Comments supporting FIRE Confinement & Operating Space

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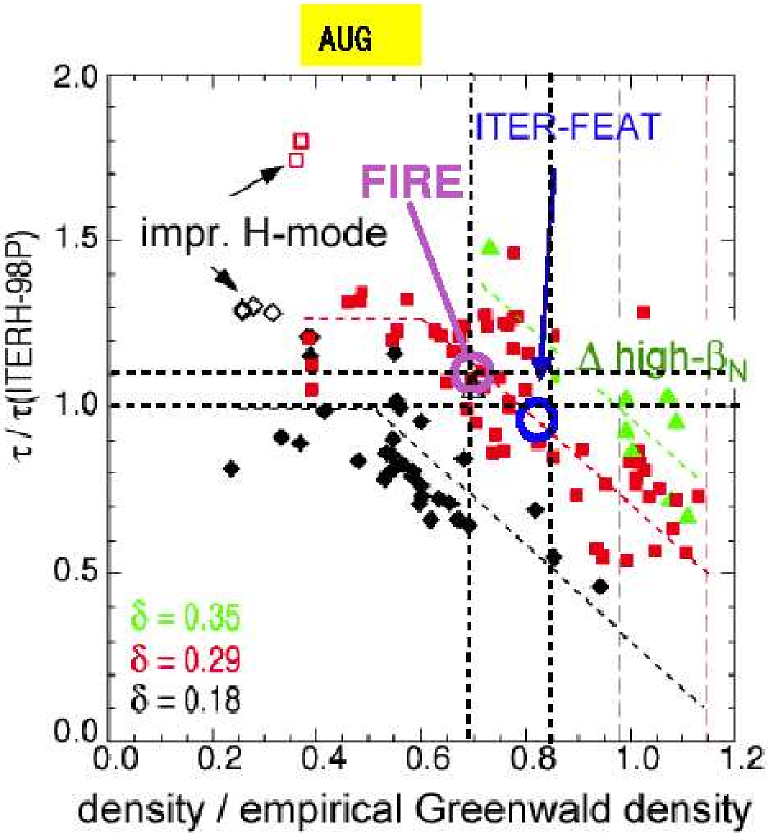
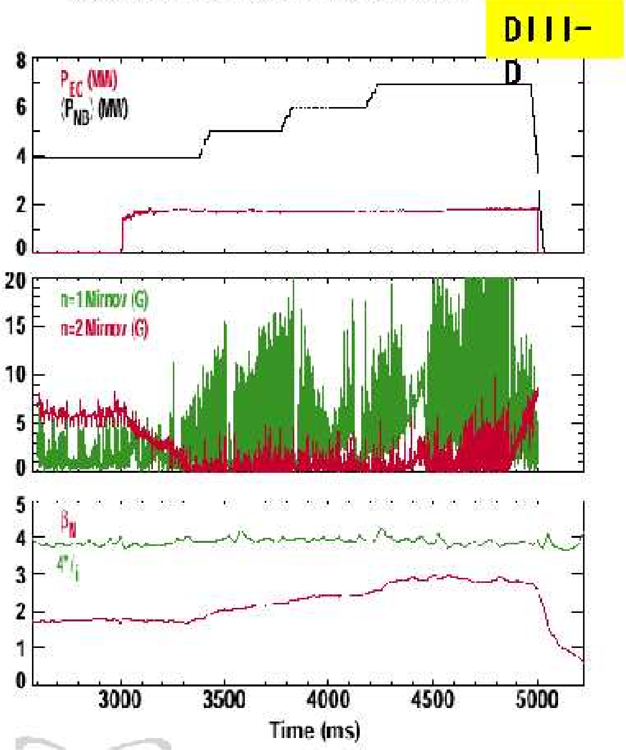
summary: Assumption of $H_{98} \sim 1.1$ supported by evidence from various tokamaks indicating that FIRE's high triangularity, modest range of n_e/n_Greenwald, and modest density peaking can provide improved confinement. (caveat: of course there are uncertainties in extrapolating global confinement scaling for all proposed burning plasmas, perhaps of order +/- 25%).

high confidence level in attainment of Q =10 results of targeted R&D

- **previous major concern: high H-factor at $n/n_{GR} > 0.85$**



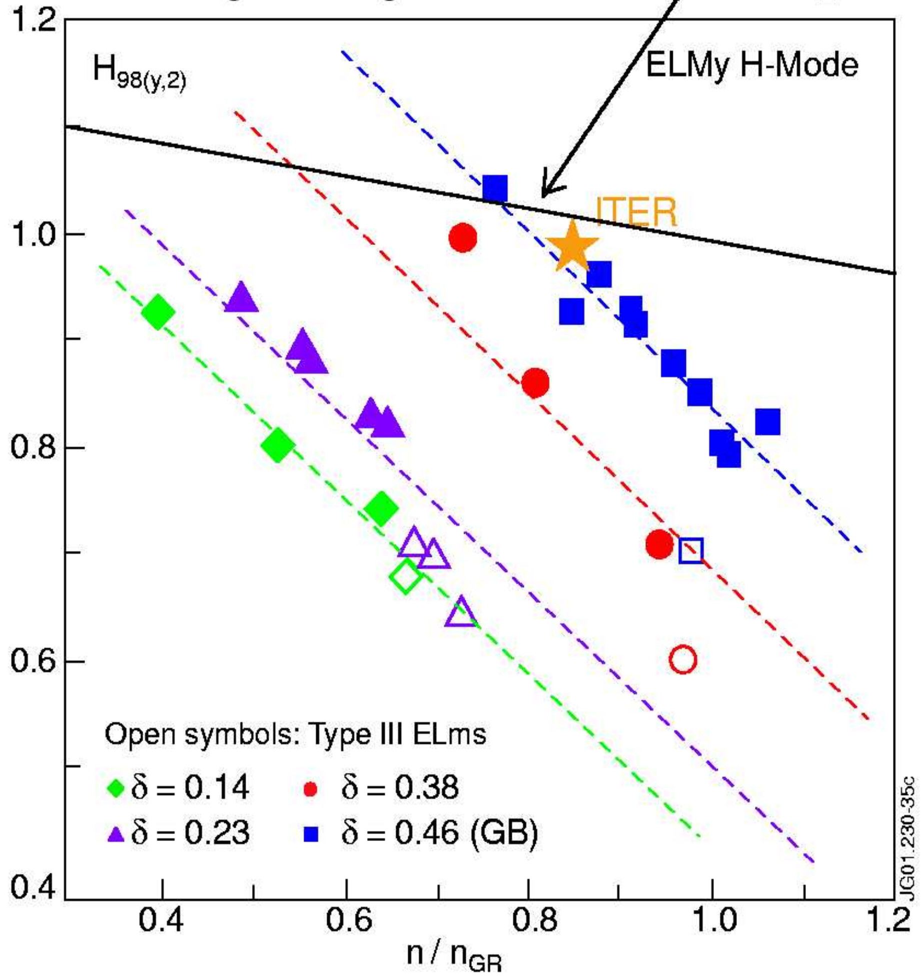
- **NTMs:**
  - **active ECRH-feedback**



  - **self-limitation: FIR-modes (AUG/JET)**
  - **control of sawteeth (JET)**

JET Confinement Depends on Triangularity and ELM Type

Expts show stronger scaling than H ~ Const - 0.16 n/n_Gr



- Higher triangularity allows higher densities at high confinement
- For all triangularities: Confinement degrades with density
- Simultaneously obtained n/n_{GW} ~ 0.9 and $H_{98(y,2)}$ ~ 1at high $\delta = 0.5$
- Trade-off between triangularity and heating power: lower δ discharges need higher P_{in}/P_{L-H}

G. Saibene, Oral 28, Poster P3.002   R.Sartori, Poster P3.003

Increasing Triangularity Enhances H-Mode Confinement

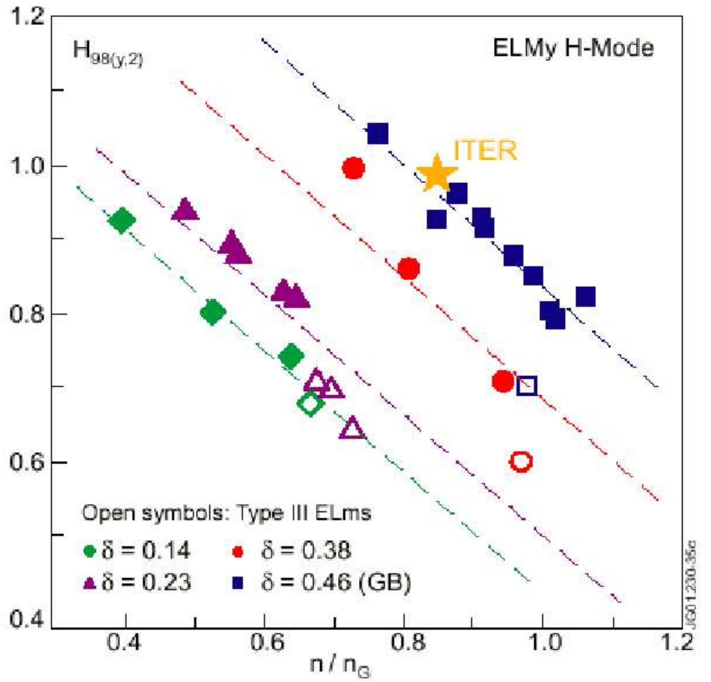


Figure 2.2-2 Confinement Enhancement Factor Relative to the ITERH-98(y,2) Scaling as a Function of n/n_G in JET[5]

- Trade-off between triangularity and heating power: lower δ discharges need higher P_{in}/P_{L-H}

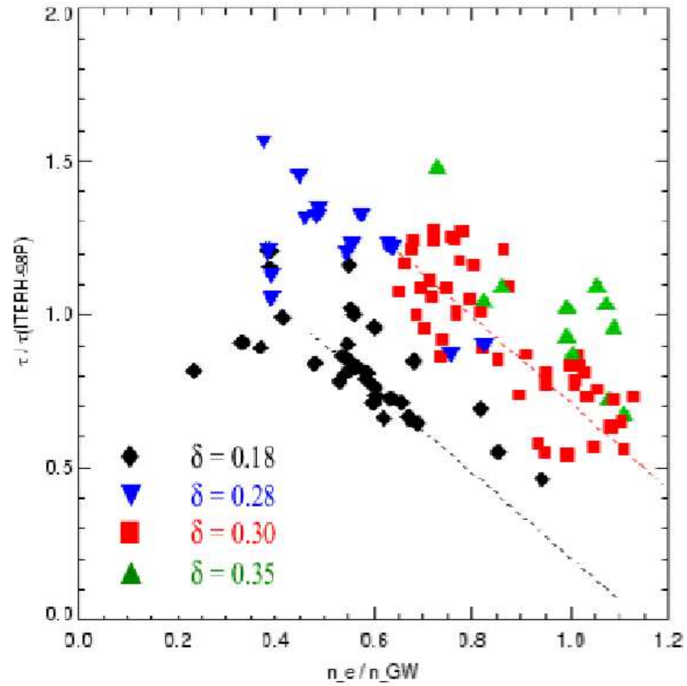
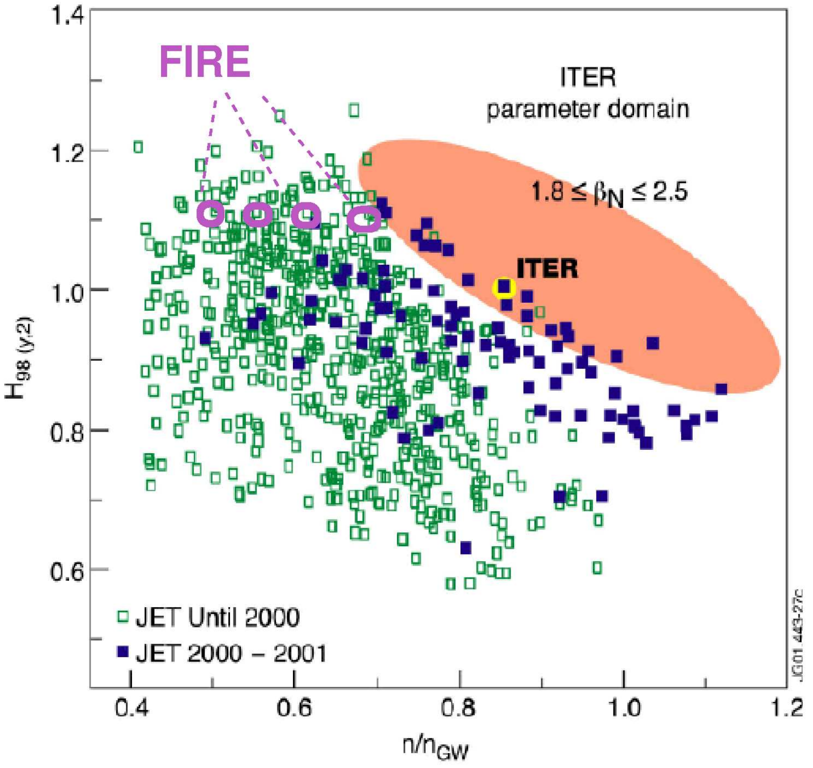


Figure 2.2-3 Confinement Enhancement Factor Relative to the ITERH-98P(y) Scaling as a Function of n/n_G in ASDEX Upgrade[6]

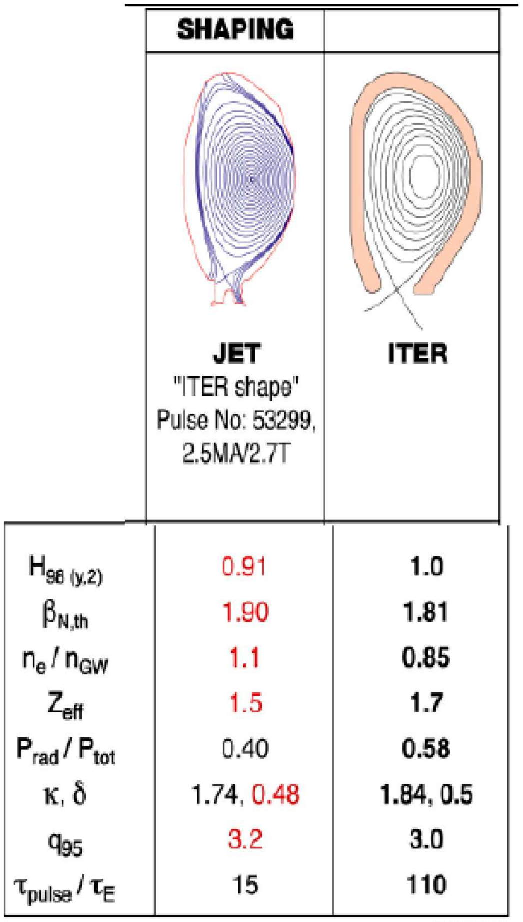
Note: triangularity is determined at the separatrix

Extracted from the ITER-FEAT Physics Basis 2001, page 11

Q =10: ITER-simulation discharges on JET

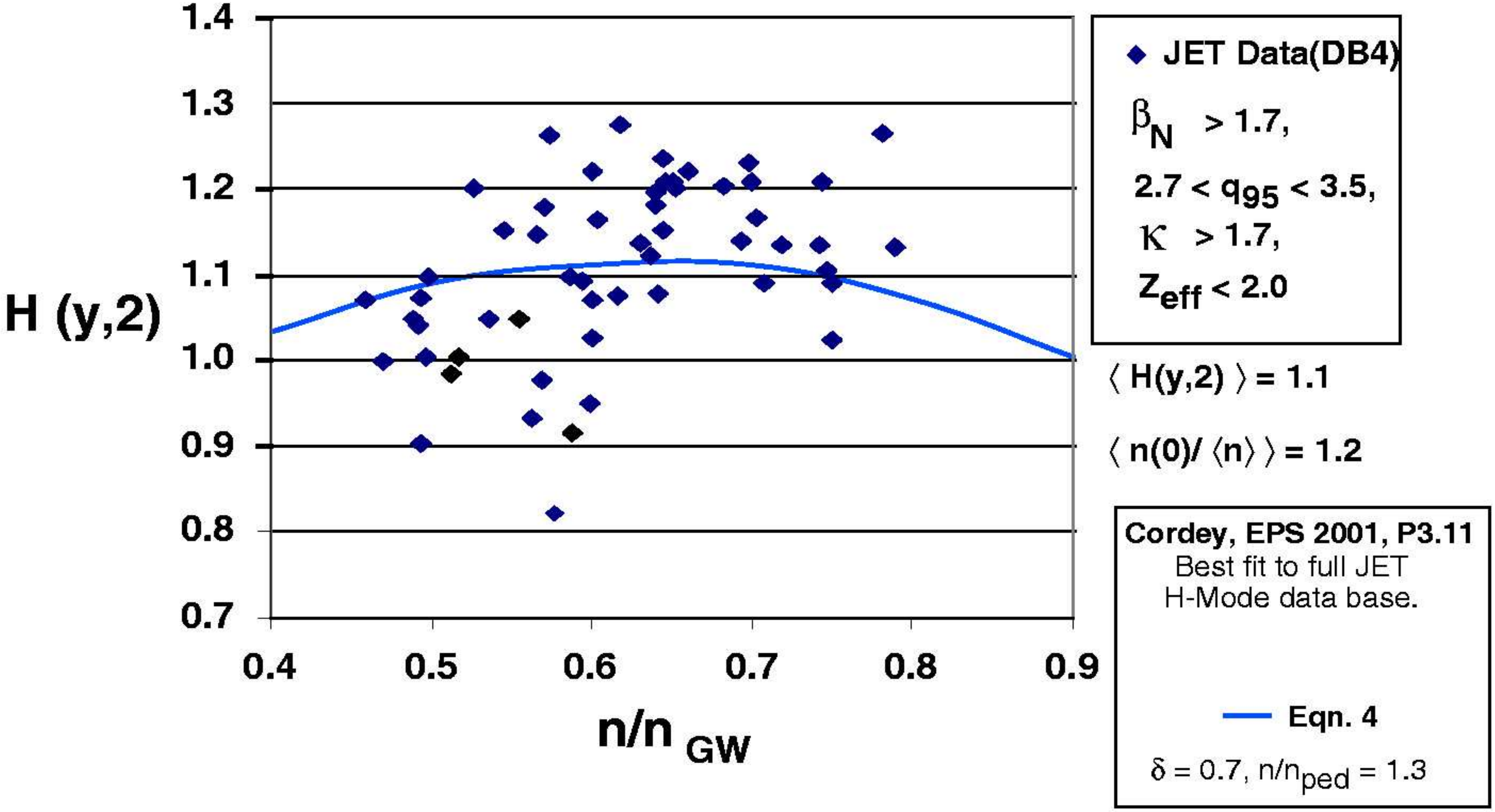


JET-operating space



	SHAPING	
	JET "ITER shape" Pulse No: 53299, 2.5MA/2.7T	**ITER**
$H_{98\ (y,2)}$	0.91	**1.0**
$\beta_{N,th}$	1.90	**1.81**
n_e / n_{GW}	1.1	**0.85**
Z_{eff}	1.5	**1.7**
P_{rad} / P_{tot}	0.40	**0.58**
κ, δ	1.74, 0.48	**1.84, 0.5**
q_{95}	3.2	**3.0**
τ_{pulse} / τ_E	15	**110**

JET H-Mode Data Selected for FIRE-like Parameters



$\beta_N > 1.7$,

$2.7 < q_{95} < 3.5$,

$\kappa > 1.7$,

$Z_{eff} < 2.0$

$\langle H(y,2) \rangle = 1.1$

$\langle n(0)/\langle n\rangle \rangle = 1.2$

Cordey, EPS 2001, P3.11
Best fit to full JET
H-Mode data base.

$\delta = 0.7$, $n/n_{ped} = 1.3$

Exploring corrections for shaping, n/n_Gr, & peaking

Cordey H-corrections:

EPS01 RMSE=9.5% fit to JET Type-I ELMs:
H_Cs0 = 0.71 + 0.33 delta_u – 1.58 (n/n_Gr-0.63)^2 + 0.58 (n/n_ped-1)

PPCF02 (draft) RMSE=9.6% fit to JET Type-I ELMs:
H_Cs2 = 0.46 + 1.35 ln(q95/q_cyl) – 0.17 n/n_Gr + 0.38 (n/n_ped-1)

ln(q95/q_cyl) suppresses influence of strong shaping?

Note02/06/26 RMSE=? Fit to all tokamaks:
H_Cs3 = 0.95 + 0.45 ln(q95/q_cyl) – 0.16 n/n_Gr

D3D appears not to have strong shaping dependence? Or systematic variations in database hides shaping dependence?

H further increases by 8% for closed divertor.
(On the other hand: H should perhaps drop some for reactor Ti/Te~1, v_rot~0, low dilution.)

Improvements in Reactor Design by Shaping & ↑ B_T

	ITER-95	ITER-FEAT	FIRE*	
R (m)	8.14	6.2	2.14	
a (m)	2.8	2	0.595	
kappa_x/k95	1.75/1.6	1.85/1.7	2.0/1.77	
delta_x/d95	~0.35/0.24	0.48/0.33	0.7/0.4	
<ne>, 10^20 /m^3	1.3	1.01	4.55	
Pfusion (MW)	1500	400	150	
Bt (T)	5.68	5.3	10	
Ip (MA)	21	15	7.7	
n_Greenwald	0.85	1.19	6.92	
<ne>/n_Gr	1.5	0.85	0.66	n_ped/<ne>=0.71 assumed for all
Palpha/(2*pi*R)	5.87	2.05	2.23	Divertor Power Loading
q_95/q_cyl	1.45	1.55	1.61	
f_s2	5.52	7.50	12.64	(1+kappa_x^2*(1+3.9*delta_x^2))

Cordey H-corrections for shaping, n/n_Greenwald, peaking:

H_Cs0	-0.20	1.03	1.18	EPS01 RMSE=9.5% JET Type-I ELMs
H_Cs2	0.86	1.03	1.08	PPCF02 RMSE=9.6% JET Type-I ELMs
H_Cs3	0.87	1.00	1.04	02/06/26 RMSE=? all tokamaks

Edge Pedestal Scalings &/or Core Transport Models probably missing strong triangularity dependence

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$$\beta_{\mathrm{Troyon}} = \frac{I}{aB} \propto \left(\frac{a}{qR}\right) [1+\kappa^2(1+2\delta^2)]$$

If global β is this sensitive to triangularity δ, (which is large only near the edge), then the edge $\beta_{pedestal}$ is probably more sensitive to δ.

Rough fit to JT60U papers gives

$$\beta_{ped} \propto [1+\kappa^2(1+10\delta^2]$$

Bateman noted global $\tau_E \propto I_p$ scalings imply

$$\chi \propto \frac{\chi_{GyroBohm}}{[1+\kappa^2(1+2\delta^2)]^2}$$

which for simplicity has been approximated by

$$\chi_{Multimode} \propto \frac{\chi_{Weiland}}{\kappa^4}$$

missing triangularity dependence. (Alternatively, if the core transport is stiff, κ and δ dependence may come in primarily from the edge or pedestal region.)

Comments added after presentation

The first few vugraphs are taken from various sources of JET (including Ongena's EPS-2001 presentation) and Asdex data, and provide strong evidence from controlled experiments that confinement improves significantly with high triangularity and lower n/n_Greenwald, perhaps with a stronger dependence than is found by fits from a broader database that mixes many types of shots together. Part of this may be due to systematic variations in density peakedness, which has yet to accounted for in the fit to a multi-machine database.

It was pointed out to me that DIII-D has results with good confinement (H ~ 1) at high density (n/n_Greenwald ~ 1.5) and low triangularity (delta ~ 0), as shown in Osborne's APS 2000 presentation. But as described in Osborne's paper, these shots have fairly strong density peaking even without pellet injection. This is apparently aided by operation in a low power regime where the Ware pinch is strong, which may go away at higher auxilliary power. To fit the multi-machine database including this DIII-D data, along with the data from other machines that show improvements in confinement at lower density and higher triangularity, will probably require accounting for changes in the density peakedness as well.

It must always be emphasized that there are still significant uncertainties in both global and pedestal scalings, and that a detailed estimate of the confidence interval of such projections remains to be done. Nevertheless, I believe the data indicates that confinement can be improved at high triangularity, lower <n_e>/n_Greenwald, and with modest density peakedness (n_pedestal/<n_e> ~ 0.7) as might be accessible in reactor scale devices such as FIRE.