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ITER CONFINEMENT CAPABILITY*

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ABSTRACT

The confinement capability of ITER was examined for a number of operational scenarios. The reference ITER physics baseline scenario ($I = 22$ MA) allows ignited burn under H-mode conditions [$\tau_E(\text{H-mode}) \sim 2 \times \tau_E(\text{L-mode})$]. At higher currents ($I = 25\text{--}28$ MA) at which ITER can operate for limited pulse duration, there is an increased ignition margin if low-q operation proves acceptable. About a factor of 2 reduction in helium ash concentration (from the baseline value of 10% to 5%) in the reference ITER scenario has about the same impact on ignition capability as increasing the plasma current by about 15% (from the baseline value of 22 MA to ≥ 25 MA). It might be possible to further optimize the ignition capability of ITER if some of the limits on operational boundaries can be relaxed by tailoring plasma profiles.

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INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) design is discussed in detail in Refs. [1,2]. The confinement capability of ITER physics and technology phase plasmas has been examined for a number of operational scenarios, using the ITER physics design guidelines [3,4]. Representative device and plasma parameters are given in Table I. A brief summary of the physics guidelines related to confinement assessments is given in the Appendix. The sensitivity of ITER performance to changes in these guidelines was investigated. Confinement scaling expressions deduced from the ITER L-mode [5] and H-mode [6] databases were used to project the ITER baseline performance. The effects of adjustments in density and temperature (pressure) profiles that can be realized from various fueling and heating scenarios (subject to sawtooth and MHD stability considerations), changes in operational boundaries, impurity and helium concentrations, allowable fusion power (P_{fusion}), predictions from other confinement scaling expressions, etc., have been considered.

CONFINEMENT PROJECTIONS

Required τ_E for Ignition and High Q

A measure of performance can be expressed as $M = P_\alpha/P_{\text{loss}} \propto T_i(0)n_{DT}(0)\tau_E \propto \beta B^2\tau_E$ [where P_α is the total alpha power, $P_{\text{loss}} = P_{\text{cond}} + P_{\text{rad}}$ is the power lost by conduction and radiation, $T_i(0)$ is the central ion temperature, $n_{DT}(0)$ is the central DT fuel ion density, τ_E is the global energy confinement time, β is the plasma beta, and B is the magnetic field]. Achievement of ITER objectives ($Q \sim 5\text{--}\infty$) will require a confinement capability of $T_i(0)n_{DT}(0)\tau_E \sim (4\text{--}8) \times 10^{21} \text{ keV}\cdot\text{s}/\text{m}^3$. (This $Tn\tau_E$ requirement is about ten times the highest value achieved in JET.) In addition, $\tau_p^{\text{He}}/\tau_E < 10$ is required to ensure that the thermal alpha-particle (He) accumulation (n_{He}/n_e) is less than 10% (where τ_p^{He} is the global thermal alpha particle containment time). These requirements are apparent from simple (steady-state) considerations of energy and particle balance equations. For profiles of the form $n, T \sim (1 - r^2/a^2)^{\alpha_n, \alpha_T}$ (nominal ITER profiles are $\alpha_p = \alpha_n + \alpha_T \approx 1.5$ with $\alpha_n \approx 0.5, \alpha_T \approx 1.0$):

$$T_{10} n_{DT20} \tau_E \approx 3 h_1 (\alpha_{n,T}) / \zeta \quad (1)$$

$$n_{He}/n_e \approx (\tau_p^{He}/\tau_E) (3T/E_\alpha) [(n_{DT}/n_e)/\zeta] \quad (2)$$

$$\begin{aligned} \zeta &= (1 + 5/Q - P_{rad}/P_\alpha) [2(n_{DT}/n_e)/(1 + n_i/n_e)] \\ &\approx [1 + 5/Q - 0.1 Z_{eff} h_2 (\alpha_{n,T}) / (n_{DT}/n_e)^2] \\ &\quad \times [2(n_{DT}/n_e)/(1 + n_i/n_e)] \end{aligned} \quad (3)$$

where $n_{DT20} = \langle n_{DT}/10^{20} \text{ m}^{-3} \rangle$ is the volume-average DT density, $T_{10} = \langle T/10 \text{ keV} \rangle$ is the density-weighted average temperature ($T_e \approx T_i \approx T$), $h_1 = (1 + 2\alpha_p)/(1 + \alpha_p)^2$, $h_2 \approx [(1 + \alpha_n)/(1 + \alpha_p)]^{1.5} [(1 + 2\alpha_p)/(1 + 2\alpha_n + 0.5\alpha_T)]$, $n_{DT}/n_e = (n_D + n_T)/n_e$, $n_i/n_e = (n_D + n_T + n_{He} + \sum_Z n_Z)/n_e = 1 - n_{He}/n_e - \sum_Z (Z-1)(n_Z/n_e)$, $E_\alpha = 3.5 \text{ MeV}$ with (typically) $\tau_p^{He}/\tau_p^{DT} \sim 1-3$. For representative ITER parameters with nominal profiles and impurity levels (see Table I), τ_E needed for ignition (or high-Q), at 1 MW/m^2 , is roughly given by

$$\tau_E(\text{needed}) \sim 3.6 \times [0.76/(0.76 + 5/Q)].$$

Database: ITER L- and H-Mode τ_E Scalings

The ITER concept is based on the expectation that H-mode confinement can be achieved for a long pulse. Recent work at ITER has concentrated on developing improved analysis and characterization of energy confinement in L- and H-mode discharges [5,6]. Detailed analysis of these databases resulted in the following reference ITER energy confinement scaling expressions.

- ITER L-mode power-law (ITER89-P) scaling [5]:

$$\begin{aligned} \tau_E^{\text{ITER89-P(L-mode)}} &= 0.048 I^{0.85} R^{1.2} a^{0.3} \bar{n}_{20}^{0.1} B^{0.2} (A_i \kappa_X / P)^{0.5} \end{aligned} \quad (4)$$

- ITER H-mode scaling (from a preliminary analysis of the ITER H-mode data for ELM-free discharges) [6]:

$$\begin{aligned} \tau_E^{\text{ITER90(ELM-free H-mode)}} &= 0.064 I^{0.87} R^{1.81} a^{0.13} \bar{n}_{20}^{0.09} B^{0.15} A_i^{0.5} \kappa_X^{0.36} P^{-0.51} \end{aligned} \quad (5)$$

where the notation is standard and the units are mks, MA, and MW with A_i = isotopic mass number (= 2.5 for DT plasma), $\bar{n}_{20}$ = line-averaged electron density in units of 10^{20} m^{-3} , κ_X = elongation at the X-point, and P = net heating power (in MW). A comparison of the ITER H-mode database with several L-mode scaling expressions (ITER89-P, Goldston, Rebut-Lallia, Odajima-Shimomura, Kaye-Big, etc.) exhibits a factor of ~ 2 improvement over the L-mode

expressions, $\tau_E(\text{H-mode}) \sim 2 \times \tau_E(\text{L-mode})$. [However, specific improvement factors corresponding to each L-mode scaling vary somewhat. For example, for the Goldston scaling, this factor is ~ 1.6 , possibly due to the fact that improvement in confinement with aspect ratio (R/a) in the database is not as strong as indicated by the Goldston expression. For the Rebut-Lallia scaling this factor is ~ 2.4 .]

H-mode operation is usually accompanied by MHD oscillations in the outer plasma layers (edge localized modes, ELMs). While large-amplitude ELMs can destroy the good confinement of the H-mode, small-amplitude ELMs lead to only a limited degradation of the energy and particle confinement allowing steady-state H-mode operation: typically $\tau_E(\text{ELMy H-mode}) \sim 0.75 \times \tau_E(\text{ELM-free H-mode})$

ITER BASELINE PERFORMANCE

For reference ITER physics baseline parameters ($I = 22$ MA, $B = 4.85$ T, $a = 2.15$ m, $R = 6$ m, $\kappa_x = 2.22$, and $P = P_{\text{net-heat}} \approx P_\alpha + P_{\text{aux}} - P_{\text{rad}} \sim 160$ MW) at $P_{\text{fusion}} \sim 1$ GW, the ITER L- and H-mode scaling expressions predict $\tau_E(\text{ITER89-P L-mode}) \sim 1.9$ s and $\tau_E(\text{ITER90 ELM-free H-mode}) \sim 5.5$ s [$\tau_E(\text{ELMy H-mode}) \sim 4.1$ s], as compared to $\tau_E(\text{needed}) \sim 3.6$ s (see Table I). Note that the H-mode scaling provides a modest margin over the requirements for ignition, and the factor of ~ 2 improvement needed over the ITER89-P L-mode scaling is within the present experimental database. Figure 1 shows the ignition requirements of the ITER physics baseline device (at 1 MW/m^2) for various confinement scalings. Shown in the figure are the minimum L-mode enhancement factors needed for ignition [$\tau_E(\text{needed}) = f \times \tau_E(\text{L-mode scaling})$] for 5% and 10% helium concentrations. For the most part, confinement enhancement factors for a variety of L-mode scalings are ~ 1.5 – 2 (except $f \geq 2$ for Kaye-Big and T-10 and $f \leq 1.5$ for Rebut-Lallia) for the 22-MA baseline scenario. The differences in enhancement factors needed are consistent with the comparison of these scalings with the H-mode database discussed earlier.

At higher currents ($I = 25$ – 28 MA) at which ITER can operate for limited pulse duration, there is an increased ignition margin if low- q operation proves acceptable. This is illustrated in Fig. 2 for nominal profiles ($\alpha_n = 0.5$, $\alpha_T = 1.0$) and impurity content (see the Appendix) with $n_{\text{He}}/n_e = 0$ – 10% . Figure 2 shows the ITER ignition capability (at nominal 1 MW/m^2) for a wide range of plasma currents ($I \sim 16$ – 28 MA, $q_\psi \sim 4.2$ – 2.4) for the reference ITER L- and

ELM-free H-mode scaling expressions. During the approach to ignition (for short-pulse duration), where $n_{He}/n_e \sim 0-5\%$, the required L-mode enhancement factor is $f < 1.5$ for $I \geq 22$ MA. For the ELM-free phase of the H-mode, ignition is predicted for plasma currents as low as 16 MA (with 10% He and $Z_{eff} \sim 1.7$).

The ITER technology phase accommodates several operational scenarios (ranging from long-pulse to steady-state) with $Q \geq 5$ and $I \approx 15-22$ MA. Access to high- Q operation depends sensitively on the MHD beta limits, current drive efficiency, bootstrap current fraction, and energy confinement (see Ref. [7] for detailed discussions on operational scenarios and technology phase performance).

SENSITIVITY OF ITER PERFORMANCE

High- Q Capability

Confinement needs are relaxed if ignition is not a requirement [see Eq. (1)]. For the ITER physics baseline device (22 MA, reference profiles, $Z_{eff} \sim 1.7$ with 10% He), the L-mode enhancement factors needed at various Q values (evaluated at 1 MW/m²) for the ITER89-P scaling can be estimated from

$$f \sim 1.9 \times [0.76/(0.76 + 5/Q)]^{0.5}$$

For example, at $Q = 10$ (which requires ~ 110 MW of auxiliary power), the needed confinement enhancement factor over the L-mode expression is $f(Q=10) \sim 1.5$, significantly lower than that required for ignition, $f(Q \rightarrow \infty) \sim 1.9$. For a short pulse duration ($n_{He}/n_e \sim 0\%$), $Q \sim 8-10$ appears to be accessible with L-mode. Although confinement requirements for high- Q operation of physics baseline scenarios are favorable, the divertor heat loads increase substantially [1,7].

Performance at Various Troyon g-Factors, Wall Loadings, or Fusion Powers

In the ITER physics baseline, the required MHD-stable beta to produce $P_{fusion} \sim 1100$ MW (neutron wall loading $L_{wn} \sim 1$ MW/m²) is $\sim 4.2\%$, corresponding to the Troyon g-factor $g_{Troyon} = \beta(\%)/(I/aB) \sim 2$. The ITER design supports operation at higher fusion power (~ 2 GW) or higher wall loading for short burn pulses corresponding to $g_{max} \sim 3$, as specified by the guidelines (see the appendix.). For most power law scalings with $\tau_E \sim P^{-0.5}$ (ITER-P, Goldston, etc.), enhancement factors required for ignition are nearly

insensitive to the assumption of g-factor (or P_{fus} , $L_{wn} \sim \beta^2 \sim g^2$), because $Tn\tau_E \sim \tau_E P^2 \sim \tau_E L_{wn}^2 \sim \text{const}$) is independent of beta. For $\tau_E \sim n^0 P^{-\alpha}$ with $\alpha < 0.5$, there is a slight reduction in the required L-mode enhancement factor f with increasing g ; f varies roughly as $g^{-(1-2\alpha)}$ (or as $L_{wn}^{-[(1-2\alpha)/2]}$). For offset linear forms ($\tau_E \sim \tau_{inc} + W_{OH}/P$), confinement capability improves at higher beta (i.e., at higher density for fixed T). In the limit of high power ($\tau_E \sim \tau_{inc}$), the enhancement factor f needed for ignition varies inversely with beta (Troyon g-factor). Contributions from the W_{OH}/P term, especially at low power levels (low g-factor), alter this variation somewhat.

Sensitivity to Plasma Current and He Content

The sensitivity of ITER ignition capability to plasma current is illustrated in Fig. 2 for reference plasma profiles. For nominal impurity and thermal alpha (10% He) levels, the L-mode enhancement factors needed for ignition (evaluated at 1 MW/m²) for the ITER89-P scaling can be estimated from $f \sim 1.9 \times [22/I \text{ (MA)}]^{0.85}$. The impact of He concentration on required plasma current (for fixed f) or on required confinement enhancement factor (for fixed I) is also evident in Fig. 2. From Eqs. (1)–(4), this can be approximated as

$$f \times I^{0.85} \sim 26.3 [0.7(1 + n_i/n_e)/(n_{DT}/n_e)^{0.9}] \times [1 - 0.075 Z_{eff}/(n_{DT}/n_e)^2]^{-0.5}$$

Figure 3 shows the trade-off between the plasma current and fuel dilution due to varying levels of He ash. The curve in Fig. 3 is normalized to the ITER baseline performance as projected by the ITER89-P scaling ($I = 22 \text{ MA}$, $f \sim 1.9$, $n_{He}/n_e \sim 10\%$, $Z_{eff} \sim 1.7$ at 1 MW/m²).

Profile Effects

It might be possible to optimize the ignition capability of ITER if some of the limits on operational boundaries can be relaxed by adjusting plasma profiles, provided that the MHD stability and favorable H-mode confinement properties can be maintained. For example, the peaking of the density profile (e.g., from nominal square-root parabolic form to square of parabolic) in the reference ITER scenario, if assumed to be possible at constant Troyon coefficient [$g = \beta(\%)/(I/aB)$] and without deleterious effects on divertor operation, has about the same impact as lowering the helium ash concentration by about a factor of 2 (from the baseline value of 10% to 5%) or increasing the plasma current by about 15% (from the baseline value of 22 MA to $\geq 25 \text{ MA}$).

It is well known that a centrally peaked density profile leads to an enhanced fusion rate (at fixed beta) and therefore decreased ignition (τ_E) requirements. To lowest order, neglecting radiation losses in Eq. (1), in the temperature regime where $\langle \sigma v \rangle \propto T^2$, the reduction in required τ_E for ignition is $\tau_E/\tau_E(\alpha=0) \propto h_1 \propto (1+2\alpha_p)/(1+\alpha_p)^2$, where $\alpha_p = \alpha_n + \alpha_T$. Also, operation in regimes with peaked density (n_e) profiles has been found to exhibit significantly improved energy confinement than that observed in standard L-mode tokamak operation with broad n_e profiles. The improvement in τ_E is noted to be $\tau_E/\tau_E(0) \propto n_e(0)/\langle n_e \rangle \propto h_\tau(\alpha_n) \propto (1+\alpha_n)$. An additional improvement in confinement can also be expected owing to the intrinsically peaked energy deposition profile associated with the fusion alpha-particle heating. Note that the attainment of centrally peaked density profiles for ITER is highly speculative because relatively deep fueling (in the absence of a strong inward pinch) is required to significantly influence the density profile shape. Also, MHD stability calculations with peaked pressure profiles (and low central shear) show decline in the Troyon g-factor (as discussed in Refs. [8,9]), thus offsetting some (or all) of the mentioned improvements. To lowest order, the combined effects of enhanced fusion rate, possible confinement improvement, and degradation in MHD stability with peaked profiles can be approximated as

$$\tau_E \sim \tau_{E0} \times [h_1(\alpha_p)h_\tau(\alpha_n)/h_\beta(\alpha_p)]$$

where

$$\tau_E(\alpha_p=0) = \tau_{E0} \propto f(I, a, R, B, Z_{eff}, \dots)$$

$$h_1(\alpha_p) \propto (1+2\alpha_p)/(1+\alpha_p)^2$$

$$h_\tau(\alpha_n) \propto \chi(\alpha_n=0)/\chi(\alpha_n) \propto \tau_E(\alpha_n)/\tau_E(\alpha_n=0) \propto (1+\alpha_n)$$

$$h_\beta(\alpha_p) \propto \beta(\alpha_p)/\beta(\alpha_p=0) \propto g(\alpha_p)/g(\alpha_p=0)$$

$$\propto [1 - (\alpha_p/4)^2]^2$$

for fully optimized MHD
profiles with small l_i (< 0.65)

Note that the expression given for $h_\beta(\alpha_p)$ is an approximate fit to detailed calculations reported in Refs. [8,9] for cases with central safety factor $q(0) \sim 1$. Figure 4 illustrates the overall effect of profile peaking on required τ_E for ignition in the 22-MA physics baseline device for fully optimized MHD profiles. There is a broad optimum near the ITER profile guidelines ($\alpha_p \sim 1.5-2$); however, current profile control with $l_i < 0.7$ is recommended [8].

TABLE I
Representative ITER Physics Baseline Parameters

Plasma current, I (MA)	22
I (MA) for short pulse	(up to 25–28)
Magnetic field, B (T)	4.85
Elongation/triangularity κ/δ (at 95% flux)	1.98/0.39
κ/δ (at X-point)	(2.22/0.58)
Safety factor, q_ψ (95%)	3.1
Helium concentration, n_{He}/n_e (%)	10
n_{He}/n_e (%) for short pulse	(0–5)
Effective charge, Z_{eff}	1.7
Nominal fusion power, P_{fus} (MW)	~1100
Nominal neutron wall load, L_{wn} (MW/m ²)	1.0
Electron density, $\langle n_e \rangle$ (10 ²⁰ m ⁻³)	1.23
D-T density, $\langle n_{DT} \rangle$ (10 ²⁰ m ⁻³)	0.9
Temperature, $\langle T_e \rangle = \langle T_i \rangle$ (keV)	10
Total plasma beta (average), β (%)	4.2
$g_{Troyon} = \beta(\%)/(I/aB)$	~2
Internal inductance, $l_i(3)$	0.65
Nominal plasma profiles, α_n/α_T	0.5/1.0
Needed for ignition:	
$T_i(0)n_{DT}(0)\tau_E$ (10 ²¹ keV s/m ⁻³)	8.5
[average $T_{10}n_{e20}\tau_E$	4.3]
τ_E (needed)	~3.6
Predictions of ITER τ_E scalings:	
τ_E (ITER-P L-mode) (s)	~1.9
τ_E (ITER ELM-free H-mode) (s)	~5.5
τ_E (ELMy H-mode) (s)	~4.1

APPENDIX

ITER Confinement-Related Physics Guidelines [3,4]

Units are mks, MA, MW, with $n_{20} = \langle n_e / 10^{20} \text{ m}^{-3} \rangle =$ volume-average electron density and $T_{10} = \langle T / 10 \text{ keV} \rangle =$ density-weighted average temperature ($T_e = T_i = T$). Where appropriate, one of two rules (x | y) may apply, referring to ("baseline performance" | "extended performance")

- Energy confinement:
 - $I \geq 22 \text{ MA}$ for ignited operation in H-mode
 - with $\tau_E(\text{required}) \leq \tau_E(\text{H-mode})$
 - $\sim 2 \times \tau_E^{\text{ITER89-P(L-mode)}}$
- ITER (89) L-mode confinement scaling [5]:
 - ITER89-power law scaling:
 - $\tau_E^{\text{ITER89-P}} = 0.048 I^{0.85} R^{1.2} a^{0.3} n_{20}^{0.1} B^{0.2} (A_i \kappa_x / P)^{0.5}$
 - where $A_i = 2.5$ (isotopic mass), $\kappa_x = \kappa(\text{at X-point})$, and $P =$ net heating power.
- ITER (90) H-mode confinement scaling [6]:
 - Typically, $\tau_E(\text{H-mode}) \sim 2 \times \tau_E^{\text{ITER89-P(L-mode)}}$
 - ITER90 H-mode scaling (preliminary):
 - $\tau_E^{\text{ITER90-H (ELM-free)}}$
 - $= 0.064 I^{0.87} R^{1.81} a^{0.13} n_{20}^{0.09} B^{0.15} A_i^{0.5} \kappa_x^{0.36} P^{-0.51}$
 - $\tau_E(\text{ELMy H-mode}) \sim 0.75 \times \tau_E(\text{ELM free H-mode})$
- Beta limit: $\beta_{\text{max}}(\%) = gI/aB$
 - $g \leq 2.5 \quad | \quad 3.0$ for ignition studies
 - $g \leq 3.0 \quad | \quad 3.3$ for steady-state operation
- Safety factor: $q_\psi(95\%)$
 - $q_\psi(95\%) \geq 3.0 \quad | \quad 2.1$ for $\kappa(95\%) < 2$
 - $q_\psi(95\%) \geq 3.0 \quad | \quad 3.0$ for $\kappa(95\%) \sim 2$ to 2.5
- Z_{eff} : impurity and thermal alpha fractions ($f_j = n_j/n_e$)
 - $f_{\text{DT}} = 1 - 2f_{\text{He}} - 6f_{\text{C}} - 8f_{\text{O}} - 26f_{\text{Fe}}$ D+T fuel ions
 - $f_{\text{He}} = 0.1 \quad | \quad 0.05$ thermal alphas
 - $f_{\text{C}} = 0.009 + 0.006(0.7/\langle n_{20} \rangle)^{2.6}$ carbon
 - $f_{\text{O}} = 0.001$ oxygen
 - $f_{\text{Fe}} = 0.0005(0.7/\langle n_{20} \rangle)^{2.3}$ iron
- Internal inductance and beta poloidal:
 - $0.55 \leq I_i(3) \leq 0.75$ all scenarios
 - $\beta_p \leq 0.75$ ignition studies
 - $\beta_p \leq 2.0$ steady-state/technology testing
 - where $I_i(3) = (2V/R) \langle B_p^2 \rangle / (\mu_0 I)^2$

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Figure Captions

Fig. 1. Confinement capability of ITER physics baseline device at 1 MW/m² (with 5% and 10% He content). Confinement enhancement factor needed for ignition [$\tau_E(\text{needed}) \sim f \times \tau_E(\text{L-mode scaling})$] for various L-mode scaling expressions. (See Refs. [1-3] for notation. ITER-P: ITER89 power law, ITER-O: ITER89 offset linear, G: Goldston, K-big: Kaye-Big, T-10: T-10, O-S: Odajima-Shimomura, R-L: Rebut-Lallia.)

Fig. 2. ITER ignition capability as a function of plasma current at 1 MW/m² (for 0-10% He) for ITER L- and H-mode scalings: $\tau_E(\text{needed}) \sim f \times \tau_E(\text{ITER L- or H-mode})$.

Fig. 3. Impact of helium concentration on required plasma current for equivalent performance (ignition) in ITER: ΔI vs n_{He}/n_e . Curve is normalized to the ITER physics baseline performance at 22 MA at 1 MW/m². Confinement model is $\tau_E \sim 1.9 \times \tau_E(\text{ITER89 L-mode})$.

Fig. 4. Effect of pressure (density) profile peaking on required $Tn\tau_E$ for ignition. Curves are normalized to flat profiles. Effects of reactivity [$\langle\sigma v\rangle$ only], reactivity + confinement [$\langle\sigma v\rangle + \chi$] and overall combined effect (heavy-shaded curve) of reactivity + MHD + confinement [$\langle\sigma v\rangle + \text{mhd} + \chi$] are shown.

ITER (22 MA) Confinement Capability @ 1MW/m²
Confinement Enhancement Factors Needed for Ignition

Figure 1

ITER Ignition Capability (@1MW/m²)
 Needed Confinement Improvement (or Degradation) vs I
 for ITER89-P L-mode and ITER90 H-mode scalings

Figure 2

Impact of Helium Concentration on Required Plasma Current for Equivalent Performance

Figure 3

Effect of Profile Peaking on Required TauE

Figure 4

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