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Arc Modelling Status Report 11/10/2018

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Outline

- Introduction – the two approaches
- The Discrete Approach
    1. Element types
    2. Arc modelling approaches
    3. ETNA benchmark cases
- The Volumetric Approach
- Summary

Introduction

The Discrete Approach

Arcs are defined at discrete points and switched on and off using simple voltage and temperature thresholds. The arc resistance is obtained using an iterative scheme. The electric conduction and thermal conduction solutions can either be solved separately (as in ETNA) or together in a coupled field solution.

The Volumetric Approach

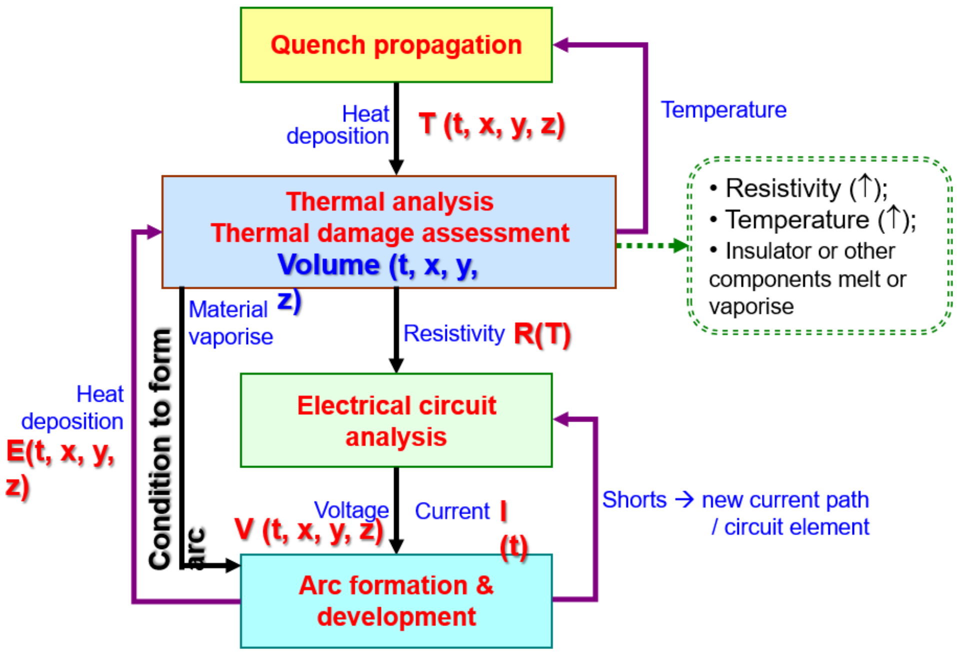
The thermal conduction, electric conduction and electrostatic solutions are obtained. The electric breakdown condition is used to model arc development within the electrostatic solution (as in ERMES).

The Discrete Approach

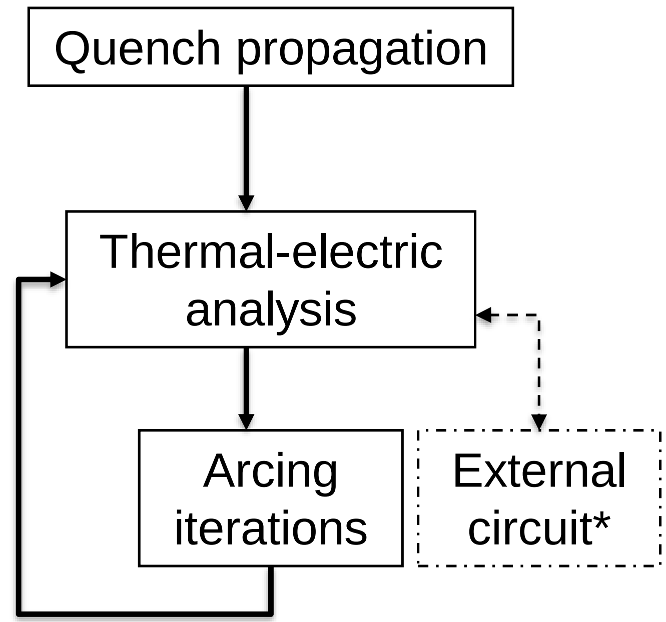
- ETNA was developed primarily to analyse the arc damage in faulted ITER coils
- ETNA is written in Python (to define the geometry) and APDL
- The geometry is hard-coded, requiring extensive rewriting for new geometries.
- A coupled field method is being developed to replicate the methodology in ETNA, but to be used with generic geometry.
- The coupled field approach means there is only one analysis environment (thermal-electric). In ETNA the thermal and electric solutions are obtained separately.

Method Comparison

ETNA



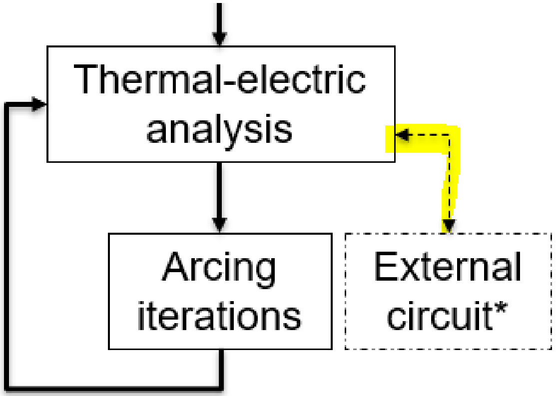
Coupled Field

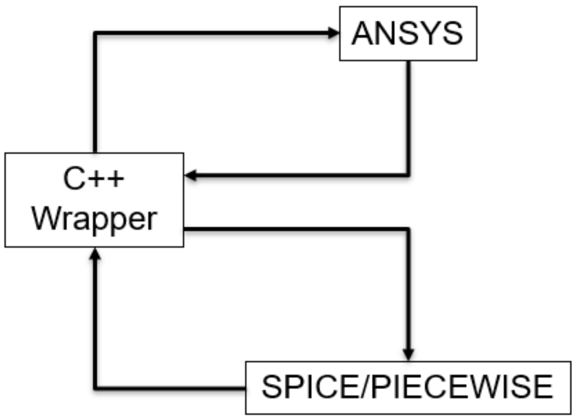


*External circuit can be built in ANSYS (as in ETNA), or with external software with read/write link

External Coupling

- In ETNA, the external circuit is included in the model using circuit elements (Circu124)
- For future analysis, a method will be investigated using global parameters to represent the external circuit
- Alternatively, it may be possible to directly couple circuit analysis software (e.g. SPICE) with ANSYS using read/write commands.





Element Types

- Element types adopted for coupled-field approach
  - Link68 (2 nodes), Shell157 (4 nodes), and Solid226 (20 nodes)

- These elements conduct heat and electric current. The joule heating effect is included in the thermal solution, which requires an iterative procedure.

Figure 68.1: LINK68 Geometry

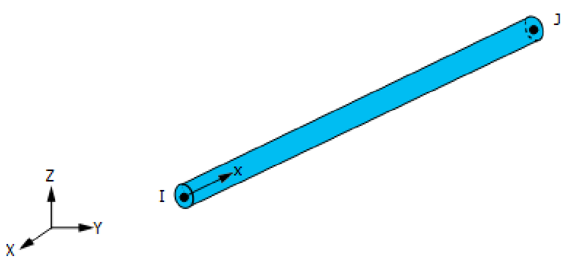


Figure 157.1: SHELL157 Geometry

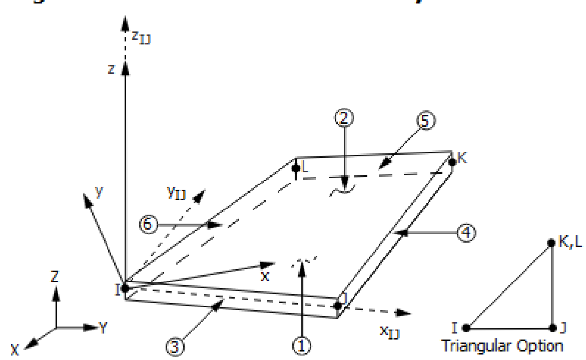
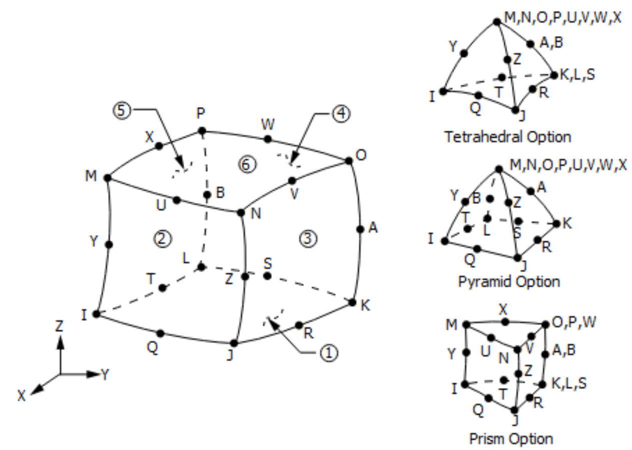
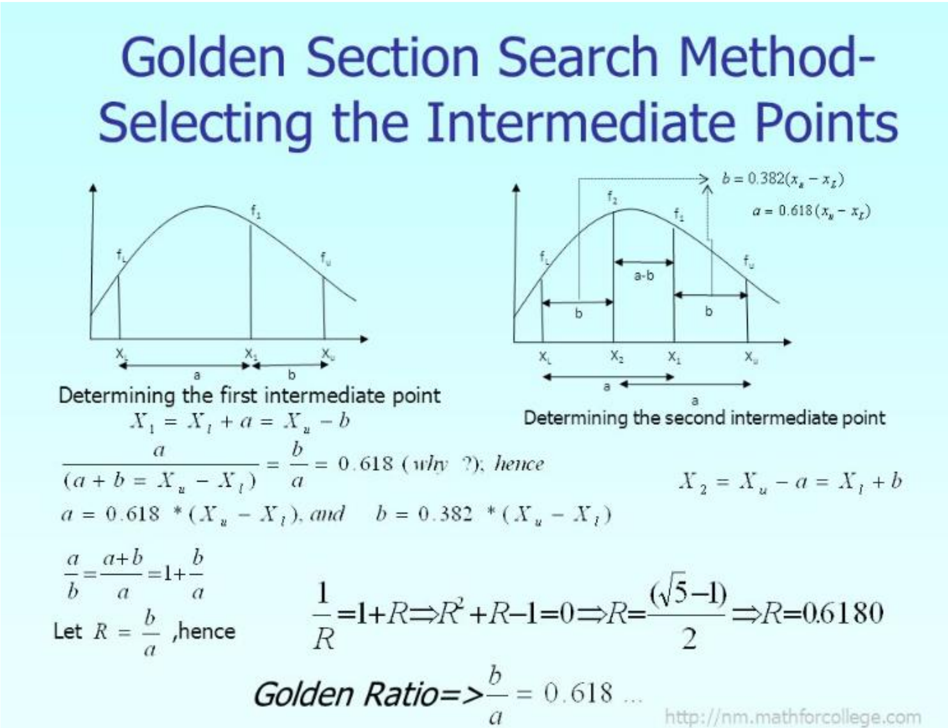
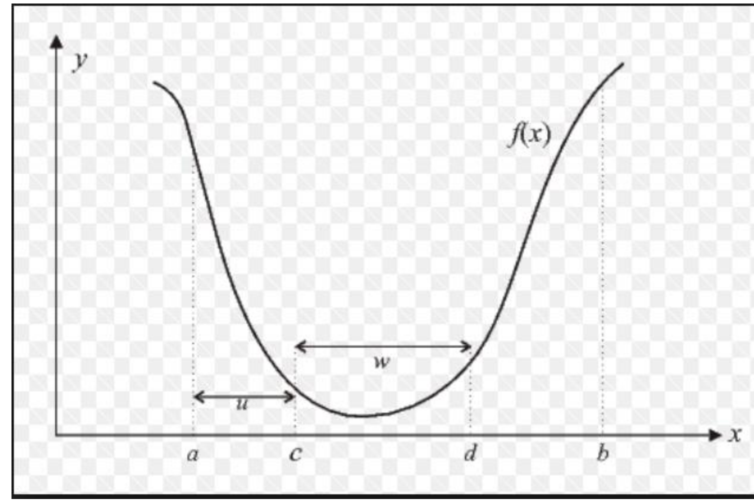


Figure 226.1: SOLID226 Geometry



Arc Iteration Procedure





Golden section search used. When the voltage delta and temperature thresholds are exceeded, the resistivity of the arc is adjusted iteratively until the calculated arc current sits on the Kronhardt arc VI curve. The resistivity can be changed during solution time so restart is not required.

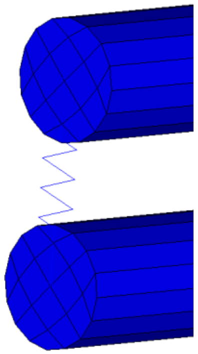
Arc Iteration Procedure

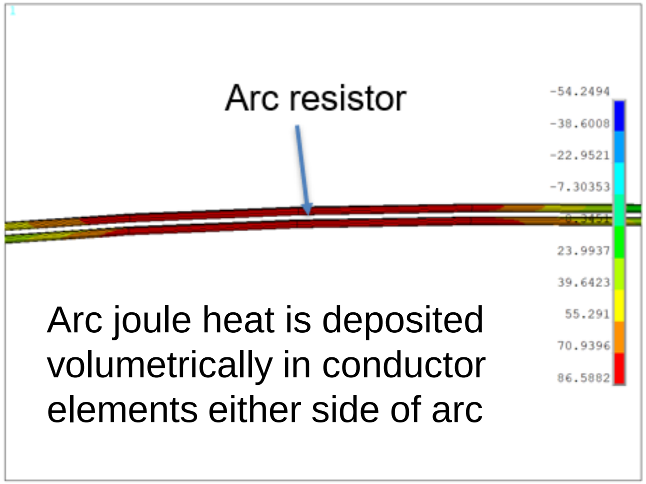
```
 time_s,e_cur,I_int,v_arc2,v_arc1,arc_dv1,arc_dv,rho_current,f_x1,f_type
45.0286 5096.54031 20196.1099 3.58726773 102.34958 98.7623125 6.871656172E-02 1.631612902E-04 15099.5696 2
45.0288 7573.98267 17876.0376 3.79587012 94.539663 90.7437929 6.871656172E-02 1.008774196E-04 10302.0549 2
45.029 10826.5383 14708.8453 4.0697612 84.285685 80.2159238 6.871656172E-02 6.238387061E-05 3882.30696 2
45.0292 14738.0857 10899.8045 4.39920446 71.9537305 67.5545261 6.871656172E-02 3.859354899E-05 3838.28119 2
45.0294 18974.9779 3012.94477 4.75614896 58.5957621 53.8396131 6.871656172E-02 2.389032162E-05 15962.0331 2
45.0296 14738.0414 10899.7434 4.40019769 71.9545205 67.5543228 6.871656172E-02 3.859354899E-05 3838.29799 2
45.0298 12950.8223 12640.1579 4.25027782 77.5898052 73.3395274 6.871656172E-02 4.768064324E-05 310.664468 2
45.03 13579.8228 12027.6072 4.30366617 75.6070517 71.3033855 6.871656172E-02 4.42096821E-05 1552.21558 2
45.0302 12950.8157 12640.1466 4.2511841 77.5906739 73.3394898 6.871656172E-02 4.768064324E-05 310.669139 2
45.0304 13184.0675 12412.9862 4.27127097 76.8556709 72.5844 6.871656172E-02 4.635485406E-05 771.081305 2
45.0306 12950.8095 12640.136 4.25208929 77.5915441 73.3394548 6.871656172E-02 4.768064324E-05 310.673491 2
45.0308 12810.7309 12776.5478 4.24074611 78.0336388 73.7928927 6.871656172E-02 4.850002602E-05 34.1831084 2
45.031 12863.8742 12724.7881 4.24567002 77.8665116 73.6208415 6.871656172E-02 4.818704965E-05 139.086129 2
45.0312 12810.7273 12776.5416 4.24164408 78.0345164 73.7928724 6.871656172E-02 4.850002602E-05 34.1856916 2
45.0314 12778.0995 12808.3133 4.23934477 78.1378274 73.8984826 6.871656172E-02 4.869345606E-05 30.213837 2
45.0316 12790.5405 12796.1931 4.24084096 78.0990355 73.8581946 6.871656172E-02 4.861957236E-05 5.65262021 2
45.0318 12798.2409 12788.6894 4.24193826 78.0751902 73.833252 6.871656172E-02 4.857390972E-05 9.55147885 2
45.032 12790.5373 12796.1877 4.24173798 78.0999144 73.8581765 6.871656172E-02 4.861957236E-05 5.6503088 2
45.0322 12793.4766 12793.3208 4.24243429 78.0910814 73.8486471 6.871656172E-02 4.860213078E-05 0.155705866 2
45.0324 12795.2931 12791.5473 4.24303612 78.0857879 73.8427518 6.871656172E-02 4.85913513E-05 3.74581893 2
45.0326 12793.4734 12793.3153 4.24333156 78.0919602 73.8486287 6.871656172E-02 4.860213078E-05 0.158056529 2
45.0328 12794.1662 12792.6362 4.24383875 78.0902101 73.8463713 6.871656172E-02 4.859801338E-05 1.52996816 2
45.033 12793.4702 12793.3098 4.24422891 78.0928391 73.8486102 6.871656172E-02 4.860213078E-05 0.160411613 2
```

Typical iteration output

Arc Modelling Approaches

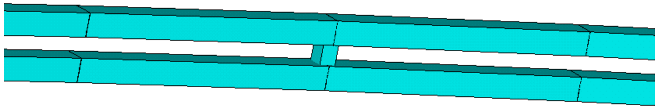
ETNA uses circuit elements for arcs



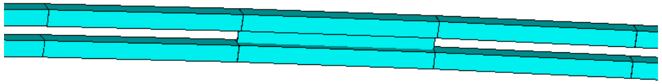


With the coupled field method, three approaches have been tested for arc modelling:

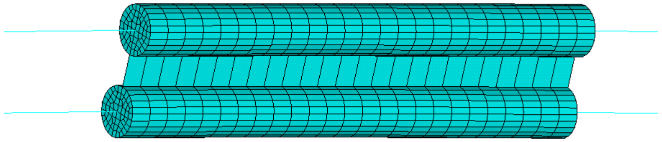
1. Link68 arc, Link68 conductors



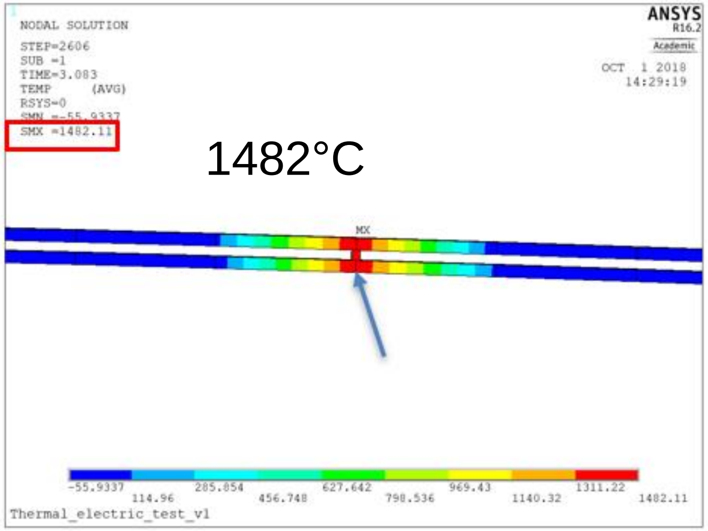
2. Shell157 arc, Link68 conductors

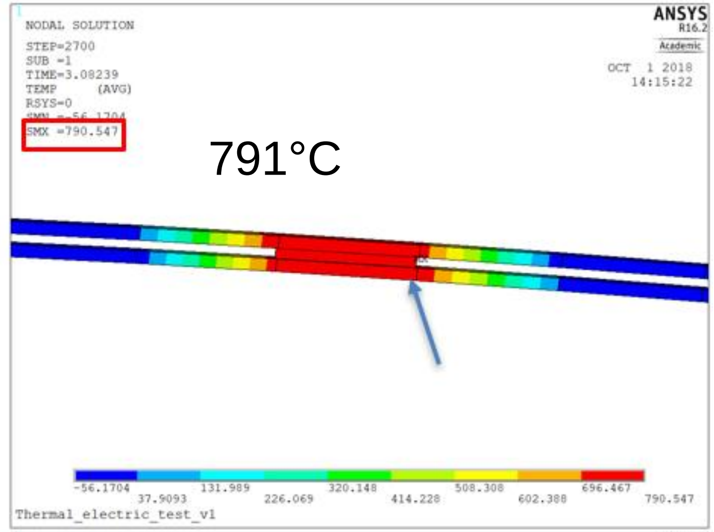


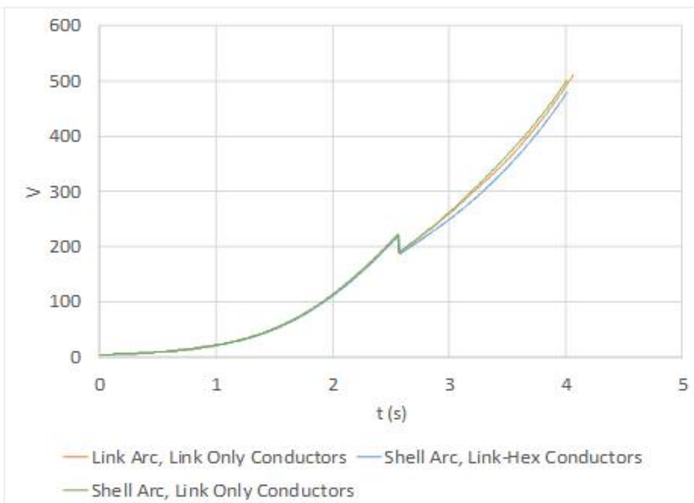
3. Shell157 arc, Solid226 conductors coupled to Link 68 conductors

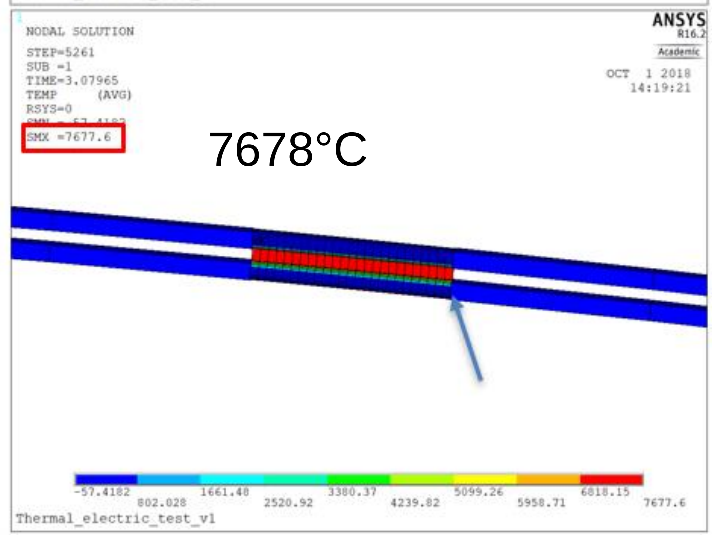


Arc Modelling Approaches







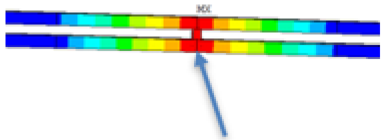


(ETNA result ~100°C)

Arc Modelling Approaches

Pros & Cons

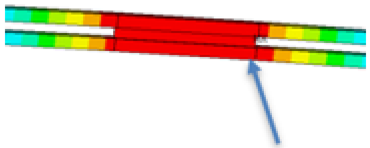
1482°C



Computationally cheap
Relatively focussed heating

Doesn’t model moving arc well

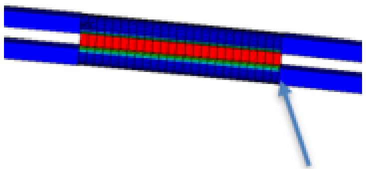
791°C



Computationally cheap
Possibly good model of moving arc

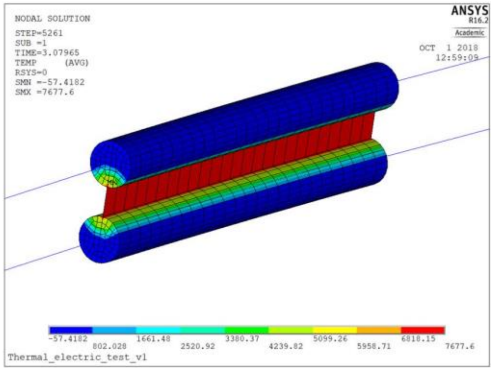
Low temperatures -> less damaging static arcs

7678°C

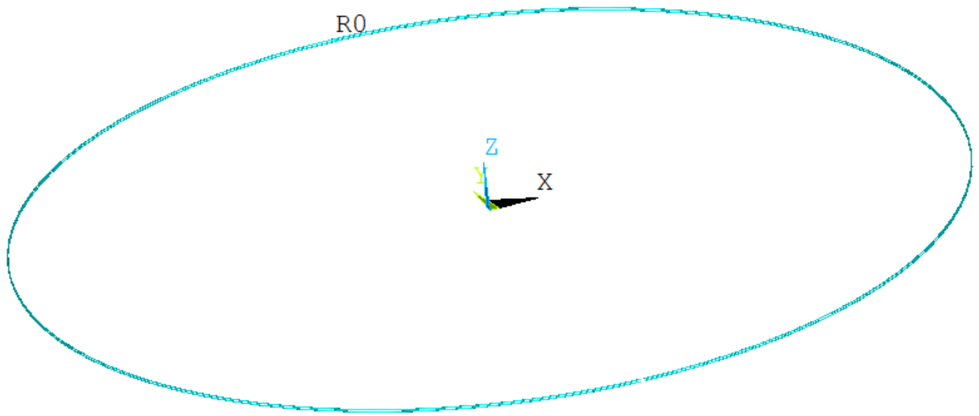


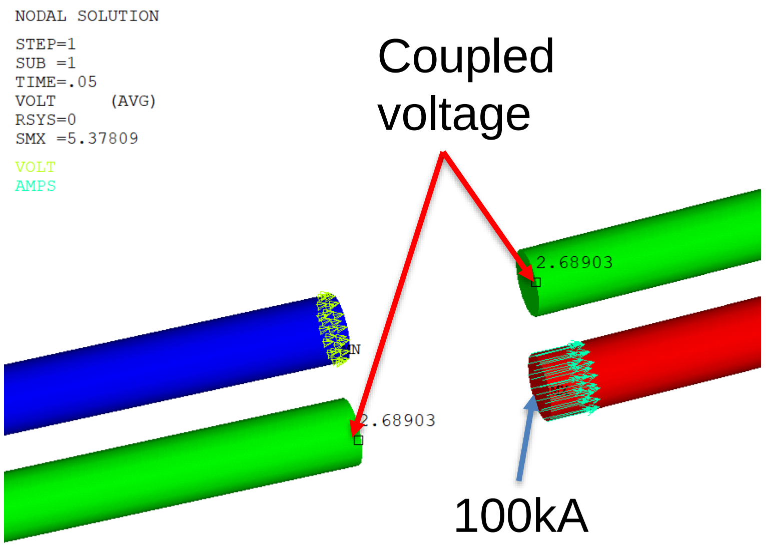
Highest temperatures, probably most realistic

Expensive



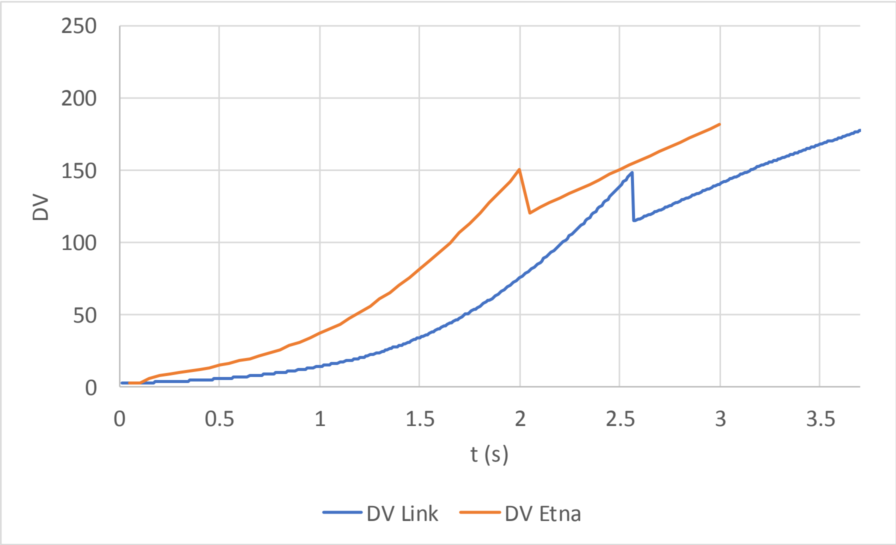
ETNA Benchmark Case 1

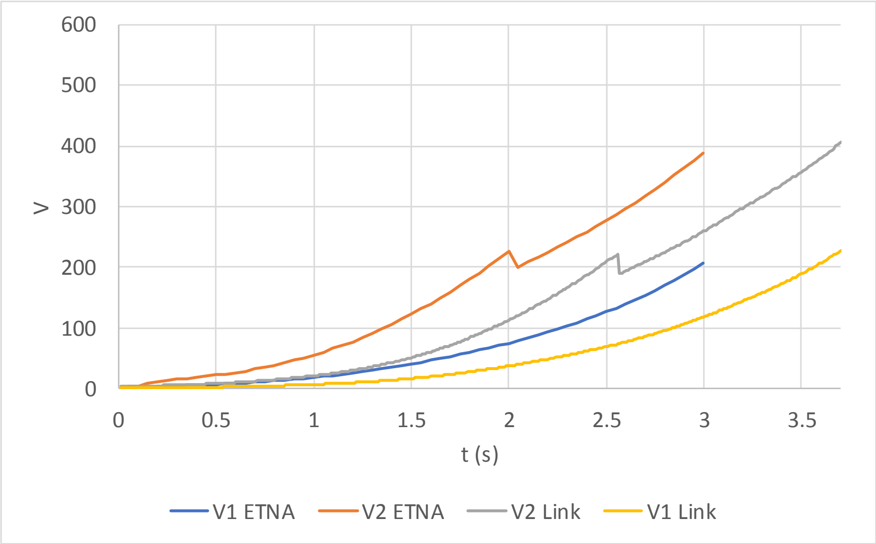




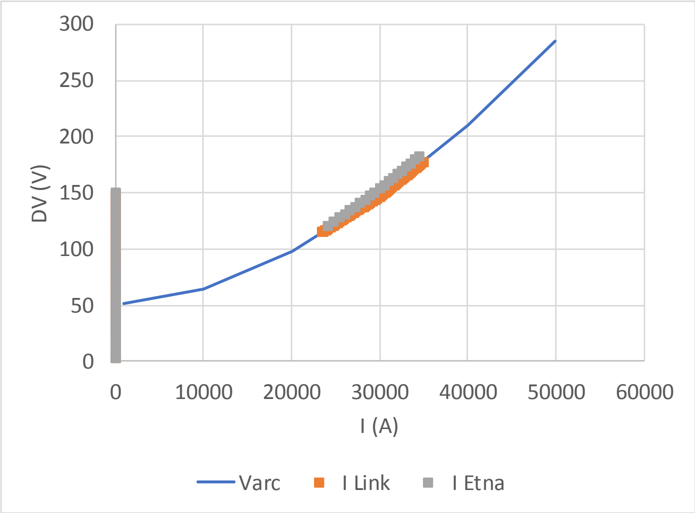
1 turn PF3 model, 1 arc, instant quench of full conductor length

ETNA Benchmark Case 1





The faster response of the ETNA model is explained mainly by the higher timestep in the ETNA run.
Both arcs burn at similar points on the VI curve.



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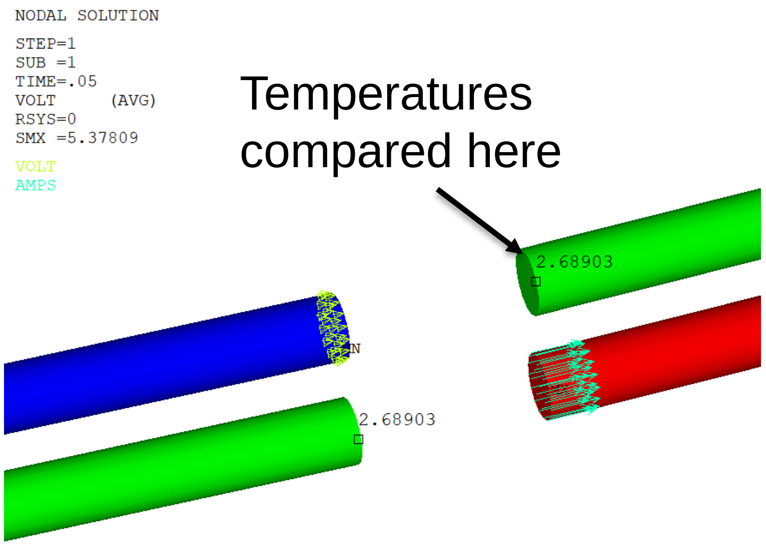
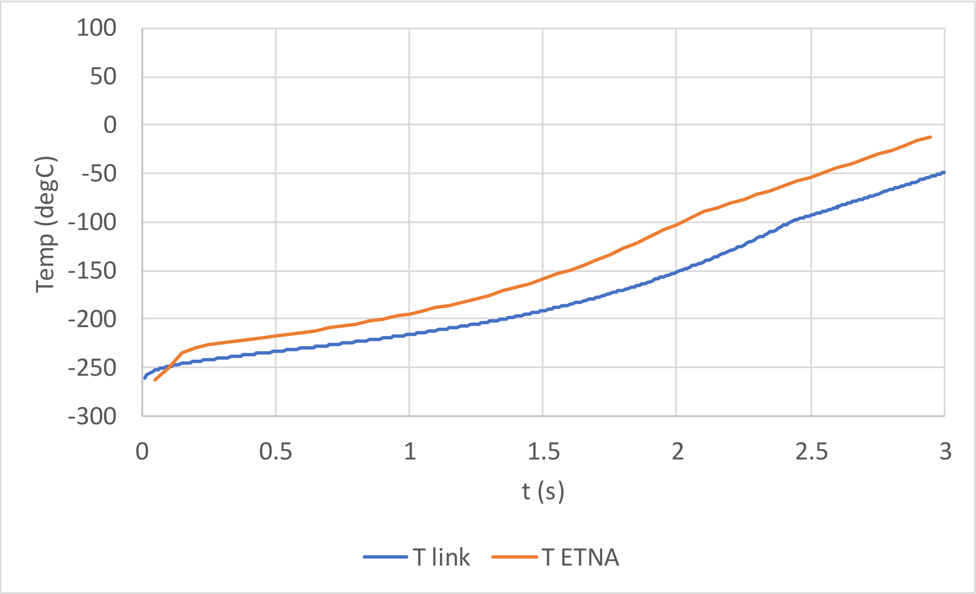
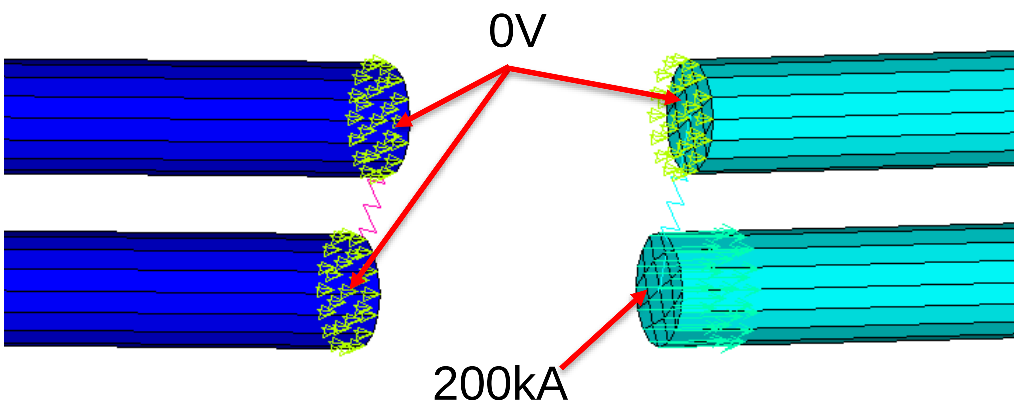
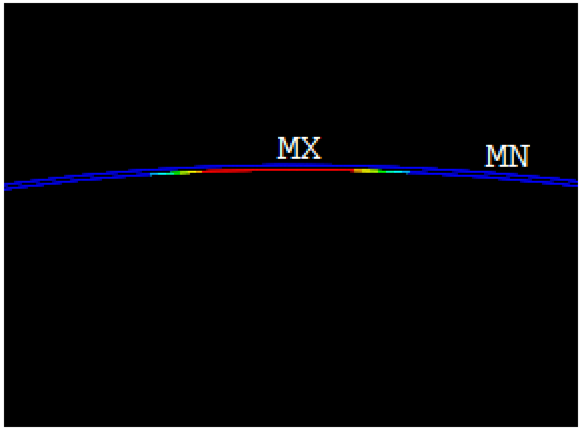
ETNA Benchmark Case 1





ETNA Benchmark Case 2



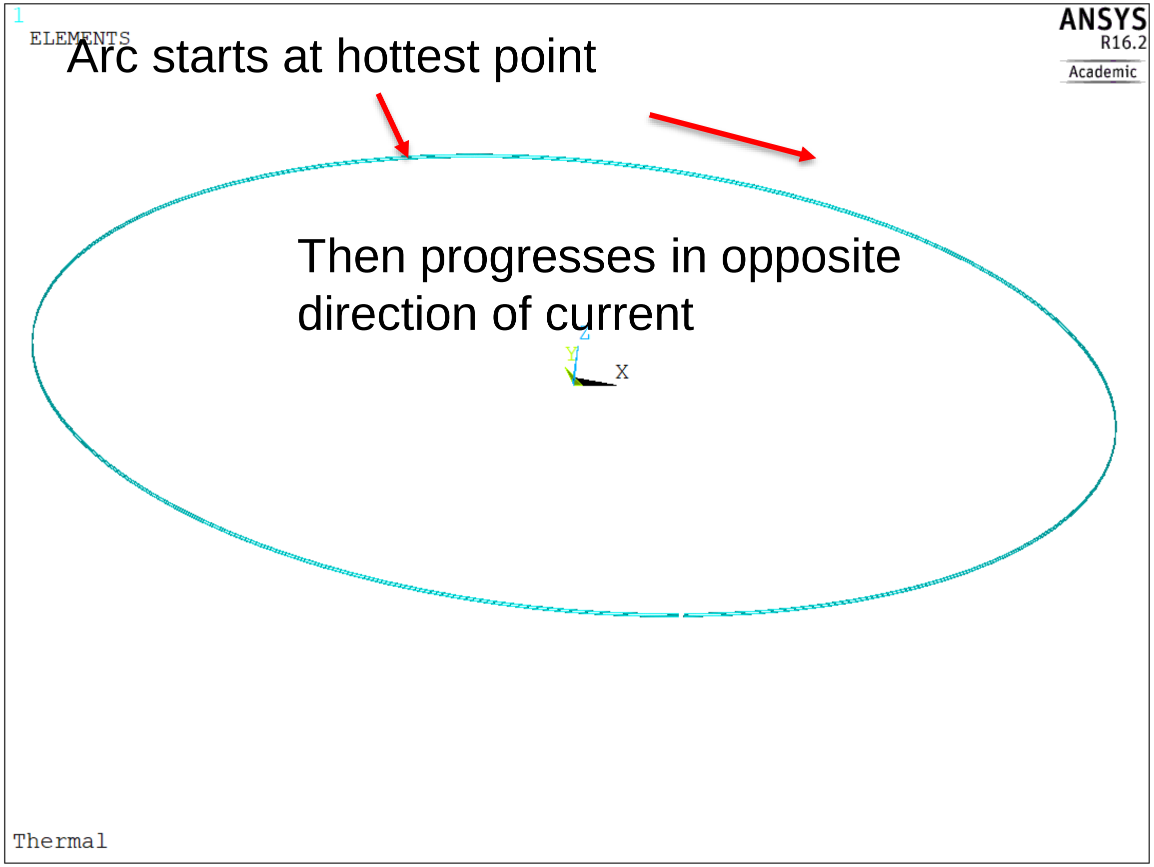


Arc can form when average temperature of conductors goes above -200degC

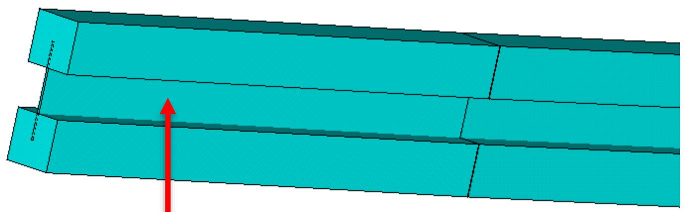
Only allow small part of lower conductor to quench (quench velocity = 0)

ETNA Benchmark Case 2

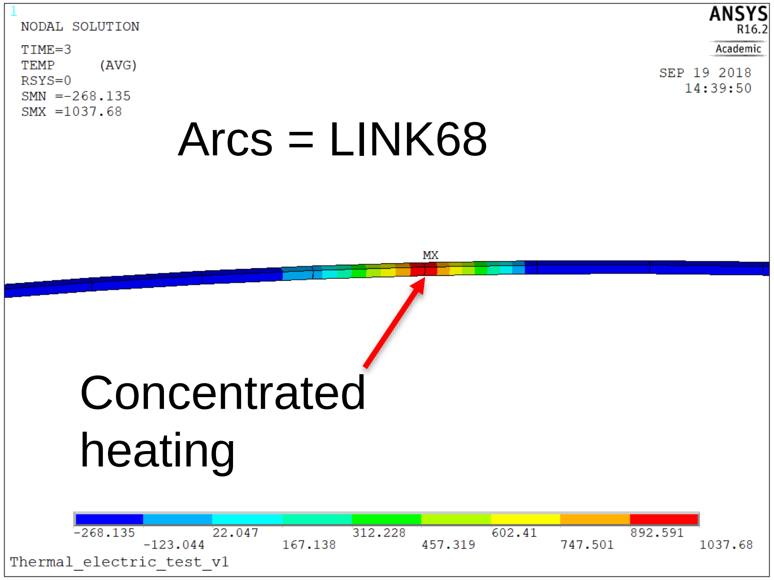
Expected behaviour:

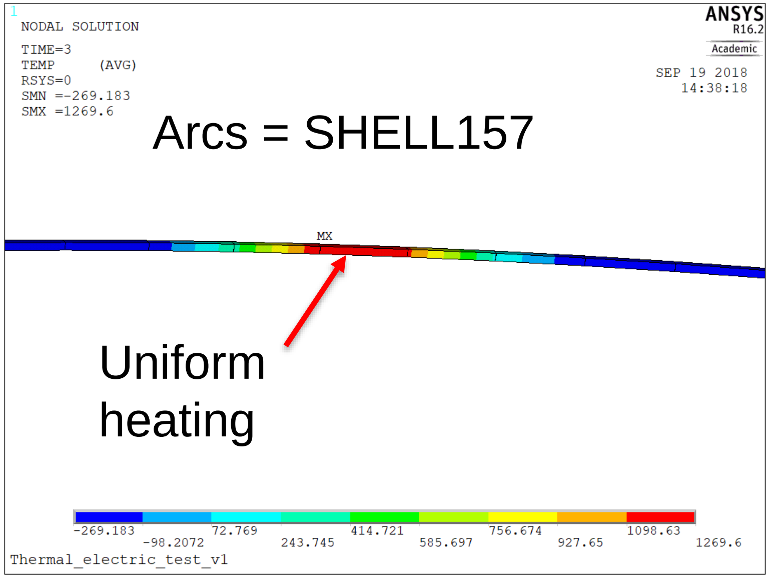


ETNA Benchmark Case 2



Arc element is shell 157

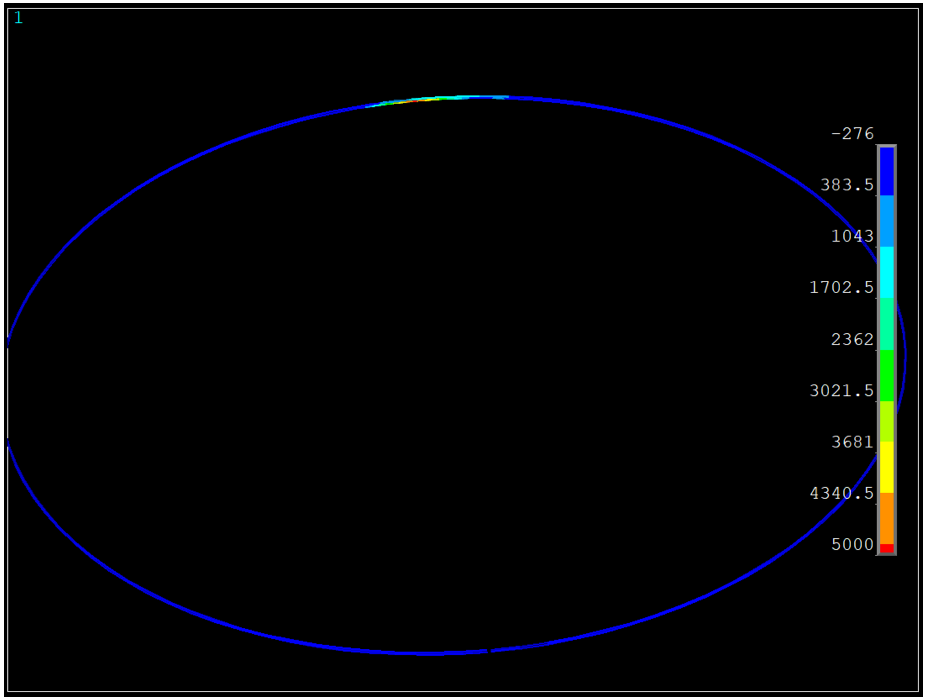




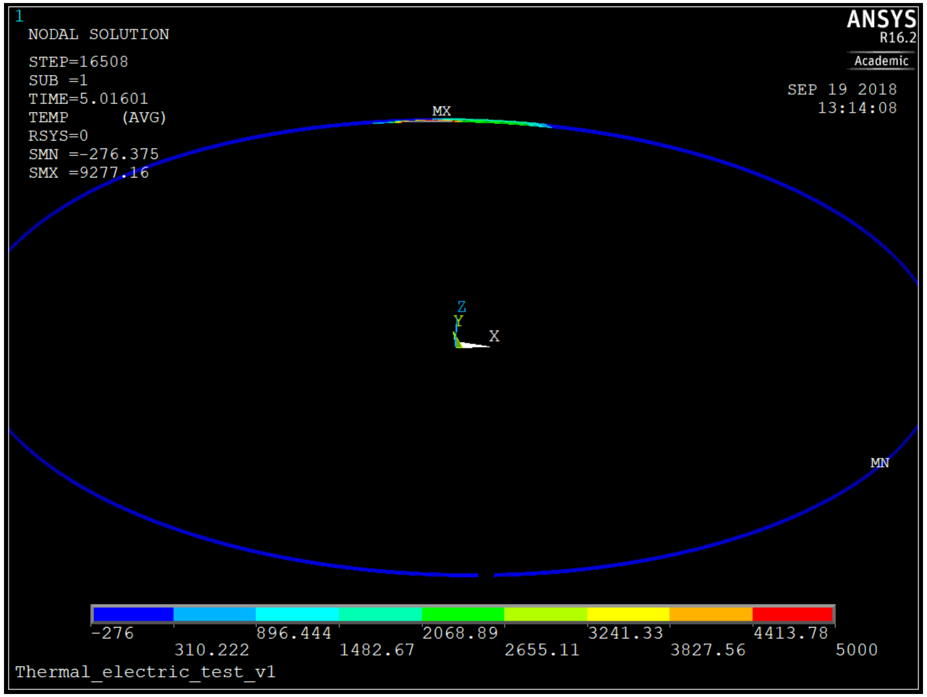
ETNA Benchmark Case 2

Temperature after 5s

ETNA



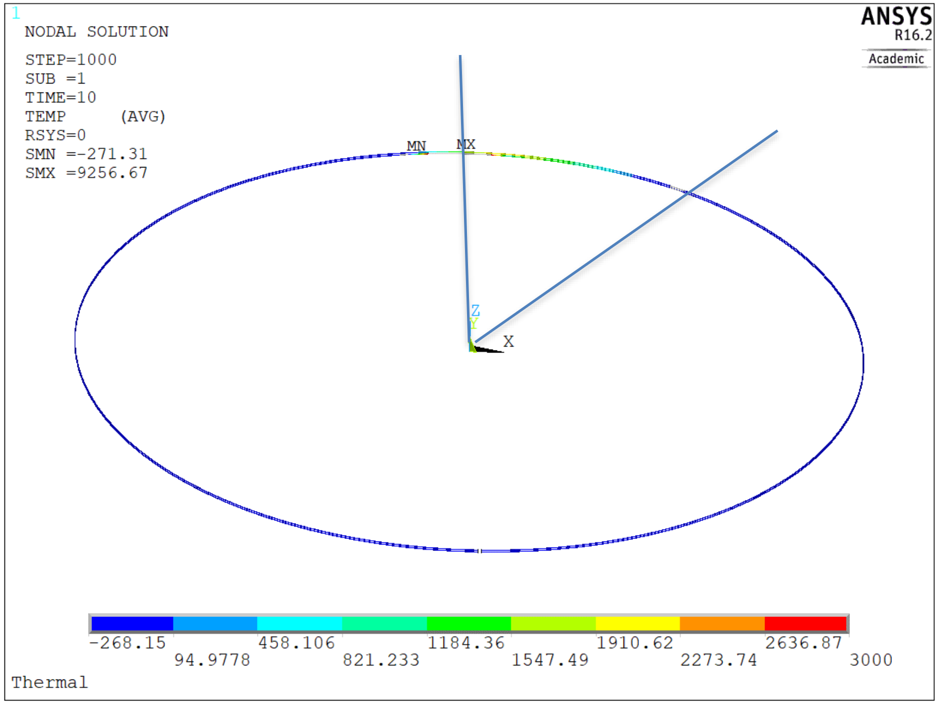
SHELL/LINK



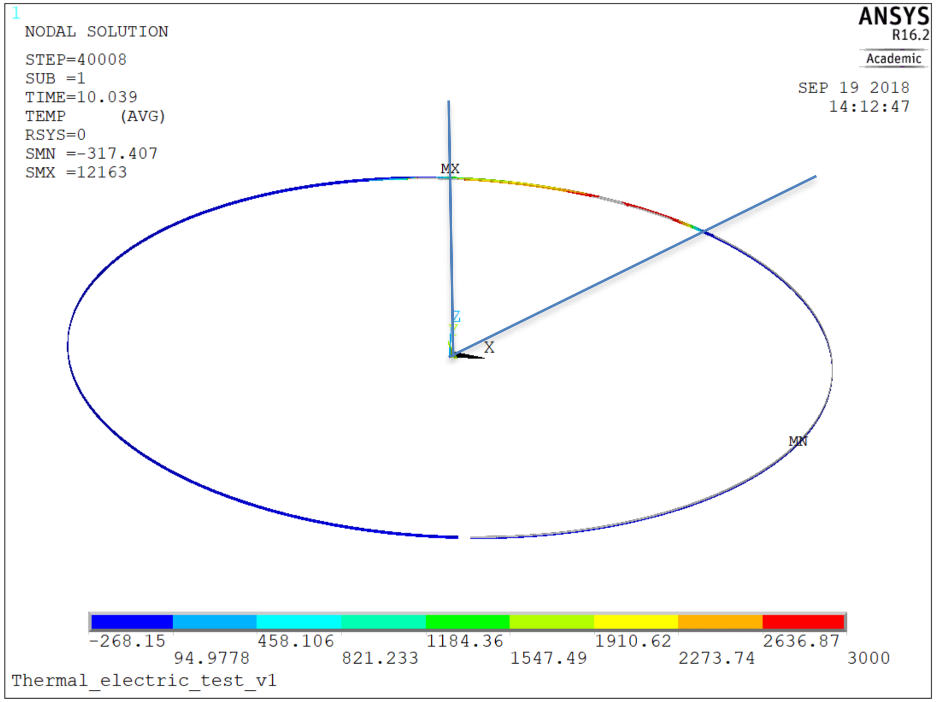
ETNA Benchmark Case 2

Temperature after 10s

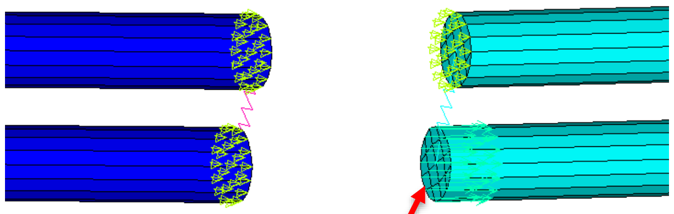
ETNA



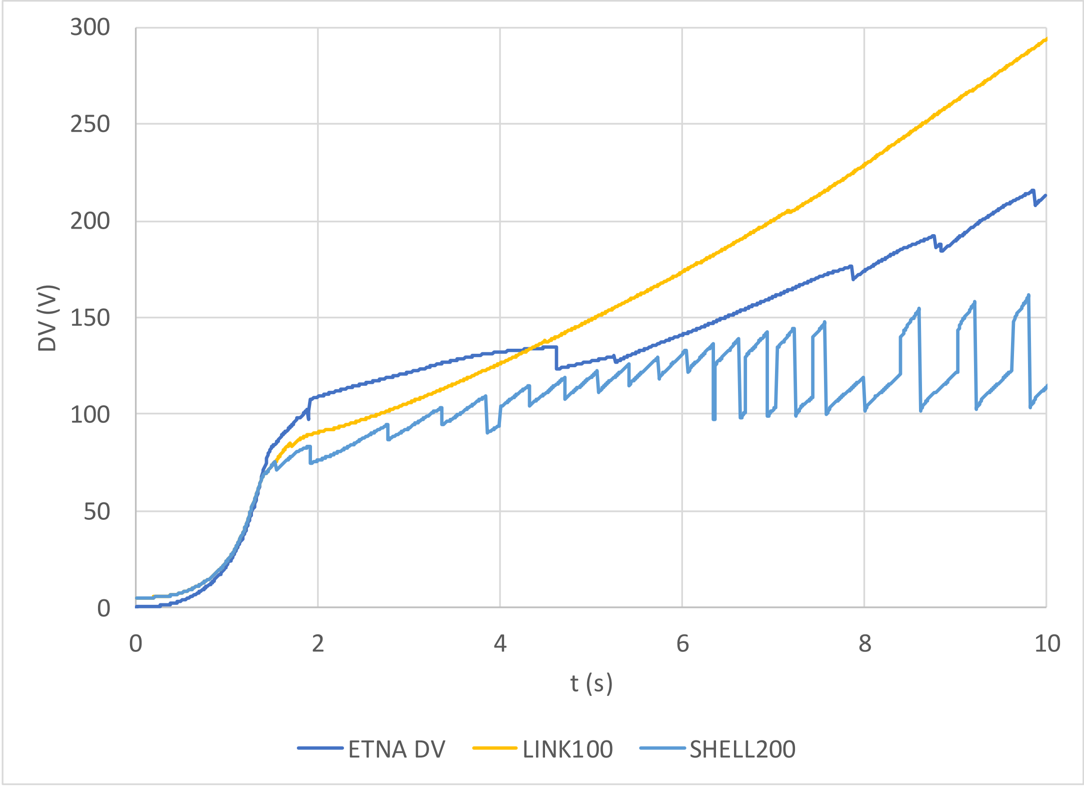
SHELL/LINK



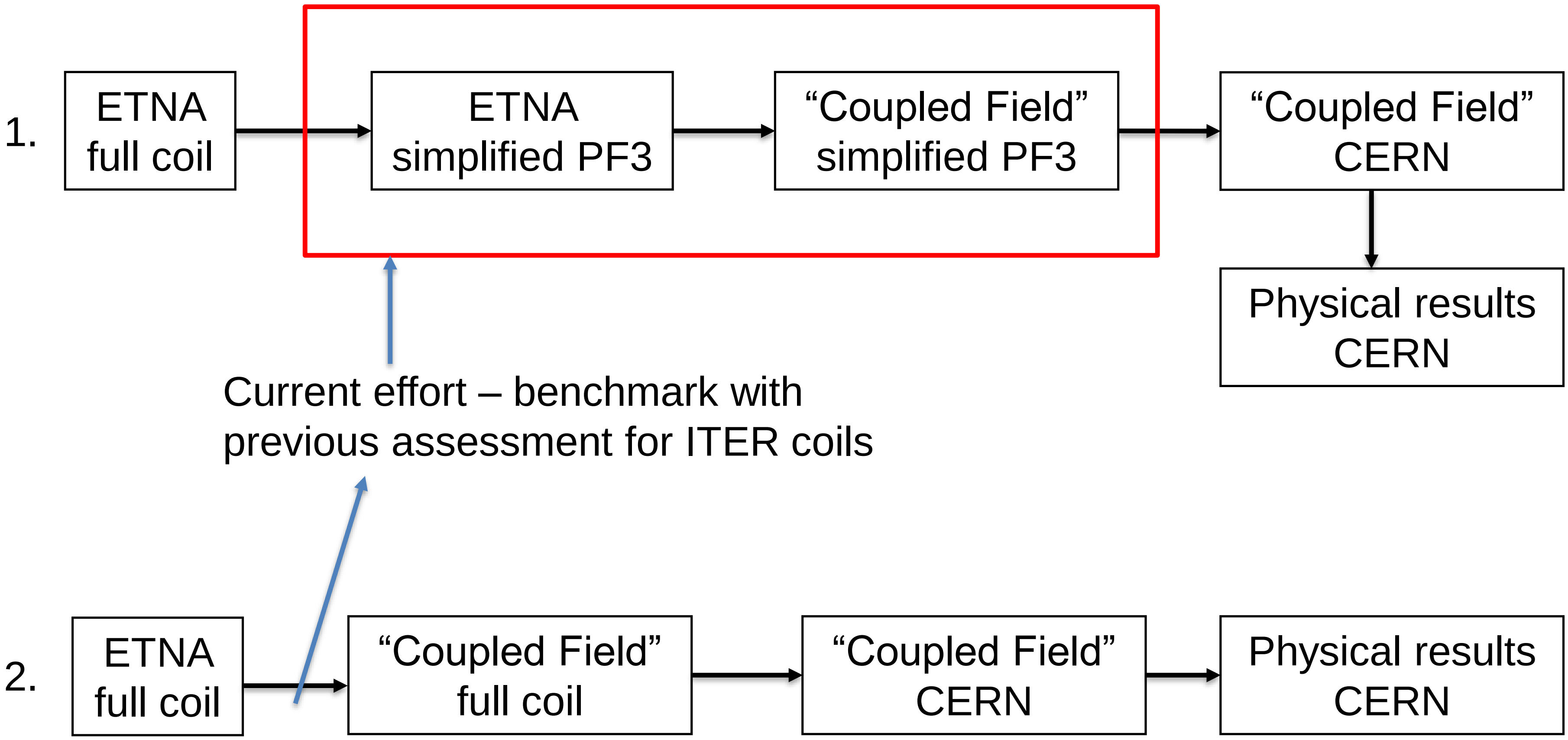
ETNA Benchmark Case 2



Voltage here



Benchmark Route



Discrete Approach Summary

- Arcs modelled at discrete locations, switched on and off using voltage and temperature thresholds (adopted for internal arcs).
- Different methods for modelling arcs. Lack of arc data makes it difficult to choose the “best” method although this may not affect the assessment of ‘macro’ damage from arc
- Effort to date has focussed on benchmarking the coupled field method against ETNA for simple cases. With a view to using the coupled field method to assess the CERN case.

Volumetric Approach

- The volumetric approach is a general model that solves the fields on a complete geometry of the coil and models the arcing behaviour by considering the electrical conductivity of the material as a function of the temperature and the maximum electric field ($E_{breakdown}$) tolerated by the insulator or gas.

- The electric part of the volumetric model has been implemented in an open-source code called ERMES, which solves the full electromagnetic field equations.

- The volumetric approach is a general model which can also be implemented in ANSYS. In ANSYS, solid 227 (thermal-electric) and solid 123 (electrostatic) are to be used to coupled the electric field simulation to improve the arc ignition conditions (from simply controlled by V and T threshold)

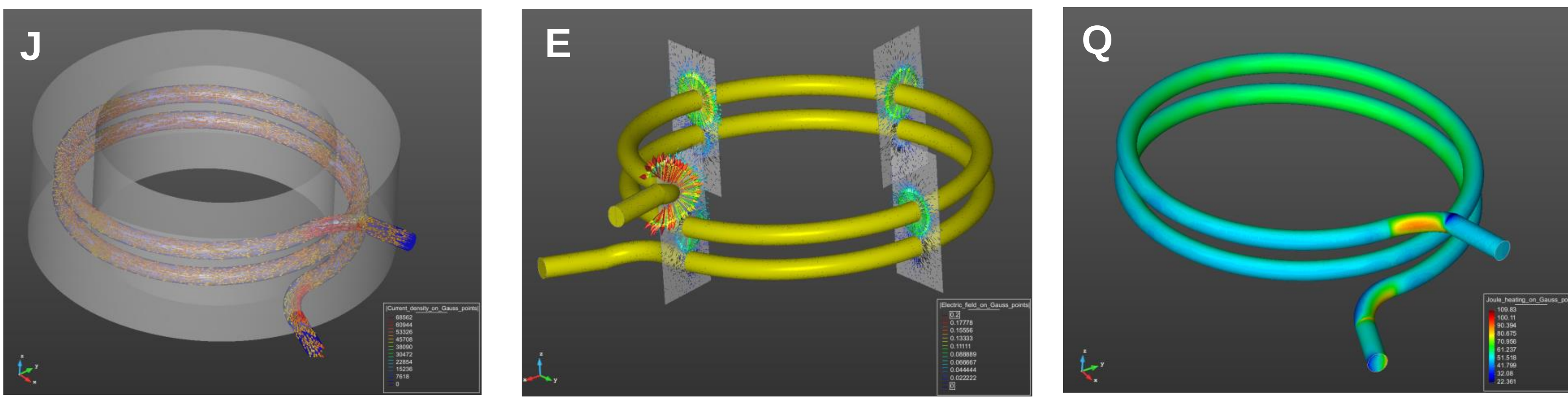
Volumetric Approach - Fields

First step consists in solving **conductivity** and **electrostatic** equations on the problem domain:

$$-\nabla \bullet ([\sigma]\nabla V) = 0 \longrightarrow \mathbf{J} = \boldsymbol{\sigma}\,\mathbf{E} \longrightarrow \mathbf{Q} = \frac{\mathbf{J}^2}{\boldsymbol{\sigma}}$$

$$-\nabla \bullet ([\varepsilon]\nabla V) = 0 \longrightarrow \mathbf{E} = -\,\nabla\,\mathbf{V} \quad \circlearrowright \quad \mathbf{E}_{\mathbf{breakdown}}$$

Inductive effects are consider in the global circuit model (L,R)

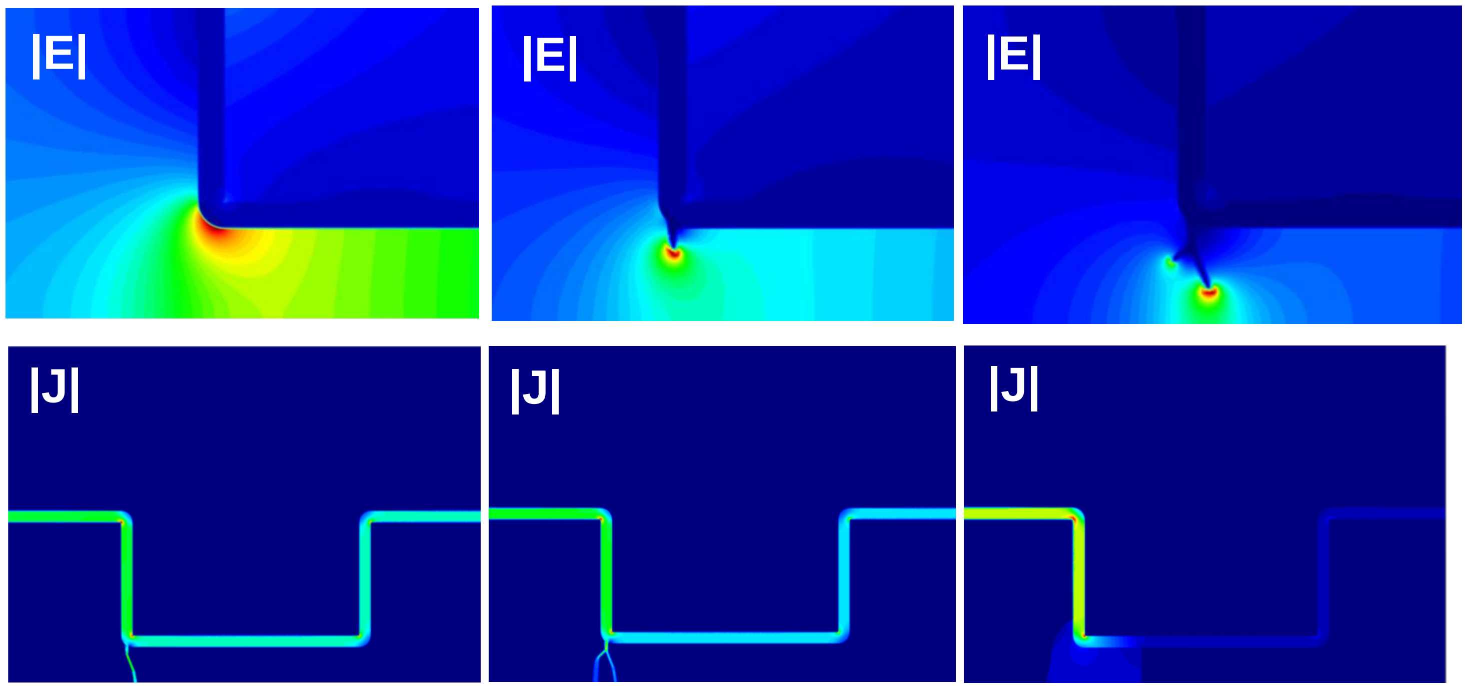


Volumetric Approach – Arc on insulators

- Intrinsic breakdown - Iterate to update $\boldsymbol{\sigma}\ (\mathbf{E}_{\mathbf{breakdown}})$

Electric field iterations when $E > E_{breakdown}$

Current distribution after breakdown front contact



- Thermal breakdown - Update $\boldsymbol{\sigma}\ (\mathbf{T}), \boldsymbol{\varepsilon}(\mathbf{T})$ with thermal results

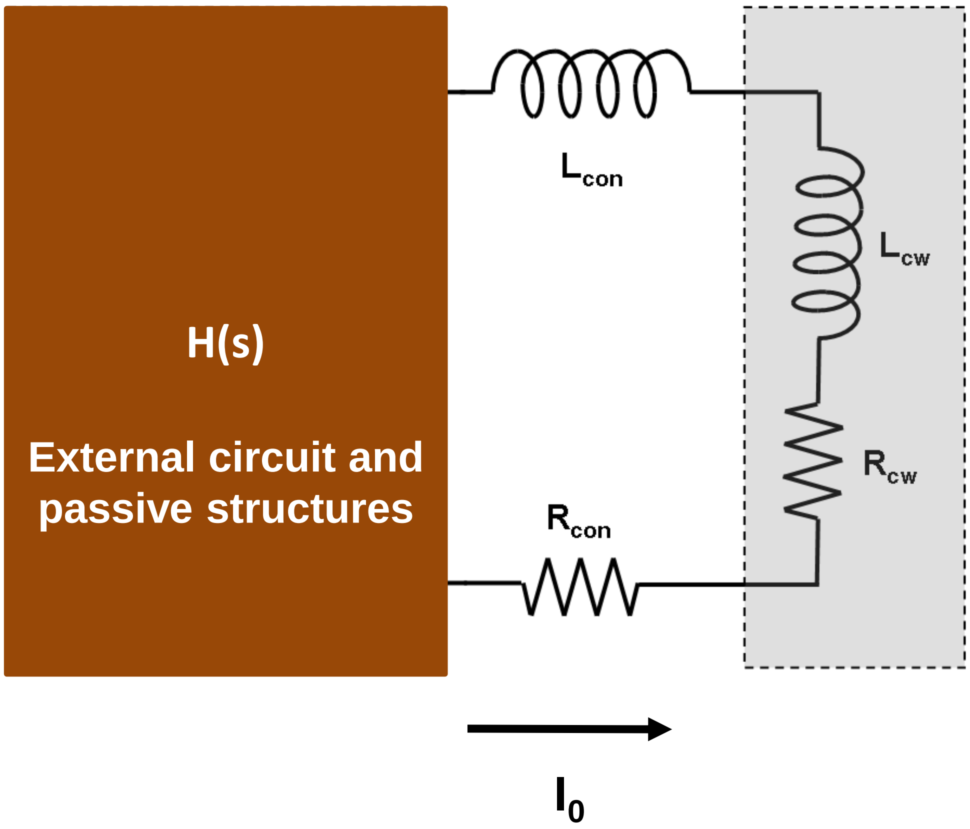
  - Linear model : $\boldsymbol{\sigma}\ (\mathbf{T}) = \frac{\sigma_0}{[1+\alpha\ (T - T0)]}$

  - Kronhardt model : $V_{arc} = V_0 + d * (1.75 + 0.012 * J^{1.75})$

$$\left\{ \begin{array}{l} \sigma(J) = \dfrac{J}{E_0 + 1.75 + 0.012 + J^{0.75}} \\ (T - T_0) = J^2 / \sigma\rho_m \end{array} \right.$$

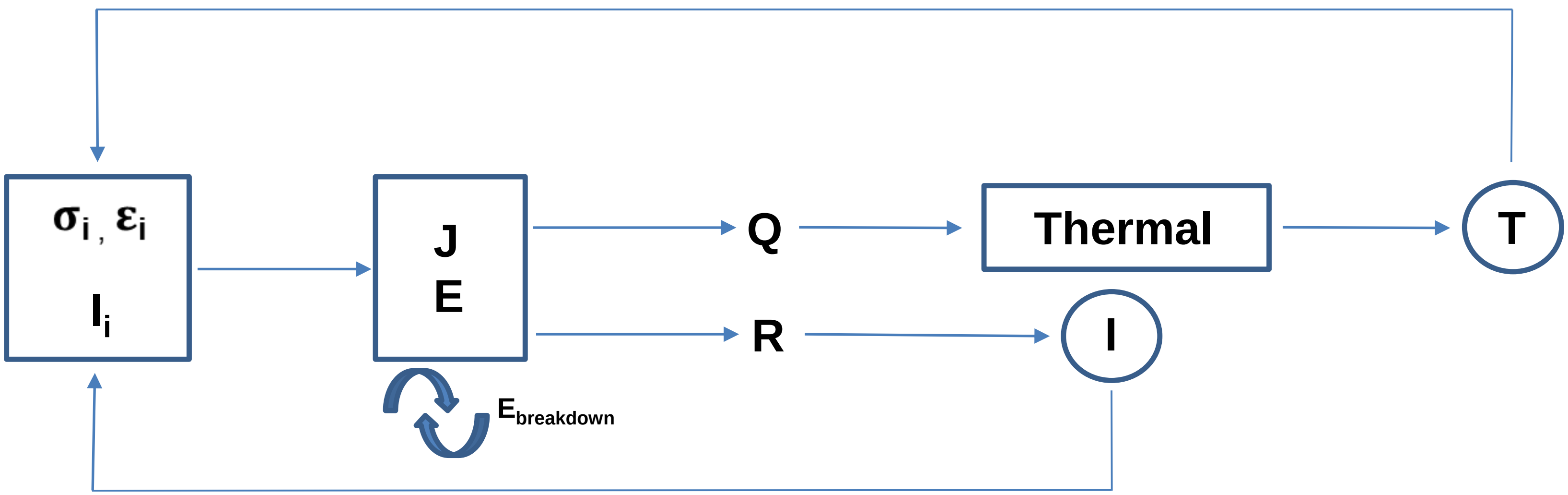
Volumetric Approach – Electric circuit

Update $\mathbf{R_{coil}}$ to obtain $\mathbf{I_{i+1}}$ using the equivalent circuit model



$$R = \frac{1}{|I|^2} \int_v \frac{J^2}{\sigma}\, dv$$

Volumetric Approach – Summary



Summary

- ETNA has been developed for arcing damage analysis of the ITER coils, using the discrete approach.
- A coupled field method is being developed using ETNA as a benchmark. This is being developed for generic geometry and could be used to assess the CERN case for benchmark.
- In parallel, a volumetric approach is being developed which is physically more representative.