



Fusion Power Plant Optimisation Through System-Code Assessment of Advanced Technologies

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1. Introduction

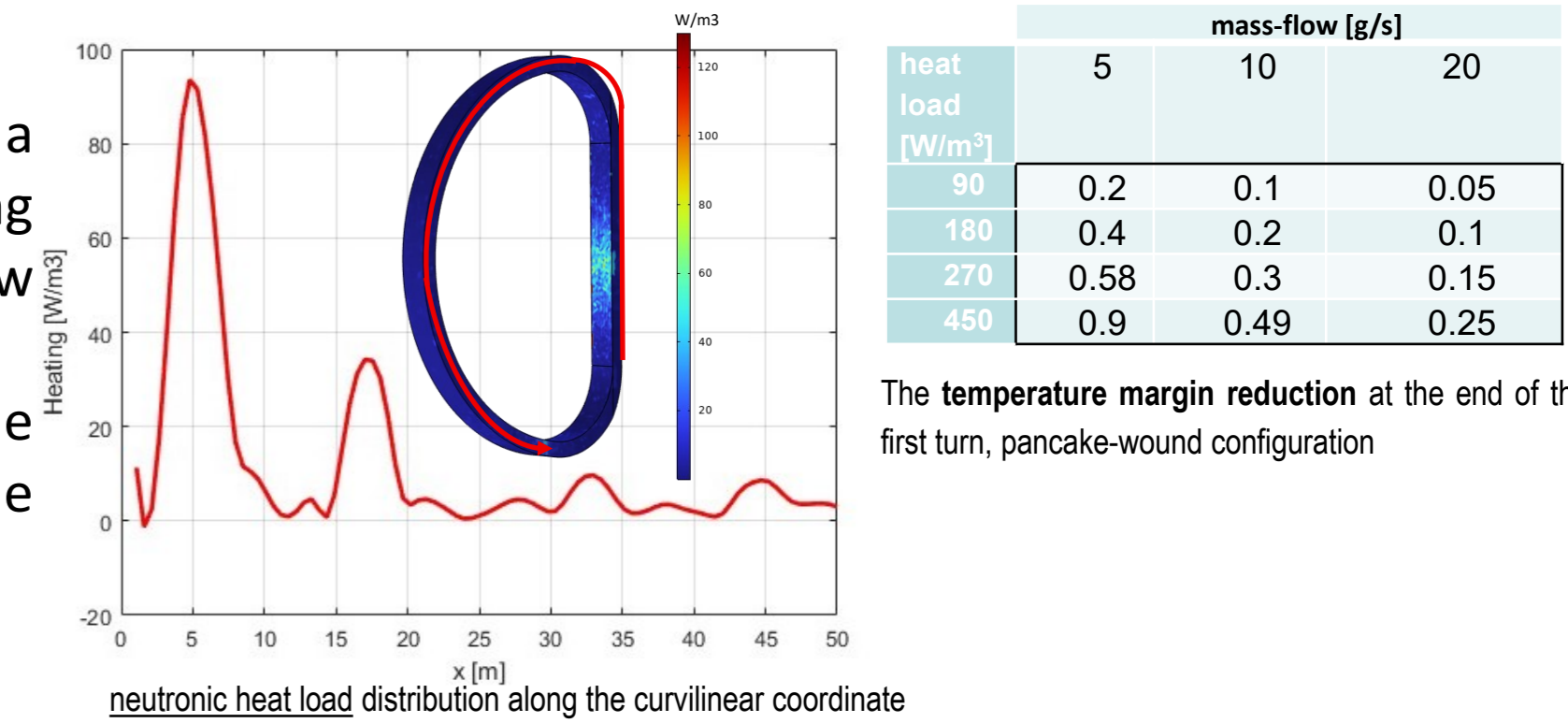
- Validated baseline:** 2025 EUROfusion LAR reference ($R_0 = 8.6$ m, $A = 2.8$, [1]), developed for a demonstration reactor and satisfying the current stakeholder requirements ($300 \leq P_{el,net} \leq 500$ MW, $\tau_{pulse} \geq 2$ h [2]).
- Motivation:** As the European roadmap evolves from a demonstration reactor towards a **Fusion Pilot Plant** and, ultimately, a commercial **Fusion Power Plant (FPP)** [7], this validated reference is used as a benchmark to quantify the **system-level benefit of emerging technologies**.
- FPP perspective:** Blanket qualification in dedicated facilities (e.g. Pilot Plant/VNS [3]) could enable optimisation around a single breeding blanket concept (e.g. WCLL or HCPB like), avoiding demonstration-driven design compromises.
- Scope:** System code (PROCESS [1]) assessment of:
 - **Advanced structural materials for the magnetic cage;**
 - **Alternative neutron shielding materials.**
- Aim:** Quantify the **system-level benefit of selected technologies on reactor size, supporting future FPP design and R&D prioritisation.**

Neutronic analysis results:

- A **reduction in VV thickness by ≈ 4 cm for the HCPB, and ≈ 20 cm for the WCLL, are possible** if tungsten is used (limit is volum. Load 50 W/m^3 [6])
- Further decrease in VV thickness possible with **relaxed nuclear heating** (ITER used 1 kW/m^3):

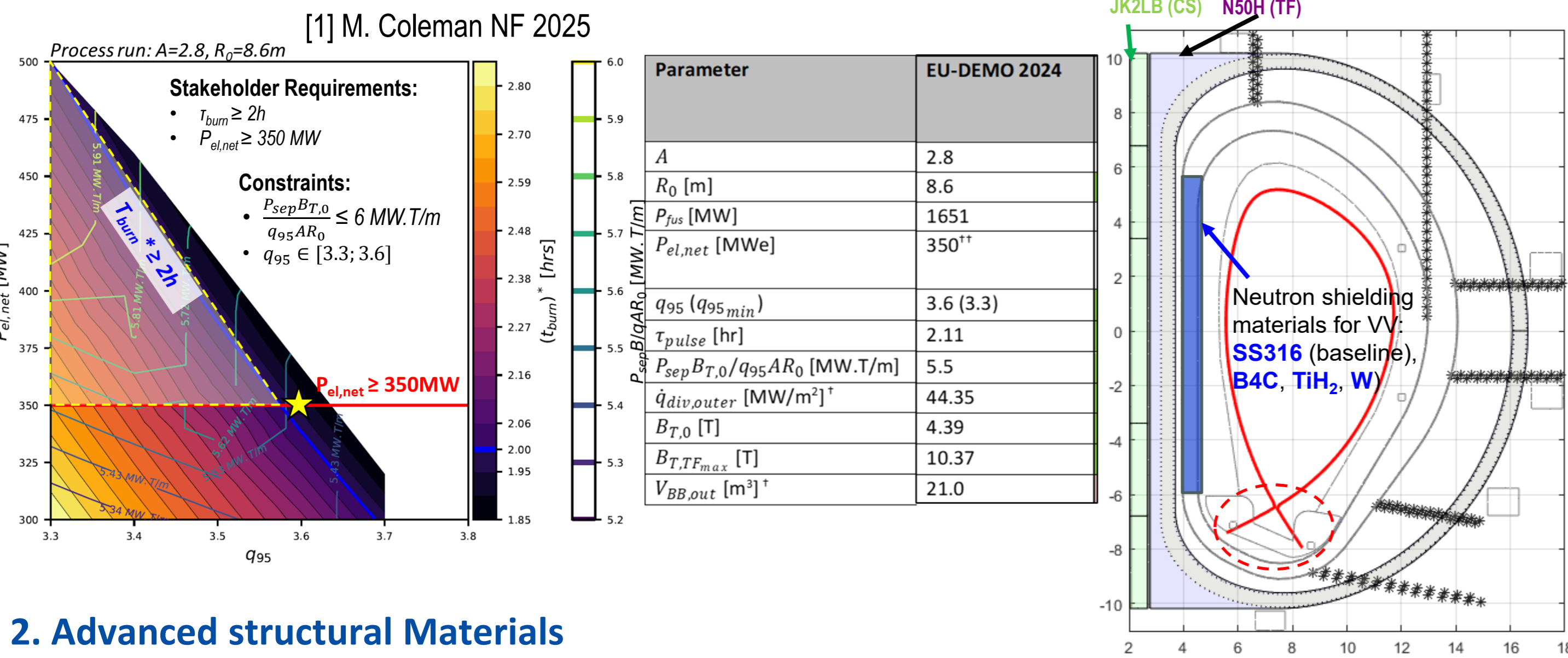
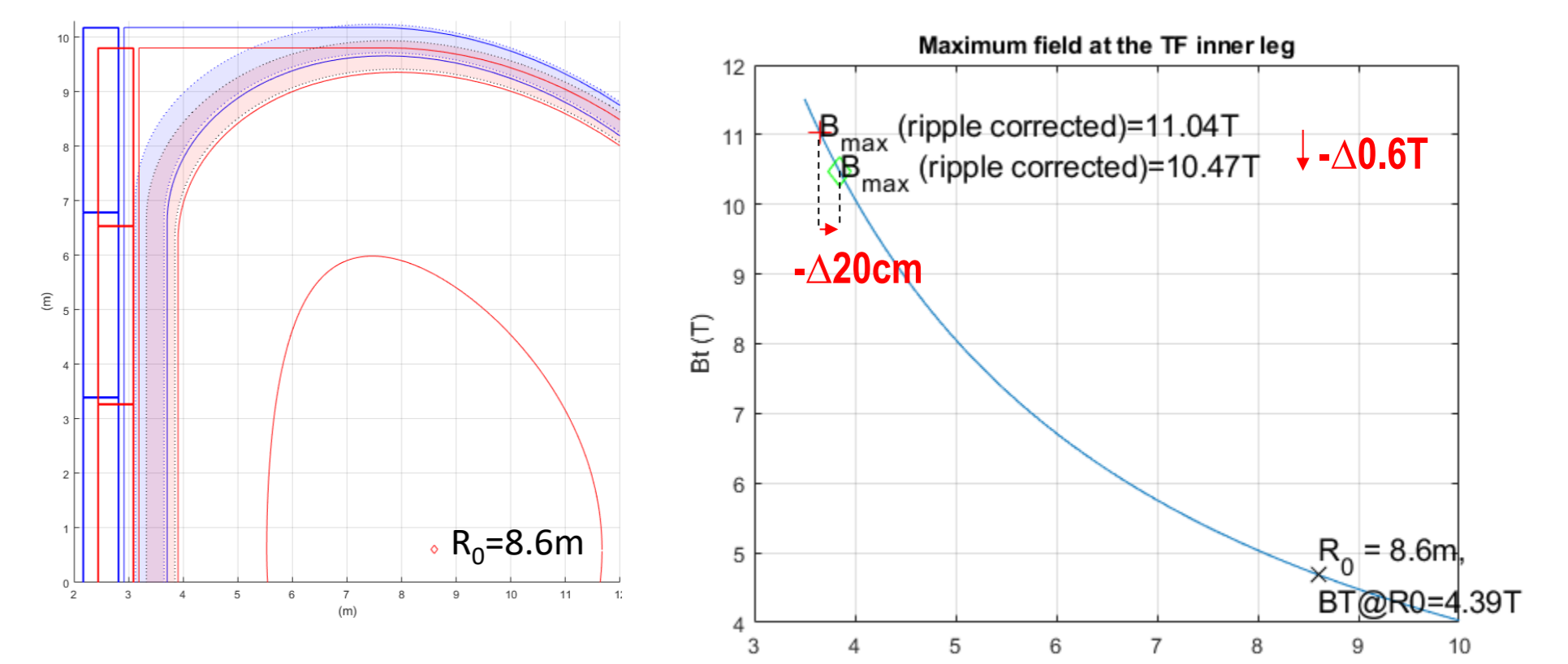
2.2 Thermo-hydraulic study

- A preliminary study [idm_2SVF55] assessed that a margin of **1.5K** would be preserved in the TF winding pack (pancake-wound) even using conservatively low mass flow rate (5g/s) until a vol. load of 450 W/m^3 .
- 450 W/m^3** allows a VV reduction of $\approx 21 \text{ cm}$ for the WCLL and 10 cm for the HCPB (fluence becoming the limit).
- PROCESS correlation implemented.**



2.3 Effects on TF system on winding pack-plasma distance

- Reduced plasma-TF distance \rightarrow **TF peak field:** $-20 \text{ cm} \rightarrow -0.6 \text{ T}$ (WCLL), $-10 \text{ cm} \rightarrow -0.3 \text{ T}$ (HCPB).
- Lower TF field \rightarrow lower **stored magnetic energy** ($\propto B^2$).
- Recovered space ($20/10 \text{ cm}$) \rightarrow **+91/+42 Wb CS flux swing** ($\approx 50/23 \text{ min}$) or further R_0 reduction.



2. Advanced structural Materials

Advanced cryogenic steels (e.g. N50-H and JK2LB) are assessed to quantify their impact on pulse duration and reactor compactness relative to the reference structural material. These materials are already under development for next-generation FPP (international programmes ongoing) and are assessed here to quantify their potential system-level benefits in terms of pulse duration and reactor compactness.

Material	Main application	International interest
JK2LB	Central Solenoid (CS)	ITER conductor jackets; reference material for high-performance CS structures
N50-H	Toroidal Field (TF) coil structures	Investigated for SPARC/CFS studies; included in the Chinese BEST/CFETR roadmap; ongoing R&D in Europe, Japan, China and the US

- Higher allowable structural stress** at cryogenic temperature Improved **fracture toughness** while maintaining adequate **fatigue performance**
- Reduced magnet structural mass, and improved overall reactor compactness.**

PROCESS within SHR, i) at constant geometry:

- N50-H (TF):** pulse duration $2.2 \rightarrow 2.7$ h
- JK2LB (CS):** pulse duration $2.2 \rightarrow 2.8$ h
- JK2LB + N50-H:** pulse duration $2.2 \rightarrow 3.4$ h

Or ii) Machine minimization: $R_0 = 8.6 \rightarrow 8.45$ m (divertor protection criterion)

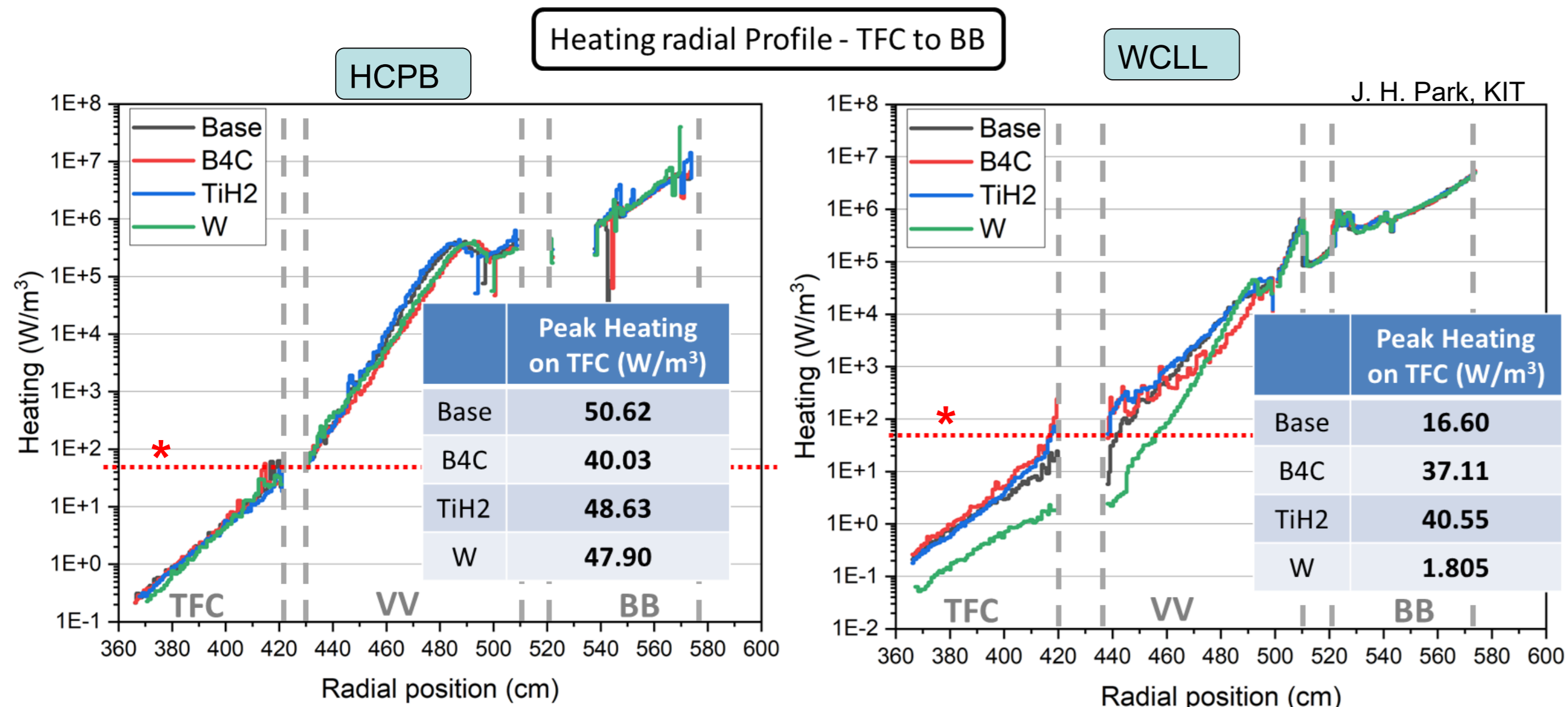
	Higher stress limits		Better fatigue performance	
	TF	N50-H	SS316	CS
σ_{TF} case	760 MPa	580 MPa		
σ_{TF} cond	879 MPa	580 MPa		
				JK2LB
				SS316-LN
				C
				m

Paris law $\frac{da}{dN} = C(\Delta K)^m$

3. Alternative Neutron Shielding Materials

Neutronic analysis using alternative shielding materials[4] (well established in fission nuclear industry) in the **Vacuum Vessel**: Tungsten (W), Boron Carbide (B₄C), Titanium Hydride (TiH₂), WRT the ITER like Steel + water assumption used as a baseline. Scan on material/coolant percentage (40% to 10%, keeping 6% steel) Requirements on magnets shielding were established in FP8 as:

- Max volumetric power density in winding pack of ***TFC $\leq 50 \text{ W/m}^3$** [5] (ITER value is 1000 W/m^3)
- Max **insulator dose** at end-of-life \leq TBD MGy (ITER is 10 MGy)
- TF **neutron fluence** at end-of-life $\leq 10^{22}$ neutrons/m² (as ITER)

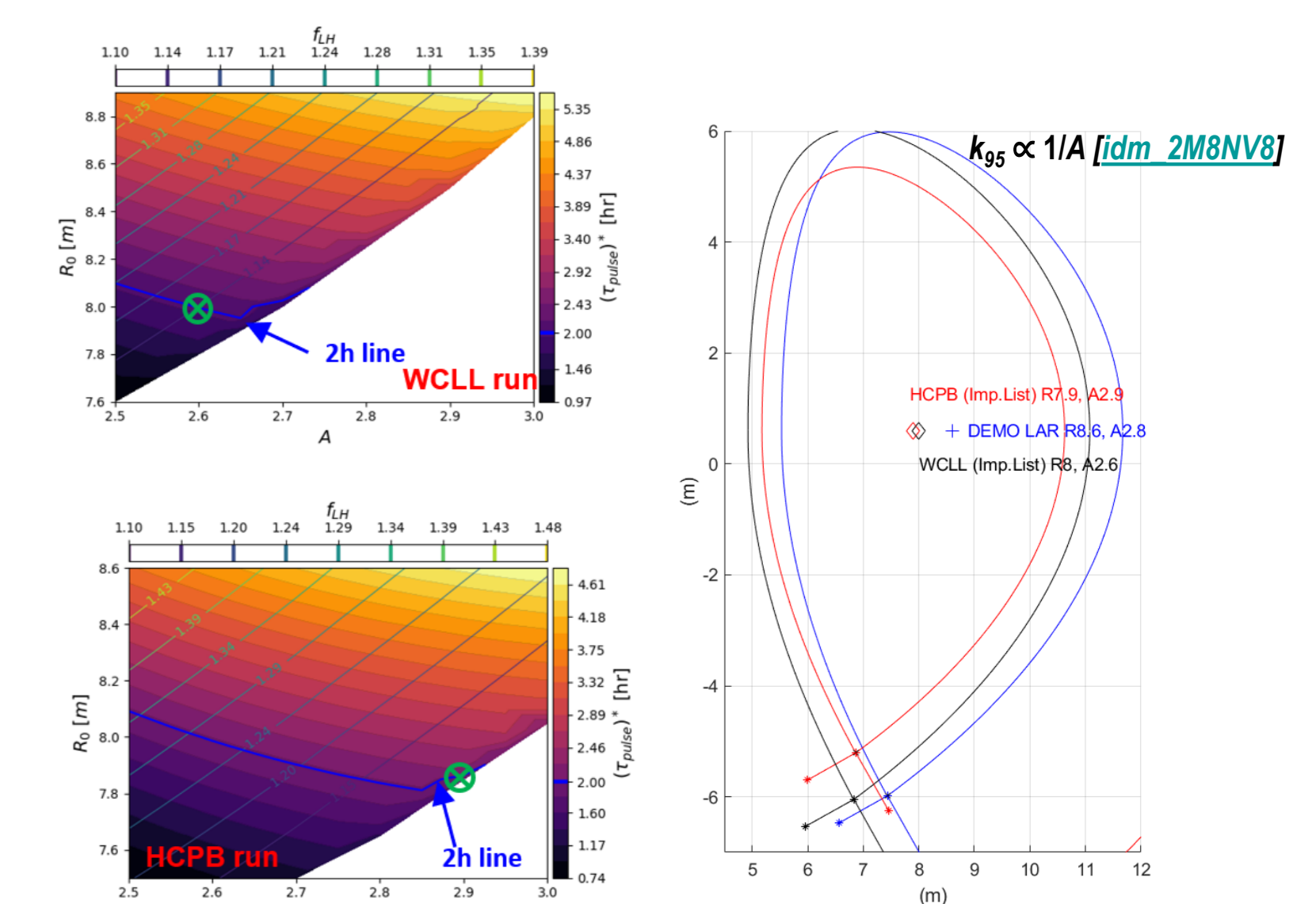


3. Integrated FPP-oriented optimisation

Optimisation target: **minimise FPP size** while preserving the current DEMO-like stakeholder requirements ($P_{el} = 350$ MWe, $\tau_{pulse} \geq 2$ h), used here as a reference baseline.

Blanket-specific optimisation exploits the superior shielding of WCLL or the higher thermal efficiency of HCPB.

	WCLL	HCPB
CS steel	JK2LB	
TFs steel	SS316	
VV thickness (inboard)	39 cm (-21 cm)	50 cm (-10 cm)
BB thickness (inboard)	80 cm	
Plasma-wall distance	15 cm* (-7.5 cm)	
ECRH heating power	15 MW (+5 MW)	
ECRH current drive	0 MW** (-40 MW)	
Energy multiplication factor	1.20	1.34
Thermal-to-electric efficiency	0.32	0.37
R_0 [m]	8.0	7.9
Aspect ratio	2.6	2.9
P_{fus} [MW]	1465	1176
$P_{el,net}$ [MWe]	350	350
q_{95} ($q_{95,min}$)	3.6 (3.3)	3.6 (3.3)
τ_{pulse} [hr]	2.19	2.50
$P_{sep,TR,0}/q_{95}AR_0$ [MW.T/m]	5.5	5.5
$\dot{q}_{div,outer}$ [MW/m ²]	42.12	45.90
$B_{T,0}$ [T]	4.09	4.58
$B_{T,max}$ [T]	9.93	10.52
I_p [MA]	19.69	16.46
R_{95} (elongation)	1.753	1.730



Results

- **Reduction of AH** (low CD efficiency $\approx 50 \text{ kA/MW}$) allows targeting lower P_{fus} while keeping P_{net,el} const.
- Combined optimisation (ITER JK2LB steel in CS / SS316LN in TF + alternative shielding) yields a compact design of $R_0 \approx 8$ m for WCLL BB and 7.9 m for HCPB, while satisfying **SHR** $P_{el} \approx 350 \text{ MW} / \tau_{pulse} \geq 2$ h.
- Adding N50-H in the TF coils allow a further decrease to R_0 7.9 m for WCLL, and 7.8 m for HCPB within **SHR**
- Optimising around a specific blanket concept** avoids compromises required by multi-purpose demonstration facilities.

4. Conclusions

- Validated LAR reference design** used as a common benchmark to quantify the system-level benefit of emerging technologies for future Fusion Power Plants.
- The methodology remains applicable as the European roadmap evolves** from demonstration reactors towards **Pilot and commercial Fusion Power Plants**.
- Blanket-specific optimisation** (e.g. WCLL or HCPB), **enabled by dedicated qualification facilities (Pilot Plant/VNS), removes** demonstration-driven design compromises.
- Advanced structural materials, alternative neutron shielding and blanket-specific optimisation** enable reactor designs approaching or below $R_0 \approx 8$ m while preserving the current stakeholder requirements.
- The proposed **workflow** quantifies the **system-level benefit of emerging technologies, supporting future FPP design and technology R&D prioritisation.**

References

- [1] M. Coleman et al. 2025 Nucl. Fusion 65 036039;
- [2] Report of the DEMO Stakeholder Group, EUROfusion (idm_2M6VKJ)
- [3] Federici NF 2023
- [4] Basic nuclear analysis handbook idm_2RYLMS
- [5] Duchateau idm_2LJZX7
- [6] A. Quartararo G2A 2025 rep. idm_2STC88
- [7] Fusion Expert Group opinion paper 2025