INSTITUTO DE INGENIERÍA UNAM

Modelling tools

Quench model for Superbend in Elmerfem

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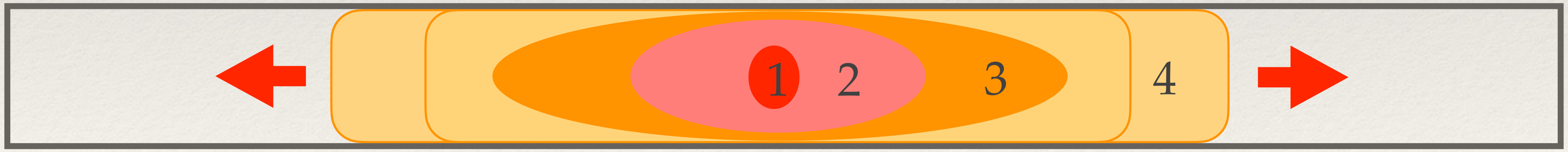
Quench in coils

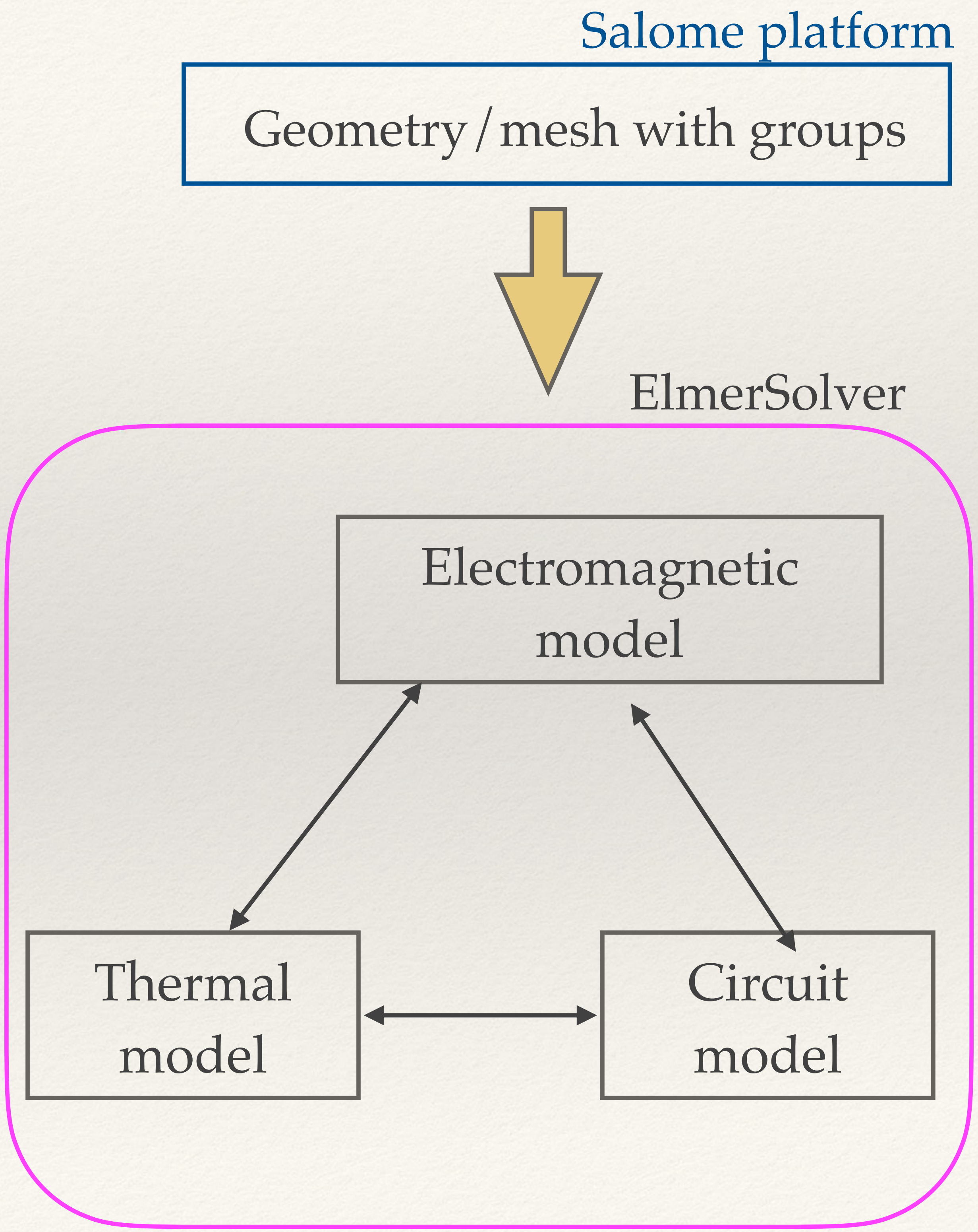
- A quench is a sudden loss of the superconducting state with a local energy dissipation in the winding leading to a heat propagation wave throughout the coil
- The initial disturbance leading to the quench is modeled as a small spherical volume within the body of the coil.

Steps of quench process:
1: Initial normal zone (first localized dissipation
2-3: Diffusion (expansion of the dissipative sone)
4: Propagation (dissipative front at constant velocity)



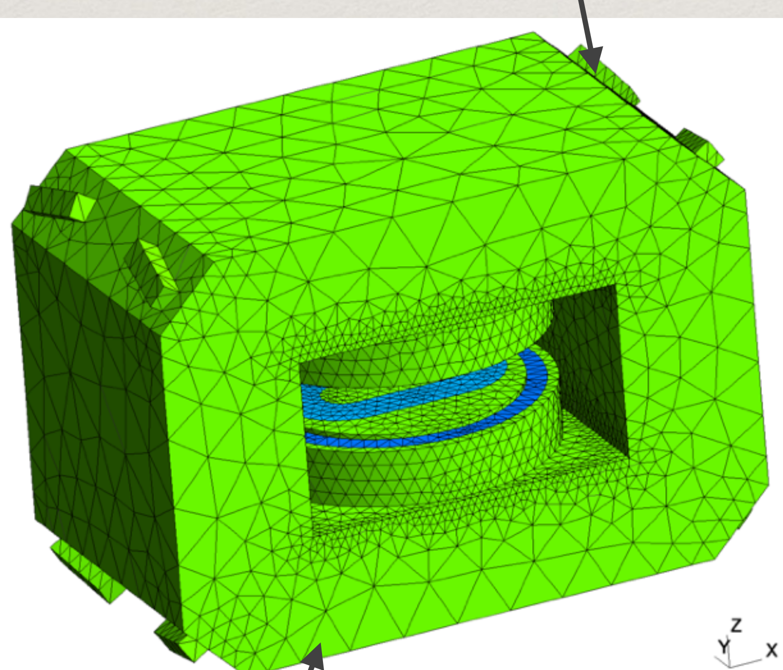
Modelling approach

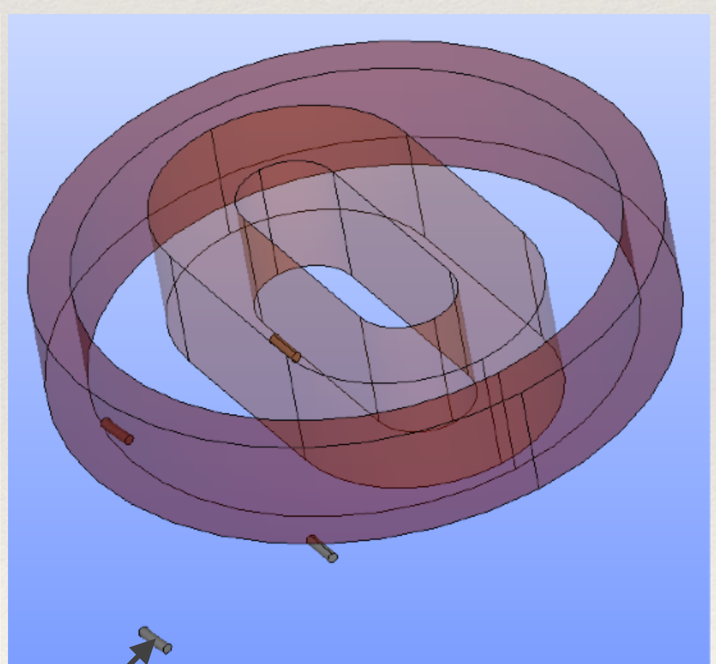
- Coupling FEM model (magnetic and thermal) and circuit model
- 3D approach using closed coil
- Transient solution
- Opensource software:
  - Salome platform: geometry builder and mesher (at this stage, groups of meshes for associating material properties and boundary conditions are defined)
  - Elmer-CSC version 9 as Multiphysics FE solver
- Operating system: ubuntu 20.04LTS

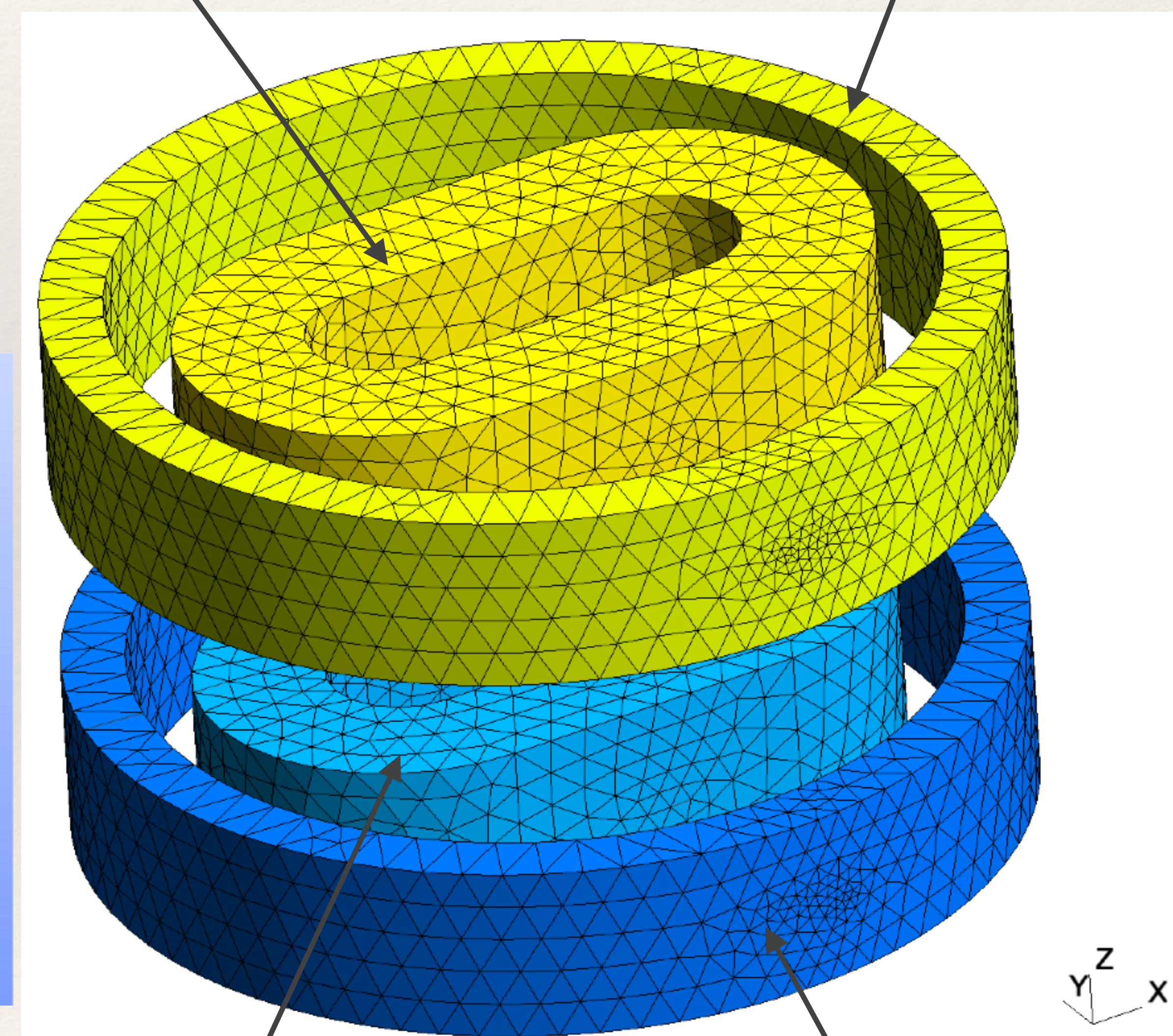


Overview of Superbend model

- Two circular coils connected in series (Circuit 1)
- Two racetrack coils connected in series (Circuit 2)
- 1 splice per coil
- Iron core attached to thermal

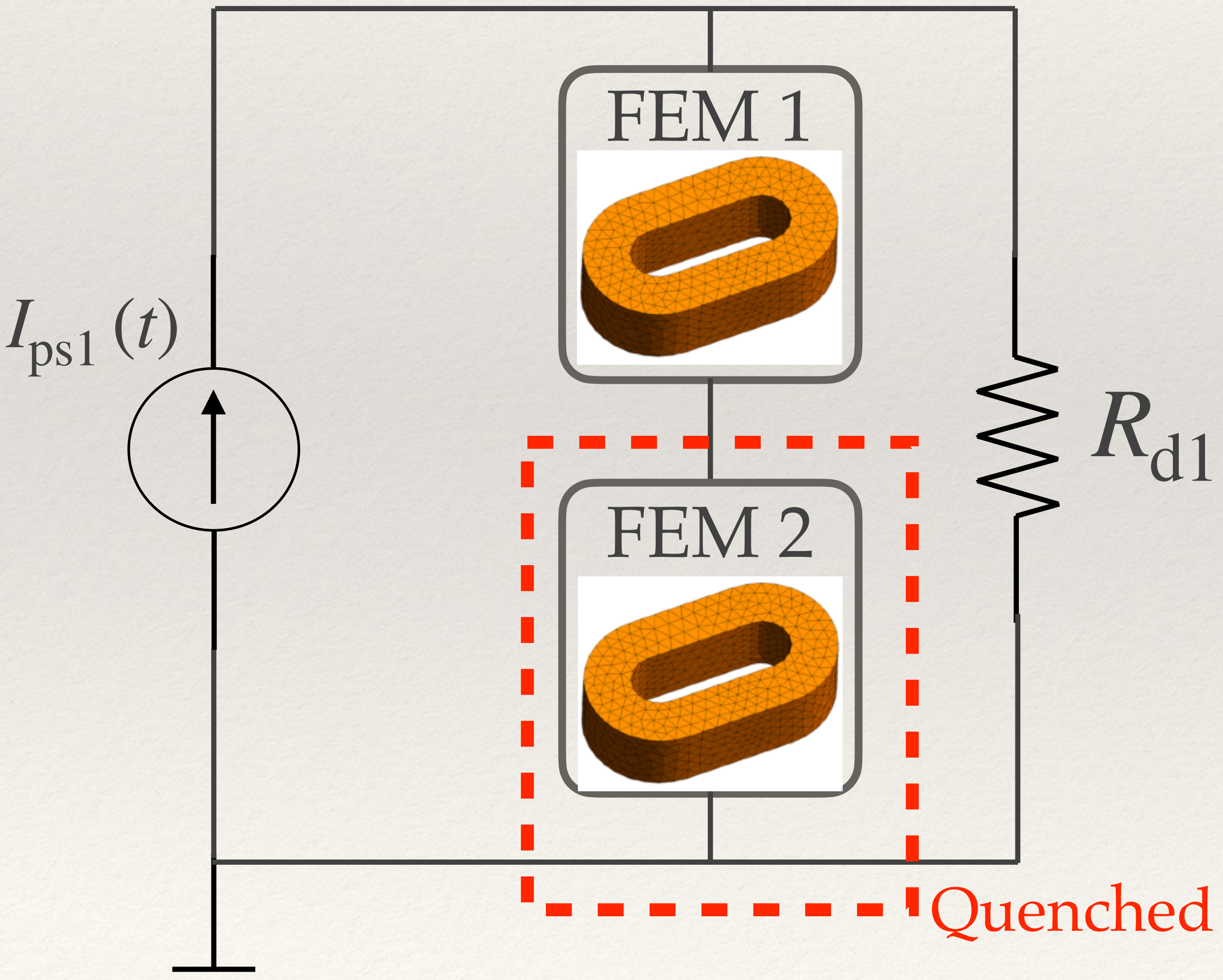




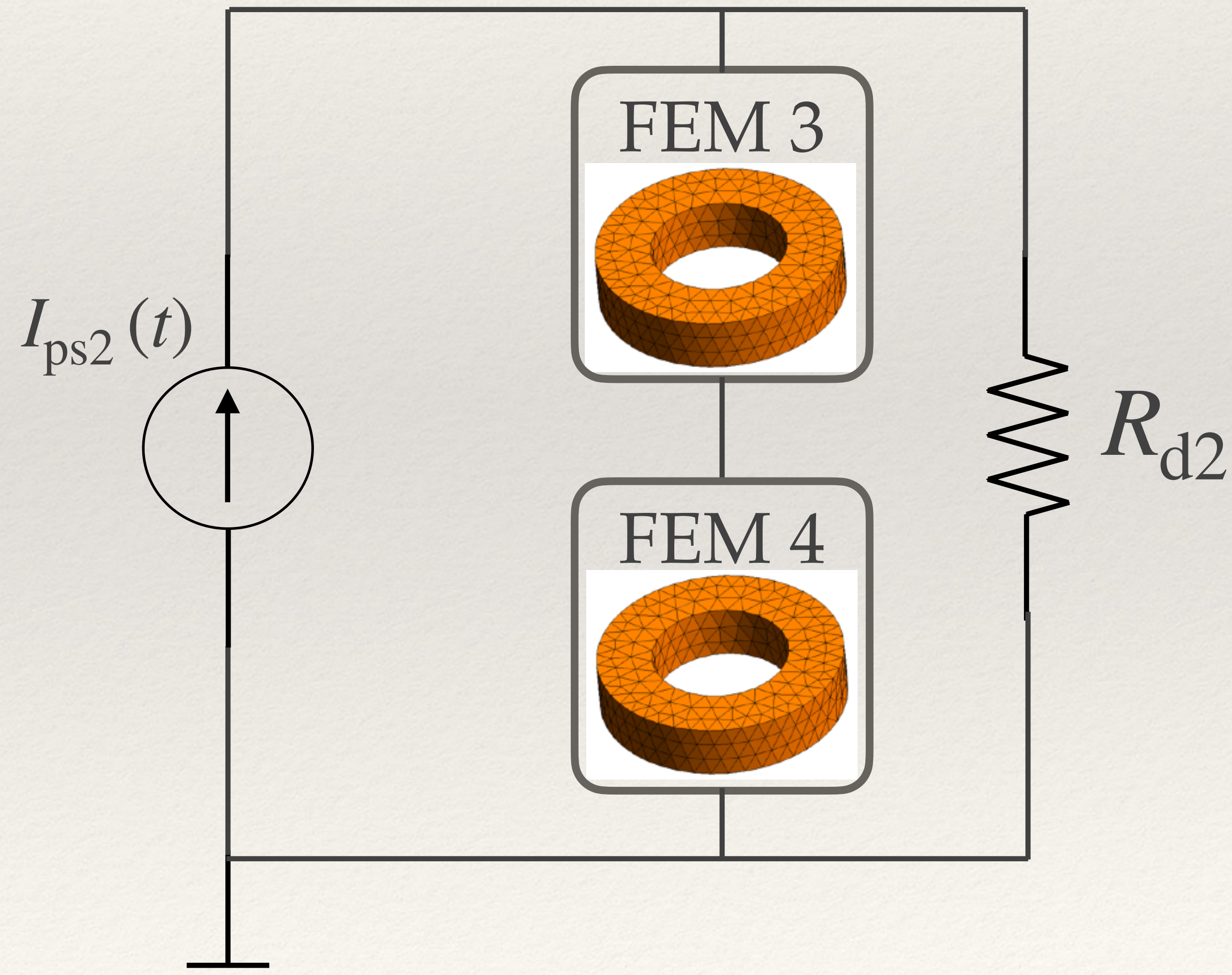


Superbend circuits

- Two DC power supplies feeding the circular coils connected in series and the racetrack coils connected in series. A dumping resistor for each set of coils.
  - Current supplies: $I_{\mathrm{ps1}}(t)$ and $I_{\mathrm{ps2}}(t)$
  - Dump resistors: R_{d1} and R_{d2}. They are equal to 3 Ω



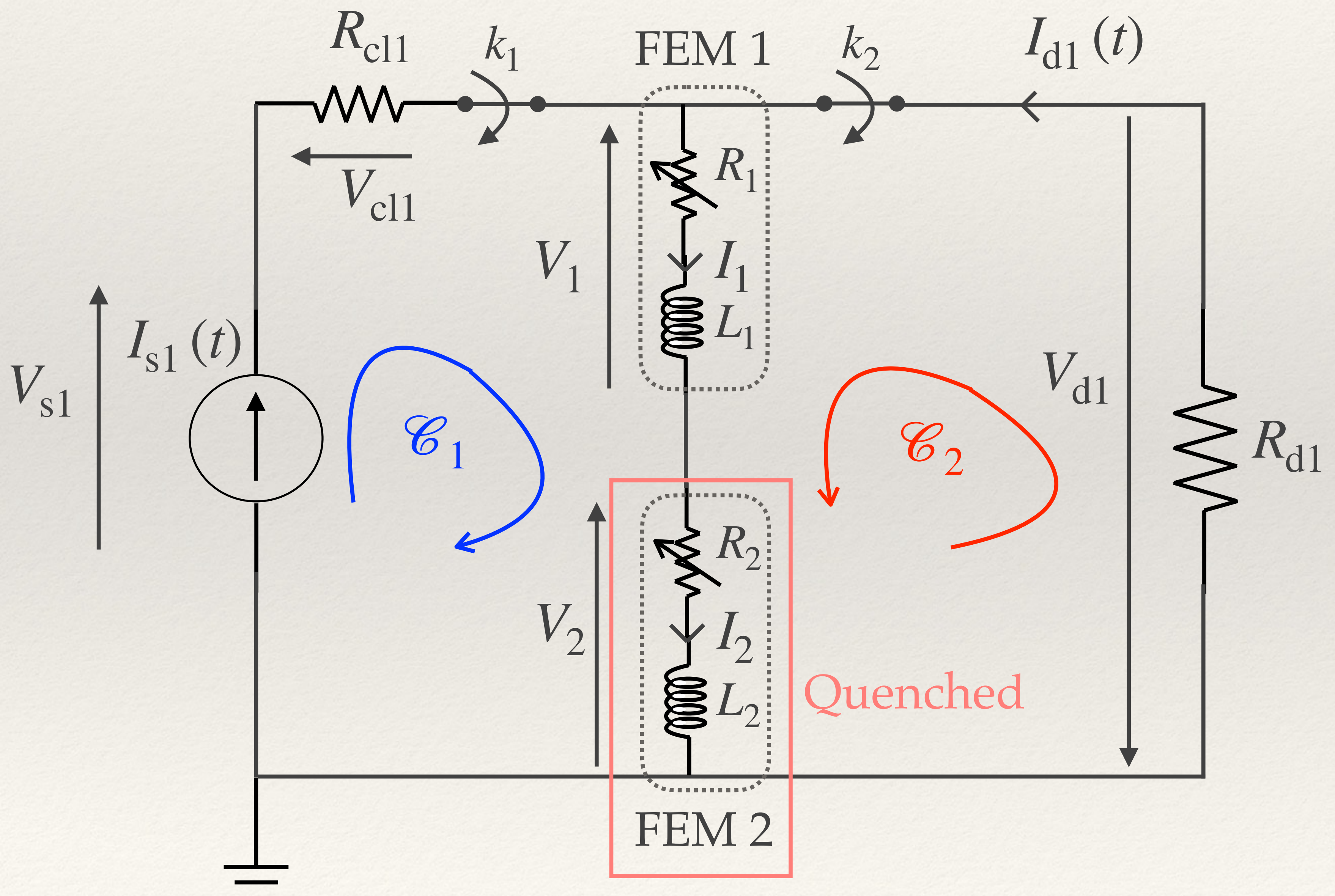
Racetrack coils 1 and 2



Circular coils 3 and 4

Circuit - quench model: racetrack coils

- The circular coils and the racetrack coils are connected in series. The same electric drawing is used to model both circuits
- $\mathbf{x} = (I_1, V_1, I_2, V_2, I_{s1}, V_{s1}, I_{d1}, V_{d1})$



0. $I_1 - I_{s1} - I_{d1} = 0$
1. FEM 1
2. $I_1 - I_2 = 0$
3. FEM 2
4. $I_{s1} = f_1$
5. $V_1 + V_2 + \overbrace{\boxed{R_{cl1} I_{s1}}}^{V_{cl1}} - V_{s1} = 0$
6. $V_1 + V_2 + V_{d1} = 0$
7. $V_{d1} - R_{d1} I_{d1} = 0$

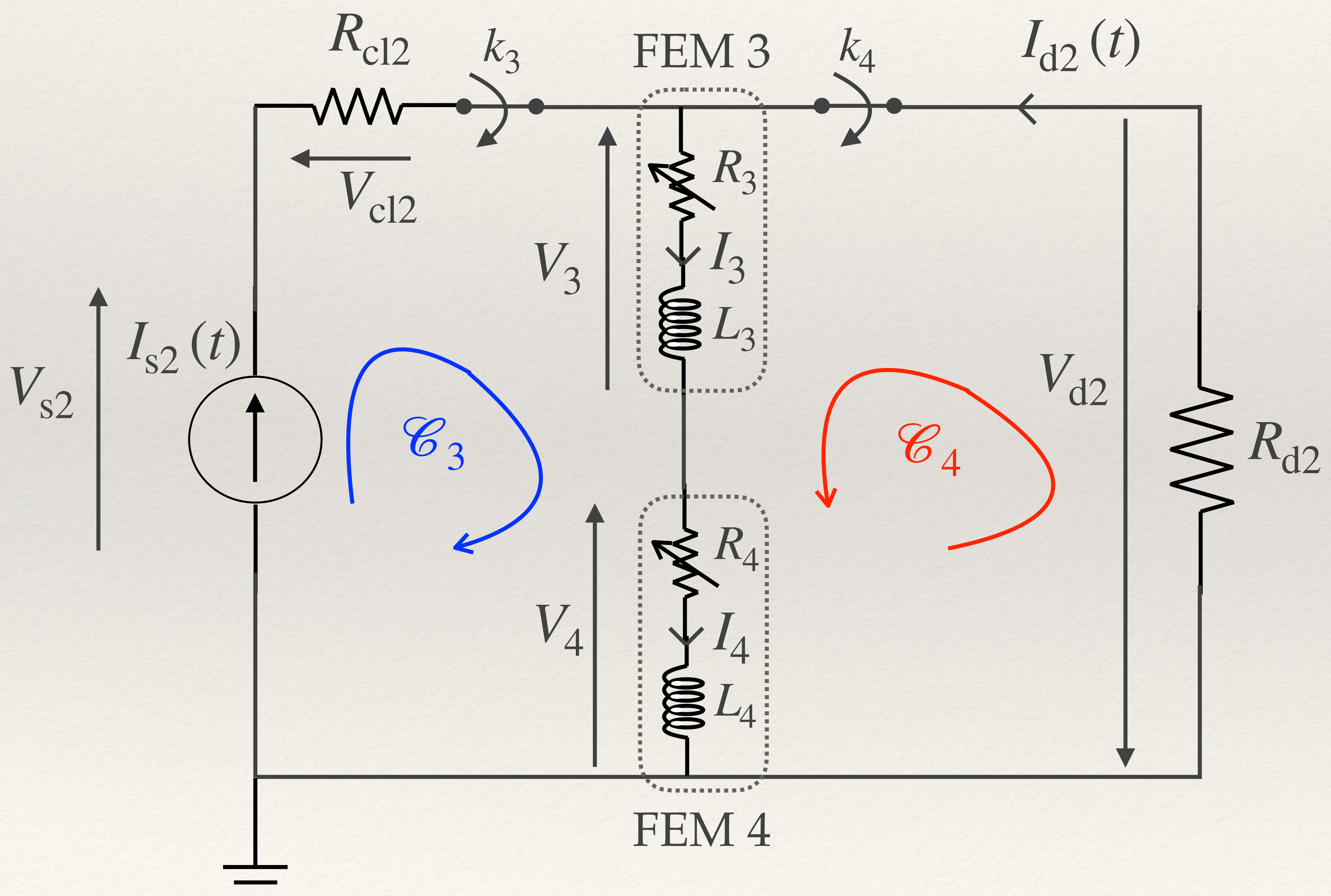
Circuit model: racetrack coils

- Circuit connections (circuit 1): matrix B
- Two circuits, one for the circular coils and one for the racetrack coils. We show the circuit model for the racetrack coils. The circuit model for the circular coils is identical replacing the subindices by the correct labelling (see next slides)

$$
\begin{array}{c}
\\
0\\ 1\\ 2\\ 3\\ 4\\ 5\\ 6\\ 7
\end{array}
\begin{array}{c}
\begin{array}{cccccccc} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array}\\
\begin{pmatrix}
1 & 0 & 0 & 0 & -1 & 0 & -1 & 0\\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot\\
1 & 0 & -1 & 0 & 0 & 0 & 0 & 0\\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot\\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0\\
0 & 1 & 0 & 1 & R_{\mathrm{cl}1} & -1 & 0 & 0\\
0 & 1 & 0 & 1 & 0 & 0 & 0 & 1\\
0 & 0 & 0 & 0 & 0 & 0 & -R_{\mathrm{d}1} & 1
\end{pmatrix}
\end{array}
\times
\begin{pmatrix} I_1\\ V_1\\ I_2\\ V_2\\ I_{\mathrm{s}1}\\ V_{\mathrm{s}1}\\ I_{\mathrm{d}1}\\ V_{\mathrm{d}1} \end{pmatrix}
=
\begin{pmatrix} 0\\ 0\\ 0\\ 0\\ f_1\\ 0\\ 0\\ 0 \end{pmatrix}
$$

Circuit model: circular coils

- $\mathbf{x} = \left(I_3, V_3, I_4, V_4, I_{s2}, V_{s2}, I_{d2}, V_{d2}\right)$



0. $I_3 - I_{s2} - I_{d2} = 0$
1. FEM 3
2. $I_3 - I_4 = 0$
3. FEM 4
4. $I_{s2} = f_2$
5. $V_3 + V_4 + R_{cl2}I_{s2} - V_{s2} = 0$
6. $V_3 + V_4 + V_{d2} = 0$
7. $V_{d2} - R_{d2}I_{d2} = 0$

Circuit model: circular coils

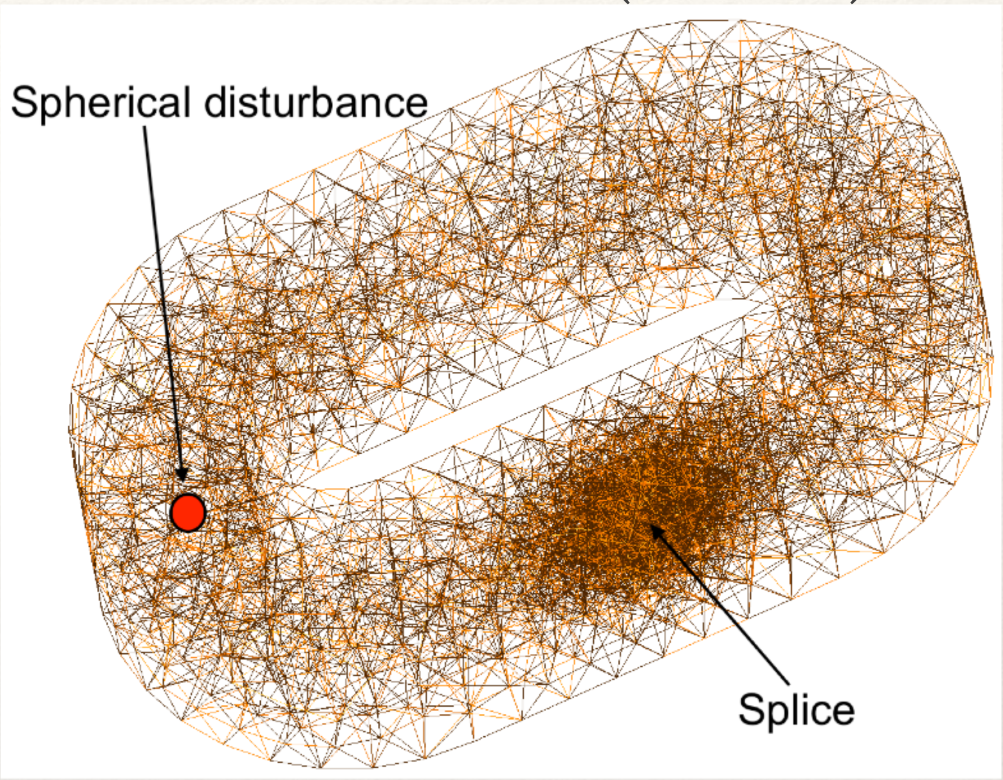
- Circuit connections (circuit 2): matrix B

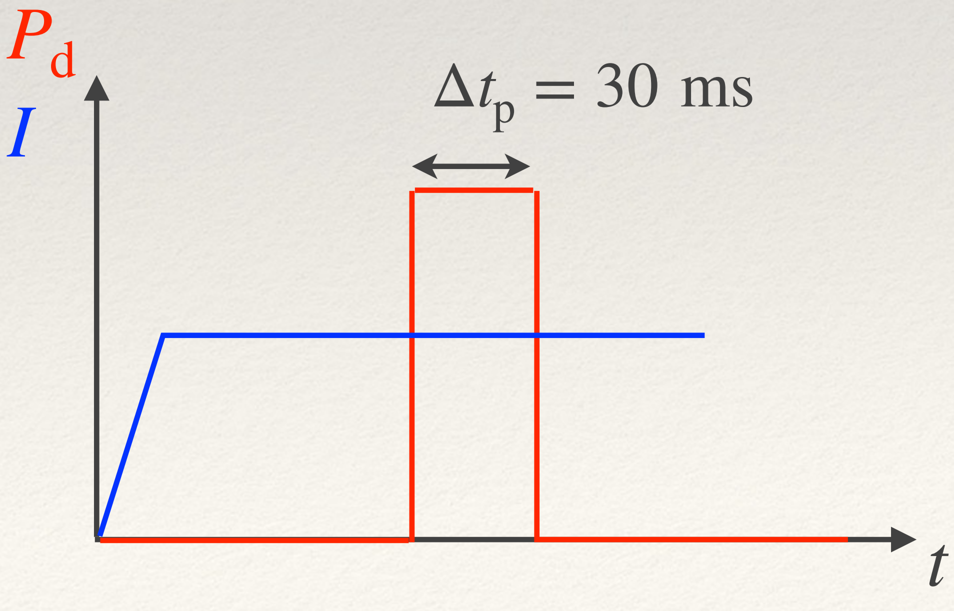
$$
\begin{array}{cc}
 & \begin{array}{cccccccc} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array} \\
\begin{array}{c} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{array} &
\begin{pmatrix}
1 & 0 & 0 & 0 & -1 & 0 & -1 & 0 \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & R_{\mathrm{cl2}} & -1 & 0 & 0 \\
0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & -R_{\mathrm{d2}} & 1
\end{pmatrix}
\end{array}
\times
\begin{pmatrix} I_3 \\ V_3 \\ I_4 \\ V_4 \\ I_{\mathrm{s2}} \\ V_{\mathrm{s2}} \\ I_{\mathrm{d2}} \\ V_{\mathrm{d2}} \end{pmatrix}
=
\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ f_2 \\ 0 \\ 0 \\ 0 \end{pmatrix}
$$

Quench model

- Quench occurs at nominal current
- The quench is detected at time t_d for a voltage threshold V_{th}= 100 mV
- The quench protection is triggered after a time delay equal to Δt_d = 100 ms
- Initial disturbance: the magnitude of the pulse power P_d is equal to 7 W. It is deposited inside a small sphere in the curve of the racetrack coil 2 for 30 ms
- Dissipation in splice due to resistive electrical contact

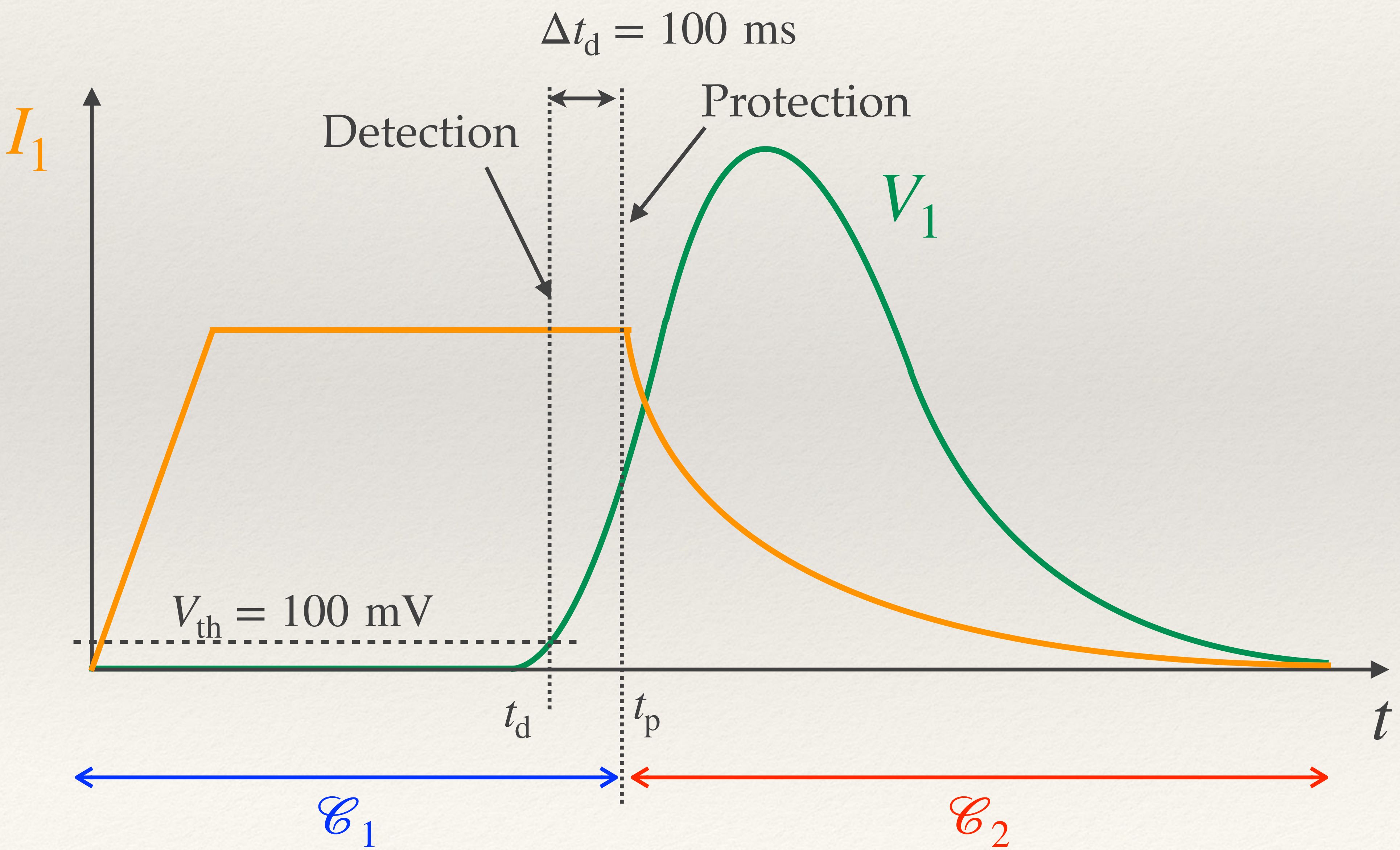
Racetrack coil 2 (FEM 2)





Current decay

- Dump resistor providing a decay time constant, $\tau = \dfrac{R}{L}$



$$L\frac{\mathrm{d}I}{\mathrm{d}t} + RI = V$$

$$I = \frac{V}{R}\exp\left(-\frac{t}{\tau}\right)$$

Additional details of the model

- Boundary conditions:
  - 50 K at the elastic straps connecting the iron core to the thermal shield
  - 4.5 K at the interface between the iron core and the helium tank
  - Heat radiation on the exposed surfaces of the iron core and the coils, $q_{\mathrm{rd}} = 0.03\ \mathrm{W/m^2}$
- Coil basic data:
  - Nb_3Sn wire (RP technology)
  - Circular coils: 82 A (nominal) / 696 runs
  - Racetrack coils: 153 A (nominal)/ 1710 turns