Analysis of Electro-Thermal Hot Spot Formation in Li-Ion-Battery-Cells

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Motivation

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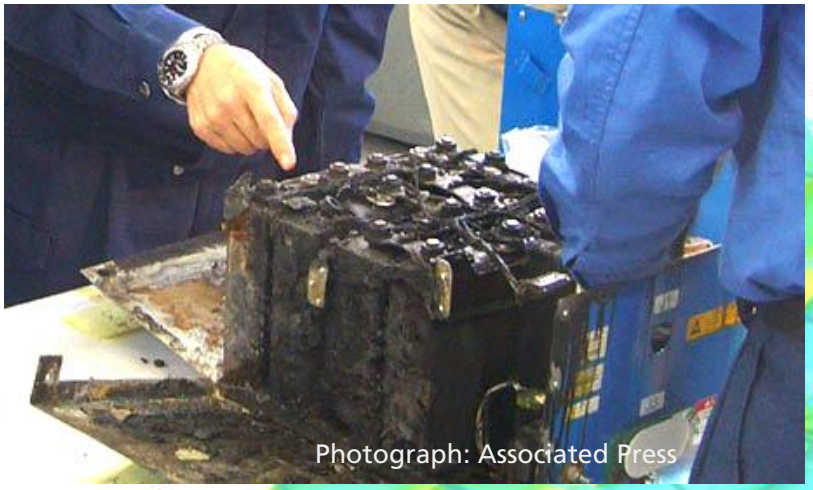
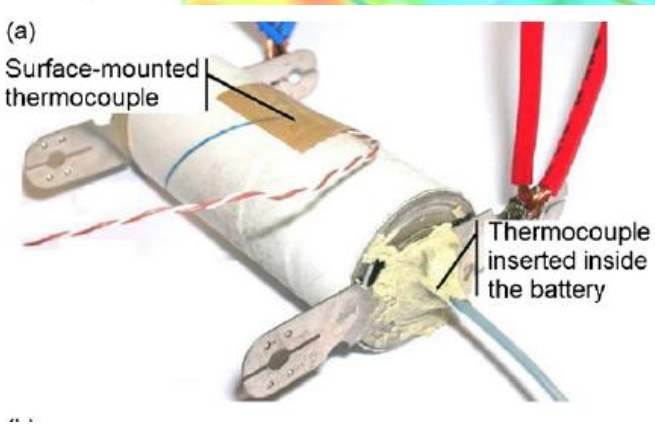
Thermal Management of Battery Cell Operation



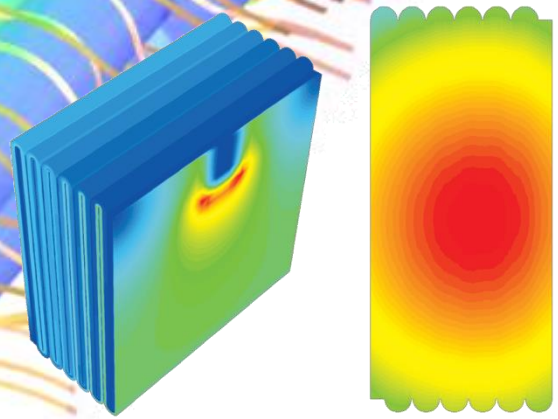
formation of thermal hot spots
⇒ risk of **thermal runaway**

limited experimental insight

modeling tools offer alternative



Forgez et al, J. of Power Sources ,195 (2010), pp. 2961-2968.



X. Hu, "Designing batteries for electric vehicles", ANSYS Advantage 2011

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Model Approach

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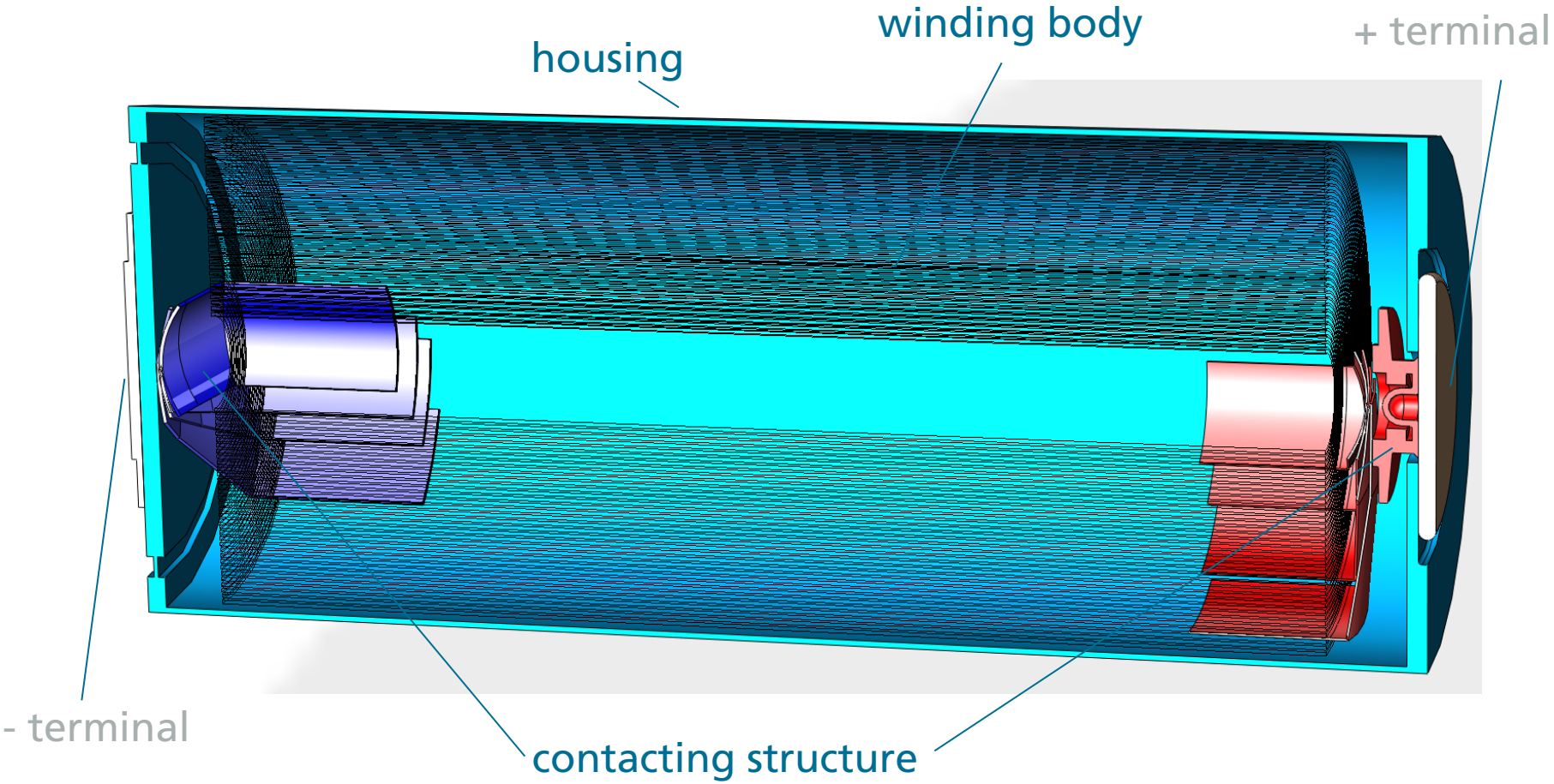
Cell Geometry

- internal cell geometry influences thermal behaviour



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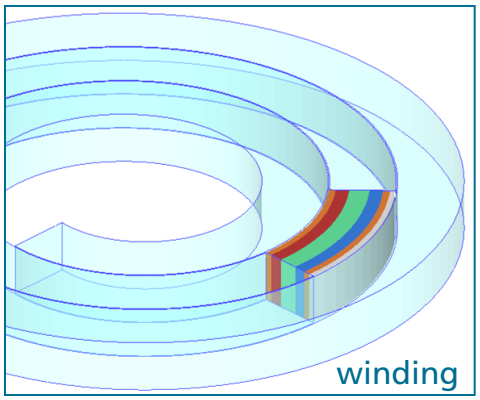
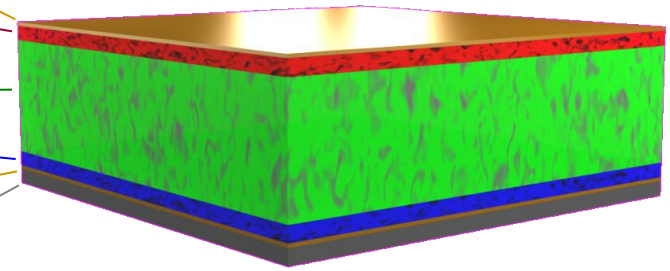
Homogenisation model for winding body

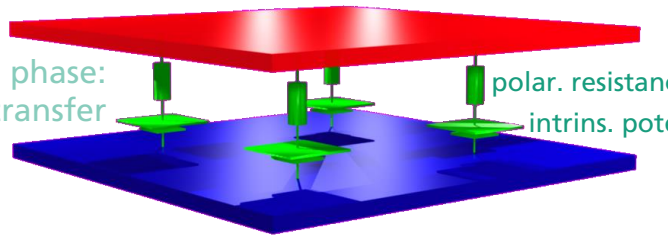


cell laminate



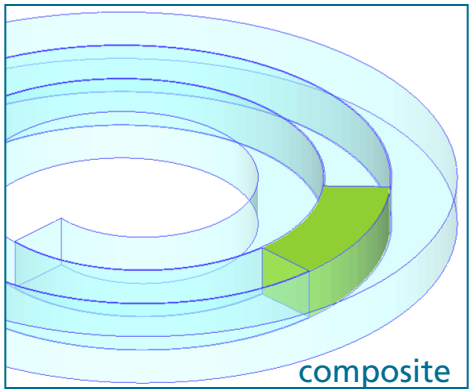
3-phase homogenised | continuum approach

cathode side current distributor phase



anode side current distributor phase

homogen. anisotropic composite



DOF:

U_{ano}

U_{cath}

T

PDE: anode side potential

$$-\nabla\left(\boldsymbol{\sigma}_{eff,ano}\cdot\nabla U_{ano}\right)=-\frac{j_{elec}}{h_{uc}}$$

PDE: cathode side potential

$$-\nabla\left(\boldsymbol{\sigma}_{eff,cath}\cdot\nabla U_{cath}\right)=+\frac{j_{elec}}{h_{uc}}$$

Constitutive equ.: el.-chem. characteristics

$$j_{elec}=\frac{U_{cath}-U_{ano}+U_0(T,\ldots)}{R_{el}^{A}(T,\,j,\ldots)}$$

electrolyte current density

PDE: thermal composite

$$-\nabla\left(\boldsymbol{\lambda}_{eff}\cdot\nabla T\right)=\sum_{d=(ano,\,cath,\,elec)}\left(\boldsymbol{\sigma}_{eff,d}^{-1}\cdot\mathbf{j}_d\right)\cdot\mathbf{j}_d+\ldots$$

Joule's + reversible heat

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Electr(o-chem)ical Characteristics

Constitutive equation for el.-chem. active phase:

$$\Delta U_{elek} - U_0(T, SoC) = R_{el}^A(T, SoC) \cdot j_{elek}$$

intrinsic electrochemical potential

cell polarisation resistivity

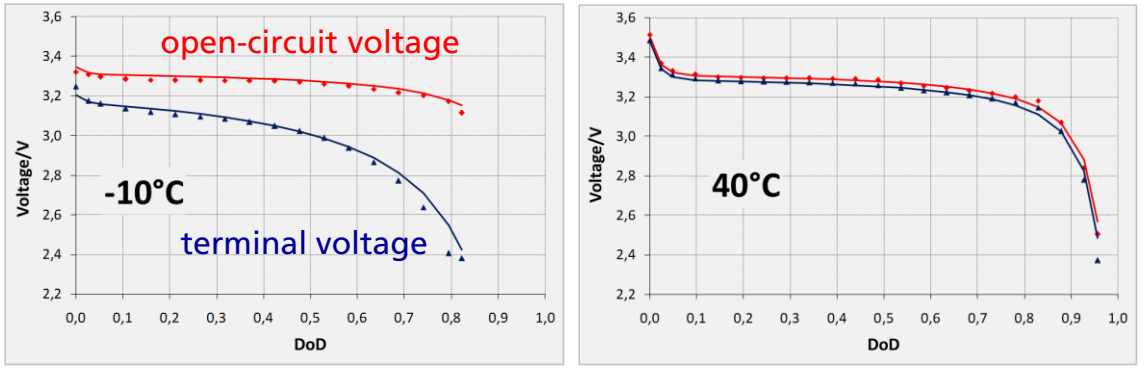
$$\Delta U_{elec} - \underbrace{\left[U_s + a(T) \cdot e^{-b \cdot DoD} - \left(d'(T) + k'(T) \cdot \frac{1}{1 - SoC}\right) \cdot SoC\right]}_{U_0(T, SoC)} = \underbrace{\left(k(T) \cdot \frac{1}{1 - SoC} + l(T)\right)}_{R_{el}^A(T, SoC)} \cdot j_{elec}$$

Empirical Approach: Shepherd's Model

C. M. Shepherd "Theoretical design of primary and secondary cells. Part 3: battery discharge equation" NRL Report 5908; May 1963

Model parameter set $c_i(T) \Rightarrow$ Calibration from comprehensive exp. cell characterisation

Verification:



points: experimental data
lines: model data

Models and Results

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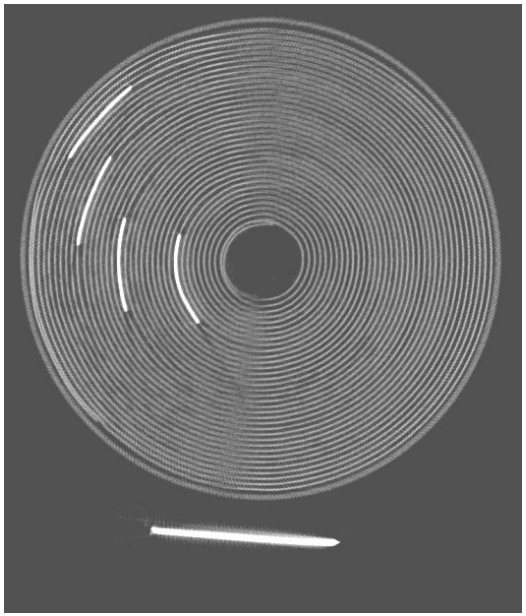
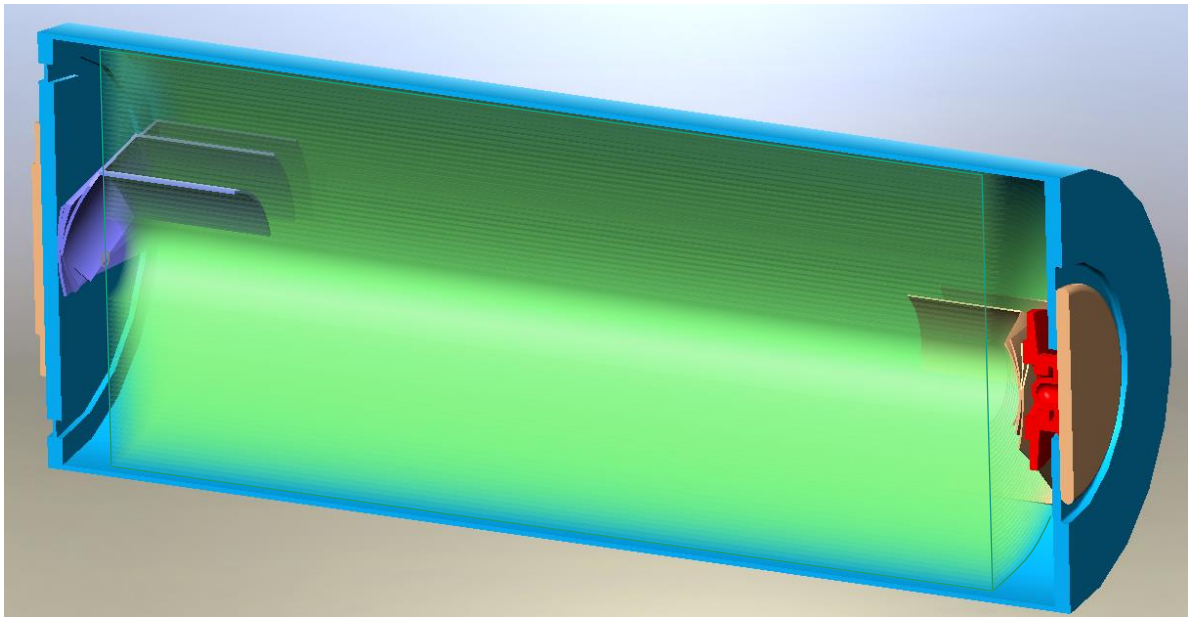
Model Geometry: Example 2

Example: cylindrical cell with separated contact tabs (LiFePo4 , ANR 26650)

- separated current collector tabs, embedded between windings
- nonhomogeneous contacting with current concentration toward cont. tabs





helical current flow + current collection ⇒ **3D-model approach**

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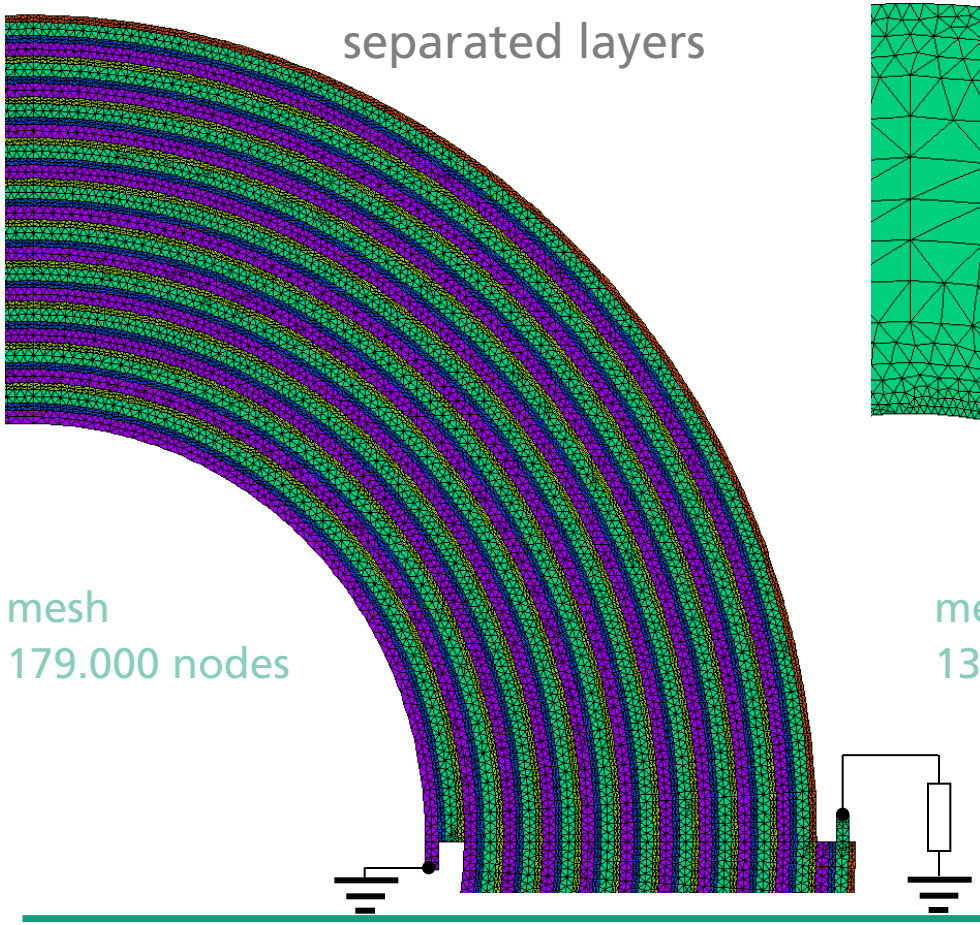
Direct Electrical Homogenisation of Winding Domain

Test in 2D-Model: end contacted winding domain (FlexPDE, 10 windings)

fully detailed model

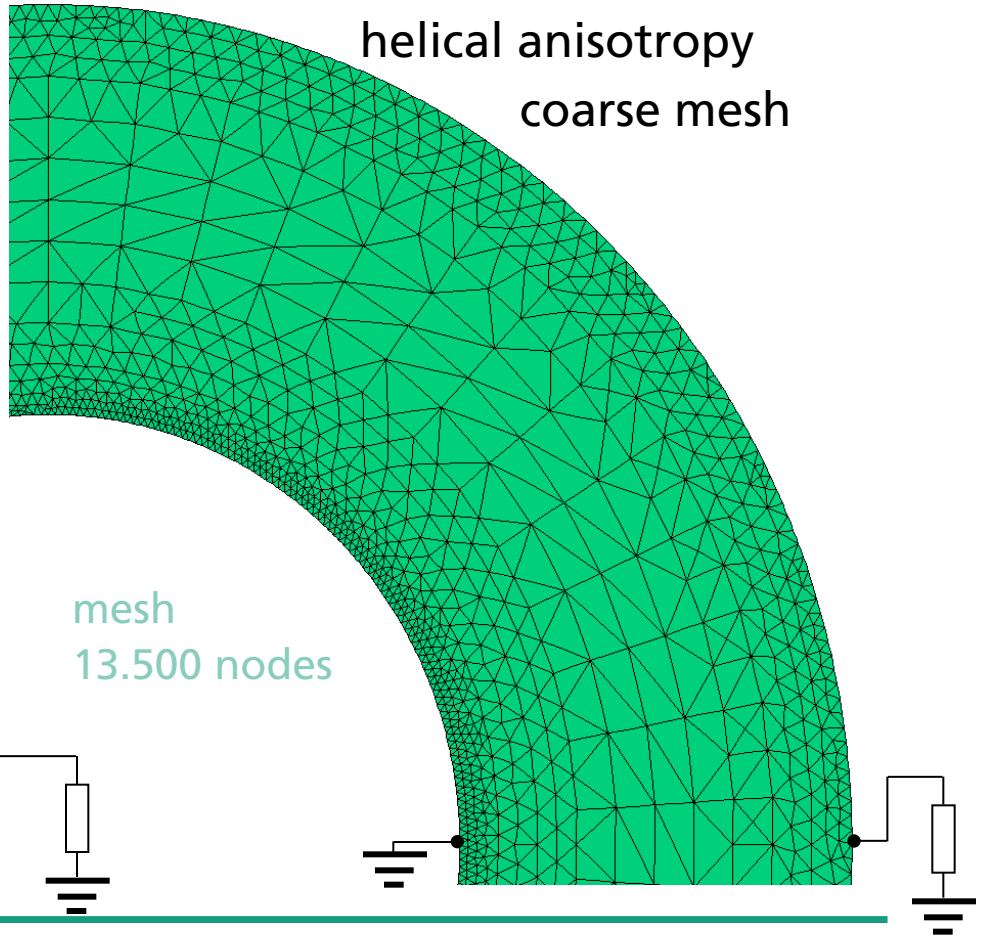
separated layers



mesh
179.000 nodes

directly homogenised model

helical anisotropy
coarse mesh



mesh
13.500 nodes

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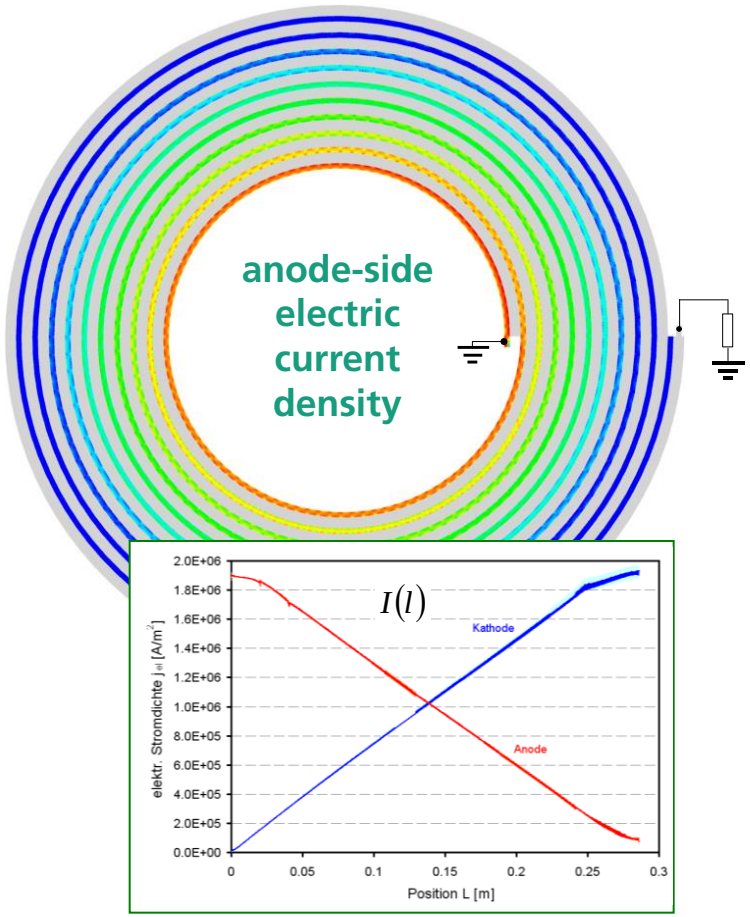
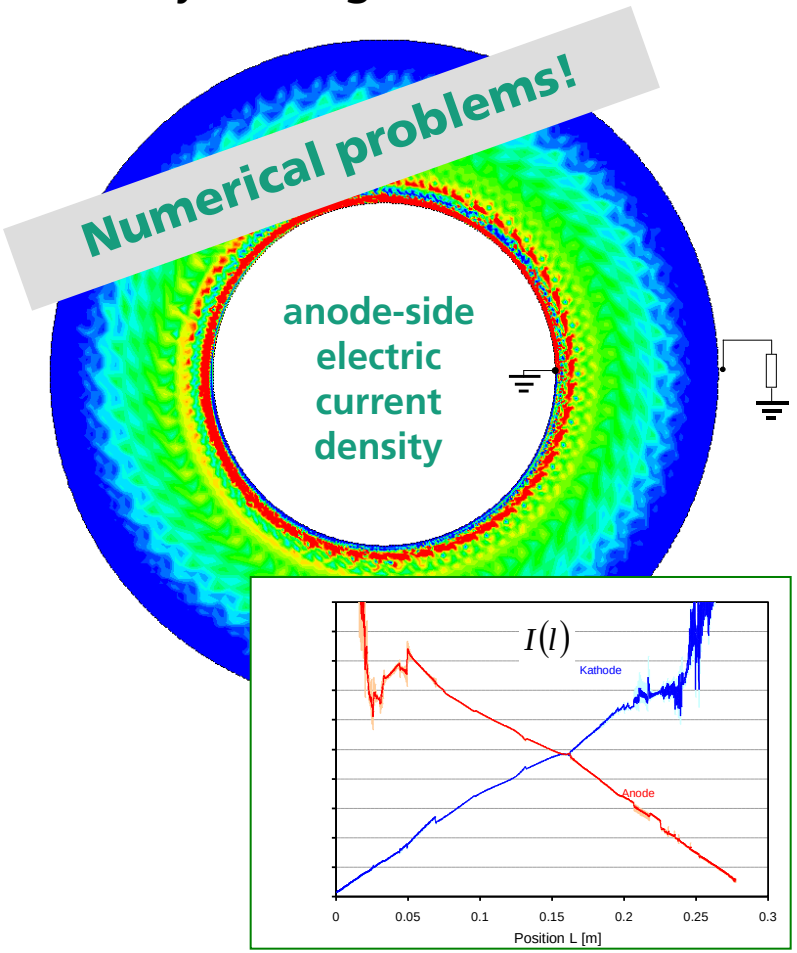
Direct Homogenisation of Winding Domain

2D-Model: end contacted winding (FlexPDE 5, 10 windings)

fully detailed model

directly homogenised model





Hybrid 2D-3D Model with Thermal ⇔ Electric Coupling

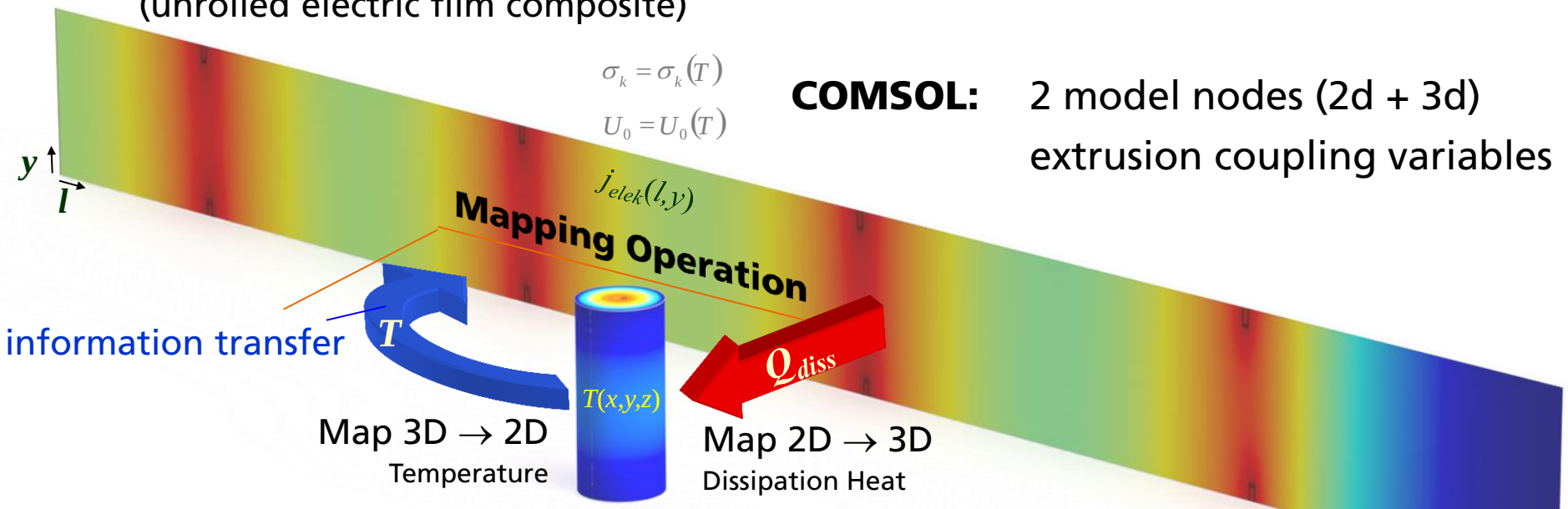
electric problem: 2D frame
(unrolled electric film composite)

$$U_{ano}(l,y),\ U_{cath}(l,y),\ j_{elek}(l,y) \rightarrow Q_{diss}(l,y)$$

$\sigma_k = \sigma_k(T)$

$U_0 = U_0(T)$

COMSOL: 2 model nodes (2d + 3d)
extrusion coupling variables



thermal problem: 3D frame
(thermal composite)

$T(x,y,z)$

$$\nabla(-\lambda \cdot \nabla T) = \dot{Q}_{th} = \underbrace{\sum_d (\sigma_{eff,d} \cdot \mathbf{j}_d) \cdot \mathbf{j}_d}_{\dot{Q}_{diss}} \underbrace{- T \cdot \frac{\partial U_0}{\partial T} \cdot \frac{j_{elec}}{h_{uc}}}_{\dot{Q}_{rev}}$$

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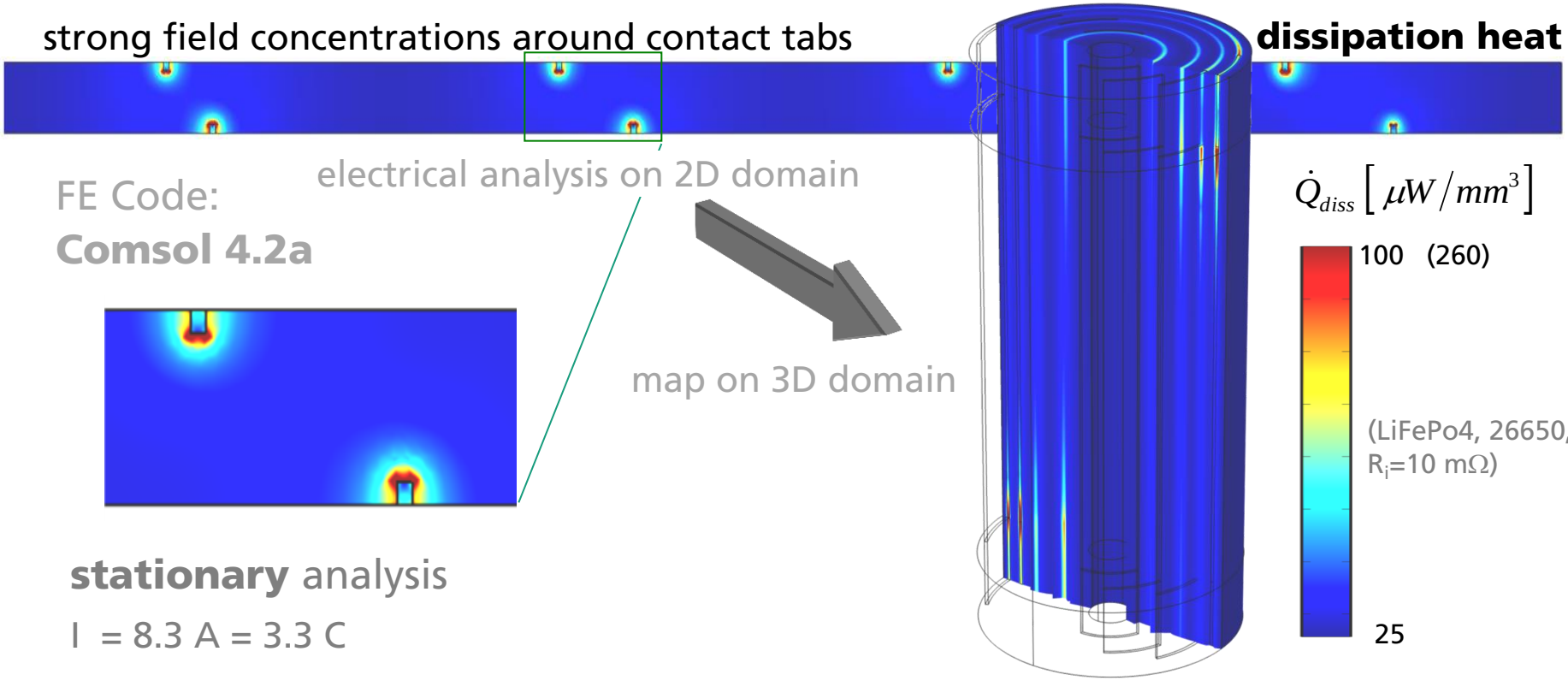
Hybrid-Model Results: 2D-electric model branch

2D ⇒ 3D Mapping of Dissipation Heat

strong field concentrations around contact tabs



stationary analysis

I = 8.3 A = 3.3 C

- **strongly localised heat sources at contact structure**
- **winding structure effect:** restriction of heat sources to single layers

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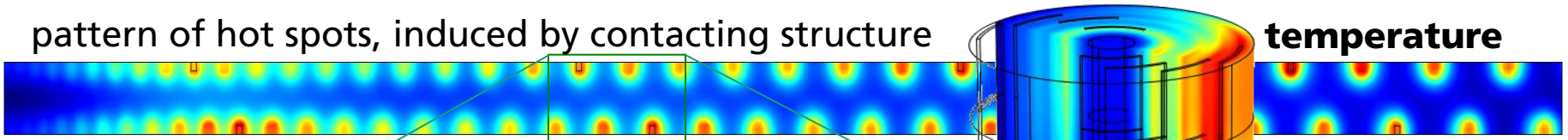
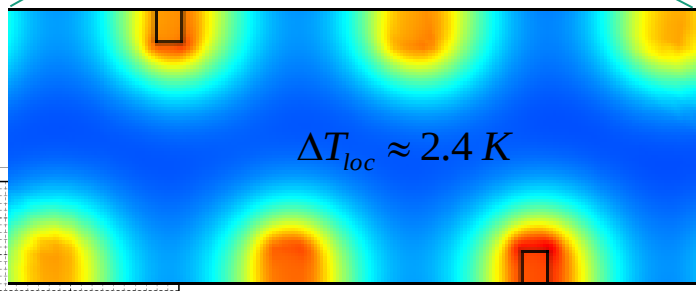
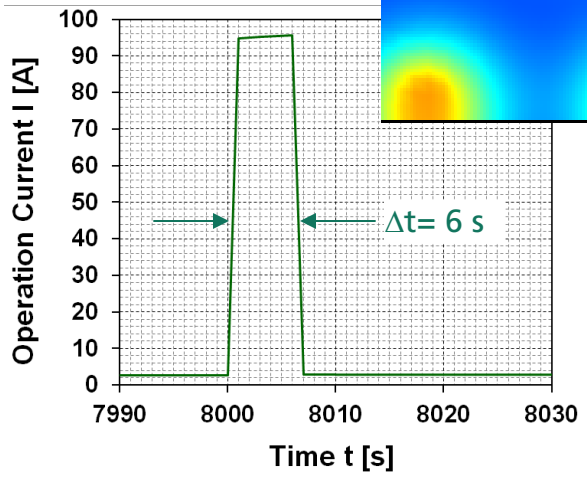
Hybrid-Model Results: 3D-thermal model branch

Transient analysis with current pulse

pattern of hot spots, induced by contacting structure







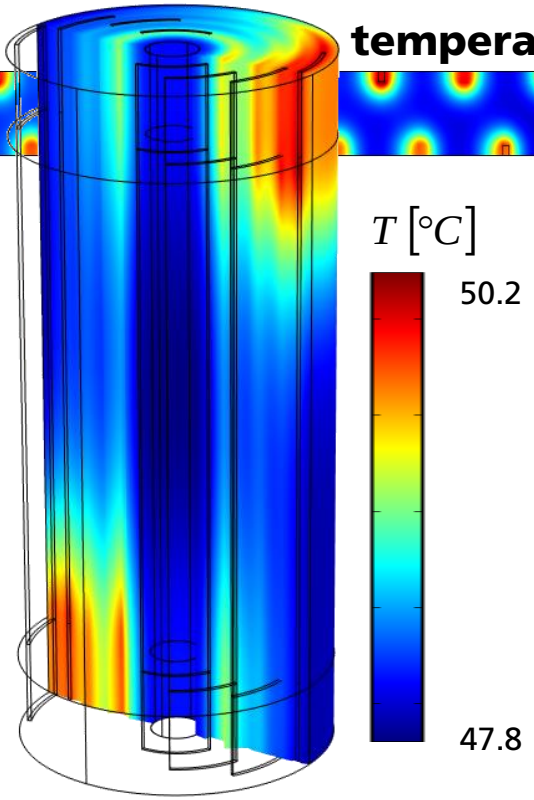
dynamic analysis

current pulse: duration 6 s

I_{max} = 95 A = 40 C

reasonable magnitude for practical operation

temperature



(LiFePo4, 26650, R_i= 10 mΩ)

high dynamic load + small area contacts ⇒ hot spot formation

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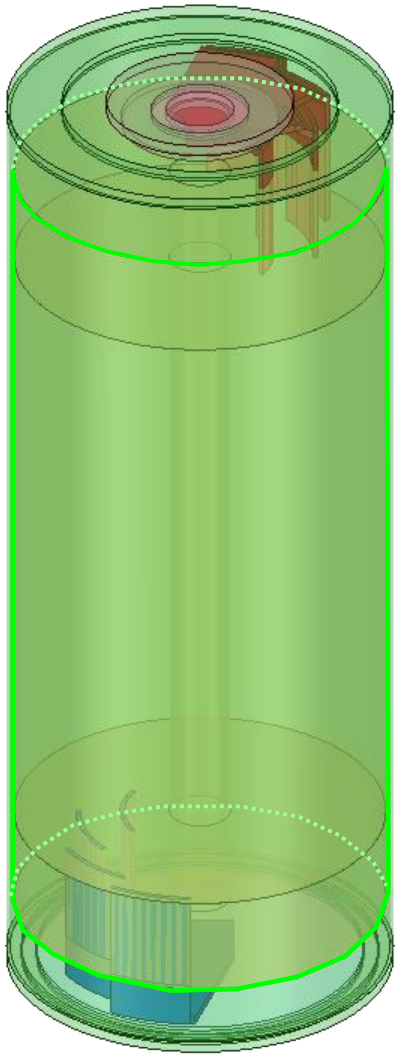
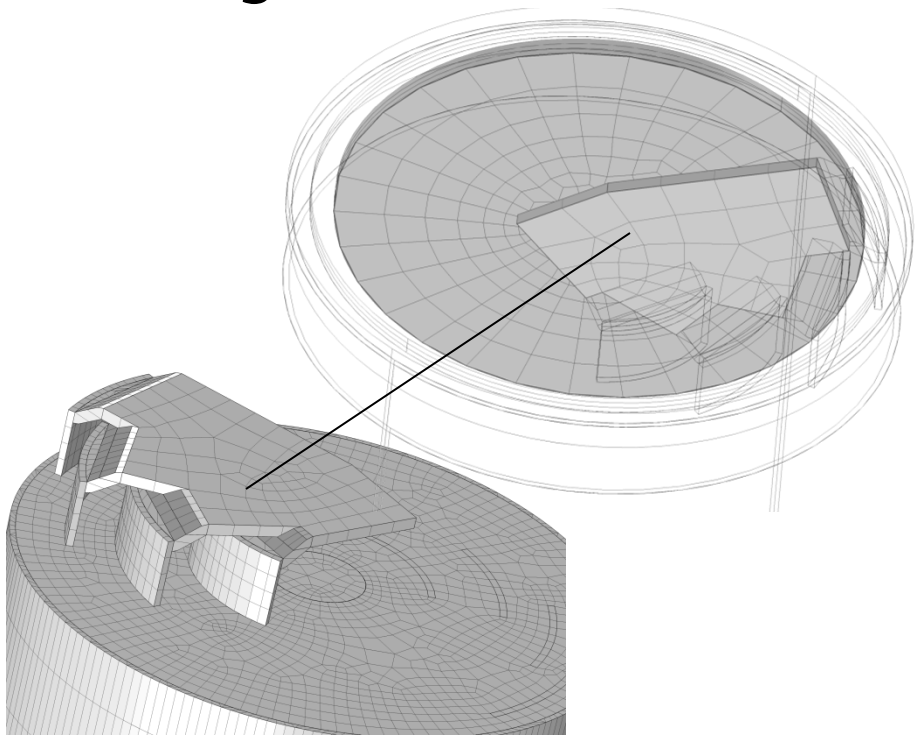
Completion: 3D-Model with Housing + Contact. Structure





Geometry/ Mesh generation

- winding domain: Comsol-generated
- add housing + contact structure: CAD-Import
- using assemblies

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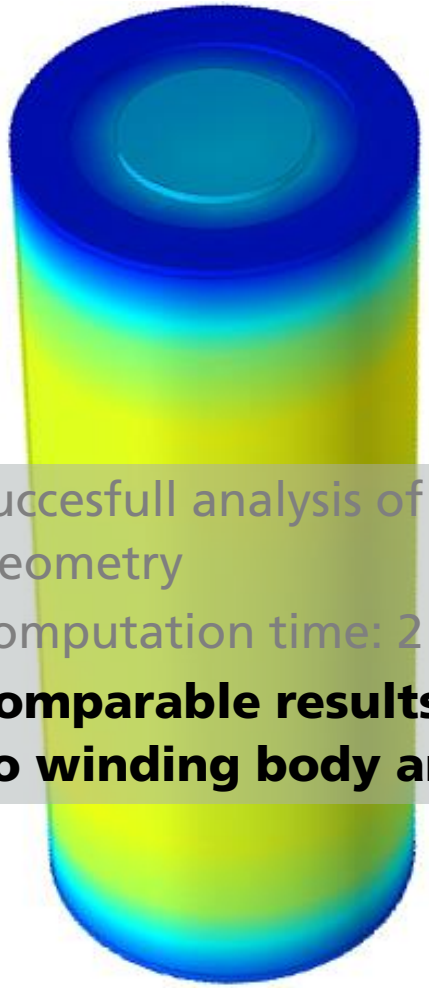
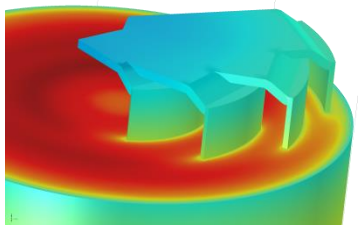
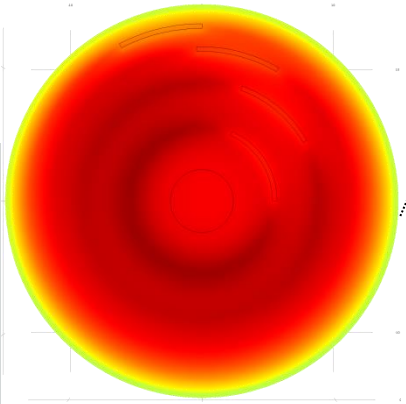
3-D Model with Housing: Results

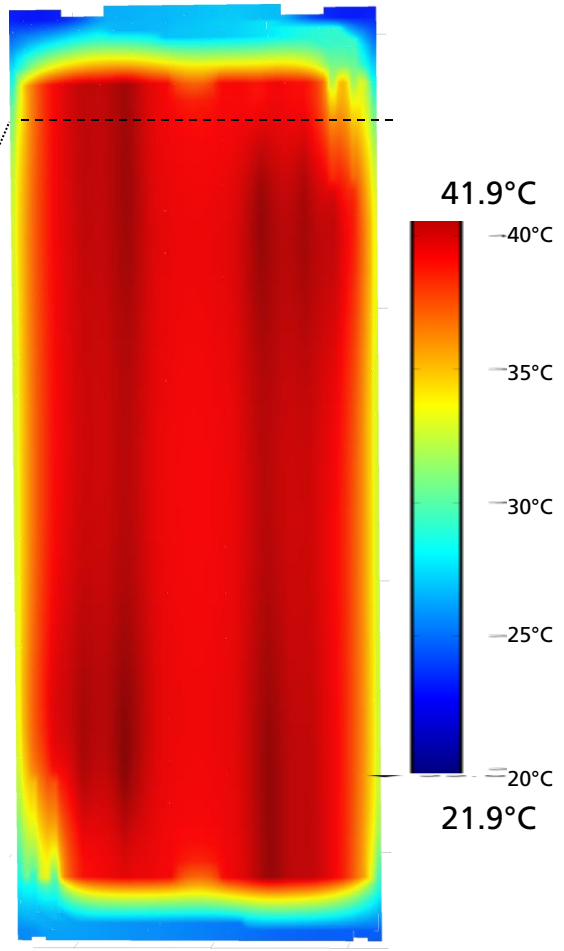


- succesfull analysis of full cell geometry
- computation time: 2 h
- **comparable results to winding body analysis**



Temperature [°C]





41.9°C<T<29.0°C

dynamic analysis I ≅ 130 A ≅ 54 C Δt= 6 s

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Summary

- **model strategy** allows to include

  effect of detailed **contacting** + **winding** structure

  and **thermal-electric coupling**

- **homogenised 3 phase model** for **winding composite**
- **simple empirical model** for **electrical characteristics**
- **hybrid 2D-electric + 3D-thermal composite approach**
- **contact structure** acts as **source** for thermal **hot-spots** in **dynamic loads**
- approach has **potential** for use in **multi-cell models**

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