Deliverable on 2025 CEA thermo-hydraulic analyses
Impact of hydraulic boundary conditions on CS operation

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Task specification

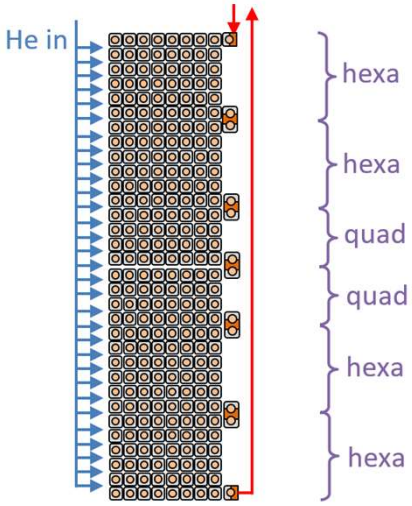
Deliverable on 2025 CEA thermo-hydraulic analyses – Impact of hydraulic boundary conditions on CS operation

Activities will focus on the **impact of boundary conditions (pressure)** on the **LTS** side of the **hybrid CS** design in burn conditions.

Recall: DEMO hybrid HTS/LTS design

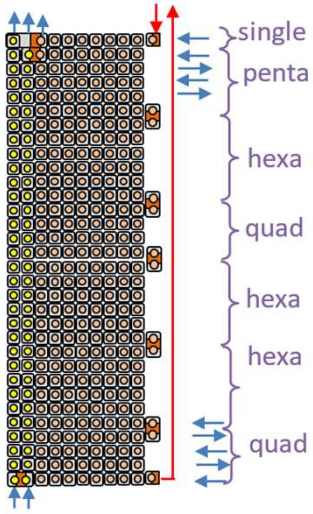
Initial LTS design

I_{cond} = 109.5 kA
NbTurns = 8
NbPancakes = 32 / module
R_e = 2.96 m
R_i = 2.25 m
B_{max} = 11.8 T
Phi_{edge} = 240 Wb

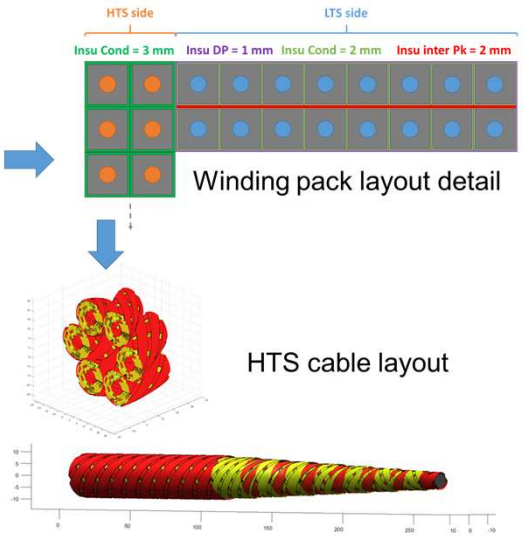


Hybrid HTS/LTS design

I_{cond} = 109.5 kA
NbTurns LTS = 8
NbLayers HTS = 2
NbPancakes = 32 / module
R_e = 2.96 m
R_i = 2.08 m
B_{max} = 14.8 T
Phi_{edge} = 281 Wb



HTS conductor design	
REBCO area [mm²]	6.9
Cu in Sc. tapes area [mm²]	518.4
Hastelloy area [mm²]	511.5
Cu tapes area [mm²]	601.2
Jacket area [mm²]	5484.8



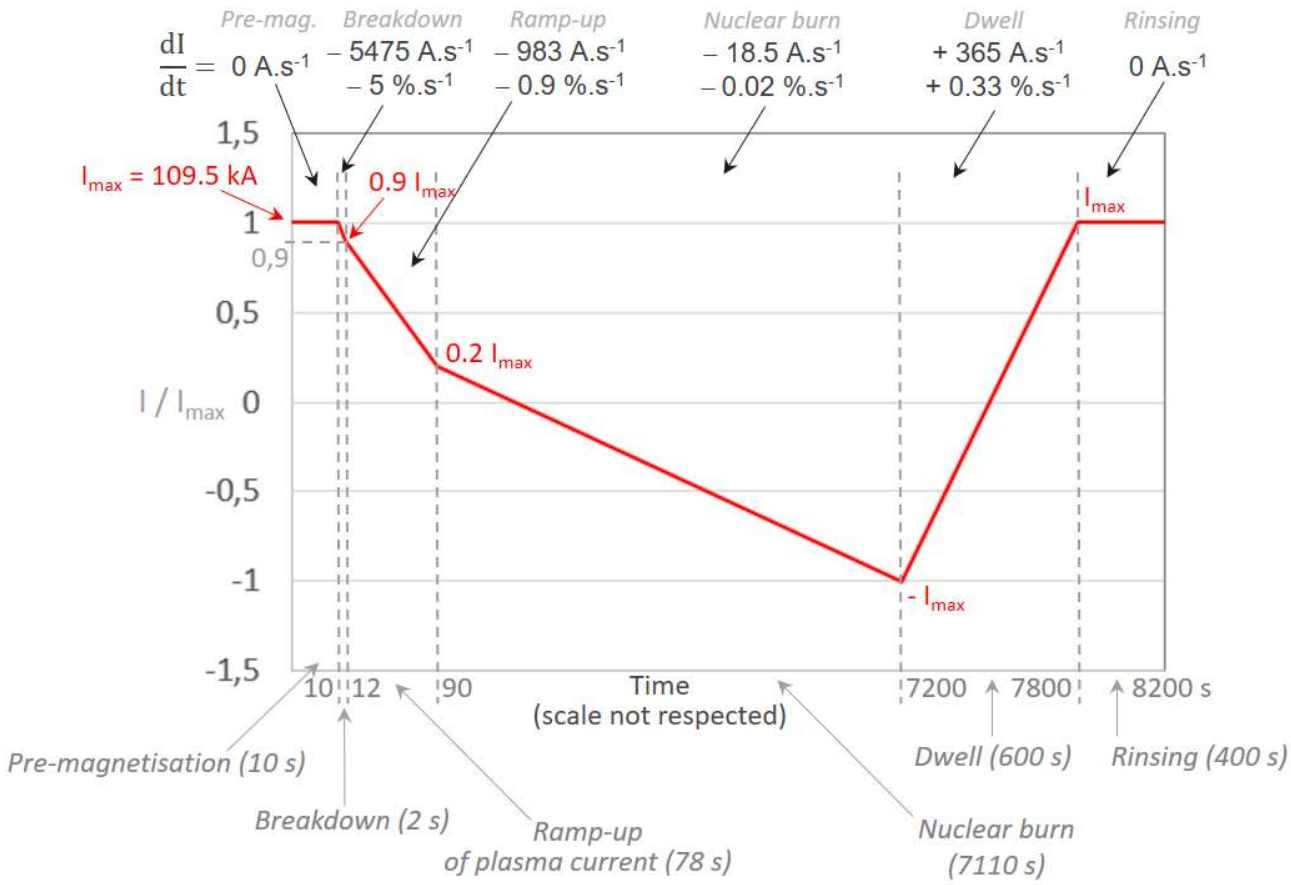
The sub-cable (1 of the 6) has 43 layers:
15 of copper tapes and 28 of REBCO tapes

Retained scenario for the study

1st scenario:

current profile in the CS

- 2 hour burn + 10 min dwell + 400 s (6min 40s) rinsing



Heat loads calculation

- AC losses

$$\Phi_{AC} = \Phi_{coupling} + \Phi_{hyst}$$

$$\Phi_{coupling} = \frac{n\tau}{\mu_0}\left(\frac{dB}{dt}\right)^2 S_{SC\ strands} \quad [\mathrm{W/m}]$$

$$\Phi_{hyst} = \frac{2d_{eff}}{3\pi}\left[1 + \left(\frac{I}{I_c}\right)^2\right] J_c \left|\frac{dB}{dt}\right| S_{non\ Cu} \quad [\mathrm{W/m}]$$

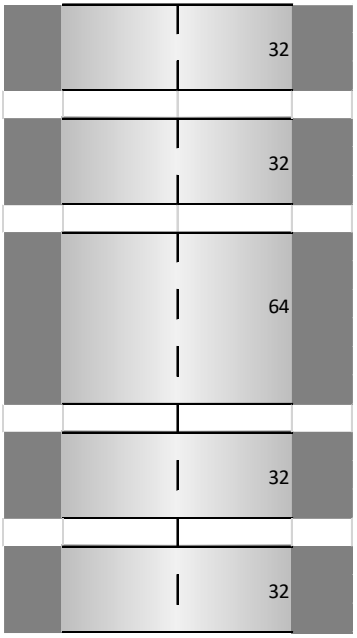
Parameters for the AC losses		
	LTS	HTS
nτ [ms]	600	300
d_{eff}	14 µm	4 mm

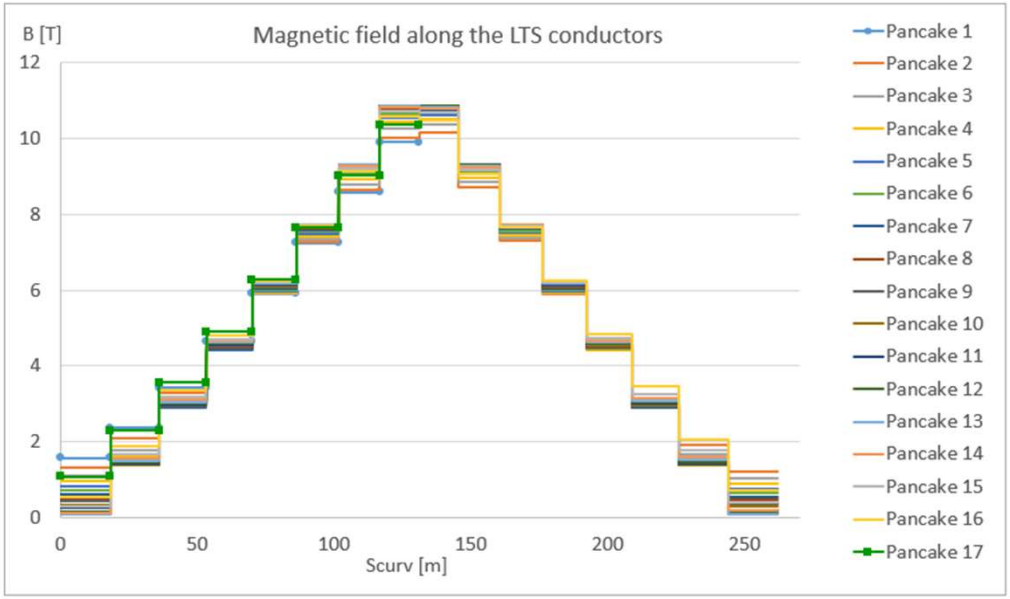
$$\mathrm{Bint} + n\tau \frac{\mathrm{dBint}}{\mathrm{dt}} = \mathrm{Bext}$$

Internal field B_{int} calculation has been implemented into THEA

Hydraulic path & Bext on LTS side

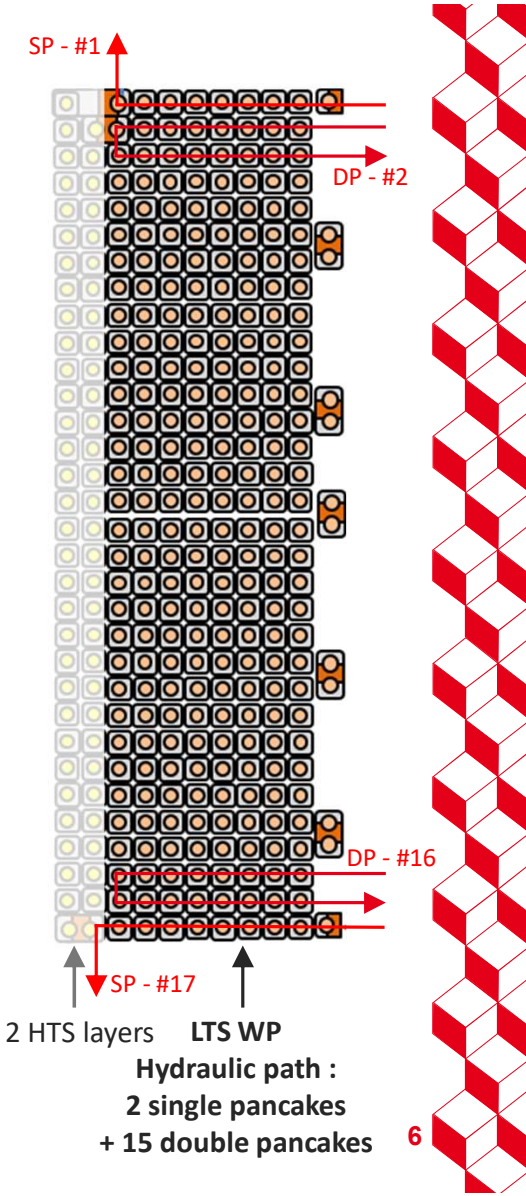
Magnetic field calculation on CS module 2 / LTS side:





LTS side – $B_{ext\ max}$ = 10.88 T

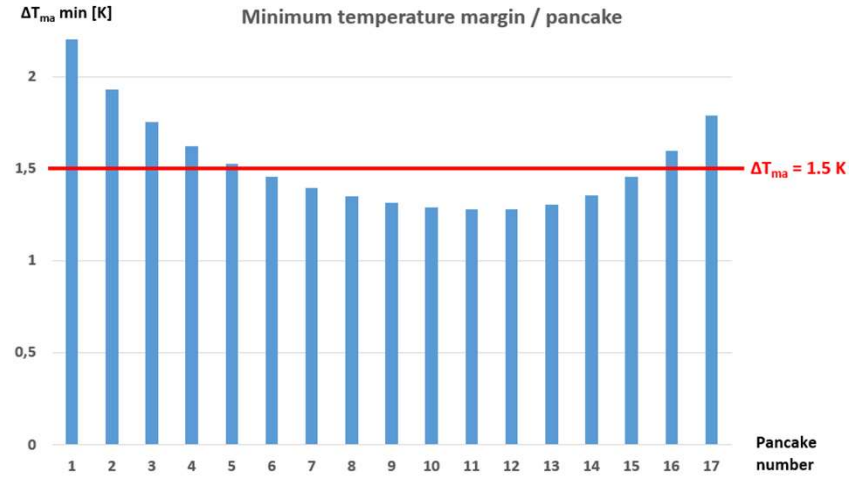
(HTS side – $B_{ext\ max}$ = 14.04 T)

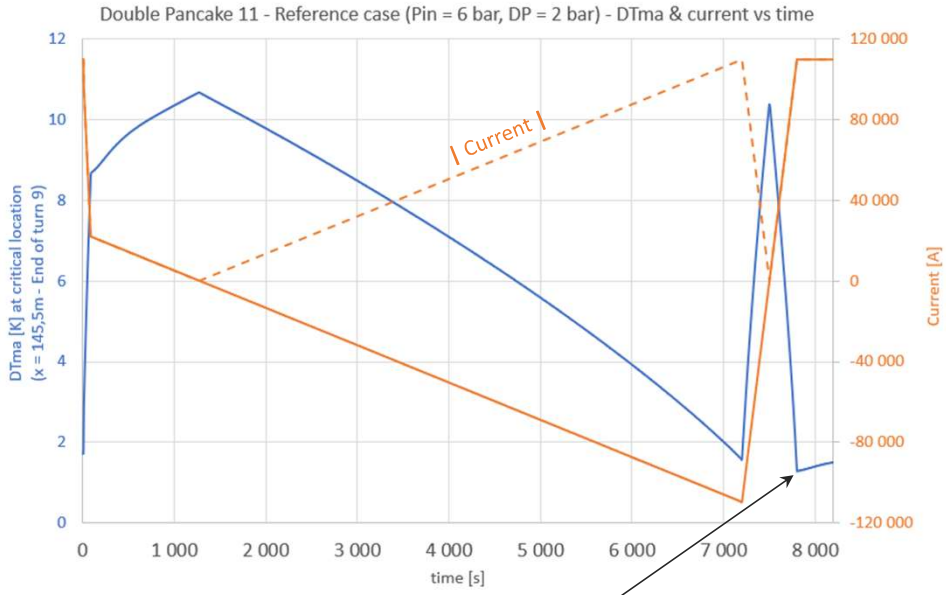


➢ Reference case : Tin = 4,5 K - **Pin = 6 bar, Pout = 4 bar (DP)** and 5 bar (SP)

Results for reference case Pin/out = 6 / 4 bar (5 bar for SP)

Pancake		ΔT_{ma} min [K]	@ Time [s]	@ S_{curv} [m]	@ T_{op} [K]	@ T_{cs} [K]	@ B_{eff} [T]
Upper	1 (SP)	2,203	7802,489	131,084	4,854	7,057	9,901
	2	1,931	7802,483	145,504	4,911	6,842	10,157
	3	1,751	7802,483	145,504	4,915	6,666	10,362
	4	1,622	7802,483	145,504	4,919	6,541	10,507
	5	1,527	7802,483	145,504	4,922	6,450	10,612
	6	1,454	7802,983	145,504	4,925	6,379	10,692
	7	1,396	7802,983	145,504	4,928	6,324	10,755
	8	1,351	7802,483	145,504	4,930	6,281	10,803
	9	1,316	7802,483	145,504	4,932	6,248	10,840
	10	1,292	7802,983	145,504	4,934	6,225	10,866
	11	**1,279**	**7801,983**	**145,504**	**4,935**	**6,215**	**10,878**
	12	1,282	7802,983	145,504	4,935	6,217	10,876
	13	1,304	7802,983	145,504	4,935	6,238	10,851
	14	1,356	7802,483	145,504	4,934	6,290	10,793
	15	1,458	7802,483	145,504	4,932	6,390	10,680
	16	1,595	7802,483	131,084	4,871	6,466	10,593
Lower	17 (SP)	1,787	7802,489	131,084	4,870	6,657	10,373





- ΔTma reached at End Of Dwell and at high field location (inner turns) for all conductors
- Critical conductor = DP 11

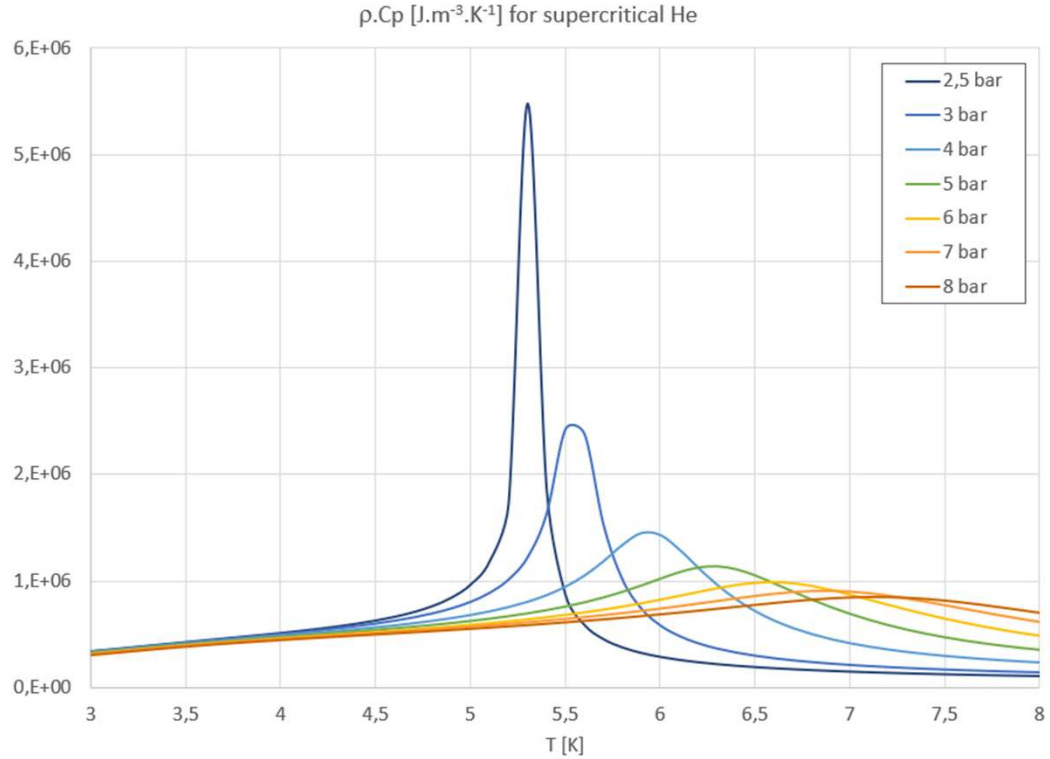
  DTma = 1,279 K

  = Tcs – (Tin + ΔTop)

  = 6,215 – (4,5 + 0,425)

  ← Maximum potential gain on margin < ΔTop = 0,425 K

Properties of supercritical He in the area of interest



- Potential interest in moving to lower P *but* gain is limited by ΔTop = 0,425 K
- SHe pressure limit → Pout > $P_{critical}$ = 2,27 bar
- Explore higher P for checking DTma decrease & other possible effects

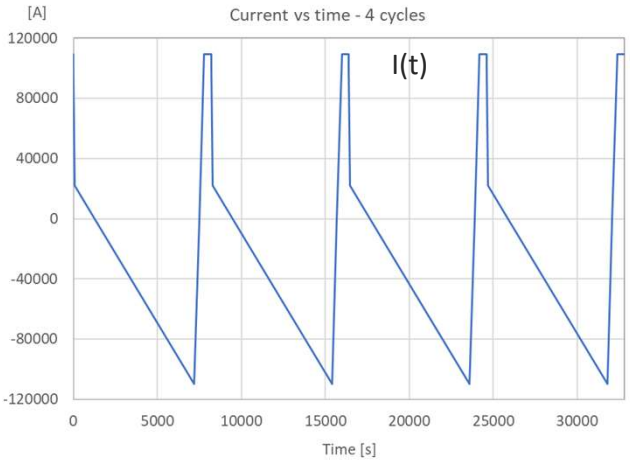
Sensitivity to Pin/Pout for the reference scenario

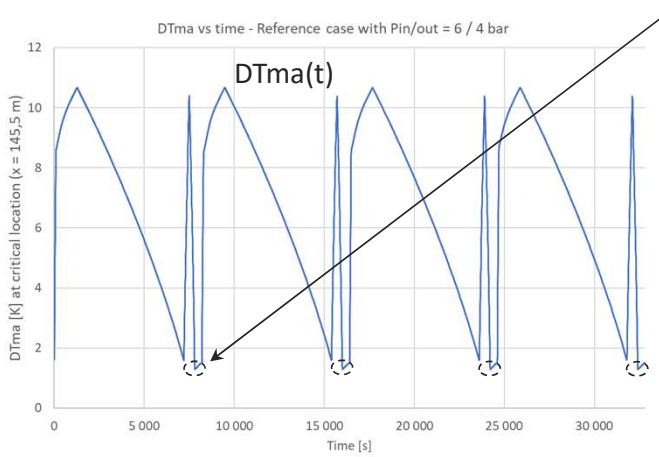
- Breakdown duration = 2s → Critical phase is current ramp-up during dwell & DTma is reached at ~ EOD (7800 s) and at end of high field region in inner turns

Results for critical conductor = DP 11

Pin / Pout [bar]	DP [bar]	DTma [K]	DTma variation [K]	DTop [K]	P @ DTma min [bar]	Mean transit time	Pcirculation [W]	Pmoy AC losses [W]	time [s]	x [m]
4,5 / 2,5	2	**1,34**	**0,06**	0,37	3,422	13min 31s	25,7	6,47	7802,5	145,5
6 / 4 (Ref.)	2	**1,28**	**-**	0,43	4,915	13min 52s	25,1	6,48	7802,5	145,5
8 / 6	2	**1,23**	**-0,05**	0,49	6,907	14min 14s	24,4	6,49	7802,5	145,5
10 / 8	2	**1,19**	**-0,09**	0,52	8,904	14min 31s	23,9	6,49	7802,5	145,5
8 / 4	**4**	**1,23**	**-0,05**	0,48	5,847	**9min 35s**	**72,6**	6,49	7802,5	145,5

- Moderate gain on DTma when reducing Pint / Pout (+ 0,06 K)
- But then, margin decrease is also limited when increasing Pin / Pout
- No point in increasing DP: Pcirculation increases drastically & minimum DTma is reached in the 1st cycle with DP = 2 bar



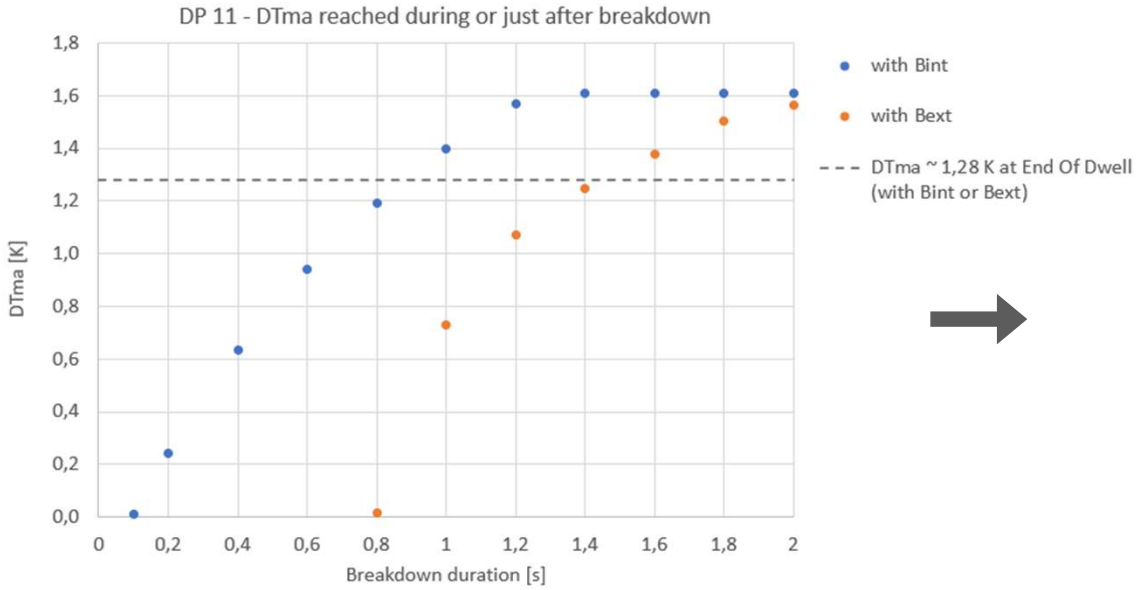


Reference case (6 / 4 bar)
DTma versus time

Simulation of 4 cycles
(32800 s ≈ 9h 7min)

Focus on the breakdown phase

- DTma sensitivity to breakdown duration (2 s for reference scenario)



- Fast variation of current and thus of B
  → Taking Bint into account is mandatory
- Breakdown becomes more critical than dwell for breakdown faster than ~ 0.9 s

- DTma sensitivity (for breakdown phase) to inlet & outlet pressures

With dtbreakdown = 0,8 s and Bint

Pin / Pout [bar]	DTma [K]	t [s]	x [m]	P [bar]	DTma variation [K]
4,5 / 2,5	1,194	10,801	123,940	5,144	~ 0
6 / 4	**1,194**	**10,801**	**124,596**	**6,656**	-
8 / 6	1,206	10,801	125,054	8,657	+ 0,012

- Increasing pressure is slightly beneficial
- P at critical point > Pin (reverse flow) → fast TH transient effects dominate
- Low impact of P at boundaries

Conclusion

- A **sensitivity analysis to P at inlet and outlet** has been performed for the LTS side of DEMO hybrid HTS / LTS CS design.

  CS pulsed operation makes **comprehension less straightforward**.

- **Reducing** the level of **pressure** operation is **slightly beneficial for DTma**, but the impact is limited (ΔTop value, critical pressure limit)

  Similarly, **increasing pressure** at boundaries **moderately reduces DTma.** If necessary, increasing operation pressure is possible, for example for cooling HTS conductors downstream of LTS ones, or if useful for the cryoplant.

- If fast current/field variation (e.g. breakdown) becomes the critical phase of the scenario, transient TH effects may have more impact than pressure at boundaries.