Overview and assessment of electrical arcing faults in ITER superconducting magnets system

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Electrical: Kim Cave-Ayland
Thermal damage: Fred Domptail
Arc: Andrew Ash, Andrew Holmes
Safety advisor: Neill Taylor
ITER Organization: Kazuya Hamada
ITER Organization: Neil Mitchell

Outline

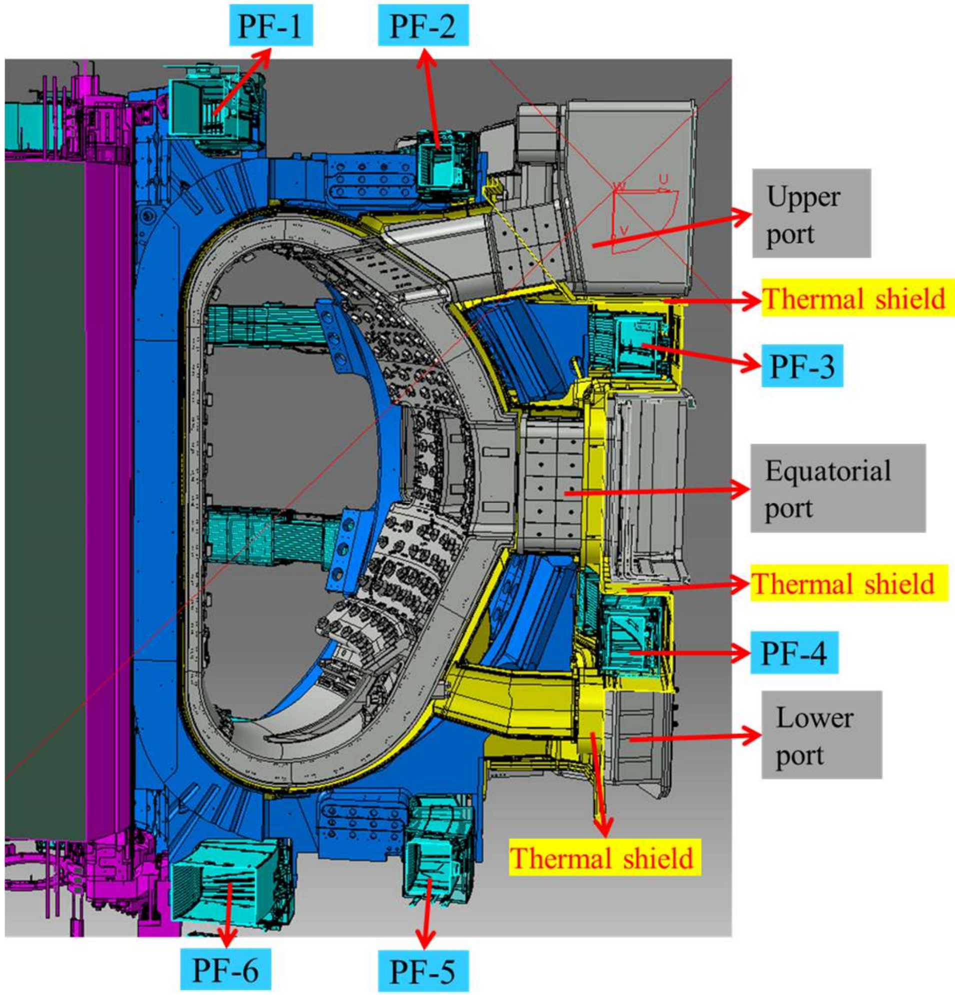
- Introduction
- Methodology
- ITER application
- Summary
- Further R&D

Introduction

- **Safety concerns to ITER superconducting magnets**
  - Large amount of magnetic energy stored in ITER superconducting coils: ~40GJ in TFC and up to ~10GJ in CS/PFC
  - The consequences (damaging magnets or adjacent components?) if the massive energy localised
  - Safety questions from French Regulator
- **Prevention/protection applied to ITER magnets**
  - Quench detection system: voltage; helium mass flow and pressure
  - Fast discharge unit to discharge stored energy
- **Previous analyses were done >10 years ago**
  - The expertise developed the analysis tools has not been maintained (retirement etc.)
  - More/further detailed and qualified analyses are required – computing technology has been developing rapidly to allow better analysis tool development

Introduction

- **Damage to magnets (internal arcs)**
  - in TF coil: unmitigated quench (benchmark vs. MAGARC-TF/INL)
  - in PF coil: unmitigated quench or electrical short in PF-3
  - In Busbar
- **Damage to adjacent components (external arcs)**
  - From coils to VV
    - Molten materials from PF-3 ➔ vacuum vessel port extension
    - External electric arcs from PF-3 to thermal shield and vacuum vessel
  - Arcs in Busbar



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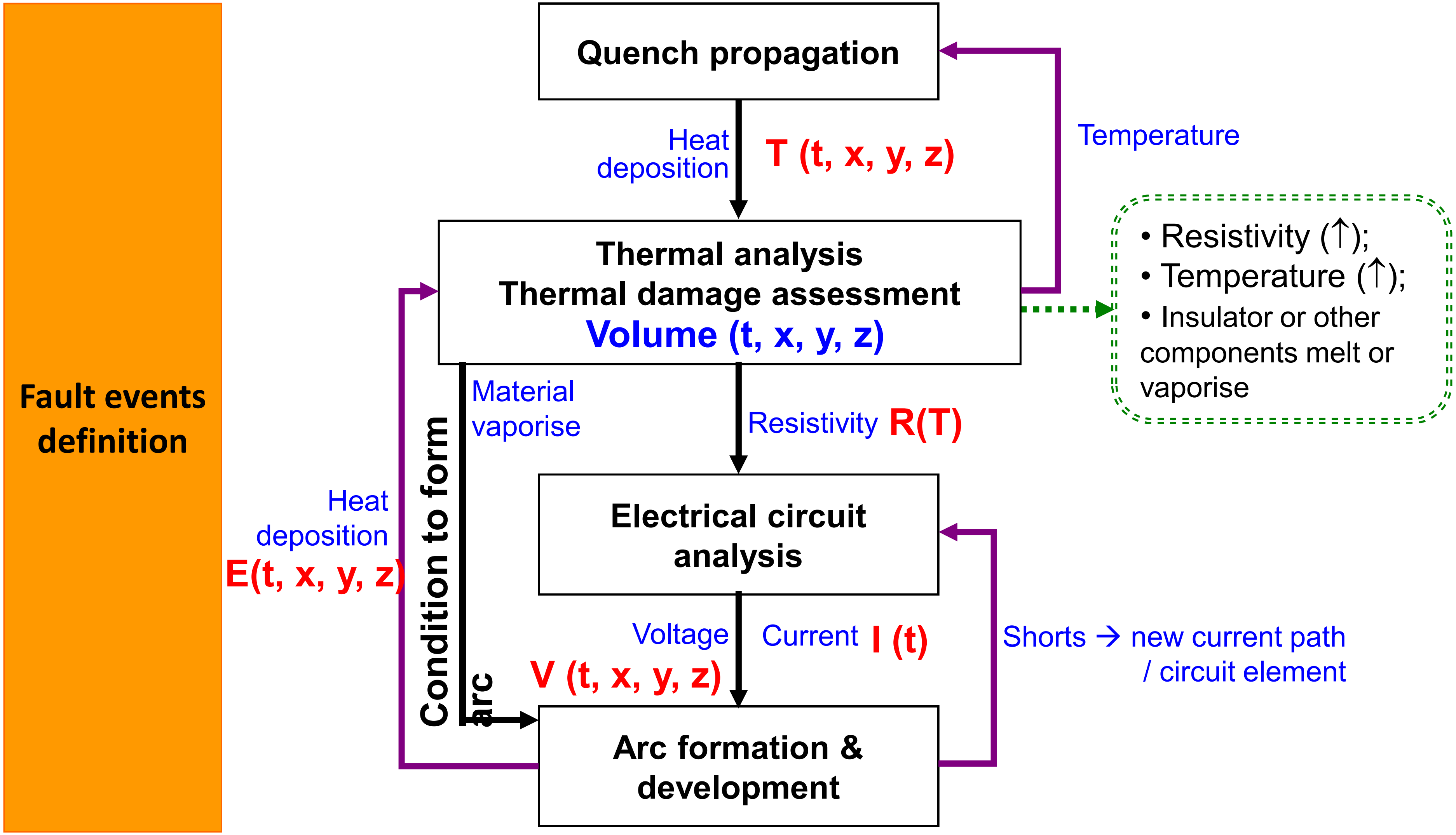
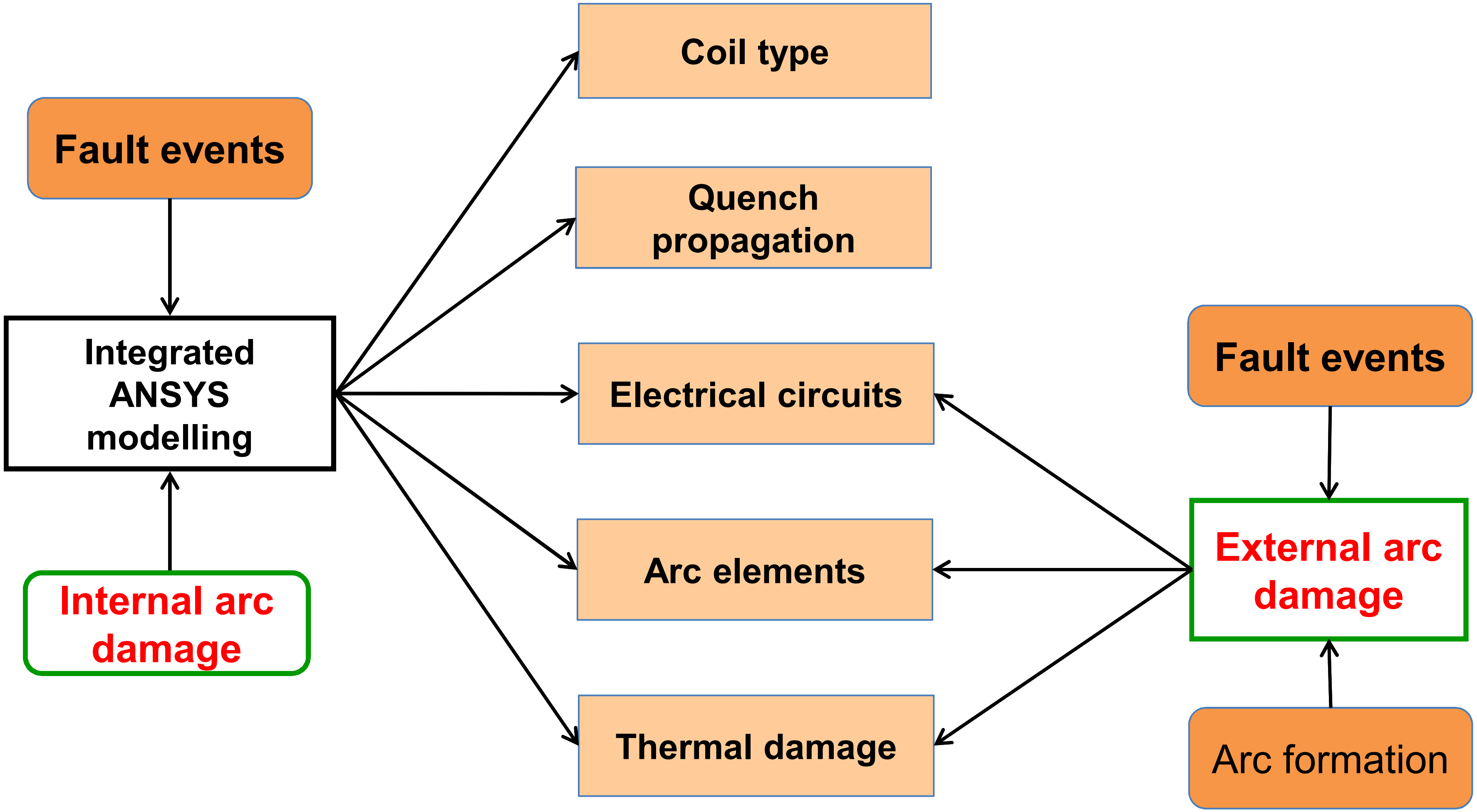
Methodology –work flowchart



Methodology



Methodology – work scope

- **Integrated ANSYS model (presentation by S. McIntosh)**
  - Python programme and APDL
    - to build geometry
    - To couple multiple physics
    - Post-processing results
  - Quench in superconductor
  - Electrical circuit
  - Arc models
  - Thermal assessment
- **Arc models**
- **Electrical simulations**
- **Thermal damage assessment**

Integrated ANSYS modelling

Simon McIntosh

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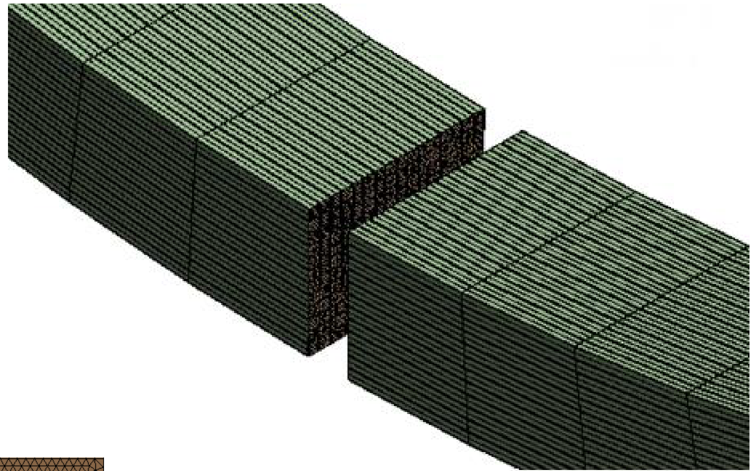
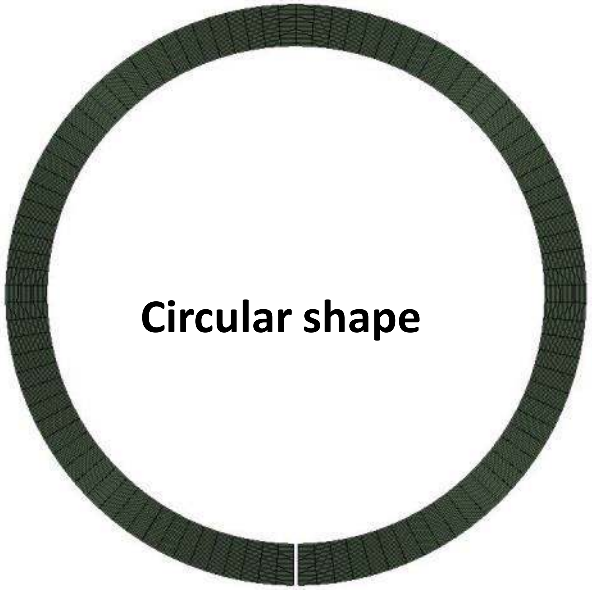
Details to be presented by Simon McIntosh

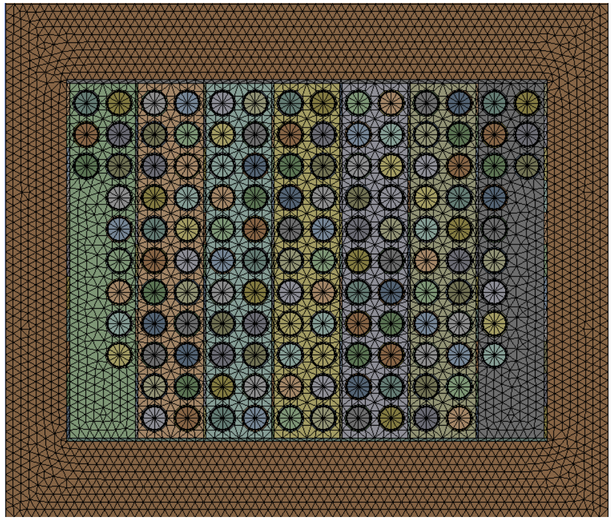
Integrated ANSYS model

- **ANSYS as platform to integrate**
  - ITER coils geometry
  - Quench + electrical network + arc + thermal damage
- **Benchmark vs. MAGARC (INL/US)**

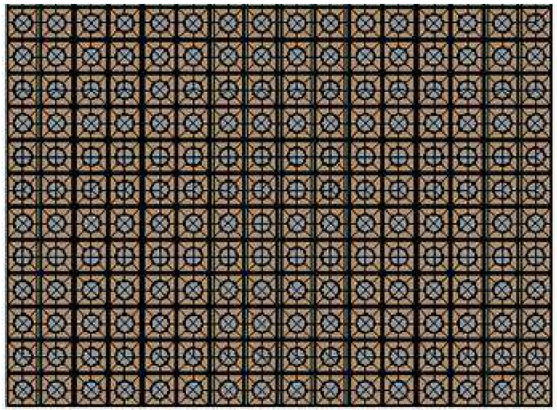




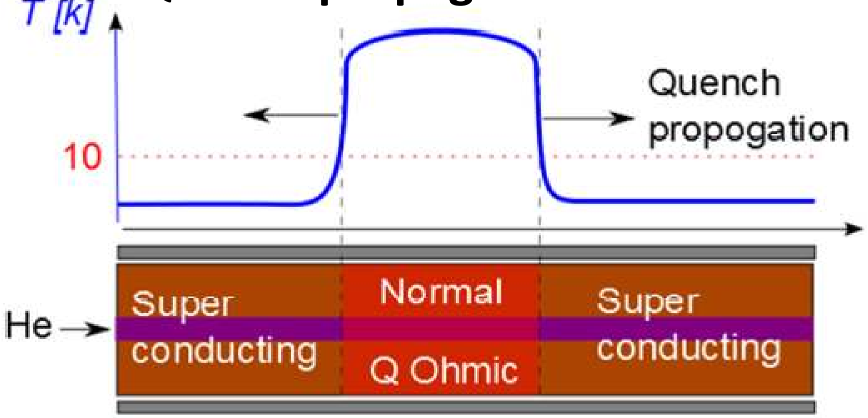
TFC cross-section



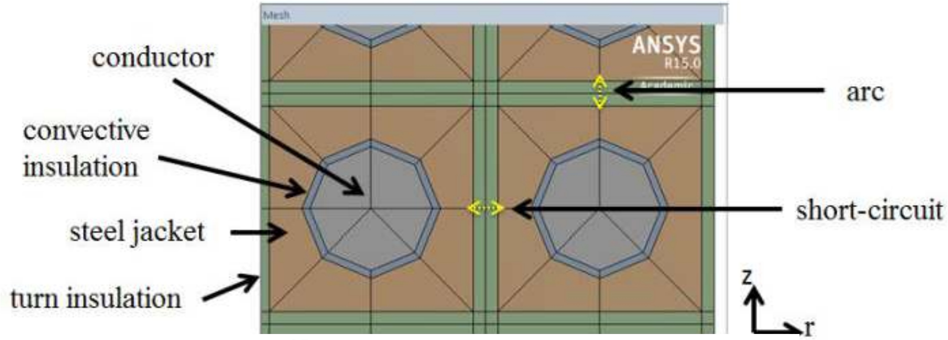
PFC cross-section

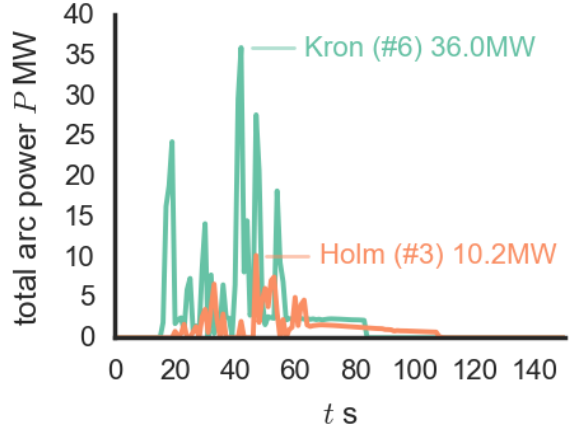


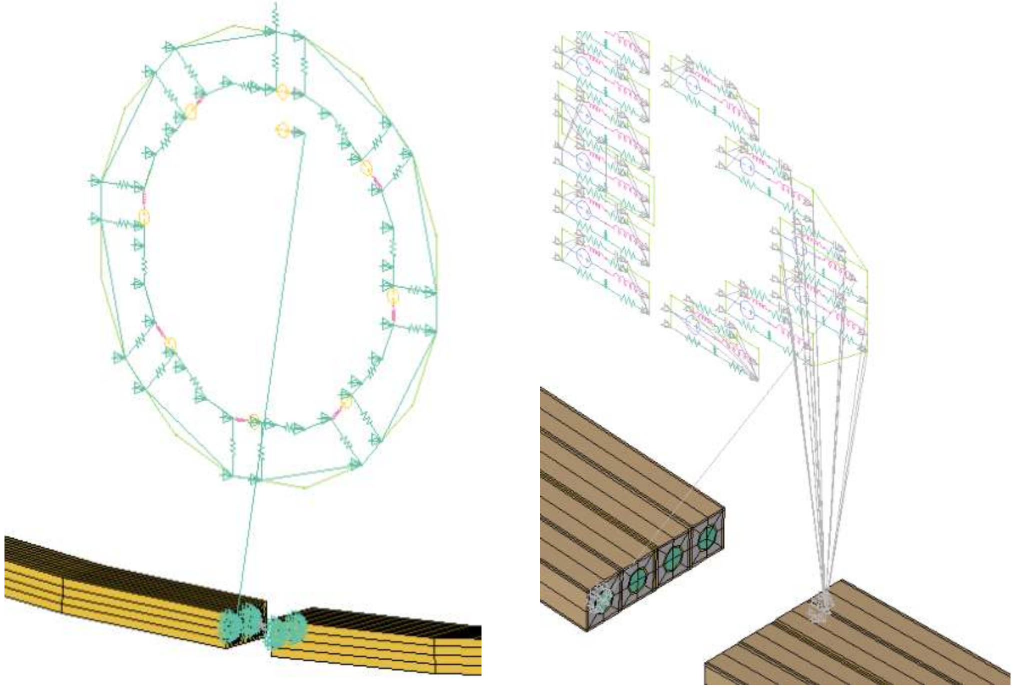
Quench propagation



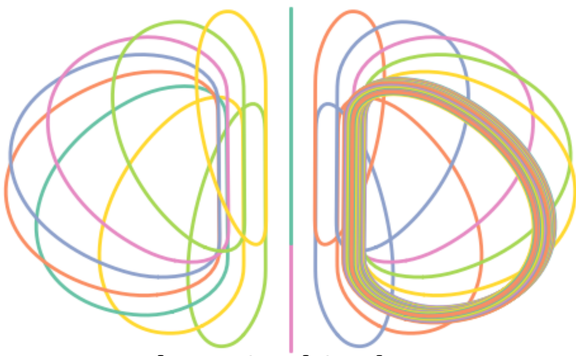
Electrical arcs





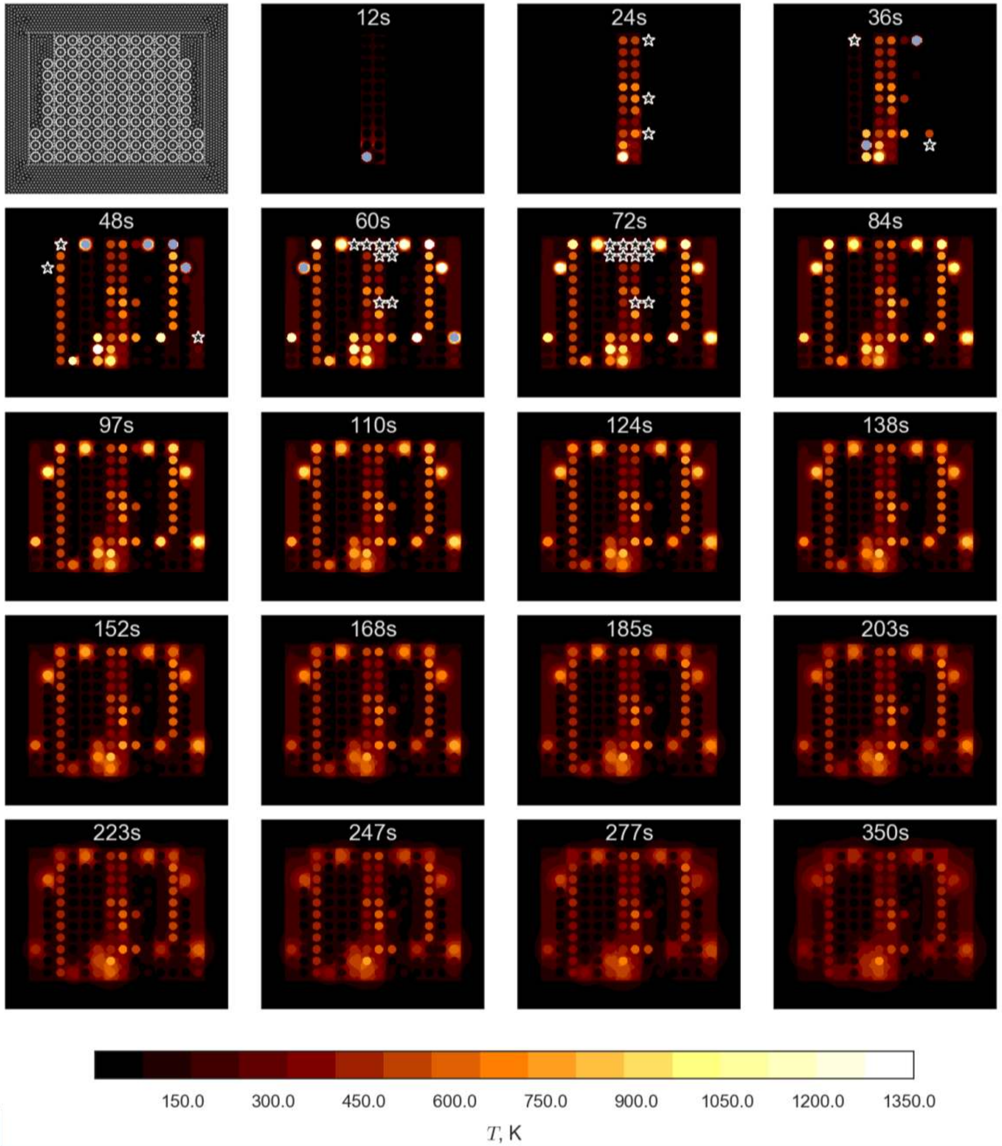


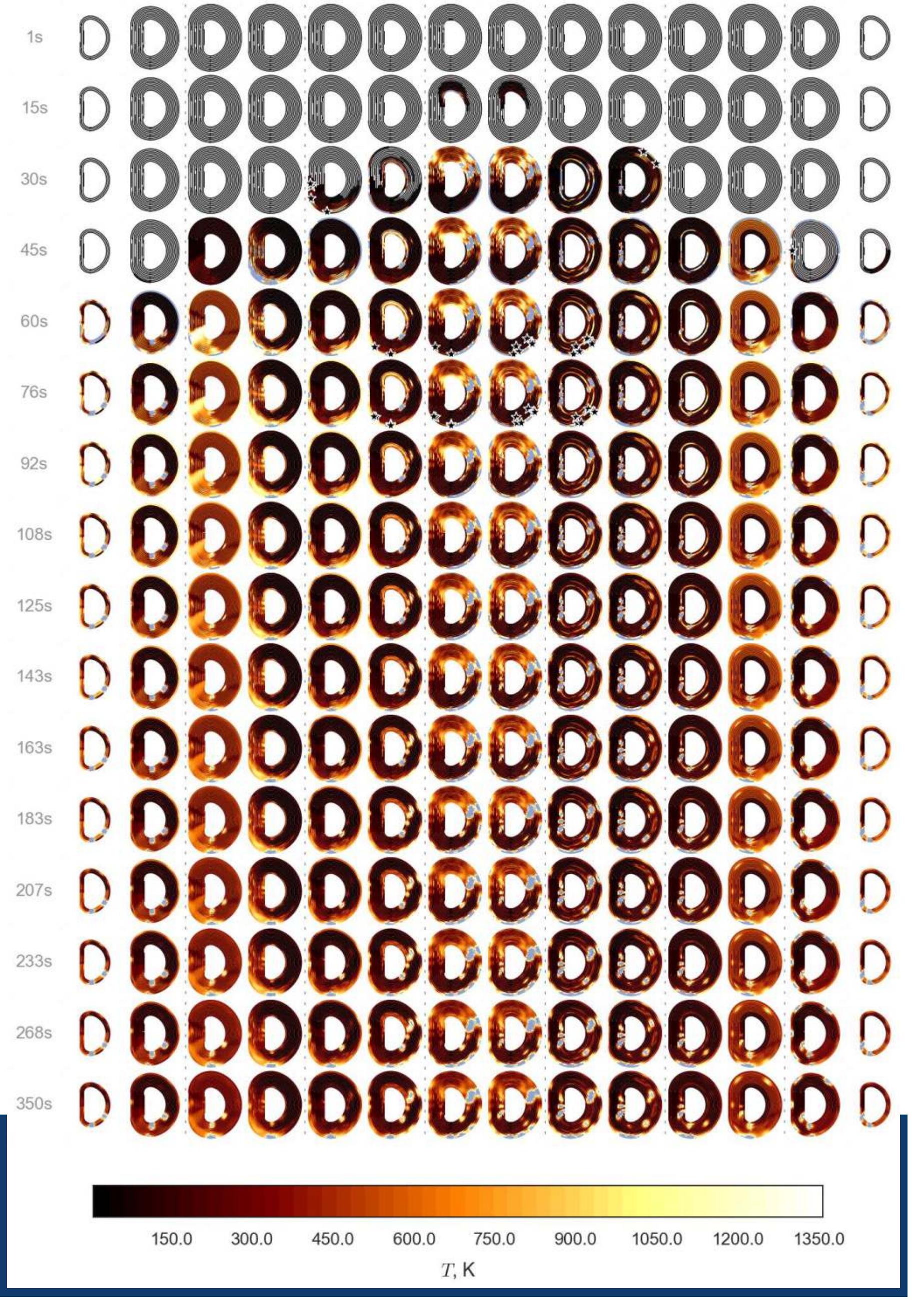
Electrical circuit



TFC electrical inductances

Results for TFC – thermal damage





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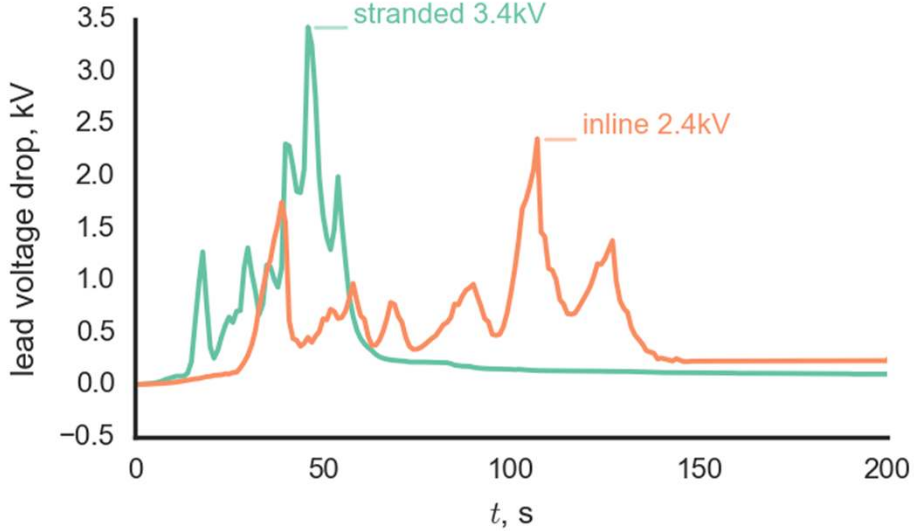
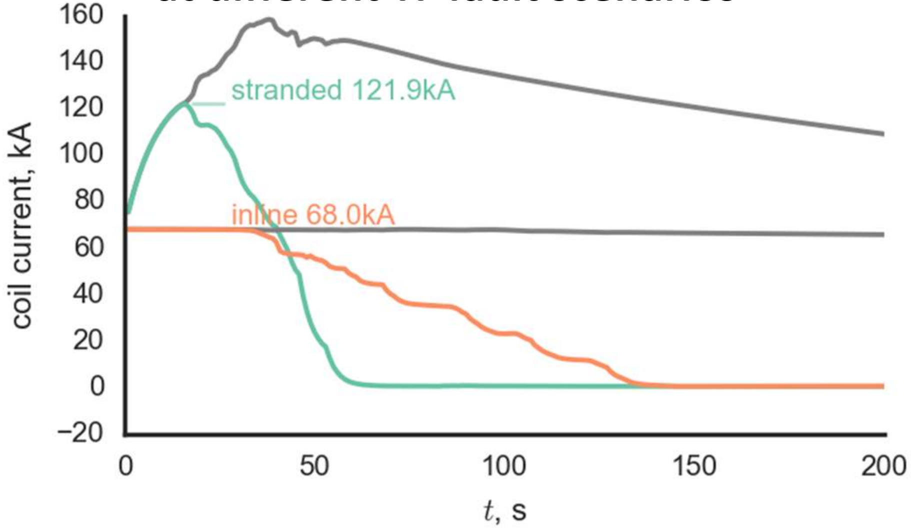
Results for TFC – V, I, power, melting volume

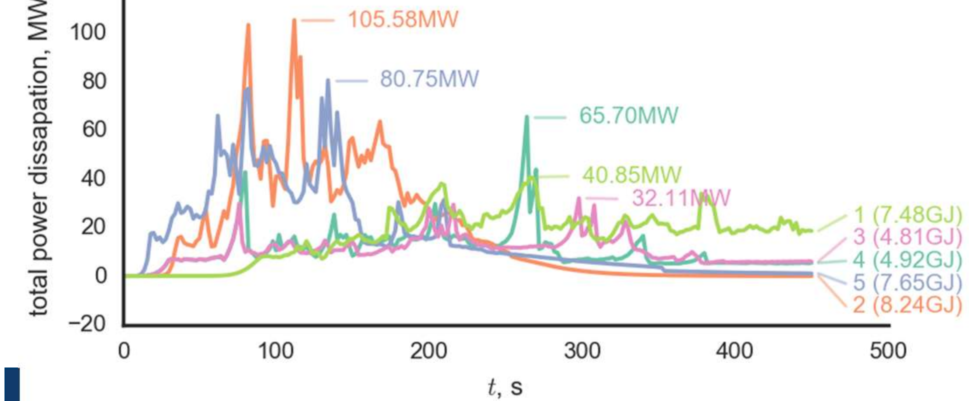
Voltage
at different TF fault scenarios



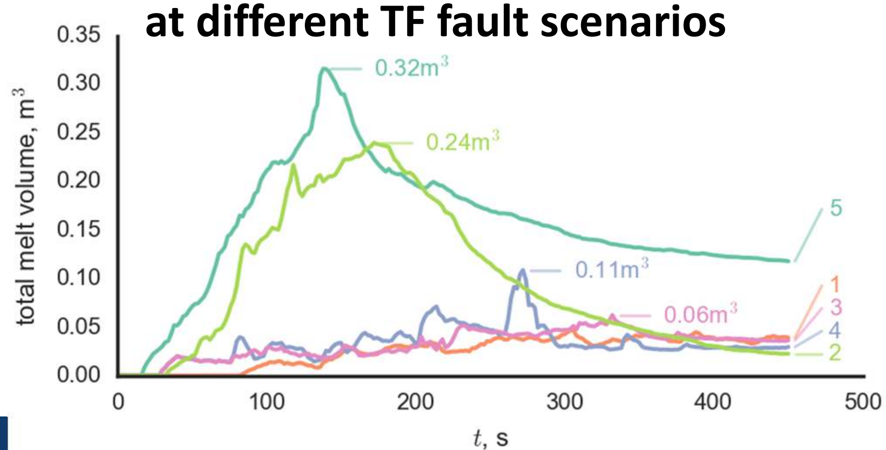
Current
at different TF fault scenarios



Dissipation power
at different TF fault scenarios



Melted volume
at different TF fault scenarios



Arc model

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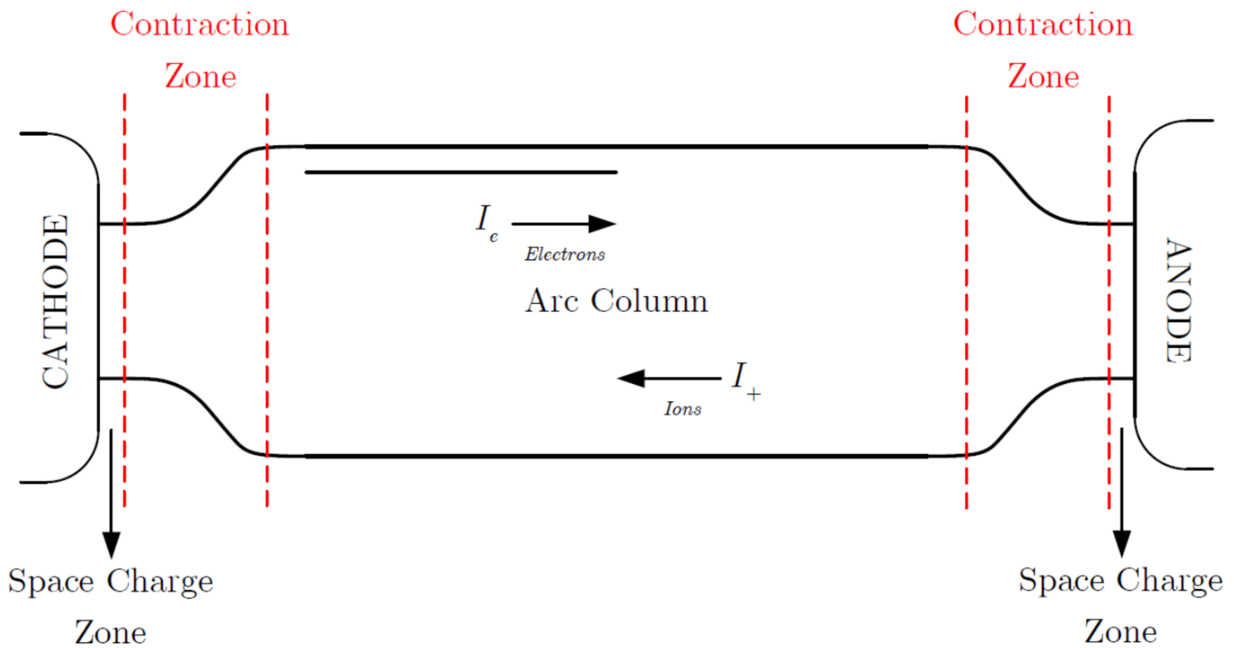
Arc models

- **Kronhardt model (constrained arcs)**
- **Holmes model (positive column)**
- **Simplified Holmes model (positive column approximation)**
- **Ayrton model (arc in air)**



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‘Kronhardt’ model

- *Einfluß von Kurzschlüssen und Lichetögen auf die Sicherheit von Magnetsystemen*, H. Kronhardt, Karlsruhe Nuclear Research Centre, 1993, (The Impact of Short-Circuits and Electric Arcs on the Safety of Magnet Systems). www.kit.edu.
- Also check: *Arcing experiments for magnet safety investigations* by Juengst, K.P.; Kronhardt, H.; Oehmann, M.; Herring, J.S. (Association Euratom-Kernforschungszentrum Karlsruhe GmbH (KFK) (Germany, F.R.)) from Fusion technology 1988. V. 2

$$V_{arc} = V_o + \Delta_g \left(1.75 + 0.012\, j^{1.75}\right)$$

V_{arc} = arc voltage drop (V)

V_o = minimum gap voltage (40 V from Ref. 6)

Δ_g = gap width (mm)

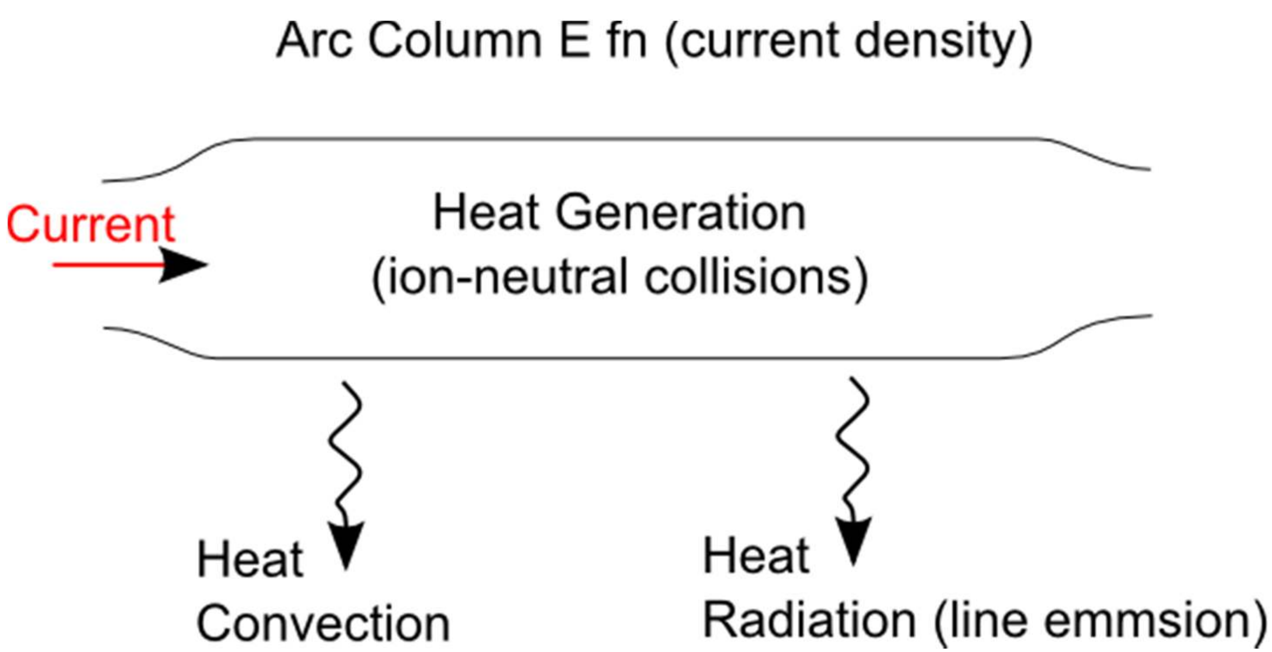
j = current density (A/mm^2) = I_{TF}/A_{arc}

6) H. Kronhardt, *Einfluß von Kurzschlüssen und Lichtbögen auf die Sicherheit von Magnetsystemen*, Insitut für Technische Physik, Kfk 5096, S. 49, Mai 1993.

Used by MAGARC (INL/US), MAGS (KIT/Germany)

'Holmes' model

- Column potential an implicit function of temperature
- Numerical solution
- Solution Implemented using relaxed Newton-Rapson method



- Pressure
- Temperature
- Diameter
- Length
- Current
- Voltage (electrical field)
- Plasma density

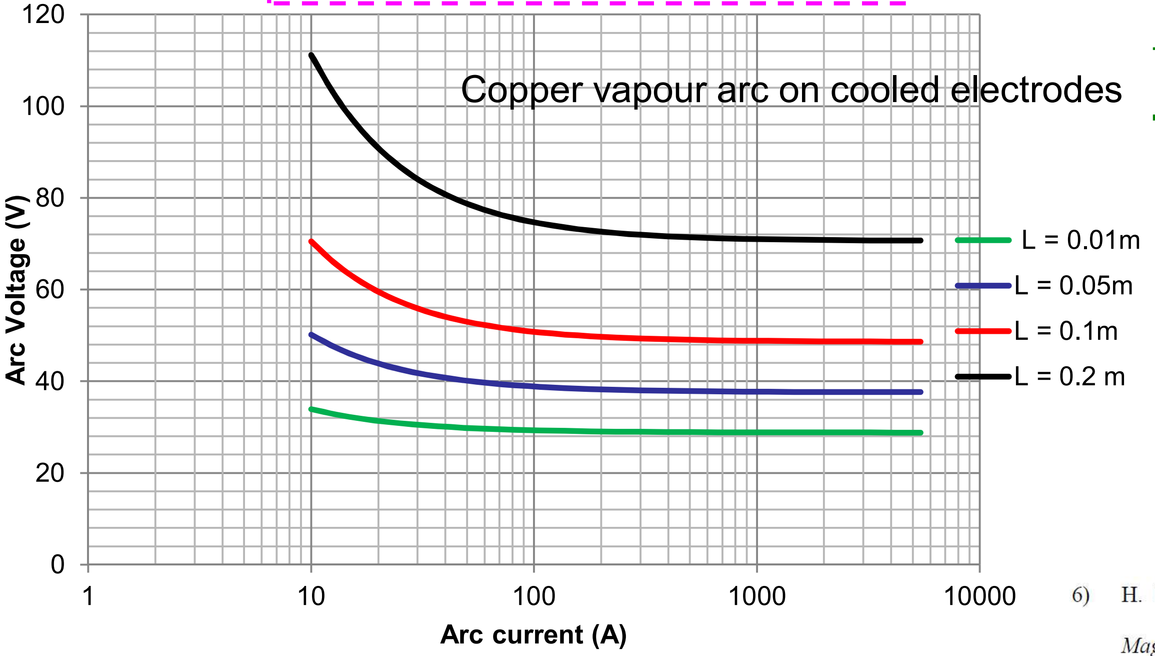
‘Ayrton’ and ‘Kronhardt’ Arc Models

- For cooled copper electrodes, the arc discharge has a negative resistance over a wide current range that depends on the column length, L

Ayrton

$$V = \alpha + \beta L + \frac{\gamma + \delta L}{I}$$

Constants	Cooled copper
α	26.6
β	2.2
γ	32.4
δ	18.65



$$V_{arc} = V_o + \Delta_g \left(1.75 + 0.012\, j^{1.75}\right)$$

Kronhardt

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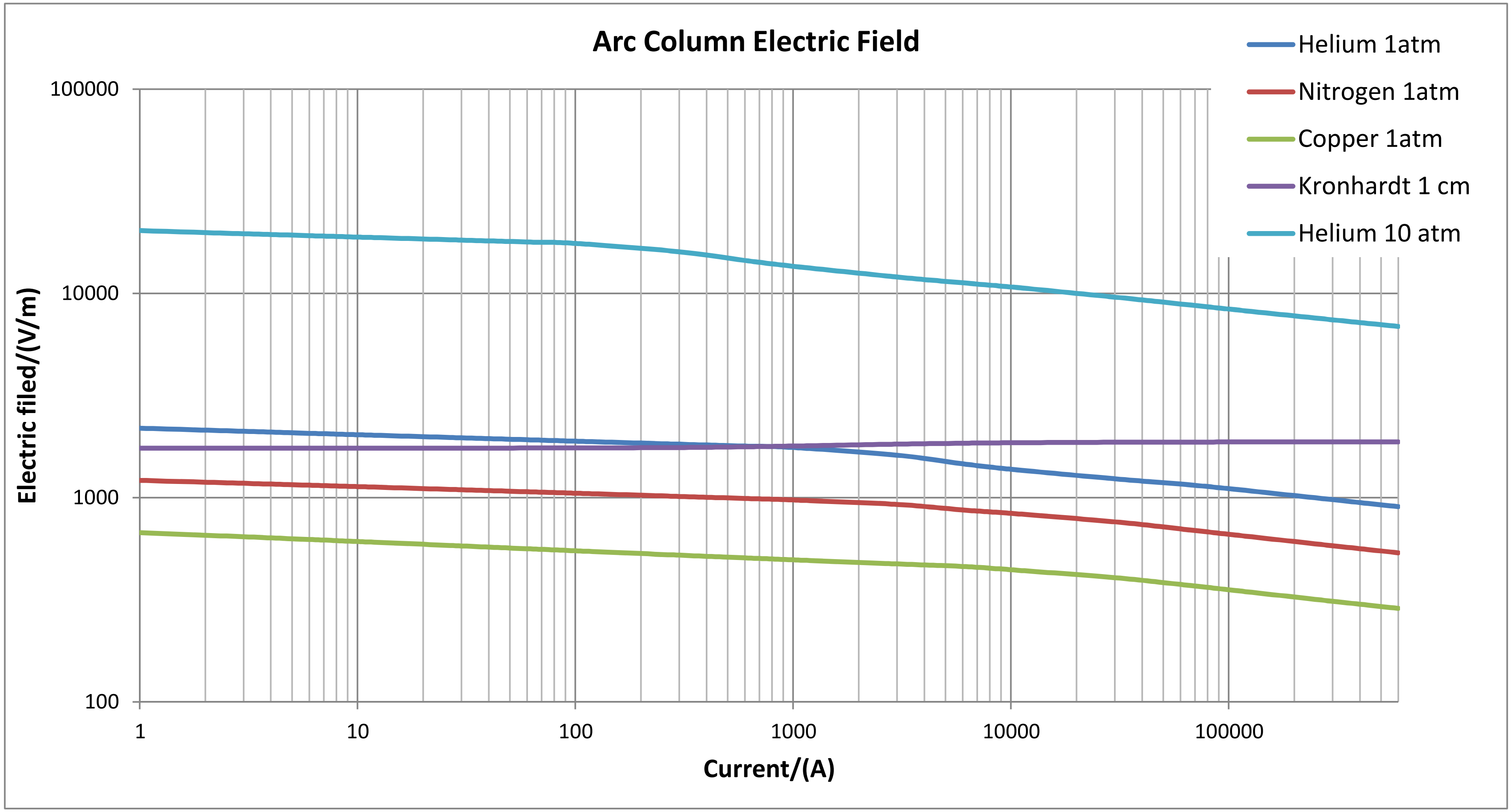
j = current density (A/mm^2) = I_{TF}/A_{arc}

B. Merrill, Annex 4B(DDD11-8);
B. Merrill, Fusion Tech, 37, 2000

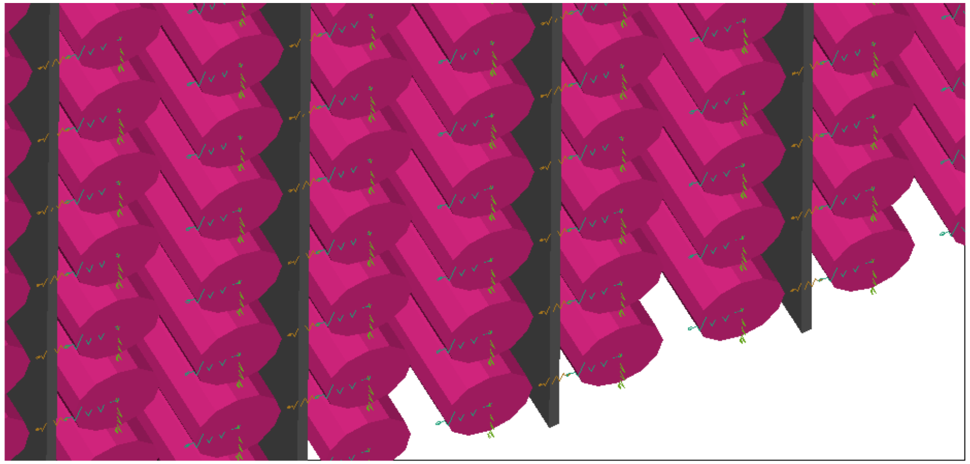
6) H. Kronhardt, *Einfluß von Kurzschlüssen und Lichtbögen auf die Sicherheit von Magnetsystemen*, Insitut für Technische Physik, Kfk 5096, S. 49, Mai 1993.

‘Kronhardt’ and ‘Holmes’ Arc Models



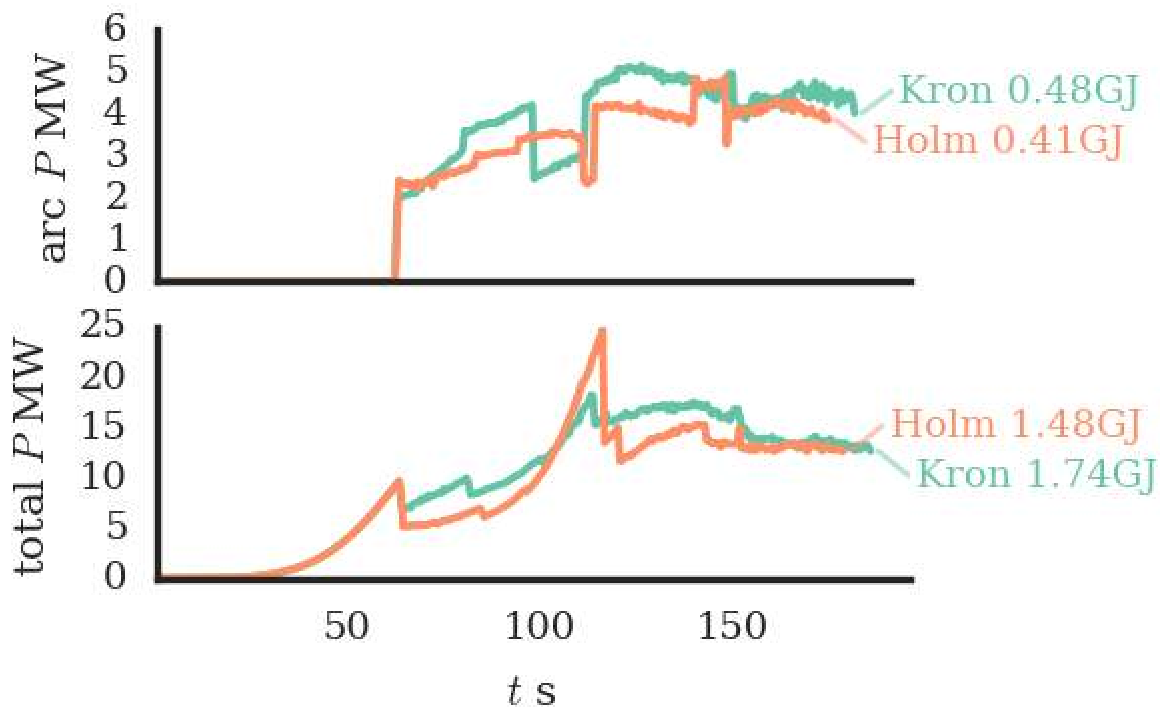
Arc model in ANSYS

- **Non-linear voltage-current characteristic**
- **Resistive circuit elements linking turns**
- **Conditions to initiate arcs**
  - T>600° C
  - ΔV>40V
- Power dissipated in arc → volumetric heating to electrically conductive elements



‘Kronhardt’ and ‘Holmes’ arcs in ANSYS model

- ‘Kronhardt’ arcs have greater power than ‘Holmes’ arcs – greater localization
- Similar total energy dissipation



Electrical simulation

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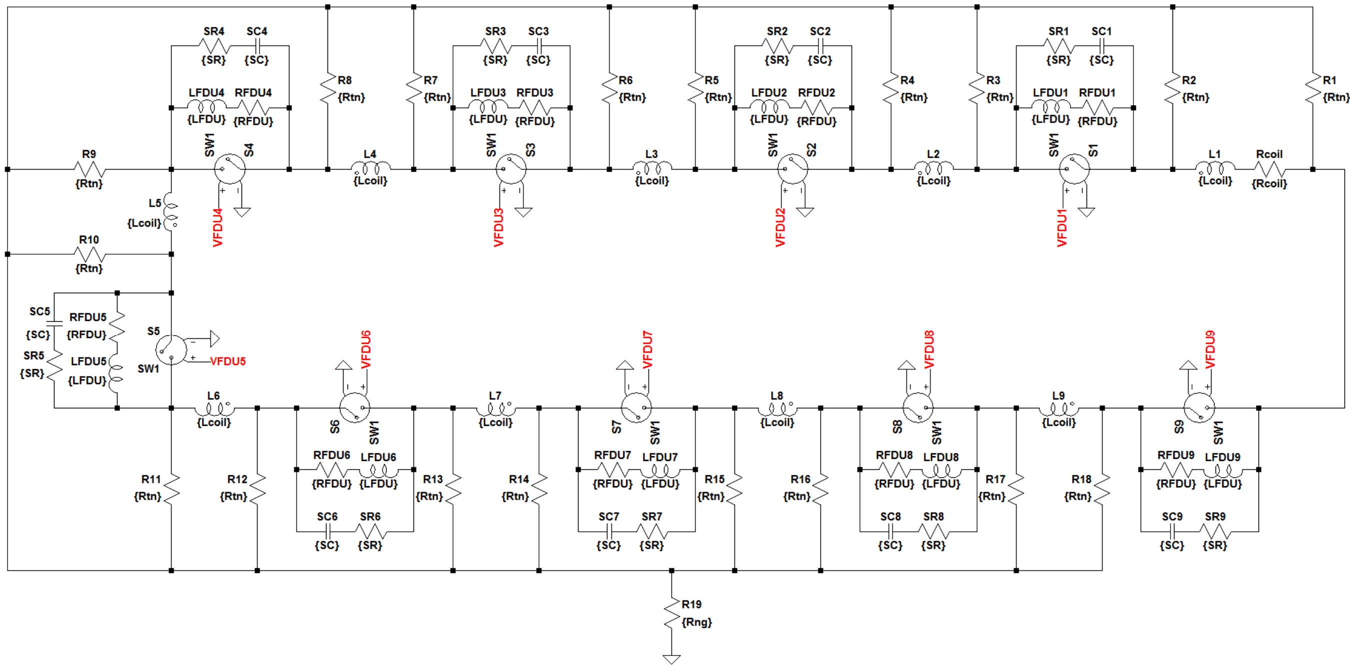
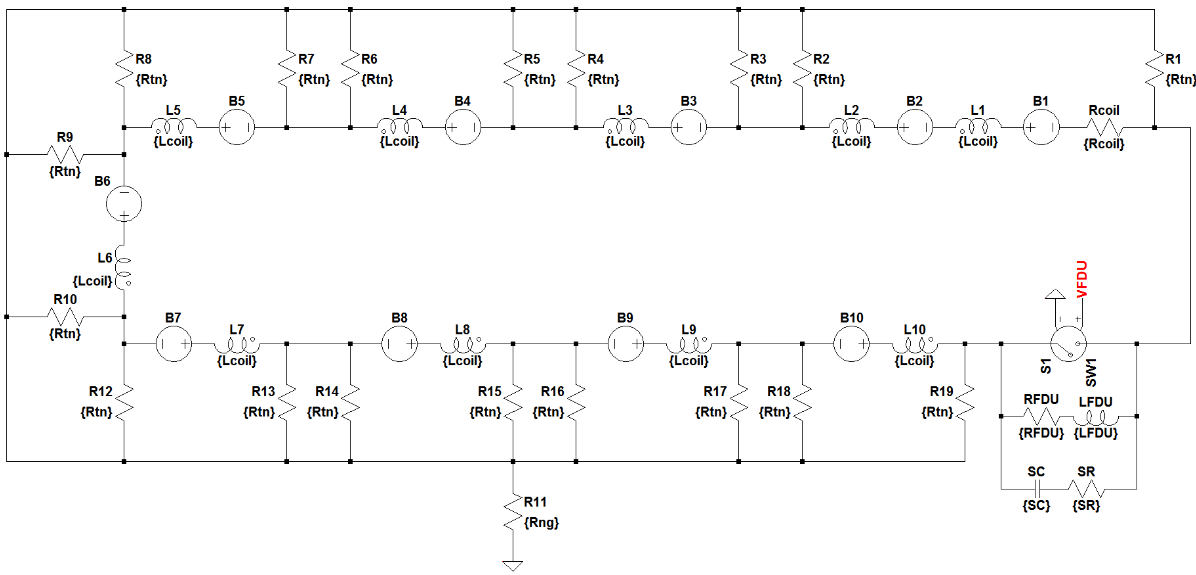
Electrical simulations

- **To guide the simplification of electrical circuits for TF and PF/CS coils to be implemented in ANSYS**
- **To verify the simplification implemented in ANSYS model**
- **To simulate the electrical responses with arcs presence in a ‘global’ circuit network → arcing V-I and power for further thermal damage assessment**
  - TF coils (FDU, busbar, surrounding structures)
  - PF/CS (FDU, busbar, surrounding structures)

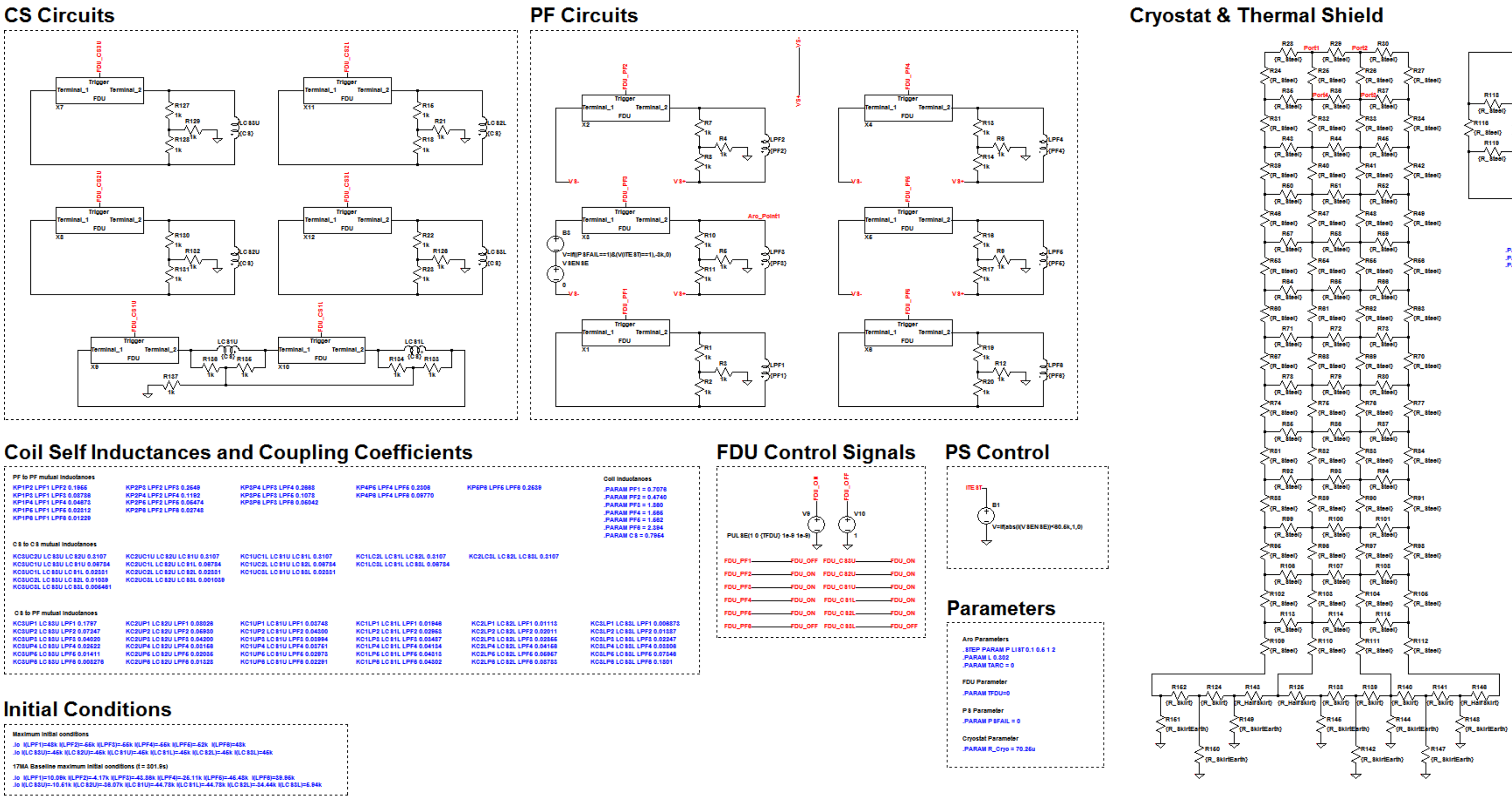
Simplified TFC circuit with FDUs



Further simplified TFC circuit with FDU for ANSYS

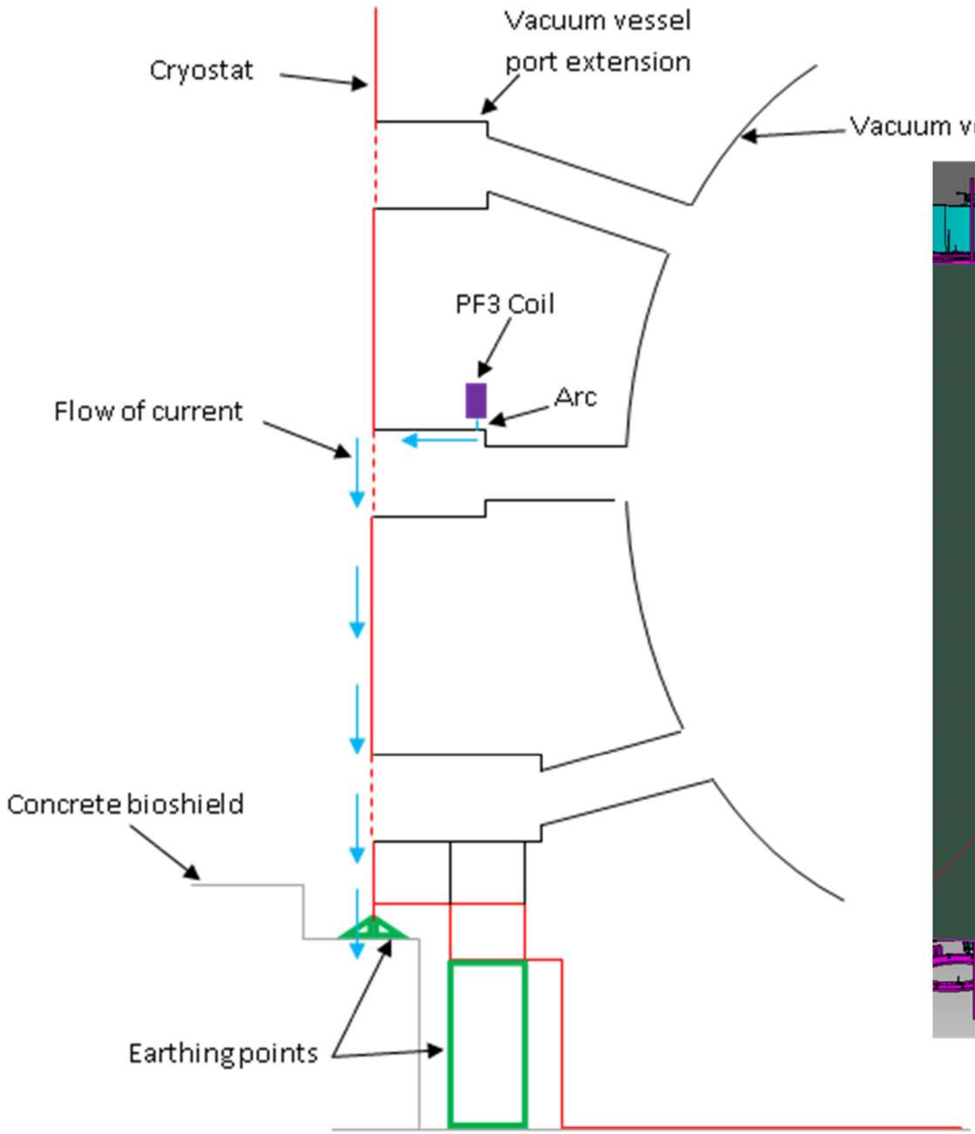


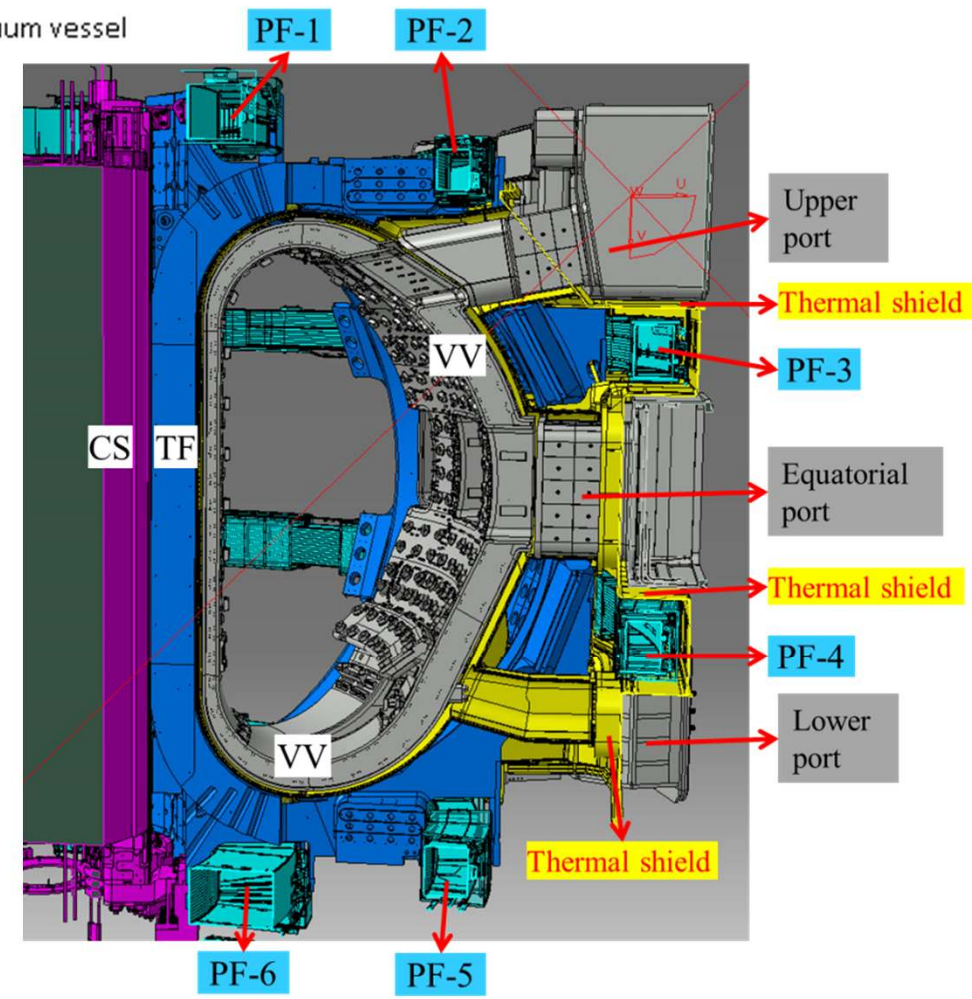
PF/CS electrical circuit + VV/TS/Cryostat



Spice model of CS and PF circuits with the cryostat and vacuum vessel port extension

New electrical paths from PF to VV/Cryostat





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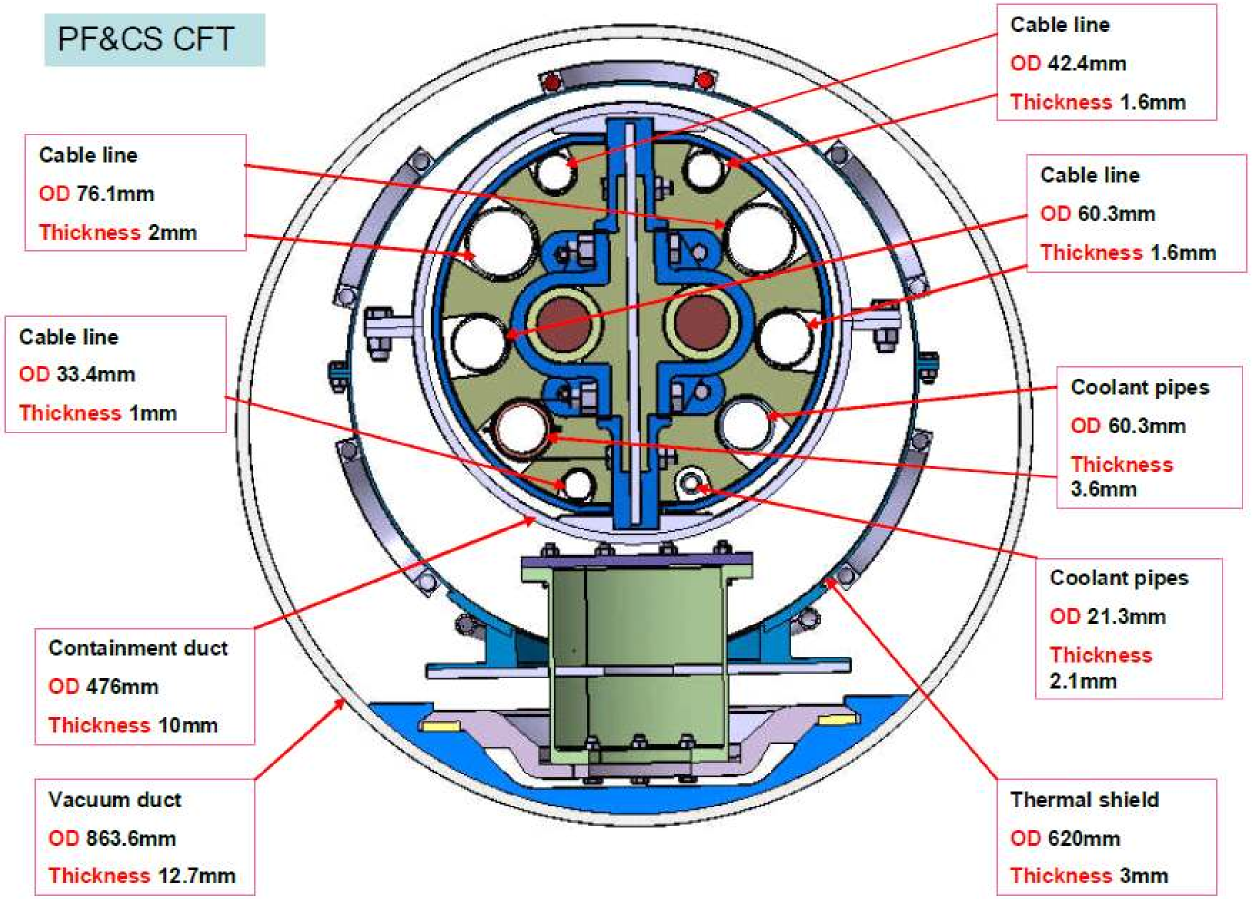
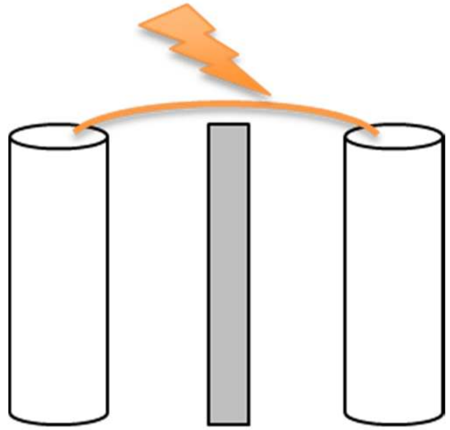
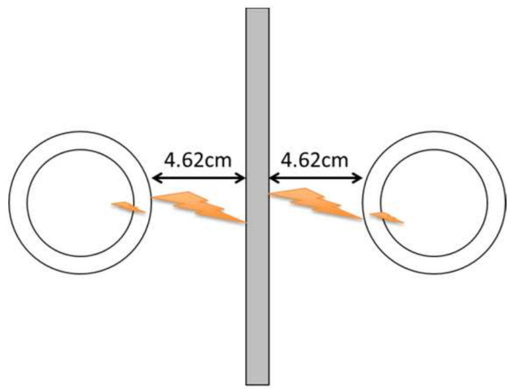
New electrical paths due to double ground fault to PF-3 busbar

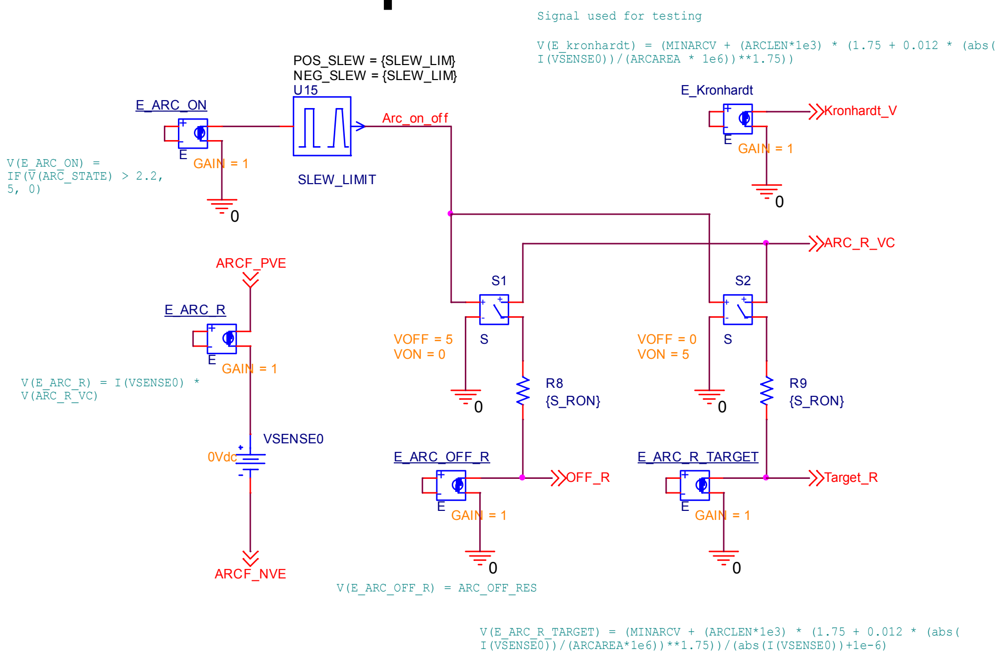


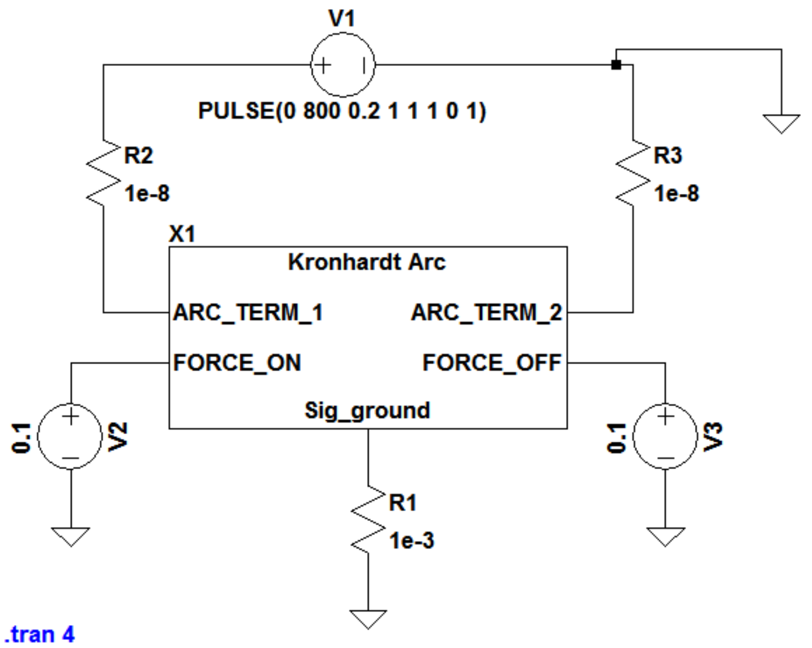




Electrical arc model

- Arc is simulated electrically (Pspice & LTspice)
- Arc is packed into one element (LTspice)
  - Easier integration
  - Multiple arcs





Kronhardt behaviour circuit (Pspice) | arc component (LTspice)

Thermal damage assessment

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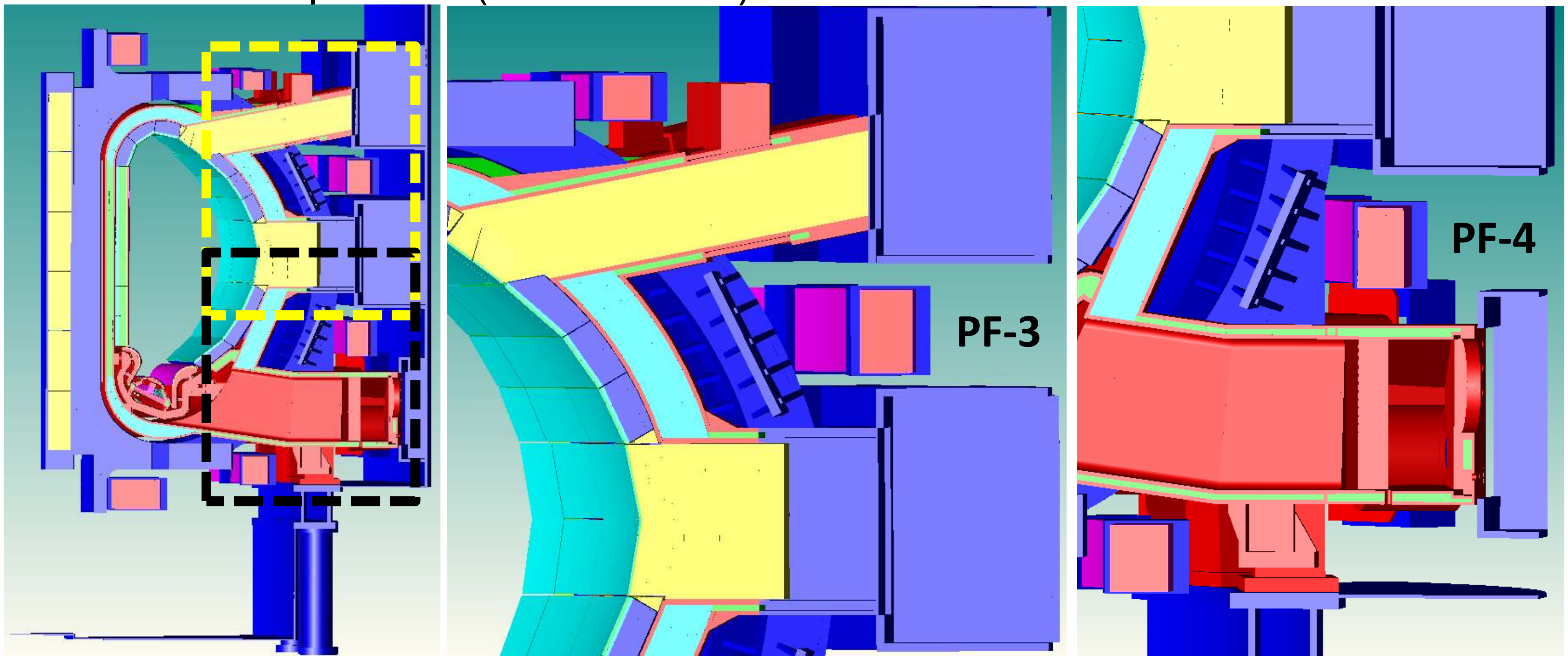
Thermal damage

- **External damage mechanism (PF→VV)**
  - Damage caused by the molten materials from coils (internal arcs)
  - Damage caused by direct electric arcs between coils and VV components (external arcs)



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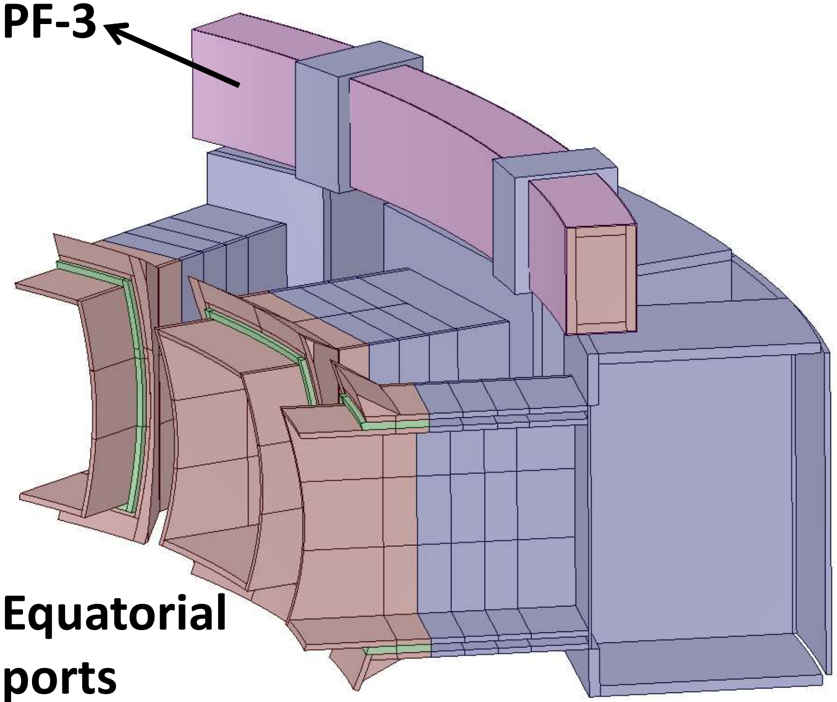
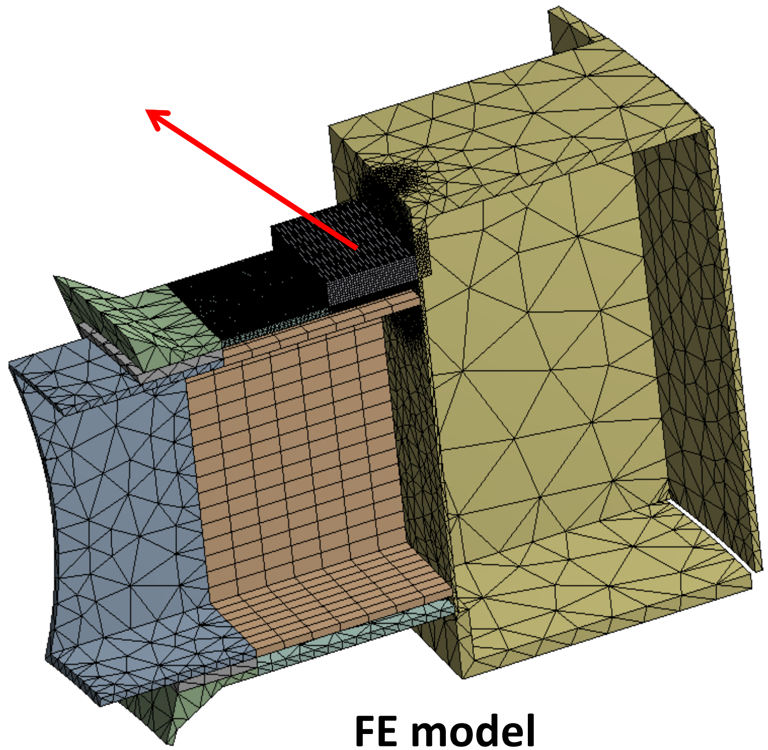
Thermal damage by molten materials

- **Approximation for WORST safety case**
- **Maximum heat transferred into VV steel plate**
  - the total energy is equivalent to the maximum stored energy (3.24GJ) in the PF-3 coil @45kA
  - Varying contact surfaces

PF-3



Equatorial ports



FE model

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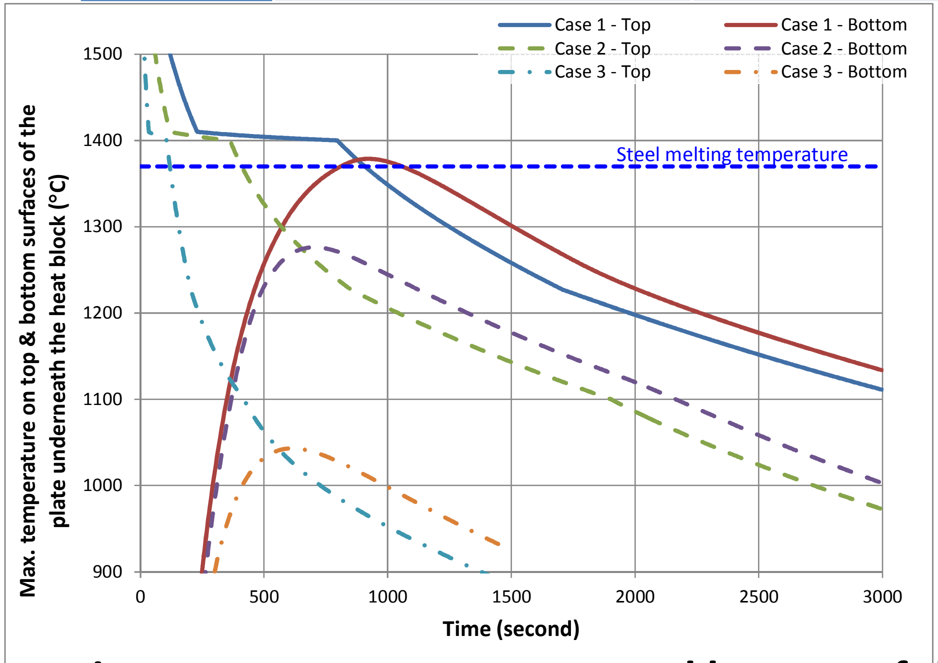
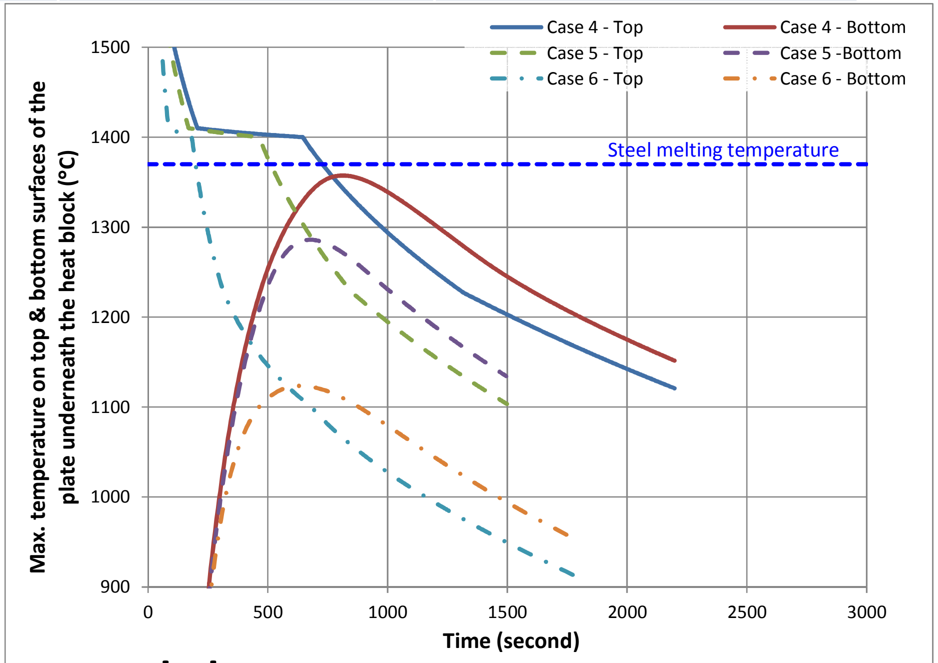
	Temperature (°C)	Volume (m^3)	Footprint (m^2)	Total energy (GJ)
Case 1	1744	0.3	1.60	3.24
Case 2	1744	0.2	1.60	2.16
Case 3	1744	0.1	1.60	1.08
Case 4	1744	0.2	1.06	2.16
Case 5	1744	0.1	0.53	1.08
Case 6	2000	0.1	1.60	1.19
Case 7	1744	0.3	0.4	3.24
Case 8	2877	0.2	1.06	3.24

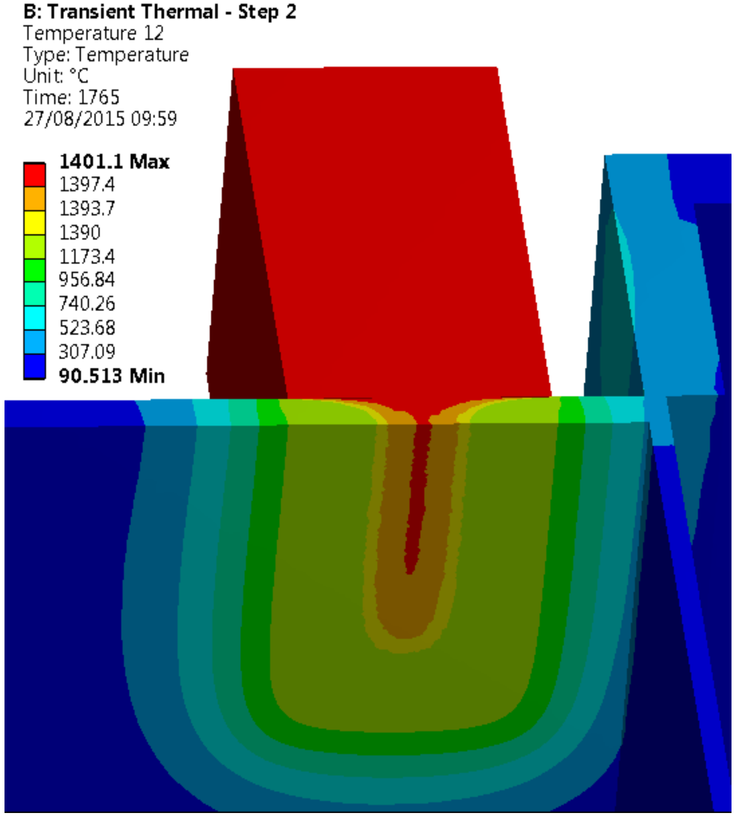




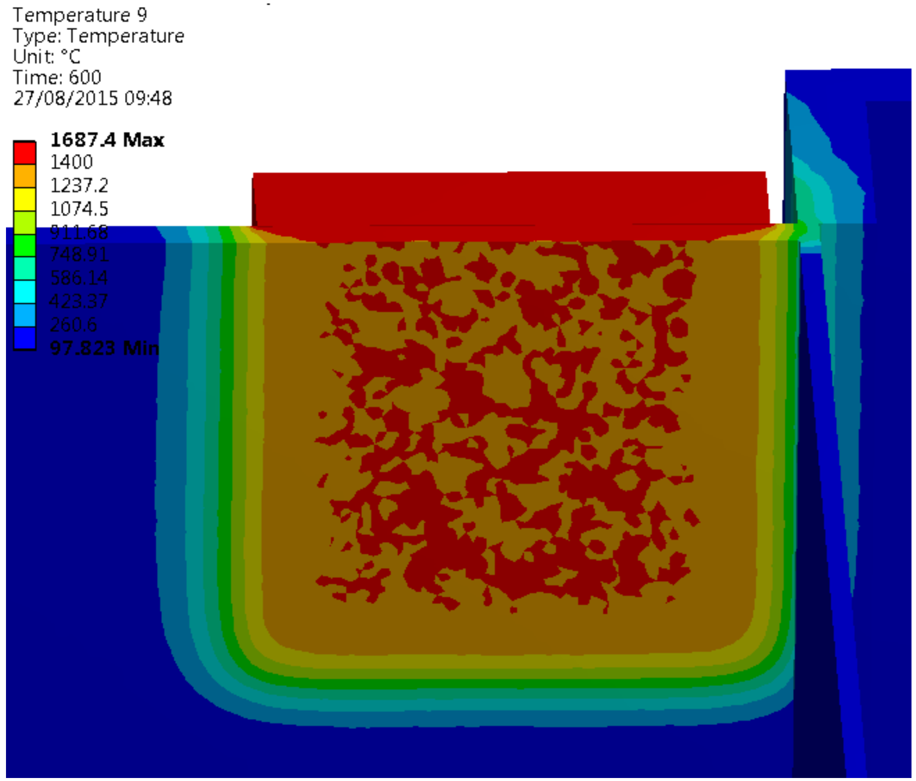
maximum temperature on top and bottom of the vessel plate

Temperature at the bottom of the 1st layer of VV/port wall

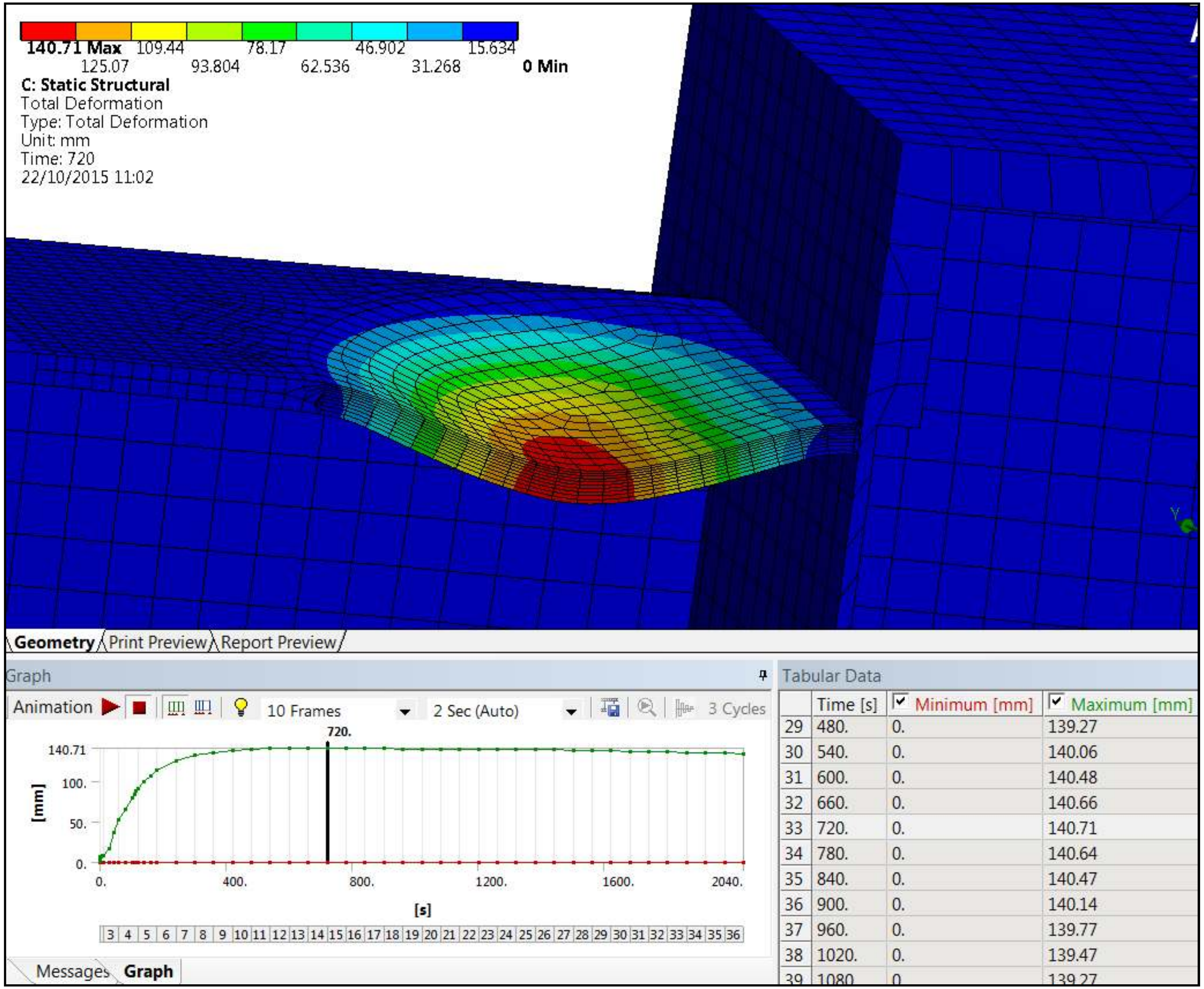
case 7 (Temperature = 1744 °C, Total Energy = 3.24 GJ, Volume = 0.3 m^3, Footprint area = 0.4 m^2)



case 8 (Temperature = 2887 °C, Total Energy = 3.24 GJ, Volume = 0.2 m^3, Footprint area = 1.06 m^2)

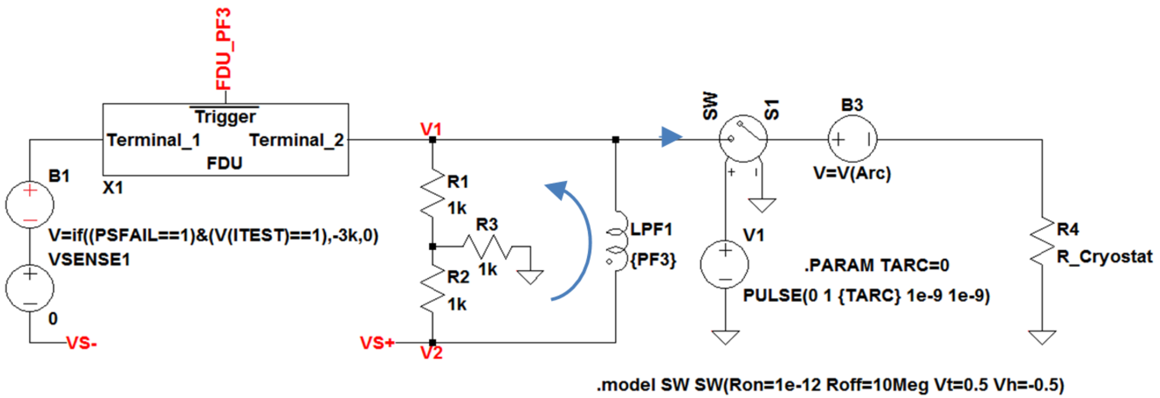


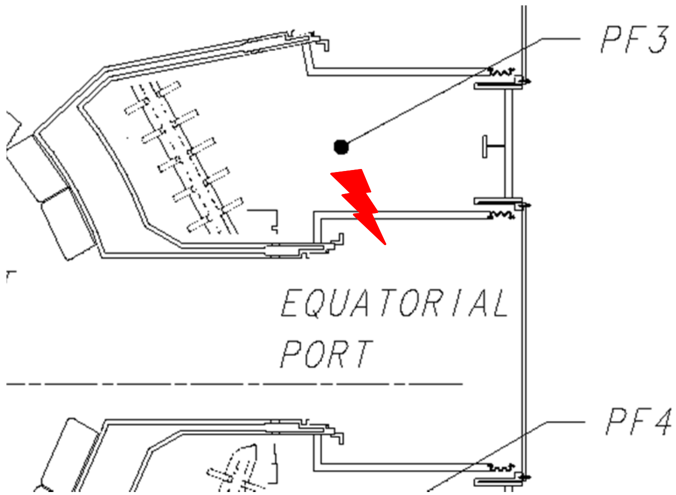
Peak deformation of the layer of EQ-port wall



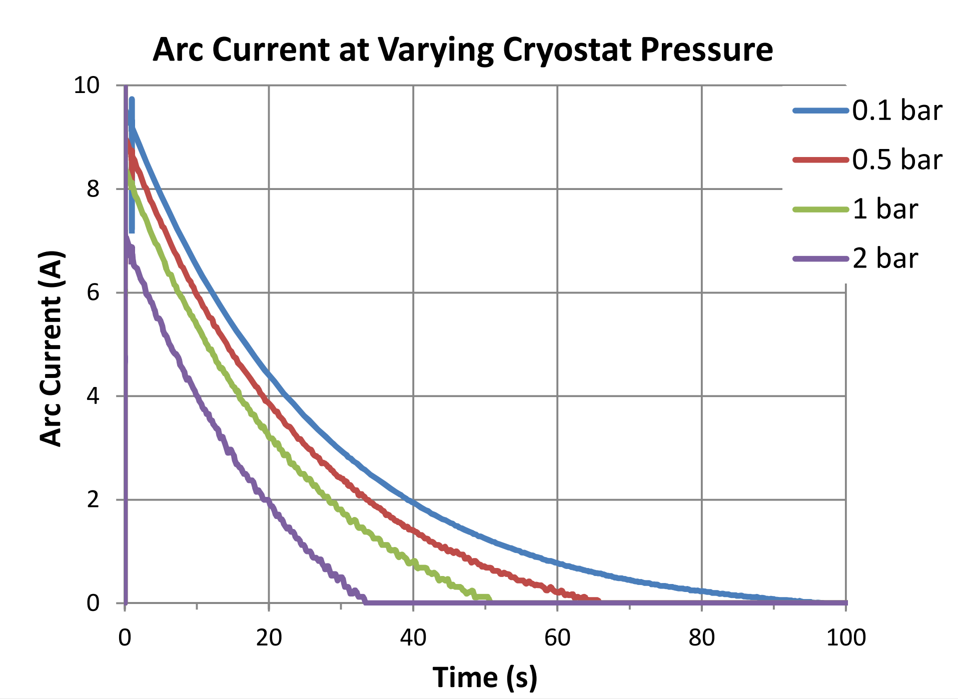
Thermal damage by arc between PF3 & VV

- **Electrical simulations used approximate Holmes arc model**
  - 4 pressures: 0.1, 0.5, 1, 2 [bar]
- **4 failure modes:**
  - Protection system operates as expected
  - PF3 FDU does not operate
  - PF3 PS and PMS fail but PF3 FDU operates
  - PF3 protection system fails completely

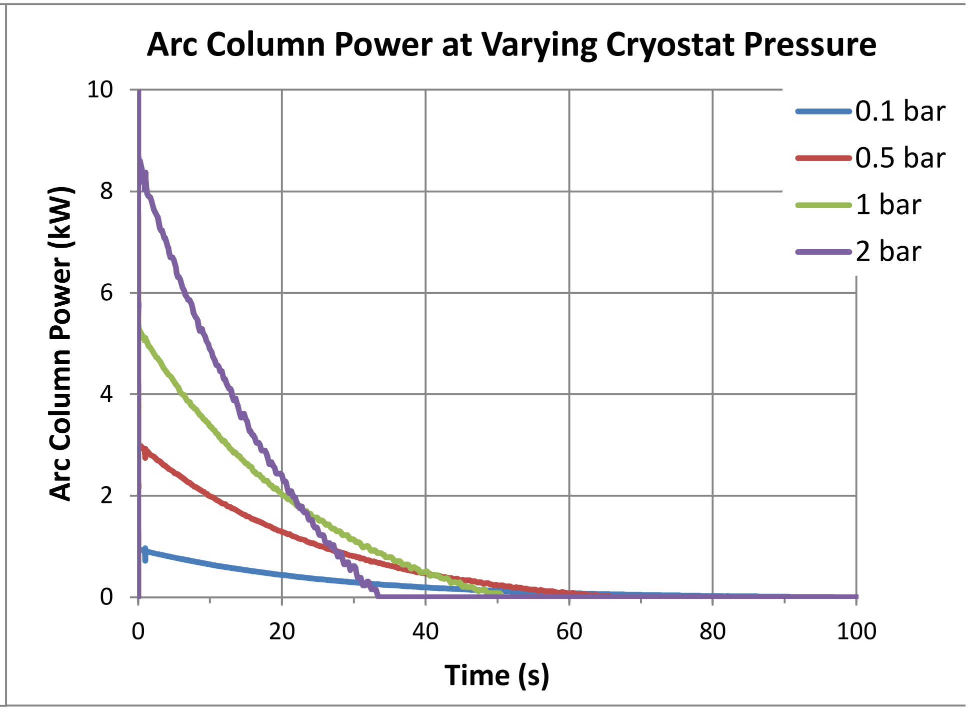




- **Arc current and column power at different pressure**
- **Failure mode: FDU on, PS off, PMS on**



Arc current

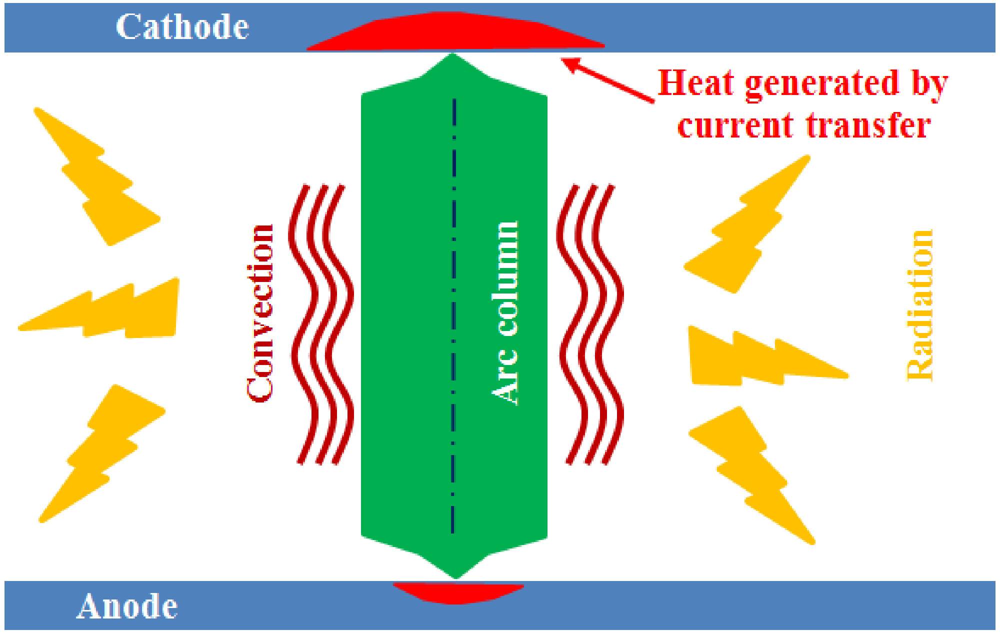


Arc power

External arcs – heat transfer

- **Unconstrained and static arc between two parallel plates**
  - The arc is considered static because its displacement can not been predicted accurately.
  - The arc is assumed to occur between the equatorial port and the PF3 coil (arc length of 0.2m)
  - It is assumed that the arc occurs between two parallel plates, the upper one being the vessel shell and the cathode (worst case).

- **Cathode spot heat**
- **Radiation**
- **Convection**



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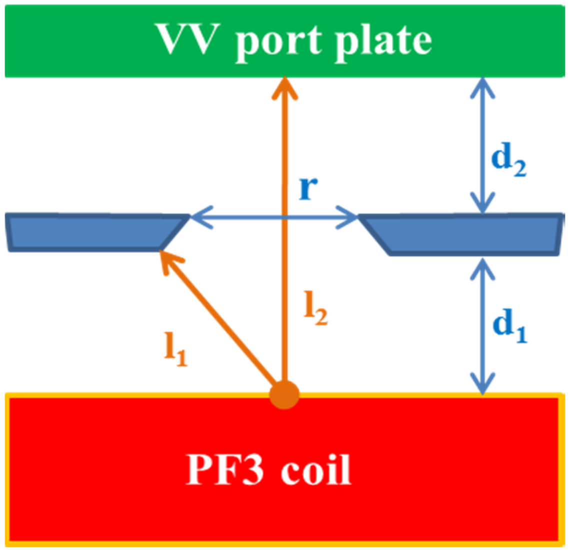
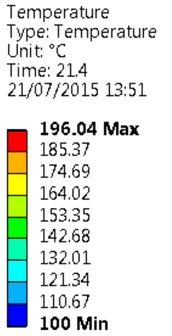
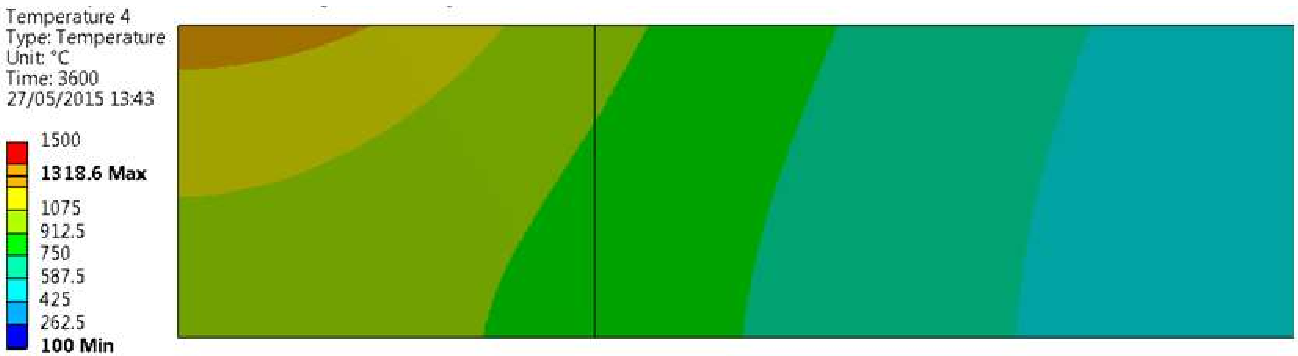
- **External arcs between PF-3 coil and VV/port wall/TS**
- **Arc current and power: not high enough; relatively short lasting**





Temperature profile of the TS layer at the peak value with evolving arc

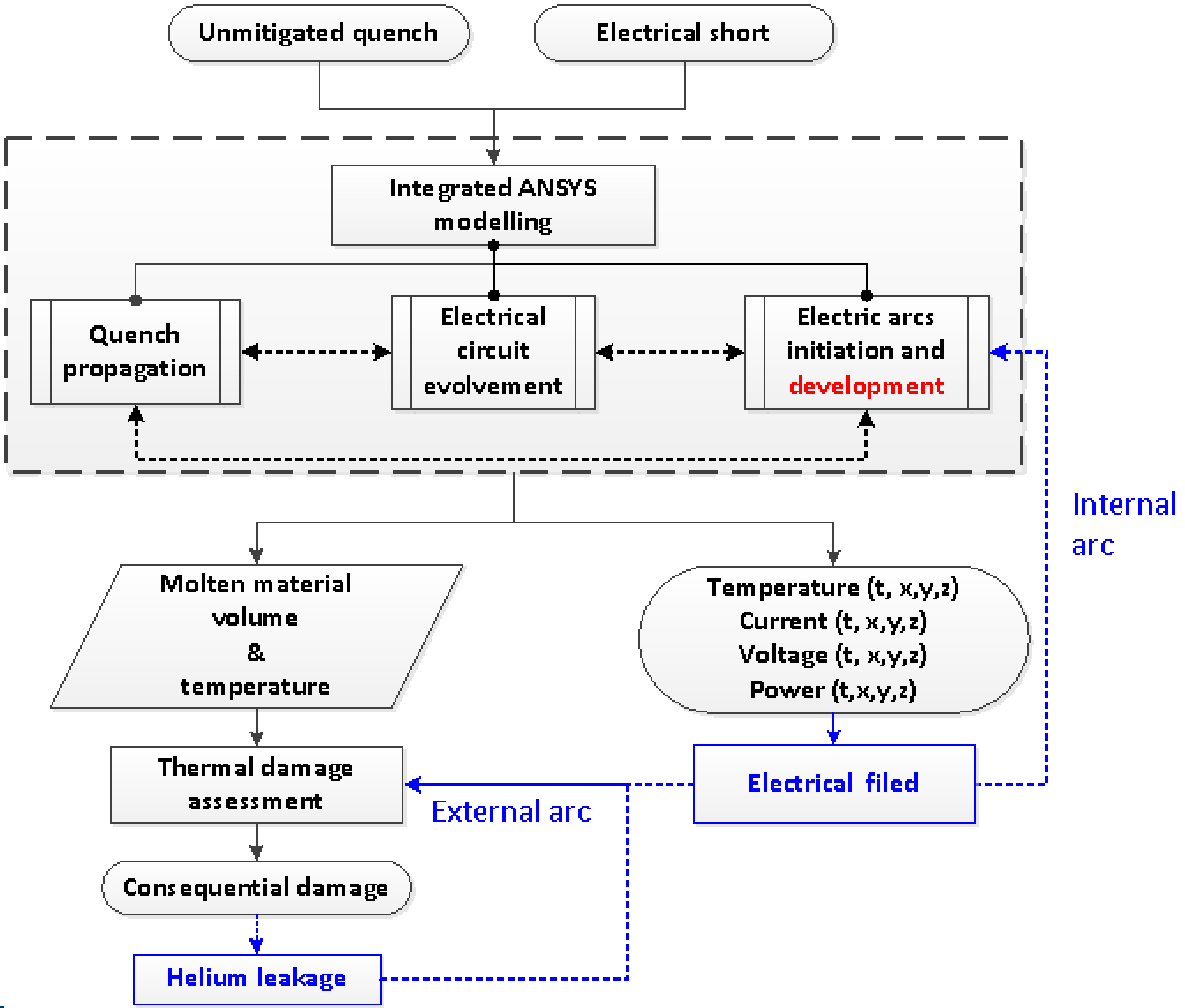


Temperature profile of the vessel port top layer at the peak value with constant arc power

Summary

- **Models development**
  - Integrated ANSYS model
    - Geometry and materials property
    - Quench
    - Electrical circuit
    - Arc models integration
    - Thermal damage
  - Electrical simulation for simplification and verification
  - Thermal damage assessment
  - Arc models
- **ITER application: arcing damage towards VV**
  - PF/CS: PF-3 coil
  - TF coil – benchmark with MAGARC (INL/US)
- **Fault/accident scenarios**

Further R&D


Unmitigated quench
Electrical short
Integrated ANSYS modelling
Quench propagation
Electrical circuit evolvement
Electric arcs initiation and development
Internal arc
Molten material volume & temperature
Temperature (t, x,y,z)
Current (t, x,y,z)
Voltage (t, x,y,z)
Power (t,x,y,z)
Thermal damage assessment
External arc
Electrical filed
Consequential damage
Helium leakage

Further R&D

- **Further development**
  - Arc models initiation and integration
  - Impact of magnetic field and induced current
  - Arc possibility in busbar
  - Integration for external arcs assessment
- **Validation and benchmark**
  - Sensitivity study for integrated ANSYS model
  - Benchmark/Validation, e.g. with LHC incident 2008
- **Consequence study extension**
  - Structural/mechanical impact on coils due to internal faults propagation
  - Helium pressure evolvement and potential impact

Back-up slides

Electrical field

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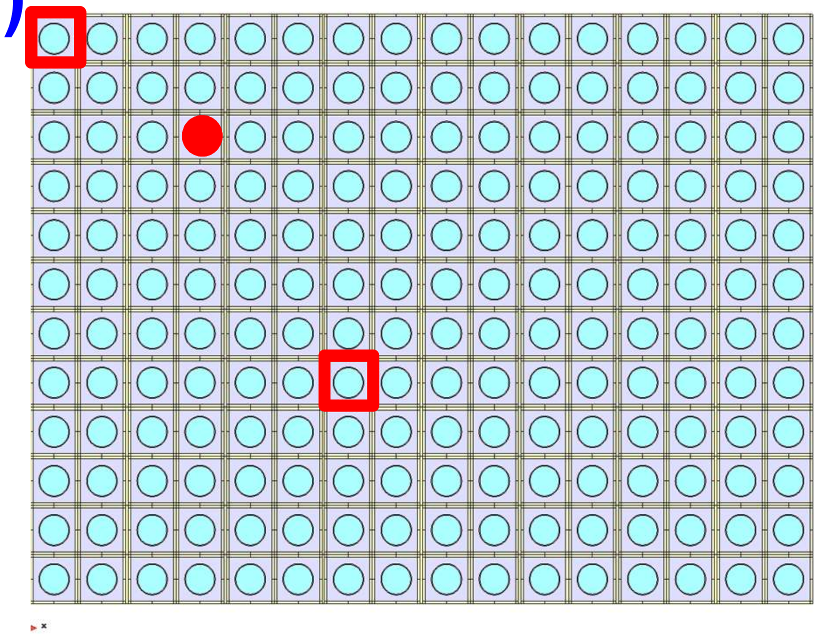
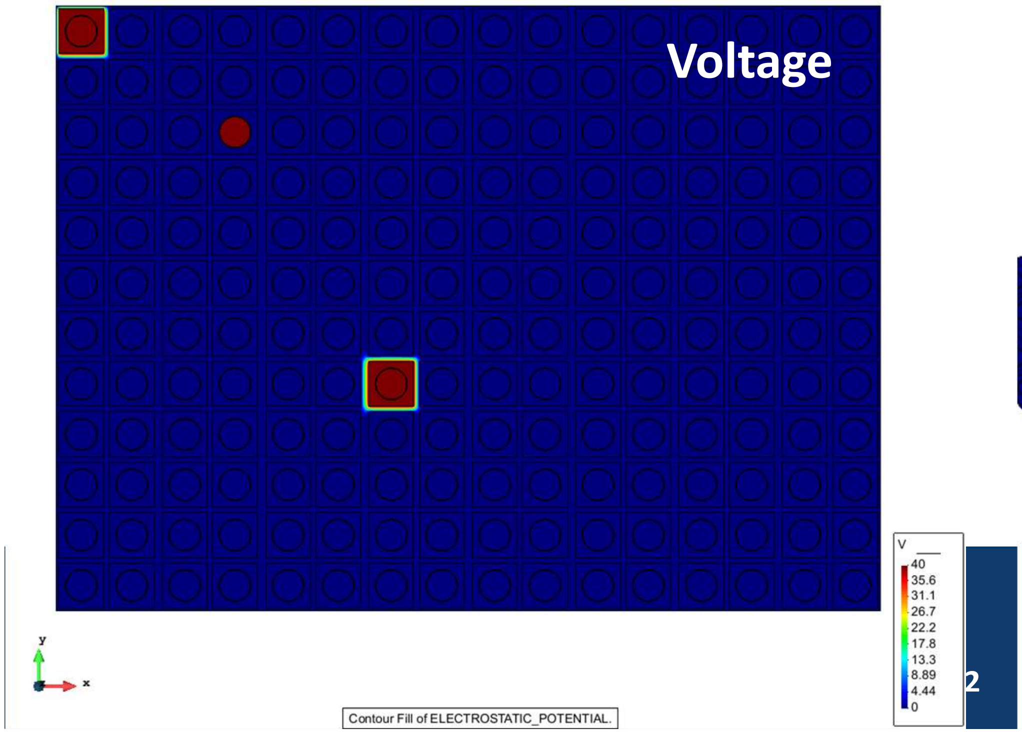
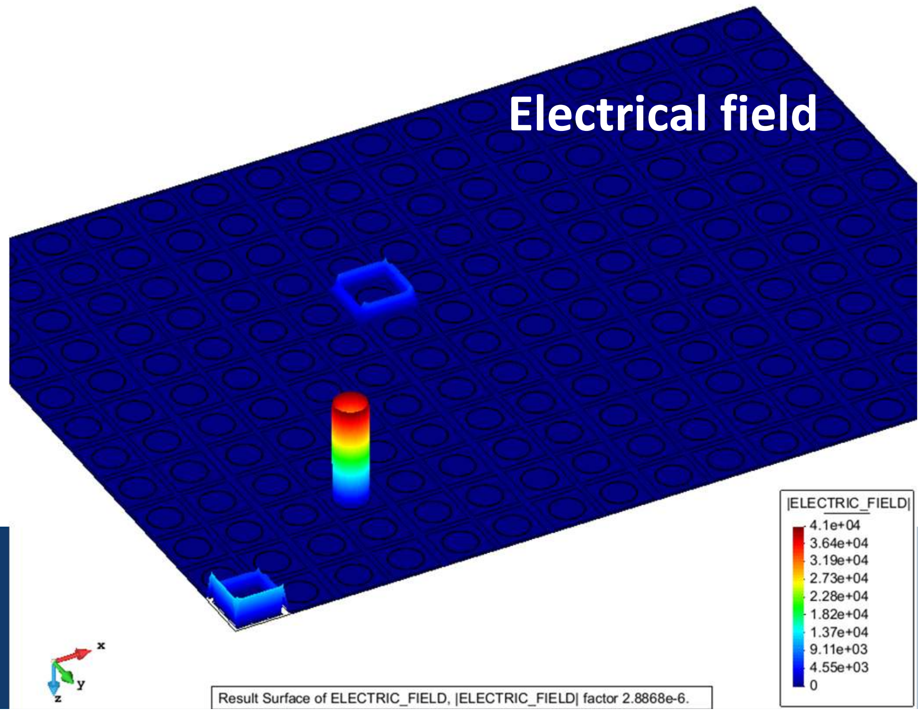
Example of electrical field (1/2)

- Voltage (40V) applied to the conductor and jackets in PFC-3 by open-source finite element software ERMES

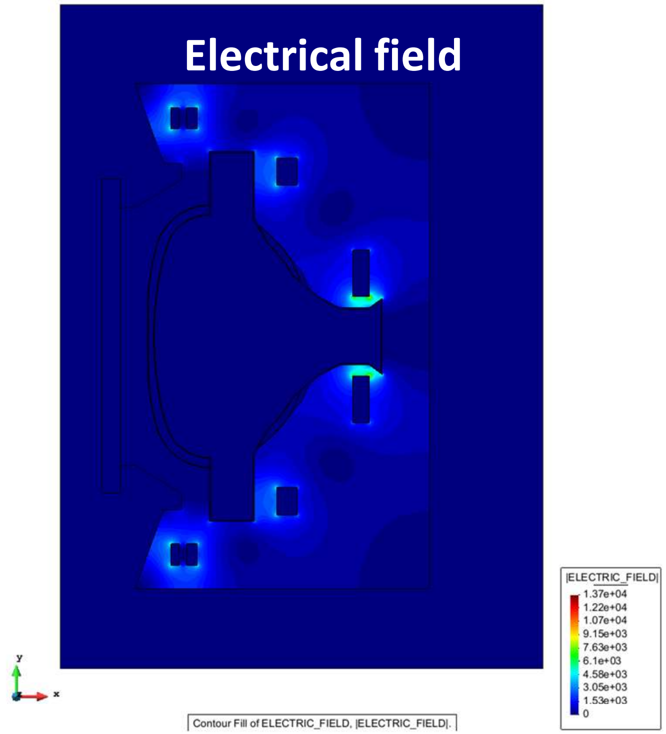


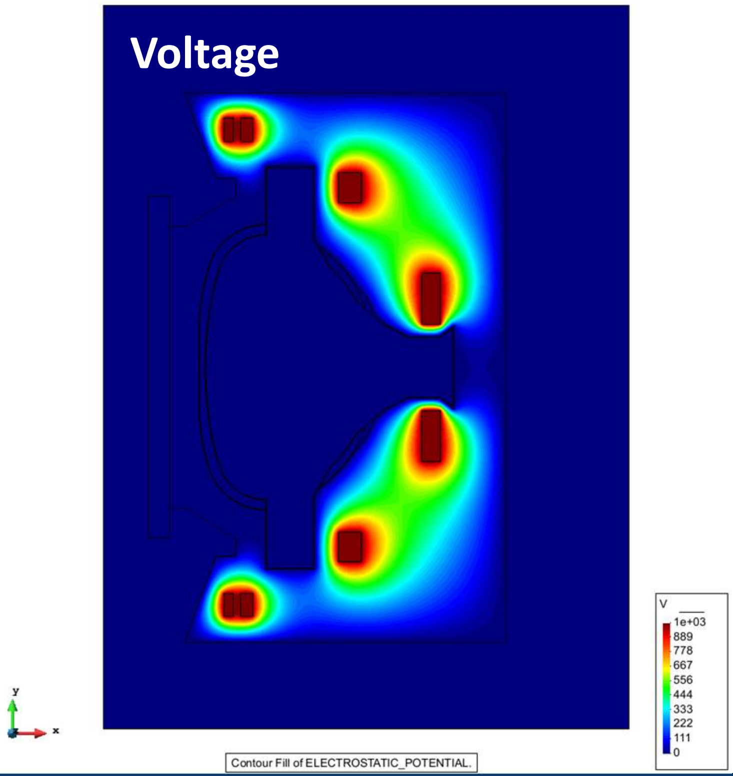


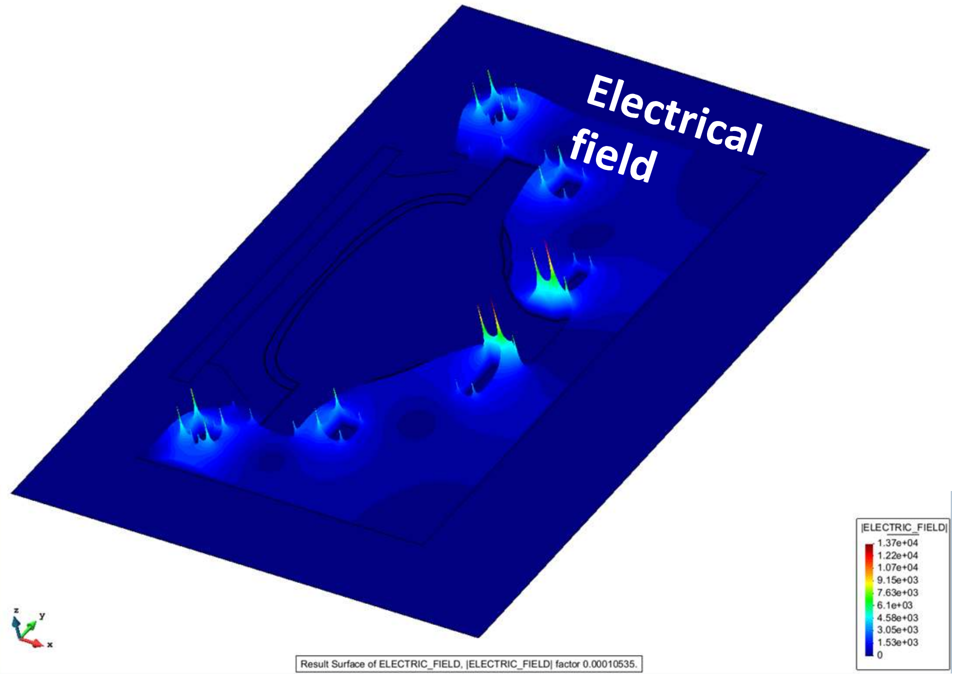


Example of electrical field (2/2)

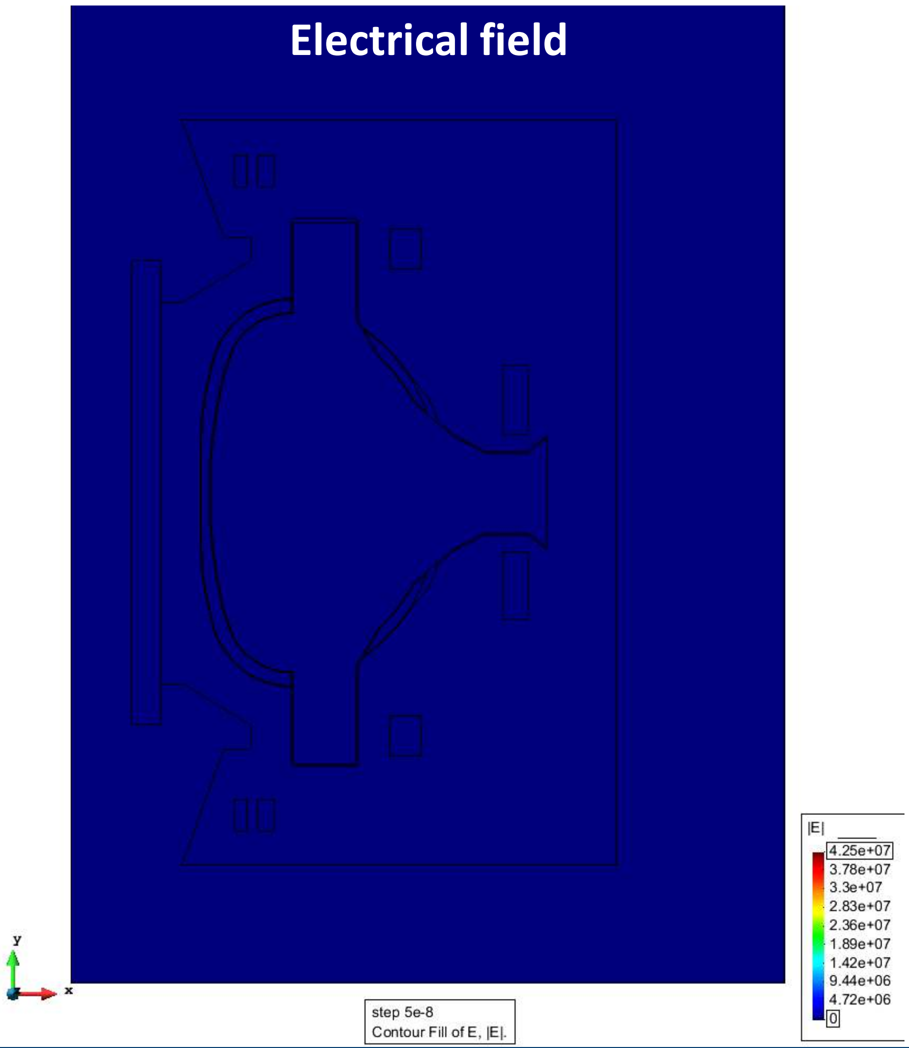
- Voltage (1kV) applied to cross-section of six PFCs by ERMES







To identify weak points for arcs



Arc pulse (1kA, 0.1ms) induced B-field