# Scenarios for physics experiments in the COMPASS Upgrade tokamak

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## Introduction

The COMPASS Upgrade tokamak [1] will have dimensions $R_0$~0.894m and a~0.275m with high-field (Bt~5T) , high-current (Ip~2MA), high-triangularity (δ~0.5) capabilities. The machine should be completed by 2025. It will be located in Prague, Czech Republic. This contribution is dedicated to the accessibility and operating parameters of the high-performance scenarios that will be used to study pedestal and edge physics. The machine will build on and expand the results of Alcator C-mod [2].

## Introducing various modes of improved edge confinement

ELMy H-mode should be accessed at the minimum power density $n_{e,min,Ryter}$ [3]:

$$n_{e,\min_{,\text{Ryter}}} = 0.7\, I_{\text{p}}^{0.34} B_{\text{t}}^{0.62} a^{-0.95} (R/a)^{0.4} 10^{19} m^{-3}$$

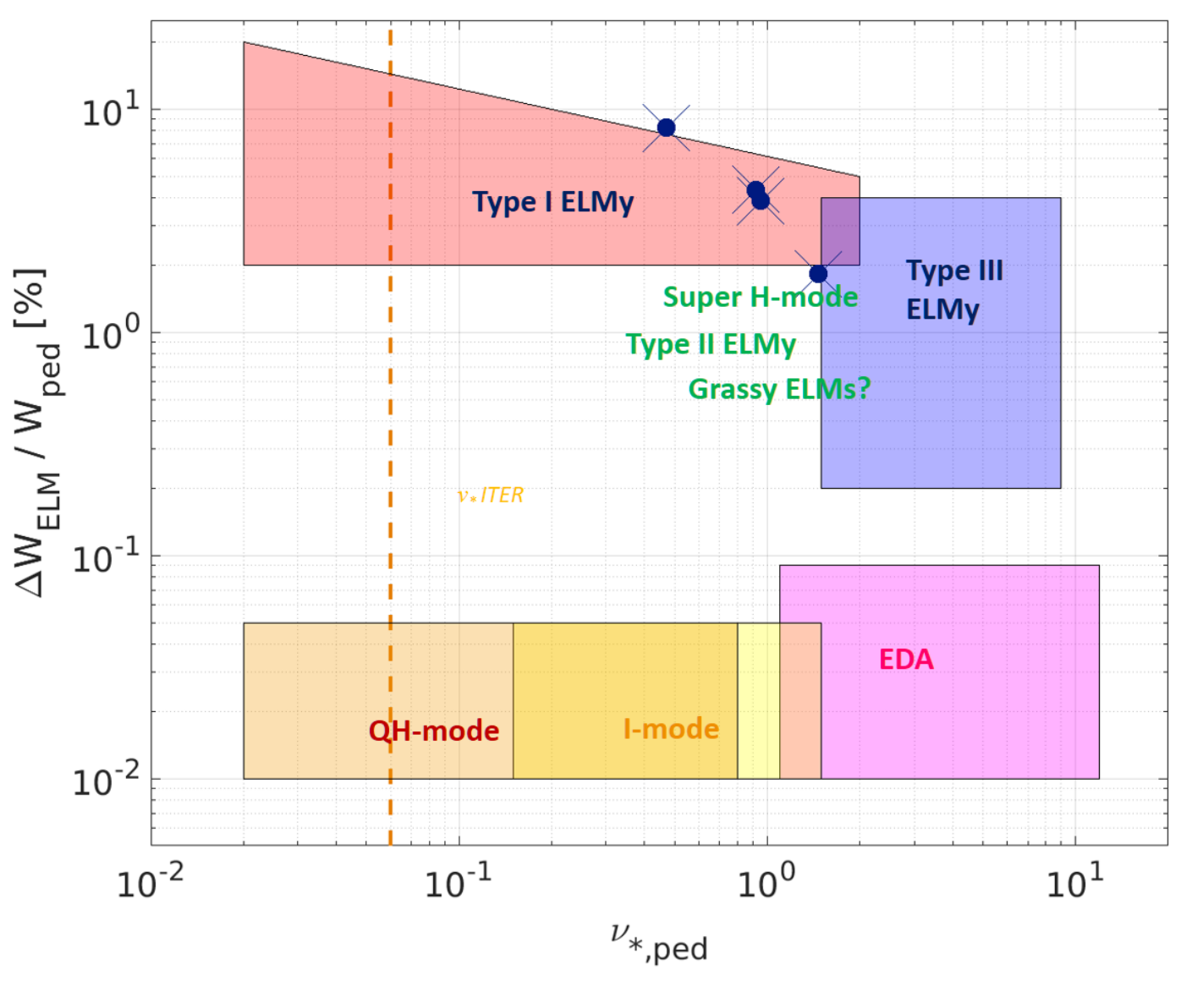
Accessibility of 3 distinct regimes of "improved" plasma confinements

- ELMy H-mode
- Enhanced D-Alpha (EDA) H-mode
- I-mode

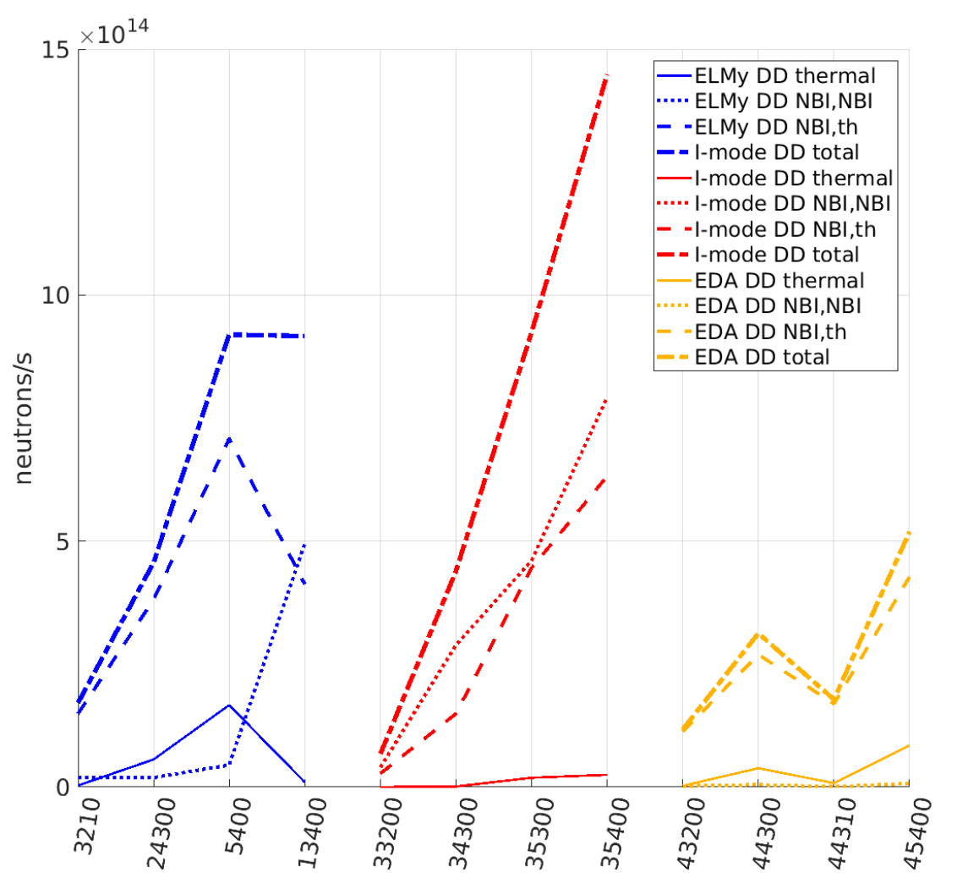
Threshold in heating power to access the ELMy H-mode : $P_{L,H_{\text{ELMy}}} = 0.0488\, n_{e,20}^{0.717} B_{\text{t}}^{0.803} S^{0.941}$ [MW]

| | Threshold power [MW] | $n_{ped}$ $[10^{20}\text{m}^{-3}]$ | $\tau_E[s]$ |
|---|---|---|---|
| ELMy H-mode [4], [5] | $P > P_{\text{L}\to\text{H}},\ n_e > n_{\text{e,min}}$ | $\simeq 2.5 B_{pol}$ | $\tau_{H98(y,2)}$ |
| I-mode | $0.162 n_{e,20} B_t^{0.26} S$ | no pedestal | $\sim 0.8\tau_{H98(y,2)}$ [8] |
| EDA H-mode [6], [7] | $0.054 n_{e,20}^{0.49} B_t^{0.85} S^{0.84}$ | $3.57 I_p^{0.52} n_{e,L}^{0.52} B_t^{-0.38}$ | $\tau_{H98(y,2)}$ |

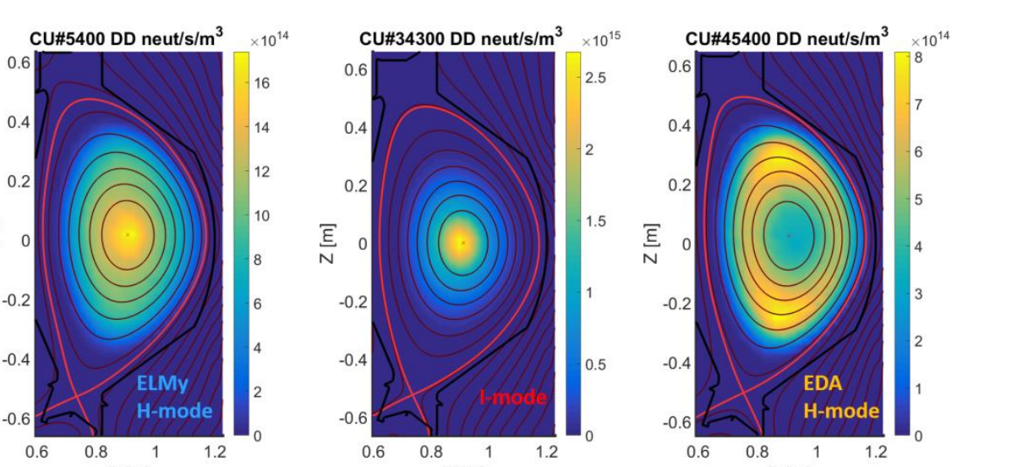
| Scenario | $B_t$ [T] | $I_p$ [MA] | $q_{95}$ | $\bar{n}_e$ $[10^{20}\ m^{-3}]$ | $P_{NBI}+P_{EC}$ [MW] | $P_{sep}$ [MW] | $n_{e,ped}$ $[10^{20}\ m^{-3}]$ | $T_{e,ped}$ [eV] | $\nu^*_{ped}$ |
|---|---|---|---|---|---|---|---|---|---|
| #3210 | 2.5 | 0.8 | 3.6 | 1.2 | 2+0 | 2.0 | 0.91 | 836 | 0.92 |
| #24300 | 4.3 | 1.2 | 4.1 | 1.9 | 3+1 | 2.8 | 1.78 | 928 | 0.95 |
| #5400 | 4.9 | 1.6 | 3.5 | 2 | 4+2 | 3.8 | 1.97 | 1361 | 0.47 |
| #13400 | 5 | 0.8 | 7.3 | 1.1 | 4+2 | 5.1 | 0.9 | 1169 | 1.46 |
| #34300 | 4.3 | 1.2 | 4 | 1 | 3+1 | 4.2 | 0.49 | 1140 | 0.47 |
| #35300 | 4.9 | 1.6 | 3.4 | 1 | 3+1 | 4.2 | 0.49 | 2467 | 0.09 |
| #35301 | 4.9 | 1.6 | 3.4 | 1 | 3+1 | 4.2 | 0.49 | 2467 | 0.09 |
| #35400 | 5 | 1.6 | 3.5 | 1 | 4+2 | 5 | 0.46 | 2136 | 0.11 |
| #43200 | 2.5 | 0.8 | 3.6 | 1.9 | 2+0 | 1.5 | 1.52 | 513 | 1.78 |
| #44300 | 4.3 | 1.2 | 4.2 | 2.5 | 3+1 | 2.2 | 2.21 | 776 | 1.47 |
| #44310 | 4.3 | 1.2 | 4.2 | 3 | 3+0 | 1.1 | 2.7 | 597 | 2.52 |
| #45400 | 5 | 1.6 | 3.6 | 3 | 4+0 | 2.2 | 2.87 | 908 | 0.93 |



*Various pedestal modes and their load on pfcs (zones based on multi-machine study shown in [18])
$\Delta W_{ELM}$ / $W_{ped}$ values according to [20]*



Total DD neutron rates



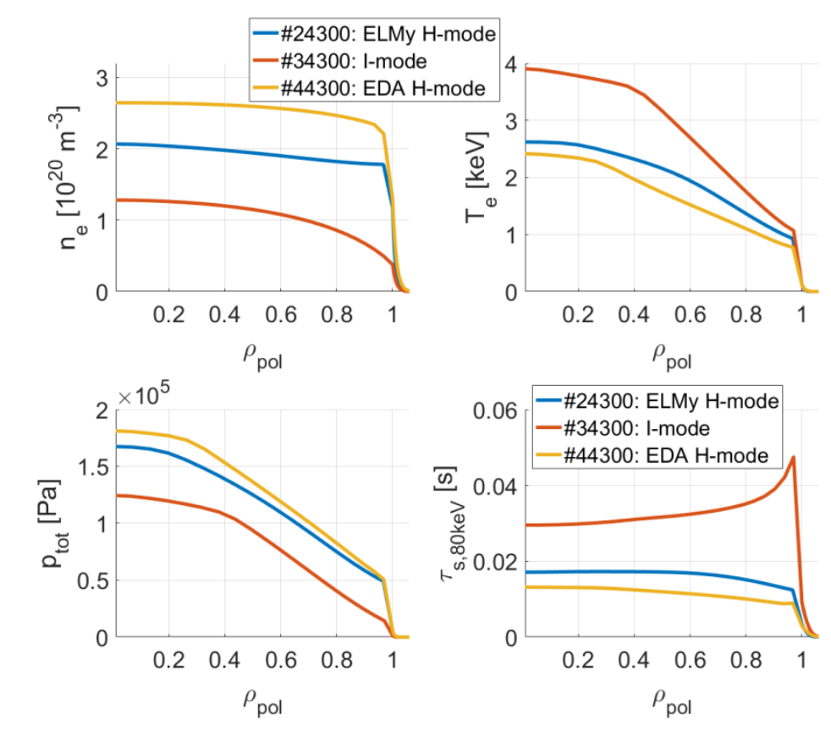
### ELMy H-mode

Ballooning critical pressure gradient limit as described in [10]:

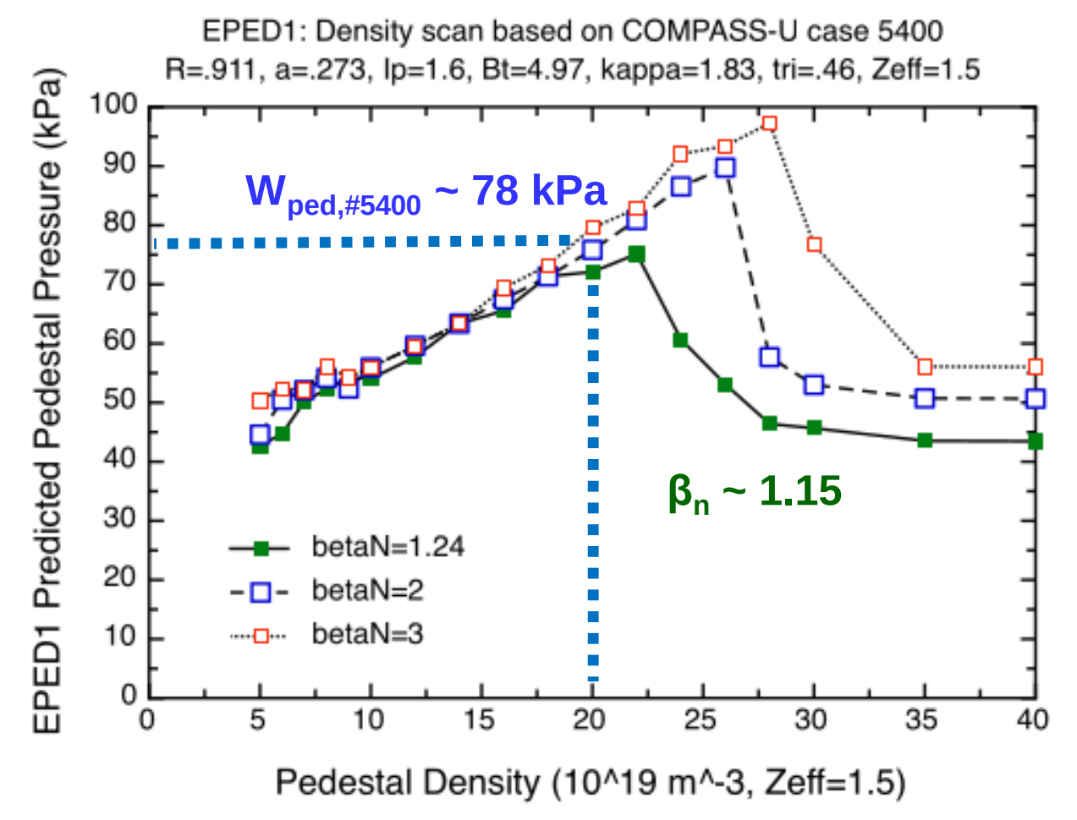
$$T_{ped} = (0.025)^2 \left( \frac{1}{4\mu_0 e} \left( \frac{B_T}{q_{95}^2} \right)^2 \left( \frac{R}{a} \right)^2 \left( \frac{\alpha_c^2}{n_{ped}} \right) \left( \frac{\pi(1+\kappa_{95})}{5} \frac{q_{cyl}}{q_{95}} \right)^2 \right)$$

$$\alpha_c = 0.4s\left(1+\kappa_{95}^2(1+5\delta_{95}^2)\right)$$

$$q_{\text{cyl}} = 5\frac{a^2 B_{\text{t}}}{I_{\text{p}}\mu_0 R}$$

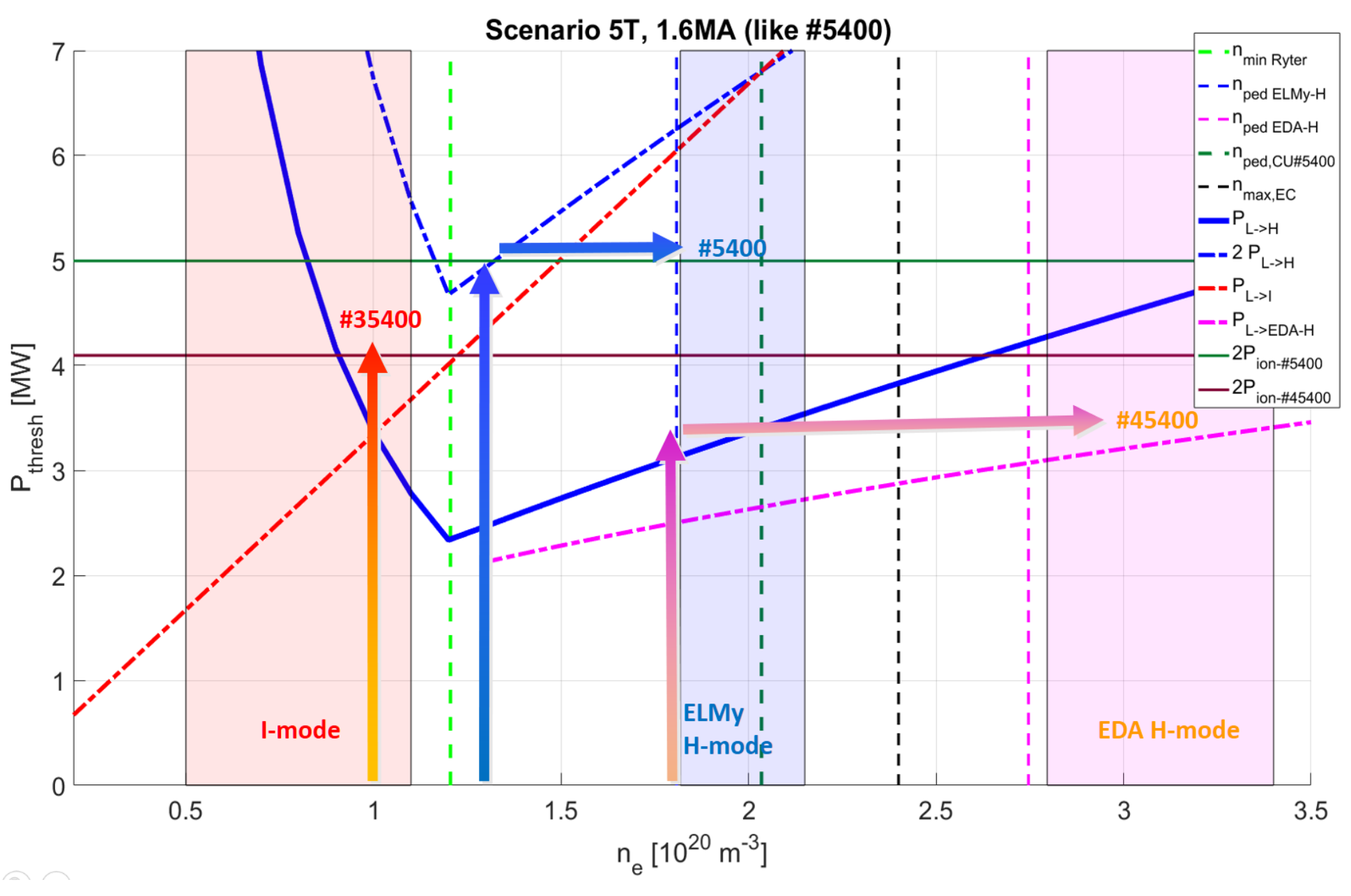


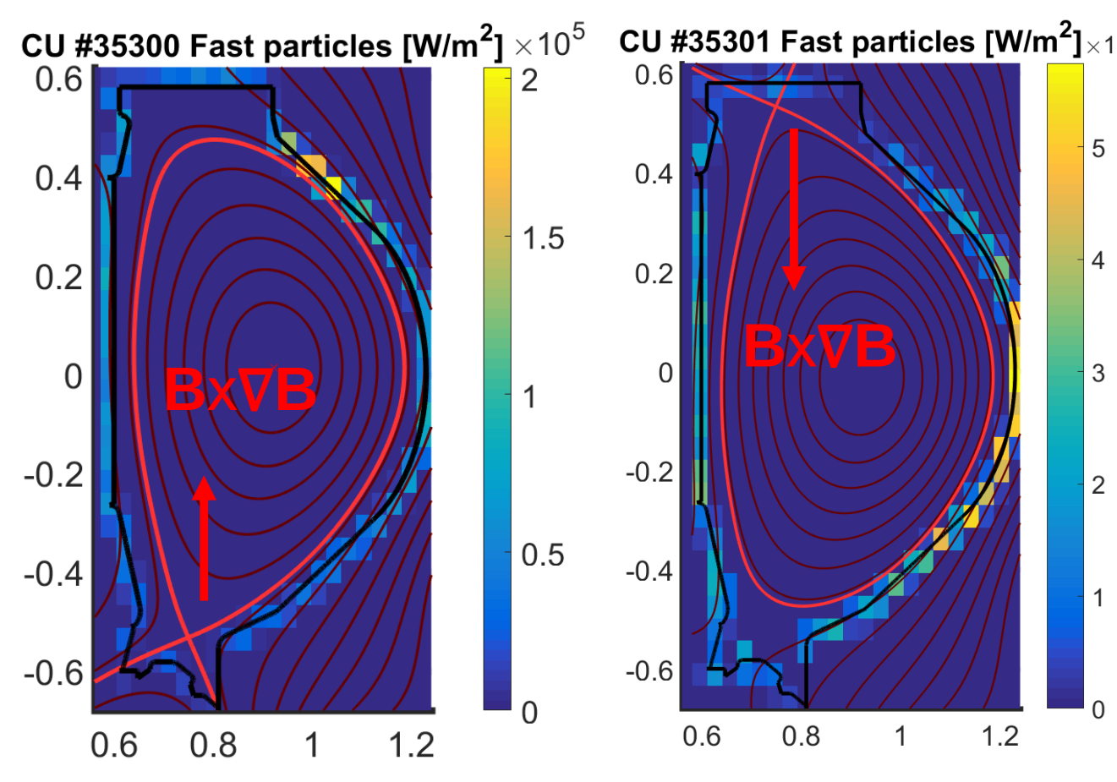
*Detailed integrated transport modelling with the METIS code [9] yields density and temperature profiles during the flat-top. The pedestal pressure obtained by our scalings in ELMy H-mode is comparable to that suggested by EPED.*



### I-mode

I-mode experiments use the unfavourable drift configuration (ion ∇B drift away from the X-point), so that $P_{L,H,ELMy}$ is increased by a factor 2. I-mode can then be sustained at moderate heating power and lower collisionality. In the LSN configuration, large amount of fast particles losses on the PFCs are to be expected.





*Fast ions and neutrals losses for two possible I-mode configurations. The deposition and additional losses due to the Toroidal Field Ripple (TFR) and the Charge-Exchange (CX) with edge neutrals were studied with the EBdyna code [15].*

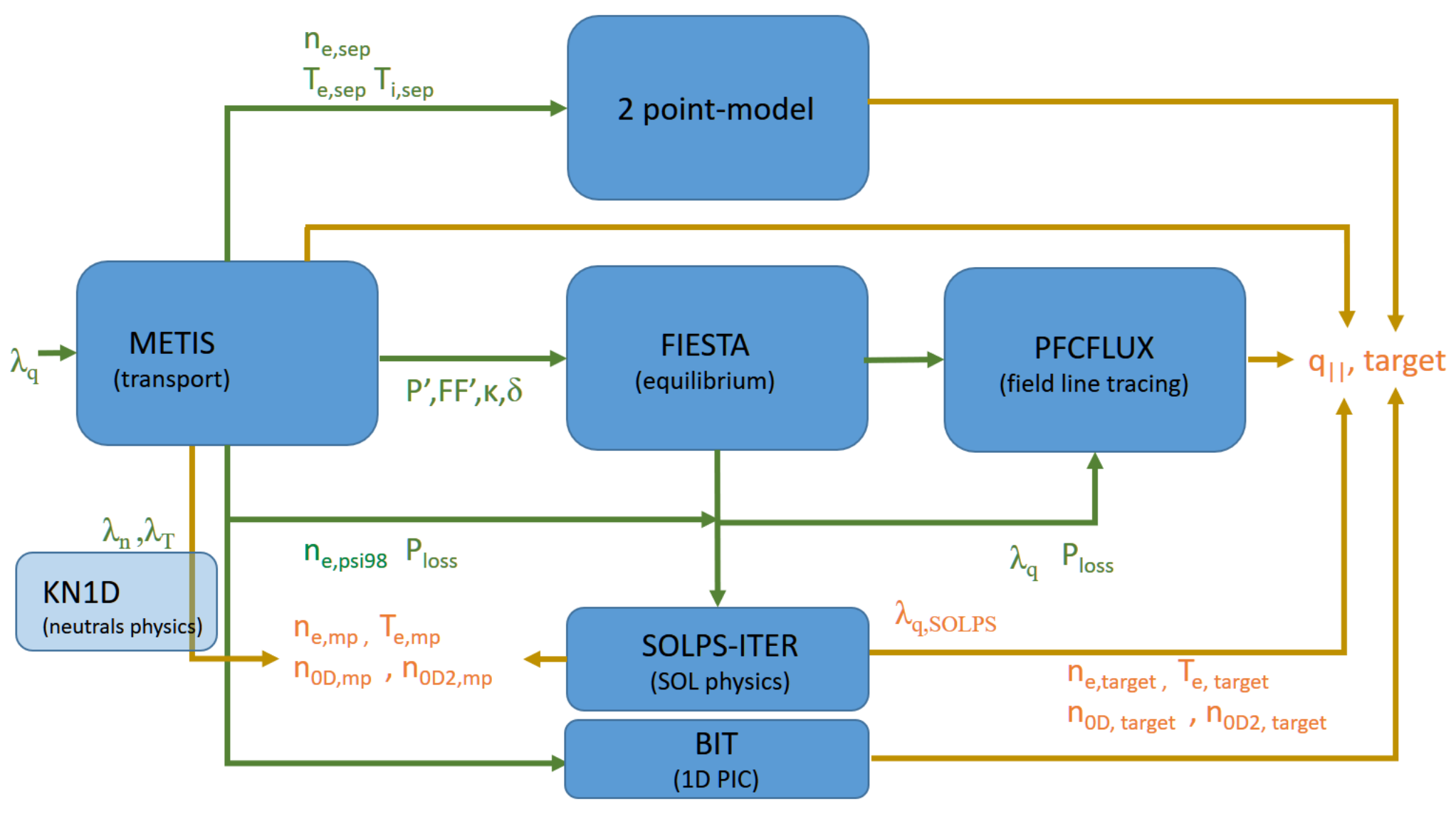
### Enhanced D-Alpha (EDA) H-mode

Experiments in C-mod showed that EDA is favoured by higher edge safety factor (q95>3.7), higher values of triangularity (δ >0.3) and higher line-averaged density prior to the L-H transition (>1.3 $10^{20}$ $m^{-3}$). A quasi-coherent mode (QCM) is observed through the fluctuation of density. The pedestal top density is significantly higher than in ELMy H-mode. This has an impact on the wall neutral density [15] .

## Footprint of the Heat Flux on the PFCs and separatrix conditions

Comparing 2 point-model parallel heat flux calculations with the tracing of the heat along the flux tube with PFCFLUX allows to check validity of separatrix conditions. PFCFLUX is using the Brunner formula [13] and scaling [14] in H-mode.

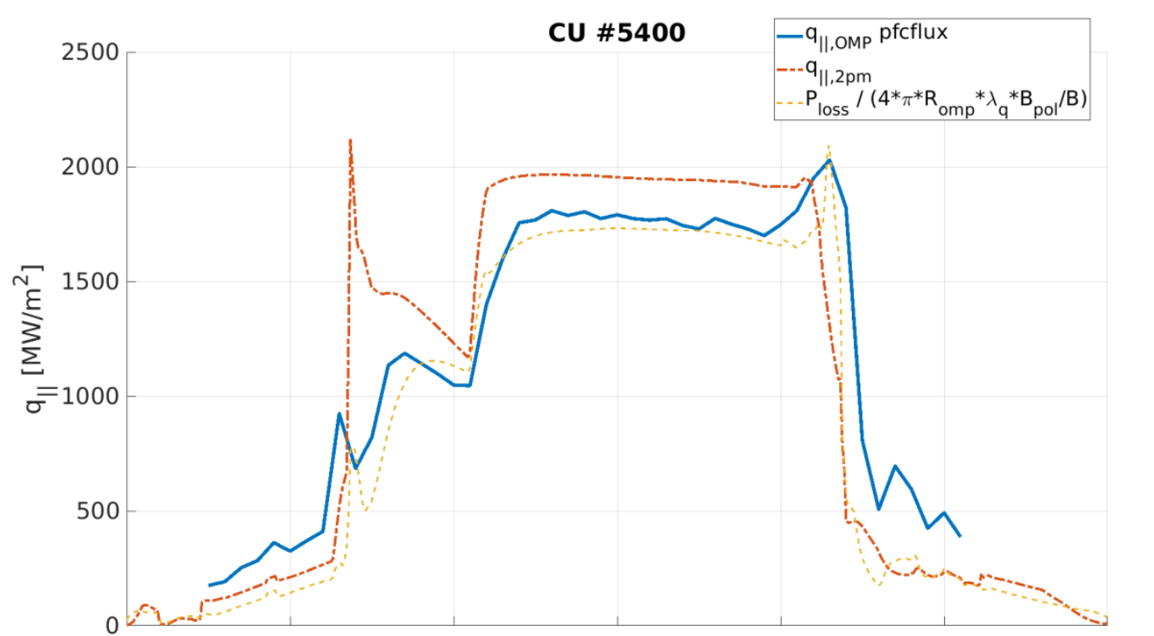
$$\lambda_q = 0.91\left(\frac{W_{\text{tot}}}{V_{\text{plasma}}}\right)^{-0.48}$$



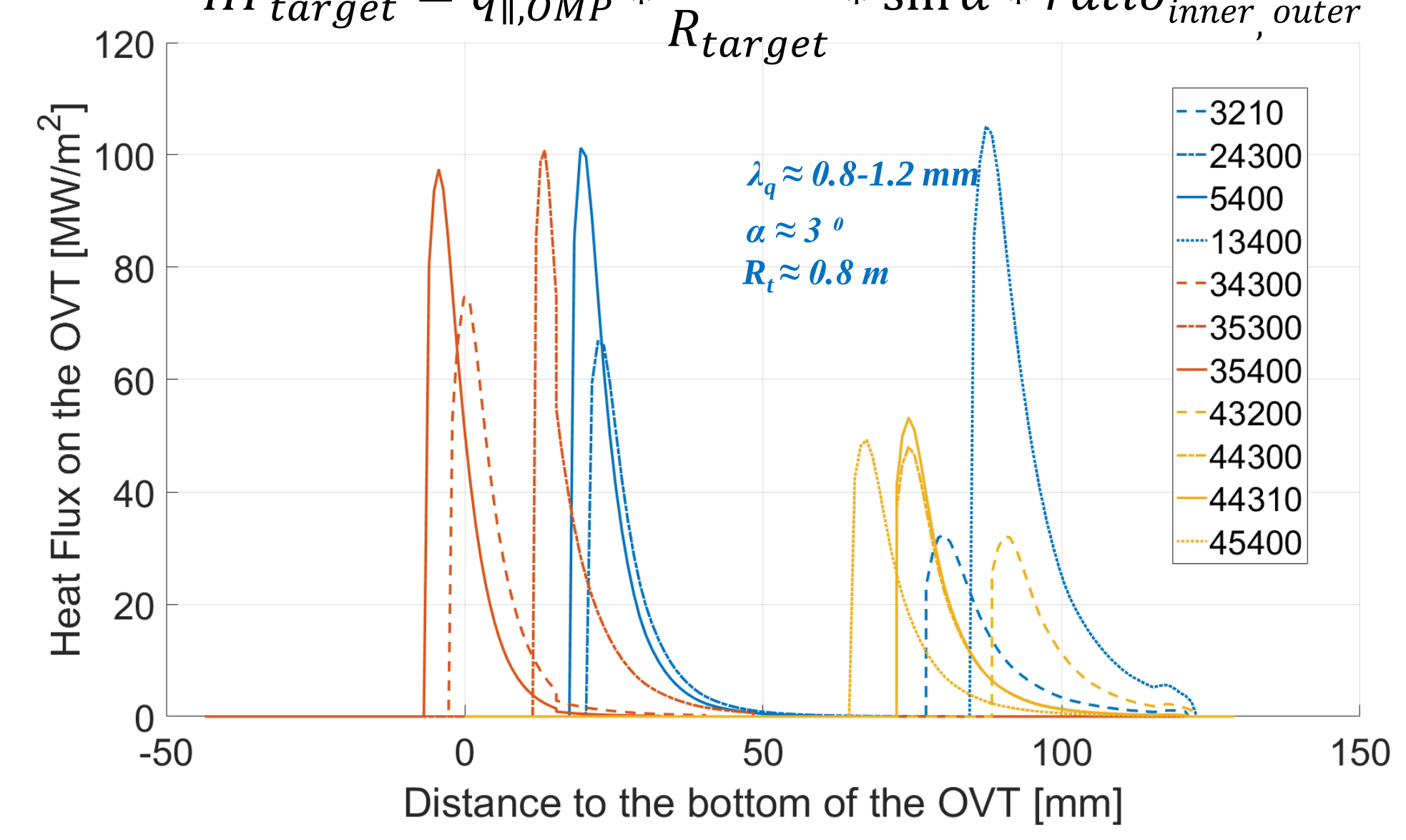
At OMP :

Limited : $q_{\|,\text{OMP}}(d) = q_{\|}(0,n) \times \left( e^{-d/\lambda_{qn}} + \frac{1}{Rq} e^{-d/\lambda_{qf}} \right)$

Diverted : $q_{\|,\text{OMP}}(d) = \frac{q_{\|0}}{2} exp\left( \left( \frac{S}{2\lambda_q} \right)^2 - d/\lambda_q \right) * erfc\left( \frac{S}{2\lambda_q} - \frac{d}{S} \right)$

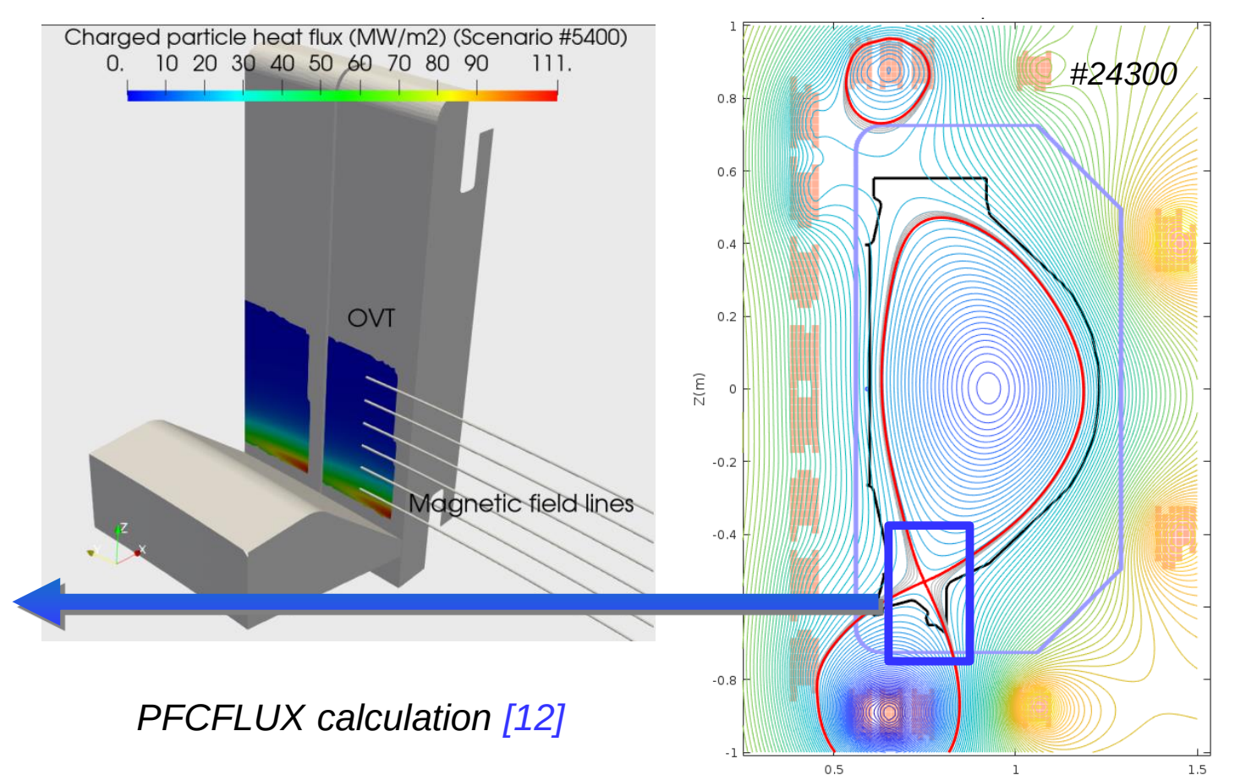


$$HF_{target} = q_{\|,OMP} * \frac{R_{OMP}}{R_{target}} * \sin\alpha * ratio_{inner,\ outer}$$



$$q_{\|} = \frac{1}{2}\gamma_{\text{sheath}} n_e \frac{T_e + T_i}{2}\sqrt{2T_e/m_i} = \frac{P_{\text{loss}}}{4\pi R\lambda_q B_{\text{pol}}/B}$$

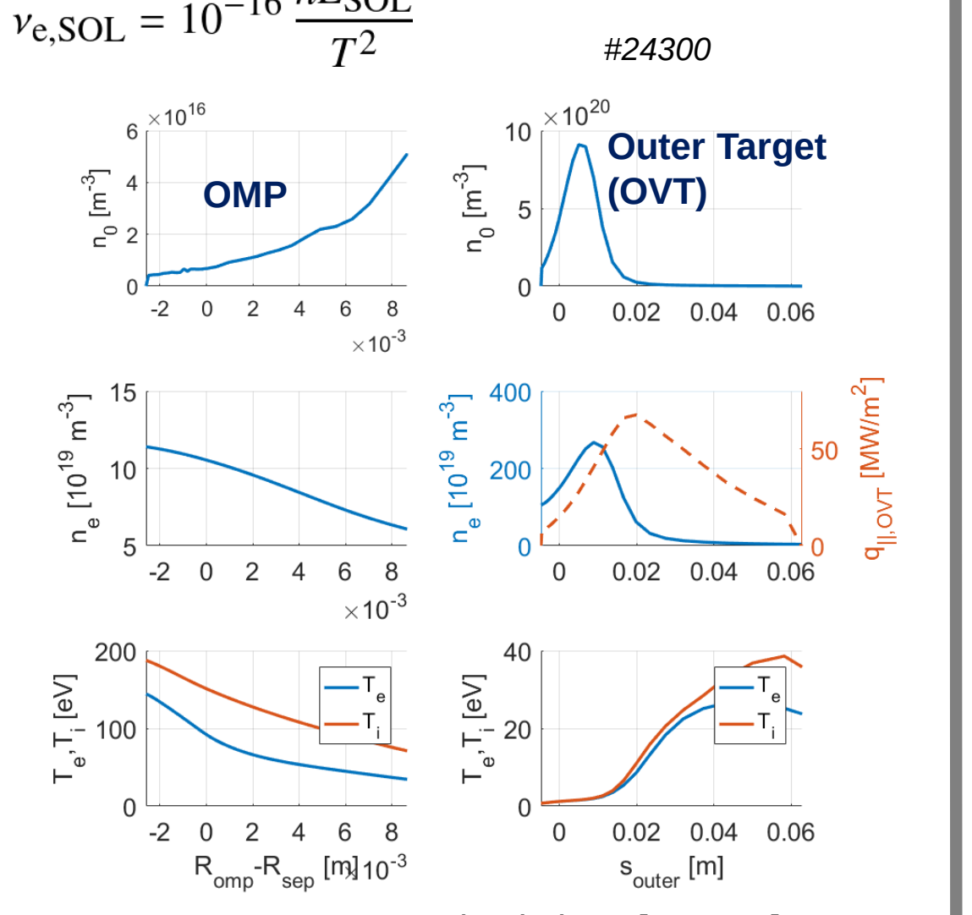
*Stangeby [11]*



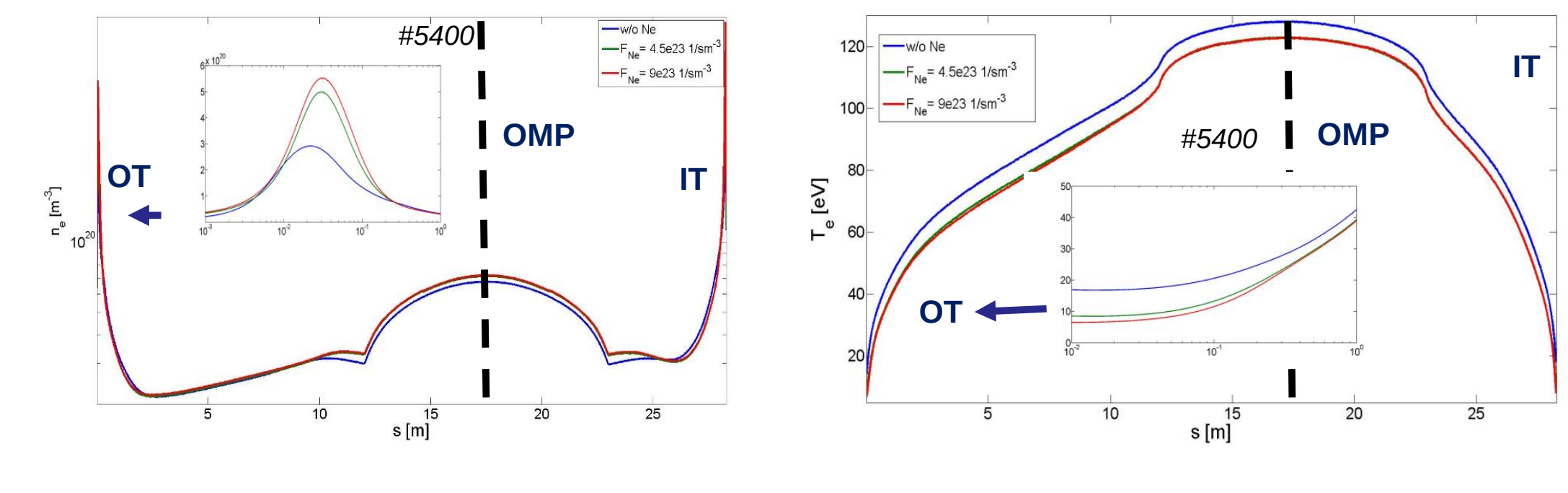
*PFCFLUX calculation [12]*

| Scenario | qpll_2pm [MW/m²] | PFCFLUX_q\|\| [MW/m²] | METIS_q\|\| [MW/m²] | ne_LCFS $[10^{20}\ m^{-3}]$ | Te_LCFS [eV] | Ti_LCFS [eV] | $\nu_{e,SOL}$ |
|---|---|---|---|---|---|---|---|
| #3210 | 524 | 561 | 644 | 0.41 | 135 | 176 | 2.7 |
| #24300 | 1475 | 1267 | 1258 | 1.18 | 132 | 176 | 7.7 |
| #5400 | 1950 | 1862 | 1781 | 1.37 | 142 | 196 | 1.1 |
| #13400 | 2302 | 3025 | 3837 | 0.42 | 313 | 561 | 1 |
| #34300 | 912 | 1405 | 1663 | 0.28 | 226 | 391 | 0.7 |
| #35300 | 1012 | 1729 | 1898 | 0.32 | 215 | 397 | 0.8 |
| #35301 | 1012 | 1205 | 1898 | 0.32 | 215 | 397 | 0.8 |
| #35400 | 1076 | 1925 | 2243 | 0.27 | 244 | 479 | 0.5 |
| #43200 | 586 | 546 | 513 | 0.79 | 92 | 127 | 10.9 |
| #44300 | 1511 | 972 | 1228 | 1.29 | 127 | 167 | 10.8 |
| #44310 | 2184 | 1074 | 624 | 1.89 | 119 | 181 | 17.8 |
| #45400 | 1874 | 1025 | 1296 | 1.89 | 115 | 146 | 16.4 |

$$\nu_{e,\text{SOL}} = 10^{-16}\frac{nL_{\text{SOL}}}{T^2}$$



*SOLPS-ITER simulations [#24300]*



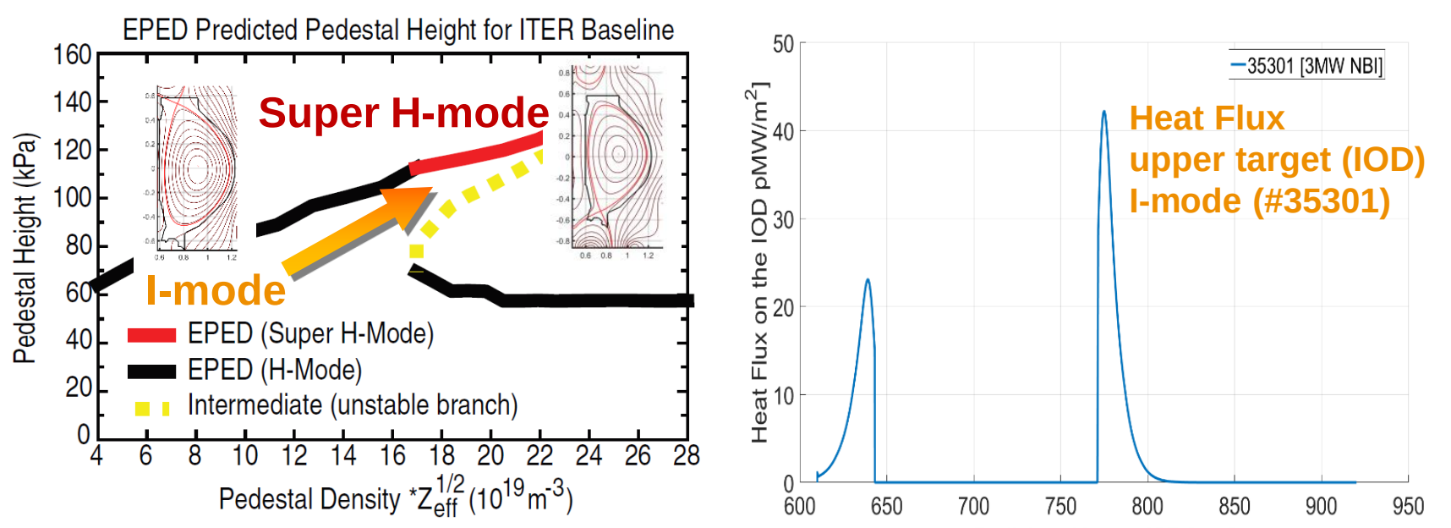
*BIT code simulations (1D PIC code) of #5400
D. Tskhakaya, et al., 25th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, 13 - 17 June 2021 (virtual).*

| Parameter | $F_{Ne}$ = 0 | $F_{Ne}$ = 4.5x $10^{23}$ $s^{-1}m^{-3}$ | $F_{Ne}$ = 9x $10^{23}$ $s^{-1}m^{-3}$ |
|---|---|---|---|
| $q_{\|\|,OD}$ [MW/m²] | 550 | 370 | 310 |
| $q_{\|\|,ID}$ [MW/m²] | 390 | 260 | 220 |
| Radiated fraction | 46% | 67% | 73% |

Power is likely to be radiated along the connection length. PIC simulations suggest at least 50% of power lost along the connection length (#5400). SOLPS-ITER simulation suggest partial detachment (#24300).

### Higher confinement: Super H-mode

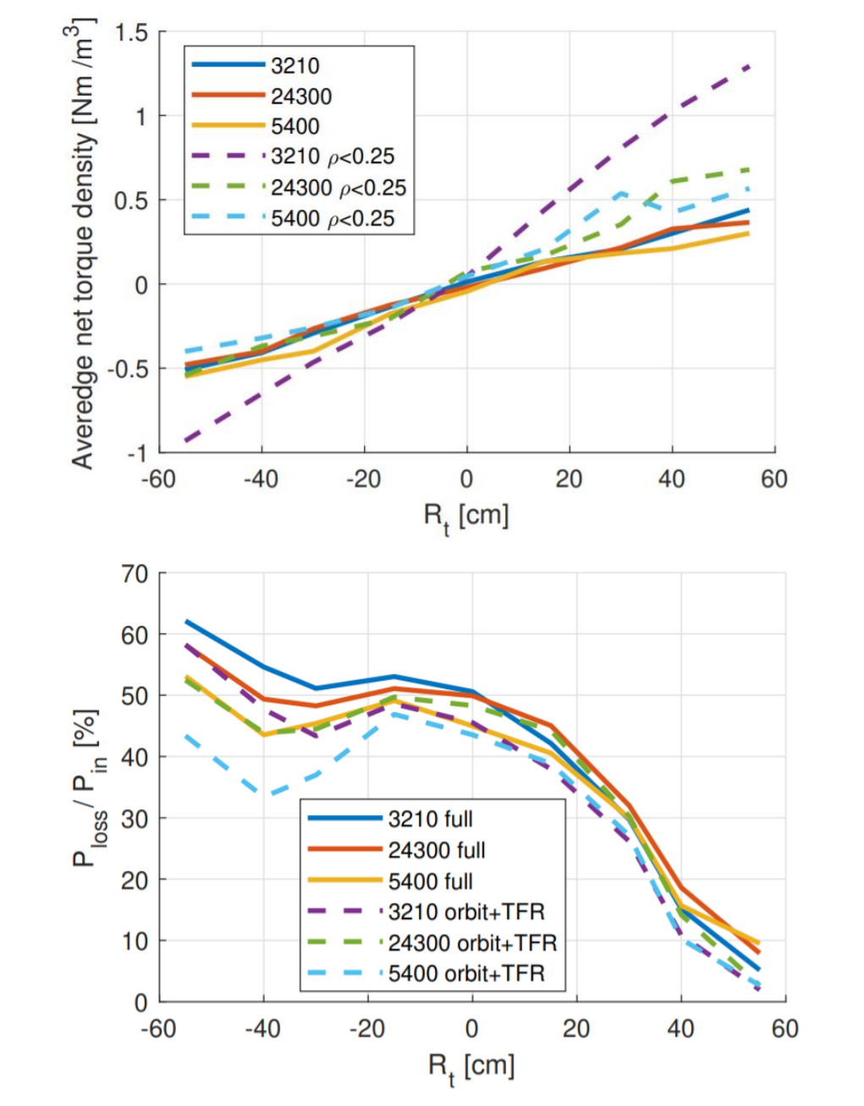
Strong shaping (triangularity > 0.35) leads to a partial decoupling of current-driven and pressure-driven instabilities. The "channel" of access to Super H-mode cycle can only be entered at low density and large pedestal temperature. In COMPASS-Upgrade, we study a transient high-power I-mode on the upper target (CU #35301) that would transition to a Lower X-point configuration.



*Super H-mode in ITER as calculated in [16]*

### Balanced torque deposition and QH-mode access

QH-mode ([17],[18]) access will involve detailed understanding of NBI torque deposition and modelling of edge plasma rotation. QH-mode can be enhanced by the use of double null shapes in COMPASS Upgrade [1]. NUBEAM calculations [19] estimate the deposited torque after calibrating the TFR loss criteria according to the full-orbit code Ebdyna. Low-input-torque plasma could be obtained in COMPASS-Upgrade with NBI heating @$R_t$~-0.35m. 'edge-harmonic mode' (EHO) and higher frequency activity (HFO) will be studied [17].



## Conclusions and outlook

Transport modelling of various confinement regimes in the upcoming COMPASS Upgrade tokamak was performed with the fast transport solver METIS. Scenarios that satisfy engineering constrains have been developed and can be used to anticipate the pedestal conditions in various edge transport barrier MHD activities. SOL modelling allows to improve the modelling of separatrix conditions for the transport solver.

## References

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