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ITER PHYSICS DESIGN GUIDELINES AT HIGH ASPECT RATIO

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The physics requirements for ITER design are formulated in a set of physics design guidelines. These guidelines, established by the ITER Physics Group during the Conceptual Design Activity (CDA, 1988-90), were based on credible extrapolations of the tokamak physics database as assessed during the CDA, and defined a class of tokamak designs (with plasma current I ~20 MA and aspect ratio A ~ 2.5-3.5) that meet the ITER objectives. Recent U.S. studies have indicated that there may be significant benefits if the ITER-CDA design point is moved from the low aspect ratio, high current baseline (A = 2.79, I = 22 MA) to a high aspect ratio machine at A ~ 4, I ~ 15 MA, especially regarding steady-state, technology-testing performance. To adequately assess the physics and technology testing capability of higher aspect ratio design options, several changes are proposed to the original ITER guidelines to reflect the latest (although limited) developments in physics understanding at higher aspect ratios. The critical issues for higher aspect ratio design options are the uncertainty in scaling of confinement with aspect ratio, the variation of vertical stability with elongation and aspect ratio, plasma shaping requirements, ability to control and maintain plasma current and q-profiles for MHD stability (and volt-second consumption), access for current drive, restrictions on field ripple and divertor plate incident angles etc.

Introduction

The physics requirements for the ITER design have been set to provide reasonable assurance that the plasma performance will be sufficient to meet the goals of ITER in both the Physics and Technology phases of operation [1]. These physics requirements are formulated in a set of physics design guidelines. The original guidelines [2] were established by the ITER Physics Group during the Conceptual Design Activity (CDA, 1988-90). On the basis of its assessment of the the present tokamak database, the ITER-CDA team developed the following general characteristics for the ITER plasma.

Plasma current	I ~ 20 MA
Aspect ratio	A = R/a ~ 2.5–3.5
Plasma beta	$\beta \sim (2.5\text{–}3) \times I/aB$
Safety factor (at 95% flux)	$q_\psi(95\%) \geq 3$
Elongation (at 95% flux)	$\kappa(95\%) \sim 2$
Impurity control	Poloidal divertor
Auxiliary heating	NB, IC, EC, or LH
Current drive	NB, LH, and possibly IC plus bootstrap current
Disruption frequency	As low as possible

NB: neutral beam, IC: ion cyclotron, EC: electron cyclotron, LH: lower hybrid

This generic design concept was refined during the CDA by applying specific physics design guidelines and various engineering, technology, and mission goal constraints [1–3].

The reference ITER-CDA point design (see Table I) had a plasma current of 22 MA , magnetic field of 4.85 T, major radius of 6 m, minor radius of 2.15 m, and a plasma elongation (at the 95% flux surface) of ~2. Although ignition and extended burn at a fusion power of ~1 GW were projected, the design point exceeds the divertor power load constraints for steady state operation. During this past year the U.S. ITER Home Team has been evaluating prospects for large aspect ratio (~4) ITER design options [4] to alleviate some of the difficulties of the present CDA design point. The U.S. studies have indicated that there may be significant benefits if the ITER-CDA design point is moved from the low-A, high-I baseline (A = 2.79, I = 22 MA) to a high aspect ratio design (HARD [4]) at A ~ 4, I ~ 15 MA, especially regarding steady-state, technology-testing performance.

For a comparison, representative device and plasma parameters for the physics baseline ITER-CDA and HARD are given in Table I. In going from lower-A (ITER-CDA) to a higher-A (HARD), at fixed wall loading and confinement capability, plasma current, fusion power, and beta (needed Troyon g-factor) decrease; whereas magnetic field, volt-second capability (burn pulse length), and plasma density increase.

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Table I
Representative ITER-CDA [1,3] and HARD [4] Physics Baseline (Ignition Mode) Parameters

	ITER-CDA	HARD
Plasma current, I (MA)	22	14.8
Magnetic field on axis, B (T)	4.85	7.1
Plasma major radius, R (m)	6.0	6.33
Plasma minor radius, a (m)	2.15	1.58
Elongation, $\kappa(95\%)$	~2	~2
Safety factor, $q_\psi(95\%)$	3.0	3.0
Nominal fusion power (MW)	1080	850
Nominal neutron wall load (MW/m^2)	1.0	1.0
Helium concentration, n_{He}/n_e (%)	10	10
Effective charge, Z_{eff}	~1.7	~1.6
Electron density, $\langle n_e \rangle$ (10^{20} m^{-3})	~1.2	~1.4
D-T density, $\langle n_{DT} \rangle$ (10^{20} m^{-3})	~0.9	~1.05
Nominal temperature, $\langle T_e \rangle = \langle T_i \rangle$ (keV)	10	10
Total plasma beta (average), β (%)	~4.2	~2.3
g_{Troyon}(needed) = $\beta(\%)/(I/aB)$	~2	~1.7
Internal inductance, $l_i(3)$	0.65	0.65
Beta poloidal, β_{pol}	~0.6	~1.1
Bootstrap current fraction, I_{bs}/I (%)	~15	~18
Volt-second capability (Vs)	~330	~460
Burn time, t_{burn} (s)	~400	~2000
Nominal plasma profiles, α_n/α_T	0.5/1.0	0.5/1.0
Needed confinement capability for ignition		
$T(0)n_{DT}(0)\tau_E$(10^{21} keV.s/m^3)	~8.5	~8.5
Confinement times, τ_E (s)		
τ_E(needed for ignition)	~3.8	~3.3
τ_E(ITER89-P L-mode prediction)	~1.9	~1.66
τ_E(ELMy H-mode prediction) = 0.75 × τ_E(ELM-free H-mode)	~4.1	~3.5

Several changes are proposed to the original ITER-CDA physics guidelines to reflect the latest (although limited) developments in physics understanding at higher aspect ratios. The critical physics issues are the uncertainty in scaling of confinement with aspect ratio, the variation of vertical stability with elongation and aspect ratio, plasma shaping requirements, ability to control and maintain plasma current and q-profiles for MHD stability (and volt-second consumption), access for current drive, restrictions on field ripple and divertor plate incident angles, etc. Modifications in some of these areas have been incorporated into the recent systems code studies of HARD [4]. In this paper, we review the ITER proposed physics guidelines at high aspect ratio.

Summary of ITER Physics Design Guidelines [2] and Modifications at High Aspect Ratio

A brief summary of the physics guidelines for the ITER-CDA design (for details, see Ref. [2] and references therein) along with changes needed for high-A design options is given here. Units are mks, MA, MW, with $n_{20} = \langle n_e/10^{20}\ m^{-3} \rangle$ = volume-average electron density and $T_{10} = \langle T/10\ keV \rangle$ = density-weighted average temperature. Nominal profiles are: $n, T \sim (1 - r^2/a^2)^{\alpha_{n,T}}$; with $\alpha_n = 0.5$, $\alpha_T = 1.0$. Where appropriate, one of two rules (x | y) may apply, referring to ("baseline performance" | "extended performance").

Energy Confinement

Specific ITER-CDA guidelines for ignited operation in H-mode were $I \geq 22$ MA at $A = R/a \sim 3$ with

$$\tau_E(\text{required}) \leq \tau_E(\text{ELMy H-mode}) \sim 2 \times \tau_E^{ITER89\text{-}P}(\text{L-mode})$$

- ITER (89) power law L-mode confinement scaling:

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

where $A_i = 2.5$ (isotopic mass), $\kappa_x = \kappa$(at X-point), $\bar{n}$ = line-averaged density, P = P(α+OH+aux−rad) = net heating power.

- ITER (90) H-mode confinement scaling:

$$\tau_E(\text{ELMy H-mode}) = 2 \times \tau_E^{ITER89\text{-}P}(\text{L-mode}) \text{ or}$$

$$\tau_E(\text{ELMy H-mode}) \sim 0.75 \times \tau_E(\text{ELM free H-mode})$$

with

$$\tau_E^{ITER90\text{-}H}(\text{ELM-free H-mode}) = 0.082\ I^{1.02}\ R^{1.6}\ B^{0.15}\ A_i^{0.5}\ \kappa_x^{-0.19}\ P^{-0.47}$$

A measure of performance is expressed by $M = P_\alpha/P_{loss} \propto T_i(0)n_{DT}(0)\tau_E \propto \beta B^2\tau_E$ [P_α is the total alpha power, P_{loss} 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 ~ 5–∞) will require a confinement capability of $T_i(0)n_{DT}(0)\tau_E \sim (4\text{–}8) \times 10^{21}$ keV•s/m^3 for nominal profiles and impurity levels (see Table I). For most scaling expressions, the confinement capability is of the form

$$Tn\tau_E \sim f(IA^\alpha)^x \qquad \text{with } \alpha \sim 1,\ x \sim 2.5$$

allowing for I-A tradeoff without impairing the confinement capability. Thus optimization of ITER by considering design points at larger aspect ratios (lower currents) is possible within the present confinement database. Although H-mode confinement database contain data with A ~ 2.5–5.5 (data for A > 3 is mostly from PBX-M indented plasmas, and some from ASDEX), high performance discharges in present day large tokamaks (JET, JT-60U, DIII-D) have A ~ 3. It is therefore expected that at high aspect ratio, such A ~ 4, there will be more uncertainty in the extrapolation of the confinement properties to ITER (in terms of scaling from equivalency of dimensionless parameters). Planned aspect ratio scaling experiments in JT-60U, DIII-D, and ASDEX-U should improve the H-mode database for high-A during the EDA.

Beta Limit: $\beta_{max}(\%) = gI/aB$

The volume-average total (thermal + fast alpha + beam) beta is held below $\beta_{tot} \leq \beta_{max}(\%) = gI/aB$. Based on

experimental results and theoretical calculations, for $\kappa \le 2$, g (Troyon coefficient) has been chosen in ITER-CDA as:

$g \le 2.5$	3.0	for ignition studies
$g \le 3.0$	3.3	with current profile control

In general, the scaling of the maximum g-value is found to be nearly independent of aspect ratio [$g \sim A^0$ for $q_\psi > 3$], if profiles are varied to produce optimal values at each aspect ratio [5]. For optimal MHD stability in high-A, operational window in internal inductance, $l_i(3)$, shifts to higher values [$l_i(3) \sim 0.75$–1.0]. Note that, for the CDA baseline ($A \sim 2.8$, $q_\psi \sim 3.1$), $l_i(3) \sim 0.65$ was required for $g \sim 3$. For higher A (and $q_\psi > 3$), $g^{max} \sim 3$ requires $l_i(3) \sim 0.9$–1.0.

Safety Factor: $q_\psi(95\%) = q_* f(\varepsilon)$

The ITER-CDA guidelines were

$q_\psi(95\%) \ge 3.0$ | 2.1 for $\kappa = b/a \le 2$

where $q_* = (5a^2B/RI)[1 + \kappa^2(1 + 2\delta^2 - 1.2\delta^3)]/2$ is the cylindrical equivalent q and $f(\varepsilon) = (1.17 - 0.65\varepsilon)/(1 - \varepsilon^2)^2$ is the geometry factor ($\varepsilon = a/R$). Typically, it is recommended that the value of $q_\psi(95\%) - q(0)$ be larger than 2 to provide sufficient global shear for stability of kink modes. [In CDA, $q_\psi(95\%) \ge 2.1$, "extended performance" case was to be used only for plasma performance evaluations for short pulse, high current operation.] It should be noted that confinement tends to deteriorate (saturation of τ_E with I) with low-q (< 3) operation due to sawtooth effect. As q_ψ decreases below 3, the frequency of disruptions increases and operational window narrows. Thus, to allow for MHD stability and to maintain favorable current scaling of confinement ($\tau_E \propto I$), $q_\psi \ge 3$ should be adopted in setting the baseline plasma current.

For higher aspect ratio, g^{max}(Troyon) tends to decrease slightly for lower q_ψ (≤ 3). Maintaining safe operating value of $g \sim 2.5$–3 requires $q_\psi(95\%) > 3.0$ (or higher) in $A \sim 4$. For all aspect ratios, the use of noninductive current drive may be needed to provide current profile control and maintain MHD stable q-profile during long-pulse, extended burn.

Configuration and Vertical Stability

ITER uses poloidal divertors for power and particle exhaust. CDA design has $\kappa(95\%) \sim 2$ and $\delta(95\%) \sim 0.4$. Empirical relationships are: $\kappa(\text{X-point}) \sim 1.12 \times \kappa(95\%)$, $\delta(\text{X-point}) \sim 1.5 \times \delta(95\%)$.

For the vertical stability, the following two requirements were set during the CDA [1]:

m_s = stability margin = $-F_{stab}/F_{destab} - 1 \ge 0.5$
γ_z = instability growth rate $\sim 100\ s^{-1}$

where m_s reflects the restoring force margin that the passive stabilizing structure provides (F_{stab} = restoring force on the plasma produced by currents induced in PF coils and passive stabilizing conductors by a vertical displacement, F_{destab} = destabilizing force on the plasma produced by the static equilibrium field) and a maximum permissible growth rate of $100\ s^{-1}$ is set as the CDA design requirement, corresponding to a peak control power of ~1 GW for a 15 cm excursion.

At higher aspect ratios with fixed plasma elongation, growth rate for vertical stability increases (less stability margin). Stability margin may be somewhat recovered with a decrease in elongation (at $A \sim 4$, reduction in κ can be as much as 10%). Note that the required control power increases with A [P(control HARD)/P(control CDA) ~ 2].

Density Limit

Density limit is set by an upper limit on the plasma edge density, provisionally characterized during the CDA as:

$$n_{e,s20}^{crit} \propto C[q_\perp^{0.57} B^{0.31}/(q_\psi R)^{0.1}]$$

where $n_{e,s}^{crit}$ = critical density at the separatrix, $q_\perp$ (MW/m^2) = mean heat flux across separatrix, and C ~ 0.5 for L-mode (depends on configuration). Although this critical density limit model describes n^{crit} well for L-mode data, the H-mode database is not sufficient to make any recommendation or generalization at high-A (or low-A). Note that high-A designs may be more susceptible to the uncertainties in density limits because of the higher density operation.

Internal Inductance and Beta Poloidal

In CDA, $A \sim 2.8$, the operational window was decribed as

$0.55 \le l_i(3) \le 0.75$	for all scenarios
($l_i(3) \sim 0.65$	nominal value)
$\beta_p \le 0.75$	ignition studies
$\beta_p \le 2.0$	long pulse/steady-state

where $l_i(3) = (2V/R)\langle B_p^2\rangle/(\mu_o I)^2$ is the internal inductance.

For recommended changes ($0.75 \le l_i(3) \le 1.0$) at high aspect ratio, see discussions under *beta limits*.

Loop Voltage, Volt-Seconds, and Pulse Length

- Resistive loop voltage, calculated using neoclassical resistivity, for $\alpha_n = 0.5$, $\alpha_T = 1.0$, $\alpha_J = 1.5$:

$$U\ (\text{volts}) \approx 2.15 \times 10^{-3}\, Z_{eff} \langle\gamma_{NC}\rangle (I_{ind} R/\kappa a^2)/(T_{10})^{1.5}$$
$$\langle\gamma_{NC}\rangle = 4.3 - 0.6A \quad \text{for } A = R/a \sim 2.5 \text{ to } 4$$

where γ_{NC} is the neoclassical resistivity enhancement factor and $I_{ind} = I - I(\text{bootstrap}) = I - I_{bs}$ is the net inductively driven current. For $A > 4$, $\langle\gamma_{NC}\rangle = \max[1, (4.3 - 0.6A)]$ could be used as a reasonable approximation.

- V•s requirement

$$\Delta\Psi_{PF}(\text{total}) = L_p I[l_i(3), \beta_p] + C_{Ejima}\mu_o R I + \Delta\Psi_{heat} + U_{loop}(I_{ind}) \times t_{burn}$$

$C_{Ejima} = 0.4$ (nominal value)
$\Delta\Psi_{heat} = 10$ V•s (resistive loss during heating to burn)
$\Delta\Psi_{burn} = U_{loop}(I_{ind}) \times t_{burn} \ge 0.1\Delta\Psi_{PF}(\text{total})$
L_p = plasma self-inductance

- Burn duration, t_{burn}

  CDA guidelines were:

  Physics studies:

  pure inductive (ignition) $t_{burn} \sim 200$ s (for $l_i(3) = 0.75$)

  current drive ($Q > 5$) $t_{burn} \rightarrow$ steady-state

  Technology testing:

  hybrid (~0.8 MW/m^2) $t_{burn} > 1000$ s

Note that in reference baseline case (Table I) $l_i(3) = 0.65$ was used (corresponding to 400 s burn time for ignition studies).

Power and Particle Control

This is one of the most difficult design problem facing the ITER-EDA. It is not possible to cover this important and complex area within the space limitations allowed here (for details see Refs. [1,2]). Briefly, the CDA guidelines were: double null poloidal divertor (operating in a high recycling mode), with operational scenarios selected such that

peak plate power loads ≤ 20 MW/m^2
peak local $T_e^{div} \leq 10$–20 eV
angle between field lines and divertor plate ~ 1.6°

In a high aspect ratio device, the angle between field lines and divertor plate decreases with the ratio of the poloidal to toroidal field ($B_{pol}/B \sim 1/A$), thus reducing the peak divertor loads. However, there may be a minimum angle (taken to be 1.6° in ITER-CDA) imposed by uncertainties in alignment, tolerances, toroidal field ripple, etc. The issue of minimum filed line angle has not yet been resolved.

Disruption Characteristics

A simplified CDA disruption characteristics were:

thermal quench time	0.1–1 ms (up to 3 ms)
current quench time	10 ms
runaway electron energy	up to 300 MeV

Because high aspect ratio designs reduce the plasma current (for a given confinement capability), the consequences of disruptions may not be as severe. The stored plasma thermal energy and the internal magnetic energy is smaller at high aspect ratios, thus the number of disruptions that the plasma facing components can support is larger (provided that the disruption frequency does not increase due to vertical instability). Because of the higher peak fields, however, toroidal field stored energy is larger for high-A devices..

Z_{eff}: Impurity and Thermal Alpha Fractions

No change is recommended, the CDA guidelines were:

$n_{DT}/n_e = 1 - 2f_{He} - 6f_C - 8f_O - 26f_{Fe}$	D+T fuel ions
$n_{He}/n_e = 0.1 \pm 0.05$	thermal alphas
$n_C/n_e = 0.009 + 0.006(0.7/\langle n_{20}\rangle)^{2.6}$	Carbon
$n_O/n_e = 0.001$	Oxygen
$n_{Fe}/n_e = 0.0005(0.7/\langle n_{20}\rangle)^{2.3}$	Iron

For $\langle n_e\rangle = (1.4 \rightarrow 0.7) \times 10^{20}$ m^{-3}, $Z_{eff} = 1.6 \rightarrow 2.0$.

Toroidal Field Ripple

There is an unfavorable increase of alpha-particle ripple losses with increasing aspect ratio, scaling roughly as A^x (with $x \sim 1$–2) for similar radial ripple $\delta(r)$ and q_ψ profiles. The limit on the ripple is approximately given as

$$\delta \leq \delta_{crit} \sim [(\varepsilon/\pi\, N_{TF}\, q)\,(\kappa/\rho_L\, q')\,,\ q' = dq/dr,\ \varepsilon = 1/A$$
$$\sim (q\, N_{TF}\, A)^{-1.5}\,(a\, B\, \kappa/q).$$

where N_{TF} is the number of TF coils and ρ_L is the gyro radius. To keep the ripple losses at the ITER-CDA level, above expression can be used to scale (normalize) the ripple amplitude from the CDA design to a new design at higher A.

Heating and Current Drive

From physics point of view, no major change in guidelines is recommended at high aspect ratio. Because of restricted access at high A, beam aiming and tangency radius consideration need to be taken into account in neutral beam system specifications. The CDA guidelines were:

CD efficiency (figure-of-merit) $\gamma_{CD} = \langle n_{20}\rangle I_{CD} R/P_{CD}$

Heating: $P_{aux} \sim 50$ MW (provided by CD system)

Bootstrap: $I_{bs}/I \sim 15$–30%, depending on A and β_{pol}

Current Drive (CD):

NB: $E_{beam} \sim 1.3$ MeV; $\gamma_{NB} \sim 0.5$; $P_{beam} \sim 75$ MW

LH: $f_{LH} \sim 5$ GHz, $P_{LH} \sim 50$ MW

IC (alternative to NB): $f_{IC} \sim 15$-80 MHz; $\gamma_{IC} \sim 0.3$; $P_{IC} \sim 130$ MW

Profile Control and plasma initiation: EC: $f_{EC} \sim 120$ GHz; $P_{EC} \sim 20$ MW

For high aspect ratio designs, because of the increase in B, and plasma density, frequencies of RF systems (EC, LH, IC, etc.) need to be determined.

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