Confinement Issues
&
Update on Physics Design Guidelines

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H-mode: Energy Confinement [cf. IPB, *NF* 1999]

$$\tau_{E,th}(\text{ELMy H-mode}) = H_{H98} \times \tau_{E,th}^{IPB98(fit)}$$

$$\tau_{th}^{fit} = C\, I^{\alpha_I}\, B^{\alpha_B} P^{\alpha_P}\, n^{\alpha_n}\, M^{\alpha_M}\, R^{\alpha_R} \varepsilon^{\alpha_\varepsilon} \kappa^{\alpha_\kappa}$$

Exponents for these empirical log-linear scalings based on ITERH.DB3

Scaling	C (10^{-2})	I (MA)	B (T)	P (MW)	n_{e19} (m^{-3})	M	R (m)	ε = a/R	κ_a	N	rmse (%)	ITER-FDR τ_E(s)
IPB98(y)	3.65	0.97	0.08	-0.63	0.41	0.20	1.93	0.23	0.67	1398	15.8	6.0
IPB98(y,1)	5.03	0.91	0.15	-0.65	0.44	0.13	2.05	0.57	0.72	1398	15.3	5.9
IPB98(y,2)	5.62	0.93	0.15	-0.69	0.41	0.19	1.97	0.58	0.78	1310	14.5	4.9
IPB98(y,3)	5.64	0.88	0.07	-0.69	0.40	0.20	2.15	0.64	0.78	1273	14.2	5.0
IPB98(y,4)	5.87	0.85	0.29	-0.70	0.39	0.17	2.08	0.69	0.76	714	14.1	5.1

IPB98(y) $\kappa = b/a$; IPB98(y,1-4) $\kappa_a = S/\pi a^2$

OLD -- IPB scaling: $\tau_E = \tau_E^{IPB98(y,1)}$

NEW -- ITER-FEAT ref. scaling: $\tau_E = \min \tau_E^{IPB98(fit)}$ ==> $\tau_E^{IPB98(y,2)}$

$$\tau_E^{IPB98(y,2)} = 0.0562\, I^{0.93}\, B^{0.15}\, P^{-0.69}\, n_{e19}^{0.41}\, M^{0.19}\, R^{1.97}\, \varepsilon^{0.58}\, \kappa_x^{0.78}$$

=> Constraints/issues: near n_{GR}, n scaling, n-δ, n(0)/n, ELM type, SN/DN

New (99/00) Data & New H-mode Confinement Database: DB3v8+ ==> DB3

New scaling expressions to come

Main features of the new data: high density (n/n_{GR}) and shape (κ,δ)

Potential new fits to DB3

- log-linear analysis
- 2-term (pedestal and core) models -- [offset non-linear]

JET example:

$$\tau_E \sim C_1\, I^{0.8}\, n^{0.6}\, R^{2.2} / P^{0.6} M^{0.2} + C_2\, I^2\, M / nPR$$

gyro-Bohm core pedestal

In terms of dimensionless variables (approximately)

$$\Longrightarrow \omega_c \tau_E \sim \langle\rho^*\rangle^{-3}(1 + c\langle\rho^*\rangle^2/\langle\beta\rangle^2)$$

τ_E degrades with β (from pedestal term), pedestal contribution & τ_E degrade at hign n (as n-->n_{GR})

Results/discussions at IAEA

L-mode: Energy Confinement [cf. IPB, *NF* 1999]

The L-mode scaling ITERL97P based on the thermal energy confinement data:

$$\tau_{E,th}^{ITERL97P} = 0.023 H_{L97}\, I^{0.96} B^{0.03} P^{-0.73} n_{19}^{0.40} M^{0.20} R^{1.83} \varepsilon^{0.-0.06} \kappa^{0.64}$$

(sec, MA, T, MW, 10^{19}m^{-3}, AMU, m).

New version of the L-mode Confinement Database is in the works

Main feature (relevant for FIRE): high-B (FTU, C-Mod)

[Old] H-mode Power Threshold [cf. IPB, *NF* 1999]

From database ITERTH DB2.1 (IPB97), assuming linear B dependence (for D plasma):

$$P_{\mathrm{thr}} = C(R/a, \kappa, q, \alpha) B_{\mathrm{T}} \bar{n}_{\mathrm{e}}^{0.75} R^2 (\bar{n}_{\mathrm{e}} R^2)^{\alpha} \quad \text{with } C = (0.45 \pm 0.1) \times 0.6^{\alpha} \quad -0.25 \le \alpha \le 0.25.$$

Versions from database ITERTH DB2.3 (IPB98): numerical coefficient & exponents

IPB98(1-5)	C (for D plasma)	$n_{e,20}$ (m^{-3})	B (T)	R (m)	a (m)	S (m^2)	rmse %
(1)	0.70	0.94	0.80	2.12			30.5
(2)	1.79	0.78	0.76	1.14	0.78		28.3
(3)	0.057	0.64	0.83			0.89	28.8
(4)	0.041	0.69	0.91			0.96	25.2
(5)	1.38	0.77	0.92	1.30	0.76		25.1

Units: 10^{20} m^{-3}, T, m, m^2, MW.

Two of these scalings are based on data from medium and large tokamaks: IPB98(4) and IPB98(5)

$$P_{\mathrm{thr}}^{\mathrm{IPB98(4)}} = 0.082 \bar{n}_{20}^{0.69} B^{0.91} S^{0.96} M^{-1}; \qquad P_{\mathrm{thr}}^{\mathrm{IPB98(5)}} = 2.76 \bar{n}_{20}^{0.77} B^{0.92} R^{1.3} a^{0.76} M^{-1}$$

=> constraints/issues: isotope scaling, scattering of data in the database, low/high-q_{ψ}, H-mode op. space close to n-limit, deviations from log-linearity, different B-n scalings in each device, $\nabla B < 0$ / $\nabla B > 0$, SN/DN?

[New] H-mode Power Threshold--ITERTH.DB3 (99.DB3)

New scaling from latest version of the threshold database (DB3)

Main drivers: recent results from C-mod & JT-60U dedicated H-mode threshold expt's

Ref: Snipes et al [to appear in Plasma Phys & Controlled Fusion]

$$P_{LH\text{-}thr}\ (99.DB3) = 2.84\ n_{20}^{0.58}\ B^{0.82}\ R\ a^{0.81}\ M^{-1}$$

[units: MW, 10^{20} m^{-3}, T, m, m, isotopic mass]

$$P_{LH\text{-}thr}\ [(99.DB3)] / P_{LH\text{-}thr}\ [IPB98(4,5)] \sim O(0.5)$$

=> constraints/issues: same as before, SN data large scattering/DN data lacking

?? $P_{LH\text{-}thr}(SN) < P_{LH\text{-}thr}(DN)$??

[New start] Int. ITB Database Activity

Hosts: JET (profile data) & JT-60U (global parameters)

Issues/concerns to be addressed:

Scaling of ITB characteristics/improved prediction capabilities

- conditions for ITB formation (threshold power scaling)
- confinement scaling for plasmas with ITB
- ITB physics models

Other/Alternative Regimes--not ELMy (type I) H-mode or ITB

H-mode variety: grassy or small ELMs, Enhanced D-alpha (EDA), Type II ELMs

RI-mode variety

Issues/concerns: see H-mode

Particle confinement-no change

In experiments $D/\chi_i \sim 1$ with range of uncertainty: $D/\chi_i \sim 0.3–1$ for design of fueling & pumping

Impurity content-no change

Beryllium: $n_{Be}/n_e \sim 2\text{-}3\%$ [or Carbon: $n_C/n_e \sim 2\%$],
Neon: $n_{Ne}/n_e \sim 0.6\%$ and/or Argon: $n_{Ar}/n_e \sim 0.1\text{-}0.2\%$,
Helium content: $\tau_{He}/\tau_E \sim 5$

Beta limit-no change

β_N	$\leq 4l_i$	Ideal MHD limit
	$\leq f(\nu_e^*)$?	NTMs [require ECCD stabilization]
	≤ 2.5	"nominal"

Safety factor-no change

$q_{\psi 95} \geq 3.0$

Density limit

$n_e/n_{GR} < 0.85$ $n_{GR}\ (10^{20}\ m^{-3}) = I(MA)/\pi[a(m)^2]$.

n --> n_{GR} ==> degredation/loss of H-mode. DIII-D, HFS pellet injection may promote improved penetration and fueling efficiency & good confinement up to $1.5n_{GR}$?

AT Modes Physics Rules--no change

Configuration/geometry

SN or DN divertor configuration

$A = R/a \sim ??$; $\kappa_{95} \approx 1.8$, $\delta_{95} > 0.35$

Confinement

$H_H \leq 1.5$ 50% better than IPB

$\tau_{He}/\tau_E \sim 5$ efficient He pumping

Operational Limits [q, β_N, n]

$q_{95} \geq 4$ with $q(0), q(min) \geq 1.5\text{-}2$

$\beta_N \leq 3.5\text{–}4$ [but $< 4 l_i$] 50% better than IPB

$\langle n \rangle \leq 1.5 \times n_{GR}$ range: $n/n_{GR} \sim 0.8\text{–}1.5$

Plasma current profile control capability

off-axis rf

Other physics rules: same as conventional tokamaks.

Comparison of physics models/requirements/constraints used [nominal-inductive]

	ITER-FEAT	FIRE	IGNITOR	Comments
Q_{DT}	≥ 10	~ 10	10-∞	
Configuration κ_{95} δ_{95}	SN ≤ 1.8 ≥ 0.35	DN <== <==	limiter <== <==	
q_{95}	≥ 3	<==	<==	
τ_E model H-mode L-mode	 IPB98H(y,2) ITERL97P	 IPB98H(y,1) ITERL97P	CM — —	
H_{H98} H_{L97}	≤ 1 (±0.2) ~ 1-??	~1 (+?) ??	n/a ??	
$P_{LH\text{-}thr}$ model P/P_{LHthr}	99.DB3.thr > 1.3	IPB97thr ≥ 1?	 n/a	need ops window with margins 1.3-1.5
β_{Nmax}	≤ 2.5	<==	<==	ECCD problems in FIRE/Ignitor if required for NTMs
n_e/n_{GW}	≤ 0.85	~0.7	n/a	easier to satisfy in FIRE & Ignitor; op points/regions well below n_{GR}
$\tau_{He}*/\tau_E$	~ 5	<==	<==	should be consistent with fueling, pumping, exhaust, profiles, op. modes
Z_{eff}	~1.6-1.9	~1.4	< 1.2	??
n-profile [α_n]	~0	~0.5	~1+	because of relative plasma size and lower op temperatures, more peaking may be possible in FIRE and Ignitor??
T-profile [α_T]	~1.3-1.5	~1	<==	transport determined
$t_{burn\text{-}pulse}$ (s)	300	20	5	