Max-Planck-Institut für Plasmaphysik

Can we understand the weak density scaling of the energy confinement time in W7-X ECRH plasmas?

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Special thanks to the Interferometer, TS, XICS, and diam. loop teams.

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SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

EUROfusion

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Motivation

- **One of the promising features of stellarators is that empirically the energy confinement time increases with density**
  - A reactor needs high density for core performance (alpha-heating and coupling to ions) and envisioned exhaust concepts (high radiation, divertor pressure,…).
  - It is believed that an economically feasible reactor needs at the very least a confinement on par with the emprical scaling ISS04, preferably 1.5 x ISS04, see [Warmer, FST, (2015)].
- **Unfortunately, W7-X is showing a weaker density scaling than ISS04, causing lower relative performance (τ_E / τ_{ISS04}) as the density is increased**
  - Keep in mind: The density scaling of W7-X is still positive, just not as strong as in ISS04.
  - Question: Does this mean we did something „wrong“ with W7-X?
  - Peaked density profiles improve the performance above ISS04 levels. Due to the fueling characteristics, this may, however, not be a viable reactor scenario.

$$\tau_{\mathrm{ISS04}} = 0.134 a^{2.28} R^{0.64} P^{-0.61} \bar{n}_{\mathrm{e}}^{0.54} B^{0.84} \iota_{2/3}^{0.41}$$

A (crude) model for global transport

- **Often, the scaling of τ_E is associated with certain transport effects**
  - Examples: „ISS04 is consistent with Gyro-bohm“ or „1/ν-transport should result in a stronger density scaling than ISS04“
- **Which physical picture lies behind such statements?**
  - **If** we assume $T_e=T_i=T$, W = 3/2·2·<n><T>V and that a diffusive ansatz describes transport:

$$P/S = -2\bar{n}\chi_{\text{eff}}\nabla T \approx \bar{n}\chi_{\text{eff}}\bar{T}/a$$

$$\tau_{\text{E}} = \frac{W}{P} = \frac{3}{2}\cdot\frac{2\bar{n}\bar{T}V}{P}$$

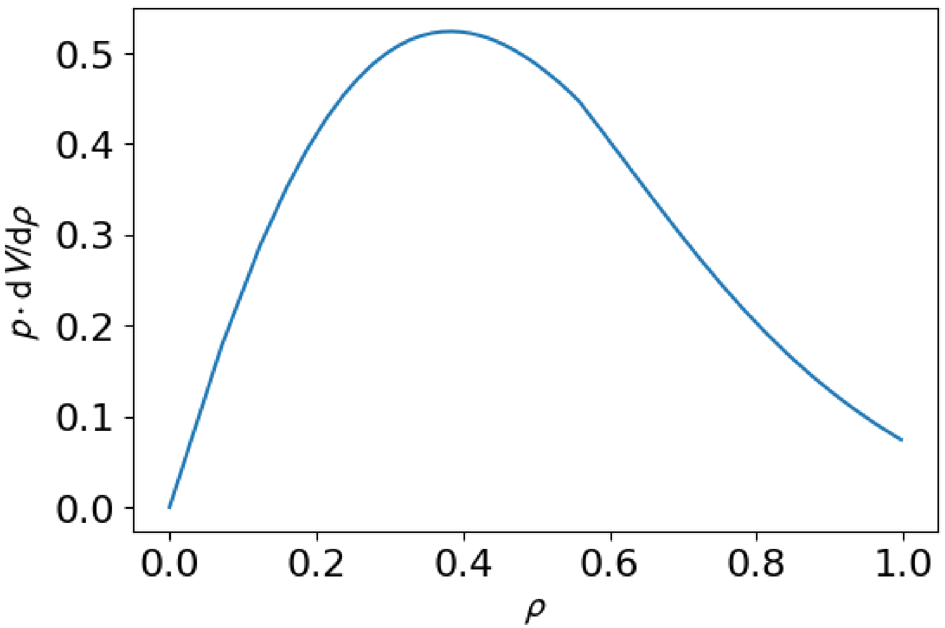
$$\tau_{\text{E}} = \frac{3V}{S}\frac{a}{\chi_{\text{eff}}} = c_{\text{geo}}\frac{a^2}{\chi_{\text{eff}}}$$

- **This could be called the *intuititve interpretation* of τ_E.**
  - However, different transport/loss mechanisms affect the plasma simultaneously at different locations. Isn‘t it just ~~bull~~ completely oversimplifield?

A (crude) model for global transport II

- **While τ_E is indeed a quantity averaging over very different phyics at different radii, it is strongly weighted towards half radius:**

$$W_{\mathrm{kin}} = \frac{3}{2} \cdot \int p(\rho) \frac{\mathrm{d}V}{\mathrm{d}\rho} \mathrm{d}\rho$$



→ Without drastic changes in the center or edge of the plasma (sudden profile peaking, high radiation,…), τ_E *may* be indicative for the transport around half radius. But this needs to be confirmed from case to case.

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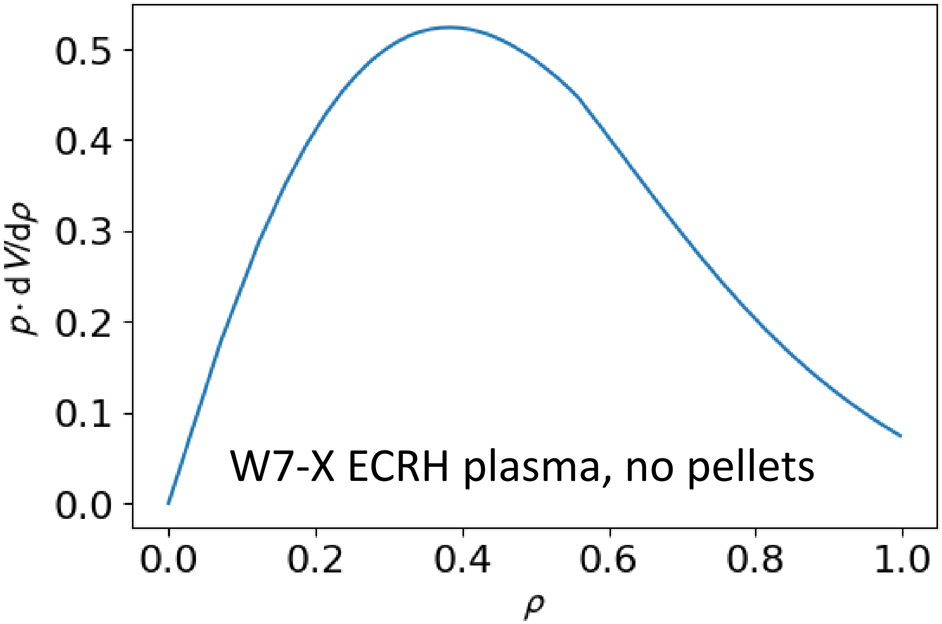

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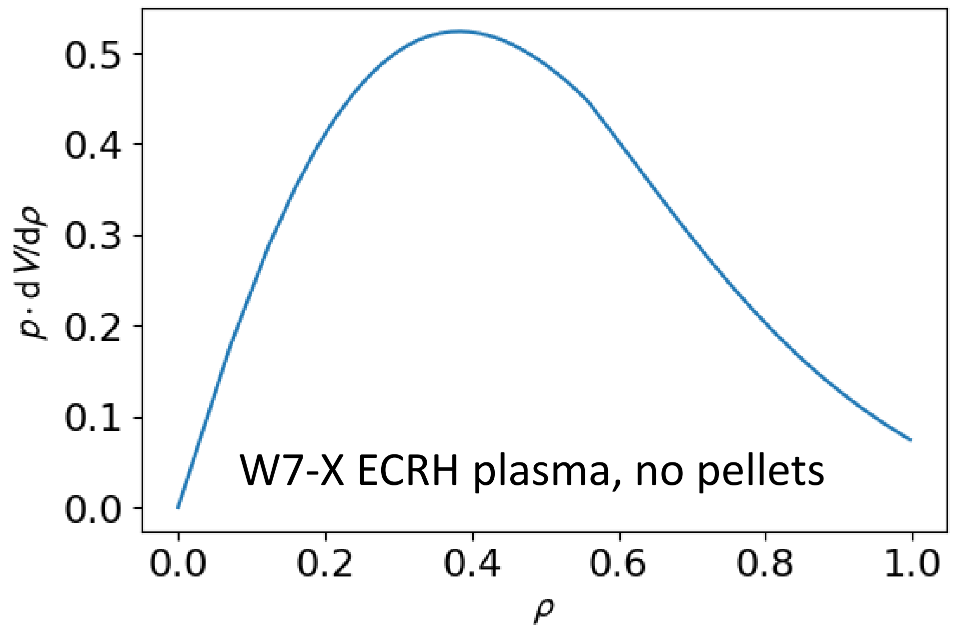

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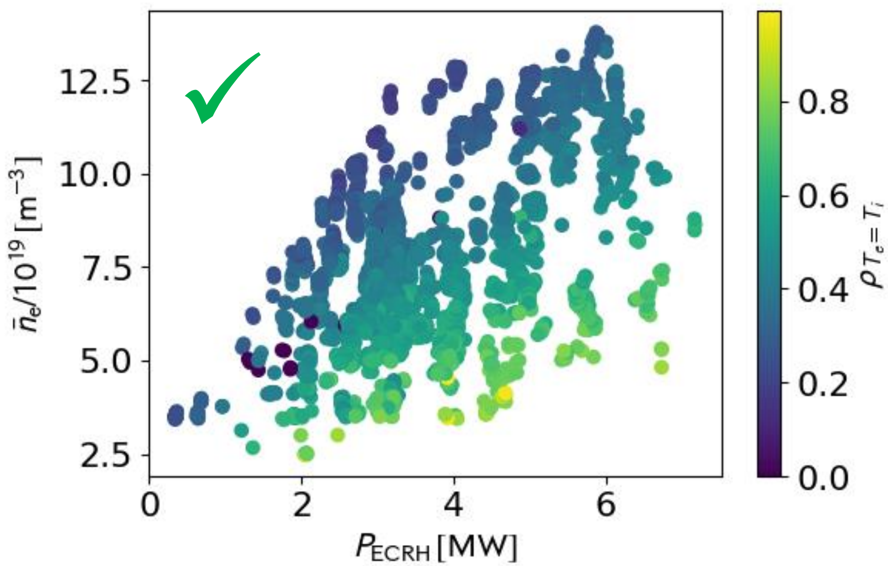
Before we go on, let's check it!

- **The *intuititve interpretation* is applicable if at ρ=0.5: T_e=T_i and if the τ_E has the same n,P-scaling as 1/χ_{eff}.**

$$\tau_{\mathrm{E}} = \frac{3V}{S}\frac{a}{\chi_{\mathrm{eff}}} = c_{\mathrm{geo}}\frac{a^2}{\chi_{\mathrm{eff}}} \qquad \chi_{\mathrm{eff}} \approx \frac{aP}{2S\bar{n}\bar{T}}$$



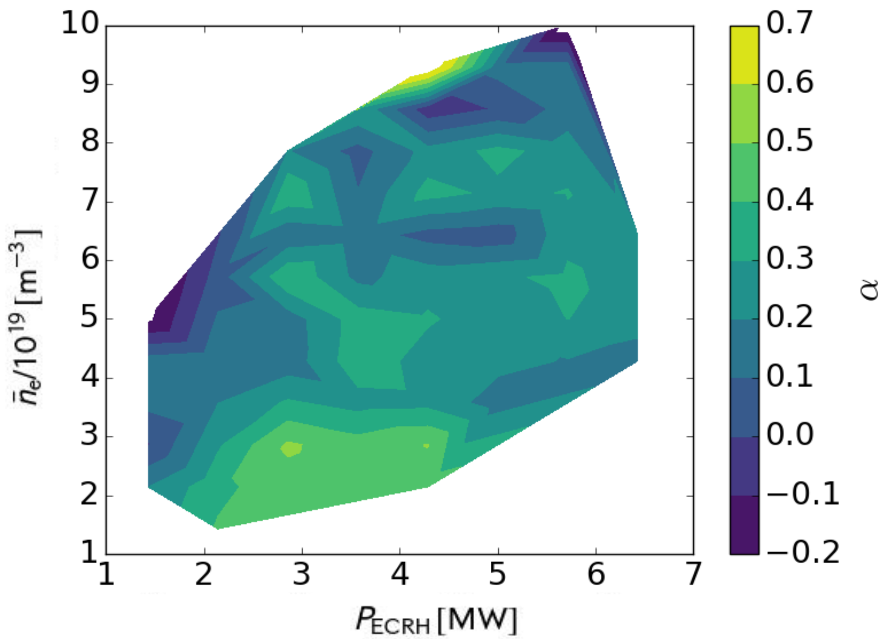
(✓)

	α (n^{α})	β (P^{β})
τ_E	0.22	-0.48
1/χ_{eff}	0.07	-0.38

→ The intuitive interpretation seems to be (somewhat) justified. χ_{eff} also shows a weak density scaling, if any (ISS04: α = 0.54). **But why?!**

Losses?

- **Radiation losses are high, but radiation front usually localized in the edge (cf. Zhang et al, EPS 2019)**
  - Weak density scaling already at $n_e > 3\text{-}4 \cdot 10^{19}$ m^{-3}
  - Similar confinement before and after boronization.
- **Charge exchange losses are low (below 10 % of P_{ECRH})**
  - Experimental verficiation currently ongoing.



→ Losses may contribute to the weak density scaling, but it is unlikely that they are causing it.

What would we expect?

- **Best guess without any knowledge**
  - Empirical cross-machine scaling ISS04

$$\tau_{\mathrm{ISS04}} = 0.134 a^{2.28} R^{0.64} P^{-0.61} \bar{n}_{\mathrm{e}}^{0.54} B^{0.84} \iota_{2/3}^{0.41}$$

  - ISS04 is consistent with a Gyro-Bohm-like transport due to microinstabilities (coincidence not excluded!): $\chi_{GB} \sim T^{3/2}$

$$\chi_{\mathrm{eff}} \propto \frac{P}{\bar{n}\bar{T}} \propto T^{3/2} \Rightarrow T \propto \left(\frac{P}{n}\right)^{2/5}$$

$$\Rightarrow \chi_{\mathrm{eff}} \propto \left(\frac{P}{n}\right)^{3/5}$$

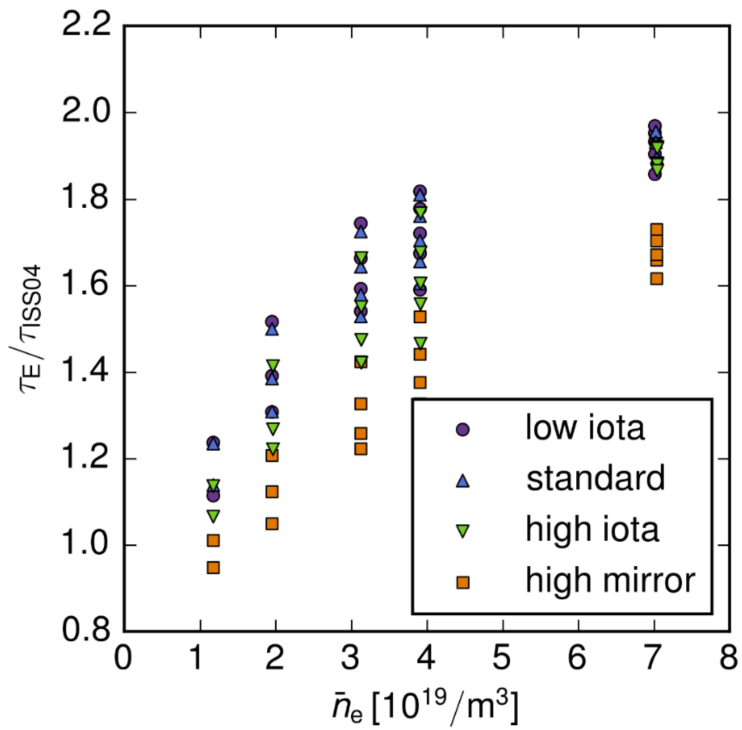
$$\Rightarrow \tau_{\mathrm{E}} \propto \left(\frac{n}{P}\right)^{3/5}$$

What would we expect? II

- **We can guess very accuratly, if the transport is dominated by NC**
  - Using NTSS/DKES, predictive runs have been made assuming turbulence only plays a major role in the edge.
  - In those, the density dependence is not a simple power law, but it is stronger than in ISS04.

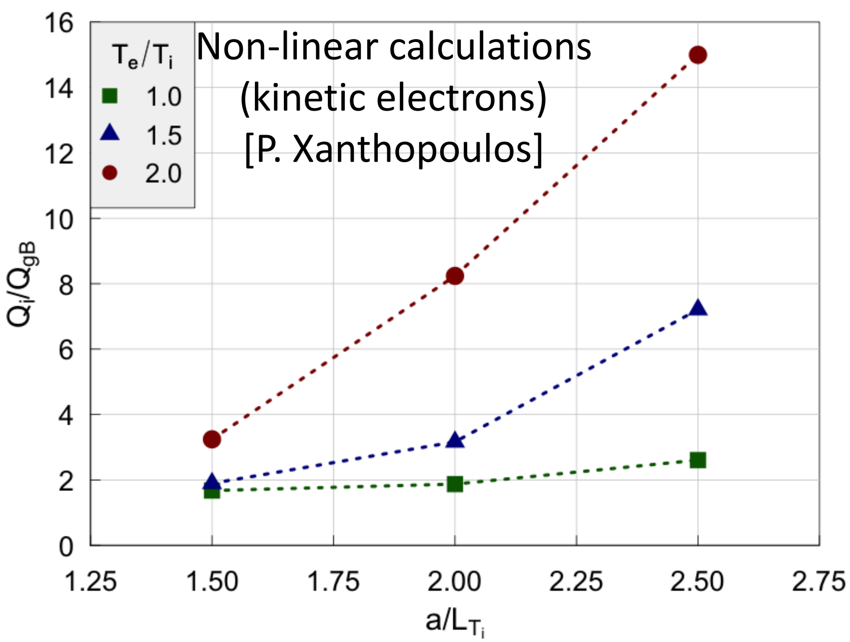
→ This together with the observation that turbulence plays a major role in OP1.2 makes it **unlikely** that the weak density scaling is **a NC effect**.

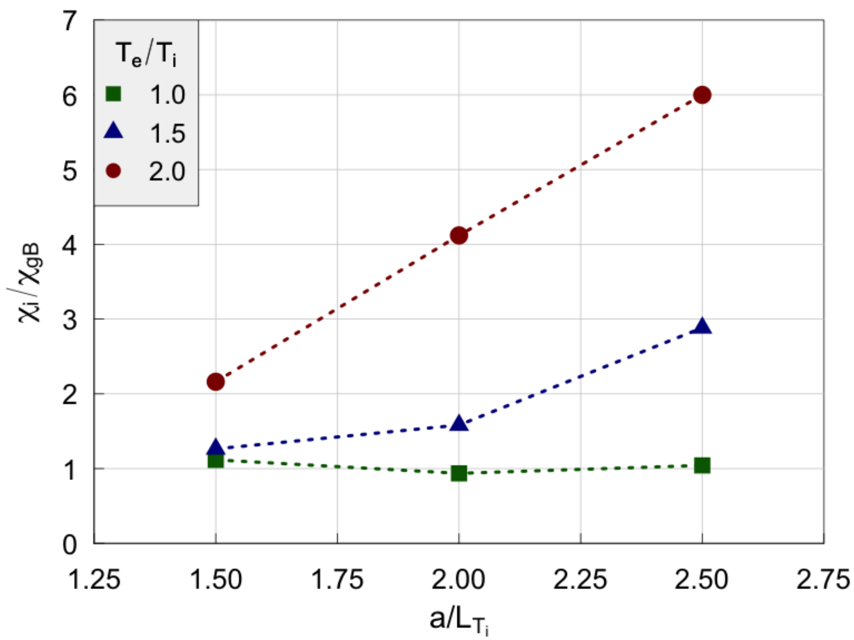
Created from Y. Turkin's NTSS runs



Turbulence

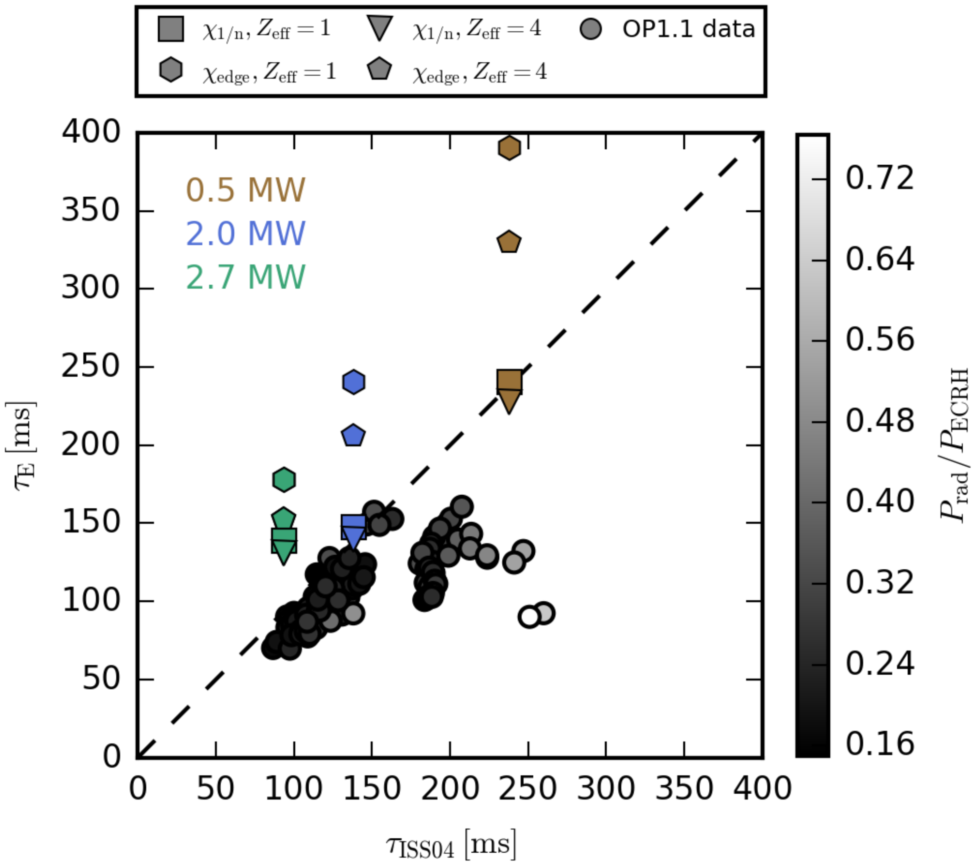
- **In the parameter space of OP1.2: Ion temperature clamped around 1.6 keV**
  - Central ion temperature basically unchanged at $n_e > 3 \cdot 10^{19}$ m^{-3} (coincidence?)
  - The clamping is currently thought to be caused by ITG turbulence.
  - Combined effect of a certain degree of stiffness of the ion transport and, more importantly, a strong increase of ITG-related transport with T_e/T_i.





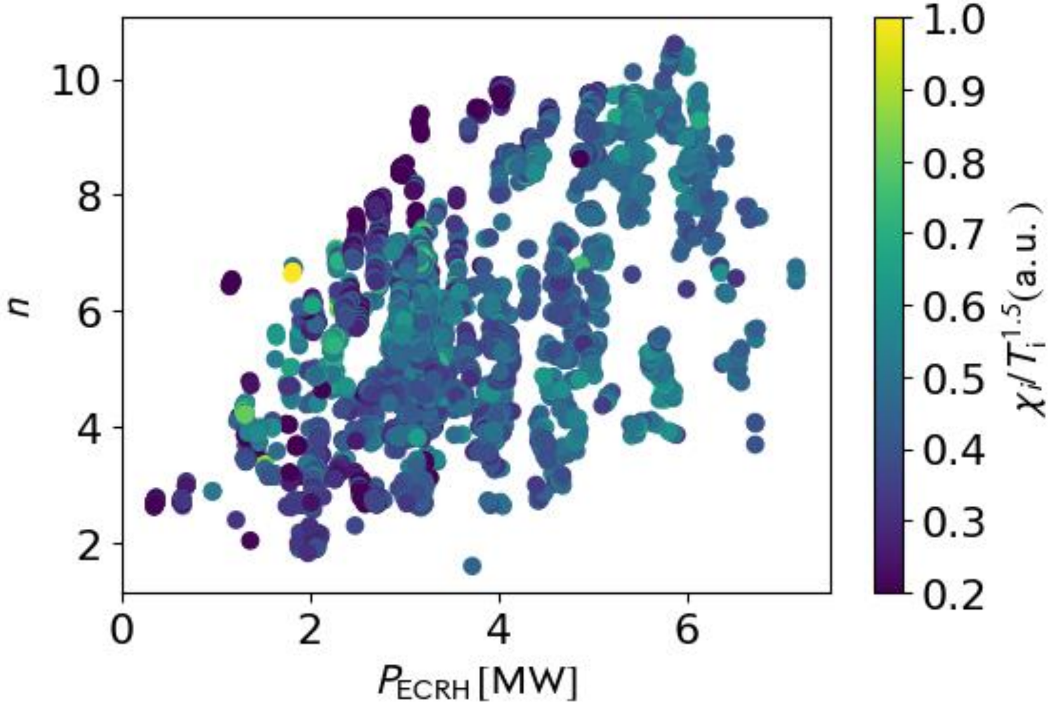
Turbulence

- **We were expecting this already in OP1.1!**
  [G. Fuchert et al, NF (2018)]



Observation

- **Indeed it seems that the ion heat diffusivity at half radius follows a gyro-Bohm scaling.**



Add more complexity

- **What if electrons and ions *were* independent?**

electrons

$$P_{\mathrm{ECRH}} - P_{\mathrm{ei}} = -nS\chi_{\mathrm{e}}\nabla T_{\mathrm{e}} + \ldots$$

$$\propto nT_{\mathrm{e}}^{5/2}$$

IF gyro-Bohm

We‘re just exploring, not claiming!

ions

$$P_{\mathrm{ei}} = -nS\chi_{\mathrm{i}}\nabla T_{\mathrm{i}} + \ldots$$

$$\propto nT_{\mathrm{i}}^{5/2}$$

IF gyro-Bohm

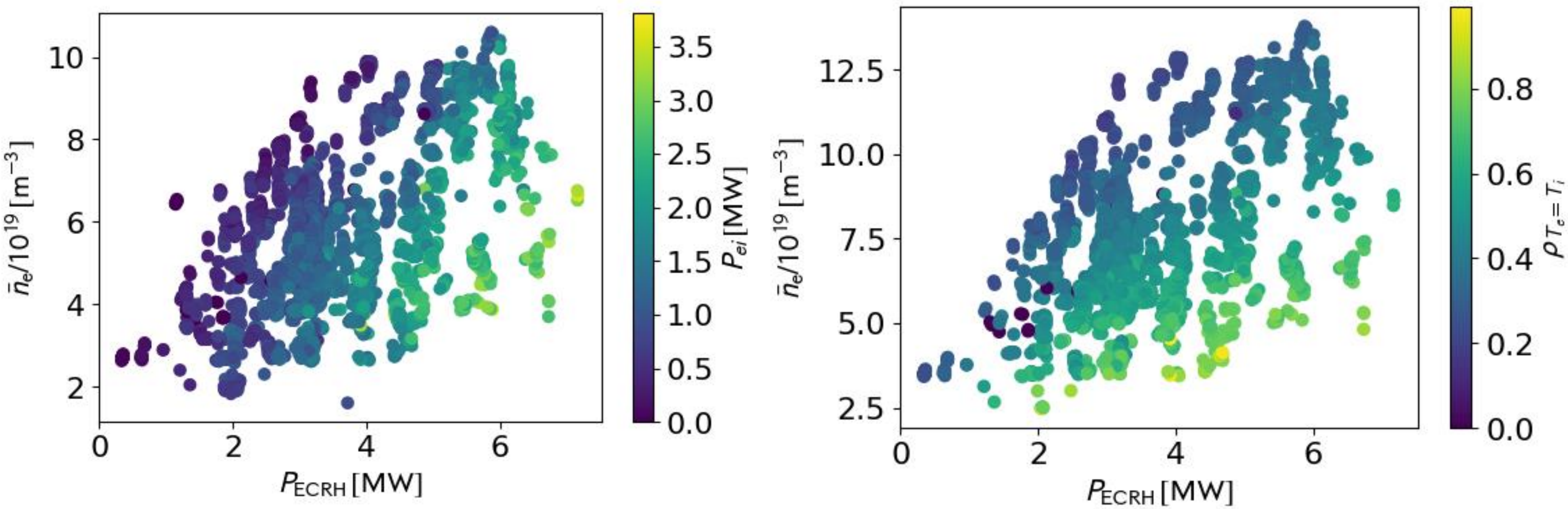
- **Scaling of T_e, T_i (aussuming independence and gyro-Bohm):**

$$T_{\mathrm{e}} \propto \left(\frac{P_{\mathrm{ECRH}} - P_{\mathrm{ei}}}{n}\right)^{2/5}$$

$$T_{\mathrm{i}} \propto \left(\frac{P_{\mathrm{ei}}}{n}\right)^{2/5}$$

Add more complexity

- **Interestingly, P_{ei} is only weakly dependant on density**
  - Not neccessarily intuitive, since the transfer power increases with n^2
  - But $T_e = T_i$ achieved at smaller radii („transfer volume“ decreases).
  - Actually, it seems that P_{ei} decreases very slightly with density (needs to be confirmed with latest profile versions).



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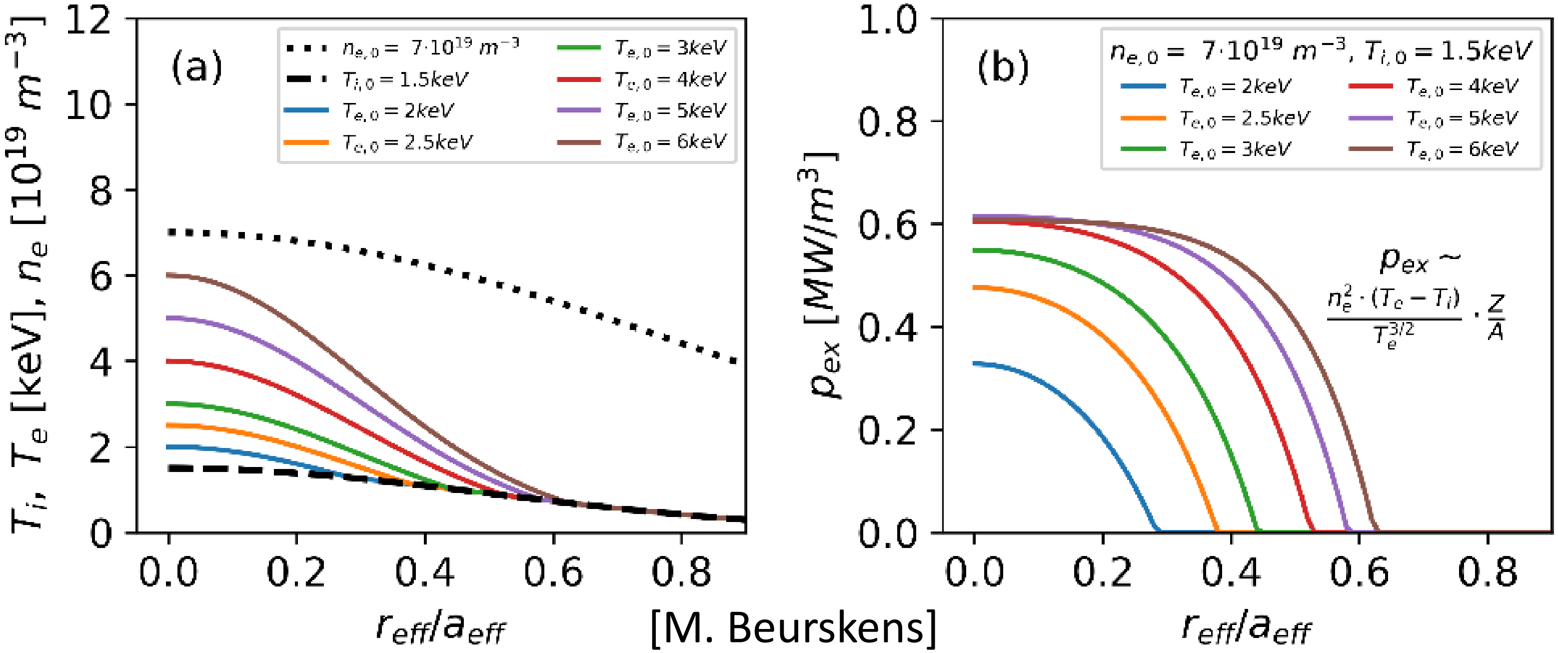


[M. Beurskens]

Add more complexity

- **Compare the scaling of T(ρ=0.5) with hypothetical $T_{e,GB}$ and $T_{i,GB}$**
  - T(ρ=0.5) shows a scaling much closer to $T_{i,GB}$.

$$P_{\mathrm{ECRH}} - P_{\mathrm{ei}} = -nS\chi_{\mathrm{e}}\nabla T_{\mathrm{e}} + \ldots$$
$$\propto nT_{\mathrm{e}}^{5/2}$$

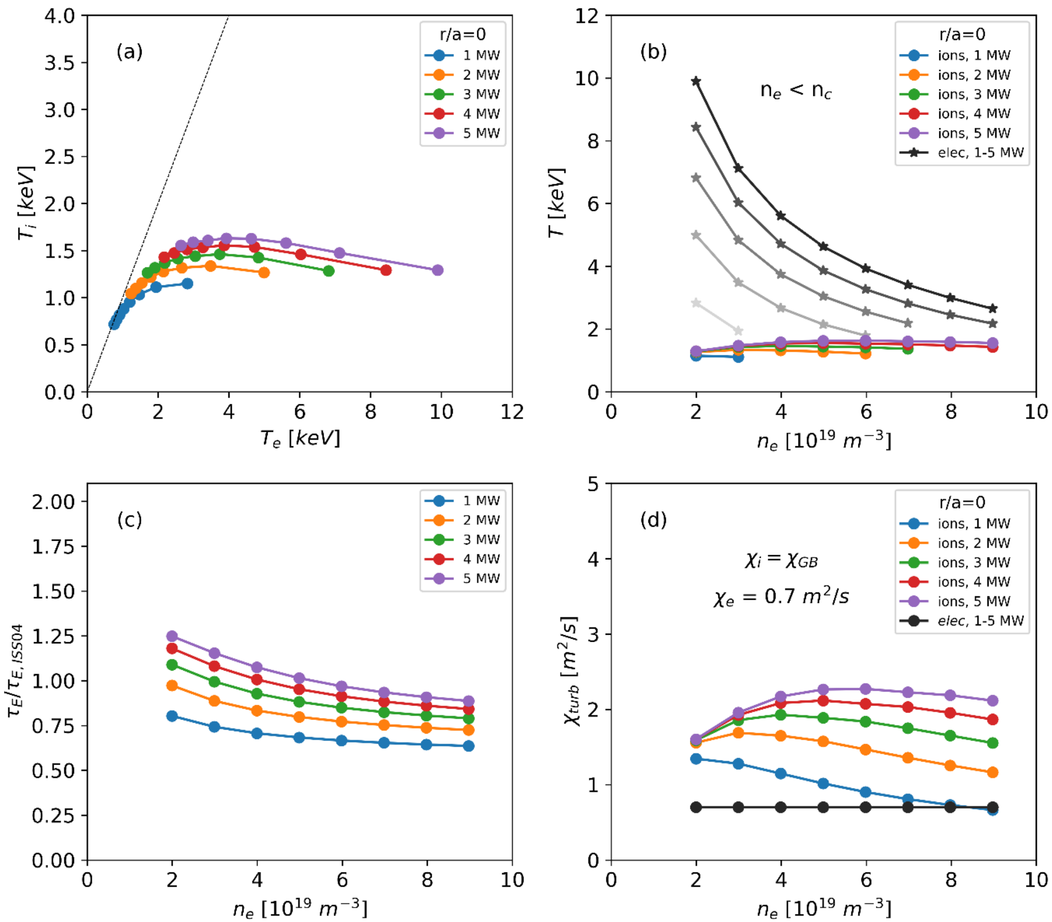
$$P_{\mathrm{ei}} = -nS\chi_{\mathrm{i}}\nabla T_{\mathrm{i}} + \ldots$$
$$\propto nT_{\mathrm{i}}^{5/2}$$

	α (n^α)	β (P^β)
T(ρ=0.5)	-0.93	0.64
$T_{e,GB}$	-0.24	0.34
$T_{i,GB}$	-0.76	0.56

$$\tau_{\mathrm{E}} \propto \frac{1}{\chi_{\mathrm{eff}}} \propto \frac{nT}{P}$$

	α (n^α)	β (P^β)
T(ρ=0.5)	0.07	0.36
$T_{e,GB}$	0.52	0.57
$T_{i,GB}$	0.24	0.44
W7-X	**0.22**	**0.48**

NTSS simulations confirm



NTSS simulation assuming:

- **Diffusive electron transport**

  $\chi_{e,turb}$ = 0.7 m^2/s (similar [Weir-NF-2021])

- **gyroBohm ion transport**

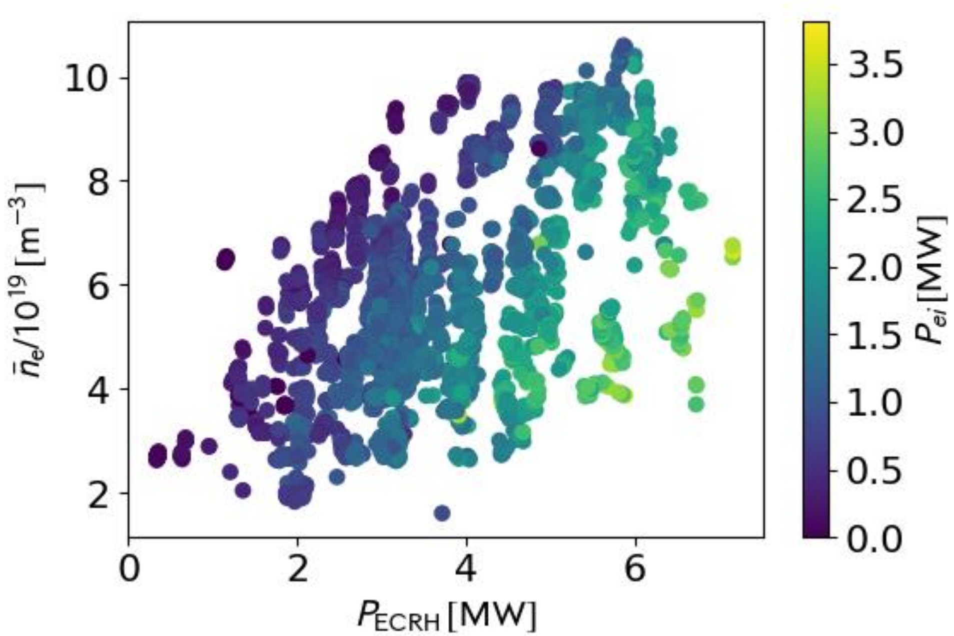
$$\chi_{i,gB} = \frac{\rho_i^2 c_i}{a} = \sqrt{\frac{m_i}{e}}\frac{T_i^{3/2}}{aB^2}$$

Vary P_{ECRH}=1-5 MW and n_e=10^{19} - 10^{20} m^{-3}

→ Saturation of T_i (clamping?) occurs

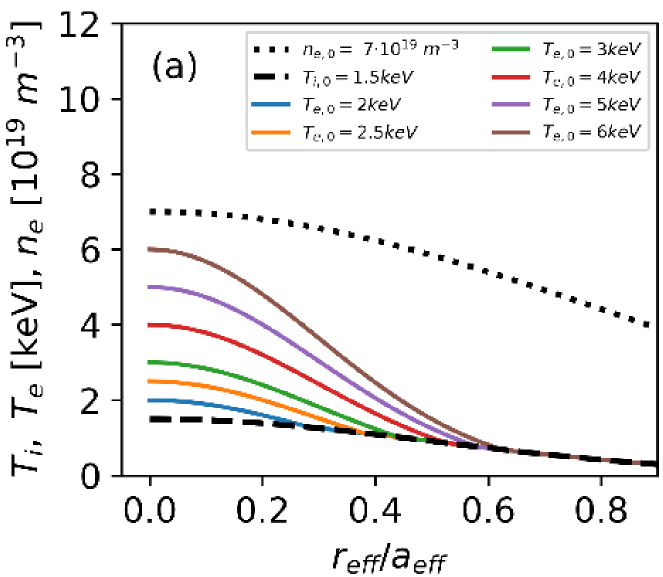
Observation

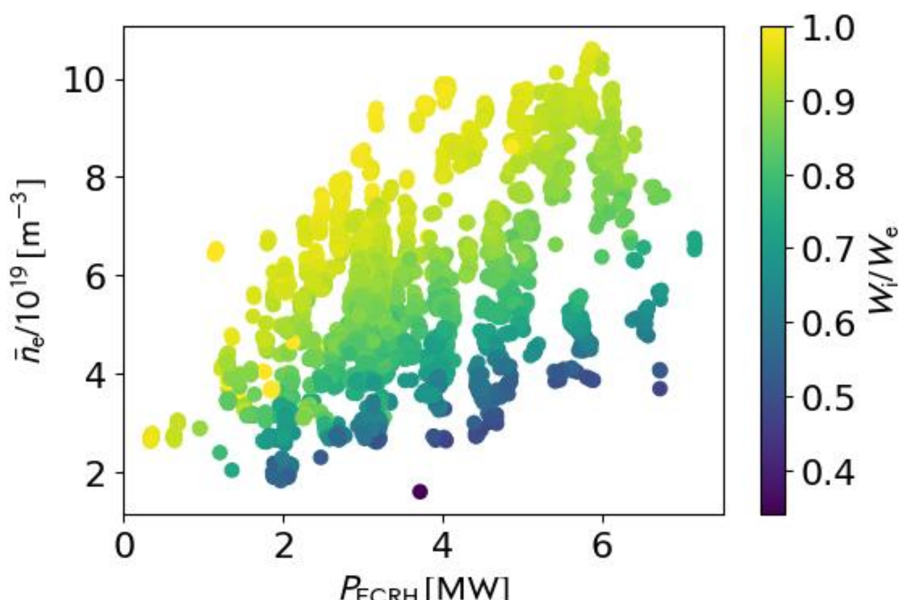
- **The temperature at half-radius behaves as if it was completely determined by the ions with a gyro-Bohm-like transport.**
  - In a sense, P_{ei} seems to be the main factor determining τ_E by propagating ist weak density scaling to $T(\rho=0.5)$.
  - Open question: Is there an effect on electron transport (other than Te being determined by P_{ei})?



Summary

- **The energy confinement time in the basic ECRH plasmas of W7-X:**
  - Seems to reflect transport and temperatures around half radius.
  - The transfer power P_{ei} seems to be a strong determining factor of both.
  - τ_E is influenced by the turbulence in two ways: By setting the actual transport level and by the strong profile dependence of P_{ei} (n, T_e and T_i).
  - The weak density scaling would then partly just describe how we go from $W_i<W_e$ to $W_i \approx W_e$ in the OP1.2b parameters space.





Pure speculation

- **Why do we not see this in the ISS04?**
  - The stellarator database includes both ECRH and NBI plasmas.
  - Some of the smaller experiments may have very low ion temperatures, showing very different physics.
  - Maybe some other experiments actually show similar depencendes, but these could get lost when comparing different machines with larger changes in the scaling parameters.

- **Is the weak density scaling an issue for fusion?**
  - Probably not, because a reactor with $T_e > T_i$ would not be attractive (we would just not build that…). But then the scaling would look different.
  - How? We do not know yet.