CONF-781031--28

CONF-881031--28

DE89 002212

TOKAMAK CONFINEMENT PROJECTIONS AND PERFORMANCE GOALS*

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ABSTRACT

One key quantity to be determined in the design of burning-plasma devices (CIT, ITER, reactors, etc.) is the level of plasma current (I) required to meet the desired plasma performance goals (ignition, high Q, etc.) and device objectives (fusion power, wall loading, current drive power, etc.). It is shown that these goals and objectives can be expressed in terms of the "figure-of-merit" parameter IA^{α}/R^{x} [$\sim f(LB^{y})$], where A is the aspect ratio, R is the major radius, L (= R, a) is the characteristic length, B is the toroidal magnetic field on axis, and the exponents $\alpha \sim 1 \pm 0.5$ and $x \sim 0$–0.5 ($y \sim 1$–2) depend on the confinement assumptions and operational limits. To reach ignition or high Q, the main goal is to optimize IA^{α}/R^{x}, subject to other engineering design constraints. In a CIT-like device (with $R \sim 2$ m, $\kappa \sim 2$, $q_{\psi} \geq 3$), the ignition requirement is $I(A/3)^{\alpha} \sim 9$–15 MA for "enhanced" L-mode (H-mode) confinement scaling expressions; an ITER-like device (with $R \sim 5$–6 m, $\kappa \sim 2$, $q_{\psi} \geq 3$) would require $I(A/3)^{\alpha} \sim 15$–25 MA. These requirements are embodied in the present CIT (with $I \sim 11$ MA, $A \sim 3.25$) and ITER (with $I \sim 18$–22, $A \sim 3.1$–2.6) designs.

INTRODUCTION

Energy confinement is a major issue for the next-generation, burning-plasma devices [Compact Ignition Tokamak[1] (CIT), International Thermonuclear Experimental Reactor[2] (ITER), etc.]. The physics of energy transport in tokamaks is not yet fully understood. Therefore, the energy confinement time in these burning-plasma devices has to be estimated from extrapolations of the available experimental data base by using empirically developed scaling expressions[3] as well as scalings derived from various theoretical models[4] for the dominant transport mechanisms. The selection of a particular scaling or transport model has a large impact on the design and parameter choices. Thus, the identification and formulation of "figure-of-merit" parameters such as $Tn\tau_E \propto f(IA^{\alpha}/R^{x}) \propto f(LB^{y})$ are useful in guiding the design efforts to optimize energy confinement and to establish trade-offs between plasma size ($L = a$, R), current (I), field (B), aspect ratio (A), etc. In this paper we formulate these figure-of-merit parameters and assess the confinement capabilities of CIT and ITER.

Unless otherwise stated, all units are mks, with T in keV, I in MA, and power in MW.

PERFORMANCE GOALS AND FIGURES OF MERIT

There are several performance indicators for tokamaks; the level of plasma current (I) is one of the most important because of the favorable scaling of confinement time τ_E and limits on plasma beta β_{crit} and density $\langle n\rangle_{max}$ with increasing I. One key quantity to be determined in the design of CIT and ITER (or any burning-plasma devices) is the rlevel of plasma current equired to meet the desired plasma performance goals ($Tn\tau_E$ – ignition, high$Q$, etc.) and machine objectives (fusion power P_{fus}, wall loading Γ_w, current drive power P_{CD}, etc.).

Here we define a fusion-related parameter

$$T_{10}n_{20}\tau_E = \langle T/10\ \mathrm{keV}\rangle\langle n_e/10^{20}\ \mathrm{m^{-3}}\rangle\tau_E$$

where $\langle n_e\rangle$ is the volume-averaged electron density and $\langle T\rangle$ is the density-weighted average temperature ($T_i \approx T_e \approx T$). The importance of this parameter derives from the fact that, in the temperature range $7 < T < 20$ keV, the D-T fusion reaction rate coefficient $\langle\sigma v\rangle \propto T^2$, and a measure of confinement capability $M \propto P_{\alpha}/P_{loss} \propto T_{10}n_{20}\tau_E$, where P_{α} is the total alpha power and $P_{loss} = P_{cond} + P_{rad}$ is the power lost by conduction and radiation. For

* Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

relatively broad (square-root parabolic density and parabolic temperature) profiles with $Z_{eff} \sim 1.5$ (5% thermal alphas plus carbon and oxygen impurities), the ignition requirement[5] is $T_{10} n_{20} \tau_E \sim 3 \pm 0.3$ for $\langle T \rangle \sim$ 7–20 keV. With a Murakami-Hugill ($n_{mu} \sim 1.5B/Rq_*$) or Greenwald ($n_{gr} \sim 0.27I/a^2$) type limit for density, the Troyon limit for beta [$\beta_{crit} \sim CI/aB$, $C \sim$ (2.5–3)%], and $q_\psi >$ 3–3.5 for MHD stability, the optimum temperature for ignition, is typically ~10 ± 2 keV for many of the confinement scaling models.[3–11]

For a wide range of confinement scaling models of the form τ_{EOH}(neo-Alcator) $\propto nL^3$ and/or τ_{Eaux}(L-/H-mode) $\propto LIf(P)$ with $f(P) \sim P^{-\gamma}$ or $\sim (C_1 + C_2/P)$, $Tn\tau_E \propto f(IA^\alpha/R^x)$. An example of the power law form of τ_E is the Goldston scaling[6]

$$\tau_E = \tau_G = 0.037 I P^{-0.5} R^{1.75} a^{-0.37} \kappa^{0.5} (A_i/1.5)^{0.5}$$
$$T_{10} n_{20} \tau_E = 2.53 \times 10^{-4} (IA^{1.37}/R^{0.12})^2$$

where $A_i \approx 2.5$ is the average atomic mass and $P = W/\tau_E = P_{aux} + P_{OH} + P_\alpha - P_{rad} \approx 9 n_{20} T_{10} R a^2 \kappa / \tau_E$ is the net heating power. An example of the offset linear form is the Rebut-Lallia scaling[10]

$$\tau_E = \tau_{RL} = C_R I l^{1.5} + C_L n_{20}{}^{0.75} I^{0.5} B^{0.5} l^{2.75}/P$$
$$T_{10} n_{20} \tau_E \propto I^3 A^2/R^{0.5} \propto (IA^{0.67}/R^{0.17})^3$$

where $l = (Ra^2\kappa)^{1/3}$, $C_R = (0.024/Z_{eff}{}^{0.5})(A_i/2)^{0.5}$, $C_L = 0.29 Z_{eff}{}^{0.25}(A_i/2)^{0.5}$, and $Tn\tau_E$ is evaluated at the beta limit ($\propto I/aB$).

Table I lists [for a given plasma shape (κ, δ) and q_ψ] the ignition/burn-related plasma performance goals in terms of the figure-of-merit parameter IA^α/R^x for a number of confinement scaling expressions (see Appendix), evaluated at the density ($n \propto I/a^2$) and beta ($\beta \propto I/aB$) limits. Also listed are the scalings of Q, P_{fus}, Γ_w, and P_{CD}. The lower bound on IA^α/R^x, in terms of confinement, is set by the containment of alpha particles ($\alpha = 0.5$, x = 0) and by the irreducible neoclassical transport ($\alpha = 3/8$, x = 0). All of the scalings show a weaker dependence on size (x ~ 0.1–0.5). Power law scalings[3,6–8] (Goldston, Kaye-Goldston, Kaye, T-10, etc.) exhibit a stronger dependence on aspect ratio ($\alpha \sim$ 0.8–1.5) than the offset linear forms[9–11] (Odajima-Shimomura, Rebut-Lallia, etc.), where $\alpha \leq 0.5$. A simple overall average scaling is $\langle\alpha\rangle \sim 1.1$, $\langle x \rangle \sim 0.4$, which can be used as a reasonable measure of confinement capability for designs with $A \sim$ 2.5–4. It should be noted that the results presented here should not be extrapolated to very high aspect ratios because the scaling of confinement with A is one of the most uncertain elements of the present experimental data base.

TABLE I.
Current, Size, and Aspect Ratio Scaling of Confinement Capability
[Evaluated at n or β limit; fixed $\langle T \rangle$ and (q, κ, δ)]

	$Tn\tau_E \sim f[(IA^\alpha/R^x)^z]$	
Confinement scaling[3–11]	At n limit	At β limit
NC Neoclassical	$(IA^{3/8}/R^0)^2$	$(IA^{3/8}/R^0)^2$
NA Neo-Alcator (OH)	$(IA^{1.5}/R^{0.5})^2$	$(IA^{1.25}/R^{0.25})^4$
G Goldston	$(IA^{1.37}/R^{0.12})^2$	$(IA^{1.37}/R^{0.12})^2$
KG Kaye-Goldston	$(IA^{1.32}/R^{0.55})^3$	$(IA^{1.3}/R^{0.5})^{3.2}$
KA Kaye (All)	$(IA^{1.2}/R^{0.68})^{2.5}$	$(IA^{1.2}/R^{0.63})^{2.7}$
KB Kaye (Big)	$(IA^{0.8}/R^{0.56})^{2.5}$	$(IA^{0.82}/R^{0.52})^{2}$
T10 T-10	$(IA^{1.5}/R^{0.5})^{2.53}$	$(IA^{1.44}/R^{0.44})^{2}$
OS Odajima-Shimomura	(IA^0/R^0)	$(IA^{0.5}/R^0)^2$
RL Rebut-Lallia	$(IA^{0.5}/R^{0.25})^2$	$(IA^{0.67}/R^{0.17})^3$
AX ASDEX-H	$(IA/R^{0.56})^2$	$(IA/R^{0.33})^3$
"Simple Average"	$(IA^{1.1}/R^{0.45})^{2.4}$	$(IA^{1.1}/R^{0.34})^{2.8}$
	[$\langle\alpha\rangle \sim 1.1$; $\langle x \rangle \sim 0.4$; $\langle z \rangle \sim 2.5$	
Q Energy gain factor	$(IA/R^0)^0$	$(IA/R^0)^{1.0}$
Γ_w Wall loading	$(IA^{1.5}/R^{1.5})^2$	$(IA^{1.25}/R^{0.75})^4$
P_{fus} Fusion power	$(IA/R^{0.5})^2$	$(IA/R^{0.25})^4$
P_{CD} Current drive power	$(IA/R^{0.5})^2$	$(IA/R^{0.33})^3$

As an example, with $n \approx n_{mu}$ and $\langle T \rangle \approx$ 10 keV, Fig. 1 shows the normalized current [$I(A/3)^\alpha$] needed for ignition as a function of plasma size (R or a) for some of the confinement scalings given in Table I for fixed plasma shape ($\kappa = 2$, $\delta = 0.4$) and safety factor ($q_\psi \approx$ 3–3.5). Because the neo-Alcator (NA) scaling represents an upper limit to confinement, in Fig. 1 we have used a combined form for τ_E, taken as $\tau_E = [(\tau_{NA})^2 + (\tau_{aux})^2]^{-1/2}$, where aux = G, KG, etc. It is also possible to consider τ_E = min(τ_{NA}; τ_{aux}). Results from detailed analysis (and Fig. 1) indicate that, for a CIT-size device (with $R \sim$ 2 m) the ignition requirement is $I(A/3)^\alpha \sim$ 9–15 MA for enhanced-L or H-mode scalings, where τ_E(H-mode) = $f \times \tau_E$(L-mode) with an enhancement factor $f \geq$ 1.4–2. For an ITER-size device (with $R \sim$ 5–6 m), $I(A/3)^\alpha \sim$ 15–25 MA is required for ignition. A similar-size ITER with noninductive current drive and a wall loading of $\Gamma_w \sim 1$ MW/m^2 would require $I(A/3) \sim$ 14–17 MA, in which $Q \sim$ 5–10 operation is possible for various current drive schemes[12] (with varying bootstrap contribution, 0–30%) requiring $P_{CD} \sim$ 75–150 MW of absorbed power.

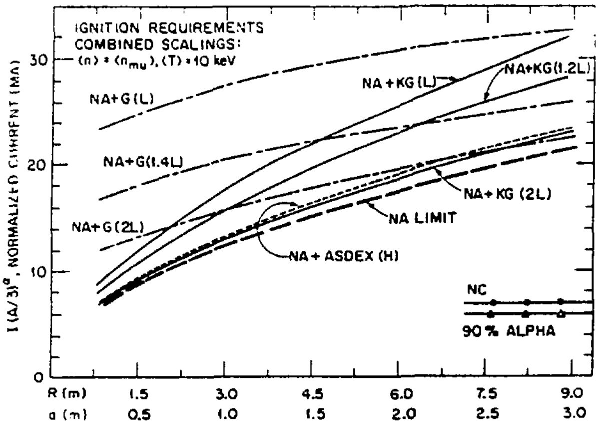

Fig. 1. Plasma current $[I(A/3)^{\alpha}]$ required for ignition vs size (R, a) for various confinement scalings (combined with neo-Alcator) for fixed plasma shape ($\kappa = 2$, $\delta = 0.4$) and $q_{\psi} \approx 3$–3.5, evaluated at ($\sim n_{mu}$, ~10 keV) (see Table I for notations).

3. CONFINEMENT PROJECTIONS

A detailed assessment of confinement projections for CIT and ITER has been carried out. The evaluation was based mainly on consideration of various empirical scaling expressions deduced from experiments, although theoretical models were also considered. Table II lists the representative device parameters for CIT and several ITER options and compares the confinement capabilities in terms of the figure of merit IA^{α}/R^{x}. In Table II, the three ITER options represent the range of machines studied by the ITER design team at Garching.[2] ITER-0 (5.8 m, 20 MA) is the machine initially used to scope out physics and engineering issues. Recently, the ITER design team picked a machine with two operating phases: technology phase (ITER-1: 5.5 m, 18 MA) and physics phase (ITER-2: 5.8 m, 22–25MA). Although there are slight differences in physics design guidelines and assumptions for CIT and ITER, for comparison purposes and uniformity we use a common set of physics assumptions ($Z_{eff} \approx 1.5$ with $n_{\alpha}/n_e \approx 5\%$, $\beta_{crit} \sim 3I/aB$, etc.).

As seen from Table II, all ITER versions have comparable performance, except for extended capability in the physics phase (ITER-2 with 25 MA) in which the performance is better. Here the performance is measured by relative magnitudes of the figure-of-merit parameter (IA^{α}/R^{x}). On the average, CIT and ITER confinement capabilities are also comparable; however, there are marked differences with respect to power law and offset linear forms of scalings. For the offset linear form (Rebut-Lallia, Odajima-Shimomura, etc.), performance is better in ITER (by as much as 50%) than in CIT. With Kaye-type scalings[3,7] (IA^{α}/R^{x} with $\alpha \sim 0.8$–1.3, $x \sim 0.5$), CIT exhibits a slightly better performance; large current in ITER is balanced with compact size and somewhat higher A in CIT. With the Goldston scaling, ITER performs better due to large current and weak size scaling.

Table II.
Representative CIT and ITER Parameters and Confinement Capabilities

Design Parameters[1,2]

	CIT	ITER-0	ITER-1	ITER-2
R (m)	2.1	5.8	5.5	5.8
a (m)	0.65	2.0	1.8	2.2
$A = R/a$	3.25	2.9	3.1	2.6
κ (at 95% flux)	2	2	1.9	1.9
δ (at 95% flux)	0.4	0.4	0.4	0.4
B (T)	10	5.1	5.3	5.0
I (MA)	11	20	18	22–25

Calculated Parameters and Confinement Capability

	CIT	ITER-0	ITER-1	ITER-2
q_* (at 95%)	2.7	2.6	2.4	2.6–2.3
q_{ψ} (at 95%)	3.2	3.2	2.85	3.2–2.9
Troyon beta limit (%)				
$\beta_{crit} = 3I/aB$	5.1	5.9	5.65	6–6.8
$= 2.5I/aB$	4.2	4.9	4.7	5–5.7
Density limit (10^{20} m^{-3})				
$\langle n_{mu}\rangle \approx 1.5B/Rq_*$	2.6	0.5	0.6	0.5–0.6
$\langle n_{gr}\rangle \approx 0.27I/a^2$	7.0	1.35	1.5	1.2–1.4
$\langle n(\text{at } \beta_{crit}, 10\text{ keV})\rangle$	5.9	1.8	1.85	1.7–2.0
Figure of merit (at β limit)				
<Average>: $IA^{1.1}/R^{0.34}$	31	35.5	34.5	35–40
G: $IA^{1.37}/R^{0.12}$	50.5	69.5	68	67–76
KG: $IA^{1.3}/R^{0.5}$	35	33	33	32–37
KA: $IA^{1.2}/R^{0.63}$	28	24	23.5	23–26
KB: $IA^{0.82}/R^{0.52}$	19.5	19	18.5	19–22
RL: $IA^{0.67}/R^{0.17}$	21	30	28.5	31–35
OS: $IA^{0.5}/R^{0}$	20	34	31	36–41

Table III summarizes the CIT and ITER ignition requirements for various scaling expressions. Given in the table are the minimum L-mode enhancement factors needed for ignition, evaluated at the beta limit (and $T \sim 10$ keV) assuming broad profiles and $Z_{eff} \approx 1.5$ with $n_{\alpha}/n_e \approx 5\%$. For CIT, the predictions with Goldston and Odajima-Shimomura scalings are the most pessimistic ($f \sim 2.1$–2.3), followed by the recent Kaye ("all" and "big") scalings[3] ($f \sim 1.8$–1.9). Ignition with L-mode is nearly accessible with the optimistic Rebut-Lallia scaling ($f \sim 1.1$). For ITER, the most pessimistic performance is with the recent Kaye (all and big) scaling expressions ($f \sim 1.9$–2.3), whereas the best performance is with the offset linear forms (Rebut-Lallia ignites with L-mode and Odajima-Shimomura requires $f \sim 1.2$–1.5). Projections with the T-10 scaling are uniform across the board, $f \sim 1.6$ for both CIT and the ITERs.

Table III.
CIT and ITER Ignition Capability:
L-mode Enhancement Factor (f) Needed for Ignition
for Various Confinement Scalings[3–11]
(Evaluated at Beta Limit $\beta \sim 3I/aB$ %, fixed T)[a]

	Confinement scaling	CIT 11 MA	ITER-0 20 MA	ITER-1 18 MA	ITER-2 22 MA
NA	Neo-Alcator	Ignited	Ignited	Ignited	Ignited
AX	ASDEX-H	Ignited	Ignited	Ignited	Ignited
G	Goldston	>2.1	>1.6	>1.6	>1.6
KA	Kaye ("all")	>1.8	>2.3	>2.3	>2.3
KB	Kaye ("big")	>1.9	>2	>2	>1.9
T-10	T-10	>1.6	>1.6	>1.6	>1.6
OS	Odajima-Shimomura	>2.4	>1.3	>1.5	>1.2
RL	Rebut-Lallia	>1.1	Ignited	Ignited	Ignited

[a] $\tau_E = \min(\tau_{NA}; \tau_{aux})$, aux = G, KA, KB, T-10, OS, RL

For the most part, attainment of ignition in both CIT and ITER relies mostly on the attainment of an enhancement (H-mode) over the L-mode confinement. With marginal or poor confinement (i.e., saturated ohmic and most L-mode scalings), ignition probability is very low and access to high-Q operation depends sensitively on the available auxiliary power (P_{aux}), which may be too large to be practical. The minimum auxiliary power requirement is obtained from the saddle point (n_*,T_*) equation. For a confinement model of the form $\tau_E \sim n^x T^y f$(others), where f(others) contains the dependence of τ_E on parameters other than n and T, the saddle point equation is[5]

$$[(1 + x)/2]P_{cond} = P_{aux} + P_{OH}$$
$$[(1 - x)/2]P_{cond} = P_\alpha + P_{rad}$$
$$(1 - y)P_{cond} = 2\,P_\alpha - 1.5\,P_{OH} - 0.5\,P_{rad}$$

where $<\sigma v> \sim T^2$ is assumed (valid for $T \sim$ 7–20 keV). Solutions to these equations give the density and temperature at the saddle point (n_*,T_*) and the required minimum P_{aux}(max). The simplest, although one of the more pessimistic, of the examples is one with τ_E = constant (i.e., x = y = 0). For reference density and temperature profiles (α_n = 0.5 and α_T = 1.0),

$$\min P_{aux}(n_*,T_*) \approx (s_1/\tau_E - s_2)V\ (\mathrm{MW})$$
$$\beta(n_*,T_*) \approx 1.68 s_1/B^2$$

where V is the plasma volume, $s_1 \approx 5.6 \times 10^{-2}(I/\kappa a^2)$, and $s_2 \approx 0.85 s_1^2$.

The ignition capability can be significantly improved with centrally peaked density and heat deposition profiles. A centrally peaked density profile leads to an enhanced fusion rate and therefore a greater margin against confinement losses. Although it may be possible to maintain peak profiles transiently in CIT (which operates for short pulses), attainment and sustainment of such peaked profiles over longer periods in ITER-like (long-pulse, steady-state) plasmas may not be compatible with the MHD stability and H-mode-like conditions needed for good confinement.

APPENDIX

Confinement Scaling Expressions

1. Neo-Alcator (NA) OH scaling:

$$\tau_{NA} = 0.07 n_{20} a R^2 q_*$$
$$q_* \approx (5a^2 B/RI)[1 + \kappa^2(1 + 2\delta^2 - 1.2\delta^3)]/2$$

2. Goldston (G) L-mode scaling:[6]

$$\tau_G = 0.037 I P^{-0.5} R^{1.75} a^{-0.37} \kappa^{0.5} (A_i/1.5)^{0.5}$$

3. Kaye-Goldston (KG) L-mode scaling:[7]

$$\tau_{KG} = C_{KG} I^{1.24} P^{-0.58} R^{1.65} a^{-0.49} \kappa^{0.28} n_{20}^{0.26} B^{-0.09}$$
$$C_{KG} = 0.055(A_i/1.5)^{0.5}$$

4. Kaye "all" (KA) L-mode scaling:[3]

$$\tau_{KA} = 0.067 I^{0.85} P^{-0.5} R^{0.85} a^{0.3} \kappa^{0.25} n_{20}^{0.1} B^{0.3} A_i^{0.5}$$

5. Kaye "big" (KB) L-mode scaling:[3]

$$\tau_{KB} = 0.105 I^{0.85} P^{-0.5} R^{0.5} a^{0.8} \kappa^{0.25} n_{20}^{0.1} B^{0.3} A_i^{0.5}$$

6. T-10 L-mode scaling:[8]

$$\tau_{T\text{-}10} \approx 0.095 aRB\kappa^{0.5} P^{-0.4} [Z_{eff}^2 I^4/(aRq_*^3 \kappa^{1.5})]^{0.08}$$

7. Odajima-Shimomura or JAERI (OS) L-mode scaling:[9]

$$\tau_{OS} = C_O \kappa a^2 + C_S I n_{20}^{0.6} B^{0.2} R^{1.6} a^{0.4} \kappa^{0.2}/P$$
$$C_O = 0.085 A_i^{0.5}$$
$$C_S = 0.069 G(q_*, Z_{eff}) A_i^{0.5}$$
$$G(q_*, Z_{eff}) = g(q_*) h(Z_{eff})$$
$$g(q_*) = [3q_*(q_* + 5)/(q_* + 2)(q_* + 7)]^{0.6}$$
$$h(Z_{eff}) = Z_{eff}^{0.4}[(15 - Z_{eff})/20]^{0.6}$$

Rebut-Lallia (RL) L-mode scaling:[10]

$$\tau_{RL} = C_R l I^{1.5} + C_L n_{20}^{0.75} I^{0.5} B^{0.5} l^{2.75}/P$$
$$l = (Ra^2\kappa)^{1/3}$$
$$C_R = (0.024/Z_{eff}^{0.5})(A_i/2)^{0.5}$$
$$C_L = 0.29 Z_{eff}^{0.25}(A_i/2)^{0.5}$$

9. ASDEX (AX) H-mode scaling:[11]

$$\tau_{AXH} = 0.1 I\, R$$

In all expressions, the units are mks with currents in MA, powers in MW, temperatures in keV, with κ and δ at 95% flux and

n_{20} $= \langle n_e \rangle / 10^{20}\ \mathrm{m}^{-3}$
= volume-averaged electron density,
T_{10} $= \langle T \rangle / 10$ keV
= density-weighted average temperature,
q_ψ $\approx q_* f(\varepsilon) \approx q_* [(1.77 - 0.65\varepsilon)/(1 - \varepsilon^2)^2]$; $\varepsilon = a/R$
= MHD safety factor,
A_i = average atomic mass $\approx$ 2.5 for a 50:50 D-T plasma,
Z_{eff} = effective charge $\approx$ 1.5 (assumed for this study),
P $= W/\tau_E = 0.24\, n_{20}\, T_{10}\, (1 + n_i/n_e)\, V/\tau_E$
$= P_{aux} + P_{OH} + P_\alpha - P_{rad}$
= net "heating" power.

Profiles: $n,T \sim (1 - r^2/a^2)^{\alpha_{n,T}}$, $\alpha_n = 0.5$ and $\alpha_T = 1.0$.

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