UNIVERSITY OF TWENTE.

Pulsed field stability and AC loss of ITER NbTi PF joints by detailed quantitative modeling

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☑ Background

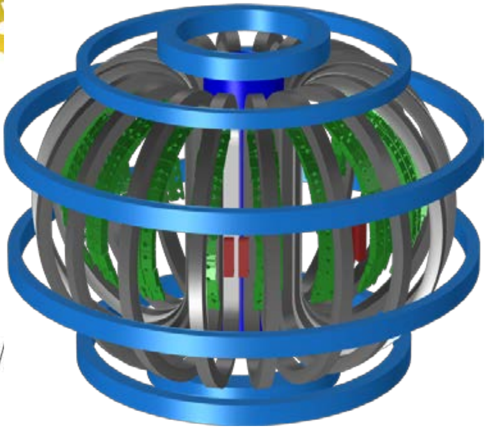
- PF joint
- model

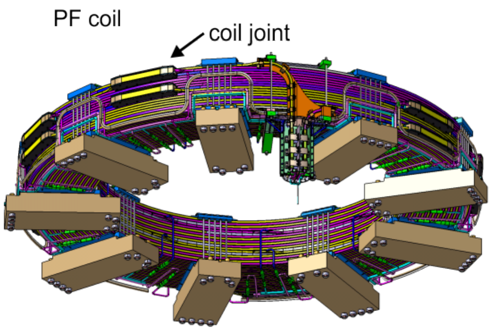
❑ Performance analysis

- Electromagnetic force
- Cable-sole mask
- Contact resistivity

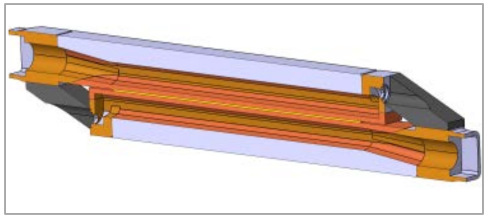
❑ Conclusion

ITER Poloidal Field (PF) coil joints

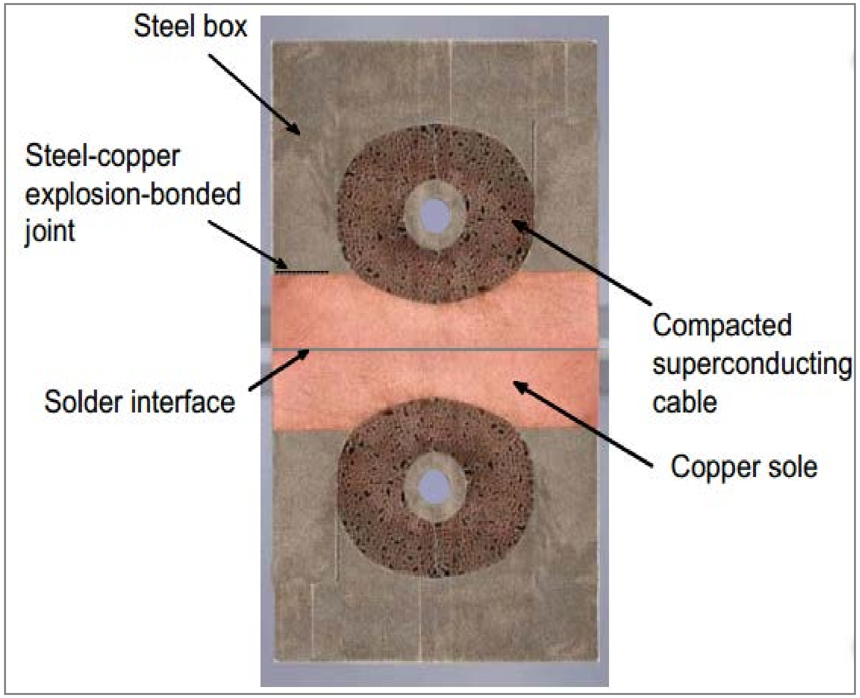




Shaking hands lap-type joint



- ITER: Six PF coils drive and provide the stability of the plasma.
- Operate in pulsed mode with current up to 55 kA, and peak field up to 5 T.
- Double pancake module.
- 100 shaking hands lap-type joints – electrical / thermal connection.



Cross-section joint

Overview of JackPot AC/DC model – Cable network

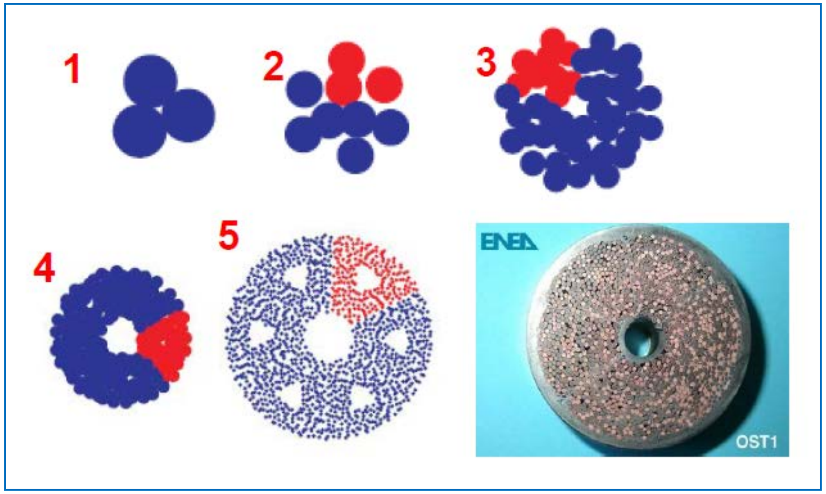
Jackpot AC/DC model – (University of Twente, Netherlands).

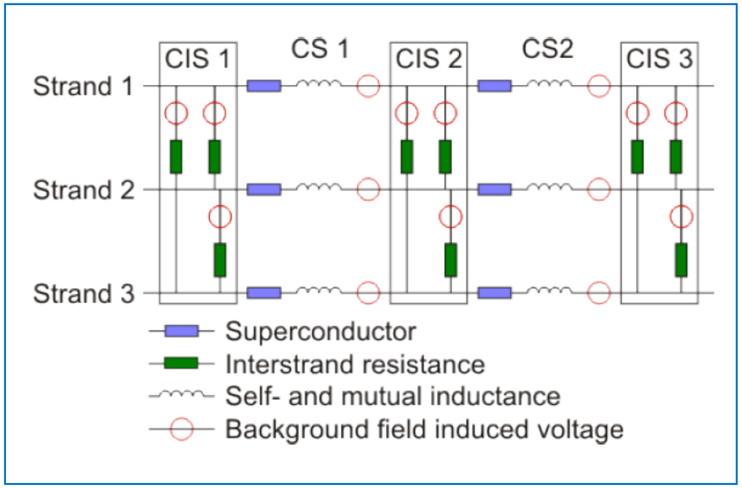
Strand level cable model, accurately describes all strand trajectories in CICC.

- Contact resistance:

  Inter-strand, inter-petal and strand to joint copper resistance
- Self and mutual inductance
- Coupling with background field

All the quantities are obtained from the geometry and the experiments thus there are no free parameters in the model.





Overview of JackPot AC/DC model – Joint network

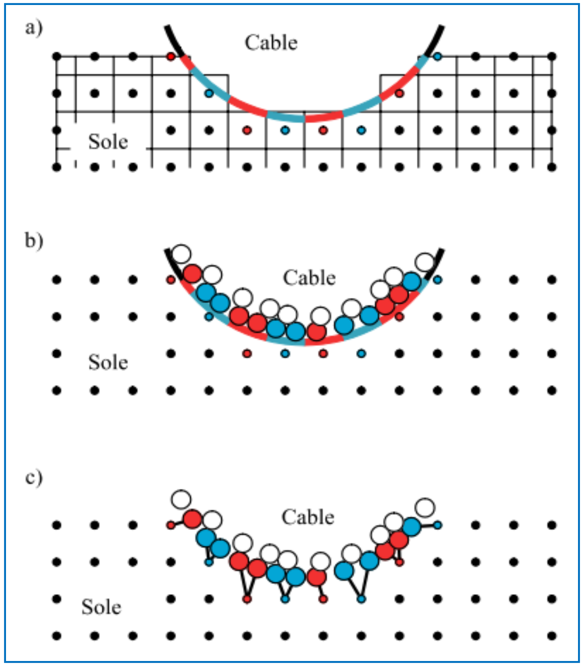
Characters:

- A Partial Element Equivalent Circuit (PEEC) model is used to simulate the copper sole.
- Transfer from electromagnetic domain into the circuit domain, enable to combine the cable model in straightforward manner.
- Mutual inductance of copper: Multi-Level Fast Multi-pole Method (MLFMM).

a) Shape of the sole: remove PEEC boxes at the cable regions.

b) Determine the strands which contact the sole.

c) Coupling and strand-to-sole contact resistance.



PF joints simulations and measurements

- PF2, PF5, PF1&6 joints, different cable patterns and joint configurations.
- PF5, PF1 and PF6 joints were simulated and also measured in the SULTAN facility.

Cable pattern of ITER PF CICCs:

	PF 1,6	PF 5	PF 2,3,4
Cable pattern	3SC x 4 x 4 x 5 x 6	(3SC x 4 x 4 x 4 +C) x 6	(((2SC + 1Cu) x 3 x 4 + C1) x 5 +C2) x 6

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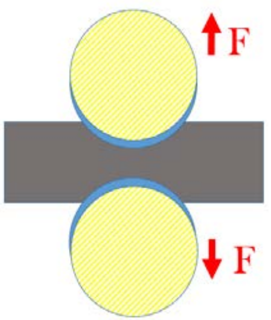
Non-linear V-I characteristic vs. electromagnetic force (1)

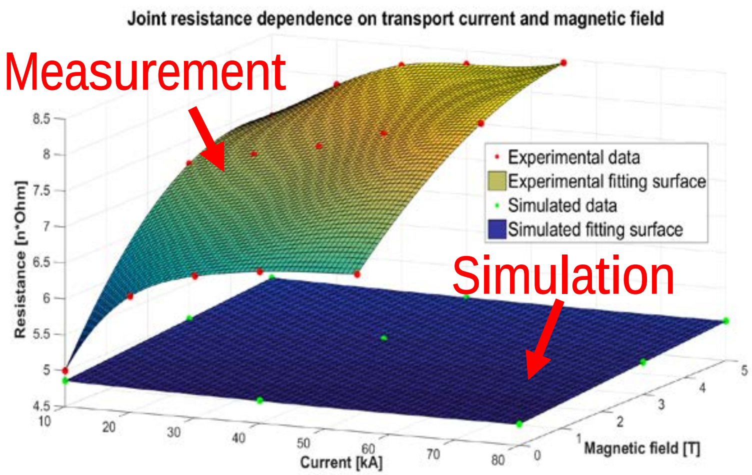
Observation:

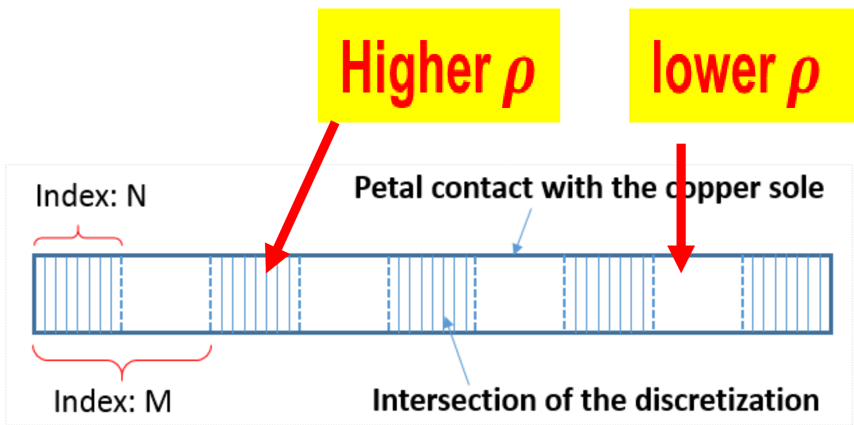
- Sample PFJEU2 measurement: Non-linear DC Voltage-Current (V-I) characteristic.
- Design criterion 5 $n\Omega$, vs. Measured variation of resistance: 3.5 $n\Omega$!!
- Probable reason: Disengagement cable-sole due to the electromagnetic force.

Method:

- Non-homogeneous contact resistance model.
- Changing the resistivity and contact area.
- High resistivity areas called “Patch”, $Patch_{ratio} = N/M$



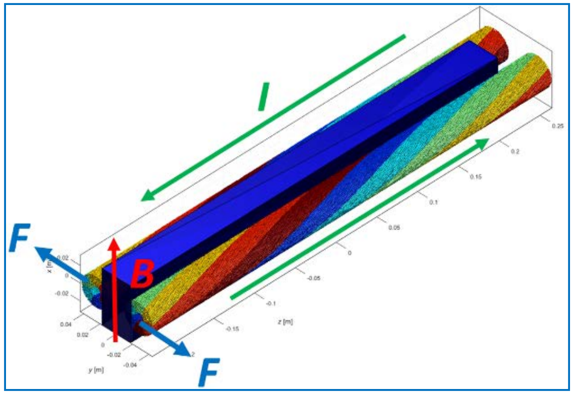




Non-linear V-I characteristic vs. electromagnetic force (2)

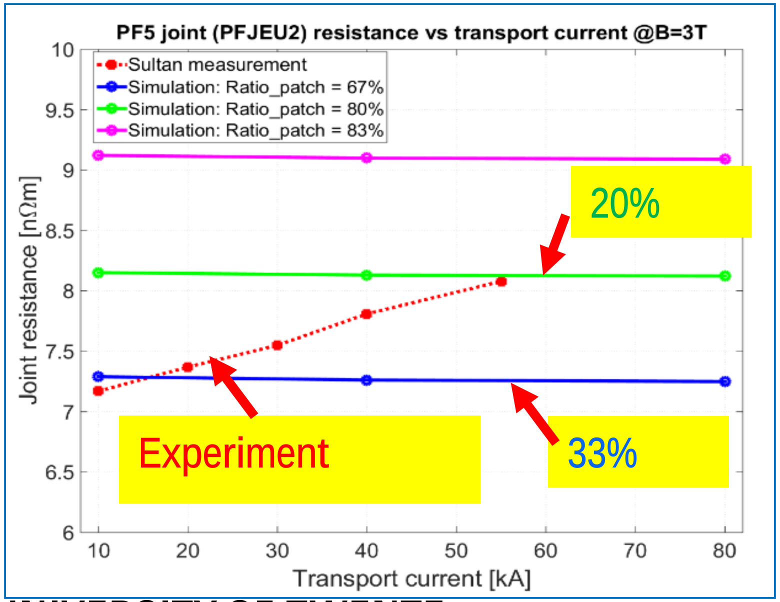
Results & Reasons:

- Enormous electromagnetic force $F = B \times I$.
  → Only **20%** effective contact area in worst case!
- Absence of the solder layer (cable-to-sole).

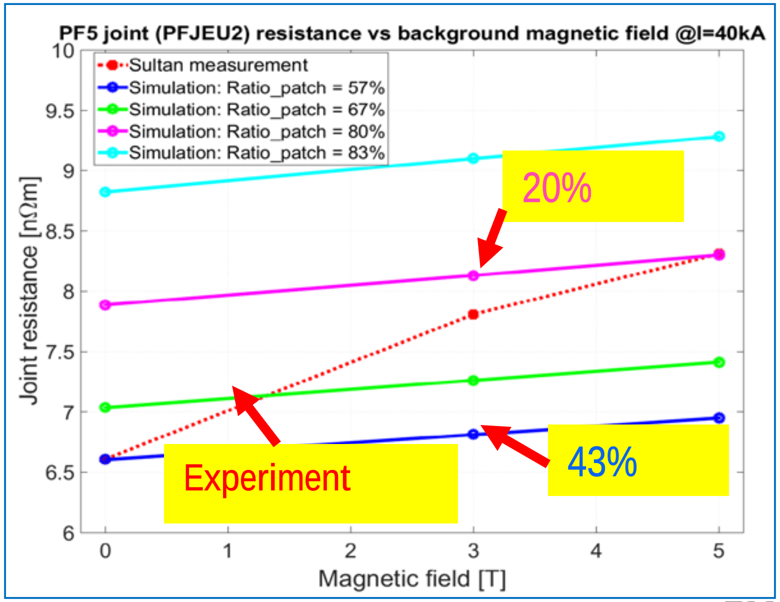


Total: Joule heating loss + AC loss + Mechanical loss.

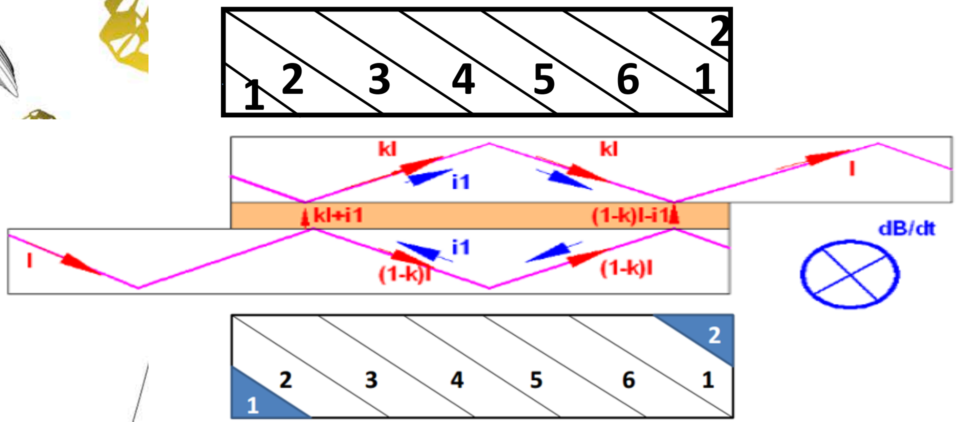
R vs Transport current:

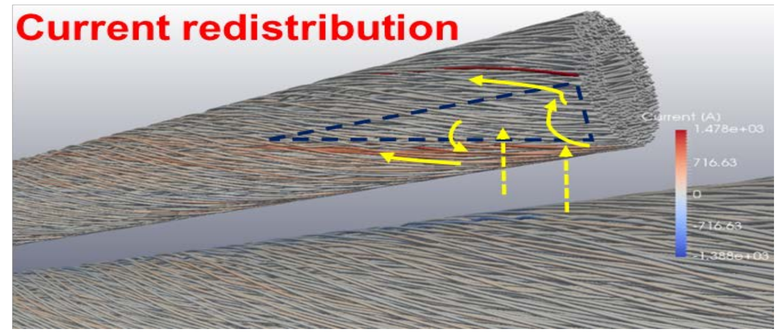


R vs Magnetic field:

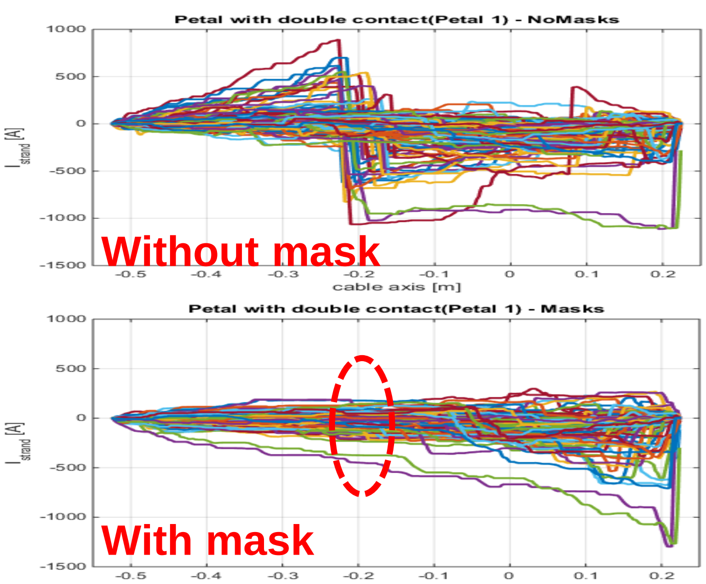


Current redistribution – Effect of Petal-Sole mask





Strand current in one petal:



- Petal double contact with the sole.
  Large induced low-resistance current loops.
  Mask: polymer (Kapton).

- Reduces large induced currents in strands from double contacted petal loops.

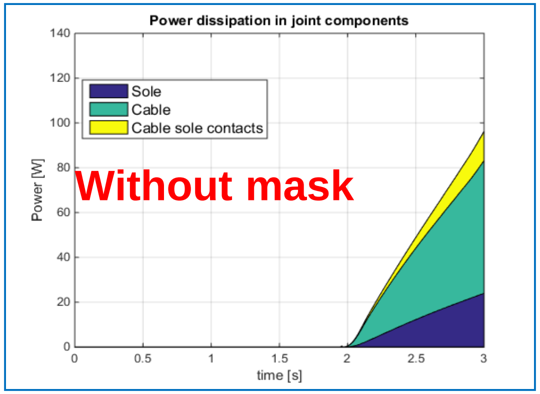
- However, currents in petals with mask is compelled to adjacent petals.
  → Increased current in other strands

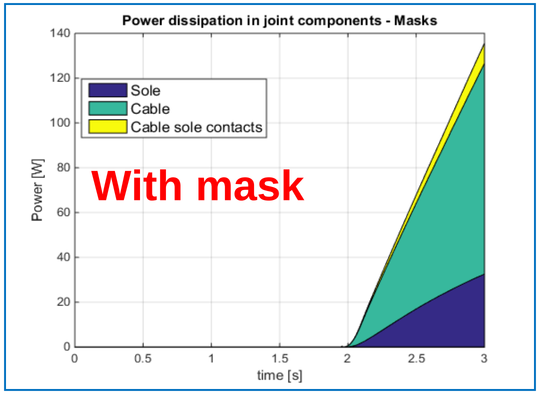
Overall, effect of masks is marginal.

Power distribution – Effect of Petal-Sole mask

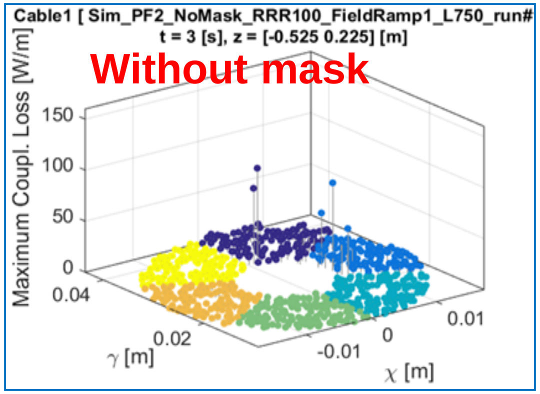
- Masks increase the joint power dissipation, correlates with mask area.
- Coupling loss redistribution between petals, increased power at interface of two petals with masks.
- Current non-uniformity caused by masks lead to severe power non-uniformity.

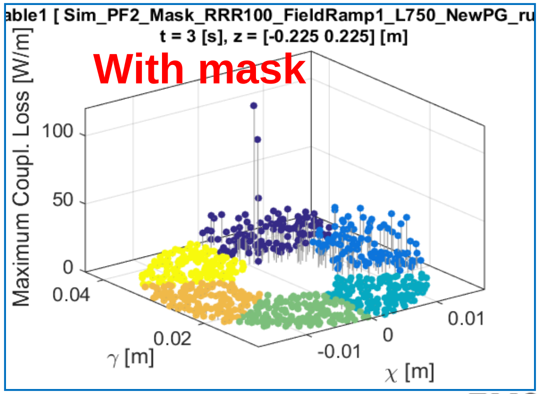
Total power dissipation:





Maximum power distribution in petals:

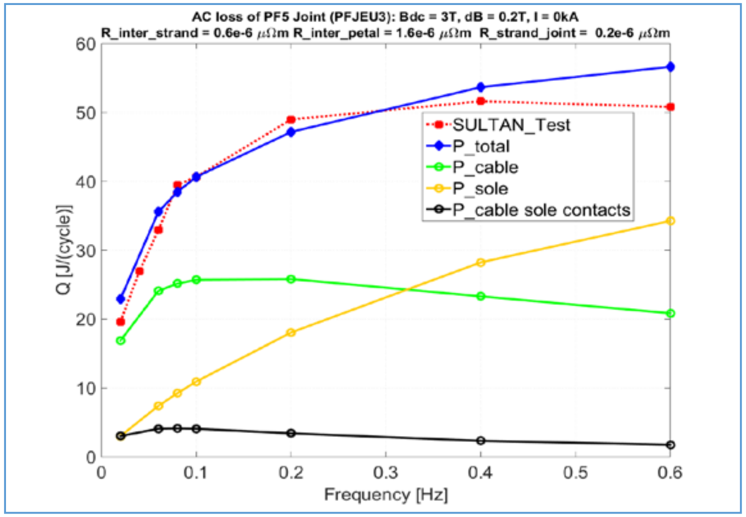


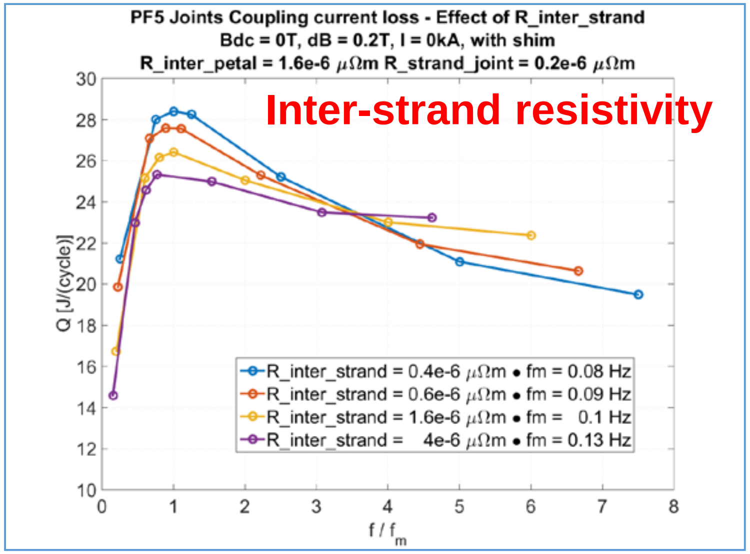


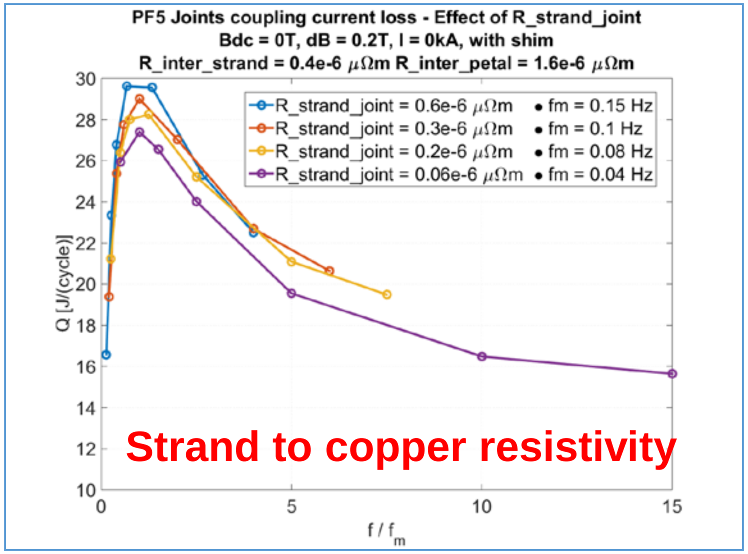
AC losses – Effect of contact resistivity

- Contact resistivity → Current distribution → power dissipation.
- Three components:
  Cable, copper sole, cable-sole contacts.

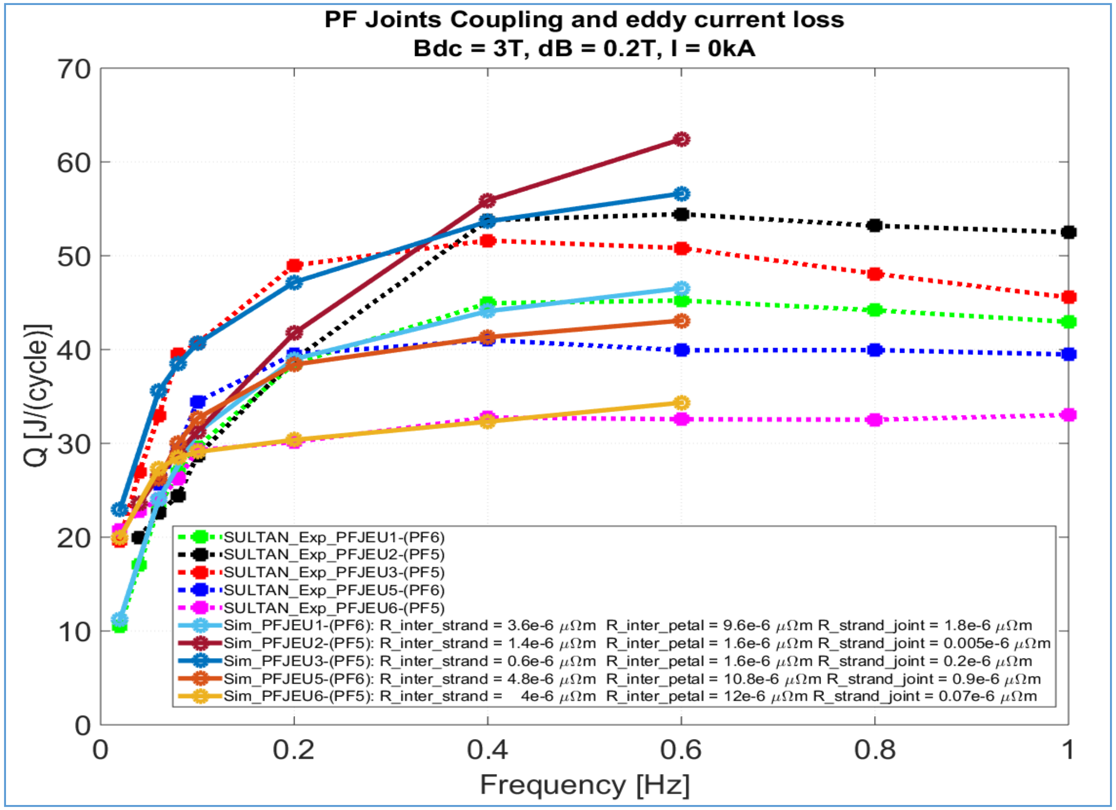
- In general, increase of inter-strand resistivity and decrease of cable-to-sole resistivity helps to reduce coupling loss.







Results of PF joints – Comparisons between simulation (UT) and measurement (SULTAN)



- Five PF joint samples simulated using measured material properties i.e. copper RRR, and realistic inter-strand, -petal and strand to sole Rc (based on experiments).
- Good agreement between simulation and Sultan measurement.
- Quantitative adjustments possible by modeling: Joint resistance (DC) and AC loss.

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Conclusion

1. Five PF (PF5 &1,6) joint samples are simulated and compared with the test results in the SULTAN facility.

2. Non-linear V-I characteristic explained by effect of electromagnetic force.

3. Effect of cable-sole masks of reducing peak strand currents is marginal; but increases joint power dissipation.

4. Parametric model studies allow quantitative design optimization, by variation of copper-, contact resistivities and application of resistivity masks.

Thank you!