Effects of Radial Profiles in the H-Regime for Ignitor

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Introduction

Ignitor is a high–field ($B_{\mathrm{T}} = 13$ T), compact (R_0 = 1.32 m) toroidal device for a near–term and cost effective study of D–T burning plasma physics. Heating is provided by Ohmic and ICRF heating.

Recently, the possibility of operating the device in a double-null configuration with the X-point (either "internal" or "external") close to the wall has been considered, as it would be advantageous to have the enhanced energy confinement usually observed in the H-regime. In Ref.[1][1], the importance of these configurations for future fusion devices has been pointed out.

Access to the H-regime raises a number of questions, among them that of the heating power P_{heat} adequacy, as this needs to be above a threshold value P_{LH} (which has an unfavourable scaling with magnetic field and density).

Zero dimensional analysis based on the equation for (steady state) global power balance is used here to explore Ignitor operating space in the H-regime.

[1] P. Rebut, *Plasma Phys. Control. Fusion* **48**, B1 (2006).

Zero Dimensional Power Balance Equation

Basic equation employed to predict Ignitor performance is steady state, global power balance equation

$$P_{\rm heat} = P_{\rm alpha} + P_{\rm ohm} + P_{\rm aux} - P_{\rm brem} - P_{\rm syn,r} = P_{\rm conv} \qquad (1)$$

where $P_{\rm conv} = W_{\rm p}/\tau_{\rm E}^*$, with $W_{\rm p}$ the plasma total energy and $\tau_{\rm E}^*$ the energy confinement time. For $\tau_{\rm E}^*$ the IPB98(y,2)[2] scaling expression is used

$$\tau_{\rm E}^* = 0.144\, I_{\rm p}^{0.93}\, B_{\rm T}^{0.15}\, \overline{n}_{\rm e}^{0.41}\, R_0^{1.97}\, \epsilon^{0.58}\, \kappa_a^{0.78}\, M_{\rm eff}^{0.19}\, P_{\rm heat}^{-0.69} \quad {\rm s} \qquad (2)$$

($\epsilon = a/R_0$, $I_{\rm p}$ is in MA, $B_{\rm T}$ is in T, R_0 and a are in m, $M_{\rm eff}$ is the average ion mass, $\overline{n}_{\rm e}$ is in 10^{20} m^{-3} and P is in MW).

Considering plasma profiles of the form $X(\rho) = (X_0 - X_a)(1-\rho^2)^{\nu_X} + X_a$ (ρ is a normalized radial variable), using explicit expressions for $P_{\rm alpha}$, $P_{\rm brem}$ and $P_{\rm syn,r}$ and introducing $Q = P_{\rm alpha}/(P_{\rm ohm} + P_{\rm aux})$, solution of Eq. (1) yields operating points for a given value of Q.

[2] ITER Physics Basis: Chapter 2, *Nucl. Fusion* **39**, 2175 (1999)

Operating Space

Operating space for H–mode regime is limited by:

- the requirement that the heating power be above a threshold for $L \rightarrow H$ transition

$$P_{\rm heat} > C_{\rm thres}\, P_{\rm LH} \tag{3}$$

  where $P_{\rm LH}$ is a value that can be predicted on the basis of scaling expressions derived from the international H-mode threshold database (DB)
- the usual operational limits for "normalized" density $\overline{n}_{\rm e}/n_{\rm GR}$ and $\beta_{\rm N}$ (as will be seen, in Ignitor operation well below these limits is easily achieved)
- for Ignitor, a more appropriate limit to consider is that in on the power flux to the wall, which will be taken here as $P_{\rm heat} < 30$ MW (however, a more thorough study of this issue is required)

Power Threshold Scalings for Access to the H-regime

In order to estimate the threshold power in Ignitor, the results of statistical analyses of the international H–mode threshold database are used in which this quantity is expressed in the form of a power law scaling. We consider different expressions

- the expression initially used for ITER-FEAT[3] based on OLS (Ordinary Least Squares) regression

$$P_{\mathrm{LH}} = 1.42\, B_{\mathrm{T}}^{0.82}\, \overline{n}_{\mathrm{e}}^{0.58}\, R_0^{1.0}\, a^{0.81}\, (2/M_{\mathrm{eff}}) \tag{4}$$

- a more recent one[4] based on a different statistical model, EVOR (Errors–in–Variables Orthogonal Regression) – in this model, the (questionable) assumption made in the OLS model that errors in P are much greater than those in other parameters is abandoned –

$$P_{\mathrm{LH}} = 0.075\, B_{\mathrm{T}}^{0.58}\, \overline{n}_{\mathrm{e}}^{0.56}\, S^{0.85}\, (2/M_{\mathrm{eff}}) \tag{5}$$

[3] J. A. Snipes et al. *Plasma Phys. Control. Fusion* **42**, A299, (2000).

[4] D. C. McDonald et al., *Plasma Phys. Control. Fusion* **48**, A349 (2006)

where S is the plasma surface area (in m^2).

- the latest expression[5] adopted by the ITER group[6]. It is derived using OLS regression on a selected subset of the international database, chosen adopting the SELEC2007 criteria for ITER like plasmas

$$P_{\mathrm{LH}} = 0.0488\, B_{\mathrm{T}}^{0.803}\, \overline{n}_{\mathrm{e}}^{0.717}\, S^{0.941}\, (2/M_{\mathrm{eff}}) \tag{6}$$

The power threshold for access to the H–regime for an Ignitor equilibrium with “external” X-point is shown in Fig. 1 as a function of (line-averaged) density for the three scalings considered. Unfortunately, results differ considerably, with the EVOR scaling predicting significantly lower values for the heating power required to access the H-regime, particularly at the higher plasma densities where a better performance is expected.

[5] T. R. Martin et al., *Journal of Physics: Conference Series* **123**, 012033 (2008).

[6] R. J. Hawryluk et al. Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) IT/1-2.

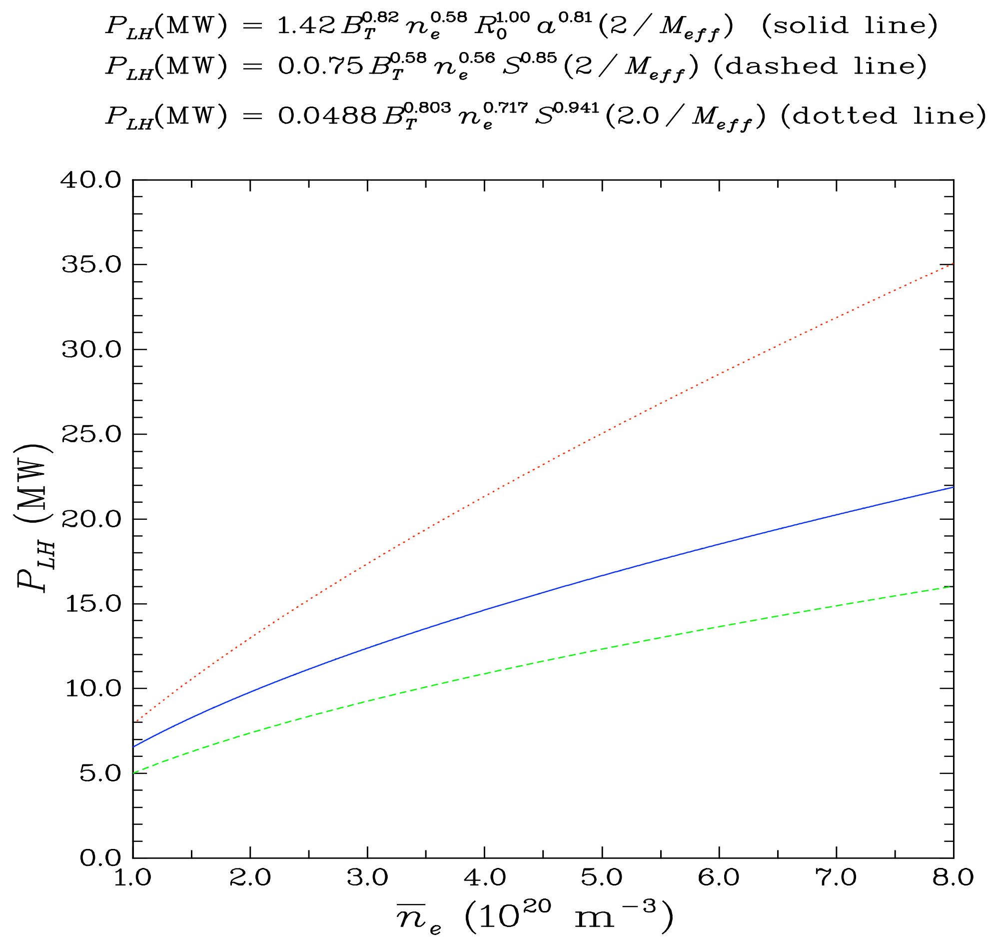

Figure 1: Threshold power for access to H-mode regime v. density for Ignitor “external” equilibrium. Different scaling expressions yields significantly different results.

Equilibria

Two possible Ignitor equilibria are considered, both with I_p = 9 MA but with the X-point "internal" or "external" to the plasma wall. Geometry parameters chosen to mimic those found with free-boundary equilibrium code MAXFEA (by Dr. Ramogida).

	a (m)	κ_{95}	δ_{95}	V (m^3)	S (m^2)	q_{95}
"external"	0.460	1.69	0.38	8.88	31.63	3.17
"internal"	0.448	1.69	0.31	8.51	31.01	2.87

Table 1: Geometry parameters for double-null configurations in Ignitor

Although the difference between the two sets of parameters is not great, the smaller dimensions in the case of an "internal" X-point lead to smaller power levels and, from the point of view of operating space analysss, to better results (see below).

Operating Space for Moderately Peaked Profile

We assume $T_e = T_i$ (in the high density regimes considered, the ion–electron thermal equilibration time is in fact short), and the presence of boron (B) and molybdenum (Mo) as impurity species, with concentrations $f_B = 1.2\%$ and $f_{Mo} = 1.0 \times 10^{-5}$, respectively. Then $Z_{eff} \approx 1.30$ and $f_{DT} = 0.90$.

Initially, we consider a temperature profile with midrange peaking ($T_0/\langle T\rangle = 2.5$) and a density profile with modest peaking ($n_0/\langle n\rangle = 1.25$), so that $p_0/\langle p\rangle = 2.90$.

For the scaling expressions (4)(5) we consider a value $C_{thres} = 1.3$ for access to the H-regime (in order to obtain a “good” H-mode); for expression (6), a less stringent condition $C_{thres} = 1.0$ is considered (in accord with what done by the ITER group in the cited paper).

In Fig. 2, contours for operation (“POPCON plots”) at Q=10 are shown in a plane $(\langle nT_e\rangle/\langle n\rangle, \overline{n}_e)$. While the space for $Q = 10$ operation is relatively ample for the first two scaling expressions, it is more limited in the case of the third.

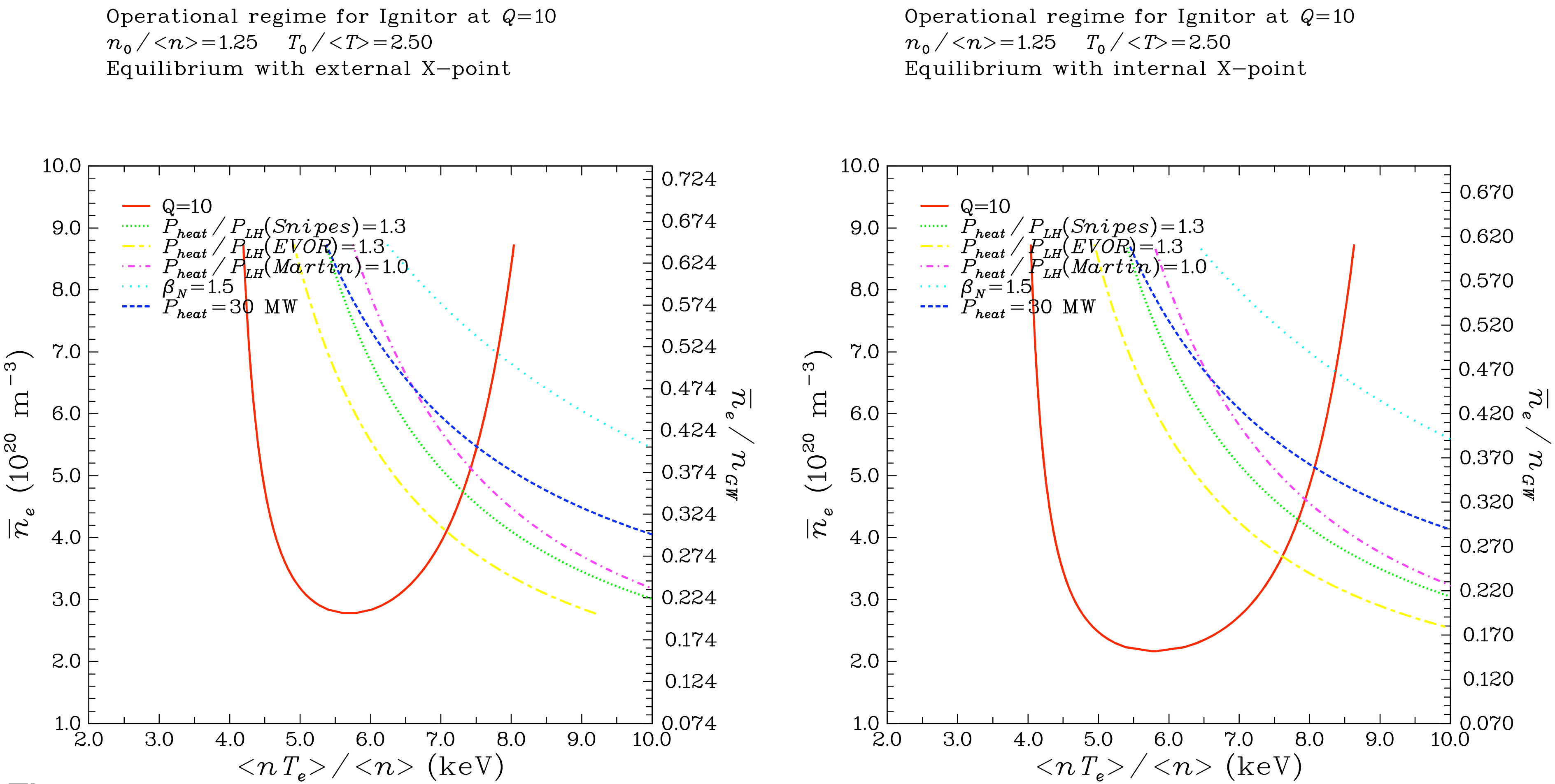

Figure 2: POPCON plots showing the operational regime for Ignitor in the H–mode for Q=10 operation and a moderately peaked pressure profile.

Operating Space for More Peaked Density Profiles

In order to improve performance (higher Q–values) we now consider more peaked pressure profiles. Since the peakedness of the temperature profile is likely to be constrained ("stiff" thermal transport), we turn to increasing the density profile peakedness

In fact, density profile peaking in the H-regime has recently attracted much attention, both experimentally and theoretically. In particular, a strong inverse correlation between density peaking and collisionality has been observed experimentally and a scaling expression has been proposed proposed in Ref.[7][7].

We thus consider increasing the density profile peakedness in steps, first to $n_0/\langle n_e\rangle = 1.4$ ($p_0/\langle p_e\rangle = 3.1$) and then to $n_0/\langle n_e\rangle = 1.6$ ($p_0/\langle p_e\rangle = 3.4$). As shown in Figs.(3)-(4), operation at $Q = 20$ and $Q = 50$ respectively becomes possible.

[7] C. Angioni et al. *Nucl. Fusion* **47**, 1326 (2007).

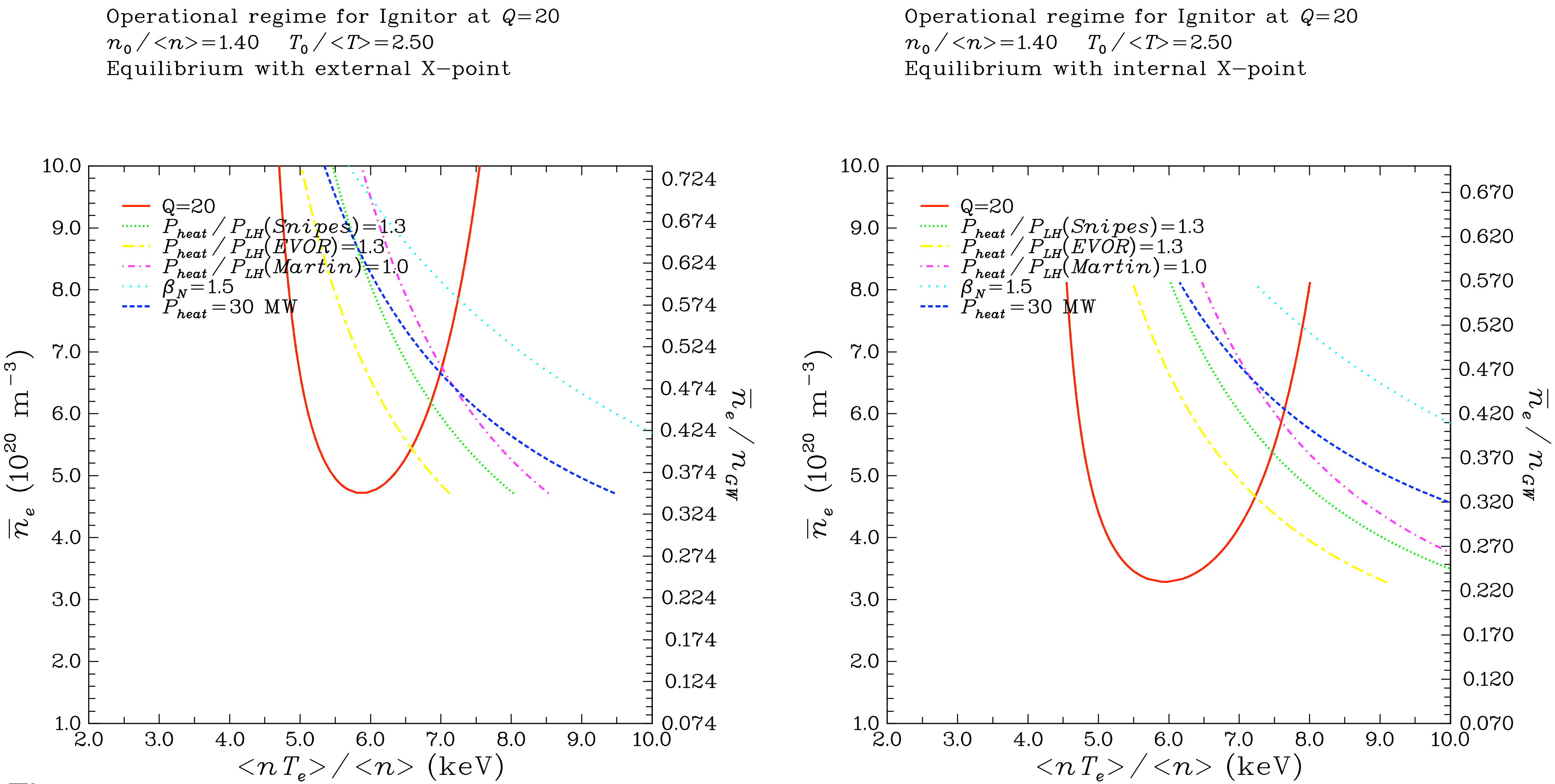

Figure 3: POPCON plots showing the operational regime for Ignitor in the H–mode for Q=20 operation

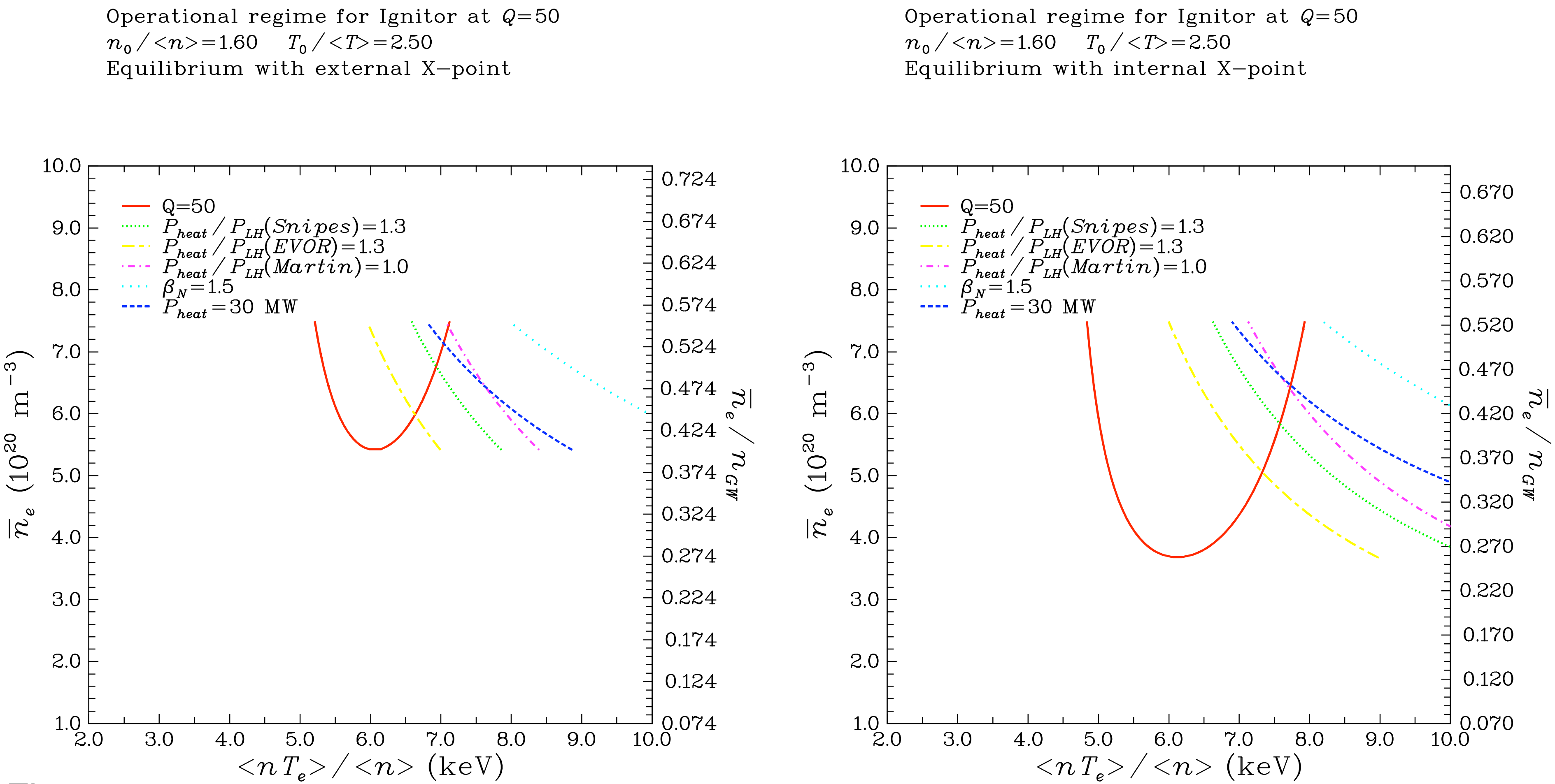

Figure 4: POPCON plots showing the operational regime for Ignitor in the H–mode for Q=50 operation

Table 2: Example of Ignitor parameters for $Q = 50$ operation ("external" X-point) with relatively peaked density profile ($n_0/\langle n_e \rangle = 1.6$) and different scaling expressions for access to the H-regime

Quantity	Symbol	"Snipes-2000" ($\times 1.3$)	EVOR ($\times 1.3$)
Central electron density (10^{20} m^{-3})	n_{e0}	9.1	8.1
Normalized electron density	$\overline{n}_e/n_{GW}$	0.50	0.45
Central electron temperature (keV)	T_{e0}	14.8	14.1
Central pressure (MPa)	p_0	4.1	3.5
Plasma energy (MJ)	W_p	16.0	13.7
Poloidal beta	β_p	0.37	0.31
Normalized beta	β_N	1.19	1.02
Alpha power (MW)	P_{alpha}	30.0	21.6
Bremsstrahlung power (MW)	P_{brem}	6.0	4.7
Syncrotron power (MW)	$P_{syn,r}$	0.7	0.6
Heating power (MW)	P_{heat}	26.3	18.7
Confinement time (s)	$\tau^*_{E,IPB98(y,2)}$	0.61	0.74
Alpha particle slowing–down time (s)	$\tau_{sl-alpha}$	0.076	0.081

Conclusions

- operating space for Ignitor in the H-regime has been examined using a zero dimensional model and various scaling expression for the power ($P_{\rm LH}$) required to access this regime
- for a relatively flat density profile ($n_0/\langle n \rangle = 1.25$), $Q = 10$ operation is possible for the three scaling expressions considered; however, power levels and “attractiveness” of operating point strongly depends on scaling for $P_{\rm LH}$
- increasing density profile peakedness, enhanced performance can be achieved. In particular, high–Q operation ($Q = 50$) is possible with $n_0/\langle n \rangle = 1.60$ for two of the scaling expressions considered. In the case of the EVOR-scaling, moreover, the operating point is very interesting as the heating power involved is rather modest (¡ 20 MW).
- for the third scaling expression considered (the Martin (2008) expression, recently adopted by the ITER group), achieving enhanced performance would require power levels that are probably be too high for Ignitor first wall.