Applying self-consistent electron heat transport and ECH deposition profile estimation in DIII-D

27th Joint EU-US Transport Task Force Meeting

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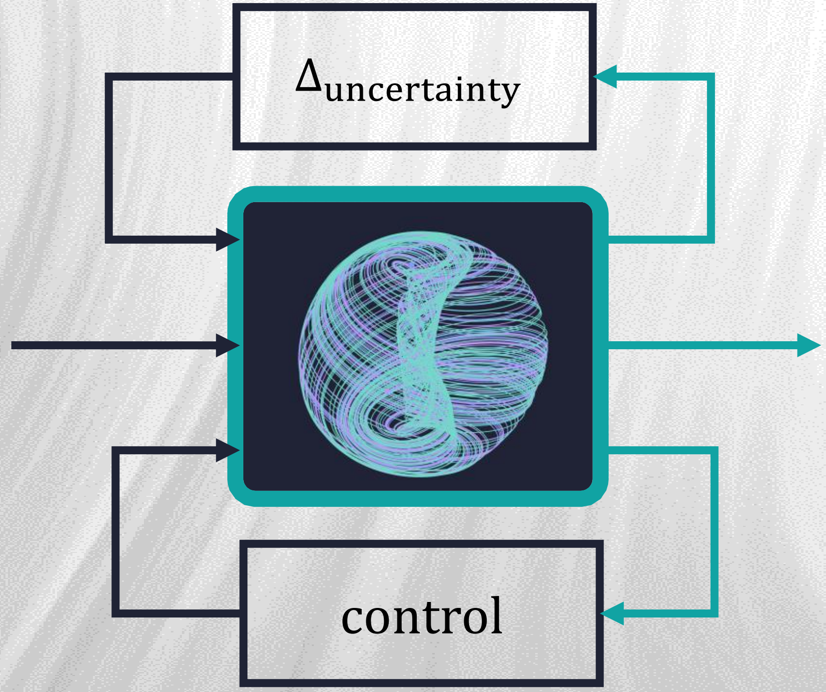
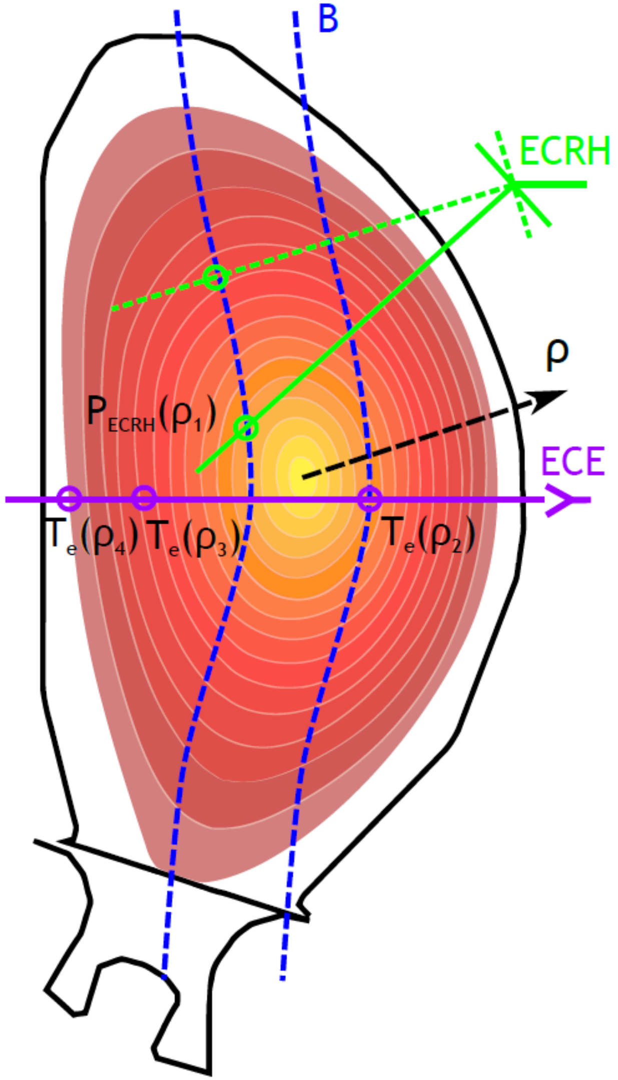
ENERGY SYSTEMS & CONTROL



Introduction

- Transport is often studied **perturbatively**[1–5]
- **Power deposition** and **transport** estimates are traditionally separated
- However, **edge turbulence** can spoil deposition localization[6–10]
- Need for **simultaneous, self-consistent estimate** of transport coefficients and power deposition profile[6,10–13]



[1] J.D. Callen *et al.* (1977). *Phys. Rev. Lett.* **38** 491–4
[2] H.J. Hatfuss *et al.* (1994). *Plasma Phys. Control. Fusion.* **36** B17–B37
[3] N.J. Lopes Cardozo. (1995). *Plasma Phys. Control. Fusion.* **37** 799
[4] F. Ryter *et al.* (2010). *Plasma Phys. Control. Fusion.* **52** 124043
[5] C.C. Petty *et al.* (2015). *Nucl. Fusion.* **55** 083011
[6] K.K. Kirov *et al.* (2002). *Plasma Phys. Control. Fusion.* **44** 2583
[7] C. Tsironis *et al.* (2009). *Phys. Plasmas.* **16** 112510
[8] A. Snicker *et al.* (2018). *Nucl. Fusion.* **58** 016002
[9] O. Chellaï *et al.* (2021). *Nucl. Fusion.* **61** 066011
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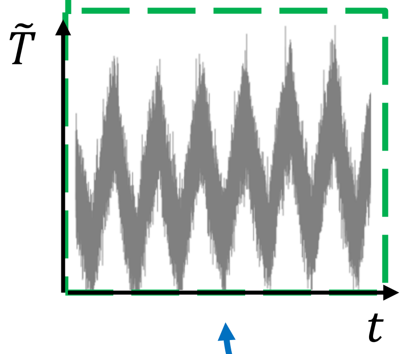
[11] E.A. Lerche *et al.* (2008). *Plasma Phys. Control. Fusion.* **50** 035003
[12] A. Manini *et al.* (2003). *Nucl. Fusion.* **43** 490-511
[13] F. Ryter *et al.* (2003) *Nucl. Fusion.* **43** 1396

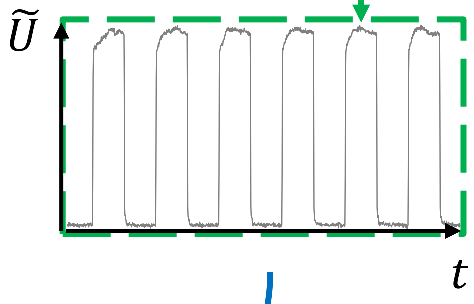
Outline

- Spatially varying, joint transport and power deposition estimates
- Assumptions and experimental checks
- Sensitivity analysis
- Experimental power deposition estimates in DIII-D
- Impact for ITER

Linearization through perturbative experiments – the model

$$\frac{\partial}{\partial t}\tilde{T}(x,t) = -\nabla \cdot [D(x)\nabla\tilde{T}(x,t) + V(x)\tilde{T}(x,t)] + K(x)\tilde{T}(x,t) + P(x)\tilde{U}(t)$$





Measured

Temperature perturbation $\tilde{T}(x,t)$

Gradient $\nabla\tilde{T}(x,t)$

Unknown

Diffusivity $D(x)/\chi(x)$

Convectivity $V(x)$

Damping $K(x)/\tau_{inv}(x)$

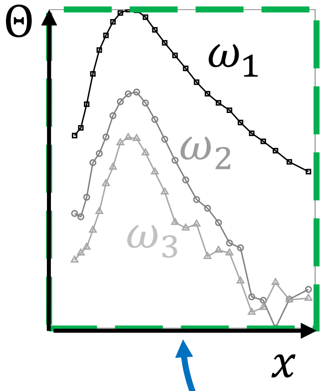
Power deposition $P(x)$

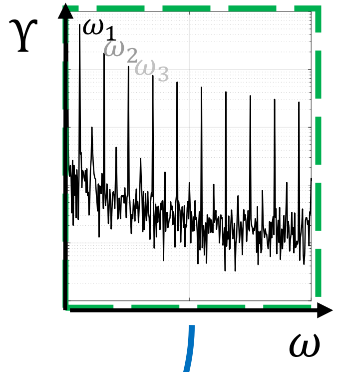
Measured

Source modulation $\tilde{U}(t)$

Linearization through perturbative experiments – frequency domain

$$i\omega\Theta(x,\omega) = -\nabla\cdot[D(x)\nabla\Theta(x,\omega) + V(x)\Theta(x,\omega)] + K(x)\Theta(x,\omega) + P(x)\Upsilon(\omega)$$





Measured

Temperature perturbation $\Theta(x,\omega)$

Gradient $\nabla\Theta(x,\omega)$

Unknown

Diffusivity $D(x)/\chi(x)$

Convectivity $V(x)$

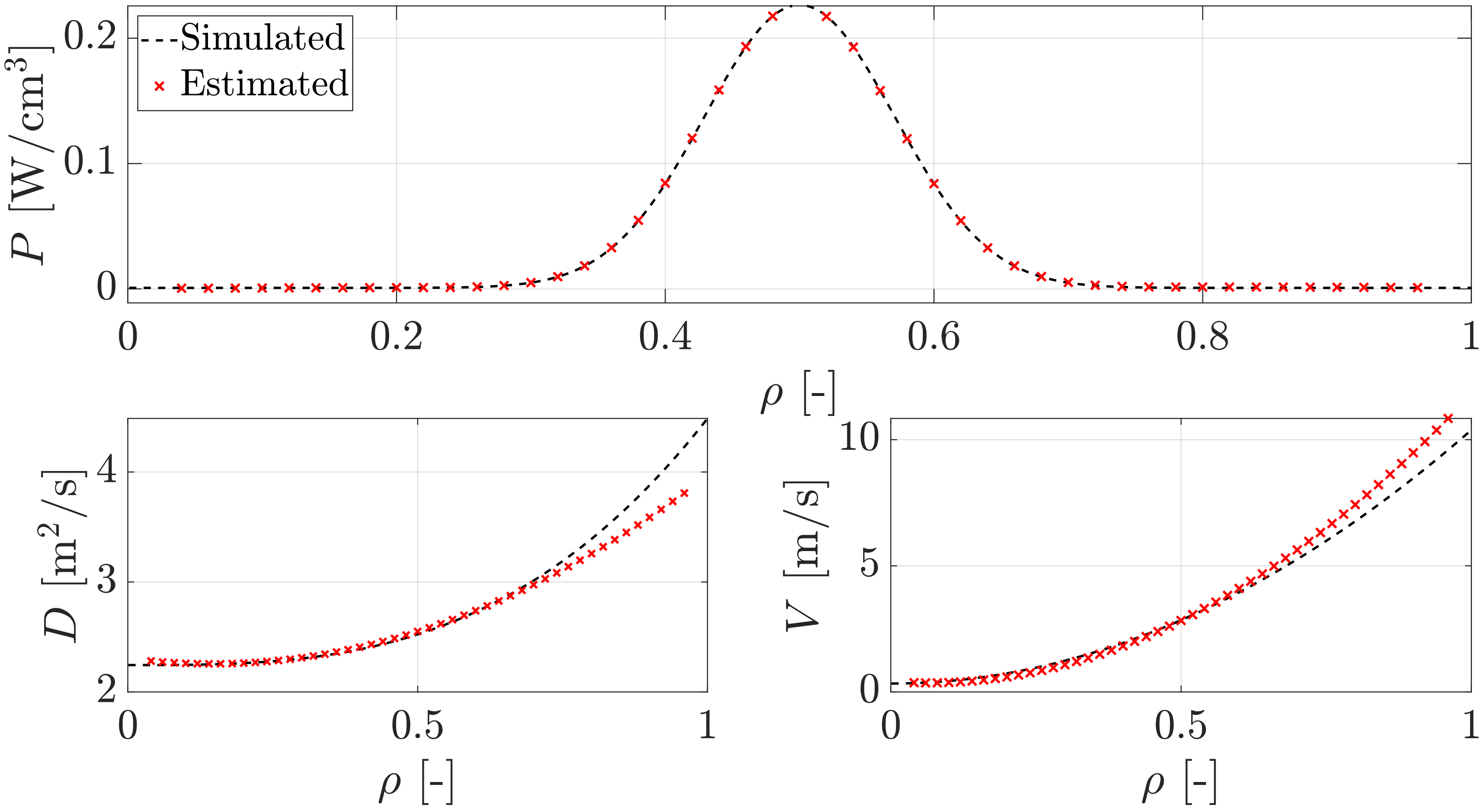
Damping $K(x)/\tau_{inv}(x)$

Power deposition $P(x)$

Measured

Source modulation $\Upsilon(\omega)$

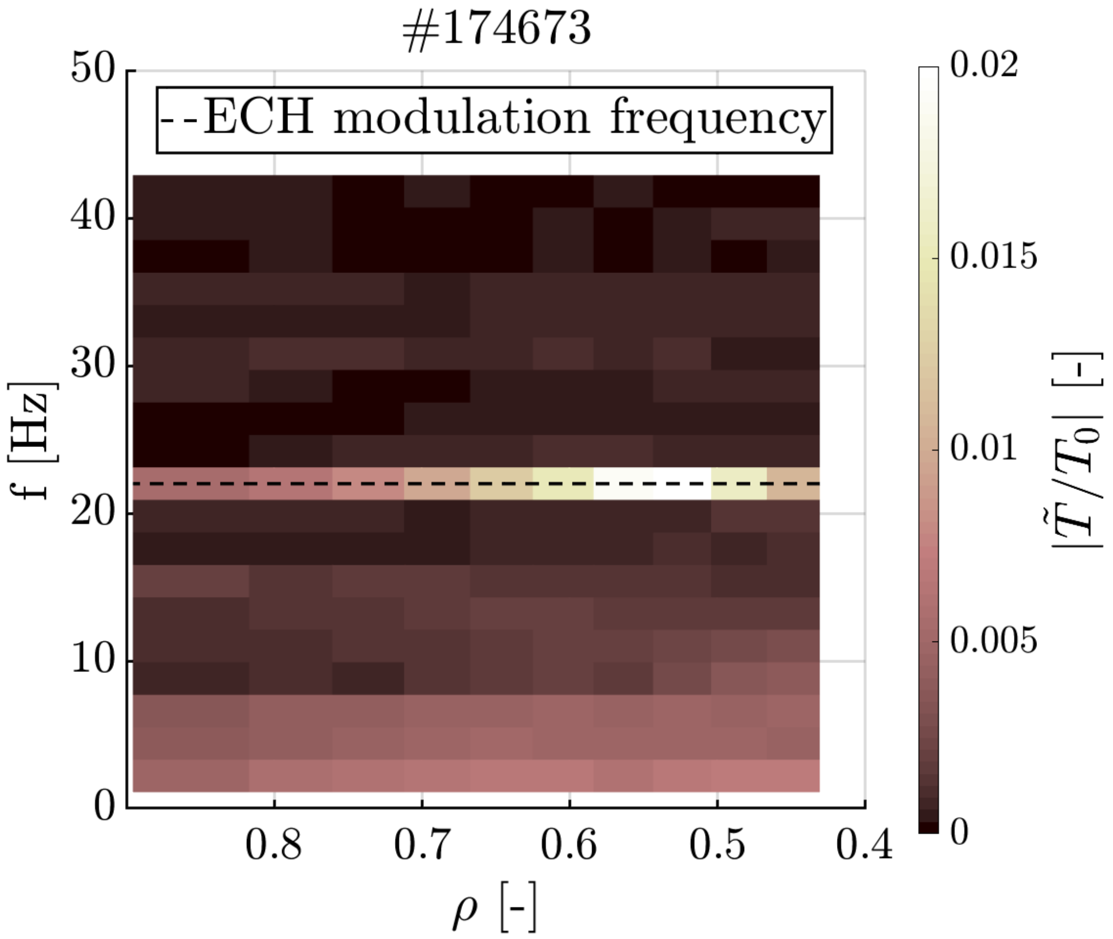
Estimation

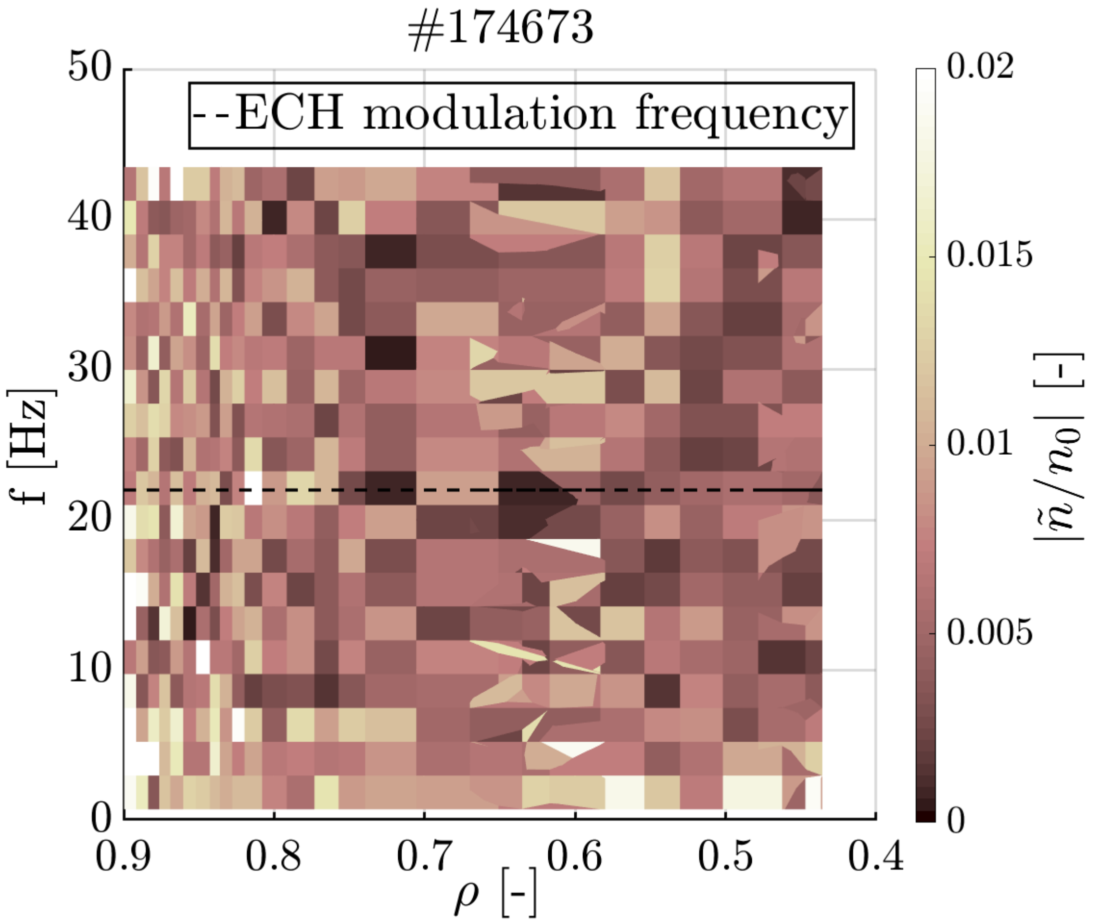


Simulated
Estimated
P [W/cm^3]
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
ρ [-]
D [m^2/s]
4
3
2
0
0.5
1
ρ [-]
V [m/s]
10
5
0
0
0.5
1
ρ [-]

Justification of model assumptions

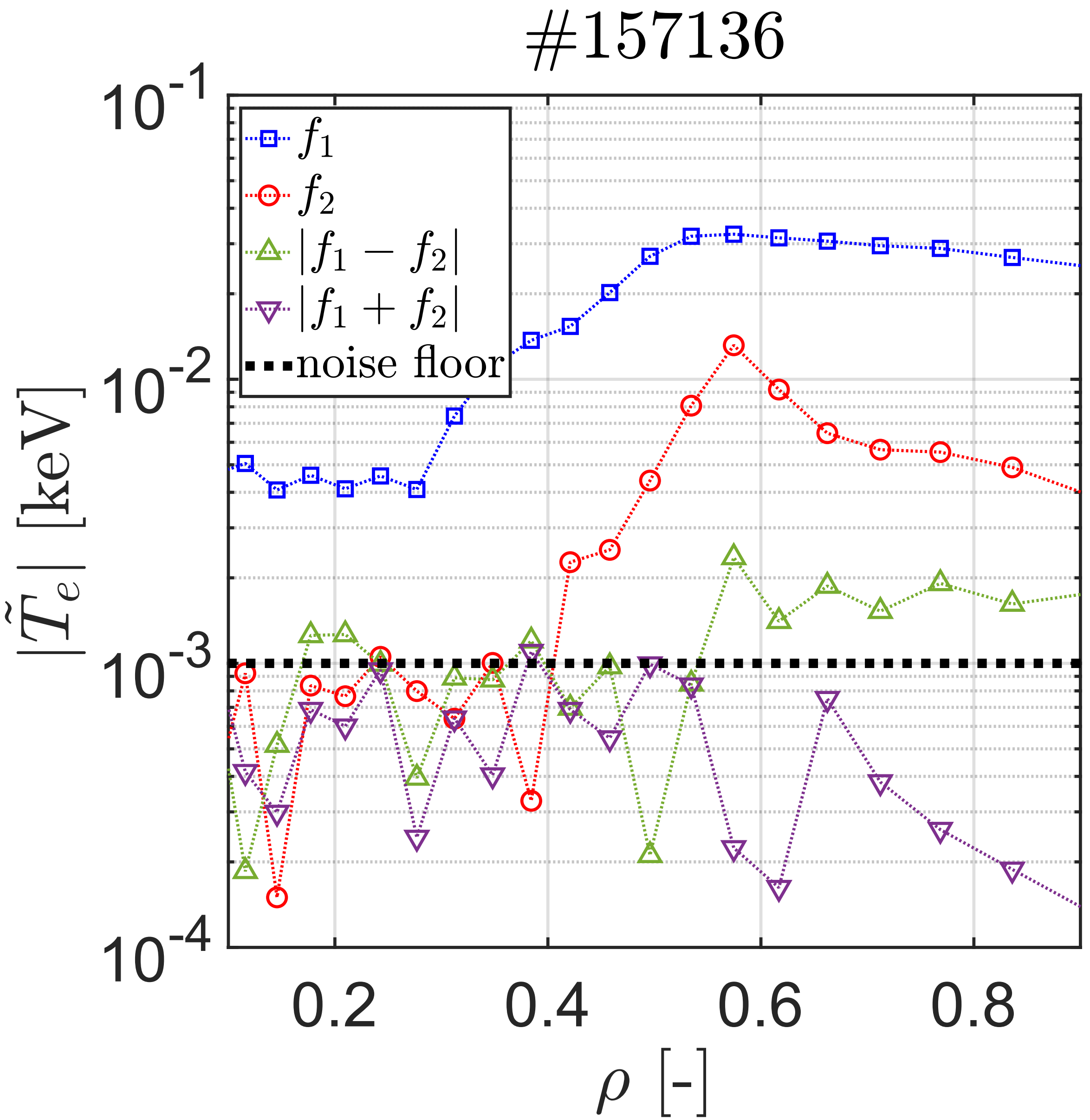
- Density is not modulated ($\frac{\partial}{\partial t} n_e = 0$)





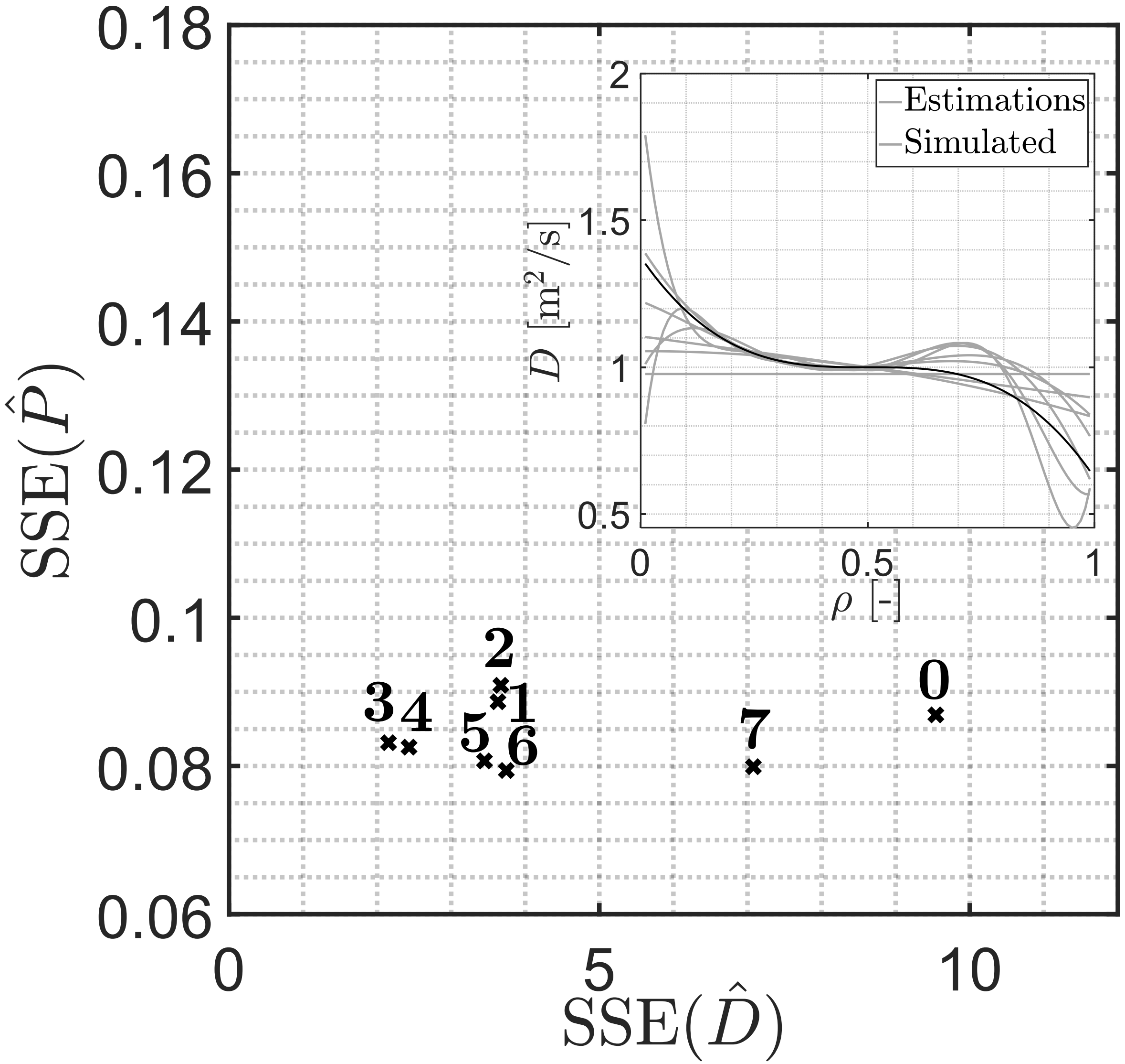
Justification of model assumptions

- Linearity of the plasma response



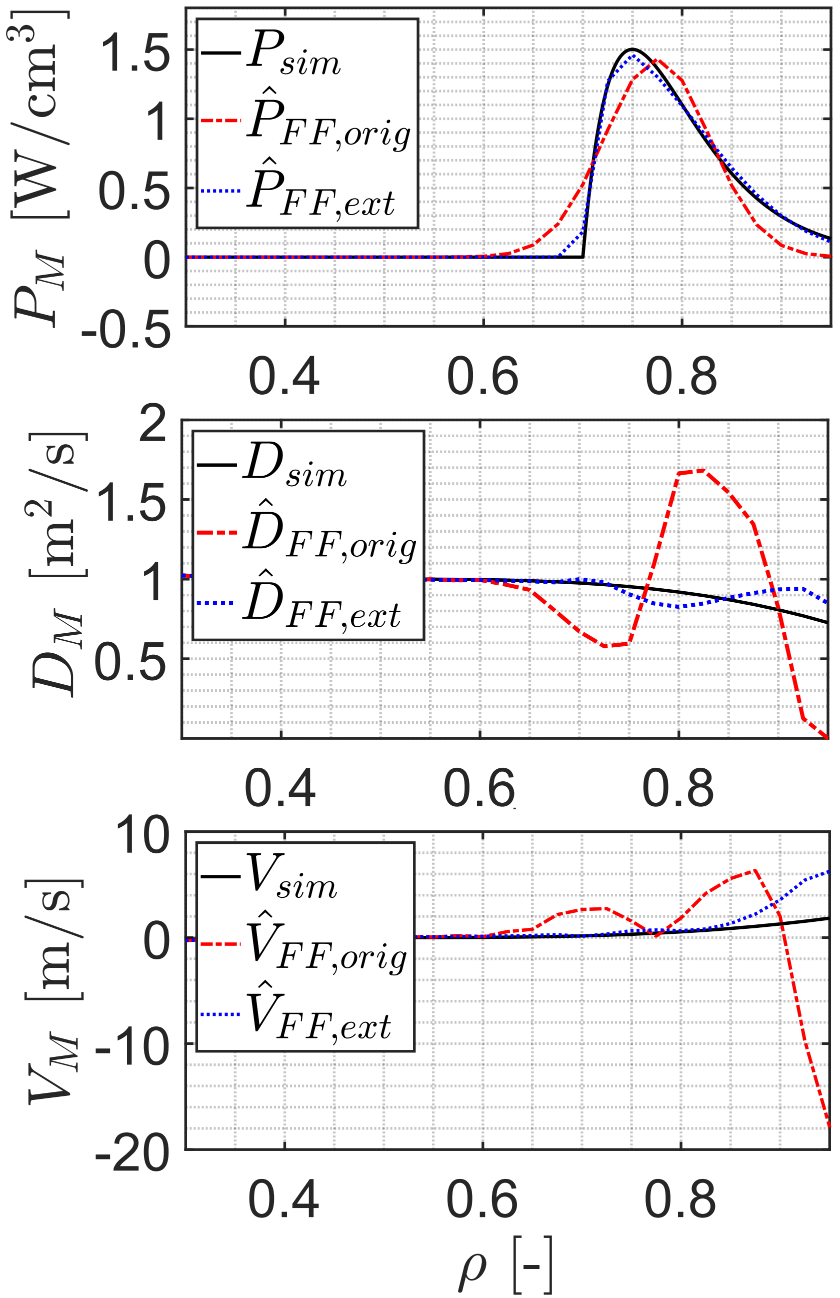
Sensitivity of model coefficients

- Sensitivity of estimates of one parameter to errors in the estimates of others
- Result: **P estimate is insensitive to variations in D and V**



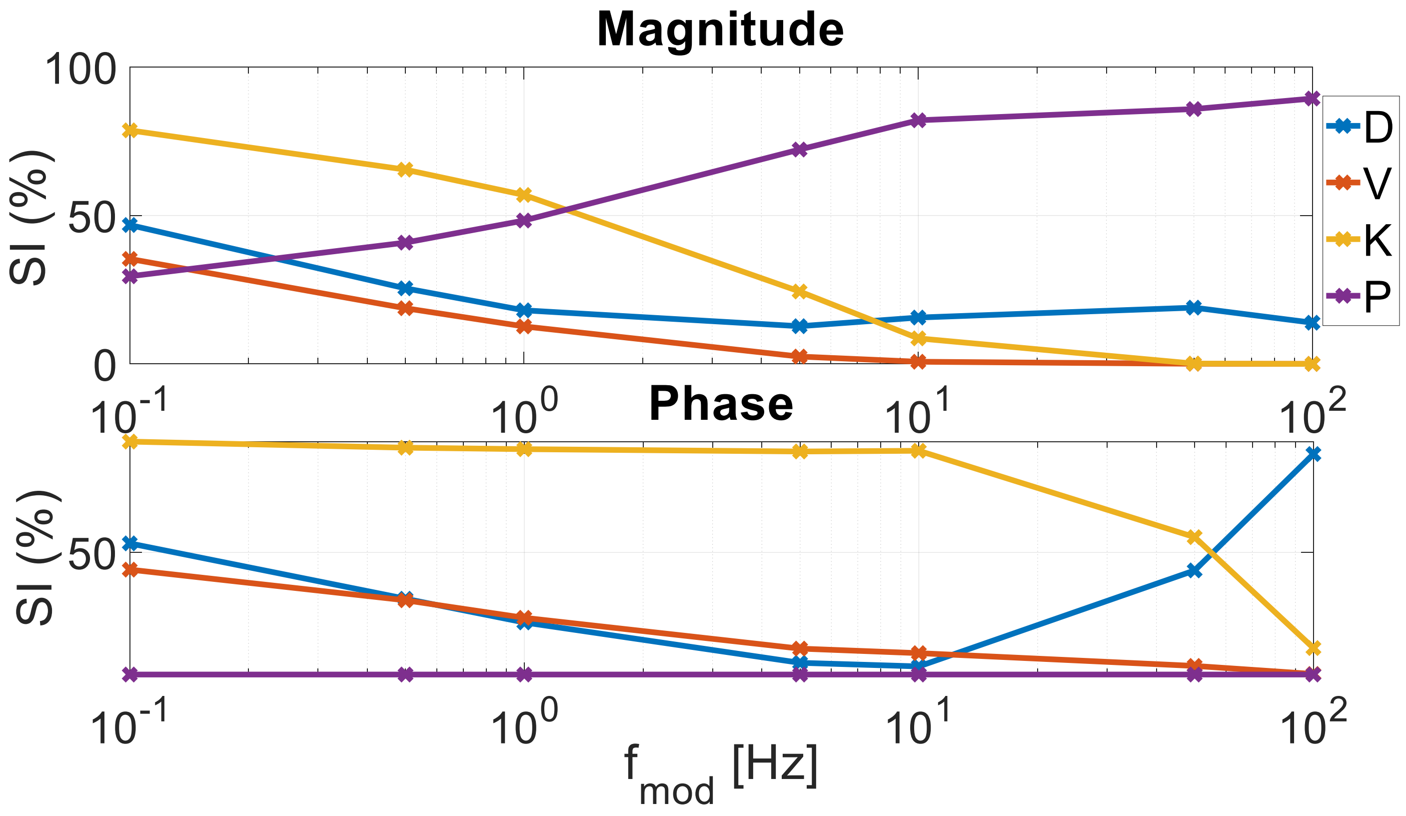
Sensitivity of model coefficients

- **Small errors in P get compensated in other parameters**
- Large deviations in D and V
- Due to different sensitivity of the temperature profile to different coefficients

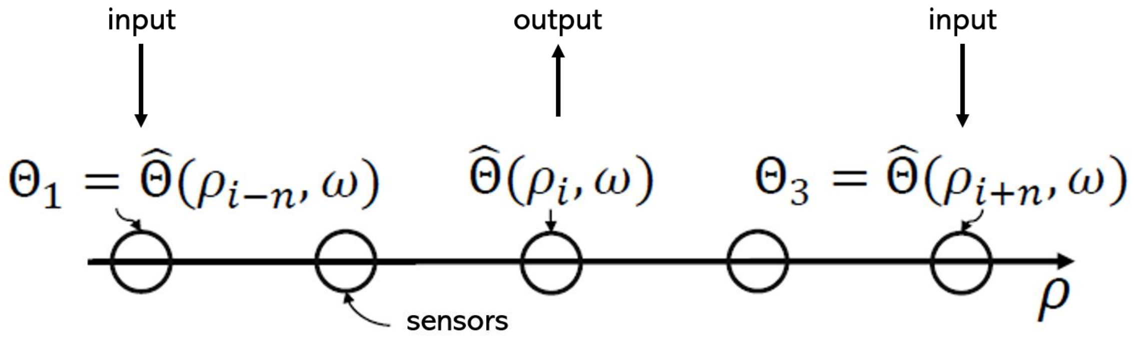


Sensitivity of model coefficients

- Sensitivity of the temperature profile to different parameters under noisy conditions
- **Depends on modulation frequency**
- The effect of **P dominates**
- Future, large devices: more deposition broadening, so joint estimation required
- Depending on the coefficient of interest, *magnitude or phase response* in *different frequency ranges*



Estimation methods: a brief overview



- **Maximum Likelihood Estimator** [1] (MLE)
  - Estimate D,V,K,P constant on subdomain
  - Taking noise covariances into account
  - Nonlinear optimization
- Frequency Domain Least Squares [2] (FDLS)
  - Parametrize spatial dependence of D,V,K,P in terms of basis functions
  - Derive closed-form linear least squares solution for hyperparameters
- Flux fit [3,4] (FF)
  - Parametrization of P as a modified Gaussian
  - Parametrize heat flux q in terms of D,V as basis functions
  - Fit the flux term to the deposition term using nonlinear optimization
- Break-in-slope[5] (BIS)
  - Trusted method, used as reference
  - Time-domain, no transport
  - Requires step in power; deposition proportional to break in temperature slope

[1] M. Van Berkel *et al*. (2014). *Automatica*. **50**. 2113–2119.
[2] R. J. R. van Kampen, *et al.* (2020) *IEEE Control Syst. Lett.*. **5**. 1681-1686.
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[4] Slief *et al.* (2022). *Phys. Plasmas.* **29**. 010703.
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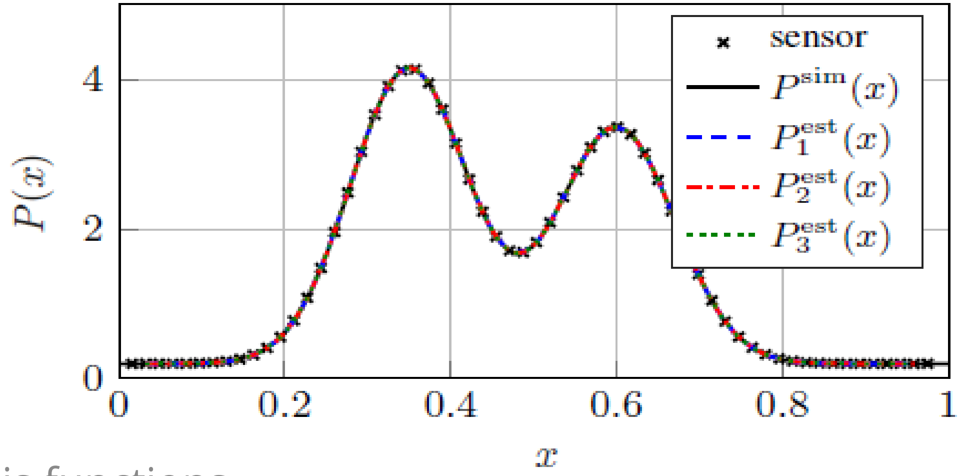

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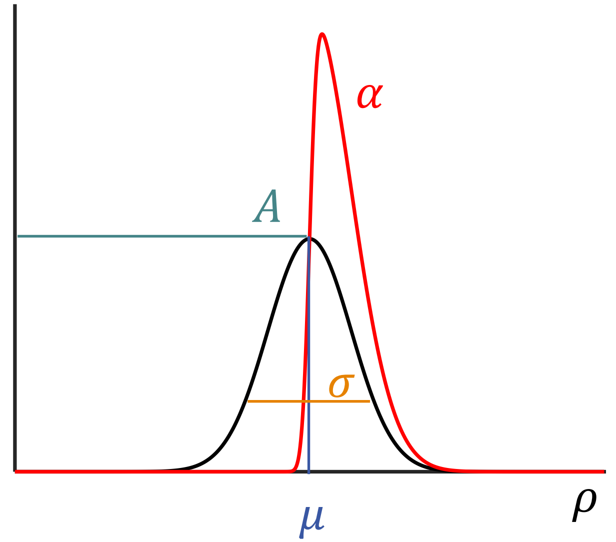

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$$\tilde{\boldsymbol{q}}_e(\rho,\omega) = \frac{1}{\rho}\int_0^1 \rho' \left(P(\rho',\sigma,\mu,A,\alpha)\,\tilde{U}(\omega) - \frac{3}{2} n_e(\rho') i\omega\Theta(\rho',\omega)\right) d\rho'$$

$$\tilde{\boldsymbol{q}}_e(\rho,\omega) = -D(\rho) n_e(\rho)\frac{\partial\Theta}{\partial\rho}(\rho,\omega) + V(\rho) n_e(\rho)\Theta(\rho,\omega)$$

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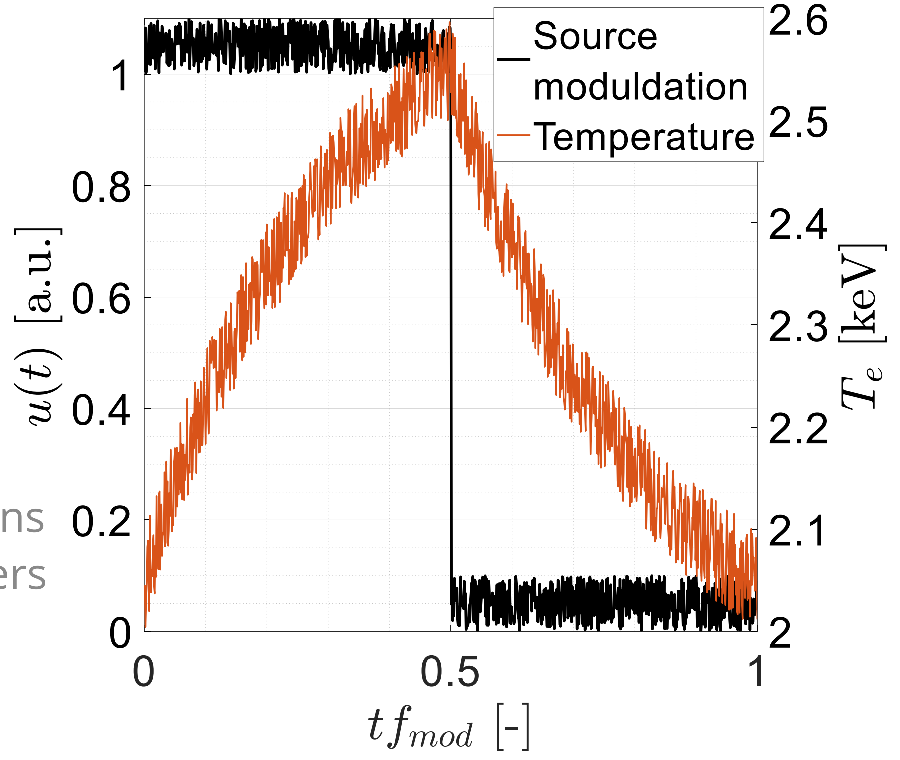

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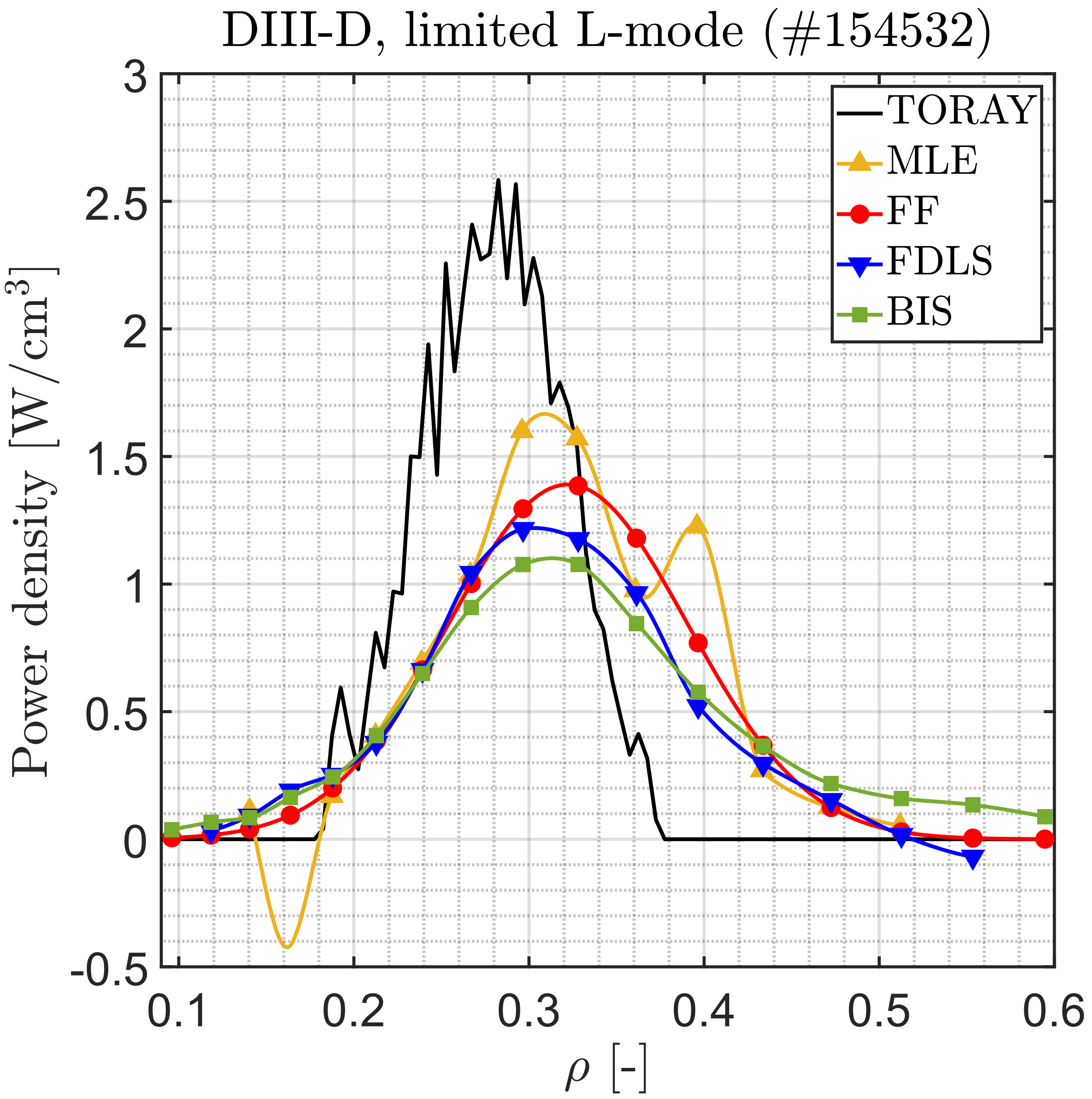
Results – DIII-D

- Estimation of P in DIII-D: factor 1.5 – 3 broadening with respect to ray-tracing[1]
- Broad agreement between different experimental methods



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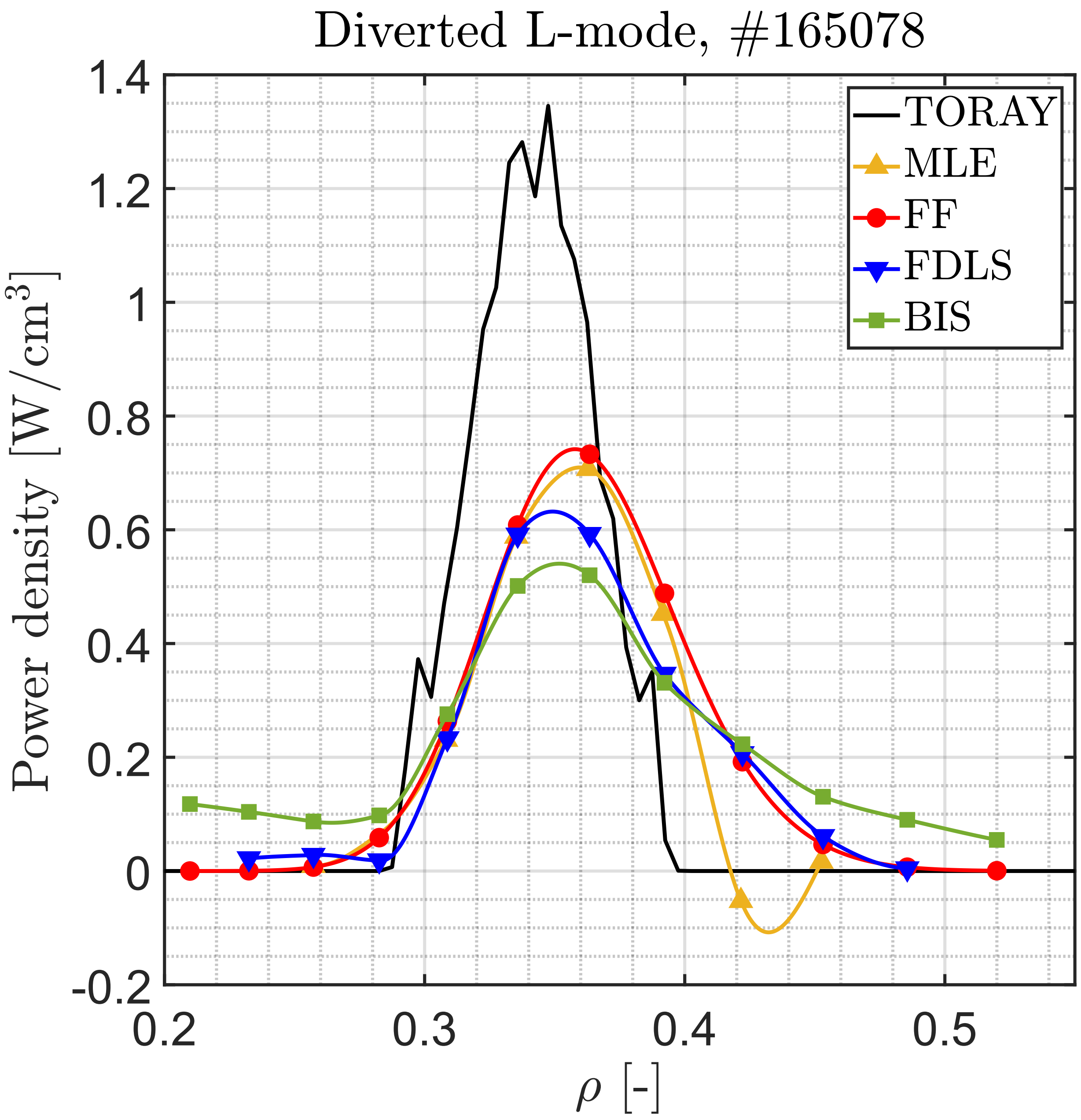

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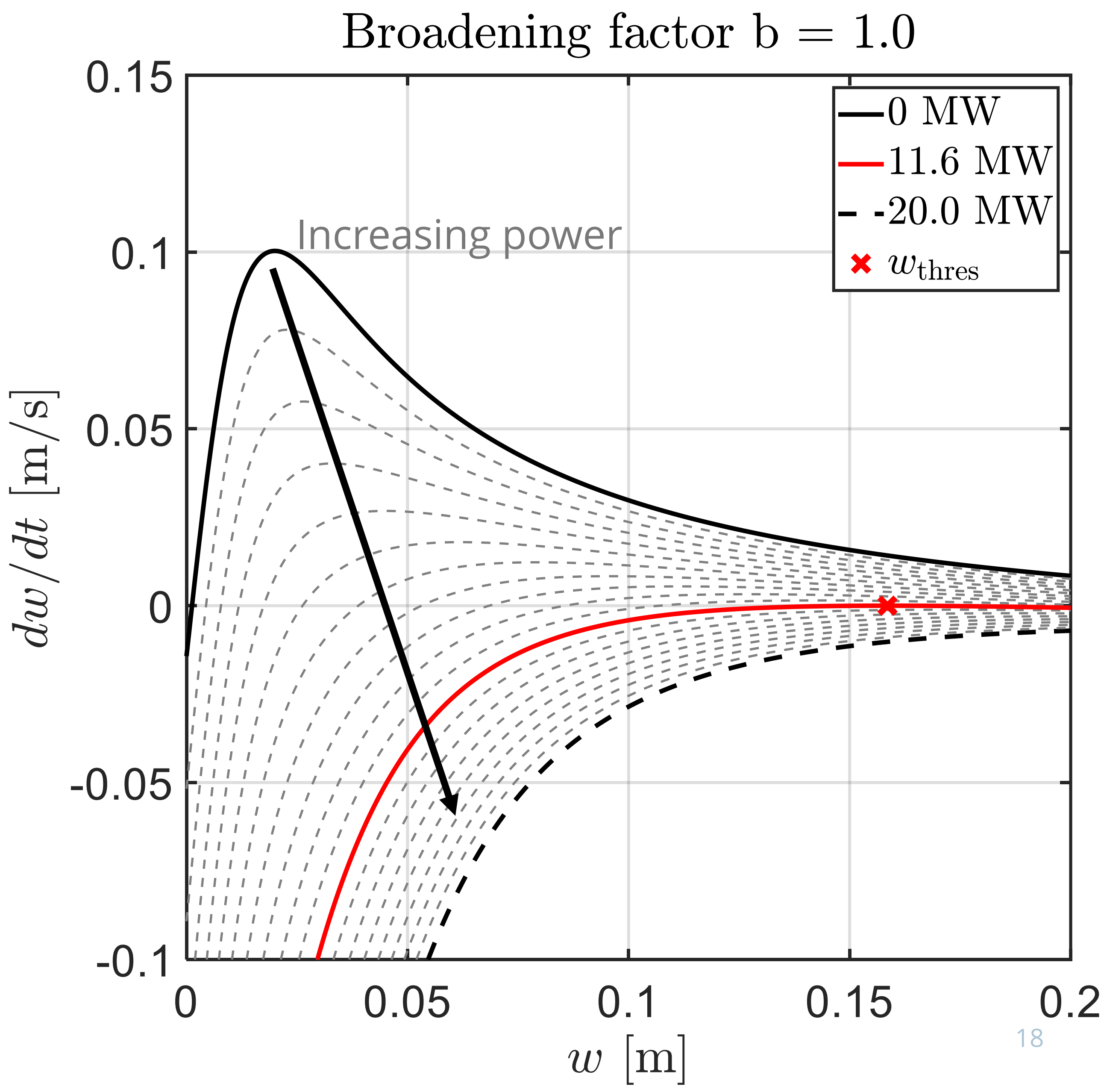
Results – Implications for ITER

- Estimation of P in DIII-D: factor 1.5 – 3 broadening with respect to ray-tracing[1]
- No broadening: business-as-usual



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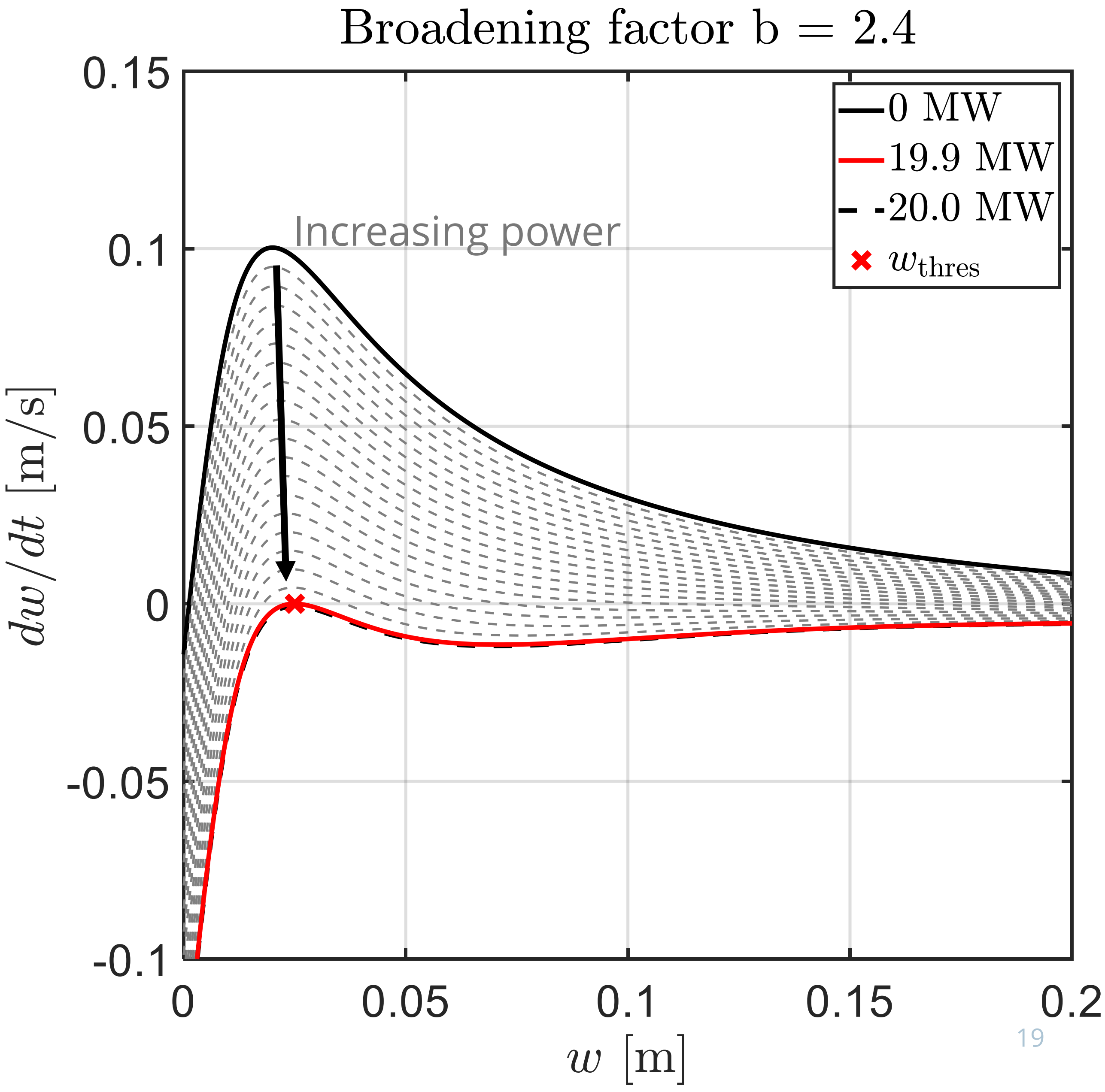
Results – Implications for ITER

- Estimation of P in DIII-D: factor 1.5 – 3 broadening with respect to ray-tracing[1]
- Edge case at factor 2.4 broadening: all available power required for suppression



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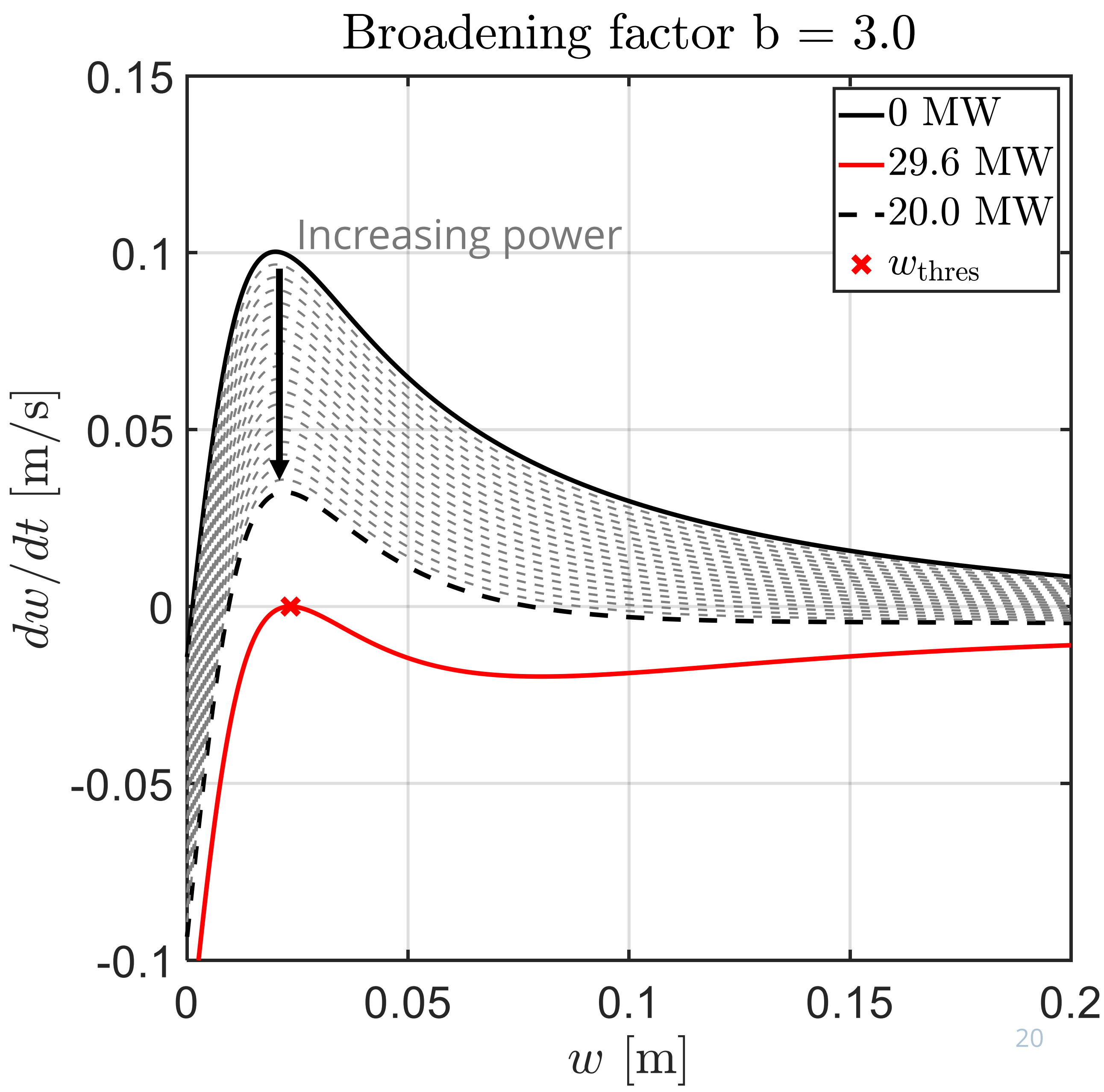
Results – Implications for ITER

- Estimation of P in DIII-D: factor 1.5 – 3 broadening with respect to ray-tracing[1]
- At factor 3 broadening, more power required than available



[1] Slief *et al.* (2023). *Nucl. Fusion* **63**. 026029.

Conclusions & Outlook

- Several methods can **simultaneously estimate any combination of D,V,K,P**
- **Key assumptions hold** in relevant experimental conditions
- **Coefficients have different sensitivities** to errors in the others
- Temperature profile sensitivity is **modulation frequency dependent**
- **Significant broadening in DIII-D** P estimates
- This could have **consequences for ITER NTM control**

Outlook:

- Joint transport coefficient estimation
- Time varying effects using Kalman filters