Superconducting Magnet Division

Magnet Note

Authors: S. Joshi, R. Gupta, and W. Sampson

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Title: **Axial Compression Fixture and Conductor Test Report on the HTS Tape Required for 25 T, 100 mm IBS Solenoid**

Copy: **Superconducting Magnet Division:**
R. Gupta
W. Sampson

Axial Compression Fixture and Conductor Test Report on the HTS Tape Required for 25 T, 100 mm IBS Solenoid

Shresht Joshi, William Sampson and Ramesh Gupta

Superconducting Magnet Division

Brookhaven National Laboratory

Upton, NY 11973 USA

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Content

Executive Summary

This note describes the experimental setup and test results addressing a key concern of the IBS magnet design arising from using "No-Insulation" coils in a large bore high field solenoid. The "No-Insulation" approach was chosen to provide a more reliable system. However this also meant a significantly higher current density in the coil. This results in increased stresses and strain on the conductor due to large Lorentz forces both along the wide face of the conductor and on the narrow face. While experimental data show that a proper choice of the amount of copper will keep the stresses on the wide face within the acceptable limit of the conductor with little degradation, there was no such data available for the stresses on the narrow face arising due to the axial forces. This has been a major area of concern since dealing with the large electro-magnetic stresses is the biggest challenge in high field, large bore solenoids; the mechanical properties of the conductors limits the performance of such magnets according to computer modelling and simulations.

Since the computed axial stress in the present IBS design, of 205 MPa on the 12 mm wide tape with 20 micron copper, is significantly higher than previously measured safe value of 107 MPa on 4 mm wide tape with 40 micron copper, experimental data was required to validate the design. Since no such data was available, BNL had to design and build a new apparatus to perform these measurements. This note summarizes the initial design, several iterations, and results in the development of this important test setup to simulate the conditions of the coils in the IBS magnet when energized. To ensure a proper optimization of the coils, three values of copper plating were examined: 20 micron, 40 micron and 65 micron.

The compression tests performed at BNL yielded lots of valuable results specific to the IBS project. The results showed that coils wound with SuperPower 2G HTS 20 µm Cu conductor can withstand compressive pressures of 205 MPa. It can operate with little to no performance degradation as per the tests performed at 77 K. Even after substantial degradation, following compressive pressures administered outside of the performance envelope set for IBS, the coil performed within the margins that are being considered for the magnet.

To simulate lifetime tests, the four 40 µm Cu coils and the 20 µm Cu coil were subjected to multiple compressive loading cycles beyond pressures calculated in simulations, 205 MPa, and numerous thermal cycles over a period of days. These tests were also conducted at higher I_c margins than those set for the IBS magnet. Throughout these tests, the coils performed well within threshold voltage limits of the coil and showed degradation that had insignificant impact on performance.

These tests validate the present design for the IBS magnet and clear the way to issue the purchase order for the conductor.

Motivation

No-Insulation High Temperature Superconducting (HTS) Magnet coils offer reliable intrinsic quench protection and the ability to tolerate local defects in the conductor or sudden changes in operation as compared to HTS coils made with metallic or non-metallic insulation. However, the no-insulation option increases the current density in the coil which, in turn, increases the stresses on the superconductor. As magnetic fields exceed 20 Tesla, the magnitude of the resulting Lorentz forces in a large bore solenoid approaches the limits of the HTS conductor. Dealing with large electro-magnetic stresses is the biggest challenge in high field, large bore HTS solenoids as the mechanical properties of the conductors limit the performance of the coil.

A key design parameter in such a large bore high field solenoid is the amount of copper stabilizer used on the second generation (2G) HTS tape made with Hastelloy substrate. A higher amount of copper provides better protection and stability at the cost of mechanical properties since copper has significantly lower mechanical strength than Hastelloy. In fact, the present design for the IBS magnet is determined by the mechanical properties of the conductor which is why a minimum amount of copper (10 micron on each side) is being used.

While the effects of orthogonal stresses on conductor/coils in the radial and azimuthal directions (on wide face of the conductor) have been studied in the literature, data on the effects of orthogonal stresses on conductors/coils in the axial direction (on the narrow side of the conductor) is only available in the literature for stresses up to 107 MPa - from a setup previously developed and tested at BNL[1]. To validate the design of the large bore IBS solenoid and to ensure proper magnet function at 25 T, a series of compressive tests on conductor with 50 micron Hastelloy were administered on SuperPower 2G HTS conductors of varying copper stabilizer layer thicknesses. The tests carried out simulate what the conductor and the coils would experience in terms of compressive loading on the narrow side of the conductor.

Introduction

The Institute of Basic Science (IBS) in South Korea requires a 25 Tesla, 100 mm bore solenoid for experiments searching for dark matter axions to explain the formation of the universe. The Superconducting Magnet Division at Brookhaven National Laboratory has designed and is in the process of constructing a 14 double pancake coil, no insulation, single layer, HTS magnet wound with SuperPower 2G HTS 20 micron copper conductor for IBS; the tape architecture in Figure 1. Lorentz force simulations[2], using ANSYS FE software, at 4 K and 25 Tesla show that parts of the magnet will be subjected to orthogonal coil stresses in the axial direction (compressive stress on the width of the conductor) up to 205 MPa, Figure 2.

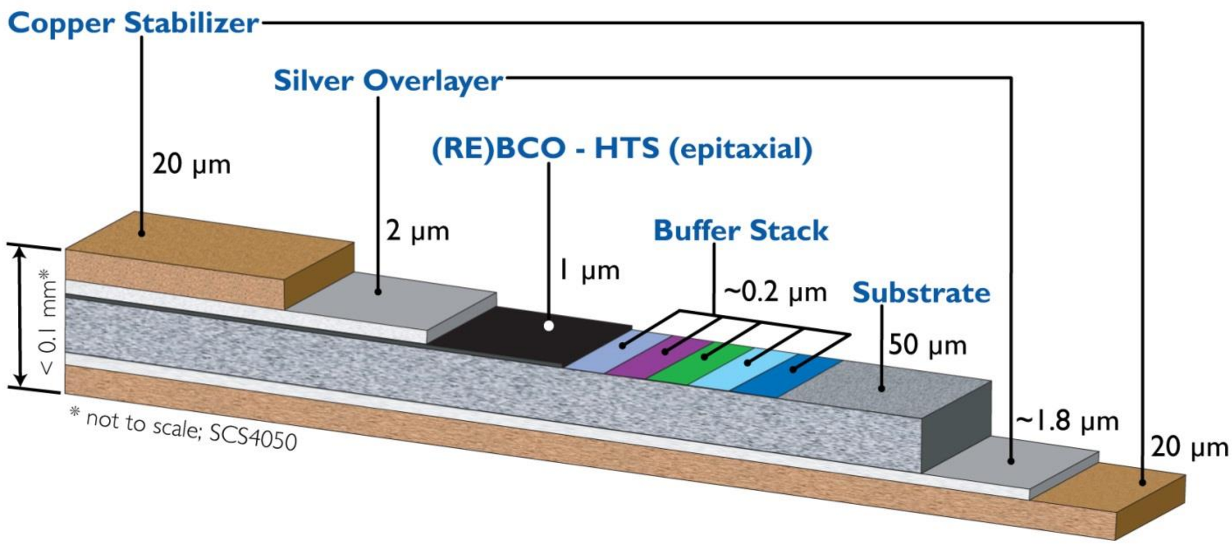


***Figure 1**: SuperPower 2G HTS 40 micron Copper conductor tape architecture*[3]

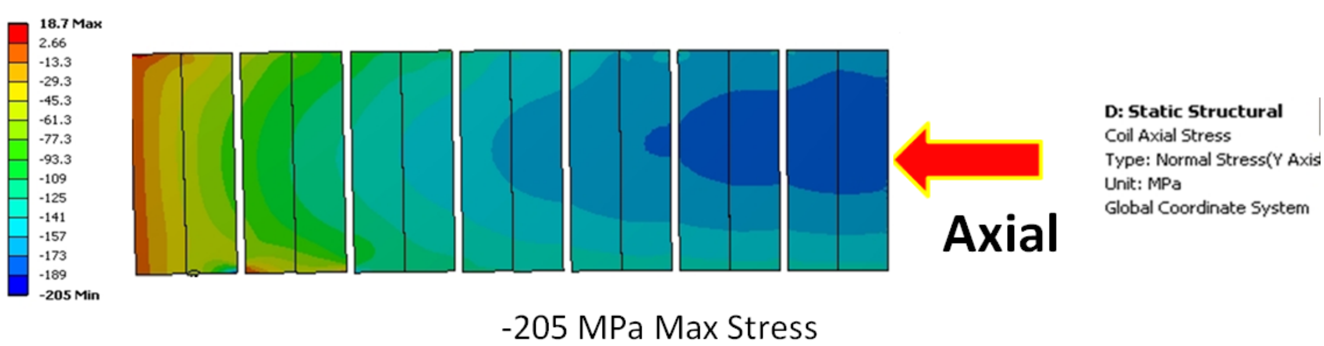


***Figure 2**: ANSYS FE simulation of orthogonal stress on coils in the axial direction at 4K & 25T*

The conductor used in the present design is based on 50 micron Hastelloy substrate and 10 micron copper stabilizer electroplated on each side making the nominal thickness of conductor roughly 75 micron. Fig. 1 shows the schematic of a typical conductor supplied by SuperPower with 20 micron copper stabilizer on each side. The mechanical properties of the conductor are primarily determined by the Hastelloy.

Ideally, these tests should be performed on the conductor with 10 micron copper stabilizer on each side (20 micron total). However, only ~10 meters of such conductor were available from SuperPower; the delivery date for a new order of 20 micron copper stabilizer conductor was given to be 4 months from the date of purchase order. considering the urgency of these tests (required to validate the conductor order and the design) and time to develop and debug the test apparatus with the conductor, most of the tests were performed with conductor in hand which had higher amounts of copper. The results, however, can be scaled by properly accounting for the areas of Hastelloy and copper.

The tests were carried out for different critical current margins (the coil is designed to have significant critical current margin) and for a number of cycles to simulate the life cycle tests in the coil. This note provides a summary of a number of the more detailed internal notes/logs. A total of 9 coils were wound and tested – 3 at room temperature, 9 at 77 K in Liquid Nitrogen. Several test fixtures were designed and built.

Experimental Setup

The initial tests were conducted on SuperPower 2G HTS 65 and 40 micron copper conductor. During the course of these high pressure tests, it was found that modifications in the initial design of the compression setup were required to develop an apparatus that would better simulate the conductor being structurally loaded in a coil wound and captured in the proposed IBS magnet. The final support structure simulates and applies the maximum axial load on the narrow face of the conductor producing conditions in the 25 T IBS magnet design. A CAD rendering of the basic fixture is shown in Figure 3.

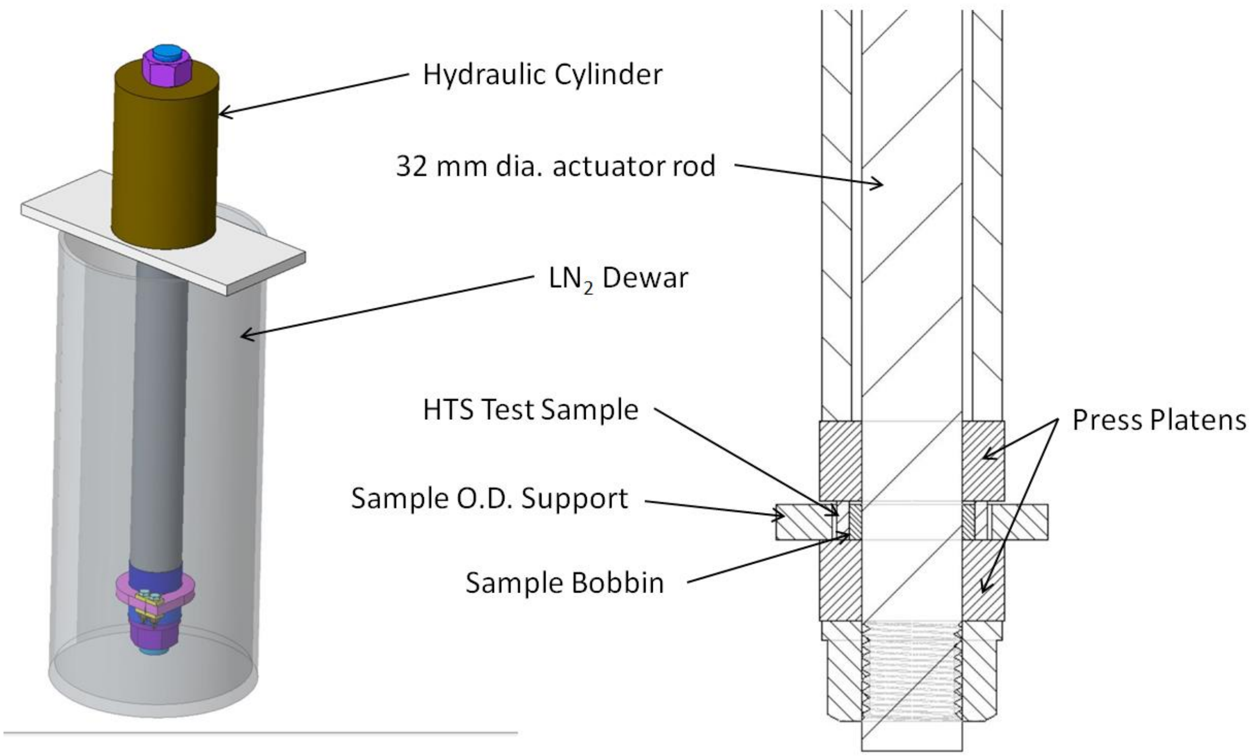


***Figure 3**: CAD rendering of the compression fixture*

The hydraulic cylinder used was an ENERPAC RCH-302 Hollow Plunger Cylinder that was manually pressurized and depressurized using an ENERPAC P-80 Hydraulic Steel Hand Pump. Compressive pressure was measured and recorded using a WIKA MODEL A-10 Pressure transmitter, Figure 4.

Figure 4: *Compressions fixture setup*

The current source used was a Hewlett-Packard 6680A 5 Volt / 875 Amp / 5 kW System DC Power Supply modified to 3.3 Volt / 1000 Amp. Signals were captured using a Hewlett-Packard 3457A Multimeter and recorded using an in-house HTBasic data acquisition program. Figure 5 shows the final test setup.

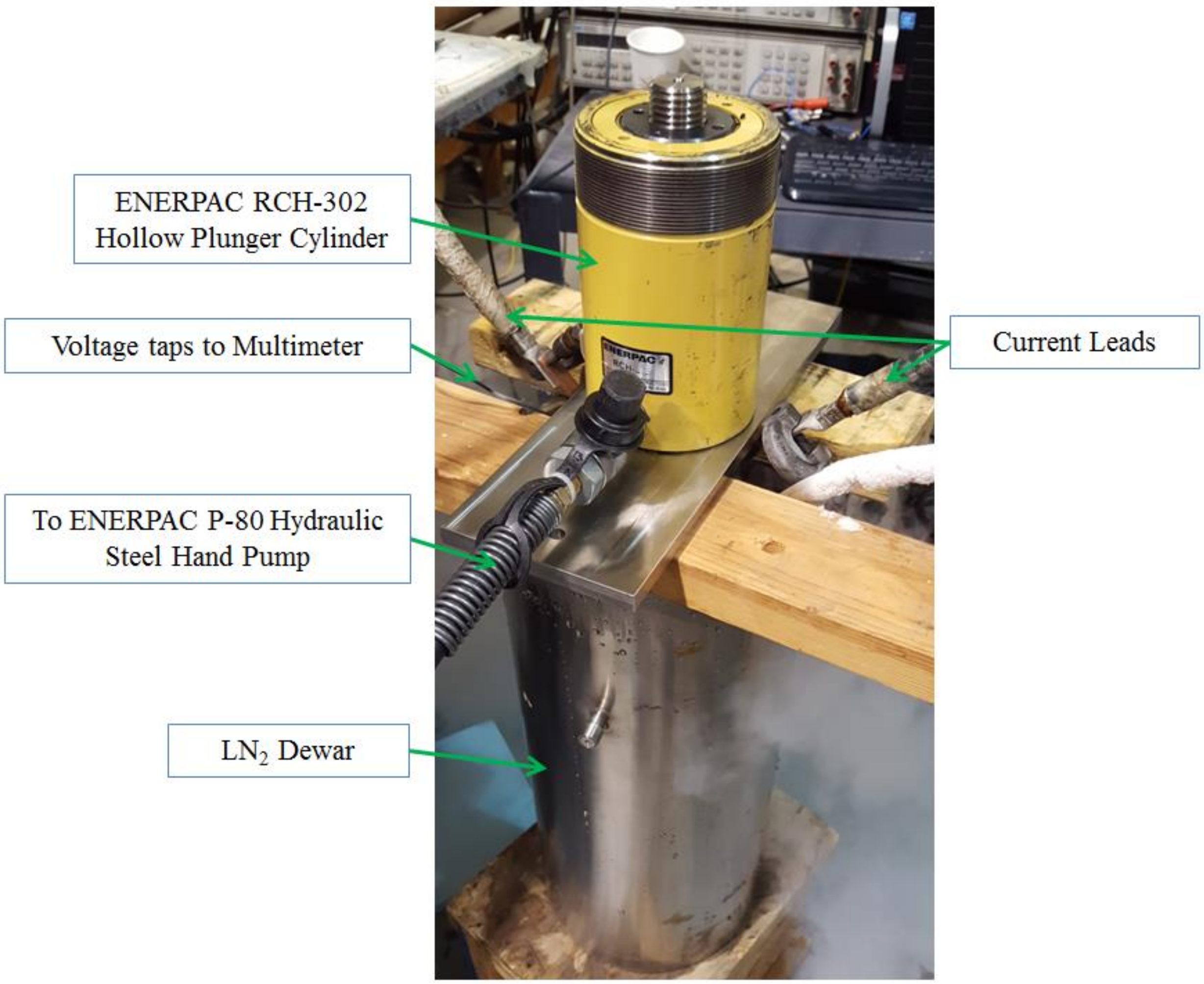


***Figure 5**: Compression Test setup*

Coil Holder Evolution

The samples were coils wound using SuperPower 2G HTS conductor of 65, 40, or 20 micron Copper Stabilizer thickness with an inner diameter (ID) of 1.5 inches and an outer diameter (OD) of 1.9 inches. The sample coil holder evolved from a Kevlar and Epoxy outer wrap to a series of Aluminum coil holders to eventually a Stainless Steel coil holder, Figure 6 – 14.

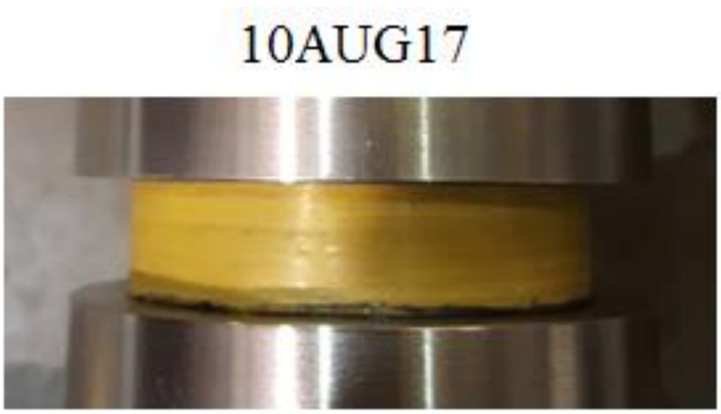


***Figure 6**: Kevlar wrapping reinforced by Epoxy – inefficient to remove and replace after every inspection and time consuming to wrap and dry*

***Figure 7**: Compression fixture with SuperPower 2G HTS 65µm Cu coil in Kevlar and Epoxy Wrapping*

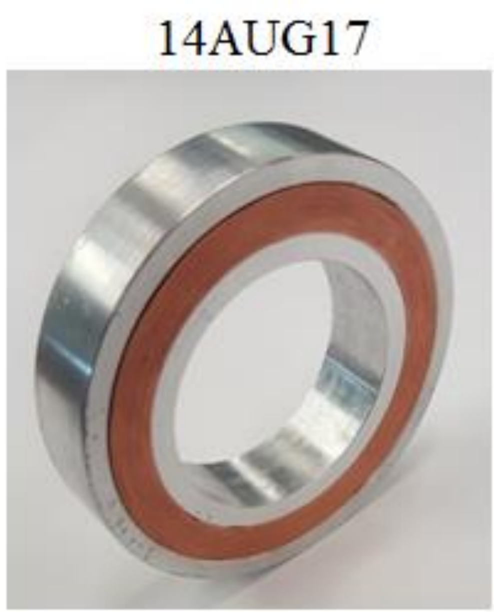


***Figure 8**: Aluminum outer ring – did not allow proper compression force distribution across sample*

25AUG17

***Figure 9**: Aluminum outer ring and single piston – left void at bottom of sample leading to improper compression force distribution*

28AUG17

***Figure 10**: Aluminum outer ring and double piston – improved design; however, Aluminum warped under compressive pressures in excess of 140 MPa*

15SEPT17 – 1st 40 μm Cu

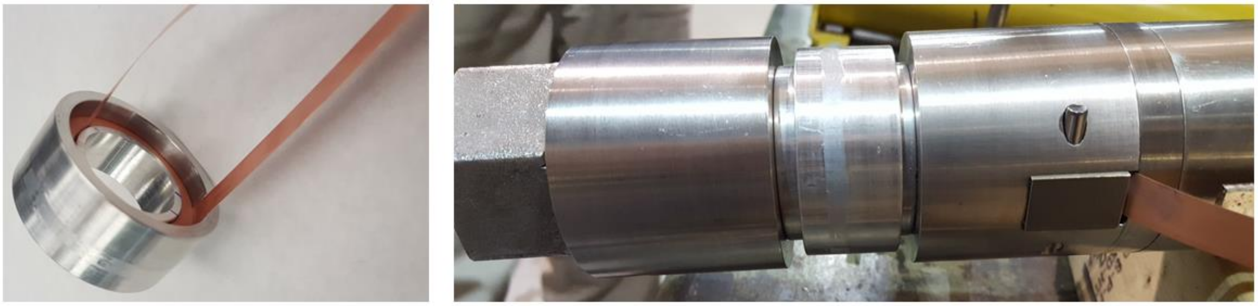


Figure 11: *Stainless Steel outer ring and double piston – optimal design*

21SEPT17 – 2nd 40 μm Cu

Figure 12: *Stainless Steel outer ring and double piston – optimal design; added 5 mil Mylar caps to top and bottom of coil for even compression force distribution and to prevent bypass current*

02OCT17 – 2nd 40 µm Cu

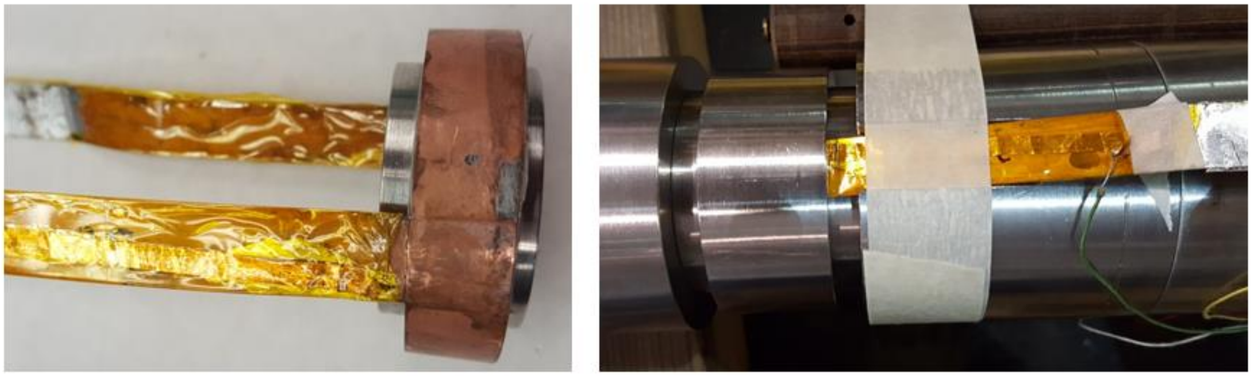


Figure 13*: In addition to the description in figure 11, added insulated lead voltage taps for more accurate data*

27OCT17 – 20 µm Cu

Figure 14*: Similar to description in figure 12, except, replaced 5 mil Mylar caps with two 5 mil Nomex (softer insulator) caps on top and bottom of coil*

Results and Discussion

SuperPower 2G HTS 65 µm Cu

4 coils were wound using 65 µm Copper stabilizer thickness conductor. The first coil wound was a 43 turn, no insulation, single layer coil using SuperPower 2G HTS 65 µm Cu conductor. Kevlar, reinforced with Epoxy, was wrapped around the coil to prevent radial forces from deforming and unwinding the coil. Figure 15 shows the I vs V curve in Liquid Nitrogen (77 K) under various compressive loading. One can see a gradual increase in degradation with compressive loading at high currents.

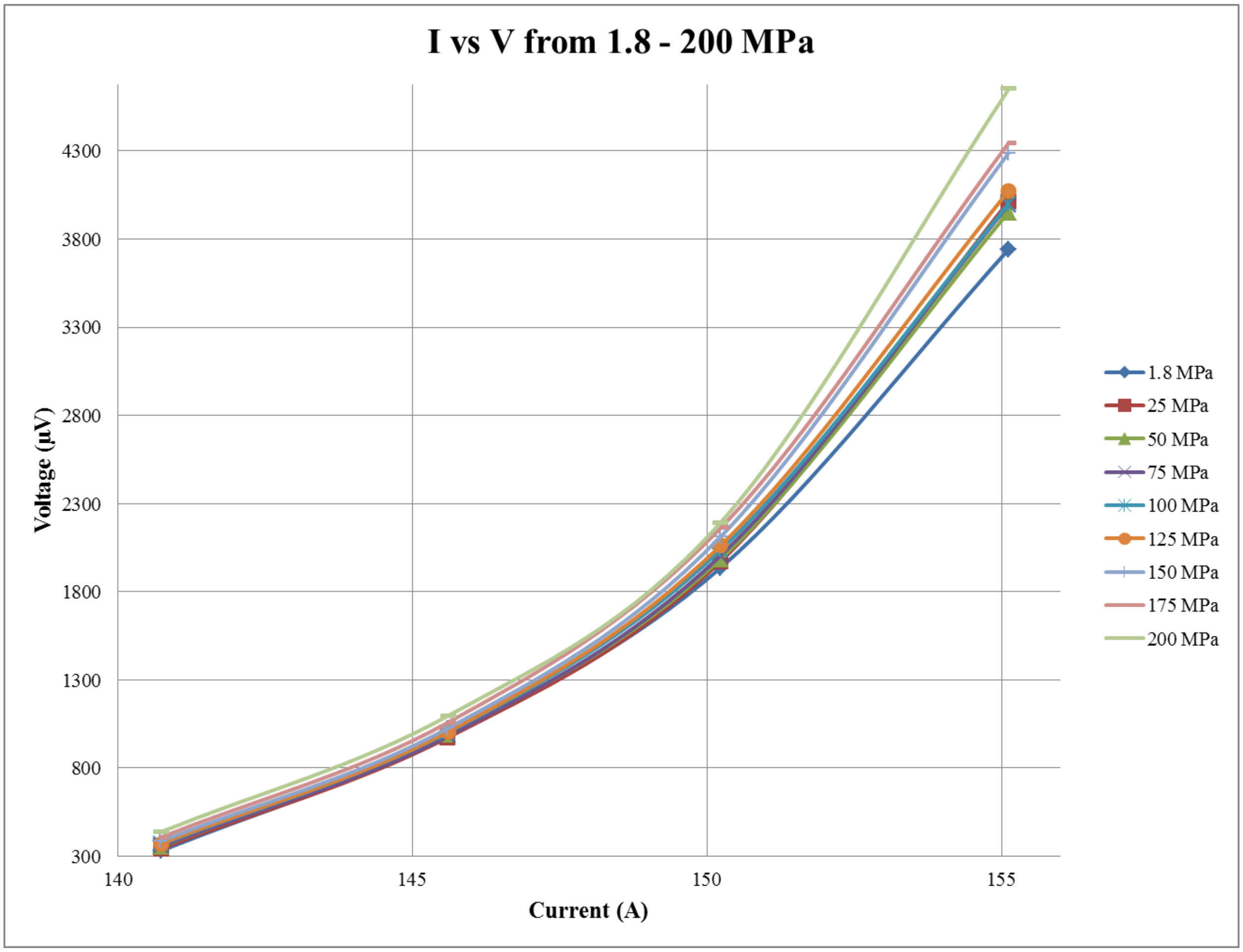


Figure 15*: I vs V for SuperPower 2G HTS 65µm Cu coil in Kevlar and Epoxy Wrapping at various compressive pressures*

As the compressive pressure was increased past 200 MPa at 77 K, an acoustic event occurred from the Dewar in the form of a “bang” sound. At this point, the resistive voltage in the coil shot up and the power supply was shut off to prevent coil damage. An I vs V for the coil was taken, Figure 16.

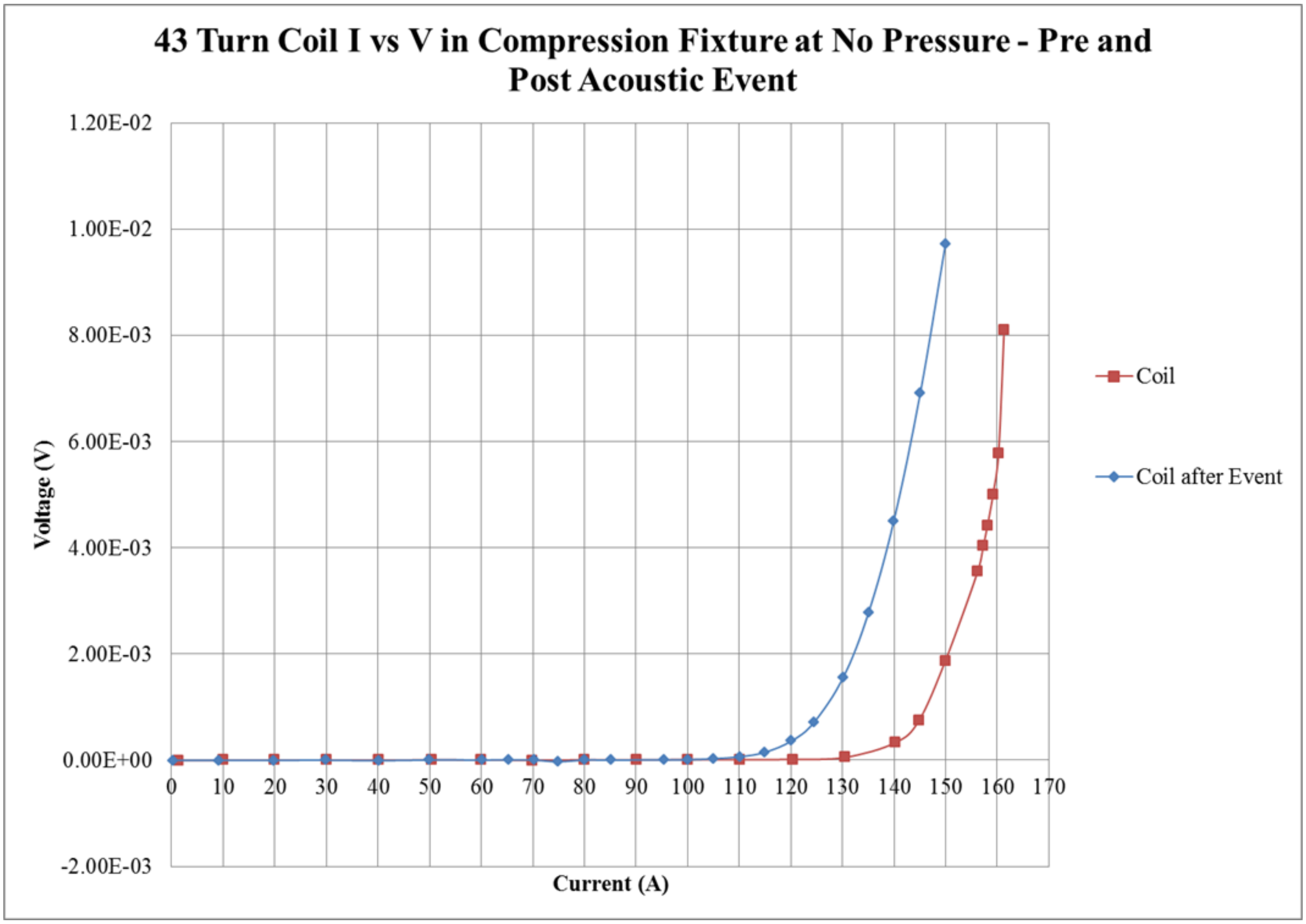


Figure 16: *I vs V for SuperPower 2G HTS 65µm Cu coil in Kevlar and Epoxy Wrapping before and after acoustic event*

The Kevlar wrapping was removed to inspect for physical deformation, Figure 17.

Figure 17: *Physical deformation in 43 turn coil after compression cycles*

A second 43 turn, no insulation, single layer coil was wound using SuperPower 2G HTS 65 µm Cu conductor. An Aluminum outer ring with a height of 460 mils (11.684 mm) was manufactured. To fit the coil to the ring, we had to remove 2 turns. The 65 µm Cu conductor coil is now a 41 turn coil, Figure 18.

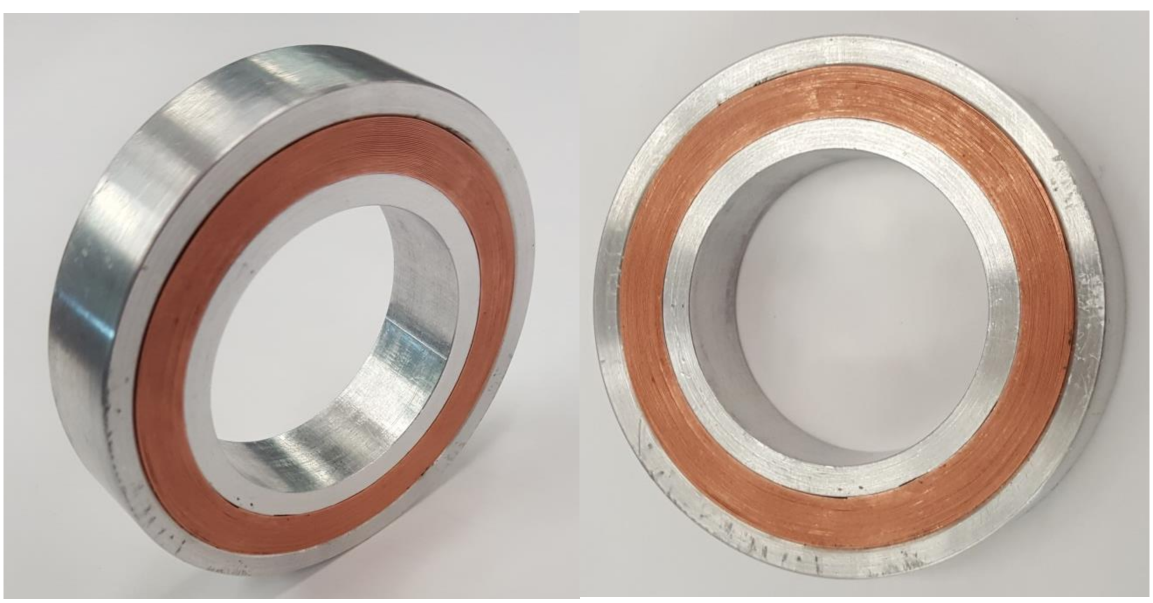


Figure 18: *Second, 41 turn, SuperPower 2G HTS 65µm Cu coil in Aluminum outer ring*

The second coil was installed into the compression fixture and compressed in increments of 25 MPa at room temperature to observe the extent of the physical deformation at various compressive loadings. The height of the coil was measured, with a feeler gauge, while under pressure using the outer ring as a reference point. Figure 19 shows the decrease in height of the coil under increased compression. [The original height of the coil was 478 mils (12.1412 mm). The coil had inelastically compressed by 2 mils (50.8 μm) due to compression loading in the prior test.]

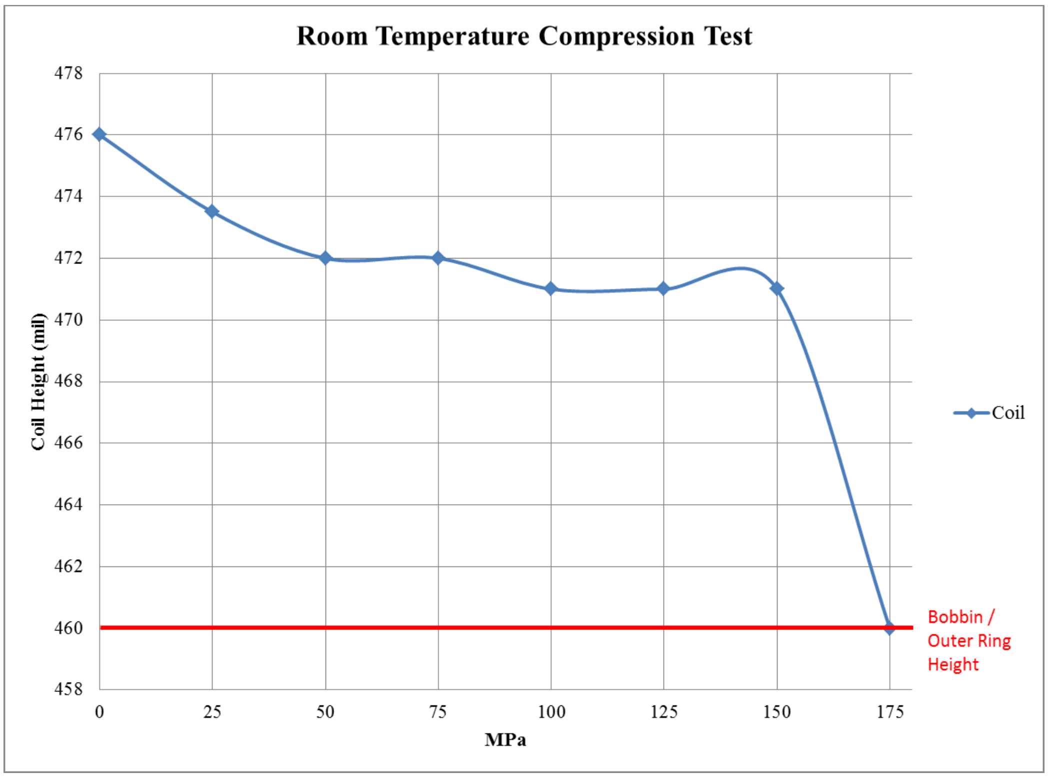
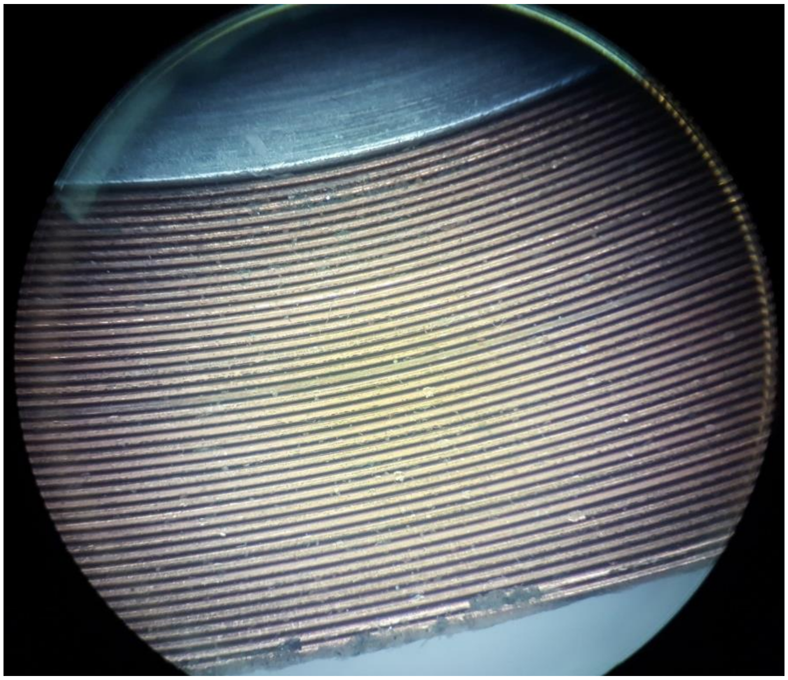


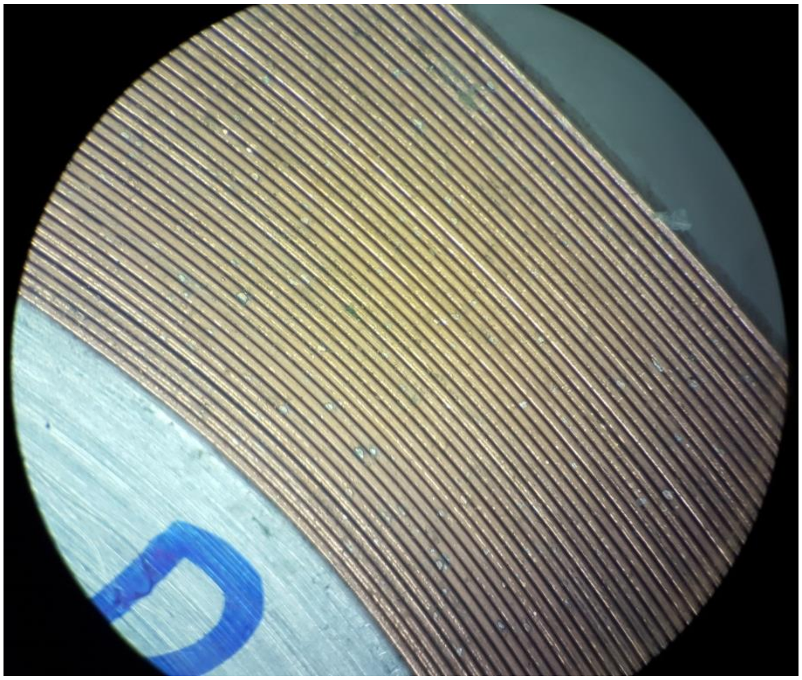
Figure 19: *Room temperature compression test*

At approximately 170 MPa, a loud acoustic bang was heard – similar to the acoustic sound heard above 200 MPa during the Liquid Nitrogen compression fixture test on the first 65 μm Cu conductor coil. The coil was removed from the compression fixture and obvious physical deformation was observed; deformation was similar to that observed in the first coil after the acoustic sound in the Liquid Nitrogen compression test. The bottom part of the coil showed microscopic edge flattening at higher compressive loadings while obvious and severe physical deformation was observed on the top.

Picture 1 and 2 show the effects of 25 MPa of compressive loading on the second coil under a microscope. One can observe no obvious physical deformation in the coil.

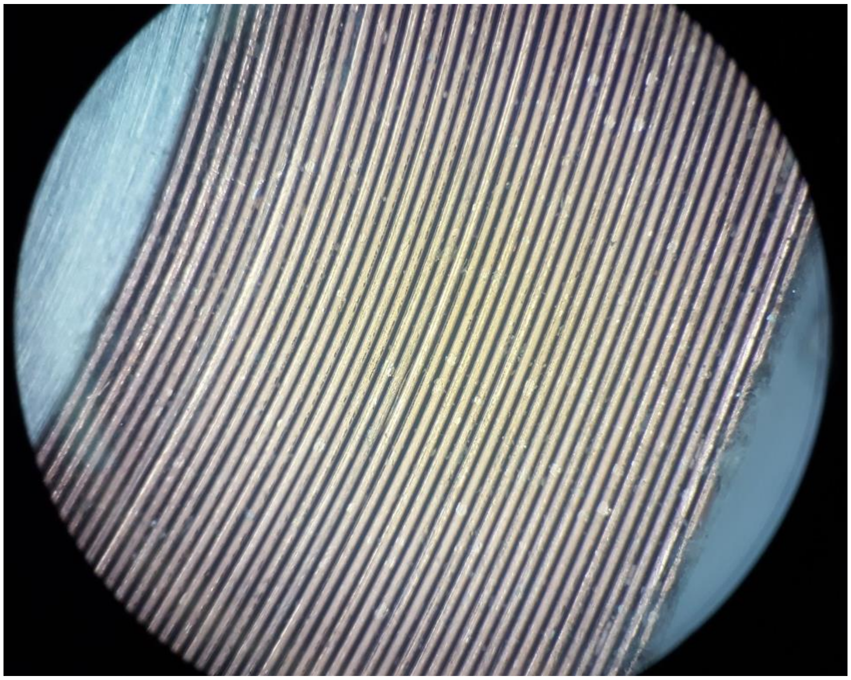


Picture 1: *Top of the coil after 25 MPa of compressive loading under a microscope*

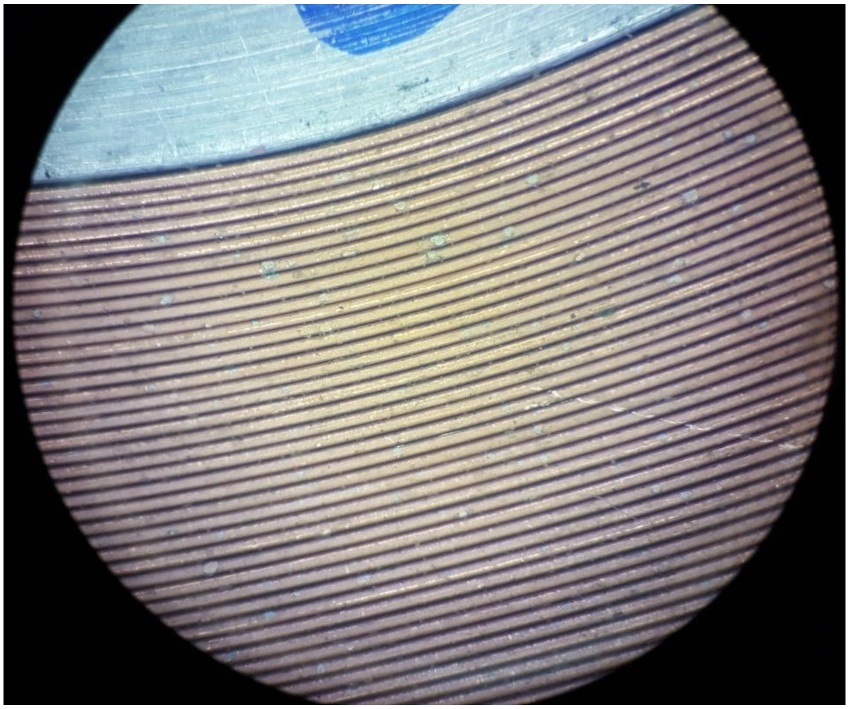


Picture 2: *Bottom of the coil after 25 MPa of compressive loading under a microscope*

Picture 3 and 4 show the effects of 100 MPa of compressive loading on the second coil under a microscope. One can observe instances of minute edge flattening on the top and bottom surface of the coil.

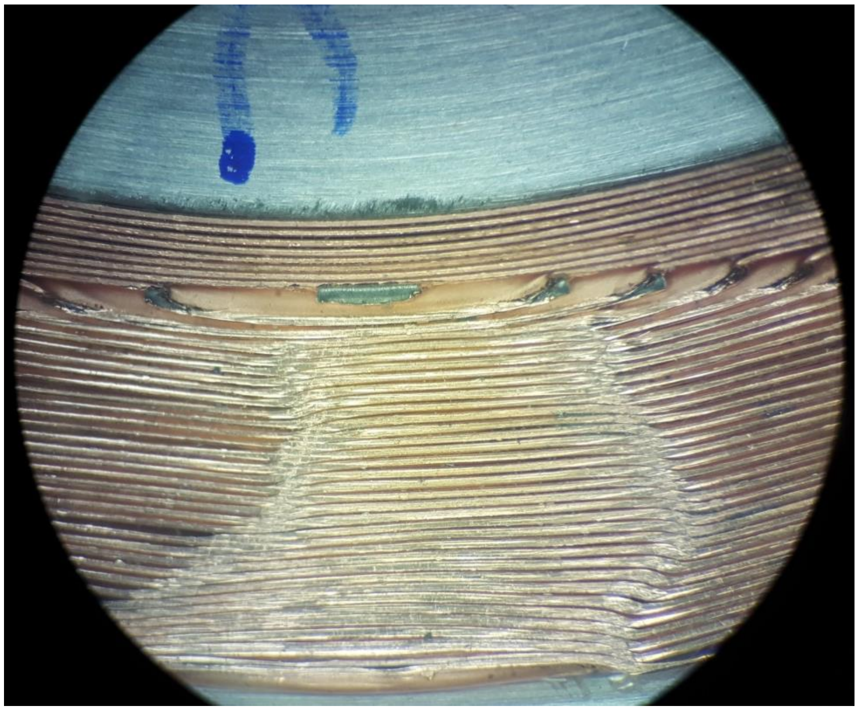


Picture 3: *Top of the coil after 100 MPa of compressive loading under a microscope*

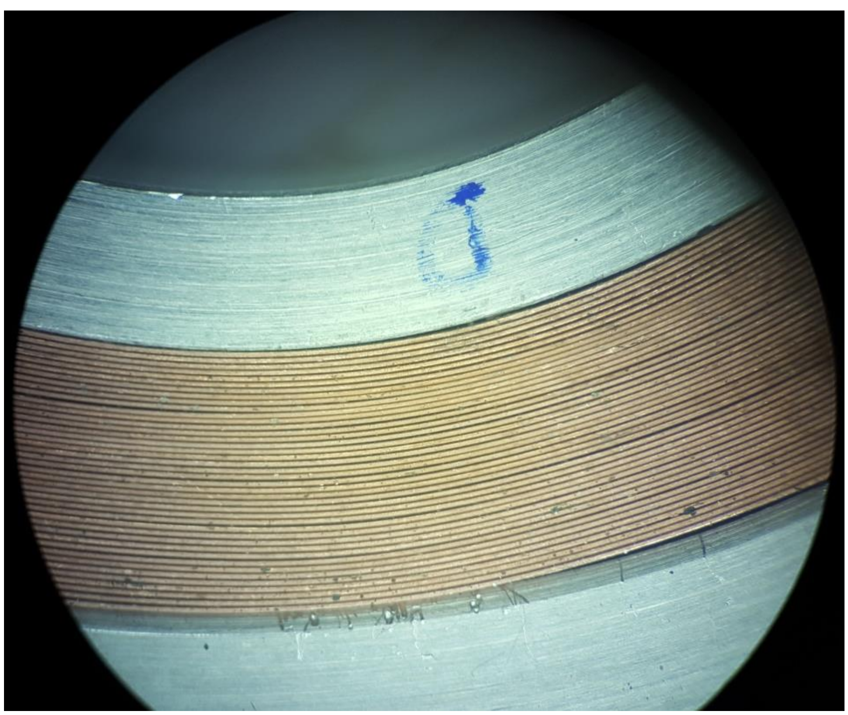


Picture 4: *Bottom of the coil after 100 MPa of compressive loading under a microscope*

Picture 5 and 6 show the effects of 175 MPa of compressive loading on the second coil under a microscope. One can observe severe physical deformation on the top of the coil while, comparatively, the bottom of the coil looks fairly intact.



Picture 5: *Top of the coil after 175 MPa of compressive loading under a microscope*



Picture 6: *Bottom of the coil after 175 MPa of compressive loading under a microscope*

Two more SuperPower 2G HTS 65μm Cu coils were wound and crushed at room temperature. These tests proved valuable in optimizing the design of the coil holder.

<u>SuperPower 2G HTS 40 µm Cu</u>

4 coils were wound using 40 µm Copper stabilizer conductor. A 50 turn, no insulation, single layer coil using SuperPower 2G HTS 40 µm Cu conductor was wound (conductor measured thickness of: 3.8 mil (96.52 µm); width: 475 mil (12.065 mm)) and subjected to compression tests in a modified Aluminum compression fixture coil holder at 77 K; Figure 20 summarizes data retrieved from multiple compressive pressure cycles and 3 thermal cycles.

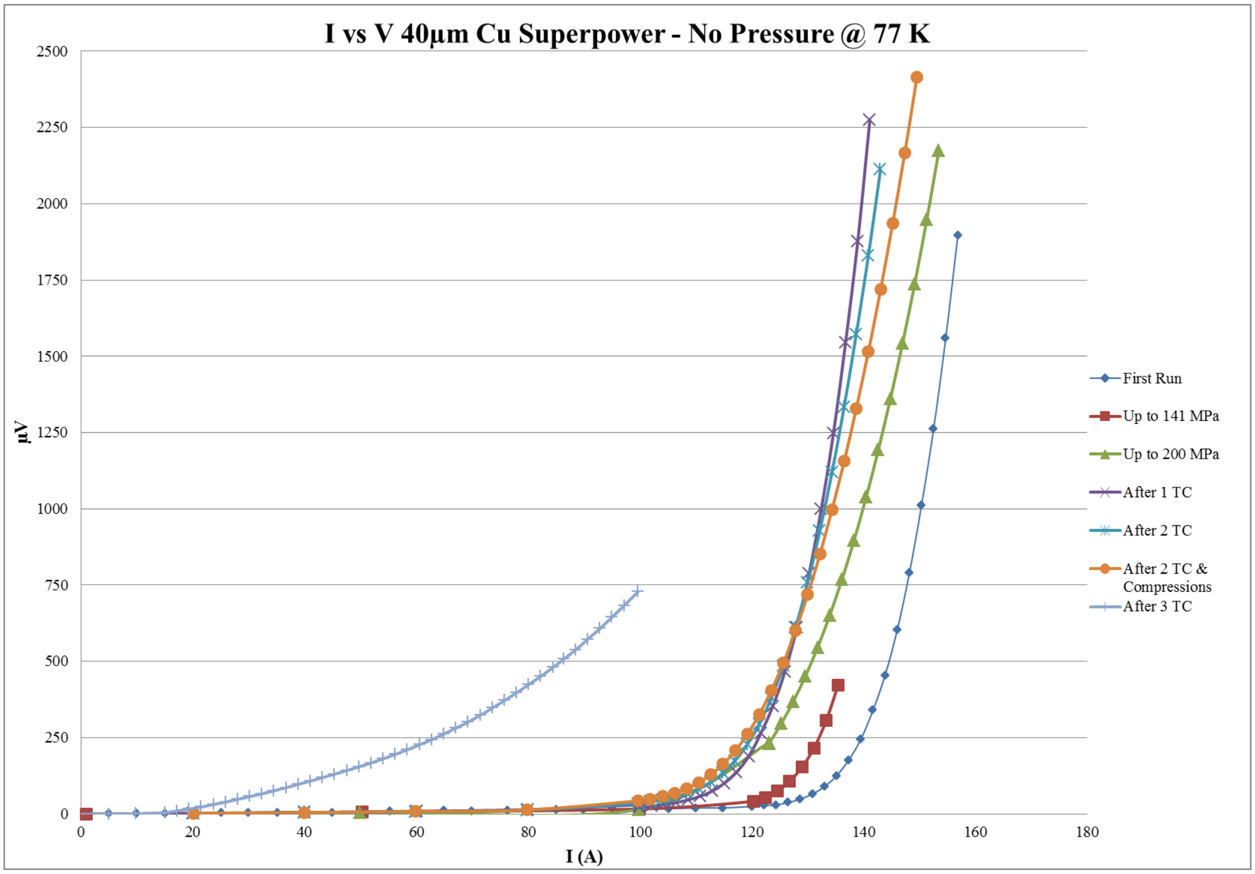


Figure 20: *I vs V for 40µm Coil through multiple compressive and thermal cycles*

Physical warping of the Aluminum coil holder was observed as it was subjected to compressive loading cycles past 140 MPa. To rectify the warping issue, for the second 40 µm Cu conductor coil, a Stainless Steel coil holder was manufactured.

A second 50 turn, no insulation, single layer coil using SuperPower 2G HTS 40 µm Cu conductor was wound (conductor measured thickness of: 3.8 mil (96.52 µm); width: 475 mil (12.065 mm)) and subjected to compression tests in a modified Stainless Steel (SS) compression fixture holder at 77 K. Two Mylar caps were installed on the top and bottom of the coil (while in the SS holder) to promote even compressive pressure distribution. As shown in Figure 21, linear resistive voltage was observed from 0 – 120 Amps.

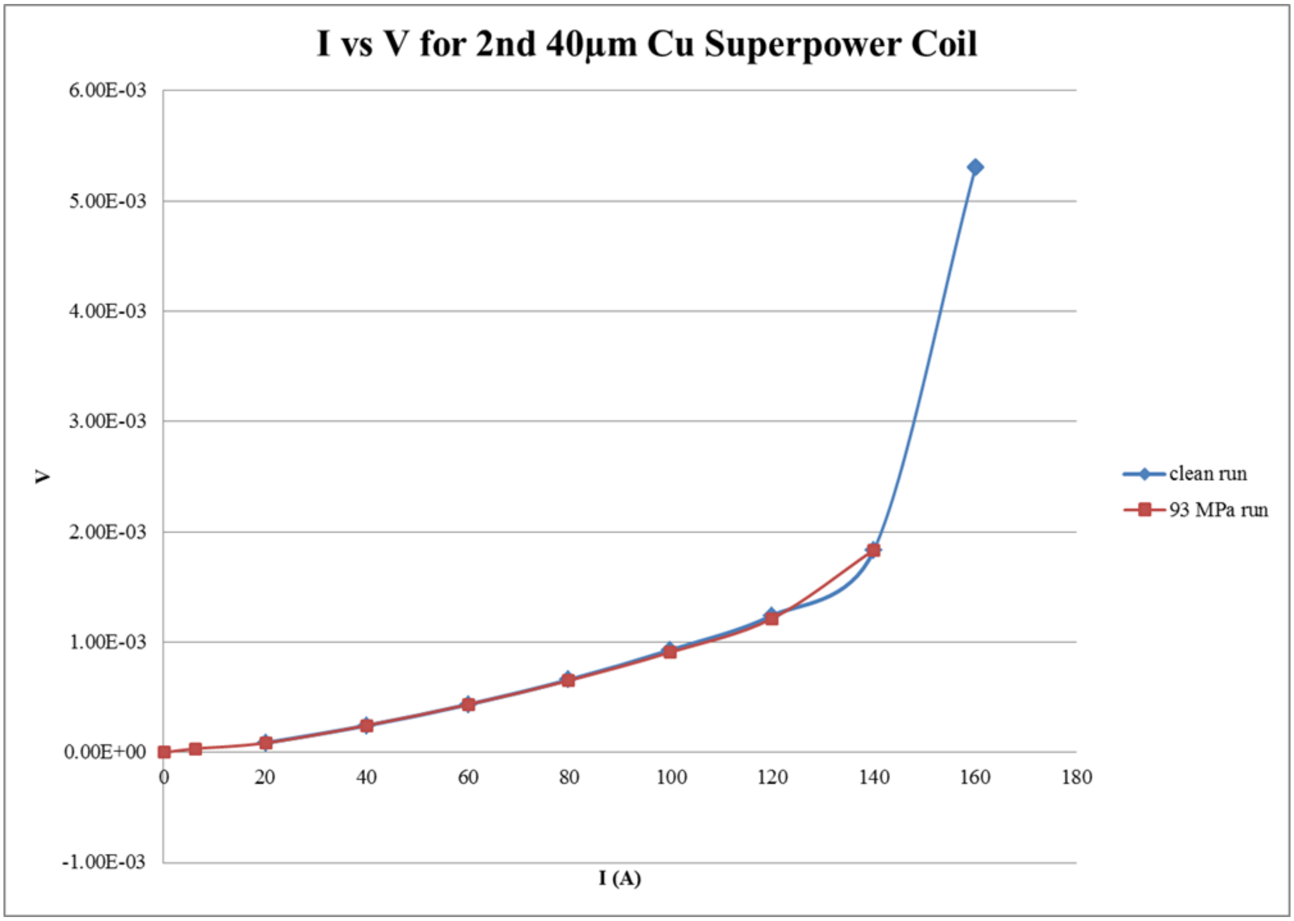


Figure 21: *Initial I vs V for 2nd 40µm Coil*

After extensive troubleshooting, the culprit was discovered to be a local deformity in the positive current lead close to the coil. To avoid this issue in future tests, an insulated voltage tap was installed and moved as close as possible (allowable by the Stainless Steel coil holder) to the coil.

Figures 22 - 25 are comparisons of the coil performance at similar compressive pressures from 02OCT17 (Mon) to 03OCT17 (Tue); coil was thermally cycled overnight.

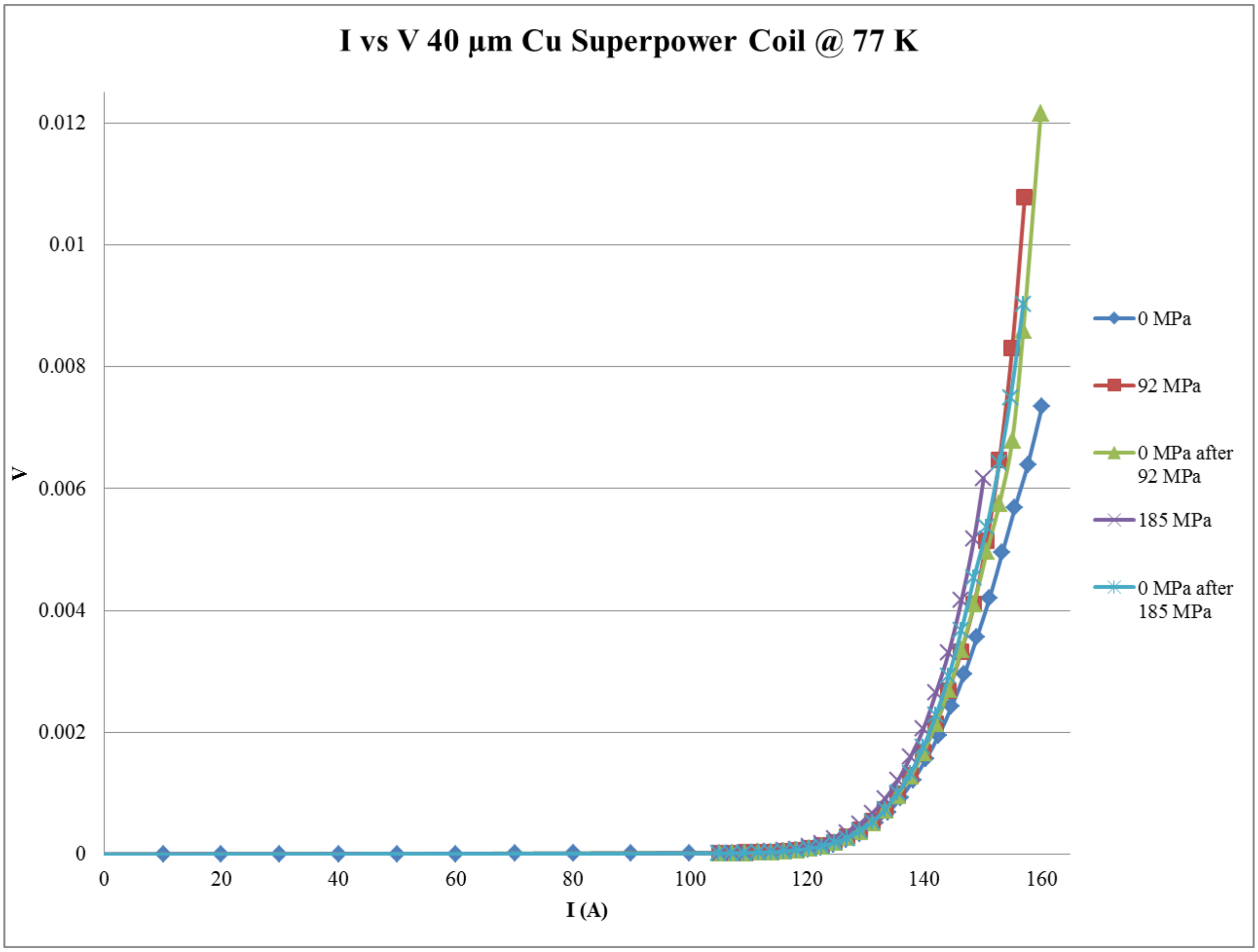


Figure 22: *I vs V for 2nd 40µm Coil @ 77K*

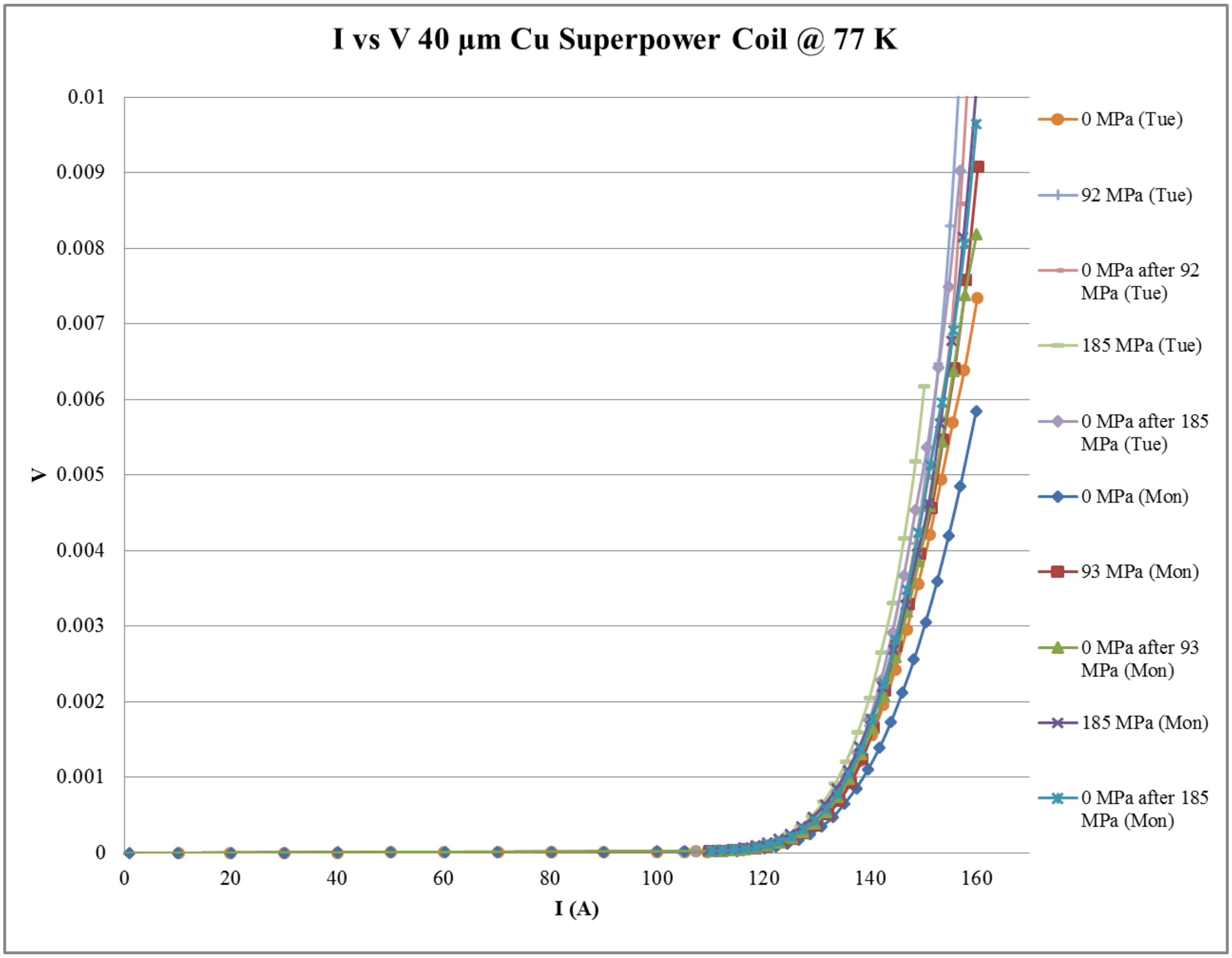


Figure 23: *I vs V for 2nd 40µm Coil @ 77K*

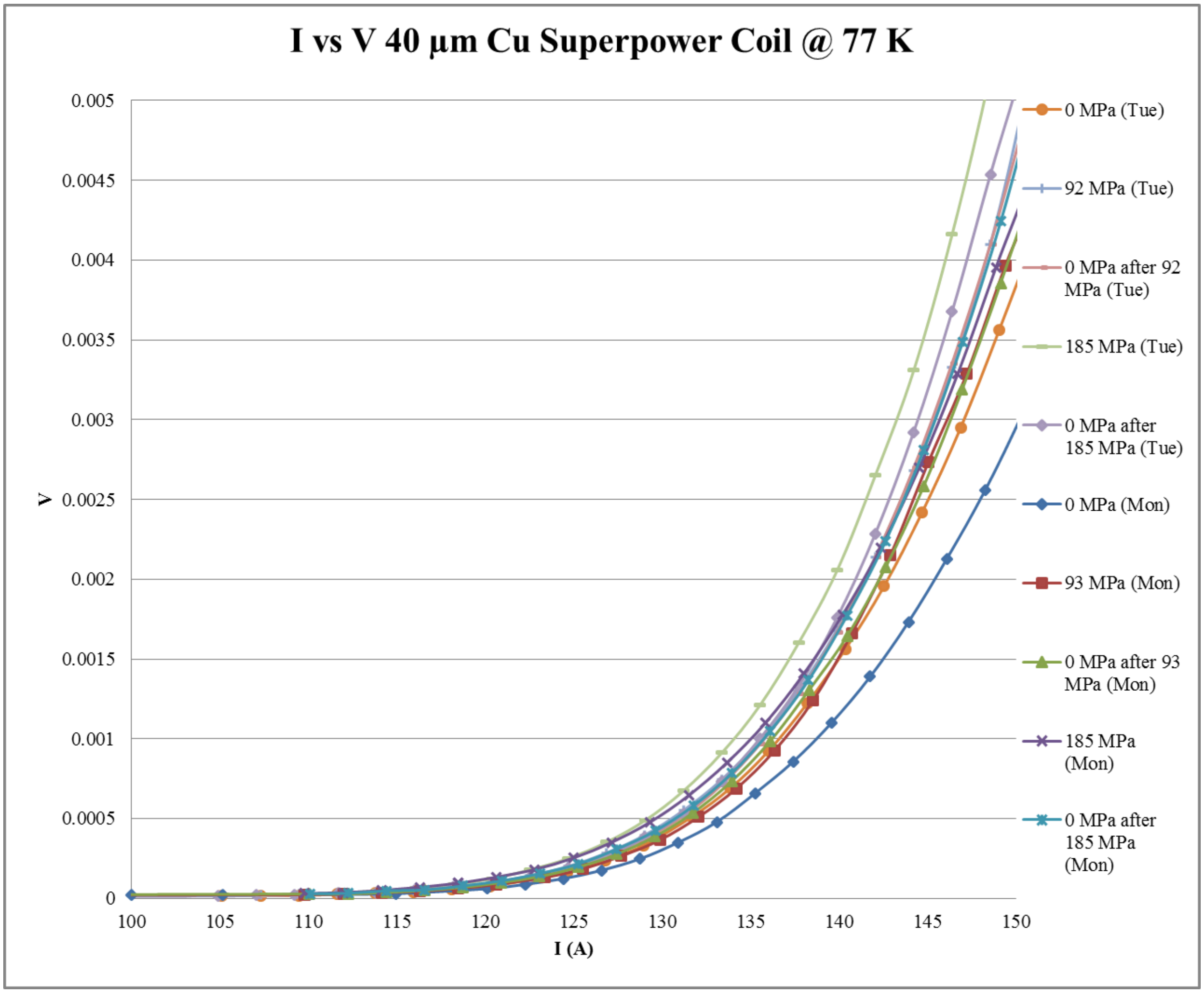


Figure 24: *I vs V for 2nd 40µm Coil @ 77K*

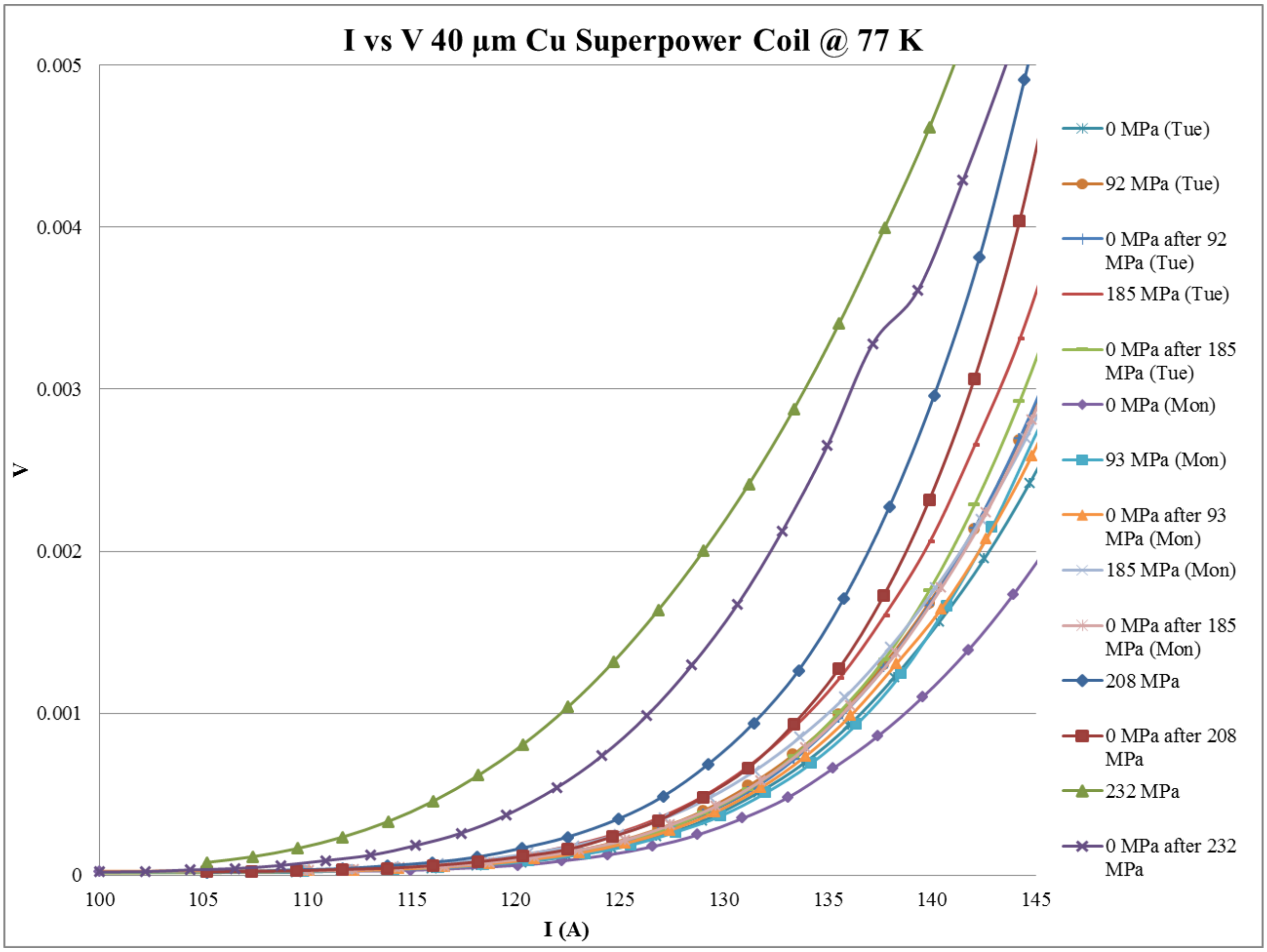


Figure 25: *I vs V for 2nd 40µm Coil @ 77K*

The above tests gave us confidence that the 40 µm Cu conductor coil could withstand compressive loading similar to that calculated for the IBS magnet. It also showed that as the thickness of the Copper stabilizer layer was decreased, the coil was able to withstand higher compressive loading – due to the increase in the Hastelloy to Copper ratio of the coil.

The coil was then subjected to compressive pressures up to 232 MPa. Figures 26 - 27 are the I vs V curves.

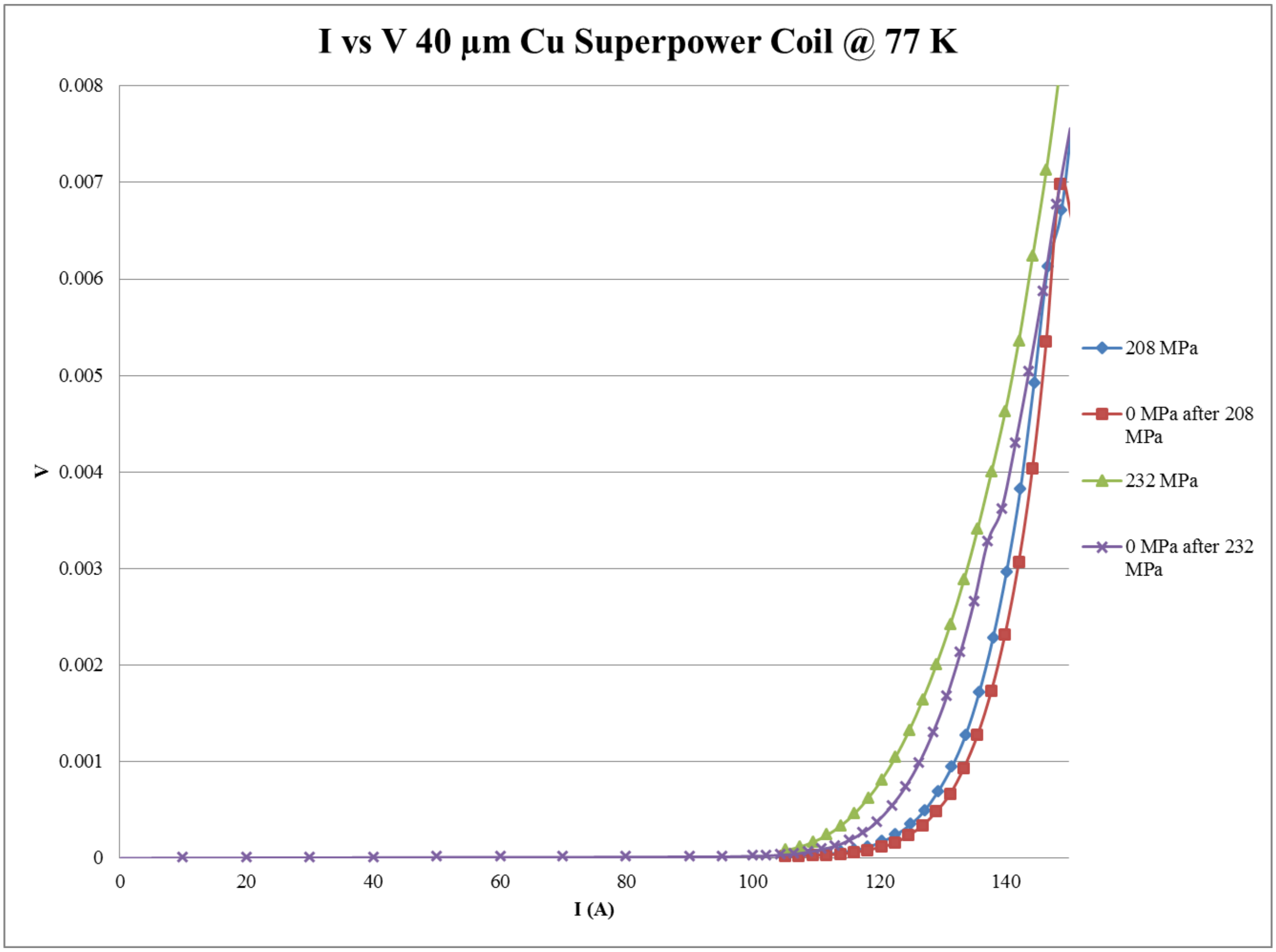


Figure 26: *I vs V for 2nd 40µm Coil with and without compressive pressure*

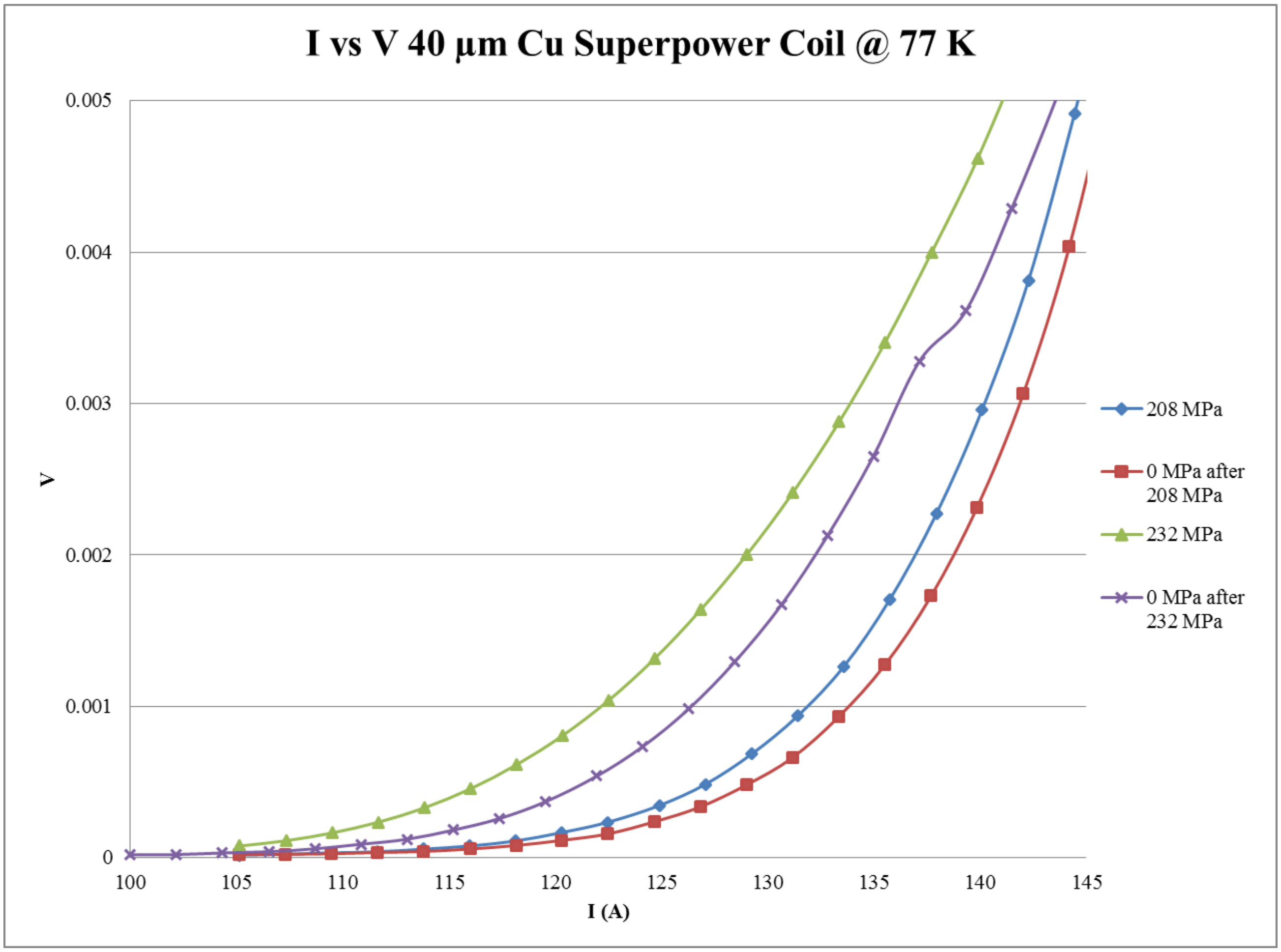


Figure 27: *I vs V for 2nd 40µm Coil with and without compressive pressure*

One of the purposes for conducting this test was to push the conductor beyond its operational envelope and observe its performance degradation. Figures 26 and 27 show that the coil can perform within the I_c margins that are being considered for the IBS magnet, which are well beyond the calculated compressive loading of 205 MPa. This test further solidified our confidence in choosing the SuperPower 2G HTS 20 µm Cu conductor for the IBS magnet.

The coil was then subjected to compressive pressures up to 255 MPa. Figures 28 - 29 show the I vs V curve.

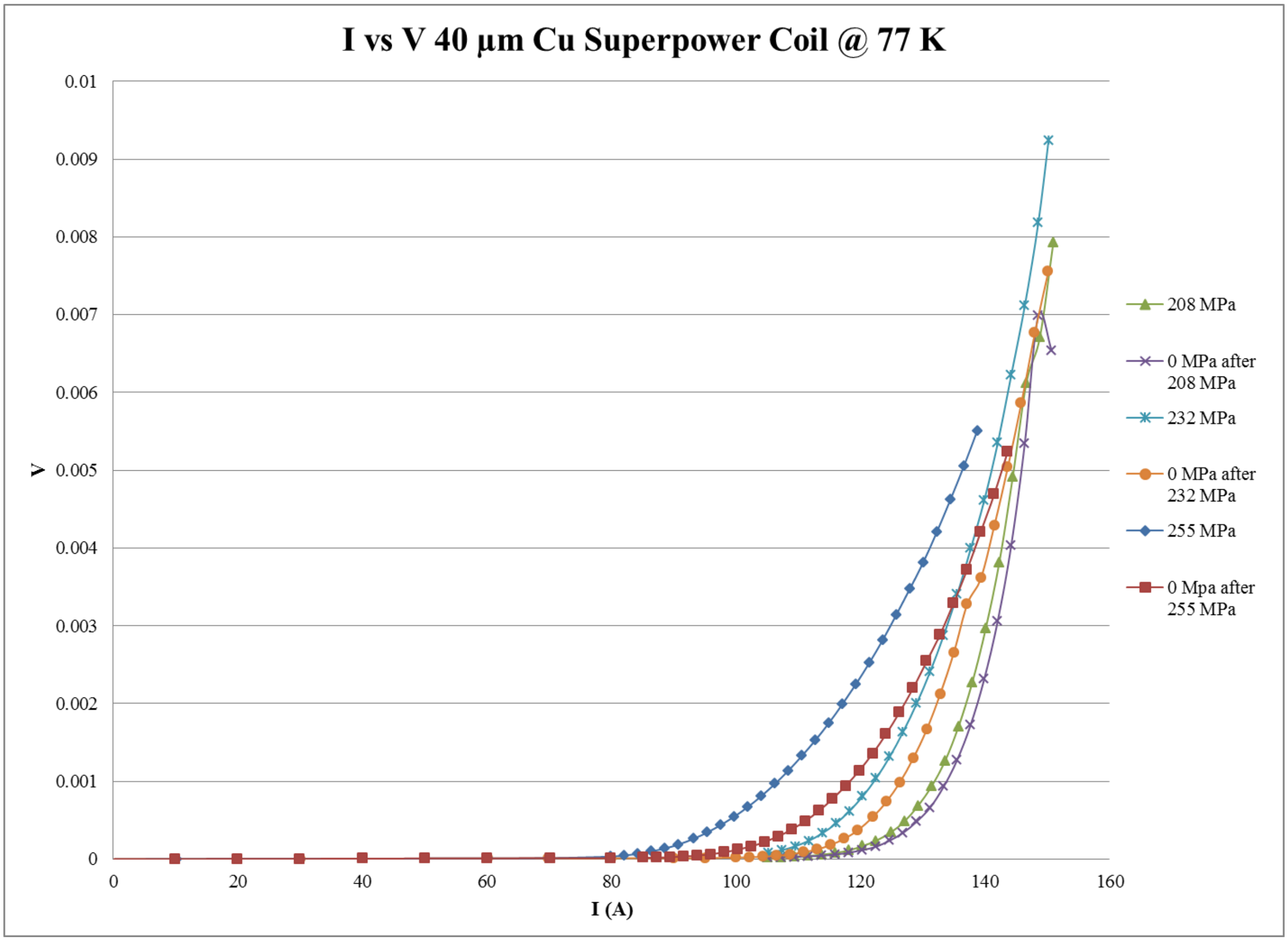


Figure 28: *I vs V for 2nd 40µm Coil with and without compressive pressure*

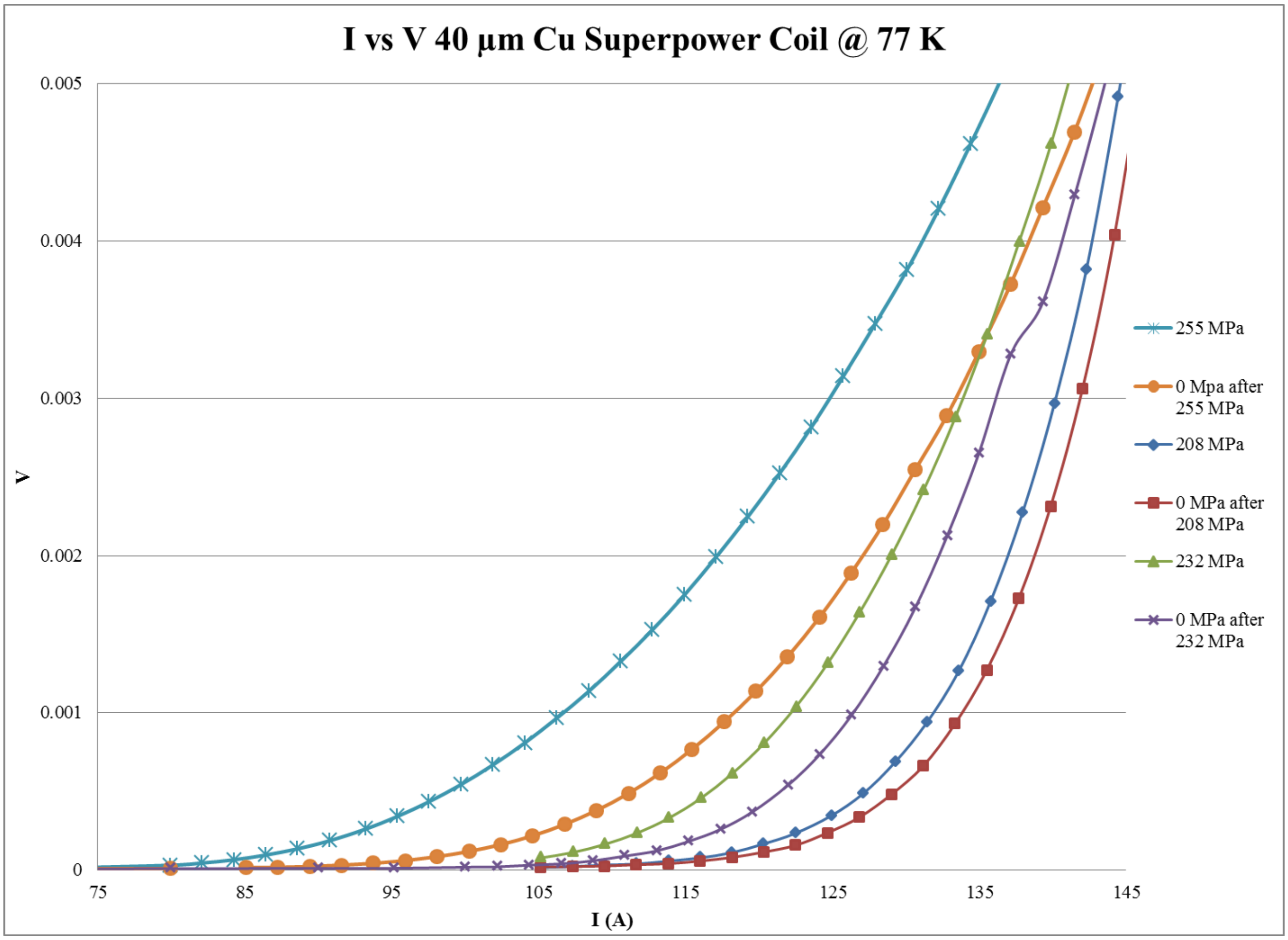


Figure 29: *I vs V for 2nd 40µm Coil with and without compressive pressure*

This test was performed to assess the breaking point of this conductor. At 255 MPa, significant conductor performance degradation was observed. The coil was removed from the stainless steel compression setup and showed minor physical deformation upon visual inspection.

A third 50 turn, no insulation, single layer coil using SuperPower 2G HTS 40 µm Cu conductor was wound (conductor measured thickness of: 3.8 mil (96.52 µm); width: 475 mil (12.065 mm)) and subjected to compression tests in a modified Stainless Steel (SS) compression fixture holder at 77 K. Two Mylar caps were installed on the top and bottom of the coil (while in the SS holder) to promote even compressive pressure distribution. Figures 30 – 31 are I vs V curves for the coil at 0 MPa.

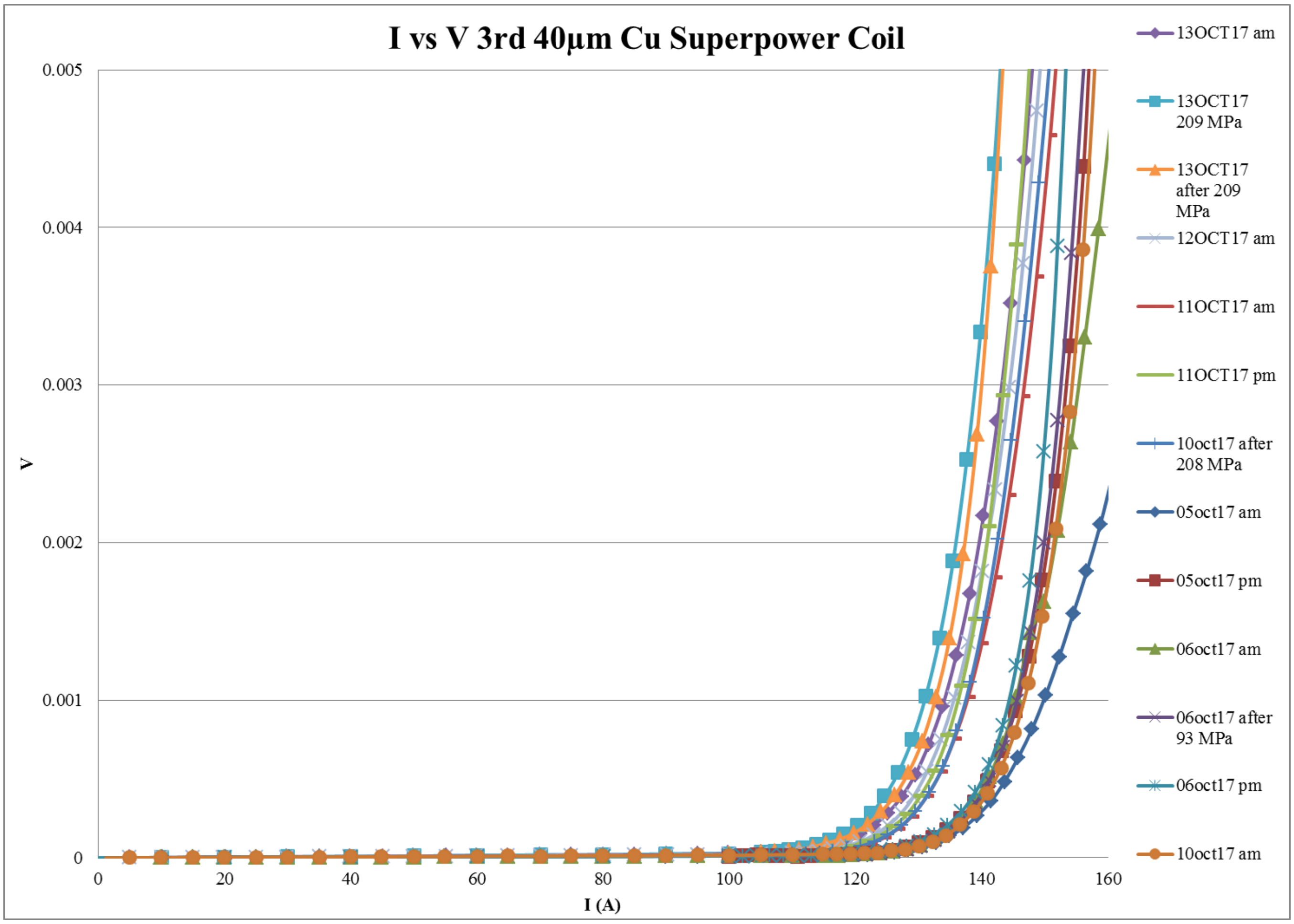


Figure 30: *I vs V for 3rd 40µm Coil throughout its test time*

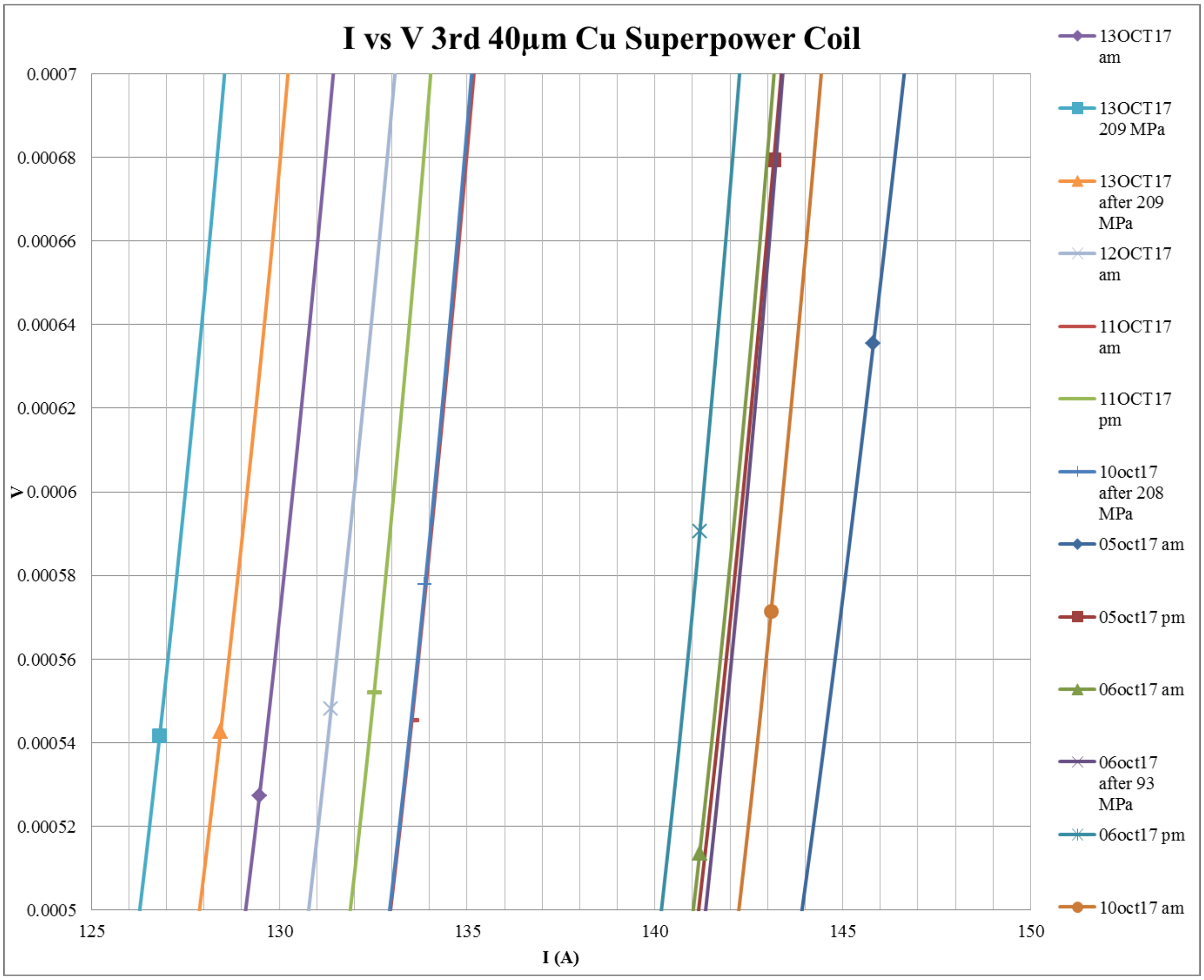


Figure 31: *I vs V for 3rd 40µm Coil throughout its test time*

Figures 30 and 31 showed us the ruggedness of the conductor. After over a week of compressive loading and multiple thermal cycling, the coil was performing well within the initial 30% I_c.

The coil was then subjected to compressive loading up 183 MPa while holding the current steady at 140 Amps, 95% the coils I_c in accordance with the 1µV/cm parameter for calculating I_c threshold voltage (700 µV for this coil). Figure 32 shows the effect, in the form of resistive voltage, of various compressive pressures on the coil at 140 A.

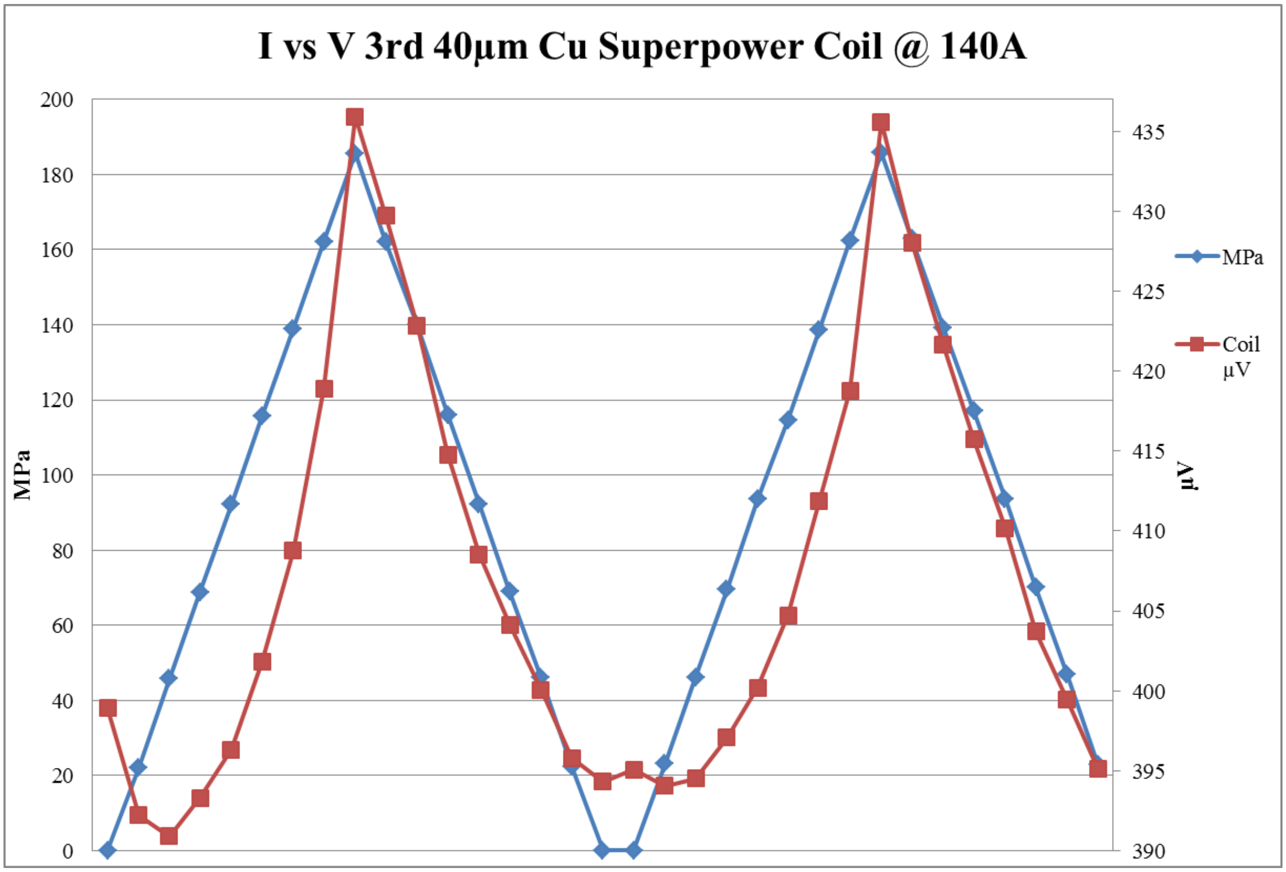


Figure 32: *3rd 40µm Coil compression behavior at 140 A*

As the compressive loading was ramped up to 183 MPa at 140 A, there was a rise in resistive voltage by 45 µV, well within performance limits (700 µV for this coil).

The coil was then subjected to 208 MPa while holding the current steady at 140 Amps, Figure 33.

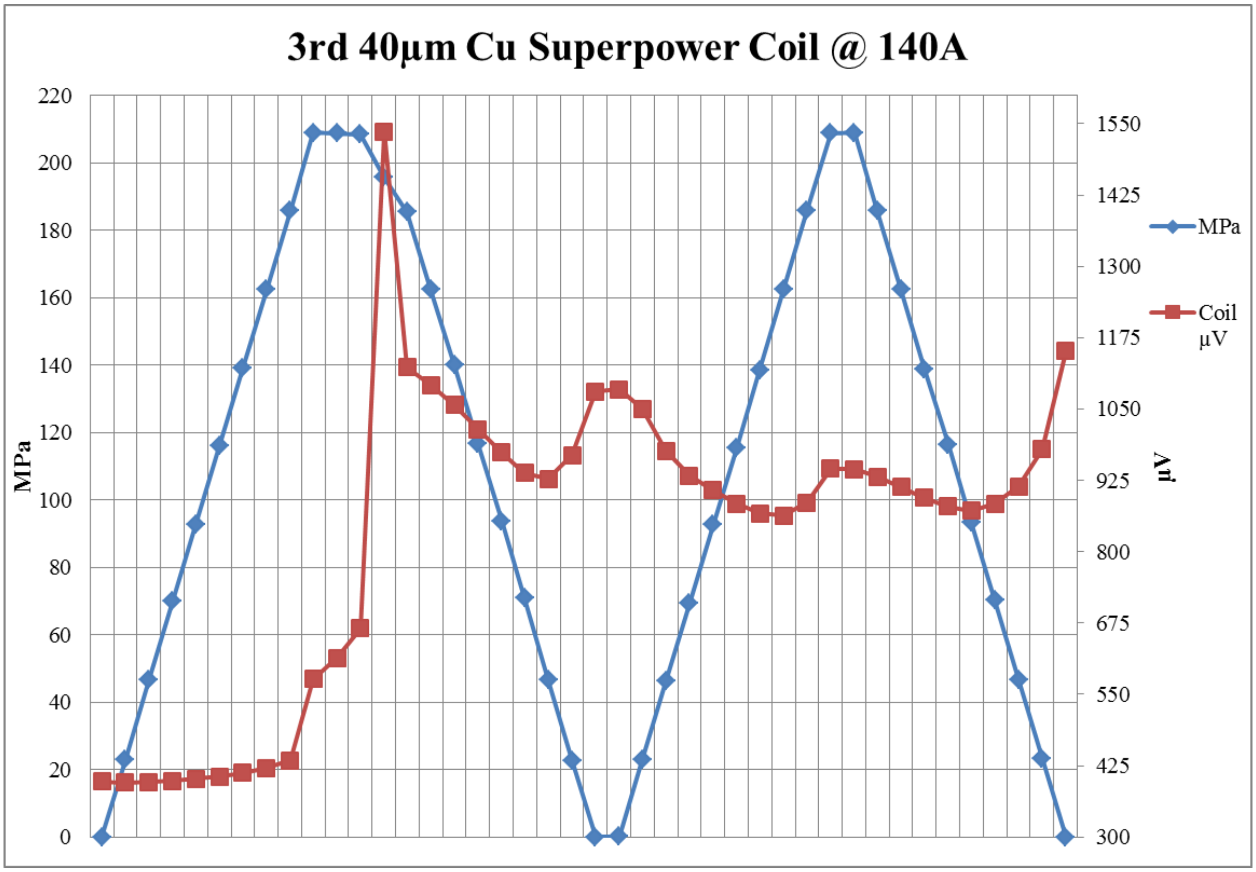


Figure 33: *3rd 40µm Coil compression behavior at 140 A*

At 208 MPa, an acoustic "bang" was heard, as seen in Figure 33, and the coil voltage jumped up by 871 µV.

Another cycle up to 208 MPa was run on the coil with the current lowered to 135 A, Figure 34 - 35.

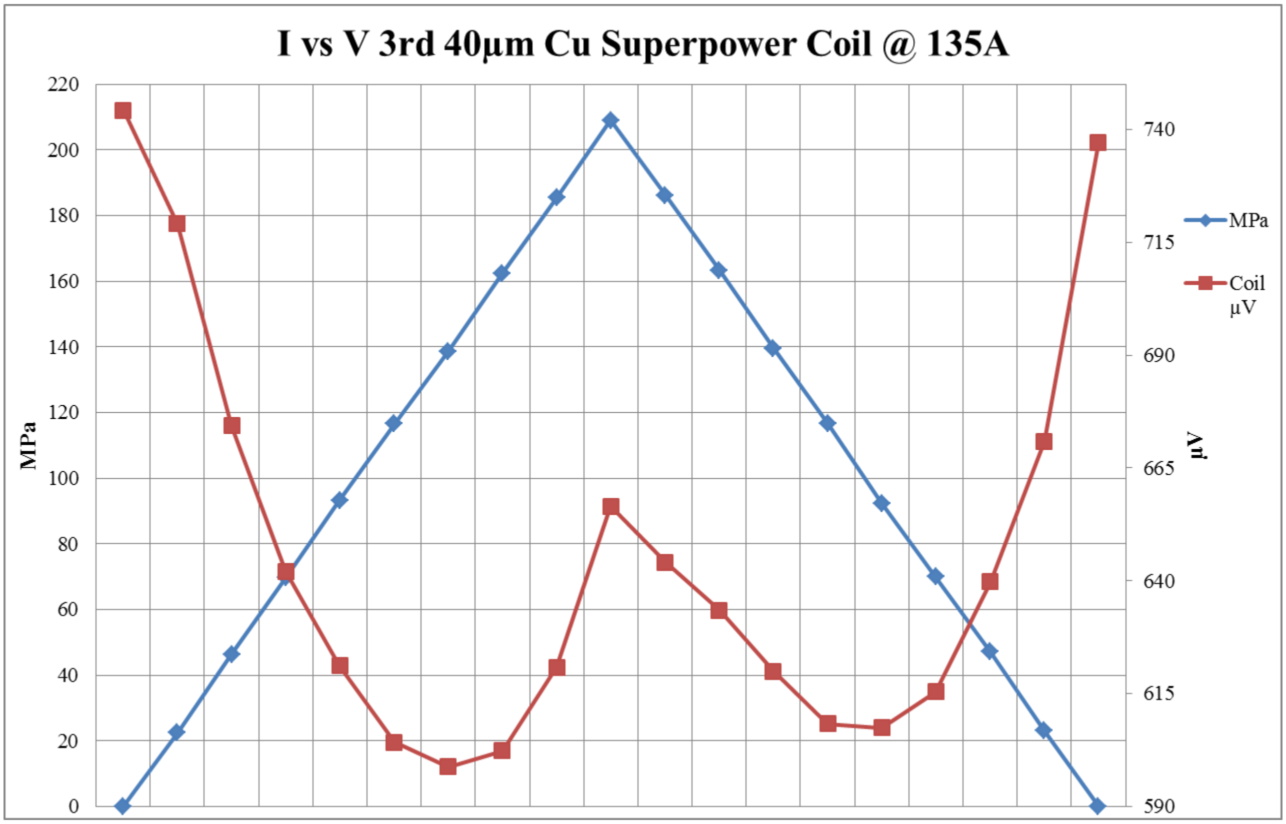


Figure 34: *3rd 40µm Coil compression behavior at 135 A*

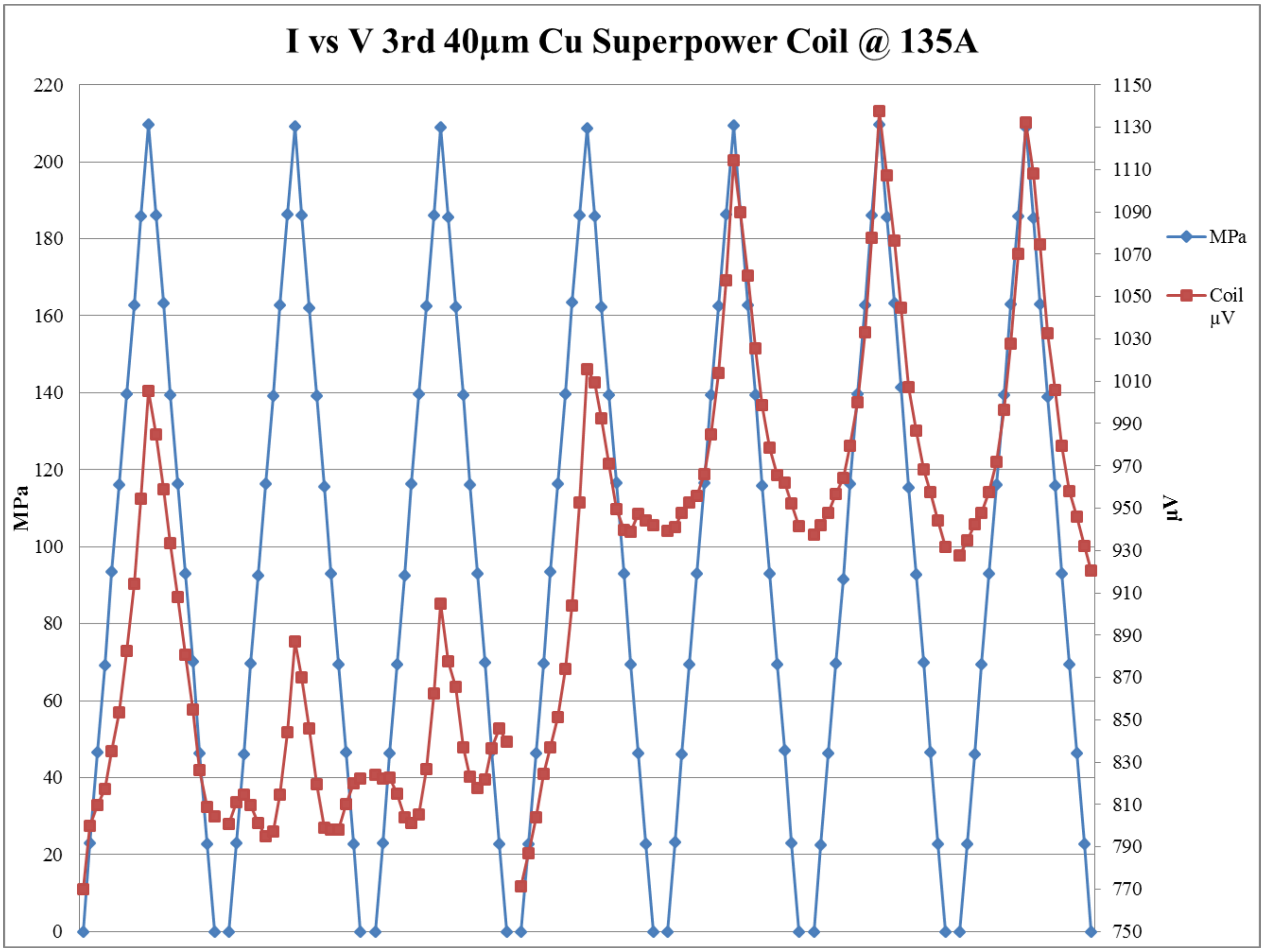


Figure 35: *3rd 40µm Coil compression behavior at 135 A*

After multiple cycles of compressive loading up to 208 MPa at 135 A, an average rise in resistive voltage by less than 200 µV was observed; well within performance limits (700 µV for this coil).

The compressive pressure was then taken up to 221 MPa, Figure 36, and eventually up to 232 MPa, Figure 37. Figures 36 and 37 show the performance of the coil at those pressures, respectively.

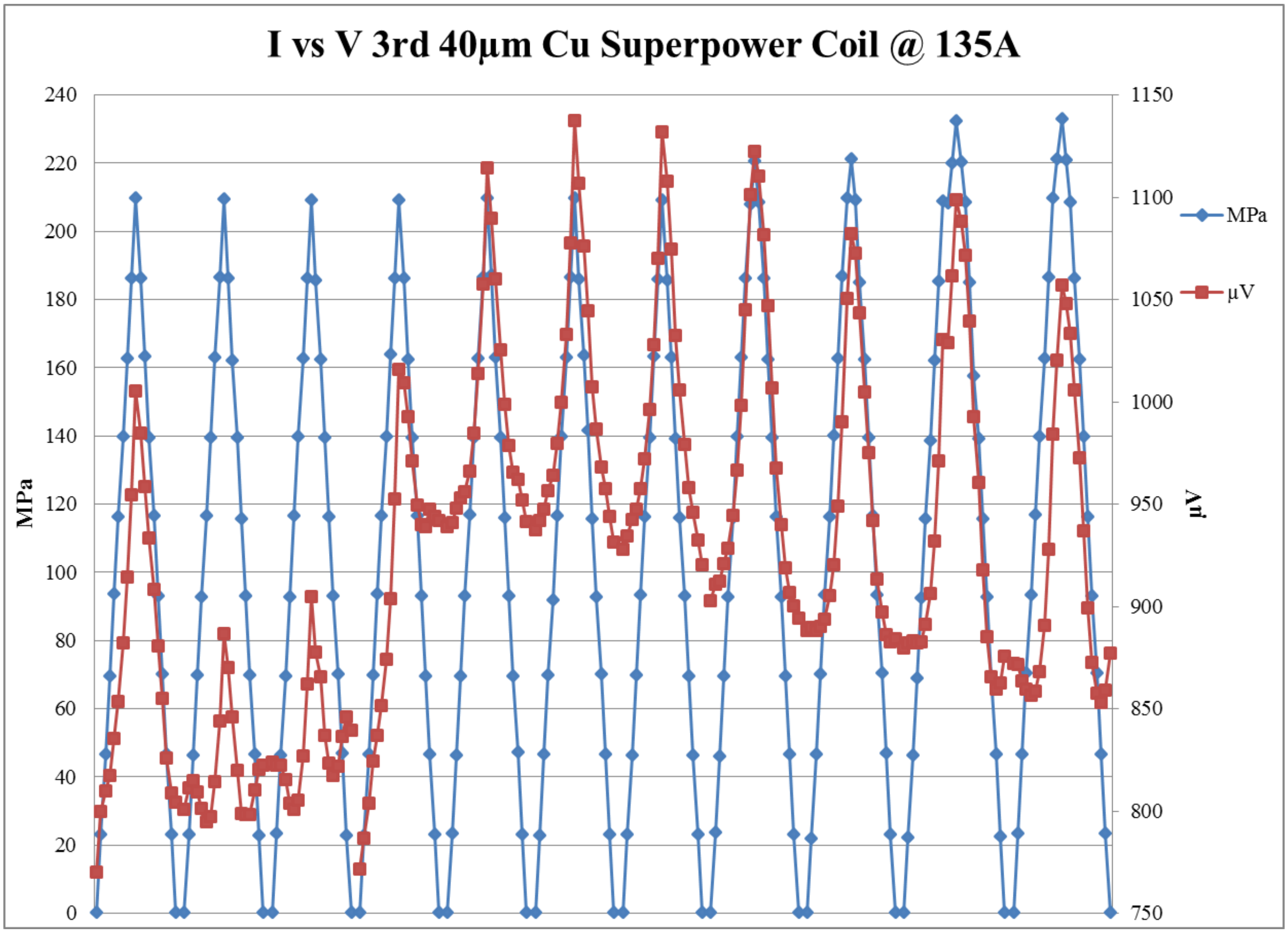


Figure 36: *3rd 40µm Coil compression behavior at 135 A*

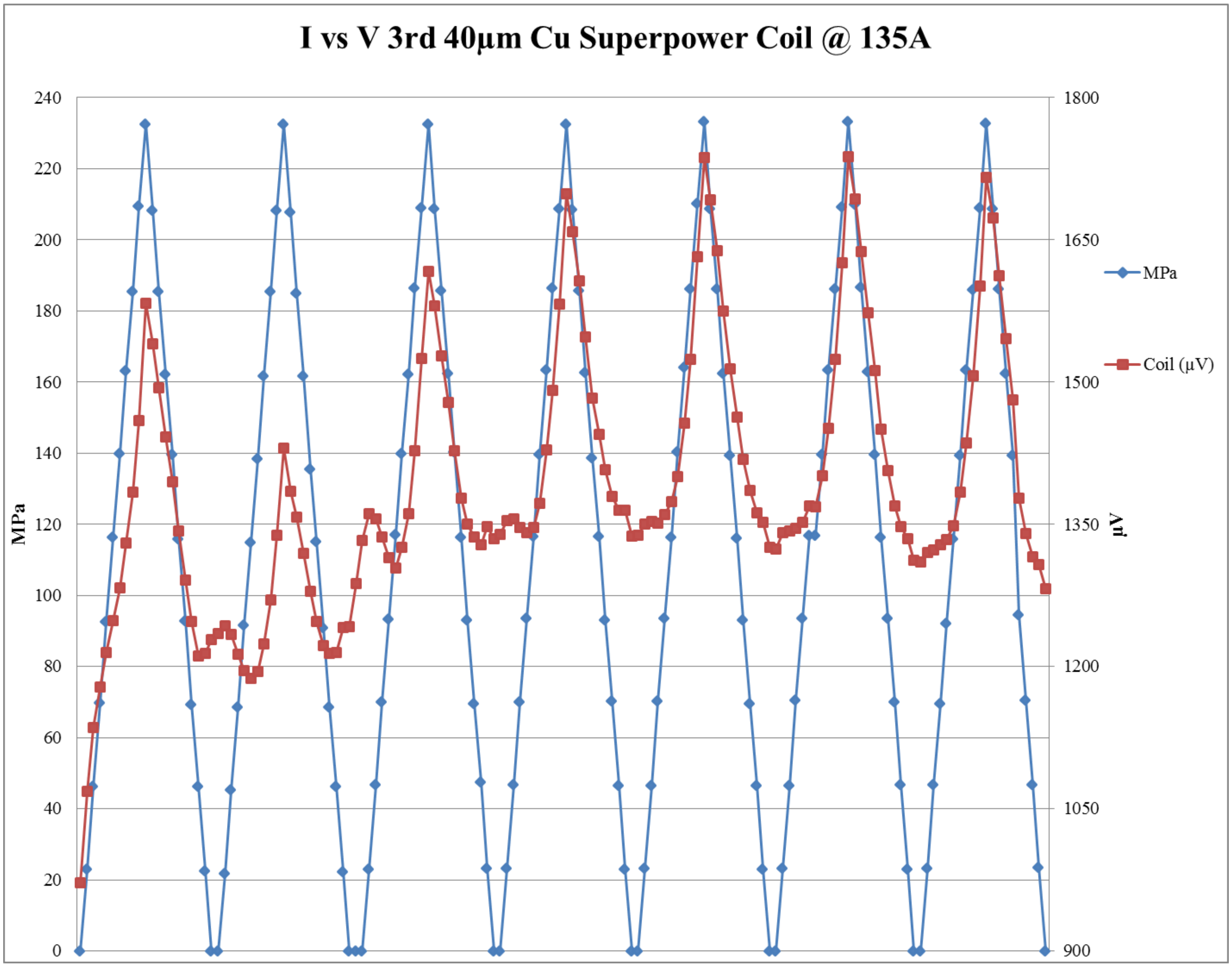


Figure 37: *3rd 40µm Coil compression behavior at 135 A*

After multiple cycles of compressive loading up to 232 MPa at 135 A, an average rise in resistive voltage by less than 400 µV was observed; well within performance limits (700 µV for this coil).

The current was then lowered to 120 Amps, Figure 38 - 39.

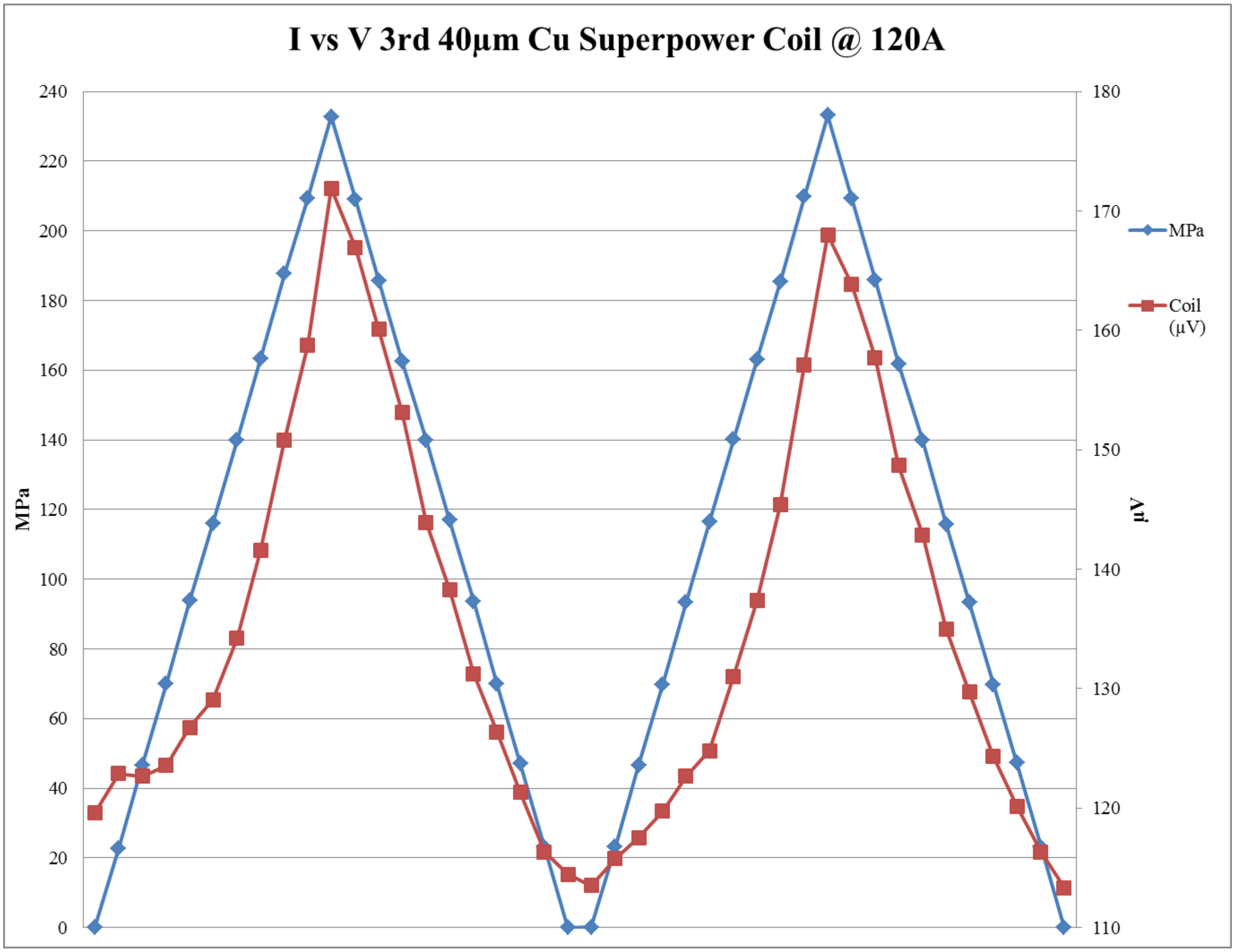


Figure 38: *3rd 40µm Coil compression behavior at 120 A*

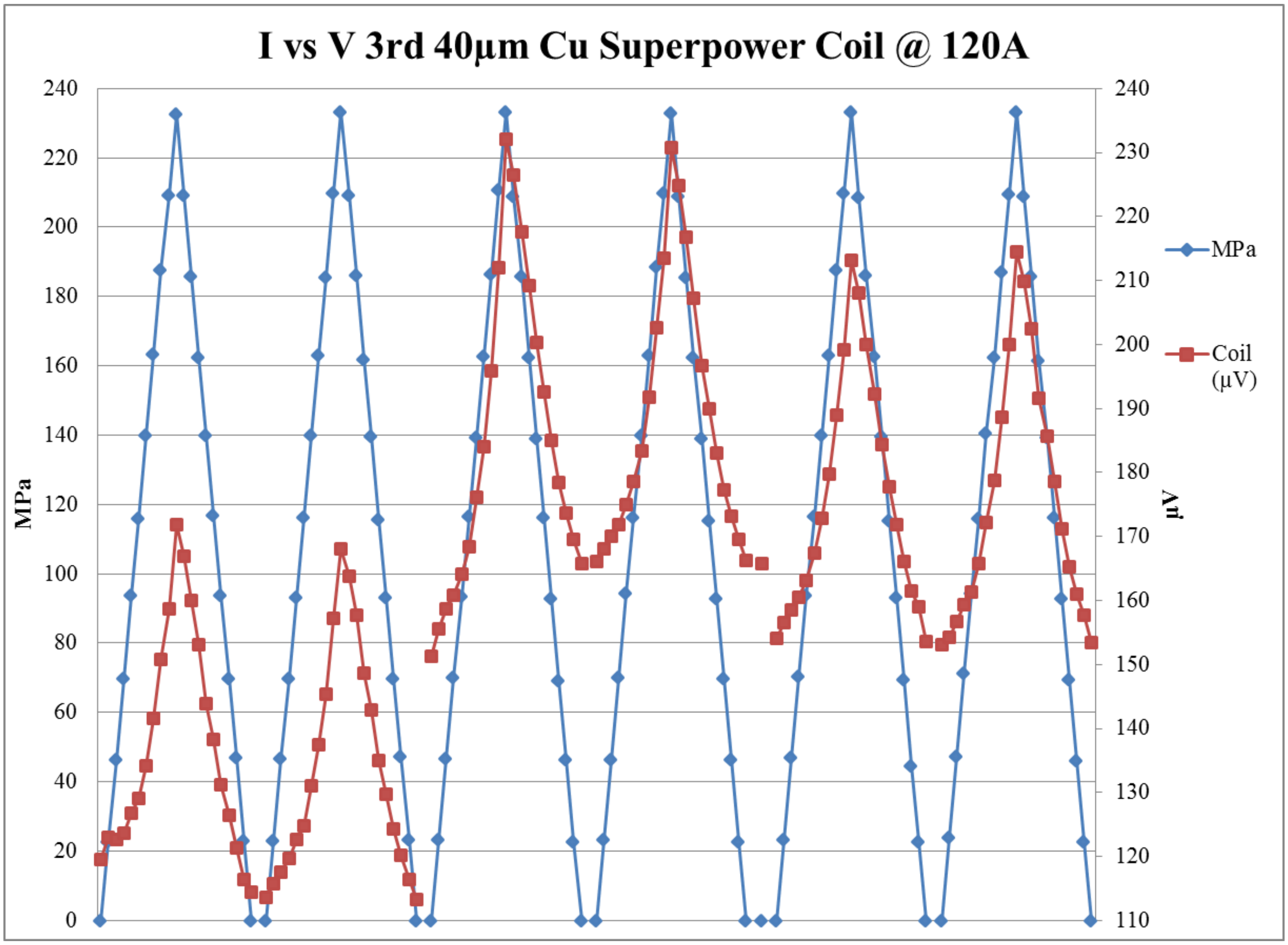


Figure 39: *3rd 40µm Coil compression behavior at 120 A*

After multiple cycles of compressive loading up to 232 MPa at 120 A, an average rise in resistive voltage by less than 70 µV was observed; well within performance limits (700 µV for this coil). These compression loading tests, Figures 32 – 39, showed that after initial performance degradation, the conductor continued to perform well within limits throughout relentless cycling. As these tests progress, we gained more confidence in the conductor's ability to deliver the performance required for IBS over an extended period of time.

The coil being built for IBS will be running at approximately 75% its I_c. Figure 40 shows the coil being subjected to various compressive pressures with the current held steady at 90 A, 2/3 its I_c.

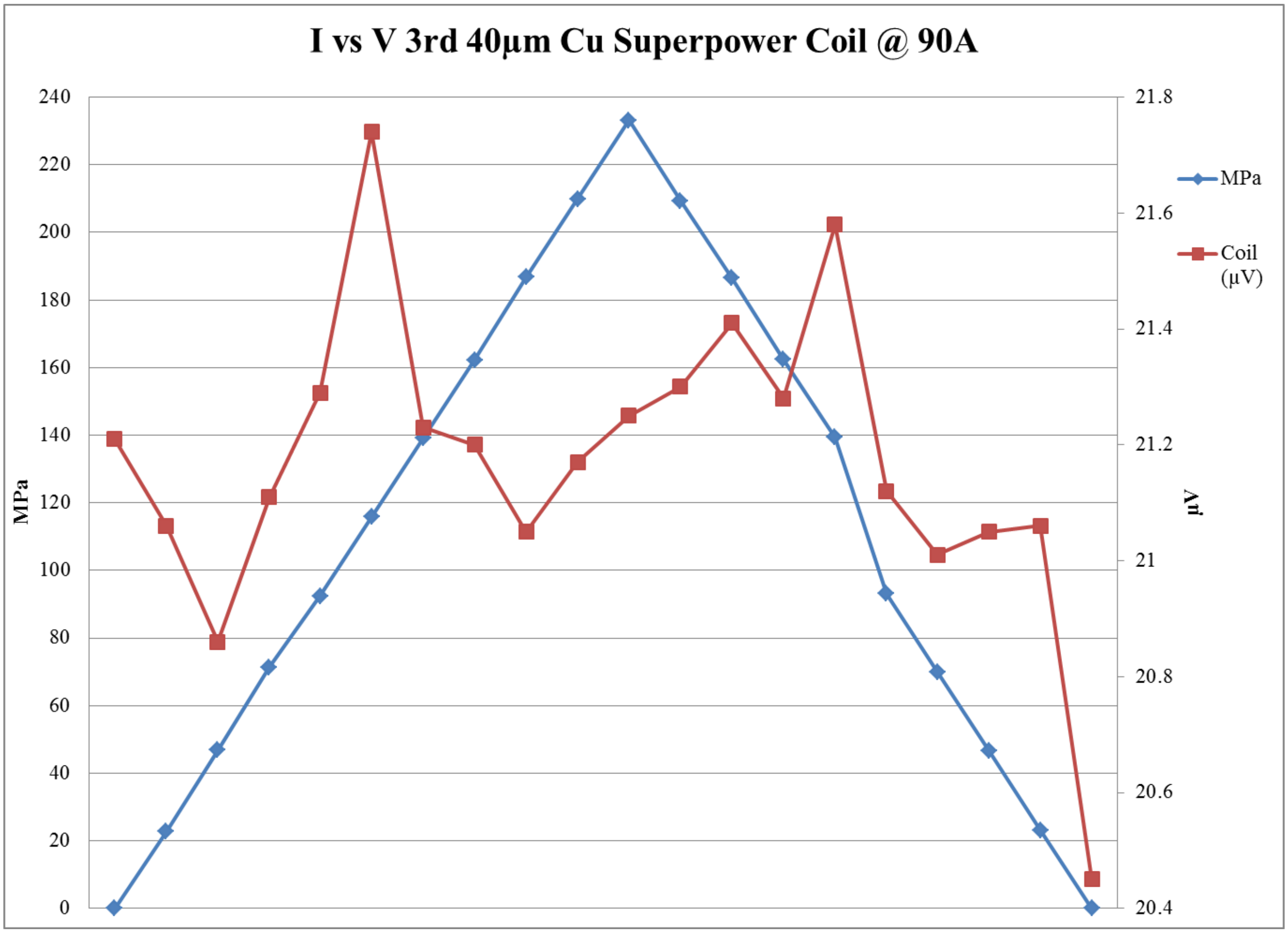


Figure 40: *3rd 40µm Coil compression behavior at 90 A*

As can be seen from Figure 40, at approximately 2/3 of its I_c, after multiple compressive pressure and thermal cycling, the coil performed well within limits. An average rise in resistive voltage of 1 µV, within the margin of error of our data acquisition system (±3 µV), was observed - it can be deduced that there was no rise in voltage up to 232 MPa at 90 A.

A fourth 50 turn, no insulation, single layer coil using SuperPower 2G HTS 40 µm Cu conductor was wound (conductor measured thickness of: 3.8 mil; width: 475 mil) and subjected to compression tests in a modified Stainless Steel (SS) compression fixture holder at 77 K. Two Mylar caps were installed on the top and bottom of the coil (while in the SS holder).

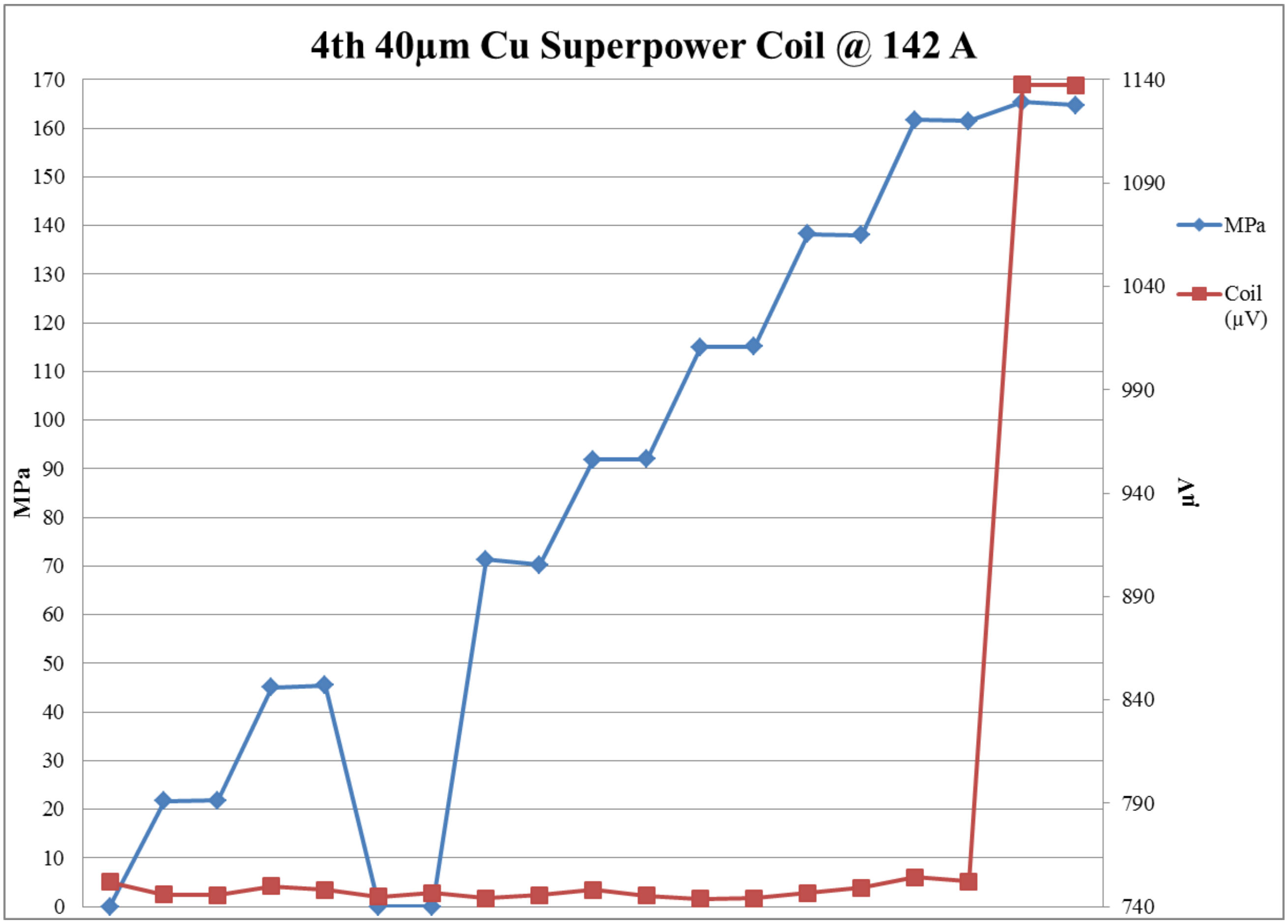


Figure 41: *4th 40µm Coil compression behavior at 142 A*

An acoustic event was observed at 163 MPa; as can be seen from Figure 41, the conductor saw a substantial increase in resistive voltage at 163 MPa.

An I vs V characterization was ran to see the effects of the compressive pressure on the conductor, Figure 42.

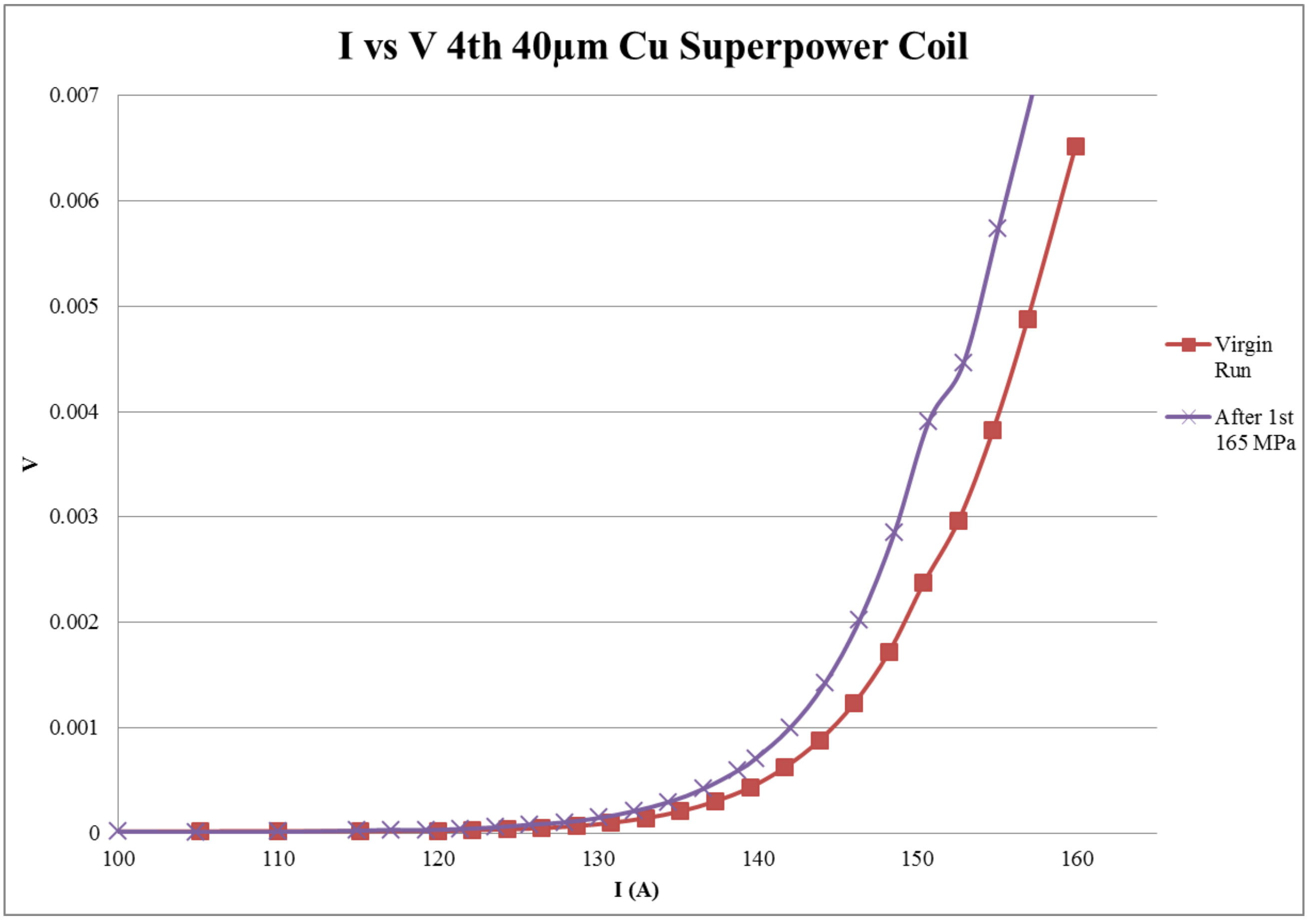


Figure 42: *I vs V for 4th 40µm Coil*

The coil was again subjected to compressive pressures up to 163 MPa with the current held steady at 140 A, Figure 43.

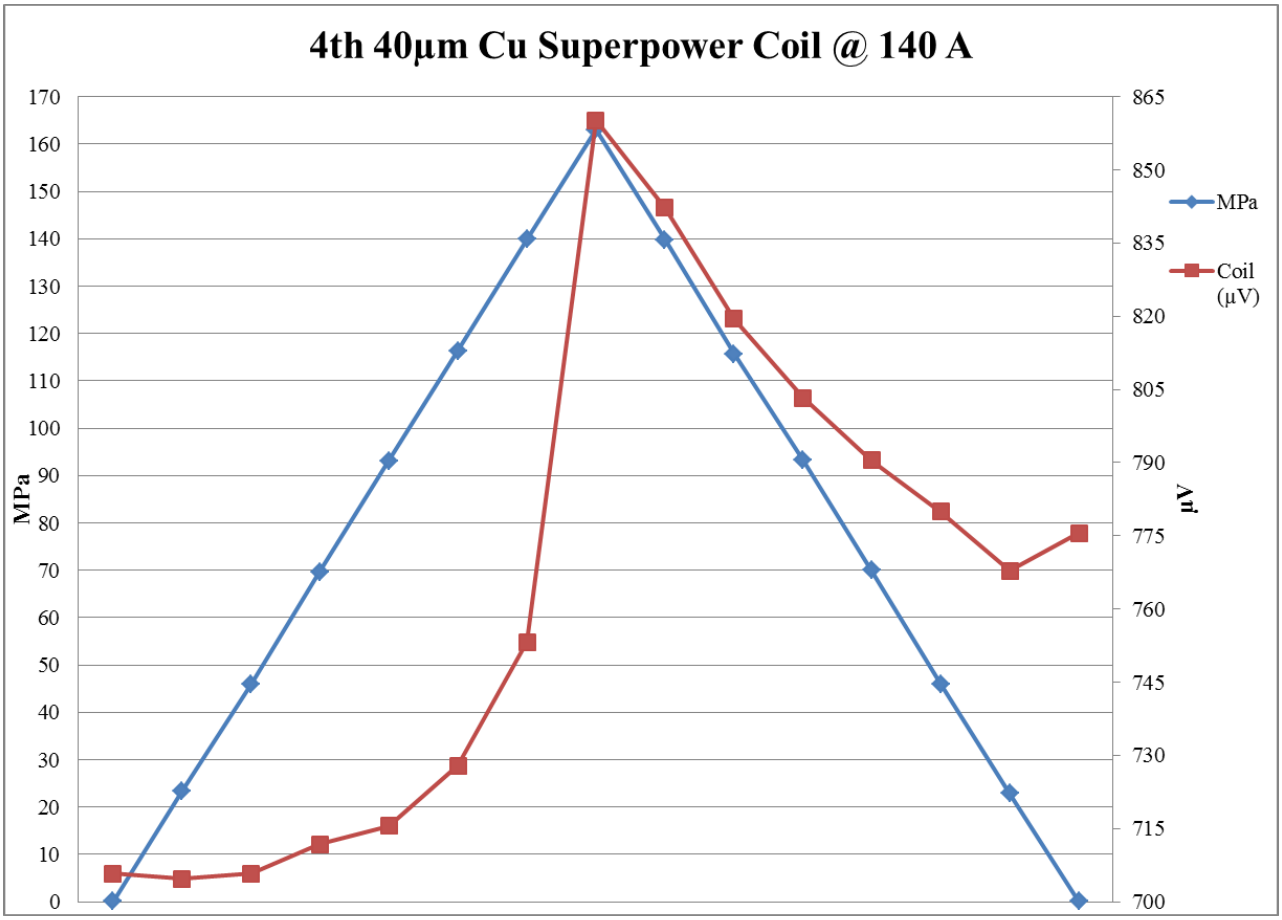


Figure 43: *4th 40µm Coil compression behavior at 140 A*

As the compressive loading was ramped up to 163 MPa at 140 A, there was a rise in resistive voltage by 150 µV, well within performance limits (700 µV for this coil).

An I vs V characterization was ran to see the effects of the compressive pressure on the conductor, Figure 44.

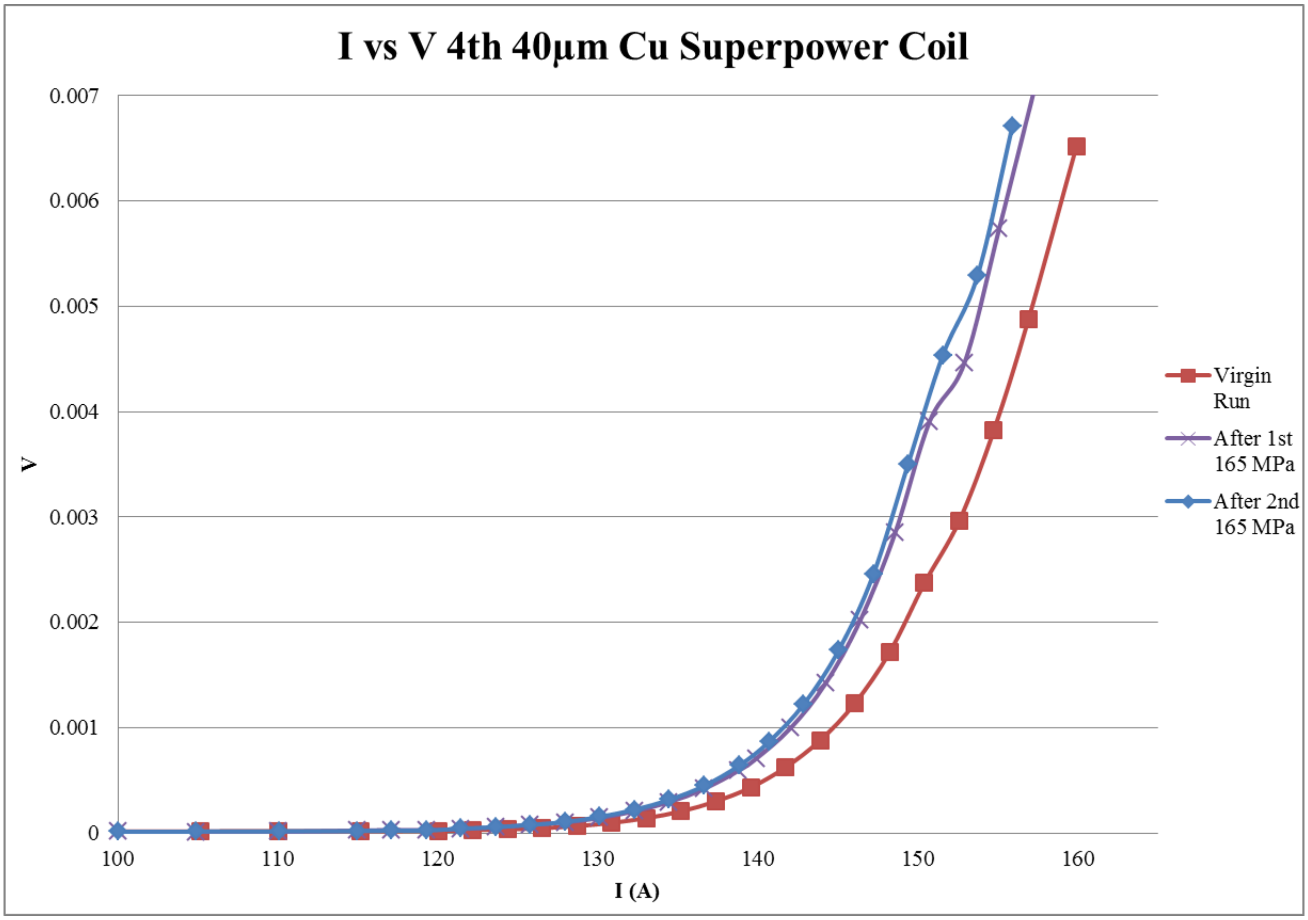


Figure 44: *I vs V for 4th 40µm Coil*

The coil was again subjected to compressive pressures up to 163 MPa with the current held steady, Figure 45.

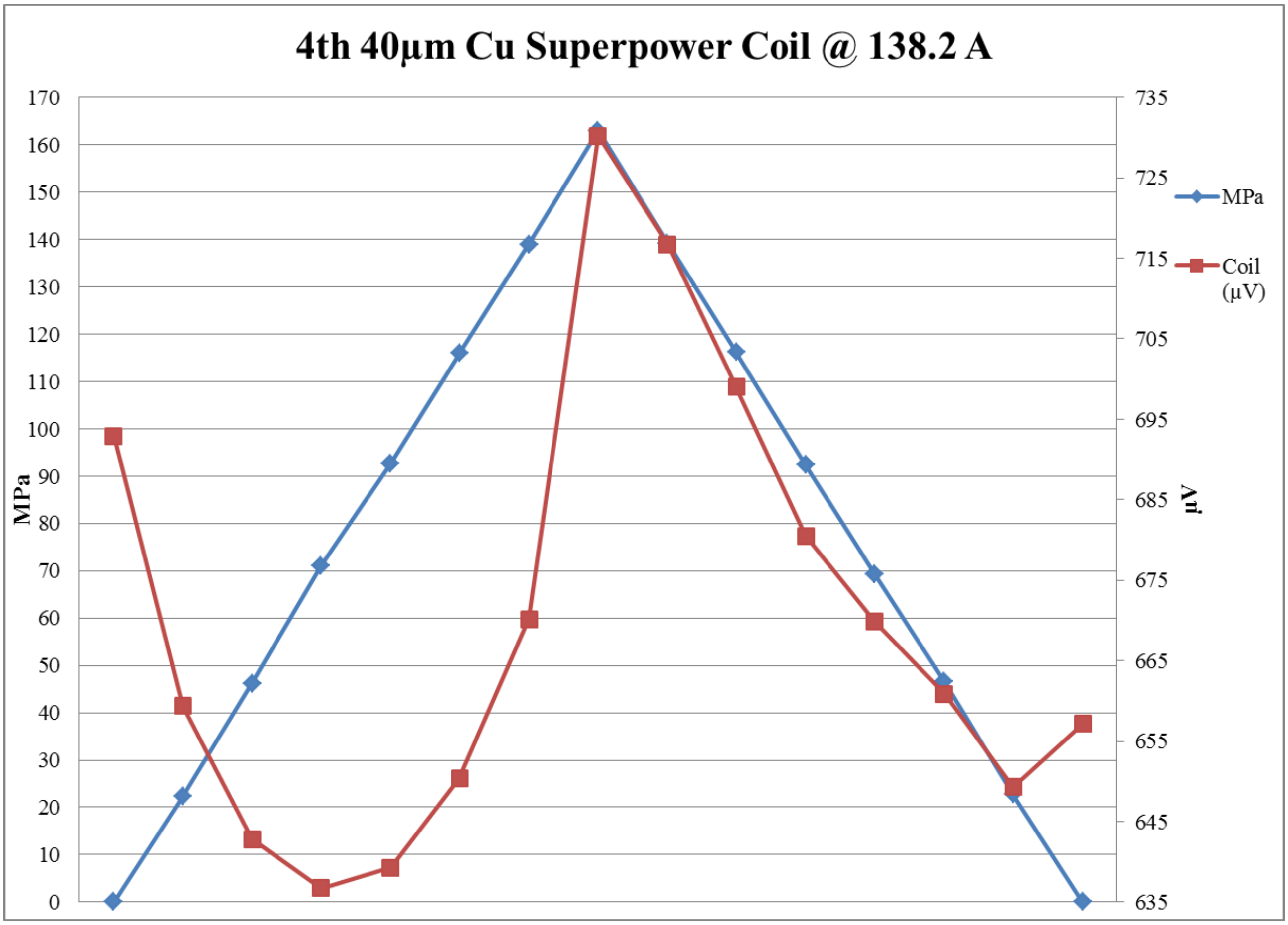


Figure 45: *4th 40µm Coil compression behavior at 138.2 A*

As the compressive loading was ramped up to 163 MPa at 138.2 A, there was a rise in resistive voltage by 90 µV, well within performance limits (700 µV for this coil).

Results from the tests run on the 40 µm Cu conductor coils build a lot of confidence in our choice of conductor for the IBS magnet. The SuperPower 2G HTS 40 µm Cu conductor exceeded all performance expectations and performed well within limits throughout relentless testing. These tests also allowed us to perfect our testing techniques and led us to the optimal coil holder design for the SuperPower 2G HTS 20 µm Cu conductor tests.

SuperPower 2G HTS 20 µm Cu

Finally, a 72 turn (9.77 meters of conductor), no insulation, single layer coil using SuperPower 2G HTS 20 µm Cu conductor was wound (conductor measured thickness of: 2.8 mil; width: 475 mil) and subjected to compression tests in a modified Stainless Steel (SS) compression fixture holder at 77 K. Two Nomex caps were installed on the top and bottom of the coil; Nomex being the optimal material for compressive loading force distribution. Figure 46 shows the initial I vs V curve for the coil.

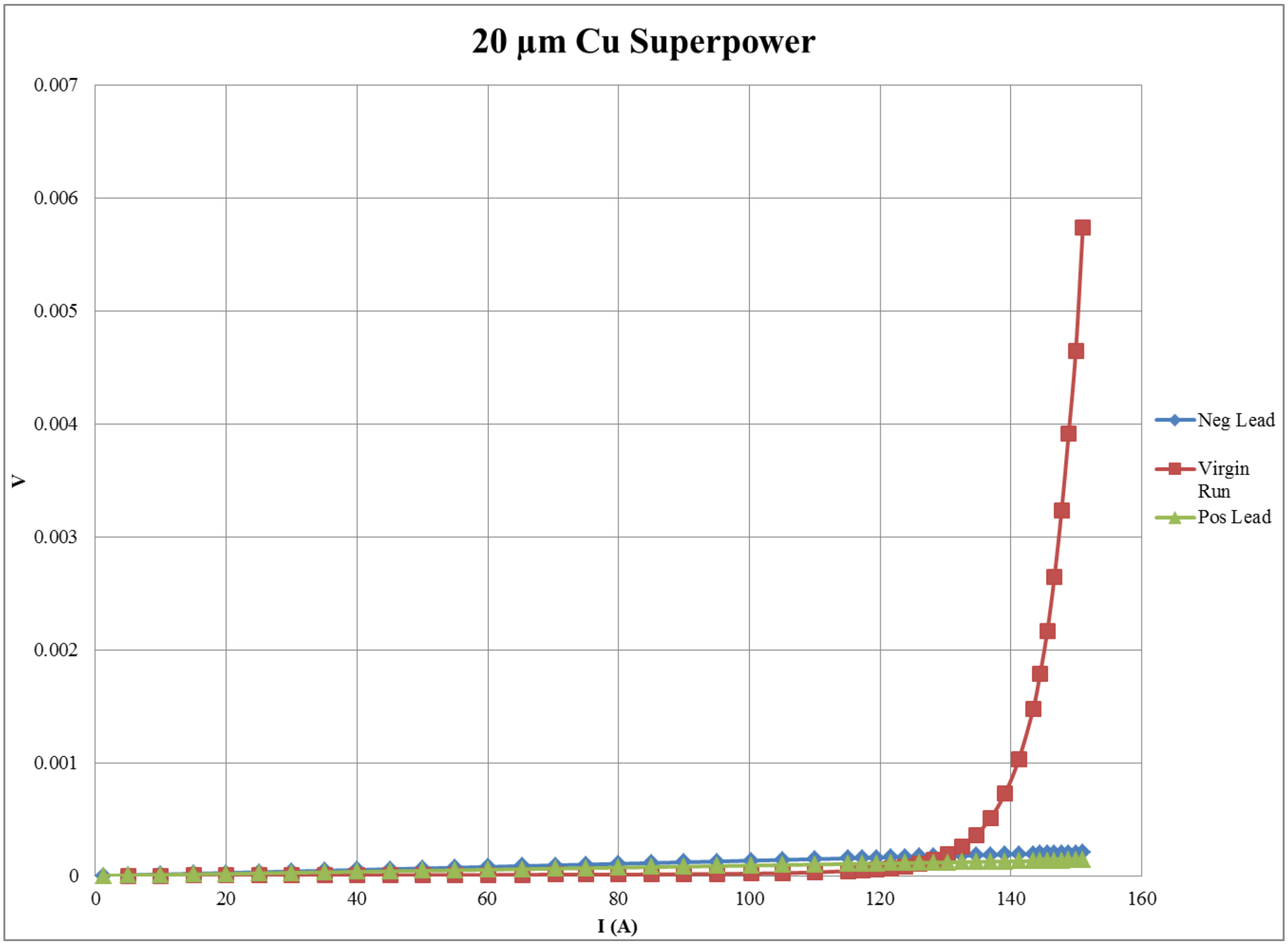


Figure 46: *Initial I vs V for 20µm Coil*

The pre-compression I_c for this coil, using the 1μV/cm parameter, was determined to be approximately 141 A (977μV – the coils I_c threshold voltage), Figure 47.

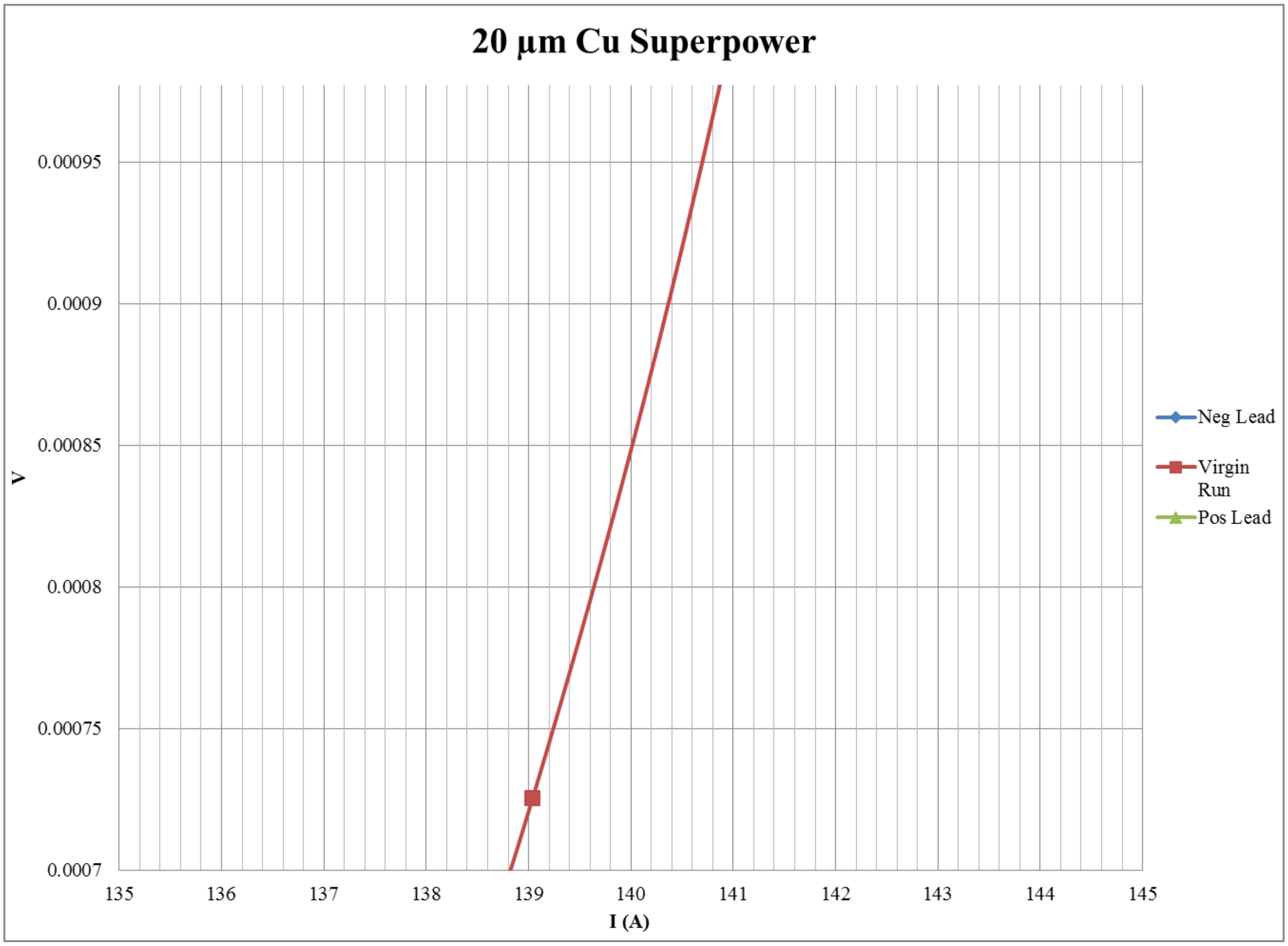


Figure 47: *Initial I vs V for 20μm Coil*

The coil was then subjected to a series of different compressive pressures, Figures 48 - 51.

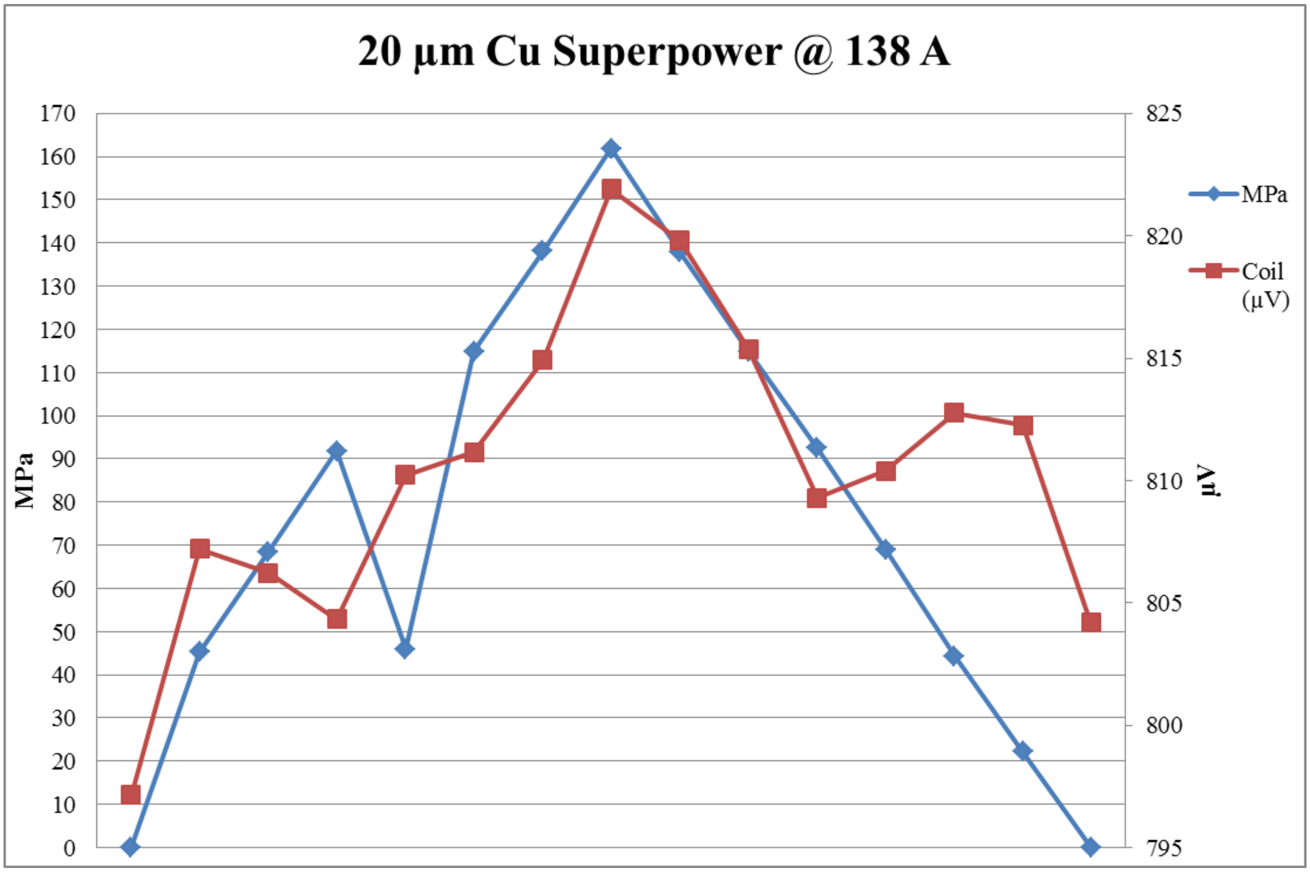


Figure 48: *20µm Coil compression behavior at 138 A*

As the compressive loading was ramped up to 163 MPa at 138 A, there was a rise in resistive voltage by approximately 20 µV, well within performance limits (977 µV for this coil).

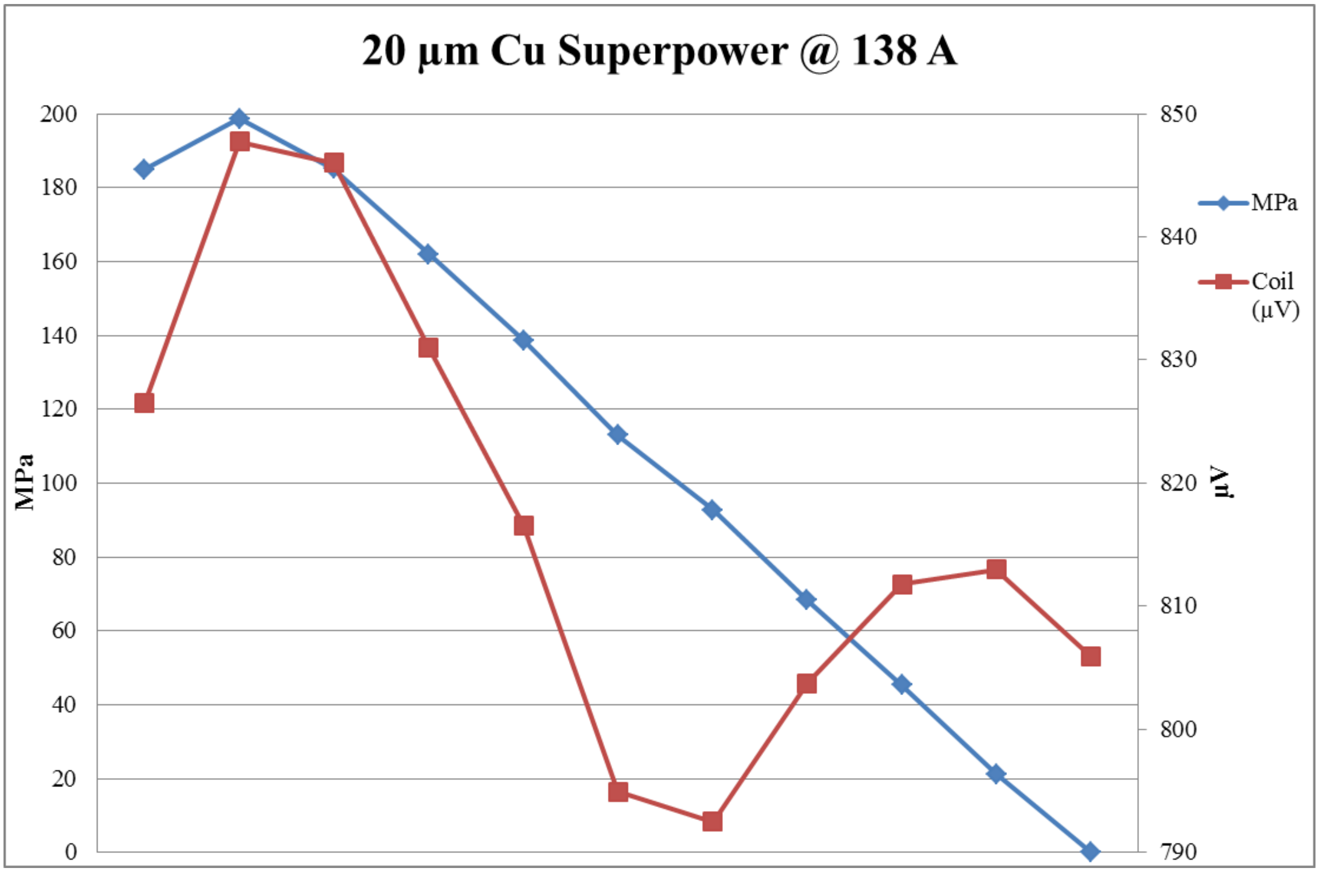


Figure 49: *20µm Coil compression behavior at 138 A*

As the compressive loading was ramped up to 200 MPa at 138 A, there was a rise in resistive voltage by approximately 45 µV, well within performance limits (977 µV for this coil).

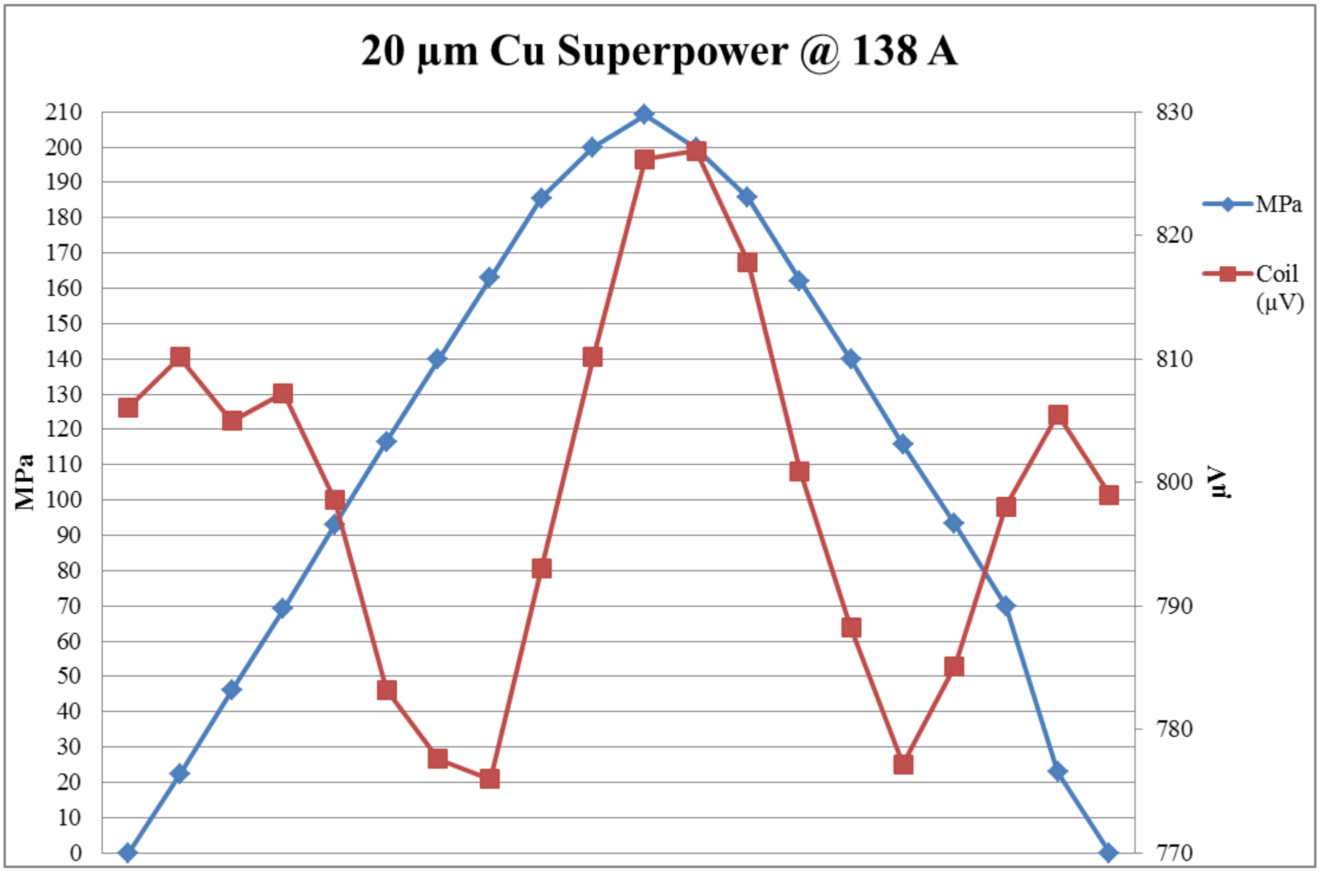


Figure 50: *20µm Coil compression behavior at 138 A*

As the compressive loading was ramped up to 210 MPa at 138 A, there was a rise in resistive voltage by approximately 50 µV, well within performance limits (977 µV for this coil).

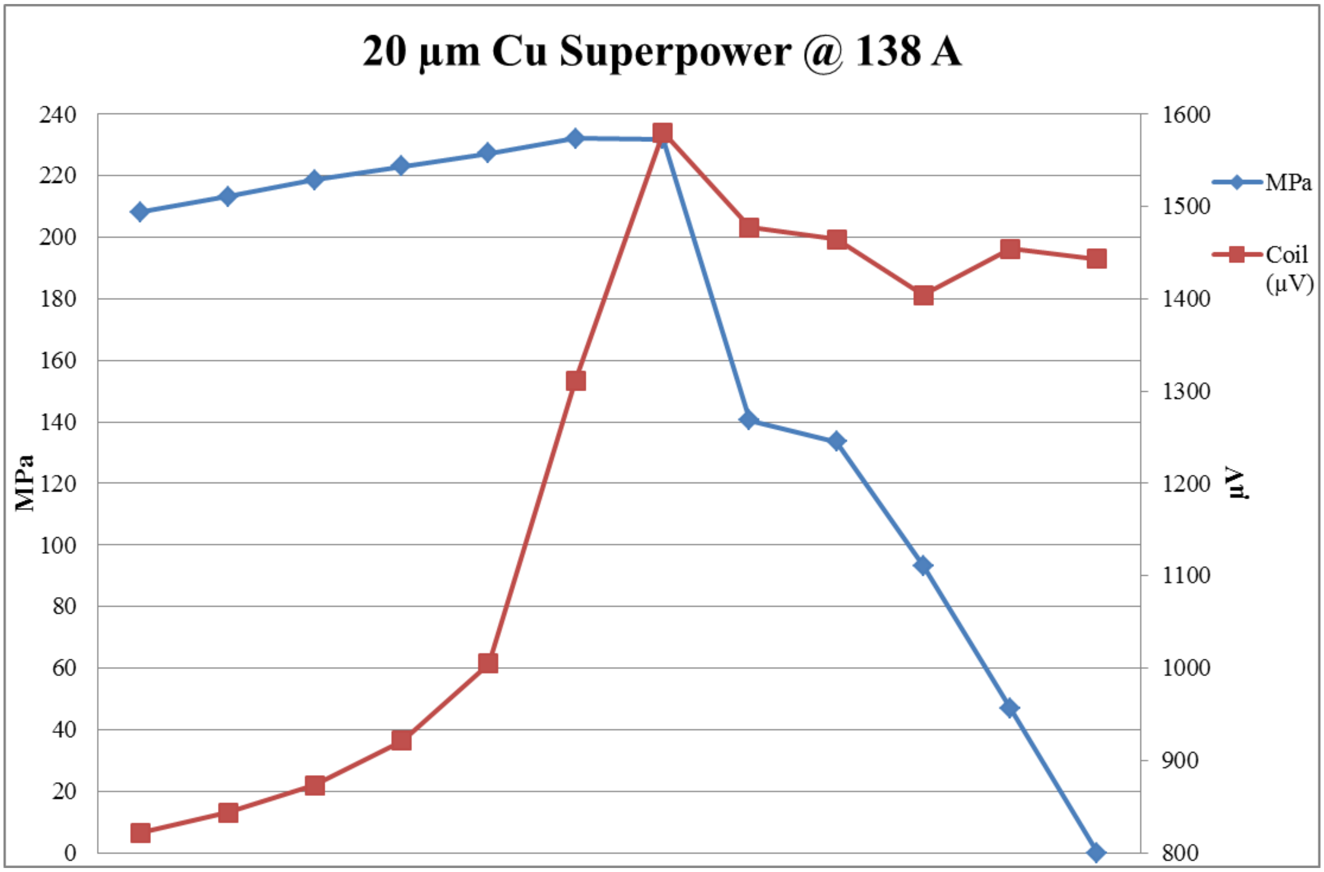


Figure 51: *20µm Coil compression behavior at 138 A*

As the compressive loading was ramped up to 232 MPa at 138 A, there was a rise in resistive voltage by approximately 800 µV. This test was performed to assess the mechanical strength limit of the 20 µm conductor.

One can be observed from Figures 48 - 51, over multiple cycles, the coil performance remained steady up until 220 MPa. Above 220 MPa, an onset of degradation was observed. Compressive pressure was maximized at 232 MPa.

A baseline I vs V curve was then recorded to see the effects of the compressive pressure on the coil, Figure 52.

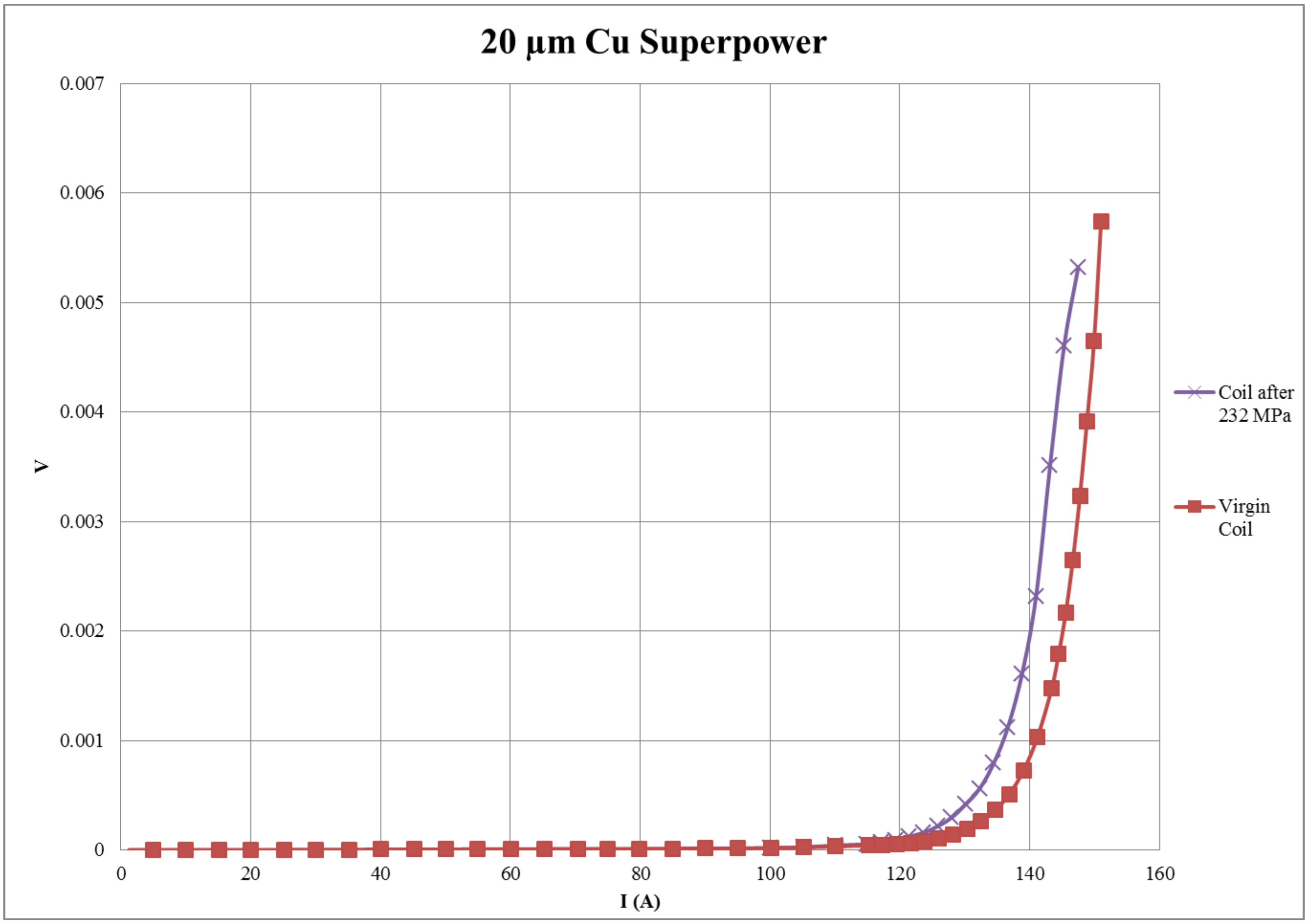


Figure 52: *I vs V for 20µm Coil*

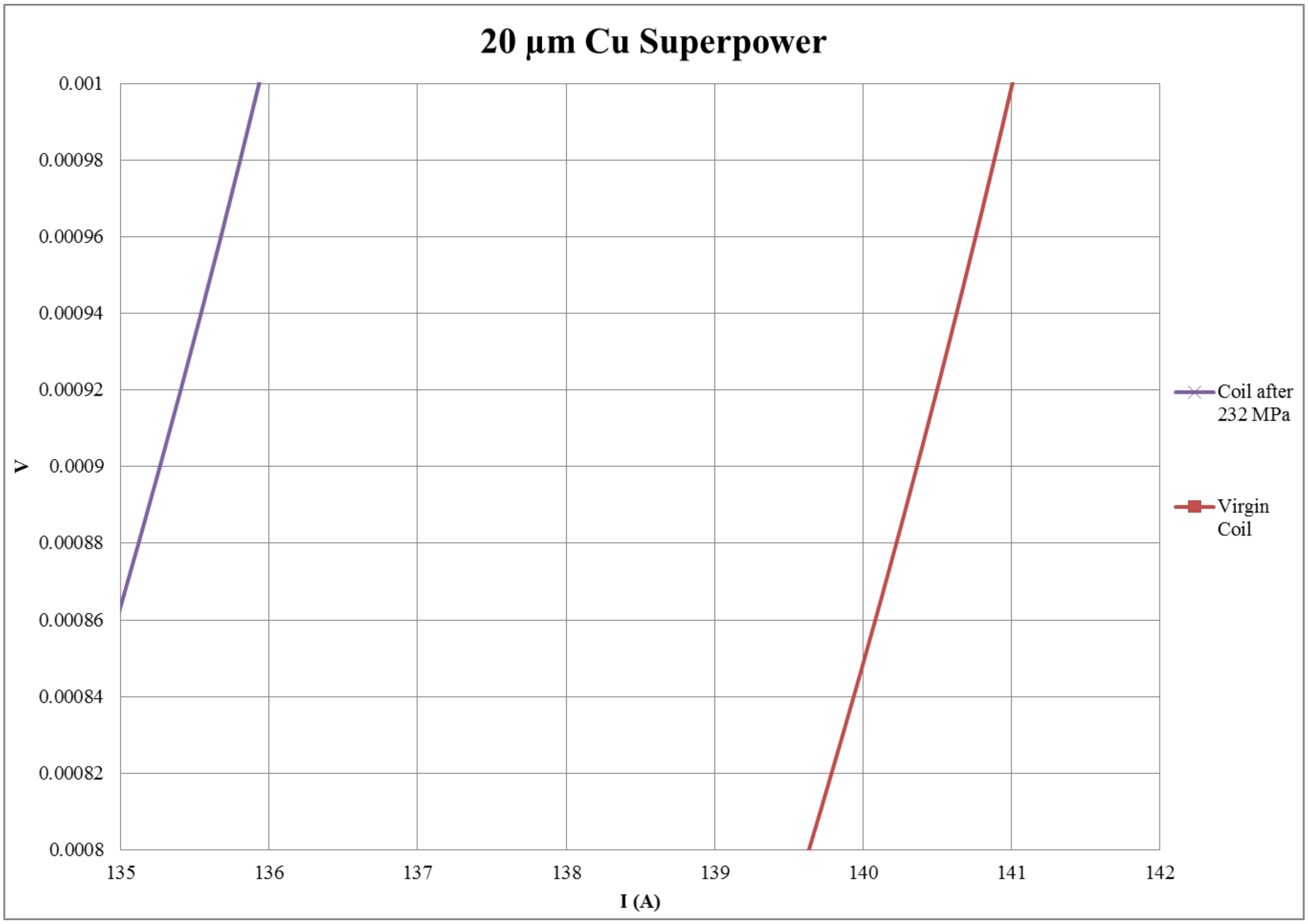


Figure 53: *I vs V for 20µm Coil*

As can be observed from the Figure 53, coil performance decreased by about 5 amps; a decrease of 3.5%. Calculations and simulations show that the IBS coil will be subjected to a maximum compressive pressure of 205 MPa. According to compressive loading cycles performed above, the 20µm Cu Superpower conductor will perform as advertised within those parameters.

Figures 54 – 55 show that at 977µV – the coils I_c threshold voltage (according to the 1µV/cm standard) – the I_c increased by 1 Amp after 1 thermal cycle.

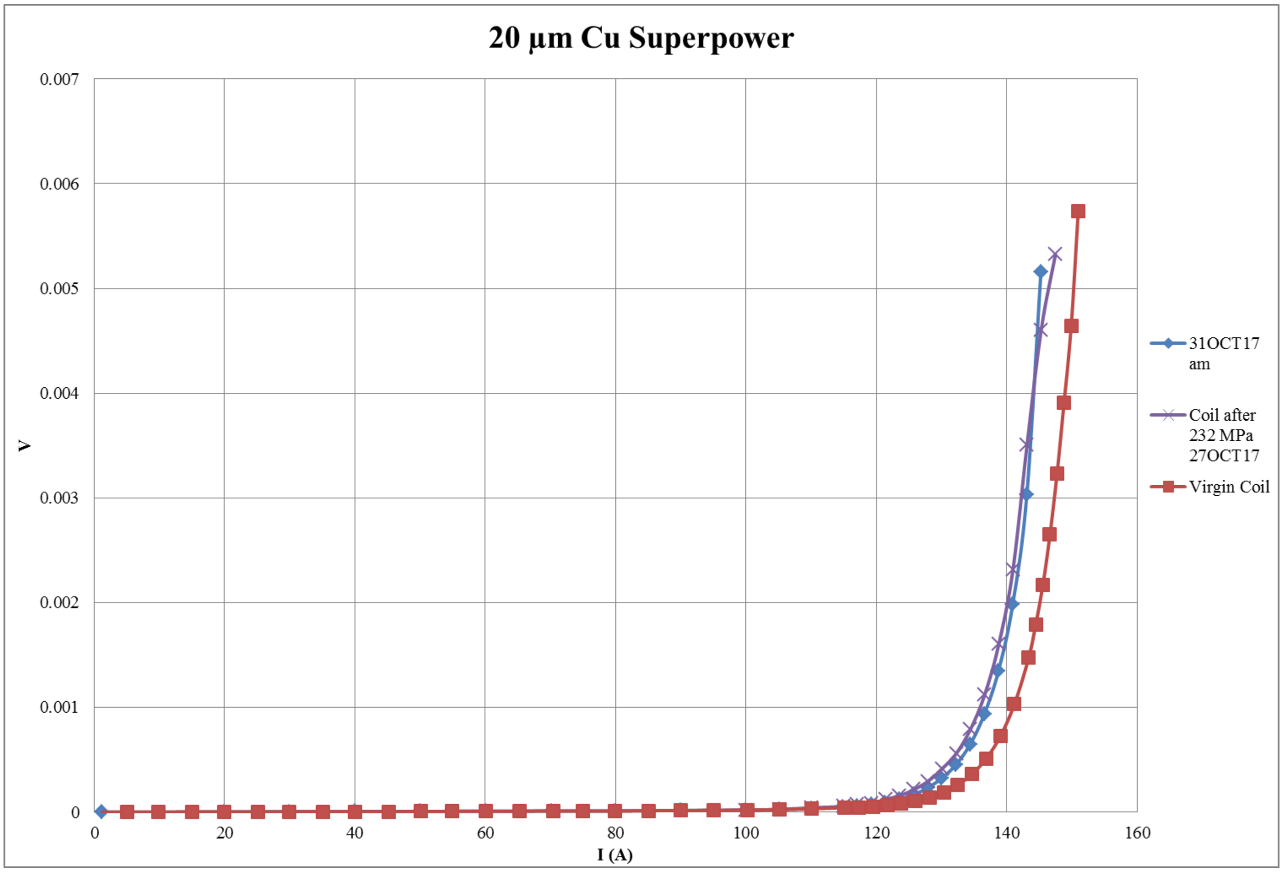


Figure 54: *I vs V for 20µm Coil*

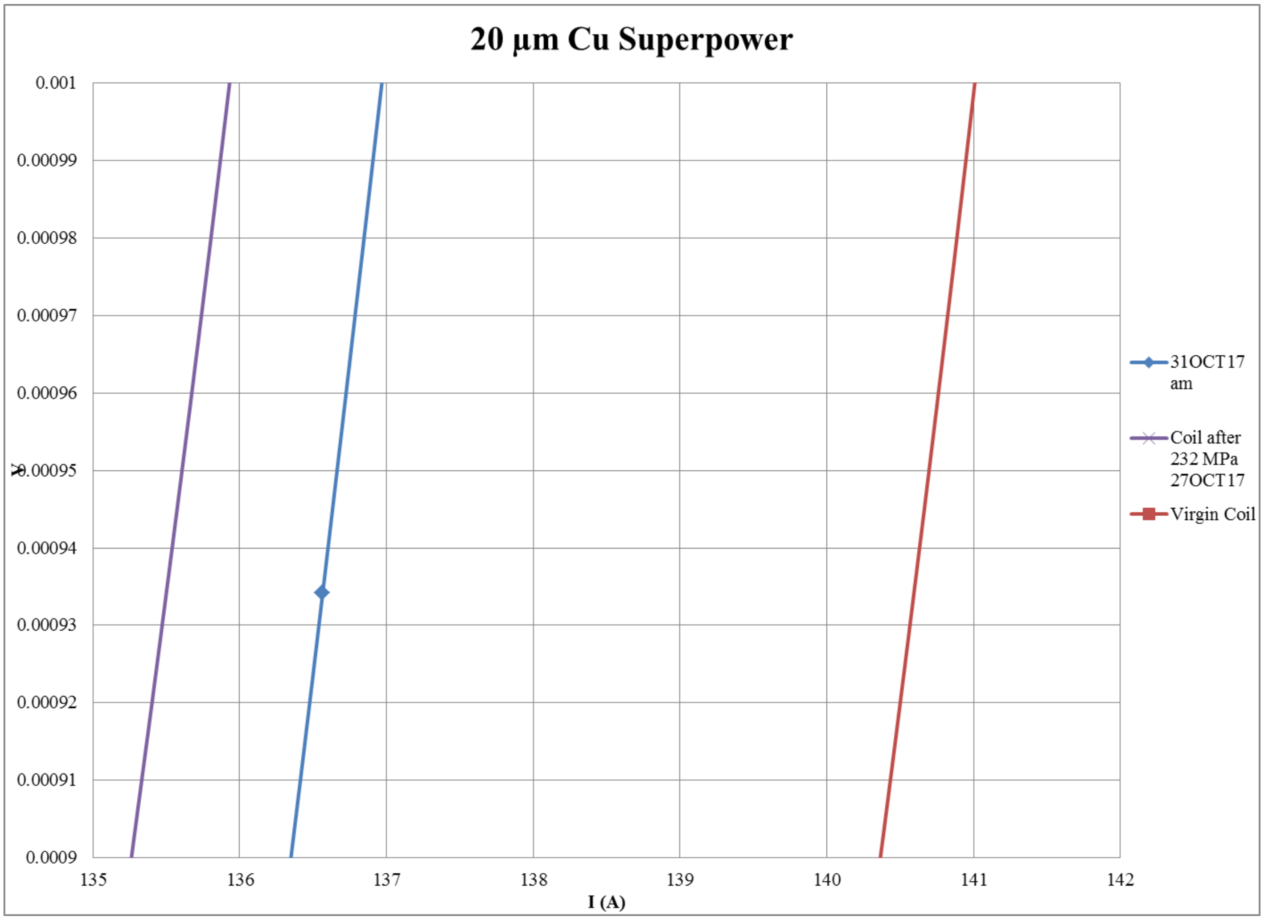


Figure 55: *I vs V for 20μm Coil*

The coil was then subjected to a range of compressive pressures up to 209 MPa at 135 A. Figure 56 shows the coil performance.

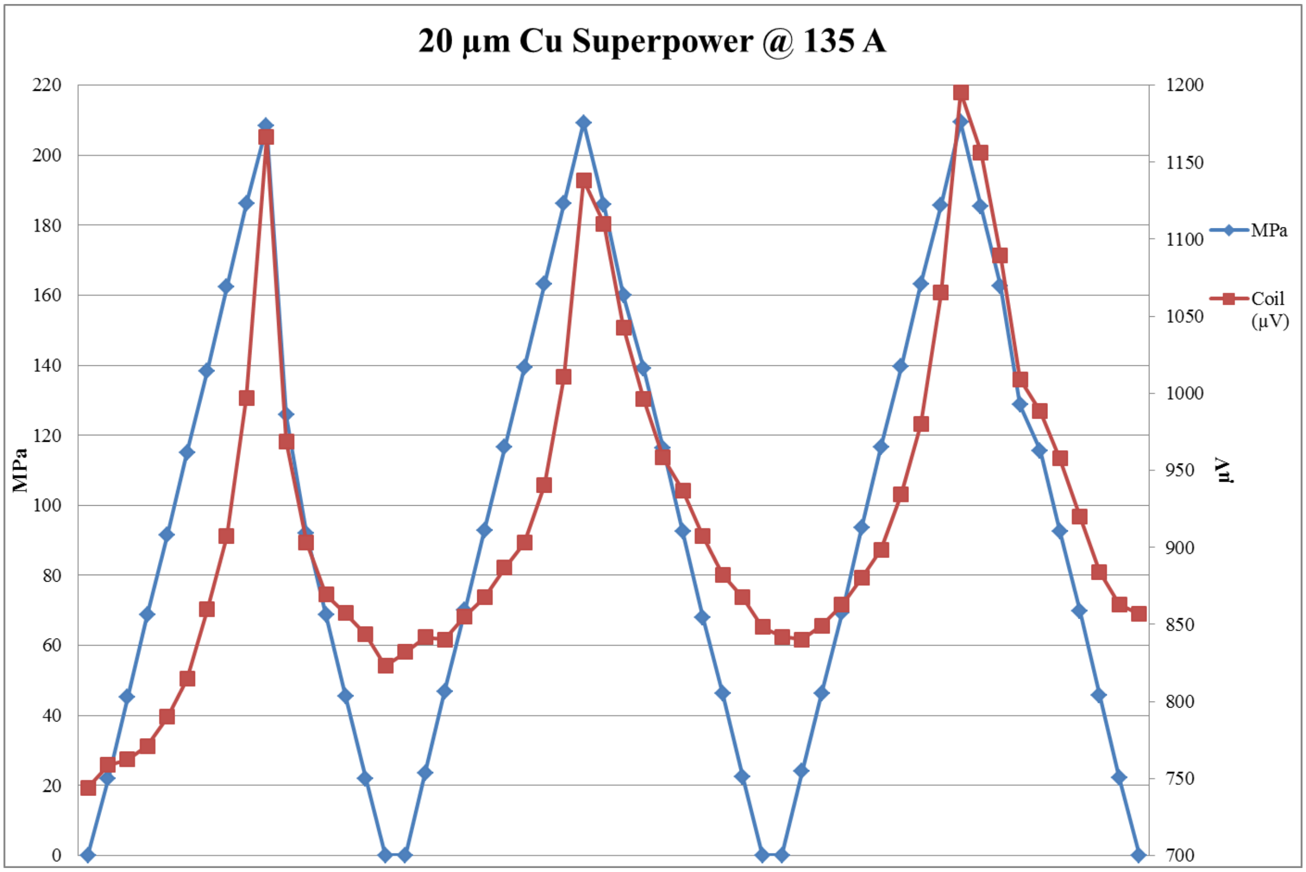


Figure 56: *20µm Coil compression behavior at 135 A*

As the compressive loading was cycled up to 209 MPa at 135 A, there was a rise in resistive voltage by approximately 350 µV. Although the IBS magnet will not be cycled at 100% I_c, this test shows that the conductor will not further degrade as the magnet is cycled.

The coil was then cycled multiple times under compressive pressures up to 232 MPa, Figure 57.

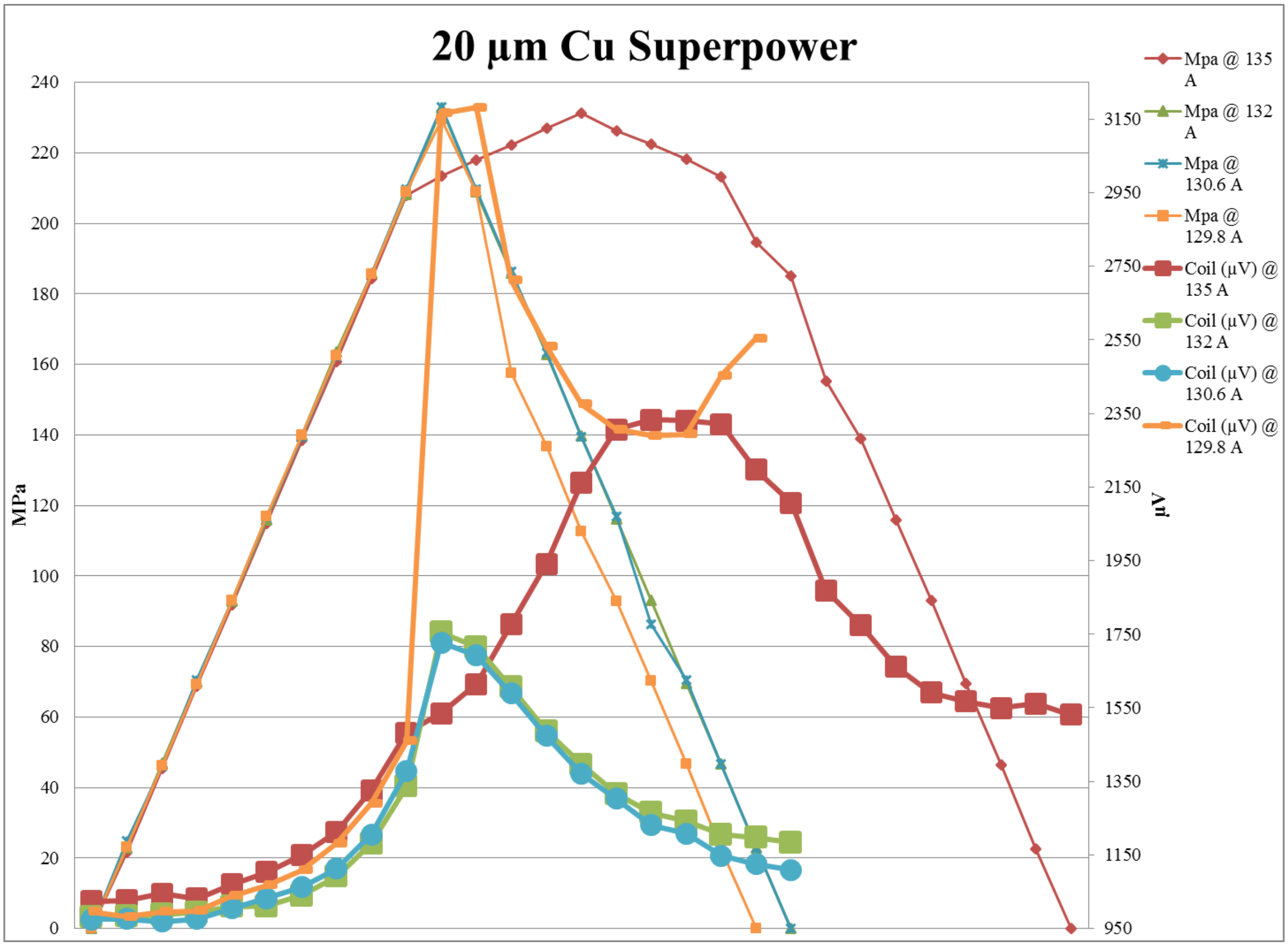


***Figure 57:** 20µm Coil compression behavior at various currents; each cycle starting around 1000µV*

In Figure 58, the thick color lines correspond to the coil voltage while the thin color line represents the compressive loading at which the voltage reading was logged. Different colors represent different compressive cycles. Each cycle was started at approximately 1000µV, representing the coils I_c threshold voltage.

After the first cycle, the coil I_c dropped from 135 A to 132 A; after the second cycle, from 132 A to 130.6 A; after the third cycle, from 130.6 to 129.8 A. During the last cycle, ran at 129.8 A, an acoustic event was observed (in the form of a loud "bang" from the Dewar) when the coil was at 232 MPa and a corresponding spike in coil voltage was observed (Orange data). At the end of this round of cycling, the coil I_c was down to 123.4 A. Through 5 compressive cycles to 232 MPa, the coil I_c went from 141 A to 123.4 A.

This test showed that the mechanical compressive loading limit for this conductor 232 MPa.

An I vs V curve, Figures 58 - 59, was then taken for coil characterization.

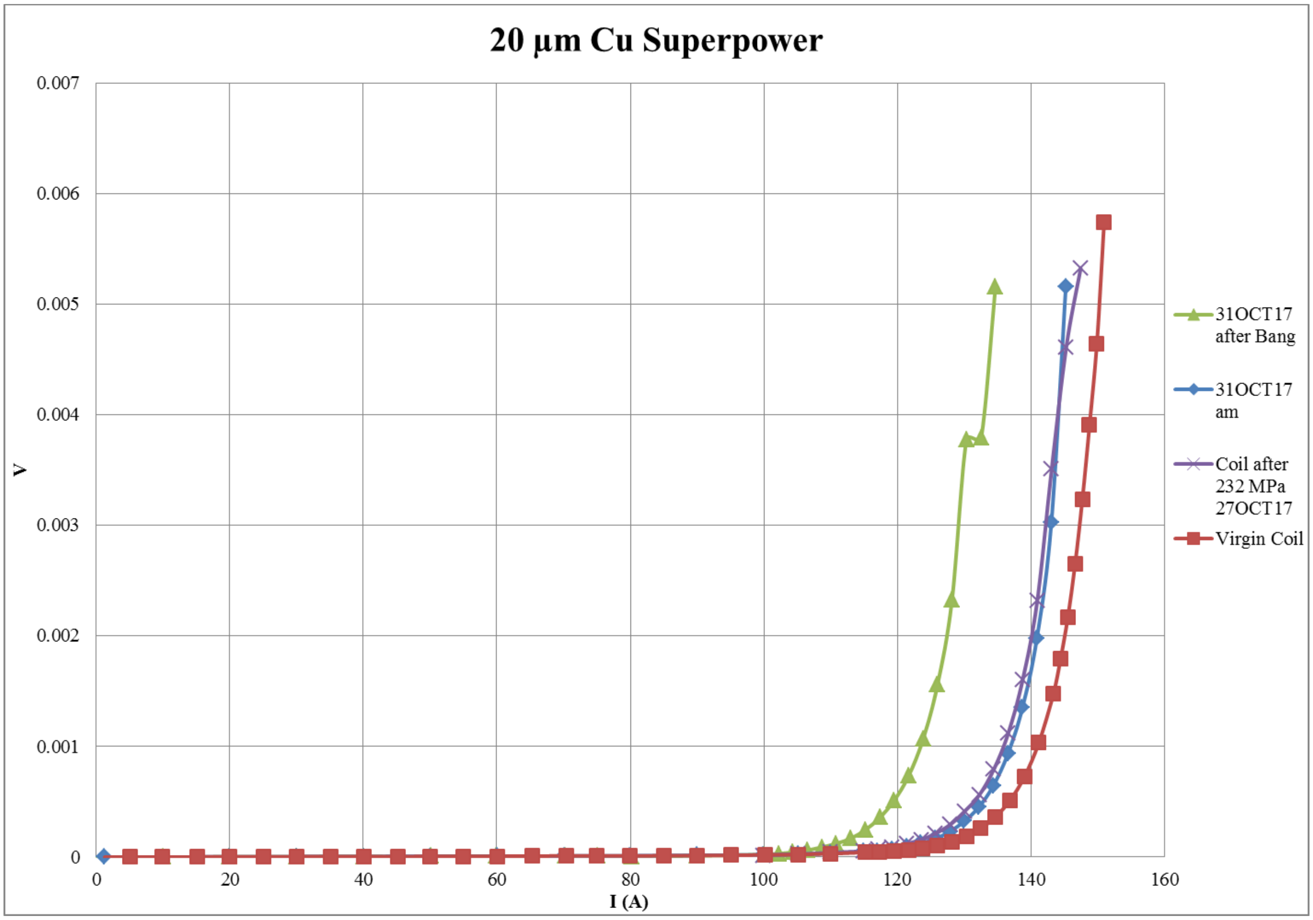


Figure 58: *I vs V for 20µm Coil*

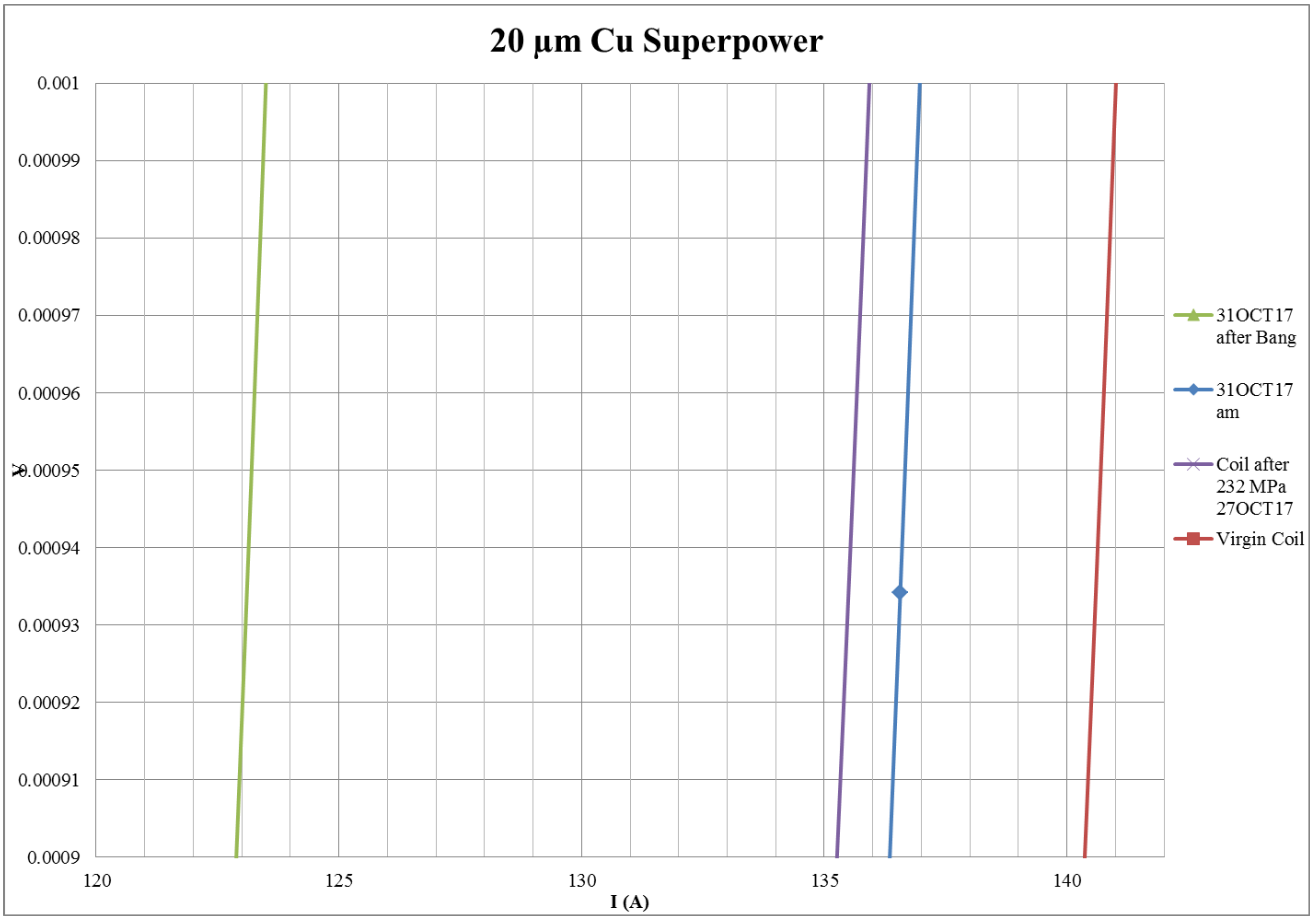


Figure 59: *I vs V for 20µm Coil*

After two days of relentless compressive loading and thermal cycling, the coil's I_c dropped by 17.6 A from 141 A to 123.4 A; a drop in I_c by 12.5%.

For purposes concerning IBS, where the magnet will be run at 50% I_c, the coil was tested for performance at 66%, 75%, and 80% its original I_c of 141 A – 93.2 A, 105.7 A, and 112.8 A, respectively. Figure 60 shows the results; the thick color lines correspond to the coil voltage while the thin color lines represent the compressive loading at which the voltage reading was logged.

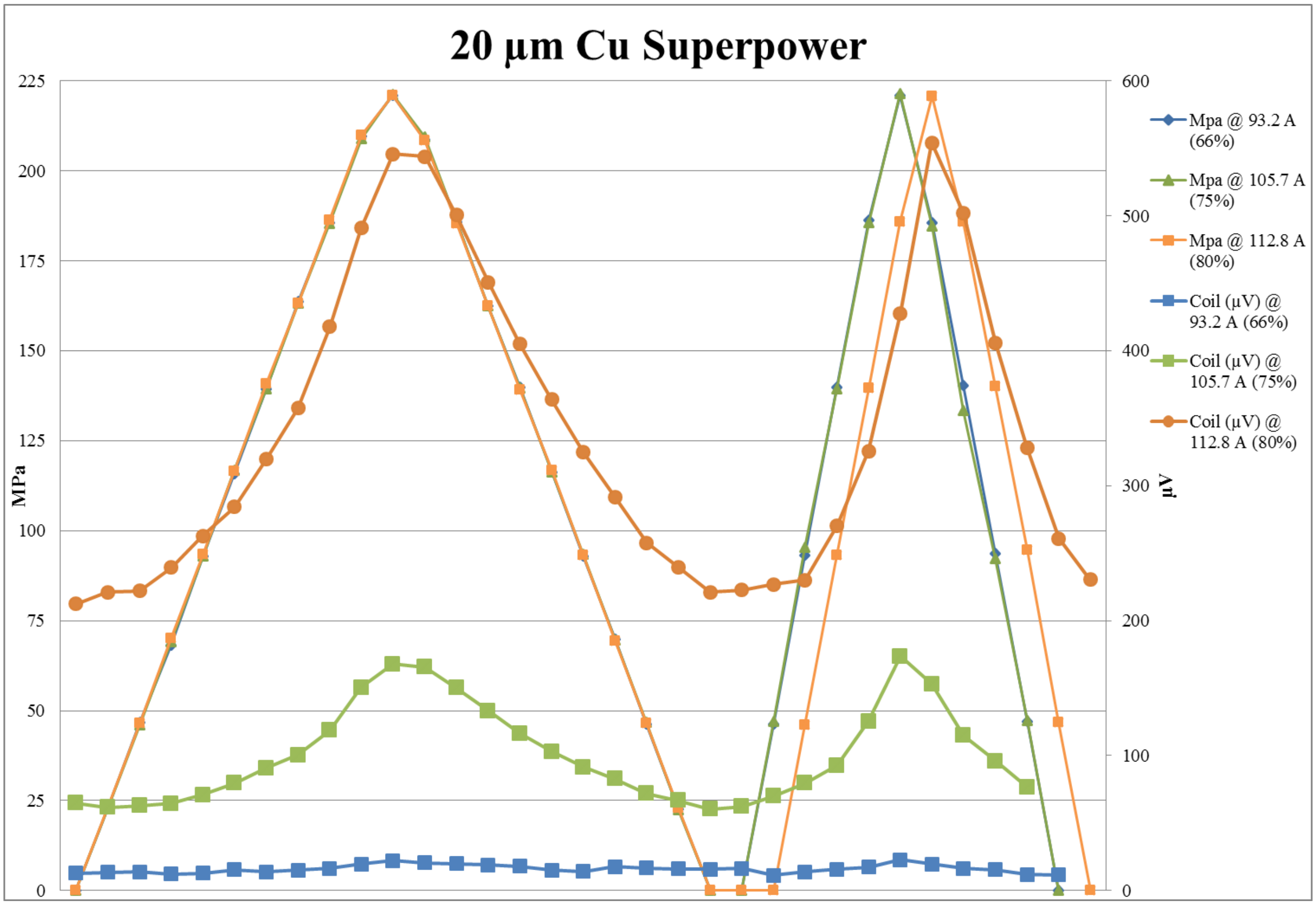


Figure 60: *20µm Coil compression behavior at 66%, 75%, and 80% original coil I_c*

One can be observed, from Figure 60, that at 66% of the original coil I_c, there was no real effect of compressive pressure on the coil; the coil already had a performance degradation of 17.6 A (a 12.5% decrease). The minor gain in voltage seen on the graph falls within the margin of error of the power supply.

At 75% of the original coil I_c, there was an increase in voltage from 0 to 220 MPa of about 100 µV. At 80% of the original coil I_c, the increase in voltage from 0 to 220 MPa was about 330 µV. All of these voltages fall well within the coils I_c threshold voltage of 977µV. The conductor performance exceeded expectations.

Figure 61 – 62 are I vs V graphs of the coil throughout two days of testing.

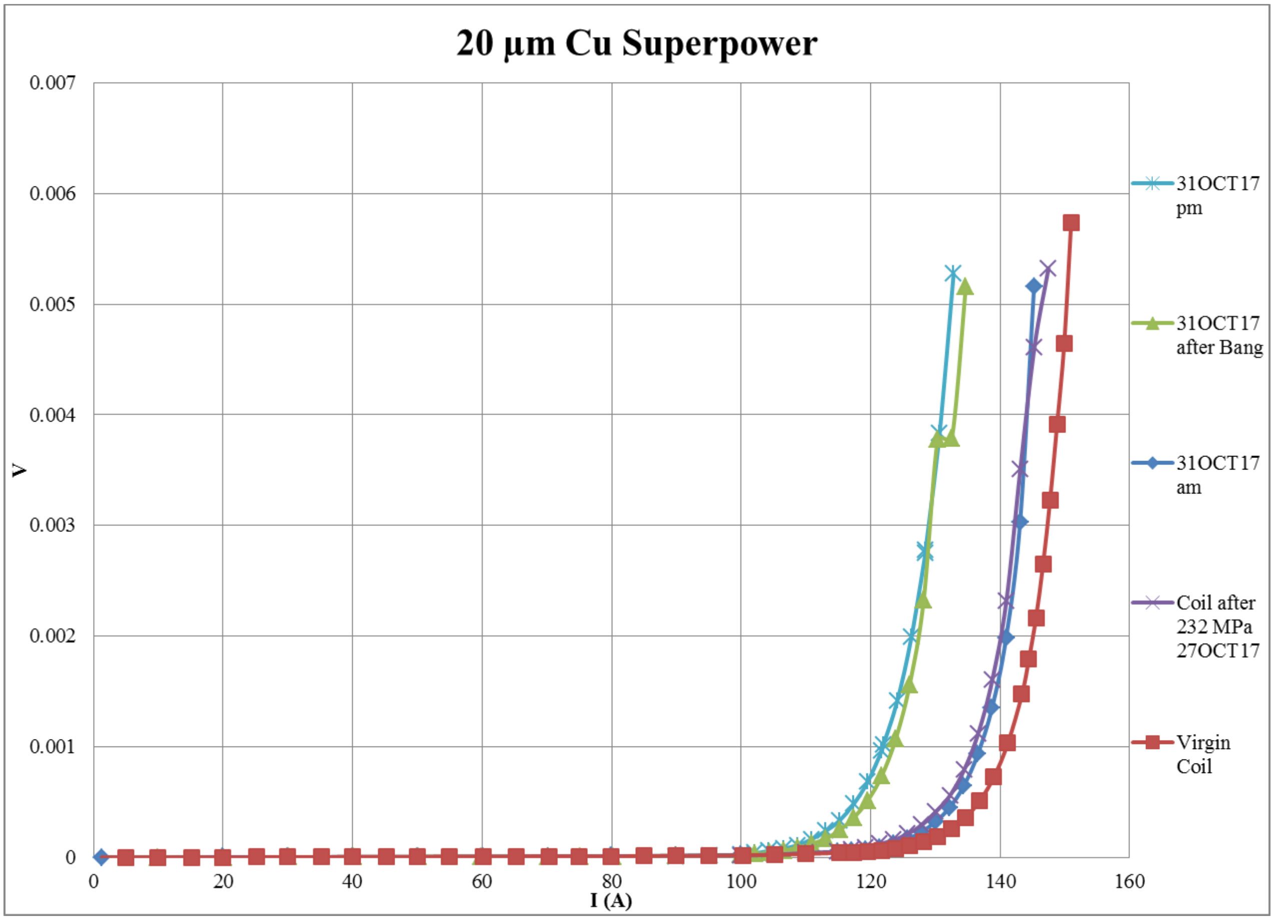


Figure 61: *I vs V for 20µm Coil*

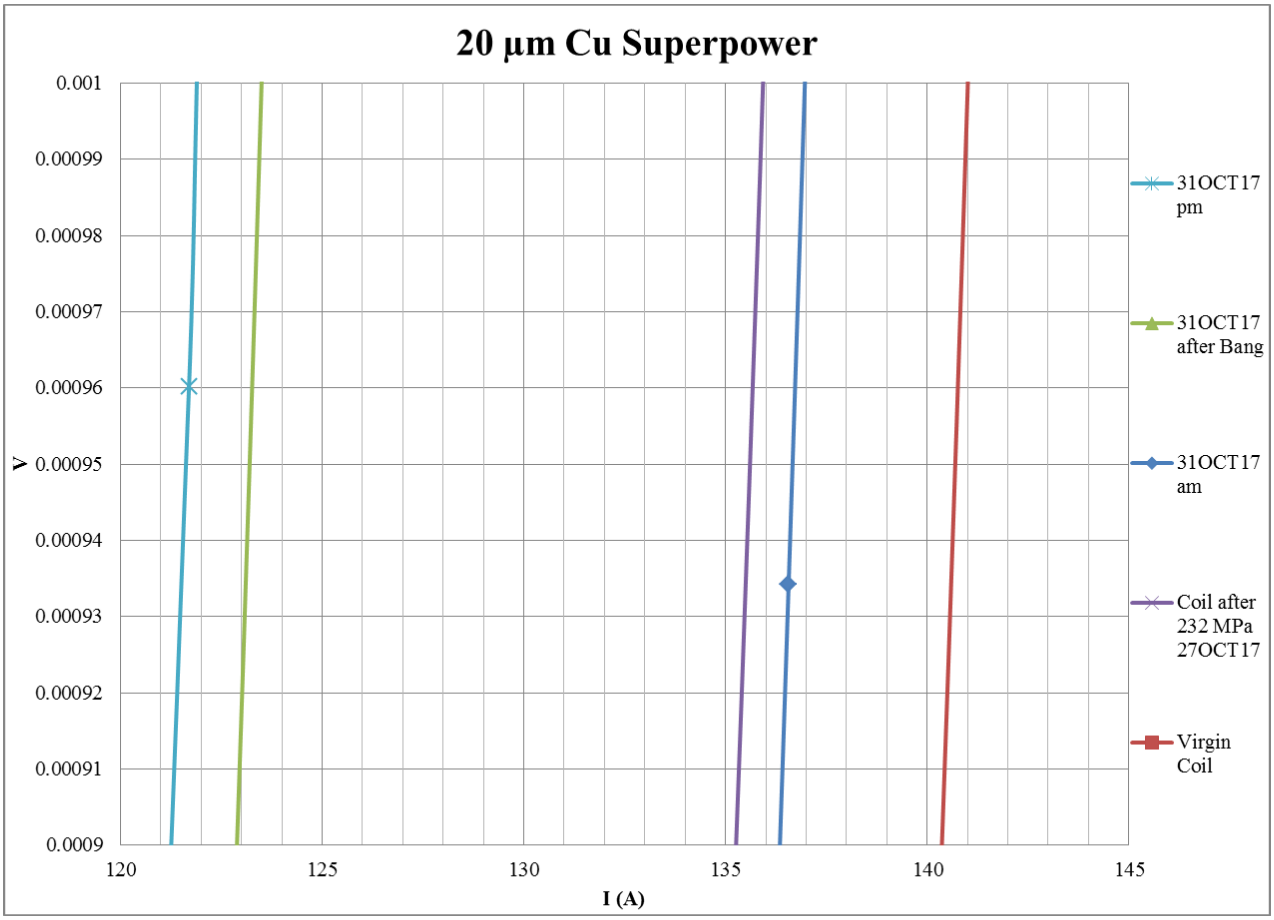


Figure 62: *I vs V for 20µm Coil*

By the end of the second day of compression testing and thermal cycling, the coil's I_c had gone down from 141 A to 122 A; a 19 A decrease, 13.5% its I_c. When the coil was subject to pressures calculated for IBS, there was little to no performance degradation on the coil. When the coil was subjected to pressures beyond those calculated for the IBS coil, performance degradation was observed, but the coil still performed within limits in the margins set for the project.

Conclusion

Throughout the tests, new compression testing apparatus and procedures were developed. They allowed for the testing of the SuperPower 2G HTS 20 µm Cu conductor under conditions similar to those the conductor may experience in the IBS magnet at 25 Tesla. The conductor was thermally cycled multiple times and was put through rigorous compression loading cycling over a period of time at pressures and I_c margins beyond the pressures and I_c margins established for the IBS magnet.

The tests summarized above built confidence in and provided validation for choosing the SuperPower 2G HTS 20 µm Cu conductor for the IBS magnet coils. The conductor performed well within limits when pushed beyond the performance envelope developed for the IBS magnet. According to the tests conducted, the conductor will endure minor physical deformation. However, this deformation will have insignificant impact on the performance of the conductor and the magnet overall.

References

1. W.B. Sampson, M.D. Anerella, J.P. Cozzolino, R.C. Gupta, Y. Shiroyanagi, "THE EFFECT OF AXIAL STRESS ON YBCO COILS", presented at 2001 Particle Accelerator Conference.
2. Cozzolino, J (Preliminary Design Review on June 22, 2017). BNL IBS SOLENOID (SINGLE-LAYER COIL) CONCEPT AND ANALYSIS [PowerPoint slides].
3. http://www.superpower-inc.com/content/2g-hts-wire