Analysis of the ITER PF coil joints under the reference operating scenario

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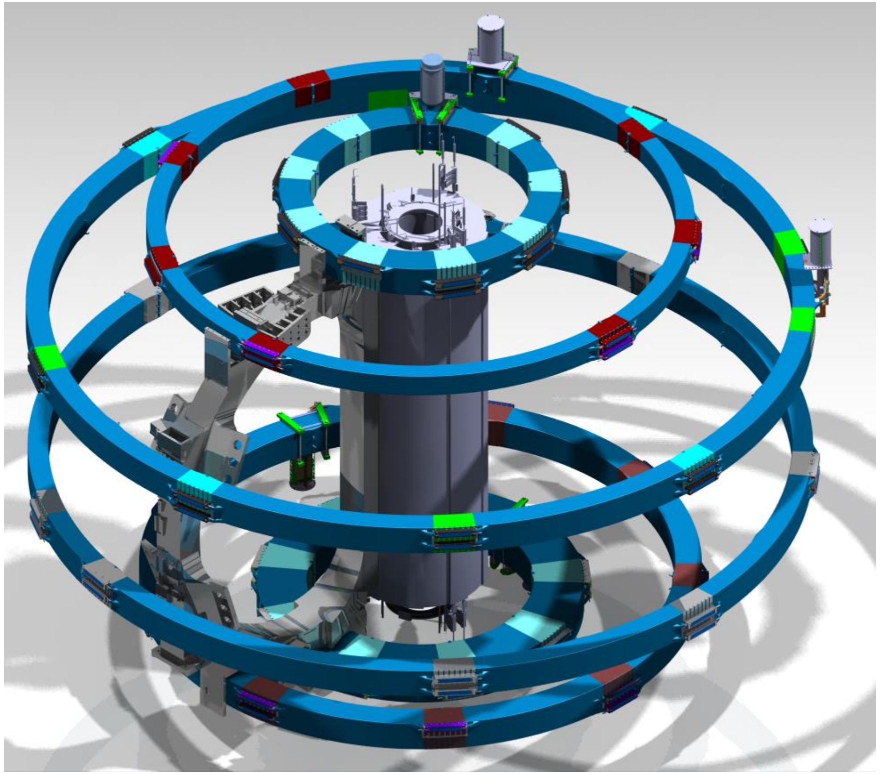
ITER PF Coils and their Joints



Six PF coils drive and provide the stability of the plasma.

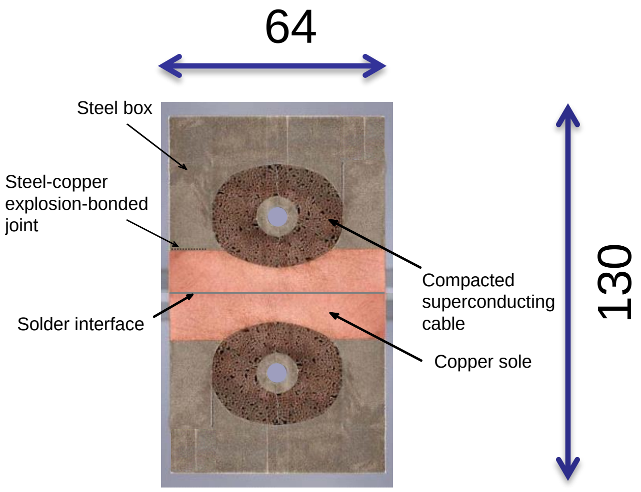
They operate in pulsed mode with currents up to 55 kA, and peak field up to 5 T.

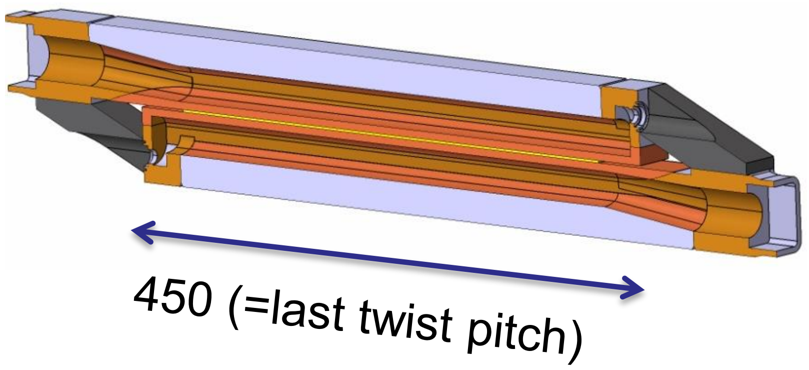
Diameter 8 ÷ 24 m, weight 200 ÷ 400 t.

PF3 needs 14 km of NbTi type CICC, while the maximum unit length is 900 m.
17 joints are required for PF3. 100 joints for all PFs.

All joints are on the coil outer radius. Accessible and reparable.

Design of the Lap Joint

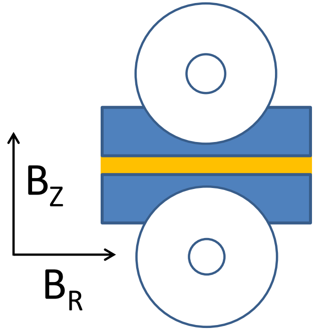




– Copper OFE, RRR~100, explosively bonded to 316L steel.
– Cable wraps removed, subcable wraps preserved in between the subcables only (50% coverage, 25% strand-strand contacts)
– Cable compacted to 25% voids (from 34% of the cable)
– Outer layer strands without Ni and soldered to copper

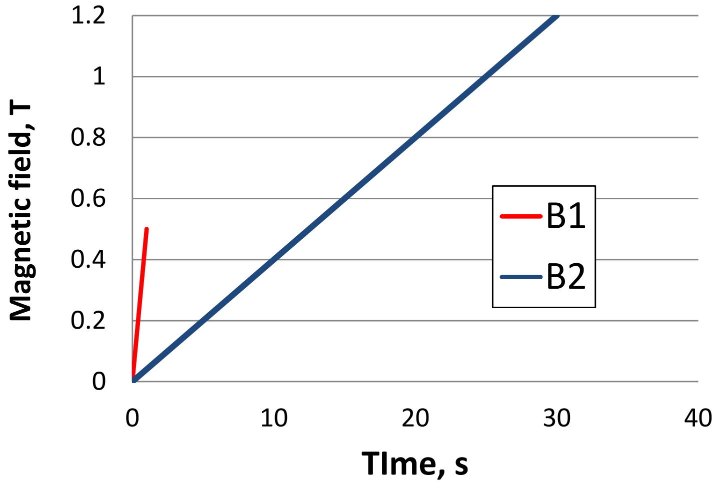
Joint Operating Conditions

Current and field on the joints varying during plasma pulse (30 min for reference 15 MA pulse).



Max B ~ 3 T

Max dB/dt ~ 0.5 T/s



Typical fast (B1) and slow (B2) field variations during plasma pulse in both (*Br* and *Bz*) directions.

Why study analytically?

This type of joints proved to be good for DC operation. $R < 2$ nΩ.

Are they equally good for operation in varying fields?

Let's study them analytically because…

- cannot test the joint in operating conditions. No test station available.
- very limited database on NbTi CICC lap joints in AC fields.
- worrying instabilities observed in PF insert middle joint.

Joint Stability Criteria

The joint is stable if two conditions are fulfilled:

1. The temperature of the superconducting strands does not reach the current sharing temperature *T*cs.

2. The stored magnetic energy (of induced current loops) does not exceed the available enthalpy in the concerned volume of the system up to *T*cs.

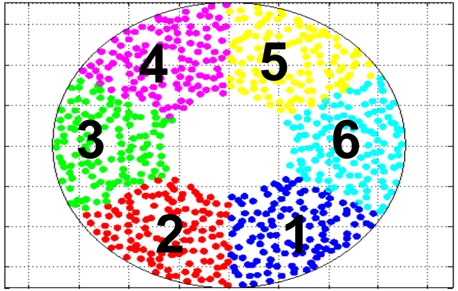
- the total available energy in He is 38 J for 2 K margin. The “allowable” induced current in the last stage subcables is derived from $0.5 \cdot Leq \cdot I^2_{loop} = 38$ J $\rightarrow$ $I_{loop} = 15.3$ kA.

Jack-Pot ACDC numerical model

Built at the University of Twente*, the model predicts current, voltage and temperature of each strand in the joint under varying fields and currents.

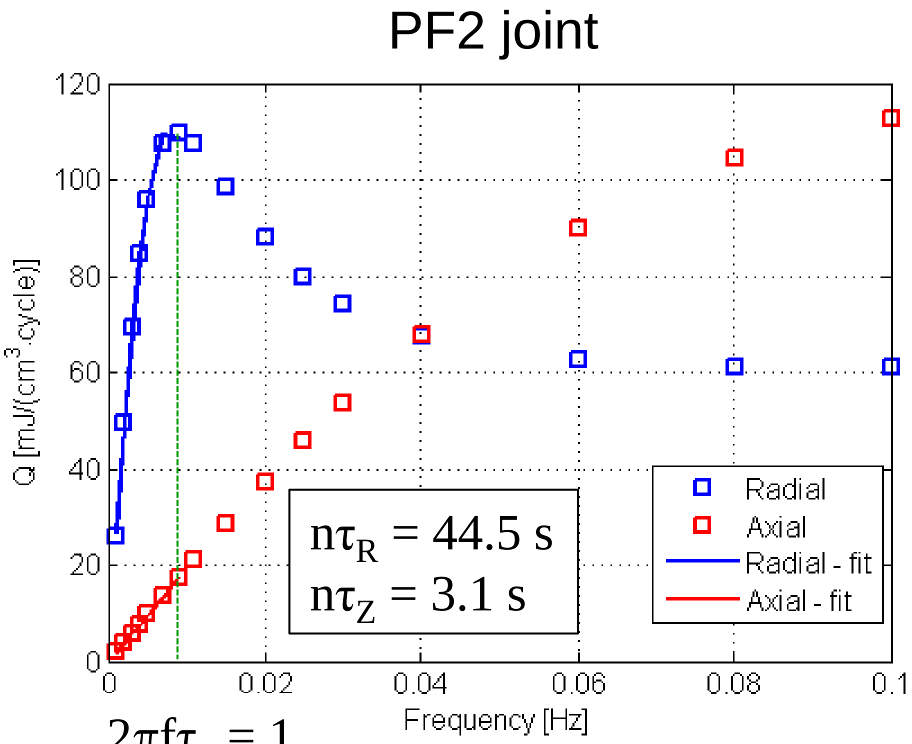
- The interstrand contact resistances are taken from the experiments on sub-size joints. The strand-copper resistance adjusted to get 1 nΩ joint.
- Realistic *V-I* characteristic of the NbTi strands.
- Temperature assumed uniform within a petal cross-section.
- Current distribution assumed uniform at some distance from the joint.

Example of PF2 model, 720 sc strands →



* E.P.A. van Lanen, J. van Nugteren, A. Nijhuis, "Validation of a strand-level CICC-joint coupling loss model," *Supercond. Sci. Technol.* vol. 25, p. 025013, 2012.

Reference design – time constants



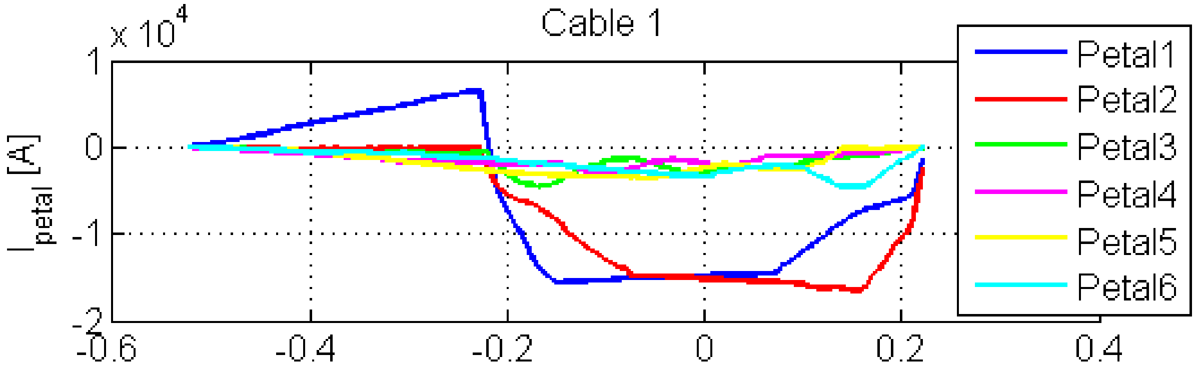
$2\pi f\tau_p = 1$

The volume for $n\tau$ evaluation is $L \cdot D_a \cdot D_c$ with L being the length of the joint, D_a - the distance between cables' axes and D_c - the diameter of the cable.

The time constant in R-direction is 19 s >> 1 s duration of the fast ramp.

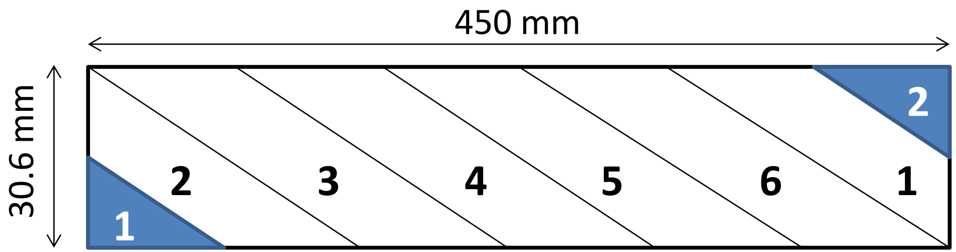
Reference design – Br fast field ramp

PF2 joint



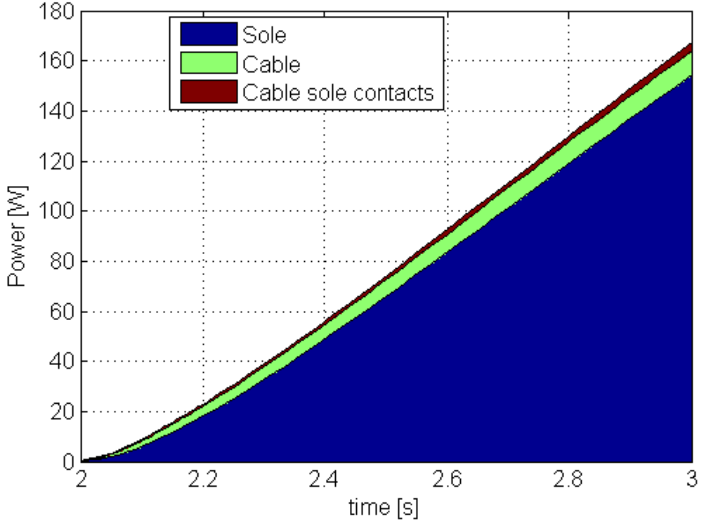
Sum of the induced currents in two petals 1 and 2 is 30 kA (>> 15kA) because these petals have double contact with the copper soil.

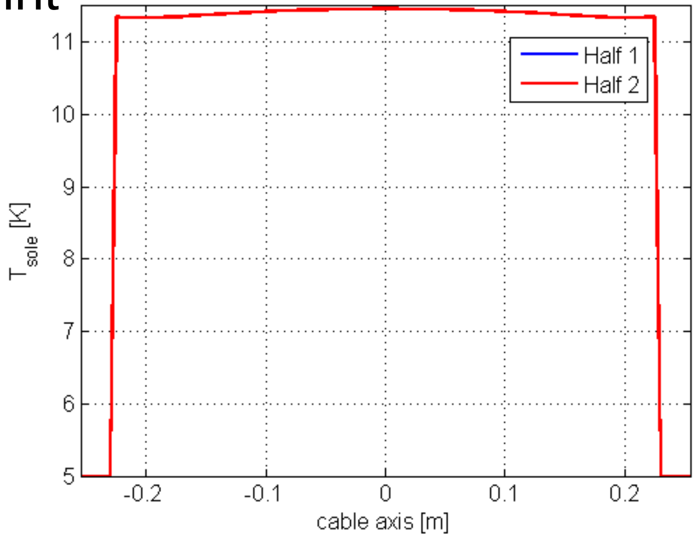
Petal footprints on the copper →



Reference design – Bz fast field ramp

PF2 joint



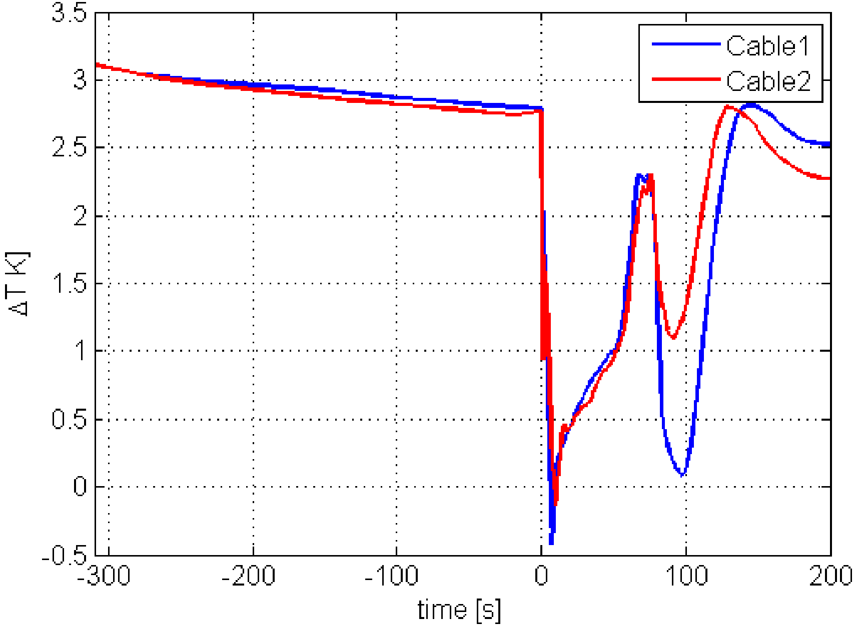


Copper sole reach 12 K at the end of the ramp due to eddy currents.

The NbTi strands in contact with the copper may get up to Tcs.

Reference design – plasma scenario

PF2 joint



The plot shows minimum (at each time step) temperature margin among all strands.

For some strands there is no margin at first seconds of plasma initiation and at 100 s.

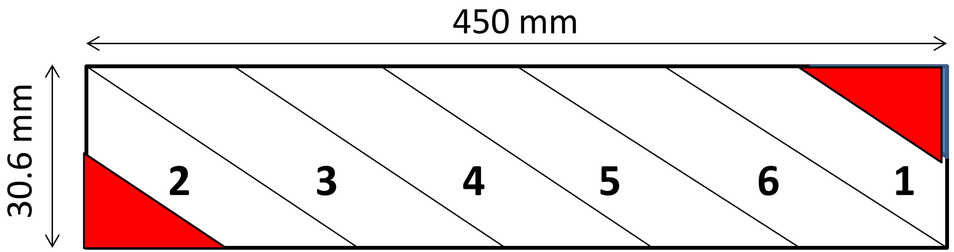
Solution

The design will be modified within the existing joint envelop.

1. Reduce the time constant in R-direction to below 2 s by adding resistive barriers in the location of double contact and in between the petals.

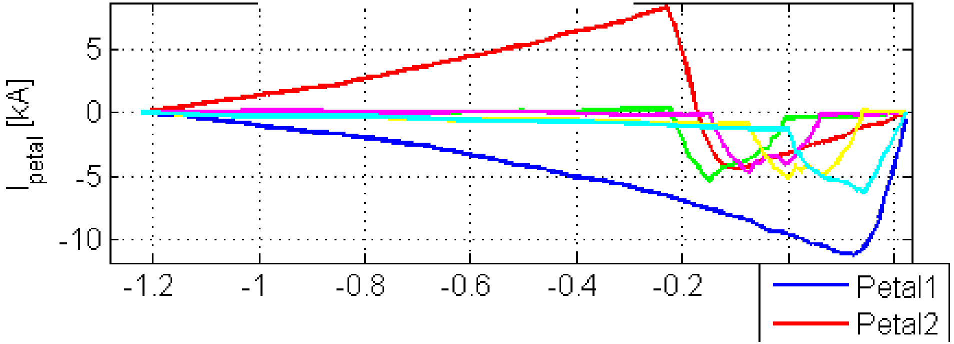
2. Use copper with RRR ~6 to reduce the time constant in *Z*-direction. This will increase the DC resistance to ~5 nΩ which is acceptable.

Note: glidcop was used in the joints of CSMC and PFIC.

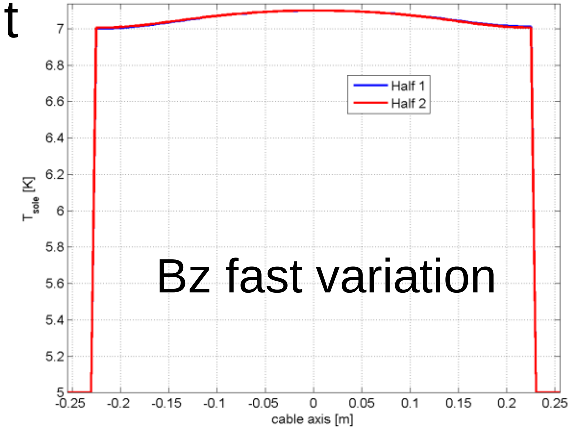


Modified design – fast field variation

Br fast variation



PF2 joint



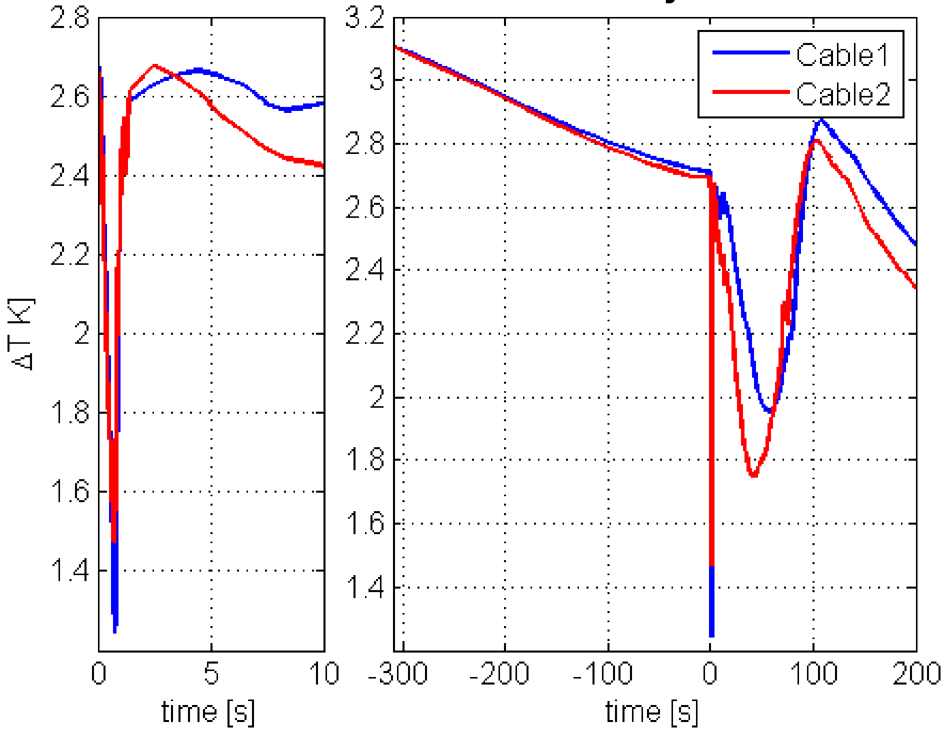
- The DC resistance became 4 nΩ. The time constant in *R*-direction became 1 s.

- Sum of the induced currents in petals 1 and 2 is below 15 kA.

- Copper sole temperature is 7.1 K.

Modified design – plasma scenario

PF2 joint



The plot shows minimum (at each time step) temperature margin among all strands.

For the modified design it remains above 1 K.

What's next?

- The proposed modifications have been agreed with the PF manufacturers in EU and RF.

- EU will make a pilot joint with the modified design and test it in the SULTAN facility (DC resistance, AC losses in *Z* and *R* directions either by copper coils or dumping SULTAN magnet) .

- AC losses of the prototype joints will be measured in UTwente facility in low frequency range.

- Sub-size joint sample will be measured in SULTAN under the field pulse representing the fast field variation B1 (not possible on full size due to geometrical constraints).

Thank you!