

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

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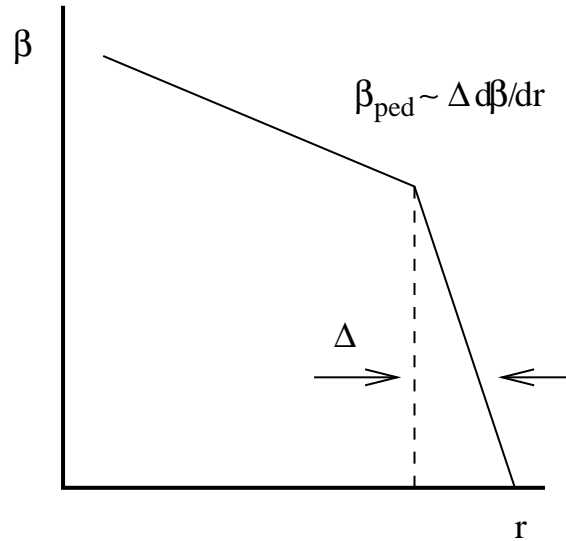
**Some of this presented by D. Meade (PPPL) at
Workshop on Burning Plasma Sciences, General Atomics, May, 2001**

Original: Workshop on Burning Plasma Sciences, December, 2000

**Extension of paper presented at 1999 Snowmass workshop,
<http://www.ap.columbia.edu/SMproceedings>
see also PPPL-3360 (1999):
http://www.pppl.gov/pub_report/1999/PPPL-3360-abs.html**

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)



- Making two assumptions (and use Uckan formula for $q_{95} R I_p / (B a^2)$):
 1. Width $\Delta \propto \sqrt{\epsilon} \rho_\theta \propto \rho q / (\kappa \sqrt{\epsilon})$ (scaling preferred by two largest tokamaks)
 2. stability limit $\partial\beta/\partial r \propto [1 + \kappa^2(1 + 10\delta^2)] / R q^2$ (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.

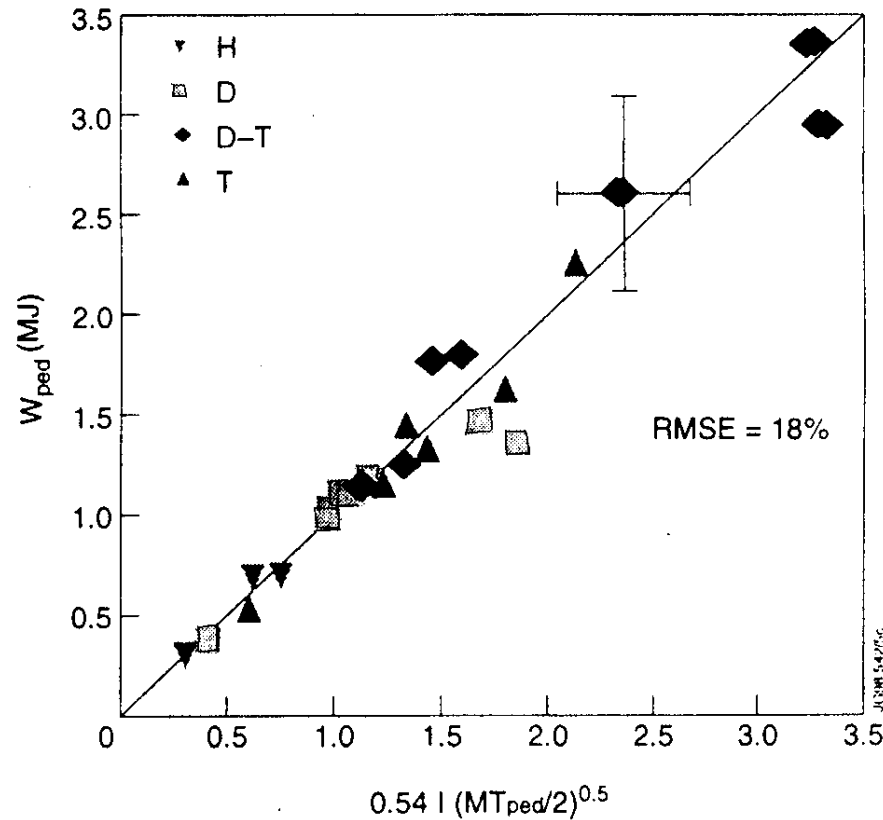


Fig. 4. Scaling of the stored energy in the pedestal (MJ) versus the fit $0.54 I (MT_{ped}/2)^{0.5}$. The symbols are H=Hydrogen, D=Deuterium, D-T=50:50 D-T mixture and T=Tritium.

Cordey + JET Team, IAEA '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

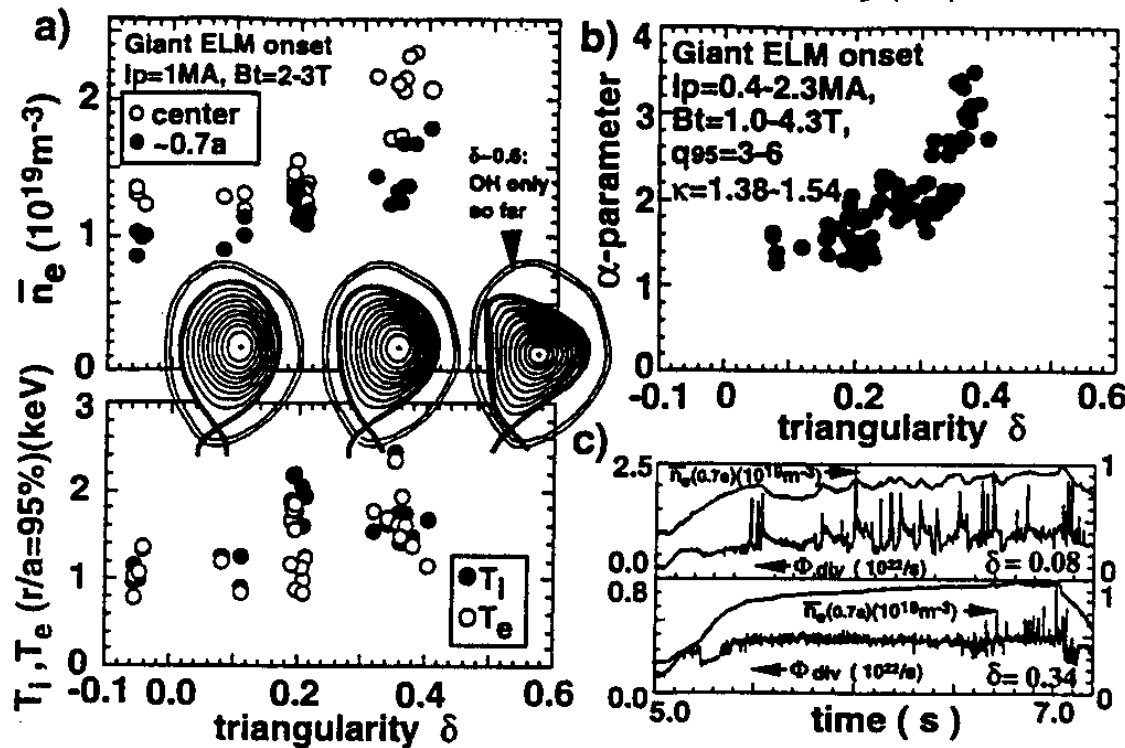


Fig. 1. a) and b): Increasing \bar{n}_e (center chord), $\bar{n}_e(0.7a)$, $T_e(r/a=95\%)$, $T_i(r/a=95\%)$ and edge α -parameter with increasing triangularity at onset of giant ELMs. c): Time traces of D_{α}^{div} and $\bar{n}_e(0.7a)$ for giant ELMs ($\delta=0.08$) and grassy ELMs ($\delta=0.34$, $\beta_p=2.4$) 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.

$\langle n_e \rangle / n_{Greenwald} = 0.74$. **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 $P_{net} \geq 1.2P_{99L \rightarrow H} = 30$ 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
↓ 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 ↓ 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
↓ 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} ↓ 30%	1.09	0.58	3.4	241	10.1	19.8	23

CAVEATS, IMPLICATIONS

- **Dimits shift $\Delta(R/L_{Trit}) \neq \text{constant}$, should depend on parameters. Core neoclassical $E \times B$ shear ignored (gets weaker at smaller ρ_*).**
- **Edge pedestal scalings very uncertain.**
- **$T_{pedestal} \propto (n_{Greenwald}/n_{ped})^2$ 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 satisfied in FIRE.**

MORE CAVEATS, FUTURE WORK

Many caveats, contradictory theories, contradictory experiments:

- edge very complicated, range of theories, most have width $\Delta \propto \rho^{2/3-1}$.
- largest machines (JT-60U, JET) support “standard” model of width $\Delta \propto \rho$ and gradient near the ideal MHD limit
- others (DIII-D) support Δ independent of ρ and/or in second stability (bootstrap 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 $\Delta \propto \rho$ 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

May 2001 Addendum

- H-mode expts give evidence of multiple regimes: ELM-free, ELMY, Type-I, -II, -III, EDA. Different experiments show different scalings for pedestal width and height.
- Different physics may be setting limits in various regimes: The model presented here (pedestal width $\Delta \propto \rho$ model with a first-stability beta limit) may be applicable in only certain regimes.
- In other regimes the edge bootstrap current may lower magnetic shear enough to lower the first stability boundary (Sugihara, EPS 1999) or even to access 2cd stability (as DIII-D expts and analysis by Osborne, Miller, et.al. suggest). However, if the edge bootstrap current gets too strong it may trigger a peeling mode (as Wilson, Snyder, etc. are studying). Studying improved mixed-regime models with Onjun, Bateman, Kritz (Lehigh).
- Hopefully these uncertainties can be reduced with the new edge database and comprehensive edge turbulence/stability simulations.