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

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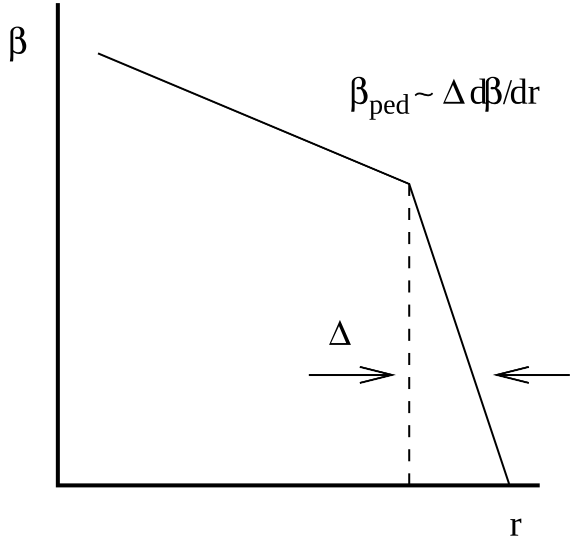
Some of this discussed by D. Meade (PPPL) at
Workshop on Burning Plasma Sciences, General Atomics, May, 2001

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

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

(Hammett, Dorland, Kotschenreuther, Beer, PPPL-3360 (1999))

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

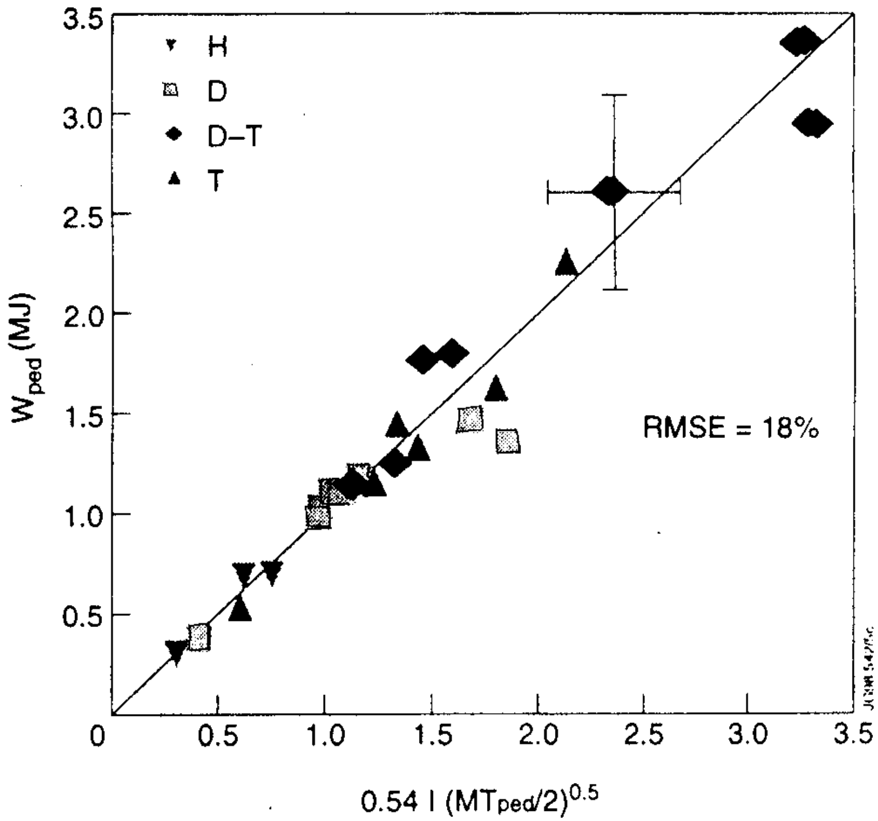


Fig. 4. Scaling of the stored energy in the pedestal (MJ) versus the fit 0.54 I $(MT_{ped}/2)^{0.5}$. The symbols are H=Hydrogen, D=Deuterium, D-T=50:50 D-T mixture and T=Tritium.

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

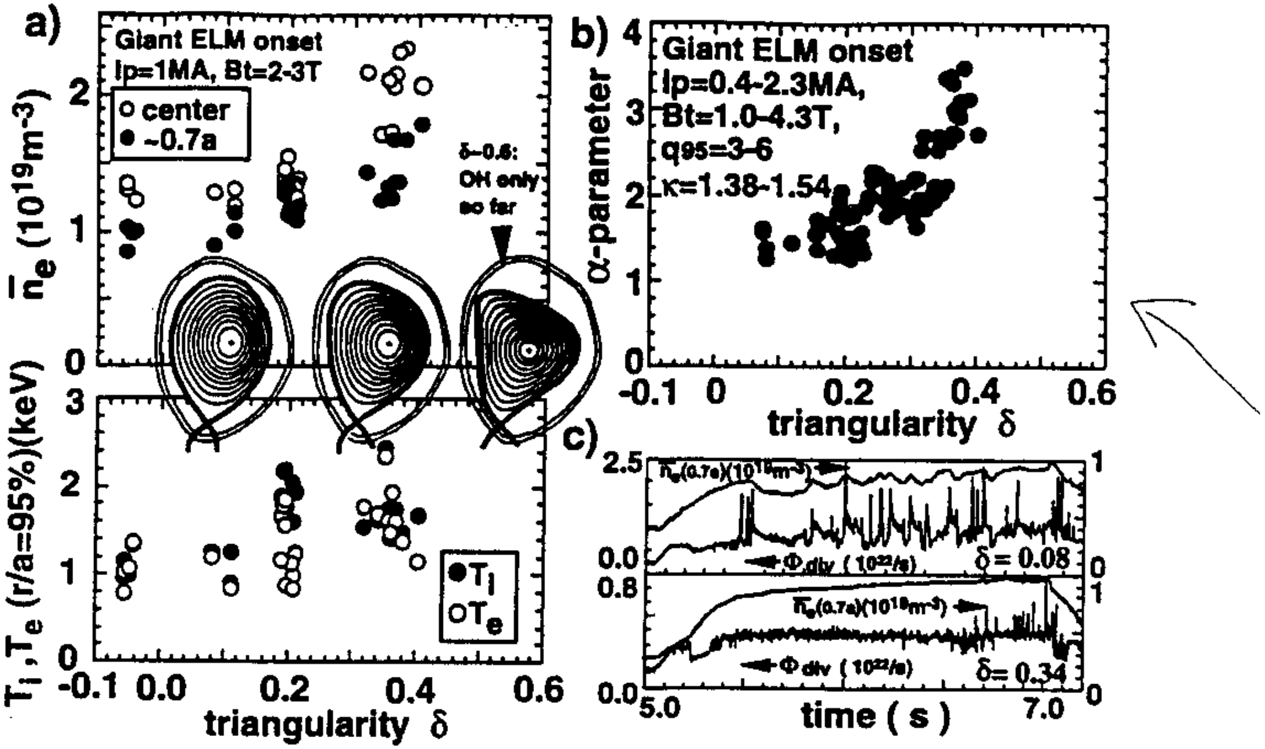


Fig. 1. a) and b): Increasing $\bar{n}_e$ (center chord), $\bar{n}_e(0.7a)$, $T_e(r/a=95\%)$, $T_i(r/a=95\%)$ and edge α-parameter with increasing triangularity at onset of giant ELMs. c): Time traces of D_α^{div} and $\bar{n}_e(0.7a)$ for giant ELMs(δ=0.08) and grassy ELMs (δ=0.34, β_p=2.4) with P_{NB}=20MW 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.

(Hammett, Dorland, Kotschenreuther, Beer, PPPL-3360 (1999))

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** $P_{net} \geq 1.2 P_{99L \rightarrow H}$ **= 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
$\downarrow T_{ped}$ 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 $\Delta(R/L_{Trit}) \neq constant$, should depend on parameters. Core neoclassical $E \times B$ shear ignored (gets weaker at smaller ρ_*).**

- **Edge pedestal scalings very uncertain.**

- **$T_{pedestal} \propto (n_{Greenwald}/n_{ped})^2$ 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 satisified 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 (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 $\Delta \propto \rho$ 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 bootstratp 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.**