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ASDEX Upgrade

Discussion on selected physics items and related uncertainties for the definition of the operational point of a reactor

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Three main elements: Confinement, density limit, L-H power

- Besides several operational aspects which can affect the accessibility of target plasma conditions (relevant ELM-free regime, sawtooth avoidance / control, …) three fundamental aspects determine a reactor design in combination with the exhaust capabilities

- Confinement level and parameters which determine it (IP, BT, R, a/R, q95, …)

- Maximum density of operation, that is, density limit

- Power requirements for the sustainment of good and stable H-mode confinement (L-H power threshold)

- On each of these three elements, critical uncertainties still remain, even from the standpoint of a completely empirical approach

- In addition, reliable physics models, which could replace empirical approaches, are still under development

H-mode Confinement: current, magnetic field and plasma size

- Confinement time increases with increasing current and increasing plasma size
- Confinement time does not change strongly with increasing magnetic field
- Confinement time decreases with increasing heating power, how much does it increase with increasing density ?
- On each of these statements we have (large) uncertainties on the precise dependencies, with a significant impact on the projections for the reactor operational point
- On several of these dependencies we have not yet reached a consolidated theoretical understanding, nor a robust predictive capability

- One question was recently raised in connection with the new DEMO design (4.4T, 18.8 MA, 8.6 / 3.0 [m])
- How does confinement change when BT, IP, k and a/R are changed at fixed q95 ?
- Do we understand dependencies of H-mode confinement in IP, BT, a/R, k and size and can we rely on the projections from scaling laws ?
- Scaling laws tell us that IP matters, not BT, can we rely on this for the new DEMO point ?

H-mode Confinement: AUG specific scaling laws [Ryter NF 2021]

Label	ζ	α_{I_p}	α_{B_T}	α_{n_e}	$\alpha_{P_{loss}}$	α_δ	$\alpha_{1+\delta}$	RMSE
1C	0.300	1.455			−0.660			0.185
1W	0.242	1.420			−0.611			0.138
2C	0.406	1.560	−0.360		−0.667			0.178
2W	0.323	1.412	−0.344		−0.609			0.132
3C	0.436	1.589	−0.384	−0.030	−0.663			0.178
3C+W	0.482	1.597	−0.467	−0.066	−0.660			0.166
ITPA IL no δ	n/a	1.311	−0.178	0.157	−0.634			
4C	0.630	1.570	−0.157		−0.740	0.300		0.142
4C+W	0.590	1.600	−0.360		−0.734	0.201		0.155
5C	0.803	1.660	−0.223	−0.096	−0.730	0.310		0.140
5C+W	0.870	1.725	−0.435	−0.153	−0.716	0.231		0.151
5C+W-B_T	0.699	1.687	−0.223	−0.116	−0.729	0.237		0.154
6C	0.369	1.692	−0.241	−0.122	−0.723		1.714	0.141
6C+W	0.471	1.736	−0.416	−0.168	−0.718		1.361	0.150
ITPA20-IL	n/a	1.291	−0.134	0.147	−0.644		0.560	

H-mode Confinement: JET specific scaling laws [Maslov NF 2020]

Table 4. Exponents for the OLS power law regression fit for the $\tau^{*}_{\mathrm{E,th}}$ parameters as defined in (4). M_{eff} was not included in JET-C2 regression due to the lack of experiments with isotopes. IPB98(y,2) scaling is shown for comparison.

	Const	I_{p}	B_{t}	q_{95}	$P_{\mathrm{l,th}}$	n_{e}	M_{eff}	R^2	RRMSE, %
IPB98(y,2)	0.0562	0.93	0.15		−0.69	0.41	0.19	—	—
JET-C1	0.073 ± 0.002	1.04 ± 0.026	0.11 ± 0.027		−0.76 ± 0.011	0.31 ± 0.015	0.20 ± 0.026	0.887	11.5
JET-C1	0.0635 ± 0.0025	1.15 ± 0.018		0.12 ± 0.028	−0.76 ± 0.011	0.32 ± 0.015	0.20 ± 0.026	0.887	11.5
JET-C2	0.0897 ± 0.002	1.175 ± 0.017	−0.09 ± 0.02		−0.63 ± 0.01	0.13 ± 0.01		0.894	10.2
JET-C2	0.095 ± 0.003	1.104 ± 0.016		−0.051 ± 0.02	−0.64 ± 0.01	0.13 ± 0.01		0.894	10.2
JET-ILW	0.059 ± 0.0022	1.16 ± 0.047	−0.22 ± 0.034		−0.585 ± 0.014	0.08 ± 0.025	0.37 ± 0.023	0.851	10.2
JET-ILW	0.066 ± 0.004	0.947 ± 0.034		−0.13 ± 0.036	−0.59 ± 0.014	0.11 ± 0.025	0.35 ± 0.023	0.846	10.4

Table 5. Regression results with triangularity and particle source instead of the plasma density.

	Const	I_{p}	B_{t}	q_{95}	$P_{\mathrm{l,th}}$	$1+\delta$	$1+S/n_{\mathrm{GW}}$	M_{eff}	R^2	RRMSE, %
JET-C1	0.068 ± 0.002	1.36 ± 0.027	0.033 ± 0.028	—	−0.74 ± 0.012	1.18 ± 0.065	−0.155 ± 0.031	0.33 ± 0.03	0.877	12.6
JET-C1	0.068 ± 0.003	1.38 ± 0.02	—	−0.01 ± 0.03	−0.74 ± 0.012	1.19 ± 0.065	−0.156 ± 0.031	0.34 ± 0.027	0.877	12.6
JET-C2	0.088 ± 0.002	1.37 ± 0.014	−0.11 ± 0.02	—	−0.66 ± 0.008	0.67 ± 0.042	−0.302 ± 0.024	—	0.904	9.9
JET-C2	0.098 ± 0.003	1.27 ± 0.014	—	−0.09 ± 0.02	−0.66 ± 0.008	0.66 ± 0.042	−0.31 ± 0.024	—	0.903	9.9
JET-ILW	0.066 ± 0.002	1.31 ± 0.029	−0.28 ± 0.03	—	−0.598 ± 0.012	0.25 ± 0.08	−0.33 ± 0.03	0.415 ± 0.02	0.871	9.56
JET-ILW	0.0836 ± 0.004	1.06 ± 0.023	—	−0.23 ± 0.032	−0.60 ± 0.013	0.30 ± 0.08	−0.33 ± 0.03	0.41 ± 0.02	0.866	9.76

Table 9. Results of the OLS regression analysis for $\tau^{*}_{\mathrm{E,th}}$ made on the reduced JET-ILW dataset with 238 samples containing $n_{\mathrm{e,SOL}}$ data.

Const	I_{p}	B_{t}	$P_{\mathrm{l,th}}$	$1+\delta$	$1+S/n_{\mathrm{GW}}$	$1+n_{\mathrm{e,SOL}}/n_{\mathrm{GW}}$	M_{eff}	R^2	RRMSE, %
0.0657 ± 0.004	1.41 ± 0.068	−0.357 ± 0.06	−0.60 ± 0.026	0.23 ± 0.154	−0.25 ± 0.054		0.39 ± 0.034	0.851	10
0.070 ± 0.004	1.38 ± 0.065	−0.301 ± 0.059	−0.62 ± 0.025	0.22 ± 0.148		−0.23 ± 0.036	0.43 ± 0.034	0.862	9.7

H-mode Confinement: multi-device scaling laws

Scaling	C (10^{-2})	I	B	n	P	R	$\kappa_a^{(1)}$	a/R	M	N	RMSE (%)	ITER τ_E (s)
IPB98(y)	3.65	0.97	0.08	0.41	−0.63	1.93	0.67	0.23	0.20	1398	15.8	6.0
IPB98(y,1)	5.03	0.91	0.15	0.44	−0.65	2.05	0.72	0.57	0.13	1398	15.3	5.9
IPB98(y,2)	5.62	0.93	0.15	0.41	−0.69	1.97	0.78	0.58	0.19	1310	14.5	4.9
IPB98(y,3)	5.64	0.88	0.07	0.40	−0.69	2.15	0.78	0.64	0.20	1273	14.2	5.0
IPB98(y,4)	5.87	0.85	0.29	0.39	−0.70	2.08	0.76	0.69	0.17	714	14.1	5.1

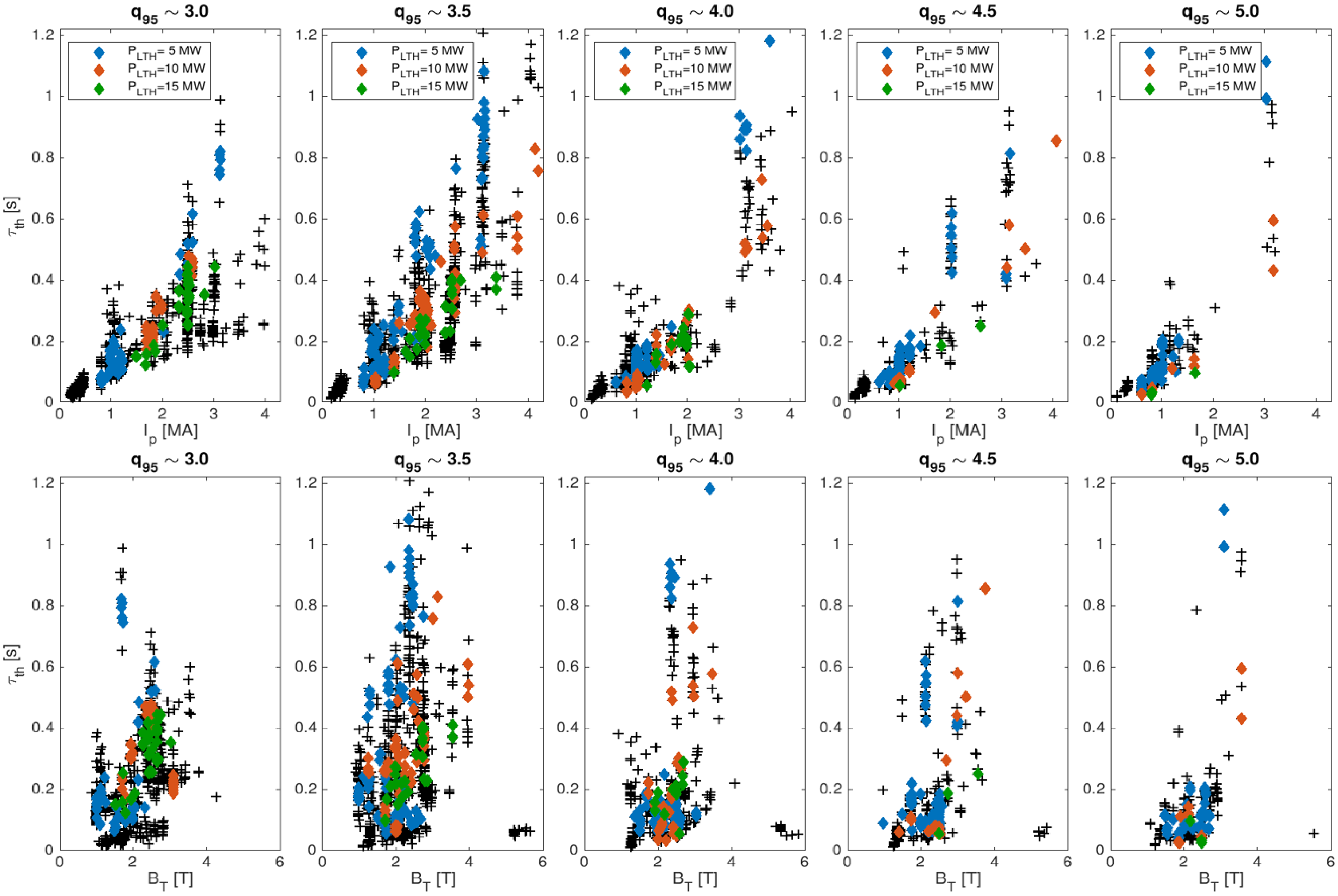
[IPB NF 1999 & Verdoolaege NF 2021]

ITPA20

$$\tau_{\mathrm{E,th}} = \left(0.053 \quad {}^{+0.030}_{-0.018}\right) I_{\mathrm{p}}^{0.98\pm0.19} B_{\mathrm{t}}^{0.22\pm0.18} \times \bar{n}_{\mathrm{e}}^{0.24\pm0.11} P_{\mathrm{l,th}}^{-0.669\pm0.059} R_{\mathrm{geo}}^{1.71\pm0.32} \times (1+\delta)^{0.36\pm0.39} \kappa_{\mathrm{a}}^{0.80\pm0.38} \epsilon^{0.35\pm0.66} M_{\mathrm{eff}}^{0.20\pm0.17},$$

$$\tau_{\mathrm{E,th}} = \left(0.067 \quad {}^{+0.059}_{-0.032}\right) I_{\mathrm{p}}^{1.29\pm0.16} B_{\mathrm{t}}^{-0.13\pm0.17} \times \bar{n}_{\mathrm{e}}^{0.147\pm0.097} P_{\mathrm{l,th}}^{-0.644\pm0.061} R_{\mathrm{geo}}^{1.19\pm0.27} \times (1+\delta)^{0.56\pm0.36} \kappa_{\mathrm{a}}^{0.67\pm0.63} M_{\mathrm{eff}}^{0.30\pm0.16}. \quad (5)$$

This relation will be referred to as **ITPA20-IL** (ITER-like)



From ITPA Conf DB,

IP and BT dependencies on windows of constant q95

From ITPA Conf DB, IP and BT dependencies at windows of q95

- All data of the ITPA 20 selection, with spherical tokamaks removed
- OLS on windows of q95 provide results which are surprisingly consistent with complete global scaling laws

q95		IP	BT	PLTH	NEL	RGEO	RMSE
3.0:	0.0707 (0.0106 / -0.0092)	1.3236 ±0.0494	-0.0330 ± 0.0441	-0.7939 ± 0.0357	0.3811 ± 0.0437	1.5895 ± 0.1152	0.1485
3.5:	0.0943 (0.0110 / -0.0098)	1.2889 ±0.0295	-0.1118 ± 0.0455	-0.8168 ± 0.0282	0.3267 ± 0.0441	1.6182 ± 0.0908	0.1591
4.0:	0.2384 (0.0360 / -0.0313)	1.4478 ±0.0435	-0.2224 ±0.0739	-0.7221 ± 0.0368	0.0408 ± 0.0474	0.8922 ± 0.1094	0.1636
4.5:	0.2088 (0.0450 / -0.0370)	1.3131 ±0.0595	-0.1957 ± 0.0993	-0.6585 ± 0.0480	0.0171 ± 0.0776	1.0566 ± 0.1454	0.2307
5.0:	0.2764 (0.0953 / -0.0709)	1.4499 ±0.0735	-0.0121 ± 0.1228	-0.7763 ± 0.0628	-0.0863 ± 0.1212	0.9457 ± 0.2397	0.1830

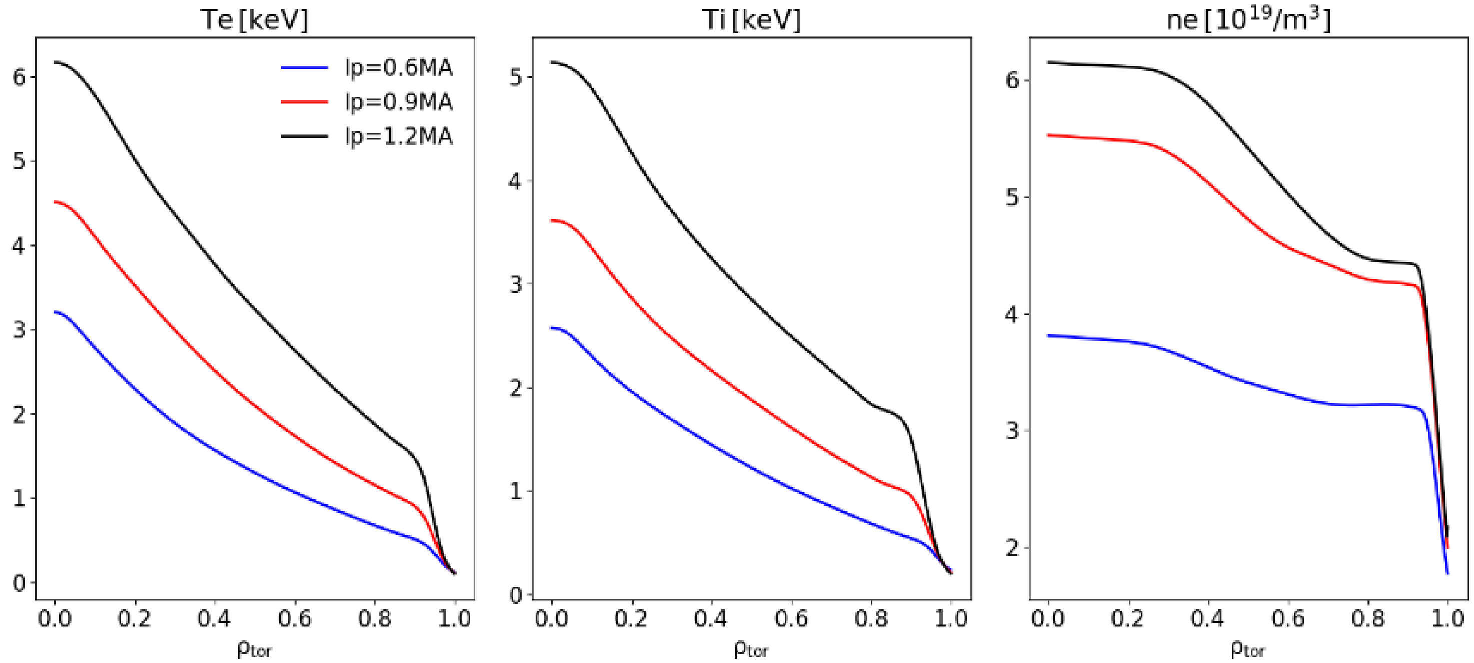
- These regressions have been only performed in order to explore dominant exponents
- They should NOT be used for predictive purposes

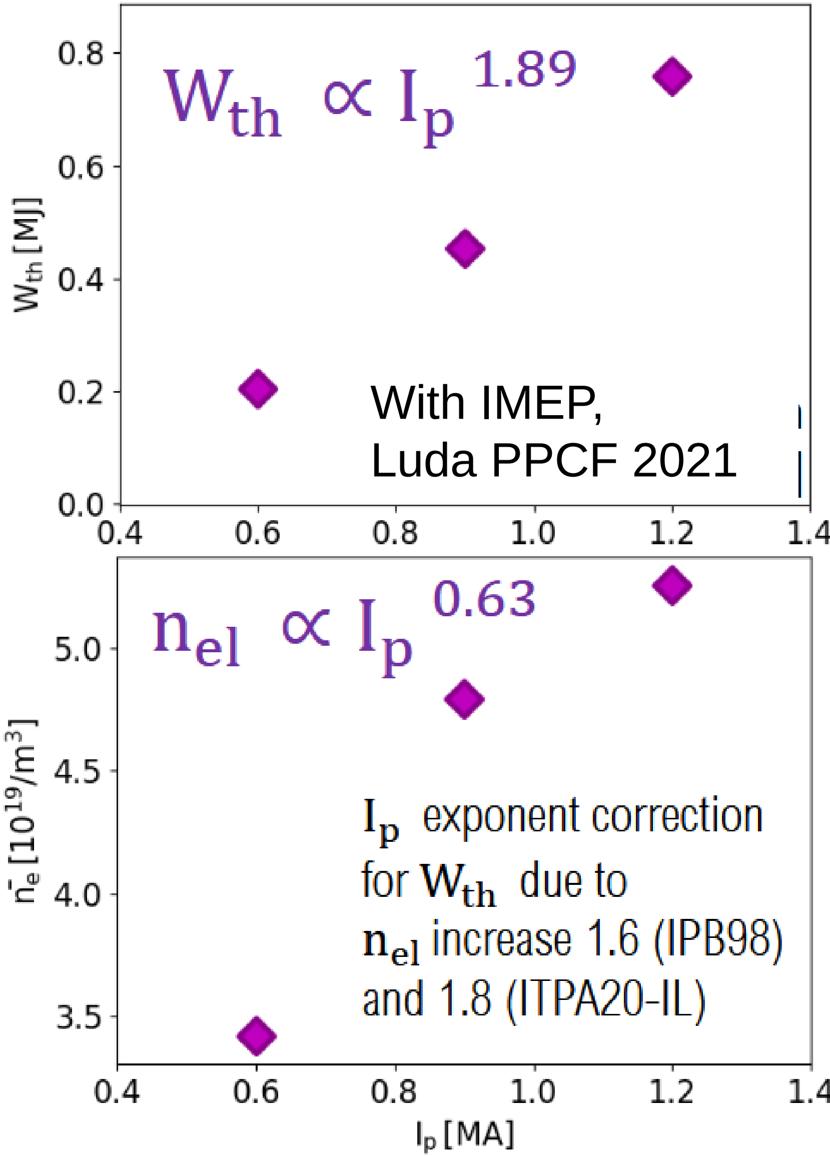
IMEP Ip virtual scan finds strong increase of confinement also concomitant with predicted density increase

- H-mode, numerical Ip scan, all other IMEP input parameters fixed (fixed gas puff, not fixed density)
- Strong Ip dependence, temperature and density increase
- Stronger than in scaling laws

$$W_{th,IPB98} \propto I_p^{\,0.93} n_{el}^{\,0.41}$$

$$W_{th,ITPA20-IL} \propto I_p^{\,1.29} n_{el}^{\,0.15}$$





Comparison IMEP vs EPED on current dependence of ped top

- IMEP predicts strong increase of ped top pressure with increasing IP (MISHKA + transport from R*<∇Te>/Te)
- IPED scaling (EPED KBM constraint with HELENA/MISHKA)) [Puchmayr Master Thesis, IPP Report 2020-11]

$$\beta_{pp} = 0.686 \cdot \kappa^{0.50} \; \widehat{\delta}^{1.68} \; \widehat{q}^{1.61} \; \beta_p^{0.33} \; \widehat{n}_e^{0.06} \; w_p^{1.29}$$

$$\Delta = w_{\mathrm{pre}} \cdot \beta_{\mathrm{pol,ped}}^{\alpha_w} \quad , \qquad \alpha_w = 0.5 \qquad \beta_{\mathrm{pol,ped}} = \frac{2\mu_0 \cdot p_{\mathrm{ped}}}{\langle B_{\mathrm{pol}} \rangle^2} \quad , \qquad \langle B_{\mathrm{pol}} \rangle = \frac{\mu_0 \cdot I_P}{L(a)}$$

- Introducing a core pressure peaking factor $p_k = p_{tot} / p_{ped}$ and making explicit the dependence on IP and other engineering parameters, one finds

$$p_{ped} \propto B_T\text{^}2.4 \quad I_P\text{^-}0.5 \quad w_{pre}\text{^}1.93 \quad R\text{^}0.6 \quad (a/R)\text{^}3.0 \quad p_k\text{^}0.5 \quad [(1+k\text{^}2)\text{^}2.4 \times k\text{^}0.75\,] \quad (1+\delta)\text{^}2.5$$

- Differences in the main assumptions of the transport constraint [KBM (EPED) and ETG-like (IMEP)] modify the scaling of the pedestal width with increasing current and the resulting pedestal top pressure
- These elements can be specifically tested against available data and new dedicated experiments, as well as with appropriate modelling, also computing the appropriate value of w_{pre}

Density limit: is the Greenwald scaling law for density limit appropriate to be used to determine the reactor operational point ?

- Increasing evidence that the Greenwald scaling law is incomplete, mainly because it does not include the dependence of density limit on the heat flux at the edge

Greenwald

[Giacomin PRL 2022]

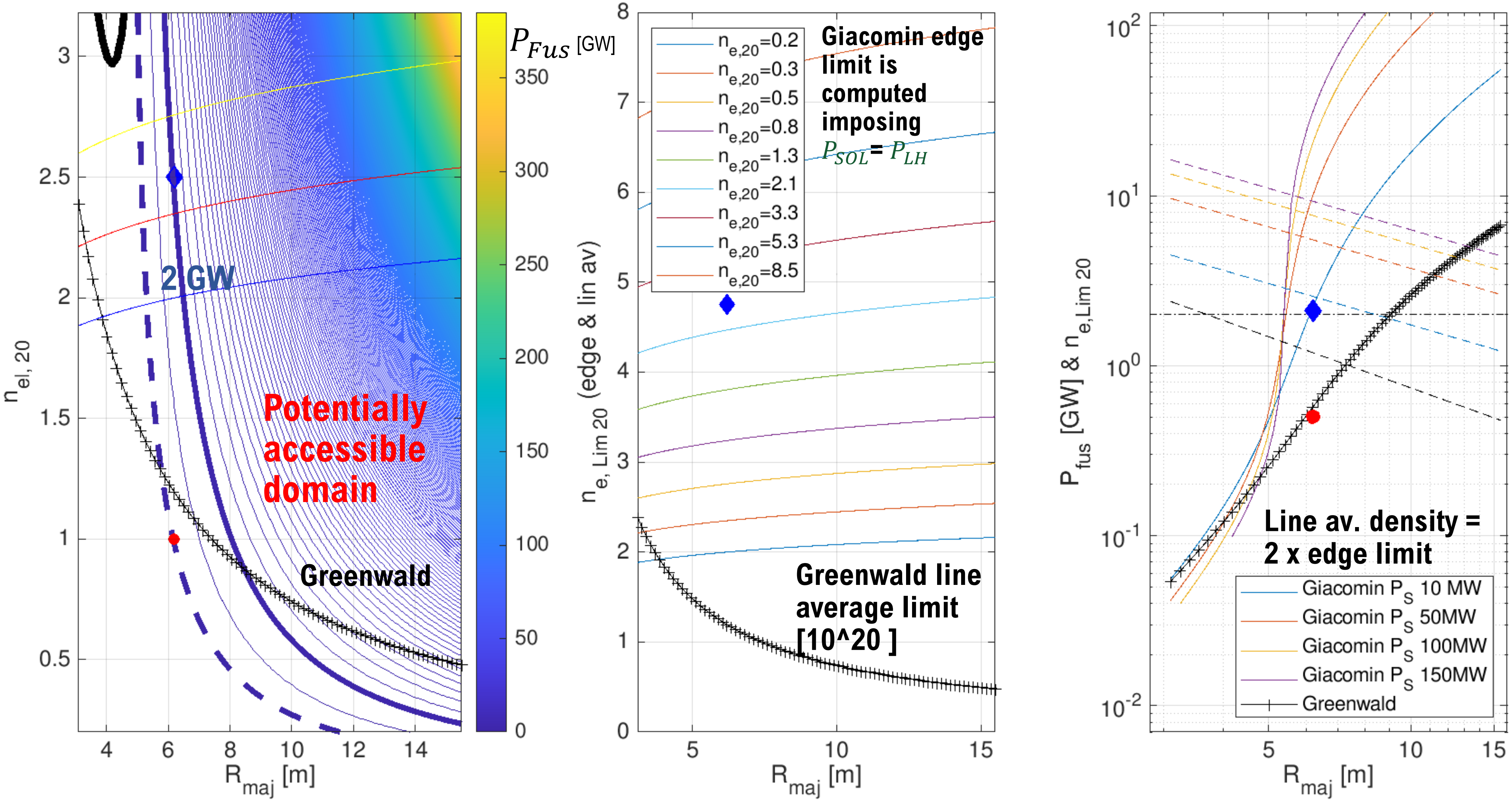
$$n_{\lim} \sim A^{1/6} P_{\mathrm{SOL}}^{10/21} R_0^{1/42} B_T^{-8/21} (1+\kappa^2)^{-1/3} \frac{I_p^{22/21}}{a^{79/42}}.$$

- Giacomin (theoretical) scaling [PRL 2022] practically implies that density limit can increase arbitrarily if power can also arbitrarily increase

  ⇒ The maximum density is determined by the maximum power than can be exhausted

- This is connected with the power required to keep the H-mode ⇒ Potential enormous impact on the reactor operational point
- Introducing Martin scaling for P_{LH} in P_{Sol} ⇒ $n_{lim} \propto$ (Ip / a) n_{el}^0.37 (R/a)^0.5 (1+k^2)^-(1/3) A^0.17
- Dependencies on P_{Sol} and B_T critical to validate the Giacomin model

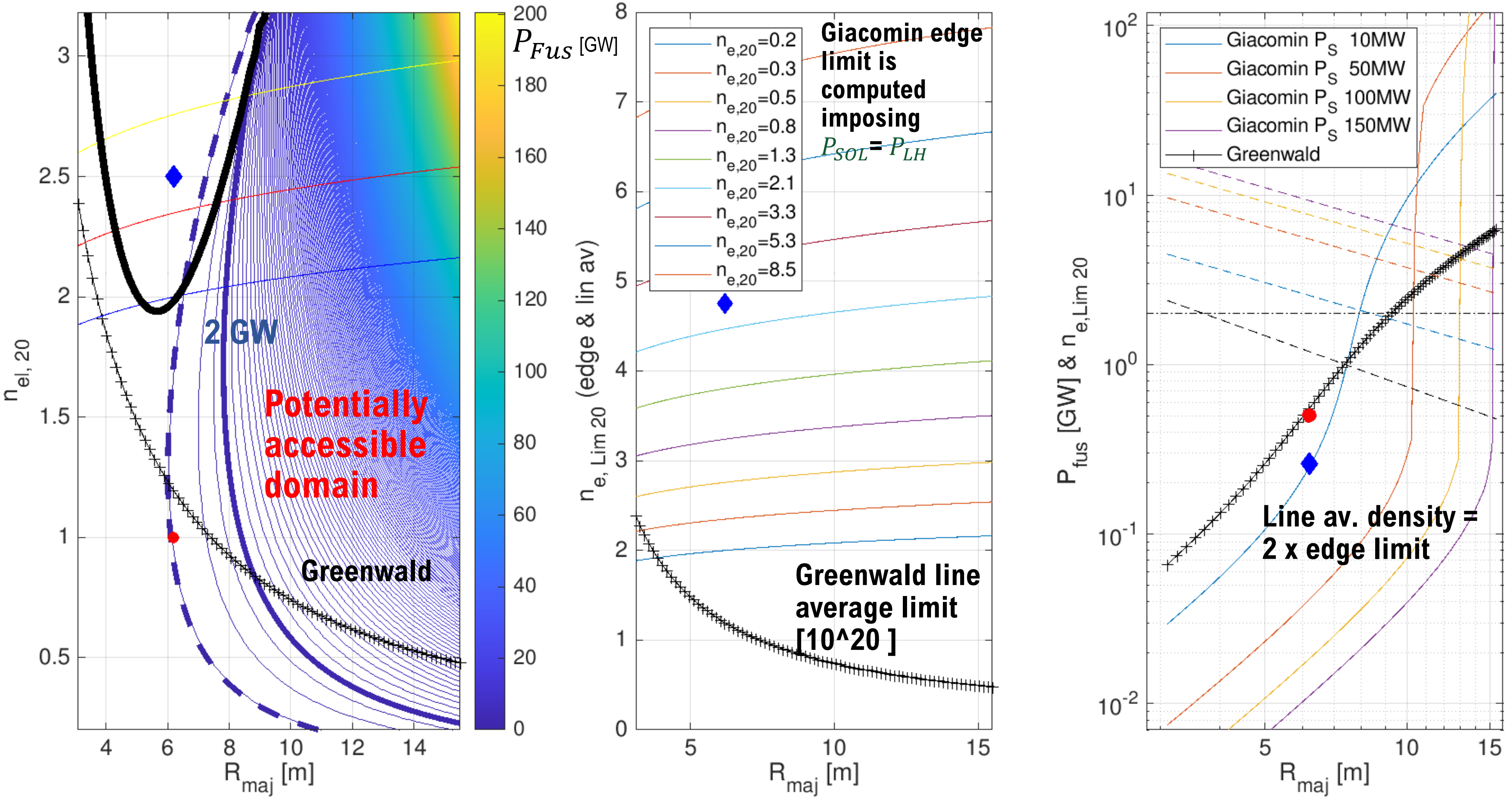
Impact of density limit, Greenwald vs Giacomin with IPB98(y,2)



- ITER BT, q95 and aspect ratio
- P_{aux} = 50 MW

For direct comparison, results are scaled to ensure P_{Fus} =500 MW for the ITER case

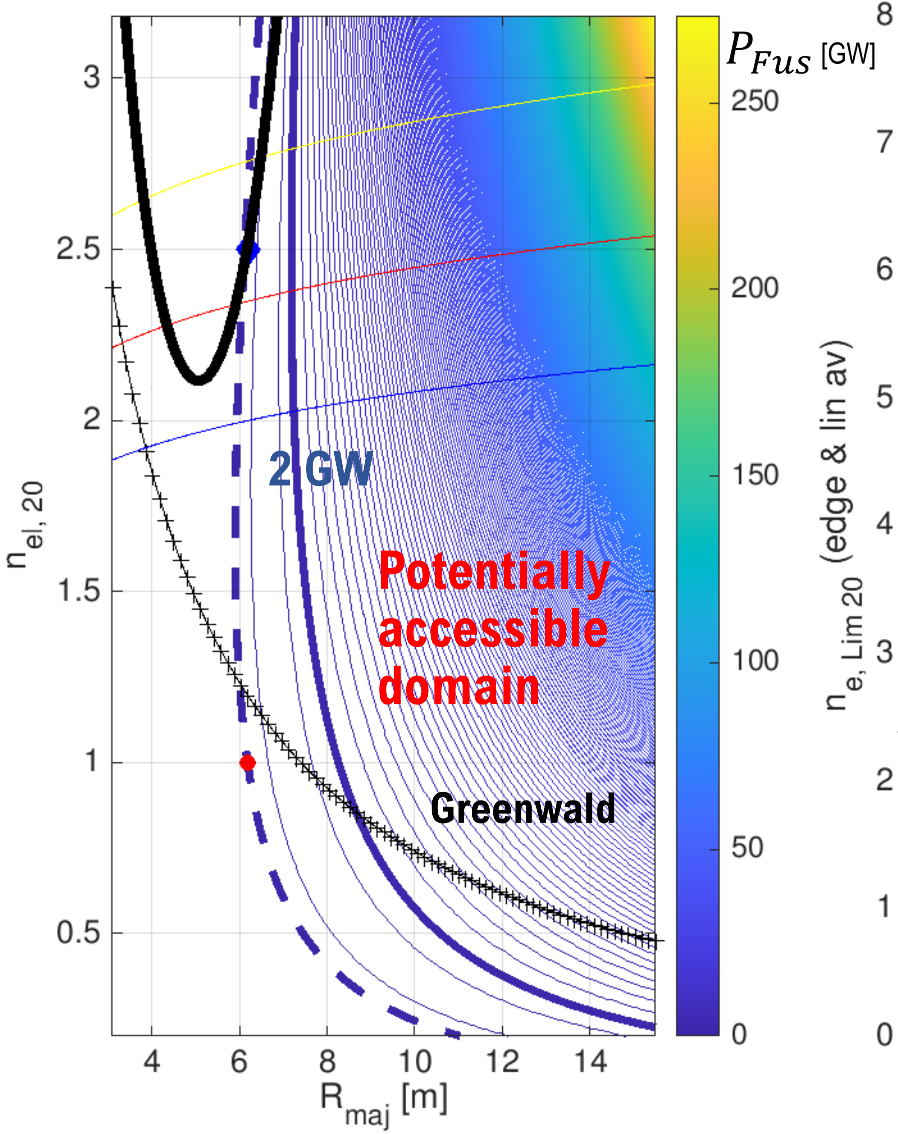
Impact of density limit, Greenwald vs Giacomin with ITPA20-IL

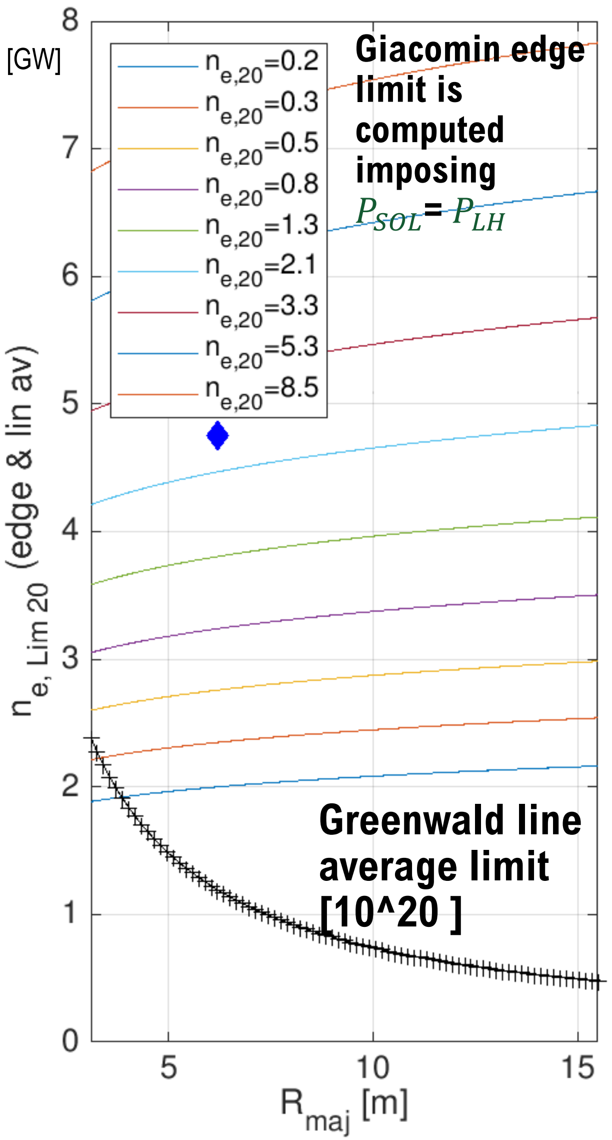


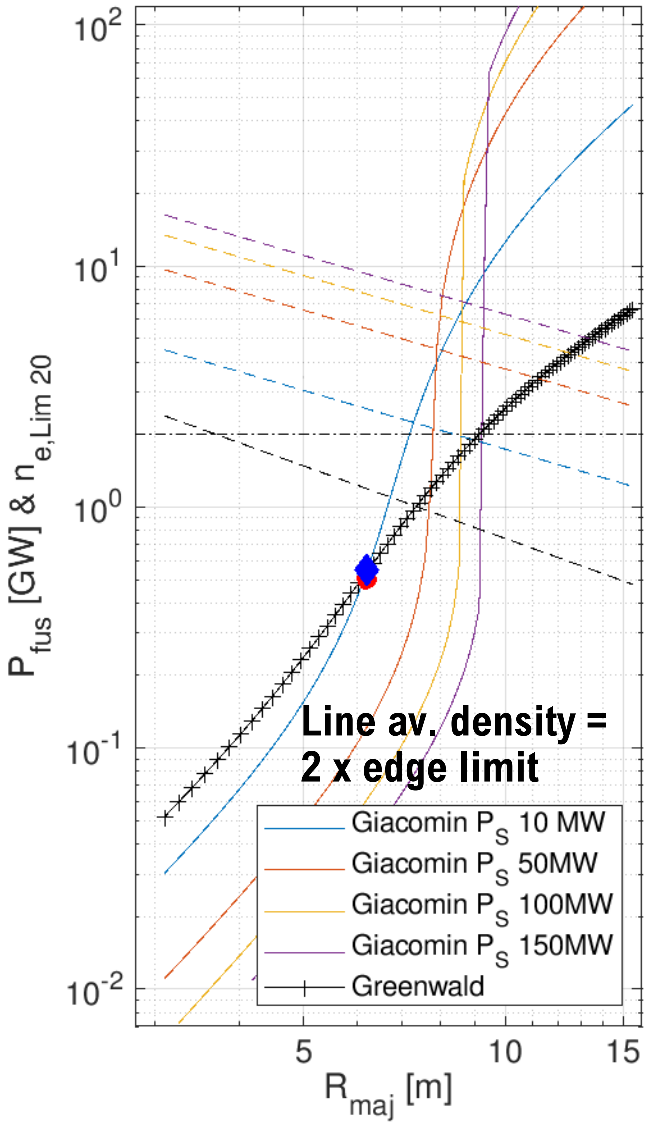
- ITER BT, q95 and aspect ratio
- P_{aux} = 50 MW
- Impact of different scaling laws is strong in the relevant range

For direct comparison, results are scaled to ensure P_{Fus} =500 MW for the ITER case

Impact of density limit, Greenwald vs Giacomin with ITPA20







- **ITER BT, q95 and aspect ratio**
- **P_{aux} = 50 MW**
- **Impact of different scaling laws is strong in the relevant range**

For direct comparison, results are scaled to ensure P_{Fus} =500 MW for the ITER case

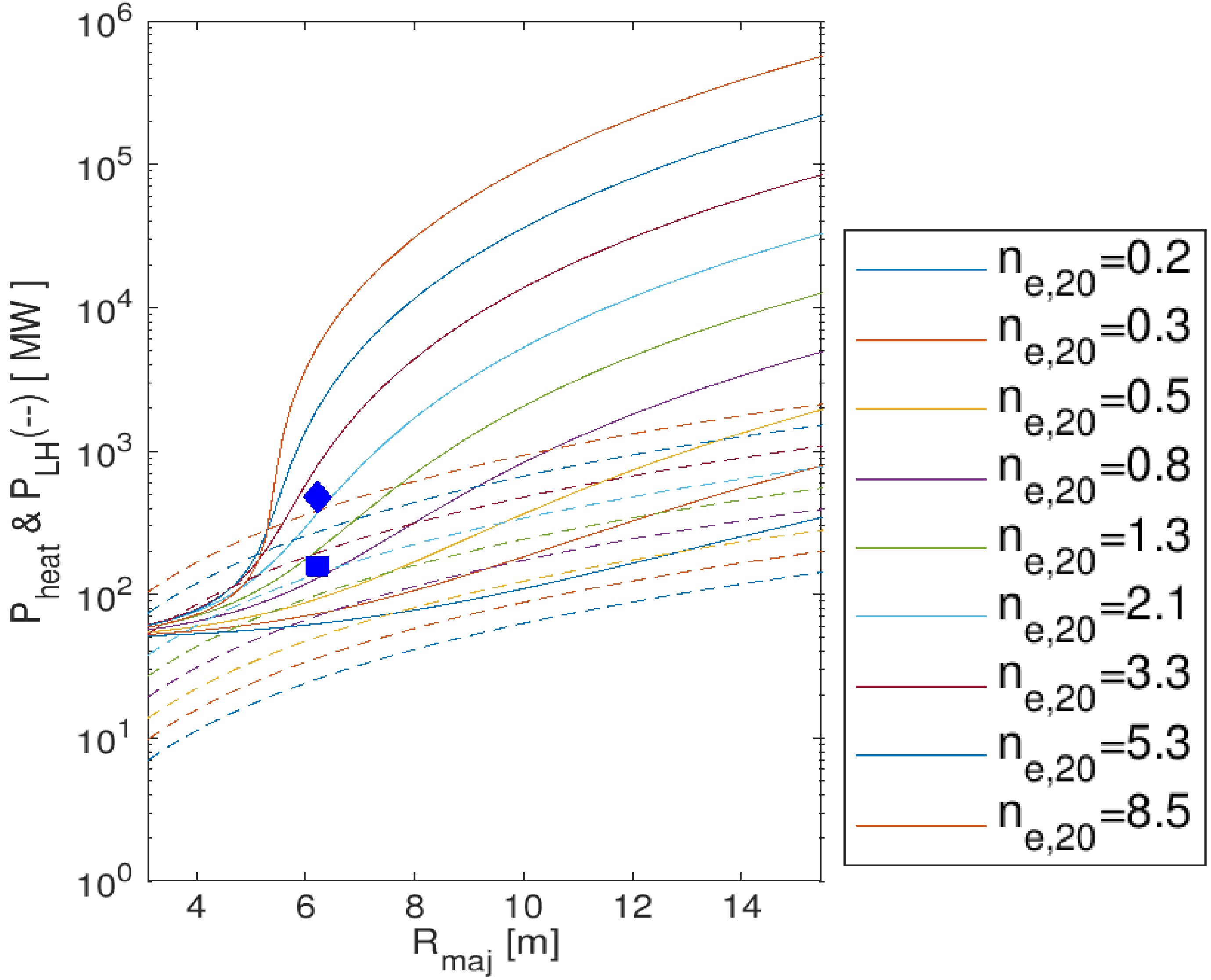
The operational space in size and density opens from 1D to 2D

- **Greenwald:**
- **Once BT, a/R, q95 and Paux are defined, for a given R there is a given Pfus at the maximum allowed density**
- **This is the situation with the Greenwald limit, at which the reactor point is constrained to be located**
- **The additional limiting condition is that P_{aux} + P_{alpha} - P_{rad} $>$ F_H x P_{LH} , which must be compatible with the exhaust capabilities**

- **Giacomin :**
- **If in contrast the density limit significantly increases with increasing power P_{SOL}, size and density practically become two independent variables**
- **The operational space where a reactor point can be chosen moves from a curve to a 2D domain**
- **The requirement that density is at the limit does not apply any longer (because there is no upper limit)**
- **Then the starting condition directly becomes the maximum power which can be practically exhausted, which is directly connected with the L-H power threshold which has to be exceeded**
- **This provides the only constraint for the domain over which the operational point can be chosen**

The only constraint is the max power which can be exhausted

- **At a density of 2.5 10^20 m^-3, ITER could produce about 2 GW of fusion power (IPB98(y,2), with a requirement in P_{LH} of 157 MW (from Martin's scaling)**
- ***This operational point does not exist according to ITPA20 (even less to ITPA20-IL), because P_{Fus} is too low to allow $P_{Heat} > P_{LH}$***
- **This density would be more than two times above the Greenwald limit, but at least three times below the Giacomin limit (with a P_{SOL} at the LH power threshold)**
- **The LH power threshold plays a critical role, because it determines the heat flux that has to be exhausted**



Entering and staying into H-mode

- Need to know the value and margins of P_{LH} for DEMO-LAR to:

  1) access from the low-density L-mode after ramp-up (~ 1.3e19 = 0.2 n_{Gw} or 2.5e19 = 0.4 n_{Gw}): n_{min} in DEMO ~ 2.1e19 @ 18.7 MA (ITER is @ 3.8e19 for BS)

  2) stay in H-mode at flattop density (~ 6.3e19): n_{HMODE} / (n_{LMODE}, n_{min}) ~ 2 - 3 (ITER similar)

  3) access would include seeding already from the L-mode phase to enter into detached H-mode → Z_{eff} / P_{rad} effect...

- It was recently pointed out [E. Delabie, WPTE meeting 16 Dec '24] that using I_p rather than B_t in high-density branch ($n > n_{min}$) → leads to lower RMS and higher extrapolated threshold power! Using Bt/q (~ Bpol) → intermediate between Bt and Ip

dataset	α^S	pre-factor	α^{B_t}	α^{I_p}	$\alpha^{B_{pol}}$	$\alpha^{<n_e>}$	$\alpha^{M_{eff}}$	D	RMSE	ITER pred. [MW] n_e=0.5 $10^{20}m^{-3}$	ITER pred. [MW] n_e=1.0 $10^{20}m^{-3}$
TC-26 (B_t)	**1**	**0.0445 ± 0.0025**	**0.569 ± 0.039**	-	-	**1.08 ± 0.03**	**0.964 ±0.032**	**1.92 ± 0.04**	**0.238**	**37.9 (D=1) / 72.8 (D=1.92)**	**80.3 (D=1)/ 154 (D=1.92)**
TC-26 (B_t,I_p)	1	0.0590 ± 0.0035	0.382 ± 0.042	0.235 ± 0.019	-	1.01 ± 0.03	1.01 ± 0.03	1.72± 0.04	0.201	61.1 (D=1)/ 105 (D=1.72)	143 (D=1)/ 246 (D=1.72)
TC-26 (B_{pol})	1	0.164 ± 0.006	-	-	0.624 ± 0.032	1.08 ± 0.02	0.997 ± 0.030	1.66 ± 0.04	0.189	54.3 (D=1)/ 90.4 (D=1.66)	115 (D=1)/ 191 (D=1.66)

→ This is indeed the case also for the subset of AUG data

- However, it has been evidenced [F. Ryter et al., NF 2014] that, for the low-density branch and the density minimum, the I_p dependence arises due to using P_{loss} instead of $P_{loss,ions}$

  - AUG + CMOD, D [M. Schmidtmayr, NF 2018]:

  → valid for the low-density branch; extend to higher density and a current scan in AUG ?

$$q_{i,fit}^{LH} = 0.0021 \bar{n}_e^{1.07\pm0.09} B_T^{0.76\pm0.2}$$

DEMO: 23(min) and 49(op) MW (Q_i)

Theoretical elements

- Recent work on NBI cases from JET [P. Vincenzi et al., PPCF 2022] shows that the $P_{loss,ions}$ is not linear going to low densities → impact of toroidal rotation? (Consistent with impact of rotation pointed out in Ryter NF 2014)

$$E_r = \partial_r T_i + T_i \partial_r \log(n) + V_\phi B_\theta - V_\theta B_\phi$$

- DIII-D shows similar trends w.r.t. I_p and torque [L. Schmitz et al., NF 2022]

- A few questions:

  - Assuming one enters H-mode at the density minimum using pure electron heating, could we then rely on the Schmidtmayr scaling? This was done in [GS Lopez et al., NF 2024], finding that the entrance EC power is sustainable for clean plasma, but increases with increasing contamination due to W or seeding (bringing back the issue of detachment from start)
  - Can one make the $P_{loss,ion}$ scaling more robust by adding other machines that use pure electron heating over a density/current scan ? (and field)
  - More critical: what about the densities past the minimum ? Is the scaling just the same or does it change due to changing transport regime or edge properties? At operational density, $Q_{i,edge}$ ~ $Q_{e,edge}$ in DEMO is expected

$$\tilde{P}_{\mathrm{loss},i} \gtrsim P_{\mathrm{L-H},i} := \left[e \frac{\Delta r \gamma_{\mathrm{turb}} \hat{\chi}_i}{1 + \hat{\eta}_i^{-1}} \right] B \, \hat{n}_e \, \hat{S} \,,$$

[R. Bilato et al., NF 2020]: η_i incorporates the edge density profile properties. Can this bring in additional dependencies ? Flatter L-mode edge density gradient → problems for the power threshold? Need to investigate this via modeling and possibly experiments

Additional considerations

- Use P_{loss} or $P_{sep} = P_{loss} - P_{rad}$. $P_{sep,i}$? [P. David et al., NF 2022; G: Birkenmeier et al., NF 2022] → role of edge radiation can't be neglected

- Role of heating systems: NB vs wave, pure electron heating vs mixed (ultimately alpha)

- The prediction of n_{min}. For example from R. Bilato et al., NF 2020: $n_{min} = C\, B^{0.54}\, I_p^{0.37}\, a^{-1.22}\, A^{0.34}$
  - *C* is a constant
  - This formula can include direct ion heating → lower minimum

- In [E. Solano et al., NF 2023] it is shown that T has both lower minimum and lower P_{loss} (or P_{sep}) → additional negative mass dependence ? Helium on the contrary shows higher n_{min} and P_{min}

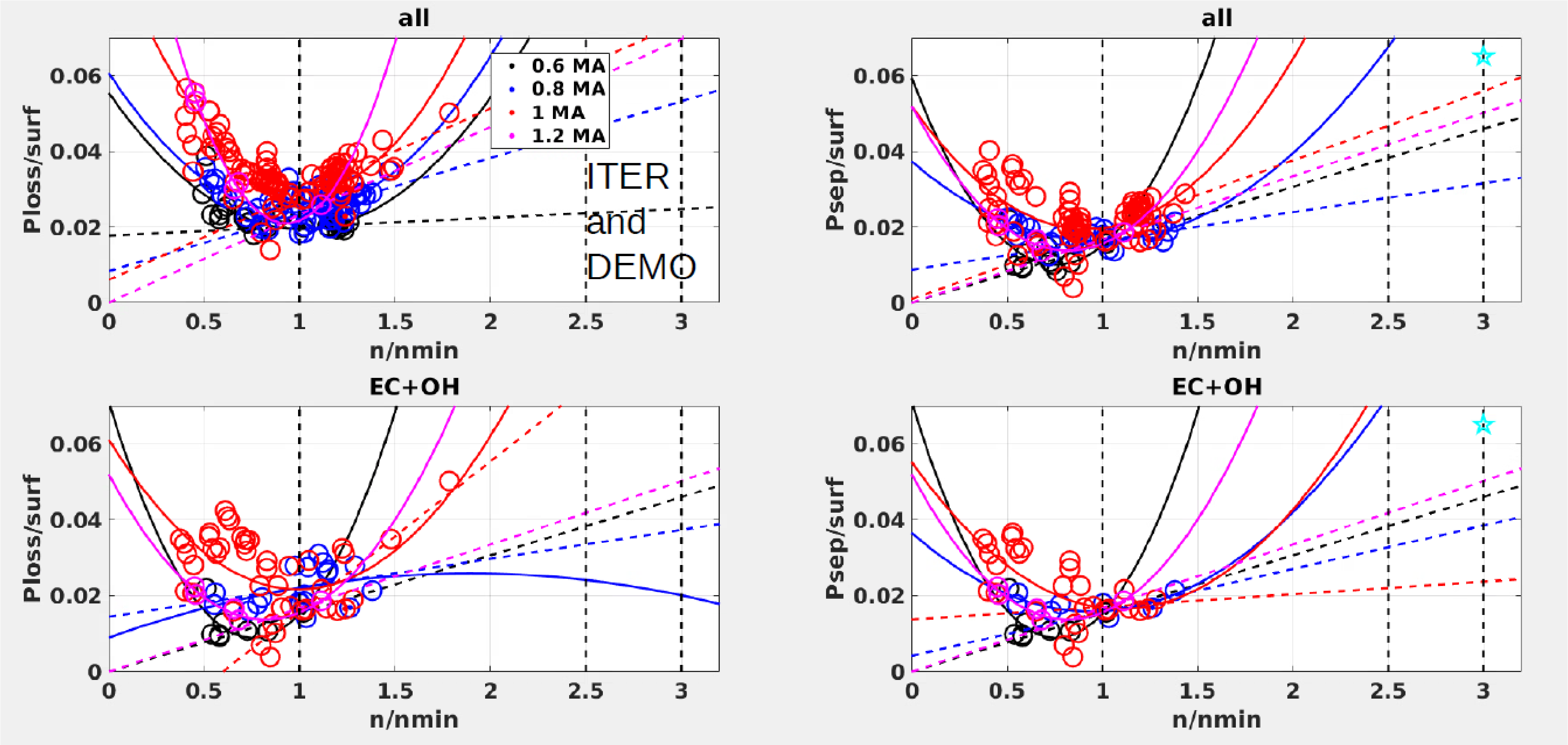
- Right of n_{min}, $P_{LH} \sim n^{0.8}$, but probably $n^{0.-1}$, obviously exponent depends on proximity to minimum, plus there could be additional density dependency due to e.g. collisionality or beta…

- U. Plank et al., PPCF 2023: $E_{r,crit}$ ~ const organizes different plasma compositions as well for AUG data

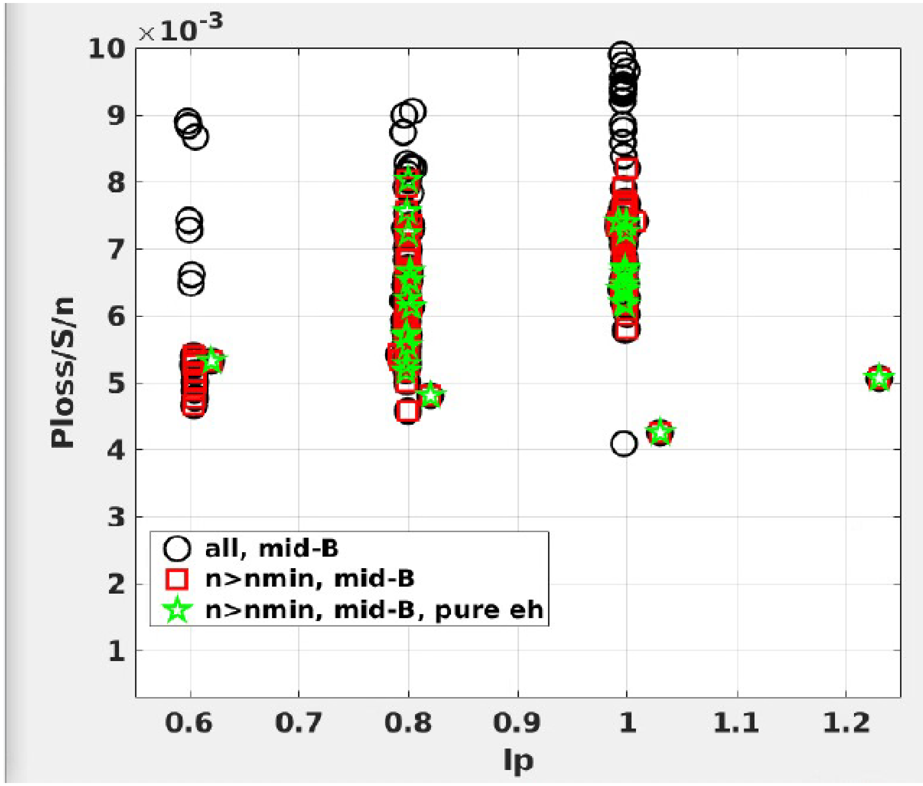
- Needs more data on the dependence of edge profiles at LH transition to put into context of which drives and stabilizing effects are at play → comparison with modeling

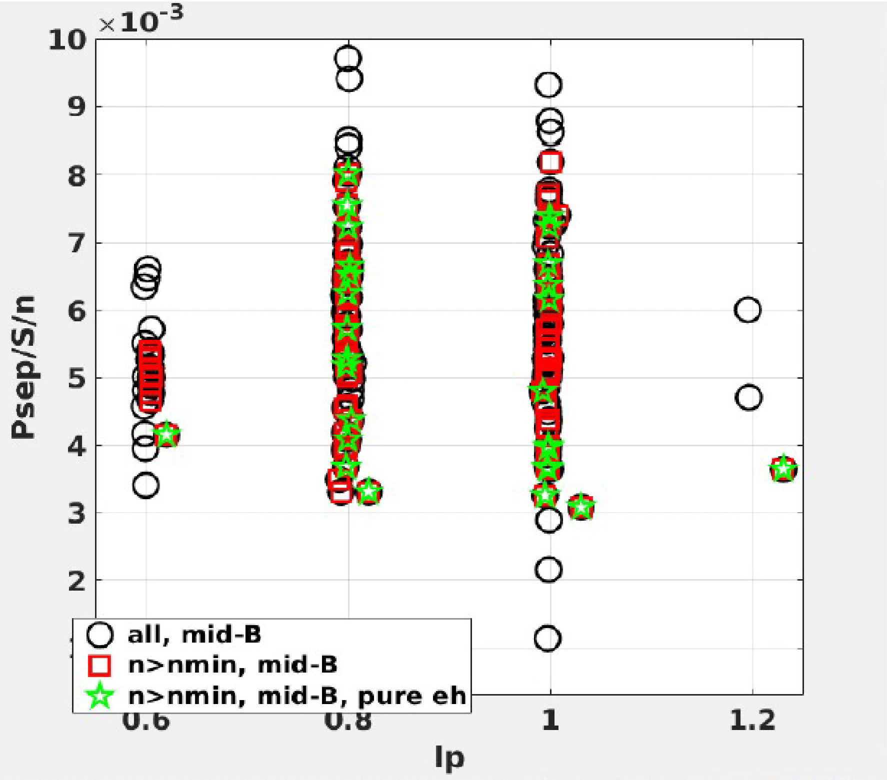
AUG database, D only, Bt ~ 2.4 T

- Reactor away from the minimum (but how to predict it robustly?) → more points to be added in future experiments
- Cyan point is $2*q_{i,Schmidtmayr}$ for DEMO-LAR n(op), B, and Surface parameters



IP dependence inside the AUG data, D only





- Using P_{loss} → clear trend with Ip also for the high density branch (***red***), and the sub-section of pure electron heating (***eh***)

- Using $P_{sep} = P_{loss} - P_{rad}$, the *eh* data do not show an Ip dependence after all, but need more data (plan to do 0.8-1.2 MA at 6.5e19 in AUG

→ Need more dedicated experiments to clarify this and look into the details of edge behavior as well

Outlook for DEMO

- Enter into H-mode: extrapolation of the power threshold from the low density branch in pure electron heated cases could be assessed on present data (caveat NBI driven transitions due to effect of rotation → what about Er ?) → Focus on minimum power (and isotope) dependencies? What about edge density gradient effect?

- H-mode @ operational density: expect $Q_i \sim P_{sep}/2$ → how does the required power threshold scale at higher densities from present experiments? Just continues linear (for $Q_{i,sep}$) without additional dependencies? P_{loss} does show an Ip dependence → artifact of heating method and analysis + proximity to minimum ?
  → needs more experiments to provide data at n/n_{min} → 3 at different currents (and fields)
  → need to look at P_{sep} as well

- From the modeling point of view: aside of the edge density gradient and the impact of the plasma current, what is the impact of lower aspect ratio on threshold physics? (more trapped particles → less drive for modes driven by parallel dynamics ?)

- Impact of edge density gradient along power trajectory → can we reach critical Er if density gradient in the L-mode plasma is weak? Use pellet to trigger H-mode?

- Experiments looking at the development of the P(LH but also HL) for $n/n_{min} > 2$ at different currents are needed