Max-Planck-Institut für Plasmaphysik

# The density dependence of the energy confinement time in W7-X: More than just a scaling law

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## 1. Motivation

- In stellarators, the energy confinement time shows a positive density dependence which is favorable for reactor-relevance. Given the large variety of stellarator configurations it is not clear if there is a universal reason behind this observation and whether it will extrapolate to reactor-relevant conditions.
- Wendelstein 7-X (W7-X) also shows such a positive density dependence. However, it is weaker than the one found in the empirical cross-machine scaling ISS04 [1] and even changes over the parameter space explored so far.
- For plasmas with only ECR heating and gas-puff fueling, transport has been shown to be mainly turbulent (in the parameter space explored so far). While turbulence seems to dominate the transport, it will be shown in the following that weak density dependence itself mainly arises from the varying degree of collisional ion heating throughout the parameter space explored.

## 2. A common model for global confinement

It is often assumed that the transport at a certain radius characterizes the global confinement. Assuming a diffusive ansatz and equal electron and ion temperatures, the energy confinement time, $\tau_E$, is proportional to the inverse of an *effective heat diffusivity*.

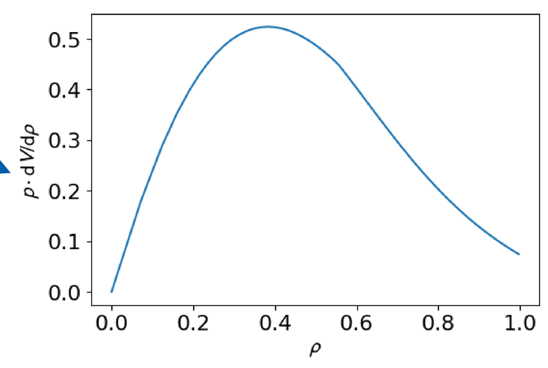
This is a very simplified model and it cannot be assumed that it applies to a specific experimental condition. However, under certain conditions it can describe the global confinement well, since the stored energy is often strongly weighted to a particular radial range. In the center, the pressure is high but the volume is low and in the edge the opposite is true. The applicability must be checked for specific experimental conditions.

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

$$\tau_E = \frac{W}{P} = \frac{3}{2}\cdot\frac{2\bar{n}\bar{T}V}{P}$$

$$\tau_E = \frac{3V}{S}\frac{a}{\chi_{\mathrm{eff}}} = c_{\mathrm{geo}}\frac{a^2}{\chi_{\mathrm{eff}}}$$

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




The applicability can be tested using experimental densities, temperatures and heating powers to evaluate the equations above and compare the scaling of $1/\chi_{\mathrm{eff}}$ and $\tau_E$ (assuming a power law). The closer their scalings, the more meaningful the results of the simple model.

$$\chi_{\mathrm{eff}} \approx \frac{aP}{2S\bar{n}\bar{T}}$$

| | $\alpha$ ($n^\alpha$) | $\beta$ ($P^\beta$) |
|---|---|---|
| $\tau_E$ | 0.30 | -0.49 |
| $1/\chi_{\mathrm{eff}}$ | 0.18 | -0.37 |

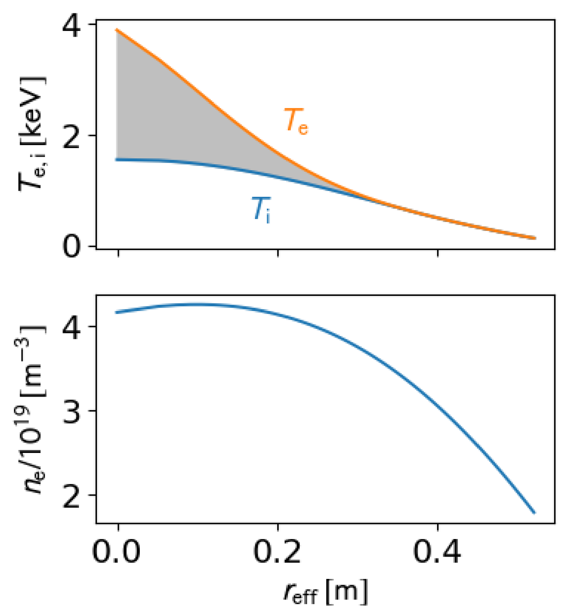
➔ The common model for global performance does not reproduce the scaling of $\chi_{\mathrm{eff}}$ precisely, but it shows the weak density scaling (even weaker) as well and may shed insight into its underlying mechanisms.

## 5. What determines $P_{ei}$?

In the ECRH experiments considered here, the ions are only heated by collisions and the transferred power is:

$$P_{\mathrm{ei}} = \int p_{\mathrm{ei}}(\rho)\mathrm{d}\rho \approx \int 38 n_e^2 \frac{(T_e - T_i)}{T_e^{3/2}}\frac{Z}{A}\mathrm{d}\rho$$

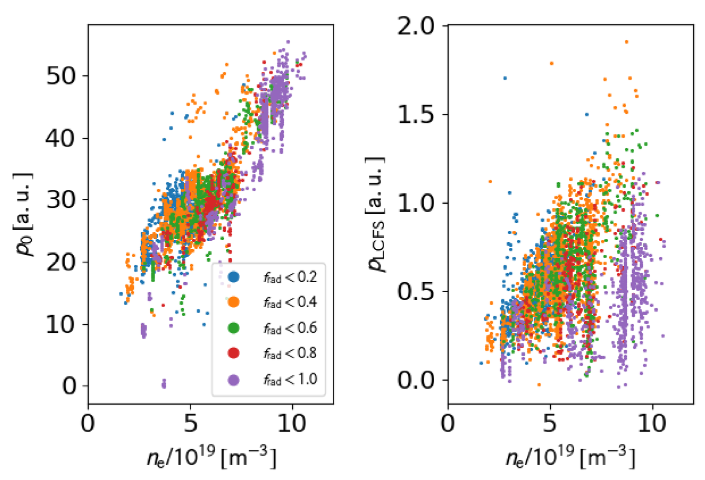
Increasing $n_e$ decreases $T_e$-$T_i$. Hence, the impact of $n_e$ on the total transfer is found to be much weaker than expected from the $n_e^2$-term alone. Interestingly, ($T_e$-$T_i$) is largest in the center, meaning that the central transport properties (determining the profile shape) have a profound impact on $T_i$ and the temperature-dependent heat diffusivity over the entire radius!




## 6. Relevance of reduced performance due to radiation.

- At densities above $7\cdot10^{19}$ m$^{-3}$, $\alpha$ seems to drop below 0.2 (see the figure in box 3). Especially during detachment, a reduction in stored energy by 10-15% is observed (see also D. Zhang, this conference).
- This reduction seems to occur mainly at the plasma edge without noticeable impact on the core pressure. This is likely due to the low degree of profile stiffness commonly observed in stellarators.
- If this effect persists at reactor-relevant conditions, it would be advantageous, since it facilitates exhaust concepts while sustaining high-performance in the plasma core.

The figure to the right shows the central (left) and edge (right) pressure as a function of the density. At low densities, an almost linear increase is seen for both regions. At high radiated fraction ($f_{rad}$=$f_{rad}$/$P_{ECRH}$), the core pressure continues to increase, while the edge pressure saturates or even collapses.



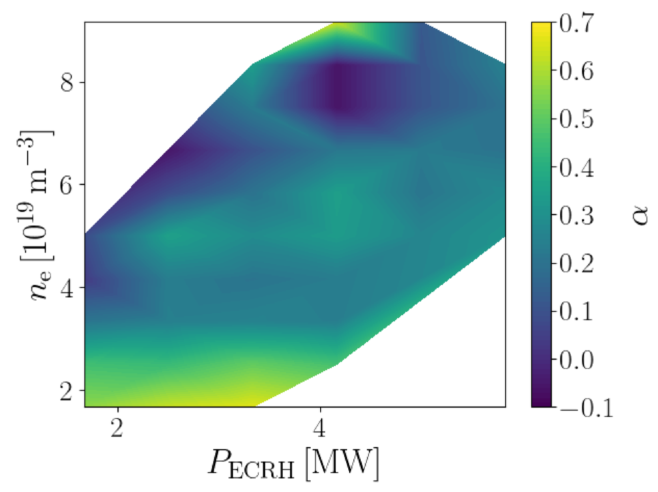

## 3. The density scaling of $\tau_E$ and possible causes

At low density ($n_e$<$3\cdot10^{19}$ m$^{-3}$), $\tau_E$ scales like $n_e^{0.6}$. At higher $n_e$, the scaling factor $\alpha$ drops to lower values (~0.3). The reason was unclear until now.

The empirical scaling ISS04 is consistent with a gyro-Bohm scaling and suggests $\alpha$ = 0.54:

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

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

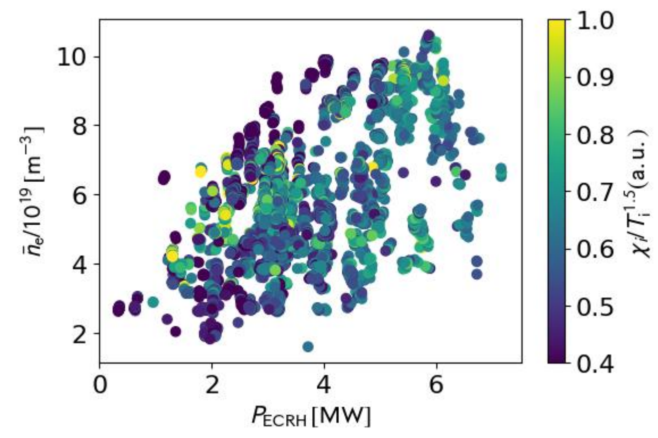



**The following mechanisms were considered to explain the weak density scaling:**

- Losses: In W7-X, radiation is strongest in the edge. Confinement is only affected if the losses approach the heating power (Possibly causing an even weaker scaling above $7\cdot10^{19}$ m$^{-3}$). Charge exchange losses are negligible.
- Neoclassical transport predicts the opposite trend for W7-X: $\alpha_{NC}$ > $\alpha_{ISS04}$
- Turbulent transport: Appears to dominate the transport according to local power balance studies (see M. Beurskens, this conference). A gyro Bohm scaling is expected for the ion heat transport if $T_e$=$T_i$. **Then why is $\alpha$<0.5?**

## 4. Reason for the weaker density scaling

Using a profile database for W7-X plasmas it is found that at half radius $T_e$ and $T_i$ are equal over most of the parameter space (with the exception of low density, high power plasmas). This is a prerequisite for the global confinement model to be applicable.




Determining $\chi_i$ at half radius from the same database, it is found that $\chi_i$ seems to follow a gyro-Bohm-like scaling (constant $\chi_i/T_i^{1.5}$). Then why does $\tau_E$ not scale accordingly?

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

- Good agreement is found between the simple model (using a gyro-Bohm scaling) and the empirical density and ion-heating power ($P_{ei}$) scaling of the temperature at half radius.

| | $\alpha$ ($n^\alpha$) | $\beta$ ($P_{ei}^\beta$) |
|---|---|---|
| T (gyro-Bohm model) | -0.4 | 0.4 |
| T (experiment) | -0.5 | 0.3 |

- Increasing the density improves confinement because the temperature decreases, not because of the higher density itself.
- Since in the ECRH plasmas considered here the ions are only heated by collisional transfer and $T_e$=$T_i$=T at half radius, T is not determined by $P_{ECRH}$, but by the power transferred from the electrons to the ions, $P_{ei}$.
- If $P_{ei}$ determines the temperature at half radius, it also determines $\chi_i$ and, hence, the level of transport. Since $P_{ei}$ itself is a function of the density and heating power, it hides the gyro Bohm scaling of T, $\chi_{\mathrm{eff}}$ and $\tau_E$. Experimentally it is found that $P_{ei}$ scales like $n^{0.75}\cdot P^{1.27}$. Then $\tau_E$ should scale like:

$$\tau_E \propto \frac{nT}{P} \propto \frac{n n^{-0.5} P_{\mathrm{ei}}^{0.3}}{P} \propto \frac{n^{0.5}(n^{-0.8}P^{1.3})^{0.3}}{P} \propto \frac{n^{0.25}}{P^{0.6}}$$

- This expectation is remarkably close to the experimental scaling ($n^{0.30}\cdot P^{-0.49}$).

In summary, the apparent disagreement between a gyro-Bohm-like transport and the experimental energy confinement time scaling disappears when taking into account that the ion temperature determines the temperature at half radius and the power transferred from the electrons to the ions itself is a function of density and heating power.

## Conclusion

● The weaker density scaling observed in ECRH plasmas with gas-puff fueling in W7-X (compared to empirical scalings like ISS04) is caused by a combination of turbulent transport and the indirect ion-heating in ECRH plasmas.

● The strong density dependence commonly observed in stellators is likely to be caused by the temperature dependence of the heat diffusivity (higher density → lower temperature → lower heat diffusivity). At least in the parameter space explored so far, this picture is too simplified due to the indirect ion-heating.

● Consequently, the observed density scaling is only valid in the parameter space where $T_e$ > $T_i$ in the core. At even higher densities and heating powers (future experimental campaigns), a return to stronger density scalings seems plausible.

● Plasma radiation seems to play a minor role in explaining the observations. The reason is that the core pressure seems to be rather independent of the edge. In a reactor that could facilitate exhaust concepts, but high-performance experiments have to verify the reactor-relevance of the observed effect.

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