

## Thermal-Hydraulic Analysis of the DEMO CS coil

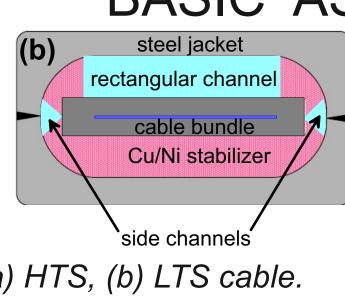
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Two alternative designs of the Central Solenoid (CS) coil were proposed by EPFL-SPC, PSI Villigen and CEA Cadarache for the European DEMO tokamak. The DEMO CS coil consists of five modules, namely CSU3, CSU2, CS1, CSL2 and CSL3, the most demanding of which is the CS1 one. Our present work is focused on the thermal-hydraulic analysis of the CS1 module designed by EPFL-SPC at the normal operating conditions during the whole plasma scenario. We take into account the realistic magnetic field distribution, heat transfer between neighboring turns, and heat generation due to AC losses. The analysis, performed using the THEA Cryosoft code, was aimed at the assessment of the minimum temperature margin and at verification if the proposed design fulfills the acceptance criteria. Obtained minimum temperature margin in layers L1-L18 was sufficiently large, whereas in L19 was slightly below the 1.5 criterion.

#### **GOAL**

- Assessment of the minimum temperature margin and verification if the proposed design fulfills the acceptance criteria.
- Provide the information for further optimization of the conductor layouts.

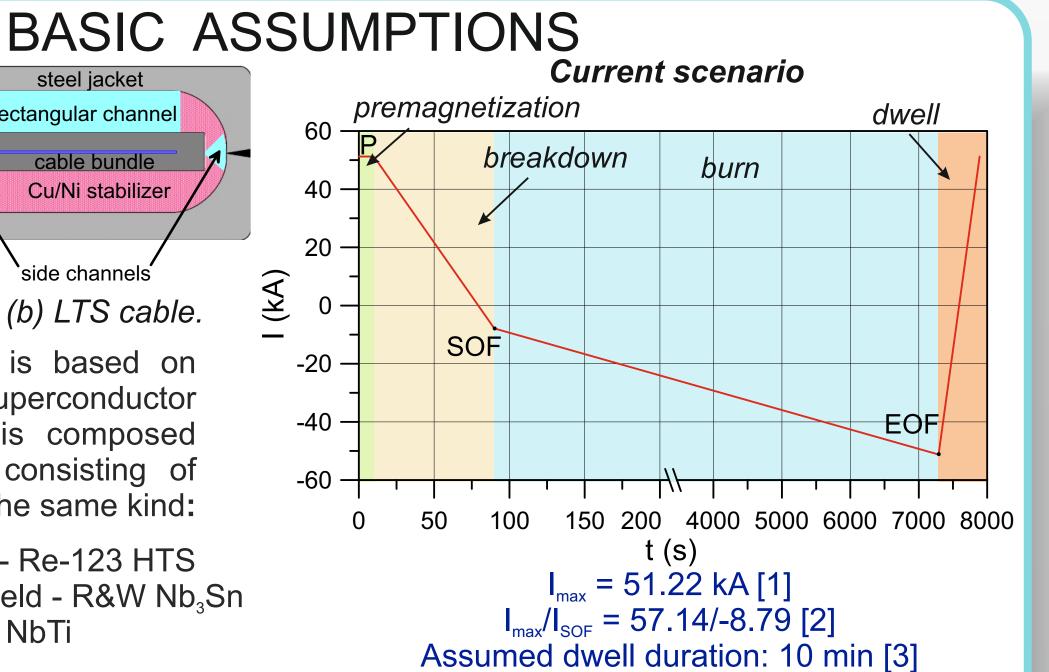


Schematic layout of a (a) HTS, (b) LTS cable. The EPFL-SCP CS1 design is based on

a layer-wound concept with superconductor grading. The winding pack is composed of 10 sub-coils (SC), each consisting of 2 layers wound with cables of the same kind:

: high magnetic field - Re-123 HTS **L5 - L14**: medium magnetic field - R&W Nb<sub>3</sub>Sn

L15 - L20 : low magnetic field - NbTi



### Conductors parameters used in the analysis: 3rd iteration of the EPFL-SPC Cs1 design [1]

		L3 999.8 1.73 86.4 69.1 6.57 206.0 206.0 141.0 1.40 2817.9										17.9	
LTS	<u> </u>	A <sub>scon</sub>	A <sub>Cu1</sub> B	A <sub>Cu2 B</sub>	A <sub>He</sub> B	<b>D</b> <sub>h В</sub>	φ	A <sub>He side</sub>	D <sub>h side</sub>	A <sub>He rect</sub>	D <sub>h rect</sub>	A <sub>stab</sub>	Ajacket
SC	(m)	(mm <sup>2</sup> )	$(mm^2)$	(mm <sup>2</sup> )	$(mm^2)$	(mm)	φ (-)	(mm <sup>2</sup> )	(mm)	$(\text{mm}^2)$	(mm)	(mm <sup>2</sup> )	(mm <sup>2</sup> )
L5	1054	109.2	109.2	12.1	79.7	0.531	0.250	41.9	2.01	112.3	12.78	305.5	2727.4
L7	1105	71.8	71.8	8.0	52.3	0.452	0.250	70.6	2.78	95.0	11.85	350.7	2589.7
L9	1155	50.0	50.0	16.7	40.9	0.481	0.250	37.1	1.94	130.4	13.75	362.3	2509.1
L11	1203	35.7	35.7	11.9	29.3	0.412	0.250	44.2	1.90	128.7	13.70	382.9	2455.7
L13	1250	26.0	26.0	8.7	21.3	0.397	0.249	56.3	1.93	120.4	13.30	397.4	2420.0
L15	1298	84.8	84.8	9.4	61.71	0.490	0.250	66.8	2.75	99.29	12.19	345.6	2675.9
L17	1348	29.2	29.2	9.7	23.89	0.419	0.250	57.4	2.02	118.71	13.21	394.1	2436.9
L19	1394	15.5	15.5	5.2	12.14	0.372	0.248	62.2	1 76	118 84	13 26	4124	2383 1

## THEA MODEL OF THE CS1 MODULE CONDUCTORS

### Assumed AC losses

The coupling loss per unit length of conductor in a field ramped at a uniform rate was calculated as:

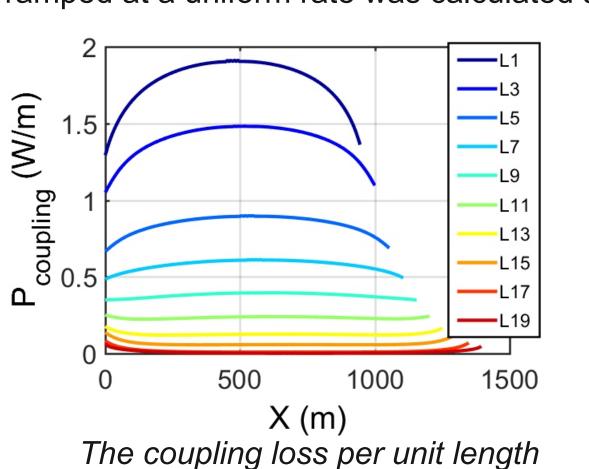
$$P_{coupling} = \frac{n\tau S}{\mu_0} \left(\frac{d\vec{B}}{dt}\right)^2 = \frac{n\tau S}{\mu_0} \left[ \left(\frac{dB_r}{dt}\right)^2 + \left(\frac{dB_z}{dt}\right)^2 \right]$$
 [4]

n – shape factor

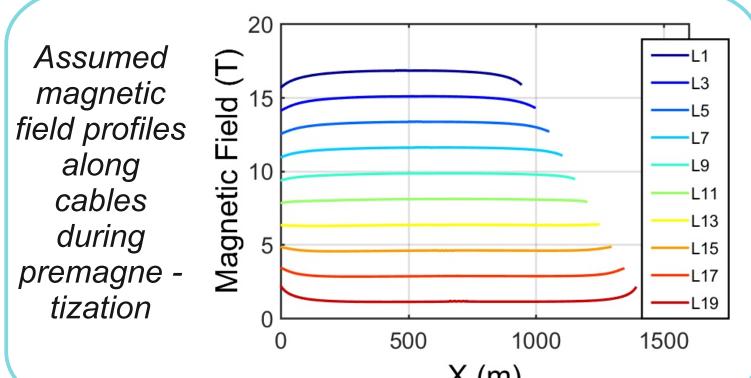
 $\tau$  – time constant dependent

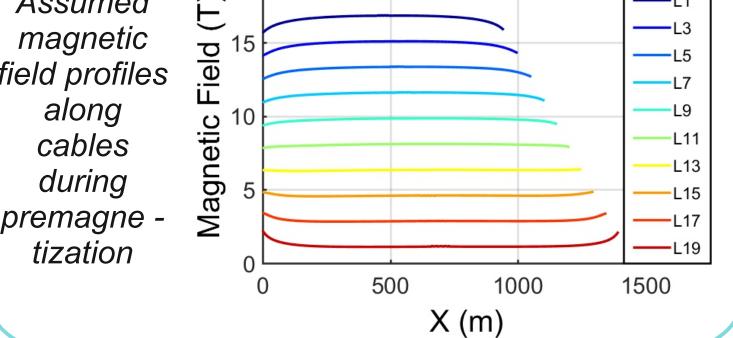
on conductor parameters S – conductor cross section excluding He and steel jacket To assess coupling losses in DEMO conductors we use the  $n\tau$  values taken from the ITER DDD [5], namely for the CS cables  $n\tau = 75$ ms

 $B_i(x)_{breakdown} \approx (B_i(x)_{SOF} - B_i(x)_P)/80 \text{ s}$  $\dot{B}_i(x)_{burn} \approx (B_i(x)_{EOF} - B_i(x)_{SOF})/3600 \text{ s}$  $\dot{B}_i(x)_{dwell} \approx \left(B_i(x)_P - B_i(x)_{EOF}\right)/600 \text{ s}$ 



of conductor during breakdown



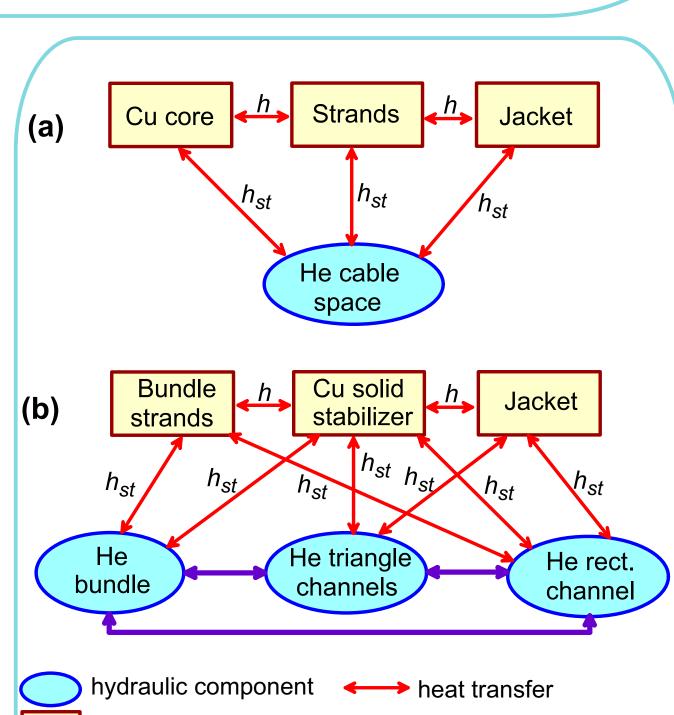


#### Friction factor correlations

Bundle region (LTS): the correlation based on the Darcy-Forchheimer momentum balance equation [6] Colling channels (LTS): Bhatti-Shah correlation for turbulent flow in smooth tube

Bundle region (HTS): correlation of the EURATOM LCT conductor [7]:

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



thermal component heat and mass transfer Links between different cable components

a) HTS: L1 - L3 b) LTS: L5 - L19

#### REFERENCES

[1] R. Wesche and X. Sarasola, "Report on CS Winding Pack Design and Analysis," Final report MAG-2.1-T004-D003, 2017, https://idm.euro-fusion.org/?uid=2MRPVA.

[2] R. Ambrosino and R. Albanese "Reference flat-top equilibria for DEMO with aspect ratio 3.1," EUROfusion internal report, unpublished. [3] G. Federici, et al., "DEMO Design Activity in Europe: Progress and Updates," to be presented at the ISFNT-13 conference.

[4] A.M. Campbell, "A general treatment of losses in multifilamentary superconductors," Cryogenics, vol. 22, no.1, pp. 3–16, Jan. 1982. [5] ITER Design Description Document. Magnets. Section 7: Conductors, ITER\_D\_2NBKXY v1.2, 2009.

[6] Bagnasco M, Bottura L, Lewandowska M, Friction factor correlation for CICC's based on a porous media analogy, Cryogenics 50 (2010) 711–719.

[7] R. Heller, et al., Conceptual Design Improvement of a Toroidal Field Coil for EU DEMO Using High-Temperature Superconductors, IEEE Trans. Appl. Supercond. vol. 26, no. 4, Jun. 2016, Art. no. 4201105.

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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Layer

#### RESULTS

#### Hydraulic analysis

No heat deposition in conductors (isenthalpic flow)  $\Delta p = 1$  bar,  $h(T_{in}, p_{in}) = h(T_{out}, p_{out}) \longrightarrow T_{out} = 4.602 \text{ K}$ 

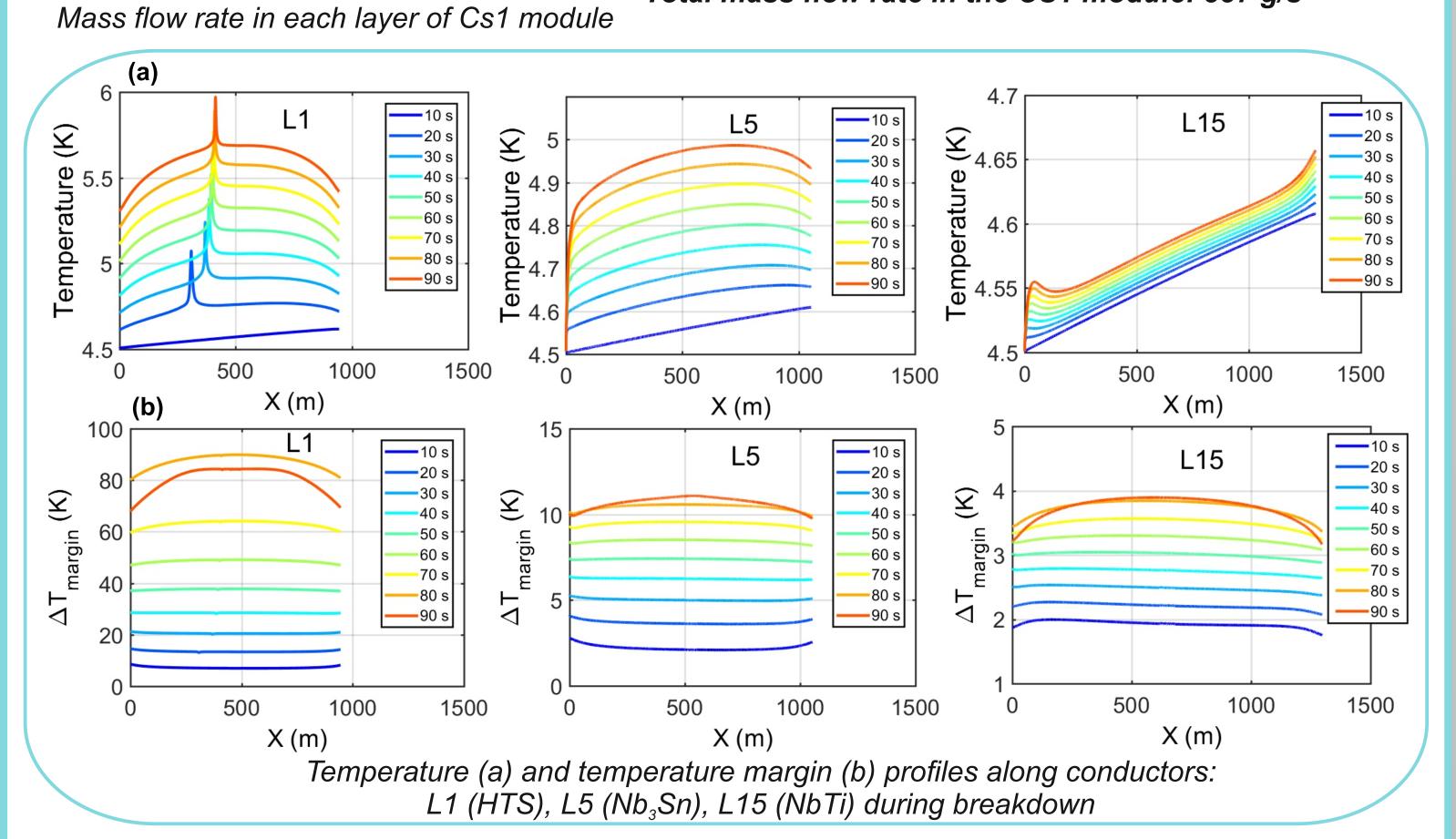
For the given pressure drop mass flow rates are obtained from:

(equation for uncompressible flow)

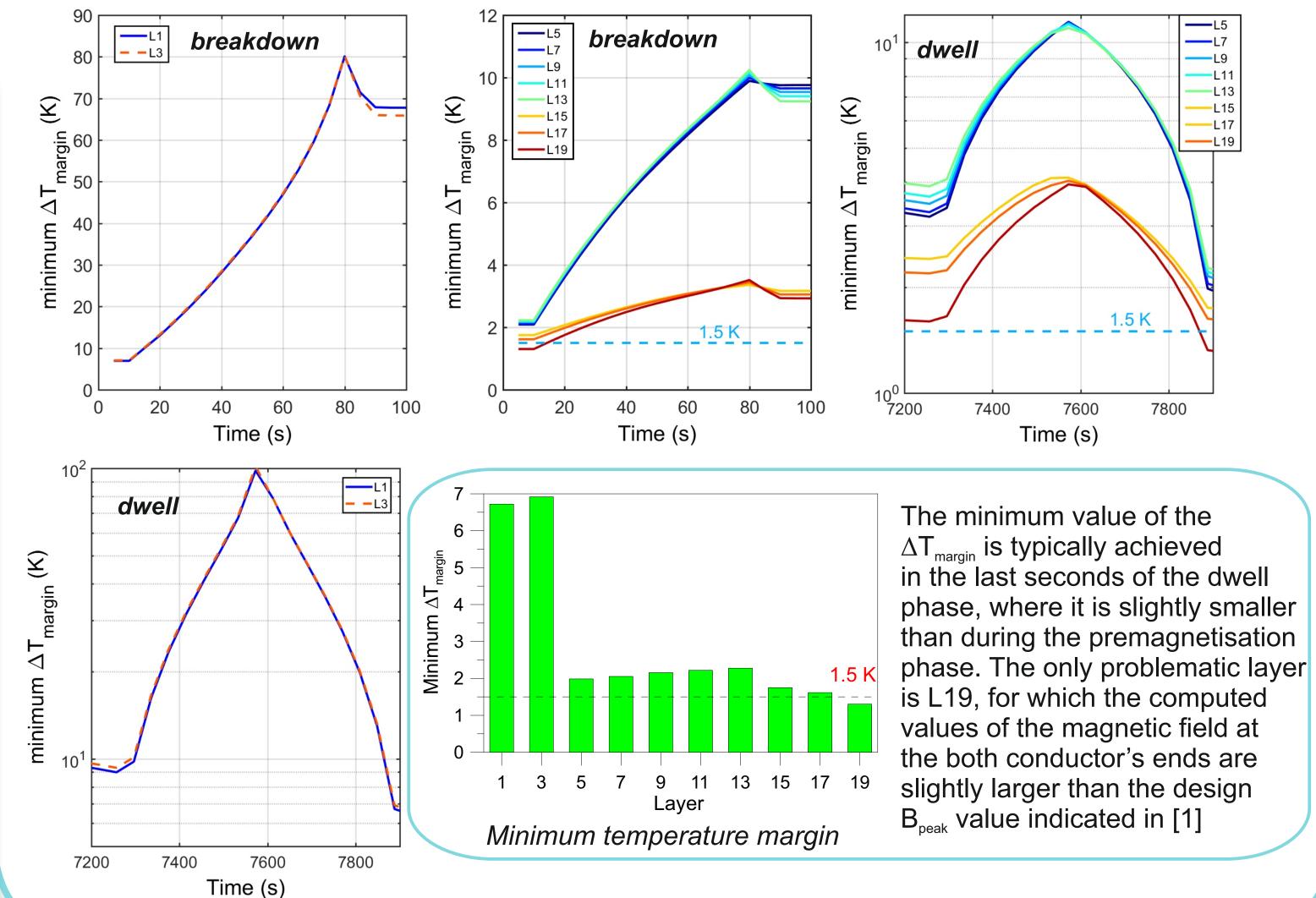
Helium properties are calculated at the reference conditions:

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

Total mass flow rate in the CS1 module: 337 g/s



Minimum temperature margin as a function of time in breakdown phase and dwell phase



#### CONCLUSIONS

- The hydraulic analysis of the CS1 coil (SPC design) was performed. The total mass flow rate in the CS1 module was assessed to be 337 g/s.
- Normal operation of the CS1 module was simulated using the THEA code during the whole plasma scenario (breakdown, burn and dwell phases). Time evolution of magnetic field profiles along the conductor, heat load due to AC coupling losses, inter-turn heat transfer and mass transfer between different channels of flow were taken into account.
- The temperature margin in the shorter conductor of each subcoil was calculated. The minimum value of temperature margin was typically achieved in the last seconds of the dwell phase.
- The computed minimum temperature margin in layers L1-L18 was sufficiently large, whereas in L19 was slightly below the 1.5 criterion.

# **EURO***fusion*

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