Case study 5

Protection of FRESCA2

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Introduction

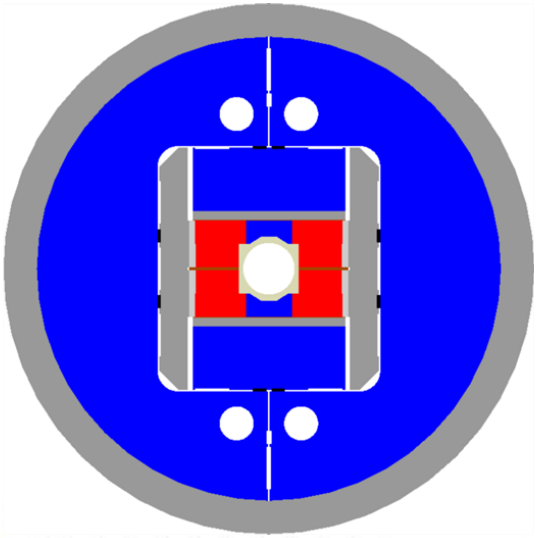
Work Package 7 of EuCARD

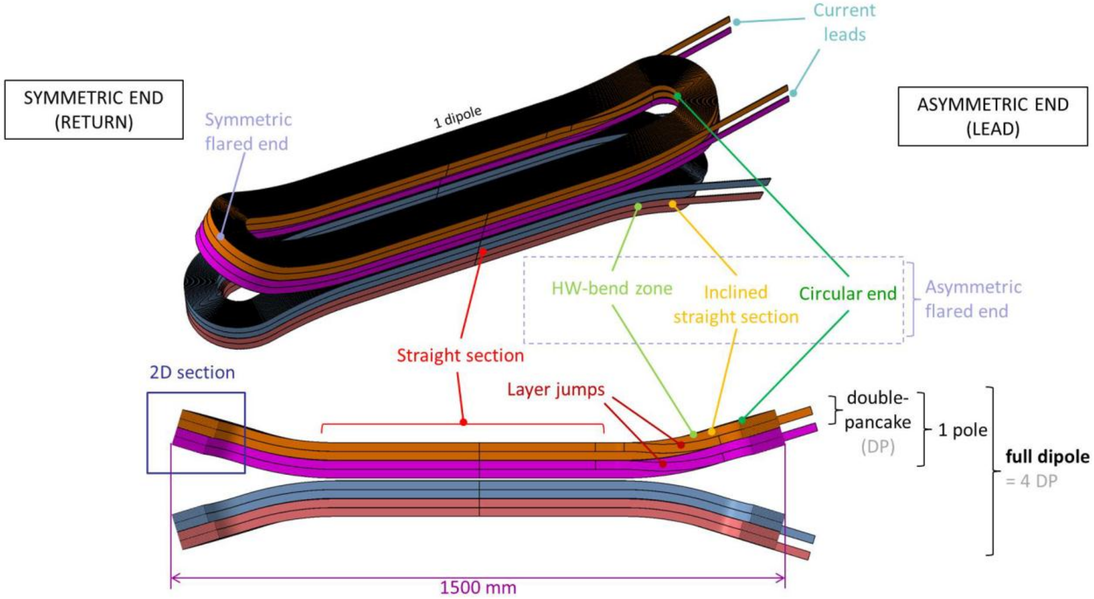
13 T dipole, 100 mm aperture, I = 10.5 kA

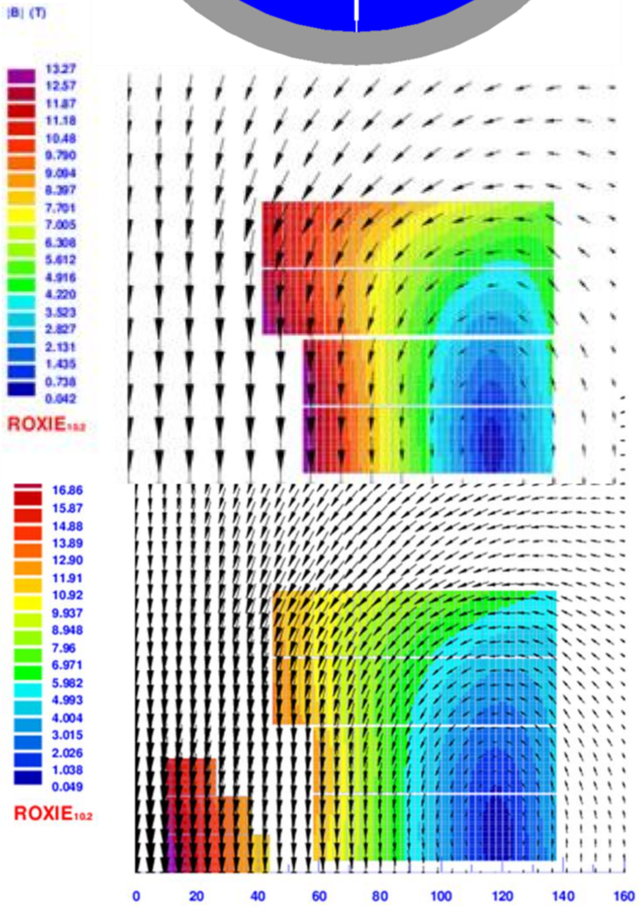
Nb_3Sn Rutherford cable,

Made of 4 double - pancakes

Associated with 6 T HTS insert







Some figures

Energy

Cold mass 293 kg and Energy 5.4 MJ

i.e. energy density 18.4 J/g

(SMES # 20 J/g !)

Uniform dissipation

- All magnet [0.118 J/mm^3] → **T_{mean} = 126 K**
  - 1 pole → **T_{mean} = 182 K**
  - $^1/_2$ pole → **T_{mean} = 276 K**

Adiabatic hot spot criteria

$$\int_{T_0}^{T_{max}} \frac{C_P}{\rho} dT = \int_0^{+\infty} j^2(t) dt$$

T : temperature,
t : time
ρ : overall resistivity,
C_p : specific heat.
j : overall current density

V_{max} = 1000 V, I = 10.5 kA → R_{dump} = 95 mΩ

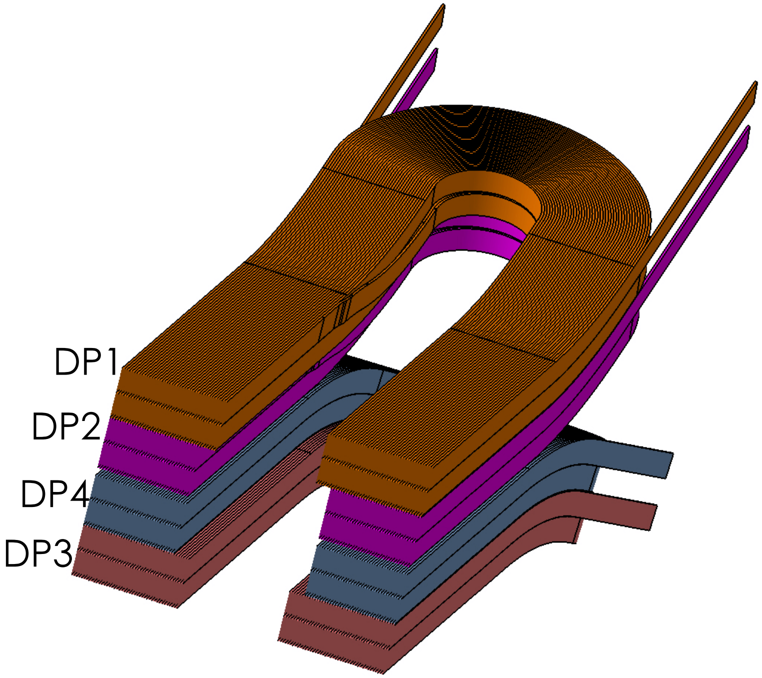
→ θ_{max} = 228 K

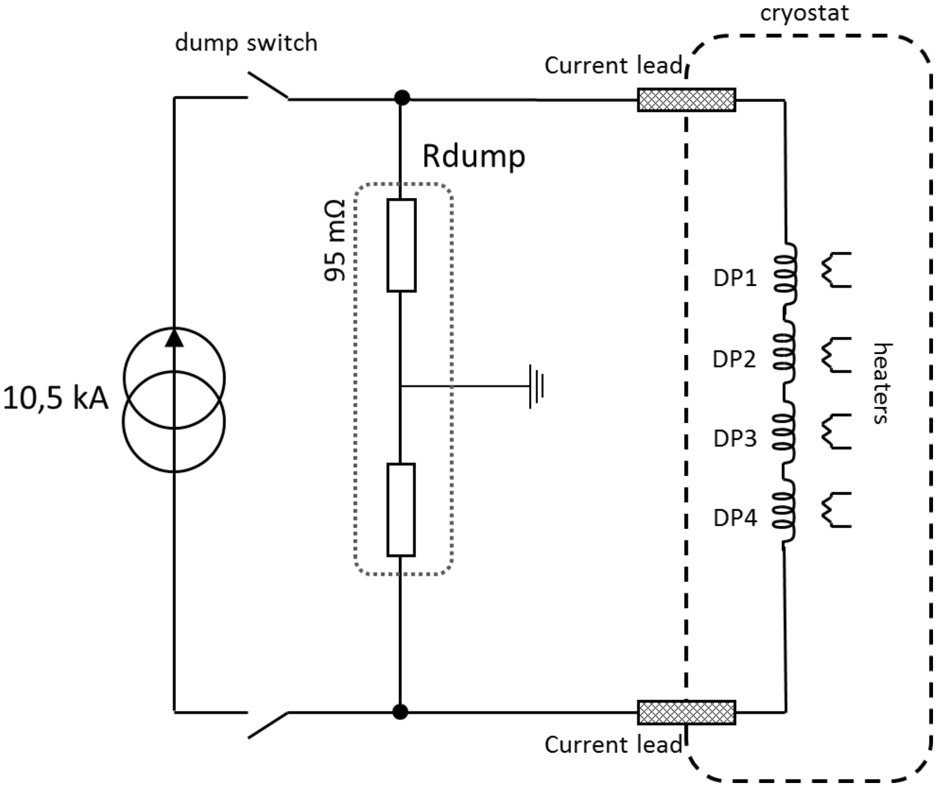
→ importance of the detection

→ Heaters will help to expand the internal resistance

Electrical protection circuit

- ✓ Protection principle based on the extraction of the magnetic stored energy into a dump resistor,
- ✓ Internal resistance, benefit of quench heaters,
- ✓ Grounding circuit ± $V_{max}/2$ to ground,
- ✓ Inductances computed with ROXIE.





Facing the computations

QTRANSIT *(QUENCH like)* **code or CAST3M*** *(FEM)* **code ?**

1. ***After the detection time***

- Opening of the contactors, heaters activation,
- 2D problem, assuming the heaters are located all along the dipole, transverse propagation
- FEM code do not need transverse propagation velocities

2. ***Before the detection time***

- 3D problem
- FEM code more dedicated

⇨ **Use of the FEM code, CAST3M**

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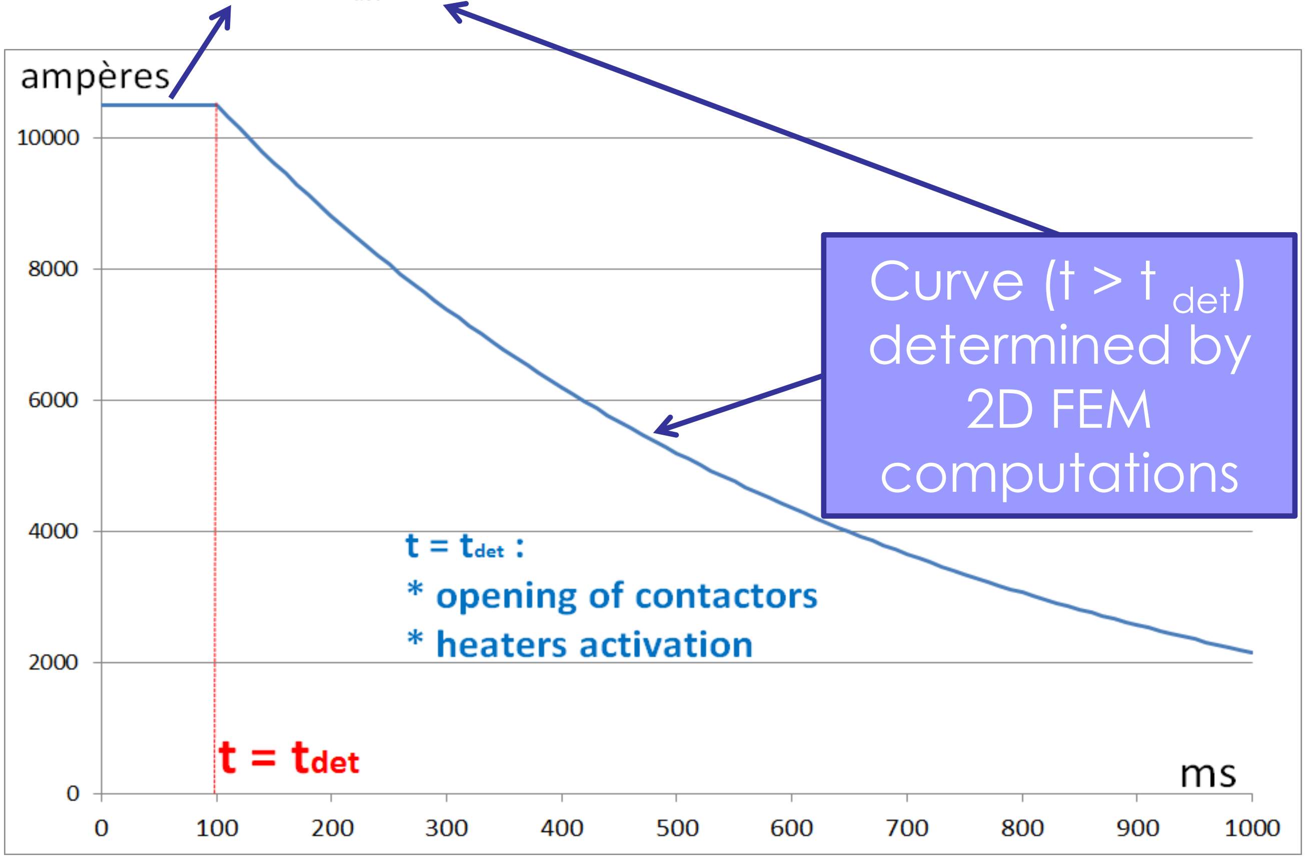
* P. Verpeaux, T. Charras, A. Millard, "*CASTEM 2000 une approche moderne du calcul des structures*", Calcul des structures et intelligence artificielle (Fouet J.M., Ladevèze P., Ohayon R., Eds), Pluralis, 1988, p. 261-271.

2D FEM computations

$$\int_{\theta_0}^{\theta_{max}} \frac{\gamma C(\theta)}{\rho(\theta)} d\theta = \int_0^{\infty} J^2(t)dt = \int_0^{t_{det}} {J_0}^2 dt + \int_{t_{det}}^{\infty} J^2(t)dt$$



Curve ($t > t_{det}$) determined by 2D FEM computations

$t = t_{det}$:

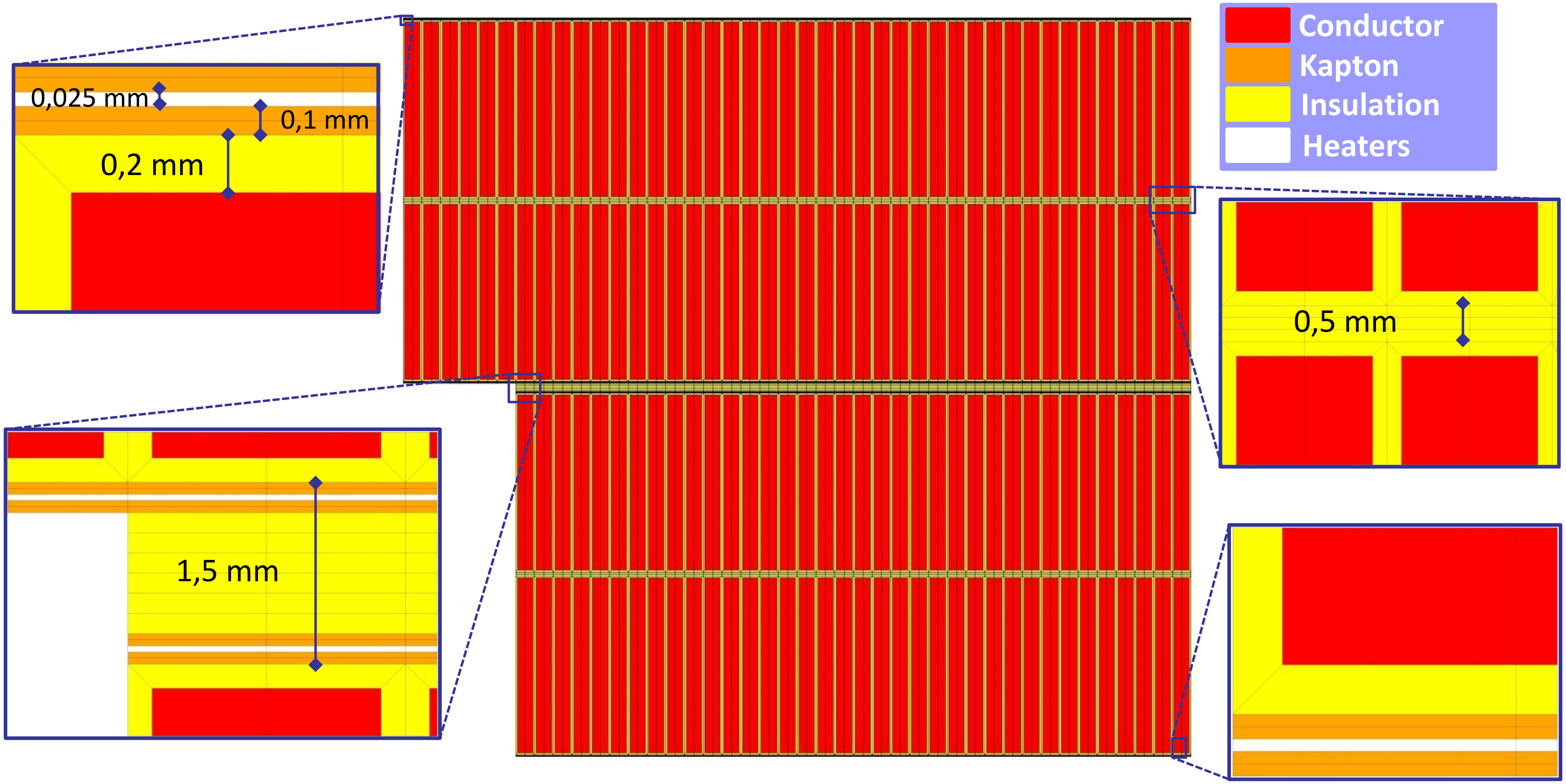
* opening of contactors

* heaters activation

The 2D FEM study gives the evolution of the current decrease vs time for $t > t_{det}$.

The maximal temperature of the *hot spot can then be calculated directly* by taking into account the detection time (nominal current during t_{det}) and the curve mentionned (current decrease for for $t > t_{det}$).

2D FEM model



Heaters are activated and the code computes *the quench propagation*, ***the current decrease*** and *the temperature distribution* within the dipole.

The heat generation is assumed linear between Tcs and Tc.

Dump resistor and 2D heaters

✓ The value of the dump resistor is *95.4 mΩ* (V = 1 kV).

✓ The code computes its temperature and value with time (adiabatic computation) ; its volume has been set so that *the voltage at its terminals remains maximum as long as possible*.

⇨ **This leads to a total volume of 2.63 liters.**

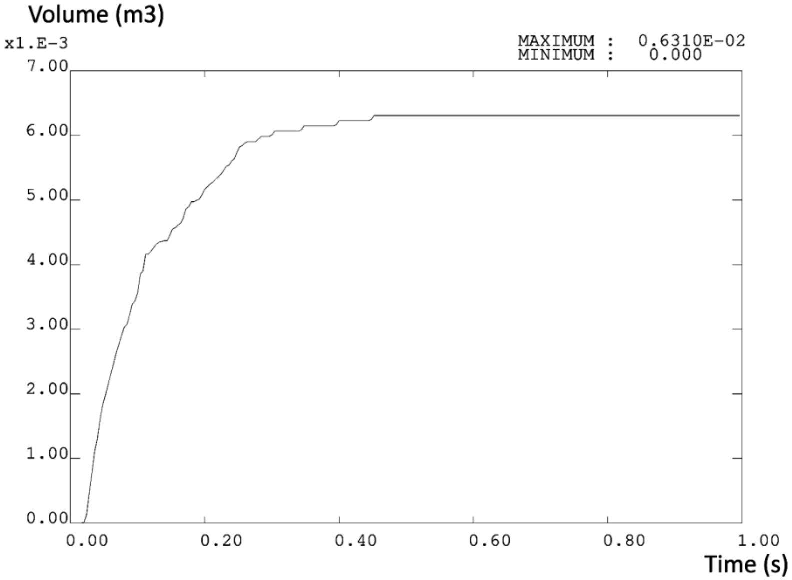
✓ We expect a heaters power of *50 W/cm^2* and the more uniform distribution.

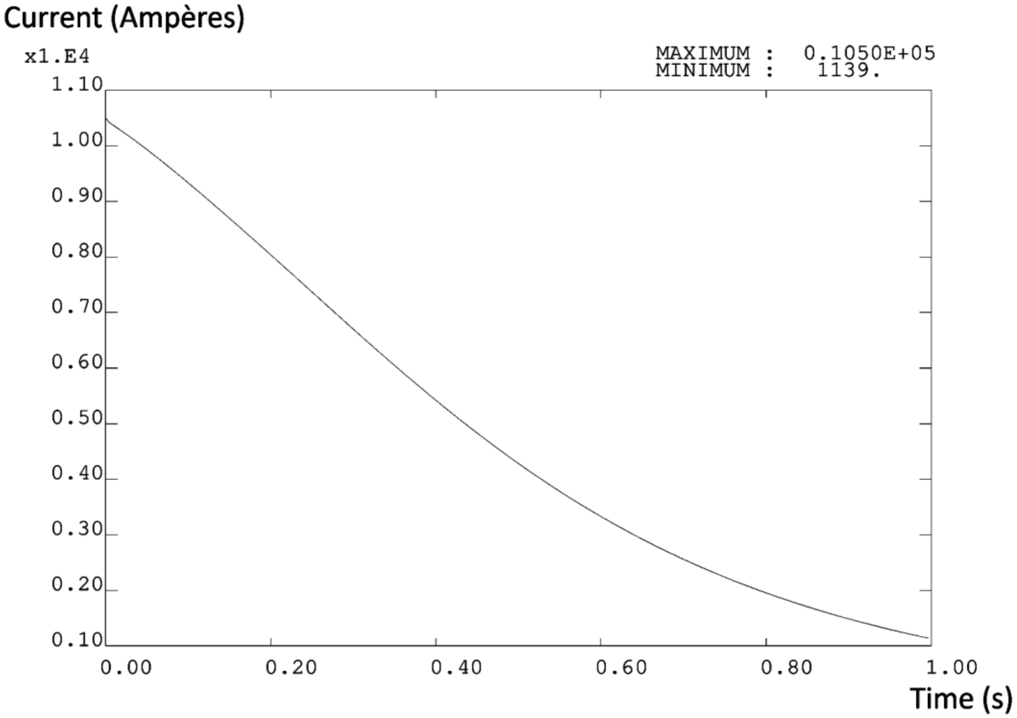
✓ But we decided to decrease this power for computations, considering the real spatial distribution of the heaters will not be uniform : it was then set at **25 W/cm^2**.

✓ **The pulse of power has been set to 50 ms.**

2D results – 4 heaters quenched volume and current

The *delay time is 20 ms*, between the activation of the heaters and the quench ignition in the dipole.
The evolution of the *quenched volume* is represented in the adjacent figure.
It takes *457 ms to totally quench the dipole*.

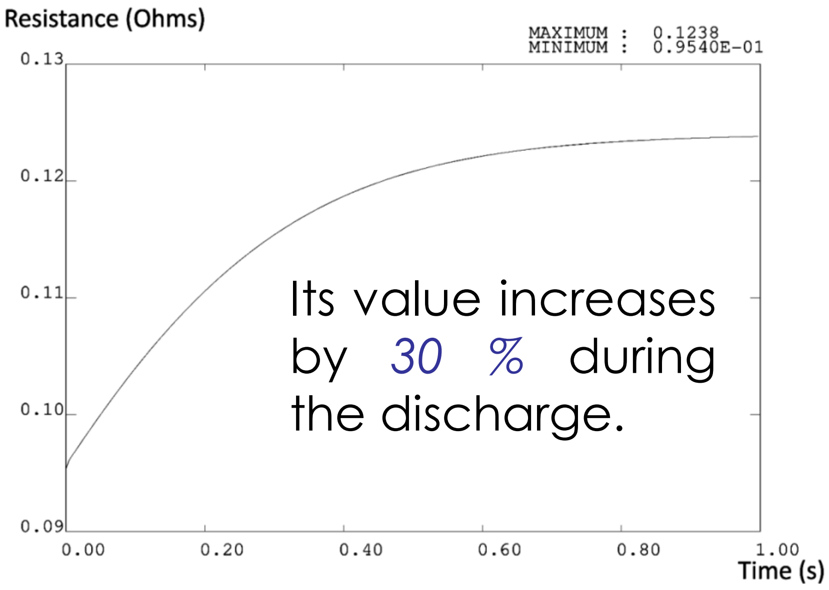




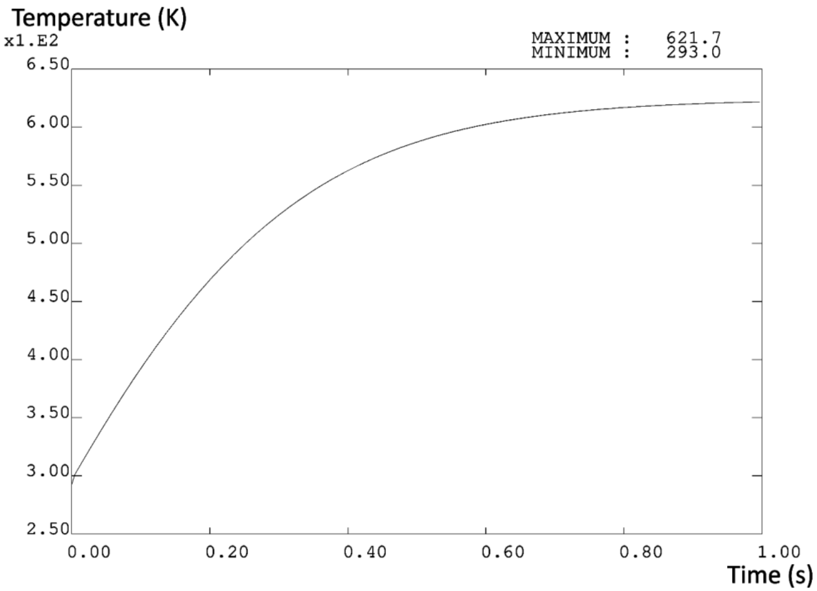
This figure shows the current decrease vs time.

The time constant (I/e) is *520 ms*.

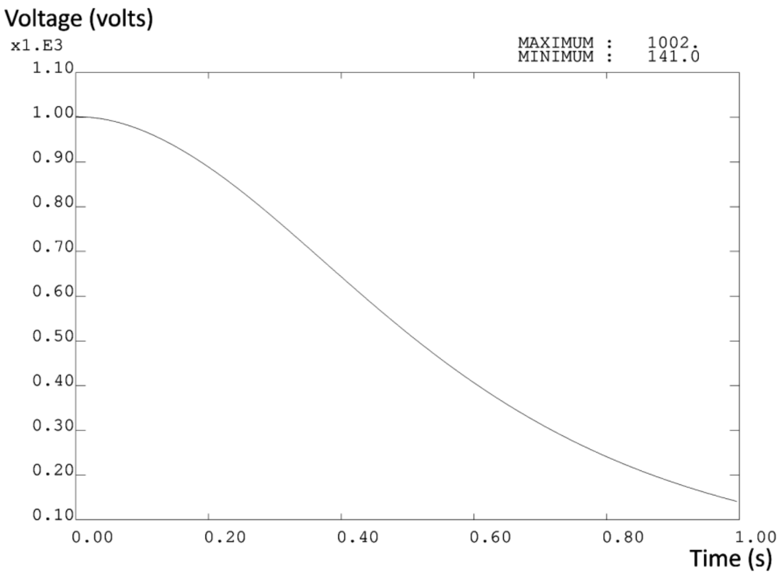
2D results – 4 heaters dump resistance



Its value increases by *30 %* during the discharge.



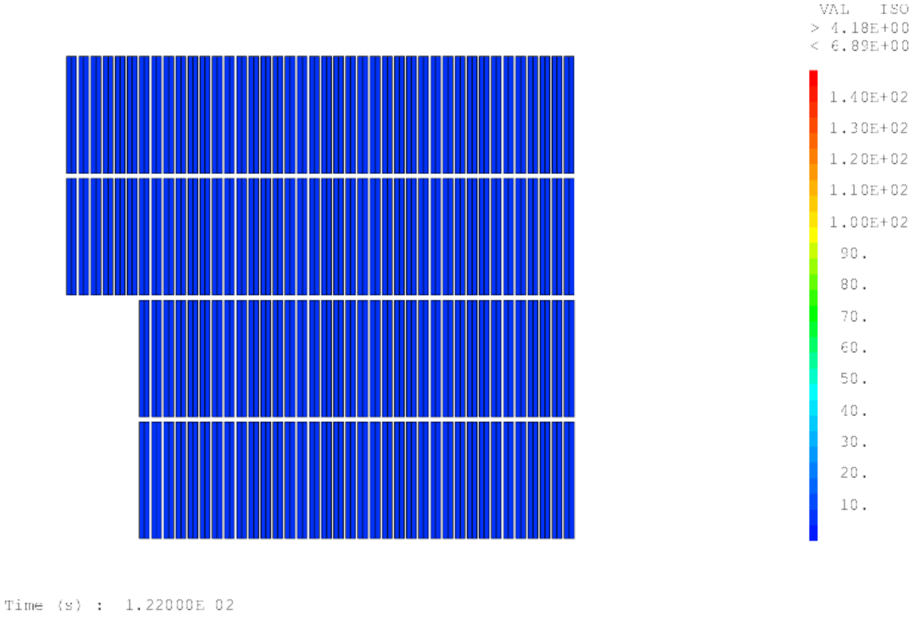
The temperature of the resistance at the end of the discharge is *622 K*, which is an acceptable value.

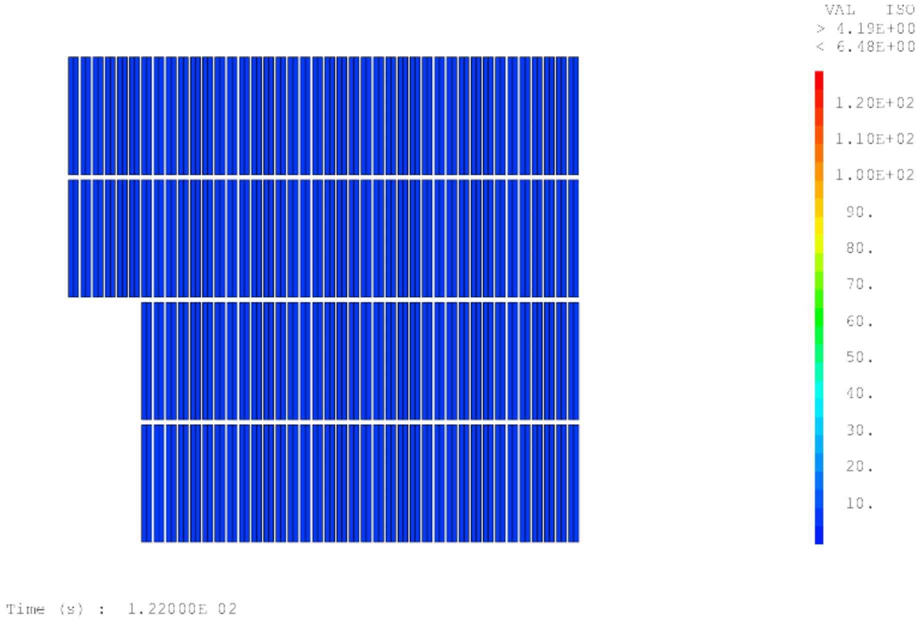


The voltage remains maximum at the beginning of the discharge (nul slope).

Temperature field evolution

2 and 4 heaters





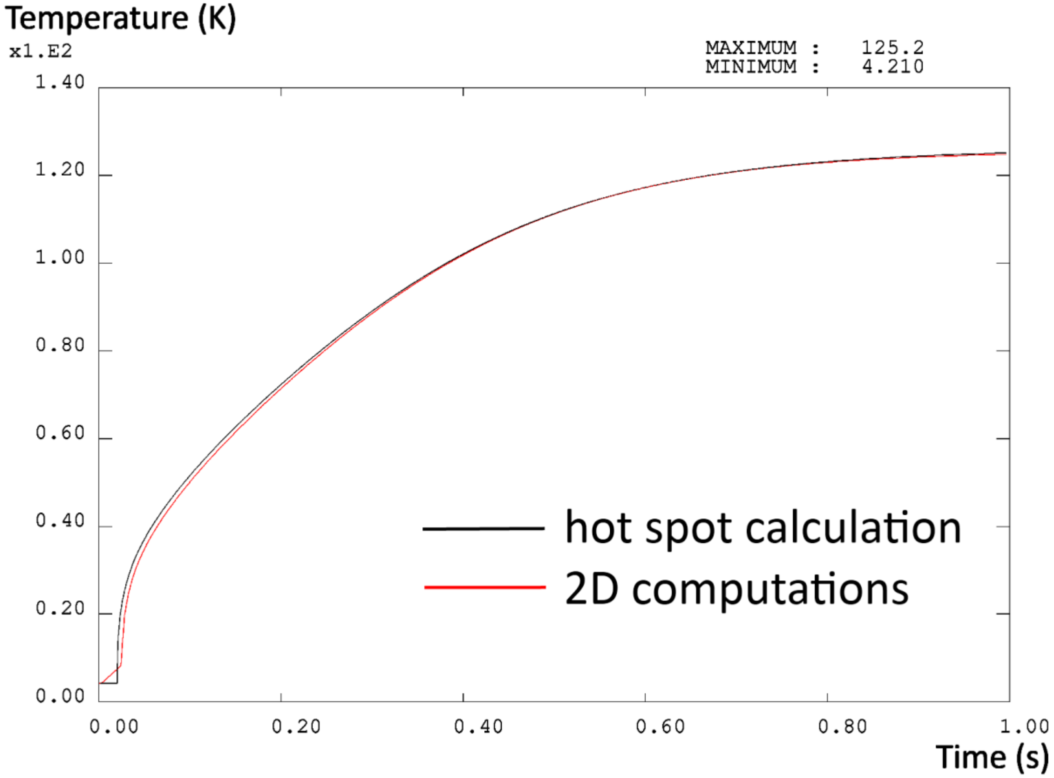
The use of 4 heaters decreases the maximal temperature in the dipole and helps *to distribute more uniformely* the temperature (lower temperatures gradients).

2D results

adiabatic hop spot criteria

From *the current evolution* (right side of the equation), the adiabatic hot spot temperature is calculated and *compared* to the maximum temperature computed by the FEM code.

$$\underbrace{\int_{T_0}^{T_{max}} \frac{C_P}{\rho} dT}_{\text{Conductor properties}} = \underbrace{\int_{0}^{+\infty} j^2(t)dt}_{\text{2D results}}$$



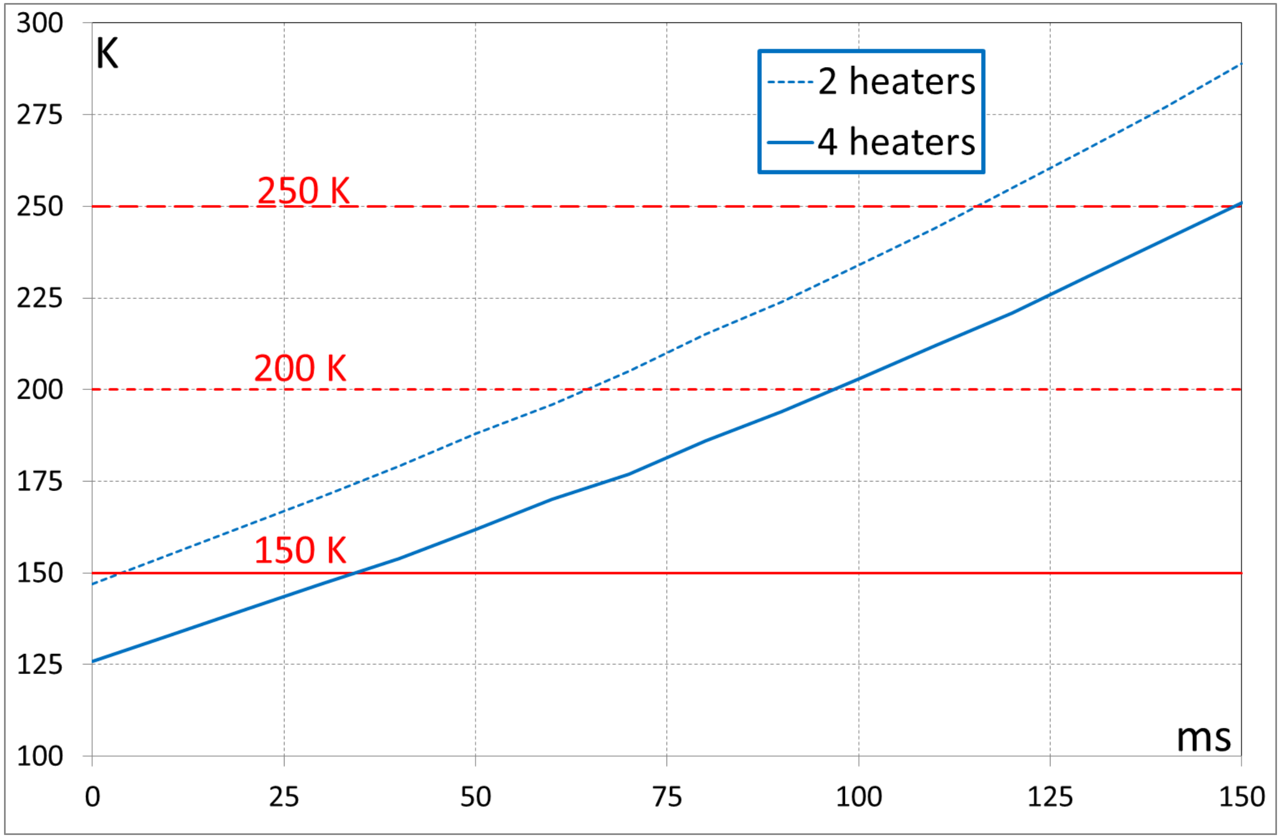
The *good accordance* between both curves allows us to compute directly (i.e. from the current evolution) the maximal temperature taking into account the detection time.

2D results

maximal temperature

The following figure gives the *hot spot temperature* in the dipole, taking into account the *detection time* t_{det}.

The detection must be *lower than 40 ms* if we want a maximal **temperature below 150 K** (4 heaters case).



Nevertheless, we expect a t_{det} # *100 ms* : the maximal temperature is # **200 K for 4 heaters**.

The max temperature difference is around 30 K between 2 and 4 heaters.

It takes 27 ms to reach the resistive voltage of 100 mV in the high-field region.

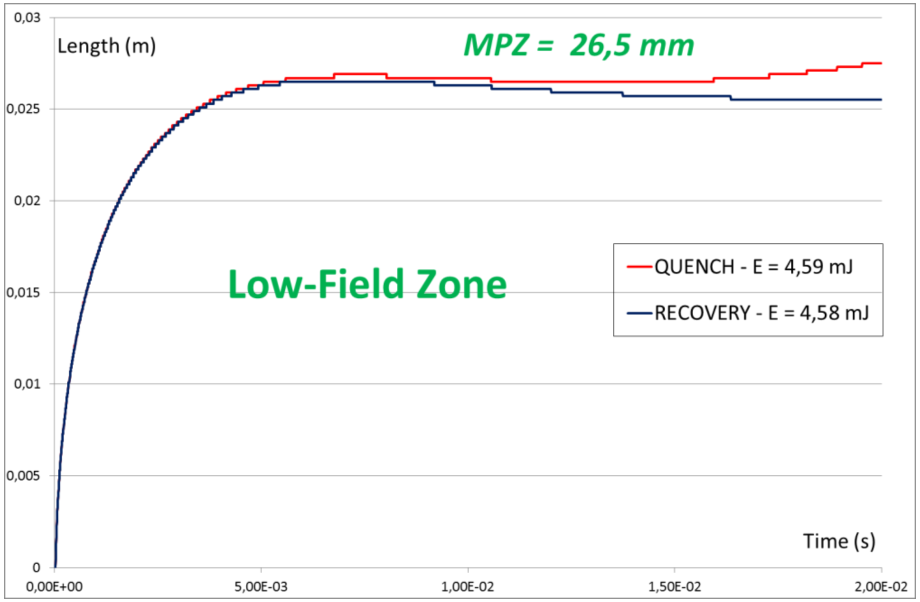
3D computations

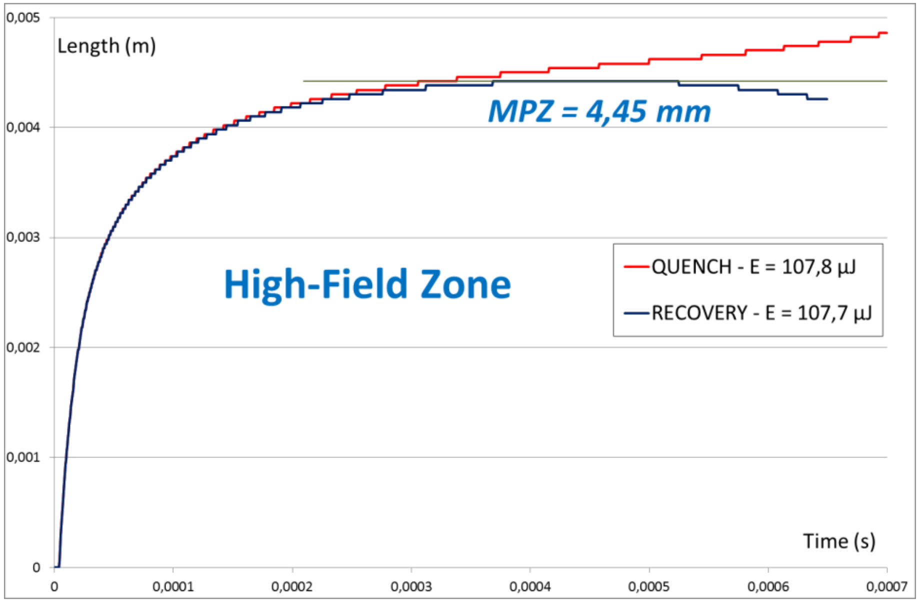
benchmark of CAST3M

The heat equation for the 1D static case without helium cooling leads to the MPZ formula :

$$l_{MPZ} = \pi\sqrt{\frac{\lambda(T_c - T_{cs})}{\rho j^2}}$$

- **High-Field Zone** (B = 13,5 T) ***l_{MPZ}* = *5 mm***
- **Low Field Zone** (B = 0,5 T) ***l_{MPZ}* = *26,5 mm***





⇨ Results of simulation are consistent with the formula

(less than 10 % deviation)

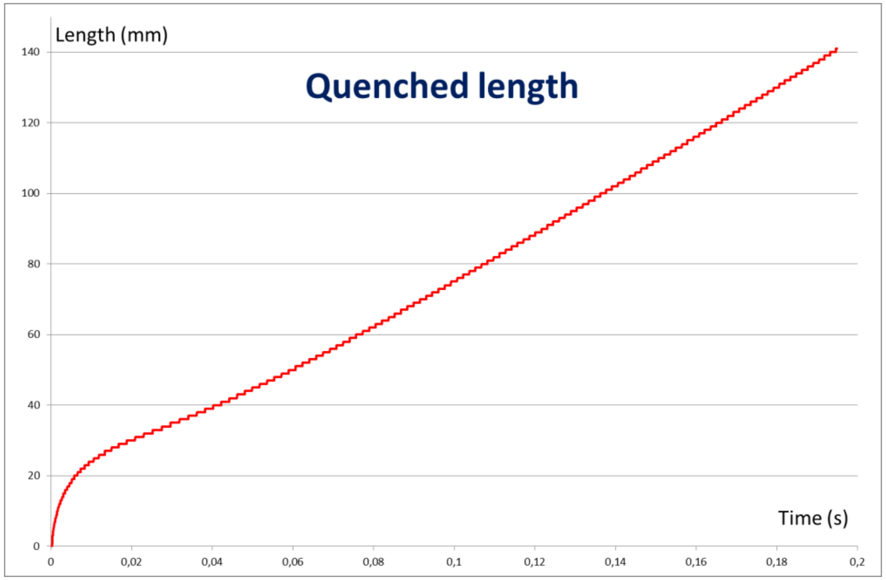
3D computations

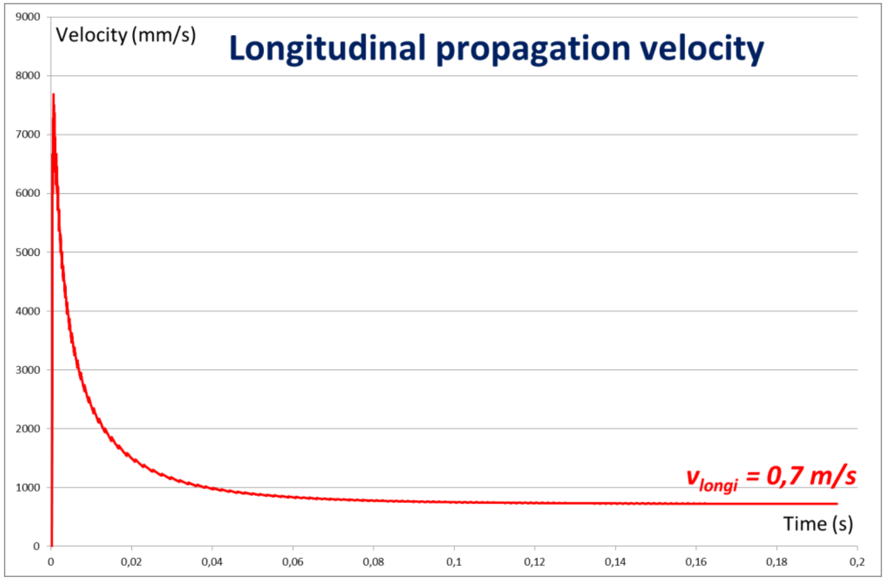
propagation in the low field zone

We simulate the *3D propagation of a quench* in the **low field region** by injecting in an unitary volume an energy larger than the MQE (so that the quenched zone extends more than the MPZ computed).

⇨ We have access to several parameters during the first instants of the propagation :

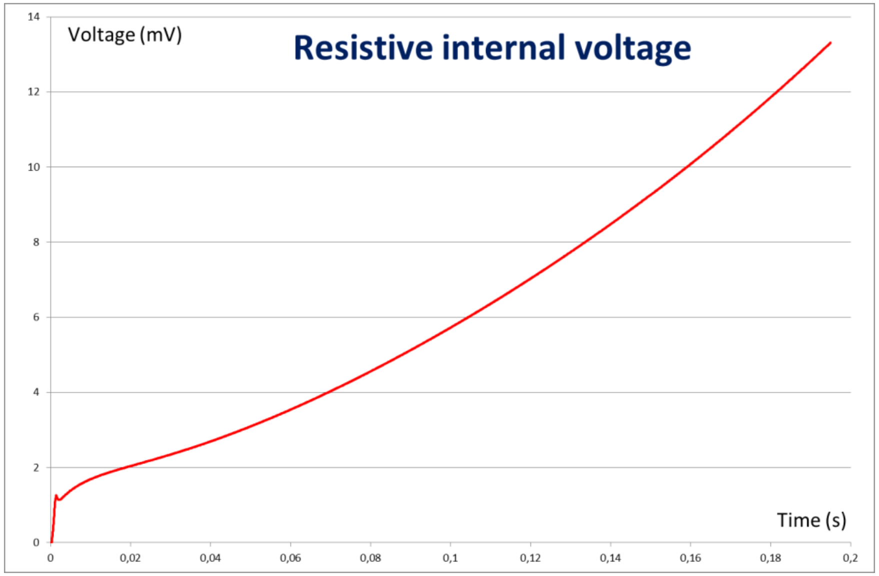
- Resistive **voltage**,
- **Temperature** within the conductor,
- Quenched **length**,
- Propagation **velocity**.

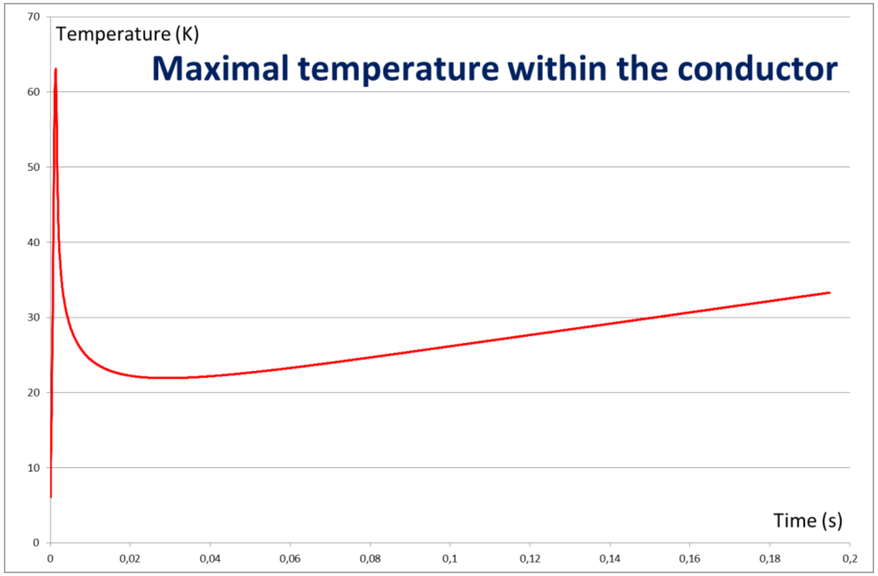




3D computations

voltage and temperature





It takes ***159 ms*** to reach a resistive voltage of ***10 mV***.
The *maximal temperature* within the conductor is then ***31 K***.

By injecting this value in our *hot spot calculation*, we can estimate the ***maximal temperature*** within the conductor at the point of ignition of the quench : the value is ***131 K***.

Conclusions

The quench study has been splitted in two parts :

❖ Before the detection : quench ignition and longitudinal propagation

⇨ ***CAST3M 3D*** has been ***benchmarked*** with very good approximation of the ***MPZ***,

⇨ The 3D computations in the ***low field zone*** show that the ***propagation is slow*** (v_{longi} = 0,7 m/s) but so is ***the temperature elevation***; with a detection threshold of ***10 mV***, the magnet is not endangered (maximal temperature of 131 K).

❖ After the detection : heaters and dump resistor, transverse propagation

⇨ Problem solved with to ***2D computations***,

⇨ ***4 heaters*** are needed to ***reduce thermal gradients***,

⇨ ***Detection time*** should be in the range ***40 to 100 ms*** (150 to 200 K, threshold voltage > 100 mV) in the high field zone : consistent with the results of the 3D LFZ computations.

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