Performance of Burning Plasma Experiments :
based on theoretical core transport models and empirical pedestal scalings

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The key transport issue for MFE burning experimental facilities is the projected performance of the device: Q = P_fus/P_ext, the ratio of fusion power produced to external power supplied. Q is important for energy economics. The fraction of alpha self-heating F= Q/(Q+5) is more relevant to scientific goals. To obtain its scientific goal, the device must have Q greater than 5 which amounts to more than 50% self-heating from the alpha particles and preferably Q greater than 10 (66% self-heating) in the D-T phase. The controllability of self heated devices within MHD stability boundaries is a an experimentally open question that must be answered in a burning plasma device. The technology goals for material wall neutronics testing or power handling depend on some required P_fus per surface or circumference, and hence depend on achieving high Q at full design P_aux. Q=10 is the nominal goal of all current designs and the maximum design P_aux is generally set by the threshold power required to obtain good H-mode confinement in a non-burning (D-only) phase.

Assessing the likelihood of performance Q in the 5 to 10 range is very difficult. All the proposed burning devices are designed by the same empirical scaling rules for the H-mode power threshold, the power dependent H-mode global energy confinement time (tau_E), and (less crucially) the operating density limit. To predict Q and the MHD stability, plasma profiles must be assumed or predicted. Given the H-mode pedestal height parameters as temperature and density boundary conditions, theory based core transport models (some) benchmarked to fundamental turbulence simulations have had consider successes in the past decade at predicting or fitting core H-mode profiles, including the formation of internal transport barriers, and global energy confinement to better than 10%. However despite basic understanding of the H-mode edge transport barrier mechanisms for formation and cyclic breakdown of its MHD stability (ELM's), there is no experimentally validated model for predicting either the H-mode power threshold, or the pedestal heights. Furthermore theoretical core transport models based on simulations are "stiff" and therefore projected profiles, energy confinement times, and Q are highly dependent on the pedestal heights (possibly as beta_ped squared) which must at present be determined by empirical scaling rules. It must be clearly understood that Q values above 5 are very hard to predict accurately: Q = 5F/(1-F) , but F α <nT>tau_E, the "fusion product" has double the uncertainty of tau_E Thus a 15% RMSE for tau_E typical of empirical fits results in a 30% uncertainty for F. A specific prediction of Q=5 thus corresponds to 2.7 < Q < 9.3 [or Q=10 to 4.3 < Q < 30].

Based on the same H-mode empirical global confinement time scalings and threshold rules augmented by detailed core transport model and H-mode pedestal studies, both ITER-FEAT, FIRE are equally likely to obtain (or exceed) their Q performance goals. IGNITOR should easily get high Q performance if it obtains a full H-mode. A key difficulty for a uniform technical assessment is the lack of a diverter in IGNITOR although an X-point on the wall is possible at a reduced current. Given that a reactor must have a divertor, and that the H-mode edge physics is the most poorly understood feature of tokamaks, an IGNITOR facility alone would not satisfy the scientific and technological needs of the fusion community. L-mode (cold edge) operation in IGNITOR is likely to have very low performance Q << 5 unless the significant enhancements are obtained. Q > 5(10) requires H-enhancement factors for L97 of 1.25 (1.4) with significant density peaking (n(0)/<n>=1.8). Such enhancements (with cold edges) and peaking have been obtained transiently but the database for this is not widely established and steady state demonstration discharges in existing tokamaks are needed

Here we outline the key transport issues for projecting Q using theoretical core transport models and empirical pedestal height rules. As we have already noted Q, particularly in this range, is a sensitive quantity to predict; thus we focus on the sources of its uncertainty and what the base program might do to improve predictability.

Theoretical core transport models and stiffness: From 1995, the international transport modeling community systematically tested a large variety of local of both empirical and theoretically motivated transport models against the ITER profile database[1]. The lesson learned, was that there are several models with comparably good statistical fits to the total stored energy (or tau-E) given the H-mode pedestal heights, but their projections of Q can vary substantially. We don't need to consider every model to illustrate this. Here we focus on the two most widely used and well documented models: the Multi-Mode models [2] and the GLF23 model [3]. Both are comprehensive theory based drift wave models including the ion temperature gradient (ITG) mode, the trapped electron mode, and the electron temperature gradient (ETG) mode. The GLF23 model was originally fit to gyrofluid simulations and was nearly as stiff as the IFS/PPPL model. Recently GLF23 has been renormed to gyrokinetic simulations and is somewhat less stiff but still very stiff: the T(0)/T_ped is not very responsive to power. The renormed GLF23 model (which takes no coefficients from experiment) has an 8.7% statistical error for tau_E over 50 DIIID, C-MOD, and JET H-mode shots [4] given the pedestal density and temperature. Multi-Mode model is nearly as good, yet because of the difference in stiffness, their Q projections differ both quantitatively and qualitatively.

Figure 1 (from Kinsey et al Ref. 4) illustrates the use of the core models with a empirical pedestal model[5]. The Q versus T_ped in Figure 1(a) are for ITER-FEAT an FIRE at their target densities and P_aux: n_line/n_G = 0.85 and 0.70; P_aux = 40 and 20MW respectively. (n_line = 1.4 n_ped consistent with existing H-mode data was assumed, and dilution consistent with Z_eff= 1.8 and 1.4 was assumed). Since the alpha heating tends to go as T^3 at low temperature and T^2 at higher temperatures, the stiffer GLF23renorm model has Q α T_ped^2 whereas the less stiff Mult-Mode model has Q α $T\_ped^{0.5}$ for ITER (at lower density and higher temperature than FIRE) and Q α T_ped for FIRE. The particular pedestal model [5] (RMS=33.5%) assumed an MHD critical pressure gradient limited by high-n ballooning modes and a pedestal width scaling like $(beta\_ped\_poloidal)^{1/2}$ R, but is characteristic of all the empirical models having T_ped α /n_ped as shown in Fig 1(b). All such MHD limited pedestals are further assumed to be independent of the power sustaining the pedestal (P_ped = P_alpha – P_brem + P_aux). The resulting dependence of Q on the operating density (n_line/n_G) is rather flat except for the Multi-Mode ITER projection. In fact for stiff models the P_fus (=5 P_alpha) α Vol n_ped^2 T_ped^2 which can be conveniently written as Vol (beta_ped_N)^2*[B^2*(I/aB)]^2 [4] where beta_ped_N = beta_ped/(I/aB) (related to the usual beta_vol_ave_N taken as a design constraint on core MHD stability; beta_vol_ave/beta_ped = 3.3 is a typical profile)

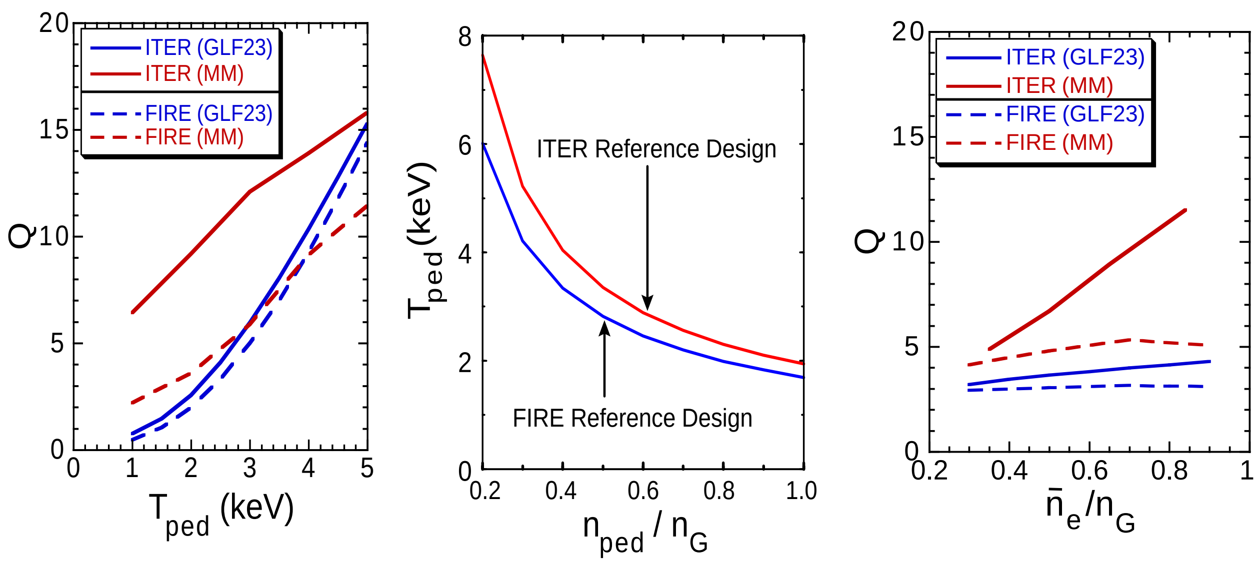


Figure_1 . from Kinsey et al Ref [4].

The most important stiffness difference between these core models is in the core response to power; this can be characterized by W_tot/W_ped α P ^{s} (in present experiments P=P_ped is just taken to be P_aux). Statistical analysis of the present H-mode global database shows the total stored energy (e.g. the H98(y,2) scaling) has W_tot α P $^{0.31m0.03}$ and a free fit to the pedestal data has W_ped (= 3 Vol n_ped T_ped) α P $^{0.31m0.03}$ also [6] . This implies s= 0 m0.06. This loose reasoning implied the core is nearly perfectly stiff (s=0). H-mode modeling studies in progress, suggest s=0.1 for GLF23renorm and s=0.2 for Multi-Mode; precise power scaling experiments are required to resolve this difference and determine the true core stiffness. Thus it is not surprising that at higher T_ped values, Q α P_aux$^{0.9}$ for GLF23renorm, but Q α P_aux$^{0.25}$ for Multi-Mode. For GLF23, this means Q (=P_fus/P_aux) and can almost be doubled by halving P_aux. In fact as illustrated in **Figure_2**, for pedestal temperatures high enough to get into the H-mode at full P_aux with Q= 5 to 10 are in fact very nearly ignited (Q infinity, 100% self heating), provided P_ped with P_aux =0 is sufficient to stay in H-mode. Typically this means P_ped must exceed 1/2 P_LH (half the LH power threshold). We must know if T_ped will fall as the P_aux is withdrawen, i.e. we need to know the power scaling for T_ped =T_ped_LH (P_ped/P_LH)$^{\sigma}$. We have just seen that a free fit of the pedestal data suggests σ = 0.31. However it is generally believed that this is a low power result. At high power (P_ped) the pedestal height is limited by MHD stable pressure gradient in the pedestal. In this high power regime, the pedestal itself should become stiff, i.e. σ is weak (or actually 0). Thus weather the tokamak can remain in a stationary ignited state (green lines) or a merely transient ignited state depends on the stiffness (P_ped dependence) of the pedestal.

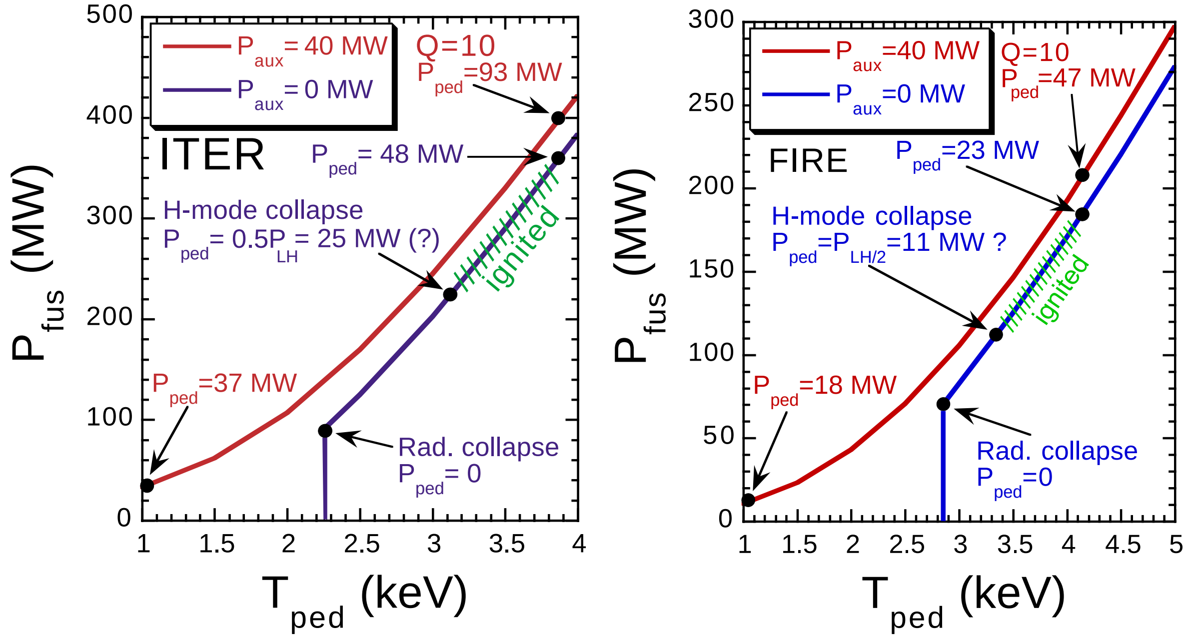


Figure 2. from Kinsey et al Ref [4].

Pedestal height and stiffness: From the work of Thomsen and Cordey [6] a free statistical fit to the pedestal data gives

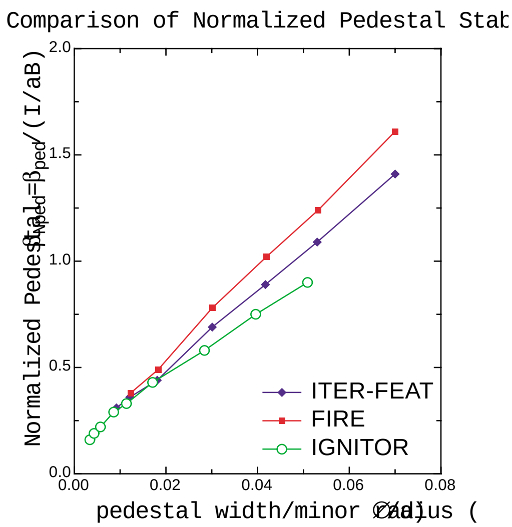
$$W\_ped = e^{-3.74}\ I^{1.71}\ R^{1.16}\ P^{0.31}\ M^{0.30}\ q\_sh^{\ 1.20} \qquad RMS = 25.4\% \qquad (1)$$

with a noticeable power dependence, but a fit with the p_ped = width_ped x dp/dr_crit limited by a high-n ballooning and constrained to be power independent, results in an MHD rule

$$W\_ped = e^{-4.61}\ I^{2}\ R\ [M / nR^{2}]^{0.13}\ q\_sh^{1.20}\ [a / R]^{-1.68} \qquad RMS = 27.3\% \qquad (2)$$

Here the width_ped α rho_pol$^{0.23}$ R$^{0.77}$ gave the best results. (q_sh = q_95/q_c). Unfortunately the statistical fits to date have only been done by lumping all the data together without distinguishing the low-power regime with the pedestal height increasing with power, and a true high power regime which pushes against the maximally allowed pressure gradient by MHD stability and where the pedestal becomes stiff and unresponsive to further increases in P_ped. Thus we should interpret the MHD pedestal rules as a maximal pedestestal heights. With this interpretation it is better to treat a dimensionless MHD quantity like beta_ped_N introduced above. The W_ped (or T_ped formulas) can be easily converted. The existence of this high power saturated regime is not widely established in all machines.

Synder [7] has examined the stability of various profiles to the edge ballooning-peeling modes with assumed pedestal widths and calculated edge bootstrap currents for maximum allowable beta_ped_N as shown in **Figure 3(a).** The MHD statistical projections shown in **Table 3(b)**, are in agreement with Synder's detailed analysis for Δ/a of 2%. Typical widths in DIIID are 1.5%-3.0% with the upper bounds on beta_ped_N slightly above the red line in (FIRE) in Snyder's figure. So we might expect more optimistic beta_ped_N's than shown, if the pedestal widths don't skrink. Experimentally it is very difficult to distinguish various models for the width, and none of the statistical fits are very precise at RMSE's typically 25-35% for beta_ped_N. Indeed if the core is stiff, Q α [Vol/P_aux] $(beta\_ped\_N)^2[B^2\ (I/aB)]^2$ at full P_aux, then a 27% scatter in beta_ped_N, means a predicted Q=5 is really 2.65 < Q < 8.10 or a predicted Q=10 is really 5.3<Q<16.2.



beta_ped_N projections

Δ	RMS/Ref	ITER	FIRE	Ignitor
$(\beta_\theta)^{0.5}R$	33.5%[5]	0.34		
$\rho\, s^2$	32.0%[5]	0.32		
$(\rho Rq)^{0.5}$	30.8%[5]	0.30		
$\rho^{0.66}R^{0.33}$	33.7%[5]	0.28		
$\rho_\theta^{0.23}R^{0.77}$	27.3%[6]	0.42	0.58	0.75

Figure 3 (a) from P. Synder stability studies and **Table 3 (b)** from Ref 5 and 6

Relative Q Figure of Merit from stiff models: Given the difficulty of making a precise performance prediction, it is useful to devise a simple figure of merit (with arbitrary scale) that can rank the proposed devices. Taking the stiff models scalings with and empirical P_LH [8]

$$P\_LH = 2.84\ M^{-1}\ B^{0.82}\ \ n\_bar^{0.58}\ R^{1.0}\ a^{0.81}\quad RMS = 26.8\% \qquad (3)$$

for full P_aux and the Thomsen-Cordey [6] MHD (Eq. 2) scaling for the pedestal beta_ped_N, we obtain (with arbitrary division by 1000)

$$Q(FoM) = [Vol/P\_LH]\ (beta\_ped\_N)^2[B^2\ (I/aB)]^2/1000. \qquad (4)$$

Machines same shape q_95 =3 , k_95 = 1.8, & R/a = 3.10, 3.60, 3.2

	n_line/n_G	P(MW)	P_LH (MW)	beta_ped_N	Q(FoM)
ITER-FEAT	0.85	40	51	0.42	5.1
FIRE	0.65	20	26	0.58	5.7
IGNITOR (9MA)	0.50	10	21	0.82	21 (*)

*H-mode scaling for the diverterless wall-separatrix operation questionable

From this it seems that ITER-FEAT and FIRE are equally likely to reach their performance goals. However, a key difficulty in making a uniform technical assessment of these devices is the lack of a diverter in IGNITOR, yet we have used H-mode scaling rules. The full bore 11MA IGNITOR was reduced to 9MA and the minor radius by 10% so IGNITOR can accommodate a separatrix on the wall. Divertorless H-modes are possible but may not have the needed high pedestals and pulse lengths for an inertialy cooled wall-separatrix maybe short. L-mode or enhanced L-mode operation in IGNITOR is assessed below with core theoretical models and global scaling rules.

Another important transport issue for burning plasmas facilities is the flexibility to obtain Advanced Tokamak operation, possibly internal barriers, and plasma rotation. Experimental scenarios are addressed elsewhere, but here we only comment that plasma rotation has been an important ingredient in obtaining high performance discharges both for MHD wall mode and error field stabilization and for internal barrier formation. Reverse shear Shafranov stabilization internal barriers might be possible but likely more difficult without rotation. No rotation was assumed in the transport modeling projections here, but work predicting rotation with GLF23renorm from 1Mev beams in ITER and its beneficial effects are discussed in a Snowmass 2002 appendix report by G. Staebler.

Q performance tables comparing with global confinement time scalings: For completeness we consider specific examples of Q performance using a fit to GLF23renorm transport code runs developed by Kinsey et al [4]. The P_fus formula is given in the **Appendix**. The formula depends on beta_ped_N which we take from Eq 2 (or Eq 1 as noted). The results of this “core-ped” model are compared with empirical global scaling rules:

The ITER98(y,2) scaling law with RMSE = 14.5%

* tau_y2 = 0.0562 $P\_ped^{-0.69} B^{0.15} I^{0.93}\ n\_19\_ave^{0.41} a^{0.58} R^{1.39} M^{0.19} \kappa^{0.78}$

has gyroBohm scaling but with significant power degradation. It has power loss scaling as $n^{1.90}\ T^{3.22}$ close to the alpha power gains.

An electrostatic (no beta dependence) gyroBohm scaling law with slight collisionality dependence (tau α $B^{-1}\ \rho_*^{-3}\ \beta^0\ \nu_*^{-0.14}\ q^{-1.7}$) from Petty, DeBoo, LaHaye, et al (May 2001 GA-A23590 in Fusion Technology) with RMSE = 16.5% compared to free fit 15.8% on ELMing H-mode database. The scaling is slightly weaker that dedicated DIIID gyroBohm H-mode experiments with no beta dependence tau α $B^{-1}\ \nu_*^{-0.35}$. The power loss scales as $n^{1.13}T^{2.2}$ which favors higher density and temperature operation.

* tau_gB1 = 0.028 $P\_ped^{-0.55} B^{0.07} I^{0.83}\ n\_19\_ave^{0.49} A^{-0.3} R^{2.11} M^{0.14} \kappa^{0.75}$

A similar gyroBohm scaling from Perkins and DeBoo with no beta or collisionality has RMSE=16.6 % with power loss scaling as $nT^{2.5}$

* tau_gB2 = 0.053 $P\_ped^{-0.6}$ $I^{0.8}$ $n\_19\_ave^{0.6} A^{-0.76} R^{2.2}$ $\kappa^{0.6676} q^{0.02}$

The L-mode scaling used evaluate IGNITOR is ITER 97L with RMSE =15.8%

* tau_97L = 0.023 $P\_ped^{-0.73}$ $B^{0.03}$ $I^{0.96}$ $n\_19\_ave^{0.40} A^{-0,06} R^{1.83}$ $M^{0.20} \kappa^{0.64}$

In detail:

P_brem used standard local formulas with profile averaging.
P_oh = V*I=2πR*$\eta_{||}$(0)*j(0)*I and j(0) assumes q(0)=1.0. The neoclassical enhancement eta_neo = 1.0 or otherwise $1./(1-(a/Rq_{95})^{1/2})^2$ as stated.

P_alpha = volume $(n\_i/n\_e)^2$ *profile_ave* $[n(r)^2 \langle\sigma v\rangle(r)/4.]$
with $\langle\sigma v\rangle$ parameterized over T(r) from Wessen [Tokamaks 1997 p.7].

Profiles used had n_peaking=0.5 and t_peaking=4. where

$T(r) = T\_ped*(t\_peaking*(1. - r^2)**(t\_peaking/2.)+edge)$
$n(r) = n\_ped*(n\_peaking*(1.- r^2)**(n\_peaking/2.)+edge)$ edge=1.(0.1) H-(L-)mode

Standard parameters and profiles used (unless otherwise stated):
n_line/n_ped = 1.4, T(0)/T_ped = 5.0, T(0)/<T>=2.6, <beta>_N / beta_ped_N = 3.32

	ITER-FEAT	FIRE	IGNITOR
R	6.2	2.14	1.33
A	3.1	3.6	2.9
κ	1.8	1.8	1.8
q_95	3	3	3
B	5.3	10.0	13.0
I	15.	7.7	11.
P_aux	40.	20.	10
n_line/n_G	0.85	0.70	0.5
Z_eff n_i/n_e	1.5 0.9	1.4 0.92	1.2 0.96

Given the profiles, the global scaling relations can be used to infer the beta_ped_N and compared with the empirical pedestal scalings Eq 2 (or Eq 1 as noted). These are given in the Tables below.

ITER-FEAT Q = P_fus/P_aux

P_aux n_line/n_G MW	core-ped model Q beta_ped_N	H98y2 Q beta_ped_N	gB1(gB2) Q beta_ped_N
40 0.86	4.9 0.42	11. 0.50	41(31) 1.1(0.86)
20	9.4 0.42	15. 0.43	71(48) 1.0(0.76)
40 0.43	6.7 0.46	4.7 0.33	7.2(5.1)0.43(0.35)
20	13 0.46	6.8 0.28	8.9(6.3) 0.42(0.27)

FIRE Q = P_fus/P_aux

P_aux n_line/n_G MW	core-ped model Q beta_ped_N	H98y2 Q beta_ped_N	gB1(gB2) Q beta_ped_N
20 0.70	4.1 0.58 4.8 0.61*	4.4 0.42 8.5 hh=1.15	10.(8.0)0.59(0.54) 33. hh=1.15
10	8.2 0.58 4.9 0.45*	2.9 0.30 8.7 hh=1.15	2.1(2.7) 0.27(0.29) 42. hh=1.15
20 0.35	5.6 0.63 7.2 0.71*	2.9 0.32	3.3 (2.6) 0.33(0.31)
10	11. 0.63 10. 0.60*	3.6 0.26	2.8 (2.6) 0.23(0.23)

*power scaled pedestal model Eq 1

There can be striking variations in Q from various global scaling, H98y2, gB1,gB2 with nearly identical RMSE goodness of fit, particularly at high Q. Several examples are found in the ITER and FIRE tables. The FIRE tables also indicate that Q can easily double or triple with hh=1.15 (an upper bound for RMSE=15%). Given this variation within the global scaling law methods themselves, there is relative agreement with the core-ped modeling method is acceptable.

FIRE at reduced aspect ratio would get better performance according to the core-ped model whereas the y2 model does not. FIRE was designed for minimum R at Q_y2 fixed. P=20 MW and n_line/n_G = 0.7

	FIRE	FIRE_LA	FIRE_LA_s
Q_H_FoM	5.7	9.1	8.6
A	3.6	3.1	3.1
R	2.14	2.2	2.14
I	7.7	9.6	9.3
B	10.	8.	8.
Q beta_ped_N core-ped	4.1 0.58 4.8 0.61*	8.2 0.69 58 1.6*	7.5 0.69 42 1.5*
Q_y2	4.2	5.3	4.7

*power scaled pedestal model

We further note (below) that including P_oh in the Q definition and adding a neoclassical resistive enhancement makes no difference for ITER and only small differences in FIRE.

Q^O=P_fus/(P_aux+P_oh) & eta_neo=1./(1-(a/Rq_{95})$^{1/2}$)^2

FIRE

P_aux n_line/n_G MW	core-ped Q^O beta_ped_N	H98y2 Q^O beta_ped_N	gB1(gB2) Q^O beta_ped_N
20 0.70	3.9 0.58 4.9 0.62*	4.2 0.43 8.3 hh=1.15	10.(7.8)0.61(0.55) 33. hh=1.15
10	7.3 0.58 5.0 0.45*	2.9 0.32 9.2 hh=1.15	2.5(2.9) 0.31(0.34) 42. hh=1.15

*power scaled pedestal model

IGNITOR Q^O=P_fus/(P_aux+P_oh) & eta_neo=1./(1-(a/Rq_{95})$^{1/2}$)^2

P_aux n_line/n_G MW	core-ped edge=1. Q^o beta_ped_N	H98y2 edge=1. Q^o beta_ped_N	L97 edge=0.1 T(0)/<T>=2.9 H Q^o Q^o(ohmic)
10 0.50	31. # 0.82 input T_edge=2. : n_edge_19 =59. 5.6 0.30 n_edge_19 =31. 4.0@ 0.30	15. # 0.45	1.0 1.6@ 1.25 4.9@ 3.5@ 1.40 12.@ 7.9@

reduced I=11-> 9MA a=0.455->0.410m @ n(0)/<n> = 1.07->1.83

Ohmic heating in IGNITOR can be significant. IGNITOR (9MA wall-separatrux) with full H-mode rules easily ignites (very large Q^o) using the core-ped model. IGNITOR (11MA) L-mode appears to require T_edge > 2.0keV with the core-ped, i.e. not a cold edge. Density profile peaking at fixed n_line/n_G does not help; density peaking at fixed n_edge/n_G does get higher Q's. Forcing a cold edge and using with L97 global scaling requires enhancements of H=1.25(1.4) for Q^o >5(10). With L97, ohmic heating alone (P_aux=0.) has a lower Q^o. These are steady state Q^o values. Nonsteady values (e.q. P_aux=10.MW and W_dot = 10MW) produce lower transient Q^o values still. Transient L97 enhancements up to 1.5 with code edge peaked density profiles have been obtained transiently in FTU (see Snowmass 2002 report appendix by F. Romenelli). We note that ITER (P_aux=40. and n_line/n_G) under the same cold edge and density peaking conditions (n(0)/<n>= 1.83) requires L97 enhancements of 1.4(1.7) for Q=5 (10). Overall, IGNITOR has equal or better confinement than ITER or FIRE under the same rules; the difference in device assessment is H-mode versus L-mode. IGNITOR is not designed with a diverter and the pedestal rules for an H-mode may not apply. Furthermore the required L-mode enhancements and with peaked density and cold edges in steady state is not well supported by the database or the core theoretical models used.

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Appendix

Fit to GLF23renorm transport model projections at q_95=3. 0 & κ=1.8. [Ref 4]. GLF23remorm reproduces W_tot/W_ped with RMSE 8.7% over 50 DIIID , JET , and C-mod H-mode shots. The P_fus fit is to numerous ITER,FIRE, and IGNITOR transport code runs varying T_ped, n_ped, and P_aux. The weak exponential coefficient on P_ped represents the model stiffness (unresponsiveness to P_ped). The first exponential factor represents variation of the ITG critical gradient.

$$* \; P\_fus = volume\,(beta\_ped\_N)^2\,[B^2(I/a/B)]^2$$

$$\times \; 5.83 \times 10^{-5}\,(n\_i/n\_e)^2 (n\_line / n\_ped)^{1.5}$$

$$\times \; \exp[2.(2.15+(1.-(n\_i/n\_e))+0.75(1.+0.5/\nu^{0.25}))/(R/a)]$$

$$\times \; \exp[2.(0.00275\, P\_ped\,(R/a)^{1.5}/T\_ped^{1.5})^2]$$

where $\nu = 0.1\, n\_line\_19\, R / T\_ped^2$ and volume = $\kappa\,(\pi a^2)\,(2\pi R)$

beta_ped_N = beta_ped/(I/a/B)

P_ped = P_fus/5. – P_brem + P_aux + P_oh

[meters, Tesla, MA, keV, MW, n_19, etc]