Pedestals and Confinement

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Global confinement is highly dependent on the pedestal height

- If the core confinement is "stiff, gobal confinement is highly dependent on the H-mode pedestal temperature, T_ped . What does "stiff" mean?

- The core is "perfectly stiff", if T(0) is linear with T_ped and independent of power P_ped.

- The theoretical core transport models in standard use, GLF23 and Multi-Mode, are not perfectly stiff, but Multi-Mode has some stiffness $T(0) \propto T\_ped^{0.3}$ and GLF23 is very stiff $T(0) \propto T\_ped^{0.7}$

- While the core theoretical transport models can predict global confinement time to better than 10% given T_ped, empirical statistical scaling models for T_ped are typically 30%. Hence for very stiff models the combination likely has less predictability for confinement time than global τ_E scaling laws, typically 15%.

- For very stiff models Q can be uncertain by 50%, and predicting the H-mode pedestal heights is the focus of our uncertainty in predicting BPX performance.

Core Transport Models

- The past decade has seen considerable progress in understanding of core transport and development of theoretical core transport models.

  - The focus has been on two comprehensive models: GLF23renorm and MutiMode

  - These theoretical drift wave based models with ExB shear stabilization have been very successful in matching the ITER profile data L- and H-mode database given the pedestal temperature and density, and in describing internal transport barriers.

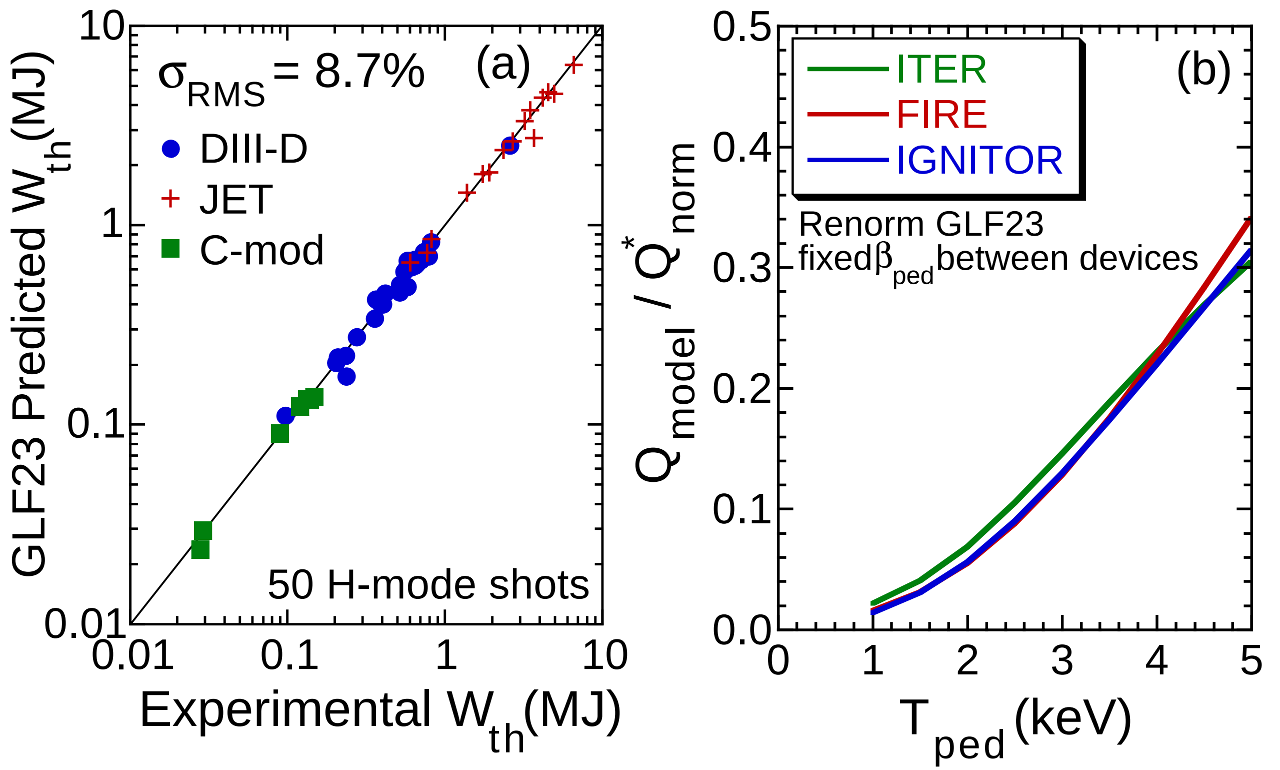
  - GLF23renorm is fit to gyrokinetic linear stability and nonlinear simulations taking nothing from data, yet predicts core stored energy with RMS 8.7%.

  - MultiMode has similarly good fit statistics.

- (a) GLF23renorm comparison with H-mode data
- (b) model Q /Q_norm vs T_ped

$$Q_{norm} = \kappa R\,(I/a)^2 (n_{ped}/n_G)^2 (n_i/n_e)^2 (n_e/n_{ped})^{1.5}\, C_{RLT}/P_{aux}$$

$$\text{with } C_{RLT} = \exp[2(2.0 + .004 P_{net})/(R/a) + 0.5(1 - n_i/n_e)]$$



(see Kinsey Sherwood talk)

Core Transport Models (cont'd)

- While both models have similar ITG and trapped electron physics and comparable RMSE fits to data, they not only have quantitatively, but qualitatively, different Q –projections.
- While GLF23renorm is not as stiff as IFS-PPPL and '96GLF23, it is still very stiff with Q having nearly inverse P_aux dependence. Approximatedly:

  $Q \quad \alpha \quad Volume \quad n\_ped^2 \; T\_ped^2 \, / \, P\_aux$ *(see Kinsey Sherwood talk)*

  - This means Q can be doubled by halving P_aux required to get into H-mode, and P_fus is insensitive to P_aux.

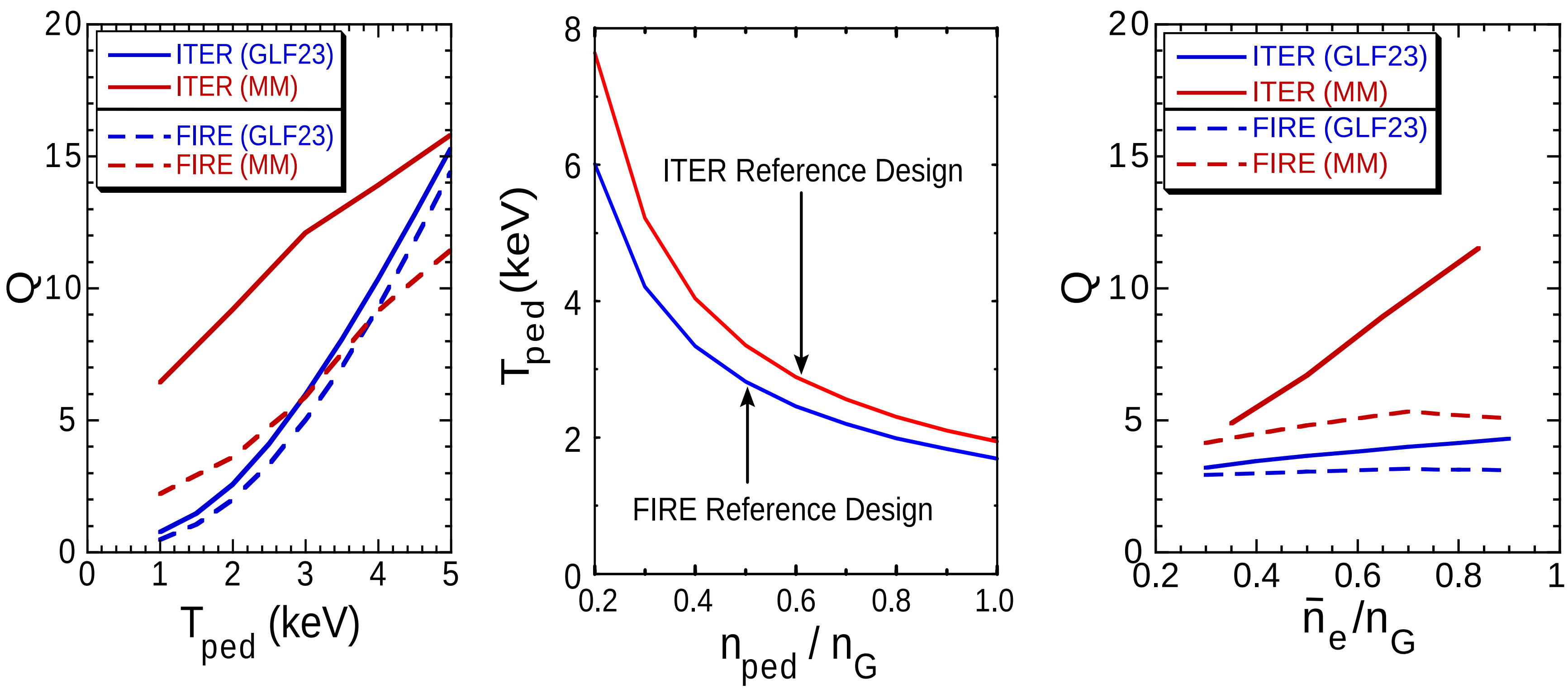
  - Since (as we will discuss), the projected T_ped α 1 / n_ped, Q depends weakly on n_ped / n_Greenwald , and pedestal projections should focus on predicting maximum

    p_ped or better beta_norm_ped = beta_ped / (I /aB)

- MultiMode as is much less stiff with $Q \quad \alpha \quad Volume \quad n\_ped^2 \; T\_ped \, / \, P\_aux^{0.25}$

Core Transport Models (cont'd)

- **Examples GLF23 / MM with Onjun-Bateman et al T_ped Model**



*** *Kinsey, Onjun, Batman, et al***

Core Transport Models (cont'd)

- Thus core transport model stiffness is a key issue, but we shouldn't need a BPX to resolve this difference.

- $W\_tot / W\_ped \ \alpha \ P^{s}$ roughly: GLF23renorm: s = 0.1, MultiMode: s = 0.2

  - Remarkably, ITER database statistical free fits over all data machine says

    $W\_tot \ \alpha \ P^{0.31}$ and $W\_ped \ \alpha \ P^{0.31}$ suggesting perfect stiffness, i.e. s=0. m 0.05

    (recent Thomsen, Cordey et al paper)

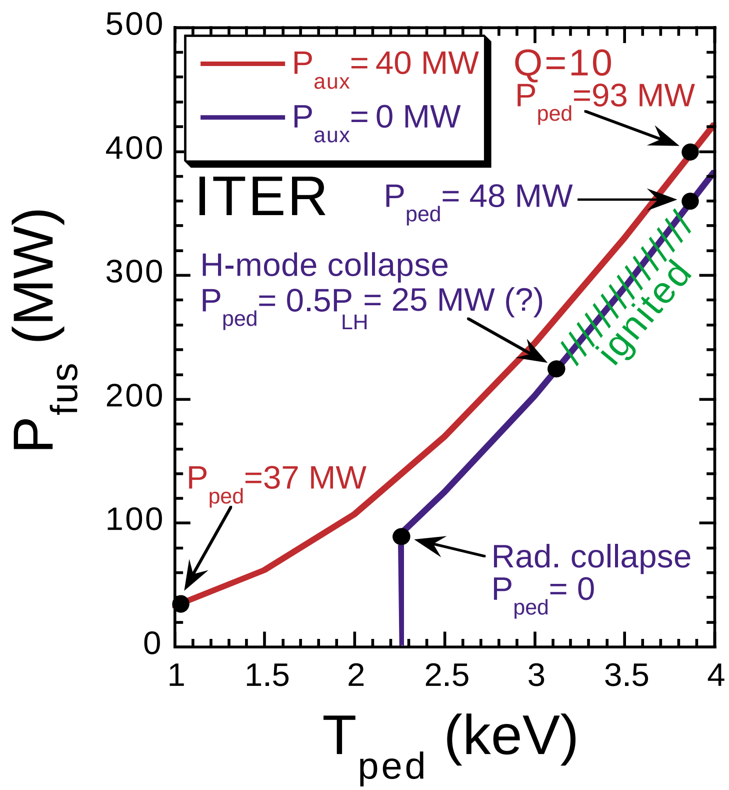
  - Precise controlled single machine P scaling data or new experiments should be able to distinguish between s=0.1 and s=0.2

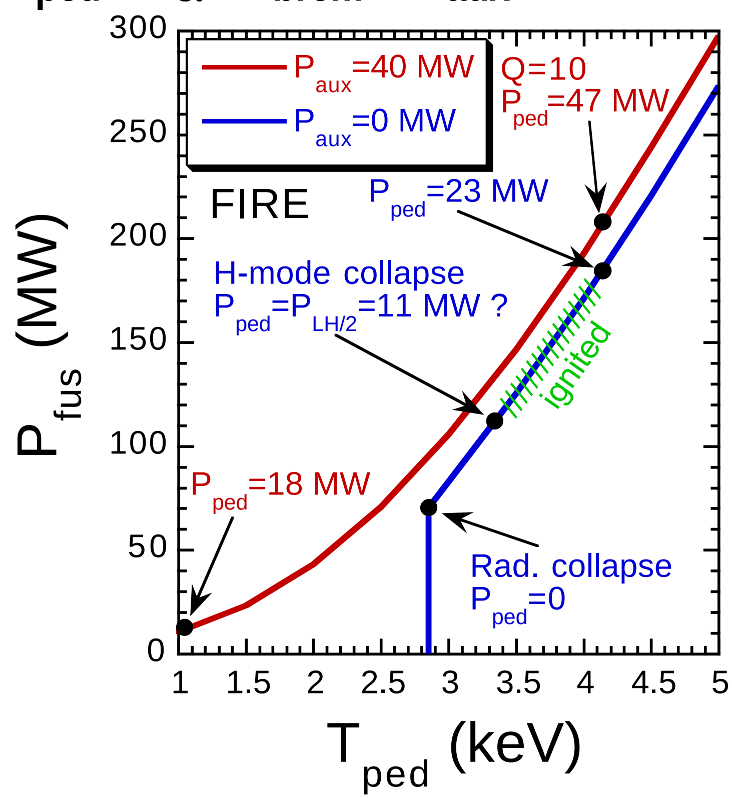
Core Transport Models (cont'd)

- Stiff cores are magical for getting high Q ....even ignition Q = infinity with $P_{aux} = 0$!!!!

  If there is enough power flow P_{ped} to maintain the pedestal temperature T_{ped}

- $P_{fus} = 5 P_{\alpha}$; $Q = P_{fus}/P_{aux}$; $P_{ped} = P_{\alpha} - P_{brem} + P_{aux} > 1/2$ P_LH





- We need to know power dependence (σ) for T_ped = T_ped_LH (P_{ped} / P_LH)$^{\sigma}$

GENERAL ATOMICS

H-mode Pedestal Height

- Although we have some understanding of how T_ped is determined, we don't have theroretical models. Projected T_ped is largely based on statistical empirical fits.
  - The "best" fits to all machine data are characterized by an RMS of 27%.
  - If core transport model projections are perfect, and $Q \alpha T\_ped^2$, then

    Q = 5 is really 2.65 < Q < 8.10

    Q = 10 5.3 < Q < 16.2

- Approaches to finding the pedestal height:
  - Free statistical fit: W_ped = 3 p_ped Volume *(e.g. Thomsen, Cordey et al paper *)*

    $$W\_ped = e^{-3.74} I^{1.71} R^{1.16} P^{0.31} M^{0.30} q\_sh^{1.20}$$ RMS = 25.4% *

  - Stat. fit of width_ped with approx. high-n MHD stability gradient constraint P^0

    p_ped = width_ped [d p / dr]_crit e.g. $width\_ped \alpha rho\_pol^{0.23} R^{0.77}$

    $$W\_ped = e^{-4.61} I^2 R [M / nR^2]^{0.13} q\_sh^{1.20} [a / R]^{-1.68}$$ RMS = 27.3% *

    or $width\_ped \alpha beta\_pol^{0.5} R^{1.0}$ is a popular choice suggested by DIIID data.

H-mode Pedestal Height (cont'd)

- Problems with statistical approaches:

  - Existing fits lump all data, when likely there is a low power P- dependent regime, and the stiff P-independent MHD fits likely apply only to a high power saturated regime.

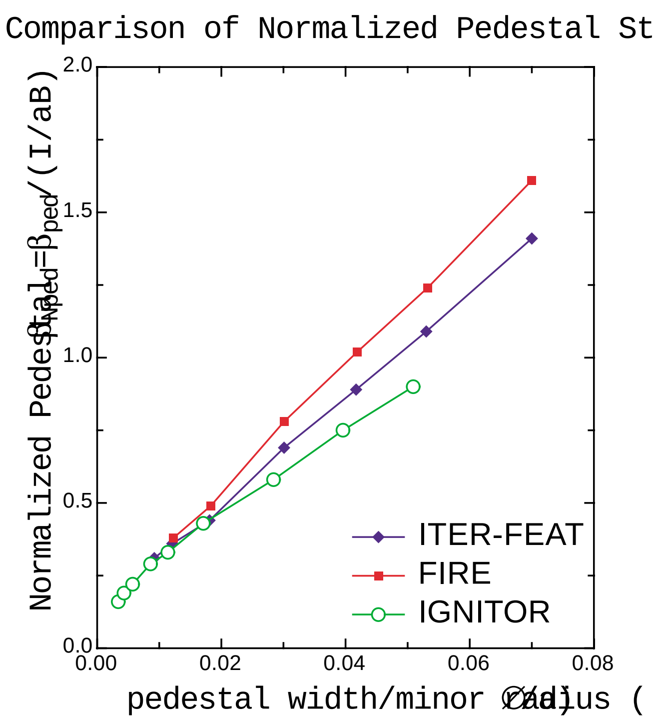
  - Detailed peeling - ballooning mode edge stability with real equilibria varying width_ped, finds that [d p / dr]_crit depends on width_ped, e. g. p_ped α width_ped$^{0.7}$ and furthermore edge stability (and ELM's) depend sensitively on edge shaping and edge bootstrap current (breaking density independence) . *(Snyder recent APS talk)*

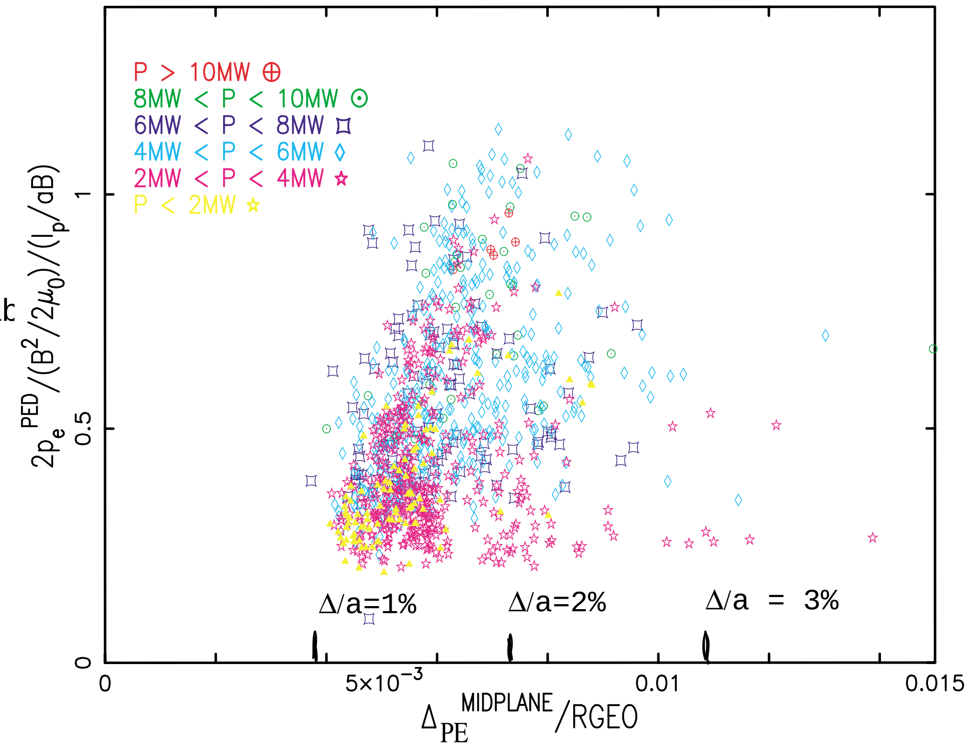
- Better not to focus on width_ped, or T_ped but instead on maximum attainable

β_N _ped : beta_norm_ped = beta_ped / (I /aB)

H-mode Pedestal Height (cont'd)

- Some example edge stability studies for $\beta_{N_}$ped vs pedestal width (Snyder)





DIIID

GENERAL ATOMICS

The physics mystery behind the pedestal

- beta_ped = (width_ped / a) (q/R) s / q^2 approx. high-n MHD stability limit

Keeping shapes (s, q, a/R) the same :

- Is the layer width determined by the MHD stability allowed ?

(width_ped / a) α (β_pol _ped)$^{0.5}$ α (n_ped T_ped)$^{0.5}$ / B_pol

- or, by the cause of the good confinement layer ?

….turbulence growth rates compared to diamagnetic ExB shear rates

(width_ped / a) α ρ_star_pol _ped α (T_ped)$^{0.5}$ / (a B_pol)

- Hard to distinguish scaling difference between ρ_star_pol _ped and (β_pol _ped)$^{0.5}$, but

ρ_star_pol _ped / (β_pol ped)$^{0.5}$ α 1/ [a n_ped$^{0.5}$] α 1 / [a B (n_ped/n_G)]$^{0.5}$

[a B] is going to get larger [ITER, FIRE, Ig] 10, 6 , 6 [JET] 4.3 but not a lot,
maybe offset with smaller (n_ped/n_G)

- **Examples from a very stiff model:**

fit to many GLF23renorm transport code runs for ITER, FIRE, IGNITOR at q_95 = 3, κ=1.8

$$P\_fus = volume\,(beta\_ped\_N)^2\,[B^2\,(I/a/B)]^2$$

$$\times\;\; 5.83\times10^{-5}\,(n\_i/n\_e)^2\,(n\_line\,/\,n\_ped)^{1.5}$$

$$\times\;\; \exp\,[2.(2.15+(1.-(n\_i/n\_e))+0.75(1.+0.5/\nu^{0.25}))\,/\,(R/a)]$$

$$\times\;\; \exp\,[2.(0.00275\;P\_ped\,(R/a)^{1.5}/\,T\_ped^{1.5})^2]$$

where $\nu = 0.1\, n\_line\_19\, R / T\_ped^2$ and $volume = \kappa\,(\pi\, a^2)\,(2\pi\, R)$

[meters, Tesla, MA, keV, MW, n_19, etc]

$$beta\_ped\_N = beta\_ped/(I/a/B)$$

$P\_ped = P\_fus / 5. - P\_brem + P\_aux + P\_oh$ $\quad$ $Q = P\_fus / P\_aux$

(see Kinsey Sherwood talk)

GLF23renorm fit core + Thomsen-Cordey MHD-pedestal rule
compared to y2 and gB_perkins H global τ_E scaling

n_line/n_ped = 1.4, T(0)/T_ped = 5.0, T(0)/<T>=2.6, <β>_N / β _ped_N = 3.32

ITER-FEAT

P_aux MW	n_line / n_G	core-ped model Q	β_ped_N	T_ped	y2 Q	β_ped_N	T_ped	gB_perkins Q	β_ped_N	T_ped
40	0.86	4.9	0.42	2.9	11.	0.50	3.5	31	0.86	6.0
20		9.4	0.42	2.9	15.	0.43	3.0	49.	0.79	5.3

FIRE

P_aux MW	n_line / n_G	core-ped model Q	β_ped_N	T_ped	y2 Q	β_ped_N	T_ped	gB_perkins Q	β_ped_N	T_ped
20	0.70	4.1	0.58	2.8	4.4	0.43	2.0	8.	0.54	2.6
		4.8*	0.61*	2.9	8.5 #	0.55	2.6	19. #	0.82	3.9
10		8.2	0.58	2.8	2.9	0.30	1.4	2.8	0.30	1.4
		5.3*	0.47*	2.3	9.7 #	0.44	2.0	24. #	0.68	3.1

* Thomsen-Cordey free-fit power scaled pedestal rule # hh=1.15