



china eu india japan korea russia usa

Electromagnetic Assessments of ITER Magnets in Safety-Related Fault Conditions (ITER/CT/13/4300000813), ITER_D_E6RDPU

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

Shanliang Zheng

Integrated model: Simon McIntosh

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

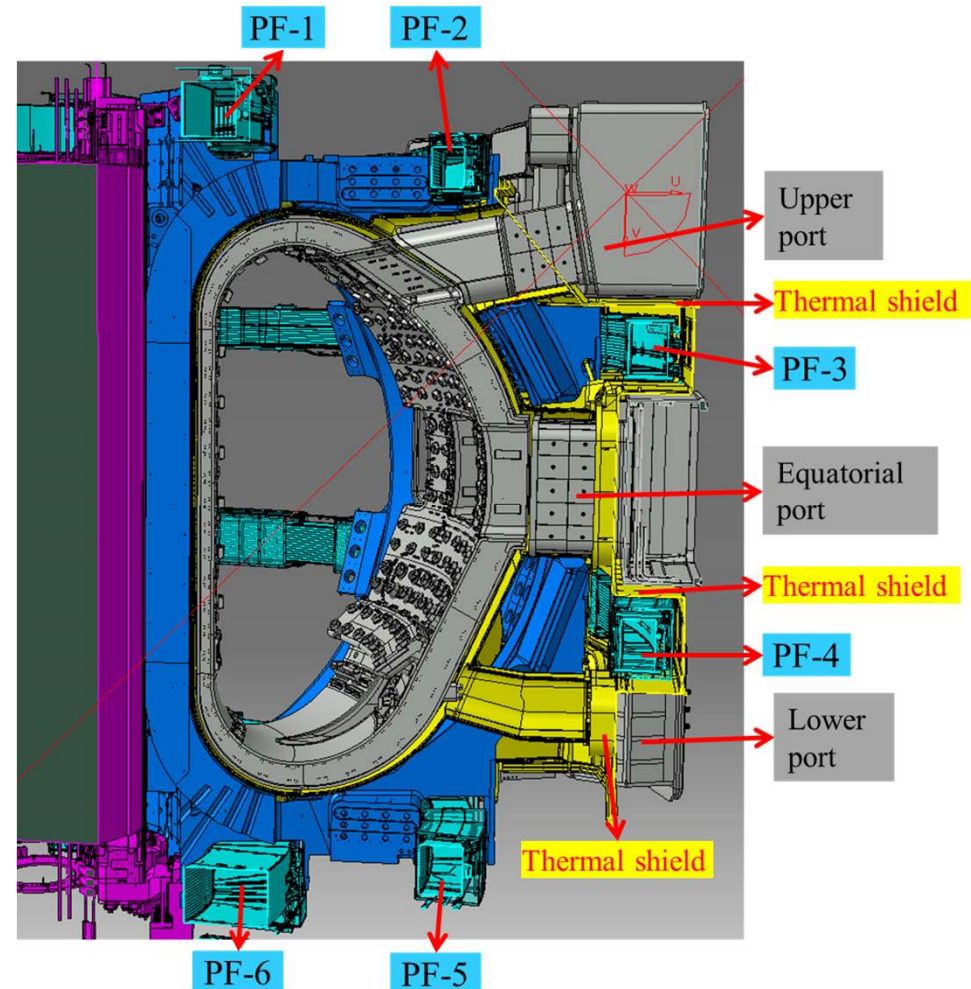
- **Introduction**
- **Methodology**
- **ITER application**
- **Summary**
- **Further R&D**

Introduction

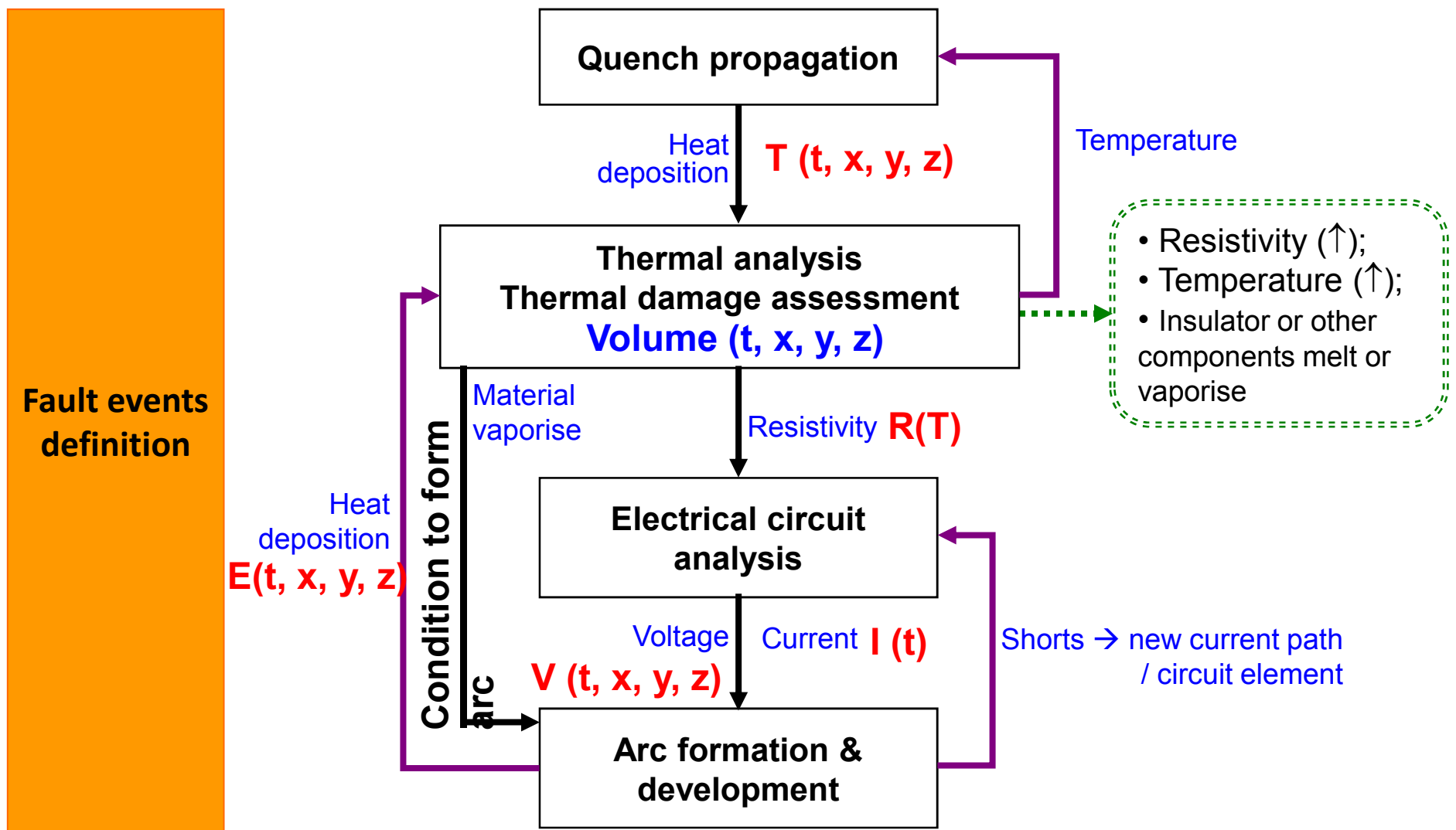
- **Safety concerns to ITER superconducting magnets**
 - Large amount of magnetic energy stored in ITER superconducting coils: ~40GJ in TFC and up to ~10GJ in CS/PFC
 - The consequences (damaging magnets or adjacent components?) if the massive energy localised
 - Safety questions from French Regulator
- **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

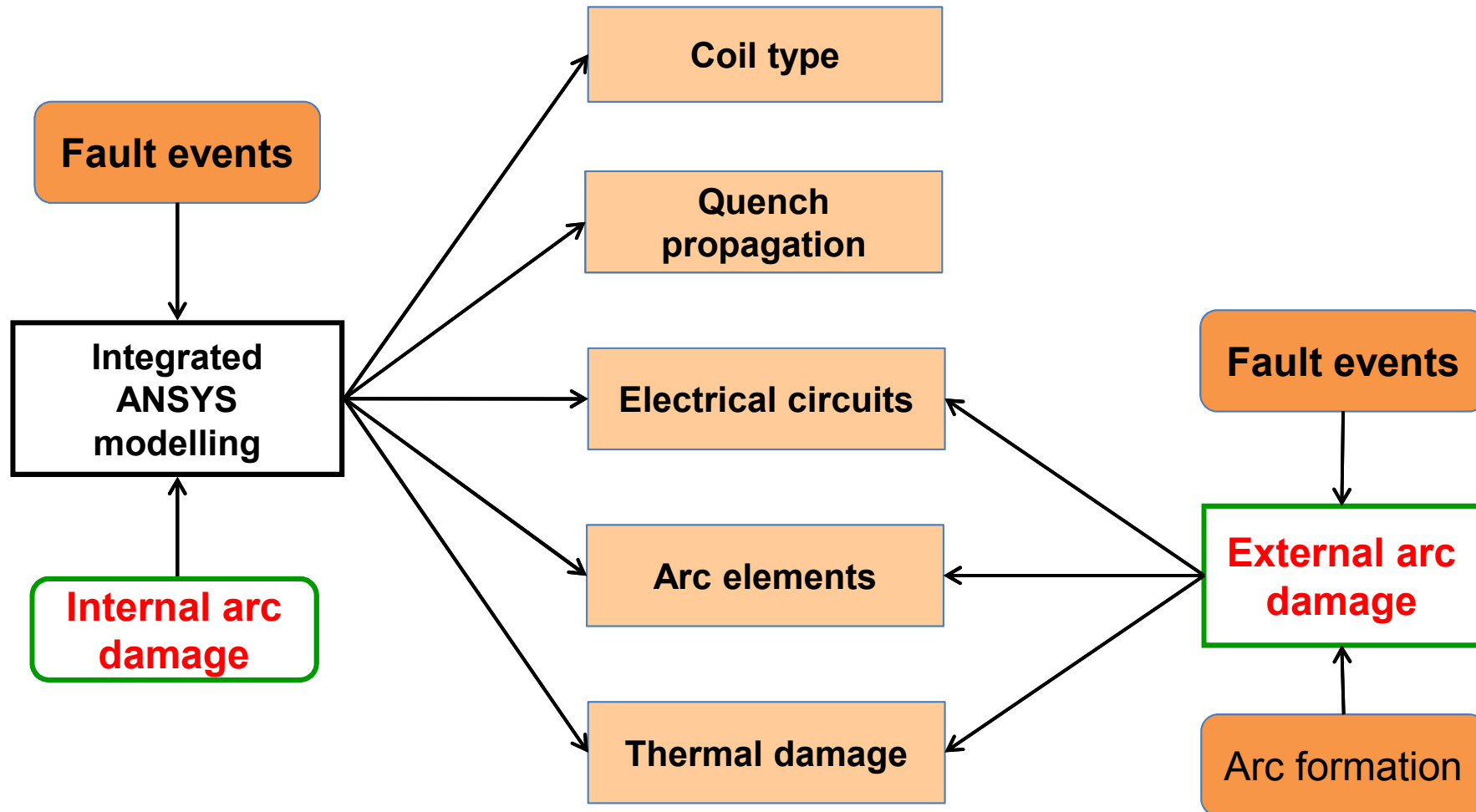
- **Damage to magnets (internal arcs)**
 - in TF coil: unmitigated quench (benchmark vs. MAGARC-TF/INL)
 - in PF coil: unmitigated quench or electrical short in PF-3
 - In Busbar
- **Damage to adjacent components (external arcs)**
 - From coils to VV
 - Molten materials from PF-3 → vacuum vessel port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



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

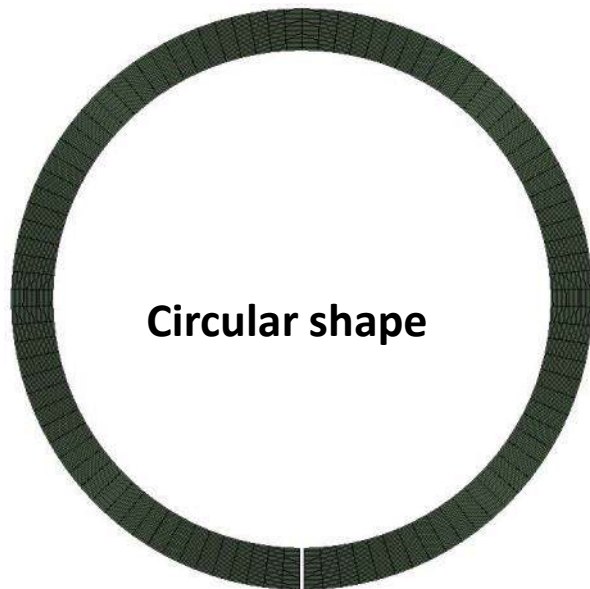
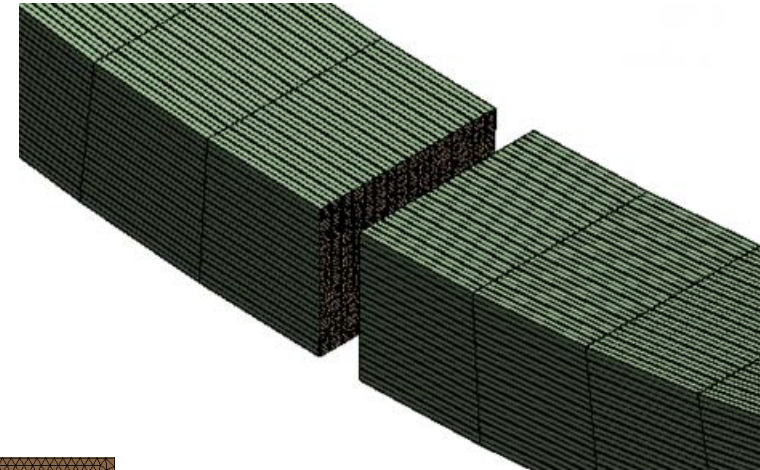
Simon McIntosh

Simon.McIntosh@iter.org

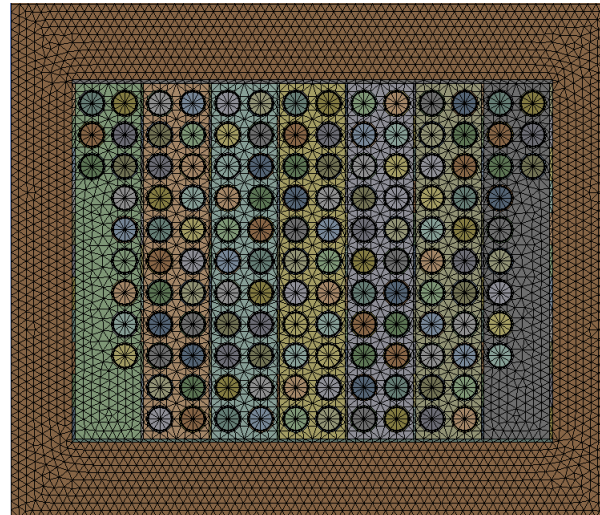
Details to be presented by Simon McIntosh

Integrated ANSYS model

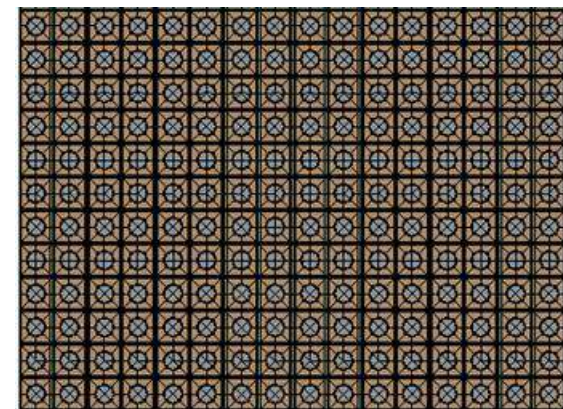
- **ANSYS as platform to integrate**
 - ITER coils geometry
 - Quench + electrical network + arc + thermal damage
- **Benchmark vs. MAGARC (INL/US)**



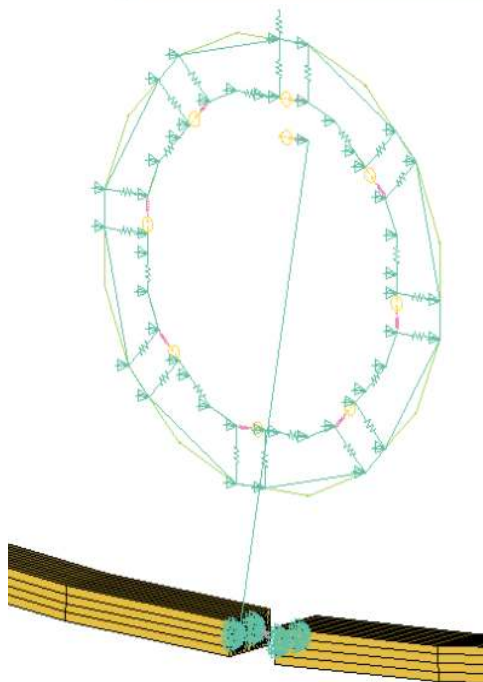
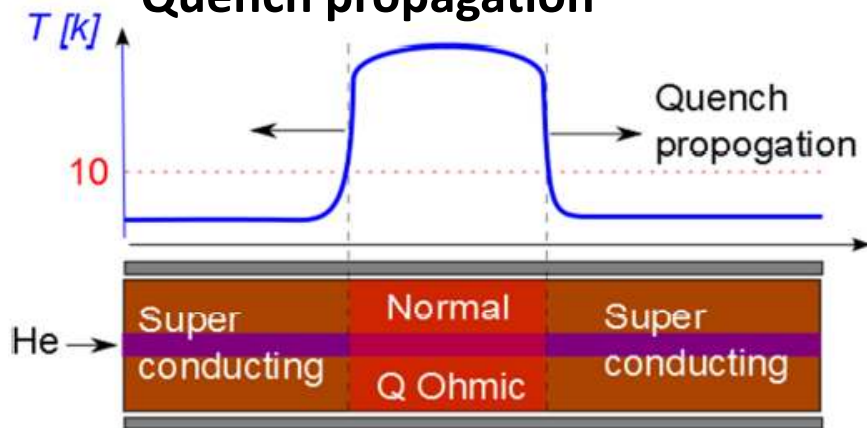
TFC cross-section



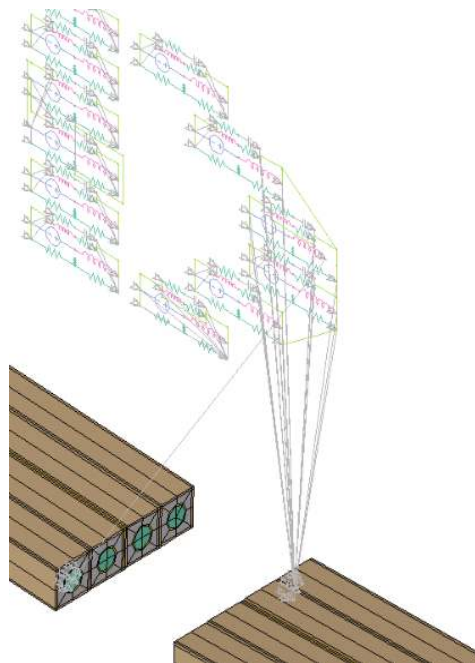
PFC cross-section



Quench propagation

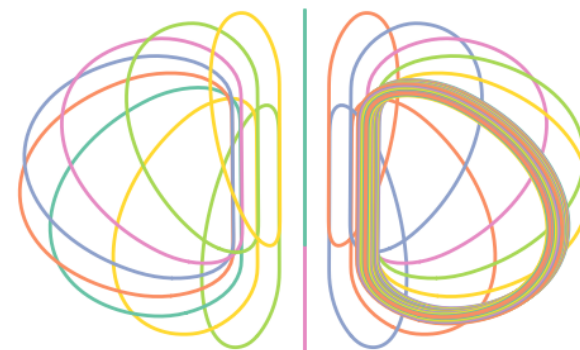
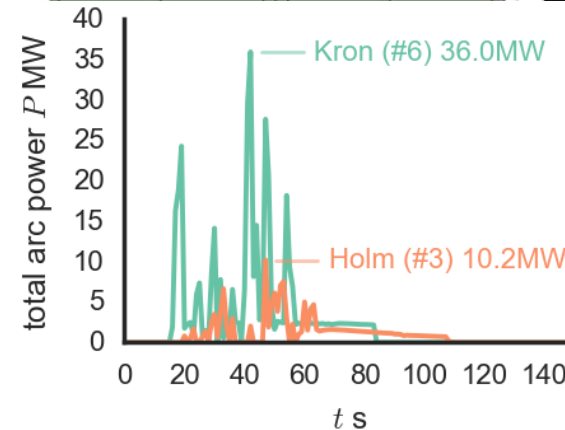
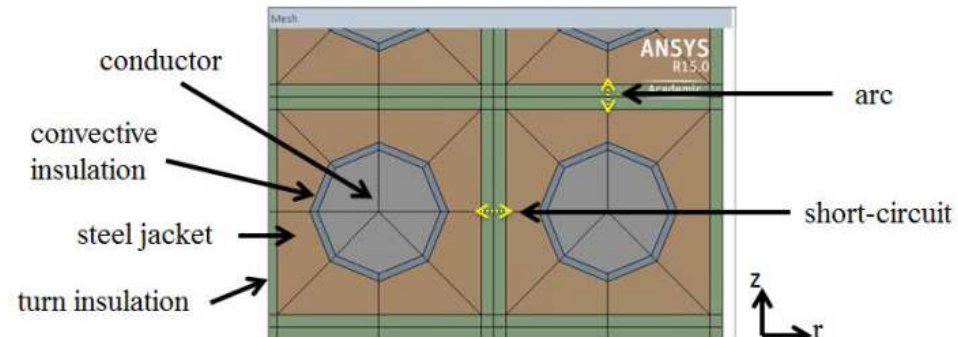


Electrical circuit

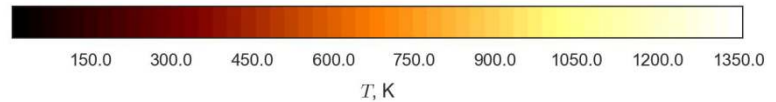
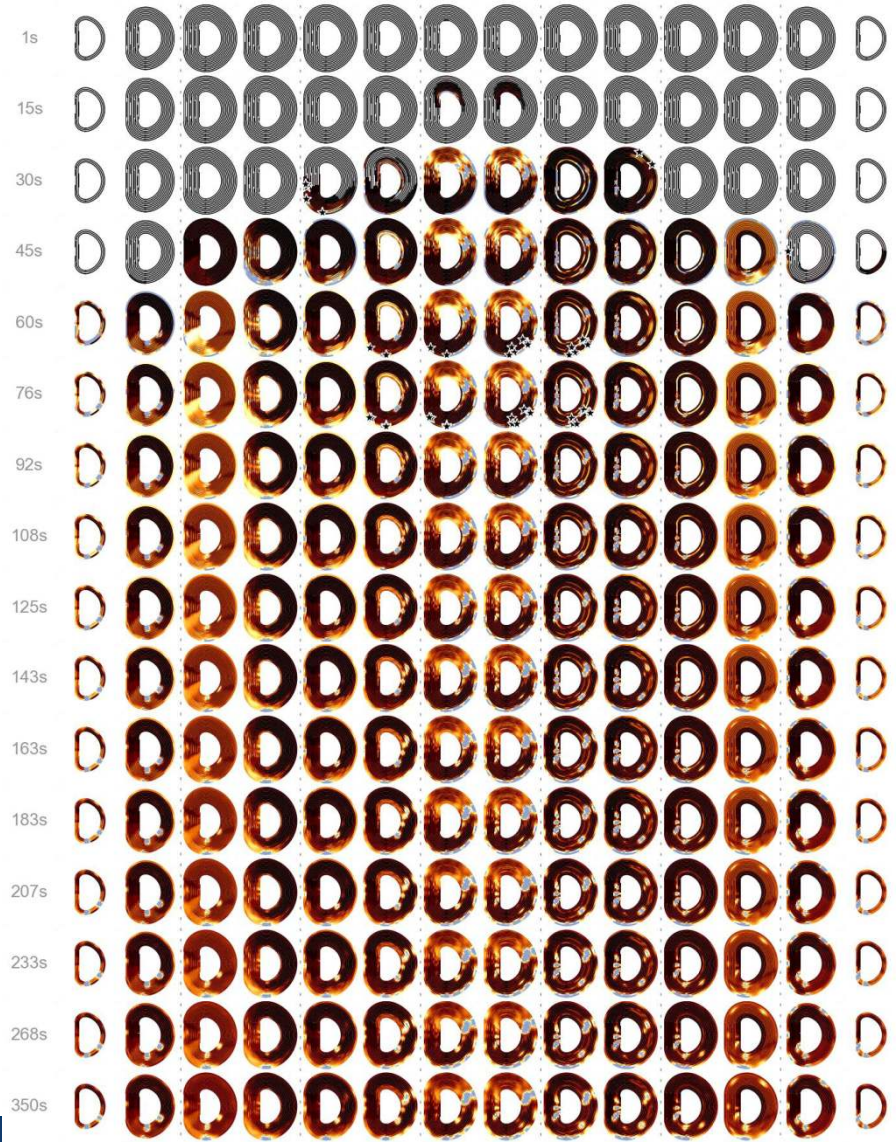
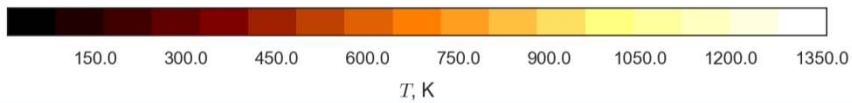
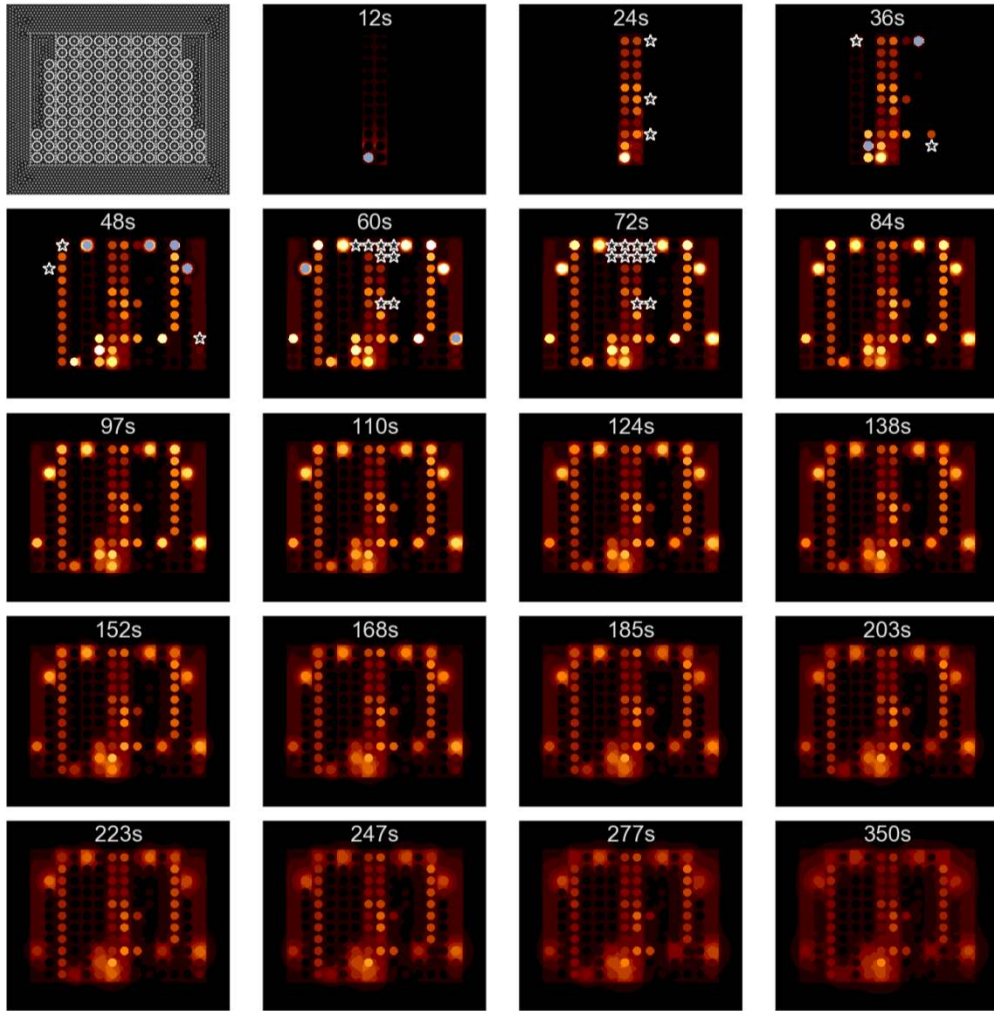


TFC electrical inductances

Electrical arcs

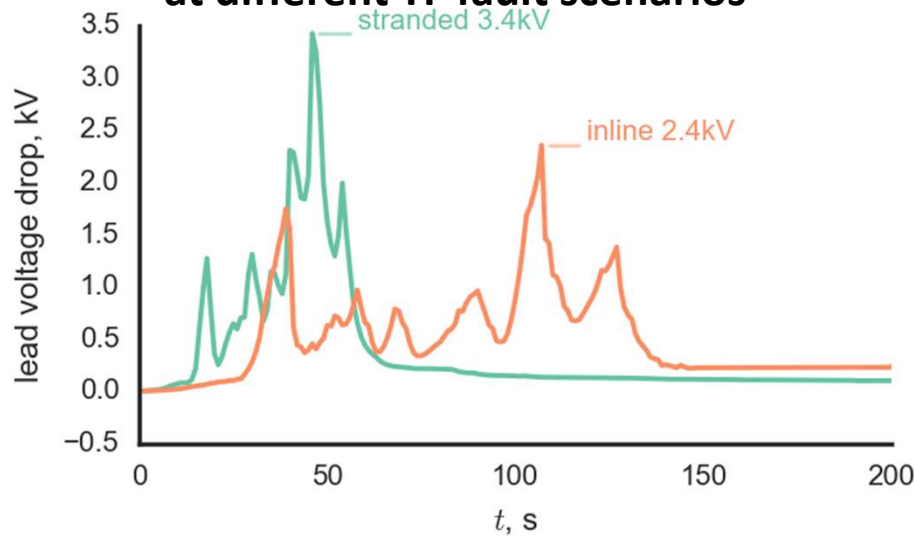


Results for TFC – thermal damage

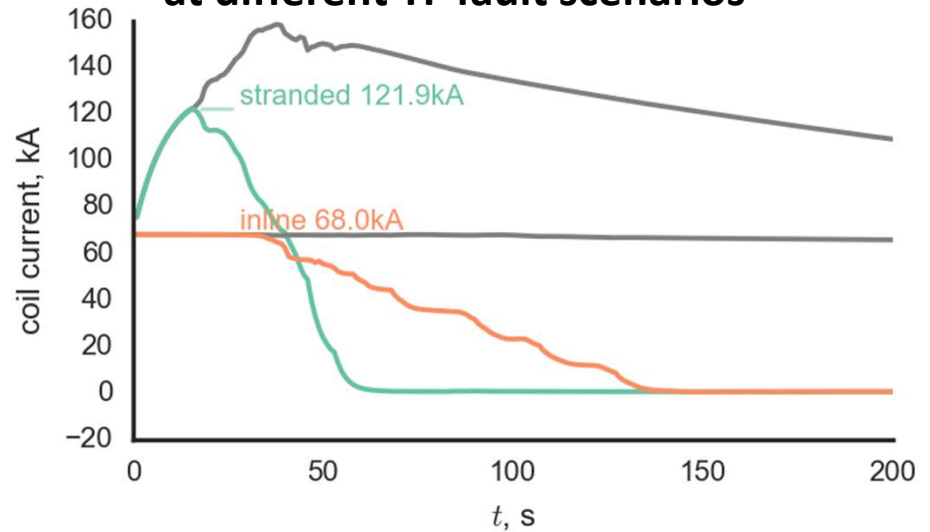


Results for TFC – V, I, power, melting volume

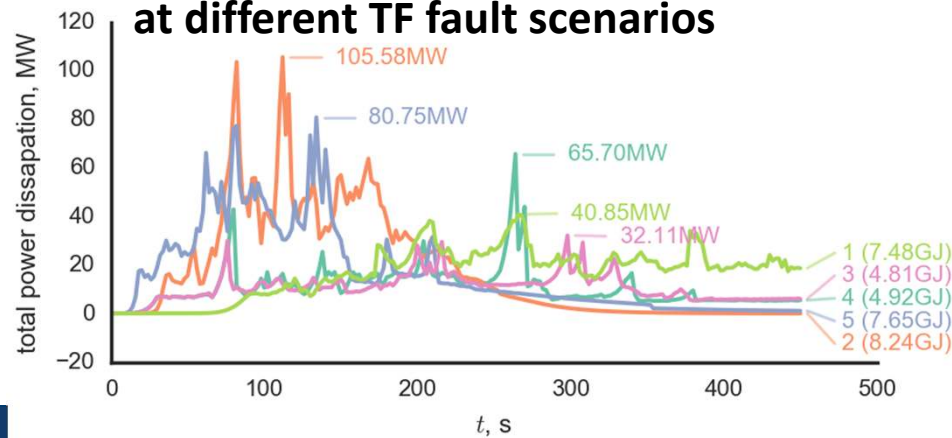
Voltage at different TF fault scenarios



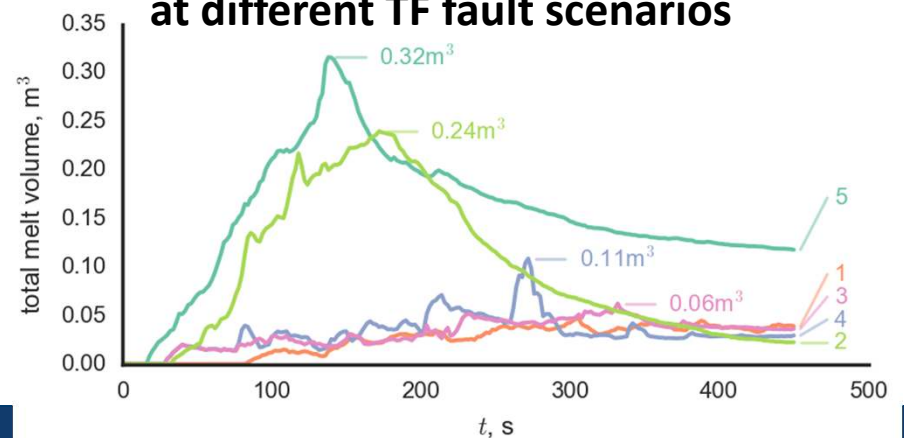
Current at different TF fault scenarios



Dissipation power at different TF fault scenarios



Melted volume at different TF fault scenarios



Arc model

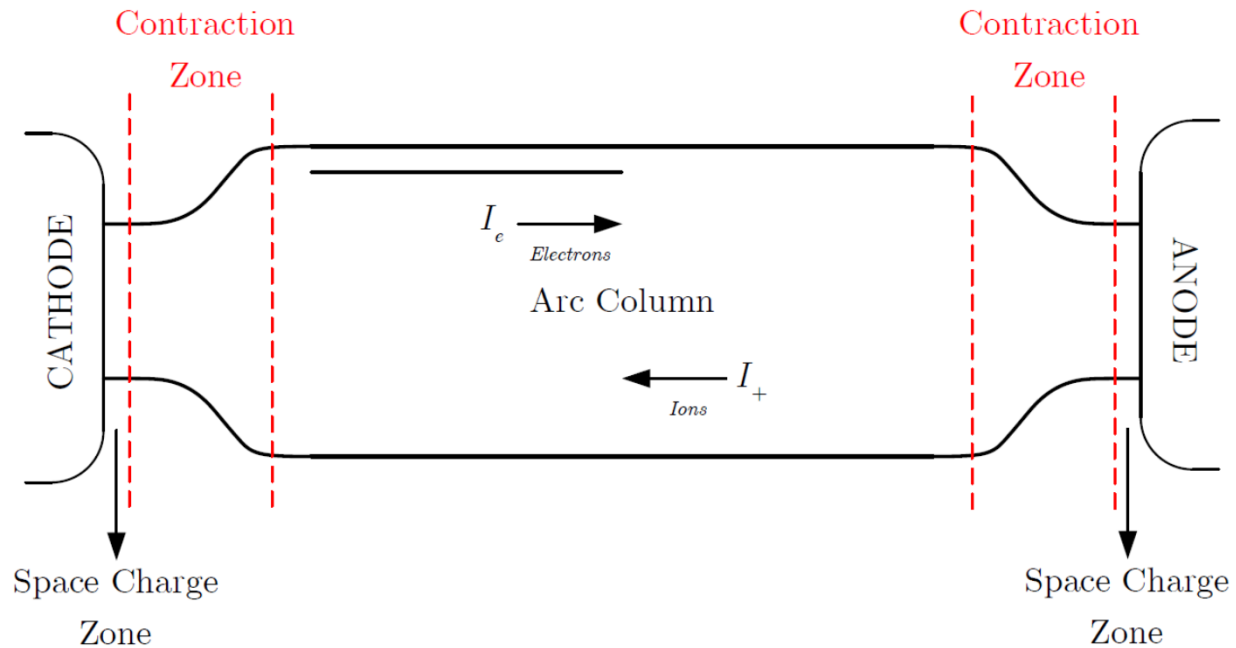
Andrew Ash, Andrew Holmes

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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)



'Kronhardt' model

- *Einfluß von Kurzschlüssen und Lichtbögen 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)

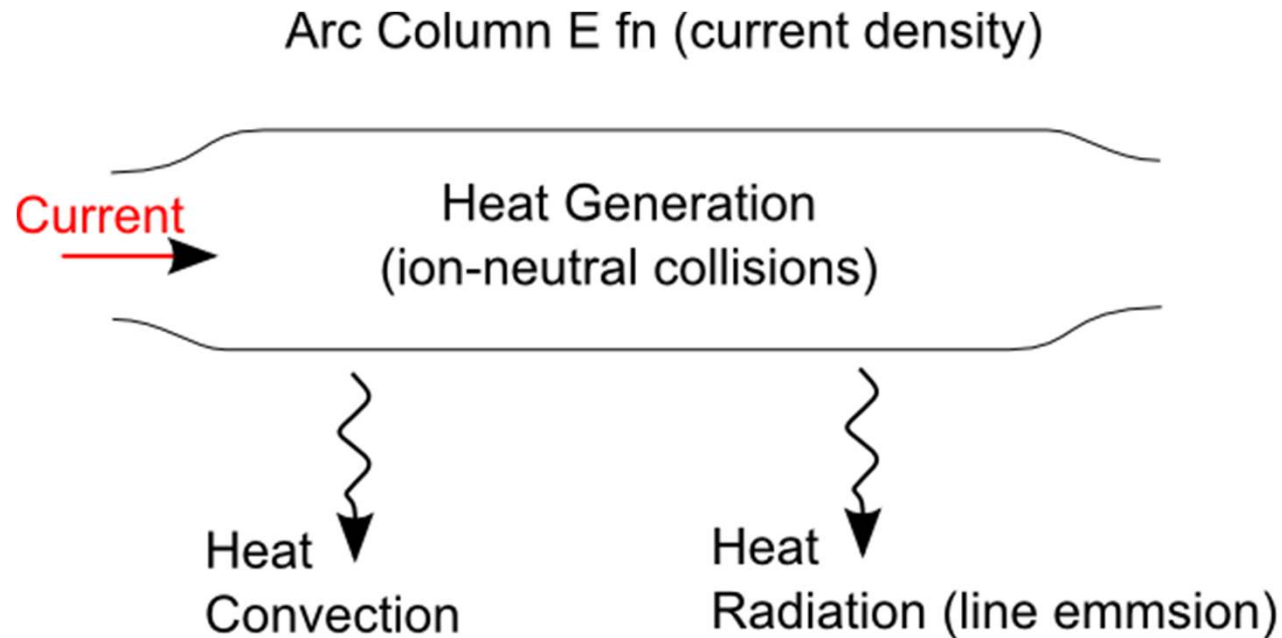
j = current density (A/mm^2) = I_{TF}/A_{arc}

6) H. Kronhardt, *Einfluß von Kurzschlüssen und Lichtbögen auf die Sicherheit von Magnetsystemen*, Institut 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



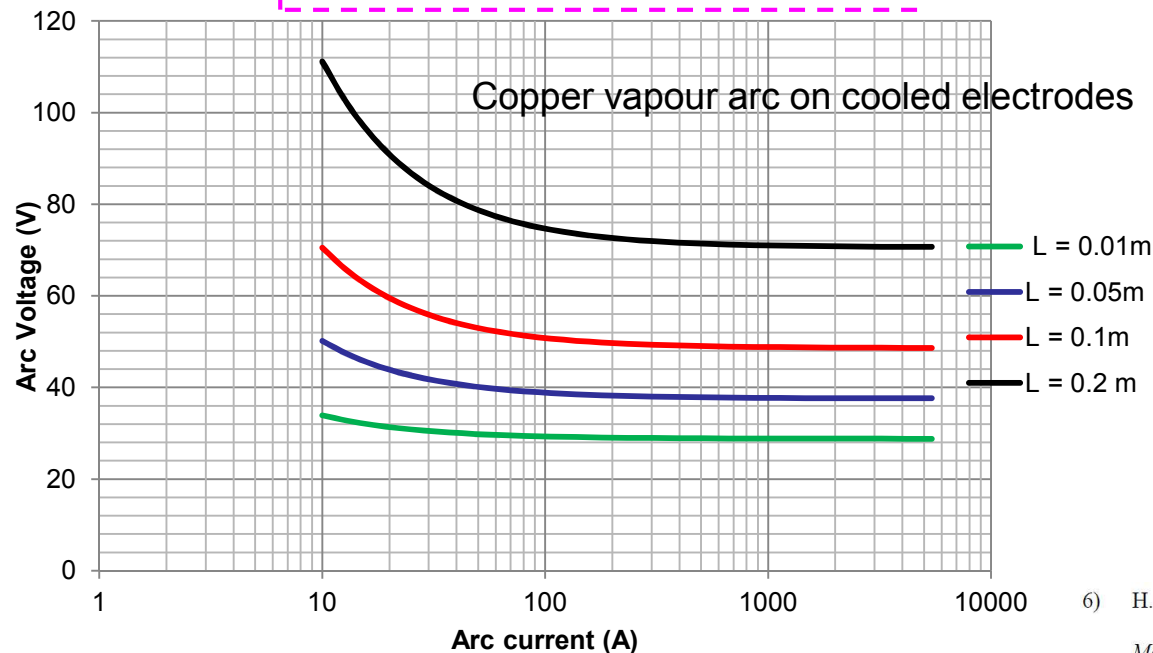
- Pressure
- Temperature
- Diameter
- Length
- Current
- Voltage (electrical field)
- Plasma density

'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

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

Kronhardt

V_{arc} = arc voltage drop (V)

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

Δ_g = gap width (mm)

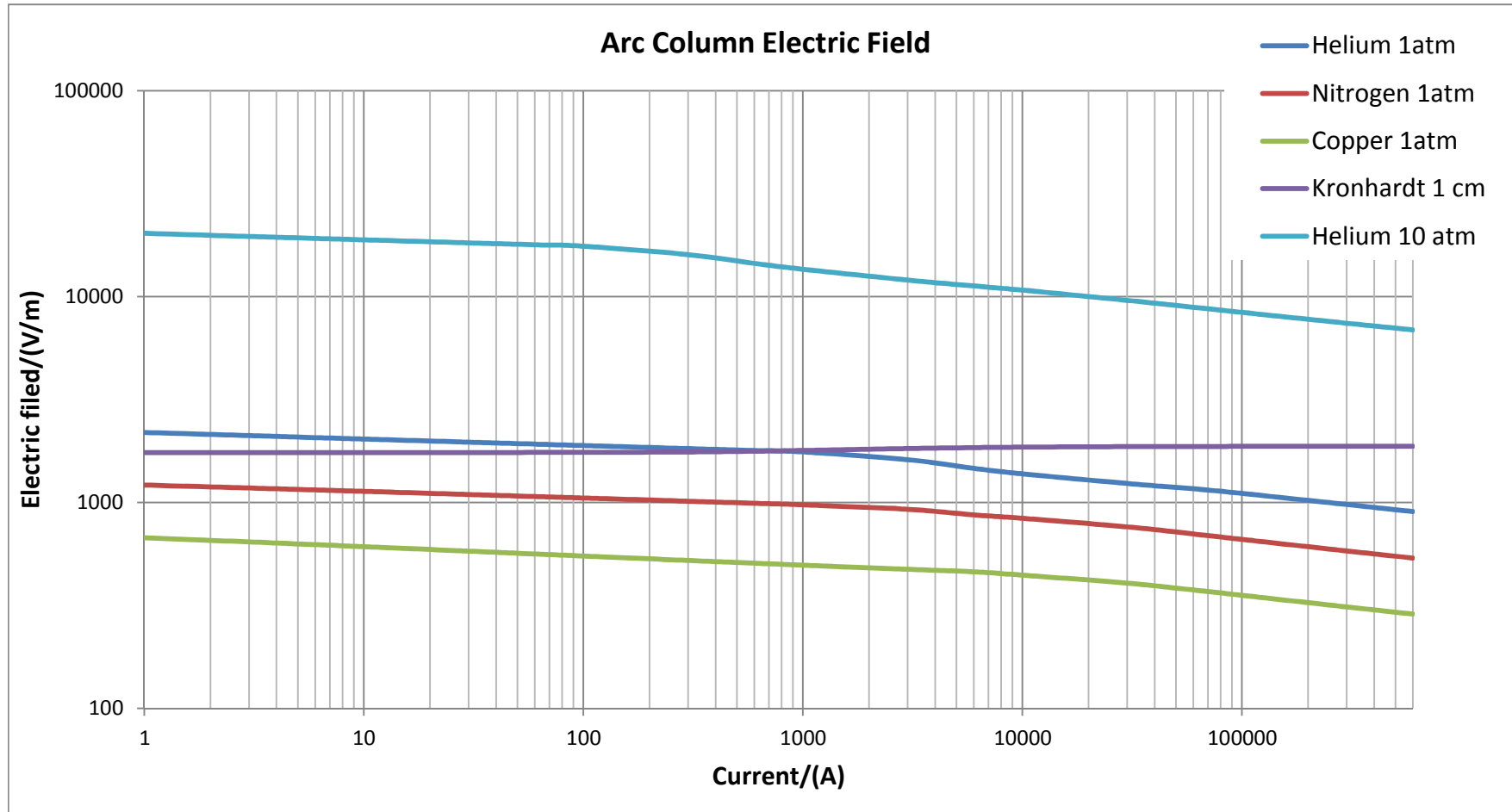
j = current density (A/mm^2) = I_{TF}/A_{arc}

B. Merrill, Annex 4B(DDD11-8);

B. Merrill, Fusion Tech, 37, 2000

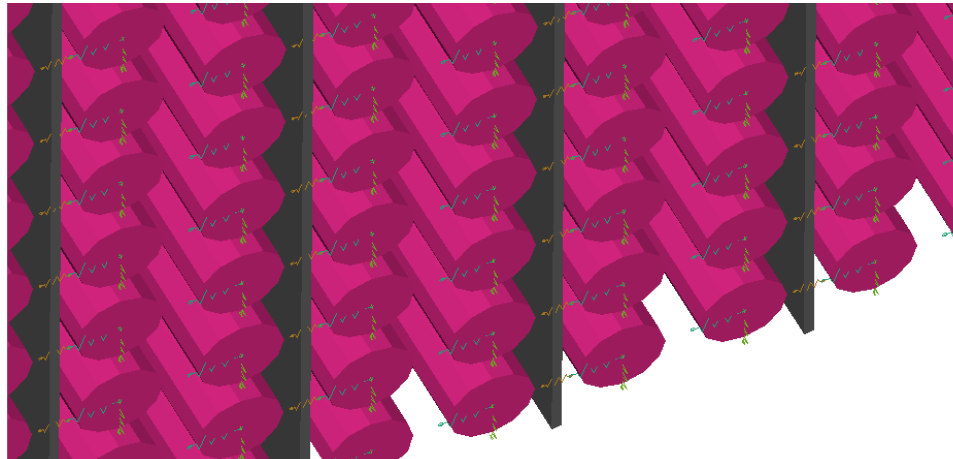
6) H. Kronhardt, *Einfluß von Kurzschlüssen und Lichtbögen auf die Sicherheit von Magnetsystemen*, Insitut für Technische Physik, Kfk 5096, S. 49, Mai 1993.

'Kronhardt' and 'Holmes' Arc Models



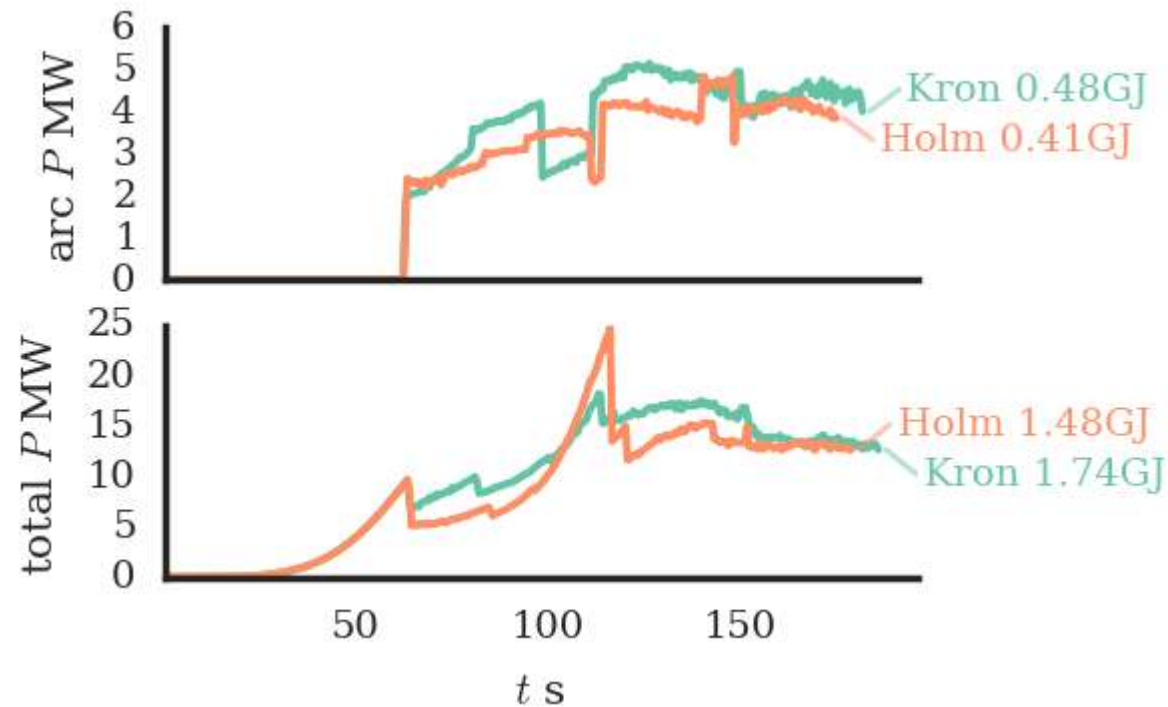
Arc model in ANSYS

- **Non-linear voltage-current characteristic**
- **Resistive circuit elements linking turns**
- **Conditions to initiate arcs**
 - $T > 600^\circ \text{ C}$
 - $\Delta V > 40\text{V}$
- Power dissipated in arc \rightarrow 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

Kim Cave-Ayland, Simon McIntosh

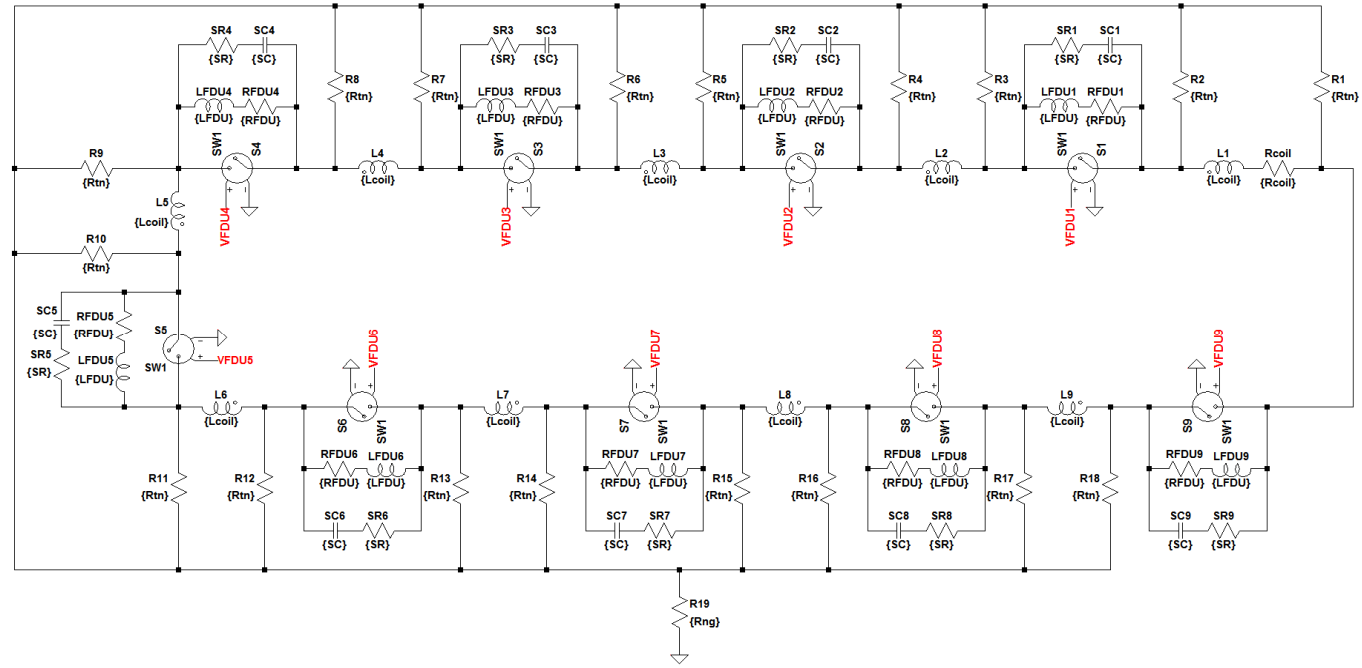
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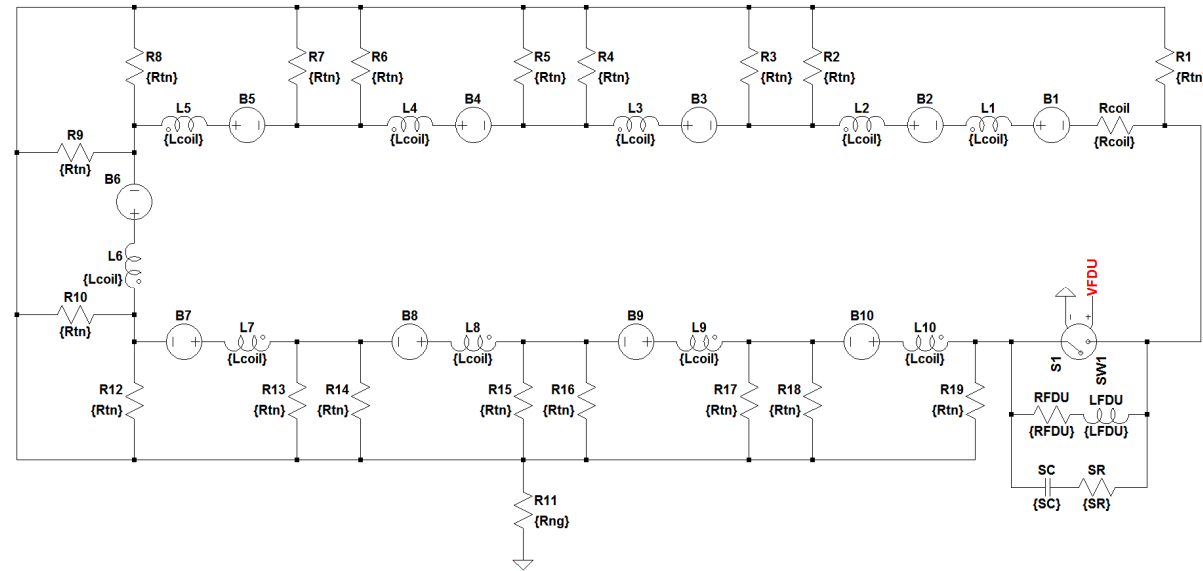
Electrical simulations

- 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

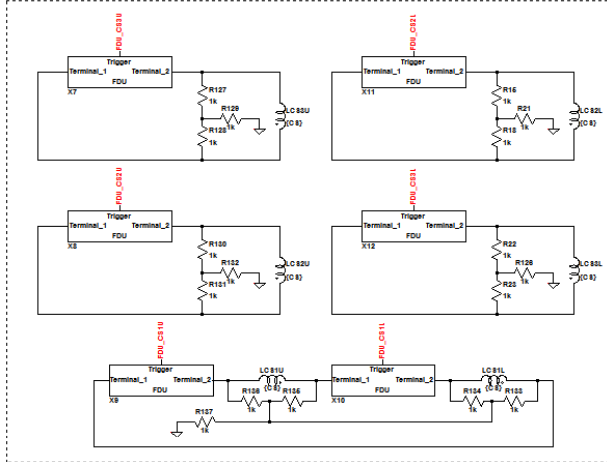


Further simplified TFC circuit with FDU for ANSYS

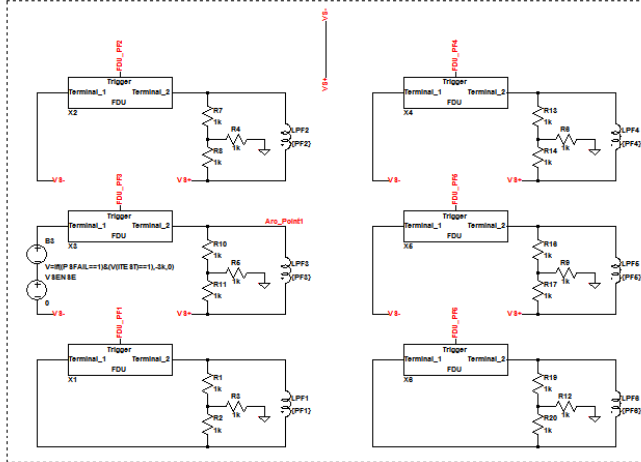


PF/CS electrical circuit + VV/TS/Cryostat

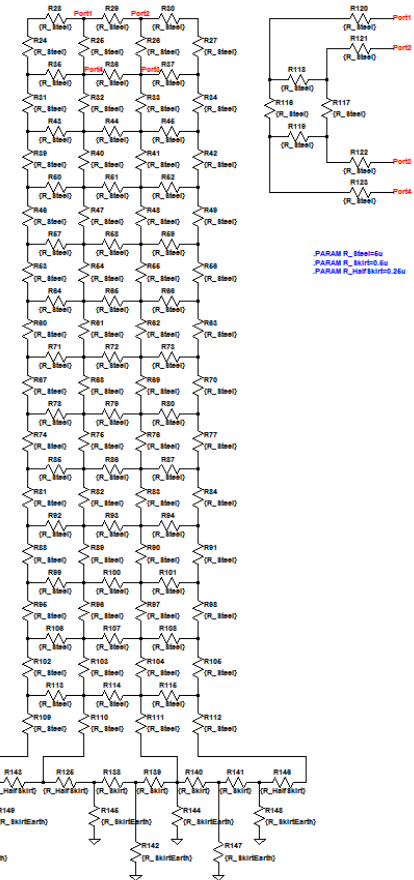
CS Circuits



PF Circuits



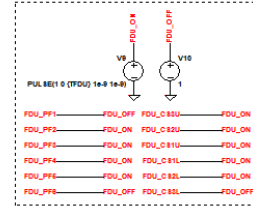
Cryostat & Thermal Shield



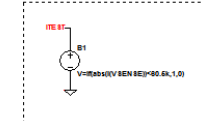
Coil Self Inductances and Coupling Coefficients

PF to PF mutual Inductances	PF to CS mutual Inductances	CS to PF mutual Inductances	Coil Inductances
KP1P2 LPF1 LPF2 0.1885 KP1P3 LPF1 LPF3 0.08738 KP1P4 LPF1 LPF4 0.04872 KP1P5 LPF1 LPF5 0.02812 KP1P6 LPF1 LPF6 0.01229	KP2P3 LPF2 LPF3 0.2648 KP2P4 LPF2 LPF4 0.1192 KP2P5 LPF2 LPF5 0.06474 KP2P6 LPF2 LPF6 0.02748	KP3P4 LPF3 LPF4 0.2865 KP3P5 LPF3 LPF5 0.1073 KP3P6 LPF3 LPF6 0.05042	PARAM PF1 = 0.7079 PARAM PF2 = 0.4740 PARAM PF3 = 1.380 PARAM PF4 = 1.066 PARAM PF5 = 1.582 PARAM PF6 = 2.264 PARAM CS = 0.7864
KC1UC1L LC 8S1 LC 8S1 0.8107 KC1UC1L LC 8S1 LC 8I1 0.08784 KC1UC1L LC 8S1 LC 8I2 0.02251 KC1UC1L LC 8S1 LC 8I3 0.01008 KC1UC1L LC 8S1 LC 8I4 0.004481	KC2UC1L LC 8S1 LC 8I1 0.8107 KC2UC1L LC 8S1 LC 8I2 0.08784 KC2UC1L LC 8S1 LC 8I3 0.02251 KC2UC1L LC 8S1 LC 8I4 0.01008	KC1UC2L LC 8I1 LC 8I1 0.8107 KC1UC2L LC 8I1 LC 8I2 0.08784 KC1UC2L LC 8I1 LC 8I3 0.02251 KC1UC2L LC 8I1 LC 8I4 0.01008	PARAM PF1 = 0.7079 PARAM PF2 = 0.4740 PARAM PF3 = 1.380 PARAM PF4 = 1.066 PARAM PF5 = 1.582 PARAM PF6 = 2.264 PARAM CS = 0.7864
KC2UC2L LC 8S1 LC 8I1 0.8107 KC2UC2L LC 8S1 LC 8I2 0.08784 KC2UC2L LC 8S1 LC 8I3 0.02251 KC2UC2L LC 8S1 LC 8I4 0.01008	KC3UC1L LC 8I1 LPF1 0.01948 KC3UC1L LC 8I1 LPF2 0.04500 KC3UC1L LC 8I1 LPF3 0.03894 KC3UC1L LC 8I1 LPF4 0.02751 KC3UC1L LC 8I1 LPF5 0.02097 KC3UC1L LC 8I1 LPF6 0.01501	KC3UC2L LC 8I2 LPF1 0.01115 KC3UC2L LC 8I2 LPF2 0.03011 KC3UC2L LC 8I2 LPF3 0.02866 KC3UC2L LC 8I2 LPF4 0.04169 KC3UC2L LC 8I2 LPF5 0.04987 KC3UC2L LC 8I2 LPF6 0.03783	PARAM PF1 = 0.7079 PARAM PF2 = 0.4740 PARAM PF3 = 1.380 PARAM PF4 = 1.066 PARAM PF5 = 1.582 PARAM PF6 = 2.264 PARAM CS = 0.7864
KC4UC1L LC 8I2 LPF1 0.01115 KC4UC1L LC 8I2 LPF2 0.03011 KC4UC1L LC 8I2 LPF3 0.02866 KC4UC1L LC 8I2 LPF4 0.04169 KC4UC1L LC 8I2 LPF5 0.04987 KC4UC1L LC 8I2 LPF6 0.03783	KC4UC2L LC 8I3 LPF1 0.008873 KC4UC2L LC 8I3 LPF2 0.01587 KC4UC2L LC 8I3 LPF3 0.02247 KC4UC2L LC 8I3 LPF4 0.03099 KC4UC2L LC 8I3 LPF5 0.07348 KC4UC2L LC 8I3 LPF6 0.101	KC5UC1L LC 8I3 LPF1 0.01948 KC5UC1L LC 8I3 LPF2 0.04500 KC5UC1L LC 8I3 LPF3 0.03894 KC5UC1L LC 8I3 LPF4 0.02751 KC5UC1L LC 8I3 LPF5 0.02097 KC5UC1L LC 8I3 LPF6 0.01501	PARAM PF1 = 0.7079 PARAM PF2 = 0.4740 PARAM PF3 = 1.380 PARAM PF4 = 1.066 PARAM PF5 = 1.582 PARAM PF6 = 2.264 PARAM CS = 0.7864
KC5UC2L LC 8I4 LPF1 0.01948 KC5UC2L LC 8I4 LPF2 0.04500 KC5UC2L LC 8I4 LPF3 0.03894 KC5UC2L LC 8I4 LPF4 0.02751 KC5UC2L LC 8I4 LPF5 0.02097 KC5UC2L LC 8I4 LPF6 0.01501			

FDU Control Signals



PS Control



Parameters

Arm Parameters
 STEP PARAM P LIST 0.1 0.6 1.2
 PARAM L 0.592
 PARAM TARC = 0

FDU Parameter
 PARAM FDU=0

P8 Parameter
 PARAM P8FAIL = 0

Cryostat Parameter
 PARAM R_cryo = 70.26u

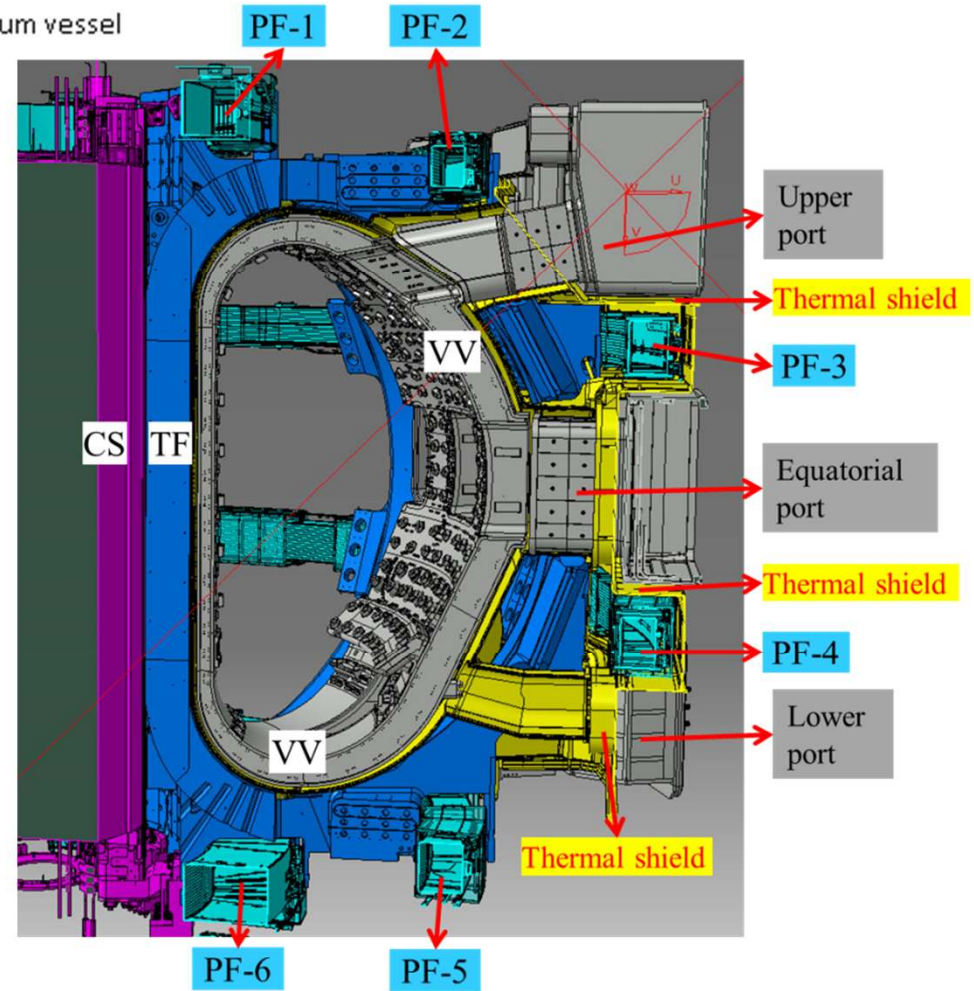
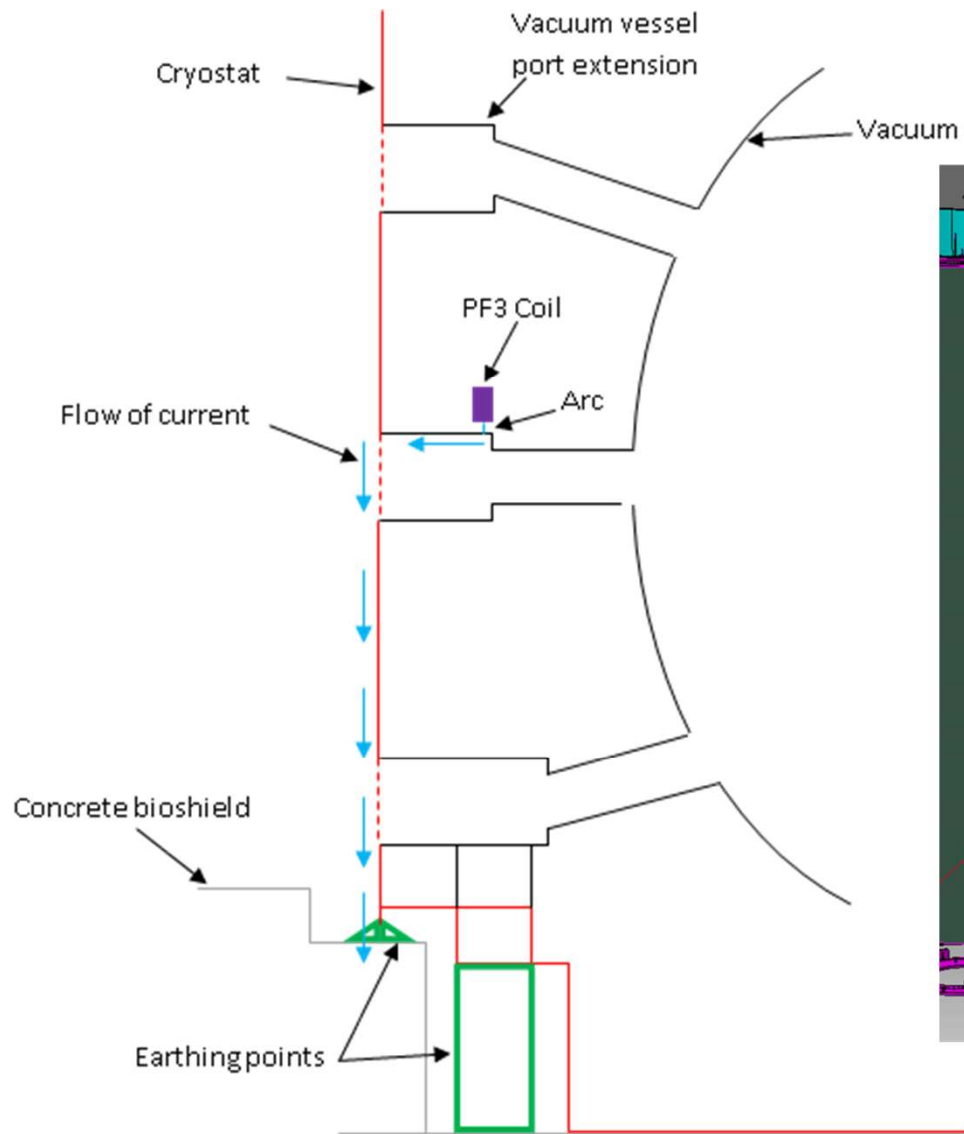
Initial Conditions

Maximum initial conditions
 I0 ILPF1=10.09k ILPF2=4.47k ILPF3=4.47k ILPF4=4.47k ILPF5=4.47k ILPF6=4.47k
 I0 LC 8S1=46k IL C 8S1=46k IL C 8I1=46k IL C 8I2=46k IL C 8I3=46k IL C 8I4=46k

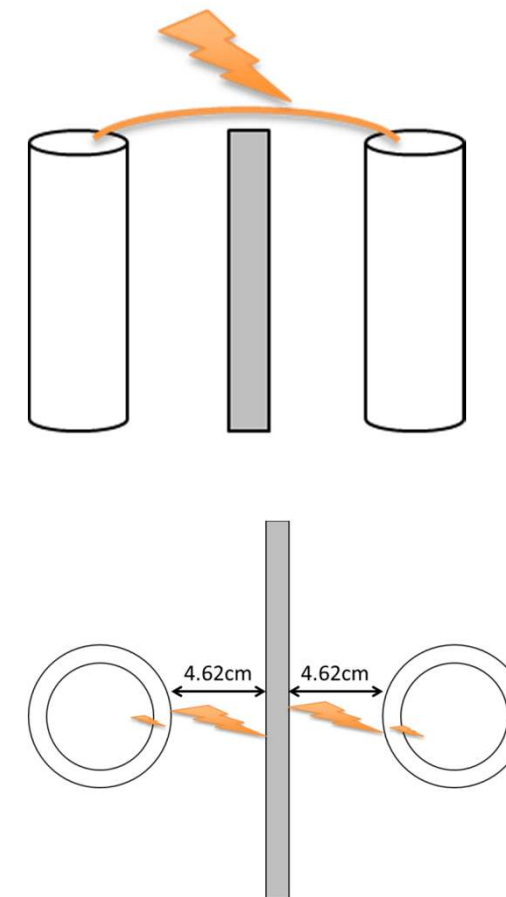
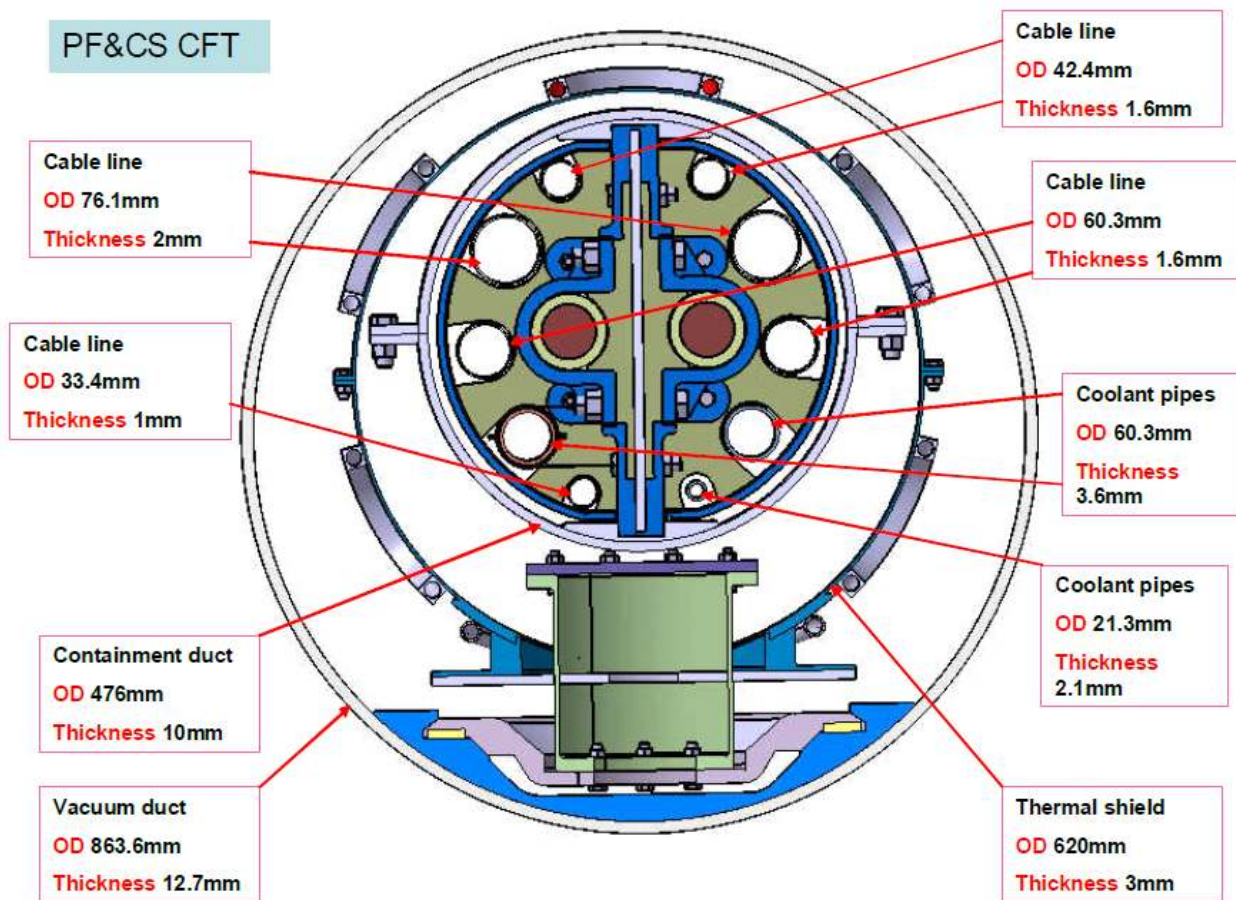
17MA Baseline maximum initial conditions (I = 501.8k)
 I0 ILPF1=10.09k ILPF2=4.47k ILPF3=4.47k ILPF4=4.47k ILPF5=4.47k ILPF6=4.47k
 I0 LC 8S1=10.81k IL C 8S1=38.07k IL C 8I1=44.75k IL C 8I2=44.75k IL C 8I3=44.75k IL C 8I4=44.75k IL C 8I5=44.75k IL C 8I6=44.75k IL C 8I7=44.75k IL C 8I8=44.75k

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

New electrical paths from PF to VV/Cryostat

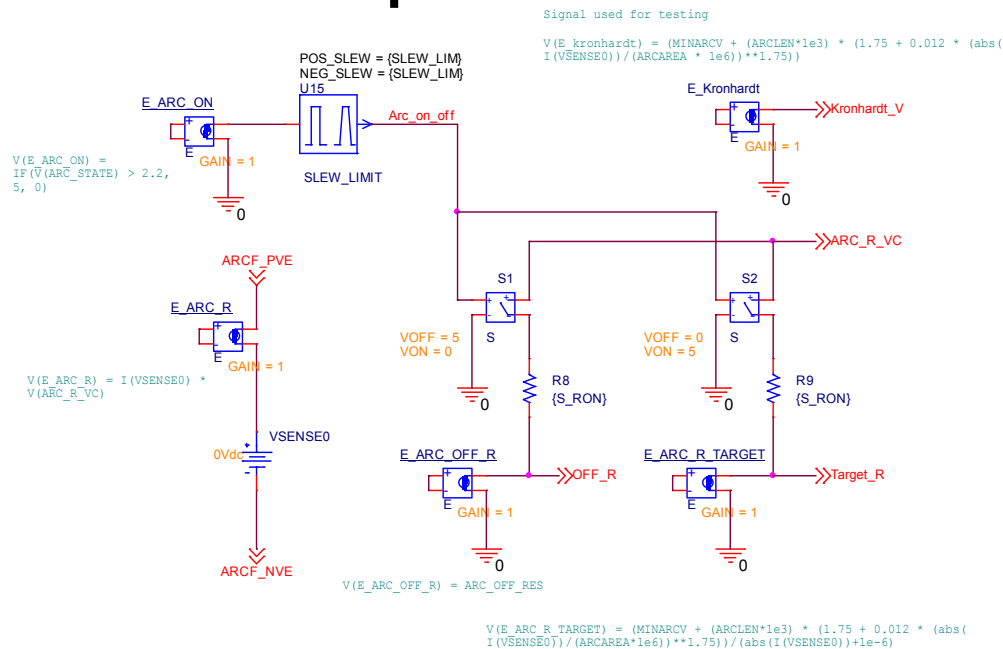


New electrical paths due to double ground fault to PF-3 busbar

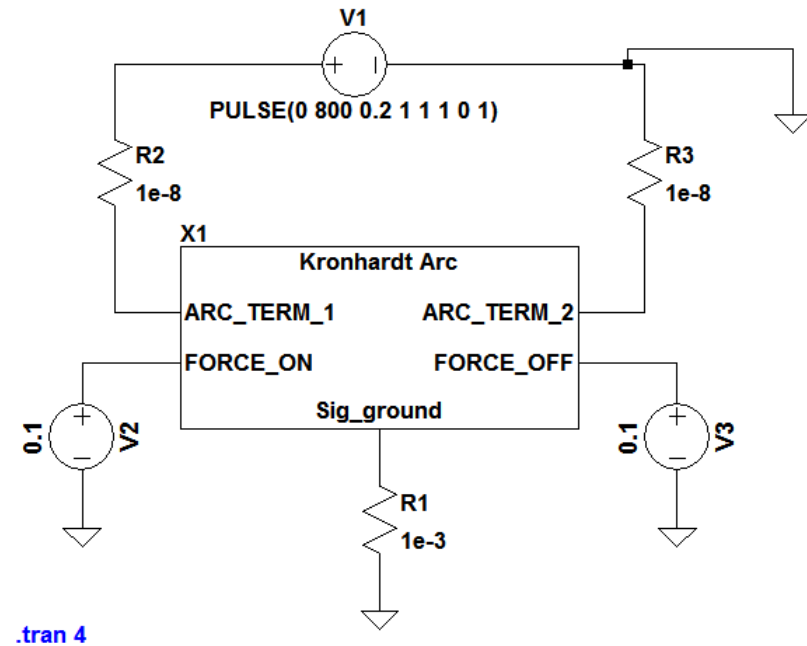


Electrical arc model

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



Kronhardt behaviour circuit (Pspice)



arc component (LTspice)

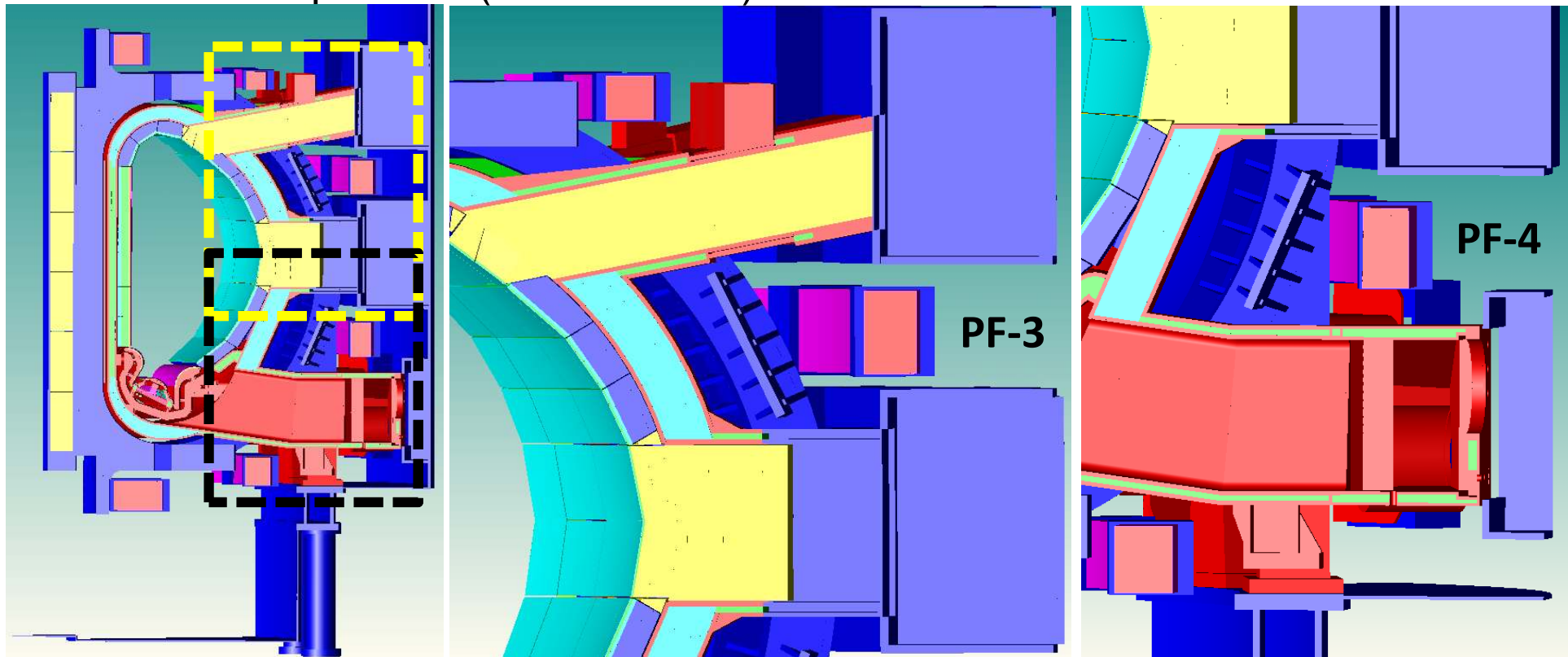
Thermal damage assessment

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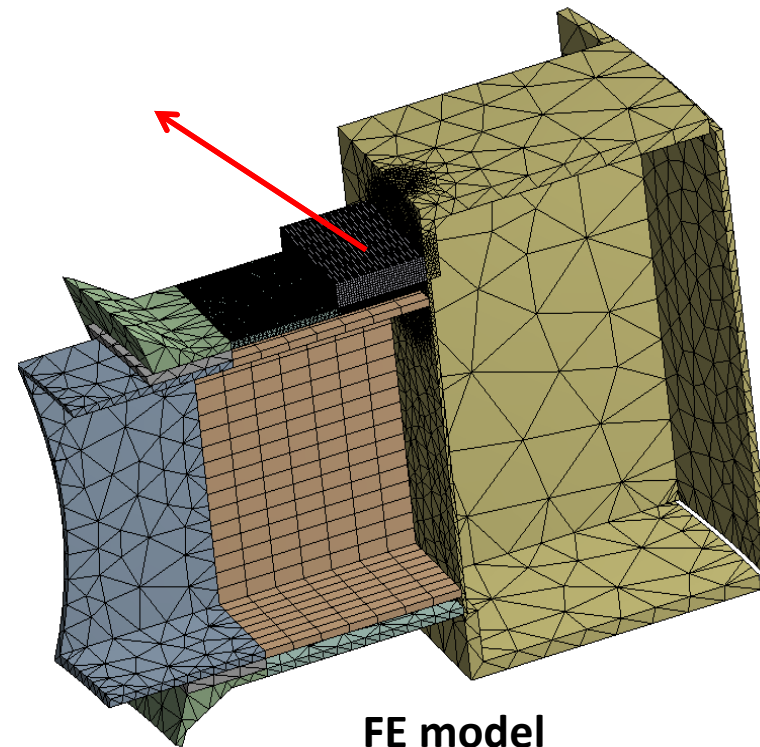
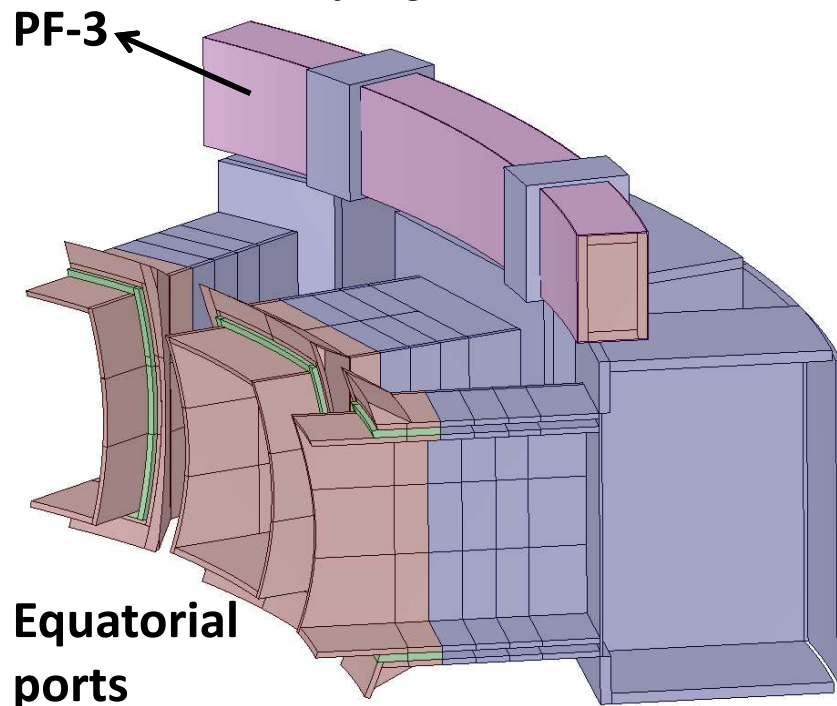
Thermal damage

- **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)

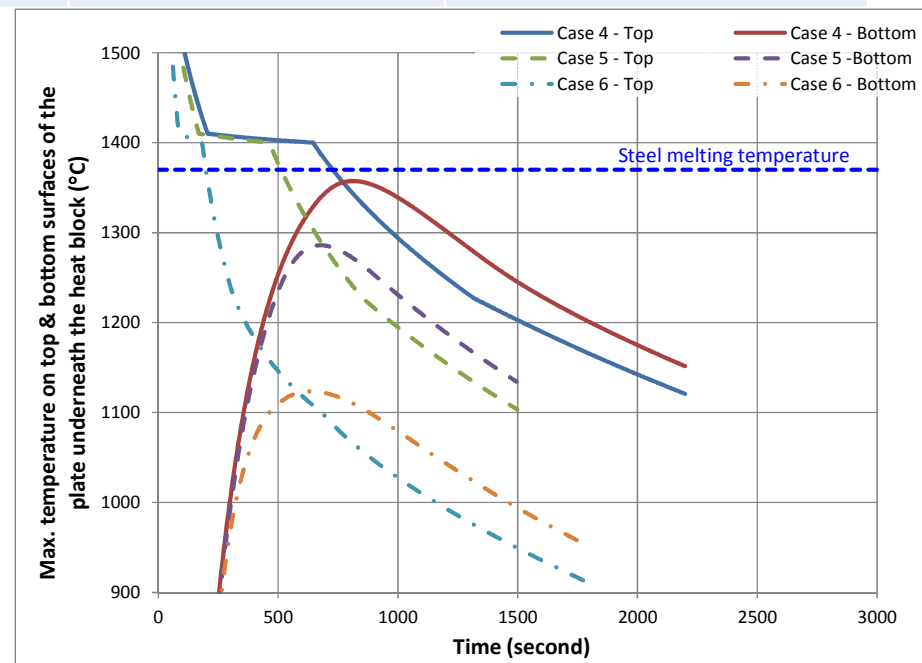
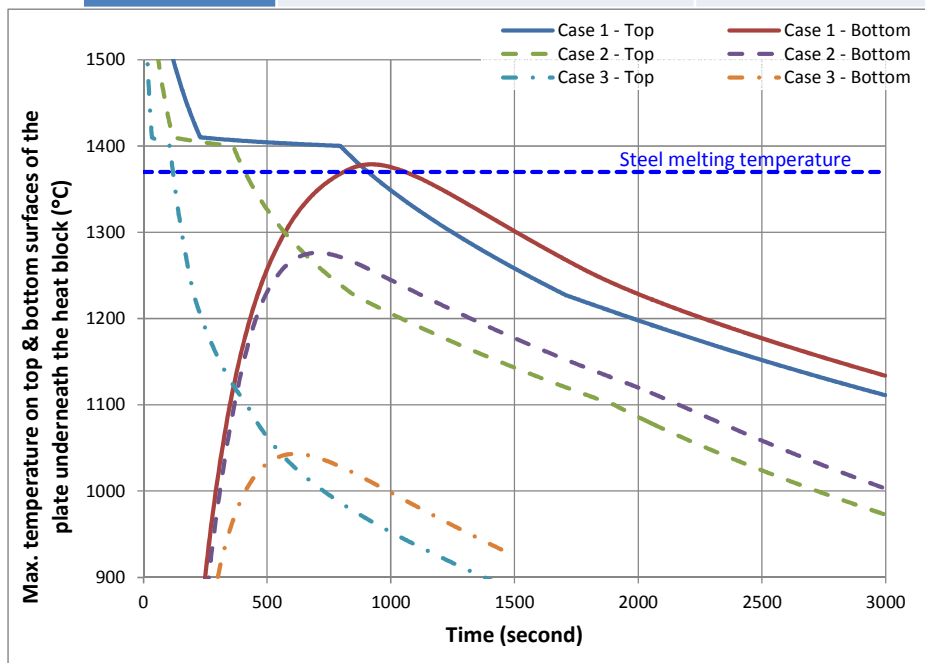


Thermal damage by molten materials

- **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



	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

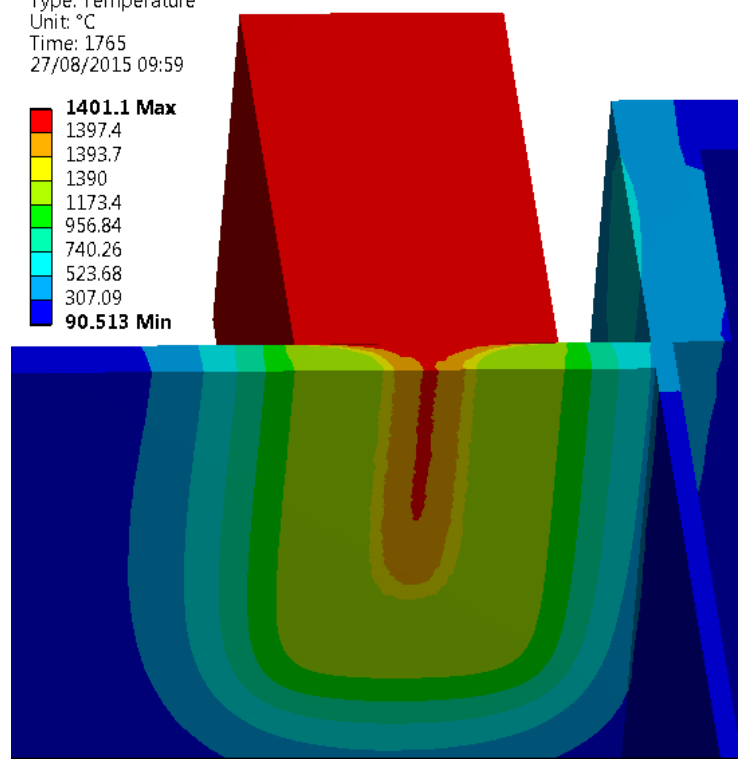
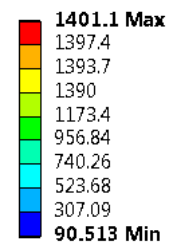


maximum temperature on top and bottom of the vessel plate

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

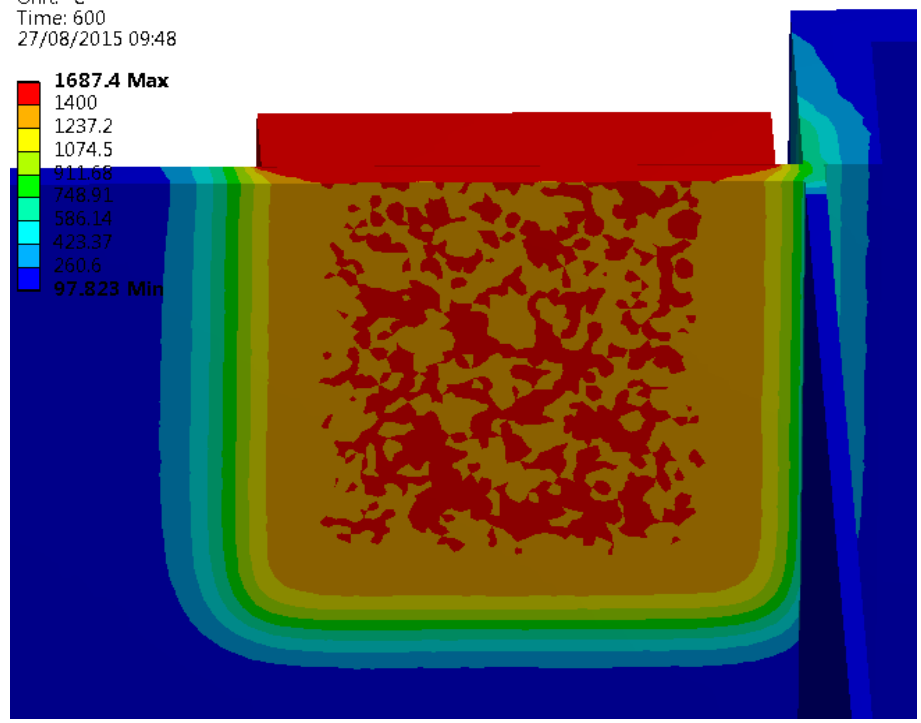
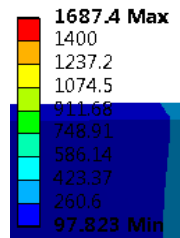
case 7 (Temperature = 1744 °C, Total Energy = 3.24 GJ, Volume = 0.3 m³, Footprint area = 0.4 m²)

B: Transient Thermal - Step 2
Temperature 12
Type: Temperature
Unit: °C
Time: 1765
27/08/2015 09:59

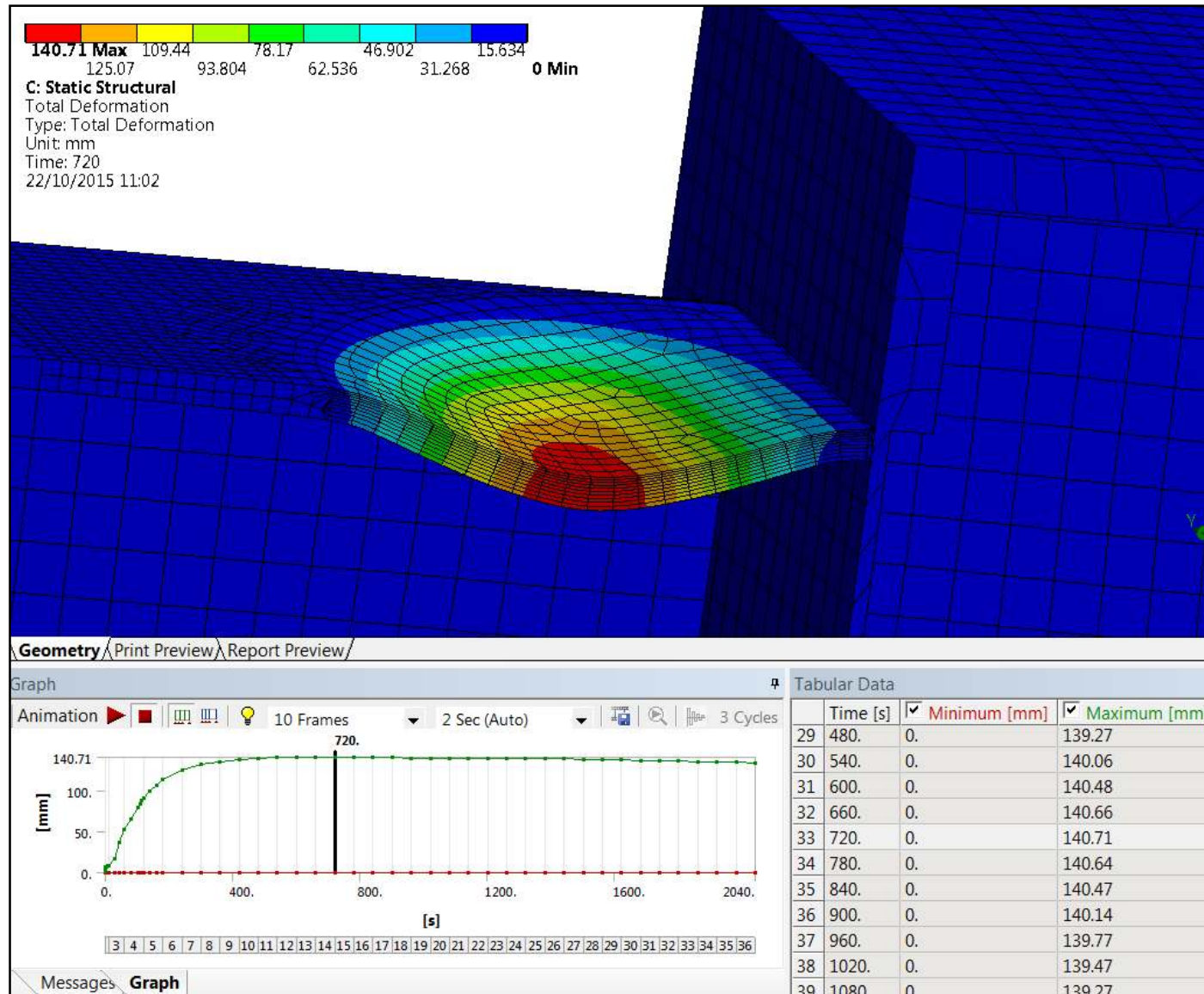


case 8 (Temperature = 2887 °C, Total Energy = 3.24 GJ, Volume = 0.2 m³, Footprint area = 1.06 m²)

Temperature 9
Type: Temperature
Unit: °C
Time: 600
27/08/2015 09:48

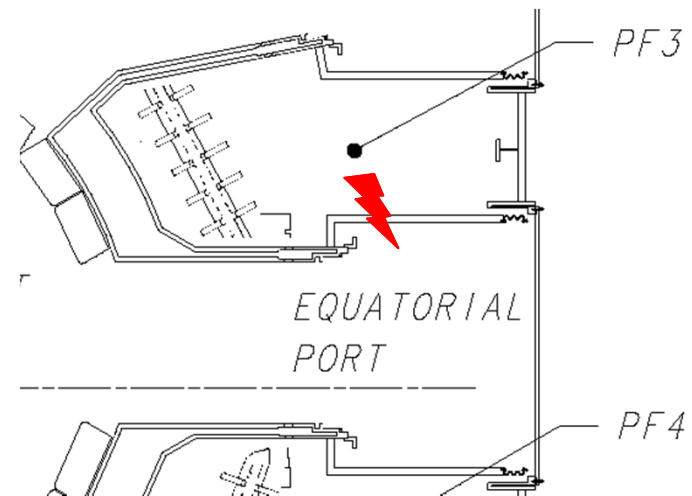
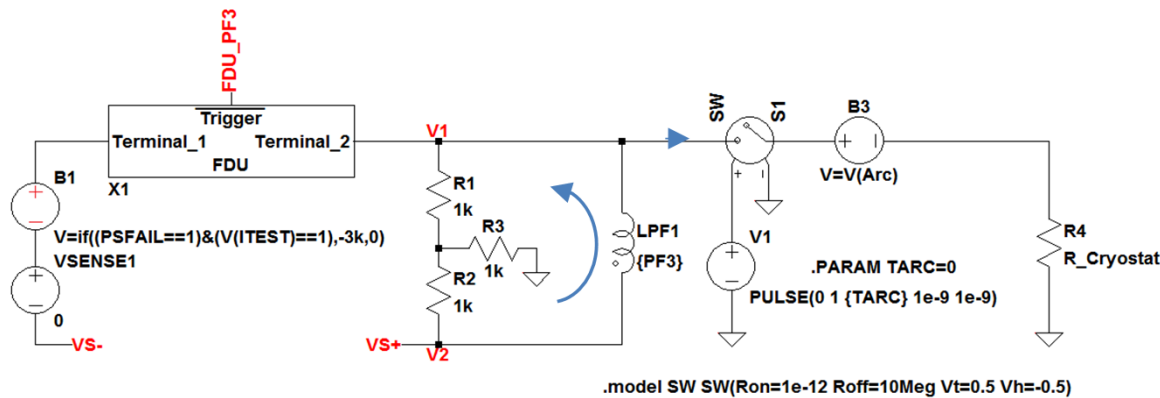


Peak deformation of the layer of EQ-port wall

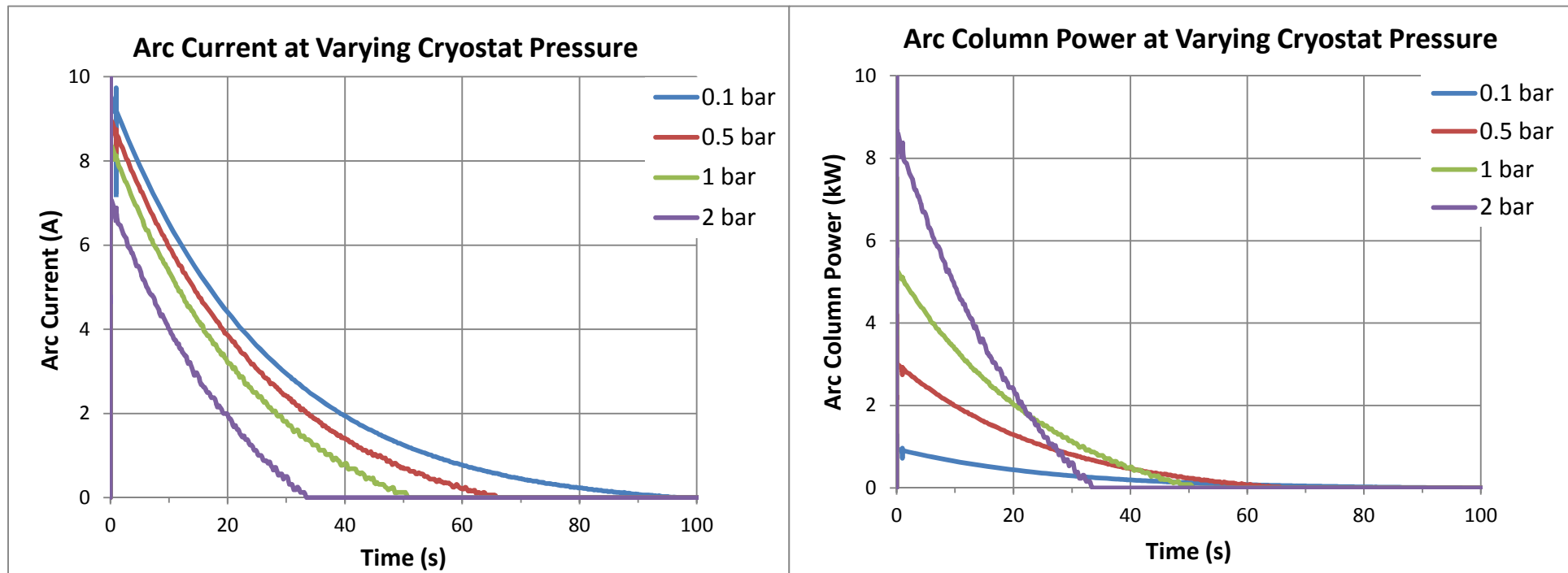


Thermal damage by arc between PF3 & VV

- **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



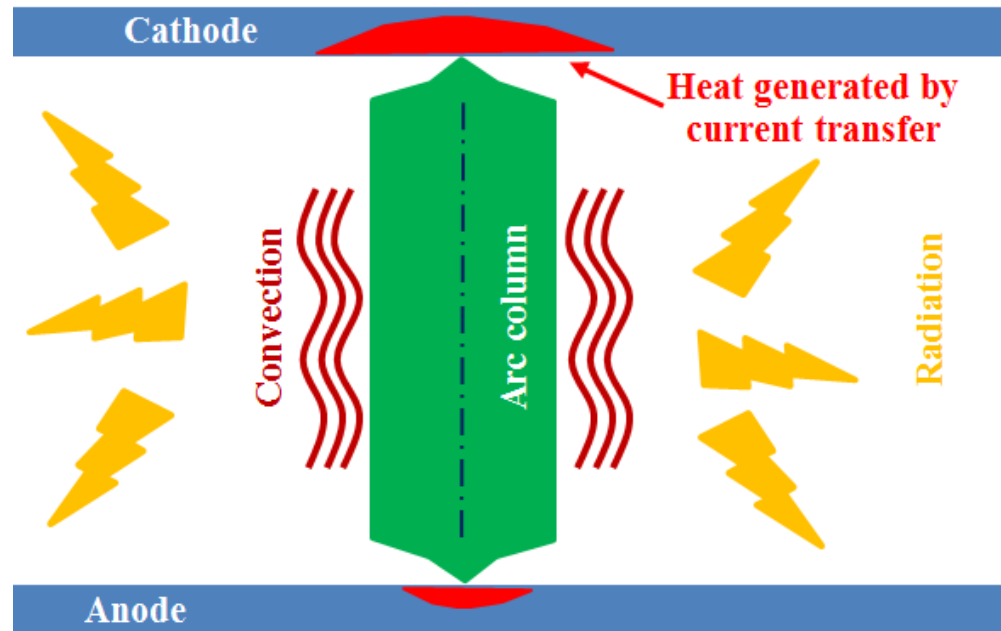
Arc current

Arc power

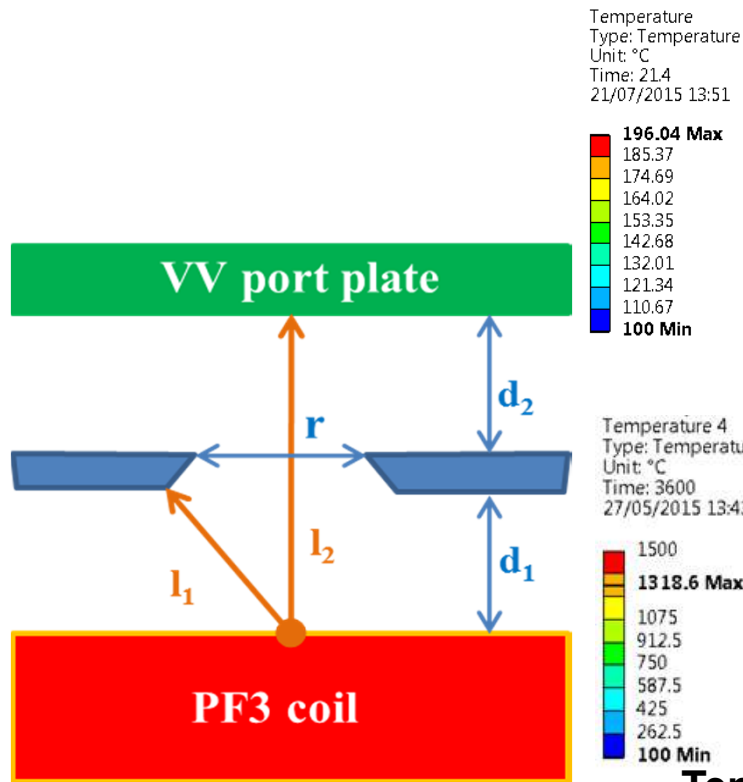
External arcs – heat transfer

- **Unconstrained and static arc between two parallel plates**
 - The arc is considered static because its displacement can not be 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**



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

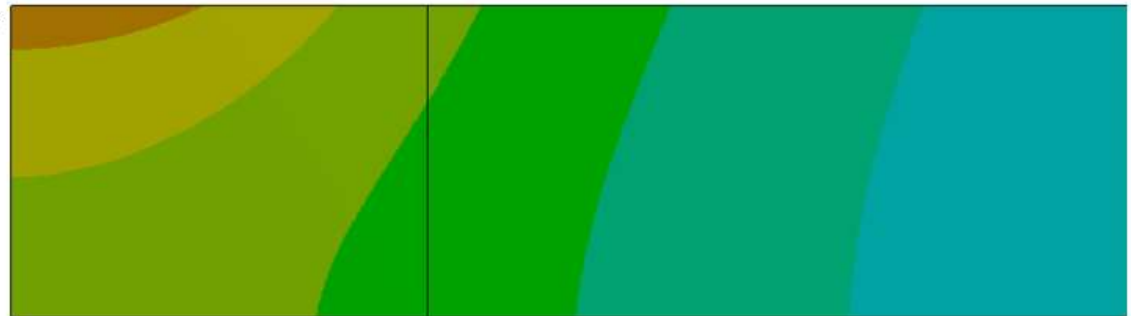


Temperature profile of the TS layer at the peak value with evolving arc



Temperature 4
Type: Temperature
Unit: °C
Time: 3600
27/05/2015 13:43

1500
1318.6 Max
1075
912.5
750
587.5
425
262.5
100 Min

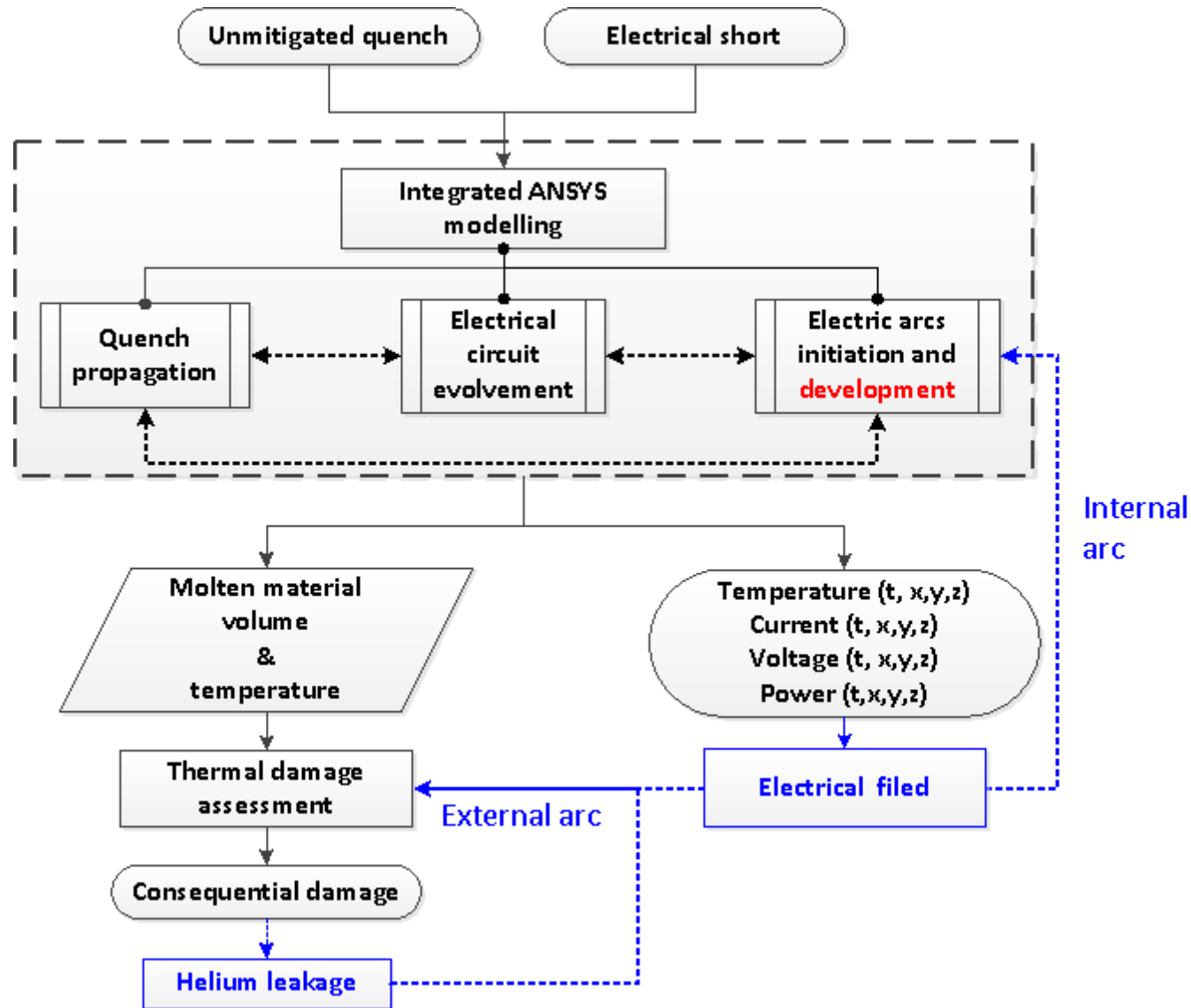


Temperature profile of the vessel port top layer at the peak value with constant arc power

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



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 evolvment and potential impact

Back-up slides

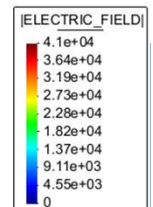
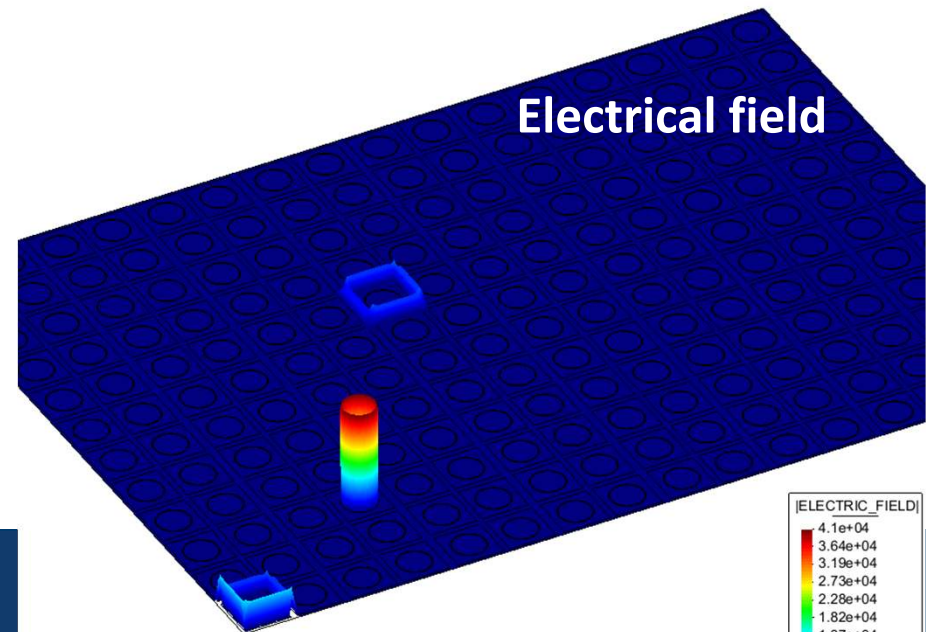
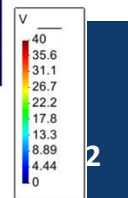
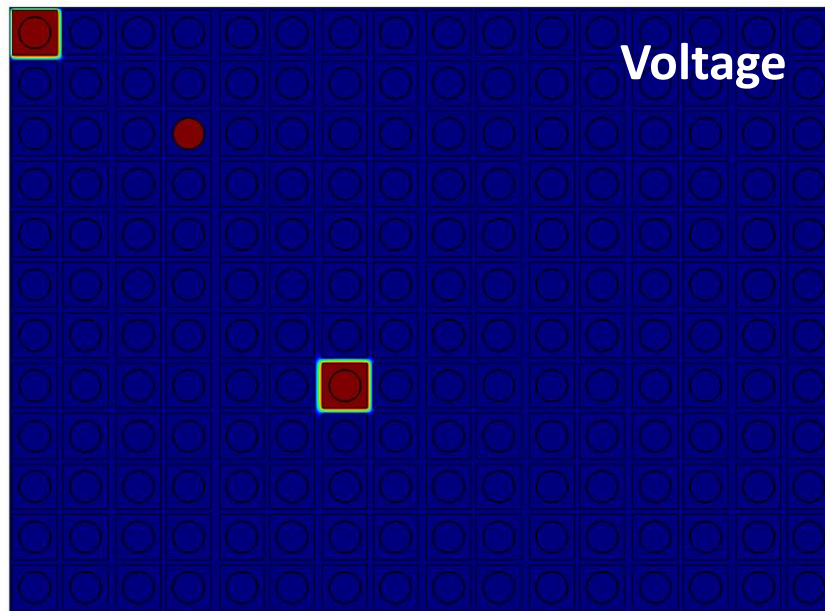
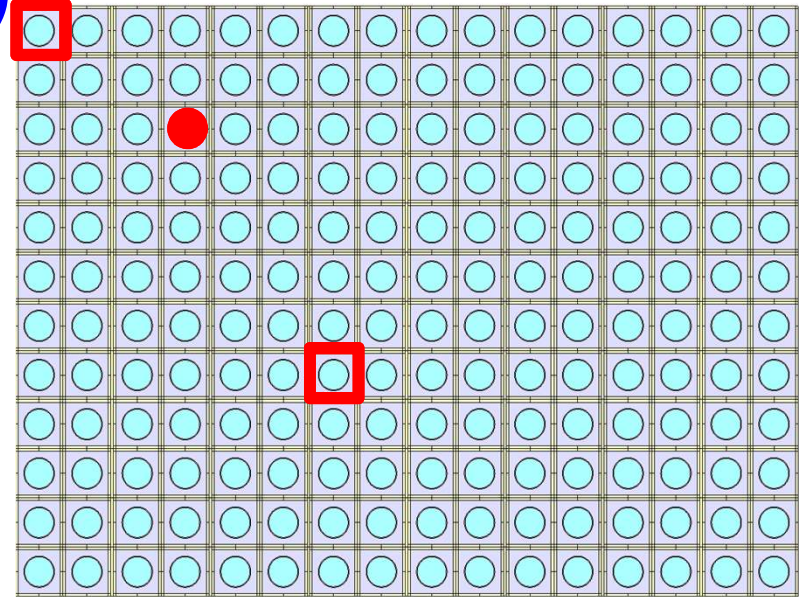
Electrical field

Ruben Otin

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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

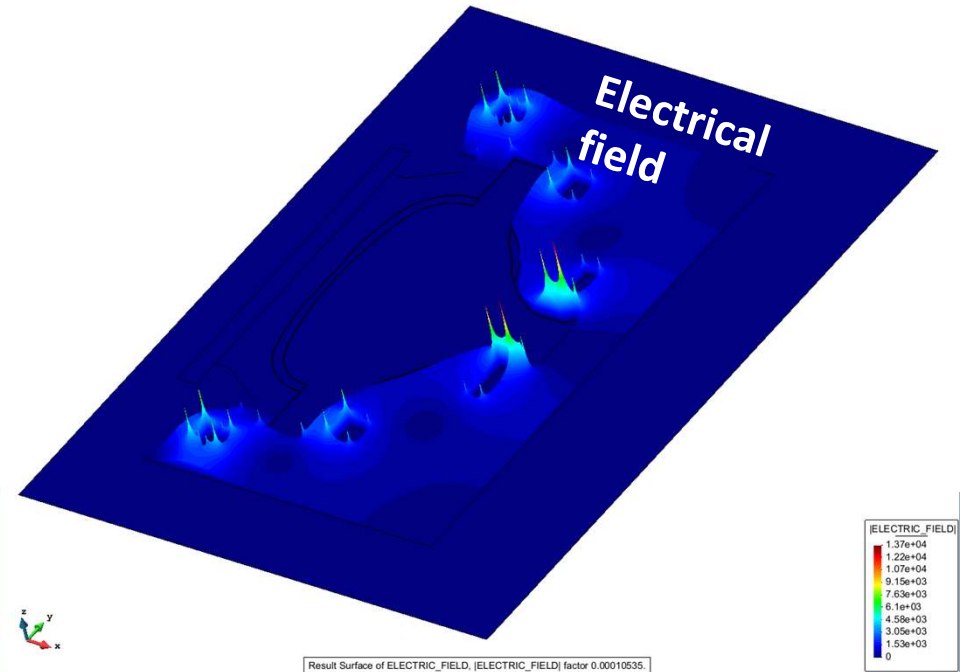
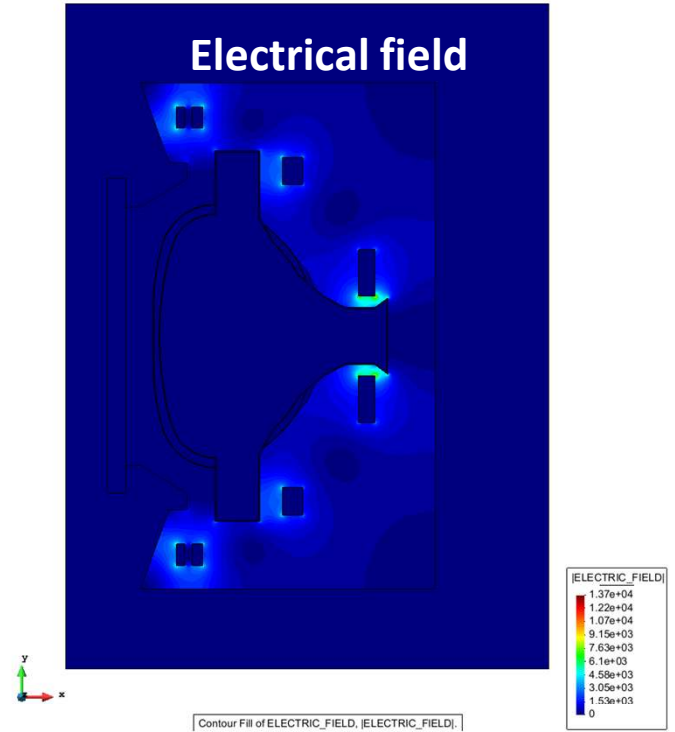
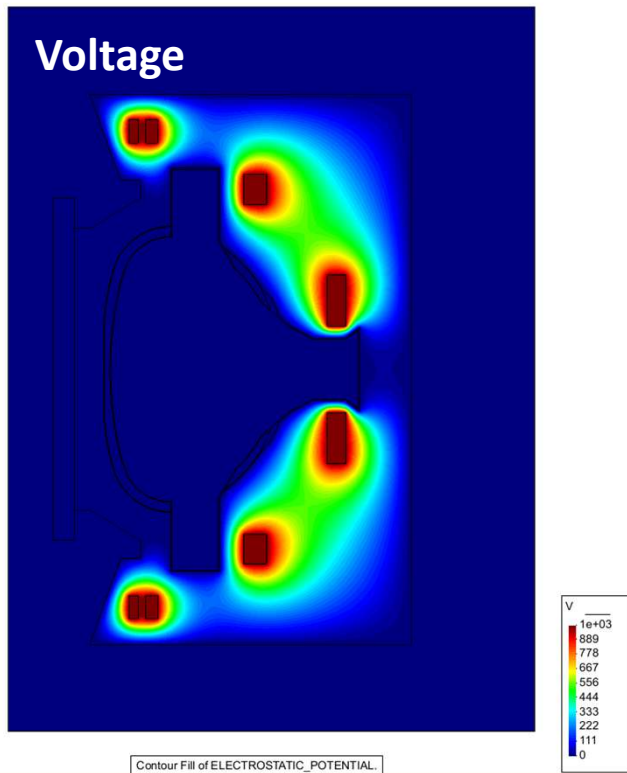


Contour Fill of ELECTROSTATIC_POTENTIAL.

Result Surface of ELECTRIC_FIELD, |ELECTRIC_FIELD| factor 2.8868e-6.

Example of electrical field (2/2)

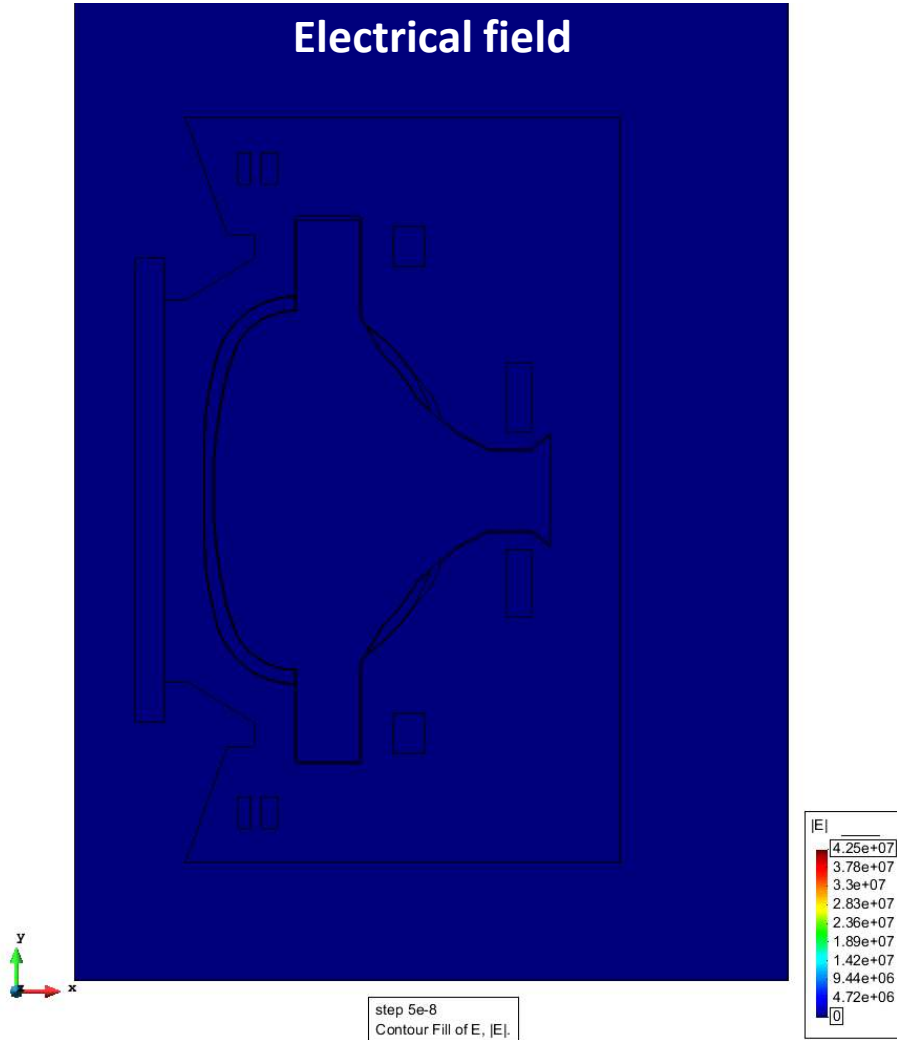
- Voltage (1kV) applied to cross-section of six PFCs by ERMES



To identify weak points for arcs

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

Electrical field



Secondary magnetic field

