Increasing the density in Wendelstein 7-X: Benefits and limitations

G. Fuchert¹, K.J. Brunner¹, K. Rahbarnia¹, T. Stange¹, D. Zhang¹, J. Baldzuhn¹, M.N.A. Beurskens¹, S.A. Bozhenkov¹, C.D. Beidler¹, S. Brezinsek², R. Burhenn¹, H. Damm¹, A. Dinklage¹, M. Hirsch¹, Y. Kazakov³, J. Knauer¹, Y. Feng¹, A. Langenberg¹, H.P. Laqua¹, S. Lazerson⁴, N. Pablant⁴, E. Pasch¹, T. Sunn Pedersen¹, E.R. Scott¹, F. Warmer¹, V. Winters⁵, R.C. Wolf¹,⁶ and W7-X team

¹Max Planck Institute for Plasma Physics, Greifswald, Germany, ²Forschungszentrum Jülich, Jülich, Germany, ³Royal Military Academy, Brussels, Belgium, ⁴Princeton Plasma Physics Laboratory, Princeton NJ, USA, ⁵University of Wisconsin-Madison, Madison WI, USA, ⁶Technische Universität Berlin, Berlin, Germany

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Empirical scaling ISS04

\[
\tau_{\text{ISS04}} = 0.134 a^{2.28} R^{0.64} P^{-0.61} n_e^{0.54} B^{0.84} t_{2/3}^{0.41}
\]

- Positive density scaling and negative power scaling ("power degradation").
- Triple product benefits from increasing the density.
- Power and density scaling agree with neoclassical plateau regime. [Dinklage, NF 47, (2007)]
- ISS04 close to a gyro-Bohm scaling: turbulent transport?
Motivation: Density scaling of the energy confinement

Neoclassical prediction for W7-X

• Neoclassical transport modeling suggests a negative power scaling close to ISS04 and a stronger positive density scaling. [Turkin, PoP 18, (2011)]

→ Increase the density!

Limitations? Empirical $\tau_E$ scaling?

[Turkin 2007 (EPS)]
Outline

Energy confinement time before boronization
• Scaling close to ISS04
• Density limited by radiative collapses

Critical density
• Comparison of analytical models with experimental observations
• Critical density before and after boronization

Energy confinement time after boronization
• Scaling after boronization
• Energy confinement time at higher densities

Summary and conclusion
Energy confinement before boronization

- Before boronization, $\tau_E$ showed a scaling close to ISS04 in hydrogen.
- Densities above $\sim 4 \cdot 10^{19} / \text{m}^3$ were only accessible transiently with pellet fuelling due to radiative collapses.

$$\tau_E \sim a_0 n^\alpha P^\beta$$

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$a_0$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard divertor</td>
<td>0.16</td>
<td>0.56</td>
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</tr>
<tr>
<td>Limiter (OP1.1)</td>
<td>0.13</td>
<td>0.75</td>
<td>-0.64</td>
</tr>
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Spread of experimental data, not error
Density scaling of the energy confinement

![Graph showing energy confinement as a function of time.](image-url)
Density scaling of the energy confinement

![](graph.png)

- $P_{\text{heat}}$
- $P_{\text{rad}}$
- $n_e / 10^{19} \text{[m}^3\text{]}$
- $W_{\text{dia}} \text{[kJ]}$

$t \text{[s]}$

24.10.2018

G. Fuchert et al., EX/3-5, IAEA-FEC 2018 Ahmedabad, India
Common phenomenon in stellarators, e.g. in

Predicting the critical density for strong edge radiation

- **Critical density from the detachment model by Itoh**
  \( \bar{n}_c = \lambda \frac{P_{\text{heat}}}{a} \)

- **Sudo density limit**
  [S. Sudo et al., Nucl. Fusion 30 (1990)]

- **Limits with different transport and radiation models**

- **Modified Itoh model for W7-AS**

- **Implicit dependences on transport and edge impurities (low Z) have to be made explicit**
  [Zanca et al., Nucl. Fusion 57 (2017)]

\[ n_{\text{Sudo}} = 0.25 \cdot \sqrt{\frac{P B}{a^2 R}} \]

\[ f_{\text{imp}} = \frac{n_{\text{imp}}}{n_e} \]

\[ \bar{n}_c = c \cdot \frac{P^{\alpha}}{f_{\text{imp}}^{\beta}} \]

\[ \bar{n}_c = \bar{n}_{c,\text{edge}} \cdot \delta \]
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<tr>
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Details on the magnetic configurations:
Critical density before boronization

- Large scatter in $n_c$
- Weaker power scaling than predicted (if any...)

Possible reasons:
- Changing impurity content (depending on heating power?)
- Profile effects, importance of edge density ($\delta$)
- Model not applicable (local effects, changing main radiator,...)

Hydrogen plasmas with central X2-heating

$$\tilde{n}_c = c \cdot \frac{P_{\text{heat}}^{0.6}}{f_{\text{imp}}^{0.4}}$$

- $n_c(f_{\text{imp}} = 5\%)$
- $n_c(f_{\text{imp}} = 25\%)$
Critical density before boronization

• Large scatter in $n_c$

• Weaker power scaling than predicted (if any...)

• Possible reasons:
  • Changing impurity content
    $\rightarrow$ under investigation
  • **Profile effects, importance of edge density ($\delta$)**
  • Model not applicable
    $\rightarrow$ local effects exist (e.g. Marfe [U. Wenzel, NF 58 (2018)]), but their importance is unclear

• Common mitigation strategies:
  • Pellet fueling (decouple core and edge density)
  • Wall conditioning by e.g. boronization [\(\rightarrow\)R. Brakel, EX/P8-17]

[G. Kocsis, T. Szepesi]
Critical density after boronization

- After boronization, radiation from oxygen and carbon lines went down significantly
  - Reduced by a factor of 5 to 10
  - Only moderate additional boron lines
  - [→ Pedersen et al., EX/9-1]

- At the same time, \( n_c \) increased by a factor of \(~3\)
  - In the scaling law this would correspond to a reduction of \( f_{\text{imp}} \) by a factor of 5 to 10

- Configurational effects are either absent or subtle
Profile effects

• $\bar{n}_c = \bar{n}_{c,\text{edge}} \cdot \delta$

• Estimate edge density by $\delta = n_0/n_{0.85\rho}$

• Significantly improved agreement with scaling for $n_e/\delta$

→ Profile effects are a major source for the scatter in $n_c$
Profile effects

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Energy confinement at higher densities

Energy confinement after boronization

• For simplicity, only X2-heated plasmas are shown
  • In O2 similar observations, but $P_{\text{absorbed}} < P_{\text{heat}}$.
• Also in these experiments a positive density scaling of $\tau_E$ is found.
• This trend can be observed even in single experiments.
• Density scaling gets weaker at high $f_{\text{rad}} = P_{\text{rad}} / P_{\text{ECRH}}$ or densities close to $n_c$.

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Energy confinement close to $n_c$

- Before boronization, the density scaling becomes weaker above $\sim 0.5 \cdot n_{c,5\%}$
- After boronization, the density scaling becomes weaker above $\sim 1.0 \cdot n_{c,5\%}$
- $f_{\text{rad}}$ increases with $n_e/n_c$
- As it was shown before, high densities as such are not an issue
Energy confinement time in W7-X

- Improves with density, roughly in-line with ISS04 ($\tau_E \sim n^{0.54}$).
- Improvement obviously limited by radiative collapses.
  - Critical density can be estimated from analytical models.
  - Boronization crucial to achieve relevant densities.

\[
\bar{n}_e [10^{19}/m^3] = c \cdot \frac{P_{\text{heat}}^{0.6}}{f_{\text{imp}}^{0.4}}
\]
Summary and conclusion

Energy confinement time in W7-X

• Not one single scaling law for the entire parameter range.
  • Unravelling the main transport/loss channels has only started.
• Plasmas with pellet-fueling [-> Bozhenkov et al., EX/P8-8] or O₂ and NBI-heating are not even included in the analysis yet.

$\tau_E$ – scalings need to take different regimes and operational limits into account. This is well established for tokamaks, but not yet for stellarators.