High Field Tokamaks for Burning Plasma Experiments

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Burning Plasma Experiments

- *The next step in the demonstration of the scientific feasibility of a tokamak fusion reactor is a DT burning plasma experiment for the study and control of self-heated plasmas.*
- *Several burning plasma experiments have been proposed over the years:*

IGNITOR, CIT, ITER, FIRE

- *The operational regime foreseen for ITER is the ELMy H-mode, for which a number of scaling laws has been derived from a vast database. One of the latest (IPB98(y,2) used for ITER-FEAT) is*

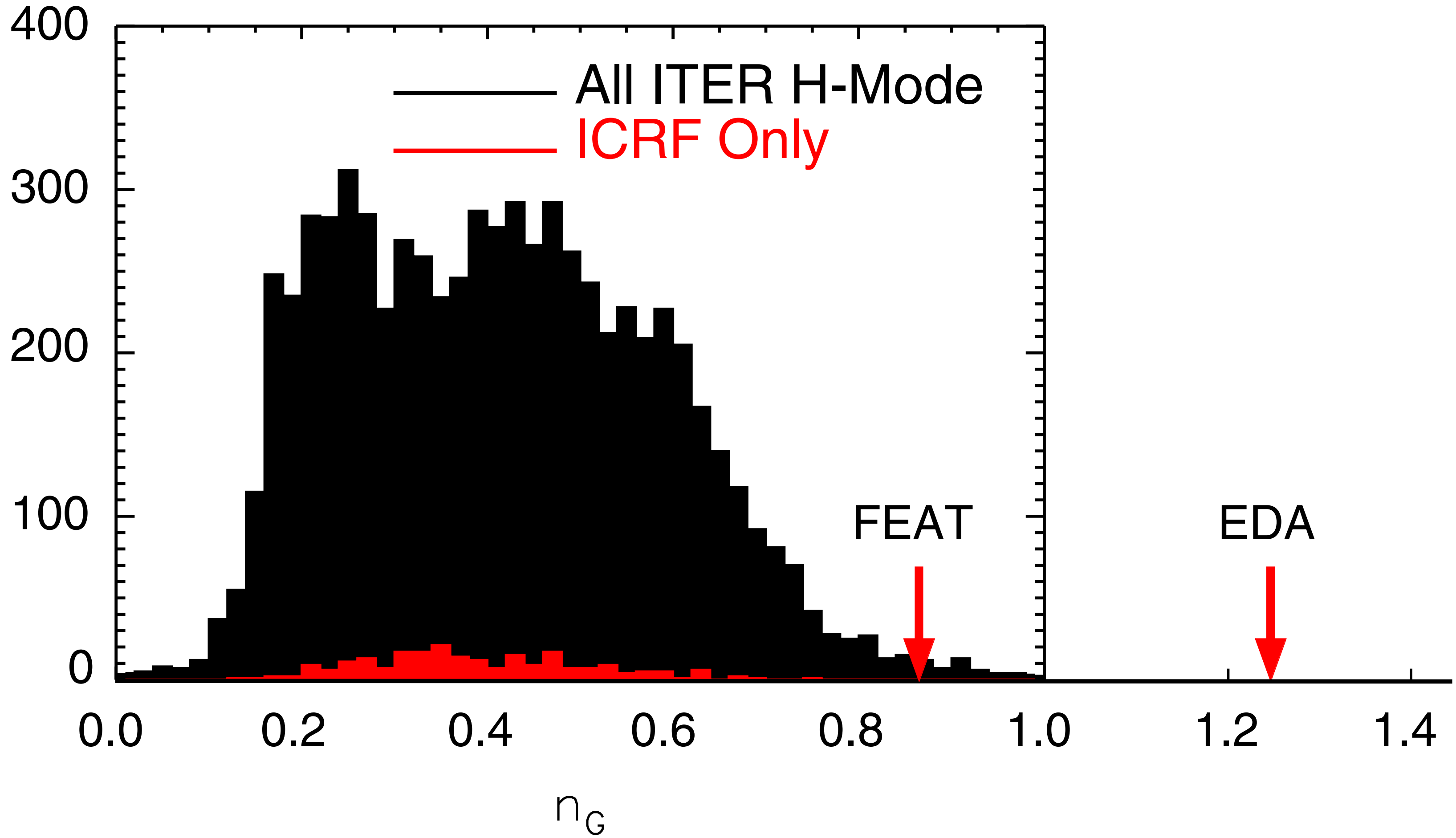
$$\tau_E \omega_c \propto \rho *^{-2.70} \beta^{-0.90} \nu *^{-0.01} M^{0.96} q_{95}^{-3.0} A^{-0.73} k^{2.3} ,$$

with the L-H transition power $P_{LH} = 3.24 M^{-1} B^{0.75} \bar{n}_{20}^{0.60} R^{0.98} a^{0.81}$.

- *ITER suffers from two serious problems:*

need for large plasma densities and betas

Plasma density histogram of ITER database



(courtesy of M. Greenwald)

confinement deterioration at large densities in JET

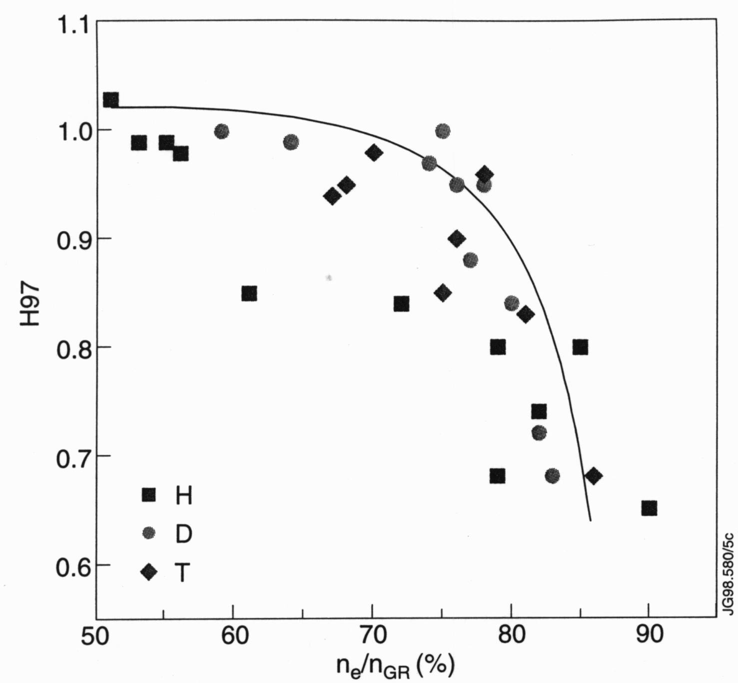
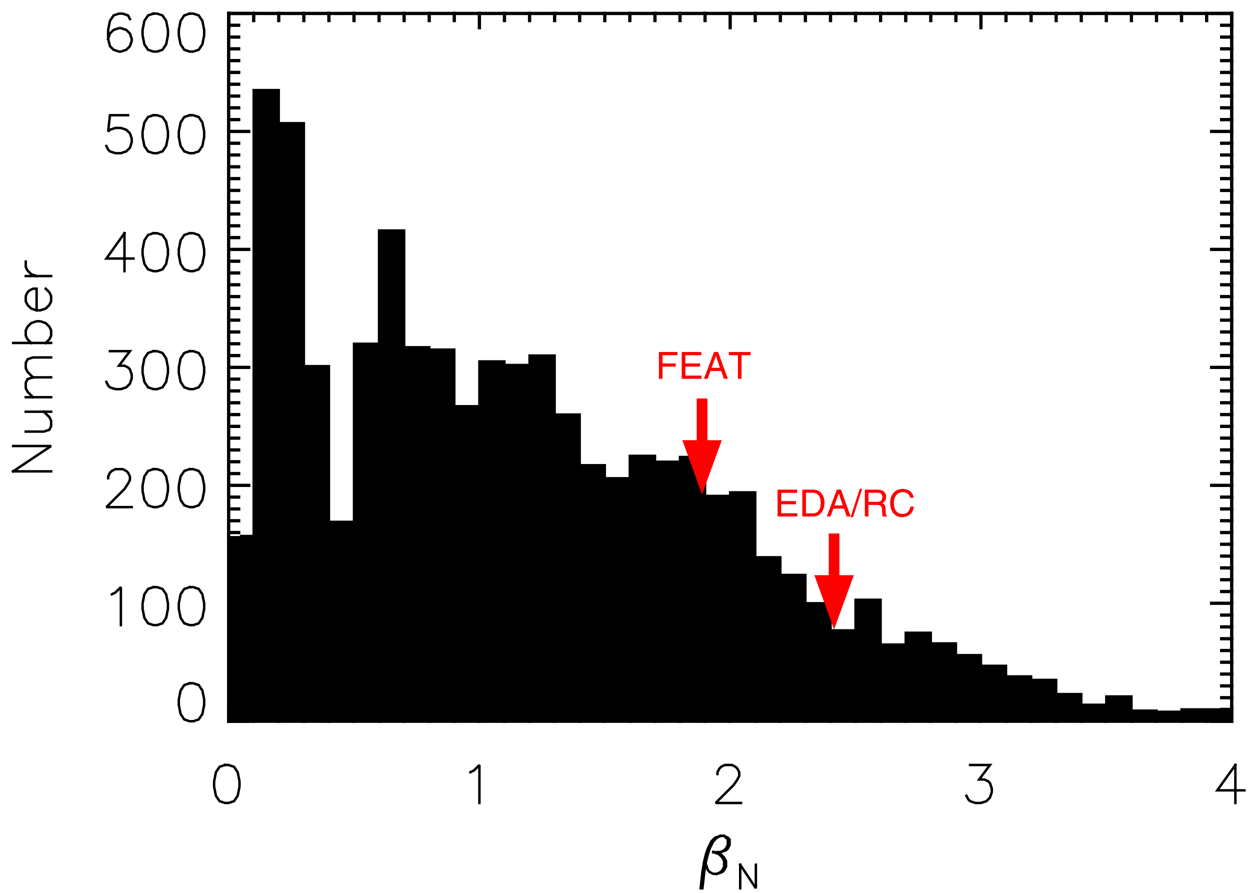


Figure 8. Confinement enhancement factor $H97$ as a function of the fraction of the GDL. Data taken in steady state, separated by isotope. The data set in the figure includes discharges with $1.7 \leq I_p$ (MA), B_t (T) ≤ 3. All the discharges included have $q_{95} \approx 3.3$ and NB input power of 10–12 MW.

*from: G. Saibene, et al., Nuclear Fusion **39**, 1133 (1999)*

β_N histogram of ITER database



(courtesy of M. Greenwald)

importance of the magnetic field

- *Another serious difficulty is the large size of ITER, which is what has delayed the construction of this apparatus so far.*
- *An increase in the magnetic field could lessen all three of these problems.*
- *The ignition criterion*

$$B^2 \beta \tau_E \propto B^{3.7} a^{2.7} \beta^{0.1} T^{-1.35} \propto G/N$$

($G=Q/(5+Q)$, Q is the energy gain, $N = \langle n^2 \overline{\sigma v} \rangle / B^4 \beta^2$) together with the neutron wall loading $P_w \propto N B^4 \beta^2 a$ (@ constant A and k) and the confinement scaling law, gives (@ constant q_{95})

$$a \propto \frac{T^{0.51} (G/N)^{0.38}}{B^{1.32} (P_w/N)^{0.02}}$$

$$\beta_N \propto \frac{(P_w/N)^{0.51}}{B^{1.34} T^{0.25} (G/N)^{0.19}}$$

$$n_G \propto \frac{(P_w/N)^{0.49} (G/N)^{0.19}}{B^{1.66} T^{0.74}}$$

ELMy H-mode scaling of the ITER-FEAT reference discharge

		ITER-FEAT	Medium-B	FIRE-like B	Ignitor-like B
B	[T]	5.30	8.0	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

@ constant A, k, q_{95} and Q

Results

- *All three high field tokamaks have lower values of β_N, and n_G than ITER-FEAT*
- *The dimensions of the case with 13 T are similar to those of Ignitor! Consequently, Ignitor could achieve Q =10 under the assumed ELMy H-mode conditions.*

  Caveat: is the ELMy H-mode accessible to Ignitor?

- *The dimensions of the case with 10 T are larger than those of FIRE*

  Caveat: this depends upon other FEAT assumptions as well (i.e., Z_{eff})

- *In the case with B =8 T:*
  - ♦ *mechanical stresses are lower than in Ignitor and Fire*
  - ♦ *the TF current density is smaller than in Ignitor and Fire*

    longer flattop (≈100 s)
  - ♦ *dimensions are smaller than those of ITER-FEAT*

    lower cost
  - ♦ *a modest increase in A (≈3.5) could allow the use of superconducting coils*

Scaling of the ITER-FEAT reflerence discharge

	FIRE @10T	FIRE @12 T	Ignitor
B [T]	10.0	12.0	13.0
T_n [keV]	8.0	8.0	7.0
a [m]	0.82	0.64	0.49
R [m]	3.14	2.45	1.38
A	3.80	3.80	2.80
k	1.77	1.77	1.83
β [%]	1.34	1.27	1.52
β_p	0.48	0.45	0.29
β_N	1.01	1.04	0.91
n_G	0.46	0.41	0.34
q_{95}	3.0	3.0	3.0
I_p [MA]	10.1	9.5	10.7
E_{TF} [GJ]	12.3	8.4	3.3
Q	10	10	10
P_w [MW/m^2]	0.75	1.1	1.65
P_f [MW]	128	114	75
P_{LH} [MW]	30.5	27	17

@ *constant q_{95} and Q*

Scaling to ignition of the ITER-FEAT reflerence discharge

	Medium B	FIRE-like B	Ignitor-like B
B [T]	8.0	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]	0.75	1.25	2.00
P_f [MW]	246	223	175
P_{LH} [MW]	40	35	29

@ *constant A, k, q_{95}*

Conclusion

- *The difficulties caused by the constraints of plasma physics and by the unavoidable high cost of a burning plasma experiment could be overcome by the use of magnetic fields ≥ 8 T.*
- *The best compromise appears to be a tokamak with a=1.1 m, R=3.85 m, A=3.5, k=1.8, B= 8 T and I=12 MA.*