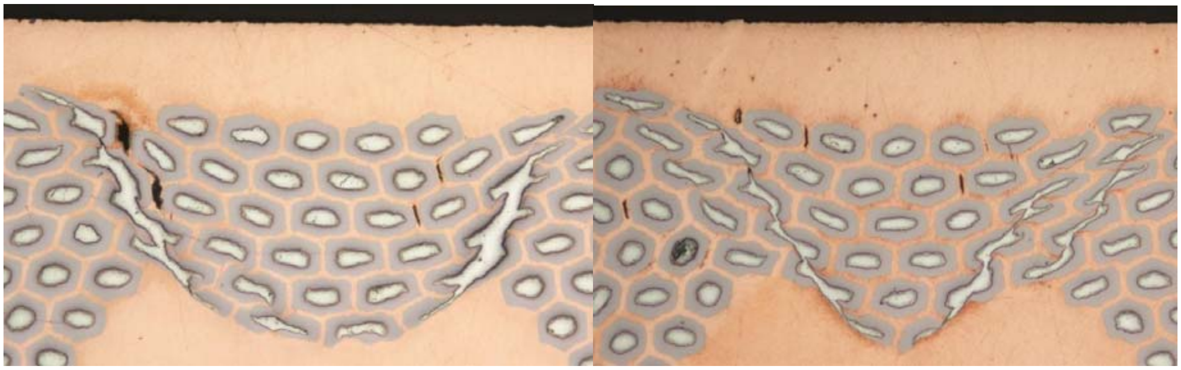


Figure 27. 30% Deformation. 10% spacing left, 15% spacing right.

The results of the microscopic examination of the deformed wires also closely correspond to those of the electrical experiments. Critical current was tested in Fermi Lab. The round and the rolled samples have been tested for critical current on Ti barrels, see Figures 28 and 29. I_c values have been evaluated using a resistive criterion with $\rho=10^{-14}$ Ω/m. Results from the analysis are summarized in the following plots. In the plot, the critical current value from the round sample, I_{c0}, is used to evaluate the I_c/I_{c0} ratio as a function of critical current with increasing deformation. All the results show that we need to improve both wires. Hence, Fermi Lab did not make the cable on these two strands.

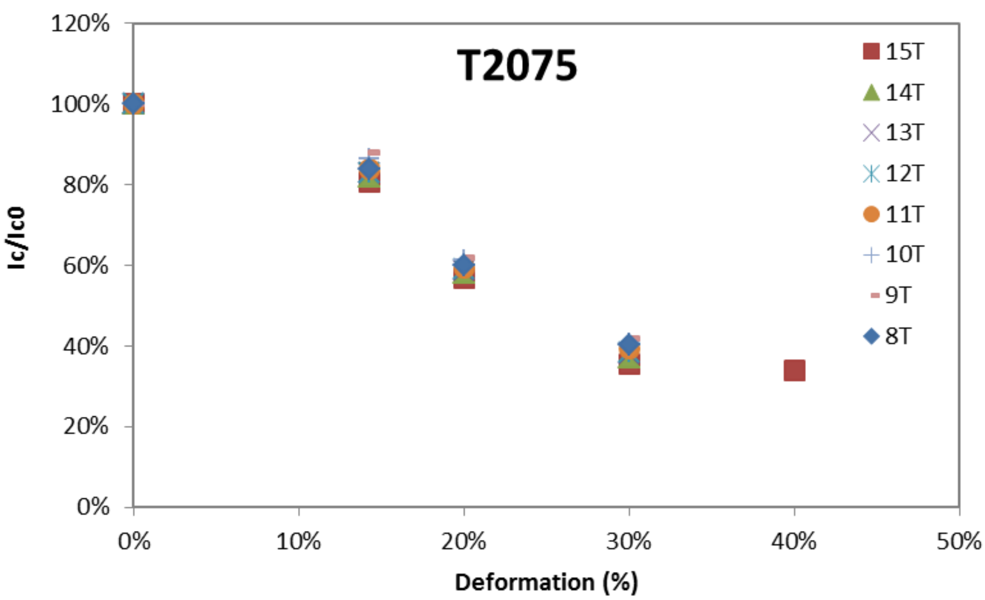


Figure 28: Critical current ratio as a function of deformation for fields from 15T to 8T for Billet T2075

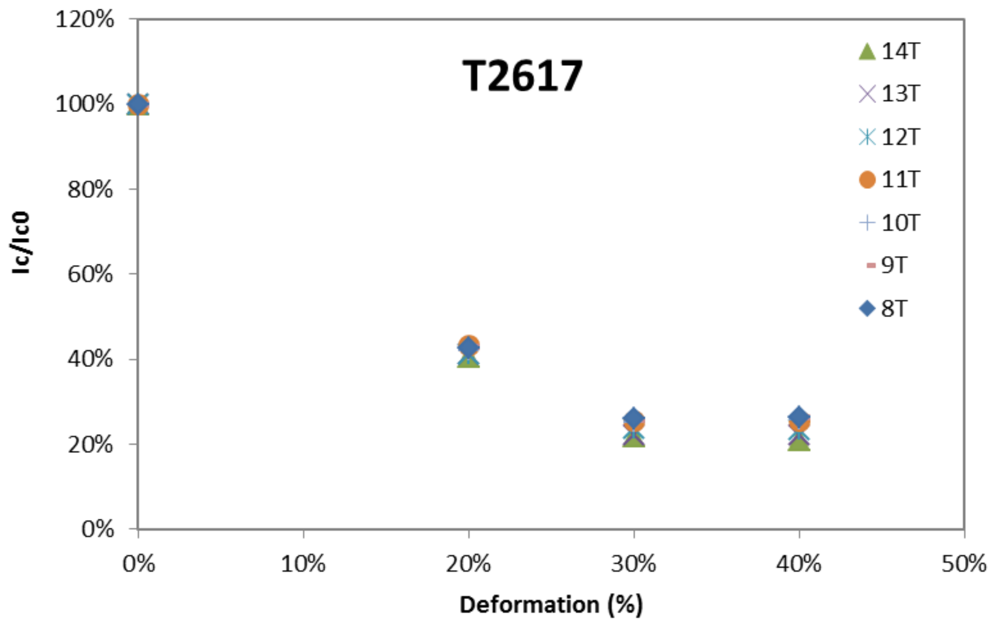


Figure 29. Critical current ratio as a function of deformation for fields from 14T to 8T for Billet T2617.

T2508: 1.5 OD billets with 10% spacing

After noticing the atypical cracking of copper between subelements, we concluded it is due to the lack of bonding between subelements. Hence, we scaled up the billet size from ¾" OD to 1.5" OD in Task 2. This billet was drawn down to 0.7 mm, its cross-section was shown in Figure 19. We provided about 1200 ft to Fermi Lab for cabling. Fermi Lab made different Rutherford cables using this strand. Four cables made of 27 strands were fabricated in a first rectangular step followed by a keystoning step, and using four different compaction factors in the keystoning, as described in Table III. The packing factor (PF) is the ratio of the strand cross sectional area with respect to that of the whole cable. Particulars of cross sections of the 1st three cables are shown in Figure 30-32.

Table III. Cabling parameters

Thickness, mm	Width, mm	PF, %
1.304	9.94	82.8
1.272	9.99	88
1.253	9.95	86
1.233	9.95	87.4

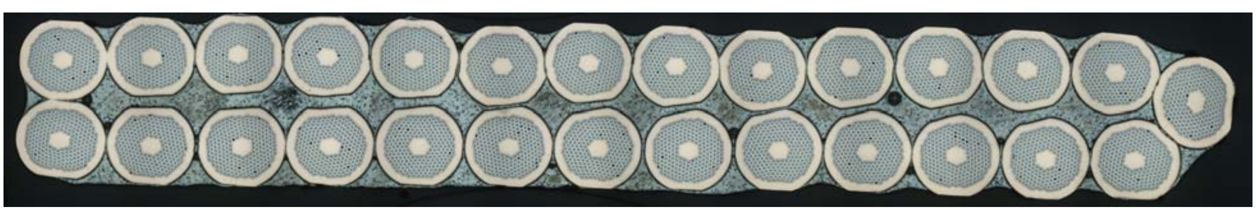


Figure 30. Cable cross-section with PF of 82.8%

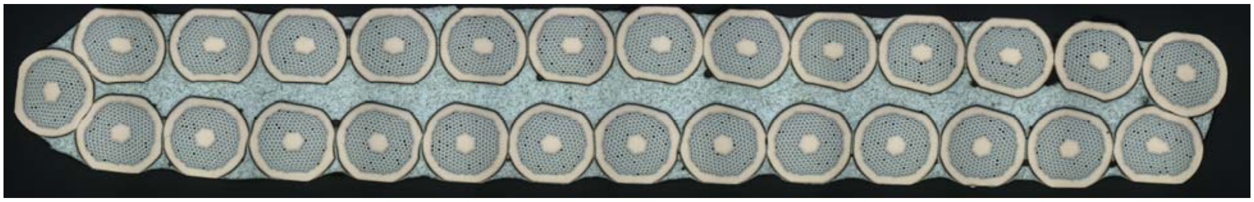


Figure 31. Cable cross-section with PF of 88%

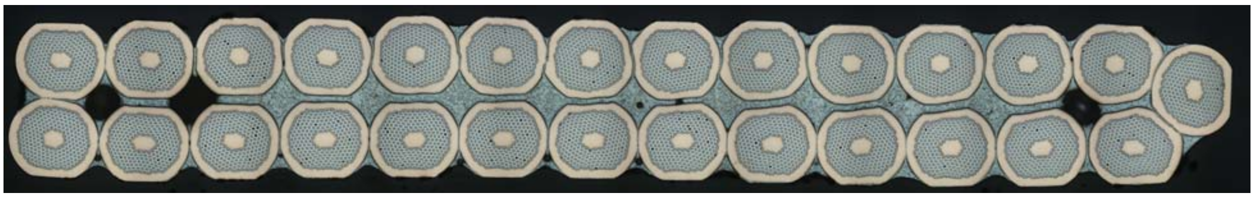


Figure 32. Cable cross-section with PF of 86%

For each cable, we selected the most distorted strands and magnified their cross-sections. Figure 33-35 are the close-up views of the mostly distorted strands in the three cables respectively. For all the three cables, we saw distortion of filaments, but did not see any Cu cracking and filament bridging in the strands. There are a couple of filament breakages seen in the strands. These are very exciting results. In this Phase II, we are proposing to increase the spacing properly to reduce distortion and avoid the filament breakage.

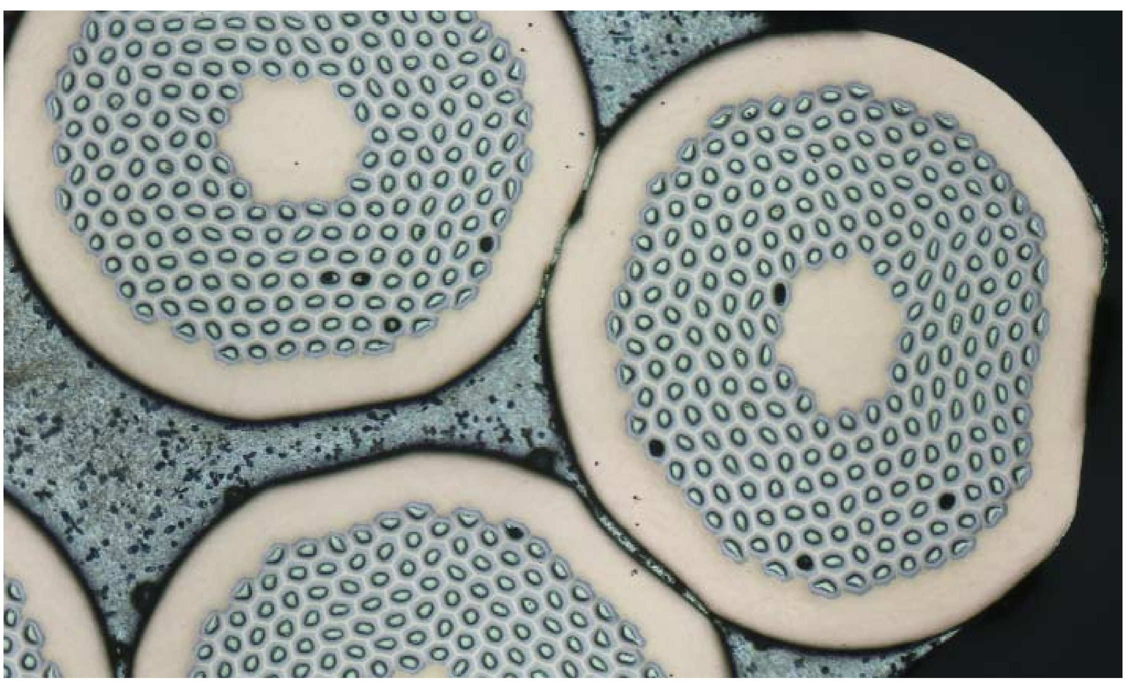


Figure 33. Close-up picture of the cable cross-section with PF of 82.8%

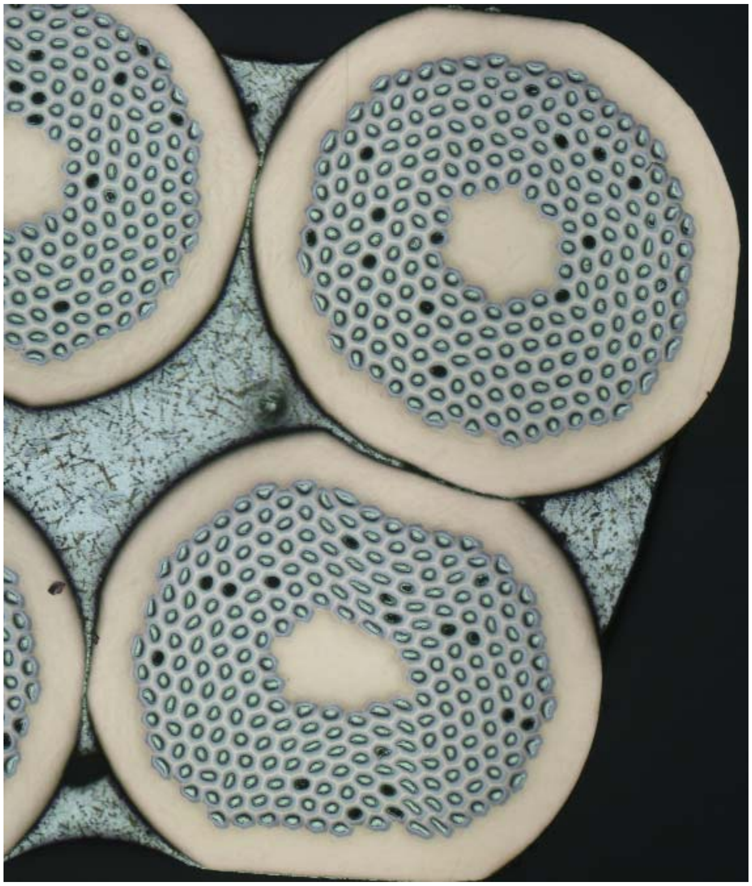


Figure 34. Close-up picture of the cable cross-section with PF of 88%

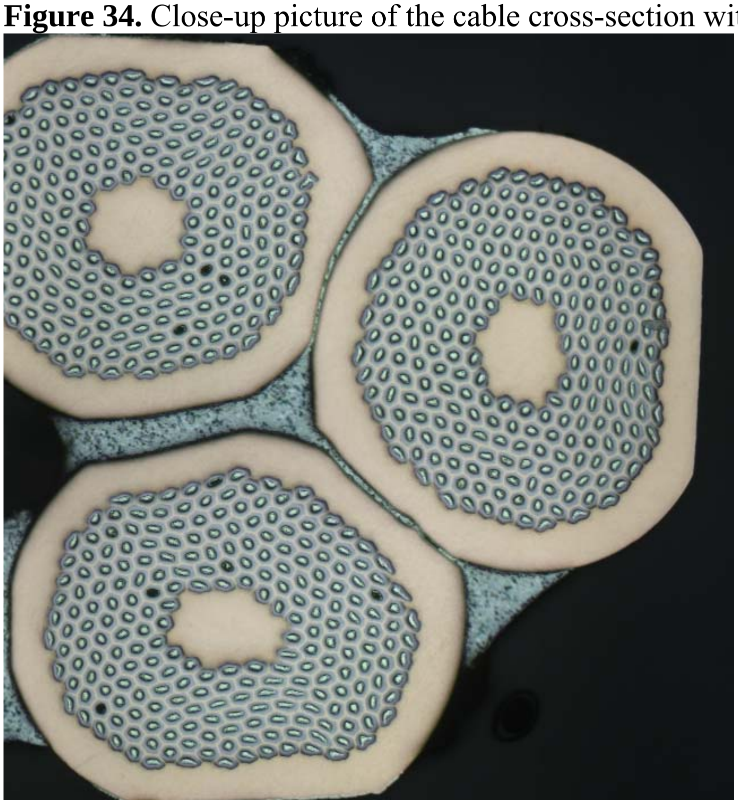


Figure 35. Close-up picture of the cable cross-section with PF of 86%

SUMMARY

During Phase I, our efforts were to reduce subelements deformation when fabricating Nb_3Sn Rutherford cables. Our first focus is on 217-sublement tube type strand. We successfully made a few billets in ¾" OD tube with different Cu spacing between subelements, and supplied the strands to Fermi Lab for cabling. Through the rolling test characterization, these types of strands did not have enough bonding between subelements to withstand the deformation. We saw copper cracking between subelements in the deformed strands. We scaled up the billet from ¾" OD to 1.5" OD, and made two billets. This greatly improves the bonding. There is no copper cracking in the deformed strands when we scaled up the diameter of the billets. Fermi Lab successfully made cables using one of this improved strands. In their cables, no Cu cracking and no filament bridging occurred. We also successfully made a couple of billets with hex OD and round ID subelements for 61-subelement restack. Due to the lack of bonding, we could not judge its cabling property properly. But we know through this experiment, we could keep the Nb round, once we select the proper Cu spacing.

In the Phase II, we will continue working on reducing the strand deformation during cabling. We will use 1.5" OD tube, and investigate the effect of Cu spacing and the Cu in the middle on deformation. We will get harder material in the middle to absorb energy from deformation. We will make round subelements for 1.5" OD billet to improve J_c of the strand. We will send strands to Fermi Lab to characterize and cable. The details of our Phase II plans are given below.

PHASE II PROJECT

Technical Objectives

In the Phase II, we will continue working on reducing the strand deformation during cabling. We will use 1.5" OD tube, and investigate the effect of Cu spacing and the Cu in the middle on deformation. We will get harder material in the middle to absorb energy from deformation. We will make round subelements for 1.5" OD billet to improve J_c of the strand. We will send strands to Fermi Lab to characterize and cable. The work details are described in the following tasks.

Task 1: Create strands with better bonding between subelements through improving the subelement assembly process and die reduction schedule.

Task 2: Make 1st 271-subelement restacked billet in 1.5" OD tube: using 20% spacing to compare with T2508 developed in Phase I.

Task 3: Make 2nd 271-subelement restacked billet in 1.5" OD tube: using 25% spacing to compare with the billet from Task 2.

Task 4. Make 3rd 271-subelement restack in 1.5" OD tube: vary Cu percentages in the middle and the outer side of the restacked billets at the same time.

Task 5. Make 4th 271-subelement restack in 1.5" OD tube: make subelments with round Nb and hexagonal Cu. This has the potential to increase the J_c up to 3000 A/mm^2 at 12 T and 4.2 K for the restacked wire.

Task 6. Make 5th 271-subelement restack in 1.5: OD tube: Use the best design from Task 2-4.

Task 7. Sent strands to Fermi Lab for Characterization and cabling.

Task 8. Characterize the Restacked Strands.

Task 9. Make strand available to National Lab for cable and small test coils