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model of interchange turbulent transport: on the correlation between scrape off layer width and core confinement in tokamaks

ID-61

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- Spectral filament paradigm: self consistent prediction of turbulent spectra (n_e, Φ) of flux driven 2D isothermal interchange turbulence
- Predicts macroscopic transport properties (flux, fluctuations) in scrape-off layer (→ SOL width λ_q) but also in the core (→ confinement time τ_E)
- SOL transport: quantitative agreement with Tore Supra data (circular plasmas), recovers impact of divertor leg length on SOL width (λ_q) in TCV, recovers multi-machine parametric sensitivity of λ_q
- Core confinement: recovers multi-machine parametric sensitivity of τ_E and correlation between core confinement and heat flux width
- Offers a flexible paradigm for addressing the optimization of power exhaust versus core confinement (key: impact of geometry in model)

2D isothermal interchange model (TOKAM2D)

Y. Sarazin et al. Phys. Plasmas 5 (12) (1998) 4214–4228

Flux driven (source S), control parameters: $g \approx \frac{\rho_S}{R}$, $\sigma_\parallel \approx \frac{\rho_S}{q_{cyl}R}$

curvature **// loss rate**

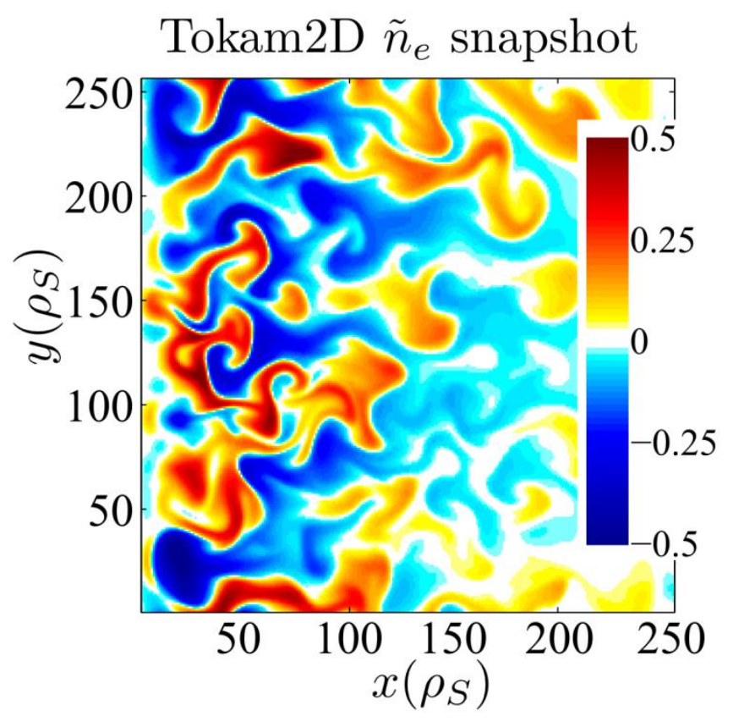
$$d_t n + D\nabla^2 n = S - \sigma_\parallel n e^{\Lambda-\Phi}$$

$$d_t\omega + \nu\nabla^2\omega = g\frac{\partial_y n}{n} - \sigma_\parallel(1 - e^{\Lambda-\Phi})$$

$$d_t = \partial_t + \{\Phi,\cdot\}$$

$$\omega = \nabla_\perp^2\Phi$$

Intermittent filamentary transport, exponential SOL, etc



Test isolated filament model

S. I. Krasheninnikov et al. J. Plasma Phys. 2008, 74, 679

Density filament: size δ_f & normalized amplitude n_f

→ drift velocity (v_f) predicted from vorticity balance

Hyp: well shaped filaments, not the case in simulations

Solution: construction of averaged filaments

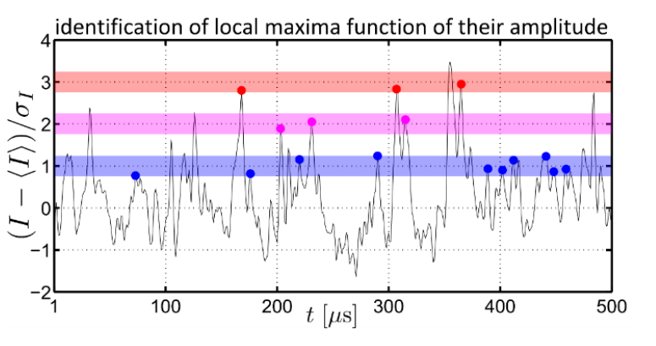
→ conditional average with event amplitude discrimination

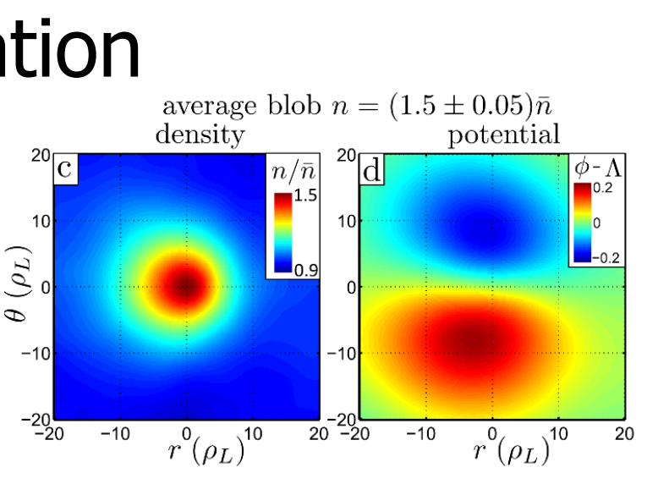
$$v_f = \frac{1}{2}\sigma_\parallel\delta_b^3\left[\sqrt{1+(\delta_0/\delta_b)^5}+1\right]$$

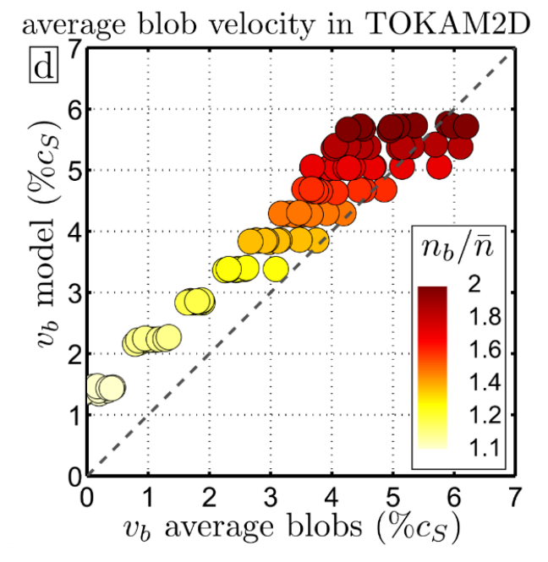
$$\delta_0 = \left(\frac{4g(n_b-1)}{\sigma_\parallel^2}\right)^{\frac{1}{5}}$$

Isolated filament model works on TOKAM2D averaged filaments

N. Fedorczak et al. Contrib. Plasma Phys. 2018;58:471–477







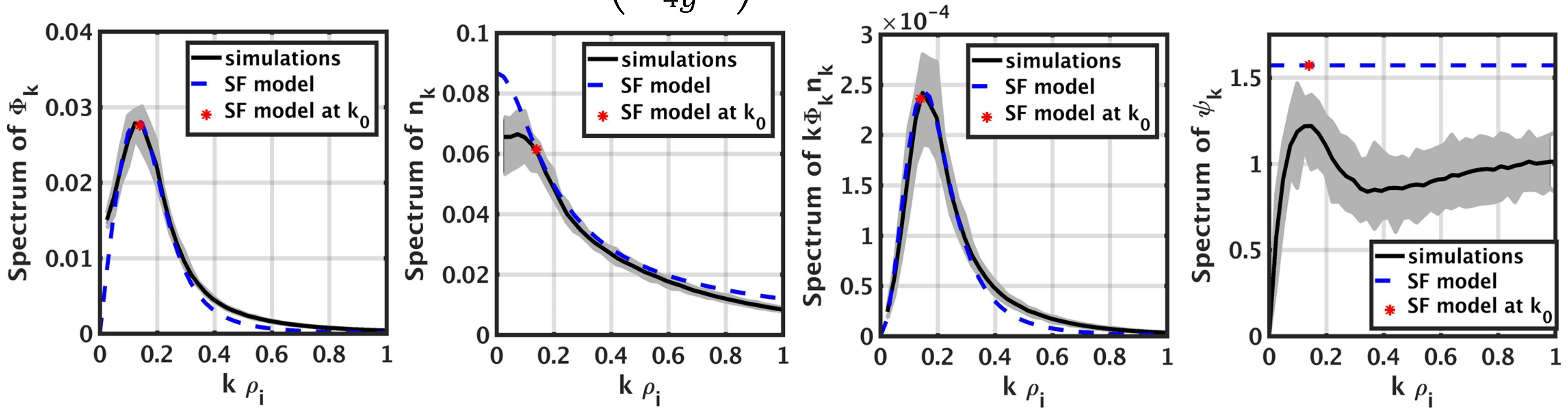
Spectral filament (SF) model

N. Fedorczak et al. Nuc. Mater. & Energy 19 (2019) 433–439

Principle: extend filament model to fluctuation spectra $v_f(\delta_f) \to \Phi(k_\theta)$ & $n_b \to n(k_\theta)$

Hyp: density & potential spectra in phase quadrature + time independent spectra (it is!)

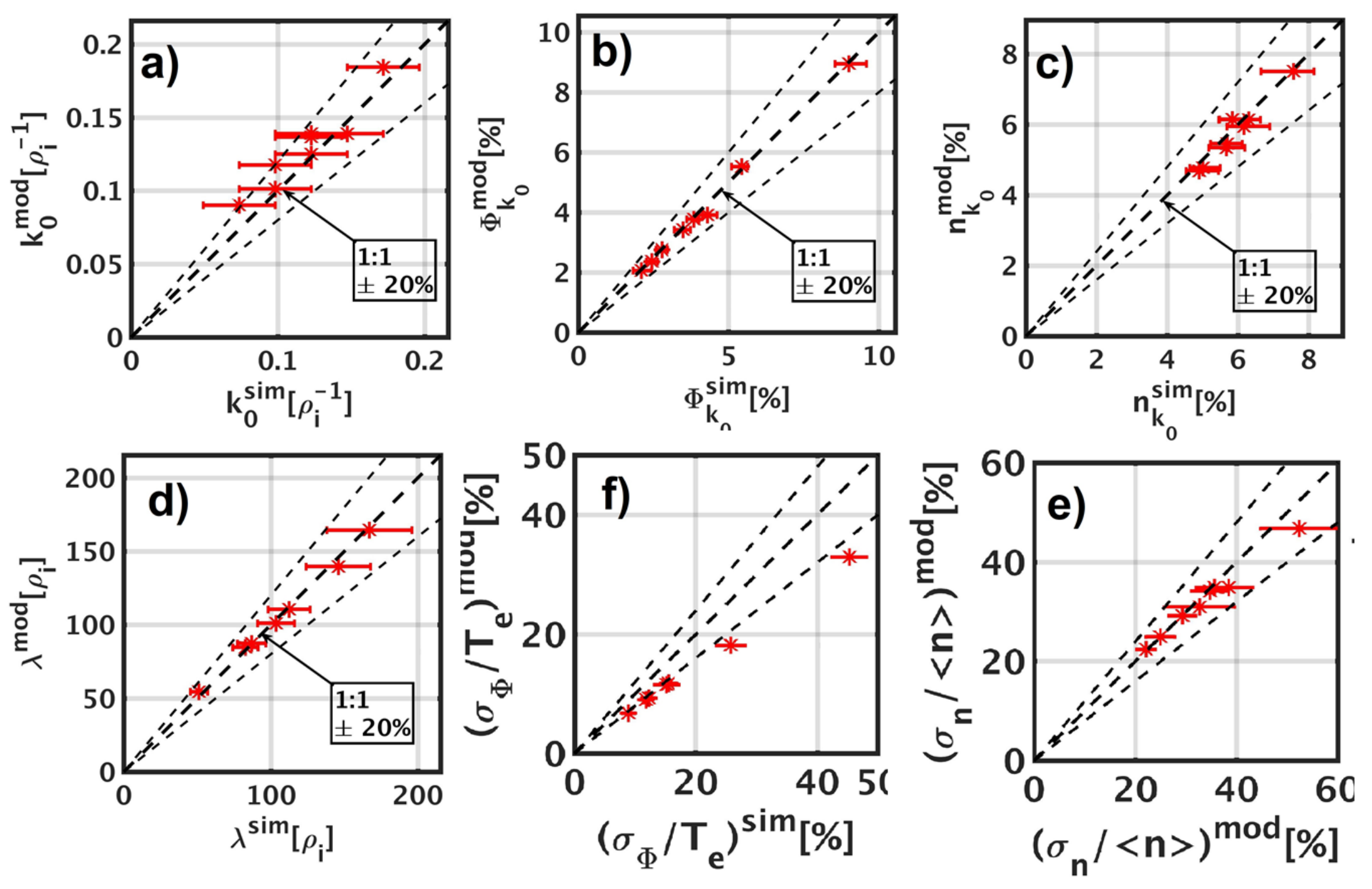
- potential: include effective viscosity from dominant mode $k^4\Phi_{k_0}\Phi_k + \sigma_\parallel\Phi_k = gk\, n_k$
- density : mixing length + ad-hoc saturation at low k $\sqrt{k^2 + k_0^2}\; n_k = \lambda_n^{-1}$
- dominant wave number $k_0 = \left(\frac{1.45\lambda\sigma_\parallel^2}{4g}\right)^{1/4}$



Spectral integrals for macroscopic quantities:

- radial flux: $\Gamma_r \equiv 8\pi^2\int k\Phi_k n_k dk = 41\,\lambda_n^{-\frac{7}{4}}\, g^{\frac{3}{4}}\,\sigma_\parallel^{-\frac{1}{2}}\;[\bar{n}c_S]$
- fluctuation levels $\frac{\sigma_n}{\bar{n}} = 12.6\,\lambda_n^{-\frac{9}{8}}\; g^{\frac{1}{8}}\;\sigma_\parallel^{-\frac{1}{4}}$ & $\frac{\sigma_\Phi}{T_e} = 4.8\,\lambda_n^{-\frac{7}{8}}\; g^{\frac{7}{8}}\;\sigma_\parallel^{-\frac{3}{4}}$
- scrape-off-layer width: $\Gamma_r \equiv \lambda_n\sigma_\parallel$ → $\lambda_n = 3.9\; g^{3/11}\,\sigma_\parallel^{-\frac{6}{11}}\;[\rho_L]$

→ Quantitative agreement with TOKAM2D simulations (scan of g & $\sigma_\parallel$)



Spectral filament model:

- stiff flux model $\Gamma_r \propto \lambda^{-\frac{7}{4}}$
- not diffusive nor convective
- intermittency disappears in spectral paradigm
- key : model of g & $\sigma_\parallel$

SF model → prediction of heat flux width & confinement time

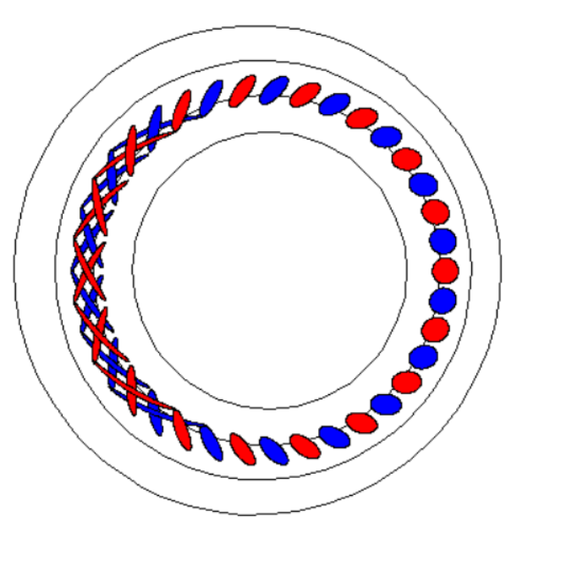
Heat flux decay length

Hyp: $\lambda_q = \alpha_q\lambda_n$, $g = \rho_L/R$ & $\sigma_\parallel = \frac{\rho_L}{L_\parallel} = \rho_L/\pi q_{cyl}R$, 2-point model for T_{sep}

$$\lambda_q = 50\alpha_q q_{cyl}^{0.63} B_{[T]}^{-0.65} R_{[m]}^{0.25}\left(\frac{A}{Z}\right)^{0.33} P_{sep[MW]}^{0.09}\;[mm]$$

Confinement time:

Hyp: density → pressure & particle flux → heat flux
vorticity // dissipation still valid (HFS decorrelation of LFS mode)
gradient scale length $\lambda \approx a$

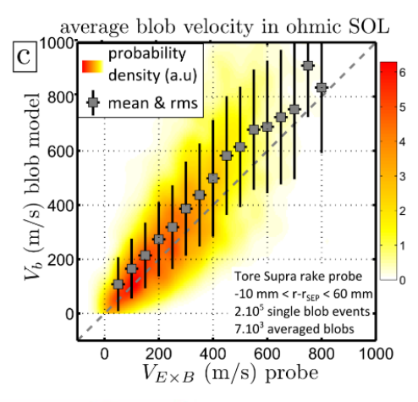


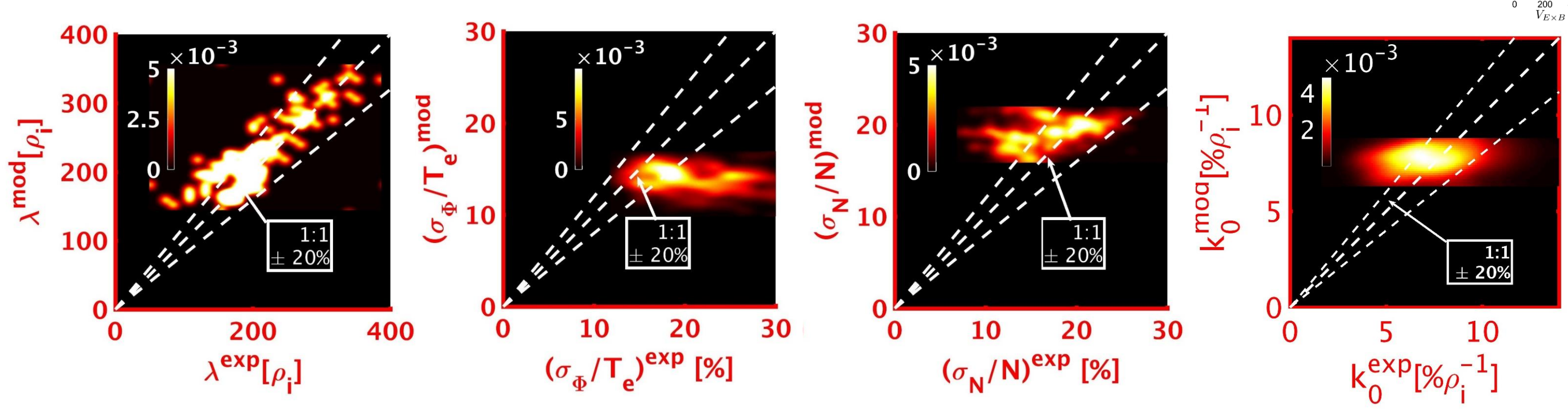
$$\tau_E = 0.007\alpha_T I_{P[MA]}^{0.2} B_{[T]}^{0.6} P_{TOT[MW]}^{-0.6} n_{e[E19]}^{0.6} M^{0.2}\, R_{[m]}^{2.8}\left(\frac{a}{R}\right)^{1.9}\;[s]$$

Model validated against broad SOL database from Tore Supra

>100 probe reciprocations with turbulence (1MHz θ-rake) & profile (tunnel) collectors

- ExB velocities of averaged filaments match with isolated filament model
- fluctuation amplitudes (n_e & Φ) and main k_θ well reproduced
- density profile decay length (λ_n) quantitatively matched





Recovers multi-machine scaling of ITER startup heat flux width

N. Fedorczak et al. Nuc. Mater. & Energy 19 (2019) 433–439

Hyp: $\lambda_q = 0.5\lambda_n$ (correlation from Tore Supra database)

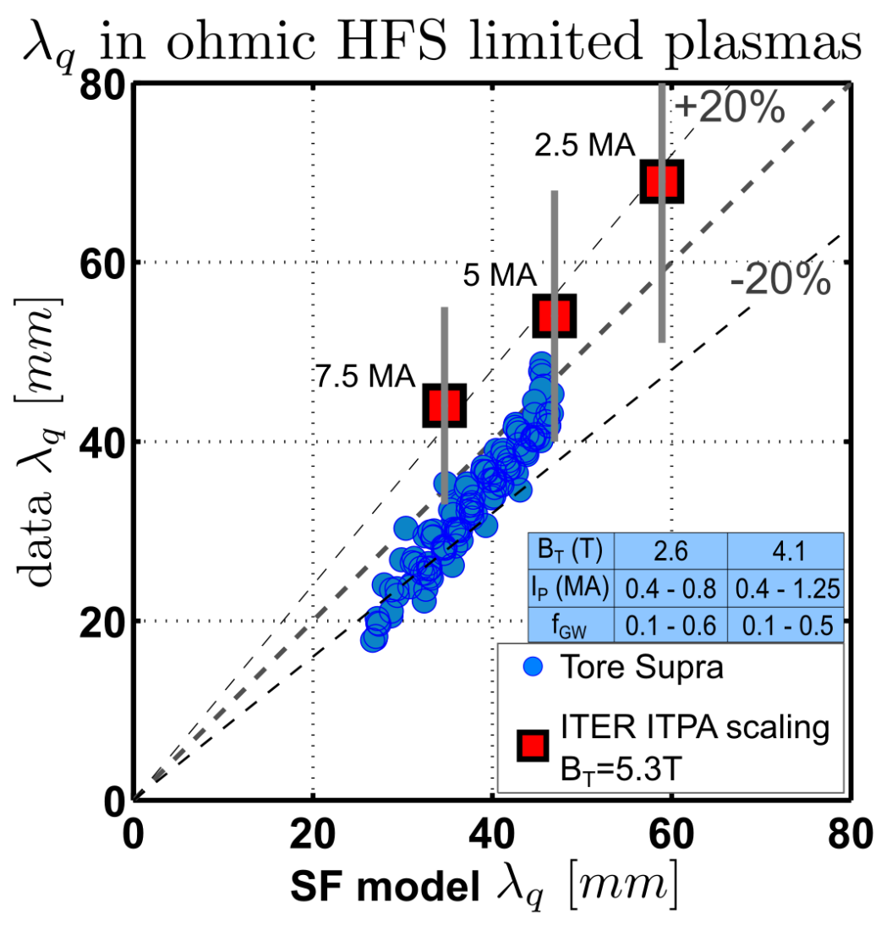
$$\lambda_q = 25 q_{cyl}^{0.63} B^{-0.65} R^{0.25}\left(\frac{A}{Z}\right)^{0.33} P_{sep[MW]}^{0.09}\;[mm]$$

- quantitative agreement with Tore Supra λ_q (ITER database)

  J Gunn et al. J. Nucl. Mater. 438 (Suppl) (2013) S184–S188,

- quantitative agreement with multi-machine prediction of ITER startup SOL width

  J. Horacek et al. Plasma Phys. Controlled Fusion 58 (7) (2016) 074005.



B$_T$ (T)	2.6	4.1
I$_P$ (MA)	0.4 - 0.8	0.4 - 1.25
f$_{GW}$	0.1 - 0.6	0.1 - 0.5

Recovers multi-machine scaling sensitivity of λ_q in H-mode

Model: $\lambda_q \propto R^{0.25}$ …

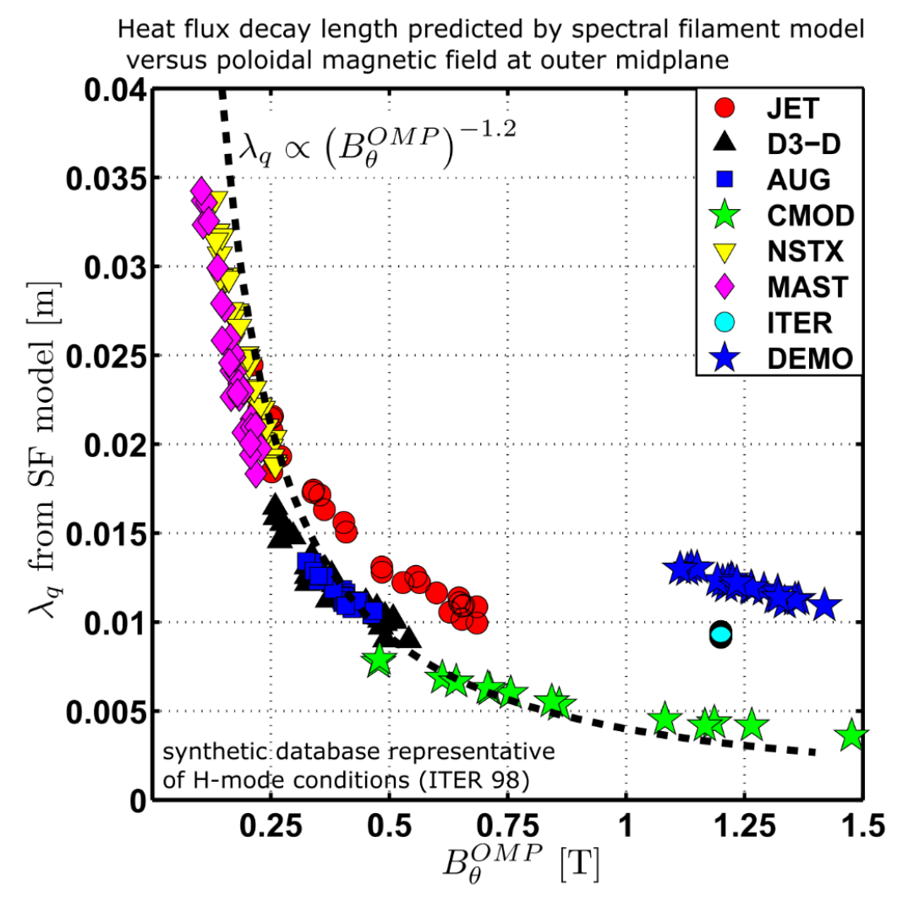
- λ_q X3-4 for ITER & DEMO compared to B_θ scaling

T. Eich et al. Nucl. Fusion 53 (9) (2013) 093031

- sounds with XGC1 results (different interpretation)

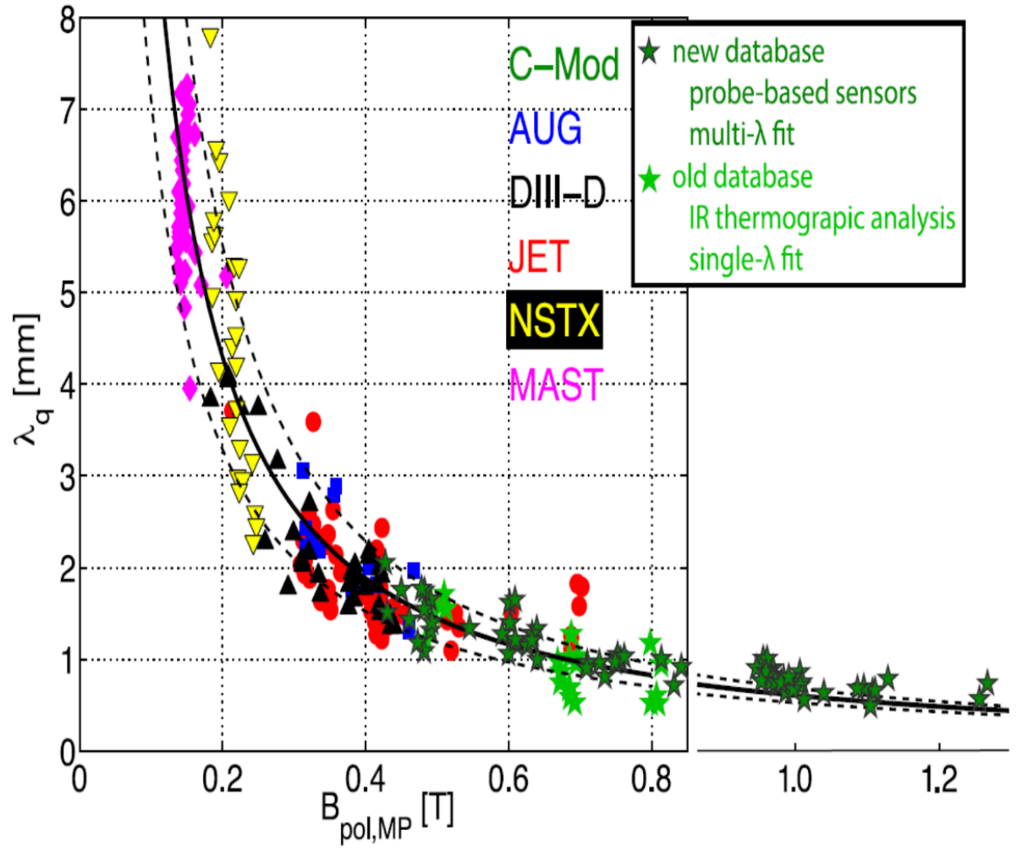
C.S. Chang et al 2017 Nucl. Fusion 57 116023

model prediction



experimental data

D. Brunner et al. Nucl. Fusion 58 (2018) 094002



Recovers impact of divertor leg length on λ_q in TCV L-mode

TCV ohmic pulses: scan of plasma current and divertor geometry gives same $\lambda_q(L_\parallel)$

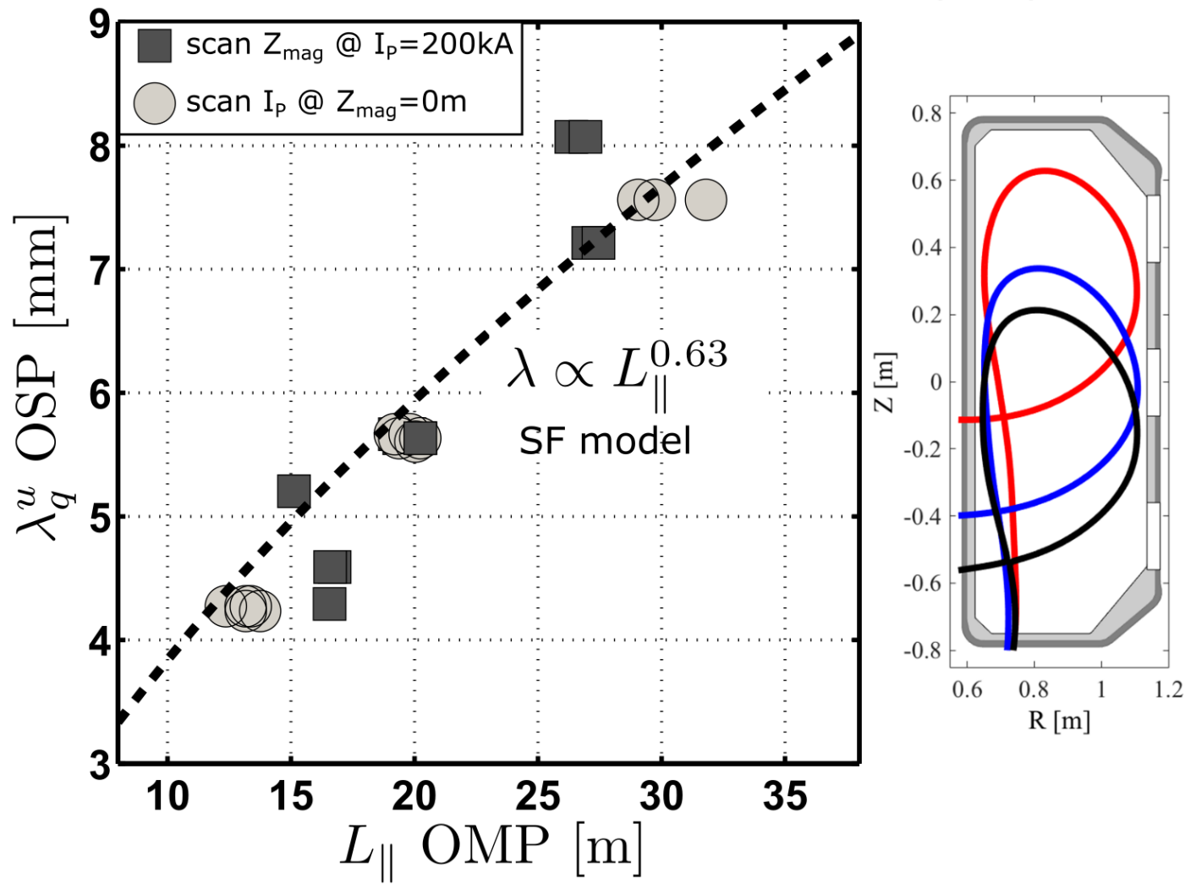
R. Maurizio et al. Nucl. Fusion 58 (2018) 016052

Model: $\lambda_q \propto L_\parallel^{0.63}$

- sensitivity recovered by the SF model
- 3D turbulent simulations show interchange along divertor leg, as the model considers

A. Gallo et al. Plasma Phys. Control. Fusion 60 (2018) 014007

TCV ohmic L-mode scan of SOL parallel connection length
IR data taken from R. Maurizio et al. Nucl. Fusion 58 (2018) 016052



Recovers global multi-machine τ_E sensitivity & correlation with λ_q

Model :

$$\tau_E \propto I_P^{0.2} B^{0.6} P_{TOT}^{-0.6} n_e^{0.6}\, M^{0.2}\, R^{2.8}\left(\frac{a}{R}\right)^{1.9}$$

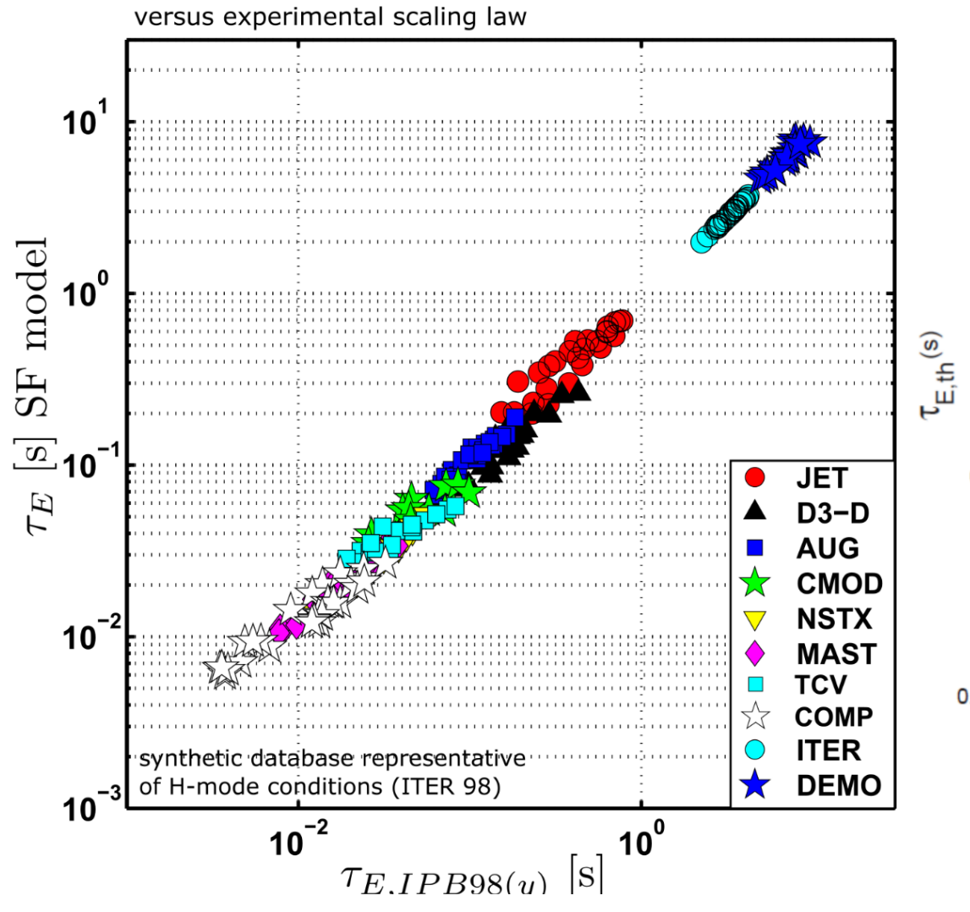
Scaling law ITER 98:

$$\tau_E \propto I_P^{1.0} B^{0.1} P_{TOT}^{-0.6} n_e^{0.4}\, M^{0.2}\, R^{1.9}\left(\frac{a}{R}\right)^{0.2}$$

- significant difference in I_P & B
- **global trend is well matched**

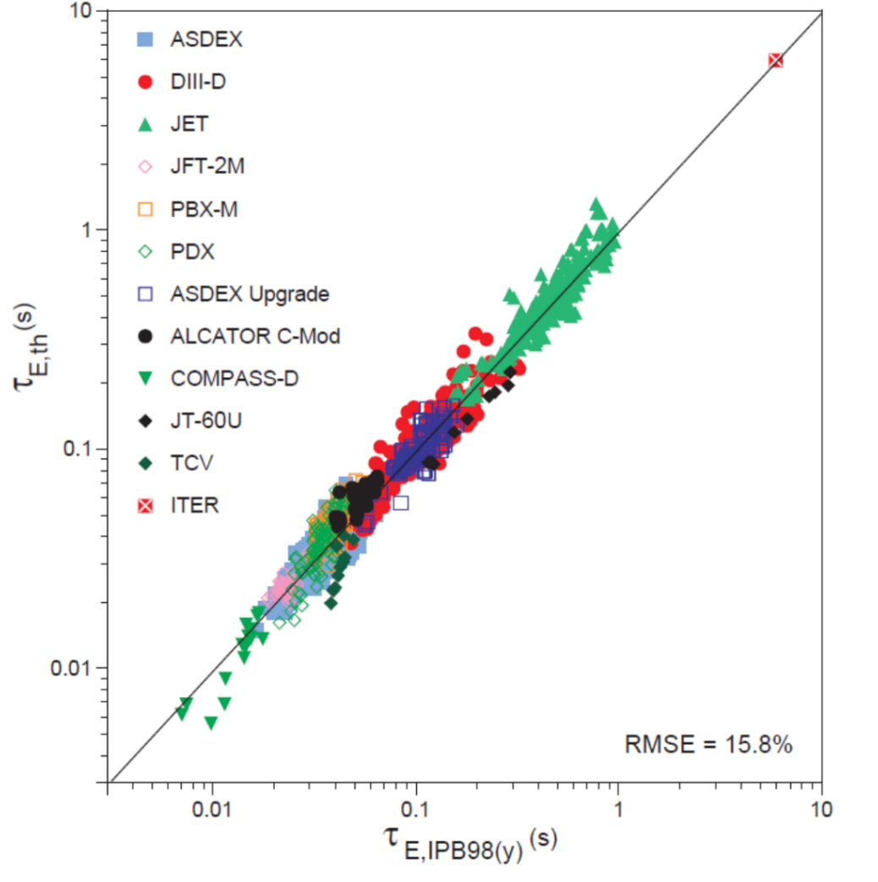
hints of correlations in exp. scaling

model prediction



experimental data

ITER Nuclear Fusion, Vol. 39, No. 12 (1999)

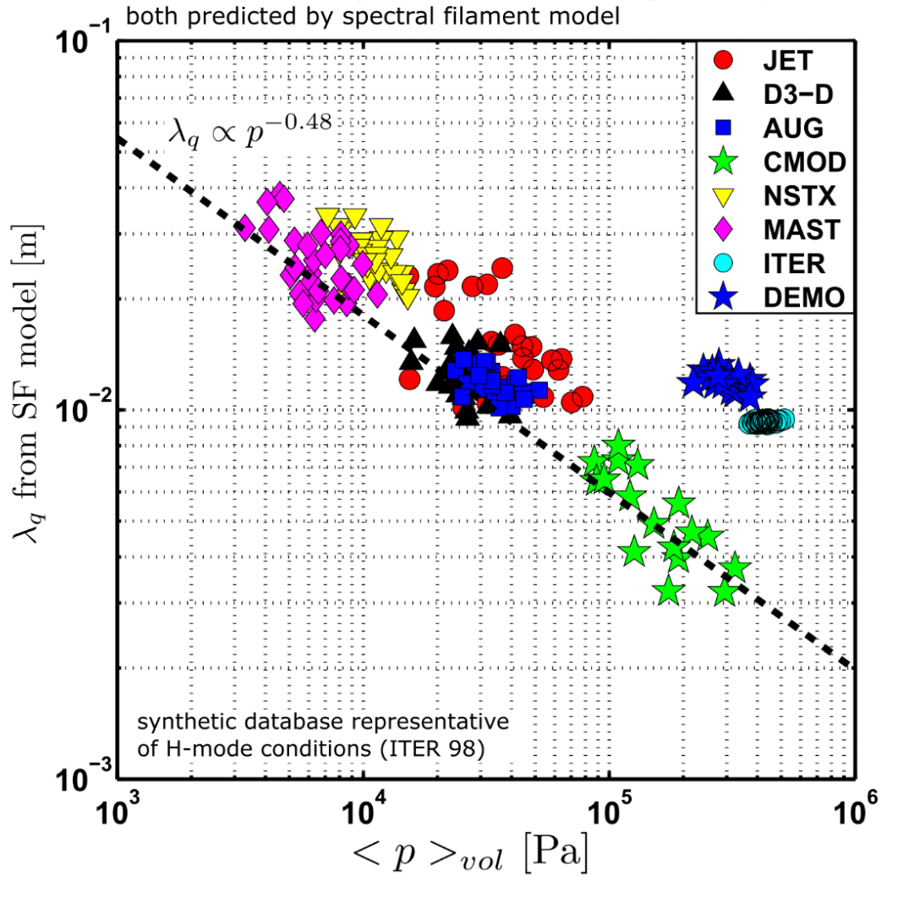


Correlation confinement vs λ_q

D. Brunner et al. Nucl. Fusion 58 (2018) 094002

- experimental correlation $\lambda_q \propto \bar{p}^{-0.48}$ across L-I-H modes in C-mod
- recovered in exp. H-mode scaling
- recovered by model on current machines, but not for ITER/DEMO

model prediction



experimental data