Ignitor Plasma Performance in the H–mode with New Scalings

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Introduction

Ignitor plasma performance in the H–mode is assessed using 0-dim modelling.

Reference equilibrium configuration is one with double X–points close to the wall – an X–point limiter configuration, as recently advocated by P. Rebut in his Alfvèn Prize Lecture[1].

Performance with reference scalings (ELMy H–mode scaling IPB98(y,2) for energy confinement time and IAEA 2002 scaling for access to the H–mode) is at first assessed.

Next performance with a "new" scaling for energy confinement with no β–dependence is considered, as well as that with a "new" scaling for access to the H–mode.

A systematic analysis of density peaking of H–mode plasmas in the JET machine has shown a strong correlation with distance from the Greenwald density limit; since we find that Ignitor plasmas are typically far from this limit, we also examine the effect that a moderately peaked density profile ($n_0/ < n >= 1.4$) has on performance.

[1] 33^{th} EPS Conference, Rome (2006) – http://eps2006.frascati.enea.it/ invited/post.htm

0–D Model

Starting point is equation for (steady state) global power balance

$$P_{\text{heat}} = P_{\text{ohm}} + P_{\text{aux}} + P_{\alpha} - P_{\text{brem}} - P_{\text{syn,r}} = P_{\text{conv}} \tag{1}$$

We use $P_{\text{conv}} = W_{\text{p}}/\tau_{\text{E}}^{*}$, with W_{p} the plasma energy, $\tau_{\text{E}}^{*} = H\,\tau_{\text{E,scal}}^{*}$ with H an enhancement factor and τ_{E}^{*} the energy confinement time as given by an appropriate empirical scaling law. The Ohmic power P_{ohm} is computed with an approximate form based on a neoclassical expression for the plasma resistivity, while for the alpha power P_{α} we follow Bosch and Hale [2].

Radiation losses are from bremsstrahlung P_{brem} and synchrotron $P_{\text{syn,r}} = \sqrt{1-\mathcal{R}}P_{\text{syn}}$, with $\mathcal{R} = 0.8$ and P_{syn} as given in Albajar et al.[3].

We also introduce the fusion gain parameter $Q = 5\,P_{\alpha}/(P_{\text{ohm}} + P_{\text{aux}})$.

[2]H. S. Bosch, and G. M. Hale, Nucl. Fusion **32**, 611 (1992).
[3]F. Albajar, J. Johner, and G. Granata, Nucl. Fusion **41**, 665 (2001).

Ignitor Parameters for H-mode Operation with Double X–Points

Ignitor parameters are $B_{\mathrm{T}} = 13$ T, $R_0 = 1.32$ m, while minor radius ($a = 0.44$ m) and plasma current $I_{\mathrm{p}} = 9$ MA are somewhat smaller than in the reference configuration. We take $\kappa_{95} = 1.73$ and $\delta_{95} = 0.4$.

Plasma radial profiles: $X(\rho) = (X_0 - X_a)(1 - \rho^2)^{\mathrm{b_X}} + X_a$. Radial integrals in Eq. (1) are performed numerically.

We take $T_{\mathrm{e}}/T_{\mathrm{i}} = 1$, and compute $f_{\mathrm{DT}} = n_{\mathrm{DT}}/n_{\mathrm{e}}$ from the quasi-neutrality equation after specifying the type and concentration $f_{\mathrm{imp}} = n_{\mathrm{imp}}/n_{\mathrm{e}}$ of the impurity species present in the plasma. We consider a plasma with boron (B) and molybdenum (Mo) as impurity species, with concentrations $f_{\mathrm{B}} = 1.2\%$ and $f_{\mathrm{Mo}} = 1.0 \times 10^{-5}$, respectively. Moreover $f_{\mathrm{He}} = 2.0\%$, so that $Z_{\mathrm{eff}} = 1.30$ and $f_{\mathrm{DT}} = 0.90$.

H–Mode Scaling Expressions

ELMy H–mode scaling IPB98(y,2)[4]

$$\tau_{\mathrm{E,scal}}^{IPB98} = 0.0590 \times I_{\mathrm{p}}^{0.93}\, B_{\mathrm{T}}^{0.15}\, A^{0.78}\, R_0^{1.39}\, a^{-0.98}\, \overline{n}_{\mathrm{e}}^{0.41}\, M_{\mathrm{eff}}^{0.19}\, P_{\mathrm{heat}}^{-0.69} \quad (2)$$

where A is poloidal cross-sectional area. When written in terms of nondimensional transport parameters (ρ^*, ν^*, β) this scaling shows a significant degradation with β, e.g. $B_{\mathrm{T}}\tau_{\mathrm{E,scal}}^{IPB98} \sim \beta^{-0.9}$.

Recently, single scan experiments in ρ^*, ν^* and β on DIII-D and JET have shown virtually no dependence on β.

In a recent work by J. W. Cordey et al.[5] the condition of the latest version of the Elmy H-mode database has been re-examined, showing that there is bias in the OLS (Ordinary Least Square) regression for some of the variables. In addressing these problems with various techniques, new scalings have been derived, some having no

[4] ITER Physics Basis Nucl. Fusion **39**, 2175 (1999).

[5] J. W. Cordey et al. Nucl. Fusion **45**, 1078 (2005).

β-dependence. In particular (Eq.(9) of Cordey's paper)

$$\tau_{\mathrm{E,scal}}^{\mathrm{no}-\beta} = 0.0360 \times I_{\mathrm{p}}^{0.85}\, B_{\mathrm{T}}^{0.17}\, A^{0.82}\, R_0^{1.21}\, a^{-1.25}\, \overline{n}_{\mathrm{e}}^{0.26}\, M_{\mathrm{eff}}^{0.11} P_{\mathrm{heat}}^{-0.45} \tag{3}$$

This scaling show no dependence on β ($B_{\mathrm{T}}\tau_{\mathrm{E,scal}}^{\mathrm{no}-\beta} \sim \beta^0$). In terms of engineering variables this is reflected in a much weaker dependence on P_{heat}.

However, it should be observed that single scan experiments carried out on JT–60[6] have shown a significant β-dependence ($B_{\mathrm{T}}\tau_{\mathrm{E,scal}}^{\mathrm{no}-\beta} \sim \beta^{-(0.6-0.7)}$). Thus the issue of the β–scaling of transport is still quite open.

[6] H. Urano et al. Nucl. Fusion **46**, 781 (2006).

Threshold for Access to H–Mode

Access to H-mode confinement require that P_{heat} be somewhat larger than a threshold value $P_{\mathrm{L->H}}$. Databases for this quantity have been developed, as well as fits based on OLS regressions. One such fit is[7]

$$P_{\mathrm{L->H}} = 3.34 \times B_{\mathrm{T}}^{0.78}\, R_0^{0.94}\, a^{0.89}\, \overline{n}_{\mathrm{e}}^{0.61}\, M_{\mathrm{eff}}^{-1.0} \tag{4}$$

Recently[8] , the validity of the assumptions leading to such fits has been questioned (in particular the one that errors in $P_{\mathrm{L->H}}$ are much greater than those in other parameters).Relaxing these assumptions lead to fits that show a weaker dependence on B_{T} than Eq. (6). One such fit (based on errors-in-variables log-linear orthogonal regression - EVOR -) is

$$P_{\mathrm{L->H}} = 0.150 \times B_{\mathrm{T}}^{0.58}\, A^{0.85}\, \overline{n}_{\mathrm{e}}^{0.56}\, M_{\mathrm{eff}}^{-1.0} \tag{5}$$

[7] J. A. Snipes et al., Proc. 19^{th} IAEA Fusion Energy Conf. , Lyon, France, 2002, paper CT/P-04, International Atomic Energy Agency (2002).

[8] D. C. McDonald et al. Plasma Phys. Control. Fusion **48**, A439, (2006).

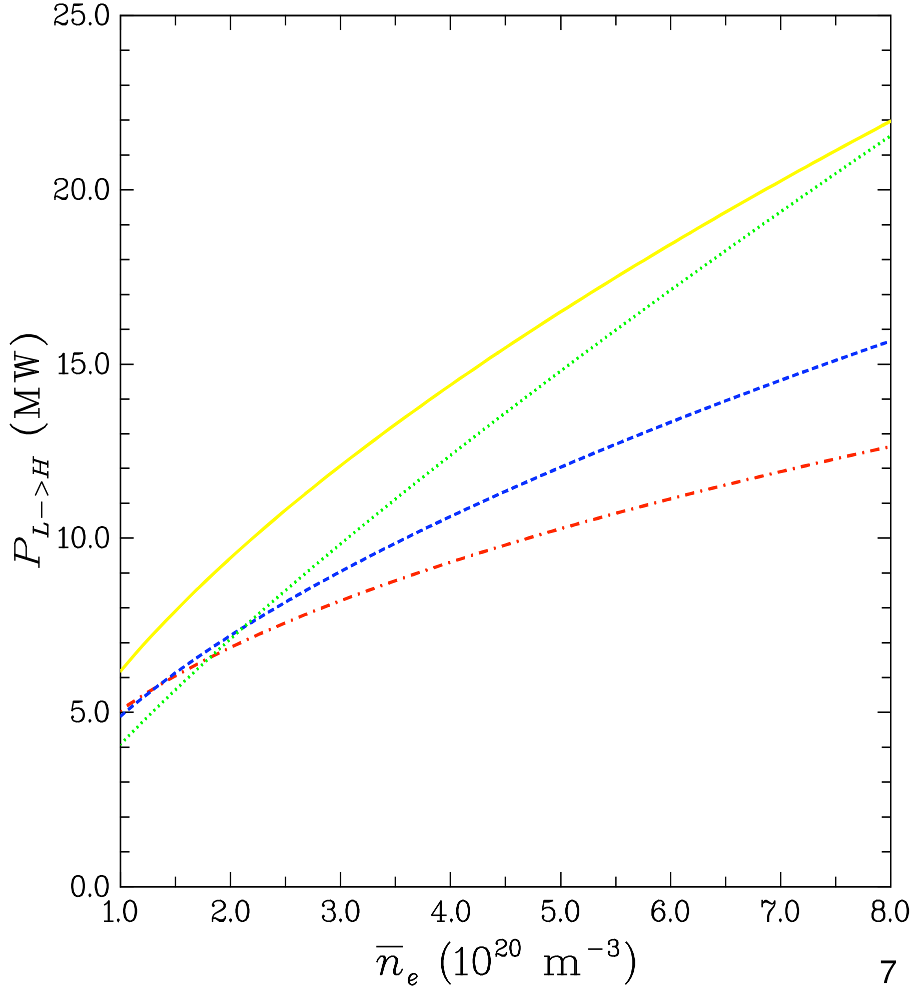
Power threshold for access to H–mode as a function of density for Ignitor D–T plasmas with differing scaling expressions. New scalings are more favourable than the 2002 one (“Snipes”, yellow line). In the following we shall consider the intermediate one (“EVOR”, blue line).

$P_{L->H}(\mathrm{MW})(\mathrm{Snipes}) = 3.34 B_T^{0.78} R_0^{0.94} a^{0.89} n_e^{0.61} / M_{eff}$ (solid line)

$P_{L->H}(\mathrm{MW}) = 0.077 B_T^{0.65} S^{0.80} n_e^{0.44} 2.0 / M_{eff}$ (dot−dashed line)

$P_{L->H}(\mathrm{MW})\ (\mathrm{EVOR}) = 0.150 B_T^{0.58} S^{0.85} n_e^{0.56} / M_{eff}$ (dashed line)

$P_{L->H}(\mathrm{MW}) = 0.120 B_T^{0.45} S^{0.96} n_e^{0.80} / M_{eff}$ (dotted line)



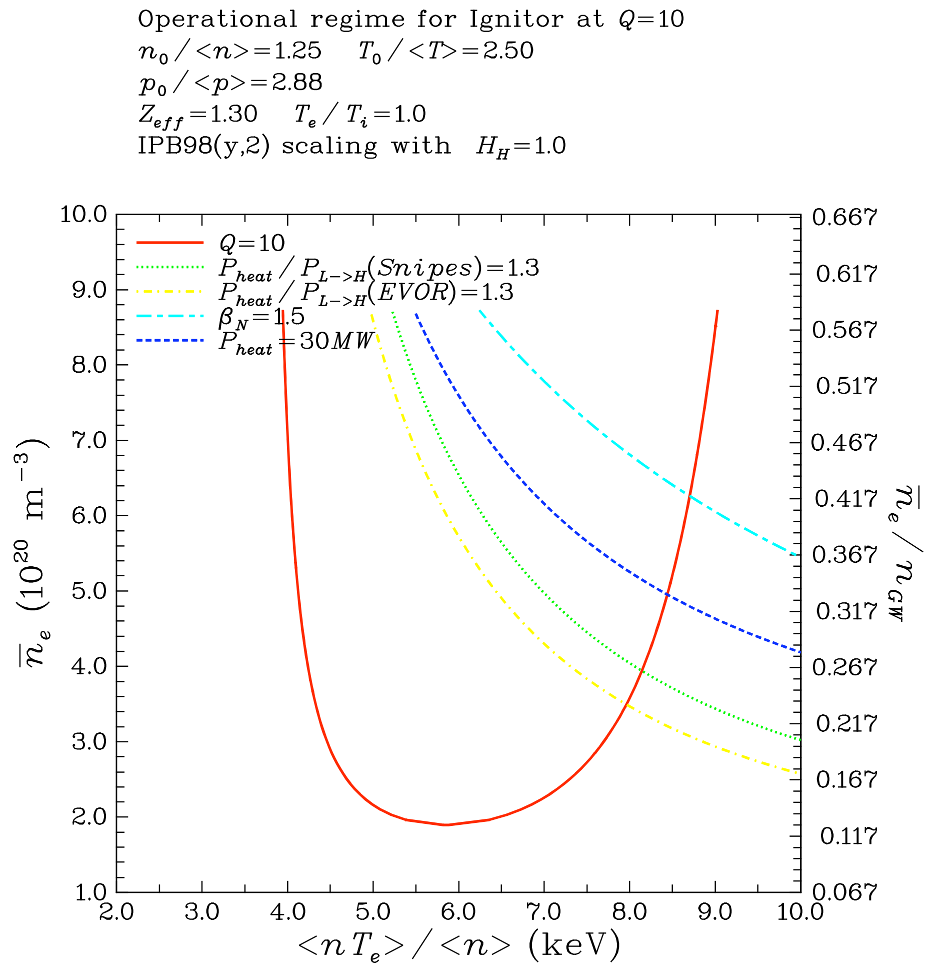
Results I: Relatively Flat Density Profile

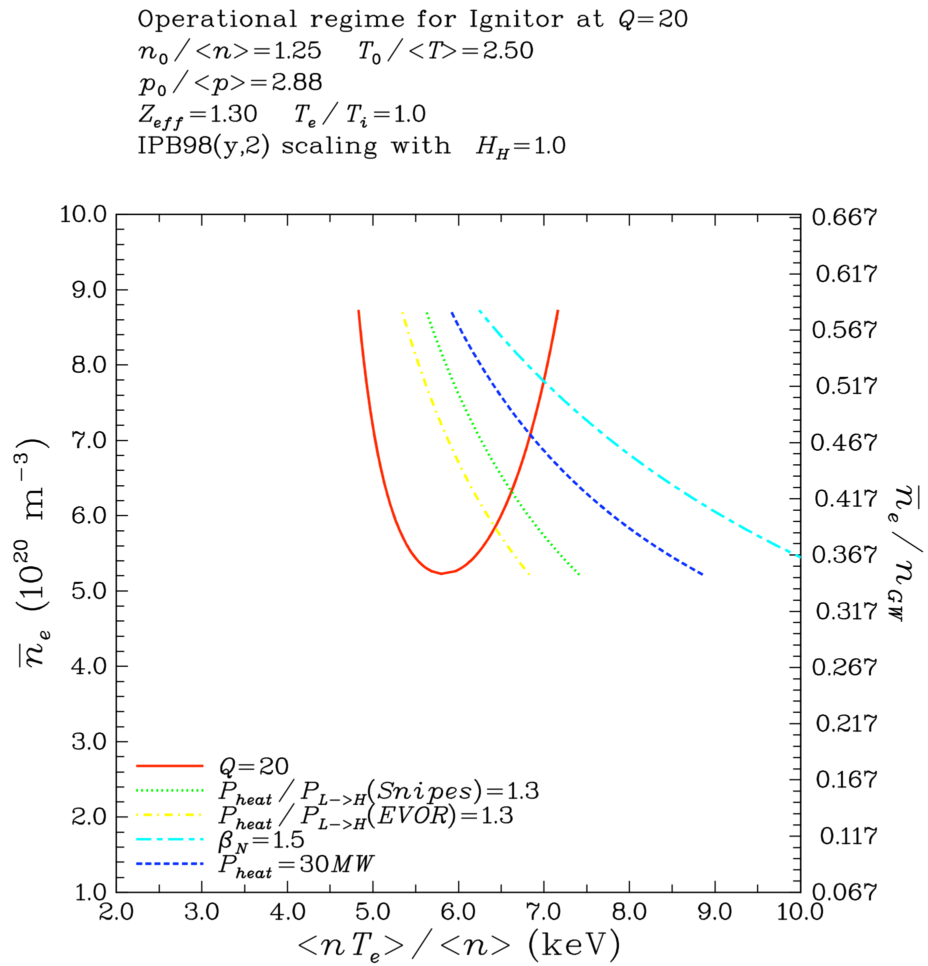
We consider at first:

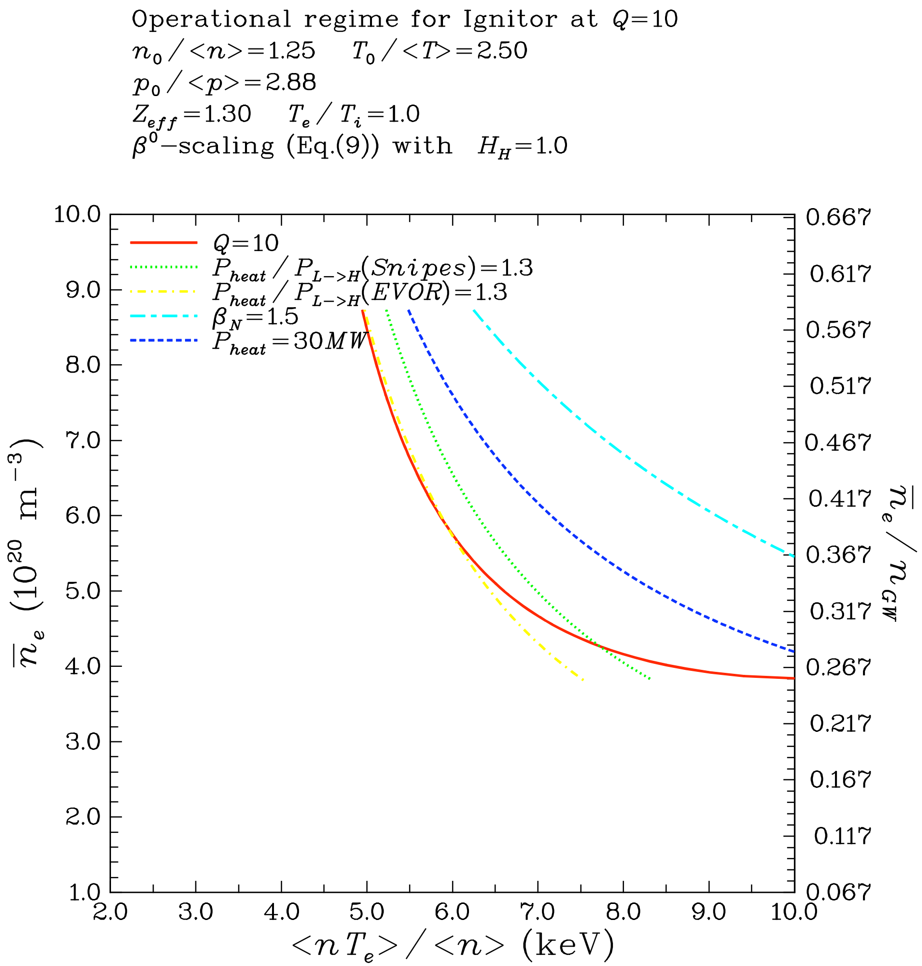
a relatively flat density profile with $\mathrm{b_n} = 0.4$, $n_\mathrm{a}/n_0 = 0.3 \rightarrow n_0/\langle n\rangle = 1.25$; a moderately peaked temperature profile with $\mathrm{b_T} = 3.0$, $T_\mathrm{a}/T_0 = 0.2 \rightarrow T_0/\langle T\rangle = 2.5$; then $p_\mathrm{a}/p_0 = 0.06$, $\rightarrow p_0/\langle p\rangle = 2.9$.

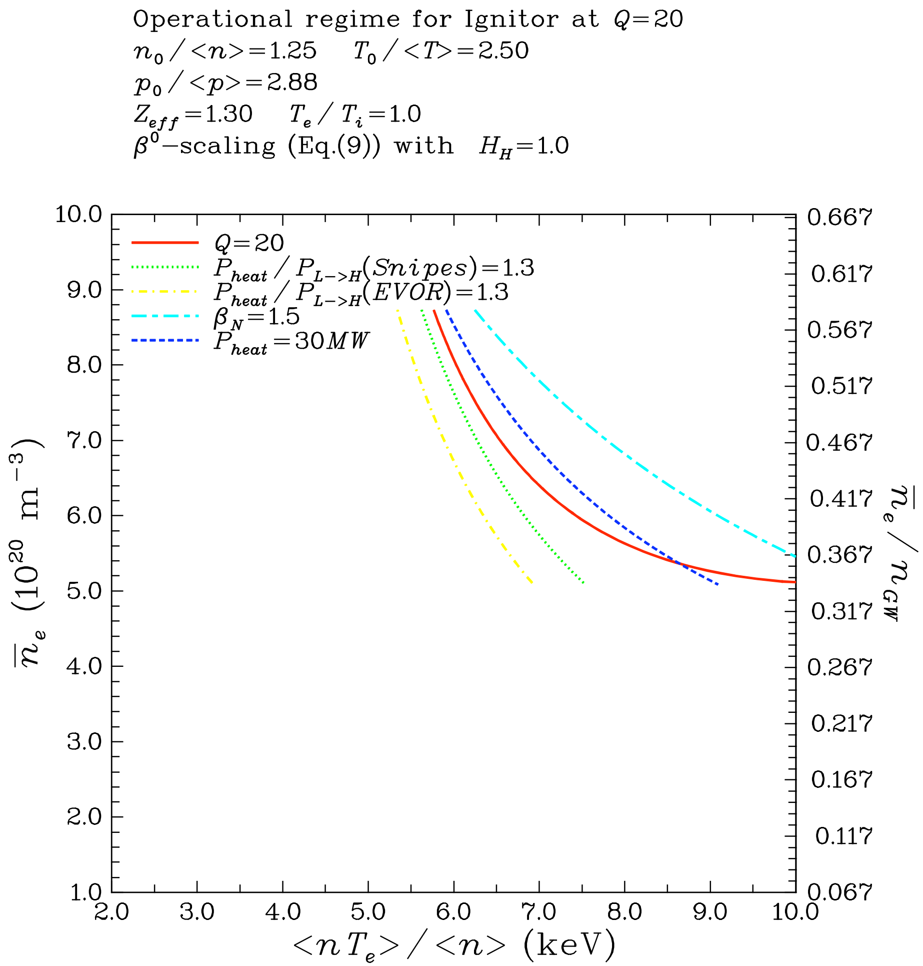
In Ignitor, operating space is limited (from “below”) by the condition that $P_\mathrm{heat} > 1.3 P_{\mathrm{L->H}}$ and (from “above”) by the condition that P_heat be not too high; here we shall consider $P_\mathrm{heat,max} = 30$ MW.

As we shall see, for Ignitor operation other typical tokamak operating limits such as the β limit and the density limit are less relevant (typically, in fact, $\beta_\mathrm{N} < 1.5$ and $n_\mathrm{G} = \overline{n}_\mathrm{e}/n_\mathrm{GW} < 0.5$).


Operational regime for Ignitor at Q=10
$n_0/\langle n\rangle$=1.25 $T_0/\langle T\rangle$=2.50
$p_0/\langle p\rangle$=2.88
Z_{eff}=1.30 T_e/T_i=1.0
IPB98(y,2) scaling with H_H=1.0
Q=10
$P_{heat}/P_{L->H}(Snipes)$=1.3
$P_{heat}/P_{L->H}(EVOR)$=1.3
β_N=1.5
P_{heat}=30MW
$\overline{n}_e$ (10^{20} m^{-3})
$\overline{n}_e/n_{GW}$
$\langle nT_e\rangle/\langle n\rangle$ (keV)
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0
2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0
0.667 0.617 0.567 0.517 0.467 0.417 0.367 0.317 0.267 0.217 0.167 0.117 0.067


Operational regime for Ignitor at Q=20
$n_0/\langle n\rangle$=1.25 $T_0/\langle T\rangle$=2.50
$p_0/\langle p\rangle$=2.88
Z_{eff}=1.30 T_e/T_i=1.0
IPB98(y,2) scaling with H_H=1.0
Q=20
$P_{heat}/P_{L->H}(Snipes)$=1.3
$P_{heat}/P_{L->H}(EVOR)$=1.3
β_N=1.5
P_{heat}=30MW
$\overline{n}_e$ (10^{20} m^{-3})
$\overline{n}_e/n_{GW}$
$\langle nT_e\rangle/\langle n\rangle$ (keV)
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0
2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0
0.667 0.617 0.567 0.517 0.467 0.417 0.367 0.317 0.267 0.217 0.167 0.117 0.067


Operational regime for Ignitor at Q=10
n0/<n>=1.25 T0/<T>=2.50
p0/<p>=2.88
Zeff=1.30 Te/Ti=1.0
β0−scaling (Eq.(9)) with HH=1.0
Q=10
Pheat/PL->H(Snipes)=1.3
Pheat/PL->H(EVOR)=1.3
βN=1.5
Pheat=30MW
ne (10^20 m^-3)
ne/nGW
<nTe>/<n> (keV)


Operational regime for Ignitor at Q=20
n0/<n>=1.25 T0/<T>=2.50
p0/<p>=2.88
Zeff=1.30 Te/Ti=1.0
β0−scaling (Eq.(9)) with HH=1.0
Q=20
Pheat/PL->H(Snipes)=1.3
Pheat/PL->H(EVOR)=1.3
βN=1.5
Pheat=30MW
ne (10^20 m^-3)
ne/nGW
<nTe>/<n> (keV)

Relevant Operating Points I

Table 1: Values of some important parameters for operation at Q=10

Case	n_{e0} (10^{20} m^{-3})	T_{e0} (keV)	W_p (MJ)	P_α (MW)	P_{aux} (MW)	P_{brem} (MW)	P_{heat} (MW)	τ_E^* (s)	β_N
IPB98/Snipes	4.8	18.9	11.9	15.6	5.4	2.5	20.0	0.60	0.90
IPB98/EVOR	4.1	18.4	9.9	10.7	2.9	1.8	13.5	0.73	0.75
β^0/Snipes	4.4	22.7	13.1	18.5	7.4	2.3	24.3	0.54	1.00
β^0/EVOR	5.7	15.3	11.4	13.7	3.7	3.2	16.8	0.56	0.87

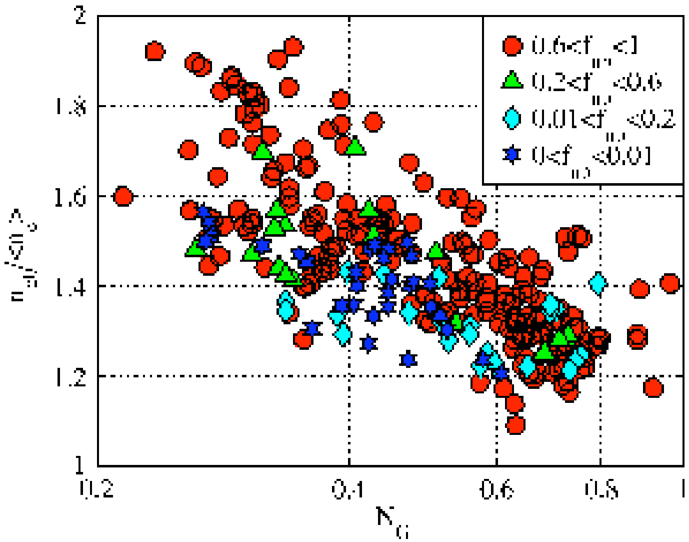
Table 2: Values of some important parameters for operation at Q=20

Case	n_{e0} (10^{20} m^{-3})	T_{e0} (keV)	W_p (MJ)	P_α (MW)	P_{aux} (MW)	P_{brem} (MW)	P_{heat} (MW)	τ_E^* (s)	β_N
IPB98/Snipes	7.8	15.6	15.9	26.7	3.7	6.0	26.6	0.60	1.21
IPB98/EVOR	6.8	14.8	13.2	18.1	1.3	4.5	17.6	0.75	1.00
β^0/Snipes	7.0	16.9	15.5	25.8	3.8	5.1	26.4	0.59	1.18
β^0/EVOR	7.0	16.9	15.5	25.8	3.8	5.1	26.4	0.59	1.18

Comments

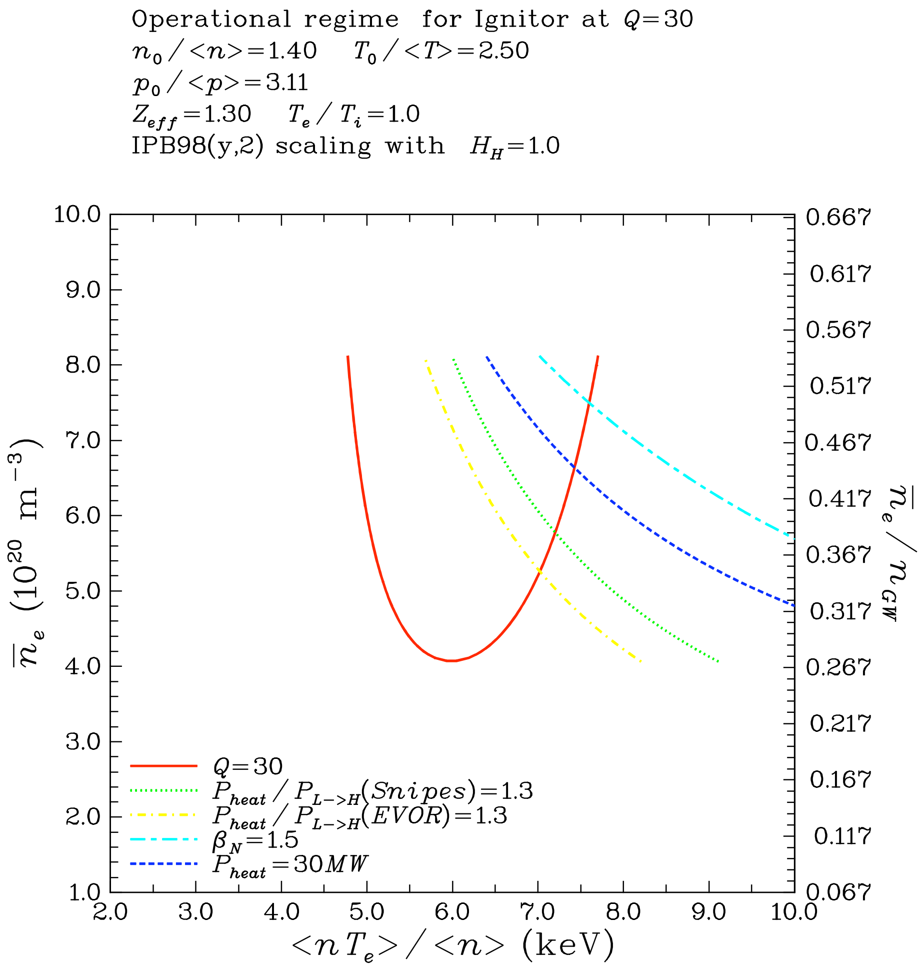
- at $Q = 10$, there is a significant operating space; typically, densities are smaller and temperatures are higher than in the reference ignition scenario;
- use of EVOR–scaling for $P_{\mathrm{L->H}}$ significantly reduces P_{heat} – a very important effect;
- instaed, use of the β^0-scaling for τ_{E}^* leads to operating points with P_{heat} somehow larger than in the case of IPB98(y,2)–scaling;
- at $Q = 20$, densities increase and temperatures decrease; P_{heat} is above 25 MW, but in the case of the combination IPB98(y,2)/EVOR;
- operating points are always far from operational limits;
- requirements for auxiliary power (at least when alpha particle power is important) are modest.

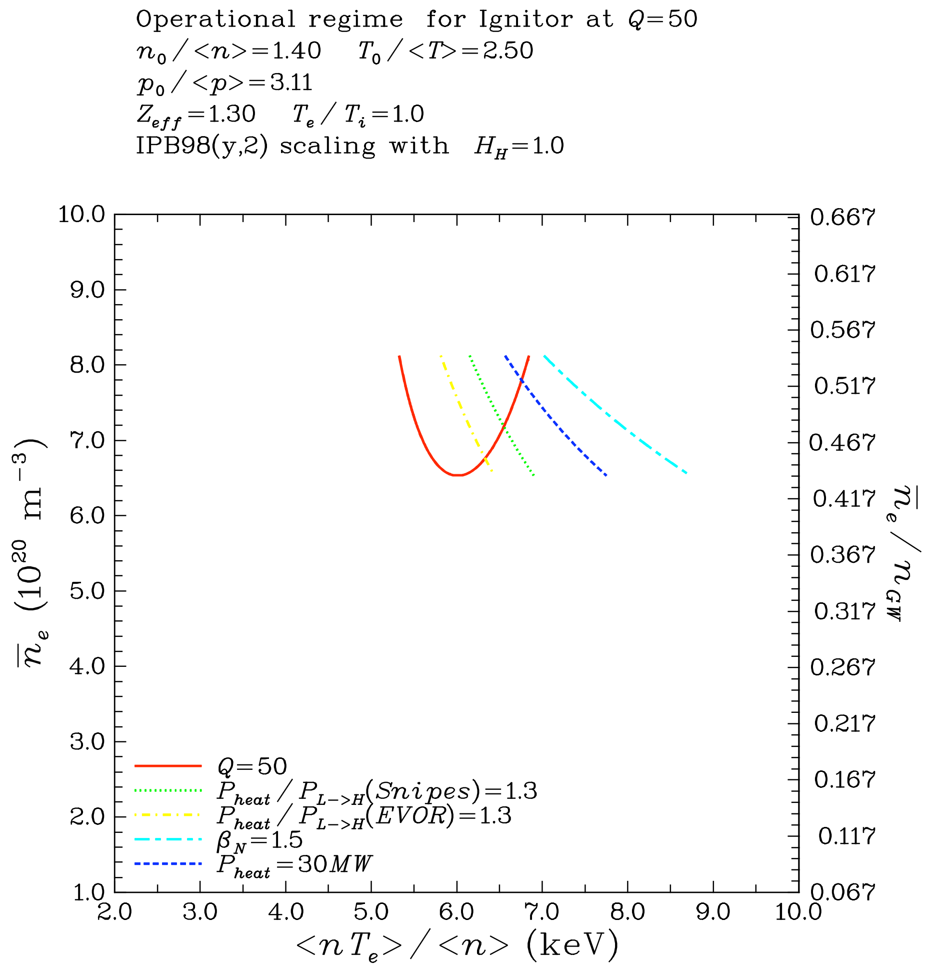
In a recent work by Weisen et al.[a], the dependence of density peaking in JET H-modes was examined and a strong correlation with $N_{\mathrm{G}} = \overline{n}_{\mathrm{e}}/\overline{n}_{\mathrm{Gr}}$ was found. Moreover, H-modes heated only by ICRH ("starred" points in the figure below) are only slightly less peaked than H-modes where heating by NBI is dominant.



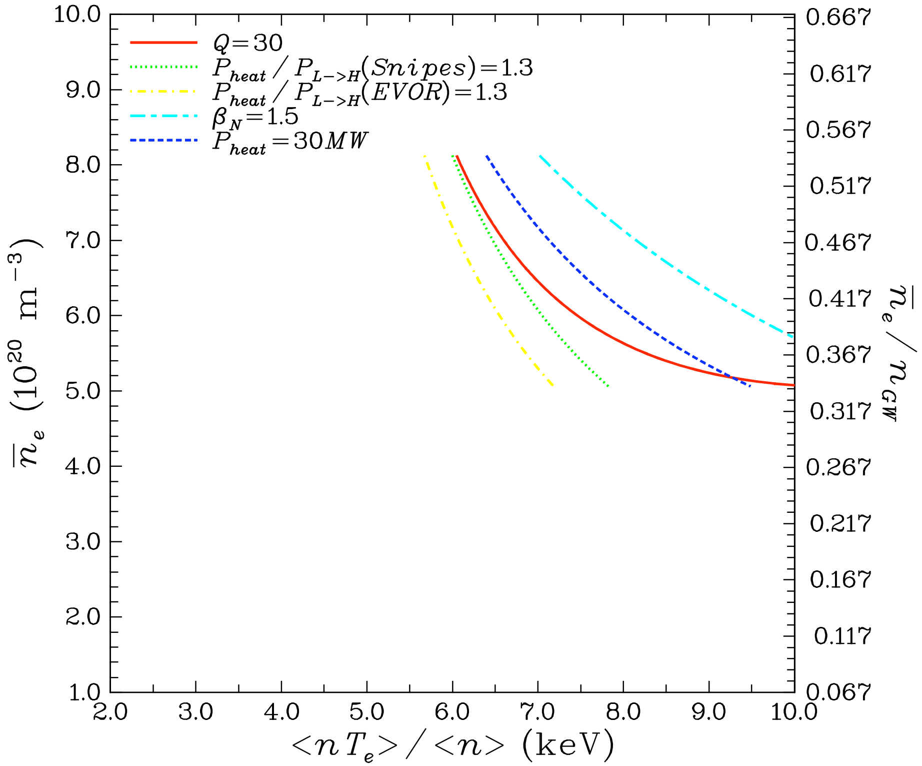
[a] H. Weisen et al. Plasma Phys. Control. Fusion **48**, A457 (2006).

As we have seen, in Ignitor H-mode operational regimes typically have $N_{\mathrm{G}} < 0.5$. So we now examine the effect of a moderately peaked density profile on the projected performance – leaving the temperature profile unchanged –. We consider a case where $n_0/\langle n\rangle = 1.40$ ($b_{\mathrm{n}} = 0.7$), so that $p_0/\langle p\rangle = 3.1$).

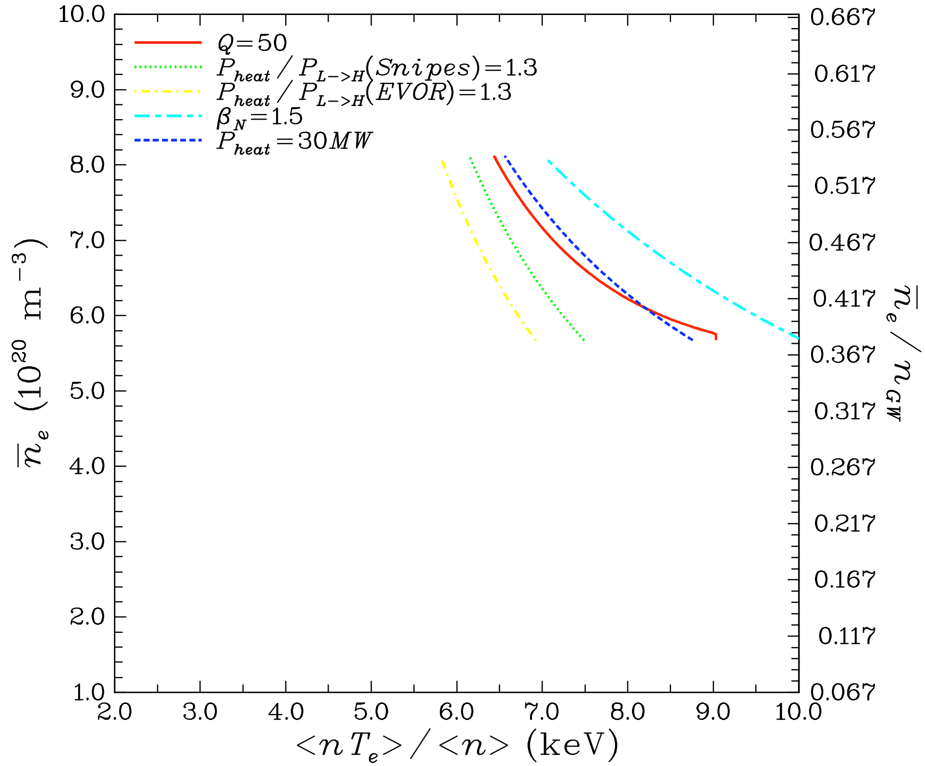

Operational regime for Ignitor at Q=30
$n_0/\langle n\rangle$=1.40 $T_0/\langle T\rangle$=2.50
$p_0/\langle p\rangle$=3.11
Z_{eff}=1.30 T_e/T_i=1.0
IPB98(y,2) scaling with H_H=1.0
$\overline{n}_e$ (10^{20} m^{-3})
$\overline{n}_e/n_{GW}$
$\langle nT_e\rangle/\langle n\rangle$ (keV)
Q=30
$P_{heat}/P_{L->H}(Snipes)$=1.3
$P_{heat}/P_{L->H}(EVOR)$=1.3
β_N=1.5
P_{heat}=30MW


Operational regime for Ignitor at Q=50
$n_0/\langle n\rangle$=1.40 $T_0/\langle T\rangle$=2.50
$p_0/\langle p\rangle$=3.11
Z_{eff}=1.30 T_e/T_i=1.0
IPB98(y,2) scaling with H_H=1.0
$\overline{n}_e$ (10^{20} m^{-3})
$\overline{n}_e/n_{GW}$
$\langle nT_e\rangle/\langle n\rangle$ (keV)
Q=50
$P_{heat}/P_{L->H}(Snipes)$=1.3
$P_{heat}/P_{L->H}(EVOR)$=1.3
β_N=1.5
P_{heat}=30MW

Operational regime for Ignitor at Q=30
$n_0/\langle n\rangle=1.40$ $T_0/\langle T\rangle=2.50$
$p_0/\langle p\rangle=3.11$
$Z_{eff}=1.30$ $T_e/T_i=1.0$
β^0–scaling (Eq.(9)) with $H_H=1.0$



Operational regime for Ignitor at Q=50
$n_0/\langle n\rangle=1.40$ $T_0/\langle T\rangle=2.50$
$p_0/\langle p\rangle=3.11$
$Z_{eff}=1.30$ $T_e/T_i=1.0$
β^0–scaling (Eq.(9)) with $H_H=1.0$



Relevant Operating Points II

Table 3: Values of some important parameters for operation at Q=30 in the case of a more peaked density profile

Case	n_{e0} (10^{20} m^{-3})	T_{e0} (keV)	W_p (MJ)	P_α (MW)	P_{aux} (MW)	P_{brem} (MW)	P_{heat} (MW)	τ_E^* (s)	β_N
IPB98/Snipes	7.6	16.2	14.9	26.0	1.3	5.0	24.6	0.61	1.13
IPB98/EVOR	6.8	15.7	13.0	19.5	0.0	3.9	18.2	0.71	1.00
β^0/Snipes	7.5	16.3	14.9	25.9	1.3	4.8	24.6	0.60	1.13
β^0/EVOR	7.5	16.3	14.9	25.9	1.3	4.8	24.6	0.60	1.13

Table 4: Values of some important parameters for operation at Q=50 in the case of a more peaked density profile

Case	n_{e0} (10^{20} m^{-3})	T_{e0} (keV)	W_p (MJ)	P_α (MW)	P_{aux} (MW)	P_{brem} (MW)	P_{heat} (MW)	τ_E^* (s)	β_N
IPB98/Snipes	9.4	14.8	16.9	32.4	0.0	7.3	27.8	0.61	1.28
IPB98/EVOR	8.5	14.1	14.5	23.5	0.0	5.8	19.5	0.74	1.10
β^0/Snipes	8.3	16.4	16.5	31.8	0.2	5.9	28.3	0.58	1.25
β^0/EVOR	8.3	16.4	16.5	31.8	0.2	5.9	28.3	0.58	1.25

Conclusions

- Use of a 0-D modelling for assessing Ignitor plasma performance in the H-mode show that high-Q operation may be achieved in Ignitor at low plasma β ($\beta_{\mathrm{N}} < 1.5$) and small normalized density ($N_{\mathrm{G}} < 0.5$); this is important since, as remarked by P. R. Rebut in the conclusions of his Alfvèn Prize Lecture, “a reactor must operate at a good distance from the operating limits, current, density, pressure”.
- Recently proposed scalings for $P_{\mathrm{L->H}}$ are less unfavourable for high field experiments making operation at high values of Q with $P_{\mathrm{heat}} < 20$ MW a distinct possibility.
- Systematic analysis of density peaking in JET H-modes showed strong correlation with N_{G} (smaller $N_{\mathrm{G}} \rightarrow$ higher peaking); typically, Ignitor operates at $N_{\mathrm{G}} < 0.5$; greater density profile peaking leads to significantly improved performance.
- These results for H–mode operation in Ignitor are quite encouraging, although more comprehensive analyses are certainly needed.