EXPLORING POSSIBLE HIGH FUSION POWER REGIMES WITH THE IFS-PPPL MODEL

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Edge pedestal scalings very uncertain, but most favor higher-field designs with stronger shaping...

• **Wide range of theory & expt. evidence:** $\Delta/R \propto \rho_{*\theta}$ **(JT-60U, JET),** $\rho_{*\theta}^{2/3-1/2}$, $\beta_{pol}^{1/2}\rho_*^0$ **(very interesting DIII-D evidence of a second stable edge, which would have a more favorable scaling to reactors)**

$\beta_{ped} \sim \Delta\, d\beta/dr$
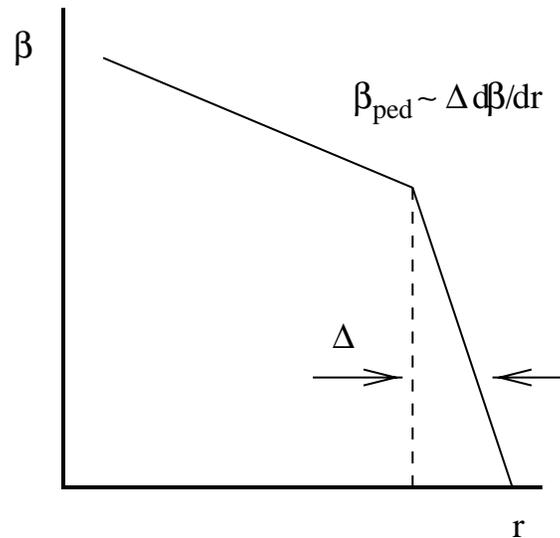
• **Making two assumptions (and use Uckan formula for $q_{95}RI_p/(Ba^2)$):**

1. **Width $\Delta \propto \sqrt{\epsilon}\rho_\theta \propto \rho q/(\kappa\sqrt{\epsilon})$ (scaling preferred by two largest tokamaks)**

2. **stability limit $\partial\beta/\partial r \propto [1 + \kappa^2(1 + 10\delta^2)]/Rq^2$ (rough fit to JT-60U, Koide et.al., Phys. Plasmas 4, 1623 (1997), other expts.), get:**

$$T_{ped} = C_0 \left(\frac{n_{Gr}}{n_{ped}}\right)^2 \left[\frac{1 + \kappa^2(1 + 10\delta^2)}{[1 + \kappa^2(1 + 2\delta^2 - 1.2\delta^3)]}\frac{(1 - (a/R)^2)^2}{(1.17 - 0.65a/R)}\right]^2 \frac{A_i R}{\kappa^2 a}$$

JET data supports $\Delta \propto \rho_{banana}$ & $\partial\beta/\partial r \propto Rq^2$ model.
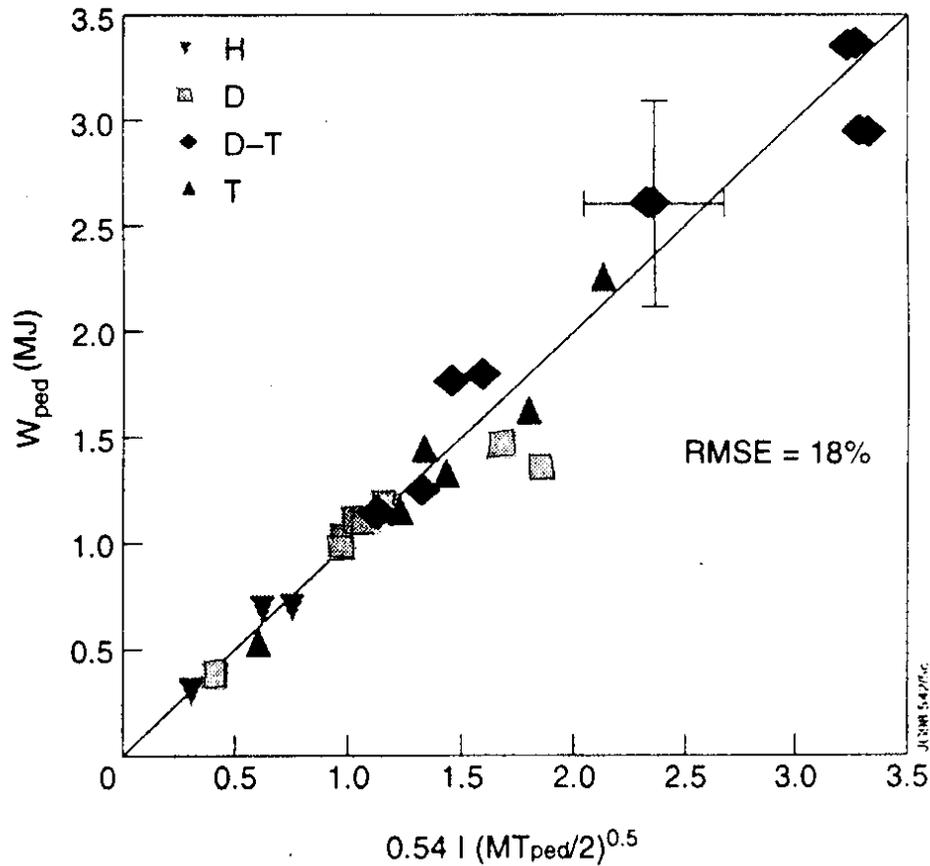

Fig. 4. Scaling of the stored energy in the pedestal (MJ) versus the fit $0.54\ I\ (MT_{ped}/2)^{0.5}$. The symbols are H=Hydrogen, D=Deuterium, D-T=50:50 D-T mixture and T=Tritium.

Cordey + JET Team, JAEA '98

JET data supports $\Delta \propto \rho_{banana}$ + $\frac{\partial\beta}{\partial r} \propto Rq^2$ model

JT-60U showed the first evidence for the $\Delta \propto \rho_{banana}$, $d\beta/dr \propto 1/(Rq^2)$ model. Also find a strong triangularity dependence.

Kamada + JT60-U
IAEA '96
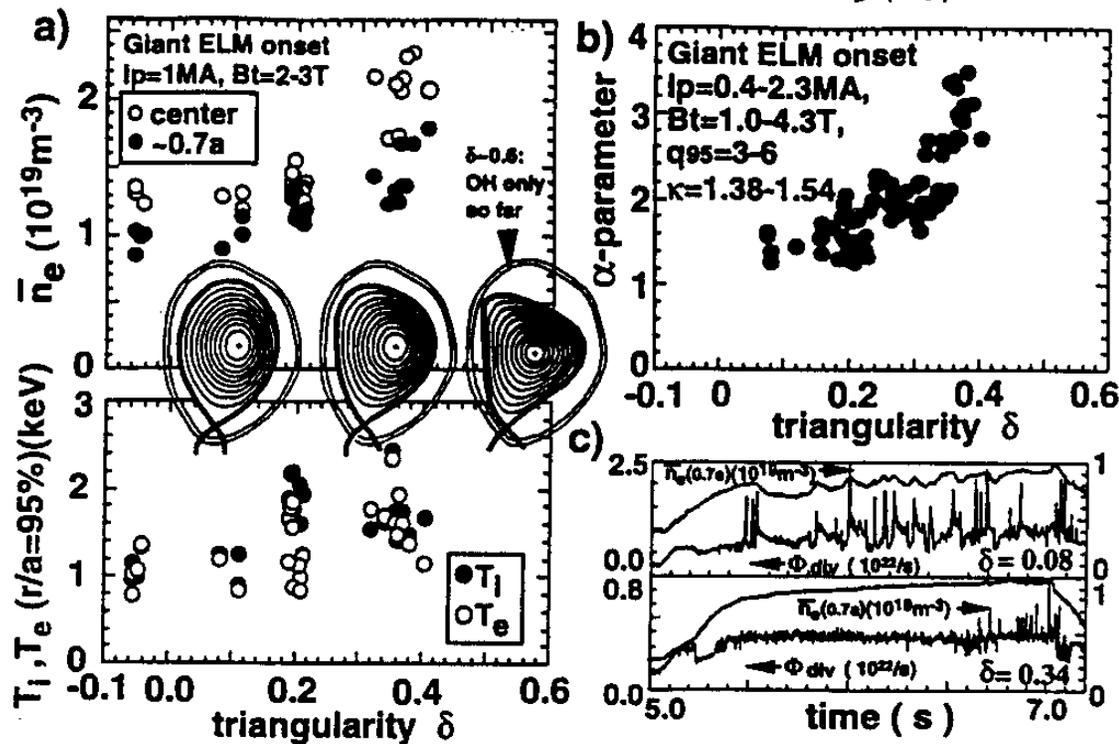
Fig. 1. a) and b): Increasing $\overline{n}_e$ (center chord), $\overline{n}_e(0.7a)$, $T_e(r/a=95\%)$, $T_i(r/a=95\%)$ and edge α-parameter with increasing triangularity at onset of giant ELMs. c): Time traces of D_α^{div} and $\overline{n}_e(0.7a)$ for giant ELMs($\delta=0.08$) and grassy ELMs ($\delta=0.34$, $\beta_p=2.4$) with $P_{NB}=20MW$ and $I_p=0.6MA$.

Some of the new reactor designs may have significantly improved pedestal temperatures

Using this T_{ped} formula (with a $\Delta \propto \rho_\theta$ assumption), and other pedestal scalings also, to scale from JET to some proposed reactor designs:

	R m	a m	B T	I_p MA	n_{ped} $10^{20}/m^3$	$\frac{n_{ped}}{n_{Gr}}$	$\frac{n_{ped}}{\langle n \rangle}$	κ_{95}	δ_{95}	T_{ped} keV if $\Delta \propto \rho_\theta\sqrt{\epsilon}$	T_{ped} keV if $5\delta^2$	T_{ped} keV if $\Delta \propto \sqrt{Rq\rho}$
JET-norm	2.92	0.91	2.35	2.55	0.4	0.40	~ 1	1.61	.17	2.1	2.1	2.1
ITER-96	8.14	2.80	5.68	21.0	1.3	1.52	1	1.60	.24	0.20*	0.18*	1.5*
lower n_{ped}	8.14	2.80	5.68	21.0	0.6	0.70	.70	1.60	.24	0.94*	0.83*	4.2*
ITER-FEAT	6.20	2.00	5.30	15.1	0.58	0.48	.65	1.70	.33	2.9	2.1	7.4
FIRE	2.0	0.53	10.0	6.44	3.6	0.48	.65	1.77	.40	4.8	3.0	6.7

* should add $(nT)_{sol}/n_{ped}$ which could be as high as ~ 0.5 keV.

Encouraging that even with the pessimistic pedestal scaling ($\Delta \propto \rho_\theta$), it may be possible to get high pedestal temperatures by going to stronger plasma shaping, higher field, smaller size, and modest density peaking.

Sensitivity of Fusion Power to Some Assumptions

Baseline assumptions:

IFS-PPPL model for $\chi_{i,e}$ **modified with** $\Delta(R/L_{Tcrit}) = 2$ **to roughly fit Dimits shift seen in gyrokinetic simulations.**

$\langle n_e \rangle / n_{\mathrm{Greenwald}} = 0.74$**. Modest density peaking,** $n_0/\langle n_e \rangle = 1.18$**,** $n_{ped}/\langle n_e \rangle = 0.65$**.**
$n(r) = (n_0 - n_{ped})(1 - (r/a)^2)^{0.5} + n_{ped}$**.**

P_{aux} **adjusted to keep** $P_{net} \geq 1.2 P_{99L \to H}$ **= 30 MW for baseline FIRE, =57 MW for baseline ITER-FEAT.**

	n_0 $10^{20}/m^3$	n_{ped} $10^{20}/m^3$	T_{ped} keV	P_{fusion} MW	Q	T_{i0} keV	P_{aux} MW
FIRE baseline case	6.75	3.6	4.8	264	620.0	18.6	0
$\downarrow T_{ped}$ 30%	6.75	3.6	3.4	142	9.7	15.3	14
flatten $n(r)$	3.60	3.6	4.8	117	22.0	21.7	5
original IFS-PPPL	6.75	3.6	4.8	155	13.0	12.9	11
original IFS-PPPL $\downarrow T_{ped}$ 30%	6.75	3.6	3.4	69	2.6	10.2	26
ITER-FEAT baseline case	1.09	0.58	2.9	192	5.8	18.3	32
$\downarrow T_{ped}$ 30%	1.09	0.58	2.0	111	2.4	15.5	45
ITER-FEAT with FIRE T_{ped}	1.09	0.58	4.8	381	816.0	23.5	0
ITER-FEAT with FIRE $T_{ped} \downarrow$ 30%	1.09	0.58	3.4	241	10.1	19.8	23

CAVEATS, IMPLICATIONS

- **Dimits shift** $\triangle(R/L_{Trit}) \neq constant$**, should depend on parameters. Core neoclassical** $E \times B$ **shear ignored (gets weaker at smaller** ρ_***).**

- **Edge pedestal scalings very uncertain.**

- $T_{pedestal} \propto \left(n_{Greenwald}/n_{ped}\right)^2$ **model has no explicit power dependence, is only a guideline limit for certain regimes (first-stability-limited type-I ELMs). Assumes** $P > P_{LH}$ **threshold. Ignores power needed to sustain pedestal against neoclassical transport, residual edge turbulence, ELMs, etc. Exploring extensions to include** ν_* **dependence of bootstrap current, ...**

- **To study edge turbulence & transport barriers scalings, need flexibility to scan pedestal density over a wide range: high** n_{Gr}**, pellet injection, divertor pumping.**

- **Compact size and strong shaping of FIRE gives high** n_{Gr} **& improved edge stability & high** $T_{pedestal}$ **potential. Lower bound on** n_{ped} **needed for divertor survival appears to be easily satisified in FIRE.**

MORE CAVEATS, FUTURE WORK

Many caveats, contradictory theories, contradictory experiments:

- **edge very complicated, range of theories, most have width $\triangle \propto \rho^{2/3-1}$.**

- **largest machines (JT-60U, JET) support "standard" model of width $\triangle \propto \rho$ and gradient near the ideal MHD limit**

- **others (DIII-D) support $\triangle$ independent of ρ and/or in second stability (boostrap current in pedestal region important in DIII-D?). C-MOD EDA differs from ELMy behaviour on other machines, Neutrals important in C-MOD?**

- **Useful cross-machine database being developed (Sugihara et.al., EPS99, ITER H-mode Edge Pedestal Expert Group Meeting, March 2000). (Sugihara uses different scaling $dp/dr \propto (1 + 9.26\delta^{3.4})$.)**

- **Detailed edge turbulence simulations rapidly becoming more realistic (Xu and Cohen (LLNL), Rogers and Drake (U. Md.), Scott, Jenko, Zeiler et.al. (Garching))**

- **Even with pessimistic $\triangle \propto \rho$ model, newer reactor designs get significantly improved pedestal temperatures by $\uparrow$ field, triangularity, and elongation (which increase Greenwald density and edge stability), and by assuming a modest density peaking**