# Testing of Large Conductors and Joints

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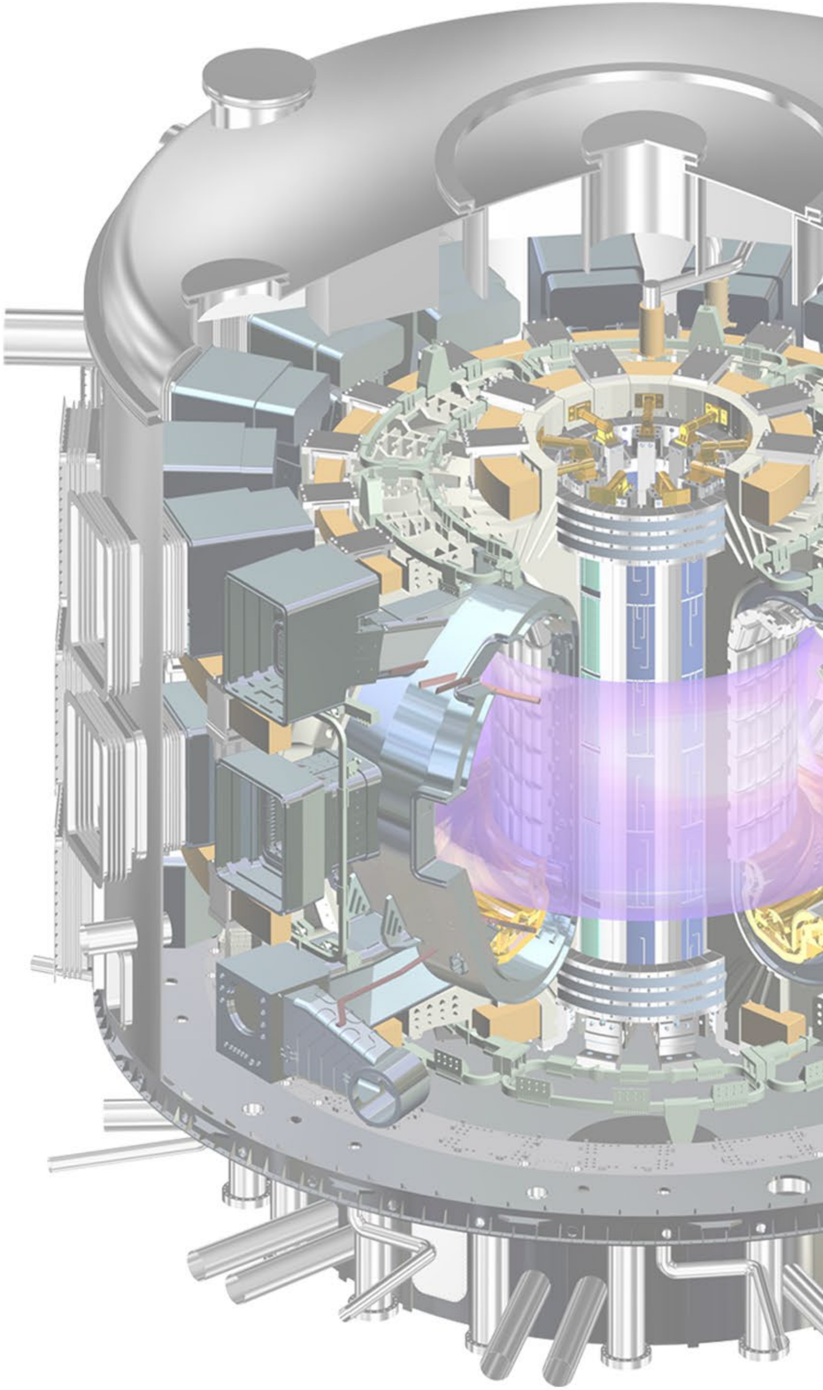
*HFVMTF meeting*

*November 21-22, 2022*



# Outline

- Historical review of the high field facilities for conductors and joints
- Purpose of the testing of conductors and joints at high field facility (testing items)
- Sample configuration
- Length configurations (total and in high field)
- Current uniformity concerns and mitigation
- Sample preparation
- Instrumentation
- Typical testing plan

# History of the high field facilities for testing large high current conductors

- Large current and size conductors are mostly fusion conductors with some other purpose conductors (NHMFL and like laboratory type facilities ), SMES that require large aperture for the sample as opposed to smaller facilities for  HEP conductors  or strand conductors
- FENIX (1991) at LLNL (retired in 1994) SULTAN (active), EDIPO (commissioned 2015 damaged in 2016), local facilities at QST and other places (Efremov Inst, ASIPP and other places)
- SULTAN was a single workhorse for almost three decades for large conductor testing, especially ITER conductor and joints
- With high demand for HTS and LTS high current conductor development for different applications there is a need for a higher field facility with high currents and variable temperatures

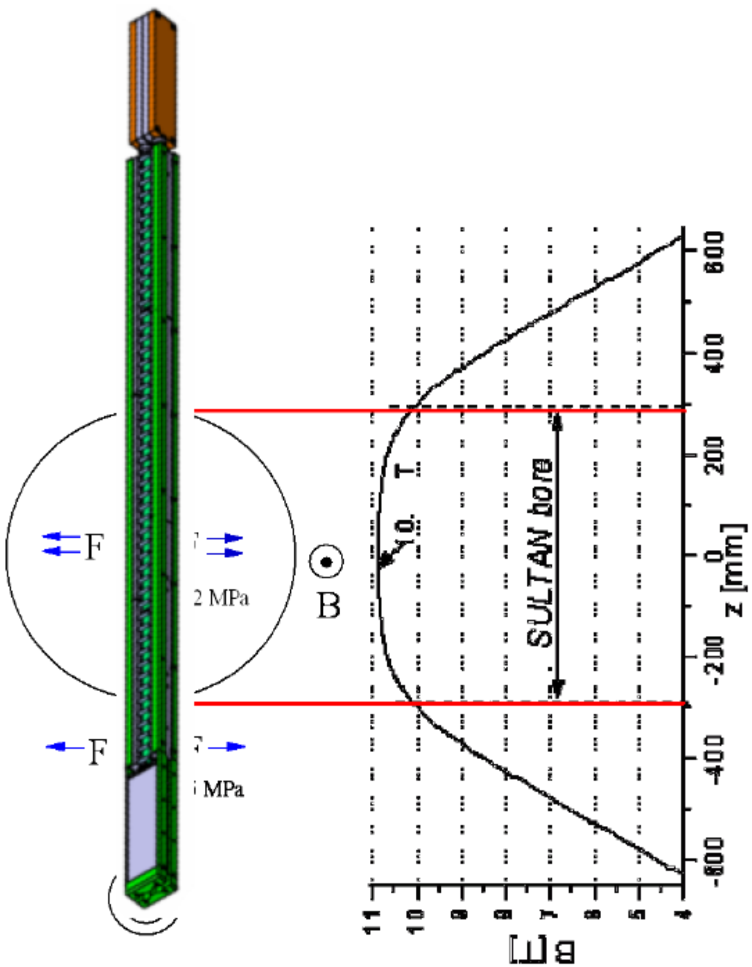
# Testing items in high field facility: conductors

- Current carrying capacity Ic(T, B, EM and WUCD cycles) or more frequently Tcs(I, B, cycles)
- AC losses before and after cycles
- Stability in varying or pulsed magnetic fields
- Stability against pulsed heat deposition
- Hydraulic impedance
- Uniformity of current distribution in cross section

# Testing items in high field facility: joints

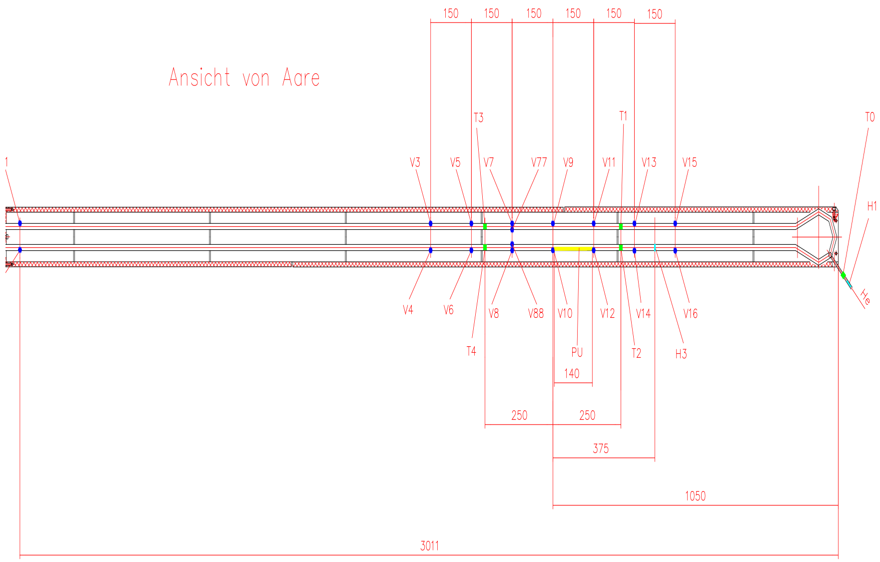
- Resistance of the joints vs B, T, sensitivity to the EM and WUCD cycles
- Tcs of the joints at operating B and I
- AC losses in the joints at different conditions
- Stability against varying or pulsed fields

# Sample configuration (large conductors)



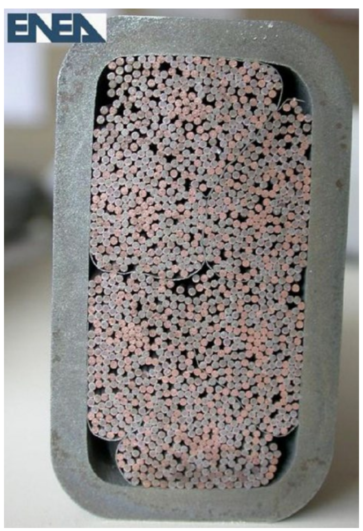

- Usual configuration is two straight legs in the supporting clamps and a bottom joint. Two terminals at the top connected to a SC transformer as a current source

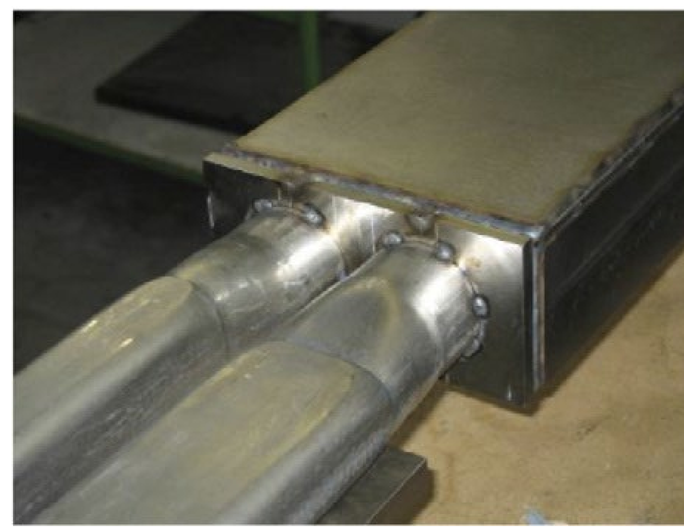
# Alternative arrangement to bottom joint: no bottom joints




Smaller conductors may not have a bottom joint bent, a hairpin arrangement

Bigger, still smaller than ITER conductors may also have a hairpin without a bottom joint with a cable sharp bend with the stripped jacket encased in a box



# Sample length and length in high field

- Length in high field gives a higher voltage in the current sharing mode. Higher voltage gives more uniform current distribution in the sample. A uniform current distribution is required to measure actual current carrying capacity of the sample
- Sample length determines transverse resistance among superconductors (wires, subcables, tapes, etc). The longer the length – the lower the transverse resistance, the more credible the results

# Sample CSJUS4 resistances outlook

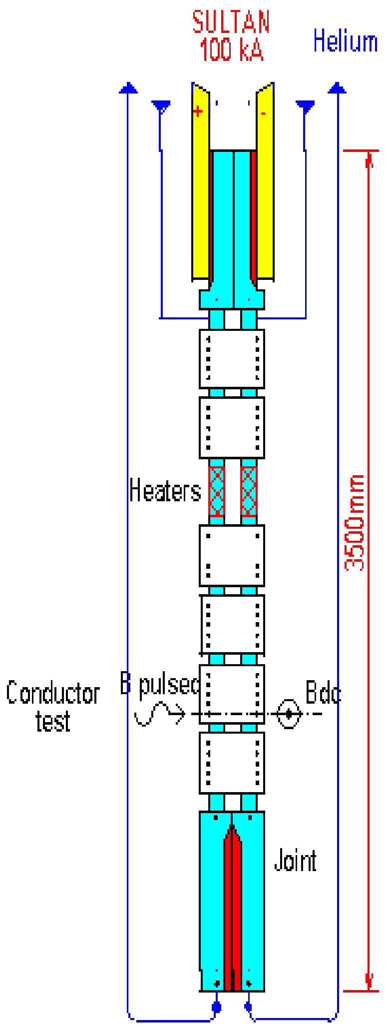
- Overall resistance of the sample is below 7 nOhm, comfortable for transformer to test in any reasonable regimes
- Up to 60 kA applied
- Coax joints are about 3 nOhms each
- Bottom joint (short sleeves) – 0.75 nOhms
- Top joints  0.4 and 0.45 nOhms

# Current supply

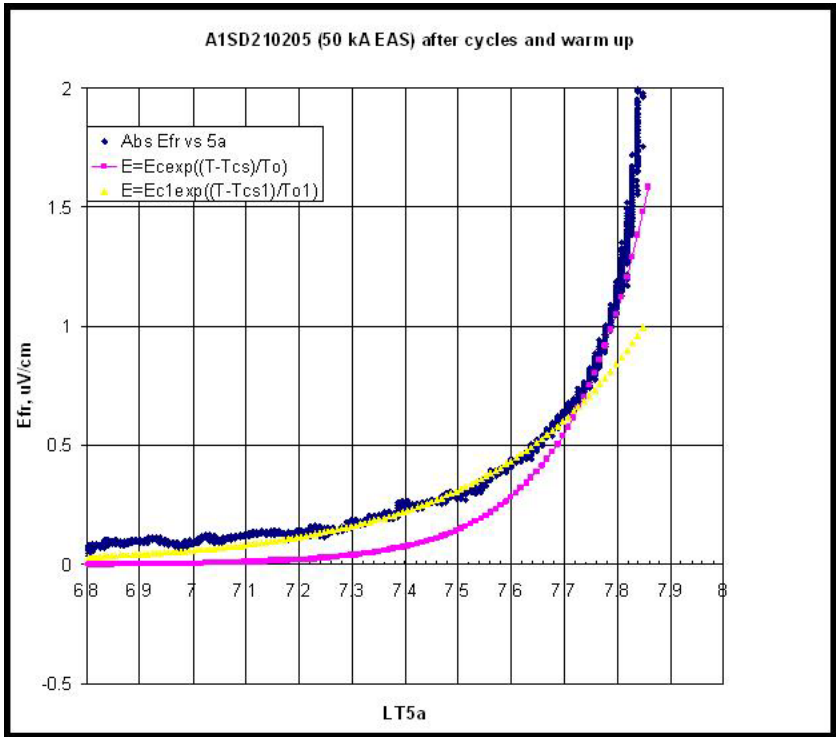
- SC transformer is much more efficient than 100 kA DC Power Supply. Make sure you have enough volt seconds to keep the current constant for 20-30 min
- Joint resistances sum must be low – 5-7 nOhms in SULTAN was sufficient
- V-T characteristics are more productive than V-I characteristics due to self heating, no parameters are steady at V-I, at V-T both I and T are fixed and known

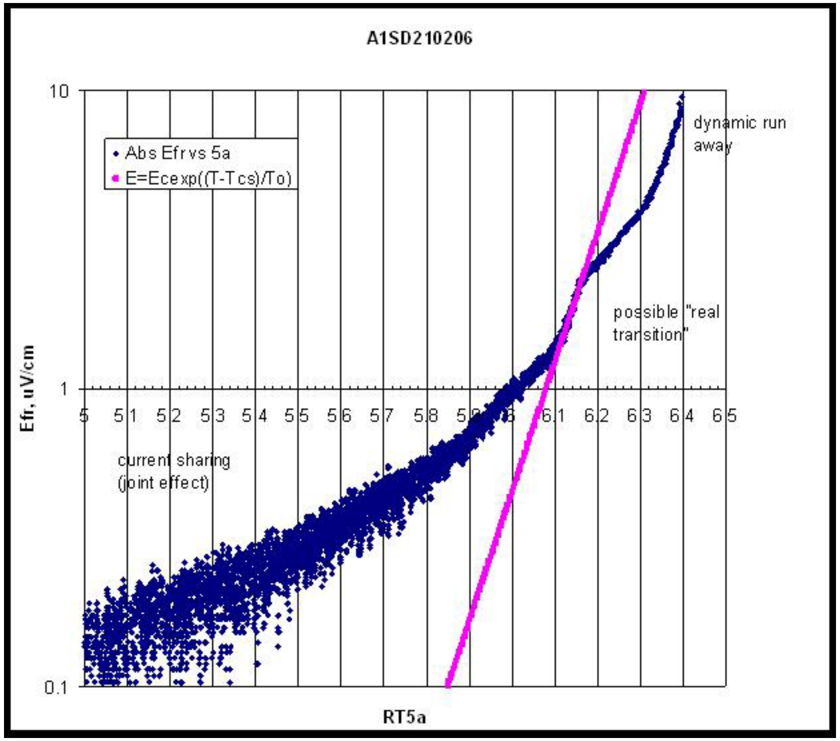
# Current uniformity

- If current is not uniform, the performance in most cases will be lower than if the current is uniform (TFAS1,2, NbTi Conductors at high currents, etc)
- How to know? Good rules of thumb is the V-T characteristic is linear in lg(V) vs T plot also, low voltage curve has no slope. It is true for all tested LTS.
- If it is distorted, the performance cannot be restored by a smart processing or by using temperature sensor as a microvoltmeter.



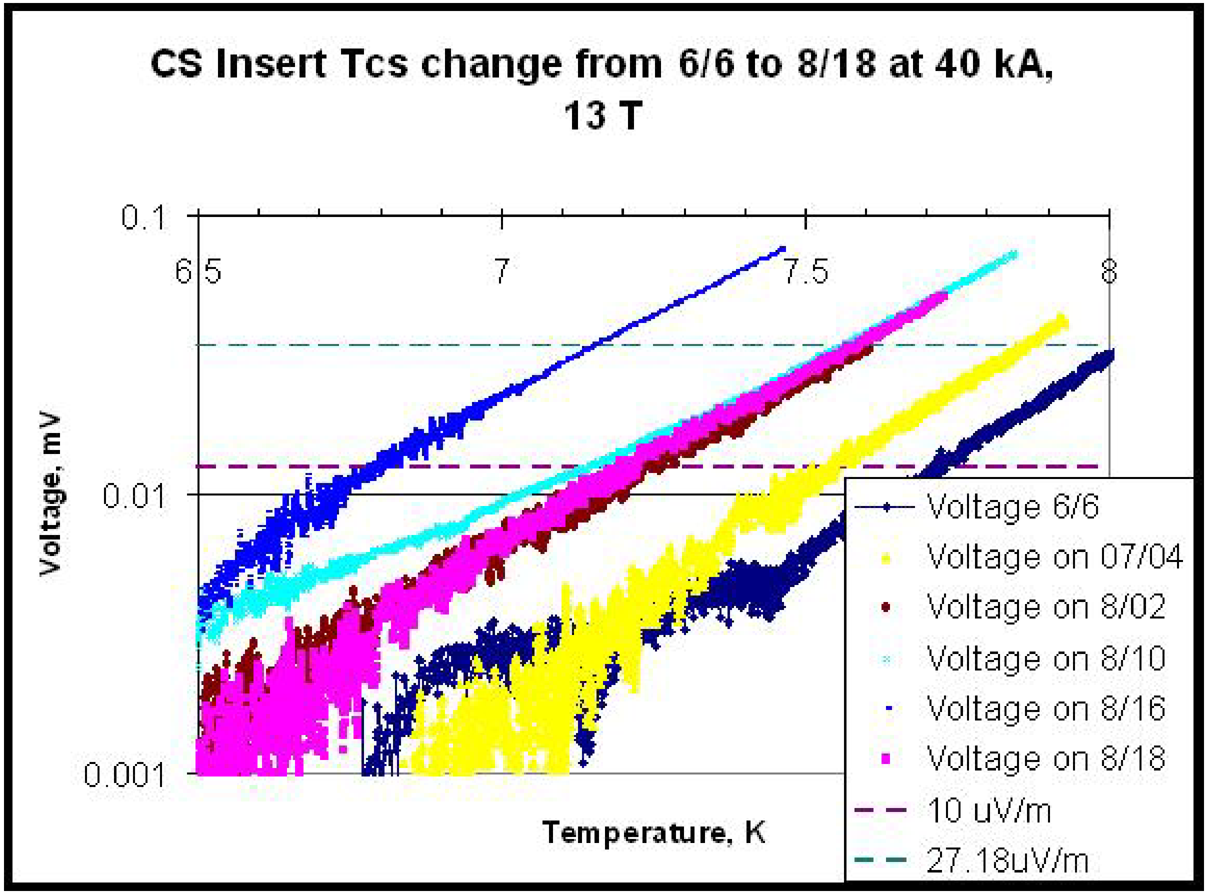
# TFAS1 are not exponential – suspect problems with samples nonuniform current



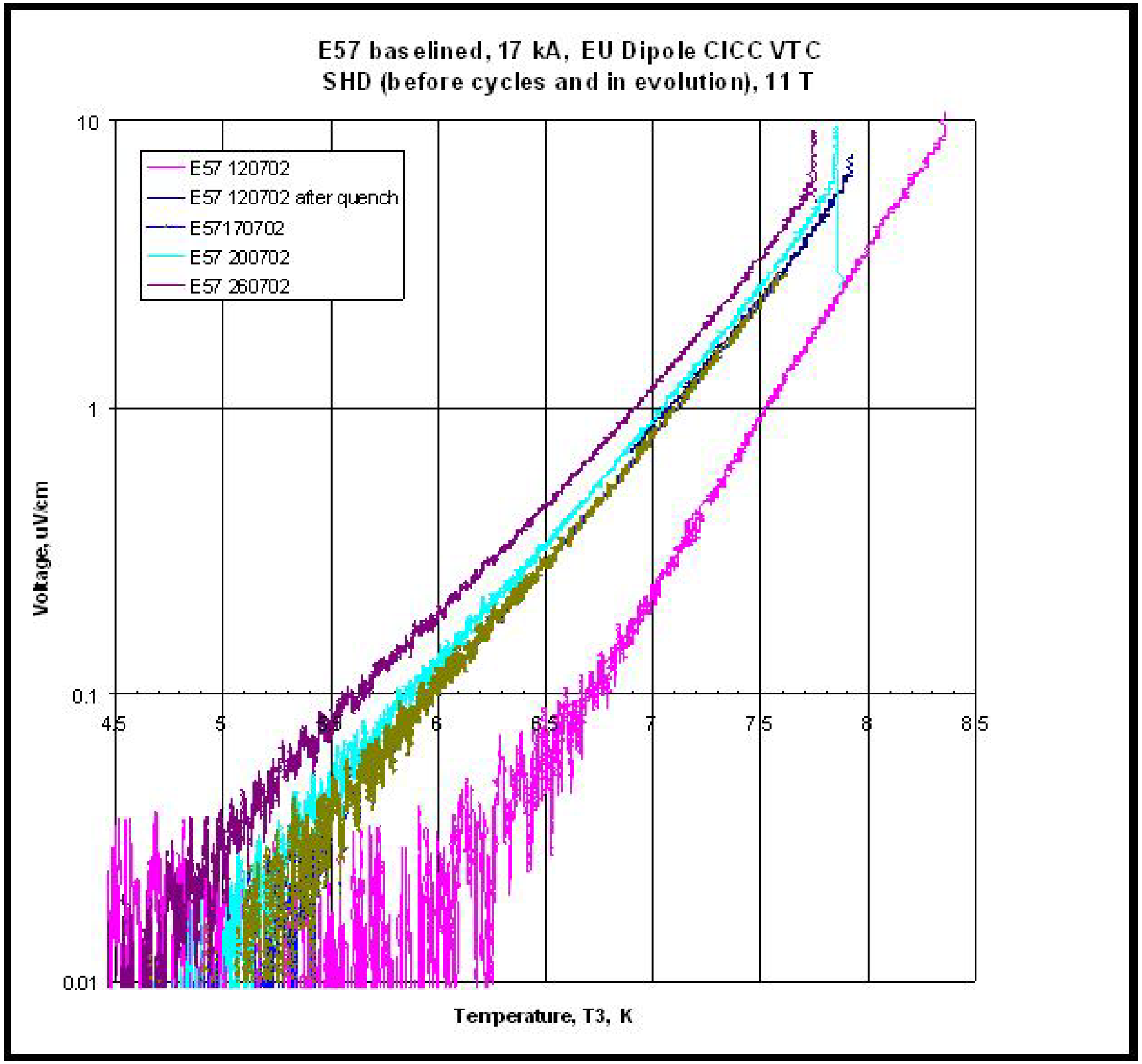



# Voltage growth is exponential with T and I

$$E = E_c \exp\left(\frac{I - I_c}{I_o} + \frac{T - T_{cs}}{T_o}\right)$$

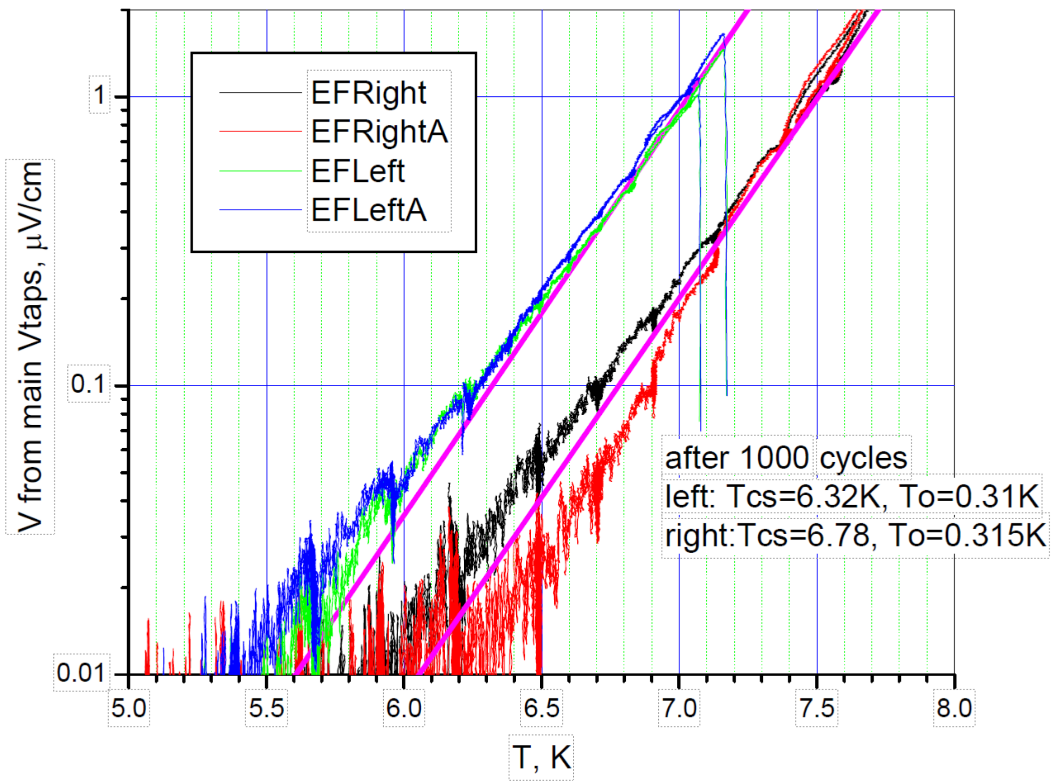


# EU dipole prototype



# First solder filled terminations US ITER sample

## Transitions after 1000 cycles in TFUS1




TFUS1 tests

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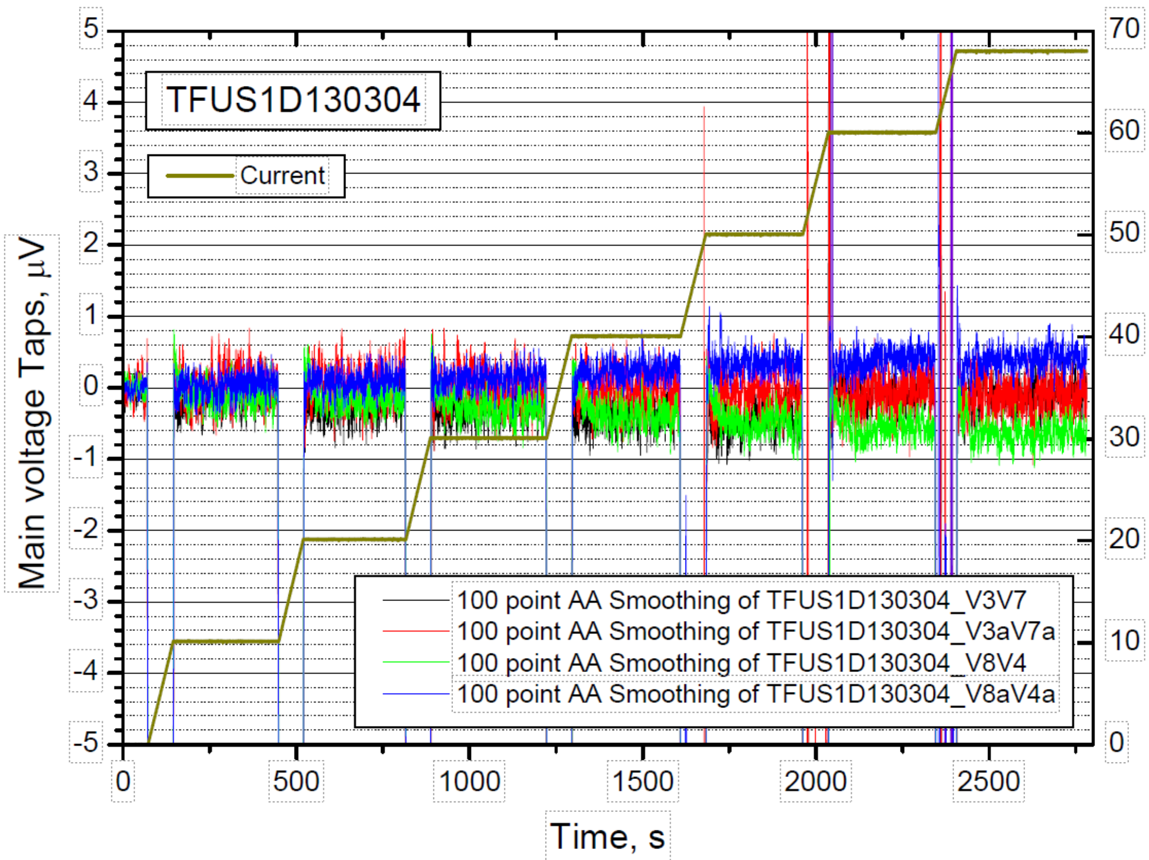
# TFUS1 performance before cycles (Tcs, Ic, joints)




Main voltage taps give low noise. All four 450 mm based VT have noise less than 0.7 µV . Such level does not need any compensation for performance assessment. First time in ITER qualification history both legs showed negligible “early voltage” noise

# How to force current uniformity

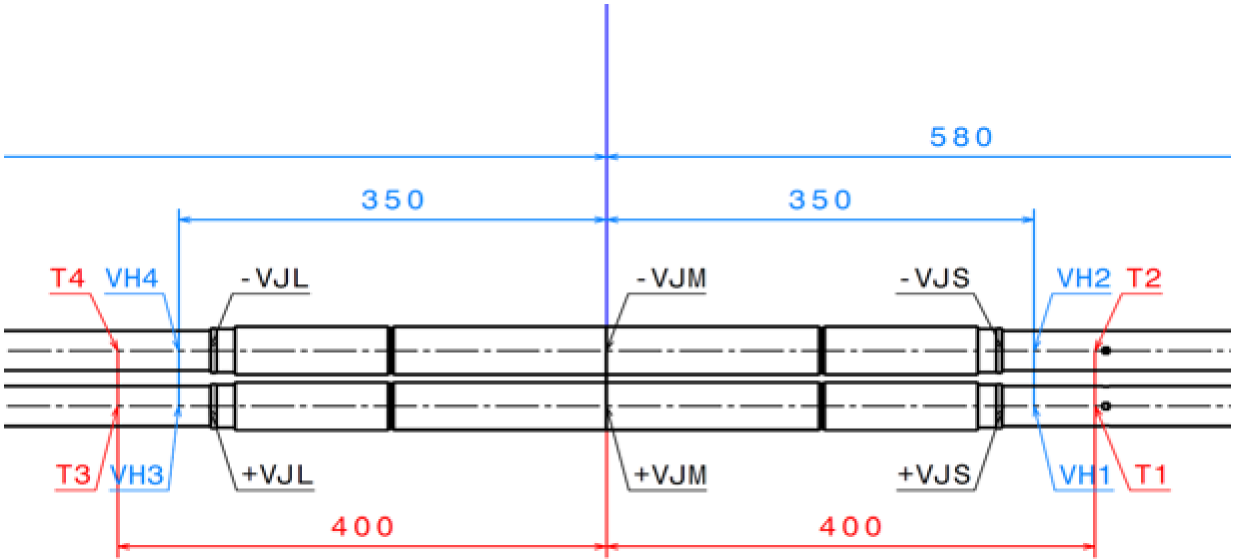
- What makes current distribution uniform?

a) High voltage along the conductors
b) Low resistance between current elements (subcables and strands)
c) Super low resistance between current elements in the terminations (solder filled terminations)
d) Conductor current sharing voltage is 0.4 meters x10$\mu$V/m=4 $\mu$V – very low, special measures needed for uniform distribution (solder filled terminations)
e) Joints voltage is higher 1nOhm*50 kA=50 $\mu$V, so samples for Joint performance testing do not need solder filling

# Conductor instrumentation and tips

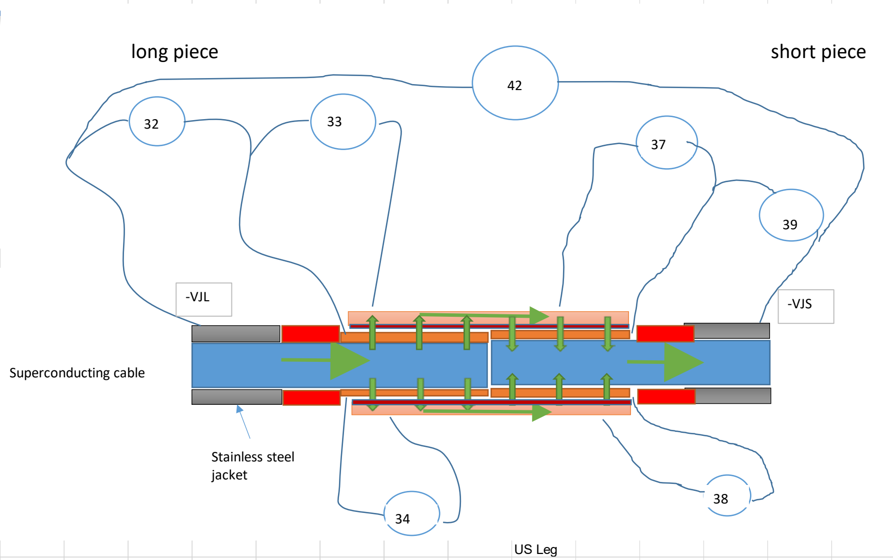
- Voltage taps across the High B (HFZ) area (give some space between voltage taps and high field portion) to allow detection of voltage of distribution
- Temperature sensors before and after HFZ for calorimetry and thermal ran away observation circumferentially around conductors
- Plug the central hole in CICC under temperature sensors to force helium in the cable for better calorimetry
- Sometimes Hall probes around conductor to detect current distribution uniformity (not a great value)
- Lower and upper joints voltages and temperature sensors as usual

# Joints instrumentation for joints in the middle of the leg (standard)



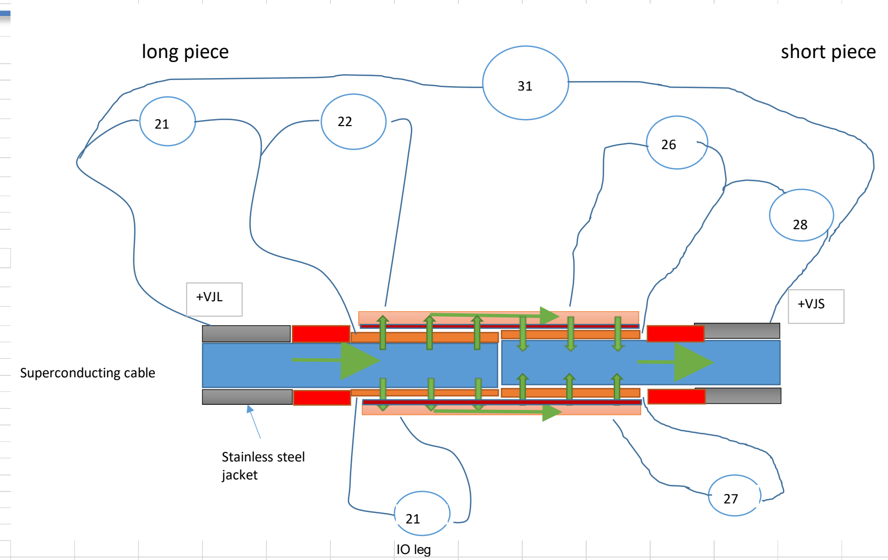
# Advanced instrumentation as in CSJUS3

Advanced instrumentation US leg




US Leg

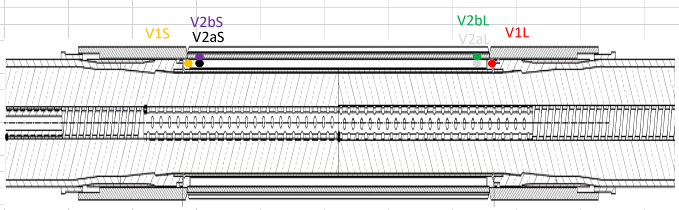
Advanced instrumentation IO leg

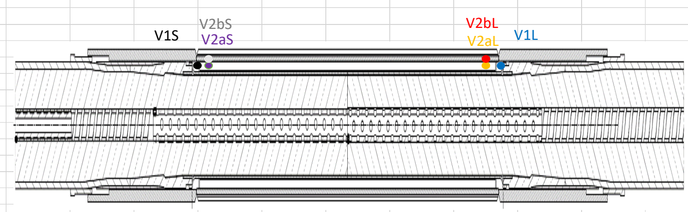



IO leg

| Voltage tap | Location | Colour |
|---|---|---|
| V1L | Long leg side. Crimp tube. | Red |
| V2aL | Long leg side. Quadrant a. | White |
| V2bL | Long leg side. Quadrant b. | Green |
| V1S | Short leg side. Crimp tube. | Orange |
| V2aS | Short leg side. Quadrant a. | Black |
| V2bS | Short leg side. Quadrant b. | Purple |

| Voltage tap | Location | Colour |
|---|---|---|
| V1L | Long leg side. Crimp tube. | Blue |
| V2aL | Long leg side. Quadrant a. | Orange |
| V2bL | Long leg side. Quadrant b. | Red |
| V1S | Short leg side. Crimp tube. | Black |
| V2aS | Short leg side. Quadrant a. | Purple |
| V2bS | Short leg side. Quadrant b. | Grey |

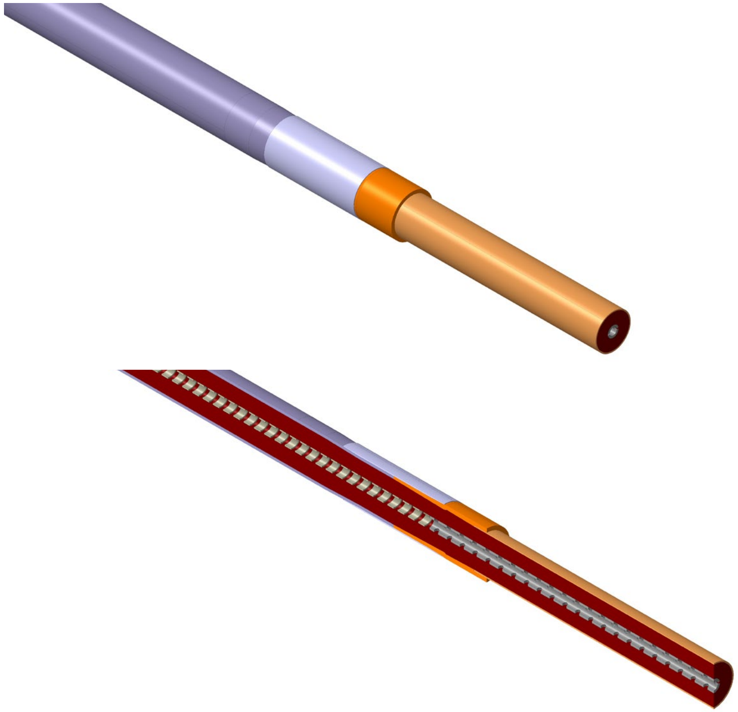


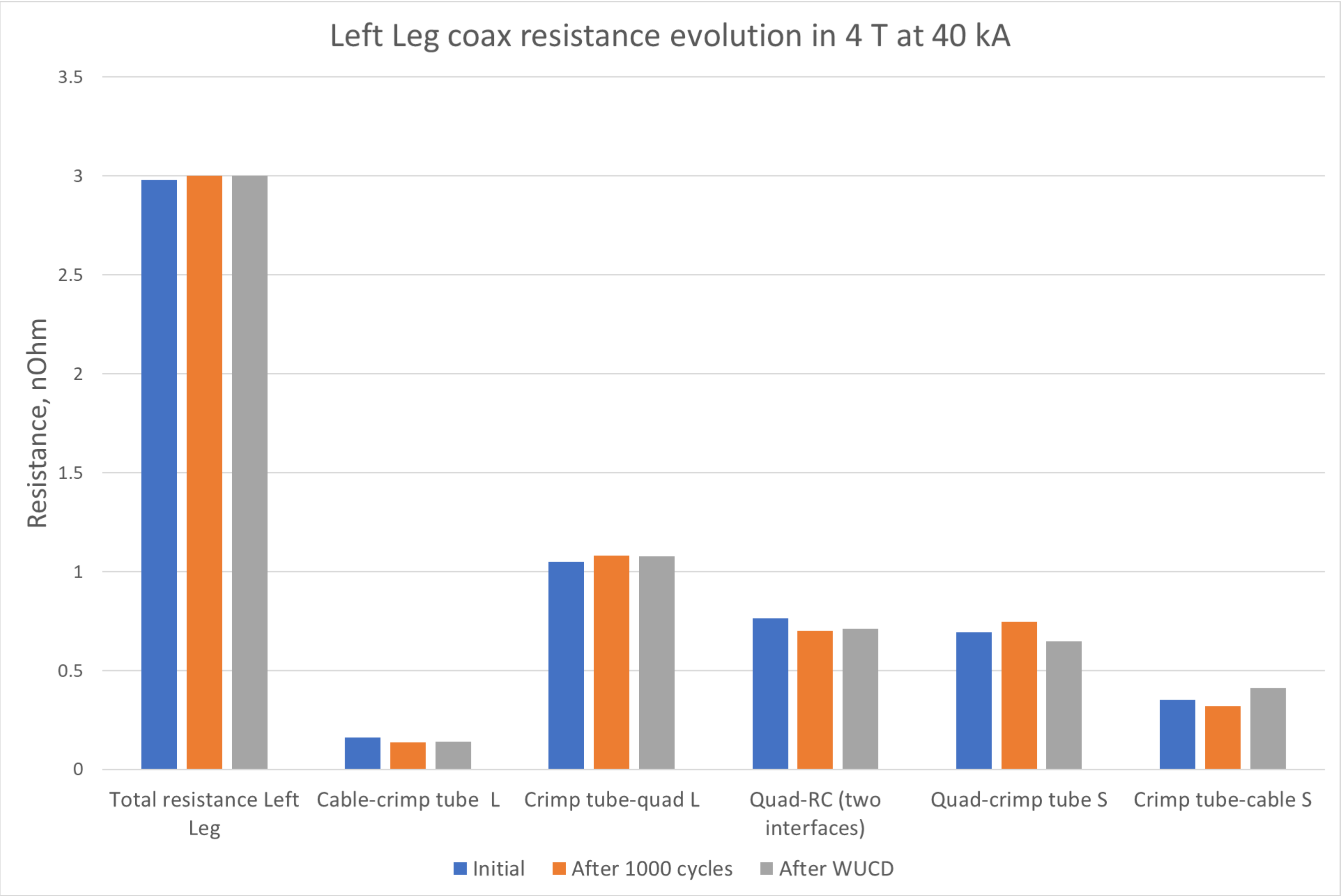

Purpose of VT – measure every interface in the joint with multiple interfaces

# CSJUS4 tested in SULTAN

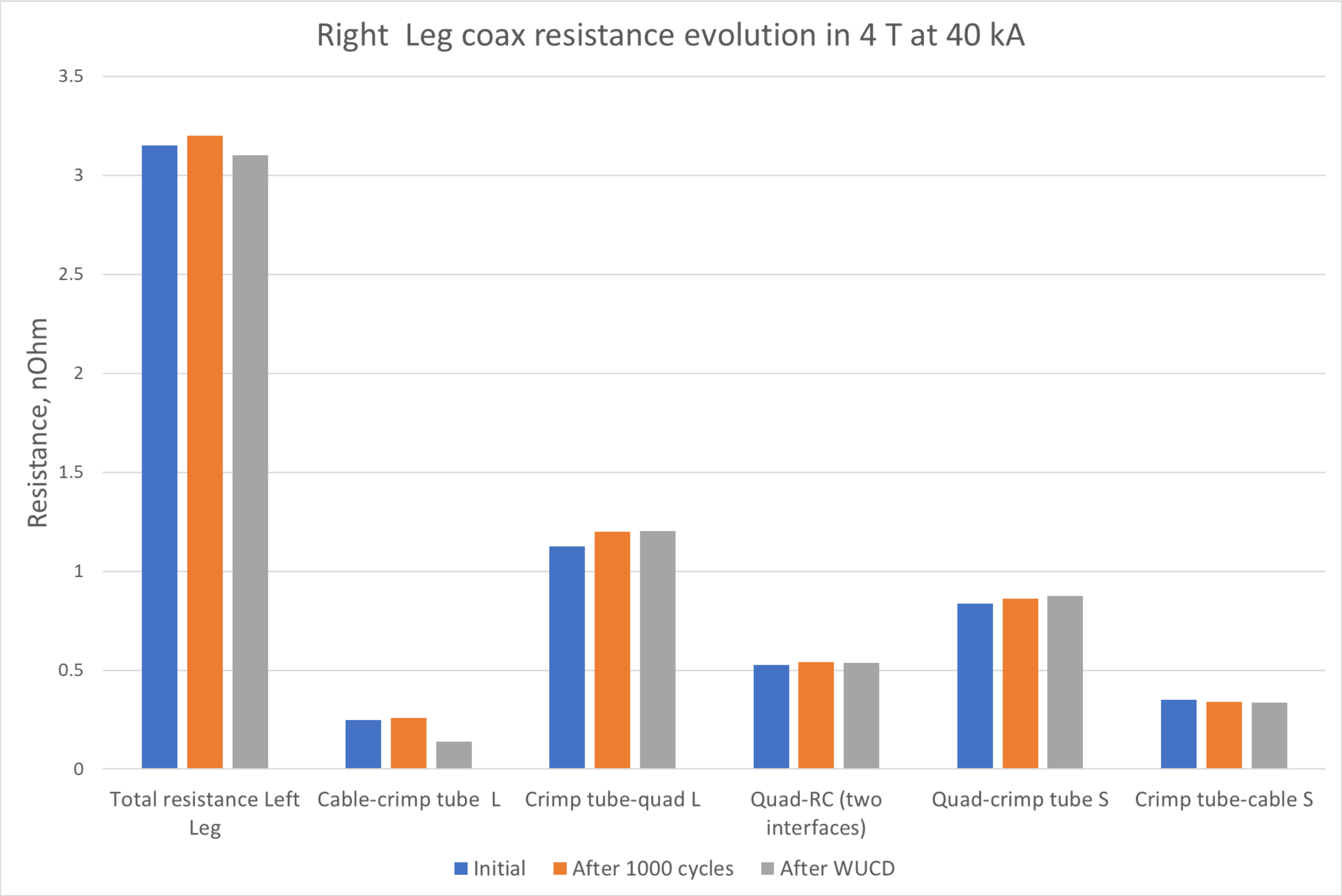
- Two legs – one is ITER IO from CSJUS3 after assembly-disassembly another one – freshly assembled at IO
- Parts supplied: conductors (JADA), Rutherford cables (LBNL), GA (legs with all terminations), SPC (upper and bottom joint terminations) and ARMEC (joint parts): quads, shells and weld strips

# Left leg evolution (from CSJUS3)



# Right leg evolution



# Discussion soldered vs Indium smashed interface between joint parts

- The main contribution in resistance are indium interfaces and cable to copper former soldered interface, both improved from the past
- Indium resistance interface by IO is noticeably better than what was demonstrated at GA in jumper tests and CSM1 and CSM2 terminations (suspect higher compaction in IO joints where Indium is squeezed to 0.2 mm in contrast to GA 0.3-0.35 mm)
- Resistance of the coax joints are good but not as good as CSJU2 repaired soldered option (2.2 nOhm vs 3 nOhm in CSJUS3 or CSUSJUS4)

# Joint quench temperatures and locations

**Tq Measurements 4T/40kA**
**Initial:**

CSJUS3d131012 /initial/ TqL=11.9 K no quench in the right leg

**After WUCD**

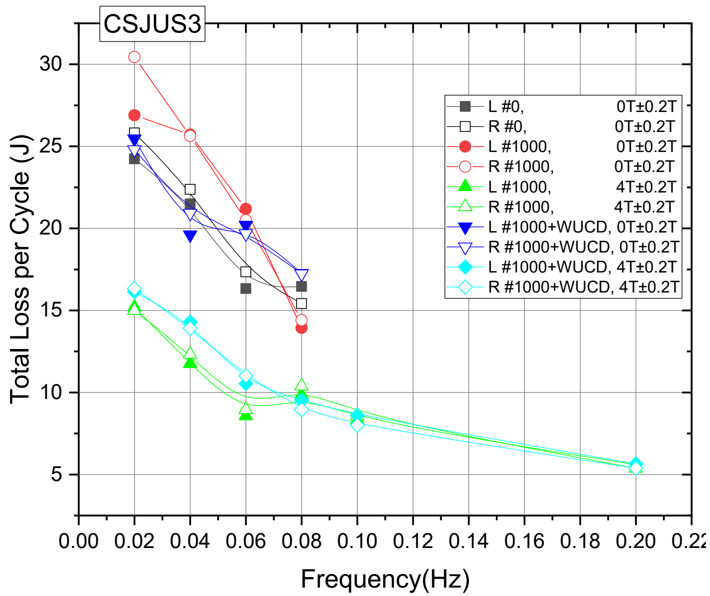
TqR=10.8 K (40 kA, 6T), quench is in the right leg, resistance is registered in both legs

Both are very high and shows significant margin
Acceptance 8 K, predicted Tq>=10 K

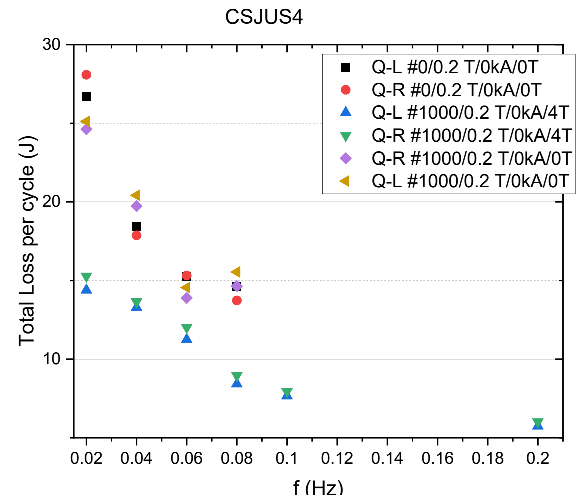
# Summary of the Tq measurements

| Run | Event and Field | Tq Indium old | Tq Indium new | Location |
|---|---|---|---|---|
| **CSJUS4D020303** | #0, 4 T | 11.9 K | >11.9 K | +VJS |
| **CSJUS4D030301** | #1000, 4 T | 11.9 K | >11.9 K | +VJS |
| **CSJUS4D080305** | #1000+WUCD, 4 T | 11.75 K | >11.75 K | +VJS |
| **CSJUS4D100301** | #1500+WUCD, 4 T | >11.75 K | 11.75 K | -V2aL/V2aS |
| **CSJUS4D030312** | #1000, 6 T | >10.7 K | 10.7 K | -V2aL/V2aS |
| **CSJUS4D080306** | #1000+WUCD, 6 T | >10.8 K | 10.8 K | -V2aL/V2aS |

# AC loss results with sinusoidal pulsing




Similar to CSJUS3 – acceptable losses




Initial condition

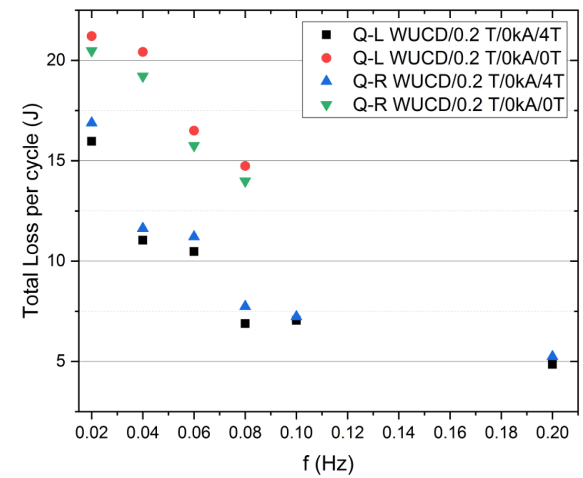
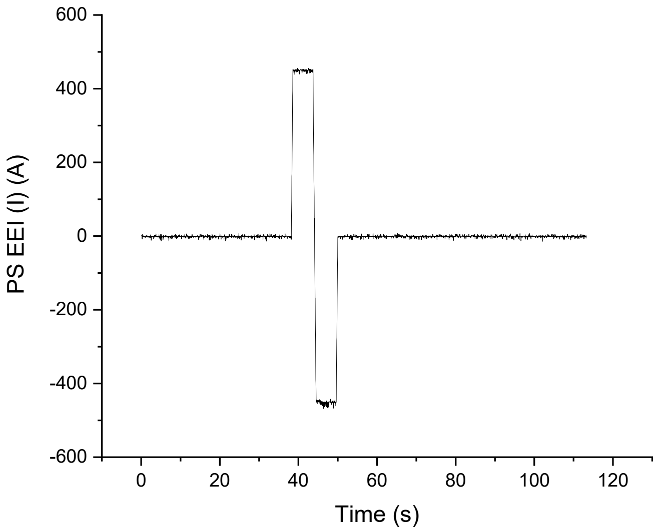
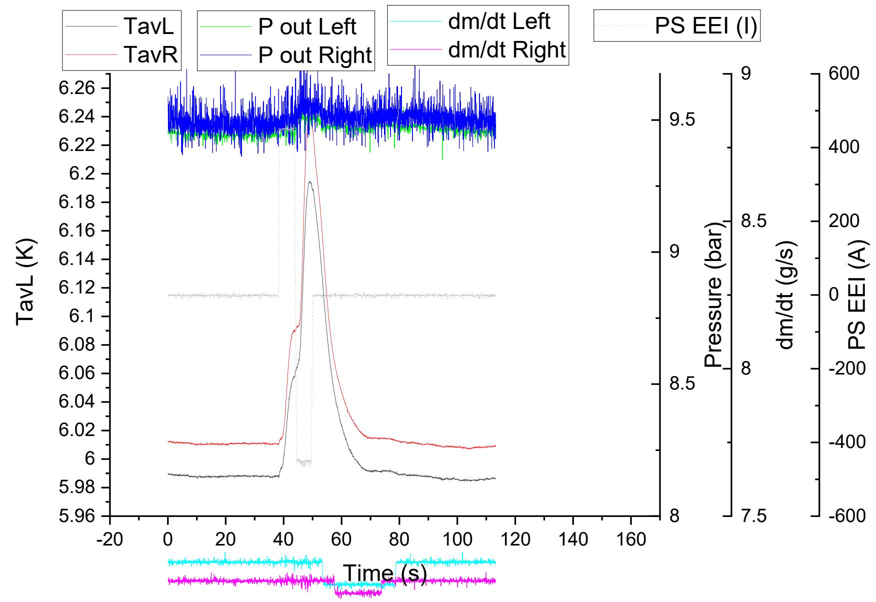



**Figure 19** *AC loss measured at pulsing amplitude: ±0.2T. The effect of background magnetic fields: 0T and 4T after Warm Up Cool Down (WUCD). L: Leg Indium Joint Old, R: Leg Indium Joint New.*

# Stability is good – no quench at a 0.8 T swing with 1 T/s at 6 K



# Stability after cycles is good

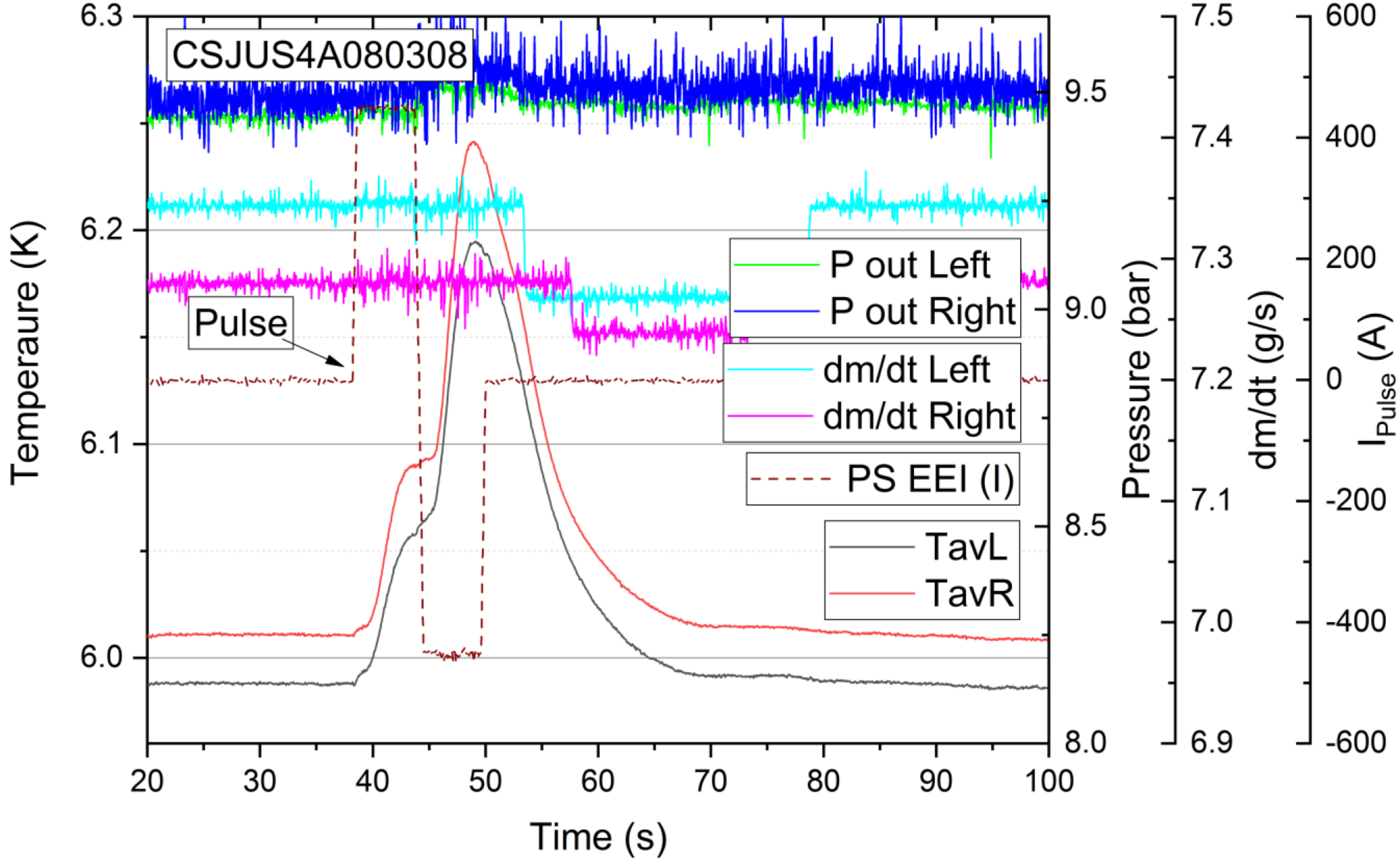



**Figure 21** *An example of the trapezoidal pulse after 1000 cycle loads and after WUCD. The initial temperature was 6.0 K and sample current was 40 kA.*

# Sensitivity to cycles is low, but not saturating

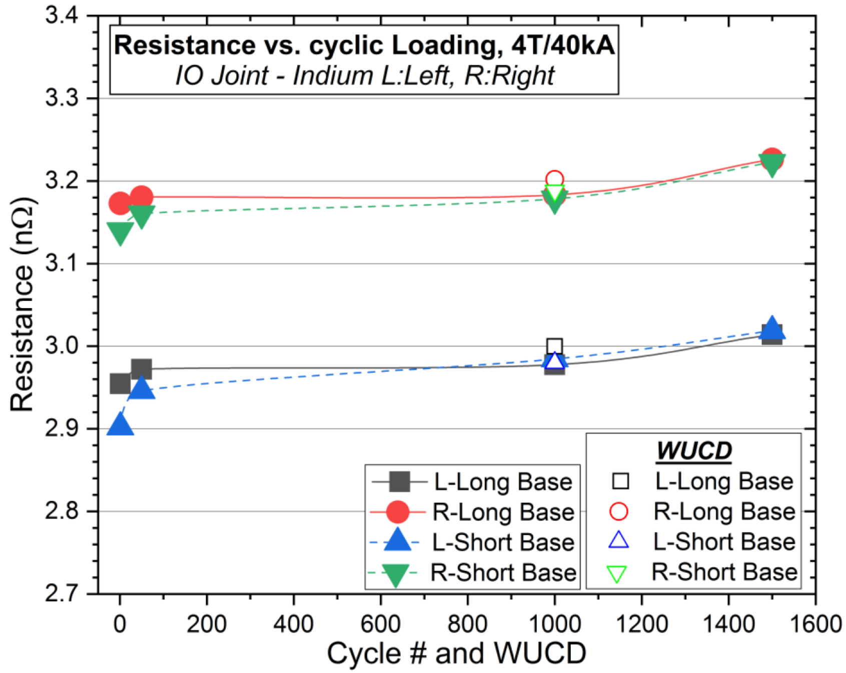



**Figure 13** *Evolution of joint Resistance with electromagnetic load cycles and WUCD, at magnetic field 4T and current 40kA.*

Assume 0.08 nOhm growth over 1500 cycles. At the most conservative assumption that it will go on for the whole campaign of 60000 cycles, it will become 6.4 nOhm, still not a problem despite exceeding of 4.1 nOhm. More cycles is desirable for characterization but not mandatory for study of the resistance vs EM cycles

# SUMMARY

- Qualification and R&D on the conductors and joints requires a flexibility from the test facility, ability to create sources of a pulsed and varying fields and heaters on top of ability to generate high field and wide range of temperatures
- DAQ is not very challenging but should have a reasonable number of channels
- Current source should have sufficient flux to hold high current for needed time
- Proper preparation of the sample is a very important item for successful testing
- It is desirable to have a possibility to move the sample vertically in the facility to measure conductor performance, then place the joints in the HFZ and characterize the joints (telescopic cryostat as in SULTAN)