High Field Tokamaks for Burning Plasma Experiments

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Abstract. A direct consequence of the ELMy H-mode regime of tokamaks is that, for a constant value of the energy gain Q, both the plasma linear dimension and the normalized plasma density and beta are decreasing functions of the toroidal magnetic field. In this paper, starting from the conditions foreseen for the latest versions of ITER, we derive the plasma parameters of three tokamak plasmas with a toroidal magnetic field of 8. 10, and 13 T.

The next step in the development of a tokamak fusion reactor must be a DT burning plasma experiment for the exploration and understanding of the physics of α-dominated plasmas. Several of these experiments have been proposed over the years – ITER being the most prominent [1].

The operational mode foreseen for ITER is the ELMy H-mode, for which a number of empirical scaling laws have been published. In general, these scaling laws are cast in the form [2]

$$\tau_E \omega_c = \rho *^{\alpha} F(\beta, \nu *, \{p_i\}) \ , \qquad (1)$$

where τ_E is the plasma energy confinement time, ω_c is the ion cyclotron frequency, $\rho * = \rho / a$ is the normalized ion Larmor radius (a=minor radius), and F is a function of the toroidal plasma beta β, the effective collision frequency $\nu *$, and a set $\{p_i\}$ of dimensionless parameters including the safety factor q_{95}, the aspect ratio A, the elongation k, the triangularity δ and the average isotopic number M. In the following, we will use the scaling given in Ref. [2]

$$\tau_E \omega_c \propto \rho^{*-2.70}\ \beta^{-0.90} \nu^{*-0.01}\ M^{0.96} q_{95}^{-3.0} A^{-0.73} k^{2.3}\ , \qquad (2)$$

where for simplicity we will neglect the weak dependence on ν^*.

In the operation of tokamaks, two parameters of crucial importance are the normalized values of plasma density $n_G = \bar{n}/n_{GW}$ and plasma beta $\beta_N = \beta/(I_p/Ba)$ (where $\bar{n}$ [10^{20} m^{-3}] is the line average electron density, $n_G = I_p/\pi a^2$ [MA, m^{-2}] is the Greenwald limit, B [T] is the toroidal magnetic field, and I_p [MA] is the plasma current). Experiments [3] indicate that the plasma confinement degrades very quickly as the value of n_G approaches unity. In the ITER-EDA design [4], n_G was chosen larger than one. In later versions of ITER (IAM [4], LAM [4] and FEAT [1]), this ratio was lowered to 0.85 – a value that unfortunately is still too large. Indeed, the database from which the scaling in Eq. (2) was derived contains a miniscule number of cases with $n_G \geq 0.85$. Moreover, one would be hard-pressed to find a scientific publication describing a stable tokamak discharge in the ELMy H-mode regime without any degree of confinement degradation, and with $n_G \approx 0.85$, $\beta_N \approx 1.8$ and $q_{95} = 3$, the latter being the values of normalized plasma beta and safety factor in the FEAT design [1]. Finally, another difficulty in ITER stems from its large size, and hence the high cost. Fortunately, all three of these problems – large density, beta and size – could lessen by operating at larger magnetic fields.

To see how important the toroidal magnetic field is for the scientific feasibility of a burning plasma experiment, let us consider the energy balance of a DT tokamak and assume that the plasma thermal losses, represented by Eq. (2), are the dominant losses of plasma energy. We have

$$B^2 \beta\ \tau_E \propto G/N\ , \qquad (3)$$

where $G = Q/(5+Q)$, Q is the energy gain, $N = \langle n^2\, \overline{\sigma v} \rangle / B^4 \beta^2$, $\overline{\sigma v}$ is the nuclear fusion rate and the brackets < > indicate the volume average.

One important engineering parameter is the average neutron power wall loading P_w, which in ITER-EDA was 1.0 MW/m^2 [1], while it was lowered to 0.5 MW/m^2 in later versions of ITER [4,5]. At constant values of q_{95}, A and k, P_w, scales like

$$P_w \propto N\, B^4 \beta^2 a \ . \tag{4}$$

This, together with Eq. (2) and (3), gives

$$\begin{aligned} a &\propto \frac{T^{0.51}\,(G/N)^{0.38}}{B^{1.32}\,(P_w/N)^{0.02}} \\ \beta_N &\propto \frac{(P_w/N)^{0.51}}{B^{1.34}\,T^{0.25}\,(G/N)^{0.19}} \\ n_G &\propto \frac{(P_w/N)^{0.49}\,(G/N)^{0.19}}{B^{1.66}\,T^{0.74}} \end{aligned} \quad . \tag{5}$$

From these equations, where the temperature T is a free parameter that we assume varying in a restricted range where N is constant, we see that the plasma linear dimension (a), and the normalized values of plasma beta (β_N) and density (n_G) are all decreasing functions of the magnetic field. On the contrary, a increases with T, while the opposite is true for β_N and n_G. Finally, Eqs. (5) show that the plasma linear dimension is insensitive to P_w.

Tables 1 and 2 show the results of scaling according to Eqs. (5) the reference discharges of ITER-RC-IAM [4] and FEAT [5] to three tokamaks with a toroidal magnetic field of 13 T (as in Ignitor [6]), 10 T (as in FIRE [7]) and 8 T. The scaling is performed keeping the values of A, k, q_{95} and Q (=10) constant. Other quantities in the tables are the average plasma temperature $T_n \equiv \langle nT \rangle / \langle n \rangle$, the poloidal plasma beta β_p, the vacuum magnetic energy E_{TF}, the fusion power P_f, and the L-H transition power P_{LH} for which we use the expression $P_{LH} = 3.24\, M^{-1} B^{0.75} \bar{n}_{20}^{0.60} R^{0.98} a^{0.81}$ given in Ref. [2]. We consider both T_n and P_w as input parameters, and for the latter we impose the constraint of making the total plasma heating power (i.e., the sum of the power of α-particles and that of auxiliary heating) larger than P_{LH}.

The linear dimensions of the case with B=13 T are very similar to those of Ignitor (a=0.47 m, A=2.8, k=1.83, I_p=11 MA). This is indeed an extraordinary result since the size of the latter has been determined using a completely different transport model [6]. Consequently, considering that Ignitor has a larger plasma current (11 MA) as well, we conclude that this experiment has the potential for reaching the same burning plasma physics objectives of ITER-RC and FEAT, i.e., Q=10. However, this is contingent upon accessing the H-mode ELMy regime, a possibility that might be jeopardized by the absence of a divertor in the Ignitor design.

On the contrary, both the linear dimensions and the plasma current of the case with B=10 T (fourth column) are substantially larger than those of FIRE (a=0.52 m, A=3.8, k=1.8, I_p=6.5 MA) [7]. Consequently, for the latter we reach the opposite conclusion than for Ignitor, i.e., that the scaling law of Eq. (2) will prevent FIRE from reaching Q=10.

Finally, the third columns of Tables 1 and 2 refer to another tokamak option with characteristics in-between those of ITER and Ignitor. Compared to the former, it has a smaller size (by almost a factor of two) and operates at the same level of P_W with lower values of β_N and n_G

The inductive flattop capability of both the ITER-IAM and FEAT designs (300-400 s) should be sufficient for the investigation of current relaxation phenomena on plasma stability and transport. However, the same type of studies could be performed with any of the high field tokamaks considered in this paper if the available volt-seconds are scaled like Ba^2. Indeed, this would make the plasma pulse length to scale like the square of the system linear dimension, i.e., like the plasma skin-time. Of course, this is contingent upon the pulse length (Δ) of the toroidal magnet. If for the latter we consider using cryogenically cooled normal conductor with a pulse length that is inversely proportional to the density of dissipated power ($\propto B^2/R^2$), we can get an estimate of the magnet flattop using the existing engineering designs of Ignitor (Δ=4 s [6]) and FIRE (Δ=20 [7]). For instance, for the 8 T option we get Δ=70 s from Ignitor and Δ=90 s from FIRE, where the discrepancy is caused by the different aspect ratios of the two tokamak designs. The conclusion, then, is that the pulse length of the 8 T option when using cryogenically cooled normal conductors is not far from the value that one gets by scaling the pulse length of ITER as the square of the plasma linear dimension. A nearly identical conclusion was reached in Ref. [8], where similar high field tokamaks were considered as possible alternatives to ITER.

The last exercise in this paper is the scaling of the reference discharge of ITER-FEAT to three ignited tokamaks having the same set of toroidal magnetic fields used in Tables 1 and 2. By constraining the power of the α-particles to be 20% larger than P_{LH}, we obtain the parameters of Table 3.

Throughout this paper we have used q_{95}=3.0, which is the value chosen for ITER. As pointed out several times by the proponents of Ignitor [6], such a low safety factor could result in a large region with q<1, where the confinement of α-particles could be jeopardized by the deleterious effects of internal m=1 plasma instabilities. However, we may increase the safety factor by lowering the aspect ratio and/or increasing the plasma elongation. For instance, in Table 2 we get q_{95}=3.6 (the value used in Ignitor [6]) with a 5% enlargement of the minor radius and by increasing the elongation to 1.8. Fortunately, both changes are beneficial for the energy confinement time (Eq. (2)).

In conclusion, the large values of n_G and β_N that are needed for obtaining an energy gain of 10 in ITER-IAM and FEAT cast serious doubts on the possibility of reaching the programmatic objectives of these experiments. This is a direct consequence of the confinement scaling law that was chosen as the physics basis of these experiments, and the low values of their toroidal magnetic fields. The same scaling law predicts that the plasma linear dimensions and the normalized values of plasma density and beta are all decreasing functions of *B*. Hence, by using a larger toroidal magnetic field than that of ITER, one can operate in a safer plasma regime with a smaller device. Tables 1 and 2 contain three options varying from an aggressive Ignitor-like tokamak with *B*=13 T, to a less technically demanding device with *B*=8 T. The improved operating regime and the smaller plasma size should greatly enhance both the physical and the practical feasibility of these experiments

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TABLE 1. ELMY H-mode scaling of the ITER-RC-IAM reference discharge to three tokamaks with a toroidal magnetic field (*B*) of 8, 10 and 13 T, respectively; values of aspect ratio (*A*), elongation (*k*), triangularity, safety factor (q_{95}) and energy gain (*Q*) are kept constant.

		ITER IAM	MEDIUM B	HIGH B	VERY HIGH B
B	[T]	5.51	8.00	10.0	13.0
T_n	[keV]	10.0	8.0	8.0	7.0
a	[m]	1.90	1.04	0.77	0.50
R	[m]	6.20	3.38	2.50	1.63
A		3.26	3.26	3.26	3.26
k		1.83	1.83	1.83	1.83
β	[%]	2.86	1.84	1.67	1.73
β_p		0.95	0.61	0.55	0.57
β_N		2.25	1.44	1.31	1.36
n_G		0.87	0.55	0.46	0.46
q_{95}		3.0	3.0	3.0	3.0
I_p	[MA]	13.3	10.5	9.7	8.2
E_{TF}	[GJ]	44	15.0	9.5	4.5
Q		10	10	10	10
P_w	[MW/m^2]	0.50	0.50	0.75	1.50
P_f	[MW]	500	148	122	104
P_{LH}	[MW]	48	29	25	21

TABLE 2. ELMY H-mode scaling of the ITER-FEAT reference discharge to three tokamaks with a toroidal magnetic field (*B*) of 8, 10 and 13 T, respectively; values of aspect ratio (*A*), elongation (*k*), triangularity, safety factor (q_{95}**)** and energy gain (*Q*) are kept constant.

		ITER FEAT	MEDIUM B	HIGH B	VERY IGH B
B	[T]	5.30	8.00	10.0	13.0
T_n	[keV]	9.0	8.0	8.0	7.0
a	[m]	2.00	1.09	0.81	0.53
R	[m]	6.20	3.39	2.51	1.63
A		3.10	3.10	3.10	3.10
k		1.70	1.70	1.70	1.70
β	[%]	2.50	1.48	1.35	1.40
β_p		0.67	0.40	0.36	0.37
β_N		1.77	1.05	0.96	0.99
n_G		0.85	0.47	0.39	0.39
q_{95}		3.0	3.0	3.0	3.0
I_p [MA]		15.0	12.4	11.5	9.7
E_{TF}	[GJ]	40	15.0	9.4	4.4
Q		10	10	10	10
P_w	[MW/m^2]	0.50	0.50	0.75	1.50
P_f	[MW]	410	122	100	85
P_{LH}	[MW]	48	28	24	21

TABLE 3. ELMY H-mode scaling of the ITER-FEAT reference discharge to three ignited tokamaks with a toroidal magnetic field (B) of 8, 10 and 13 T, respectively; values of aspect ratio (A), elongation (k), triangularity, and safety factor (q_{95}) are kept constant.

		TOK #1	TOK #2	TOK #3
B	[T]	8.00	10.0	13.0
T_n	[keV]	8.0	8.0	8.0
a	[m]	1.26	0.93	0.65
R	[m]	3.92	2.89	2.02
A		3.10	3.10	3.10
k		1.70	1.70	1.70
β	[%]	1.69	1.62	1.45
β_p		0.45	0.44	0.39
β_N		1.20	1.15	1.03
n_G		0.62	0.55	0.44
q_{95}		3.0	3.0	3.0
I_p	[MA]	14.3	13.2	12.0
E_{TF}	[GJ]	23.0	14.5	8.4
Q		∞	∞	∞
P_w	[MW/m^2]	0.750	1.25	2.00
P_f	[MW]	246	223	175
P_{LH}	[MW]	40	35	29