HTS MODELLING 2016
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https://events.unibo.it/htsmodelling2016

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Multi-scale model of rSFCLs in EMTP-RV power system transient simulator

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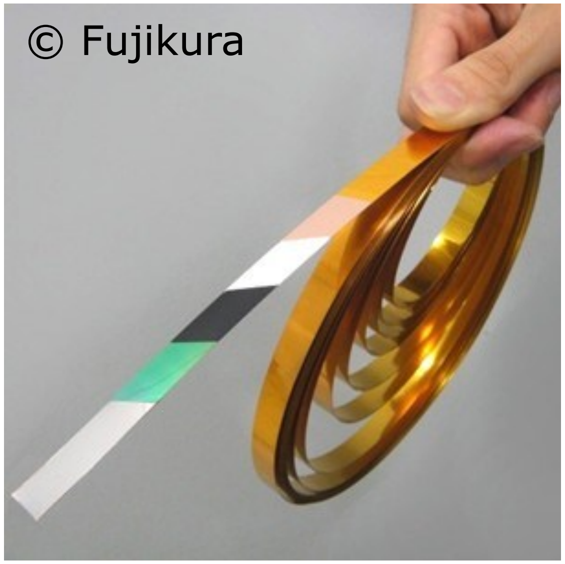
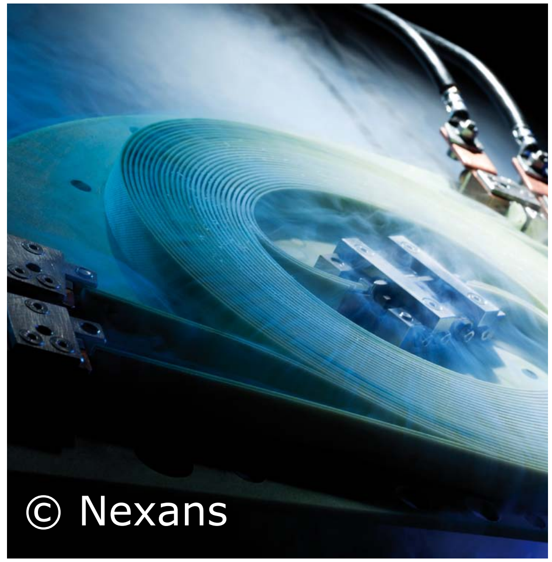
WHY MULTI-SCALE?

WHY MULTI-SCALE? BECAUSE LIFE IS MULTI-SCALE!



Materials and basic wires

→



Assemblies (e.g. coils)

→

Devices

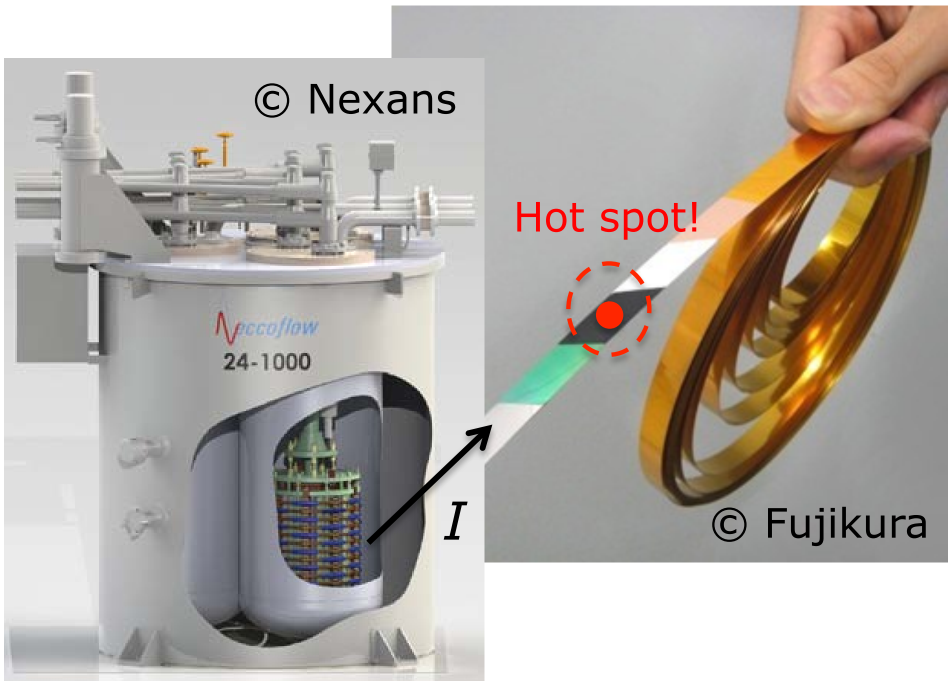
Systems

μm to km length scales!

DEVICE VS. SYSTEM MODELS

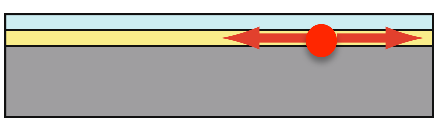
Critical phenomena must be taken into account → Here: hot spots!

FEM is convenient, but not ideal to couple with system equations



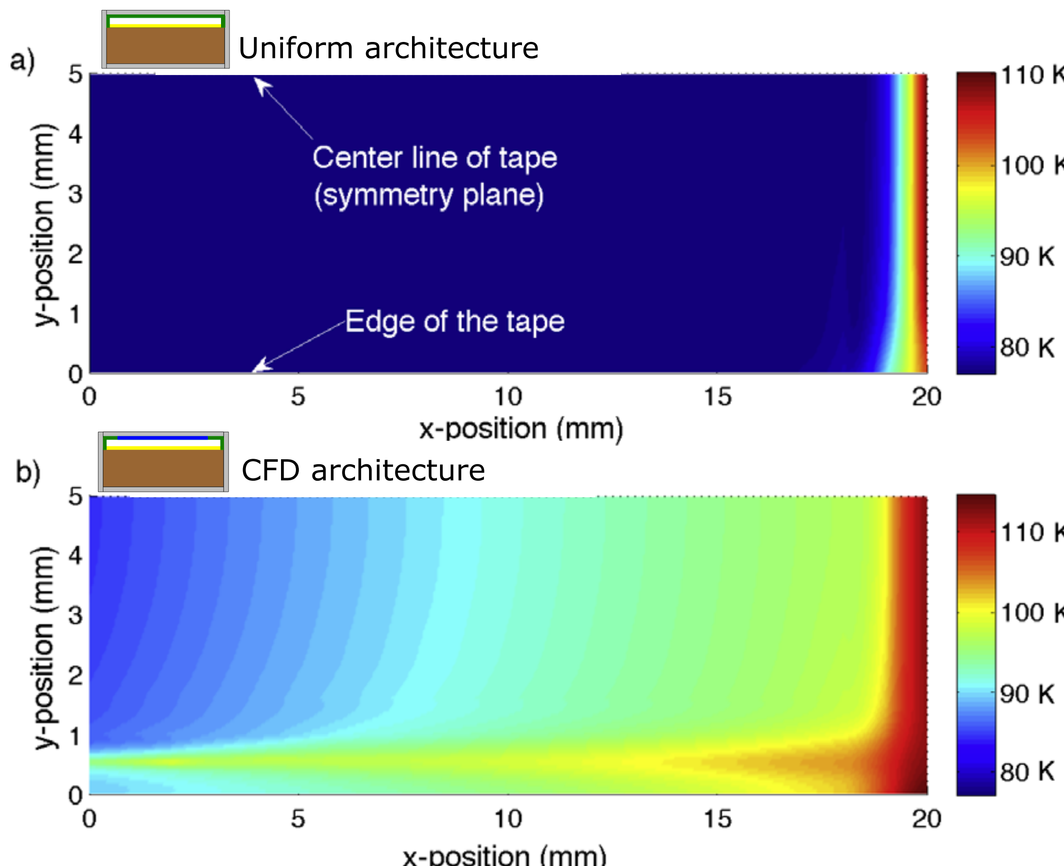
Prop. velocity?
Max temp?

Hot spot & normal zone propagation



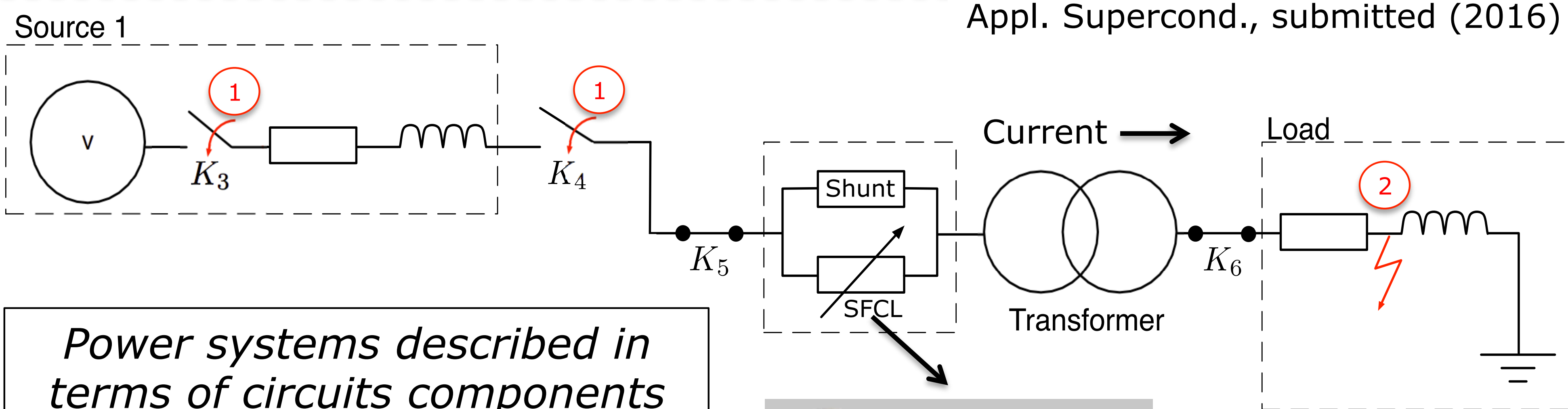
F. Roy et al., *Physica C*, 469 (2009)

C. Lacroix et al., *Supercond. Sci. Tech.* 27 (2014)



DEVICE VS. SYSTEM MODELS

C.-H. Bonnard al., IEEE Trans. Appl. Supercond., submitted (2016)



Power systems described in terms of circuits components

Device model must be compatible with system representation

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DEVICE VS. SYSTEM MODELS

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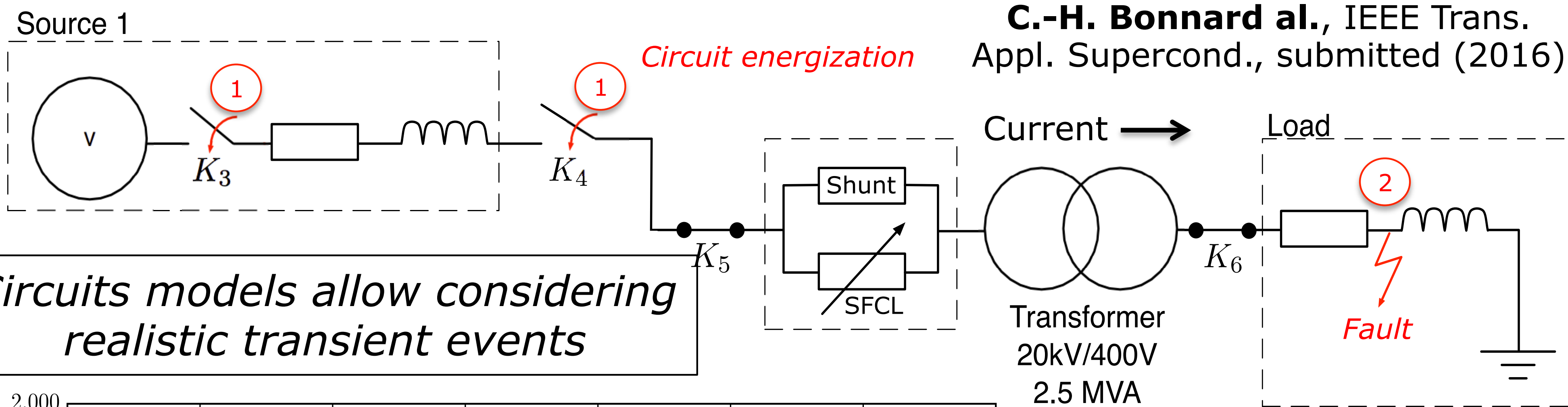
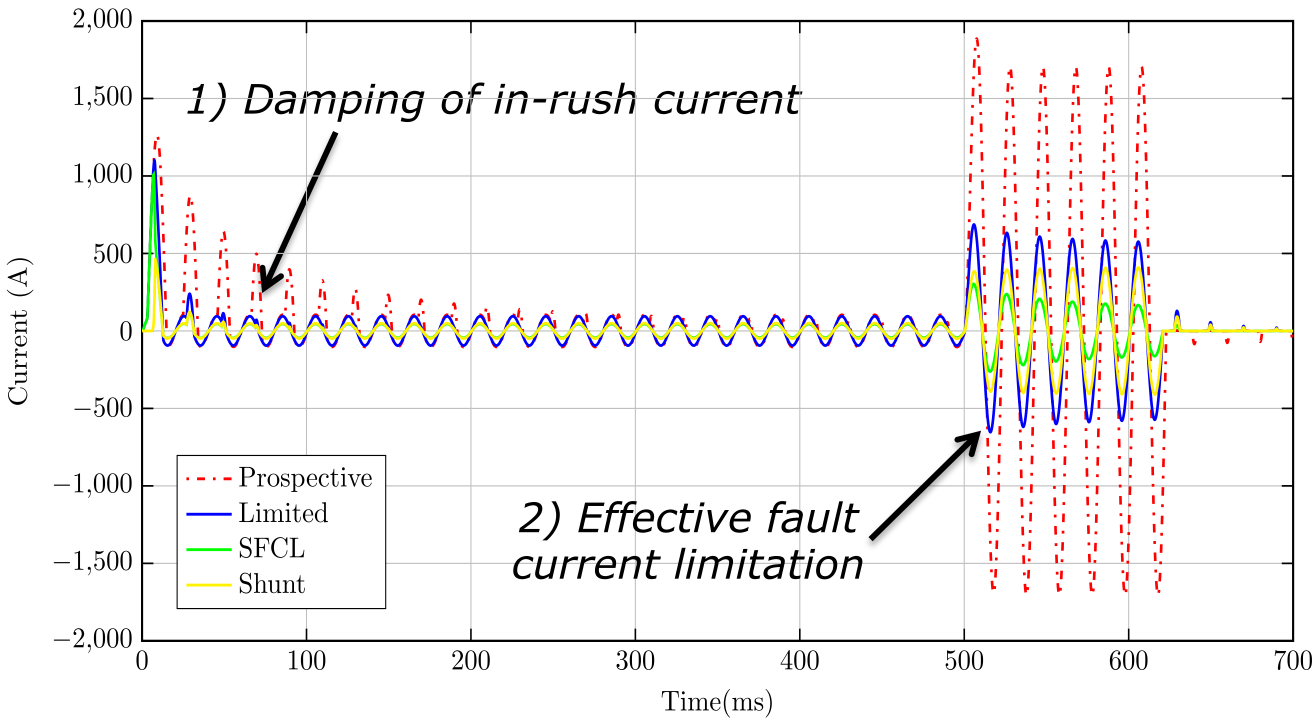


Circuits models allow considering realistic transient events



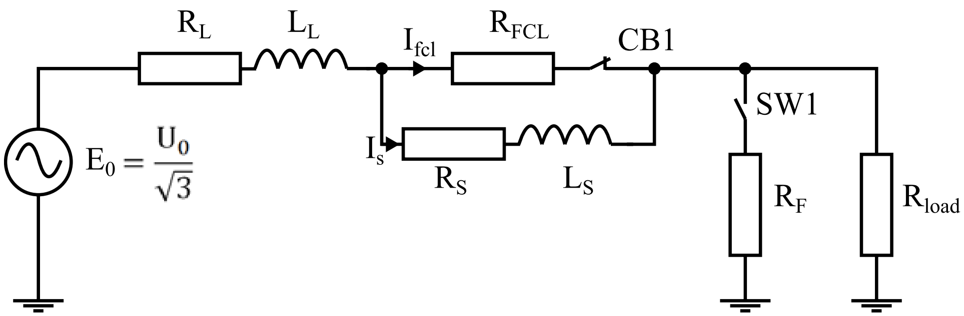
Various types of transient excitations can happen

Hot spot probability of occurrence is highly function system parameters

DEVICE VS. SYSTEM MODELS

Need for scalable multi-scale simulations

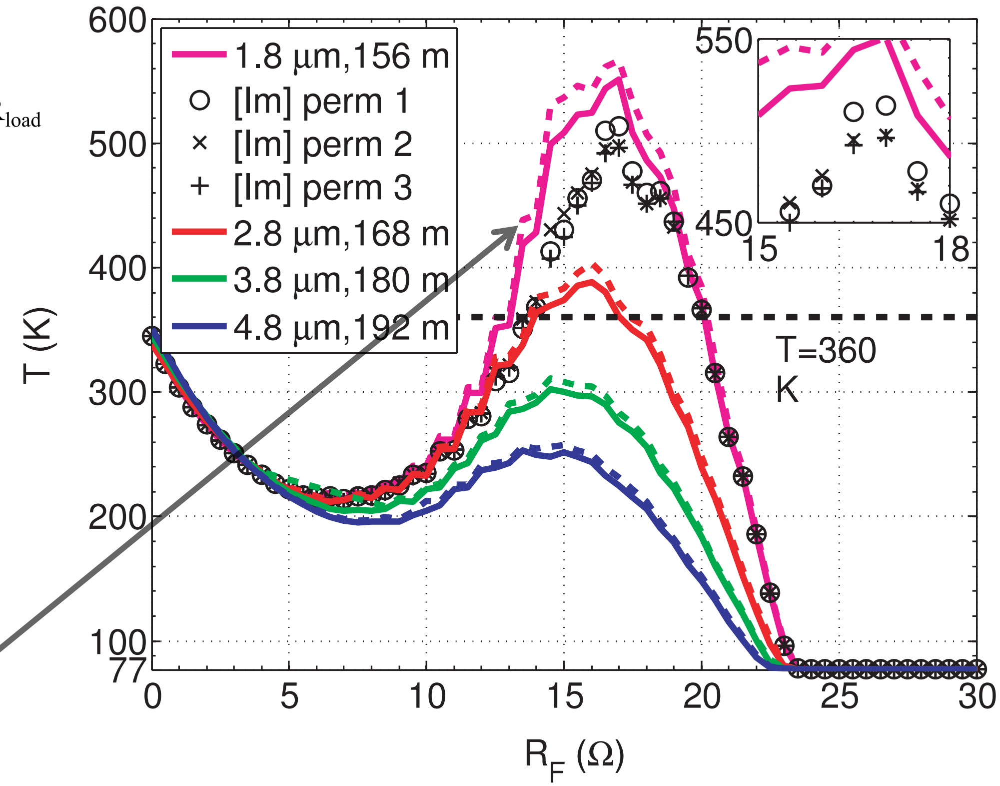
- Local temperature elevation in SFCL vs. fault impedance



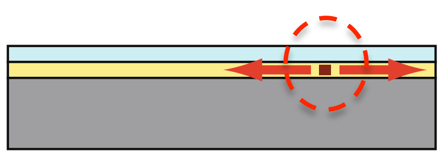
Simulink model

Mixture of **micro** and **macro**

Max temperature after 100 ms of a fault



Hot spot & normal zone propagation



D. Colangelo and B. Dutoit, *Supercond. Sci. Tech.*, 25 (9), p. 095005, 2012.
F. Roy et al., *Physica C*, 469 (15), p. 1462, 2009.

MULTI-SCALE MODEL: OPTIONS

1) Co-simulation (horizontal)
   - Requires an interface between device and system simulators
   - Exchange of data between two commercial codes is difficult
   - Inclusion of more than 2 length scales hardly possible

2) System equations in device simulators (bottom-up)
   - Challenging because of heterogeneity/complexity of system equations
   - Few commercial codes offer this flexibility

3) Device equations in system simulators (top-down)
   - Challenge: write a device simulator within a system simulator
   - Option available in many commercial codes (dynamic-link lib.)
   - If well done, no limit on level of detail: true multi-scale!

MULTI-SCALE MODEL: OPTIONS

- Tool selected: EMTP-RV — The reference for power systems transients

http://emtp-software.com

- Features:

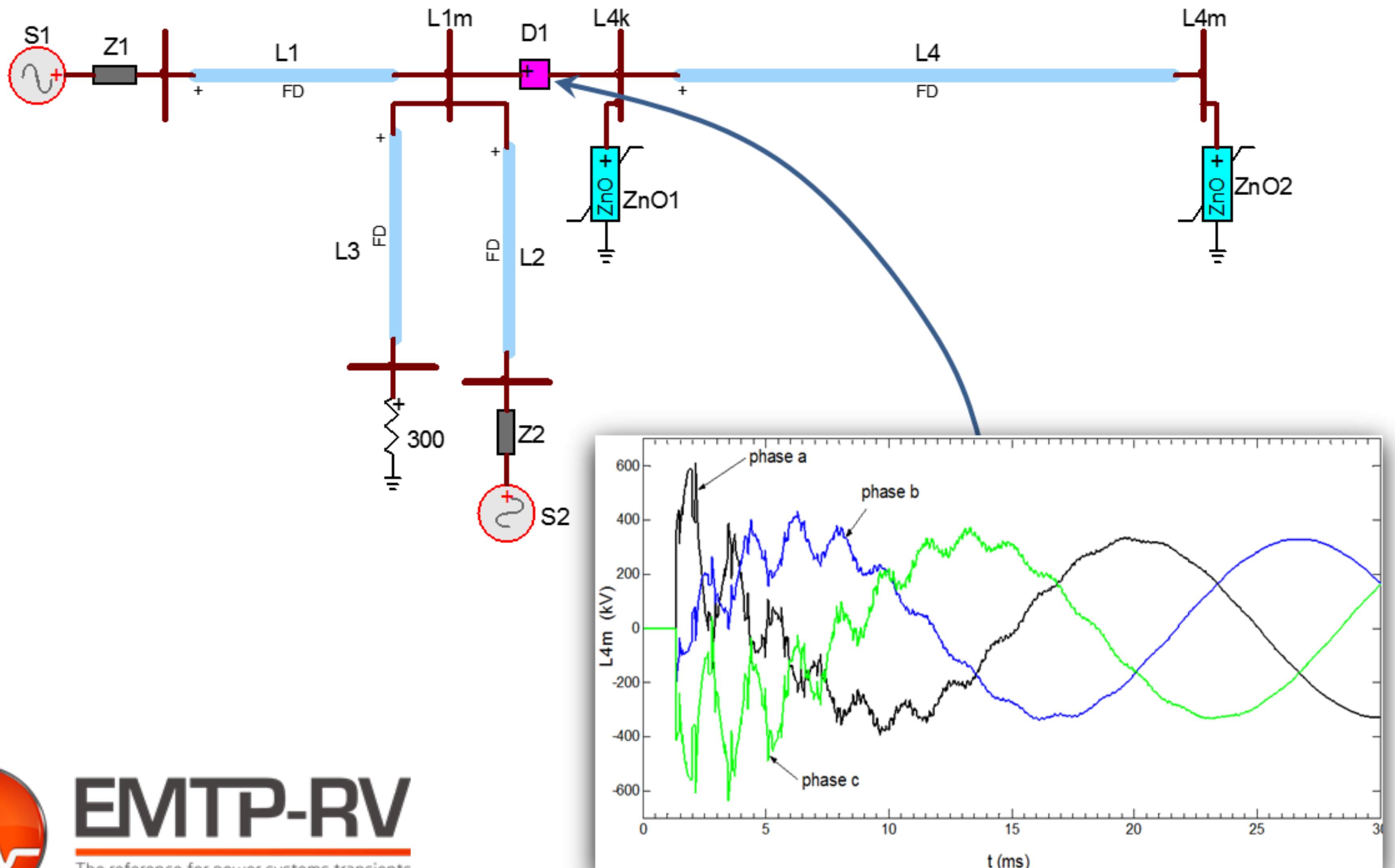
→ Power system transient simulator for **large-scale systems**
→ Nearly 50 years of model and code developments behind it
→ Typical types of problems investigated:

-Insulation coordination	-Power electronics and FACTS
-Switching surges	-Wind generation
-Ferroresonance	-Lightning surges
-HVDC	-Network analysis
-Protection	-Series compensation
-Shaft torsional stress	-Switchgear
-Synchronous machines	**-Short-circuits & fault currents**

Major users in industry / rich library / open env.

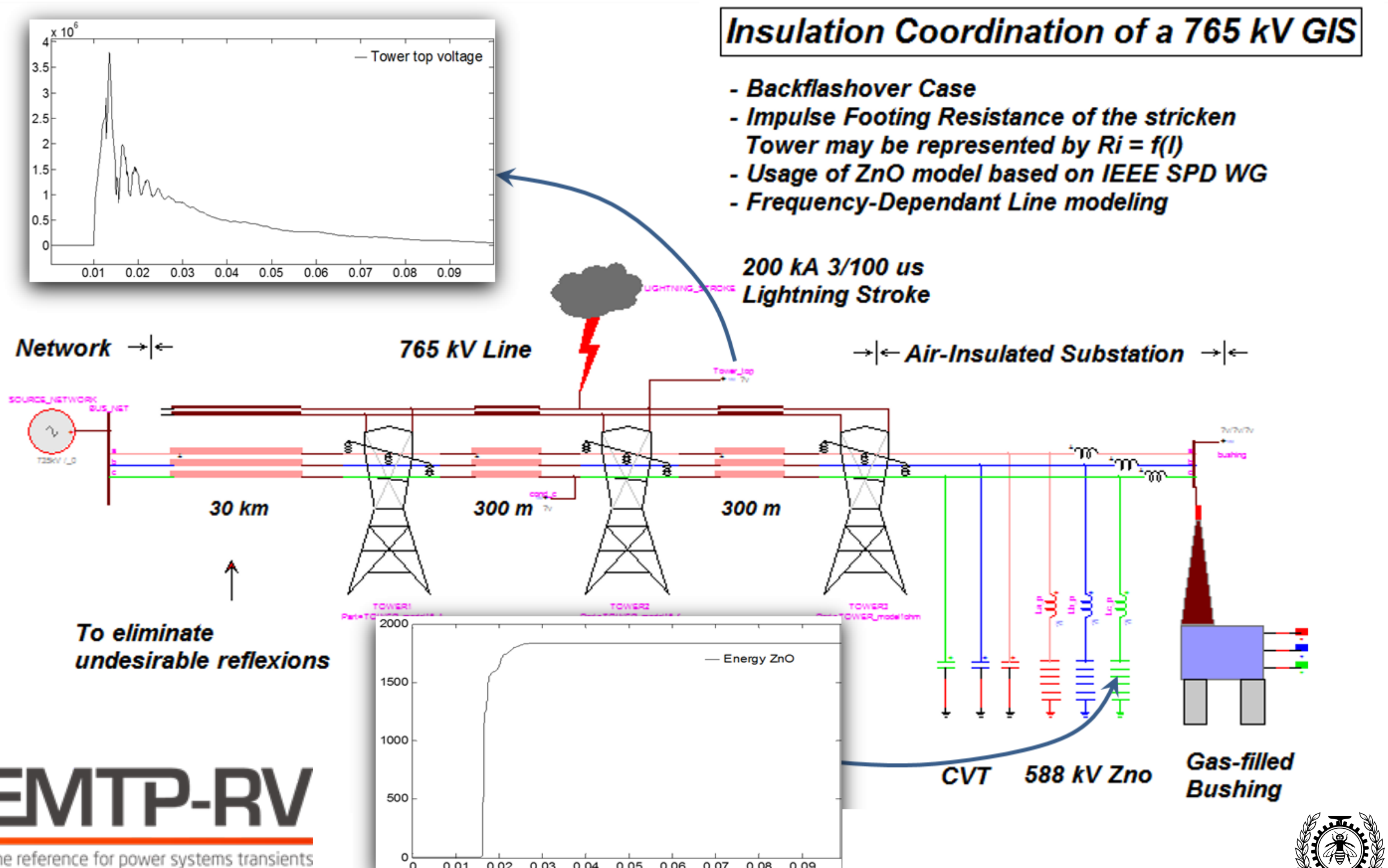
EMTP-RV: EXAMPLES OF APPLICATIONS

- Switching transients on transmission lines



EMTP-RV: EXAMPLES OF APPLICATIONS

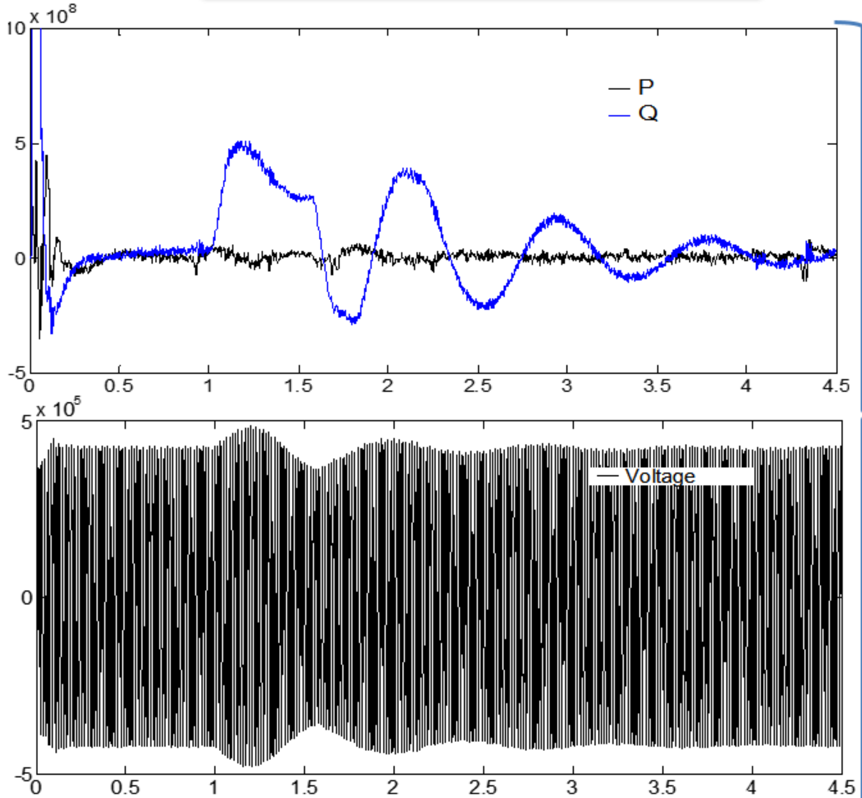
- Insulation coordination upon lightning strikes

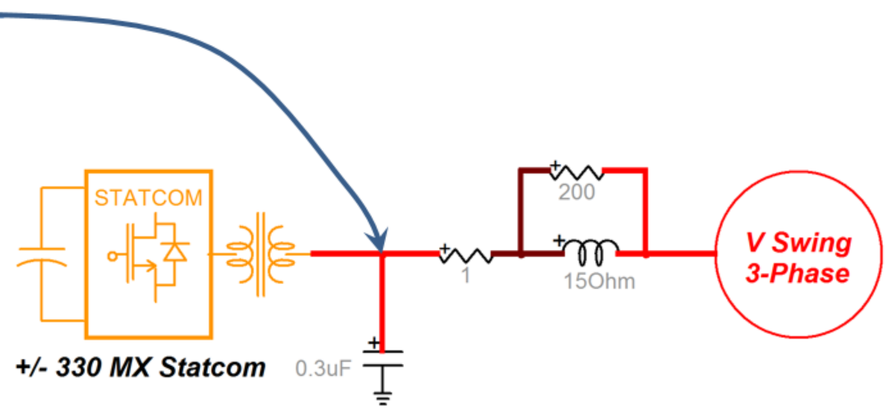


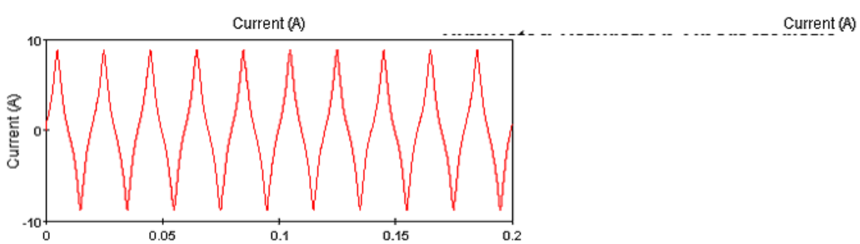
EMTP-RV
The reference for power systems transients

EMTP-RV: EXAMPLES OF APPLICATIONS

- Power electronics for voltage regulation







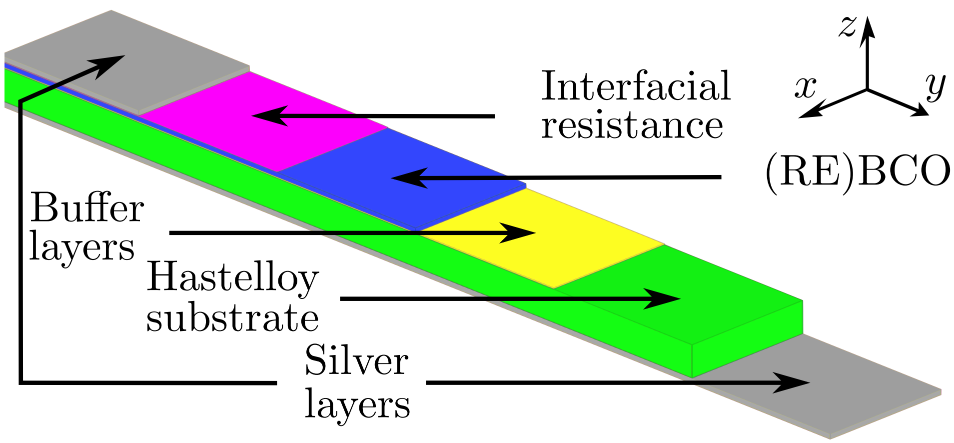
GENERAL CONSIDERATIONS

- EMTP-RV: not the only choice, but a good one for us since:
  - Used by many major utilities and device manufacturers
    - Good vector to promote superconducting device models
  - Optimized to solve large-scale networks (more than 100,000 components!)
  - Rich device libraries
    - Cables, transformers, machines, control devices, etc.
    - Many types of nonlinear elements
  - Relatively “open environment” that allows creation/addition of new library elements by
    - assembling existing elements;
    - writing user codes (dynamical-linked library - DLL)

  - Main development realized in Polytechnique Montreal (!)

THE MODEL

- Electro-thermal model of an HTS tapes
  - including all interfacial effects, symmetries, etc.
  - inductive effects neglected (OK in rSFLCs)



Coupling variables:

$$T = \text{Temperature}$$

$$Q_J = \text{Electrical losses } (\vec{E} \cdot \vec{J})$$
$$= \nabla V \cdot \sigma(T, \nabla V) \nabla V$$

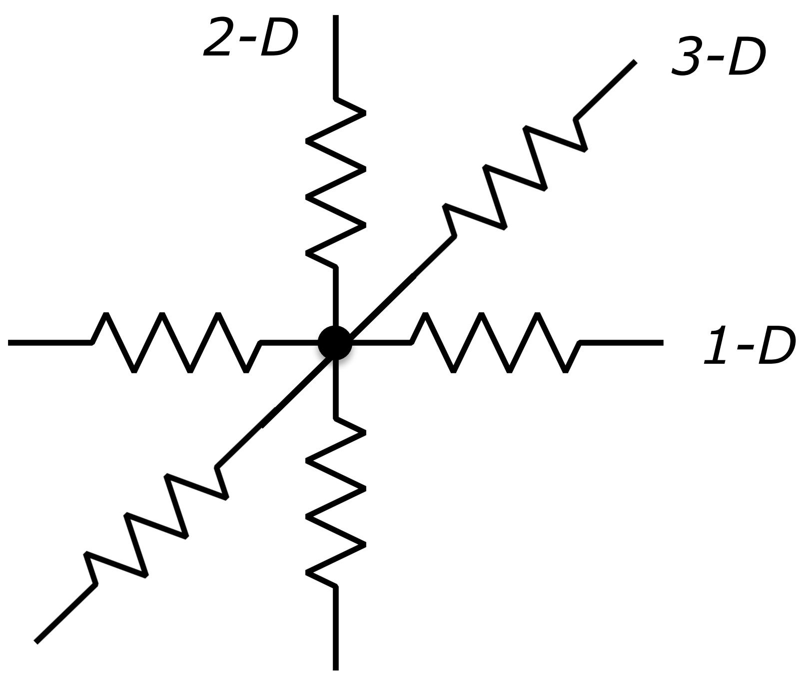
$$\nabla \cdot \big(\sigma(T, \nabla V) \nabla V\big) = 0$$

$$\rho_m C_p(T) \frac{\partial T}{\partial t} = \nabla . (\kappa(T) \nabla T) + Q_J$$

Boundary conditions and constraints

THE MODEL

- Discretization approach: **old good resistor network**
  - Directly compatible with a circuit simulator
  - Dimensionality easy to adjust

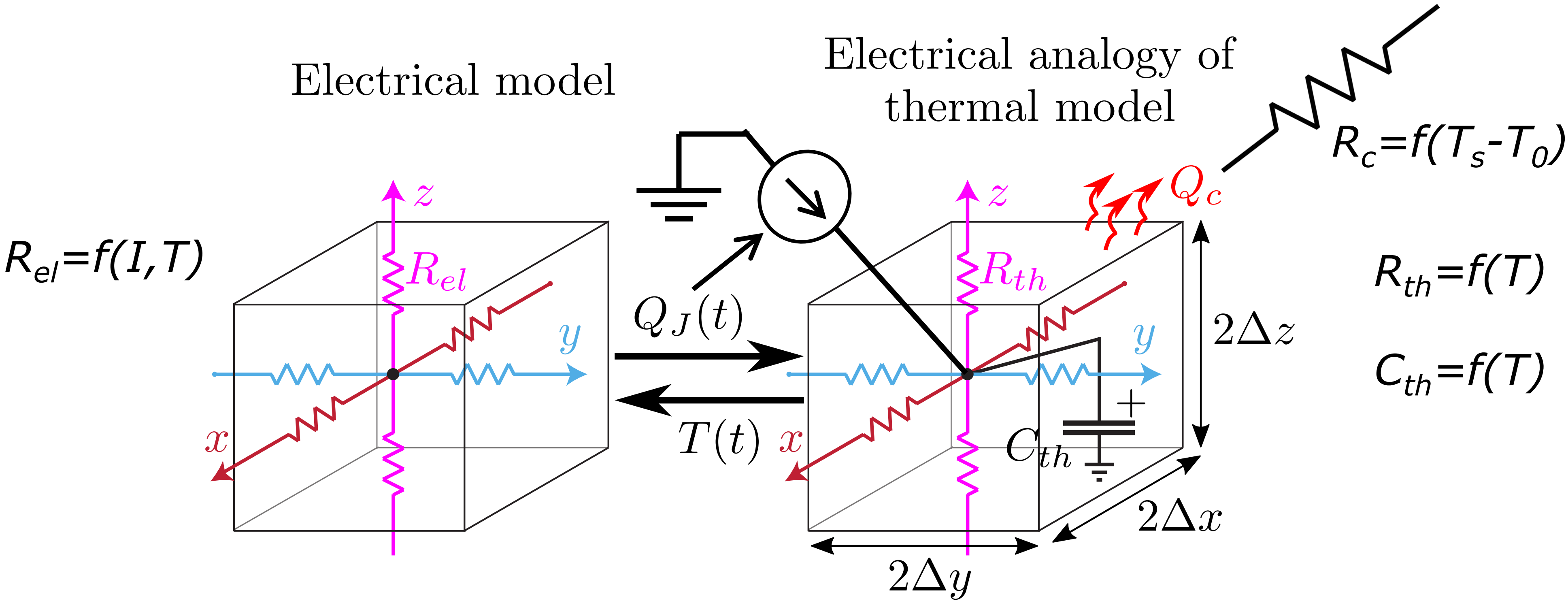


In appearance, similar to the finite difference method

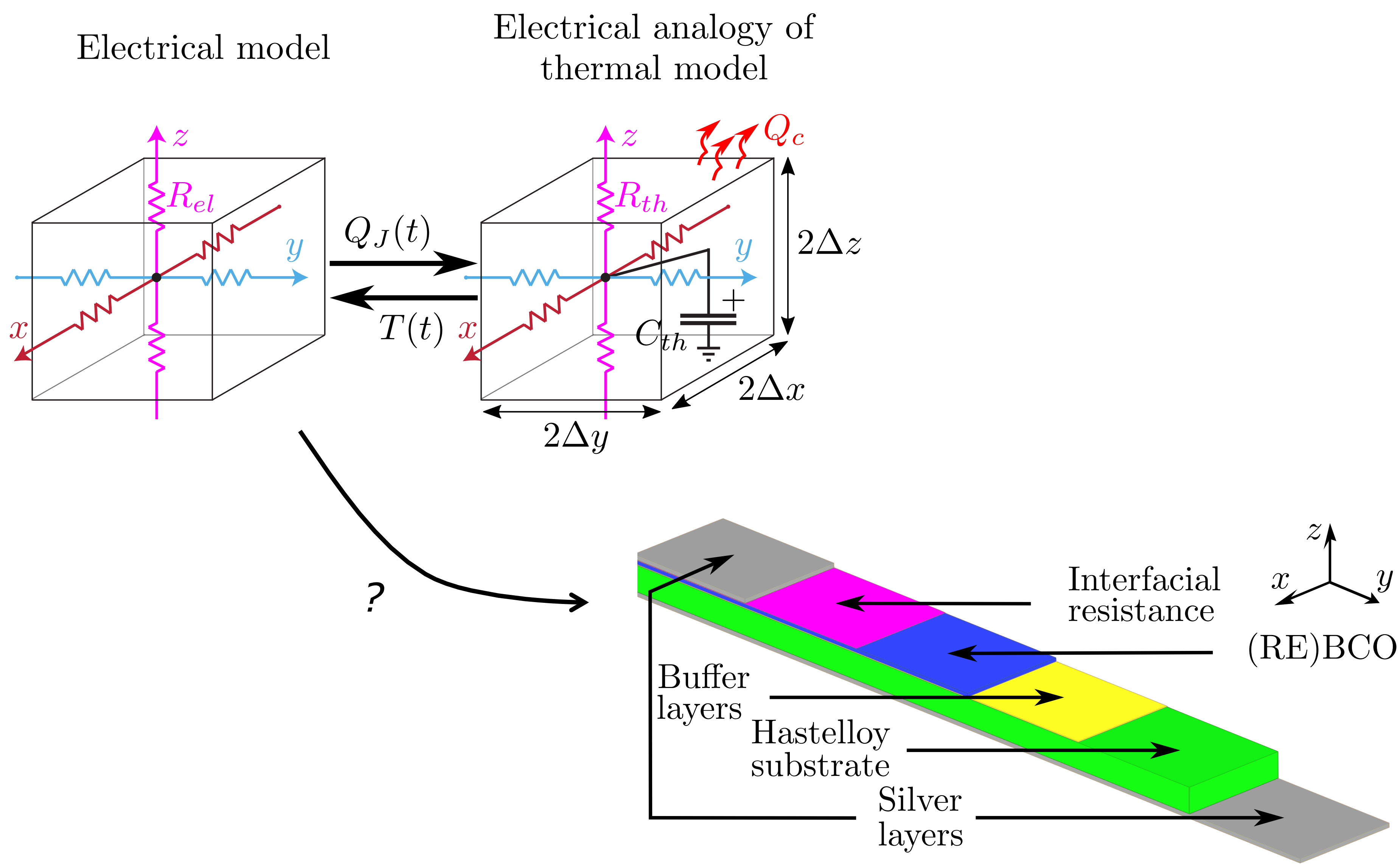
In fact: closer to a finite volume method (laws of conservation)

THE MODEL

- Our building block in EMTP-RV
  - Basic 3-D (or less) electro-thermal element
  - All resistors and capacitors are nonlinear (!)

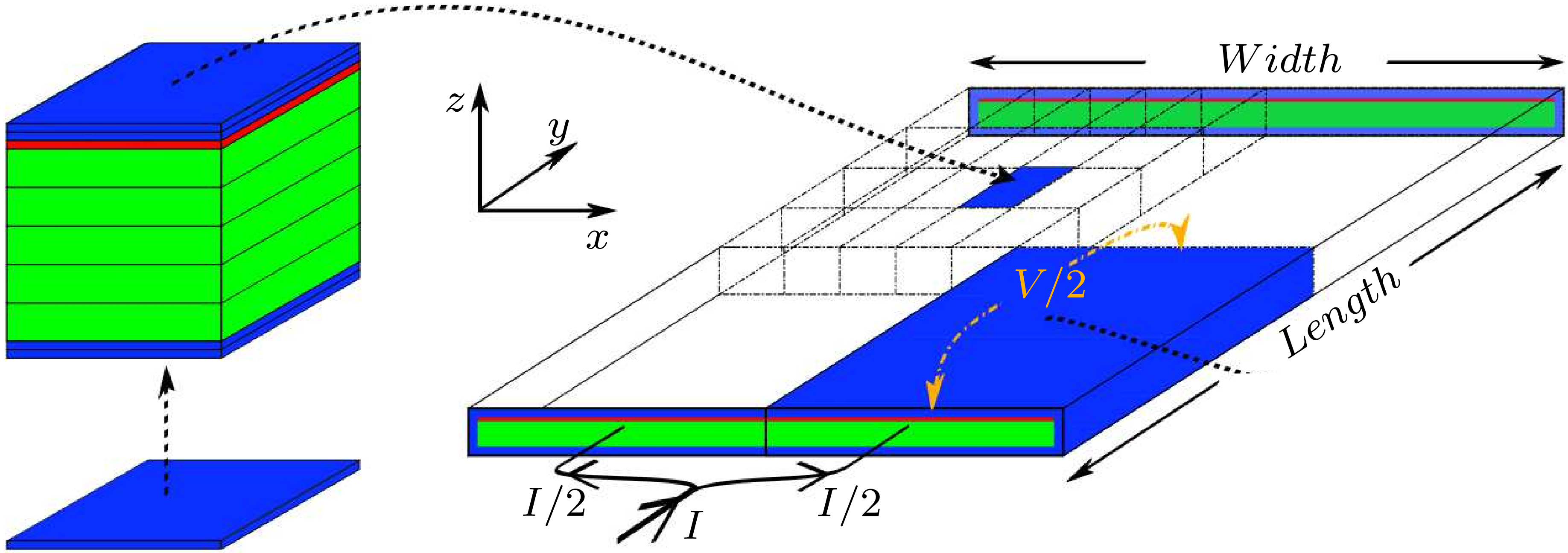


THE MODEL

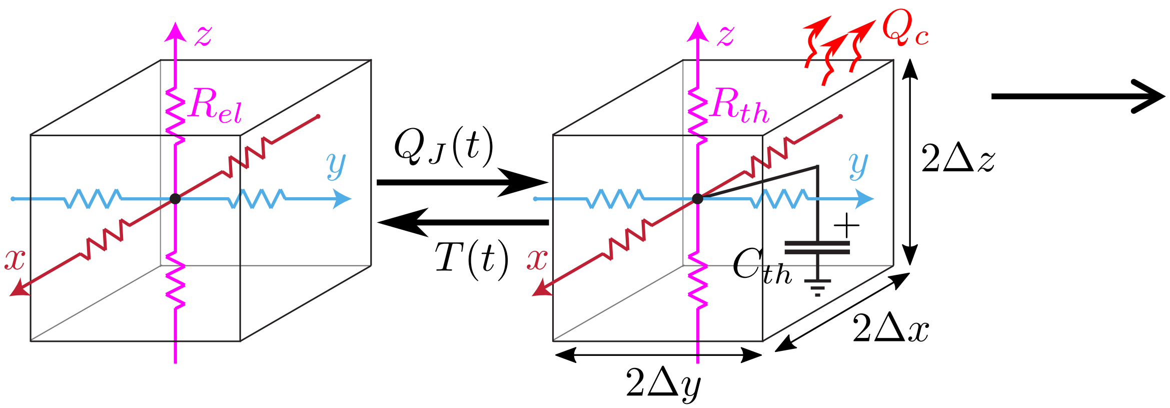


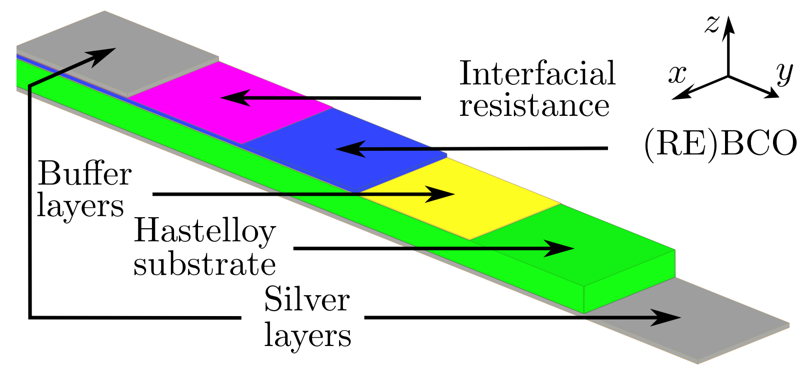
Electrical model
Electrical analogy of thermal model
z
R_{el}
y
x
$Q_J(t)$
$T(t)$
z
Q_c
R_{th}
y
x
C_{th}
+
$2\Delta z$
$2\Delta x$
$2\Delta y$
?
z
x
y
Interfacial resistance
(RE)BCO
Buffer layers
Hastelloy substrate
Silver layers

THE MODEL

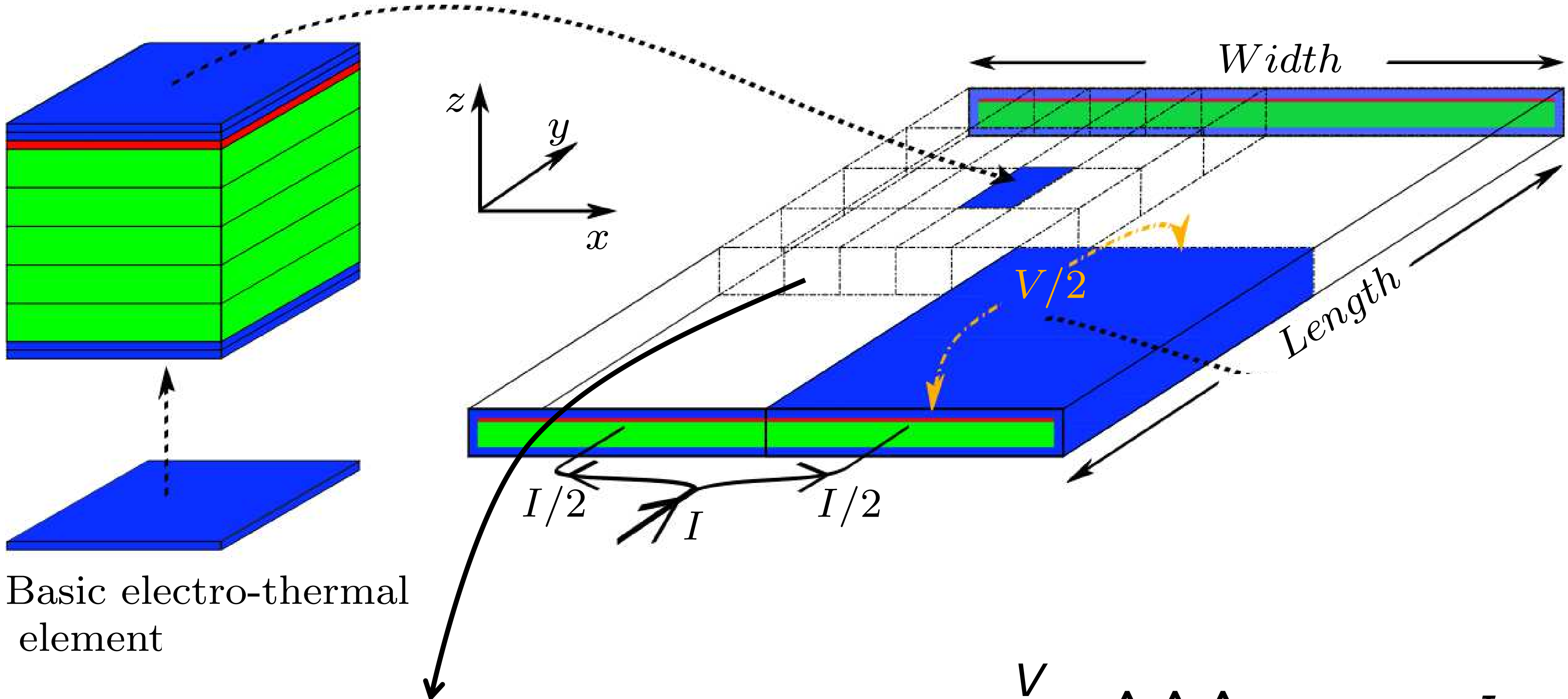


Basic electro-thermal element



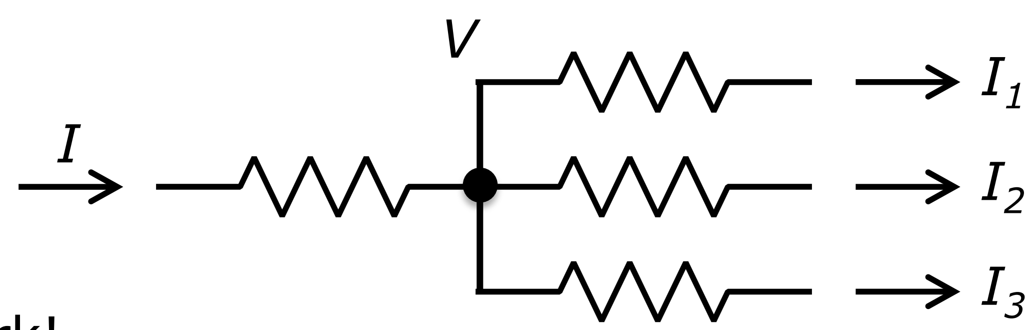


THE MODEL



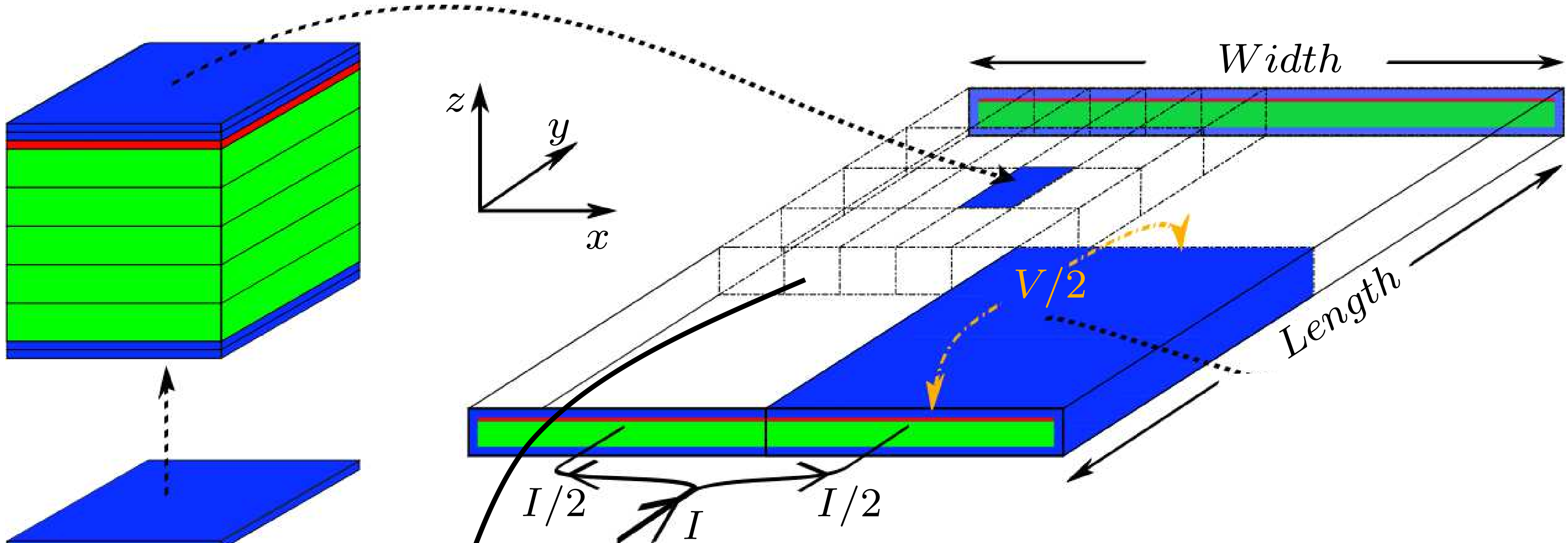
Basic electro-thermal element

Connection of big blocks with small blocks:



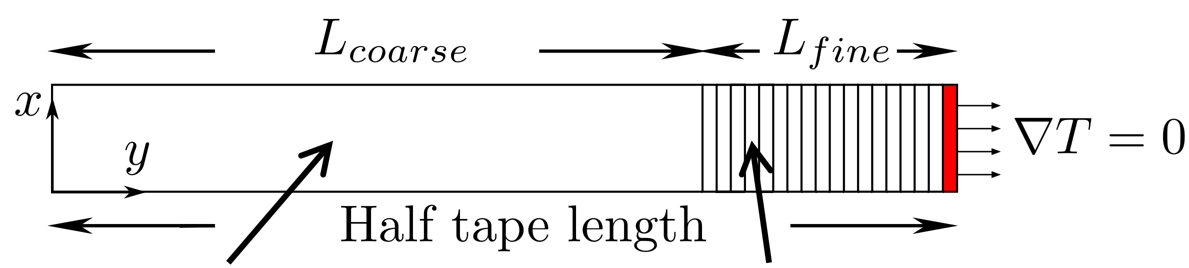
Kirchhoff laws do all the work!

THE MODEL



Basic electro-thermal element

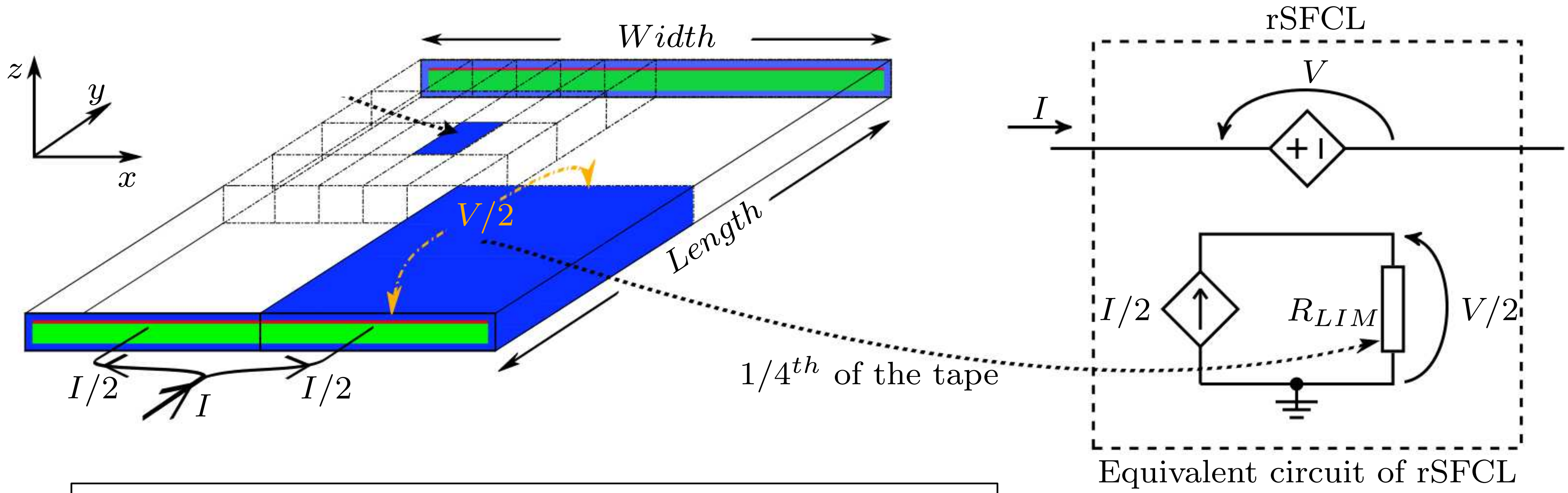
Connection of elements of different lengths:



For instance: one element of 100 m with elements of 50 microns

THE MODEL

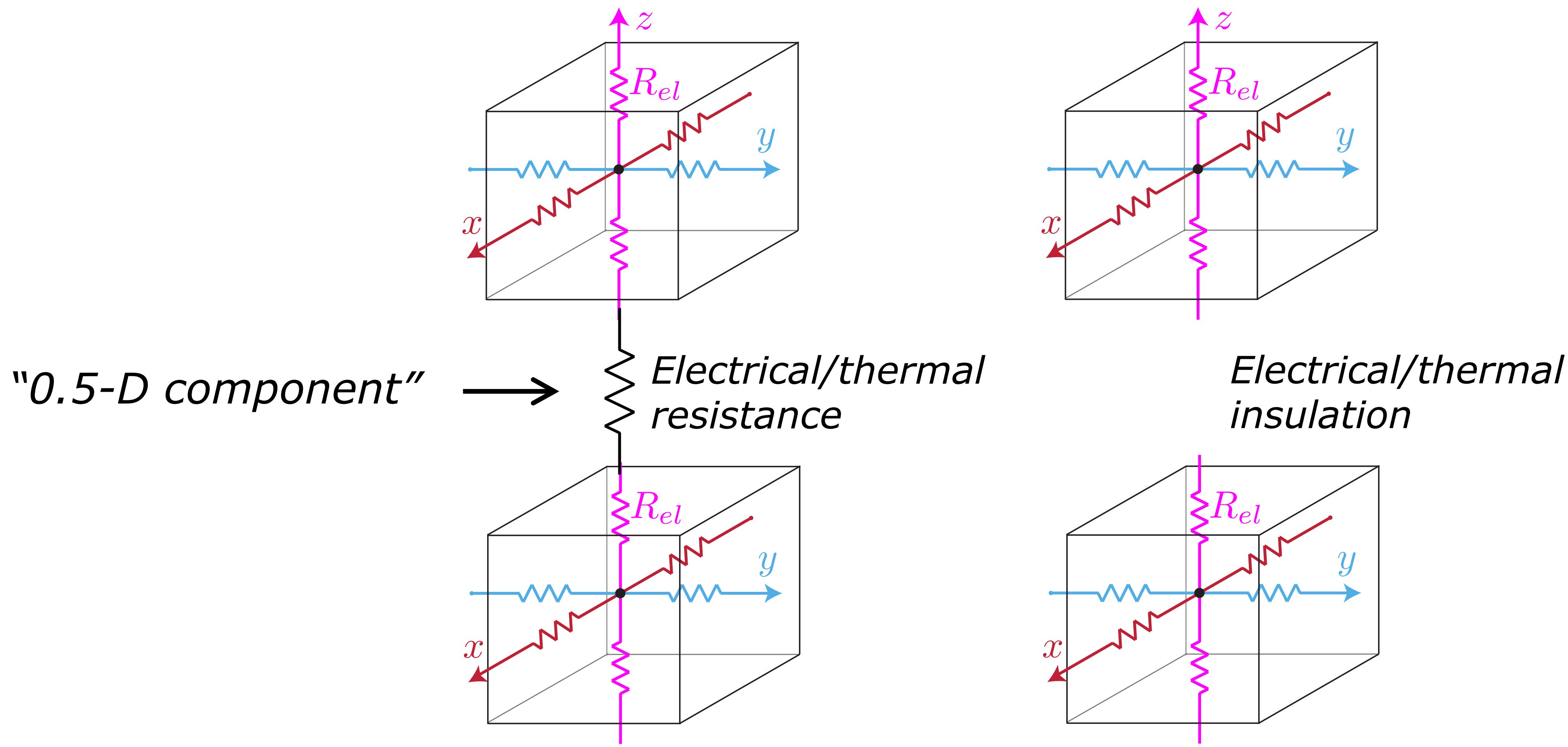
- Periodic conditions & symmetry planes handled through controlled voltage and current sources
  - Saves a huge amount of computation time



In this example:
only 25% of original model is simulated

THE MODEL

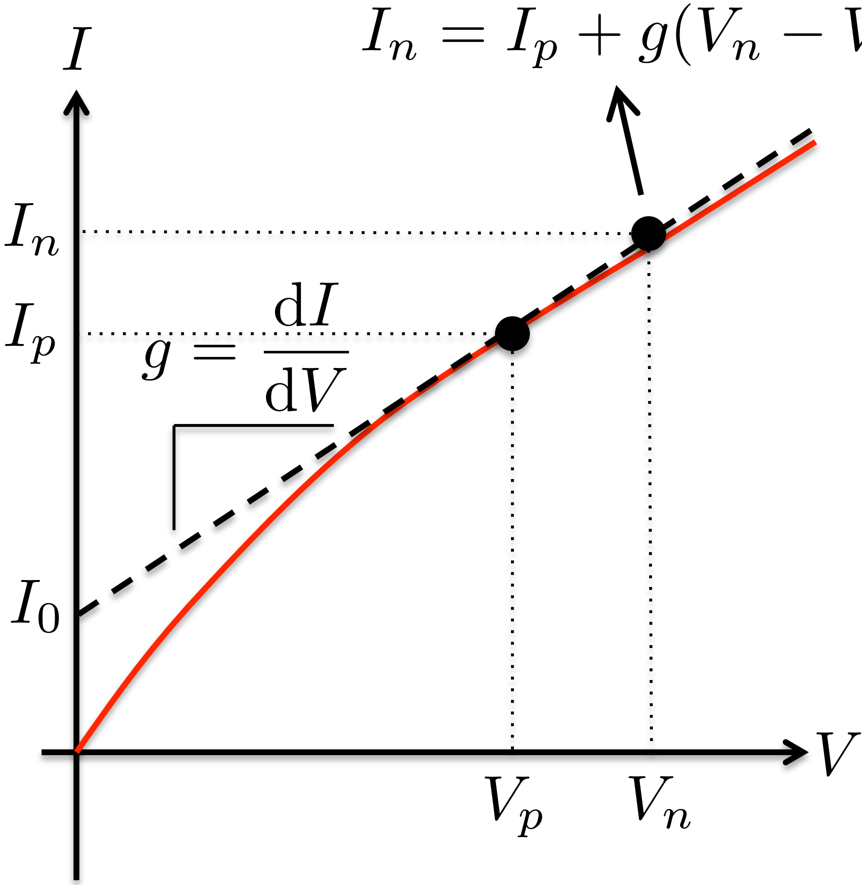
- Implementation of interfacial effects



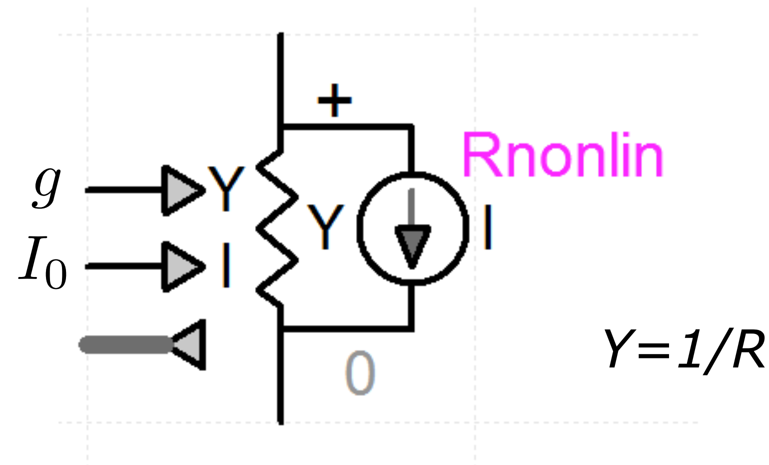
THE MODEL

- Implementation of nonlinear resistances in EMTP-RV

$$I_n = I_p + g(V_n - V_p) \longrightarrow \begin{aligned} I_0 &= I_p - gV_p \\ I_n &= I_0 + gV_n \end{aligned}$$



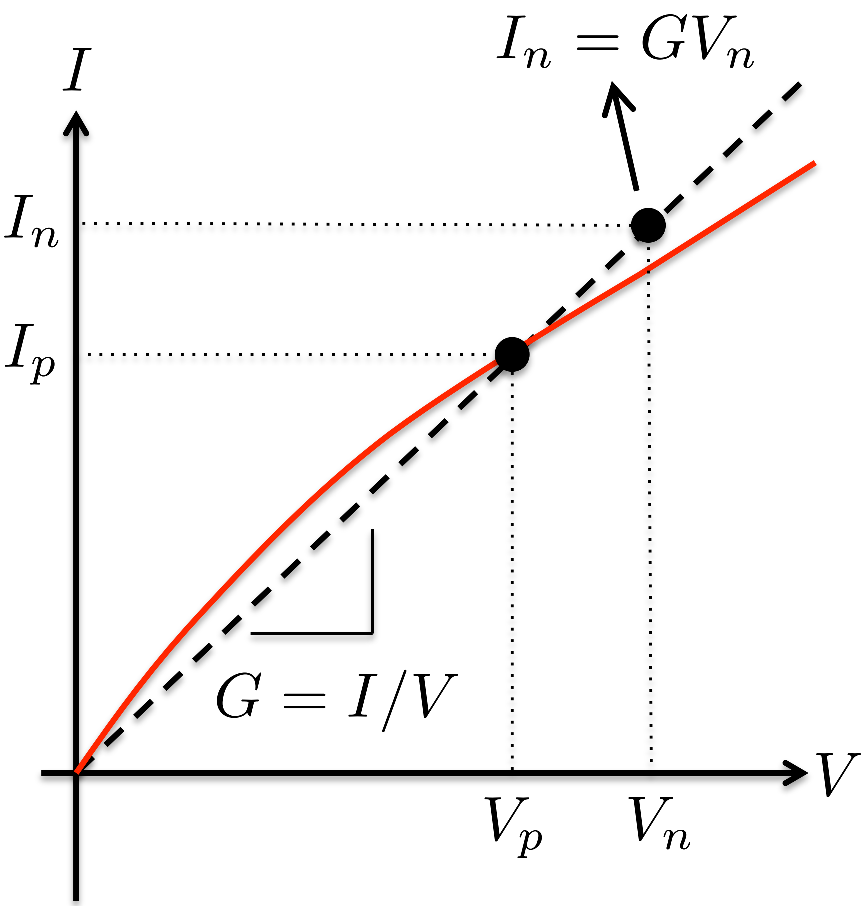
Newton method



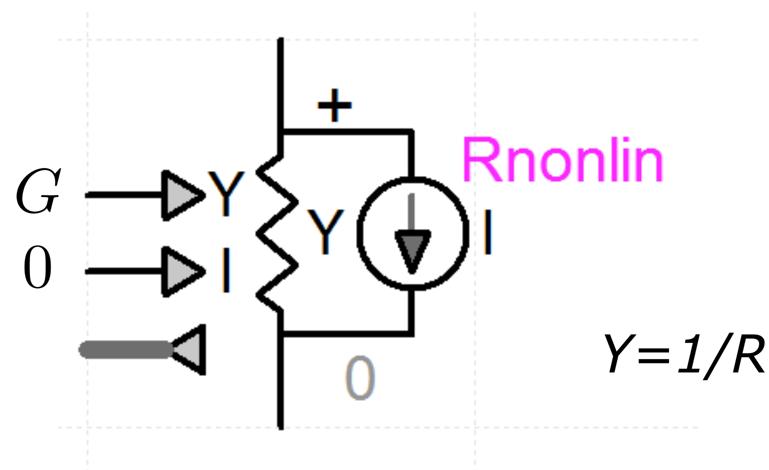
EMTP-RV element:
Nonlinear admittance (Y)

THE MODEL

- Implementation of nonlinear resistances in EMTP-RV



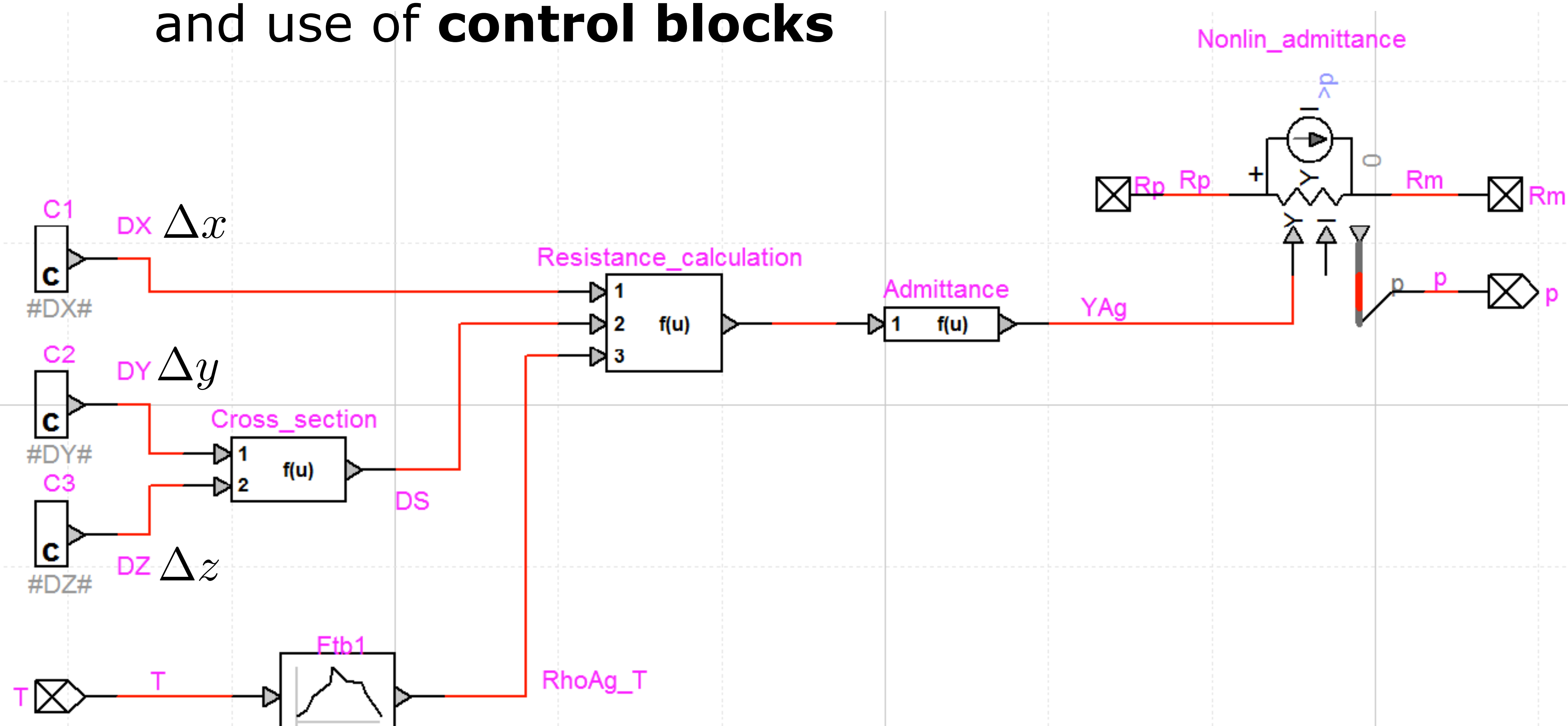
Fixed-point method



EMTP-RV element: Nonlinear admittance (Y)

THE MODEL

- Temperature dependant elements: fixed point-method and use of **control blocks**



THE MODEL

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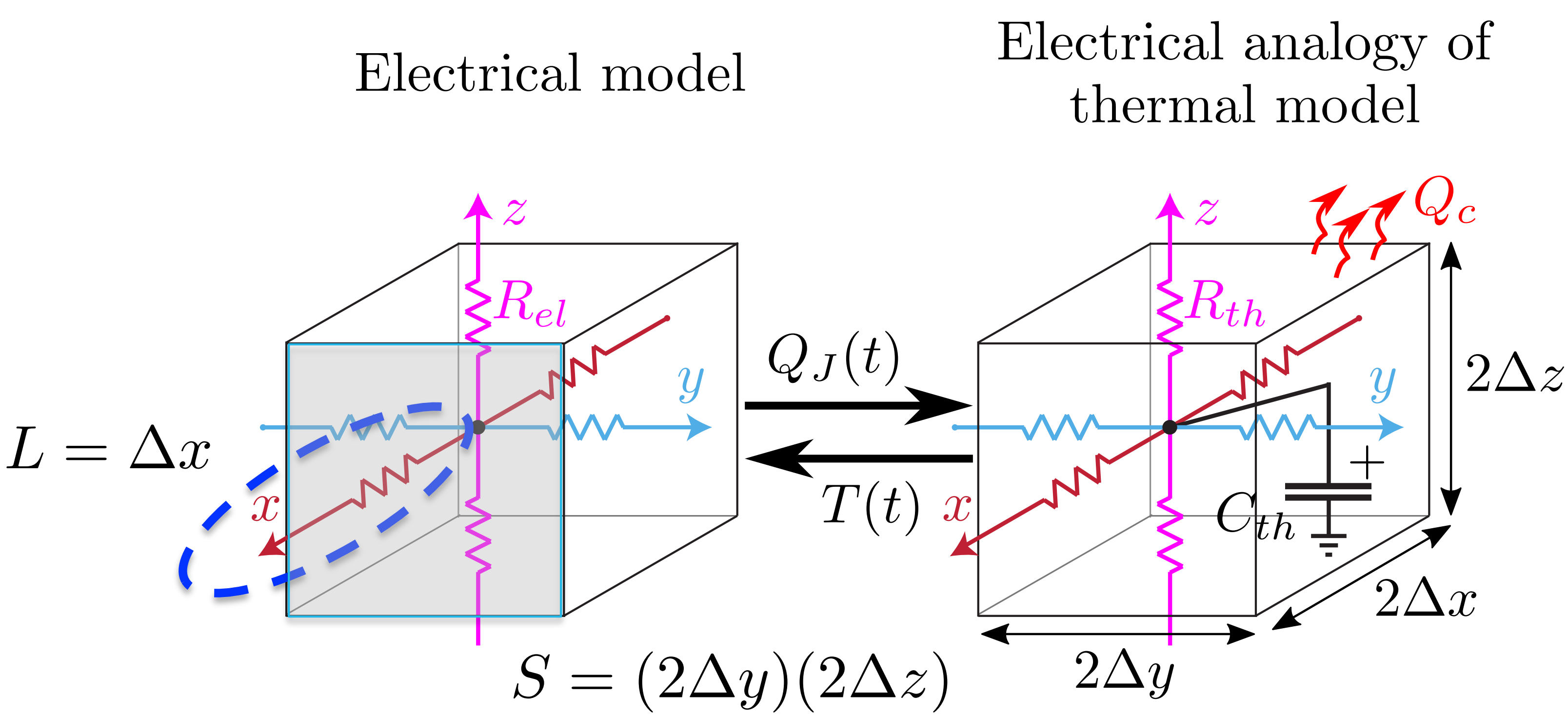

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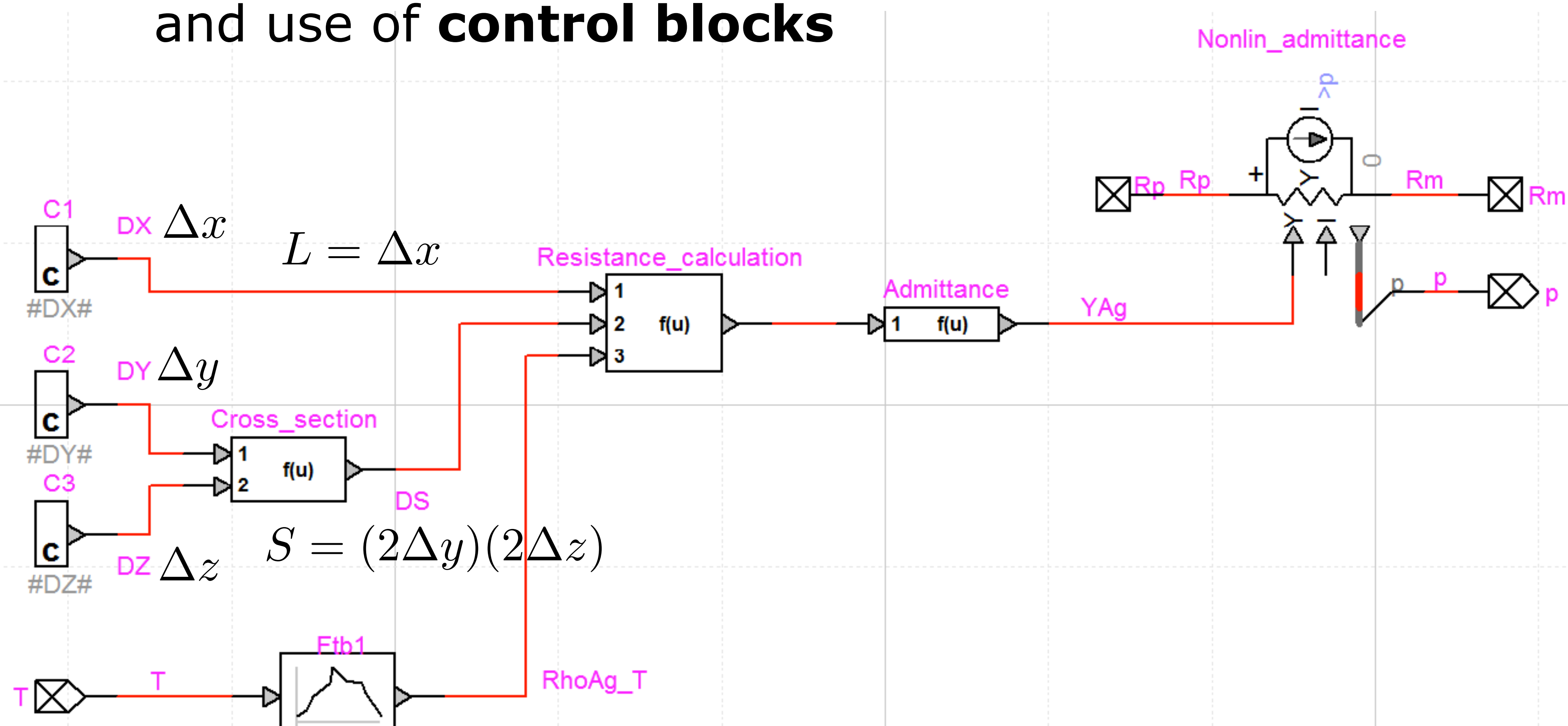
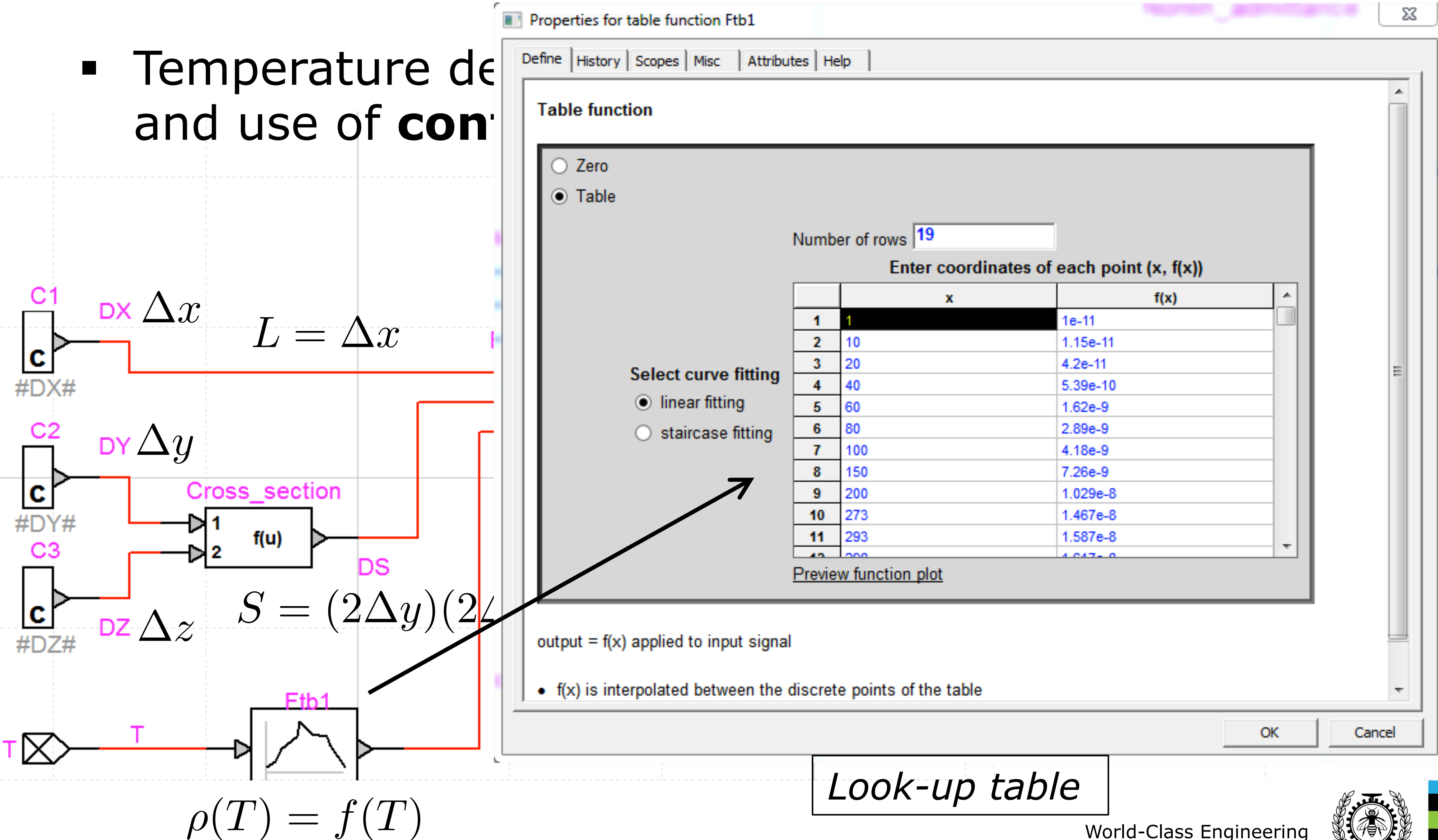


THE MODEL

- Temperature de… and use of **con…**



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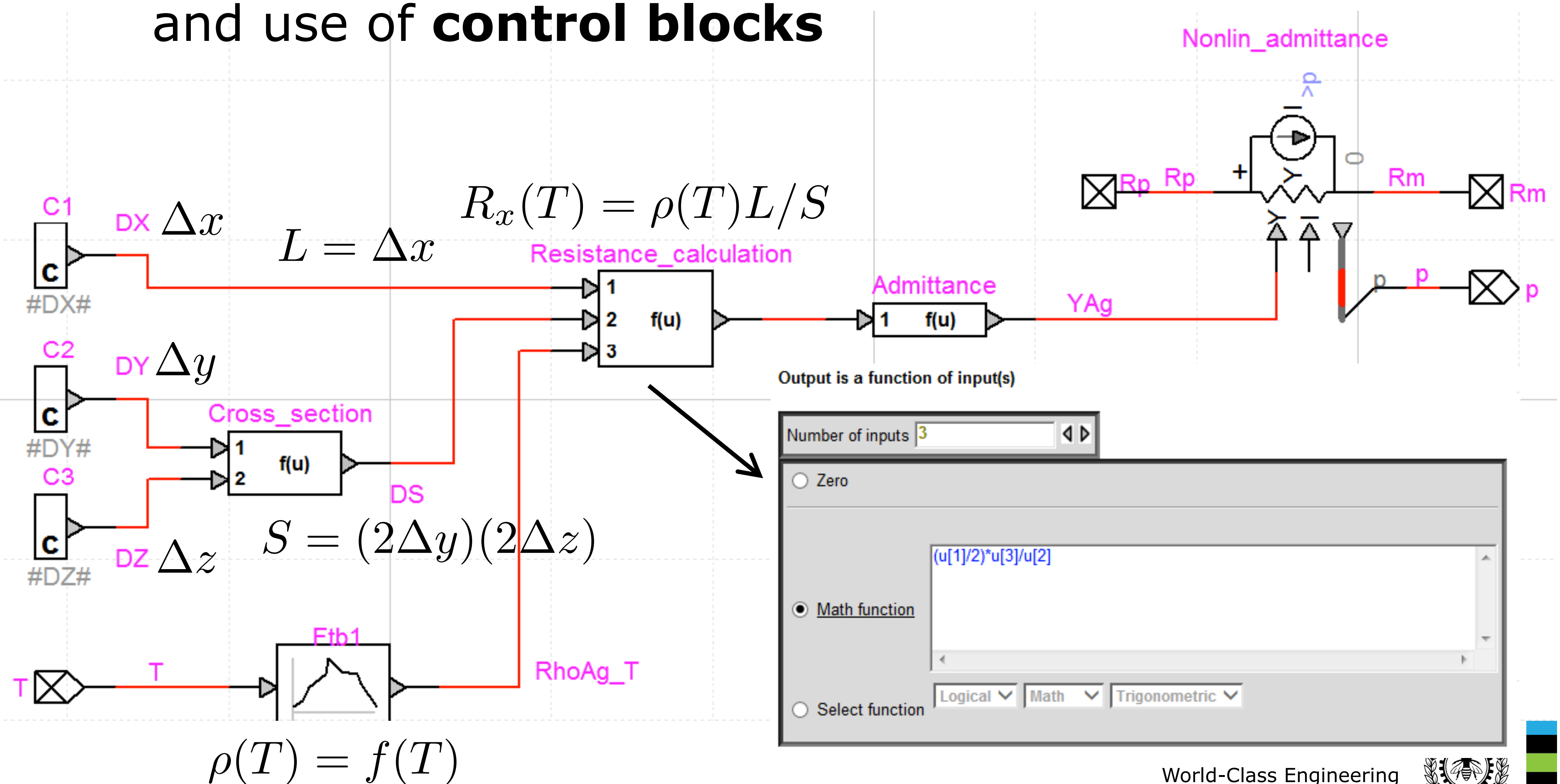

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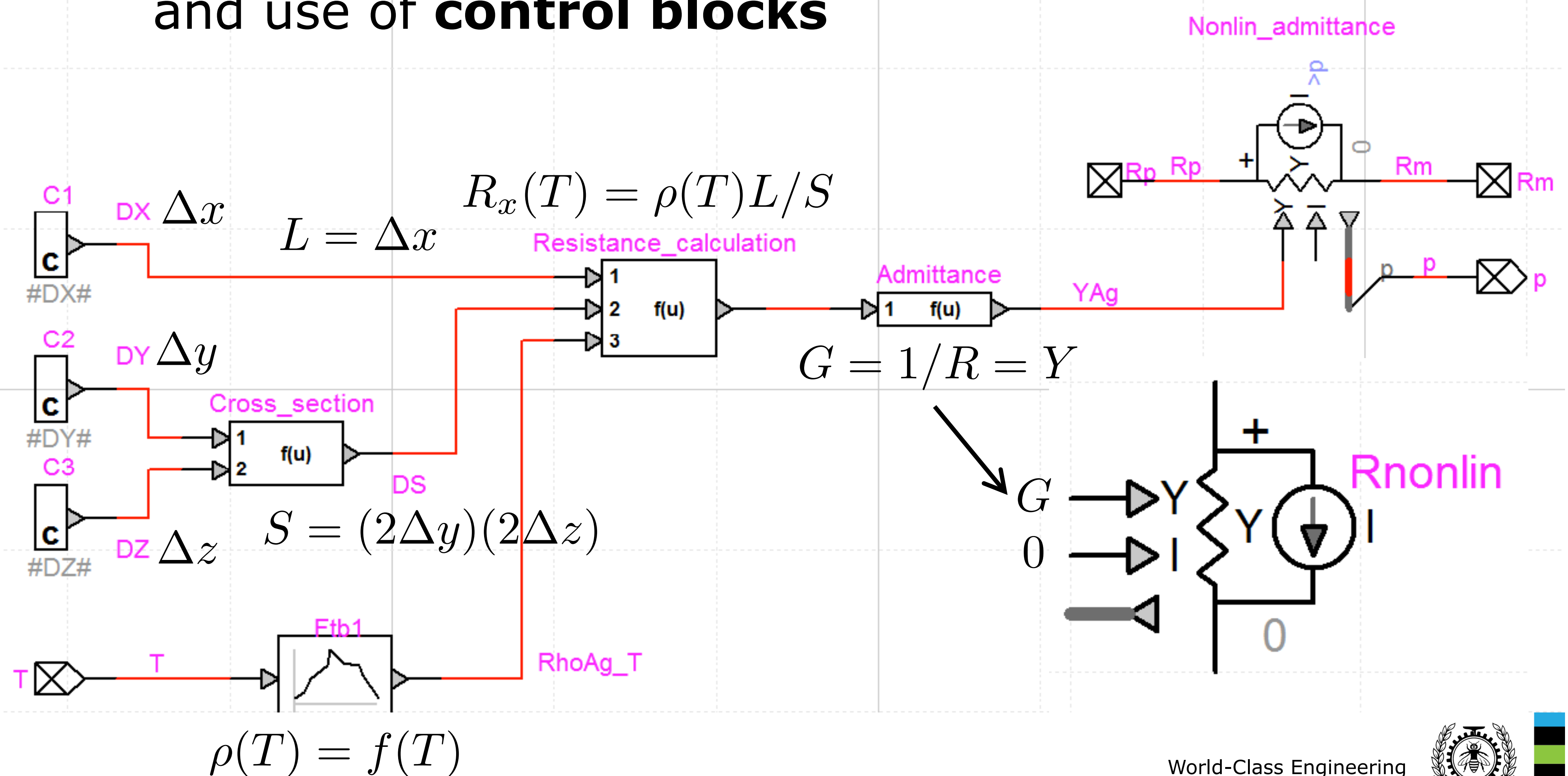

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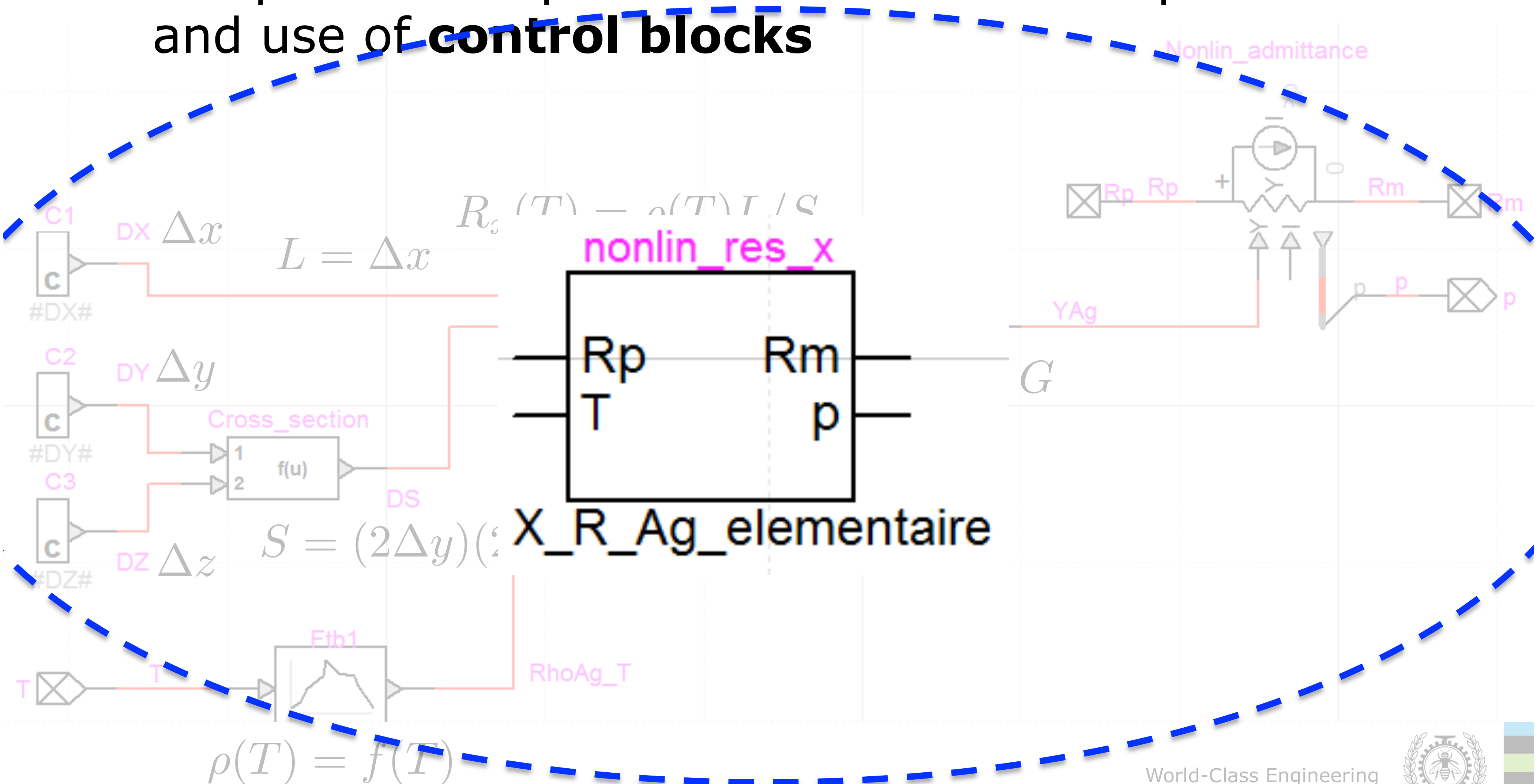


THE MODEL

- Superconductor elements
  - Control block approach proved to be very unstable
  - Reason:
    - Control blocks introduce a delay of 1 time step
    - with high nonlinearity, very small time steps (ns range!) might be required to converge
  - Alternative approach:
    - Integrate a user-code in the form of a DLL file (Dynamic-Link Library)
    - The code has to be written in Fortran or C++
  - Pre-compiled once, then materials parameters can be changed from the GUI of EMTP-RV

THE MODEL

- Superconductor model

$$\rho_{PL}(J,T) = \frac{E_c}{J_c(T)}\left(\frac{|J|}{J_c(T)}\right)^{n-1}$$

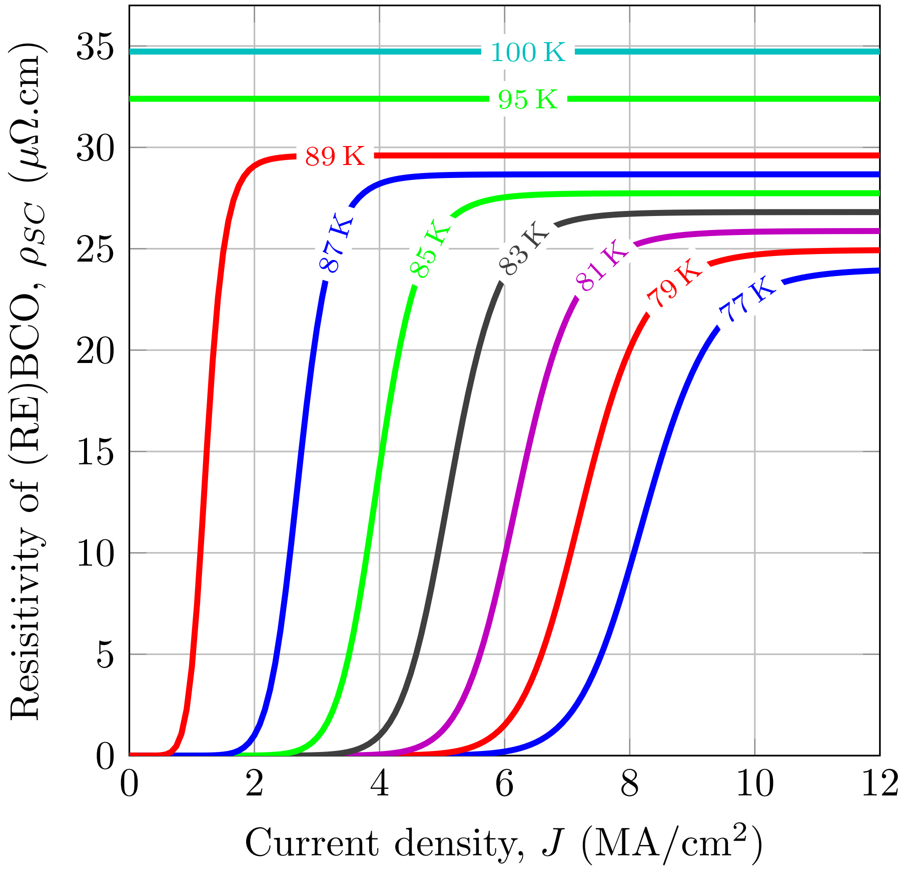
$$J_c(T) = J_{c_0}\left(\frac{T_c - T}{T_c - T_0}\right)$$

$$\rho_N(T) = \rho_{T_c} + \alpha\,(T - T_c)$$

$$\rho_{SC}(J,T) = \frac{\rho_{PL}(J,T) \times \rho_N(T)}{\rho_{PL}(J,T) + \rho_N(T)}$$

Parameters	Value	description
E_c	1 μV/cm	Critical electric field criterion
J_{c0}	2.5 MA/cm^2	Self-field critical current density
n	15	Power law exponent
ρ_{T_c}	30 $\mu\Omega$.cm [1]	Norm. state resistance at T_c
α	0.47 $\mu\Omega$.cm/K [1]	Temperature coefficient
T_c	90 K	Critical temperature
T_0	77 K	Temperature of LN$_2$ bath

[1] Deduced from Friedmann *et al.* [23] by averaging the normal state resistivity along the *a* and *b* crystallographic axes.



$$R_{SC}(I,T) = \rho_{SC}(J,T)L/S$$

THE MODEL

- Superconductor model

$$\rho_{PL}(J,T) = \frac{E_c}{J_c(T)}\left(\frac{|J|}{J_c(T)}\right)^{n-1}$$

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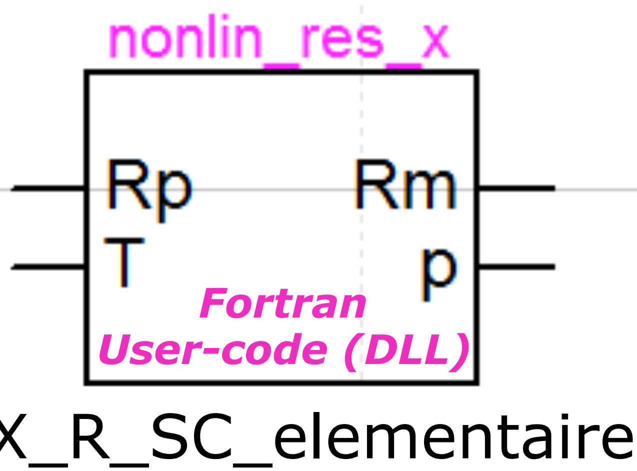

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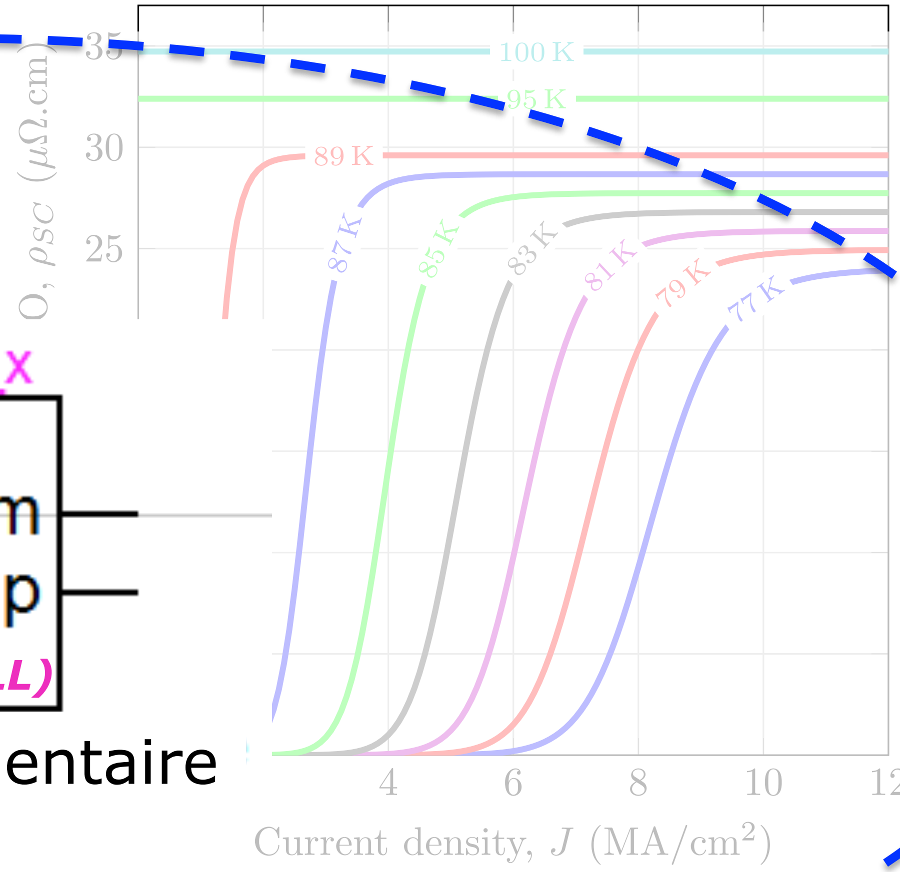
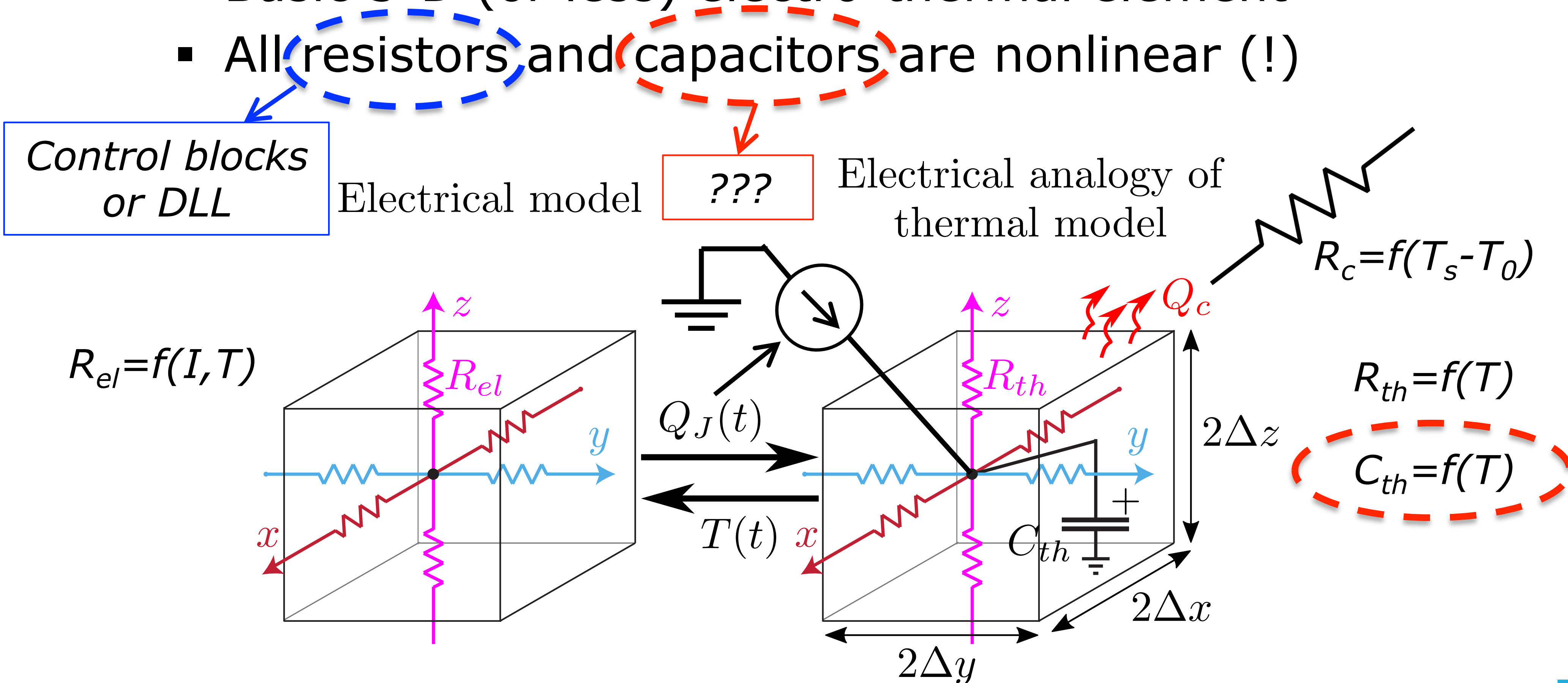


$$R_{SC}(I,T) = \rho(J,T)L/S$$

THE MODEL

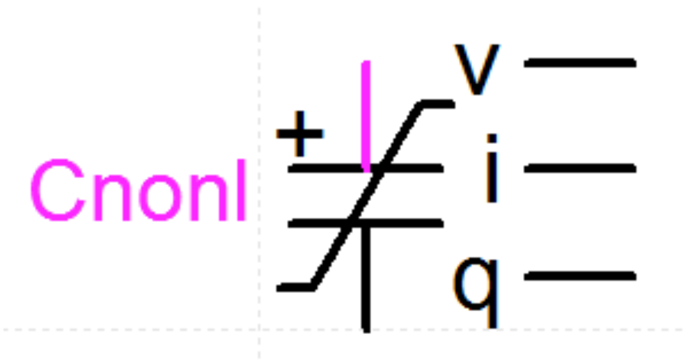
- Our building block in EMTP-RV
  - Basic 3-D (or less) electro-thermal element
  - All resistors and capacitors are nonlinear (!)



THE MODEL

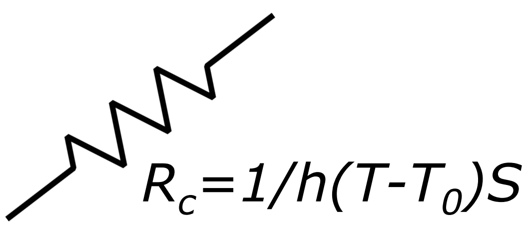
- Nonlinear thermal capacitors
  - Temperature dependence of specific heat is VERY important in rSFCLs
  - In the electric analogy, $C_{th}(T)=C(V)$
  - But there is no nonlinear capacitor in most circuit simulators! (especially in power system simulators)
  - Solution:
    - Another DLL code!
  - Main features:
    - Trapezoidal integration
    - Look up table for *C(V)*
    - Table read from a file (no need to recompile to change material properties)

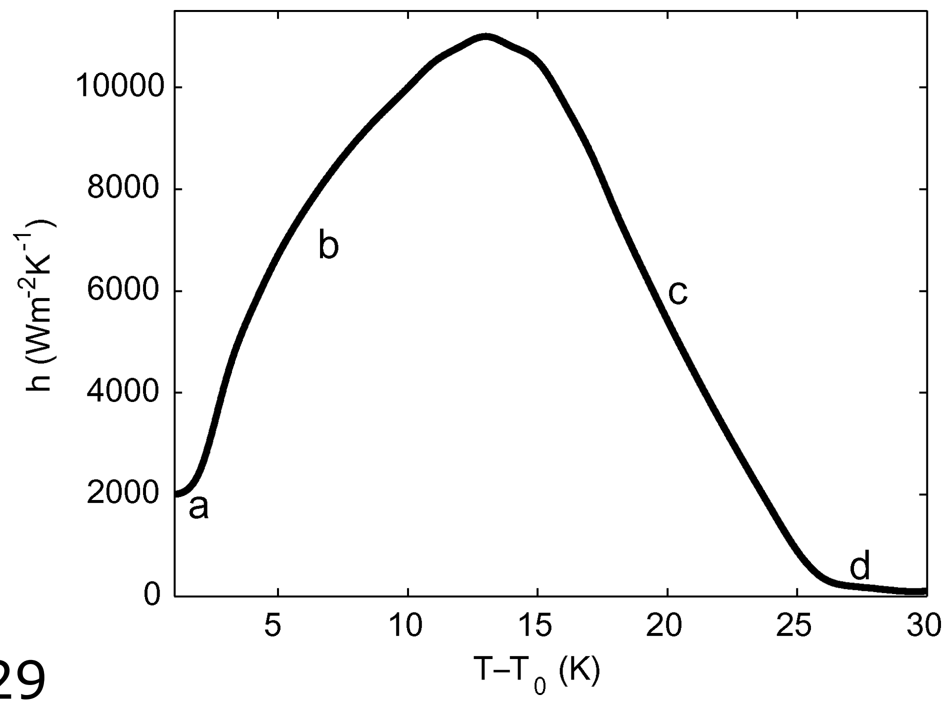
$$i = C(V)\frac{\mathrm{d}V}{\mathrm{d}t}$$



THE MODEL

- Nonlinear convection cooling
  - Critical aspect for assessing thermal stability of rSFCLs
  - Modelled with control blocks as described above
  - For instance:

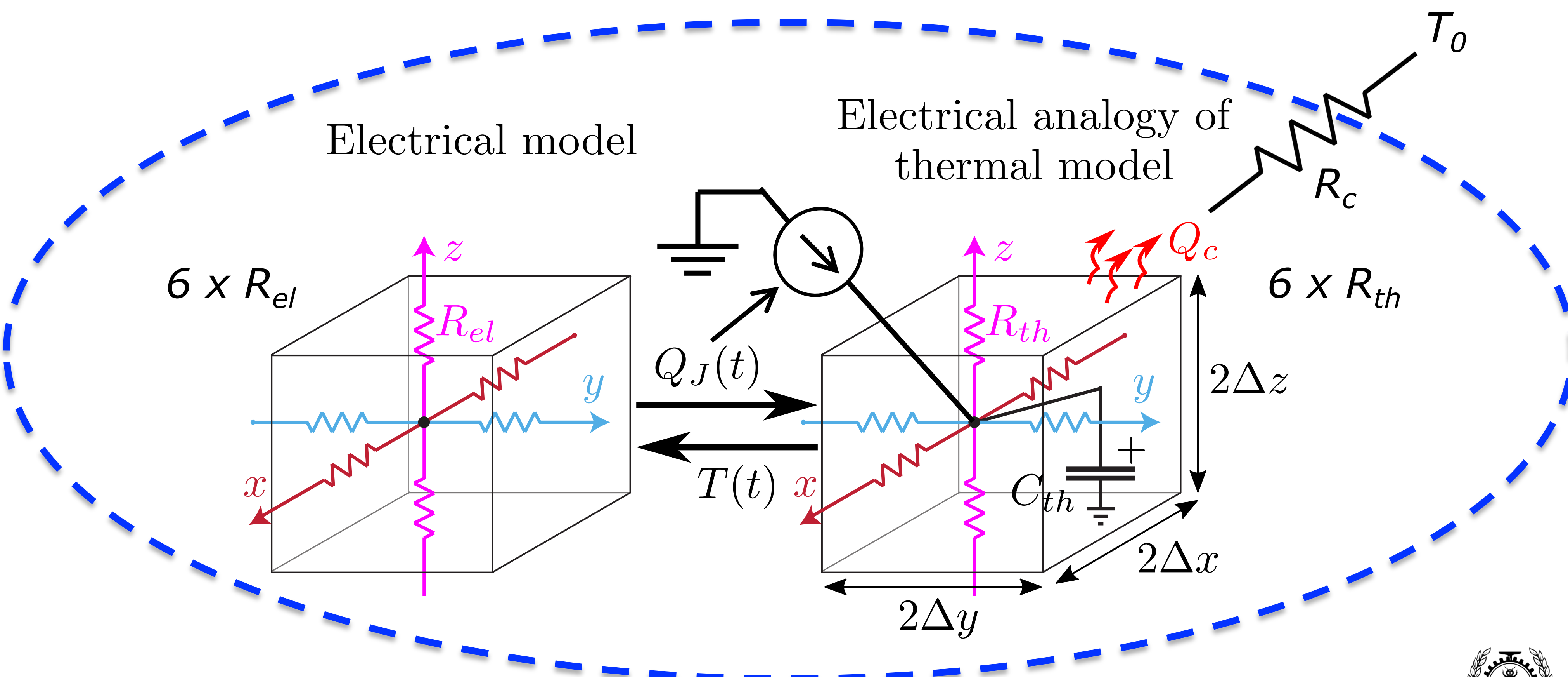




Roy et al. **IEEE Trans. Appl. Supercond.** (2008) 18(1) p.29

THE MODEL

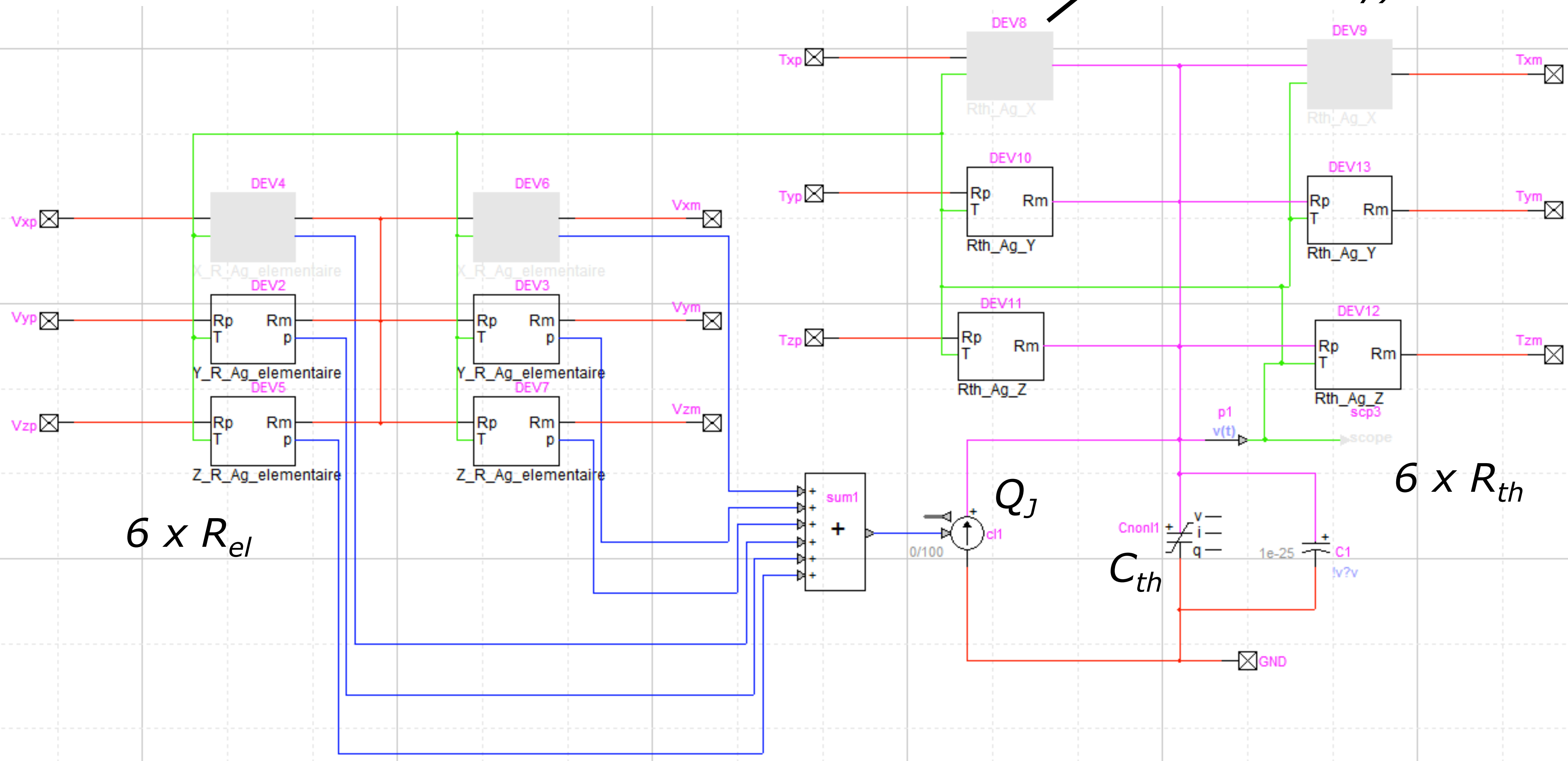
- Our building block in EMTP-RV
  - Basic 3-D (or less) electro-thermal element



THE MODEL

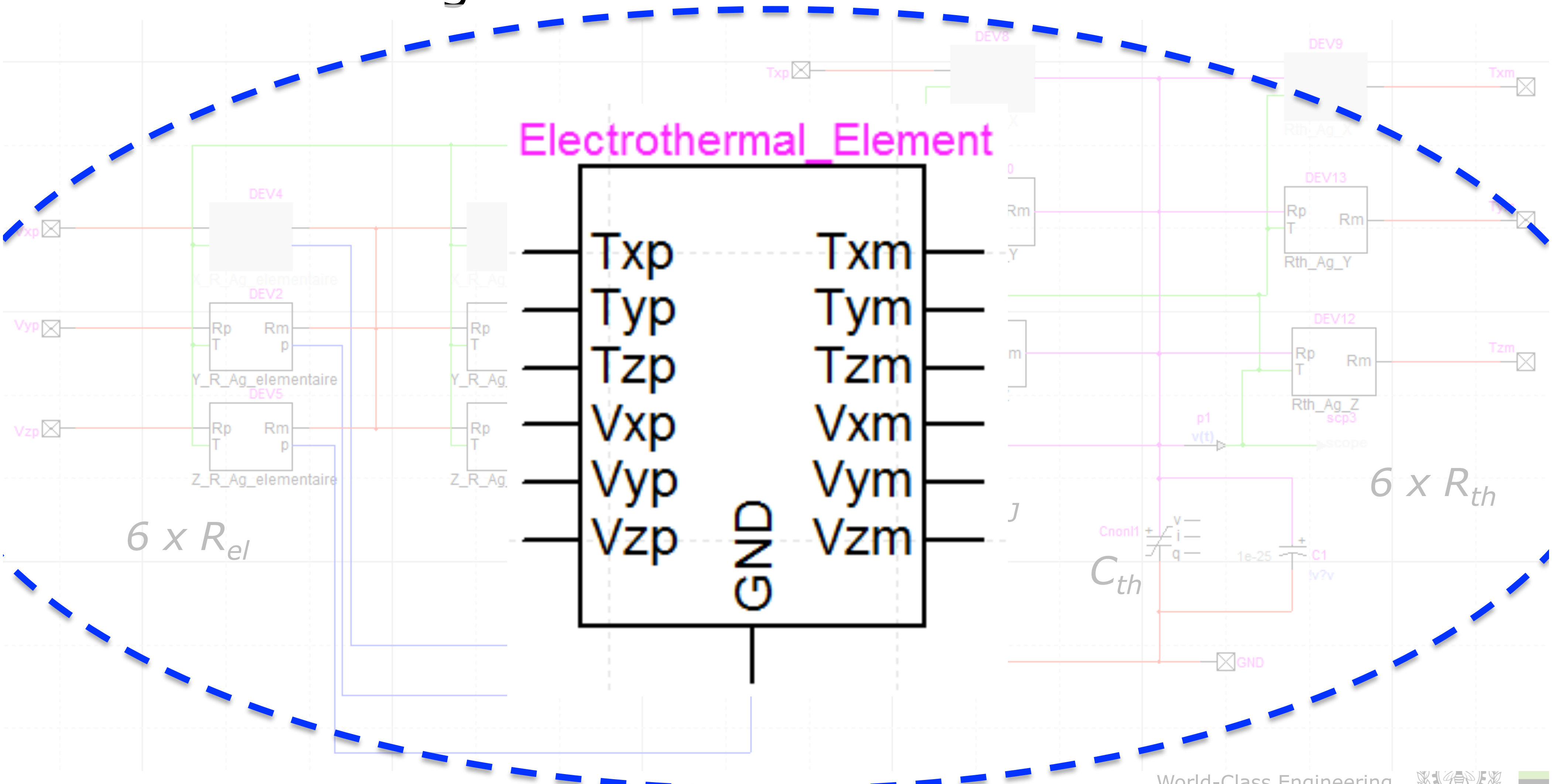
- Our building block in EMTP-RV

Unused blocks can be disabled (reduction of dimensionality)

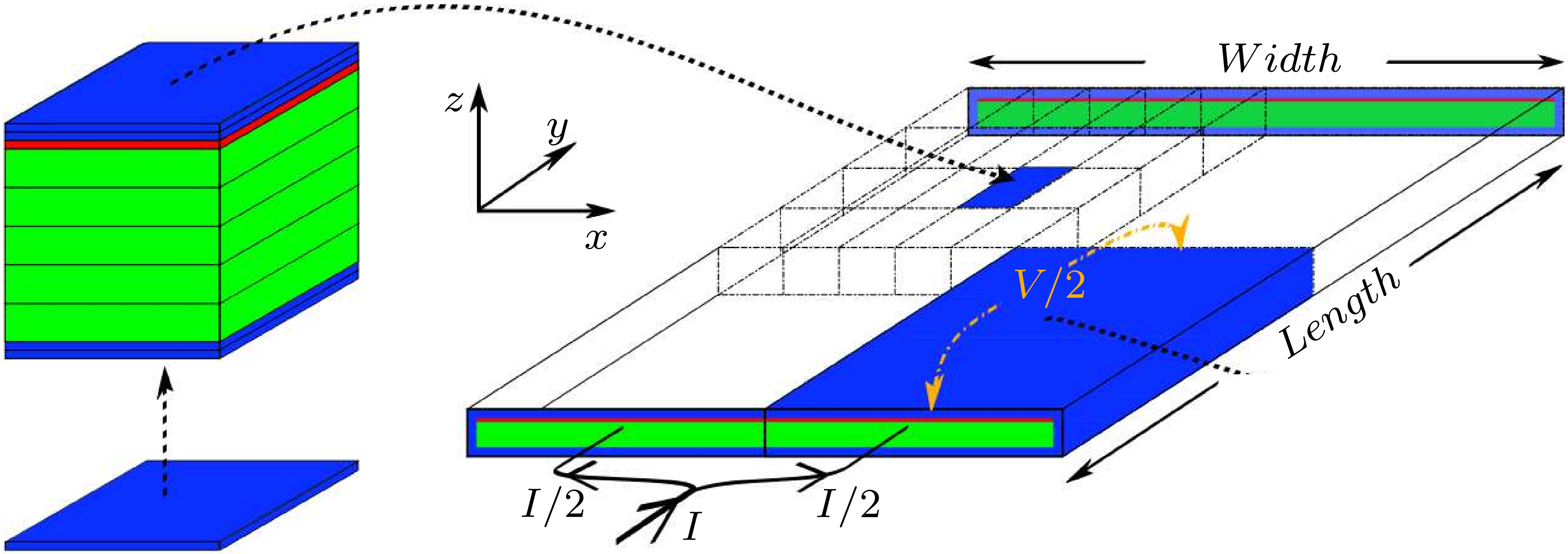


THE MODEL

- Our building block in EMTP-RV

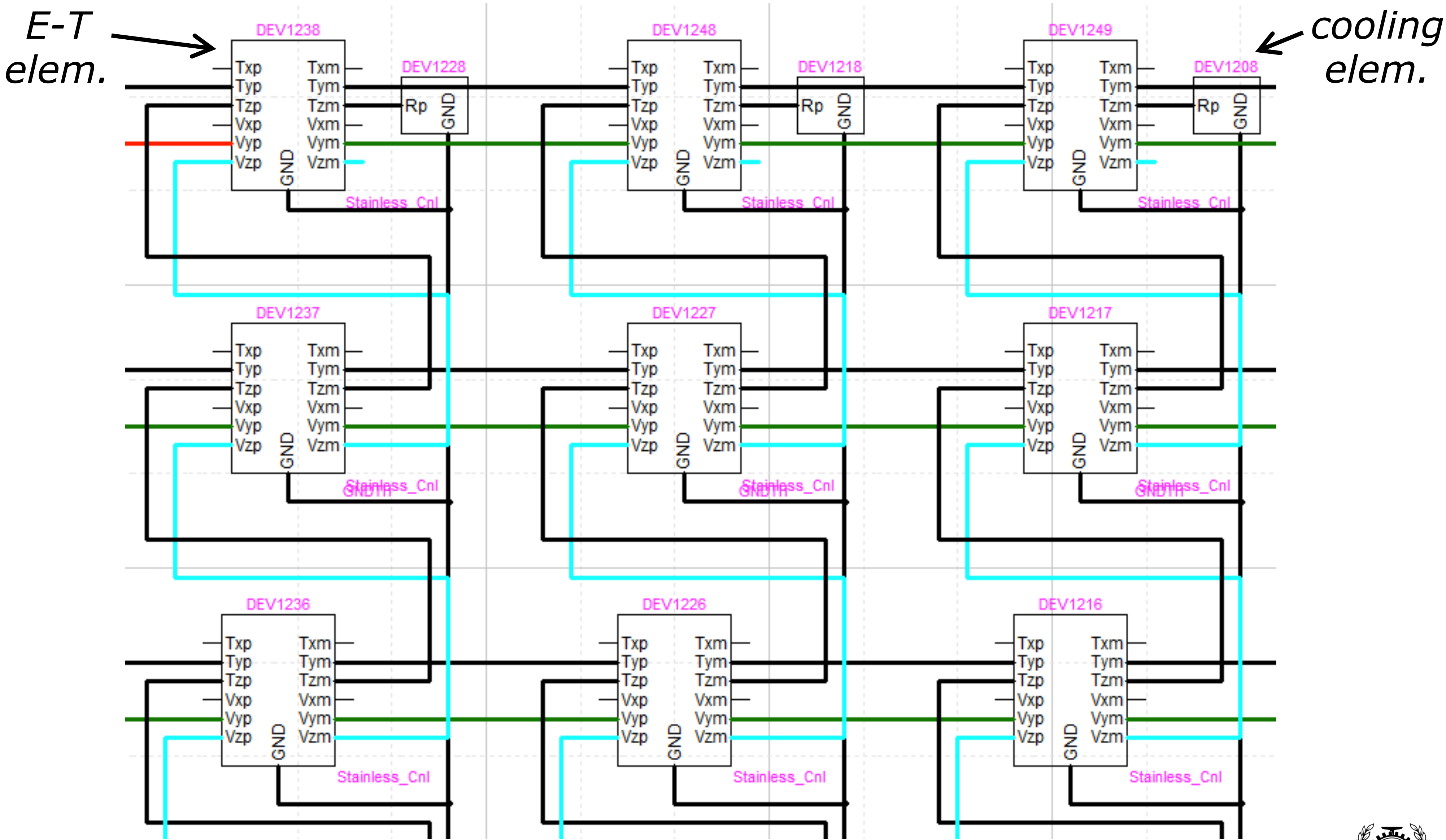


THE MODEL



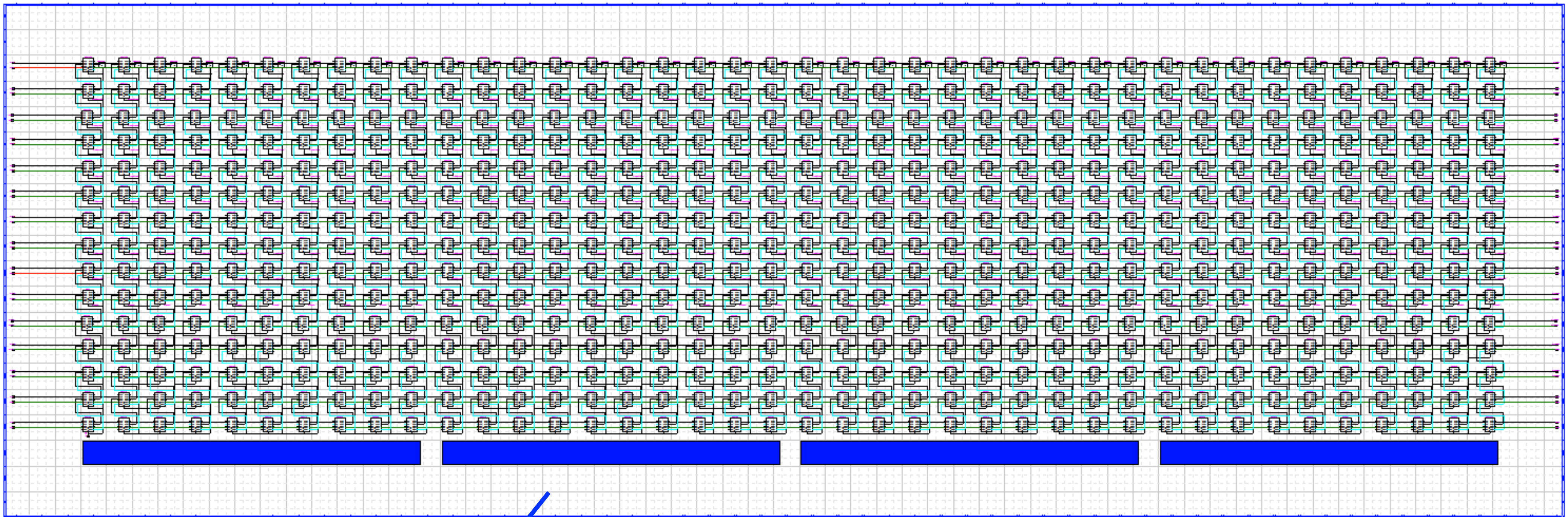
Basic electro-thermal element

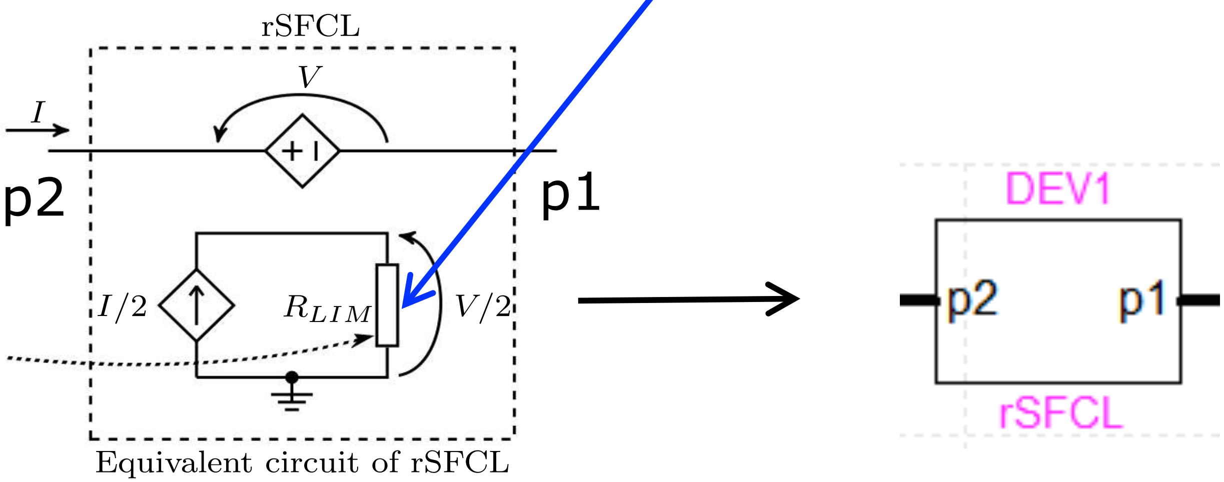
THE MODEL



E-T elem.
cooling elem.
DEV1238
DEV1228
DEV1248
DEV1218
DEV1249
DEV1208
DEV1237
DEV1227
DEV1217
DEV1236
DEV1226
DEV1216
Txp Typ Tzp Vxp Vyp Vzp
Txm Tym Tzm Vxm Vym Vzm
GND
Rp
Stainless_Cnl
GNDTH

THE MODEL

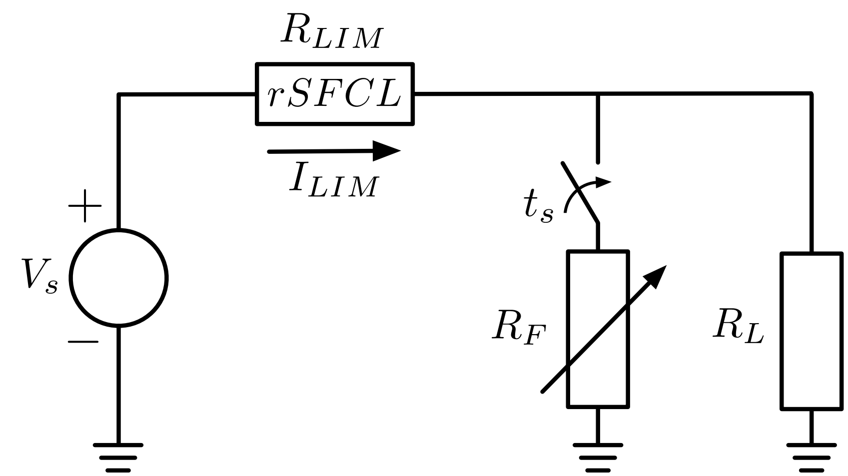


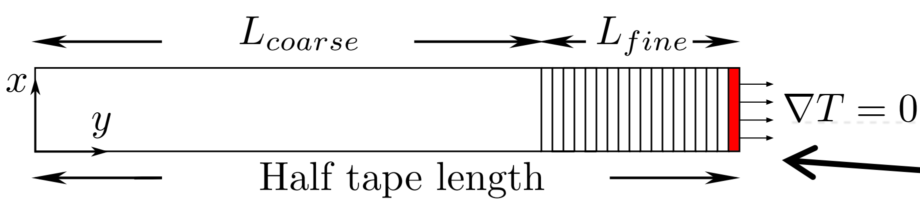


Final rSFCL block!

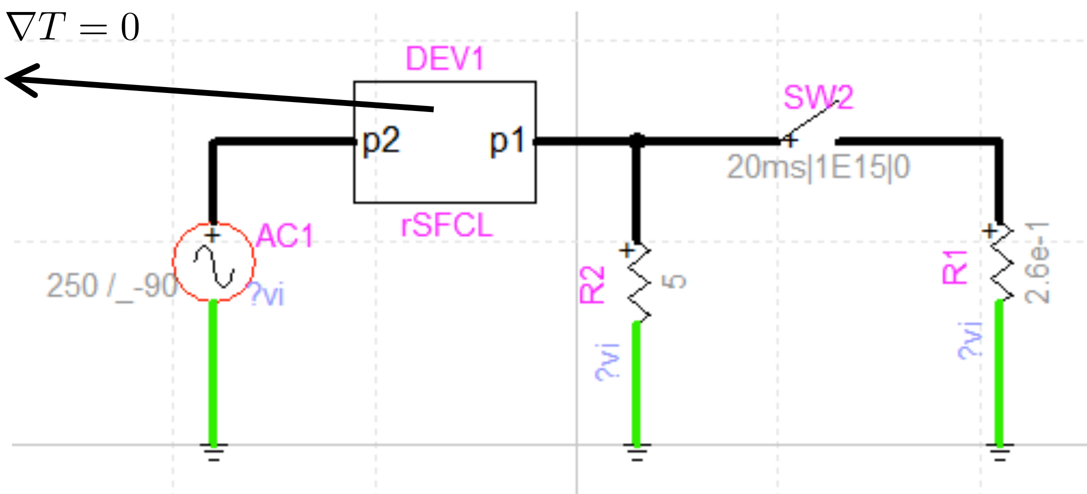
- rSFCL in simple radial power system

Schematic:



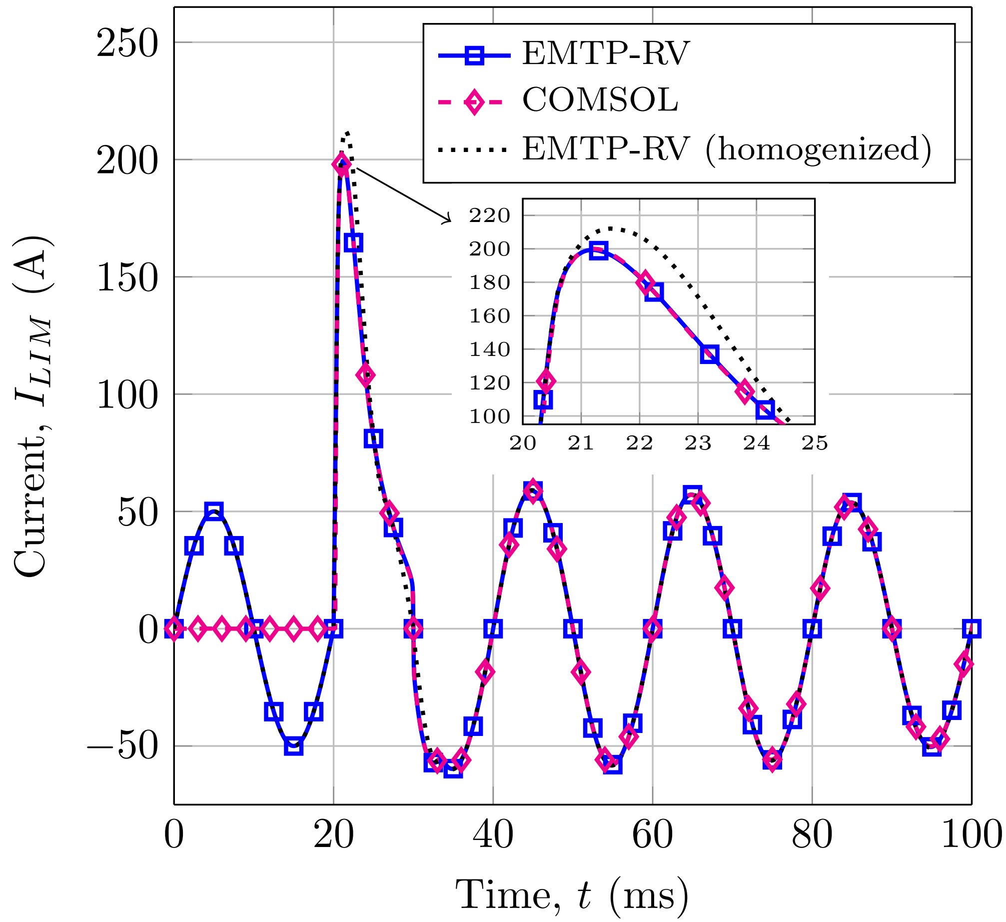


EMTP-RV model:



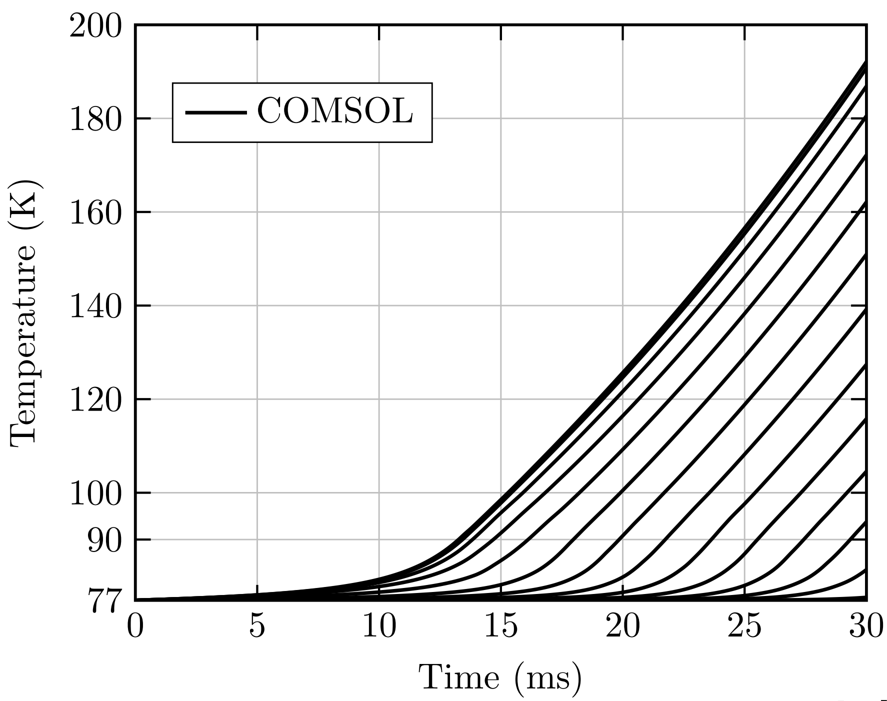
VERIFICATION OF MODEL

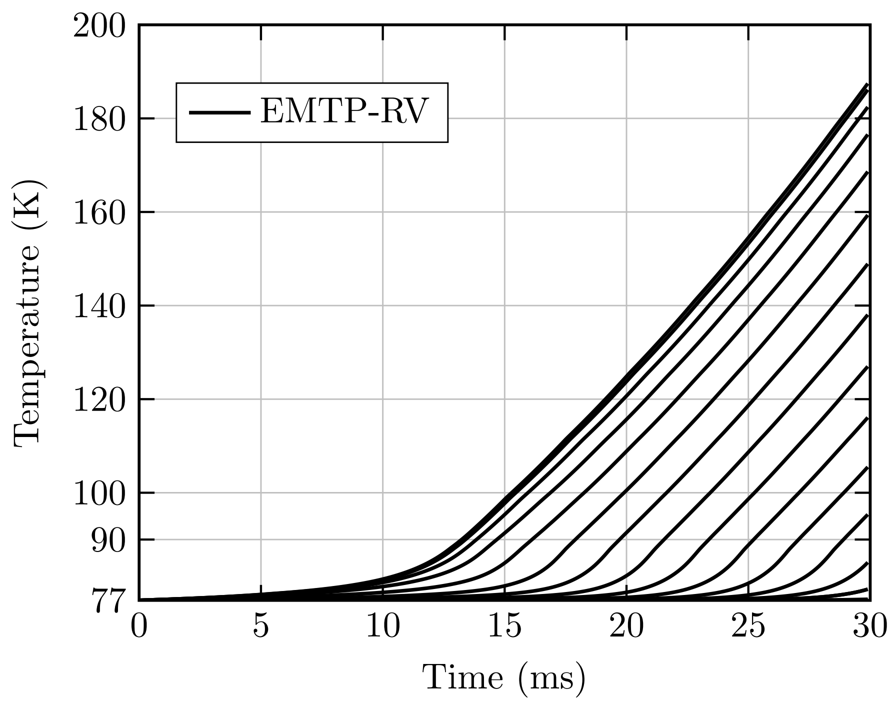
- Heavily compared against finite element method
  - Fault current limitation → Macroscopic effect



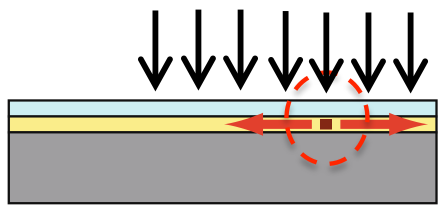
VERIFICATION OF MODEL

- Heavily compared against finite element method
  - NZPV calculations → Microscopic effect



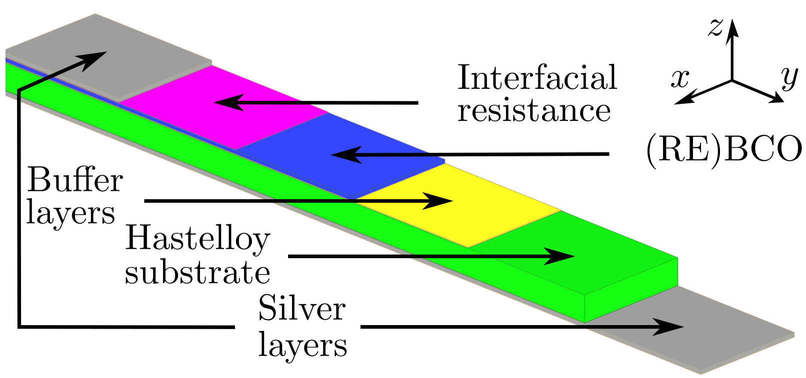


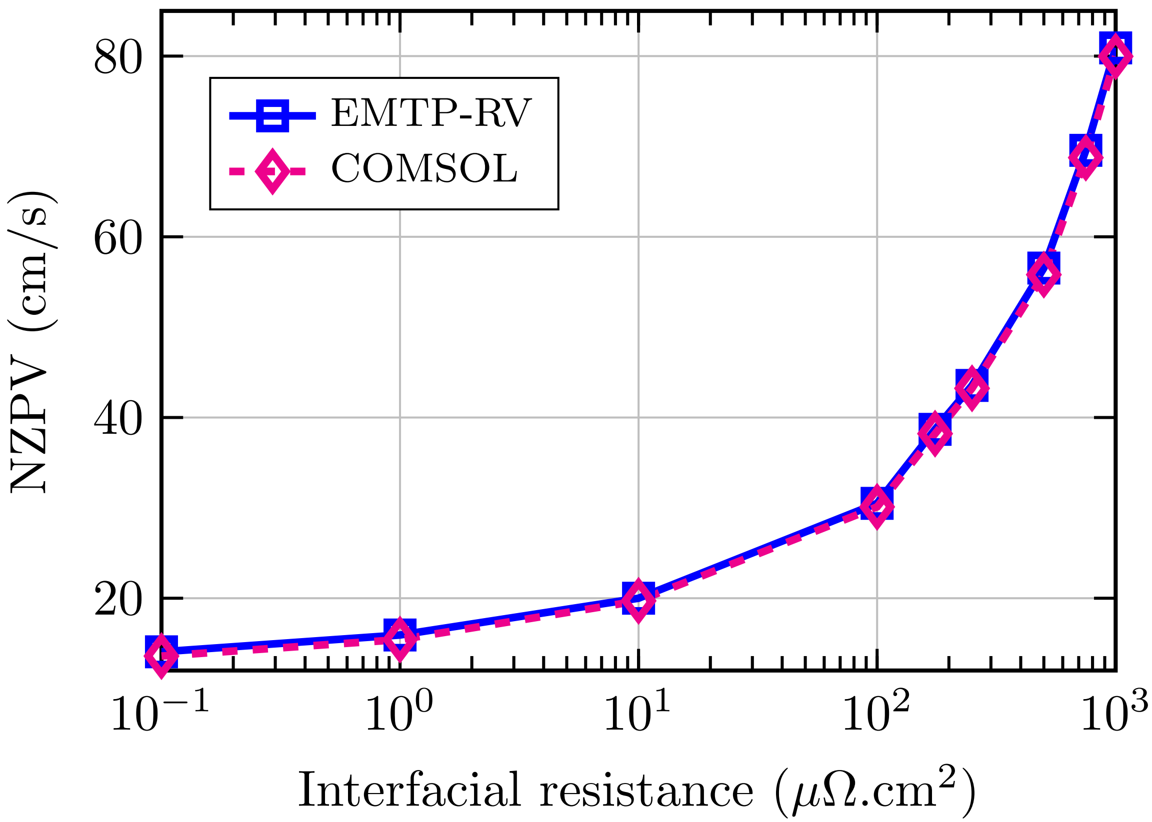
Hot spot & normal zone propagation



VERIFICATION OF MODEL

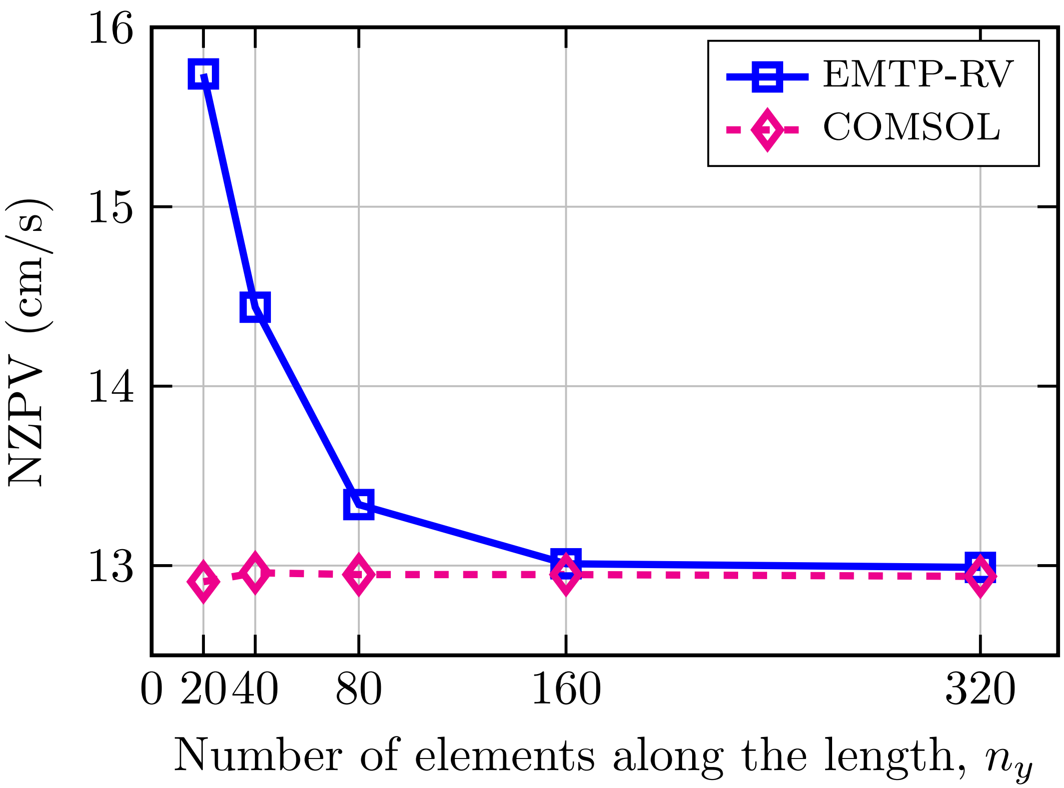
- Heavily compared against finite element method
  - Impact of interfacial resistance on NZPV → Microscopic effect

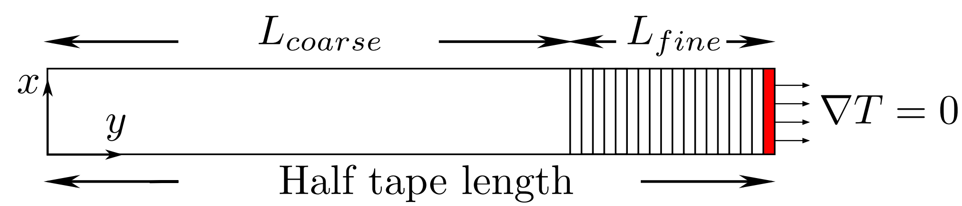




VERIFICATION OF MODEL

- Required discretization
  - Highly function of your needs!
  - Example below for NZPV calculations:

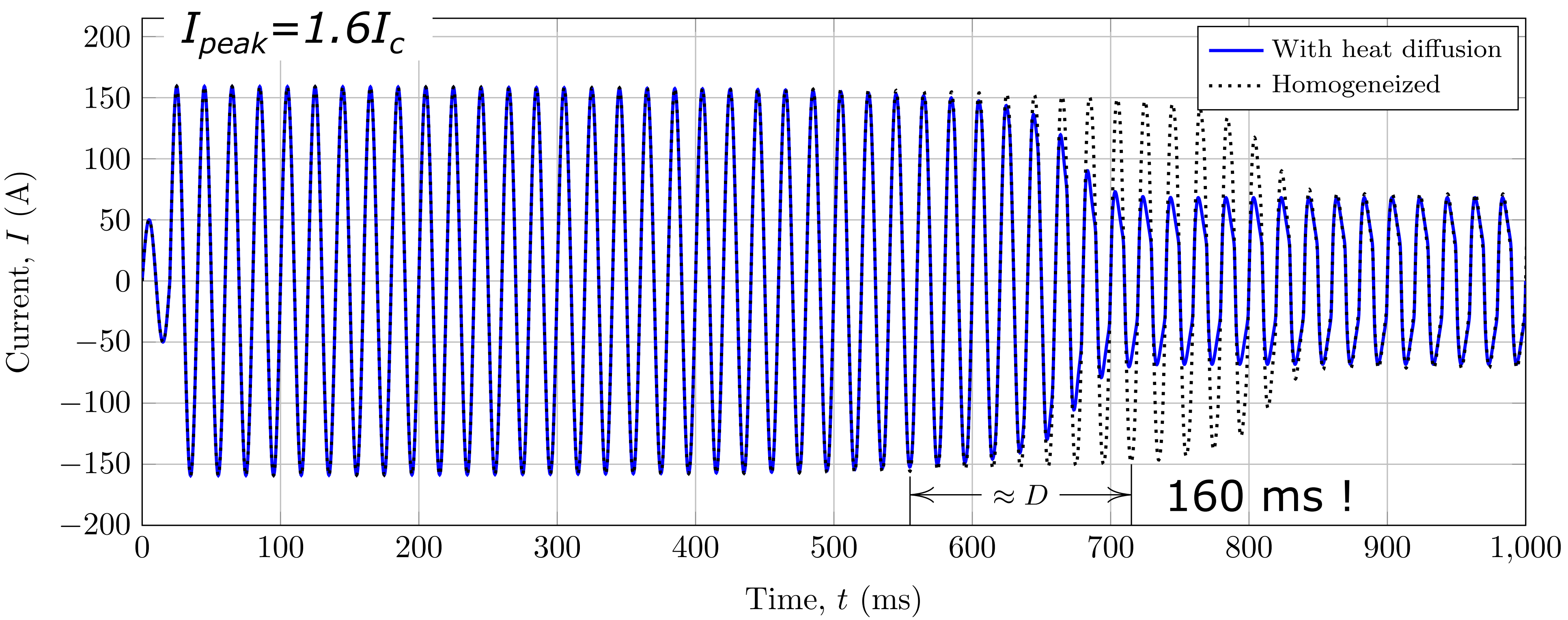




L_{fine}=5 mm

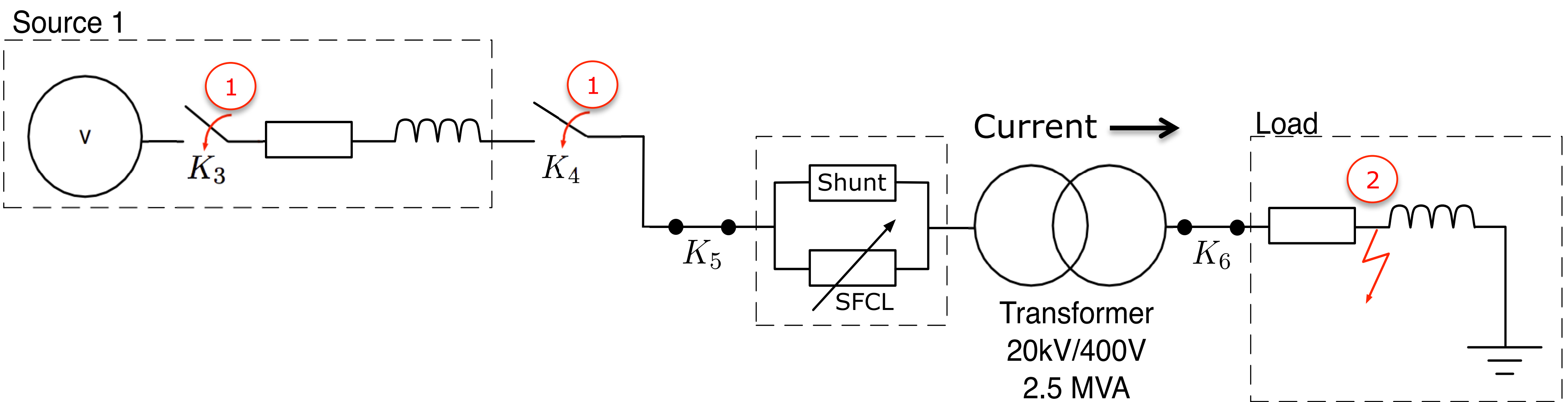
PRACTICAL APPLICATION

- Validation of the popular "homogenized model" of an rSFCL

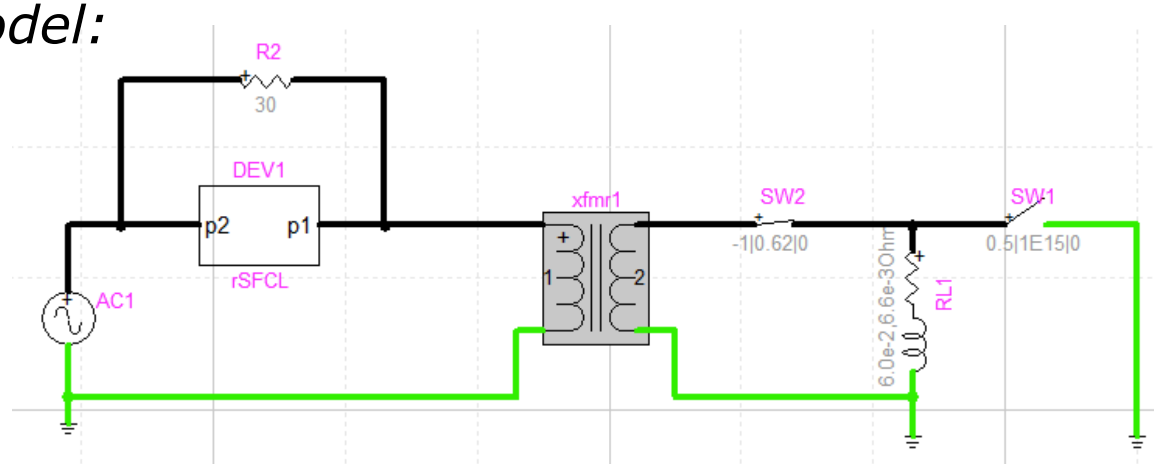


In low over-current regimes, the homogenized model can induce a very important delay in triggering the limitation (not a hot spot issue!)

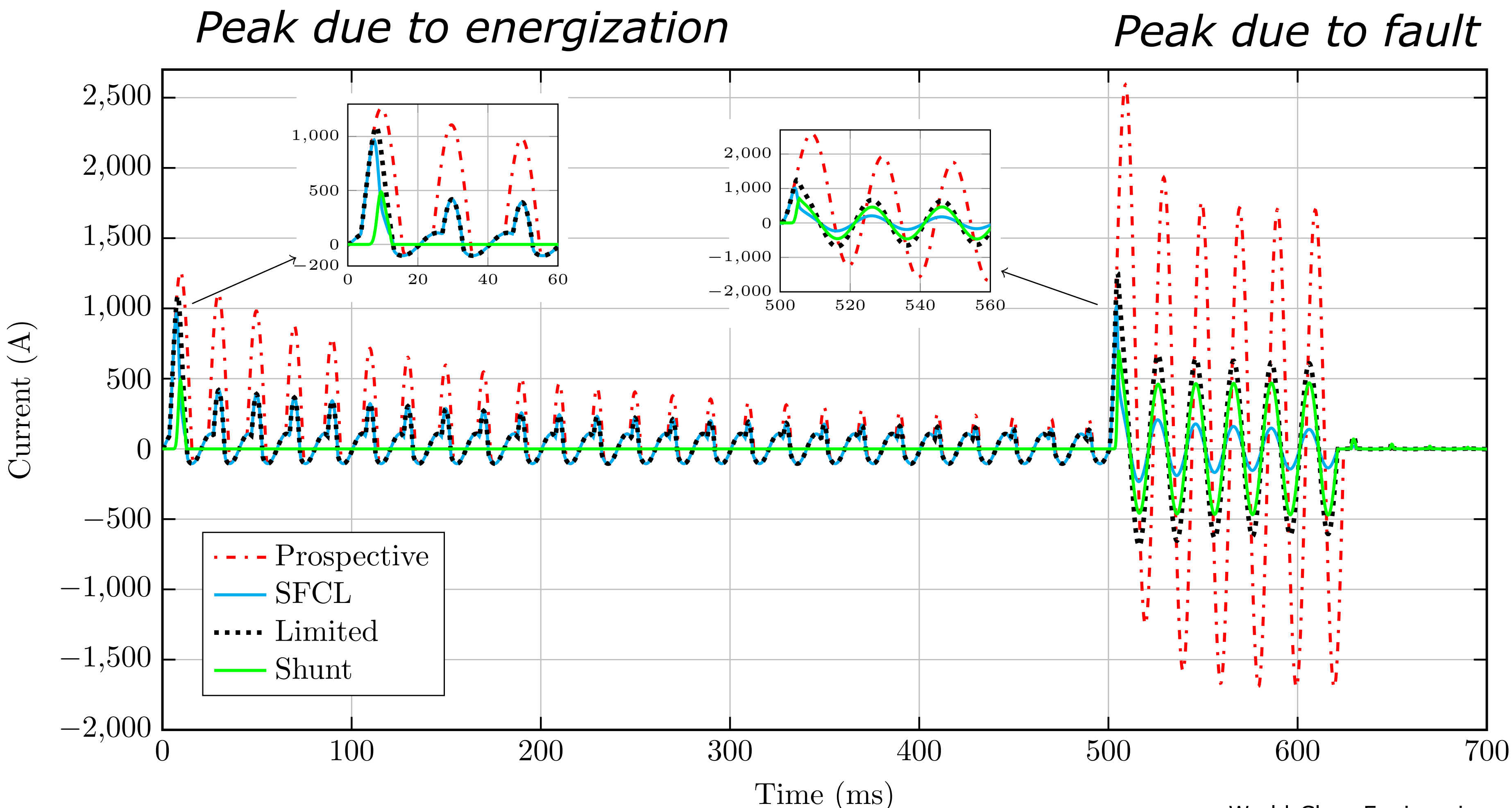
- More involved: rSFCL & transformer energization



EMTP-RV model:

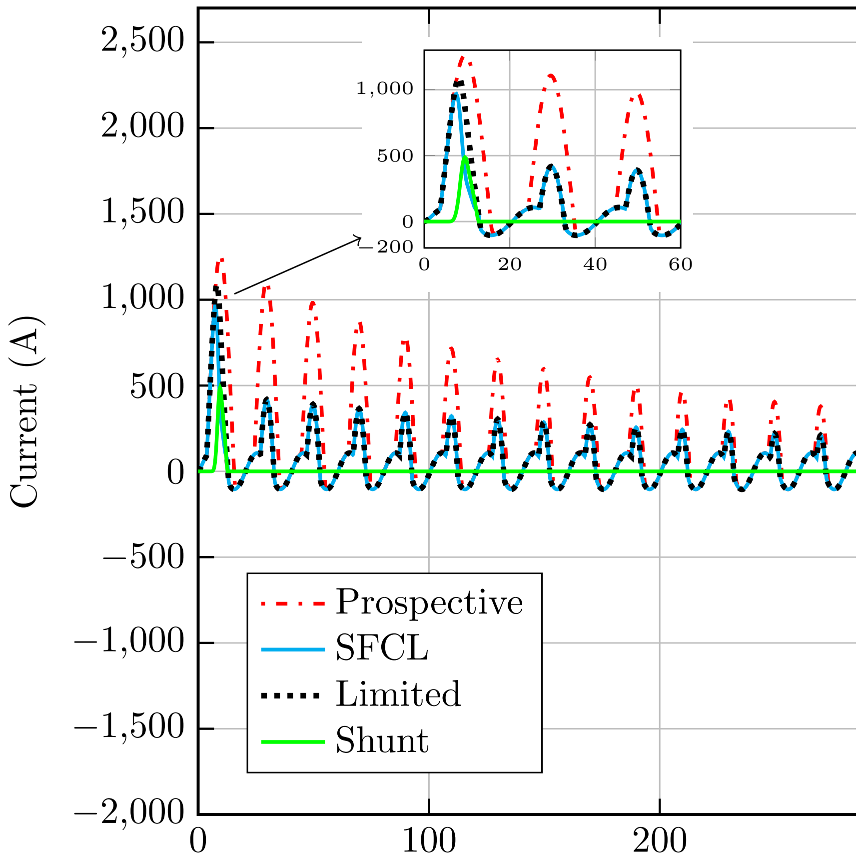


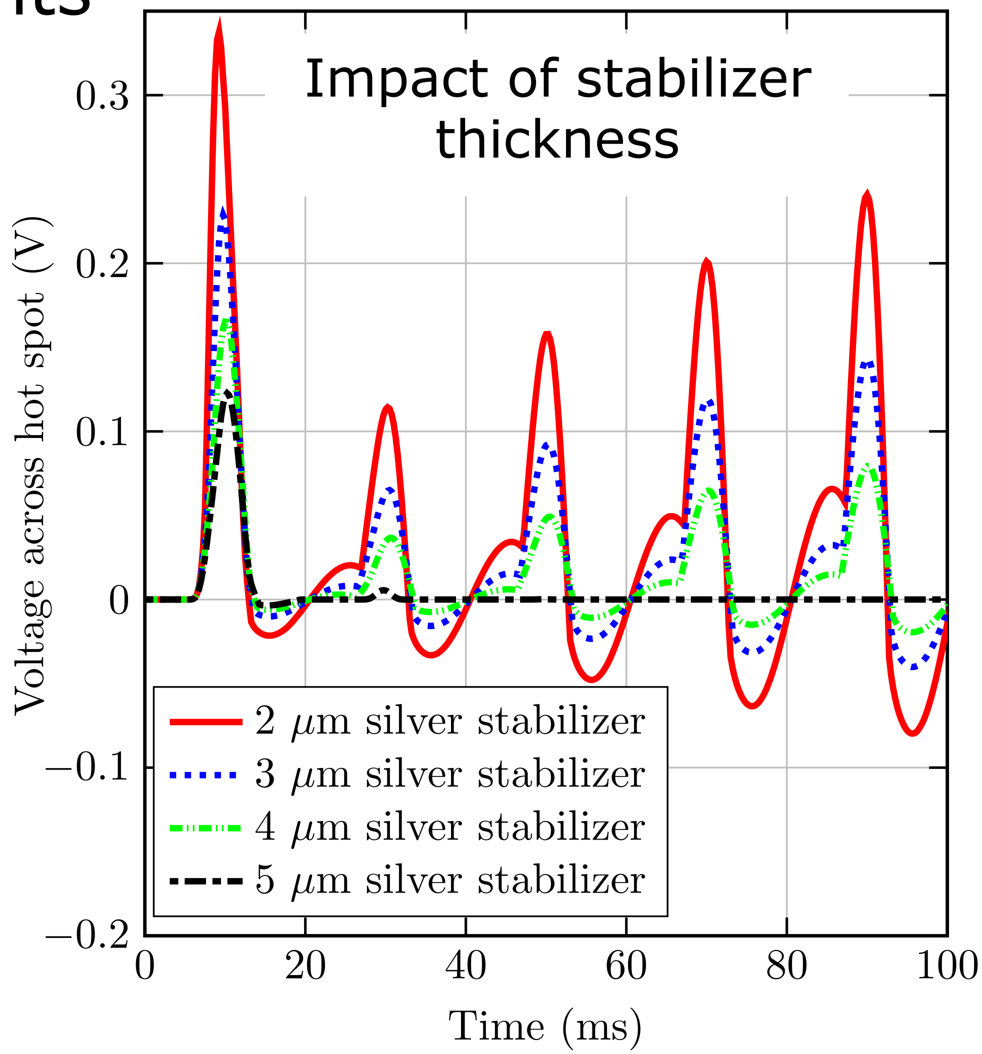
- More involved case: rSFCL impact on common power system transients



- More involved case: rSFCL impact on common power system transients

Peak due to energization





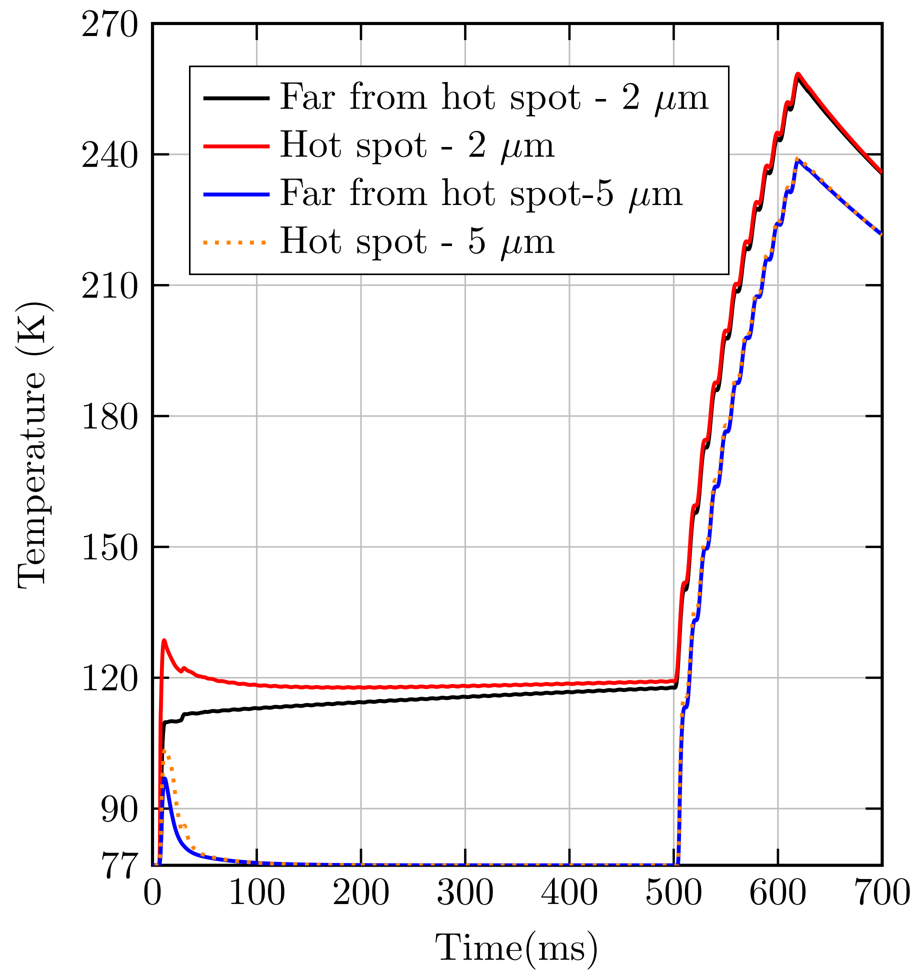
APPLICATION EXAMPLES

- More involved case: rSFCL impact on common power system transients

  → On-load recovery after transient over-current

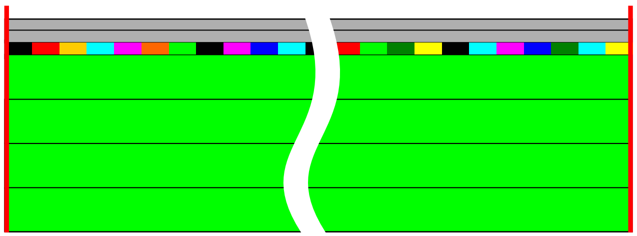
  → min and max temperature along tape

  → etc.



PERSPECTIVES

- Multi-scale models + professional power system transient simulator opens a world of possibilities
  - Optimization of tape architecture **under realistic network operating conditions**
    - Various type of stabilizers
    - Tapes with accelerated NZPVs
    - I_c inhomogeneities
    - etc.
  - Robustness of rSFCLs under various transients
  - Investigation of the impact of rSFCLs in AC and DC power systems **with realistic device behaviour**
  - etc.



POSSIBLE IMPROVEMENTS

- Model still heavy in terms of number of components
  - many control blocks and nonlinear devices

- Would be desirable to integrate more components into the DLL file

- An hierarchy of models of increasing complexity would help to enable optimal multi-scale modelling

CONCLUSIONS

- A true multi-scale model of rSFCLs have been developed in the EMTP-RV software

- The model has been heavily verified against FEM
  - Proper discretization remains a delicate issue

- Multi-scale models are of interest for both
  - Manufacturers (and researchers)
  - Power system engineers

2 different worlds!

- Implementation in a major commercial code **bridges a gap** between these two worlds
  - A public version should be released within a few months

REFERENCES

[1] C.-H. Bonnard, F. Sirois, C. Lacroix and G. Didier, “Multi-scale model of resistive-type superconducting fault current limiters based on 2G HTS coated conductors,” submitted to Superconductor Science and Technology, May 2016.

[2] C.-H. Bonnard, F. Sirois, C. Lacroix and G. Didier, “Application of a multi-scale model of resistive-type superconducting fault current limiters in power system simulators,” submitted to IEEE Transactions on Applied Superconductivity, July 2016.