13_040219_CLN_01.doc

***TO: DISTRIBUTION***
***FROM: C NEUMEYER***
***SUBJECT: ANALYSIS OF TF COMMISSIONING ISTP RESULTS***

This memo serves to document the TF-related results of ISTP-001 conducted between 1/16 and 1/20/4 to commission the new TF coil system and to restart NSTX. In addition it discusses the rationale for the present TF operating envelope of 4.5kG/1.0 second and outlines plans for follow-on work required to justify higher operating levels.

*Summary*

TF shots in the ISTP-001 Test Plan consisted of four TF-only shots at increasing levels which imposed equal increments of in-plane EM load and approximately equal increments of $\int i^2(t)dt$, followed by two additional test shots which include combined field out-of-plane loads. These latter two shots are representative of plasma operation and form the basis for the combined field 50% and 100% level standard daily test shots. The shots were planned[1] in advance of the ISTP and were analyzed using the FEA models with the aim of comparing predicted quantities to measured quantities as part of the ISTP.

The ISTP test results show areas of agreement as well as areas of disagreement with the analytic predictions. Also, the joint-to-joint variation is larger than anticipated. And, the results are not generally consistent with the prototype testing in terms of the effect of applied EM loads versus joint resistance. Therefore follow-on activities have been initiated to develop refinements to the analytic model with the aim of benchmarking it against the measurements. Another round of prototype tests may be performed as well.

In the interim, the present operating envelope allows 4.5kG and a maximum $I^2T$ of 3.6e9$A^2$-sec, which represents 56% of the in-plane EM load, 75% of the out-of-plane EM load, and 77% of the maximum thermal load, with respect to the 6kG design basis case.

This envelope is judged to be safe, despite the aforementioned discrepancies, based on the fact that the energy dissipation at the worst case joints is estimated to be of the same order as that allowed for in the analysis of the design basis 6kG pulse. The situation is really far more complex, however, considering the non-uniform current densities, pressures and conductivities (electrical and thermal) along the joint, along with the time dependencies of the thermal diffusion away from the joint. Nevertheless, an encouraging factor is that stable operation at 4.5kG has been demonstrated. But clearly more work

[1] "TF Recommissioning Sequence", 13_031203_CLN_01.doc

needs to be done to develop a reliable predictive model and a better understanding of the behavior. At this time efforts are underway to develop modified FEA models which represent the locality of the joint in greater detail than previously. The expectation is that the greater level of detail will lead to better agreement between the predicted voltage, temperature, and strain measurements, and that the model will still predict acceptable conditions at 6kG.

*General Questions To Be Addressed*

1) Does measured behavior agree with analytic model?

- How much difference exists between measurements and predictions?
- Does model need to be changed?
- Does operating envelope need to be reconsidered?

2) Do all joints of the same type behave the same way?

- What variation exists joint-to-joint?
- Are any joints significantly different than others?

3) Is behavior changing as more load cycles are applied?

*Measurement Details*

Voltage across each joint is measured using probes as shown in figure 1 below.

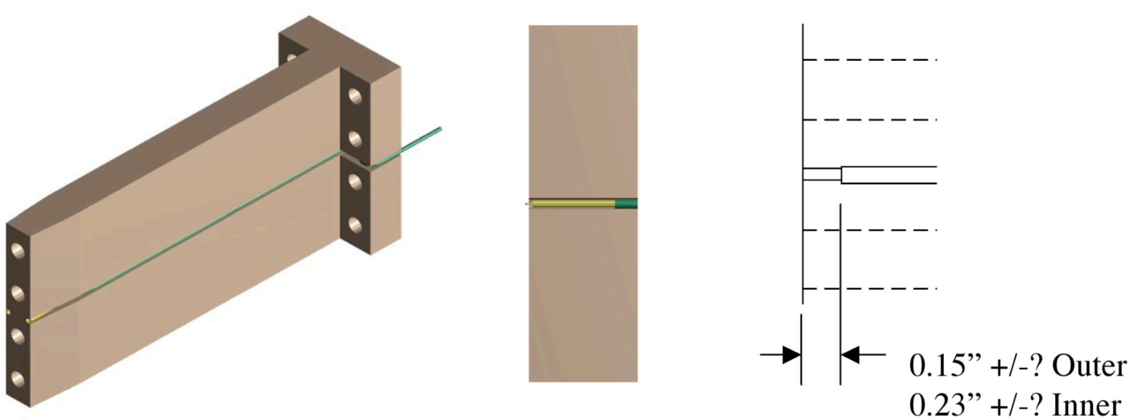



*Figure 1 – Voltage Probe Arrangement*

Voltage drop necessarily includes bulk resistance effect due to distance over which probe barrel is in contact with copper. Nominal dimensions are shown in the figure. However, due to the final clean-up machining step, the tolerance on this dimension is unknown, and could be quite variable.

Theoretical resistance measurement is based on the following curve showing the effect of contact pressure on contact resistivity.

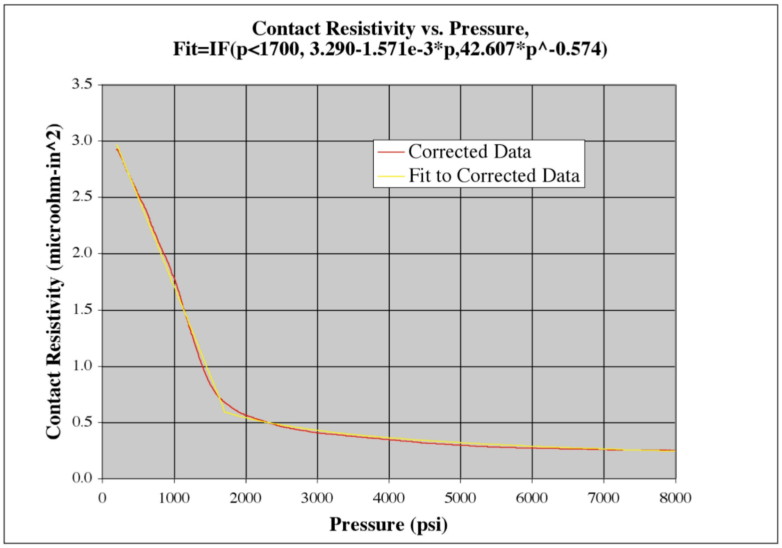



*Figure 2 – Contact Resistivity vs. Pressure*

On this basis, and the nominal flag stud tension, predicted resistances under no load at 20C are as shown in Table 1.

TABLE 1 – PREDICTED JOINT RESISTANCE VALUES

| | Outer Layer, Nominal | Inner Layer, Nominal | |
|---|---|---|---|
| Probe Gap | 0.15 | 0.23 | in |
| Height | 5 | 5 | in |
| Width | 0.781 | 1 | in |
| Hole Dia | 0.563 | 0.563 | in |
| Groove Dia | 0.048 | 0.048 | in |
| Groove Depth | 0.142 | 0.142 | in |
| CSA | 2.90 | 3.99 | in^2 |
| 20C Bulk Resistance | 0.035 | 0.039 | microohm |
| Force | 20000 | 20000 | lbf |
| Pressure | 6906 | 5011 | psi |
| Contact Resistivity | 0.114 | 0.224 | microohm-in^2 |
| Contact Resistance | 0.039 | 0.056 | microohm |
| Temperature(200A) | 20 | 20 | C |
| Bulk Resistance(200A) | 0.035 | 0.039 | microohm |
| Total Resistance(200A) | 0.074 | 0.095 | microohm |

The above predicts an average resistance of around 75 nano-Ohm (nΩ) for the outer layer flags and 95 nΩ for the inners, whereas the actual measured values[2] following initial installation had averages of 40 nΩ and 75 nΩ. The following figure gives an indication of the kind of variability initially measured.

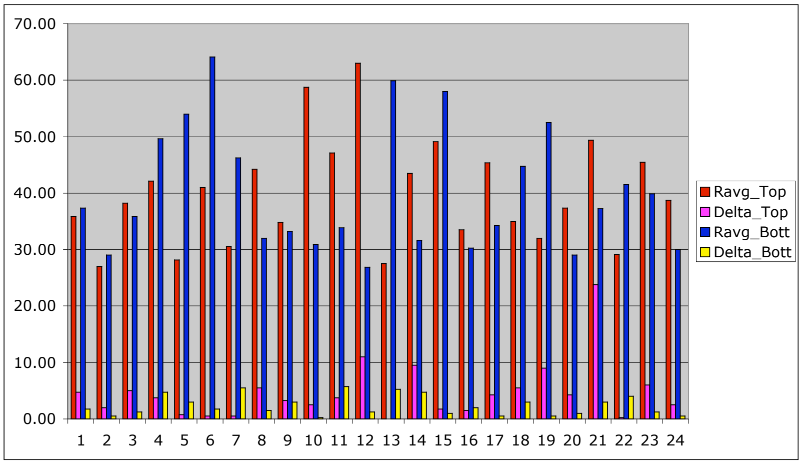



*Figure 3 – Outer Flag Joint Resistance (nΩ) vs. Joint Number,*
*Average of "A" and "B" probes,*
*and difference between "A" and "B" probes*

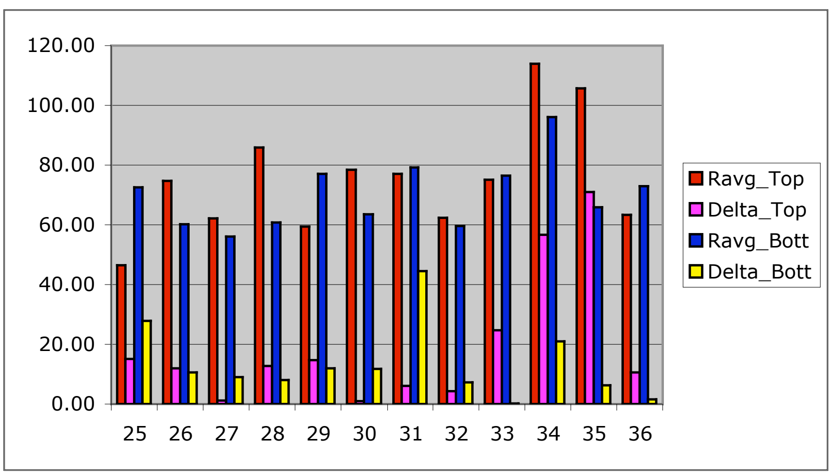



*Figure 4 – Outer Flag Joint Resistance (nΩ) vs. Joint Number,*
*Average of "A" and "B" probes,*
*and difference between "A" and "B" probes*

[2] TF Joint Measurements by H Schneider and R Marsala 12/12/3

TABLE 2 – FIRST 200A MEASUREMENT
OF JOINT RESISTANCES

| Location | nΩ |
|---|---|
| Ravg_Outer_Top | 40 |
| Ravg_Outer_Bott | 40 |
| Ravg_Outer | 40 |
| Rstdv_Outer | 10 |
| Ravg_Inner_Top | 75 |
| Ravg_Inner_Bott | 70 |
| Ravg_Inner | 73 |
| Rstdv_Inner | 17 |

Strain and temperature probes are installed in four flags (2 top (1 inner, 1 outer) and 2 bottom (1 inner and 1 outer) and their shear shoes as indicated in the figure 5.

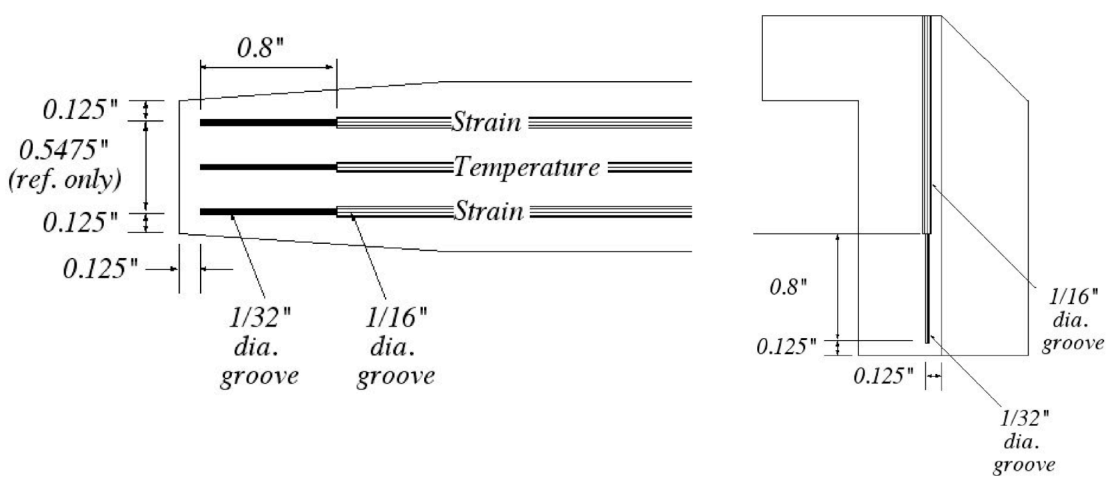



*Figure 5 – Contact Resistivity vs. Pressure*

It is noted that the temperature probes have an active length of ~ 0.75” and are epoxied into a groove. Per the manufacturer, the time response of the probe time alone is 30mS, but the response in this configuration, with the epoxy, is not known at this time. The range of the probes is 0-150C, and the scale factor is TBD volts/ºC (i.e. TBD degrees/volt).

The range of the strain probes is –2500 (compression) to 200 (tension) microstrain. The strain probes have an active length of ~ 0.4” and are also epoxied into grooves.

G-10 rods were affixed to several flag ends and displacement transducers affixed to the umbrella structure to measure the toroidal displacement at the ends of the rods as a measure of the angular twist of the TF bundle. Total radius out to the transducers is TBD inches on outer flags and TBD inches on inner flags, so the scale factor is TBD inch/degree for the outers and TBD inch/degree on the inners. Then, considering that the scale factor of the probe is 10V/inch, the final signal scale factor is TBD volts/degree (i.e. TBD degrees/volt) on the outers and TBD volts/degree (i.e. TBD degrees/volt) on the inners.

One displacement transducer was affixed to the top of the machine to measure the axial displacement of the TF bundle at the spline with respect to the umbrella cover. The scale factor is 10V/inch (i.e. 100mils/volt).

*ISTP Shot Summary*

Shot list and FISO signal conditioner channel usage is shown in the following table.

# TABLE 3 – ISTP SHOT SUMMARY

| Shot | Date | Itf (kA) | PF/OH (%) | Comments | FISO#1 | FISO#2 | FISO#3 | FISO#4 | FISO#5 | FISO#6 | FISO#7 | FISO#8 | 19_19 Probes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 110752 | 1/16/04 | 26.7 | 0 | Analysis Case #1 | Top Outer Flag Temp FOE#8 | Bot Inner Flag Temp FOE#13 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Inner Flag Strain FOE#14 | Bot Inner Flag Strain FOE#12 | Top Inner Flag Strain FOE#2 | Top Inner Flag Strain FOE#1 | TFJ_19_19_V=B |
| 110755 | 1/16/04 | 37.8 | 0 | Analysis Case #2 | Top Outer Flag Temp FOE#8 | Bot Inner Flag Temp FOE#13 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Inner Flag Strain FOE#14 | Axial Delta L FOE#19 | Top Inner Flag Strain FOE#2 | Top Inner Flag Strain FOE#1 | TFJ_19_19_V=B |
| 110757 | 1/16/04 | 46.2 | 0 | Analysis Case #3 | Top Outer Flag Temp FOE#8 | Bot Inner Flag Temp FOE#13 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Inner Flag Strain FOE#14 | Axial Delta L FOE#19 | Top Inner Flag Strain FOE#2 | Top Inner Flag Strain FOE#1 | TFJ_19_19_V=B |
| 110758 | 1/16/04 | 53.4 | 0 | Analysis Case #4 | Top Outer Flag Temp FOE#8 | Bot Inner Flag Temp FOE#13 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Inner Flag Strain FOE#14 | Axial Delta L FOE#19 | Top Inner Flag Strain FOE#2 | Top Inner Flag Strain FOE#1 | TFJ_19_19_V=B |
| 110790 | 1/19/04 | 26.7 | 0 | Repeat of Analysis Case #1 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Inner Flag Strain FOE#14 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B |
| 110791 | 1/19/04 | 37.8 | 0 | Repeat of Analysis Case #2 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Inner Flag Strain FOE#14 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B |
| 110792 | 1/19/04 | 46.2 | 0 | Repeat of Analysis Case #3 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Inner Flag Strain FOE#14 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B |
| 110793 | 1/19/04 | 53.4 | 0 | Repeat of Analysis Case #4 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Inner Flag Strain FOE#14 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B |
| 110795 | 1/20/04 | 26.7 | 0 | Repeat of Analysis Case #1 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Outer Shear Key Strain FOE#15 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B TFJ_SPARE_01=A |
| 110796 | 1/20/04 | 37.8 | 0 | Repeat of Analysis Case #2 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Outer Shear Key Strain FOE#15 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B TFJ_SPARE_01=A |
| 110797 | 1/20/04 | 46.2 | 0 | Repeat of Analysis Case #3 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Outer Shear Key Strain FOE#15 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B TFJ_SPARE_01=A |
| 110798 | 1/20/04 | 53.4 | 0 | Repeat of Analysis Case #4 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Outer Shear Key Strain FOE#15 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B TFJ_SPARE_01=A |
| 110799 | 1/20/04 | 26.7 | 50 | Analysis Case #5 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Outer Shear Key Strain FOE#15 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B TFJ_SPARE_01=A |
| 110803 | 1/20/04 | 53.4 | 100 | Analysis Case #6 | Top Outer Flag Temp FOE#8 | Top Shear Key Strain FOE#5 | Top Outer Flag Strain FOE#6 | Top Outer Flag Strain FOE#7 | Bot Outer Shear Key Strain FOE#15 | Axial Delta L FOE#19 | Top Outer Flag Rotation FOE#17 | Bot Inner Flag Rotation FOE#20 | TFJ_19_19_V=B TFJ_SPARE_01=A |
| | | | | | | Notes: | | | | Notes: | | | |
| | | | | | | Changed from TFJ_FISO_CH2 to TFJ_3232SP02 1/20 11:00 am after 110798 | | | | Changed from TFJ_FISO_CH6 to TFJ_3232SP01 1/20 9:00 am after 110793 | | | |

*FISO Probe Details*

FISO probe details are given in the following table.

TABLE 4 – FISO DETAILS

| Extension Fiber | Probe | SN | Cal Fac | Range | Units | Location | Top/Bott | Inner/Outer | Box# | Turn# | LH/RH | FISO CH# <= 110790 | FISO CH# <= 110795 | FISO CH# |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | Temperature | T020506I | 4328585 | 0 to 150 | Degree C | Flag | Top | Inner | 4 | 27 | | | | |
| 2 | Strain | | N-1003970 | -2500 to 200 | Micro Strain | Flag | Top | Inner | 4 | 27 | LH | 7 | | |
| 1 | Strain | | N-1003818 | -2500 to 200 | Micro Strain | Flag | Top | Inner | 4 | 27 | RH | 8 | | |
| 4 | Strain | | N-1003805 | -2500 to 200 | Micro Strain | Shoe | Top | Inner | 4 | 27 | | | | |
| 18 | Displacement | | 8056624 | 0 to 150 | Mils | Flag | Top | Inner | 6 | 25 | | | | |
| 8 | Temperature | T020506L | 4317553 | 0 to 150 | Degree C | Flag | Top | Outer | 10 | 21 | | 1 | 1 | 1 |
| 6 | Strain | | N-1003821 | -2500 to 200 | Micro Strain | Flag | Top | Outer | 10 | 21 | LH | 3 | 3 | 3 |
| 7 | Strain | | N-1003836 | -2500 to 200 | Micro Strain | Flag | Top | Outer | 10 | 21 | RH | 4 | 4 | 4 |
| 5 | Strain | | N-1003834 | -2500 to 200 | Micro Strain | Shoe | Top | Outer | 10 | 21 | | | 2 | 2 |
| 17 | Displacement | 04495F01 | 8056837 | 0 to 150 | Mils | Flag | Top | Outer | 12 | 23 | | | 7 | 7 |
| 13 | Temperature | T020519B | 4296505 | -40to 250 | Degree C | Flag | Bott | Inner | 4 | 27 | | 2 | | |
| 12 | Strain | 04495A07 | N-1003832 | -2500 to 200 | Micro Strain | Flag | Bott | Inner | 4 | 27 | LH | 6 | | |
| 14 | Strain | 04494A06 | N-1003816 | -2500 to 200 | Micro Strain | Flag | Bott | Inner | 4 | 27 | RH | 5 | 5 | |
| 15 | Strain | 04495A05 | N-1003873 | -2500 to 200 | Micro Strain | Shoe | Bott | Inner | 4 | 27 | | | | 5 |
| 20 | Displacement | | 8056581 | 0 to 150 | Mils | Flag | Bott | Inner | 12 | 31 | | | 8 | 8 |
| 10 | Strain | | N-1003791 | -2500 to 200 | Micro Strain | Shoe | Bott | Outer | 10 | 21 | | | | |
| *BROKEN* | Strain | 04495A04 | N-1003759 | -2500 to 200 | Micro Strain | Flag | Bott | Outer | 10 | 21 | LH | | | |
| 11 | Strain | | N-1003813 | -2500 to 200 | Micro Strain | Flag | Bott | Outer | 10 | 21 | RH | | | |
| 9 | Temperature | T020506M | 4300510 | 0 to 150 | Degree C | Flag | Bott | Outer | 10 | 21 | | | | |
| 19 | Displacement | | 8056773 | 0 to 150 | Mils | Spline | Top | | | | | | 6 | 6 |

*Shot Details and Analysis Predictions*

Specifications and shot numbers for the 6 types of test shots is given in the following table.

TABLE 5 – SHOT DETAILS

| | Shot | Bt | dT | Tflat | PF | Time | ITF | IOH | IPF1A | IPF1B | IPF2 | IPF3 | IPF5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 110795 | 2.25 | 11 | 1 | 0% | SOFT | 26.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | | | | | EOFT | 26.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2 | 110796 | 3.18 | 23 | 1 | 0% | SOFT | 37.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | | | | | EOFT | 37.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3 | 110797 | 3.90 | 36 | 1 | 0% | SOFT | 46.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | | | | | EOFT | 46.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 4 | 110798 | 4.50 | 50 | 1 | 0% | SOFT | 53.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | | | | | EOFT | 53.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5 | 110799 | 2.25 | 50 | 1 | 50% | SOFT | 26.7 | -12.0 | 0.0 | 0.0 | 0.0 | -2.5 | 0.0 |
| | | | | | | OHSS | 26.7 | 12.0 | -7.5 | 0.0 | -10.0 | 10.0 | 10.0 |
| | | | | | | EOFT | 26.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 6 | 110803 | 4.50 | 50 | 1 | 100% | SOFT | 53.4 | -24.0 | 0.0 | 0.0 | 0.0 | -2.5 | 0.0 |
| | | | | | | OHSS | 53.4 | 24.0 | -15.0 | 0.0 | -10.0 | 10.0 | 10.0 |
| | | | | | | EOFT | 53.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Corresponding analytic predictions are given in the following table.

TABLE 6 – ANALYTIC PREDICTIONS

| | | #1 | | #2 | | #3 | | #4 | | #5 | | | #6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SOFT | EOFT | SOFT | EOFT | SOFT | EOFT | SOFT | EOFT | SOFT | OHSS | EOFT | SOFT | OHSS | EOFT |
| Outer Flag | delta T (degC) | 0.4 | 8.1 | 1.3 | 16.8 | 2.7 | 25.8 | 4.6 | 35.5 | 0.4 | 5 | 8.1 | 4.6 | 33.2 | 35.5 |
| | Flag Strain A (μS) | 51 | 133 | 166 | 329 | 290 | 532 | 409 | 716 | -220 | 474 | 133 | -184 | 809 | 716 |
| | Flag Strain B (μS) | 51 | 133 | 166 | 329 | 290 | 532 | 409 | 716 | 455 | -165 | 133 | 533 | -3 | 716 |
| | Shoe Strain B (μS) | 4 | 6 | 8 | 10 | 11 | 14 | 14 | 14 | 12 | -4 | 6 | 15 | -11 | 14 |
| | Twist Angle (deg) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0 | 0.1 | 0.1 | 0 |
| Inner Flag | delta T (degC) | 0.1 | 2.2 | 0.3 | 4.5 | 0.7 | 7 | 1.3 | 9.6 | 0.1 | 1.4 | 2.2 | 1.3 | 6.3 | 9.6 |
| | Flag Strain A (μS) | 7 | 1 | 13 | 21 | 19 | 31 | 26 | 44 | -12 | 30 | 1 | -8 | 78 | 44 |
| | Flag Strain B (μS) | 7 | 1 | 13 | 21 | 19 | 31 | 26 | 44 | 27 | -11 | 1 | 73 | 1 | 44 |
| | Shoe Strain B (μS) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Twist Angle (deg) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.18 | 0.25 | 0 | 0.27 | 0.31 | 0 |
| Axial Expansion | (mils) | | 35 | | 70 | | 113 | | 156 | | | 35 | | | 156 |

*TF-Only Shots*

The following results focus on the outer layer turn number 21 on the top of the machine which is referred to as 21_21. This is one of the turns which was instrumented with the fiber optic strain and temperature probes. Response of the voltage probes on 21_21 to the four TF-only shots is shown in figure 6.

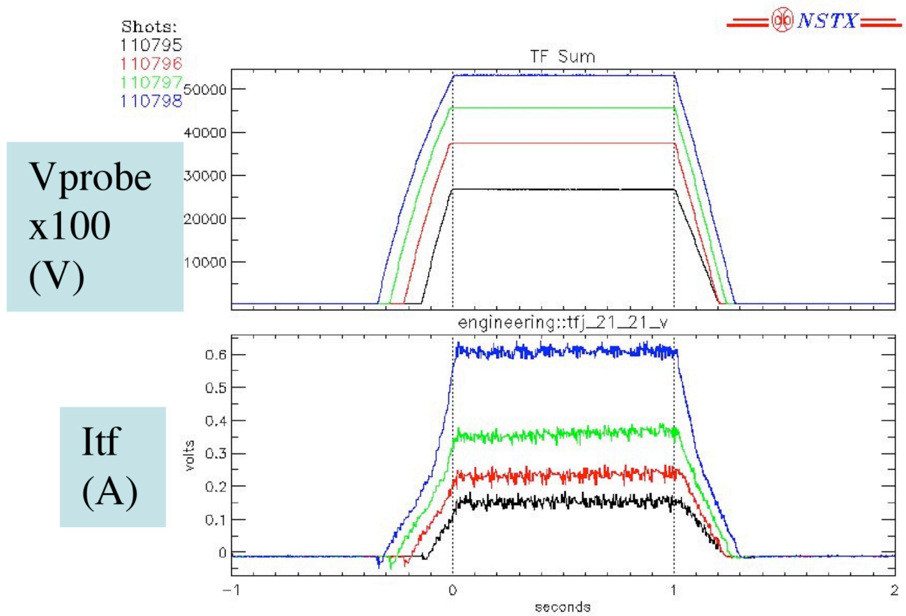



*Figure 6 – Voltage Probe Response to In-Plane Loading*

Response of the temperature probe on 21_21 to the four TF-only shots is shown in figure 7. The behavior of the last shot (110798) is noticeably different than the others.

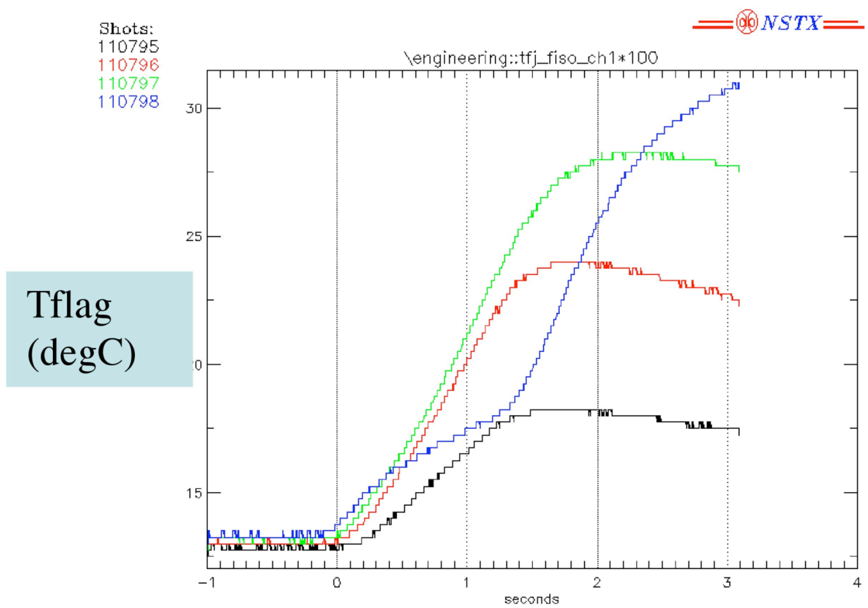



*Figure 7 – Temperature Probe Response to In-Plane Loading*

The temperature pattern during the pulse (t < 1.2) is counterintuitive, considering that the four pulses have equal increments of $\int i^2(t)dt$. However, the temperatures are noted to redistribute some time after the pulse (t ≥ 2 seconds) into a pattern which follows the $\int i^2(t)dt$.

Response of the flag strain probes on 21_21 to the four TF-only shots is shown in figure 8. Again, the behavior of the last shot (110798) is noticeably different than the others. Also, on the third shot (110797) a difference begins to develop between the strain probes on either side of the joint. Note that strain develops both as a function of the EM loads and of the temperature. After t=1.2 seconds or so, the EM field is off and the remaining strain can be attributed solely to temperature, and the strain level is noted to equalize on the two probes after this time. It is noted, further, that both the EM (in-plane) and thermal loads result in positive strain at this location. So, the most likely explanation for the last shot is that the temperature at the probe location was less (during the pulse) than during the prior shot, which is consistent with the observations in figure 7. One would expect, for pure in-plane loading, that there would be no side-to-side variation but clearly some effect is present here (most noticeably in the third shot (110797).

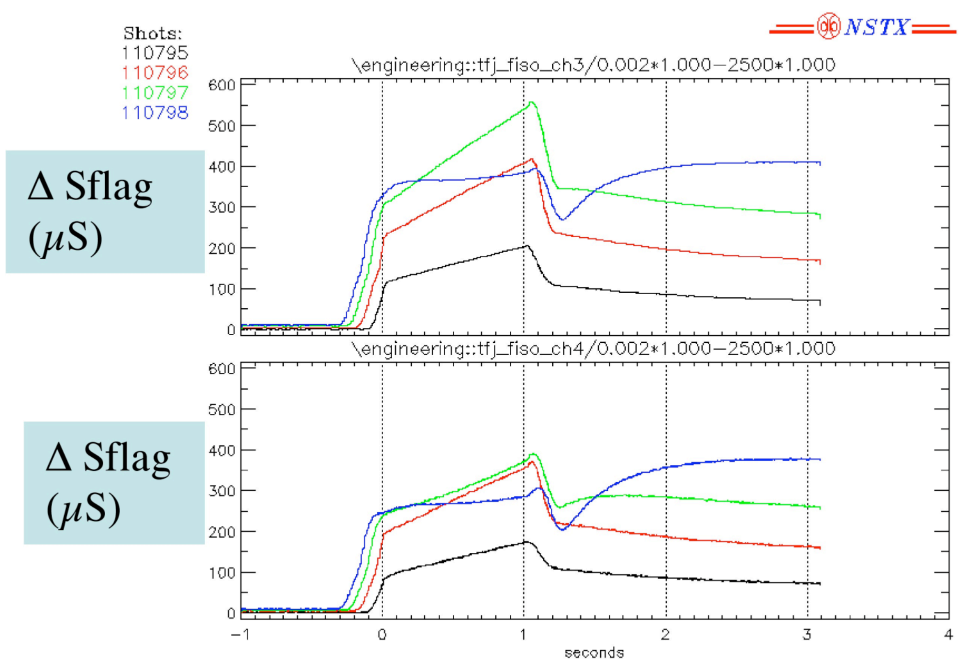



*Figure 8 – Flag Strain Probe Response to In-Plane Loading*

Response of the shear shoe strain probe on 21_21 to the four TF-only shots is shown in figure 9. Increasing levels of compression are noticeable in the last two shots, which one would expect at the shear shoe begins to pick up load.

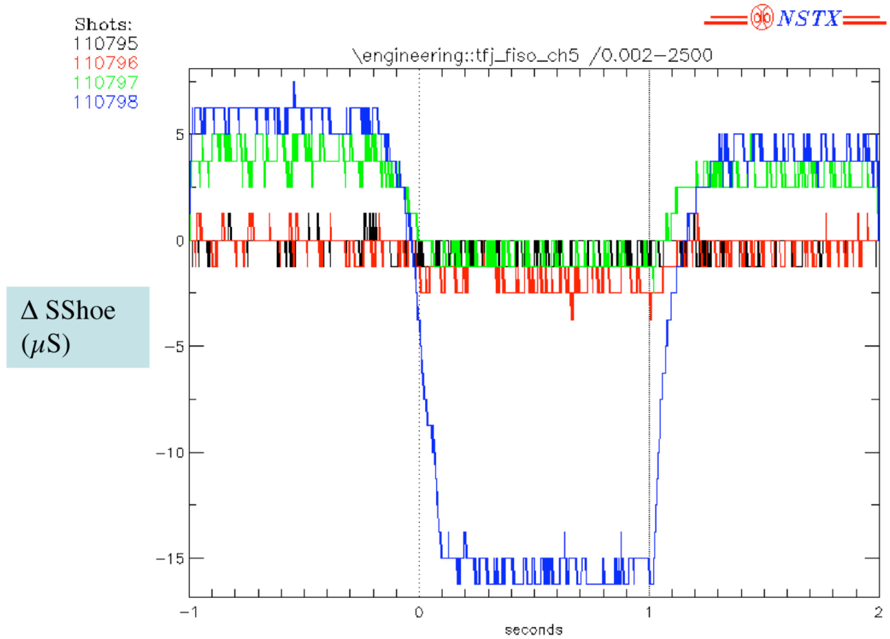



*Figure 9 – Shoe Strain Probe Response to In-Plane Loading*

Response of the axial displacement probe to the four TF-only shots is shown in figure 10. It is noted that the peaks occur at the end of flat top (t=1.0) and that after the EM load goes away (t ≥ 1.2 seconds) only the thermal effect remains.

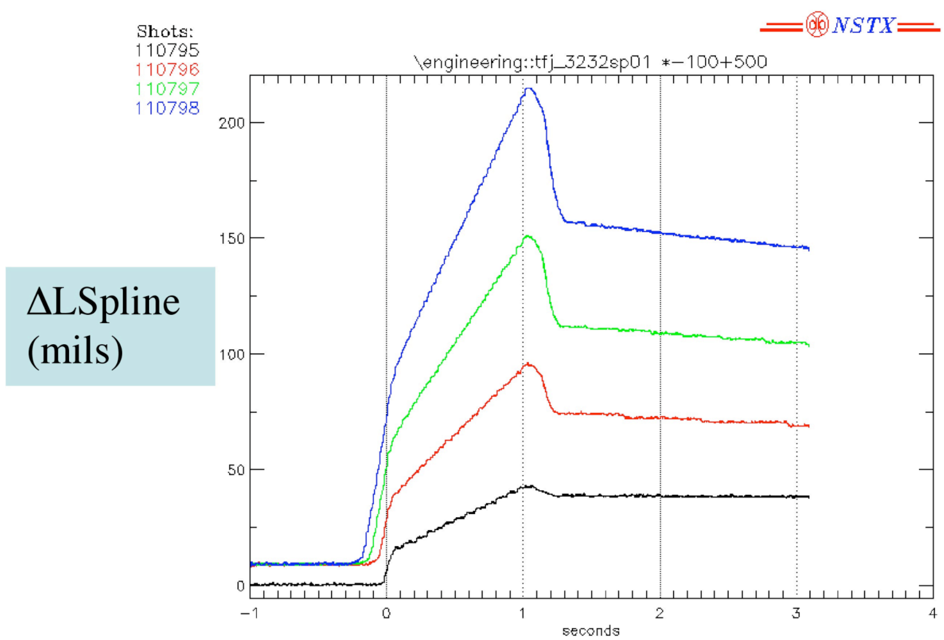



*Figure 10 – Shoe Strain Probe Response to In-Plane Loading*

*Combined Field Shots*

Voltage probe response to the two combined field shots (110799:50% and 110803:100%) are shown overlaid with the TF-only shots with the same TF level (110795 and 110798) in figure 11. Also shown are the OH waveforms. Other PF coil waveforms are not shown, but are of less significance. The effect of the OH is clearly evident on the combined field signals.

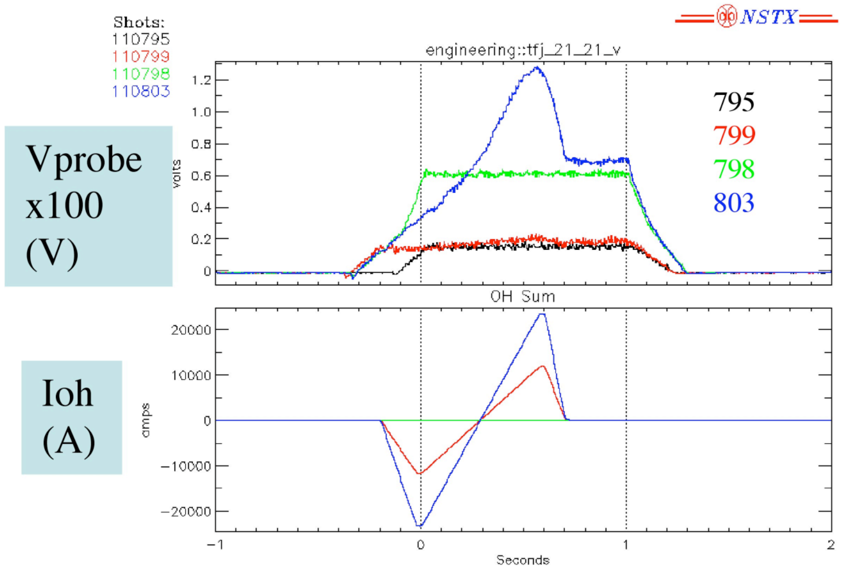



*Figure 11 – Voltage Probe Response*

Temperature probe response to the two combined field shots are shown overlaid with the TF-only shots with the same TF level in figure 12. No significant difference is noted between the in-plane and out-of-plane cases.

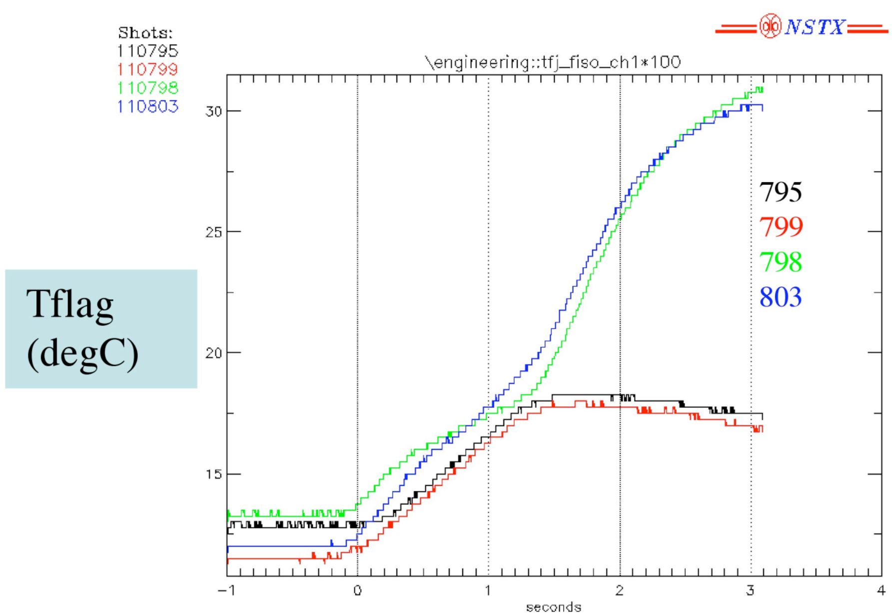



*Figure 12 – Temperature Probe Response*

Response of the flag strain probes on 21_21 to the combined-field shots is shown in figure 13. The effect of the OH is clearly evident, causing a response which is has an inverse relationship on the two sides of the flag, i.e. when one goes up, the other goes down, and vice-versa.

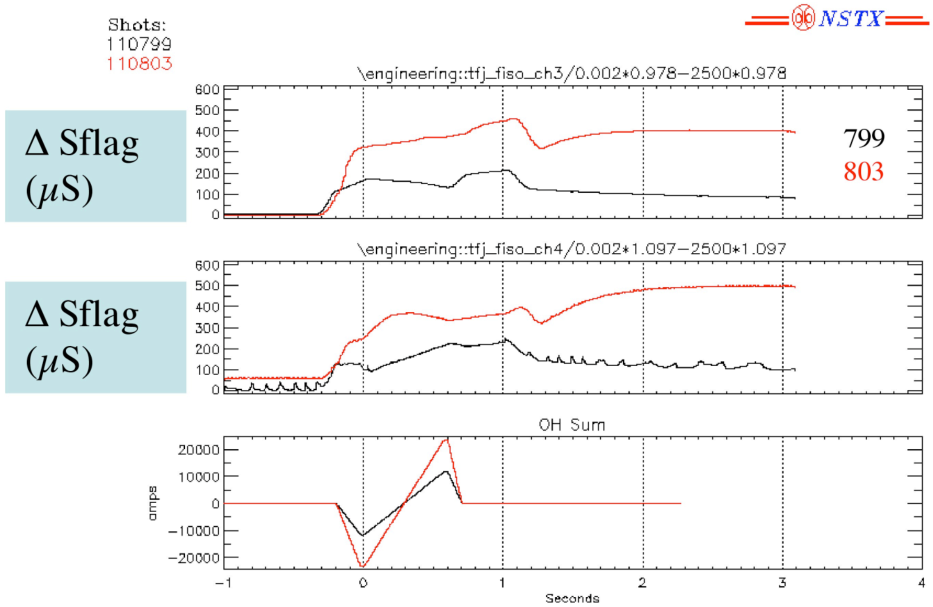



*Figure 13 – Flag Strain Response*

Response of the axial displacement to the combined field shots is shown in figure 14. Additional effects due to the operation of the OH and PF systems are noted.

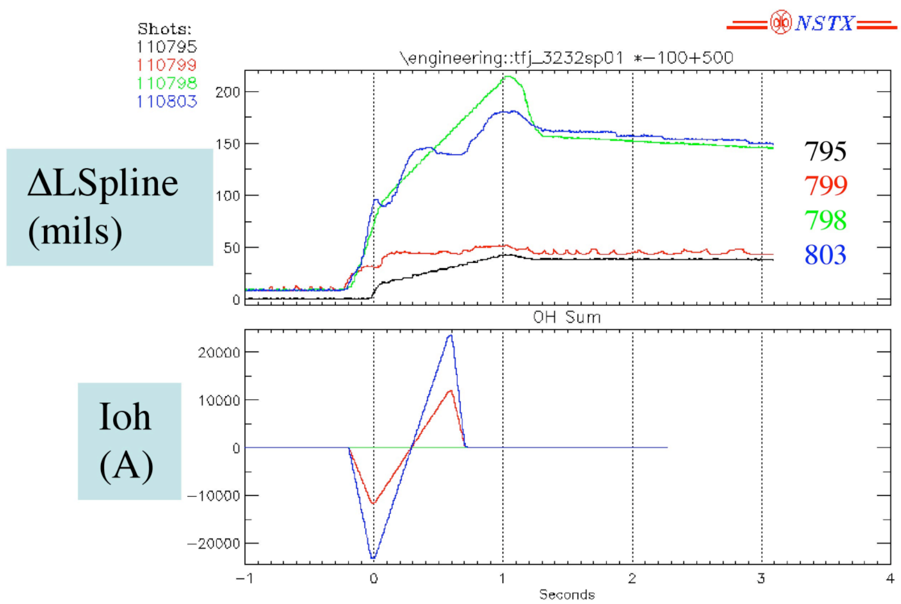



*Figure 14 – Axial Displacement with Combined Field Loading*

Figure 15 shows an overlay between the nominal combined field shot (110803) and another subsequent shot (110809) during which an OH fault occurred, and a rapid shutdown of the OH took place. It is postulated that the OH drives eddy currents in the umbrella cover such that, when the OH current is decreasing in magnitude, an attractive force is developed between the coil and the cover, causing a downward deflection. Then, when the current stops (and its derivative goes to zero), the cover is released from the force and undergoes a mechanical vibration.

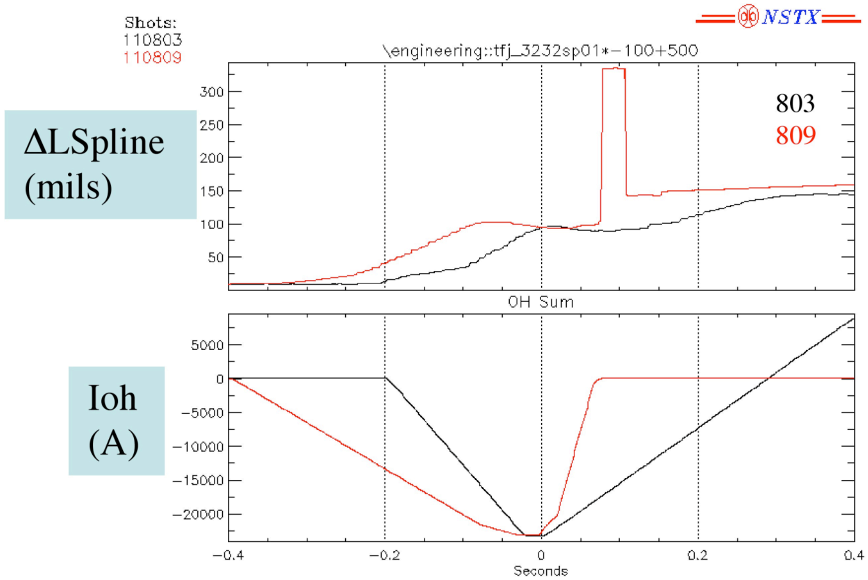



*Figure 15 – Axial Displacement During OH Misoperation*

Response of the angular twist at the end of flag TBD_TBD to the combined field shots is shown in figure 16. The twist during the pure in-plane shots is unexpected. The effect of the OH in the combined field shots is clearly evident.

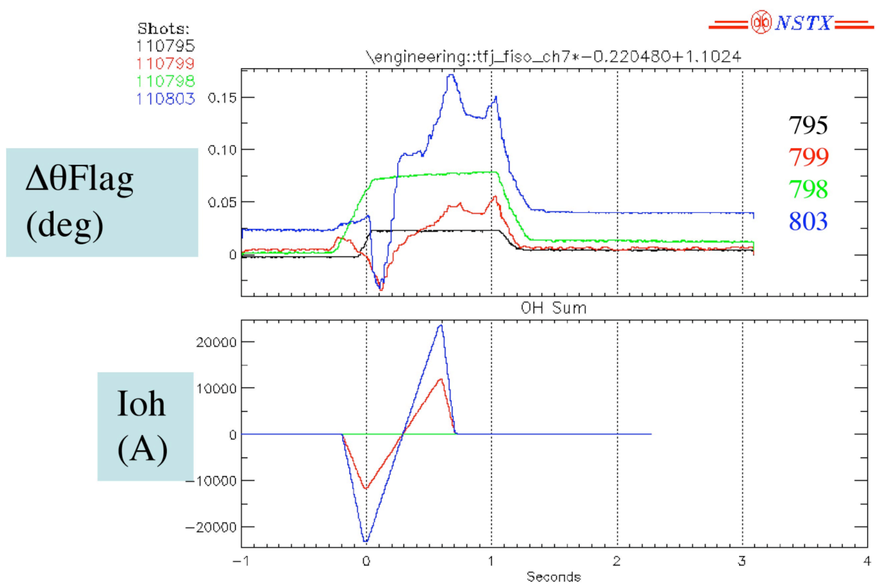
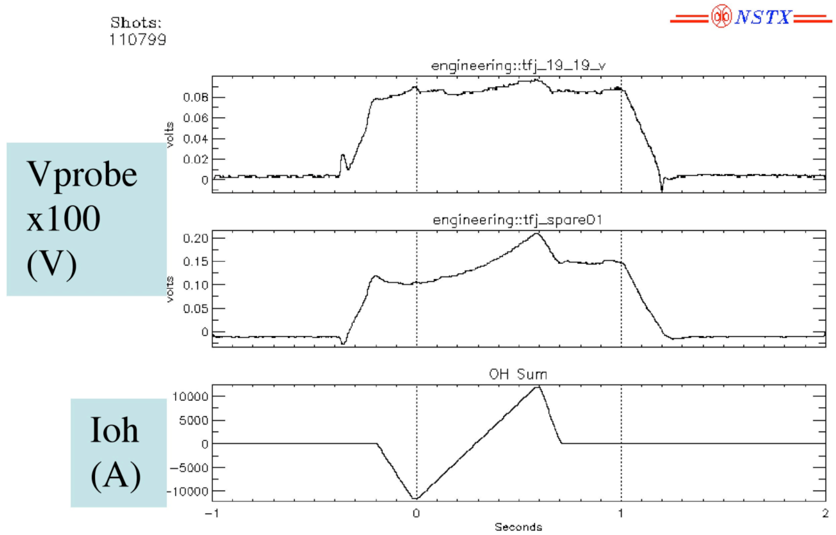
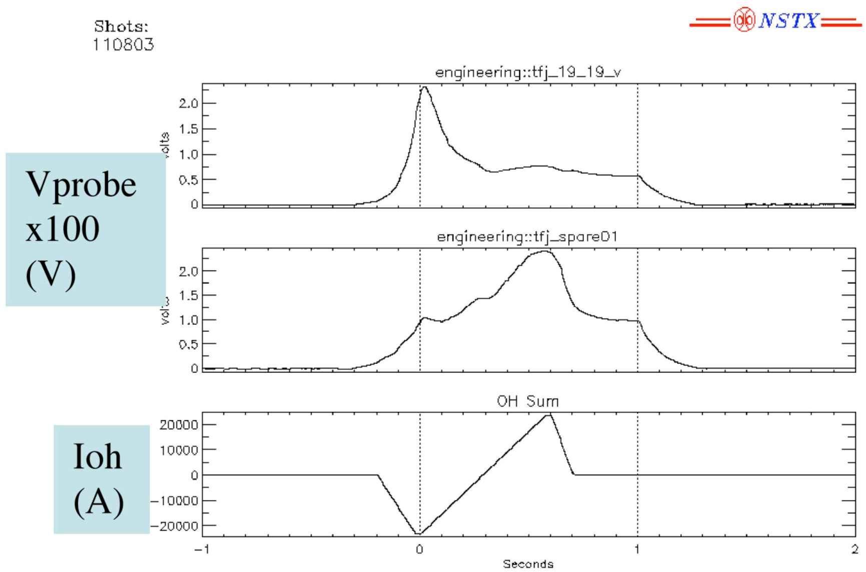
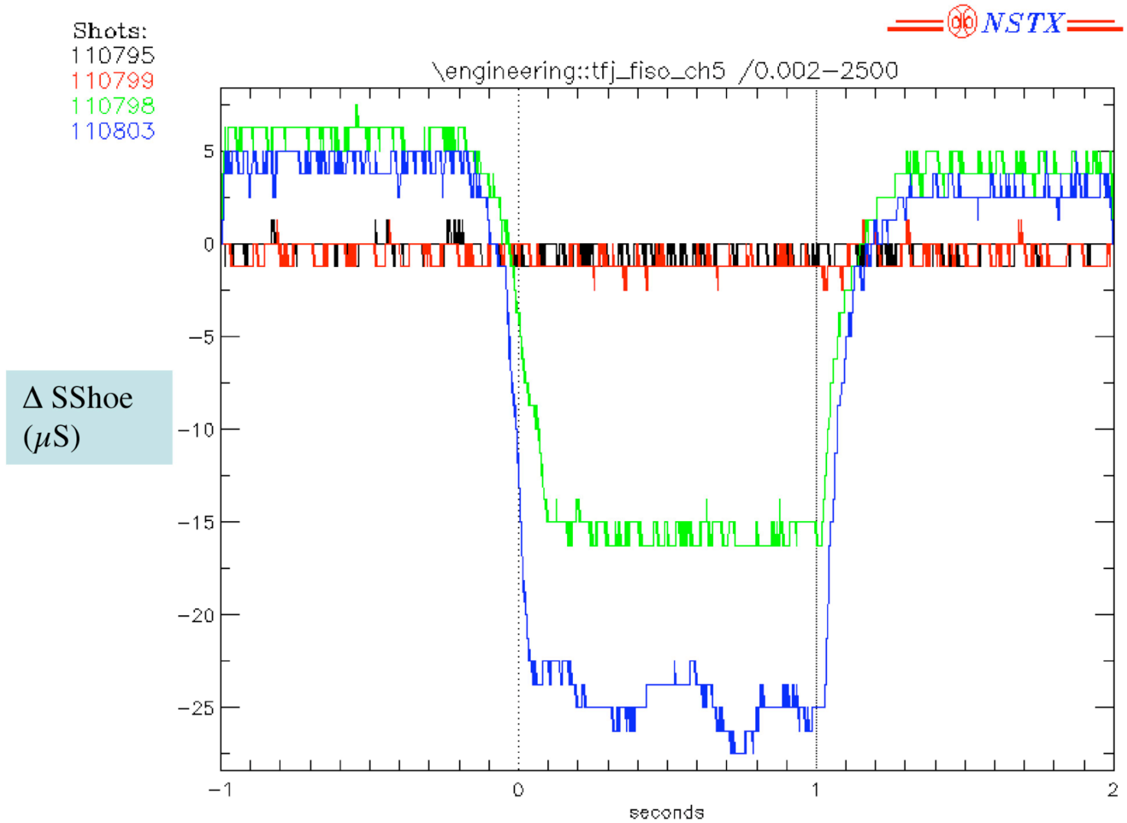


*Figure 16 – Angular Twist of Outer Layer Flag*

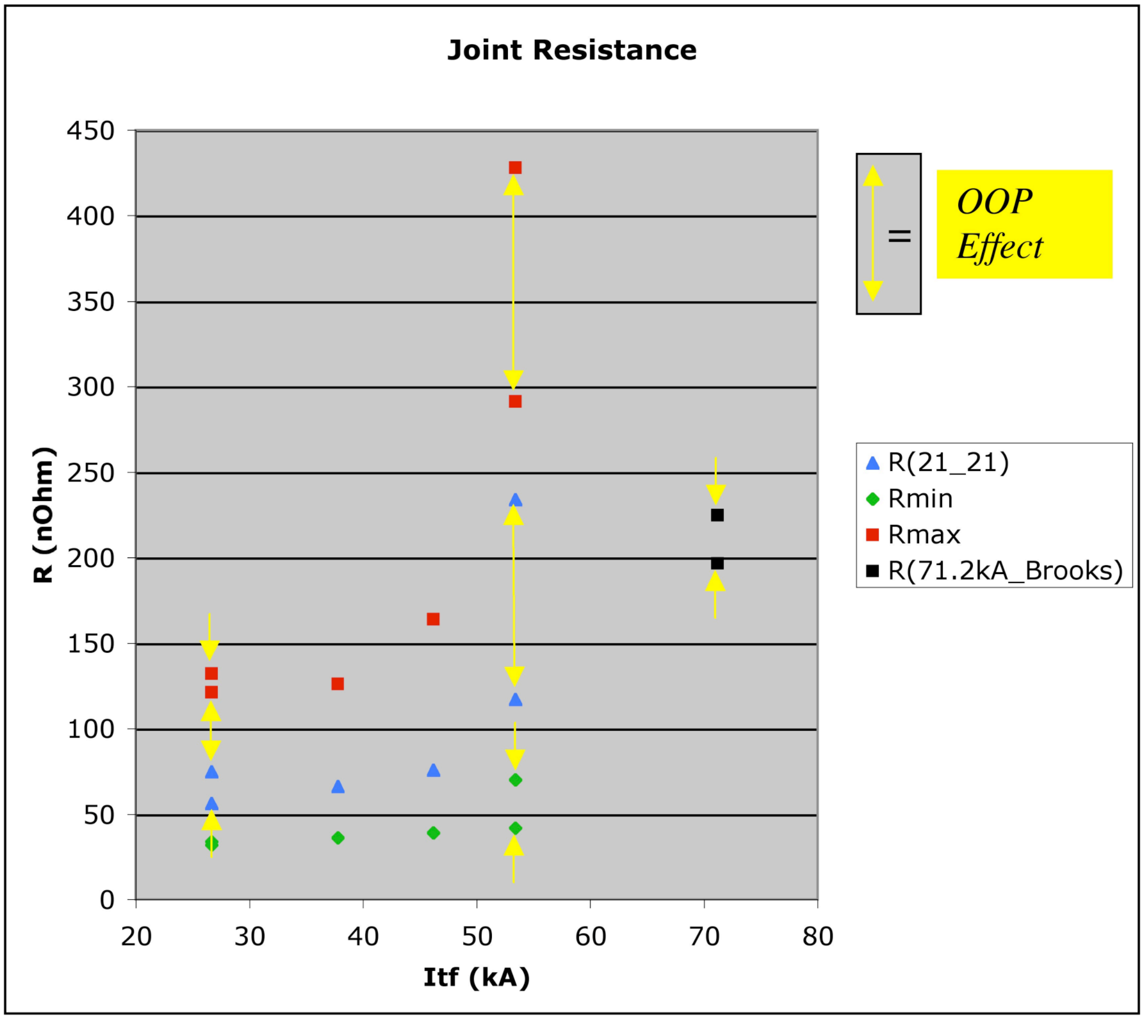

Shots:
110799
NSTX
engineering::tfj_19_19_v
engineering::tfj_spare01
OH Sum
Seconds
volts
Vprobe
x100
(V)
Ioh
(A)

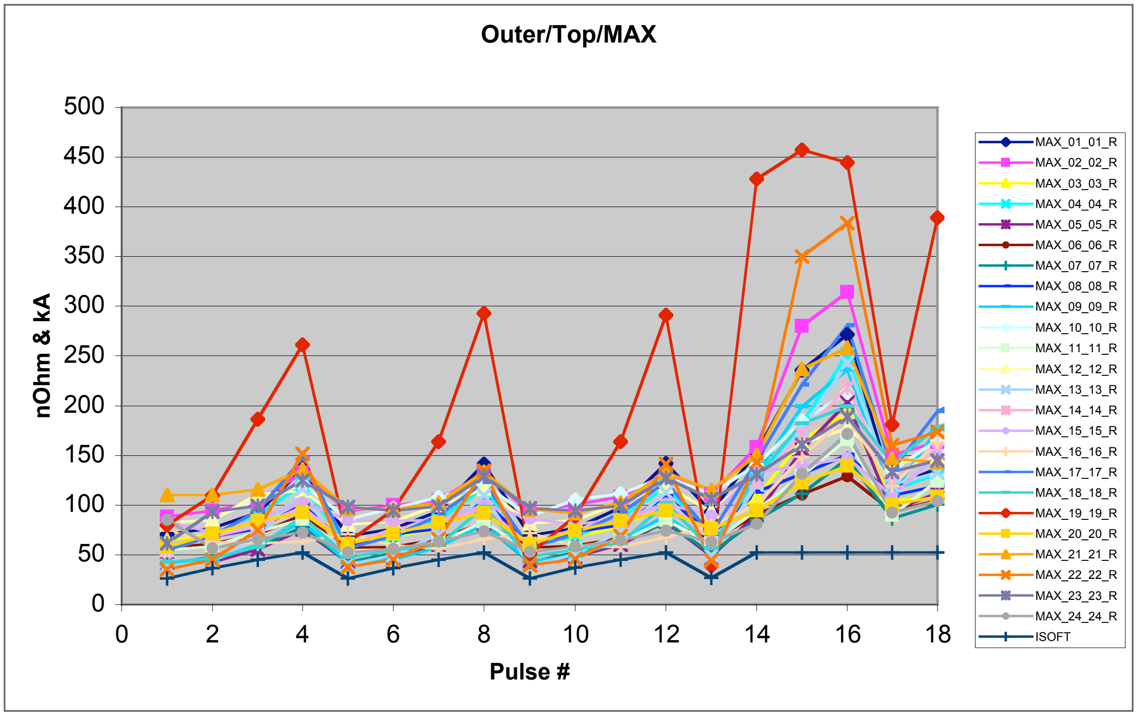

Shots:
110803
NSTX
engineering::tfj_19_19_v
engineering::tfj_spare01
OH Sum
Seconds
volts
Vprobe
x100
(V)
Ioh
(A)

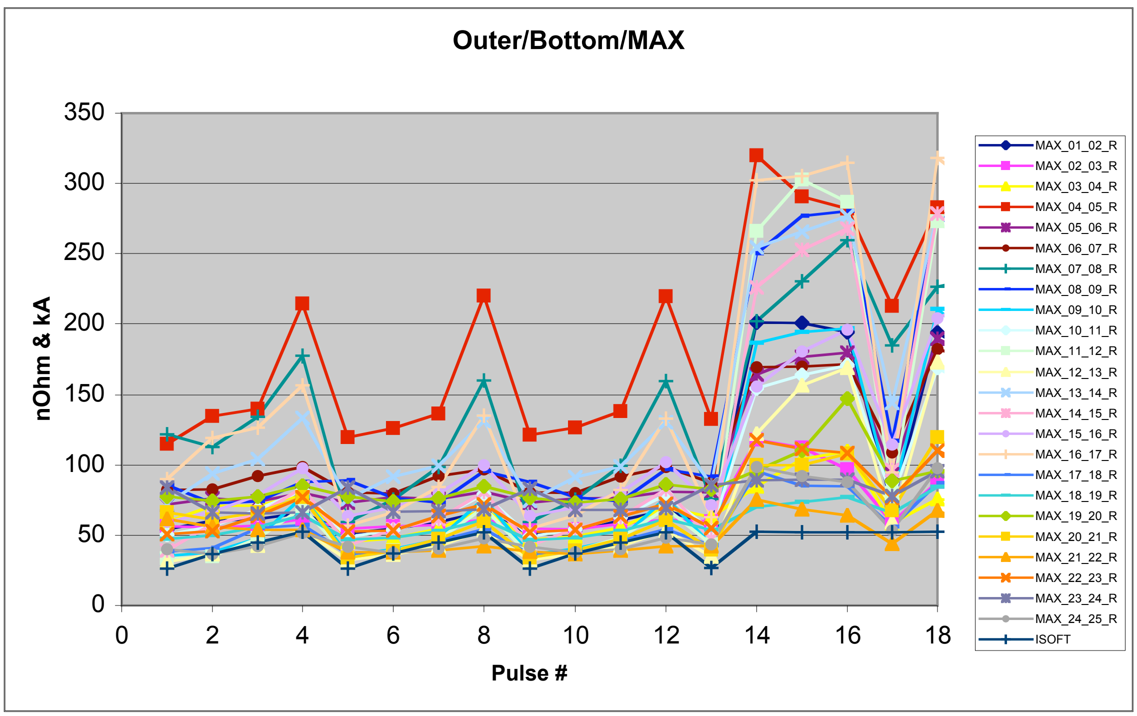



*Comparison between Measurements and Analytic Predictions*

<u>Resistance</u>


Joint Resistance
R (nOhm)
Itf (kA)
0
50
100
150
200
250
300
350
400
450
20
30
40
50
60
70
80
=
OOP Effect
R(21_21)
Rmin
Rmax
R(71.2kA_Brooks)

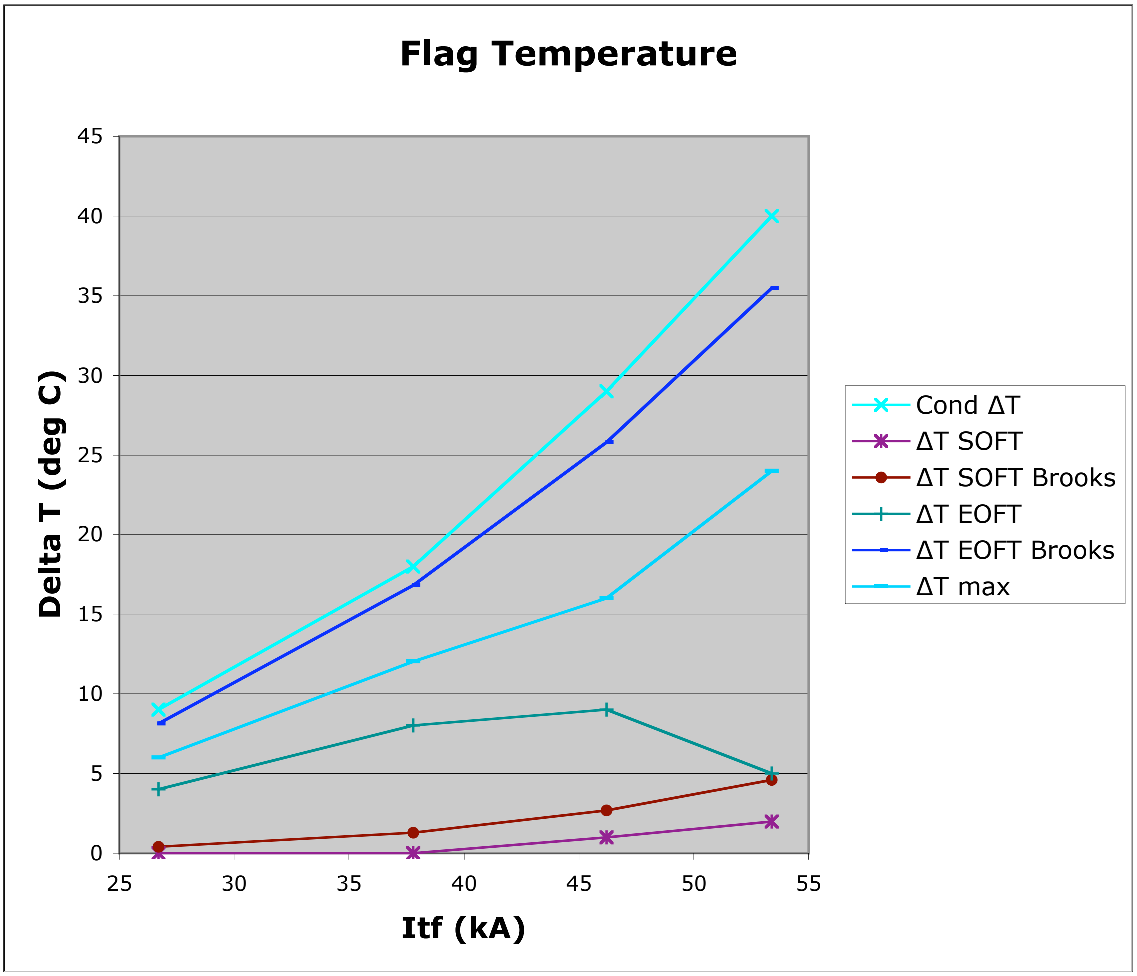


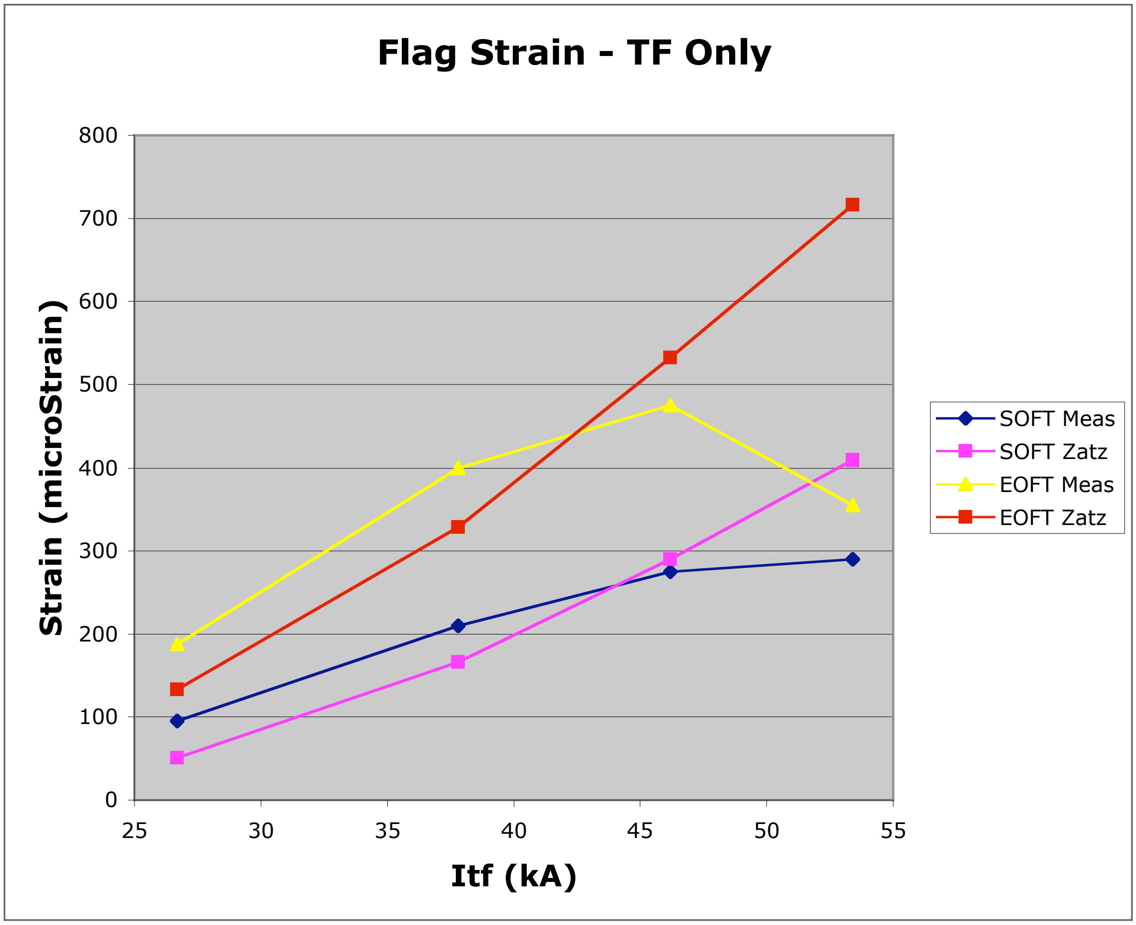

| Pulse # | Shot # |
|---|---|
| 110795 | 9 |
| 110796 | 10 |
| 110797 | 11 |
| 110798 | 12 |

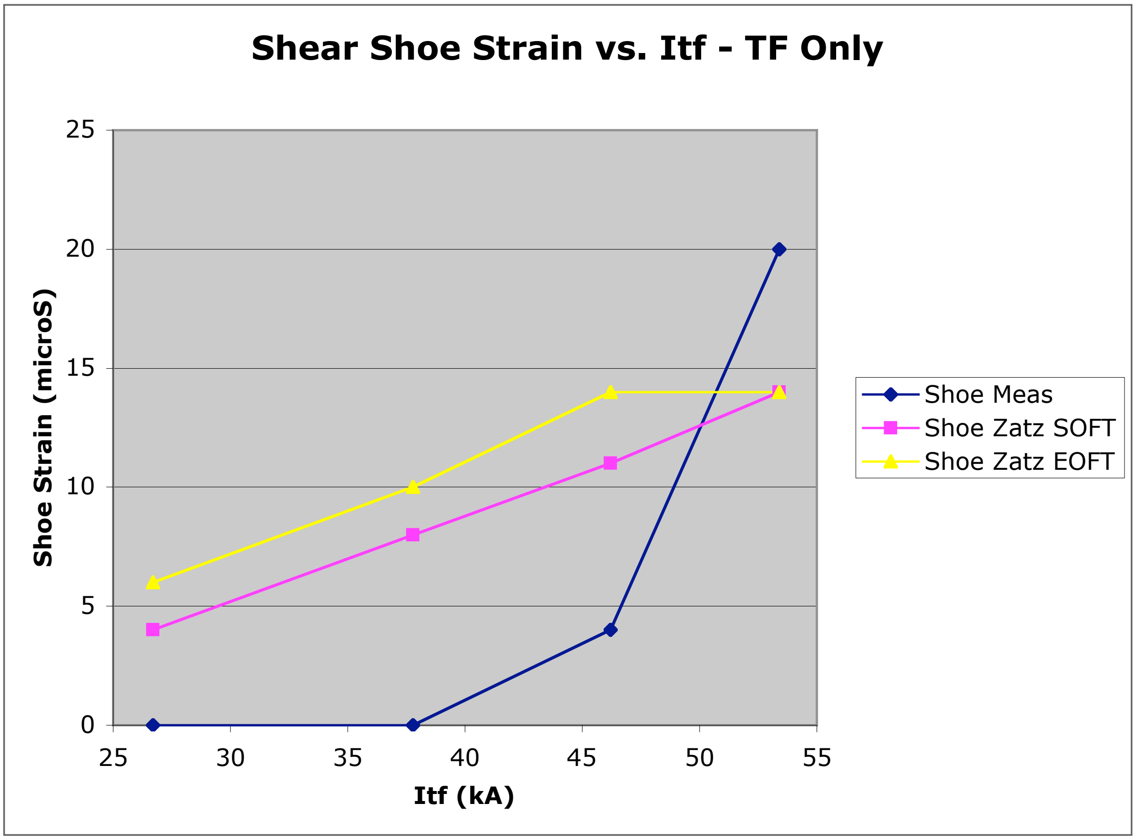
| | |
|---|---|
| 110799 | 13 |
| 110803 | 16 |

<u>Temperature</u>

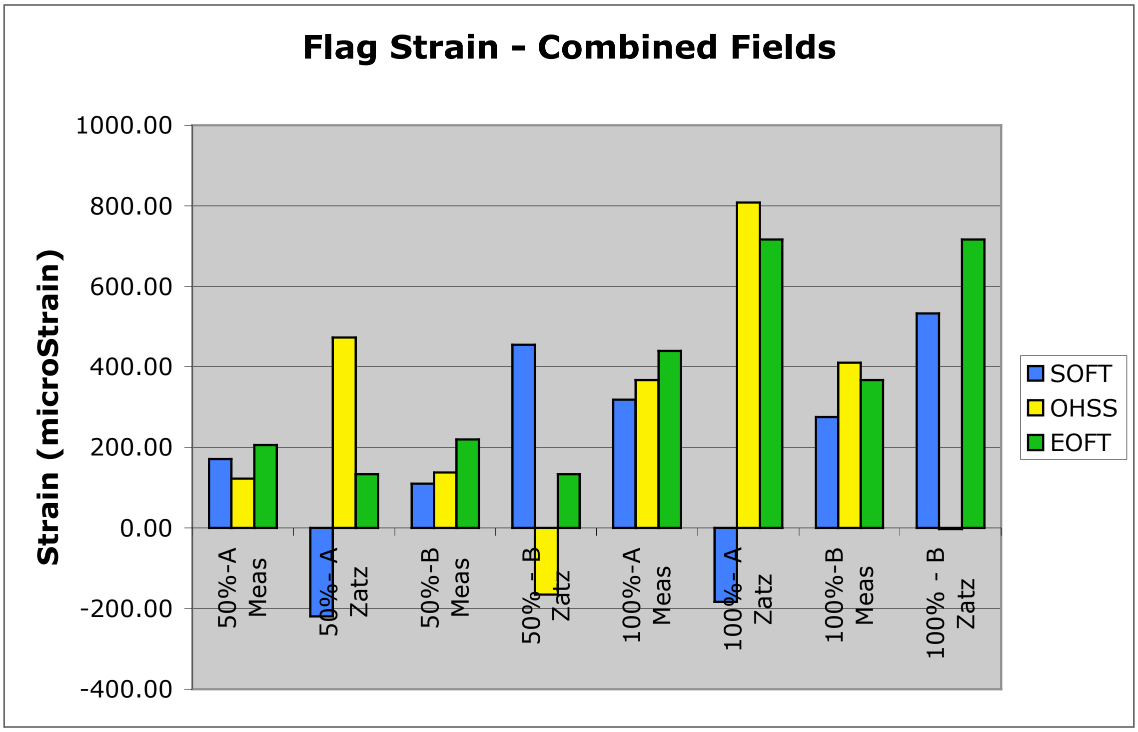



<u>Strain</u>

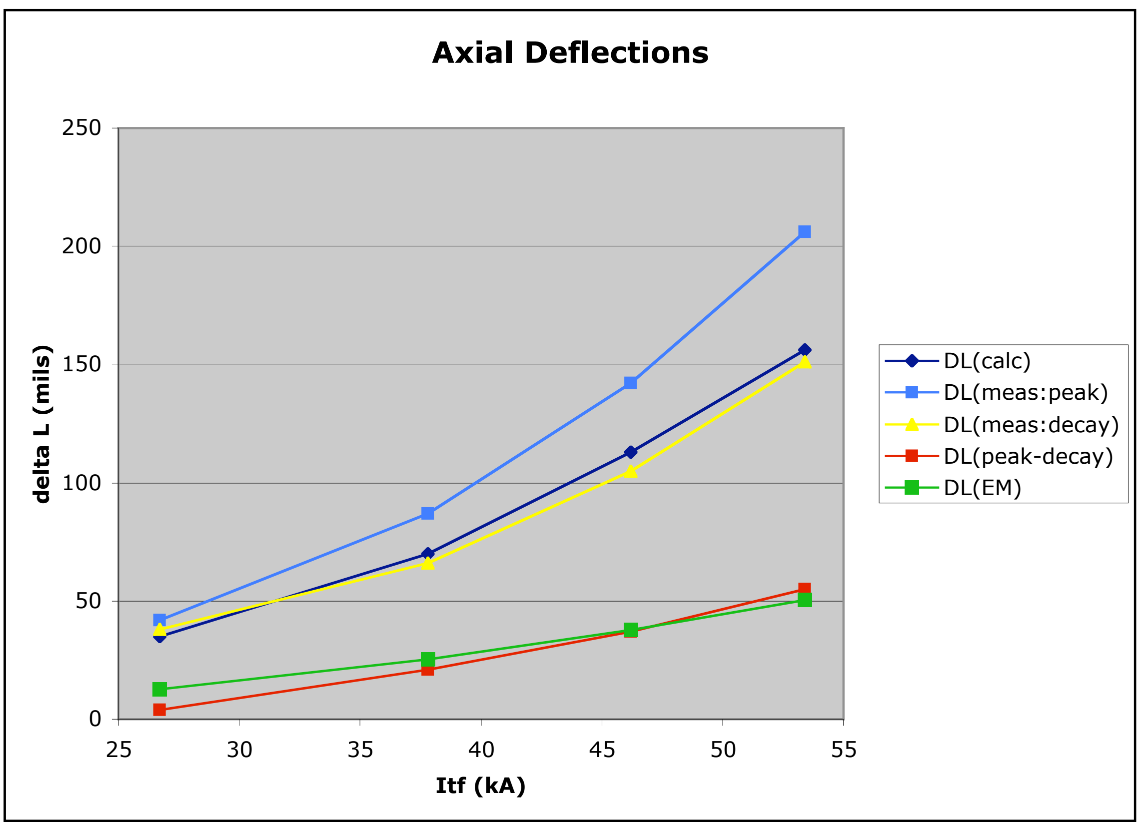

Flag Strain - TF Only
Strain (microStrain)
800
700
600
500
400
300
200
100
0
25
30
35
40
45
50
55
Itf (kA)
SOFT Meas
SOFT Zatz
EOFT Meas
EOFT Zatz

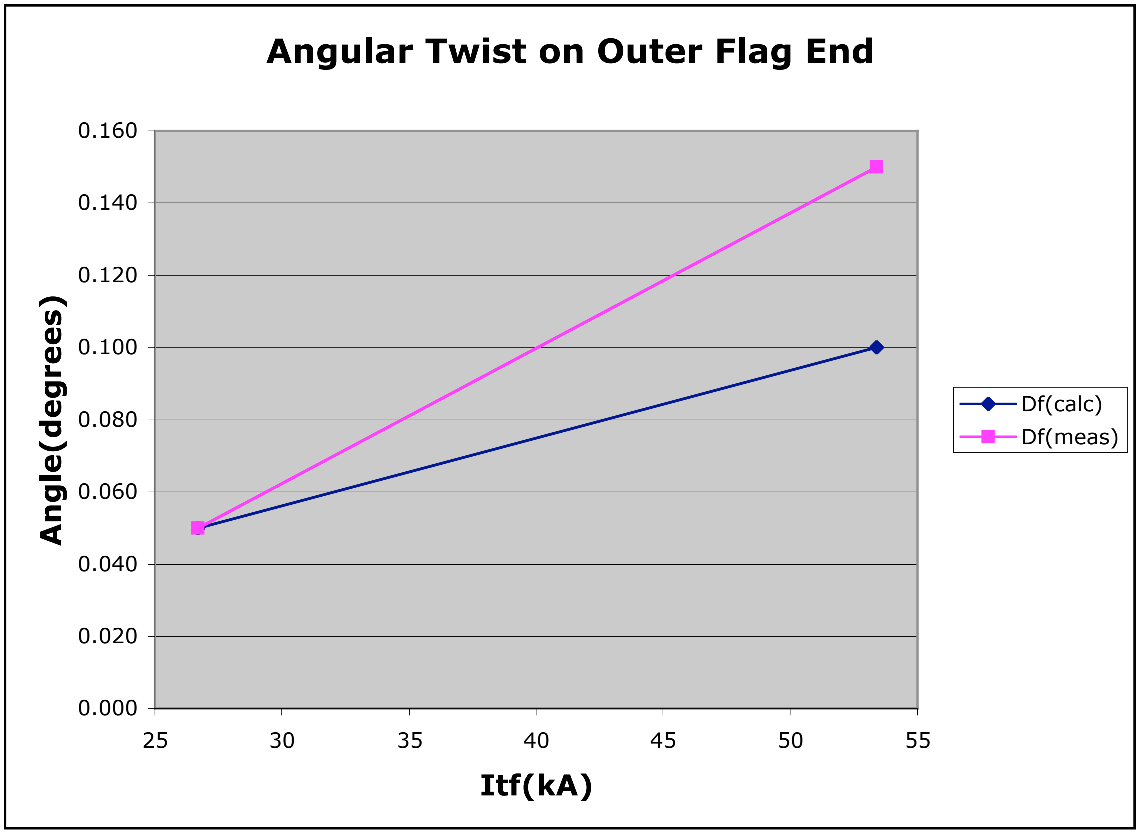


Shear Shoe Strain vs. Itf - TF Only
Shoe Strain (microS)
25
20
15
10
5
0
25
30
35
40
45
50
55
Itf (kA)
Shoe Meas
Shoe Zatz SOFT
Shoe Zatz EOFT



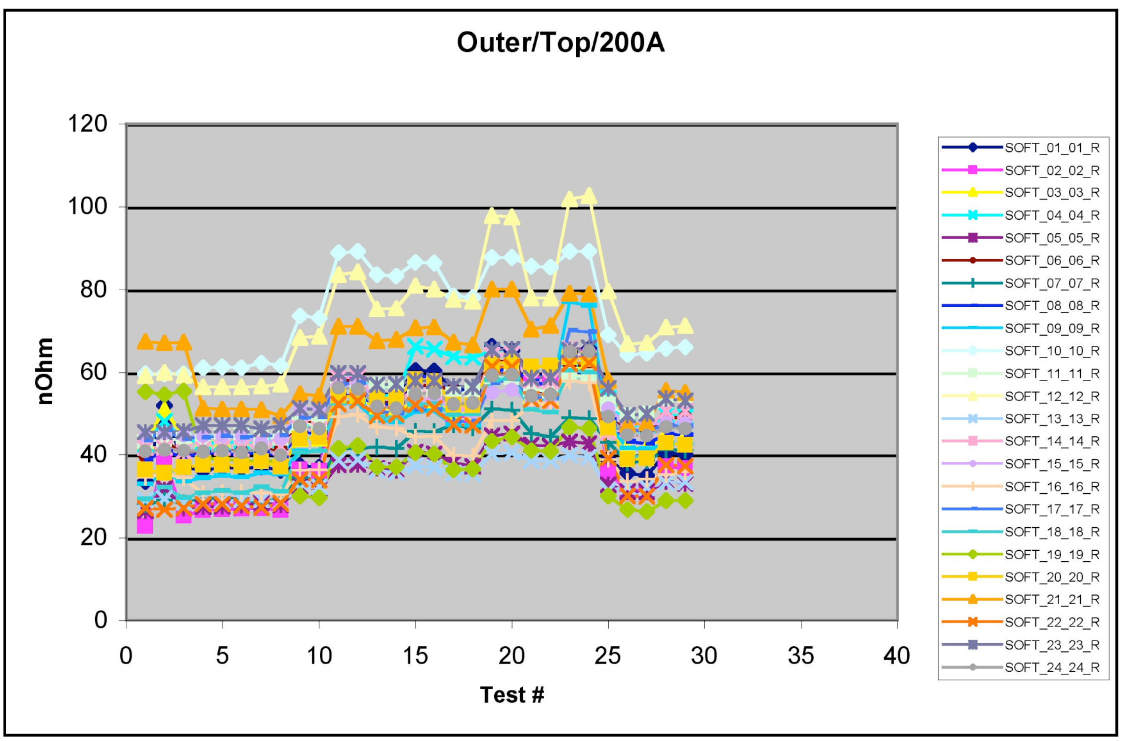

<u>Displacement</u>



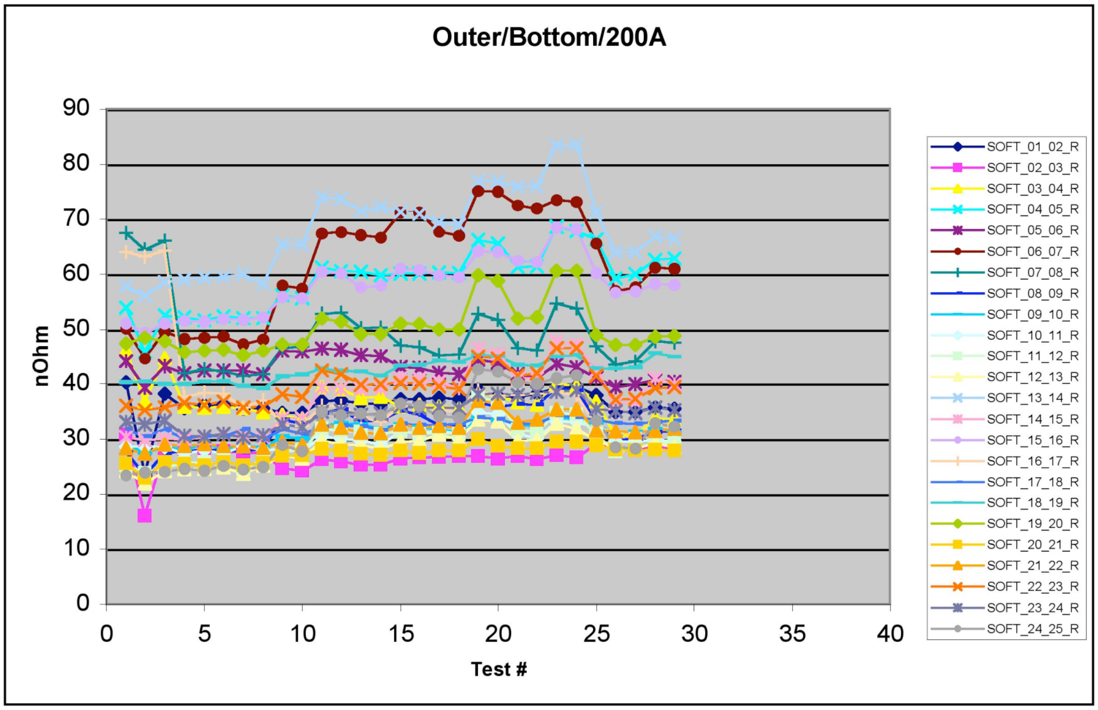


Angular Twist on Outer Flag End
Angle(degrees)
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
25
30
35
40
45
50
55
Itf(kA)
Df(calc)
Df(meas)

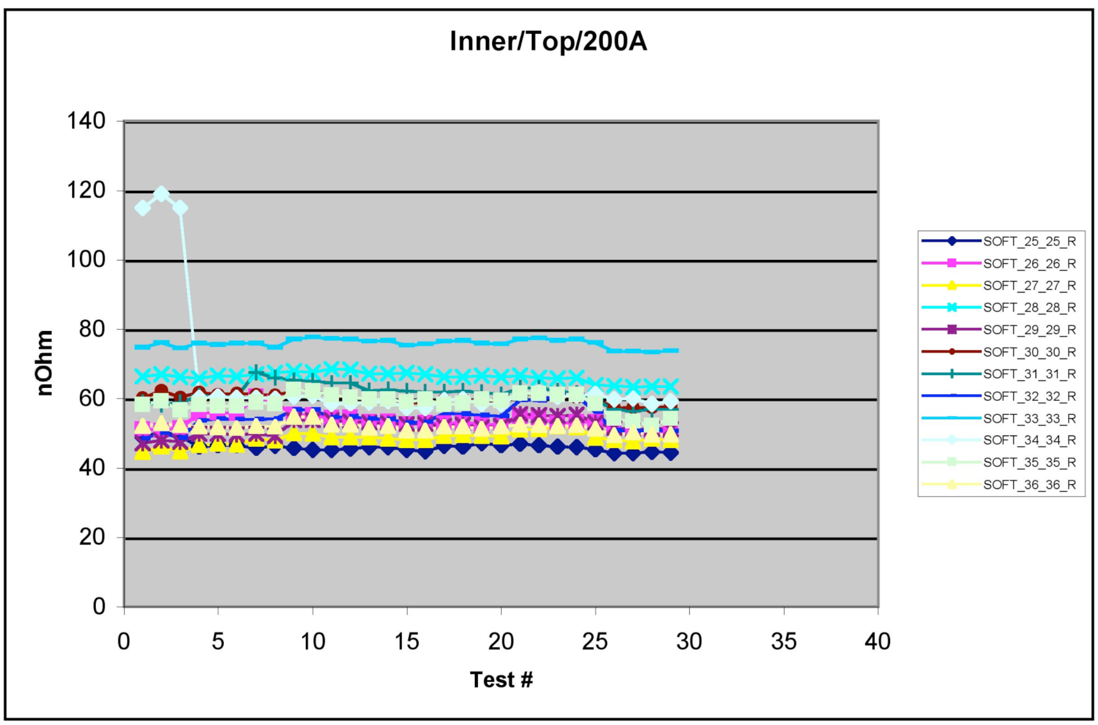

*Trends*



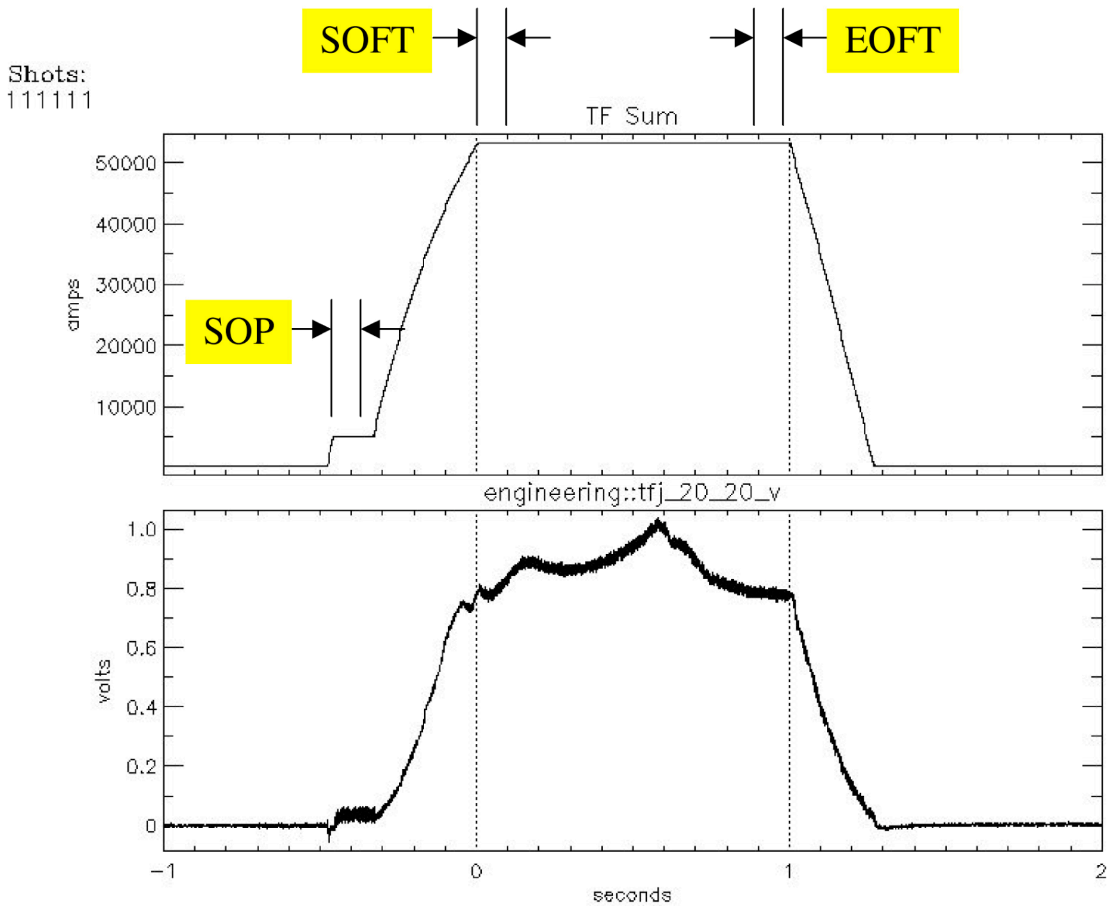
Outer/Top/200A
nOhm
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
Test #
SOFT_01_01_R
SOFT_02_02_R
SOFT_03_03_R
SOFT_04_04_R
SOFT_05_05_R
SOFT_06_06_R
SOFT_07_07_R
SOFT_08_08_R
SOFT_09_09_R
SOFT_10_10_R
SOFT_11_11_R
SOFT_12_12_R
SOFT_13_13_R
SOFT_14_14_R
SOFT_15_15_R
SOFT_16_16_R
SOFT_17_17_R
SOFT_18_18_R
SOFT_19_19_R
SOFT_20_20_R
SOFT_21_21_R
SOFT_22_22_R
SOFT_23_23_R
SOFT_24_24_R



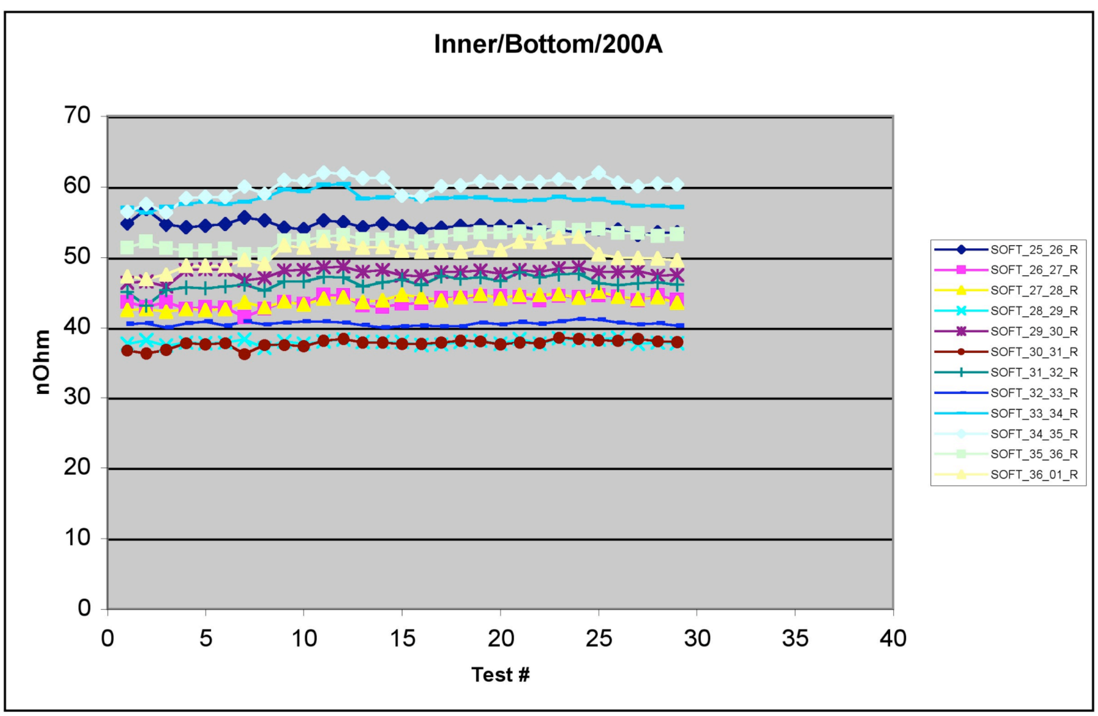
Outer/Bottom/200A
nOhm
Test #
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
35
40
SOFT_01_02_R
SOFT_02_03_R
SOFT_03_04_R
SOFT_04_05_R
SOFT_05_06_R
SOFT_06_07_R
SOFT_07_08_R
SOFT_08_09_R
SOFT_09_10_R
SOFT_10_11_R
SOFT_11_12_R
SOFT_12_13_R
SOFT_13_14_R
SOFT_14_15_R
SOFT_15_16_R
SOFT_16_17_R
SOFT_17_18_R
SOFT_18_19_R
SOFT_19_20_R
SOFT_20_21_R
SOFT_21_22_R
SOFT_22_23_R
SOFT_23_24_R
SOFT_24_25_R

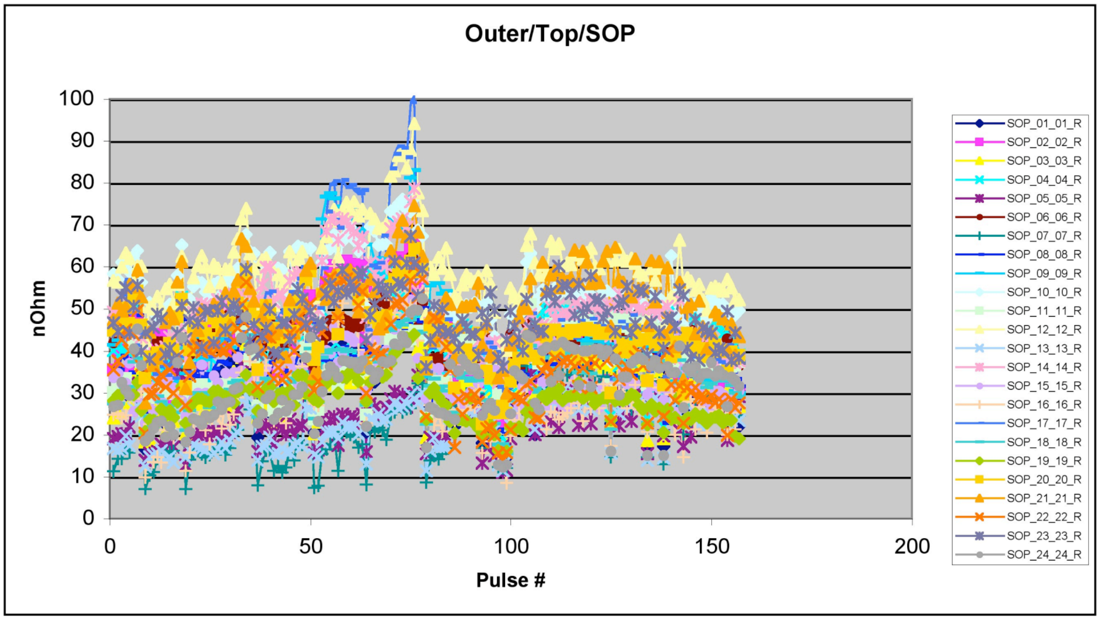
Inner/Top/200A
nOhm
Test #
0
20
40
60
80
100
120
140
0
5
10
15
20
25
30
35
40
SOFT_25_25_R
SOFT_26_26_R
SOFT_27_27_R
SOFT_28_28_R
SOFT_29_29_R
SOFT_30_30_R
SOFT_31_31_R
SOFT_32_32_R
SOFT_33_33_R
SOFT_34_34_R
SOFT_35_35_R
SOFT_36_36_R



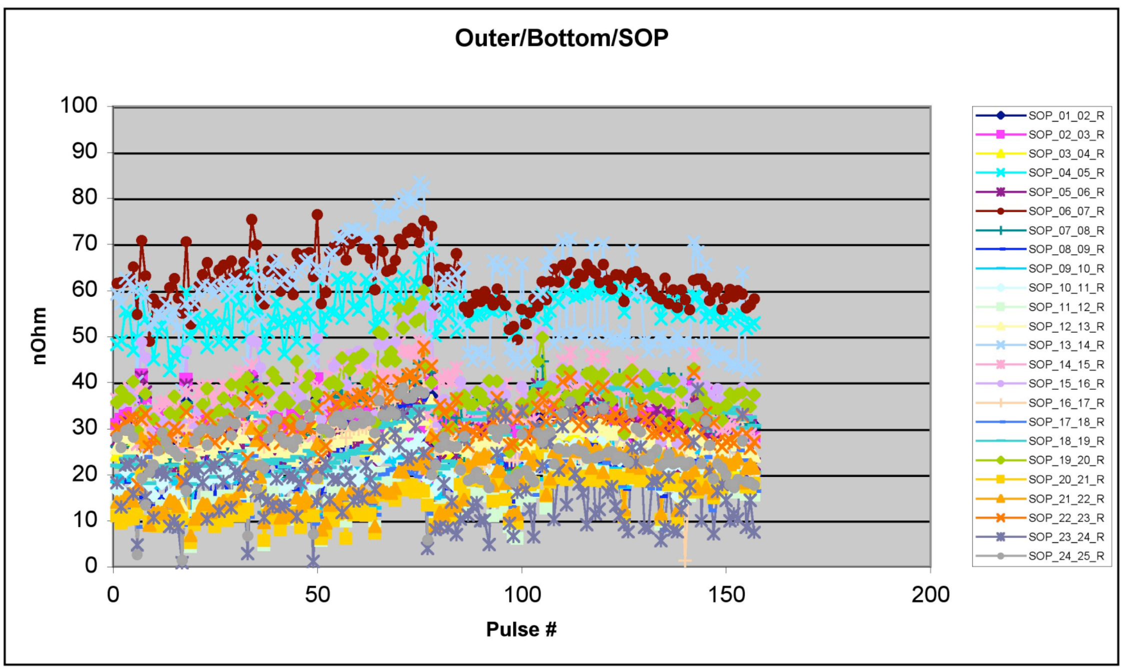
SOFT
EOFT
SOP
Shots:
111111
TF Sum
amps
50000
40000
30000
20000
10000
engineering::tfj_20_20_v
volts
1.0
0.8
0.6
0.4
0.2
0
-1
0
1
2
seconds

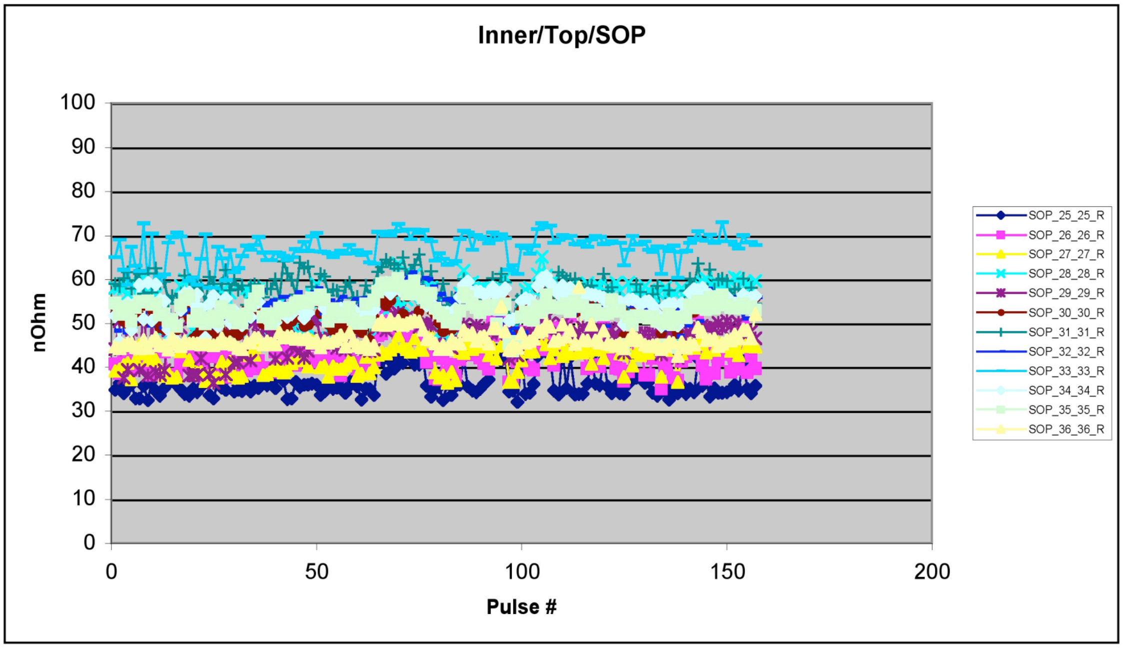
Inner/Bottom/200A
nOhm
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
Test #
SOFT_25_26_R
SOFT_26_27_R
SOFT_27_28_R
SOFT_28_29_R
SOFT_29_30_R
SOFT_30_31_R
SOFT_31_32_R
SOFT_32_33_R
SOFT_33_34_R
SOFT_34_35_R
SOFT_35_36_R
SOFT_36_01_R



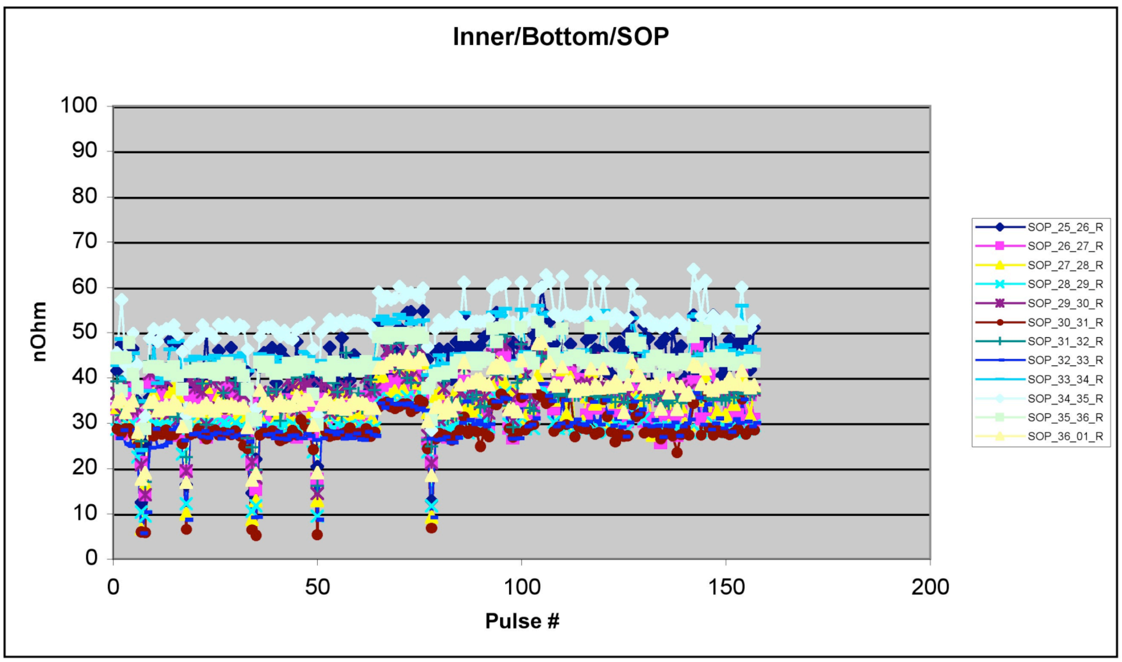
Outer/Top/SOP
nOhm
Pulse #
SOP_01_01_R
SOP_02_02_R
SOP_03_03_R
SOP_04_04_R
SOP_05_05_R
SOP_06_06_R
SOP_07_07_R
SOP_08_08_R
SOP_09_09_R
SOP_10_10_R
SOP_11_11_R
SOP_12_12_R
SOP_13_13_R
SOP_14_14_R
SOP_15_15_R
SOP_16_16_R
SOP_17_17_R
SOP_18_18_R
SOP_19_19_R
SOP_20_20_R
SOP_21_21_R
SOP_22_22_R
SOP_23_23_R
SOP_24_24_R

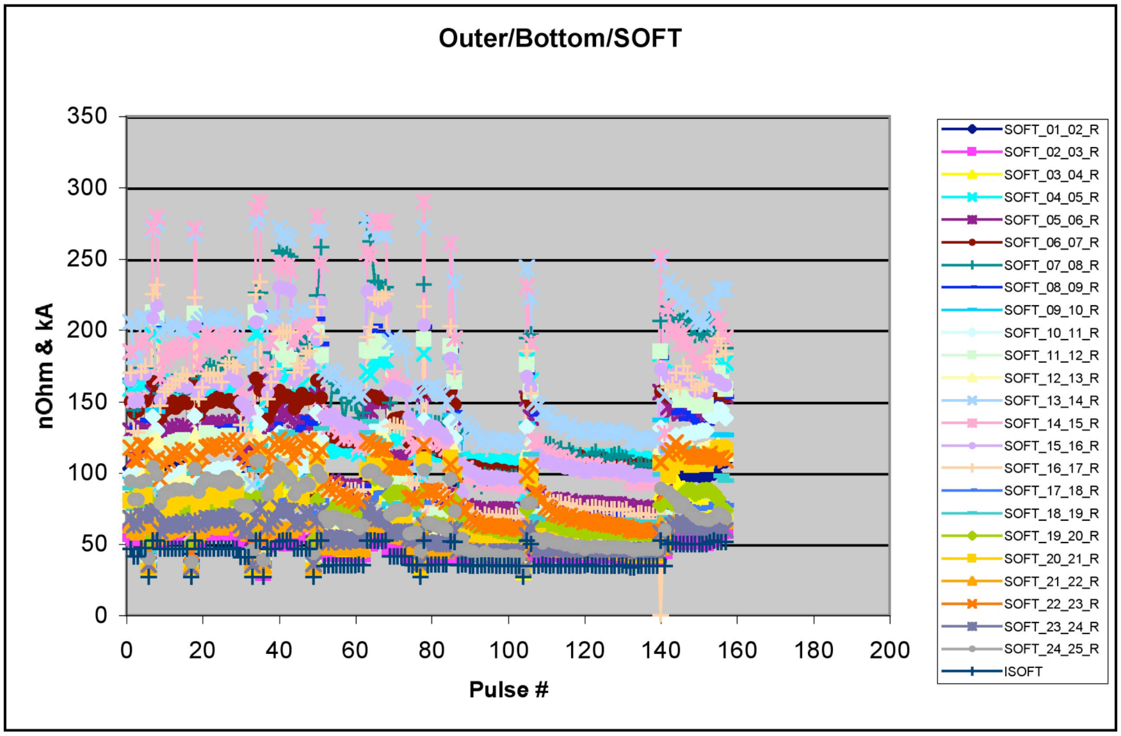
Outer/Bottom/SOP
nOhm
Pulse #
SOP_01_02_R
SOP_02_03_R
SOP_03_04_R
SOP_04_05_R
SOP_05_06_R
SOP_06_07_R
SOP_07_08_R
SOP_08_09_R
SOP_09_10_R
SOP_10_11_R
SOP_11_12_R
SOP_12_13_R
SOP_13_14_R
SOP_14_15_R
SOP_15_16_R
SOP_16_17_R
SOP_17_18_R
SOP_18_19_R
SOP_19_20_R
SOP_20_21_R
SOP_21_22_R
SOP_22_23_R
SOP_23_24_R
SOP_24_25_R

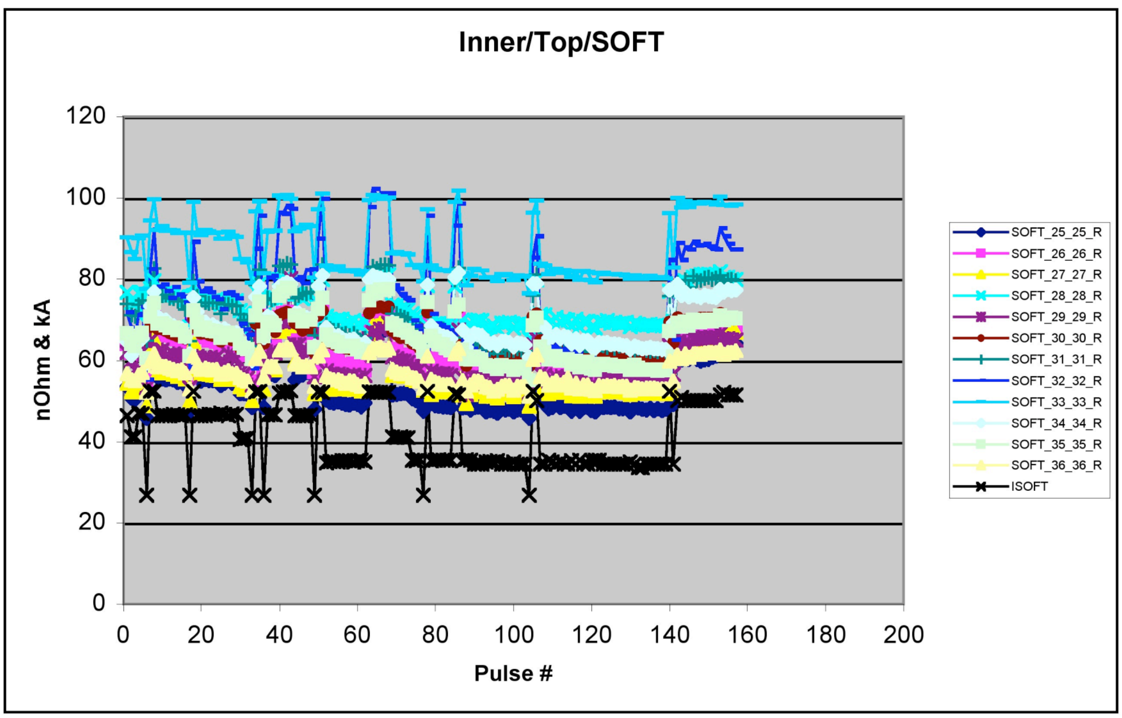


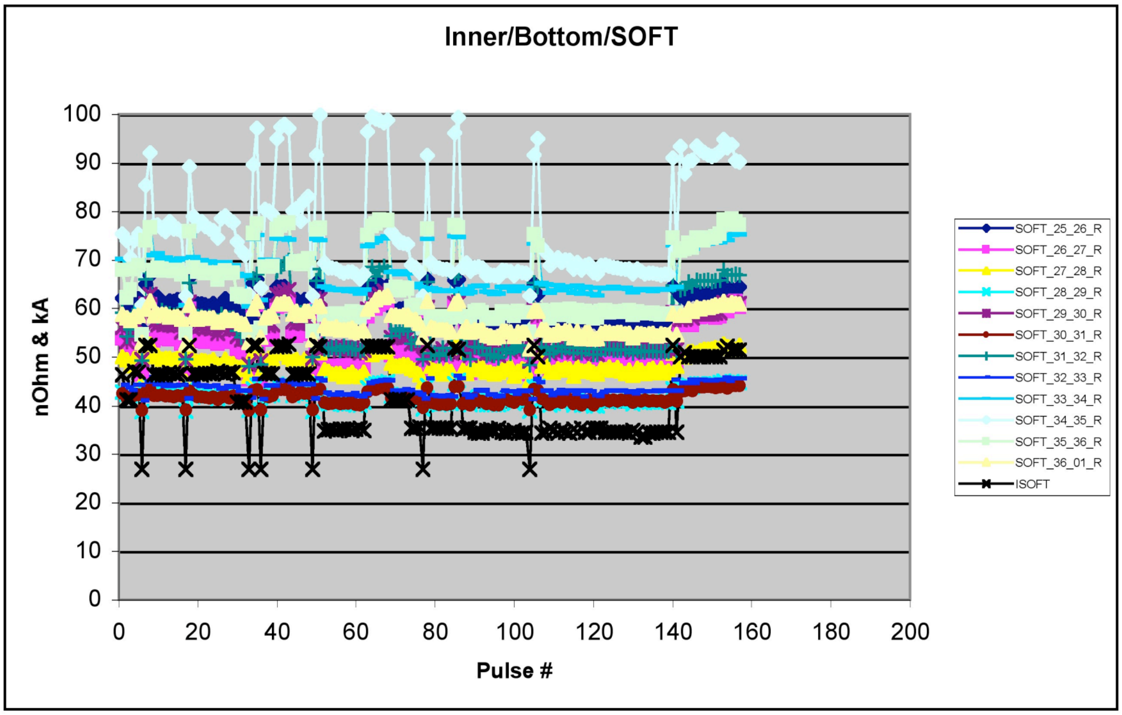
Inner/Top/SOP
nOhm
Pulse #
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
SOP_25_25_R
SOP_26_26_R
SOP_27_27_R
SOP_28_28_R
SOP_29_29_R
SOP_30_30_R
SOP_31_31_R
SOP_32_32_R
SOP_33_33_R
SOP_34_34_R
SOP_35_35_R
SOP_36_36_R

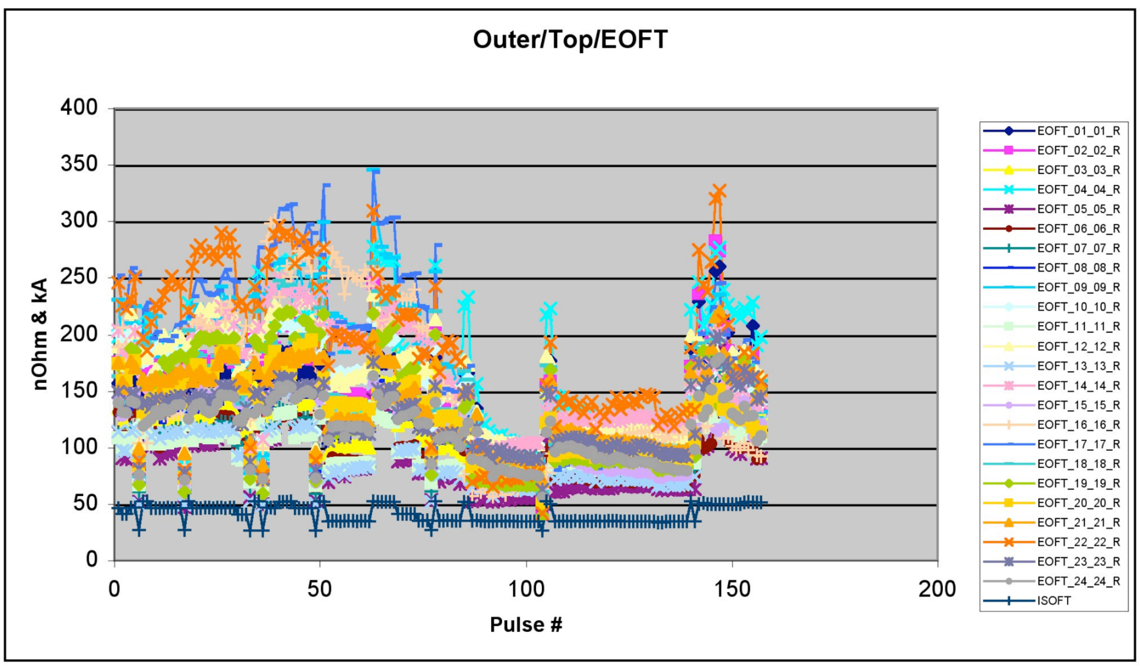



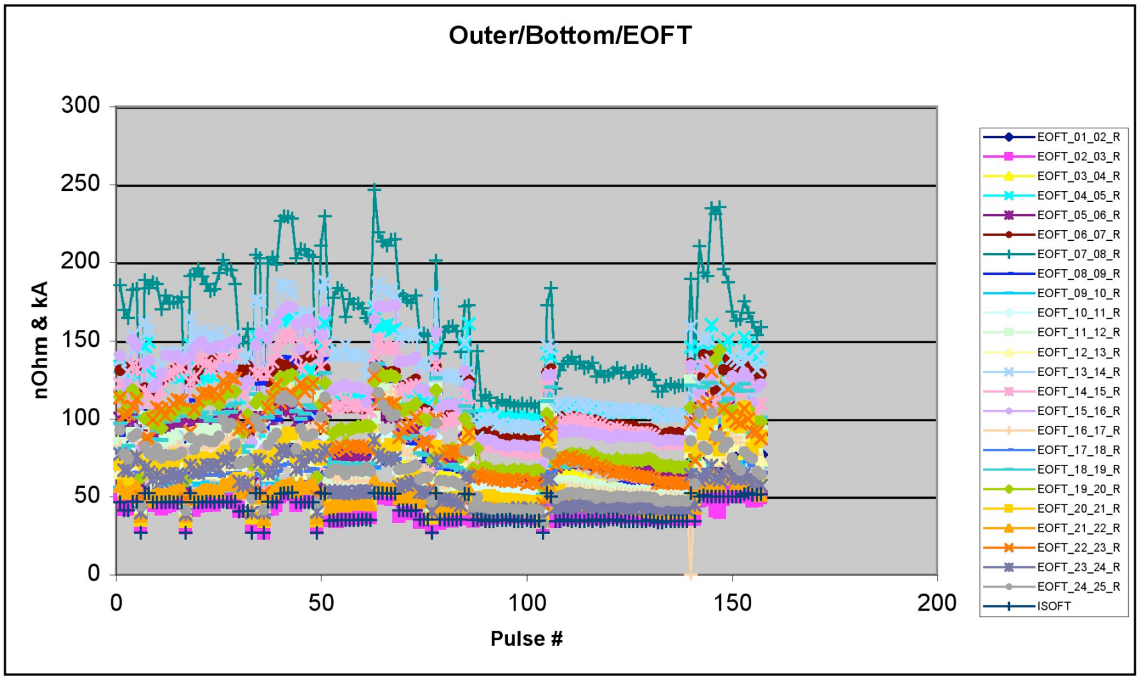
Inner/Bottom/SOP
nOhm
Pulse #
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
SOP_25_26_R
SOP_26_27_R
SOP_27_28_R
SOP_28_29_R
SOP_29_30_R
SOP_30_31_R
SOP_31_32_R
SOP_32_33_R
SOP_33_34_R
SOP_34_35_R
SOP_35_36_R
SOP_36_01_R


Outer/Bottom/SOFT
nOhm & kA
Pulse #
SOFT_01_02_R
SOFT_02_03_R
SOFT_03_04_R
SOFT_04_05_R
SOFT_05_06_R
SOFT_06_07_R
SOFT_07_08_R
SOFT_08_09_R
SOFT_09_10_R
SOFT_10_11_R
SOFT_11_12_R
SOFT_12_13_R
SOFT_13_14_R
SOFT_14_15_R
SOFT_15_16_R
SOFT_16_17_R
SOFT_17_18_R
SOFT_18_19_R
SOFT_19_20_R
SOFT_20_21_R
SOFT_21_22_R
SOFT_22_23_R
SOFT_23_24_R
SOFT_24_25_R
ISOFT

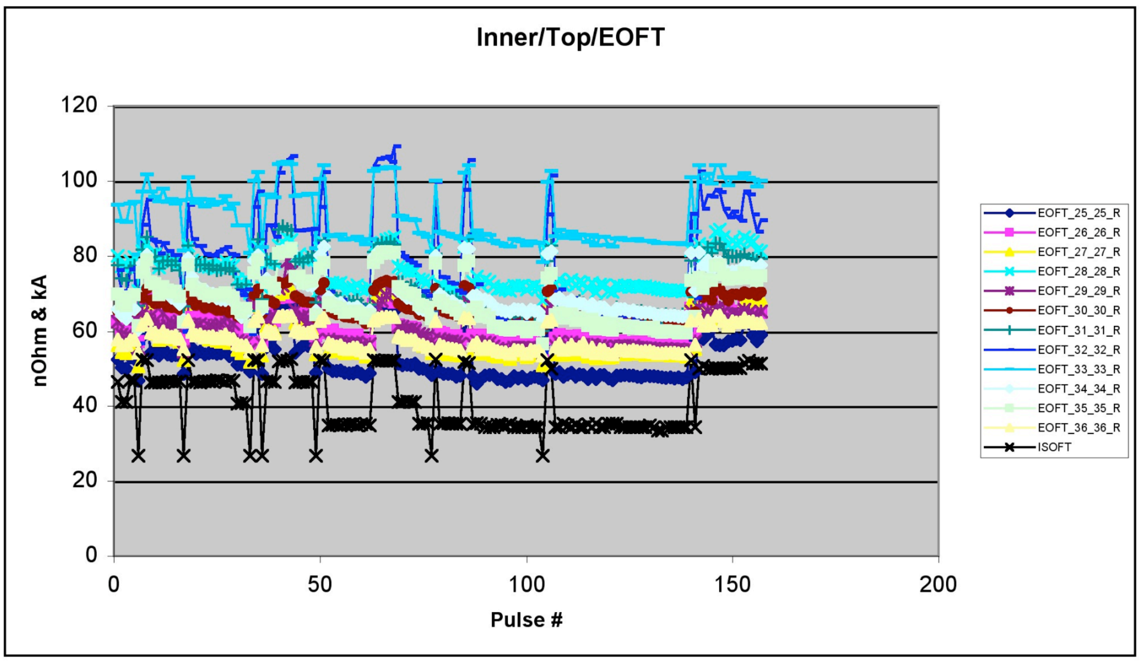

Inner/Top/SOFT
nOhm & kA
Pulse #
SOFT_25_25_R
SOFT_26_26_R
SOFT_27_27_R
SOFT_28_28_R
SOFT_29_29_R
SOFT_30_30_R
SOFT_31_31_R
SOFT_32_32_R
SOFT_33_33_R
SOFT_34_34_R
SOFT_35_35_R
SOFT_36_36_R
ISOFT


Inner/Bottom/SOFT
nOhm & kA
Pulse #
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
180
200
SOFT_25_26_R
SOFT_26_27_R
SOFT_27_28_R
SOFT_28_29_R
SOFT_29_30_R
SOFT_30_31_R
SOFT_31_32_R
SOFT_32_33_R
SOFT_33_34_R
SOFT_34_35_R
SOFT_35_36_R
SOFT_36_01_R
ISOFT

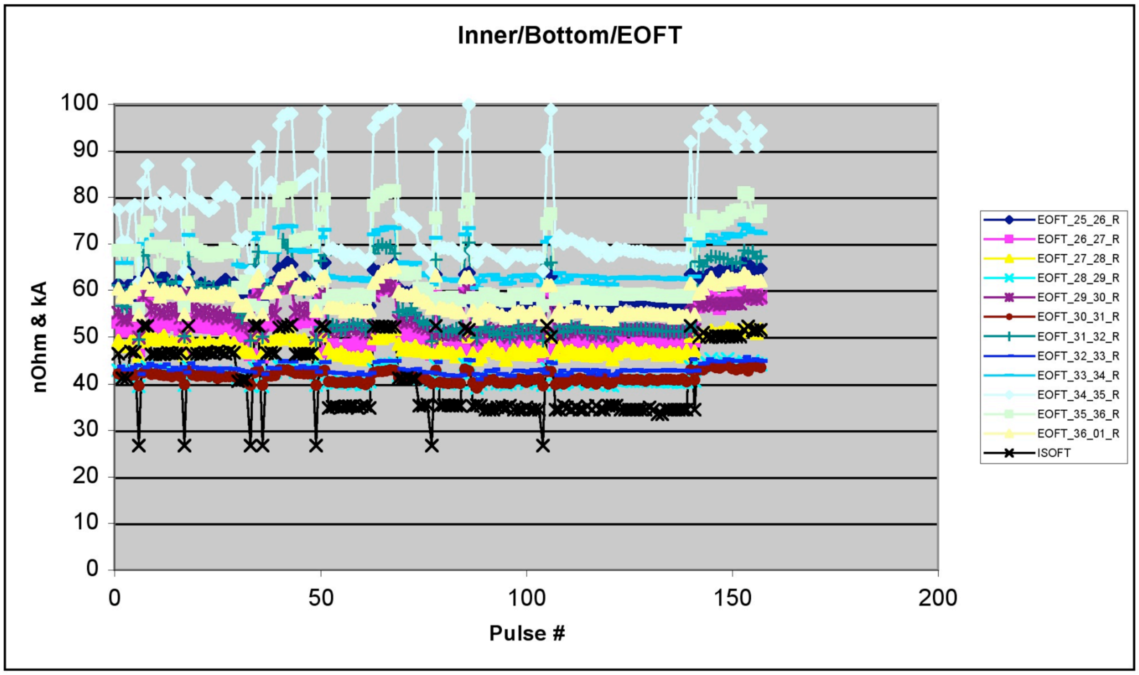

Outer/Top/EOFT
nOhm & kA
Pulse #
400
350
300
250
200
150
100
50
0
0
50
100
150
200
EOFT_01_01_R
EOFT_02_02_R
EOFT_03_03_R
EOFT_04_04_R
EOFT_05_05_R
EOFT_06_06_R
EOFT_07_07_R
EOFT_08_08_R
EOFT_09_09_R
EOFT_10_10_R
EOFT_11_11_R
EOFT_12_12_R
EOFT_13_13_R
EOFT_14_14_R
EOFT_15_15_R
EOFT_16_16_R
EOFT_17_17_R
EOFT_18_18_R
EOFT_19_19_R
EOFT_20_20_R
EOFT_21_21_R
EOFT_22_22_R
EOFT_23_23_R
EOFT_24_24_R
ISOFT



Outer/Bottom/EOFT
nOhm & kA
Pulse #
300
250
200
150
100
50
0
0
50
100
150
200
EOFT_01_02_R
EOFT_02_03_R
EOFT_03_04_R
EOFT_04_05_R
EOFT_05_06_R
EOFT_06_07_R
EOFT_07_08_R
EOFT_08_09_R
EOFT_09_10_R
EOFT_10_11_R
EOFT_11_12_R
EOFT_12_13_R
EOFT_13_14_R
EOFT_14_15_R
EOFT_15_16_R
EOFT_16_17_R
EOFT_17_18_R
EOFT_18_19_R
EOFT_19_20_R
EOFT_20_21_R
EOFT_21_22_R
EOFT_22_23_R
EOFT_23_24_R
EOFT_24_25_R
ISOFT

Inner/Top/EOFT
nOhm & kA
Pulse #
120
100
80
60
40
20
0
0
50
100
150
200
EOFT_25_25_R
EOFT_26_26_R
EOFT_27_27_R
EOFT_28_28_R
EOFT_29_29_R
EOFT_30_30_R
EOFT_31_31_R
EOFT_32_32_R
EOFT_33_33_R
EOFT_34_34_R
EOFT_35_35_R
EOFT_36_36_R
ISOFT



Inner/Bottom/EOFT
nOhm & kA
Pulse #
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
EOFT_25_26_R
EOFT_26_27_R
EOFT_27_28_R
EOFT_28_29_R
EOFT_29_30_R
EOFT_30_31_R
EOFT_31_32_R
EOFT_32_33_R
EOFT_33_34_R
EOFT_34_35_R
EOFT_35_36_R
EOFT_36_01_R
ISOFT