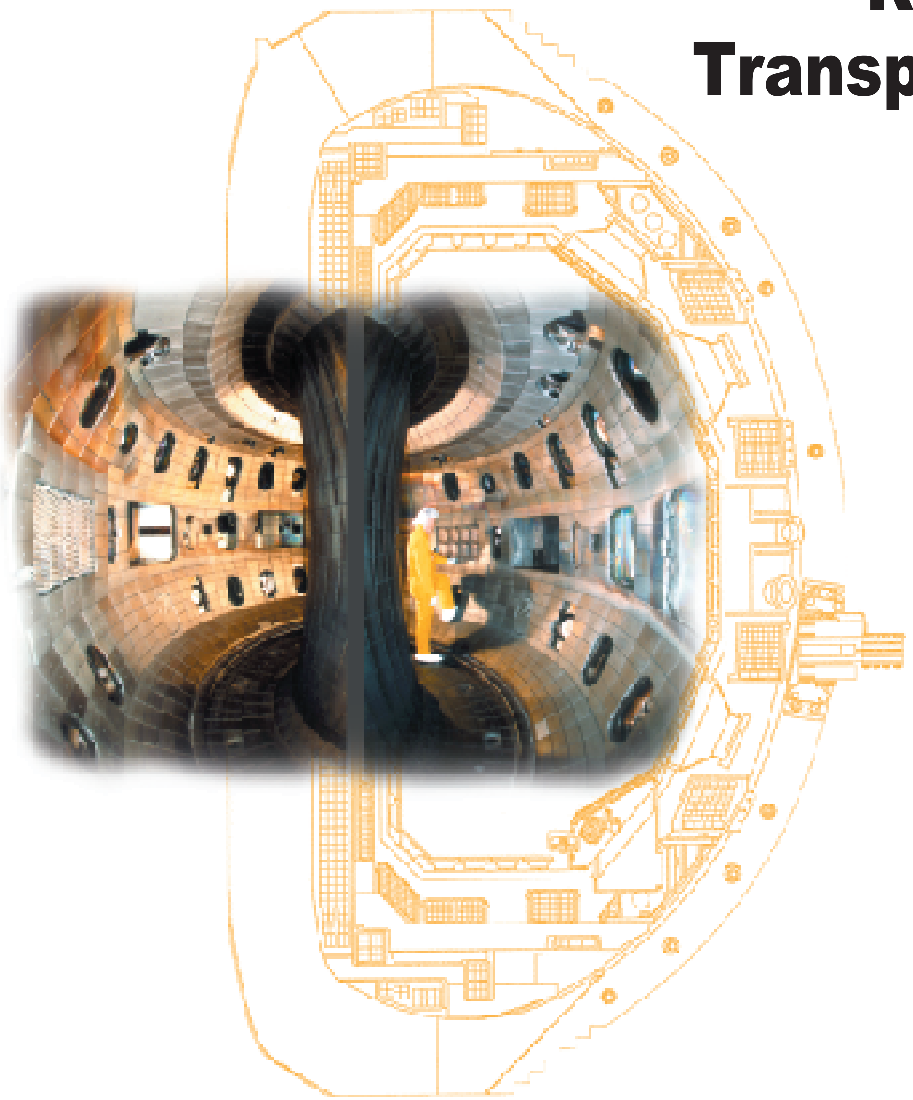
Renormalization of the GLF23 Transport Model & Burning Plasma Projections on a Universal Curve of Q versus Tped



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DIII-D
NATIONAL FUSION FACILITY

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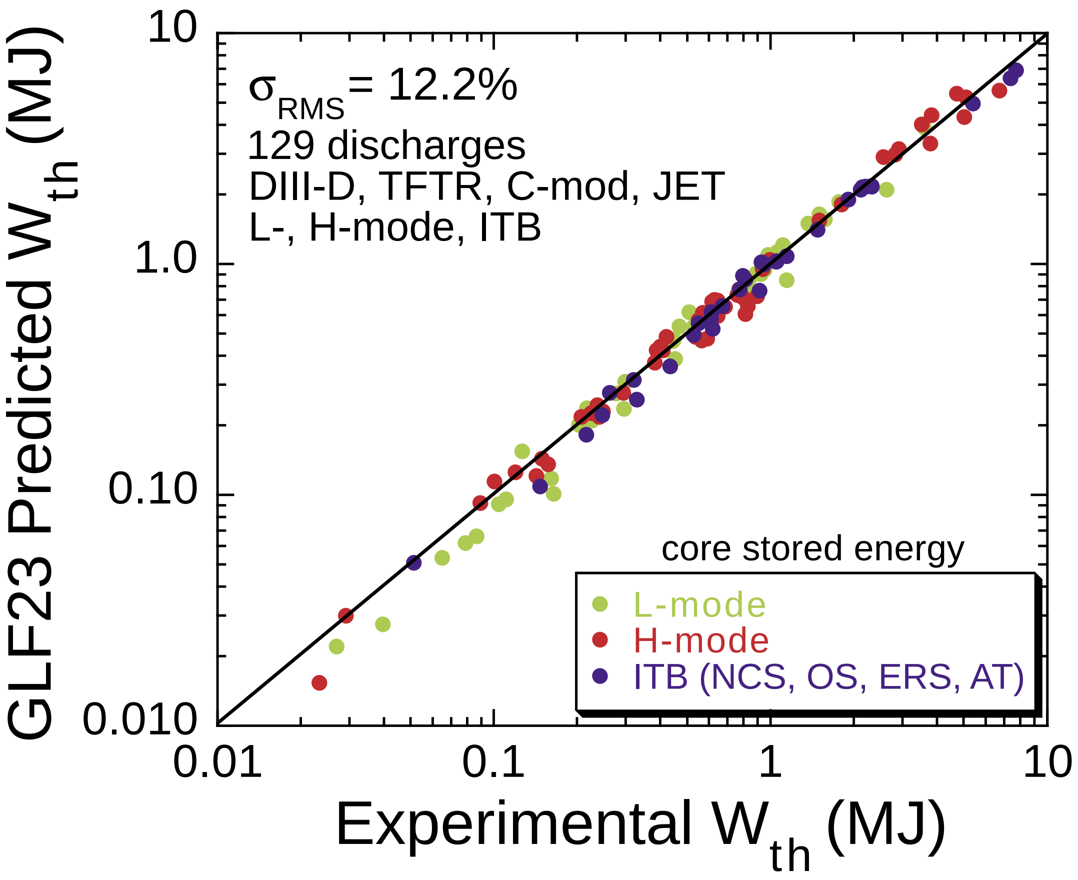
Main Points

- GLF23 transport model has been renormalized
- Predicted fusion gain Q sensitive to temperature profile stiffness and assumed auxiliary heat power
- Global formula that fits GLF23 fusion projections is found
- Fusion power scales with pedestal beta, $P_{fus} \propto (\beta_{ped})^2$
- Ignition possible for reasonable pedestal beta values that are expected to be MHD stable
- Need to know the power scaling and width of H-mode pedestal pressure in order to predict fusion Q accurately

GLF23 Transport Model Based Upon Turbulence Simulations Shows Agreement With Profiles Across Various Confinement Regimes

- **Statistics computed core stored energy (subtracting pedestal region) using exactly same model used for ITB simulations**



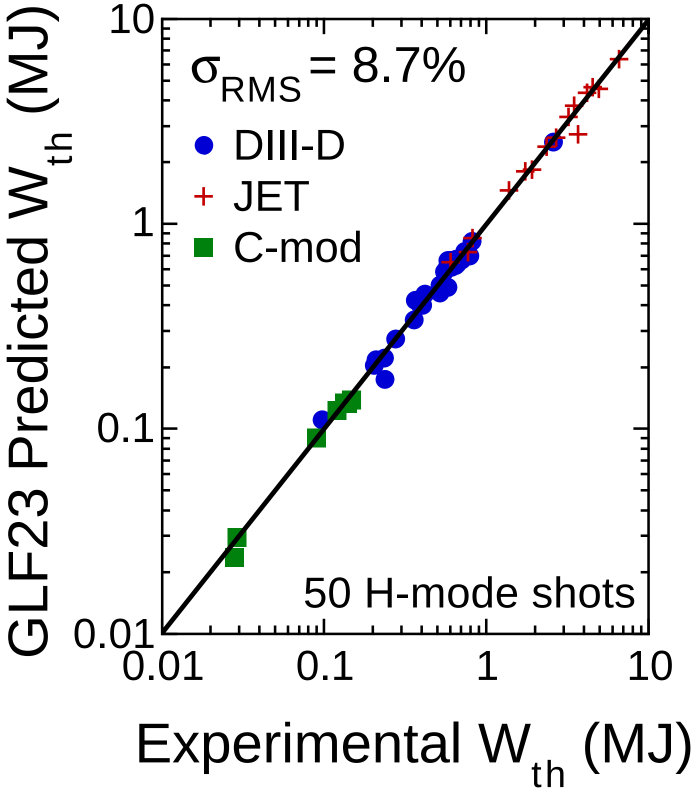
* T_e , T_i , v_ϕ
predicted for ITBs

* 72 DIII-D, 20 JET, 28 TFTR, 9 C-mod

Recent Gyro-kinetic Simulations of ITG/ETG Turbulence Motivates a Renormalization of the GLF23 Model

- **For parameters used to normalize GLF23, gyro-kinetic ITG mode simulations predict a factor of 4 lower saturation level than gyro-fluid simulations**
- **ETG mode simulations show that electron thermal transport levels are significantly larger than when assuming a square root of the mass ratio scaling from ITG simulations**
- **GLF23 refit using a 50 shot H-mode database from DIII-D, C-mod, JET where normalizing coefficients for ITG and ETG modes were adjusted separately to minimize rms error in stored energy**

σ_{ori} = 10% ➔ σ_{renorm} = 8.7%

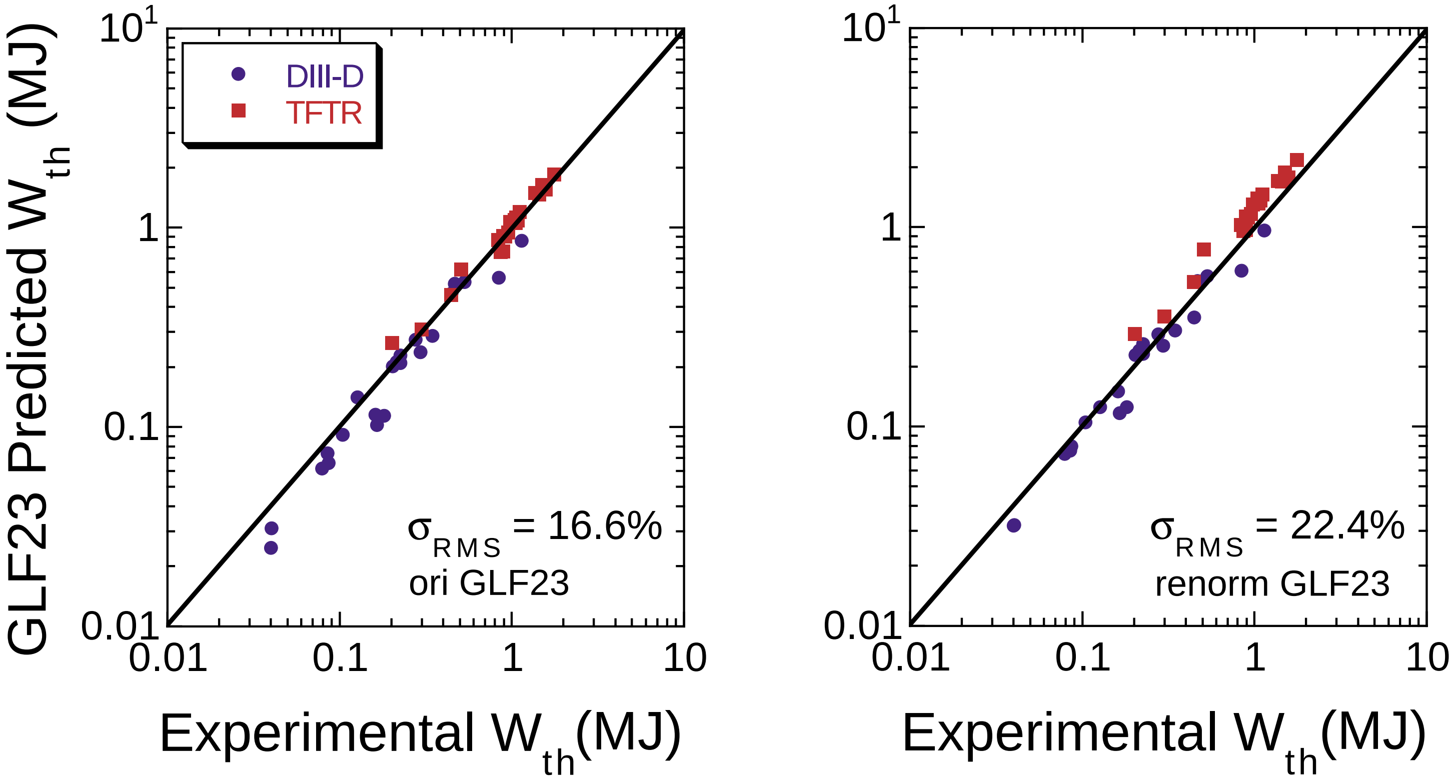


C_{ITG}=0.27 C_{ETG}=4.8 New fit

($C_{ITG/ETG}$ =1.0 in original GLF23)

Renormed GLF23 Model Does Not Agree as Well With L-mode Profile Database Compared to Original Model

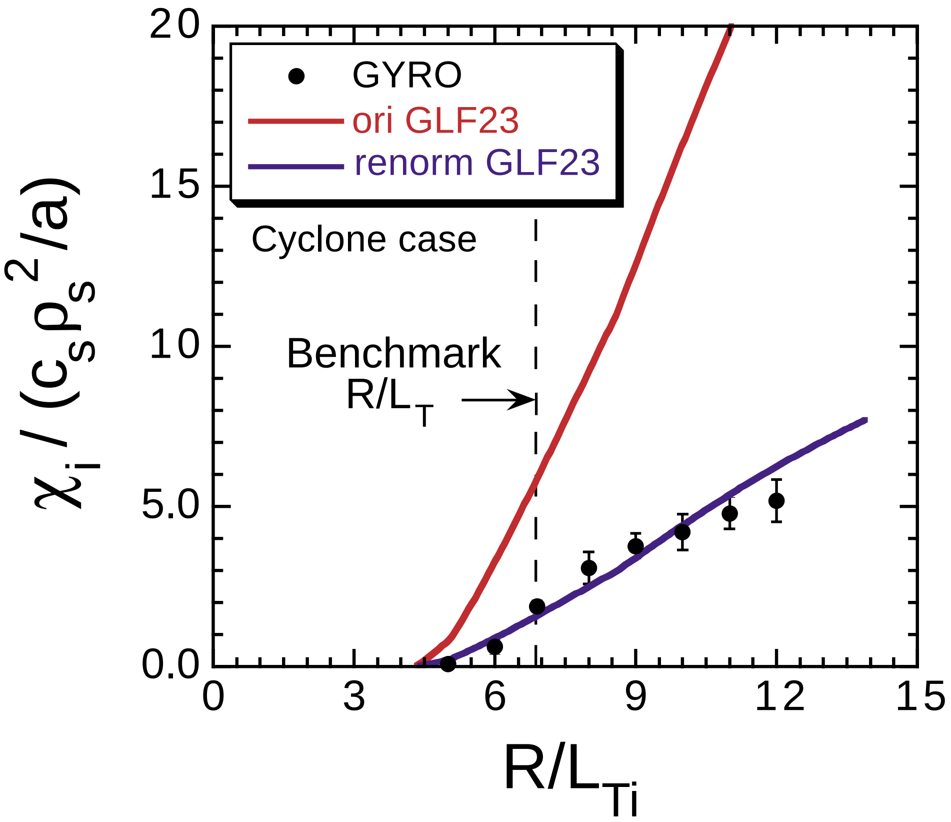
- **Statistics computed for core stored energy (subtracting pedestal region)**
- **RMS error increased from σ =17% to 22%),**
- **Agreement better for DIII-D (σ =21%->16%), worse for TFTR (σ =10.5%->28%) geometric effects and/or TEM physics ?**



43 L-mode discharges

Renormed GLF23 Model Shows Agreement With Gyro-kinetic ITG Simulations of Cyclone Test Case

- **Ion heat diffusivity via ITG mode computed using GYRO gyro-kinetic code w/ adiabatic electrons for Cyclone test case* (Waltz, Candy)**
- **Original model, normalized to gyro-fluid simulations, overpredicts diffusivity by more than a factor of 3 at experimental R/L$_{Ti}$**
- **Renormed GLF23 model shows excellent agreement over a range of R/L$_{Ti}$ for Cyclone parameters**



* Dimits, et al., Phys. Plasmas 7, 969 (2000)

Burning Plasma Projections

- The GLF23 model has been uniformly applied to ITER-FEAT, FIRE, and IGNITOR and the fusion performance assessed
  - Renormed model used
  - Temperature profiles predicted while computing the effects of ExB shear and Shafranov shift stabilization
  - Toroidal rotation velocity assumed to be zero
  - Density profiles, equilibrium, heating sources taken as inputs
  - Assumed same plasma shape, safety factor profile
  - Alpha heating, Ohmic heating, Bremsstrahlung, synchrotron radiation self-consistently computed
- Fusion power predicted for a range of pedestal temperatures
- Both conventional H-mode (flat density, monotonic q-profile) and AT scenarios (density peaking, reversed shear) considered
- Densities in FIRE and IGNITOR scaled so pedestal β same as in ITER to keep α-stabilization at pedestal fixed

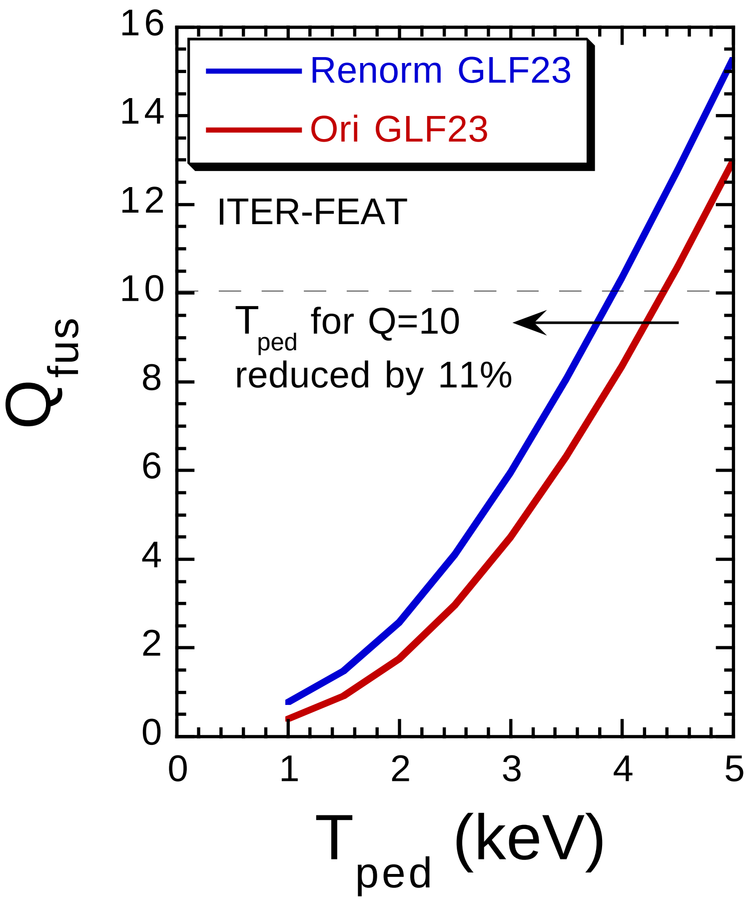
Burning Plasma Design Parameters

Physical Qty	IGNITOR	FIRE	ITER-FEAT
R (m)	1.33	2.14	6.20
a (m)	0.46	0.60	2.00
κ	1.80	1.80	1.80
δ	0.40	0.40	0.40
B_T(T)	13.0	10.0	5.30
I_P (MA)	12.0	7.70	15.0
$\bar{n}_e$ (10^{20}m^{-3})	8.5	4.8	1.0
n_e / n_G	0.50	0.70	0.85
Z_{eff}	1.20	1.40	1.50
P_{Aux} (MW)	10.0	20.0	40.0

$n_G = I_P/(\pi a^2)$ Greenwald density limit

Fusion Projections Using Renormed GLF23 Somewhat More Optimistic Than Original Model

- **Increase in ETG mode stiffness somewhat offsets decrease in ITG/TEM mode stiffness leading to a small increase in fusion performance**
- **Stiffness is a measure of how fast the transport increases once the critical gradient is exceeded**
  - **Stiff → large diffusivity**
  - **Profiles unresponsive to additional power**
- $P_{fus} = 5\,P_{\alpha}$, Q= P_{fus}/P_{aux}
- **Required T_{ped} for Q=10 reduced by 11% from 4.4 keV to 3.9 keV**
- **Q scales approximately as $(T_{ped})^2$**



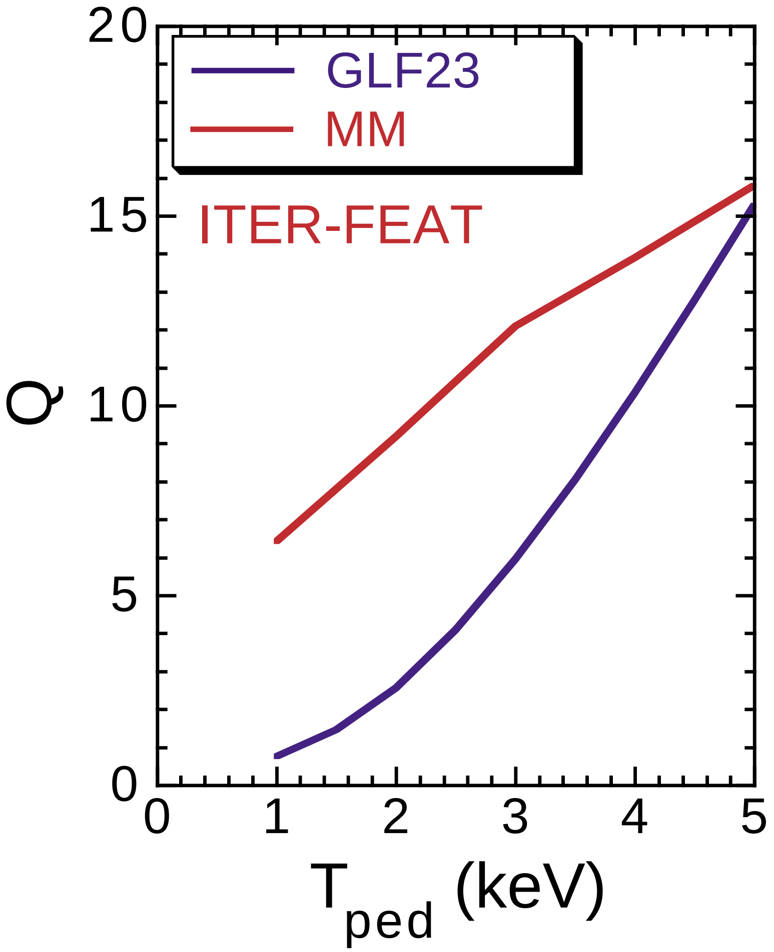
Fusion Projections From Competing Drift Wave Based Models Sensitive to Stiffness of Core Transport

- GLF23 (stiff) and Multi-mode (less stiff) transport models predict very different levels of performance

  $Q \propto (T_{ped})^{1.8}$: GLF23

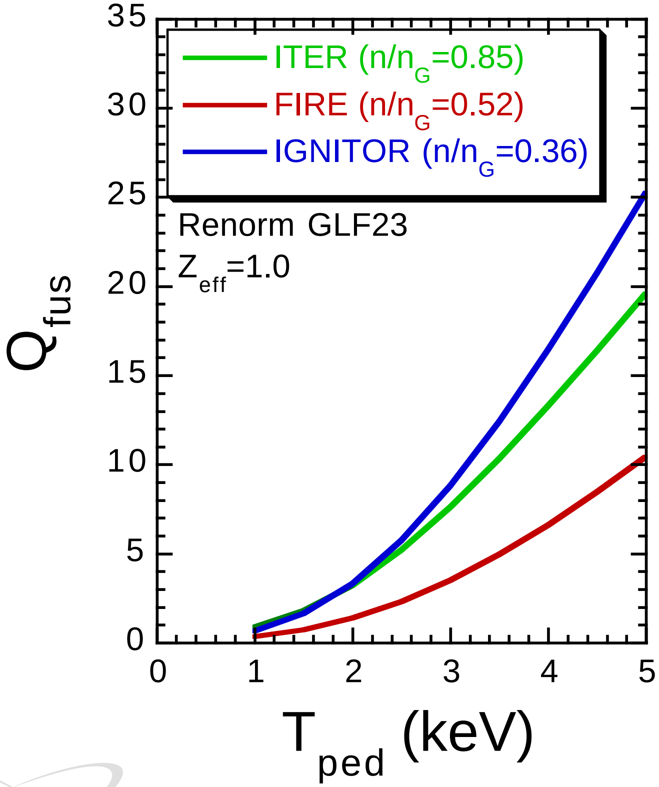
  $Q \propto (T_{ped})^{0.6}$: MM

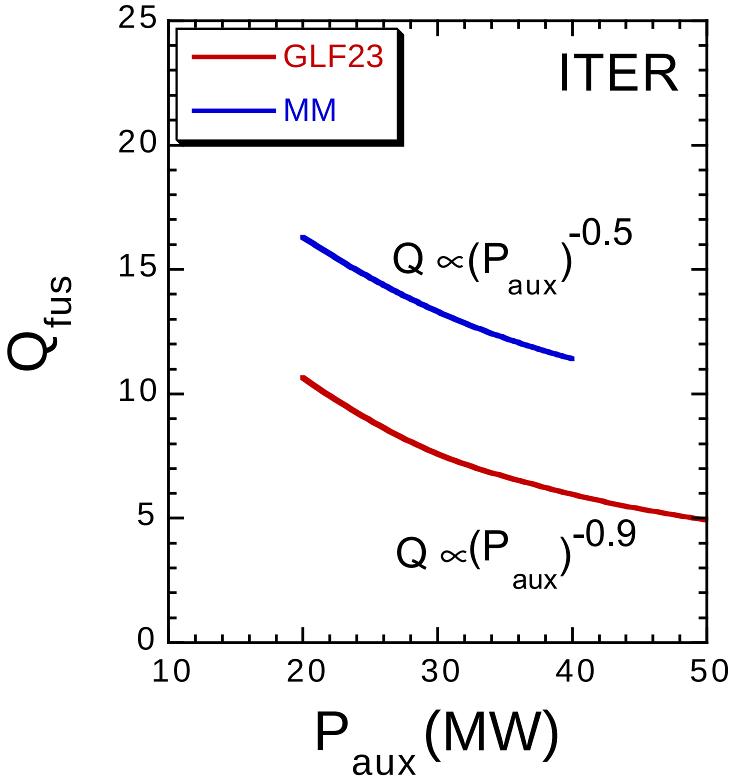
- Both drift-wave based models that agree with experimental data equally well
- Models agree at high T_{ped} but differ significantly at low T_{ped}
- Identifying the true stiffness of the core transport needs to be resolved ! Carefully designed experiments are needed



Comparing Fusion Gain Q Between Various Proposed Burning Plasma Devices Can Be Misleading

- Predicted fusion gain, $Q=P_{fus}/P_{aux}$, is highly dependent on assumed P_{aux}
- Compare 3 devices at same β_{ped} for a given n_{ped} by changing density
- Need better method for comparing performance between devices



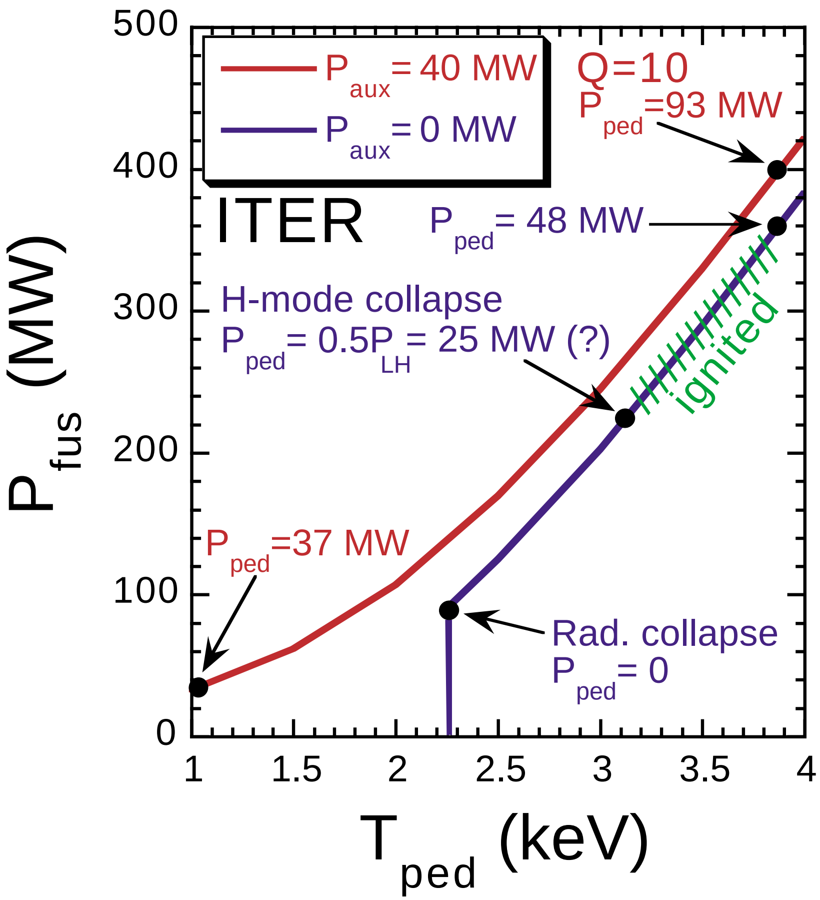


Pedestal Temperature for Sustaining H-mode Ignition (ITER)

- For P_{aux}=40MW and $\bar{n}_e/n_G$=0.85, Q=10 obtained at T_{ped}=3.9 keV
- Auxiliary power in ITER at Q=10 can be turned off and H-mode maintained at same T_{ped}
- Ignition possible at T_{ped} > 3.2 keV where pedestal power is higher than H->L power threshold (P_{LH}/2=25 MW)

$$P_{LH} = 2.54\, M^{-1} B^{0.82} n^{0.58} R^{1.0} a^{0.81}$$

- Profiles collapse when radiation limit approached at minimum T_{ped}
- Need $T_{ped}=CP^{\sigma}_{ped}$!

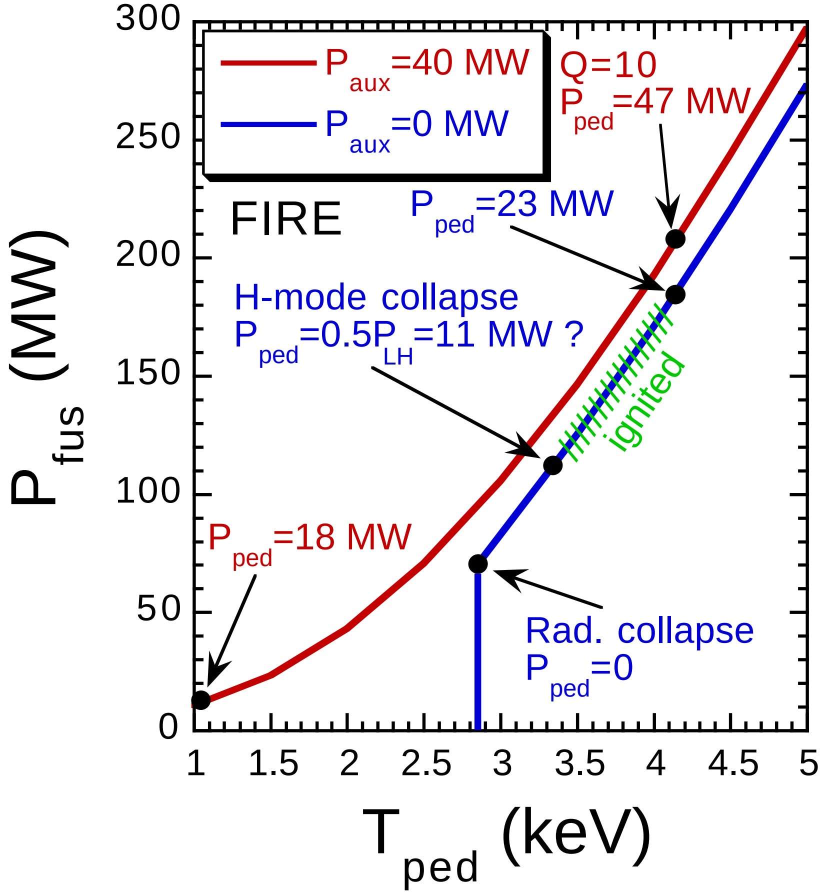


$$P_{ped}=P_{\alpha}-P_{rad}+P_{aux}$$

JEK - Sherwood 2002

Pedestal Temperature for Sustaining H-mode Ignition (FIRE)

- For P_{aux}=20MW and $\bar{n}_e/n_G$=0.7, Q=10 obtained at T_{ped}=4.15keV
- Ignition possible at $T_{ped} > 3.3$ keV where pedestal power is higher than H->L power threshold ($P_{LH}/2$=11 MW)
- Fusion gain similar to ITER for $\bar{n}_e/n_G$=0.7



$$P_{ped}=P_\alpha-P_{rad}+P_{aux}$$

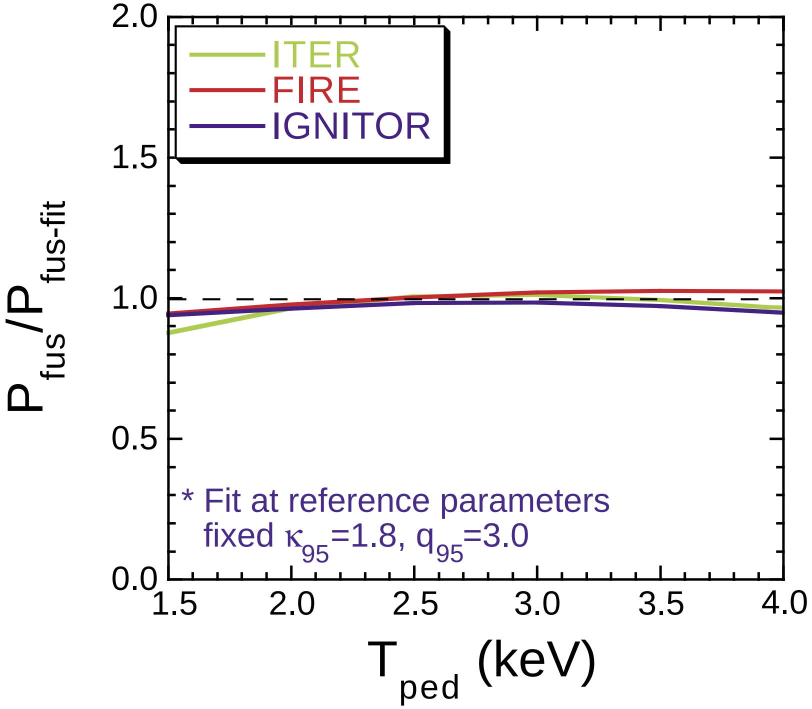
GLF23 Predictions Follow a Universal Curve With a Fit to the Fusion Power That is Device Independent

- Seek simple formula characterizing fusion performance that is general
- Take $P_{fus} \propto n_i^2 V F(T)$ where

  $V = \kappa(\pi a)^2(2\pi R)$ is the volume
- P_{fus} from GLF23 scales as $(T_{ped})^{1.8}$
- Define fusion power fit to GLF23 runs

  $$P_{fus}^{fit} = V {\beta_{ped}^{N}}^{2} [B^2 I/(aB)]^2 (n_i/n_e)^2 C_{form}$$

  where C_{form} is a form factor with dilution, peaking and critical gradient corrections



$$C_{form} = K\,(\bar{n}_e/n_{ped,e})^{1.5} \exp[2(2.15+(1-n_i/n_e)+.75(1+\nu^{-0.25}))/(R/a)]$$
$$\exp[2(+.00275 P_{net}\,(R/a)^{1.5}/({\beta_{ped}^{N}}^{0}\,T_{ped}^{1.5}))^2]$$

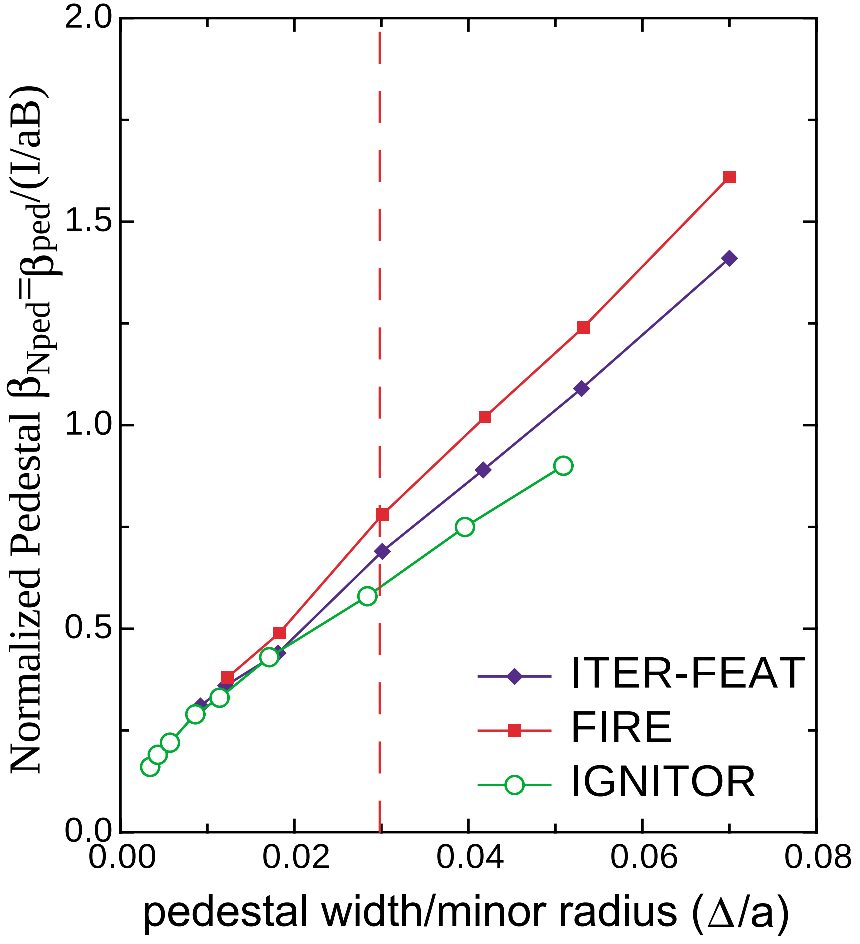
with $K=6.7\text{x}10^{-5}$, $P_{net} = P_{aux} + P_{\alpha}$, $\beta_{ped}^{N} = \beta_{ped}/(I/aB)$, $\nu = \langle n_e \rangle R/T_{ped}^2$

* revised after Sherwood

MHD Stability Constraints On Normalized Pedestal Beta

- MHD stability computed using ELITE code (P. Snyder, P1C08)
- Limits due to intermediate-n peeling-ballooning mode instabilities
- Assuming a pedestal width of 0.03 times the minor radius sets a limit of β^{N}_{ped}=0.7

Normalized Pedestal Stability Limits



Pedestal Beta Requirements for Fusion Performance

		w/ P_{aux}			Ignition‡			
Device	$0.5P_{LH}$	Q	β^N_{ped}	P_{ped}	Q	β^N_{ped}	P_{ped}	P_{fus}
ITER-FEAT	25	10	0.70	93	∞	0.56-0.70	25-46	230-368
FIRE	11	10	1.08	49	∞	0.87-1.08	11-23	112-185
IGNITOR †	23 ?	10	0.48	26	∞	0.59-0.48	23-12	171-104

Device	I/(aB)	P_{aux}	$\bar{n}_e/n_G$	n_{ped}
ITER-FEAT	1.42	40	0.85	0.88
FIRE	1.29	20	0.70	42.2
IGNITOR	1.86	10	0.50	73.8

* $P_{LH} = 2.54\, M^{-1} B^{0.82} n^{0.58} R^{1.0} a^{0.81}$

** P (MW), T (keV), B (T), n (10^{20} m^{-3}), R (m), a (m)

*** $n_{95} = 0.85\bar{n}_e$

‡ β^N_{ped} range for Q=∞ :
min @ 0.5 P_{LH}, max @ Q=10 β^N_{ped}

† IGNITOR is a limiter device,
P_{LH} scaling unkown

Summary

- Motivated by recent gyro-kinetic simulations, the GLF23 model has been renormalized using a 50 shot H-mode database
  - Agrees well with ITG simulations for Cyclone test case
  - RMS error reduced somewhat for H-mode profile database
  - Less stiff -> small increase in fusion Q using renormalized model
- Predicted fusion gain sensitive to temperature profile stiffness
  - we need carefully designed experiments to test stiffness in plasma core

$Q \propto (T_{ped})^{1.8}$: GLF23 $Q \propto (T_{ped})^{0.6}$: MM

- Global formula fitting GLF23 fusion predictions has been found
- Fusion power scales as $(\beta_{ped})^{2}$
- Ignition possible for reasonable pedestal beta values that have been shown to be MHD stable (widths near 3% of minor radius)
- We need to know the power scaling and width of the H-mode pedestal beta in order to predict the fusion Q accurately