Analyses of the ITER Poloidal Coil joints cold test results.

MT25 Meeting, Amsterdam

30 August 2017

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Agenda

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- Inductance
  - Transport current path
  - Load cycling, variation of cable and joint type.
- Resistance
  - External field dependence
  - Load cycling
- Conclusions

Introduction.

Resistive Joints in ITER PF Coils

The design of ITER Poloidal Coils contains 88 internal joints connecting individual conductor lengths. Satisfying restrictions from operating condition, manufacturability and serviceability, these joints were designed as twin-box “shaking hands” concept.

Verification Tests

Due to limitations of PF coil tests prior to tokamak assembly, joints design and manufacturing process has to be qualified and validated. Samples (Figure 1), built to production processes were tested at fields up to 5T (perpendicular to the joint) and currents up to 55kA in 4K environment. Positive applied current generated repulsive load, and therefore was used to simulate load cycling. Separate set of coils was used to measure AC loses, however these results are not in the scope our study.

The Goal of This Study

We focus on DC resistance and inductance results of 5 samples with were manufactured with the following variations:

- 3 different facilities (F4E, ASIPP, SNSZ)
- 2 different cables (PF5 and PF6)
- different compaction and nickel removal processes

While joint resistance is one of the acceptance criteria, therefore has been analysed before, the inductance was not, As will become clear, it could provide us with the new information on joint performance versus different variables.

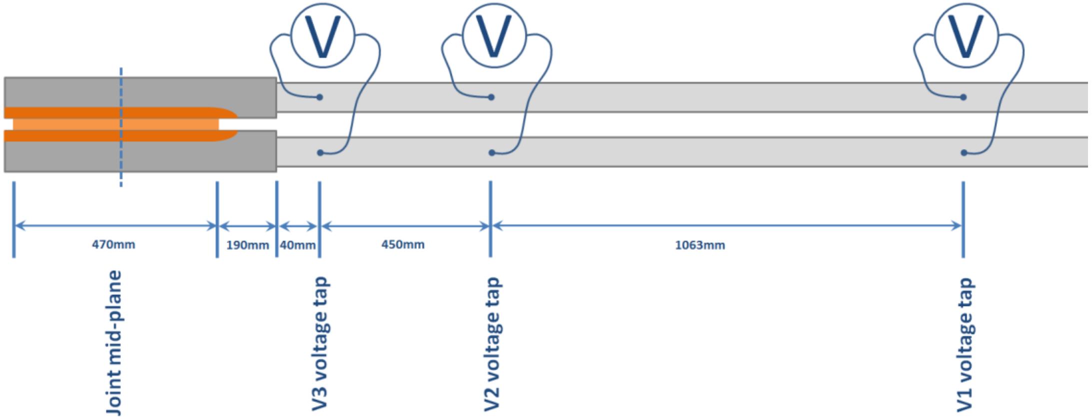

Figure 1: *Joint sample geometry and voltage taps locations.*

Inductance: transport current path.

Calculation Approach

Inductance values for each voltage tap location were calculated and compared with measured values, extracted from voltage taps during current increase steps. Resistive component, measured in steady state, was subtracted.

Nominal Design Results

For nominal design it was assumed that the current passes through the whole joint area, and joint mid-plane of 235mm (Figure 1) was used for inductance calculation. However, calculation results deviated from averaged measured values by as much as 32% (Table 1).

235mm	PF5 conductor			PF6 conductor		
	calc., [μH]	meas., [μH]	Δ, %	calc., [μH]	meas., [μH]	Δ, %
L40	0.29	0.21	27.2	0.25	0.17	31.8
L490	0.58	0.51	11.1	0.51	0.47	9.0
L1550	1.24	1.17	6.0	1.10	1.03	6.8

Table 1: *Joint sample inductance. Calculation results based on 235mm mid-plane*

Modified Current Path Results

Changing the mid-plain distance to 109mm brings deviation down to 7% (Table 2) and indicates that the transport current crosses joint through the first half only. Thus, it suggests that current sharing between sub-cables and between strands is much higher than assumed.

109mm	PF5 conductor			PF6 conductor		
	calc., [μH]	meas., [μH]	Δ, %	calc., [μH]	meas., [μH]	Δ, %
L40	0.21	0.21	1.8	0.19	0.17	6.9
L490	0.50	0.51	-1.9	0.44	0.47	-5.0
L1550	1.17	1.17	0.3	1.03	1.03	0.5

Table 2: *Joint sample inductance. Calculation results based on 109mm mid-plane*

Inductance: load cycling, variation of cable and joint type.

Load Cycling

Inductance did not show any significant dependence from load cycling. Conductor-only inductance (L1550 minus L490), for each sample, matches calculated values pretty well (Table 3).

	calc., [μH]	meas., [μH]
PF5	0.67	0.65
PF6	0.59	0.56

Table 3: *Inductance for 1063mm distance between V1 and V2.*

Cable Type Variation

The segregation by cable type is very clear for all 5 samples (Figure 2, left). However, inductances measured close to the joint (V3) showed that the PFJRF2 sample value, which has PF6 cable, now lies together with PF5 samples (Figure 2, right) and does not match it's calculated inductance.

Manufacturing Process Variation

Unlike other PF6 samples, PFJRF2 did not have electrochemical process (nickel reverse-plating) applied to it's strands – a process designed to improve strand-to-copper bonding. PFJRF2 sample had nickel removed mechanically, like other samples falling in PF5 conductor group. Lower inductance values are in line with improved conductivity strand-to-copper for electrochemically treated samples and correspond to 75mm reduction of joint mid-plane.

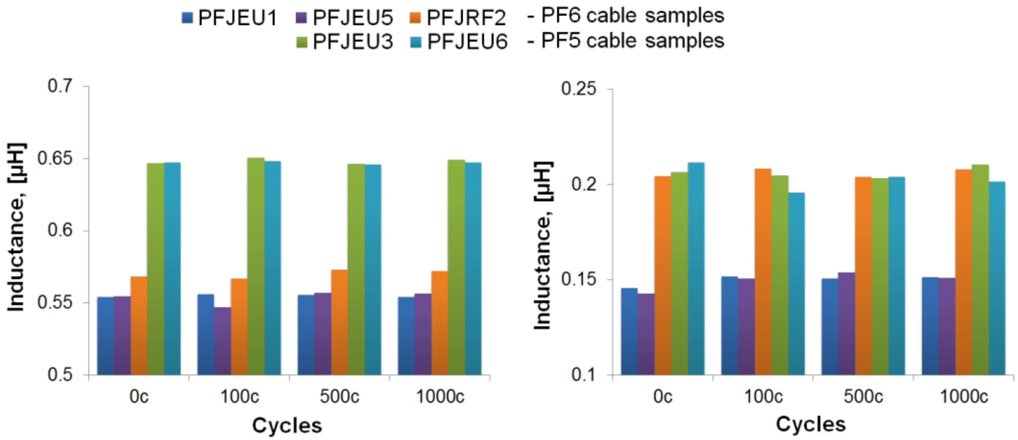

Figure 2: *Inductance for cable-only section (left) and joint section for each sample by load cycle.*

Resistance: External field dependence

Reversed variable axis

To plot resistance versus field, values measured at negative current had the sign applied to the field value (-55kA and 3T became 55kA and -3T). Both, joint and cable resistance for PF5 samples (Figure 3, red points) showed variation with field larger than PF6 samples, especially for cable (by a factor of 9), which points to a possible underlying cause in the cable design itself.

Joint Resistance

The trend for the joint resistance can be explained by repulsive force on two halves of the joint (degradation of joint quality) however, the degree of joint resistance variation was quite moderate, which points to good quality of manufactured verification joints.

Cable resistance

Significant field dependence of the cable resistance points to possibly mechanical nature of the effect, but requires more samples to be fully understood.

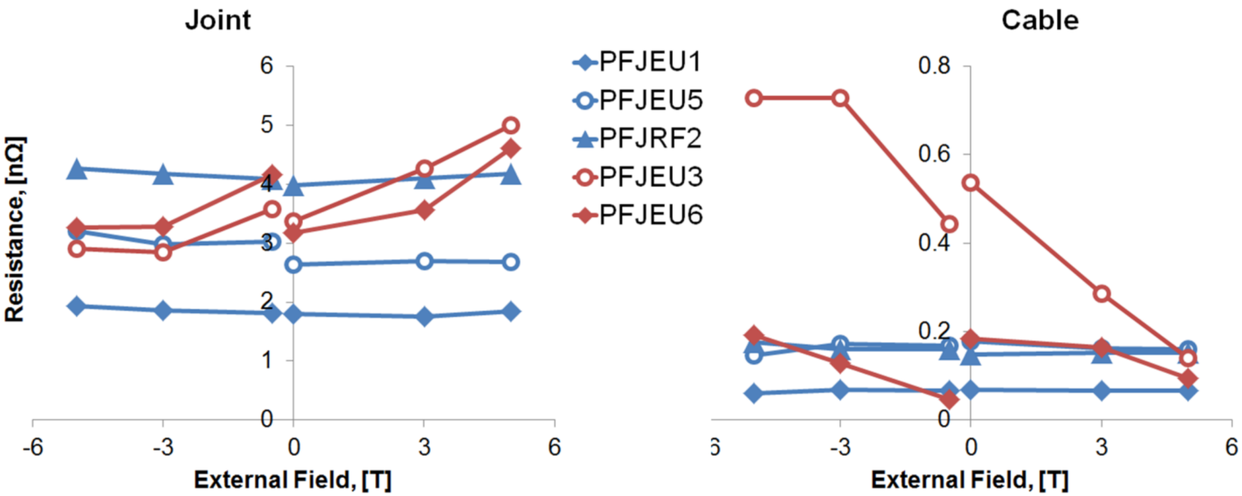

Figure 3: *Resistance vs. Field for Joint and cable-only section.*

Resistance: Load cycling

Load Cycling

Load cycling of total 1000 cycles was applied to each sample via repulsive EM force applied to the joint. Selected steps for intermediate measurements were 100 cycles and 500 cycles. After each step resistance measurement at 3T was performed.

Joint Resistance

Joint resistance indicated increase after each step, however very different from sample to sample (from 1% to 40%). On top of that, the measurements done under repulsive force, always shown higher degradation (Figure 4), with the amount seemed to be manufacturer-dependent, but more samples needed to verify.

Cable resistance

For the cable measurements however, the conductor type segregation is more obvious. PF6 samples did not show any significant change with cycling, unlike PF5 samples which indicated significant decrease (opposite to the joint behaviour), up to a factor of 4.

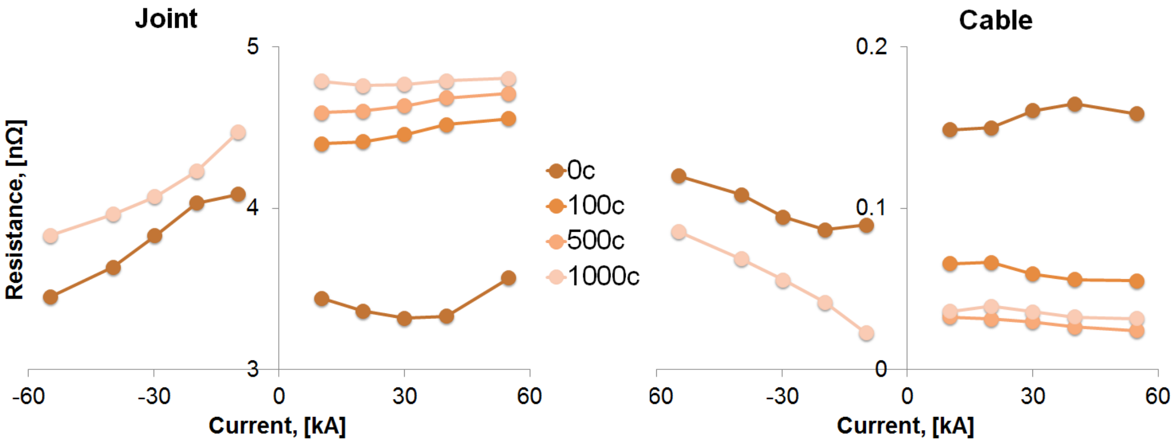

Figure 4: *Resistance vs. Current for different load cycle steps, for Joint and Cable-only sections. PFJEU6 (PF5 cable type) sample chosen for illustration.*

Conclusions

- Inductance study highlighted that joint mid-plane (effective current path) is much shorter than expected from geometry, and could become even shorter for the samples with more effective strand cleaning process.

- Field study did not find any significant field dependence for PF6 conductor. The field dependence for the PF5 joint aligned with the magnitude of repulsive EM force, however PF5 cable field dependence remains not fully understood.

- Resistance study of the cable component under reverse current polarity has indicated non-symmetric behaviour, most likely originating from mechanical movement of the strands

- Cyclic load tests, confirmed joint resistance increase with cycling, however also shown improvement (reduction) of cable resistance. Since the cable is superconducting, the resistive component can only come from the strand-to-strand (or sub-cable-to-sub-cable) current sharing which is triggered by the presence of the joint.

Thank You!

Acknowledgement

Test samples have been provided by F4E, ASIPP, and SNSZ through EU, CN, and RF Domestic Agencies. Special thank you goes to SPC SULTAN test facility, for providing raw data records for analysis.