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Thermo-hydraulic simulation of the ITER PF coil joints based on their coupling losses calculated with JackPot-AC

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Outline

- Objective for temperature calculation
- JackPot-AC coupling loss model
- Hysteresis loss model
- Thermal model
- Results
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Temperature calculation workflow

- Coupling loss model has only linear components; no strand saturation is included;
- As a result, the temperature distribution is not calculated simultaneously, but afterwards;
- The algorithm is as follows:

1. Calculate coupling losses, no saturation in strands
   - If strand currents exceed their critical current, it is assumed that a quench will happen anyway;
2. Calculate the magnetic field at strand locations;
3. Calculate the critical current assuming constant temperature
   - First opportunity for checking instability;
4. Calculate hysteresis loss (requires critical current)
5. Calculate temperature distribution (and if necessary, calculate the critical current again based on this temperature)

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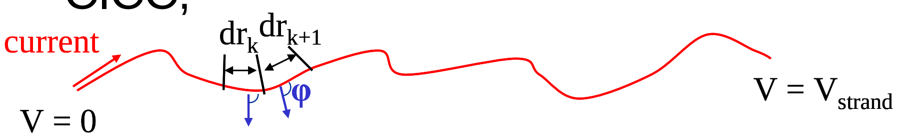
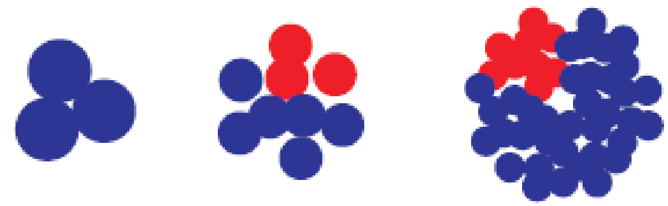
Overview of JackPot-AC network model

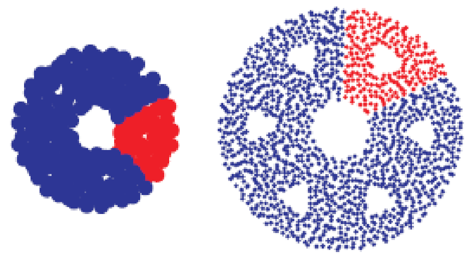
- Cable model that accurately describes *all* strand trajectories in CICC;

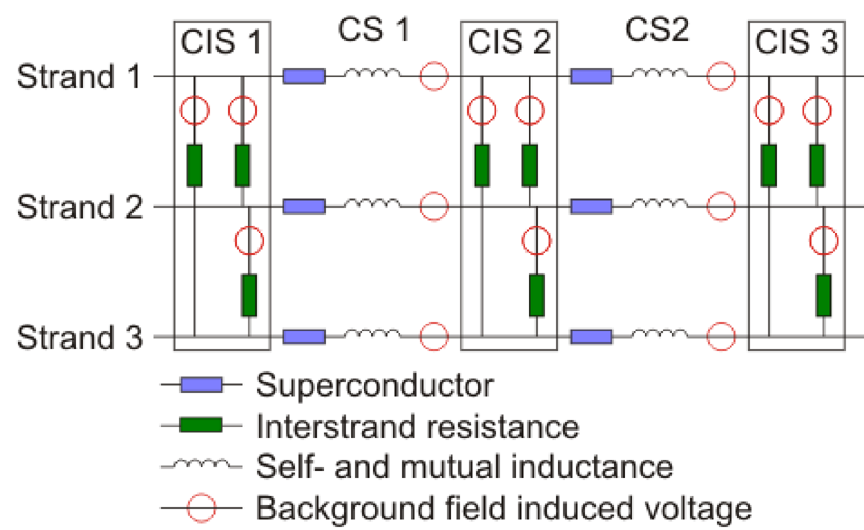


- Simulated strand trajectories are used to:
  - Calculate interstrand contact resistance distribution;
  - Strand-to-joint's copper sleeve contact resistance distribution;
  - Mutual inductances
  - Coupling with background field



Cable cross section from JackPot simulation





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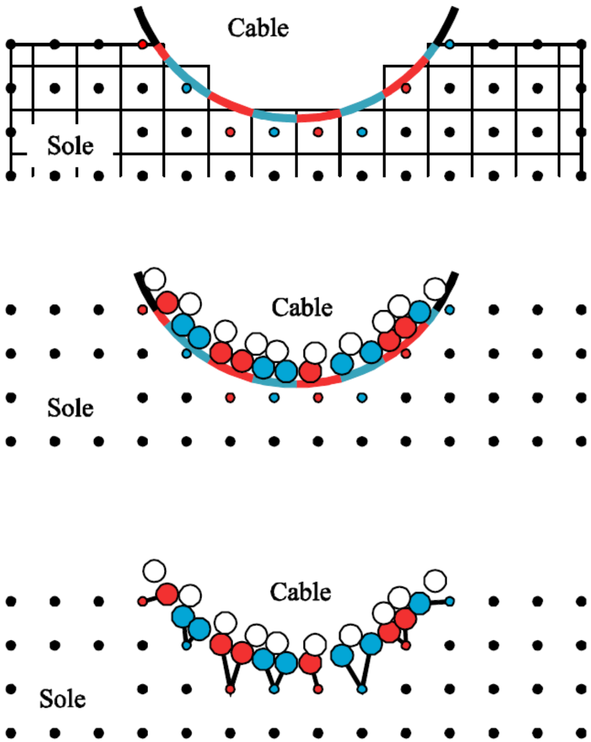
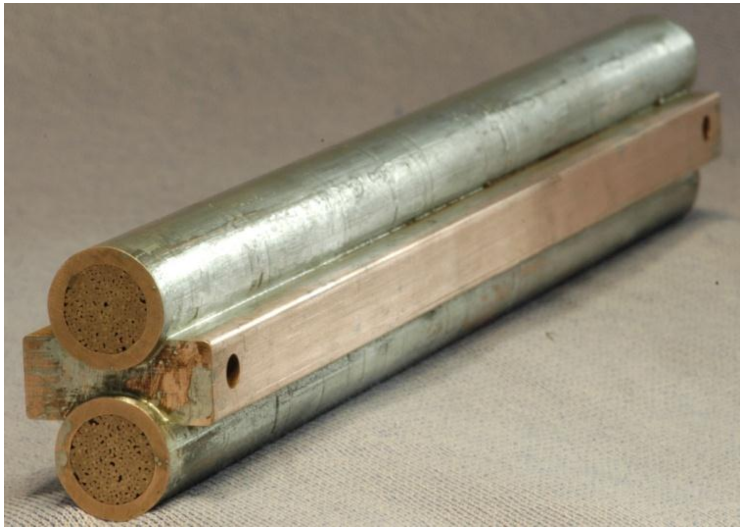
Overview of JackPot-AC copper sole model

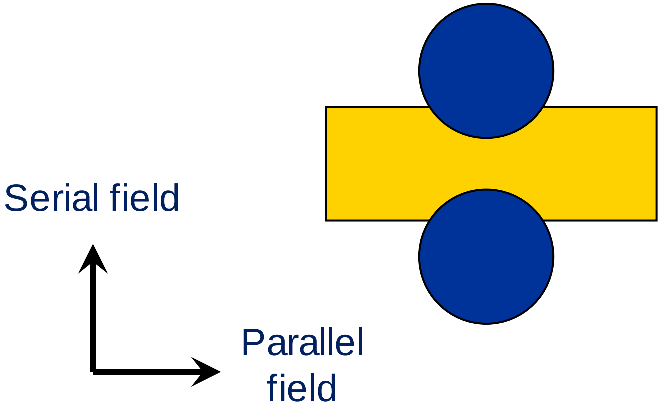
- A Partial Element Equivalent Circuit (PEEC) model is used to simulate the copper sole;
- This results in an electrical network that can easily be coupled to the cable model;
- The shape of the sole is approximated by removing PEEC boxes at the cable locations
- The coupling between the voltage nodes of the copper sole and the strands is determined from the geometric data;
- Similar to the interstrand resistances, the strand-to-sole resistances depend on the contact area between strands and the cable periphery.



Validation JackPot-AC joint coupling loss model

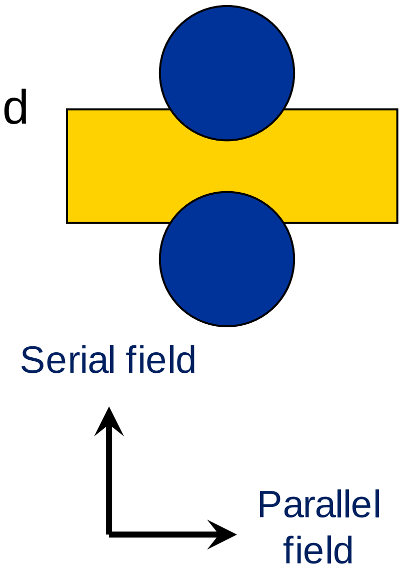
- The joint model has been validated with measurements on a mock-up joint;
- Interstrand and strand-to-joint contact resistivity were determined from interstrand resistance measurements on sub-size CICCs;
- Additional measurements were carried out on one cable and the copper sole separately;
- The measurements were done with different orientation of the harmonic background field.

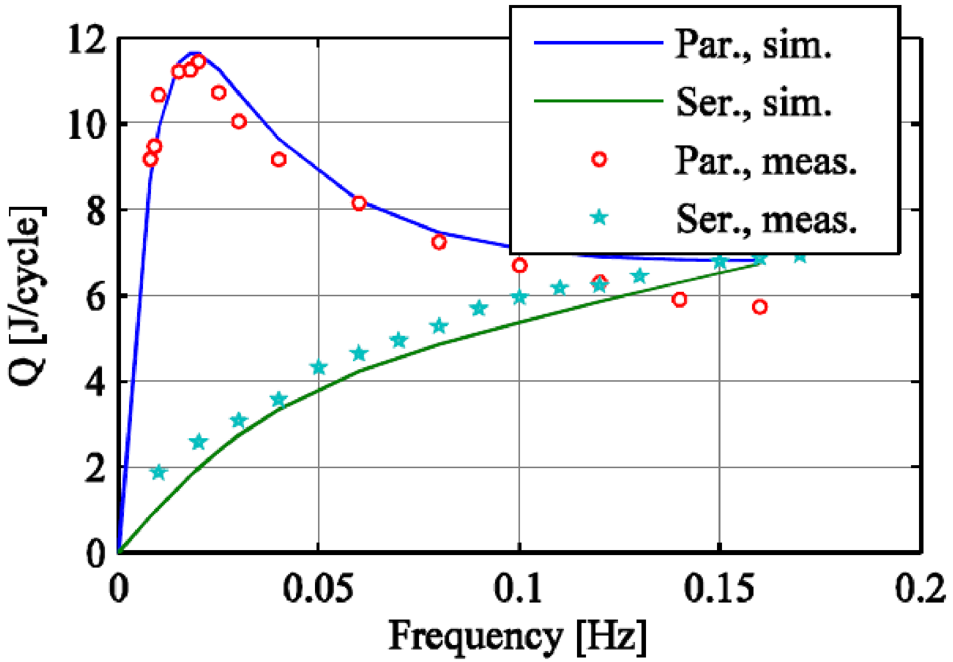




Validation JackPot-AC joint coupling loss model

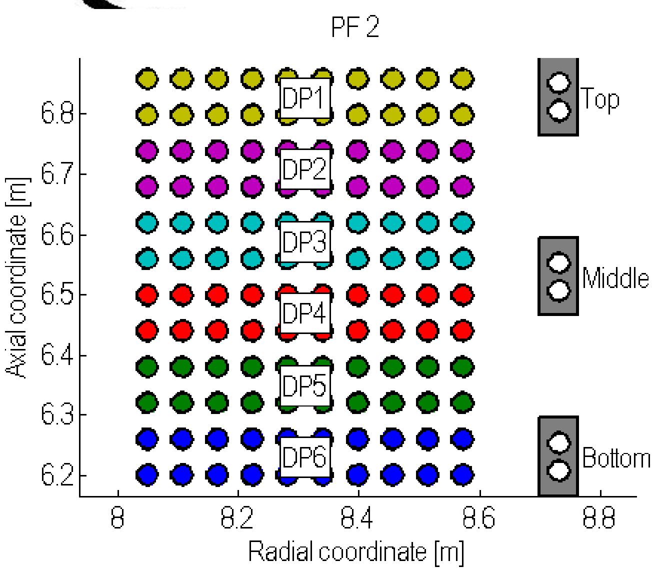
- Good agreement between measurement and simulation;
- Expected deviation due to hysteresis loss and intra-strand loss in the measurements, which are not included in the model;
- Peak power dissipation in “parallel” field at much lower frequency than in “serial” field due to the inter-cable coupling loops.

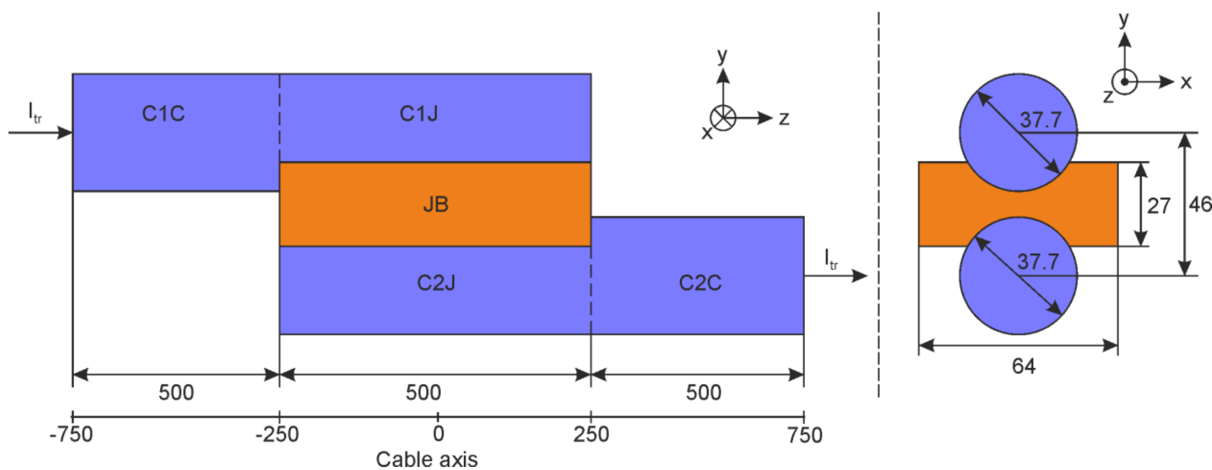




Simulation conditions for an ITER PF joint

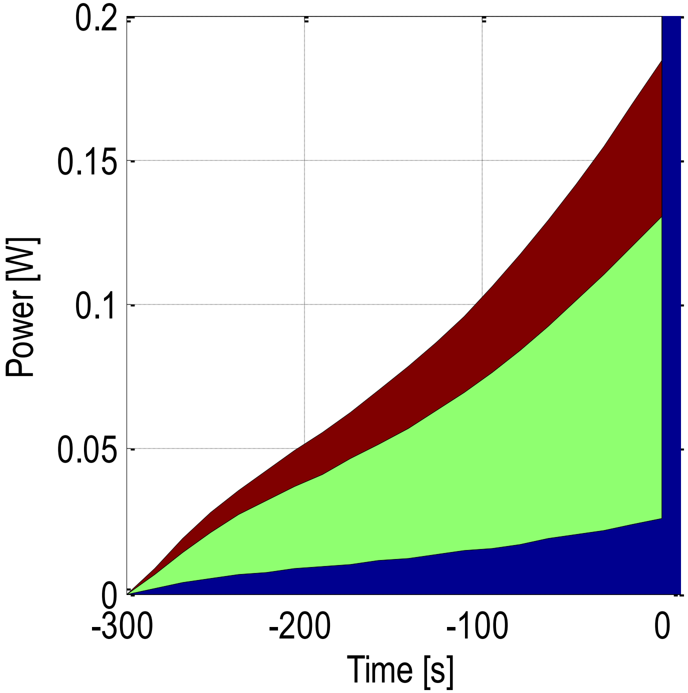
- Three locations for the joints are used;
  - The radial field components are stronger in the “Top” and “Bottom” joints than in the “Middle” joint;
- Transport current distribution among strands is assumed homogeneous at current entry and exit;
- To allow for current distribution among strands outside the joint region, an extra 0.25 m of cable is added at both ends of the joint in the simulation.
- The joint RRR is 100.

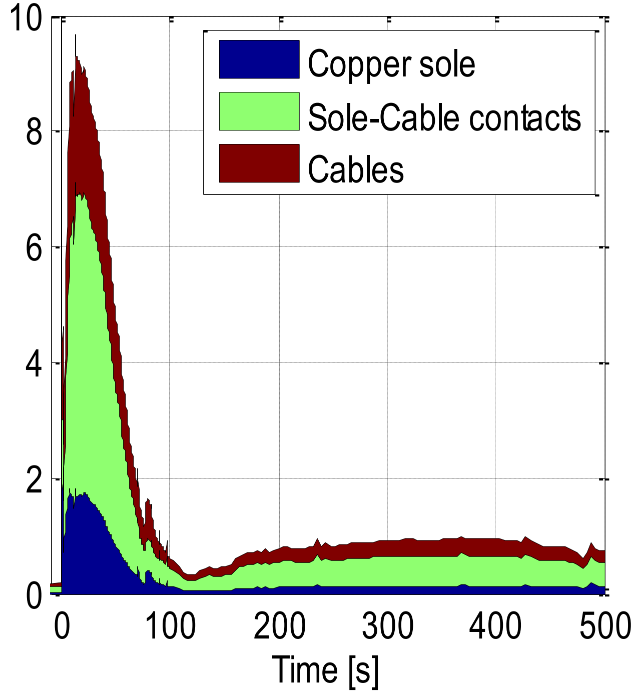




Coupling loss in the PF2-top joint at the start of a 15 MA plasma scenario

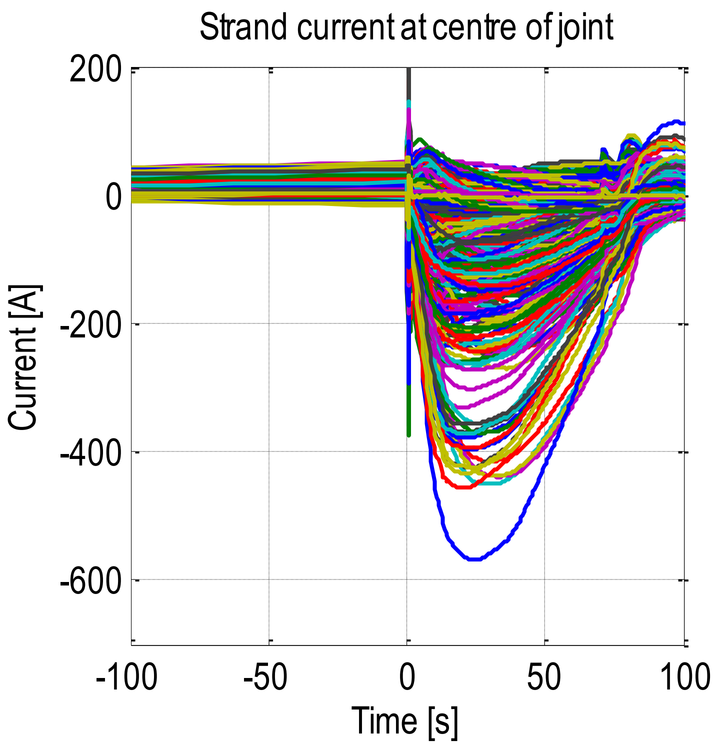
- A 300 second linear coil current ramp precedes the start of the plasma scenario (left figure);
- This is included in the simulations to have an initial current distribution;
- The power dissipation includes both the effects of dB/dt and of the transport current.

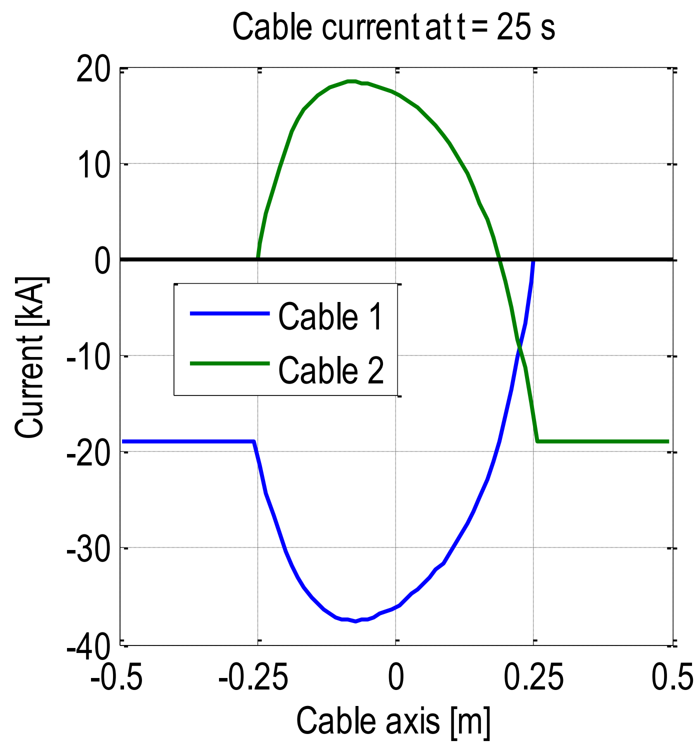




Strand currents in PF2-top Cable 1

- The left figure shows the strand currents of Cable 1 in the centre of the joint versus time;
- The clear bias towards negative values is caused by inter-cable coupling currents due to the radial field component;
- It’s effect is made clear by the right figure, which shows the total cable current along the length of the two cables at t = 25 seconds.





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Hysteresis model

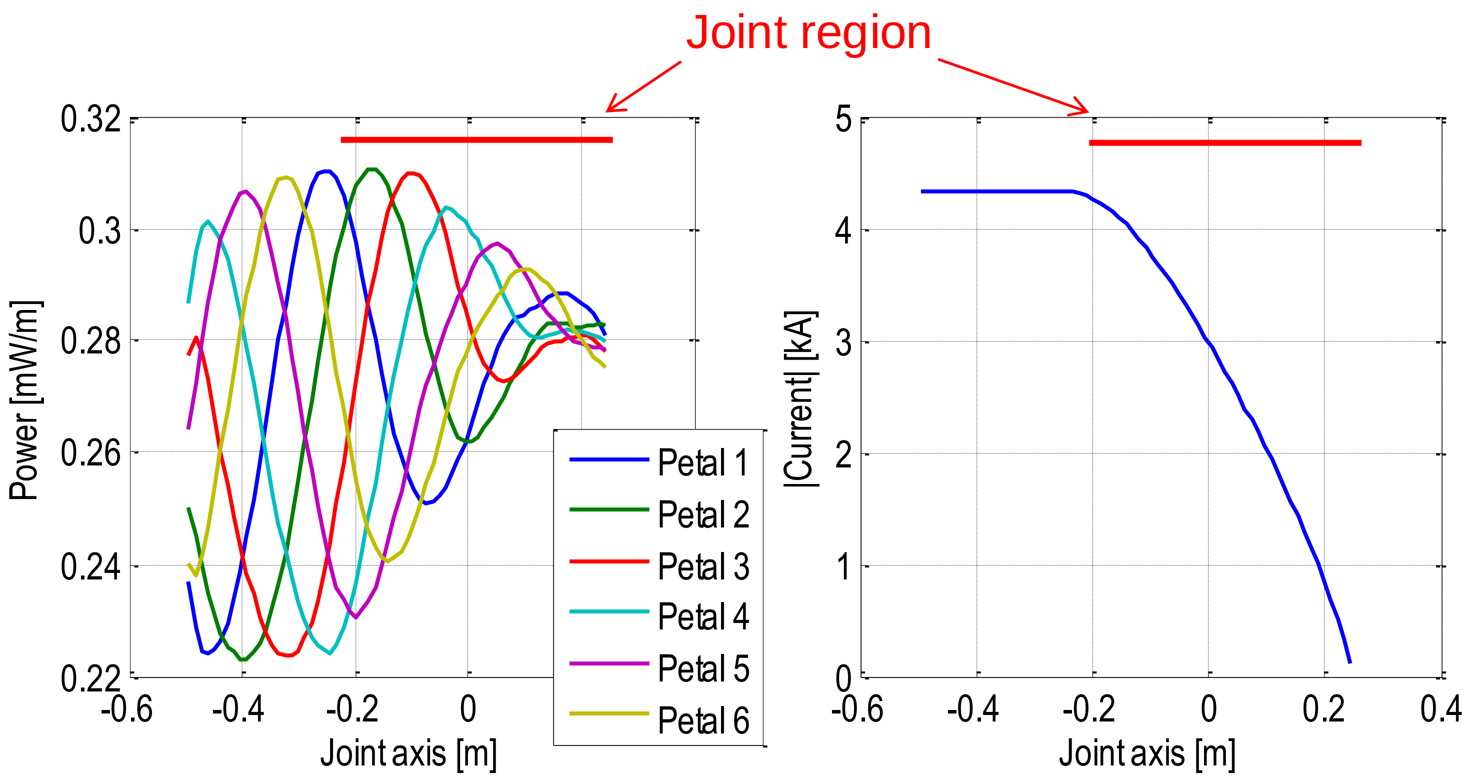
- The model assumes full filament penetration during the whole campaing. In general, the penetration field is only a few tenths of teslas;
- The equations for calculating the transient hysteresis loss are

$$\frac{dP_{hyst}}{dz} = \frac{2I_c}{3\pi}\left[1+\frac{I_t^2}{I_c^2}\right]\cdot\left|\frac{dB}{dt}\right| d_{eff} k_{nonCu}$$

  - I_c = critical current
  - I_t = transport current
  - d_{eff} = effective filament diameter
  - k_{nonCu} = fraction of non-copper material
- This includes both the change of the background field and the change of the transport current

Hysteresis loss in PF5-middle Cable 1 at start of scenario

- In the cable region the field on the strands is either amplified or reduced due to the transport current (-0.5 < axis < -0.25 meter);
- As a result, the hysteresis loss alternates along the length;
- Inside the joint, the transport current decays; the hysteresis loss becomes more homogeneous



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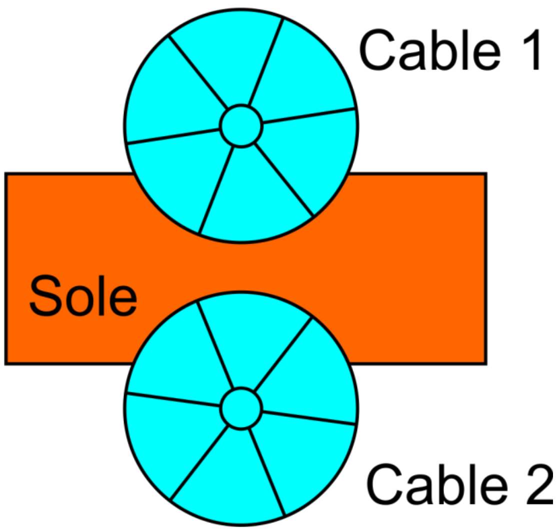
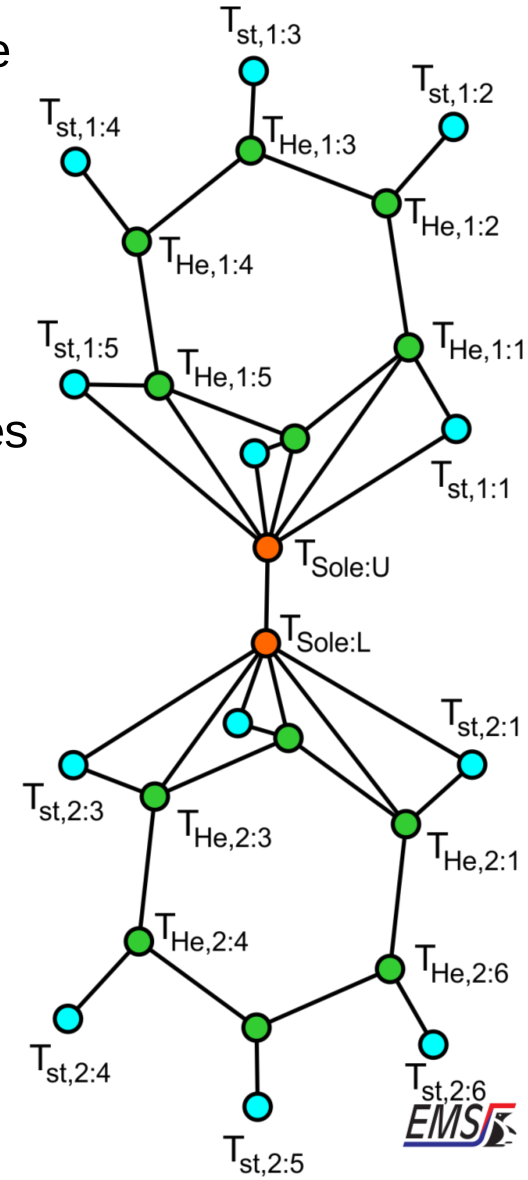
Overview of thermal model

- The temperature distribution is calculated along the length of the joint for:
  - Individual strand bundles of both cables
  - Helium inside these bundles
  - Upper and lower half of the joint box
- Thus, for PF joints, a total of 26 temperature profiles are calculated





Equations for the strand bundle

- The density (ρ_{st}), heat transfer coefficient ($h_{st\text{-}He}$), strand-helium wetted perimeter (C_{st}) and heat conductivity (k_{st}) are assumed constant;
- A quadratic fit for the $c_{p,st}$ (specific heat) versus temperature is taken;
- Direct heat exchange between strand bundles does not take place;
  - This exchange is covered by the helium;
- Contact term is a function of position to account for the rotation of the petal, and the partial contact between the cable and the copper sole.

$$A_{st}\rho_{st}\frac{\partial c_{p,st}T_{st,n}}{\partial t} = A_{st}k_{st}\frac{\partial^2 T_{st,n}}{\partial z^2} - C_{st-He}h_{st-He}\left(T_{st,n}-T_{He,n}\right) - C_{st-sole}h_{st-sole}\left(T_{st,n}-T_{sole}\right) + \frac{dP_{st,n}}{dz}$$

Heat exchange with helium

Heat exchange with sole

Power dissipation in strand bundle

Equations for the copper sole

- The density (ρ_{Cu}), heat transfer coefficients ($h_{sole\text{-}He}$ and $h_{sole\text{-}sole}$), joint-helium wetted perimeter (C_{sole}) and heat conductivity (k_{Cu}) are assumed constant;
- A quadratic fit for the $c_{p,sole}$ (specific heat) versus temperature is taken;

$$A_{sole}\rho_{Cu}\frac{\partial c_{p,Cu}T_{sole}}{\partial t} = A_{sole}k_{Cu}\frac{\partial^2 T_{sole}}{\partial z^2} - C_{sole-He}h_{sole-He}\left(T_{sole}-T_{He}\right) - C_{sole\_sole}h_{sole-sole}\left(T_{sole}-T'_{sole}\right) + \frac{dP_{sole}}{dz}$$

Heat exchange with helium
Heat exchange with other half of sole
Power dissipation in strand bundle

Equations for the helium flow

- The heat transfer coefficient ($h_{He\text{-}He}$) inter-petal wetted perimeter (C_{He_He}) are assumed constant;
- Linear interpolation is used from data for the density (ρ_{He}) and specific heat ($c_{p,He}$) versus temperature relationship;
- A fixed mass flow rate ($\dot{m} = A_{He} \cdot v_{He} \cdot \rho_{He}$) is assumed
- Pressure is 5 bar.

$$A_{He}\rho_{He}\frac{\partial c_{p,He}T_{He,n}}{\partial t} = A_{He}k_{He}\frac{\partial^2 T_{He,n}}{\partial z^2}$$

$$-\dot{m}\cdot c_{p,He}\frac{\partial T_{He,n}}{\partial z}$$ ← Helium flow

$$-C_{st-He}h_{st-He}\left(T_{He,n}-T_{st,n}\right)$$ ← Heat exchange with cable

$$-C_{sole-He}h_{sole-He}\left(T_{He,n}-T_{sole}\right)$$ ← Heat exchange with sole

$$-\sum_{i=1}^{6}C_{He\_He}k_{He\_He}\left(T_{He,n}-T_{He,i}\right)$$ ← Heat exchange with other petals

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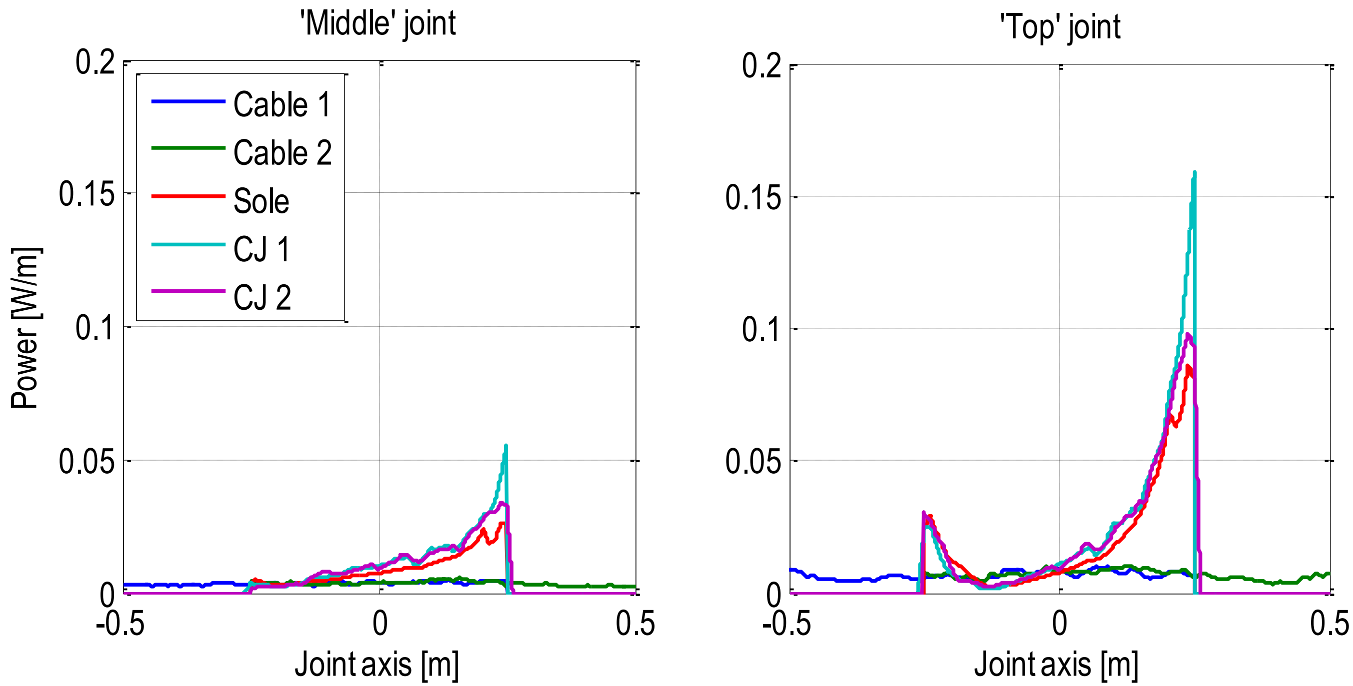
PF5: Power dissipation along joint length

- The power dissipation is calculated along the length of each component (strand bundle, joint half)
- Shown here is the result at the start of the plasma scenario (t = 0 s);
- CJ = cable-to-joint contact layer;
- Biased power due to coupling currents between cables



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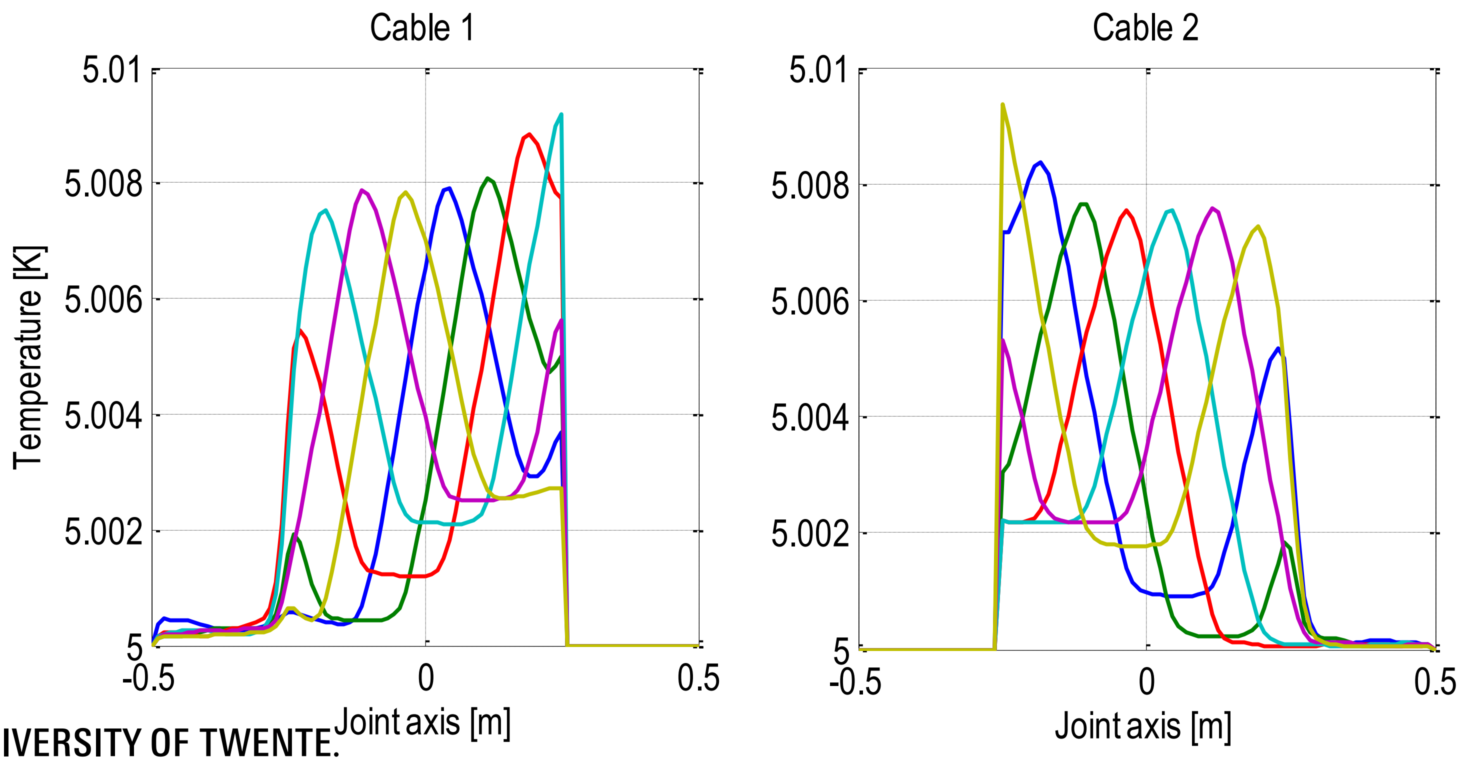
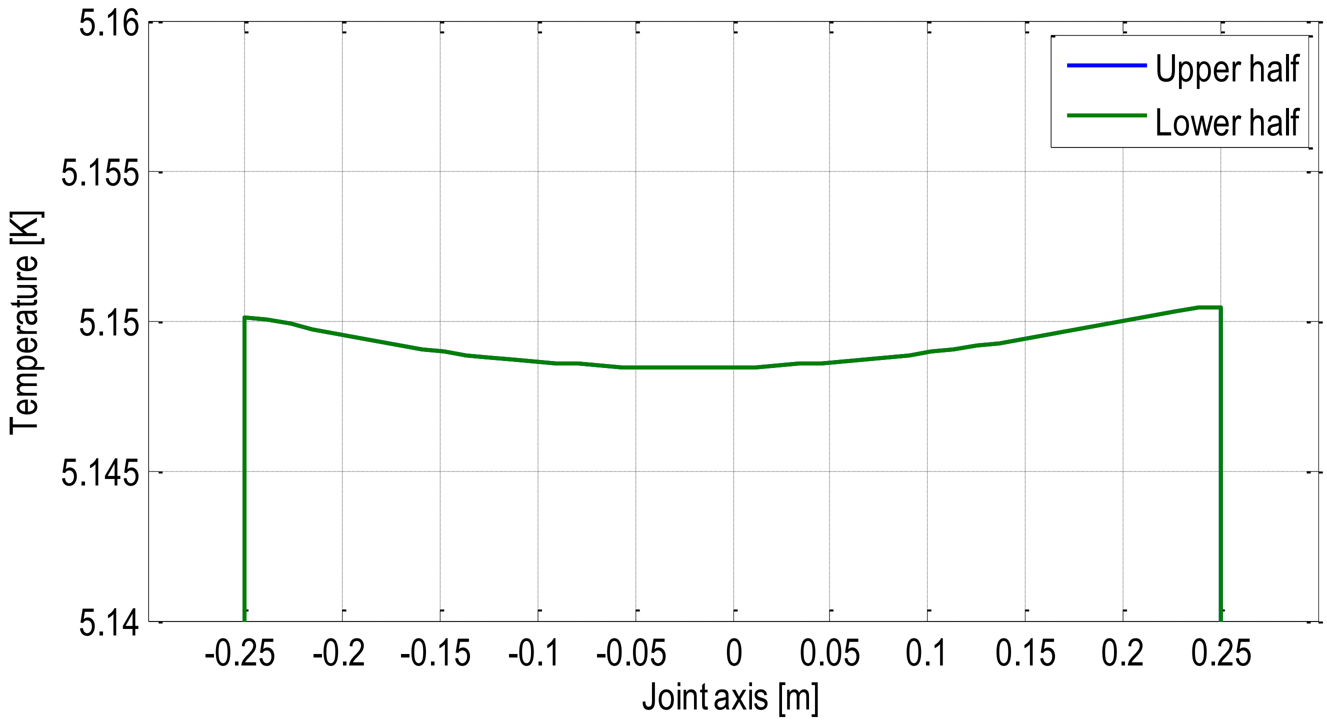
PF5-top: Petal temperature distribution at start of scenario

- Results at start of the scenario (t = 0 s);
- Despite biased power dissipation, the temperature profiles are equivalent in both cables;
- Periodicity of the temperature is due to the rotation of the cable in the joint and periodic contact with the copper sole.



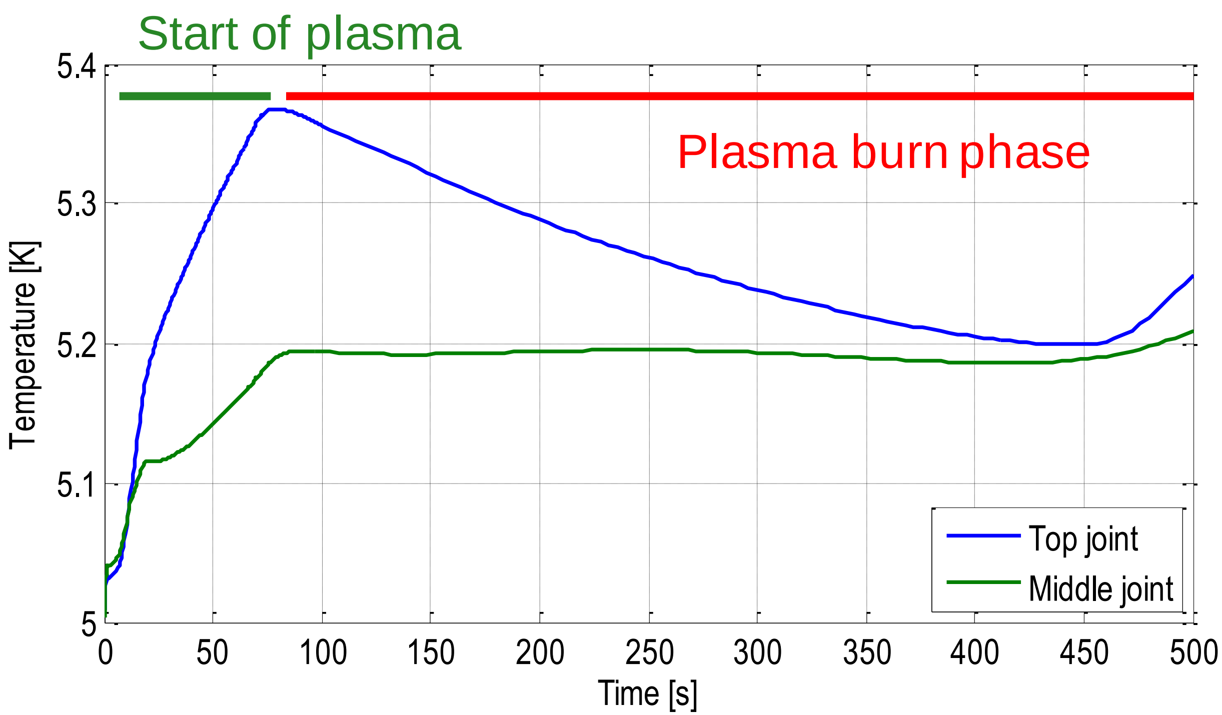
PF5-top: Copper sole temperature

- Results at start of the scenario (t = 0 s);
- Temperature profile identical for both joint halfs;
- High thermal conductivity leads to smoothing of the temperature distribution;
- Considerably higher temperature in the copper sole than in the cables.



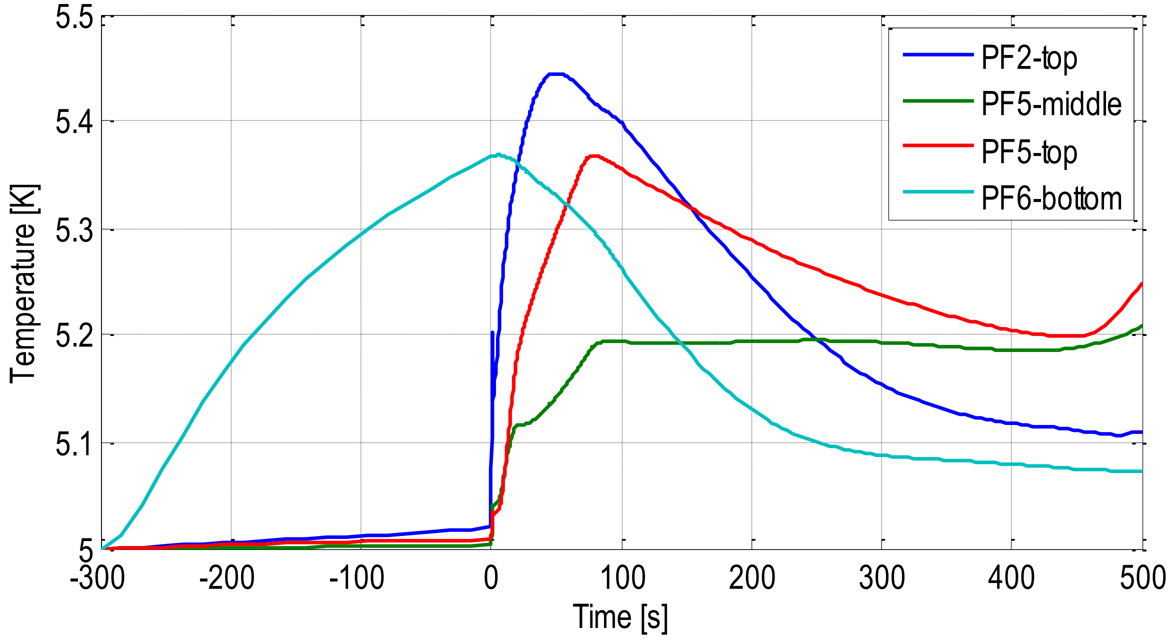
PF5: Evolution of temperature during the scenario

- The temperature is shown at the downstream-end of the “hottest” petal (identical geometries were taken for the “top” and “middle” joints);
- The stronger radial field in the “top” joint leads to a +0.15 K higher temperature after the start of plasma;
- This temperature difference decays during the plasma burn phase, when the dB/dt and dI/dt are much smaller.



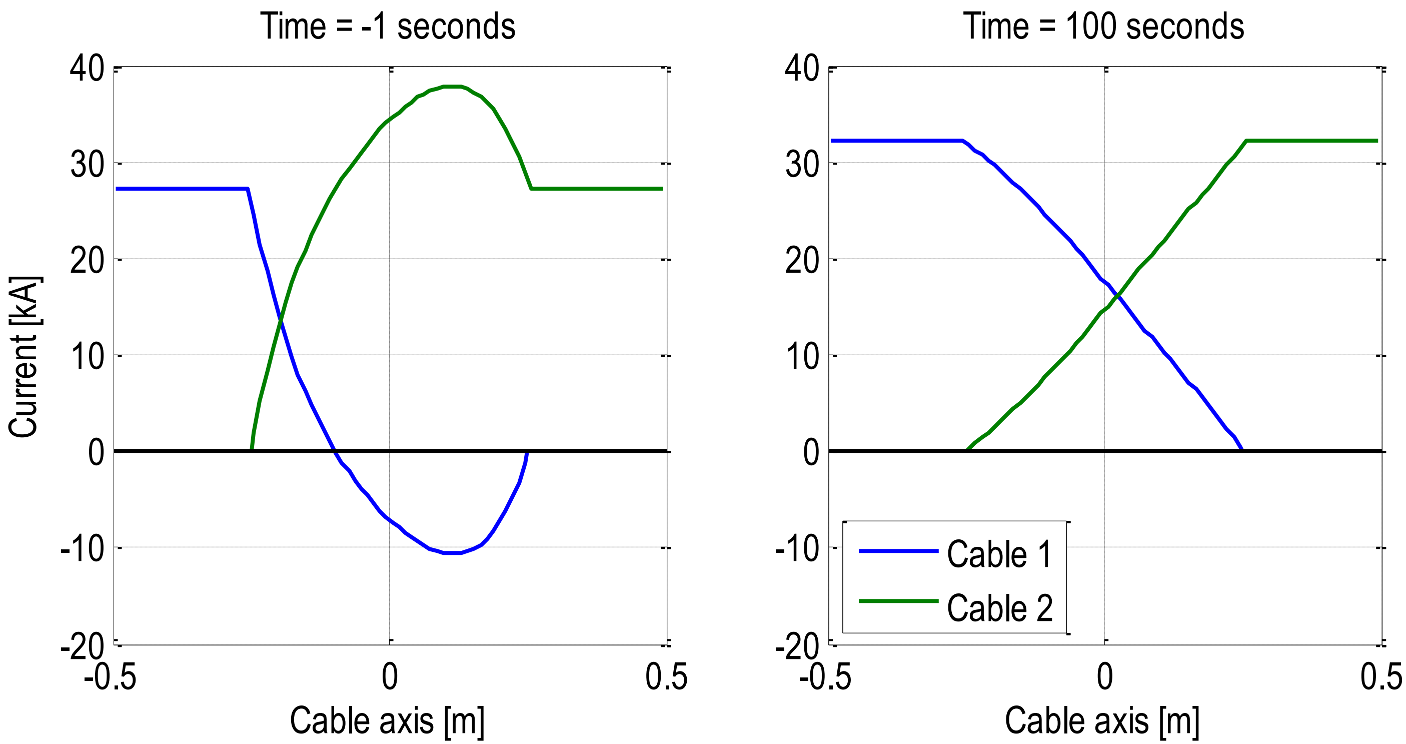
Performance of other joints

- Other joints have been simulated as well, which show similar temperature behaviour during the plasma scenario;
- The PF6-bottom joint shows a large temperature increase during the current ramp preceding the scenario;
- During the scenario, its temperature decreases, whereas the transport current increases…



PF6-bottom: Inter-cable coupling currents

- The PF6 coil starts the scenario with a high transport current;
- As a result, it also has a high dB/dt during this phase, with a considerable radial component for the bottom joint;
- This results in much larger coupling currents before the scenario (left figure) than during the scenario (right figure).



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- JackPot-AC, The coupling loss model for CICC joints has been expanded with a thermal model;
- Although these models are not coupled, they serves as a powerful analysis tool for CICC joints;
- The copper sole smears out non-uniform power dissipation along the cable axes;
- The radial field component causes a considerable coupling current between the cables in joints at the edges of a coil, compared to joints in the middle;
- As a result of these coupling currents, a more than 0.15 K peak temperature difference is observed in the simulation of the PF5 joints;
- Similar coupling currents increase the peak temperature of the PF6 bottom joint to more than 0.35 K above the inlet temperature before the start of the plasma scenario.