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Thermal-hydraulic analysis of the HTS DEMO TF coil

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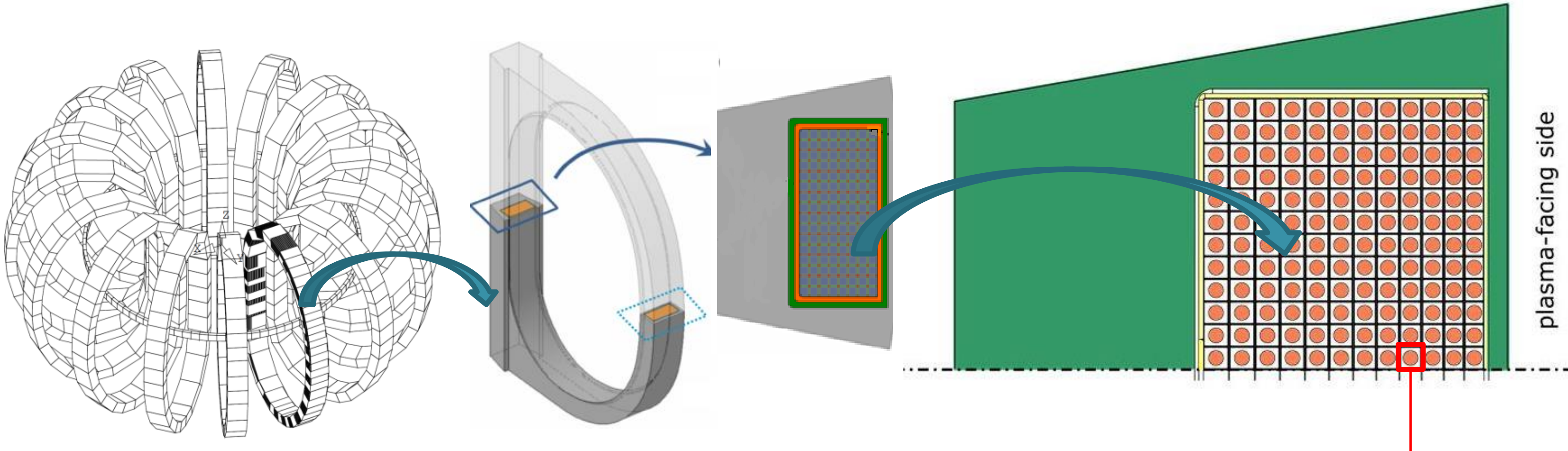
What is DEMO?

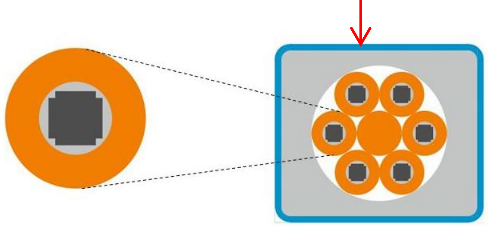
DEMO - a prototype fusion power plant [1]

- Step between ITER and a commercial power plant
- Net electricity production of a few hundreds MW
- DEMO construction has to start in the early 2030s to achieve fusion electricity by 2050

[1] Romanelli F., Barabaschi P., *et al.*, A roadmap to the realisation of fusion electricity. EFDA 2012

DEMO Toroidal Field (TF) coils





Three designs of LTS winding pack of the DEMO TF coil, namely WP#1, WP#2 and WP#3, were developed by EPFL-SPC (Switzerland) [1], ENEA – Frascati (Italy) [2] and CEA (France) [3], respectively. Most recently a new DEMO TF winding pack concept based on REBCO HTS conductors was proposed by KIT [4]

[1] K. Sedlak, et al., Fus. Eng. Des., vol. 124, pp. 110-113, Nov. 2017.
[2] L. Savoldi, et al., Fusion Eng. Des., vol. 124, pp. 45-48, Nov. 2017.
[3] A. Torre, et al., IEEE Trans. Appl. Supercond., vol. 27, no. 4, Jun. 2017, Art. no. 4900705.
[4] M.J. Wolf, et al., IEEE Trans. Appl. Supercond., vol. 26, no. 2, Mar. 2016, Art. no. 6400106

Goal of the present study

Our study is focused on the thermal-hydraulic analysis of the two most recent iterations of the KIT design (Option 8 and 9) using the simplified models developed by our team and the THEA code by CryoSoft . It was aimed at:

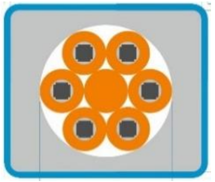
- assessment of the maximum total mass flow rate in the TF coil,
- verification if the proposed designs fulfill the acceptance criteria:
  - **minimum $\Delta T_{marg} > 1.5$ K**
  - **$T^{quench}_{jacket\ max} < 150$ K, $T^{quench}_{strands\ max} < 250$ K**

The analysis included the following stages:

- hydraulic analysis,
- heat removal analysis,
- assessment of the maximum hot spot temperature during quench.

Composition of conductor and winding pack (I)

- 6 CrossConductor (CroCo) monolithic strand located around a copper core and embeded in a SS jacket
- Layer wound winding pack (12 layers)
    - **Option 8:** 1-in-hand winding (25 turns, $\mathbf{I_{op}}$ **= 46 711 A**)
    - **Option 9:** 2-in-hand winding (2 x 12 turns, $\mathbf{I_{op}}$ **= 49 595 A**)



CroCo characteristics

Parameter	Unit	Value
Diameter	mm	10.4
width tape_1	mm	4
width tape_2	mm	3
Number of tapes _1	-	30
Number of tapes_2	-	10
A_Cu_tapes	mm^2	6
A_Cu_total	Mm^2	68.05
A_Hastelloy	mm^2	7.50
A_REBCO	mm^2	0.20
A_Ag	mm^2	0.60
A_solder	mm^2	9.40
I_c of tape (12 T, 4.2 K)	A/mm	67
I_c of CroCo (12 T, 4.2 K)	A	10050

Cable characteristics

Parameter	Unit	Value
Number of CroCo’s	-	6
Cable space diameter	mm	31.2
Central core diameter	mm	10.4
A_Cu in CroCo’s	mm^2	408.28
A_Cu in core	mm^2	84.95
A_Solder	mm^2	56.41
A_REBCO	mm^2	1.21
A_Ag	mm^2	3.60
A_Hastelloy	mm^2	45.00
A_He	mm^2	165.4
A_Jacket	mm^2	954.85 (L1)
I_c (12 T, 4.2 K)	A	72850
I_{op}/I_c	-	0.65

Composition of conductor and winding pack (II)

- Cable design is the same for different layers (no grading), due to large size of CroCo
- Jacket thickness increases in the radial direction and remains constant (6.95 mm) in the toroidal direction

Layer	Conductor size non-insulated (mm x mm)	Jacket radial thickness (mm)	Option 8 Cable length (m)	Option 9 Cable length (m)
1	45.1 x 38.2	3.5	1096	2 x 526
2	45.1 x 38.2	3.5	1105	2 x 530
3	45.1 x 42.2	5.5	1113	2 x 534
4	45.1 x 42.2	5.5	1122	2 x 538
5	45.1 x 44.2	6.5	1130	2 x 542
6	45.1 x 44.2	6.5	1138	2 x 546
7	45.1 x 46.2	7.5	1146	2 x 550
8	45.1 x 46.2	7.5	1154	2 x 554
9	45.1 x 48.2	8.5	1161	2 x 557
10	45.1 x 48.2	8.5	1169	2 x 561
11	45.1 x 50.2	9.5	1176	2 x 564
12	45.1 x 50.2	9.5	1182	2 x 567

Turn insulation	1.5 mm
Layer insulation	2 mm
Ground insulation	10 mm

Basic assumptions

- Operating conditions:

  $T_{in} = 4.5\text{ K}$, $p_{in} = 6\text{ bar}$, $\Delta p = 1\text{ bar}$

- Fanning friction factor correlation developed for the EURATOM LCT conductor [5]:

$$f_{LCT}(\mathrm{Re}) = \frac{1}{4} \cdot \begin{cases} 47.65 \cdot \mathrm{Re}^{-0.885} & \text{for } \mathrm{Re} < 1500 \\ 1.093 \cdot \mathrm{Re}^{-0.338} & \text{for } 1500 < \mathrm{Re} < 2 \cdot 10^5 \\ 0.0377 & \text{for } \mathrm{Re} > 2 \cdot 10^5 \end{cases}$$

Conductors of this type have not been tested for pressure drop yet. Predicitve capability of the friction factor correlation should be verified experimentally.

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[5] D. S. Beard, W. Klose, S. Shimamoto, and G. Vecsey, “The IEA Large Coil Task development of superconducting toroidal field magnets for fusion power,” Fusion Eng. Des., vol. 7, no. 1/2, pp. 1–230, 1988.

Hydraulic analysis - model

No heat deposition in conductors (isenthalpic flow), $\Delta p = 1$ bar

$$h(T_{in}, p_{in}) = h(T_{out}, p_{out}) \Rightarrow T_{out} = 4.602\ \mathrm{K}$$

For the given value of pressure drop mass flow rates ($\dot{m}$) in each conductor are obtained from:

$$\frac{\Delta p}{L} = \frac{2\dot{m}^2 f}{D_h \rho A_{He}^2}$$ momentum balance equation for uncompressible flow

where helium properties are calculated at the reference conditions:

$$T_{ref} = (T_{in} + T_{out})/2$$

$$p_{ref} = (p_{in} + p_{out})/2$$

Heat removal analysis – model

$\dot{Q}_L$ - heat deposition rate per unit length of conductor (W/m)

$$\begin{cases} \dot{m}\dfrac{dh}{dx} = \dot{Q}_L(x) & (1) \\[2ex] \dfrac{dp}{dx} = -\dfrac{2\dot{m}^2 f\,(\mathrm{Re})}{D_h\,\rho(T,p)A_{He}^2} + v^2\dfrac{d\rho}{dx} & (2) \end{cases}$$

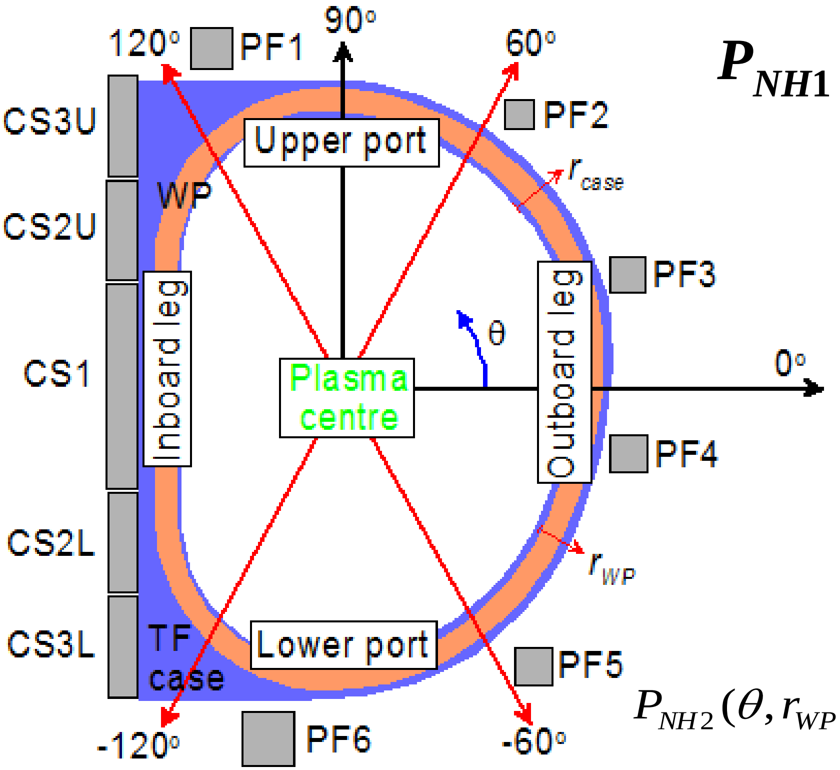
$$\frac{dh}{dx} = C_p(T,p)\frac{dT}{dx} + \frac{1}{\rho(T,p)}\left[1-\alpha(T,p)\cdot T\right]\frac{dp}{dx}$$

$$\begin{cases} T(0) = T_{in} \\ p_i(0) = p_{in} \end{cases}$$ boundary conditions for Eqs. (1),(2)

mass flow rate as well as temperature and pressure profiles along each conductor for a given heat deposition rate

Heat removal analysis – heat deposition

Expected value of the nuclear heat (NH) load, deposited in the TF case and in the WP due to neutron irradiation, was estimated by integrating the formula [6]:



$$P_{NH1} = 50\ \mathrm{W/m^3} \cdot \exp(-r_{case}/0.140\ \mathrm{m}) \quad (1)$$

Eq. (1) served as a reference for the present WP designs, so it was retained as a basic approach in our analysis. However, the most recent neutronic study, provided the new more advanced formula for NH load in the WP [7]:

$$P_{NH2}(\theta, r_{WP}, z) = \begin{cases} 2.5\ \mathrm{W/m^3} \quad \text{for} -60^{\circ} < \theta < 60^{\circ} \\ 50\ \mathrm{W/m^3} \cdot \exp(-r_{WP}/0.125\ \mathrm{m}) \\ \qquad\qquad \text{for} -120^{\circ} < \theta < 120^{\circ} \\ 20 + 16|z|\ \mathrm{W/m^3} \quad \text{for}\ 60^{\circ} \le \theta \le 120^{\circ} \\ \qquad\qquad \text{or} -120^{\circ} \le \theta \le -60^{\circ} \end{cases}$$

[6] L. Zani, U. Fischer, “Advanced definition of neutronic heat load density map on DEMO TF coils,” Memo for WPMAG-MCD-2.1/2.2/ 3.3, v. 1.0, 2014, https://idm.euro-fusion.org/?uid=2MFVCA

[7] M. Coleman, “Advanced definition of neutronic heat load density map on DEMO TF coils,” Memo for WPMAG-MCD-2.1/2.2/3.3, v.2.0, 2016, https://idm.euro-fusion.org/?uid=2MFVCA

Heat removal analysis – T_{cs} calculation

Scaling law for REBCO [8]**:**

$$J_C(B,T) = A\frac{B_0(T)^{\beta}}{B}\left(\frac{B}{B_0(T)}\right)^{p}\left(1-\frac{B}{B_0(T)}\right)^{q}$$ critical current density

$$B_0(T) = B_0(0)\left(1-\frac{T}{T_0}\right)^{\alpha}$$ critical magnetic flux density

$A = 1.82962\cdot 10^{8}\,\mathrm{A/(m^2\,T^{\beta-1})}$ $B_0 = 132.5\ \mathrm{T}$ $T_0 = 90\ \mathrm{K}$

$\alpha = 1.54121$ $\beta = 1.96679$ $p = 0.5875$ $q = 1.7$

For a given operating current density J_{op} we computed T_{cs} as a function of B by solving the equation:

$$\boxed{J_C(B,T_{cs}) = J_{op}}$$

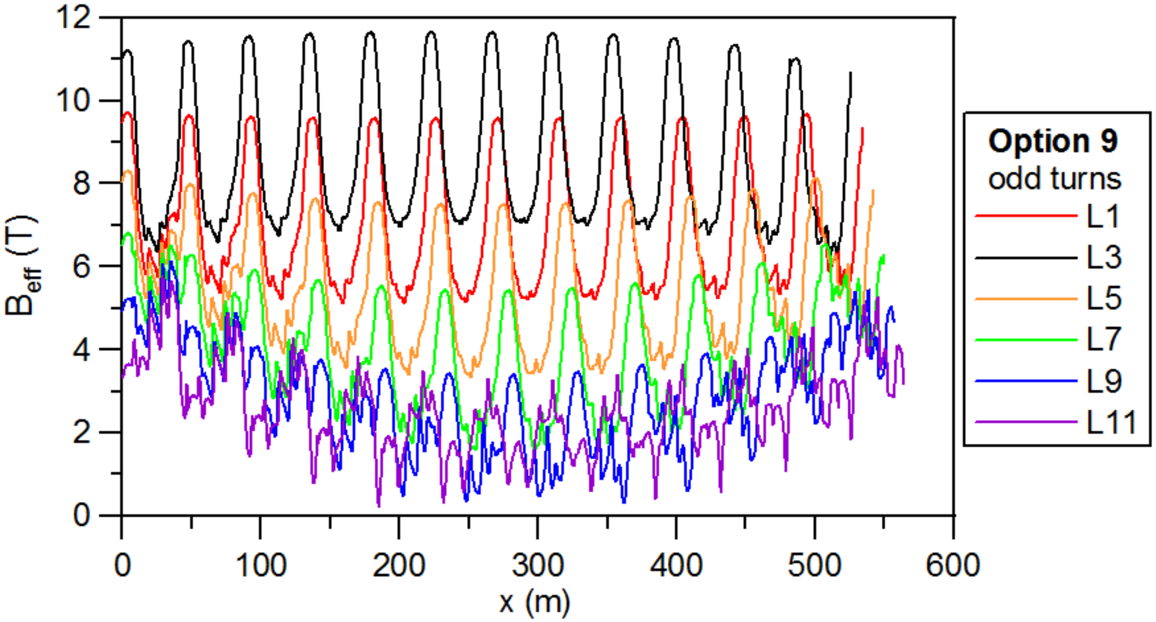
[8] R. Heller, et al., IEEE Trans. Appl. Supercond., vol. 26, No. 4, Jun. 2016, Art. No. 4201105

Heat removal analysis – calculation of ΔT_{marg}

In our earlier studies, e.g. [9], the minimum ΔT_{marg} for the layer wound coils was estimated conservatively in the simplified way as:

$$\Delta T_{marg\ min} = T_{cs}\,(B_{max}) - T_{out}\ .$$

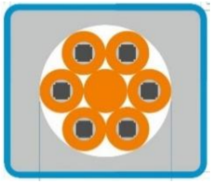
In the present work we introduced to the heat removal model the computed effective magnetic field profiles along the cables and $\boldsymbol{\Delta T_{marg\ min}}$ was found as the minimum of $\boldsymbol{T_{cs}\,(B(x)) - T(x)}$.

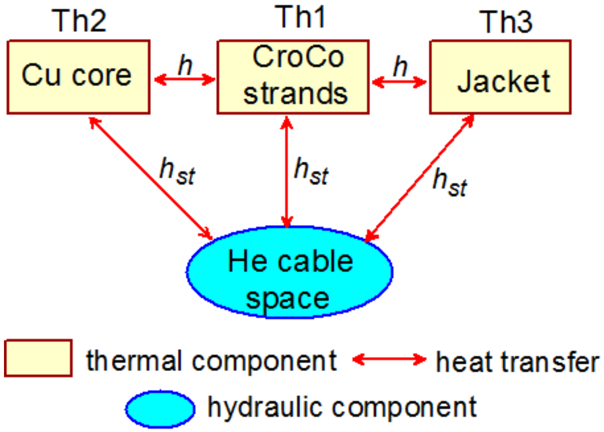


Magnetic field profiles along the selected cables computed with the M'C code from CryoSoft.

[9] M. Lewandowska, et al., IEEE Trans. Appl. Supercond., vol. 26, no. 4, Jun. 2016, Art. no. 4205305

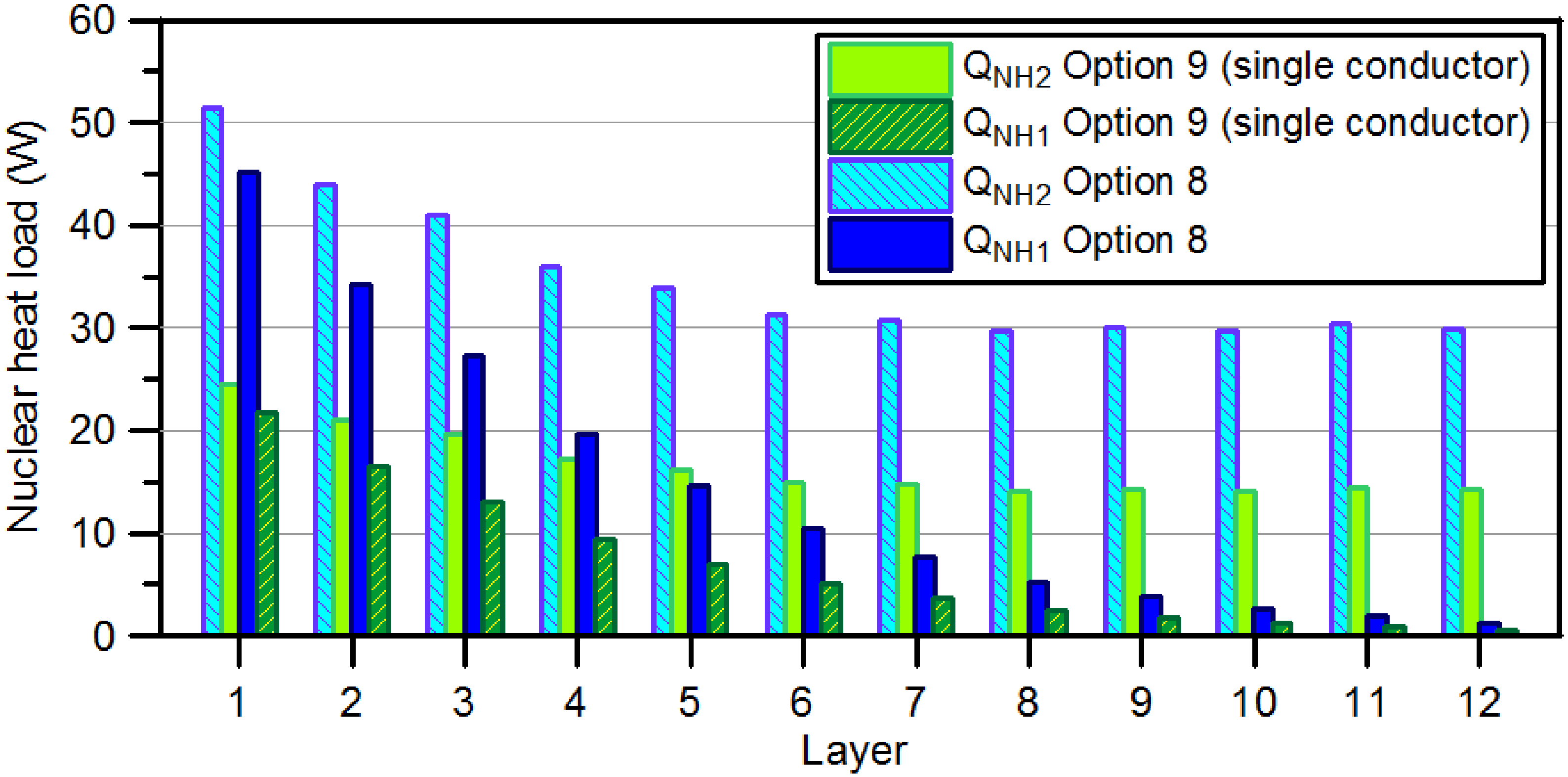
THEA model



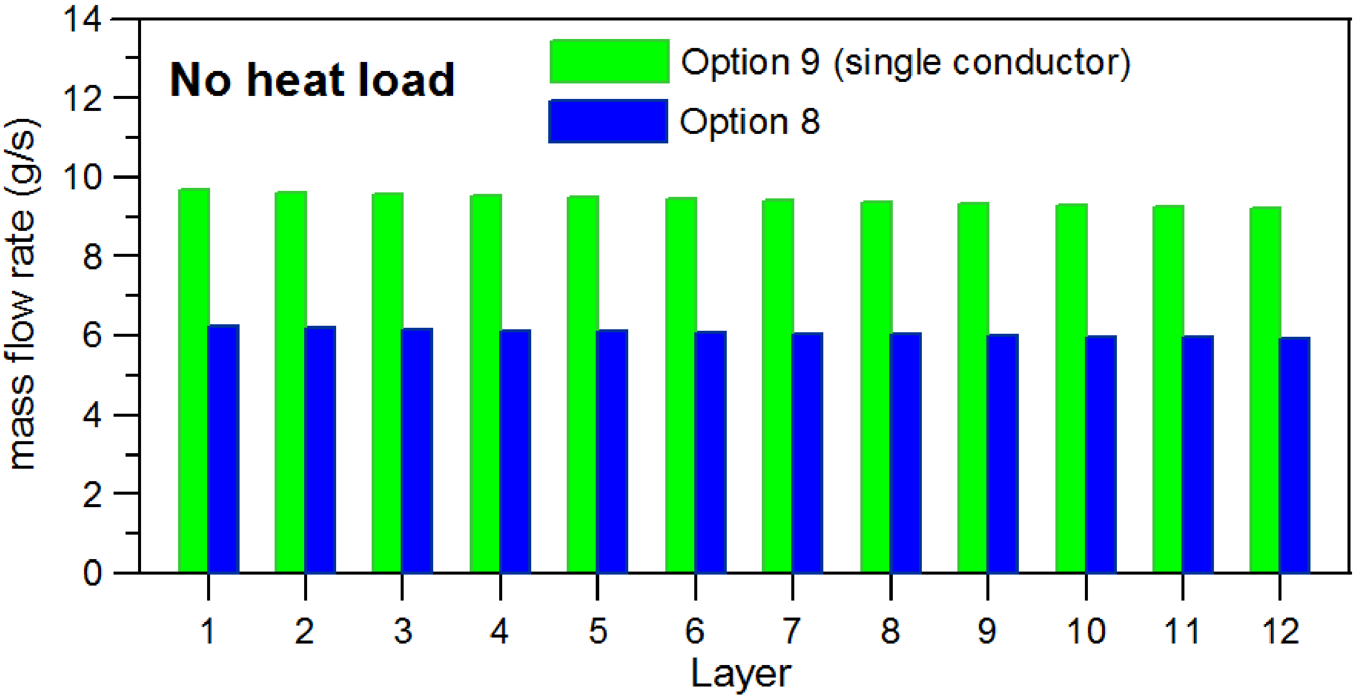


- Coupling Th1-Th2 and Th1-Th3 via thermal resistances $R=1/(hp)$, where h = 500 W/(m^{2}K)
- Full cable length carrying 46 711 A (opt 8) / 49 595 A (opt 9) subjected to the expected effective magnetic field and NH load was simulated.
- The adiabatic and fixed pressure (infinite reservoir) boundary conditions were imposed at both ends of each cable.
- The obtained steady state temperature, pressure and mass flow profiles served as the initial conditions for the subsequent quench simulation.
- Quench was initiated by a heat disturbance of length 10 cm and duration 100 ms imposed at one of the ΔT_{marg} minima. The disturbance energy was planned to be 2 x MQE.
- In quench simulation we used refined initial mesh with automatic adaptivity. In the 1 m long refined region around the disturbance location the distance between nodes was 2 cm, in the rest of a cable – 25 cm.
- The quench detection threshold is set at 0.1 V, with an additional delay of 1.1 s before the start of exponential current dump with the characteristic time τ = 27 s.

Results – heat deposition in conductors



Results - hydraulic analysis



Option	Total mass flow rate (g/s)		
	No heat load	Q_{NH1}	Q_{NH2}
8	72.9	72.0	70.6
9	226.6	225.9	224.9

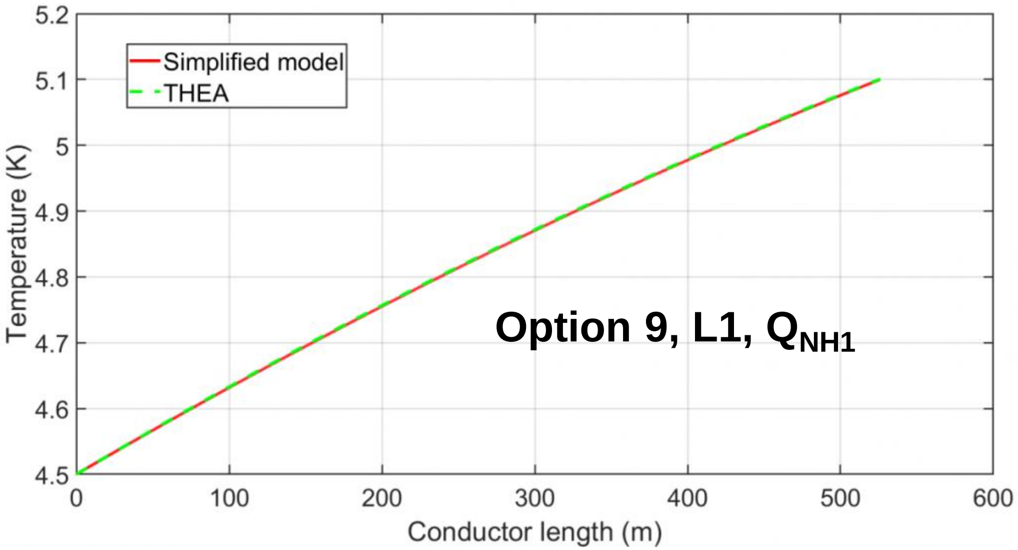
For comparison:

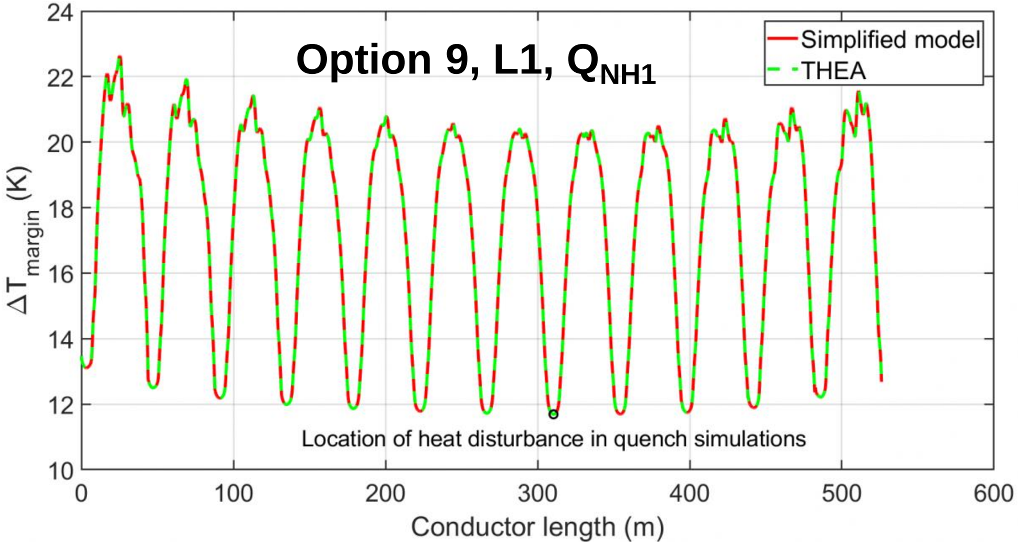
In LTS TF coils at no heat load:

MIN total massflow: **57 g/s** (WP#2)

MAX total massflow: **203 g/s** (WP#3)

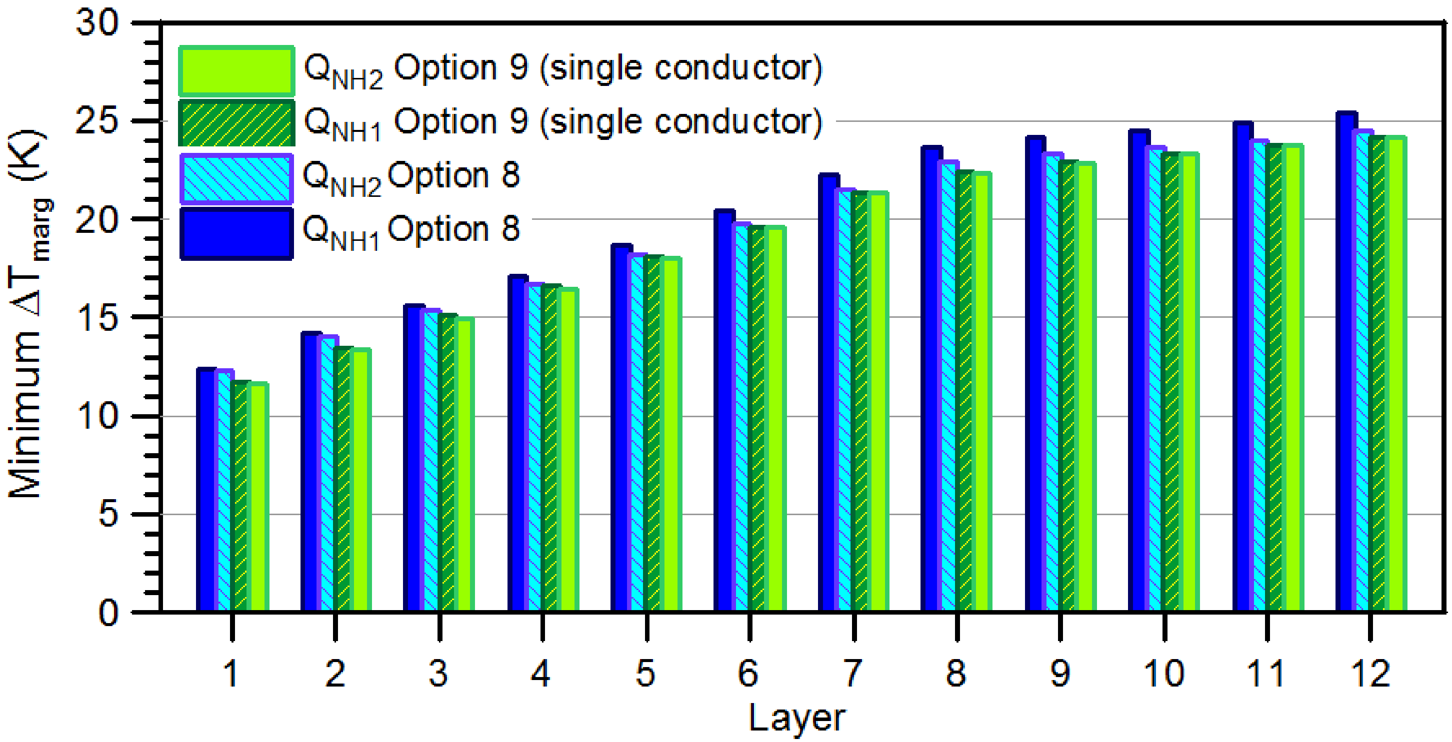
Results – heat removal analysis (I)





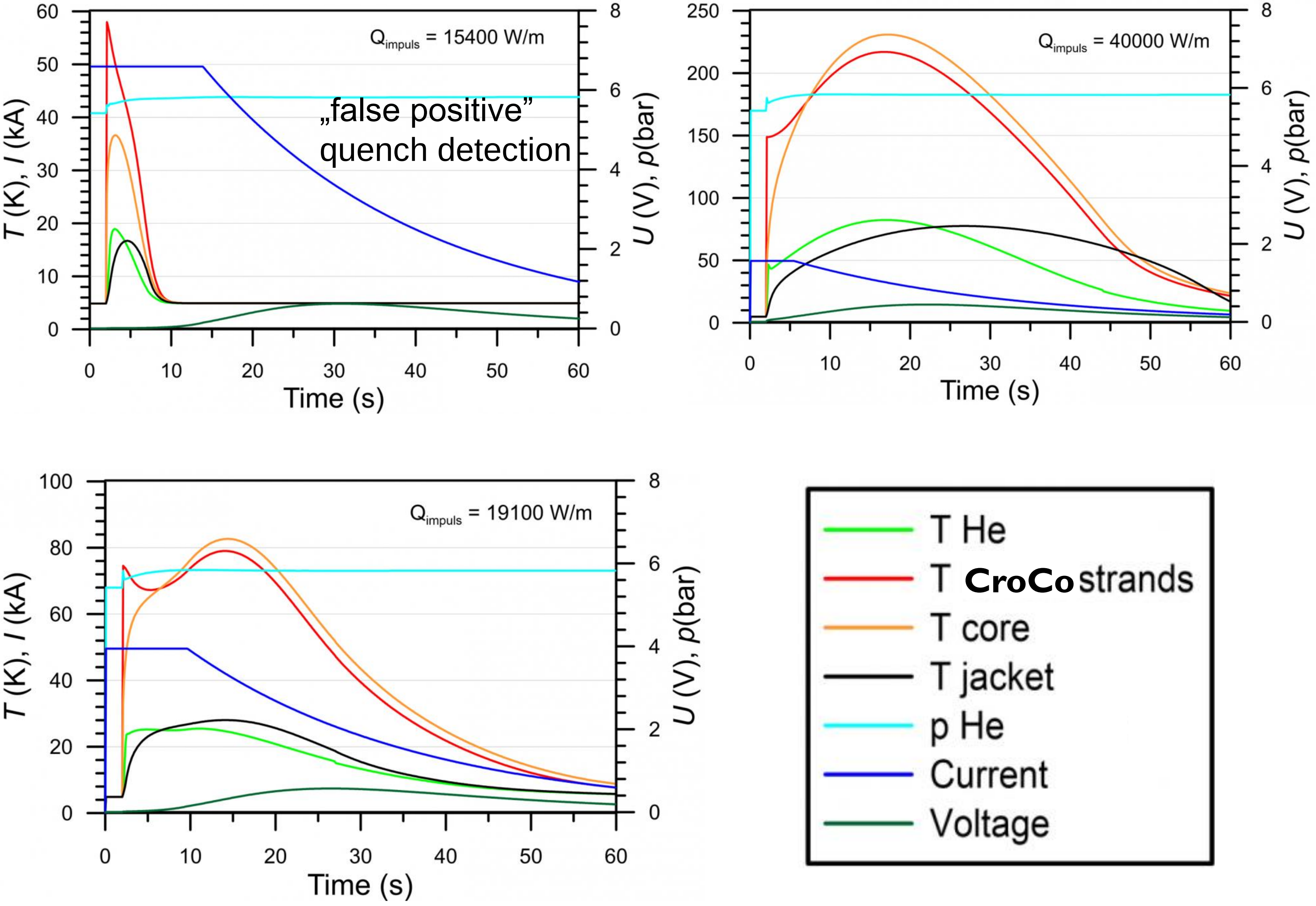
- Steady state temperature, pressure and ΔT_{marg} profiles obtained with THEA and with the simplified model agree very well ☺
- Minimum of ΔT_{marg} is typically located at one of the T_{cs} minima in one of the last turns.

Results - heat removal analysis (II)

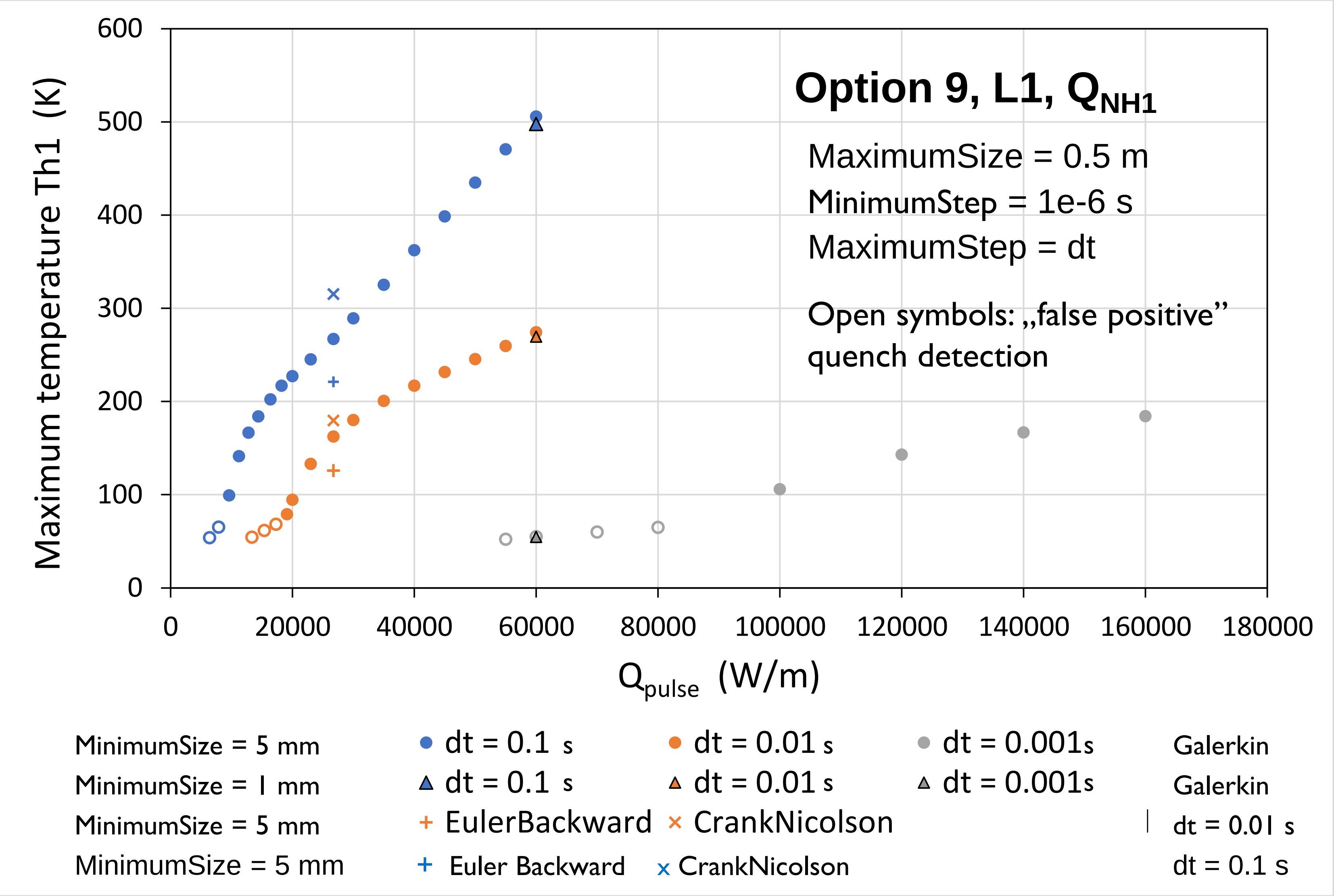


Minimum ΔT_{marg} is much larger than the 1.5 K criterion and much larger than ΔT_{marg} in all LTS WP#1-WP#3 conductors.

Results - quench analysis (I)


„false positive” quench detection

Results - quench analysis (II)



Option 9, L1, Q_{NH1}

MaximumSize = 0.5 m
MinimumStep = 1e-6 s
MaximumStep = dt

Open symbols: „false positive" quench detection

Summary and conclusions

- Thermal-hydraulic analysis of the DEMO TF coil design based on the HTS CroCo conductors was performed using simplified models and the THEA code.
- Predictive capability of the friction factor correlation used in the analysis should be verified experimentally.
- The maximum total mass flow rate in the TF coil was assessed to be 73 g/s (Option 8), and 227 g/s (Option 9).
- The computed temperature margin obtained for both considered NH load maps varied in the range 11.6 – 24.5 K, which is much larger than in all the LTS TF coil designs.
- MQE assessment was problematic due to the occurence of „false positive" quench detections
- MQE value was very sensitive to the choice of the MaximumStep value.
- The value of the maximum hot spot temperature was sensitive to the choice of integration method and MaximumStep value.
- The maximum hot spot temperature significantly increases with the disturbance energy (for comparison: in the LTS WP#1 L1 cable the T_{max} increased only about 10 K, when Q_{pulse} varied in the range 340 – 5e4 W/m [1])
- Ideas how to reliably estimate the hot spot temperature are very welcome.

Thank you for your attention

We would like to thank Kamil Sedlak (EPFL-SPC) for providing us the magnetic field maps.

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Question Time