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

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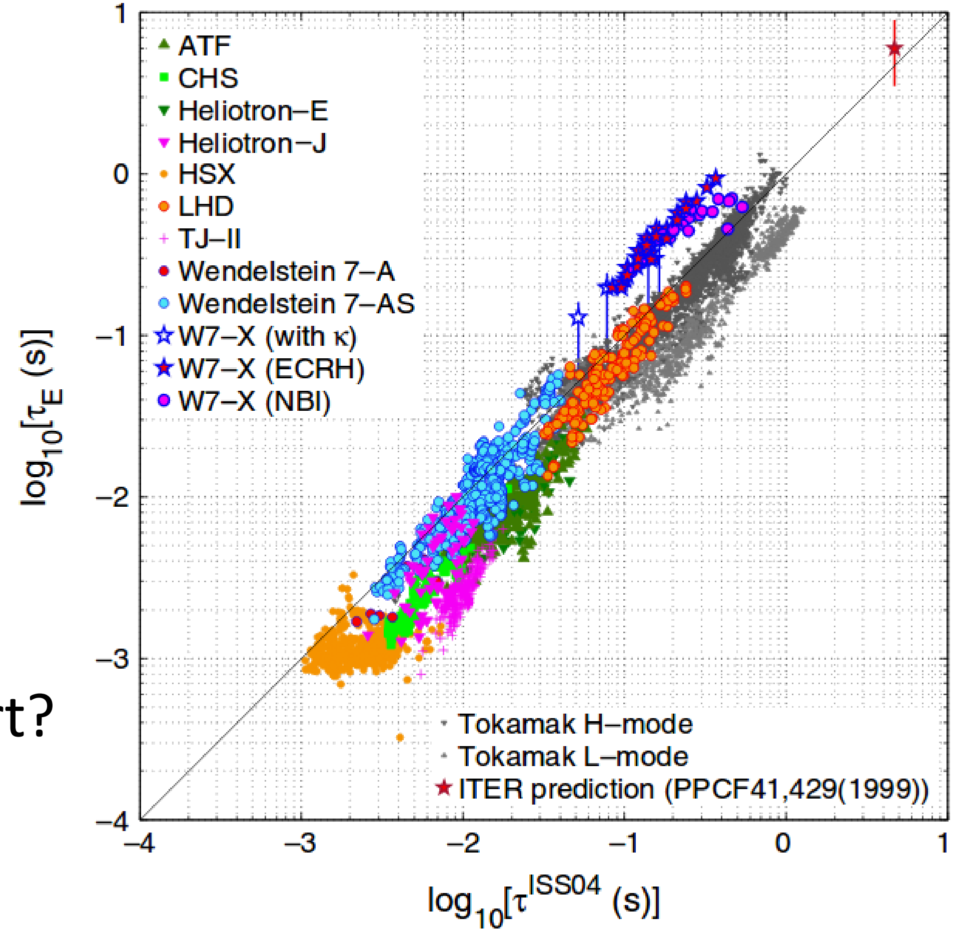
# Motivation: Density scaling of the energy confinement

## Empirical scaling ISS04

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

- 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?

[Dinklage, NF 47, (2007)]



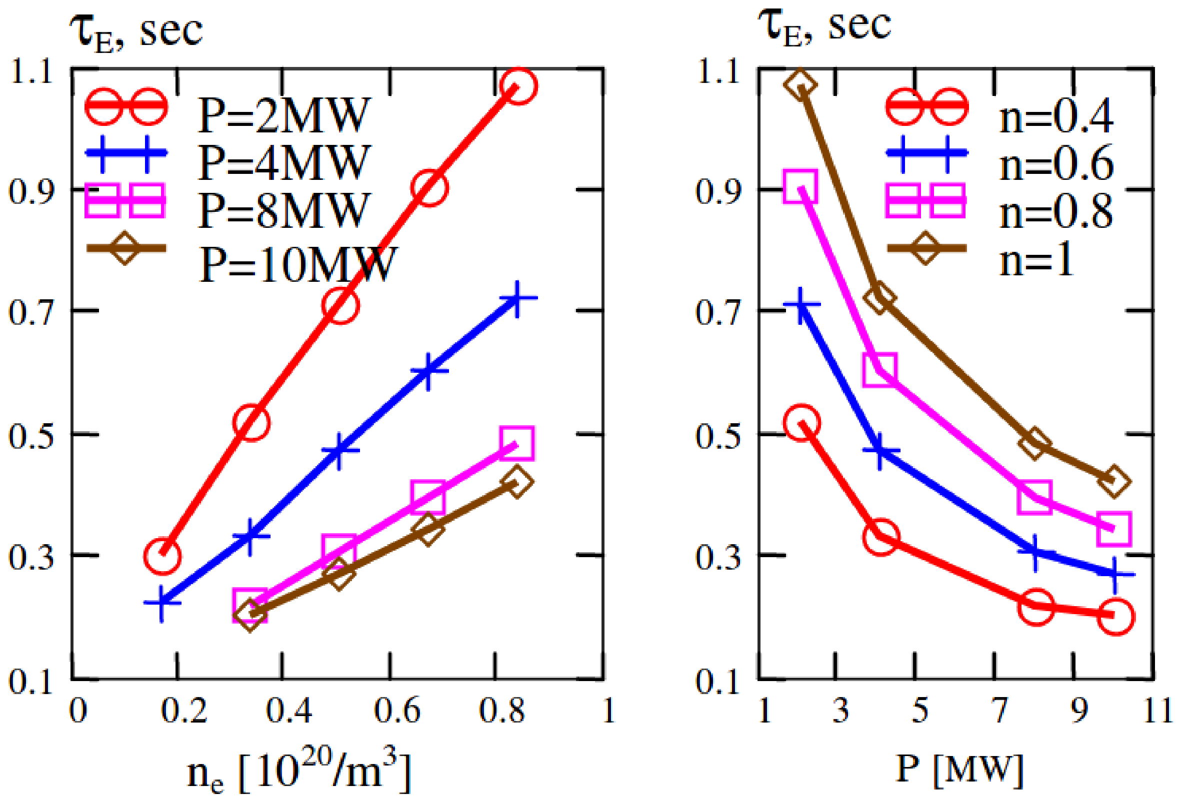
# Motivation: Density scaling of the energy confinement

**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 boronizatoin

**Energy confinement time after boronization**

- Scaling after boronization
- Energy confinement time at higher densities

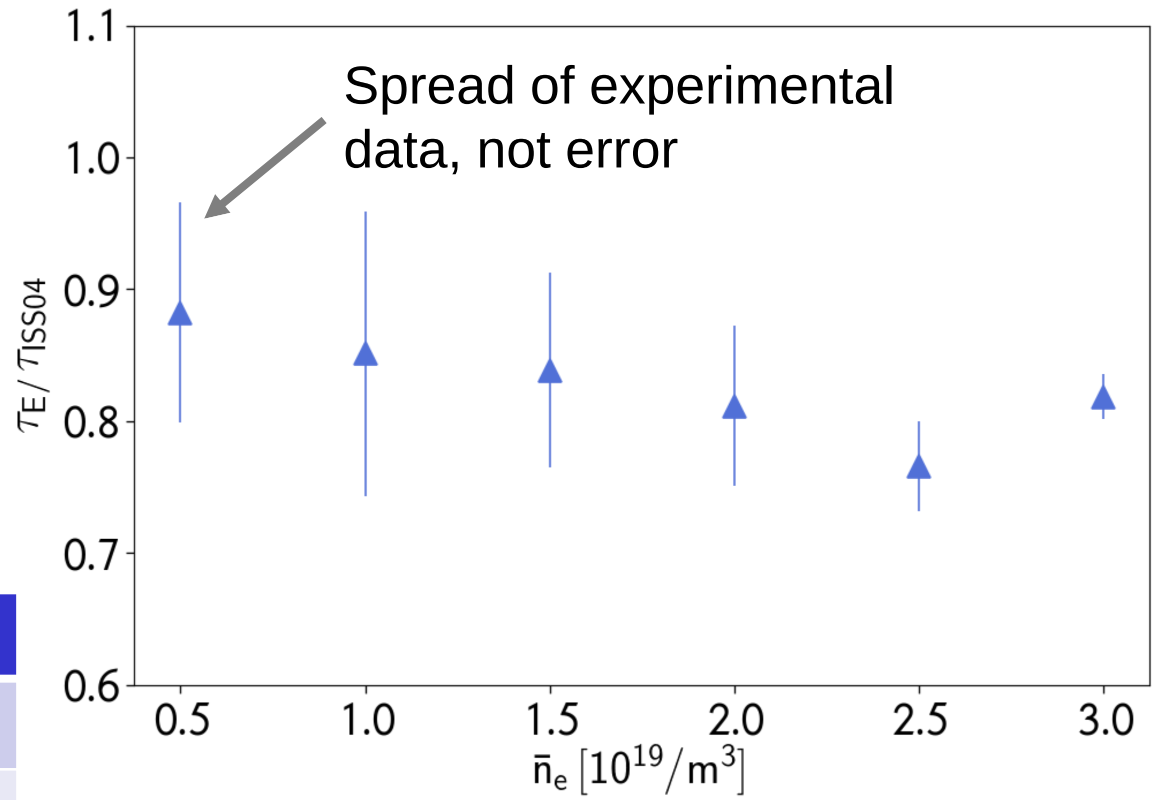
**Summary and conclusion**

# Energy confinement before boronization

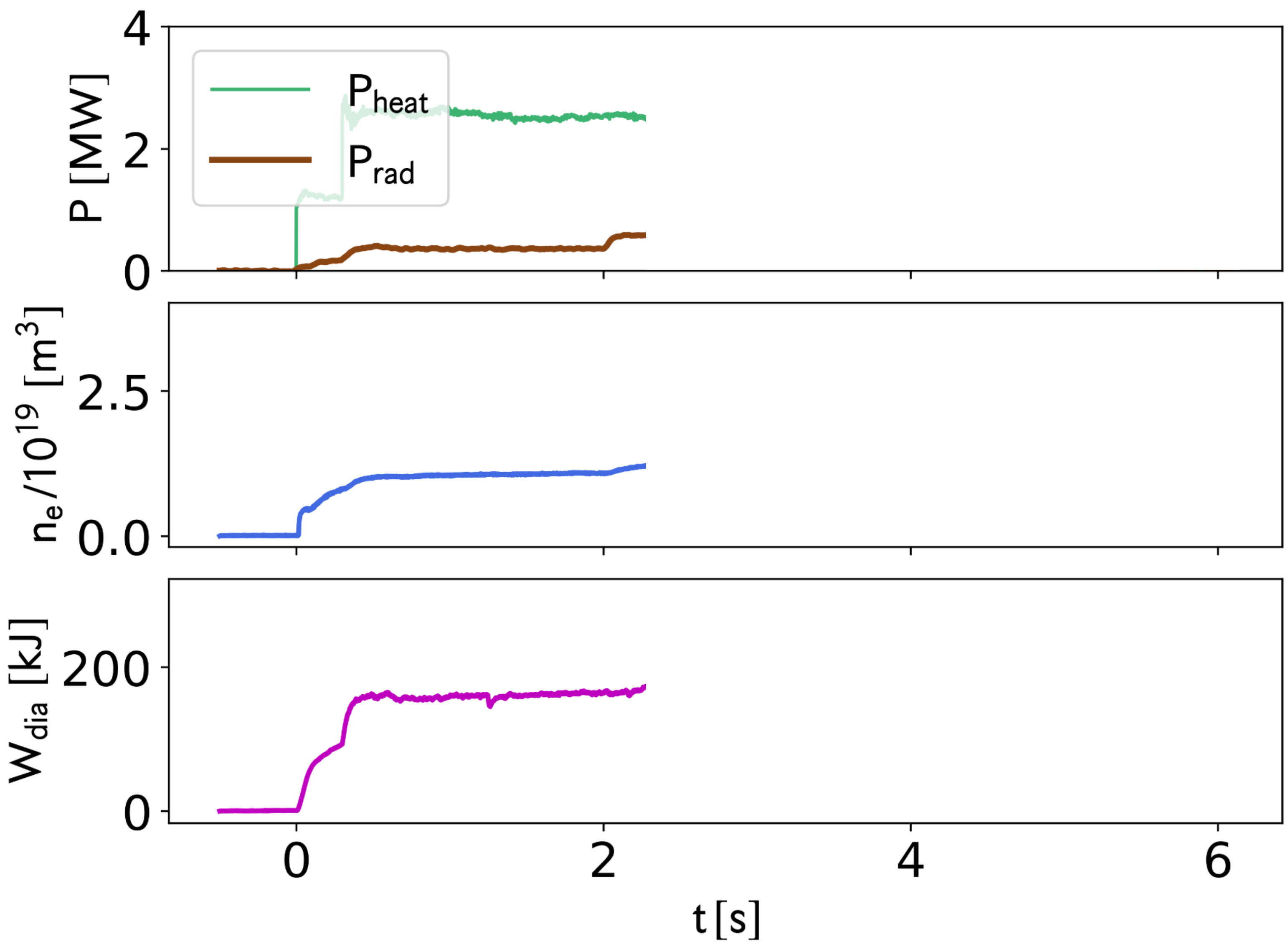
- **Before boronization, $\tau_E$ showed a scaling close to ISS04 in hydrogen.**
- **Densities above ~ $4 \cdot 10^{19}$ /m$^3$ were only accessible transiently with pellet fuelling due to radiative collapses.**

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

| Scenario | $a_0$ | $\alpha$ | $\beta$ |
|---|---|---|---|
| Standard divertor | 0.16 | 0.56 | -0.78 |
| Limiter (OP1.1) | 0.13 | 0.75 | -0.64 |
| ISS04 | - | 0.54 | -0.61 |



# Density scaling of the energy confinement



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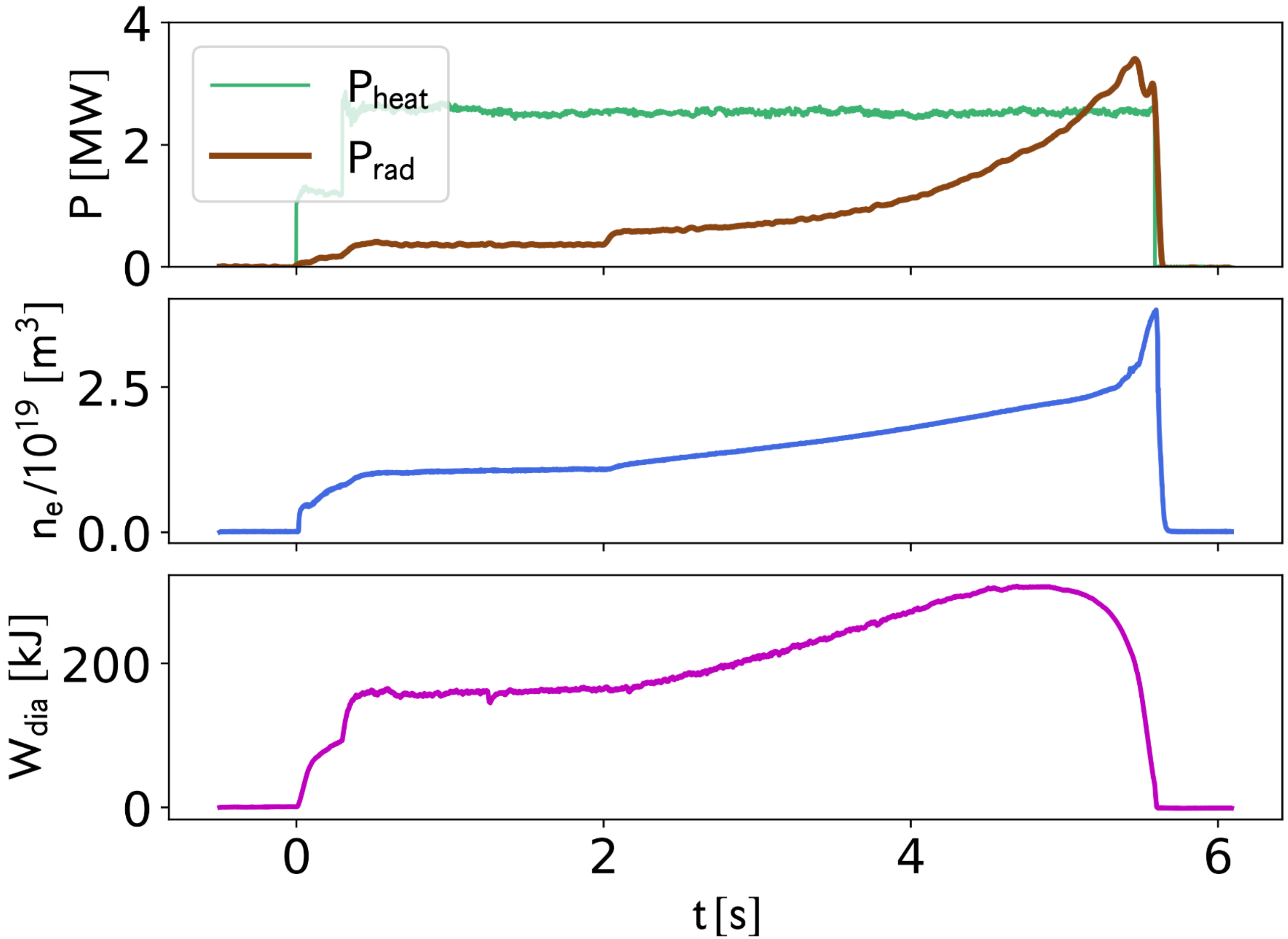

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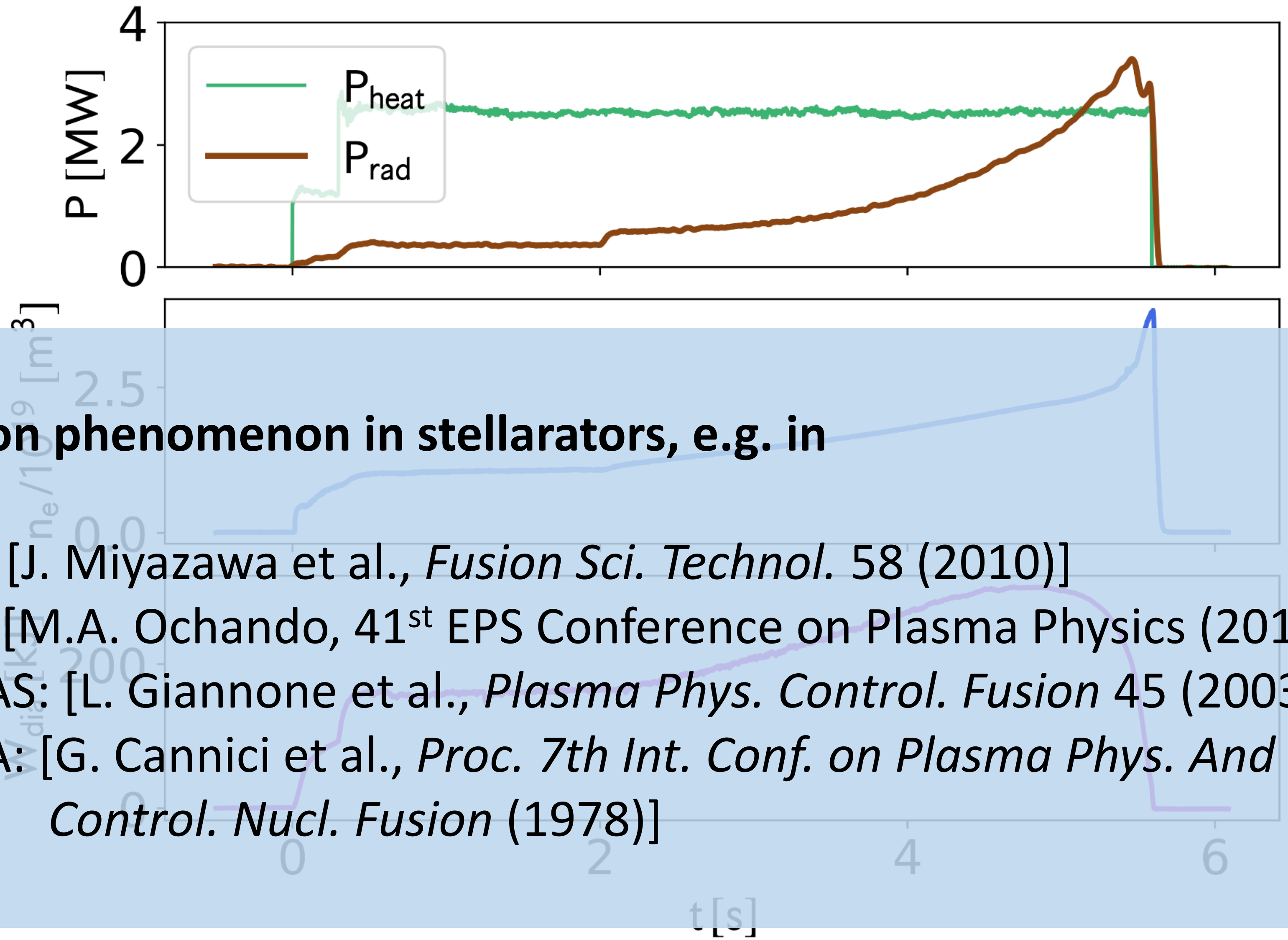


**Common phenomenon in stellarators, e.g. in**

- LHD: [J. Miyazawa et al., *Fusion Sci. Technol.* 58 (2010)]
- TJ-II: [M.A. Ochando, 41st EPS Conference on Plasma Physics (2014)]
- W7-AS: [L. Giannone et al., *Plasma Phys. Control. Fusion* 45 (2003)]
- W7-A: [G. Cannici et al., *Proc. 7th Int. Conf. on Plasma Phys. And Control. Nucl. Fusion* (1978)]

# Predicting the critical density for strong edge radiation

- **Critical density from the detachment model by Itoh**
  [K. Itoh and S. Itoh, J. Phs. Soc. Jpn. **57** (1988)]
- **Sudo density limit**
  [S. Sudo et al., Nucl. Fusion 30 (1990)]
- **Limits with different transport and radiation models**
  [H. Wobig, *Plasma Phys. Control. Fusion* 42 (2000)]
- **Modified Itoh model for W7-AS**
  [L. Giannone et al., Plasma Phys. Control. Fusion 45 (2003)]
- **Implicit dependences on transport and edge impurities (low Z) have to be made explicit**
  [Zanca et al., Nucl. Fusion 57 (2017)]

$$\bar{n}_\mathrm{c} = \lambda \frac{P_\mathrm{heat}}{a}$$

$$n_\mathrm{Sudo} = 0.25 \cdot \sqrt{\frac{PB}{a^2 R}}$$

$$f_\mathrm{imp} = \frac{n_\mathrm{imp}}{n_\mathrm{e}}$$

$$\bar{n}_\mathrm{c} = c \cdot \frac{P_\mathrm{heat}^\alpha}{f_\mathrm{imp}^\beta}$$

$$\bar{n}_\mathrm{c} = \bar{n}_\mathrm{c,edge} \cdot \delta$$

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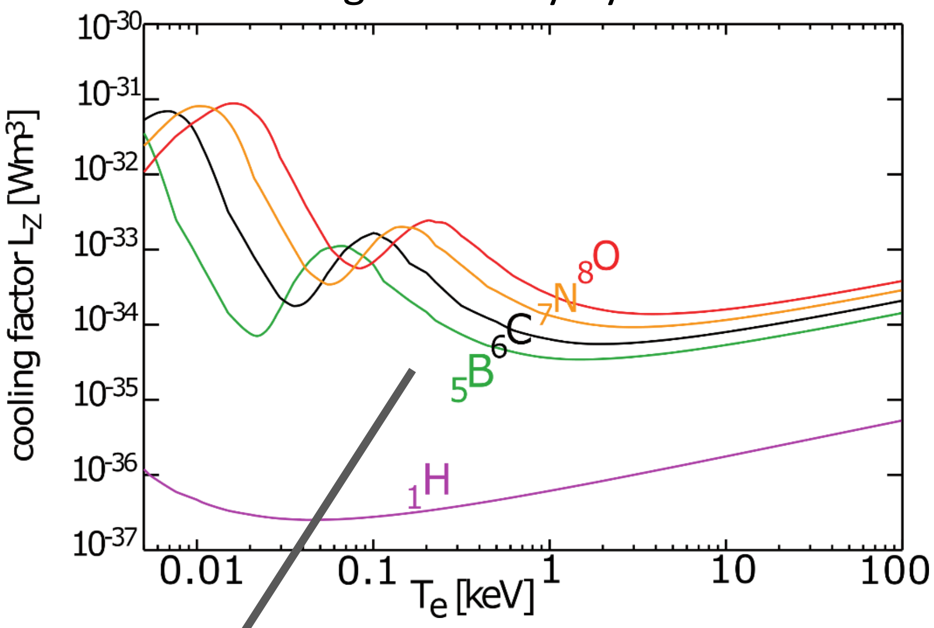
Image courtesy by T. Pütterich




$$f_{\mathrm{imp}} = \frac{n_{\mathrm{imp}}}{n_{\mathrm{e}}}$$

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$$f_\mathrm{imp} = \frac{n_\mathrm{imp}}{n_\mathrm{e}}$$

$$\boxed{\bar{n}_\mathrm{c} = c \cdot \frac{P_\mathrm{heat}^{\alpha}}{f_\mathrm{imp}^{\beta}}}$$

W7-X

$$\boxed{\bar{n}_\mathrm{c} = c \cdot \frac{P_\mathrm{heat}^{0.6}}{f_\mathrm{imp}^{0.4}}}$$

| Configuration | c |
|---|---|
| Standard | 0.56 |
| High-iota | 0.59 |
| High-mirror | 0.57 |

Details on the magnetic configurations:
[J. Geiger et al., Plasma Phys. Control. Fusion **57** (2015)]

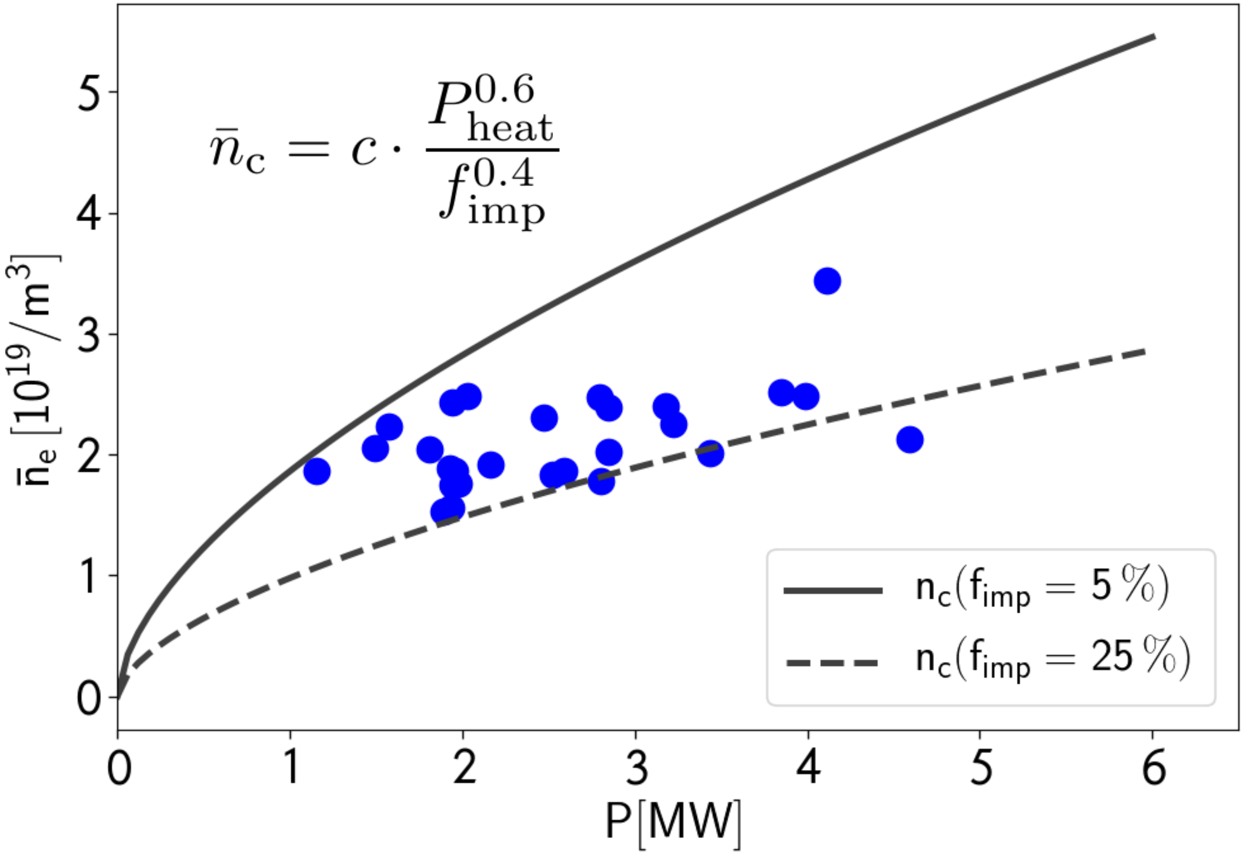
# Critical density before boronization

- **Large scatter in $n_c$**

- **Weaker power scaling than predicted (if any…)**

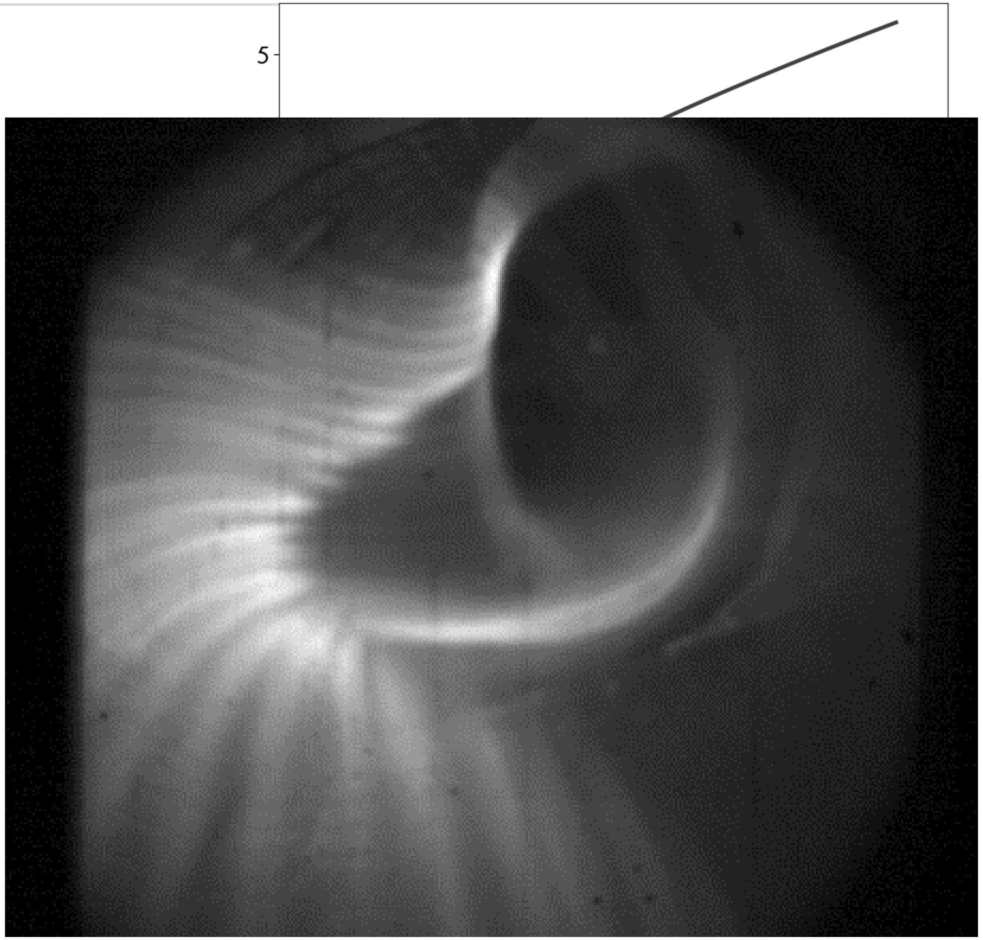
- **Possible reasons:**
  - Changing impurity content (depending on heating power?)
  - Profile effects, importance of edge density (δ)
  - Model not applicable (local effects, changing main radiator,…)

**Hydrogen plasmas with central X2-heating**



# Critical density before boronization

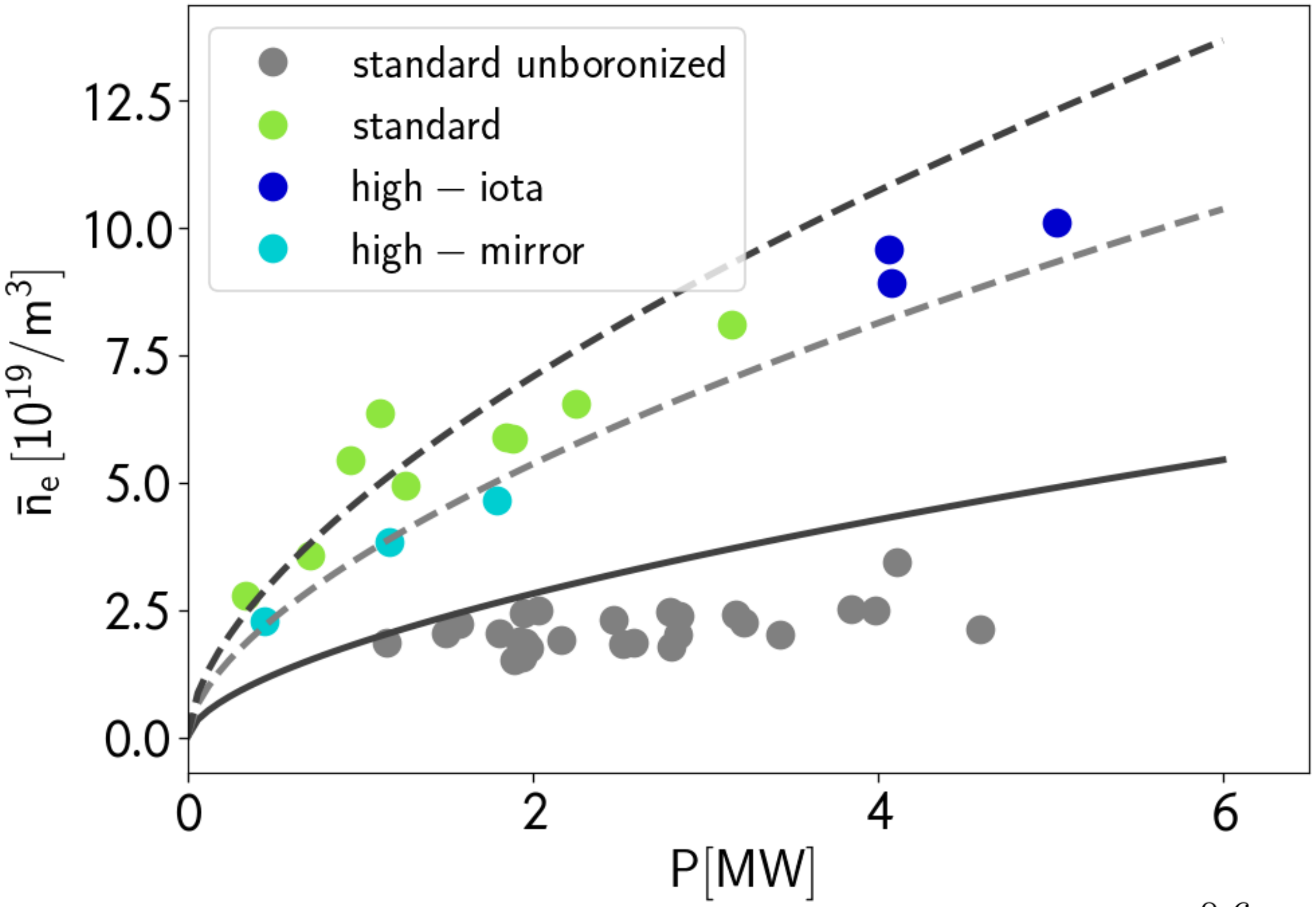
- **Large scatter in $n_c$**
- **Weaker power scaling than predicted (if any…)**
- **Possible reasons:**
  - Changing impurity content
    → under investigation
  - Profile effects, importance of edge density (δ)
  - Model not applicable
    → local effects exist (e.g. Marfe [U. Wenzel, NF 58 (2018)]), but their importance is unclear
- **Common mitigation strategies:**
  - Pellet fueling (decouple core and edge density)
  - Wall conditioning by e.g. boronization [->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 $f_{imp}$ by a factor of 5 to 10
- **Configurational effects are either absent or subtle**

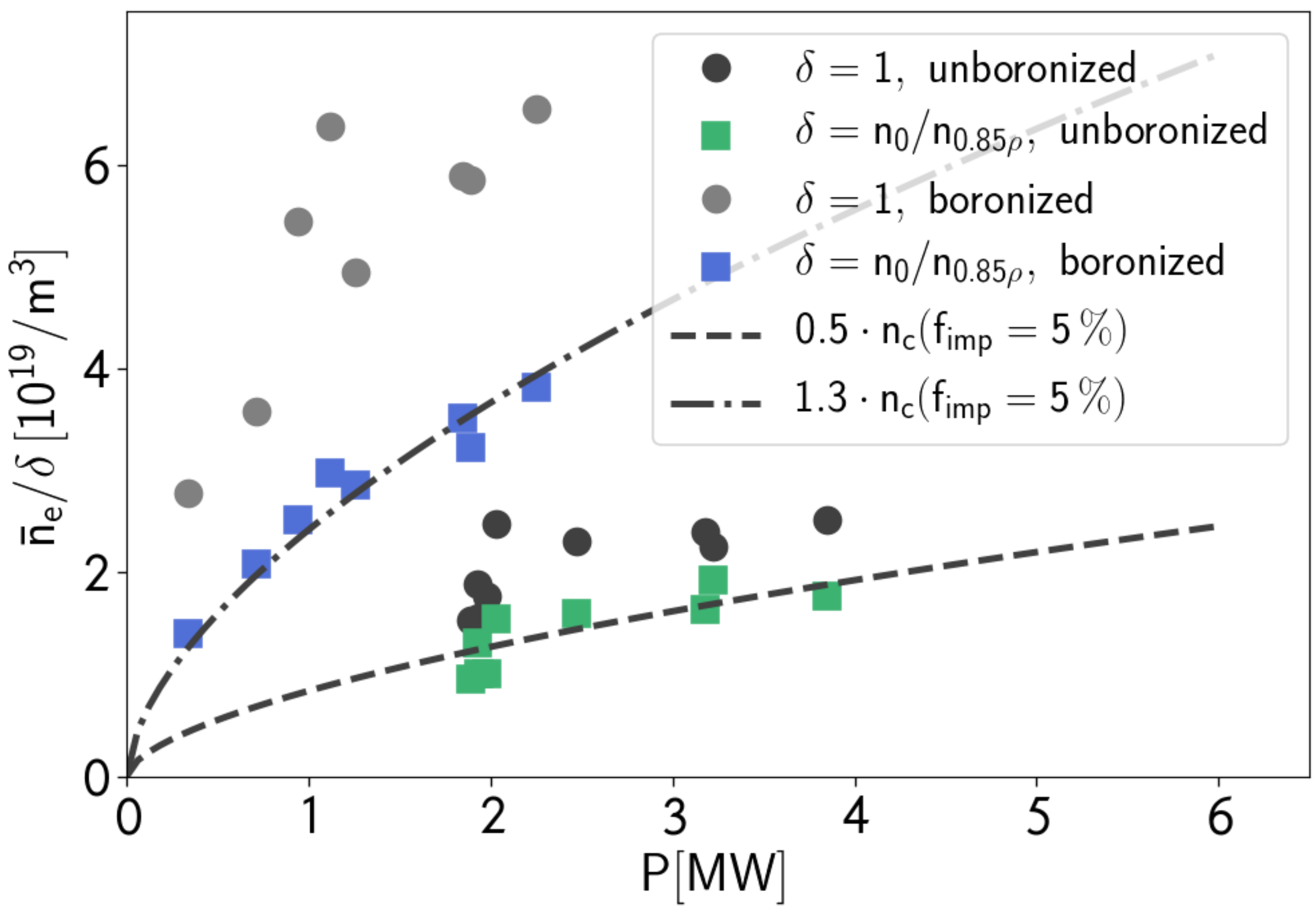



$$\bar{n}_c = c \cdot \frac{P_{heat}^{0.6}}{f_{imp}^{0.4}}$$

# Profile effects

- $\bar{n}_\mathrm{c} = \bar{n}_\mathrm{c,edge} \cdot \delta$
- **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 $n_c$**



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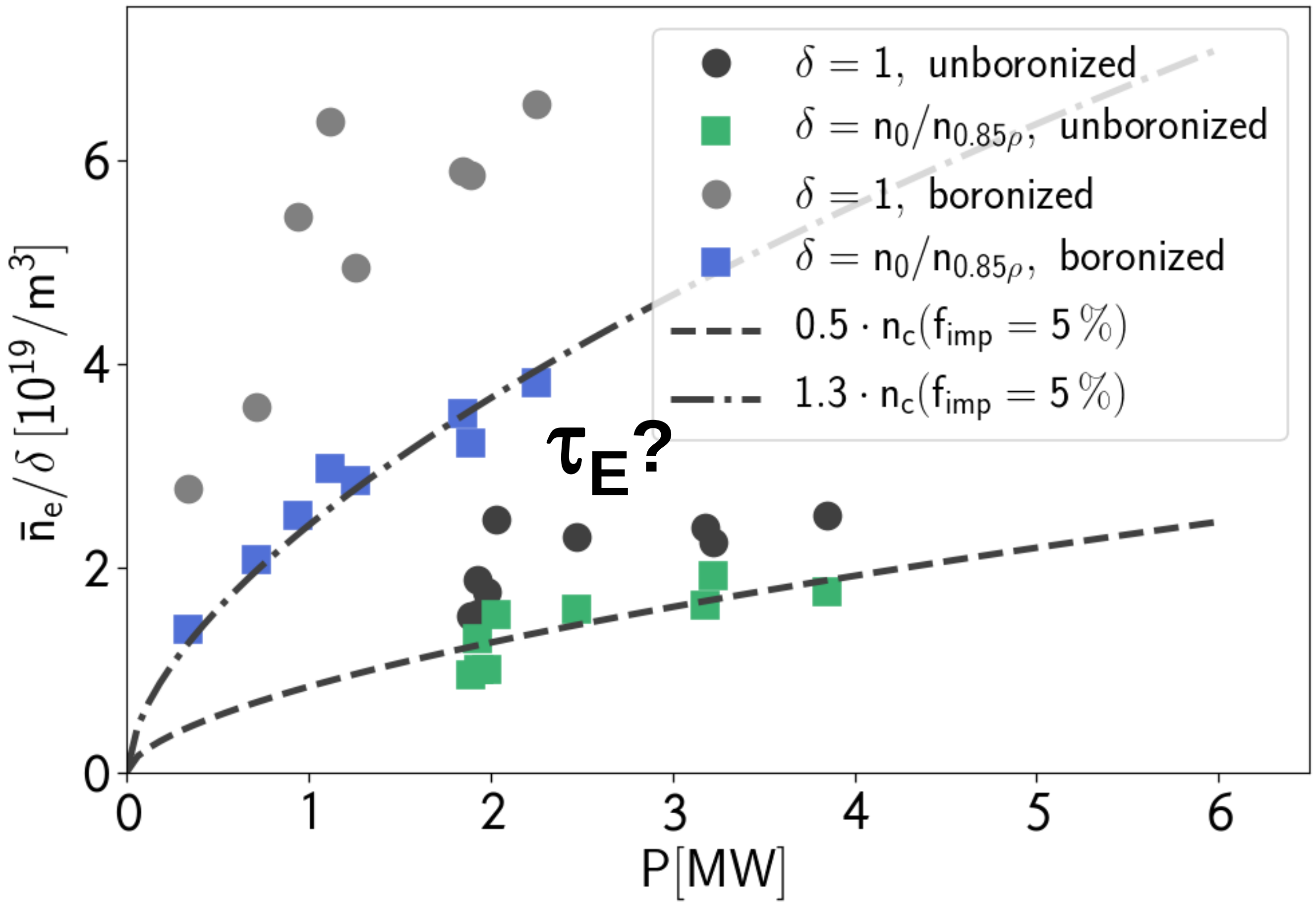
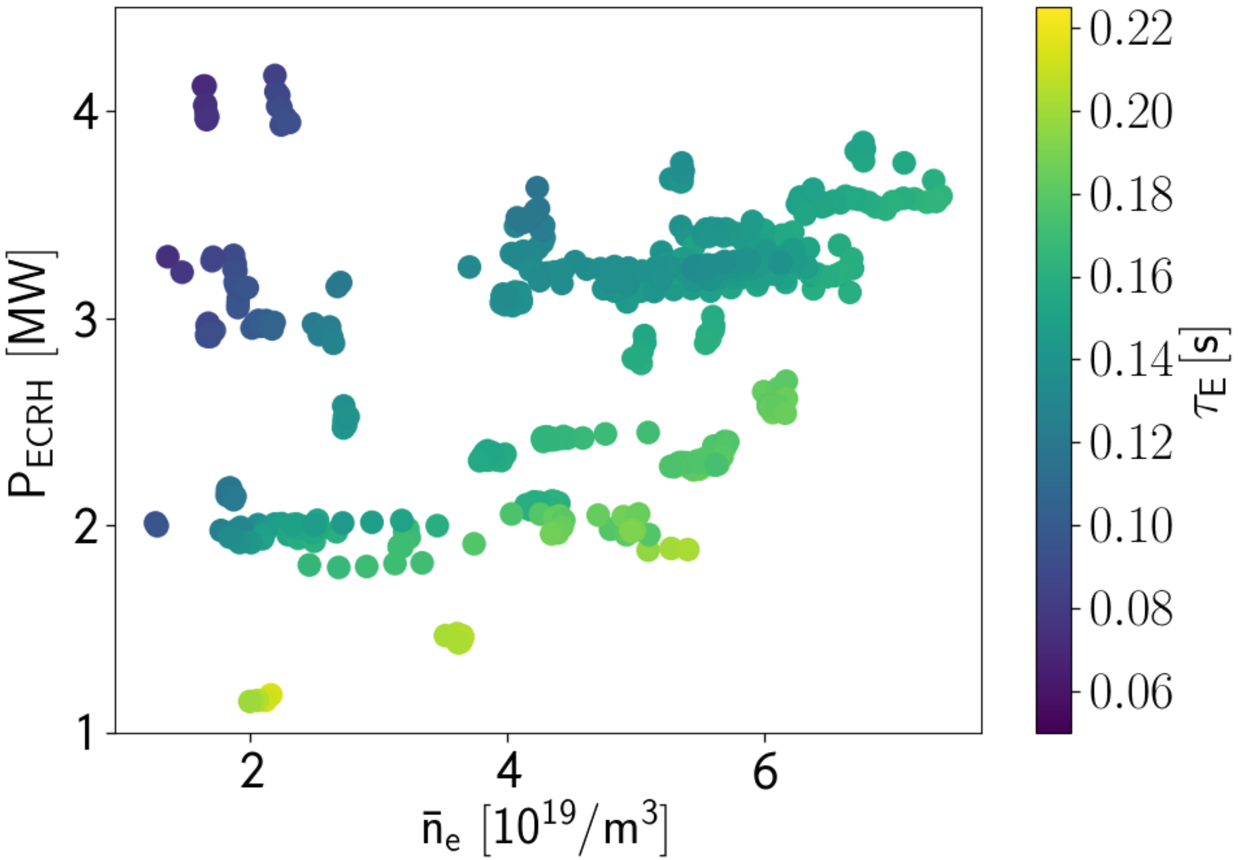


# Energy confinement at higher densities

**Energy confinement after boronization**

| Scenario | $a_0$ | $\alpha$ | $\beta$ |
|---|---|---|---|
| After boronization | 0.16 | 0.38 | -0.59 |
| ISS04 | - | 0.54 | -0.61 |

- **For simplicity, only X2-heated plasmas are shown**
  - In O2 similar observations, but $P_{absorbed} < P_{heat}$.
- **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 $f_{rad}=P_{rad}/P_{ECRH}$ or densities close to $n_c$.**



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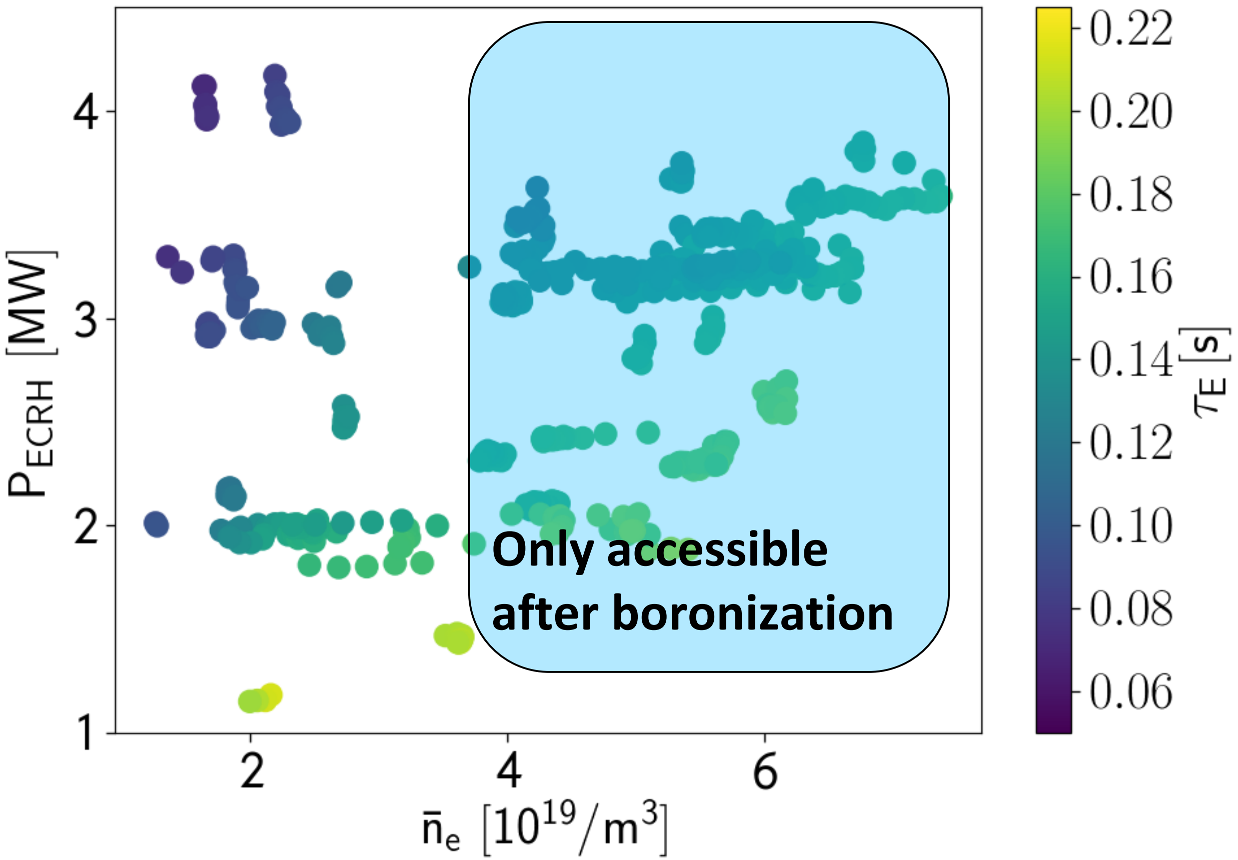

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| … $n_e > 4\cdot10^{19}$ /m$^3$ | 0.11 | 0.62 | -0.64 |
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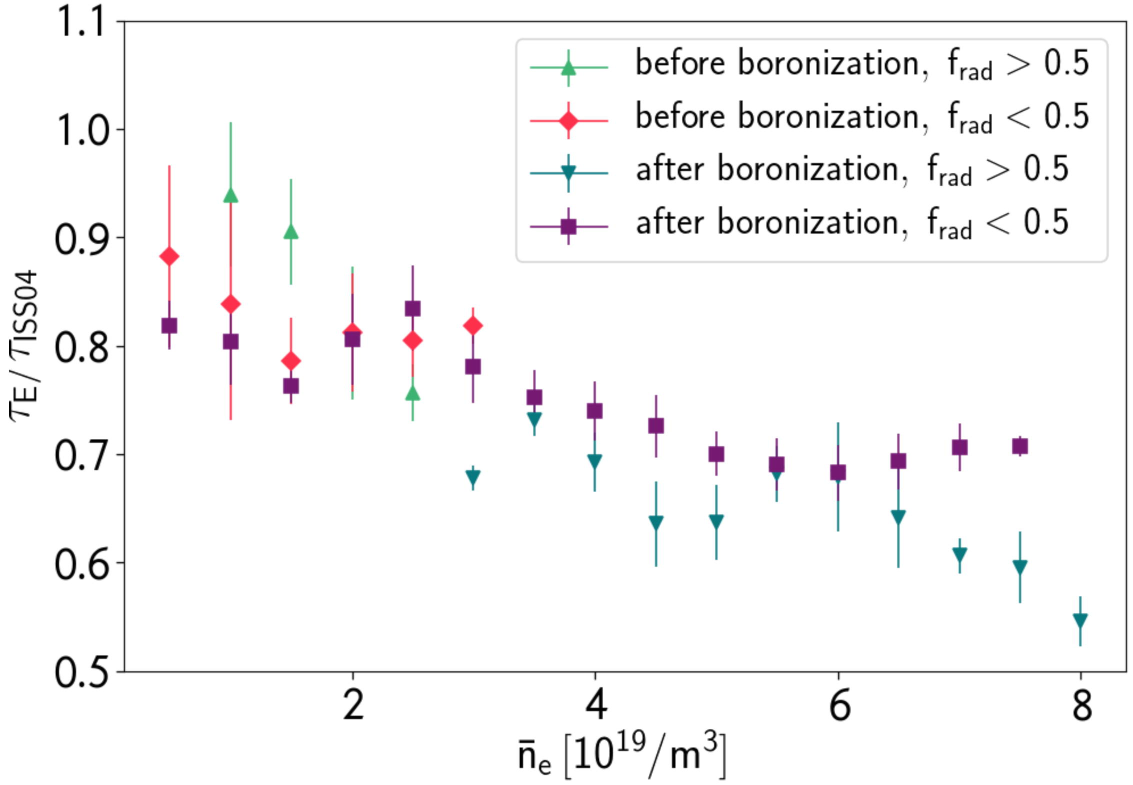

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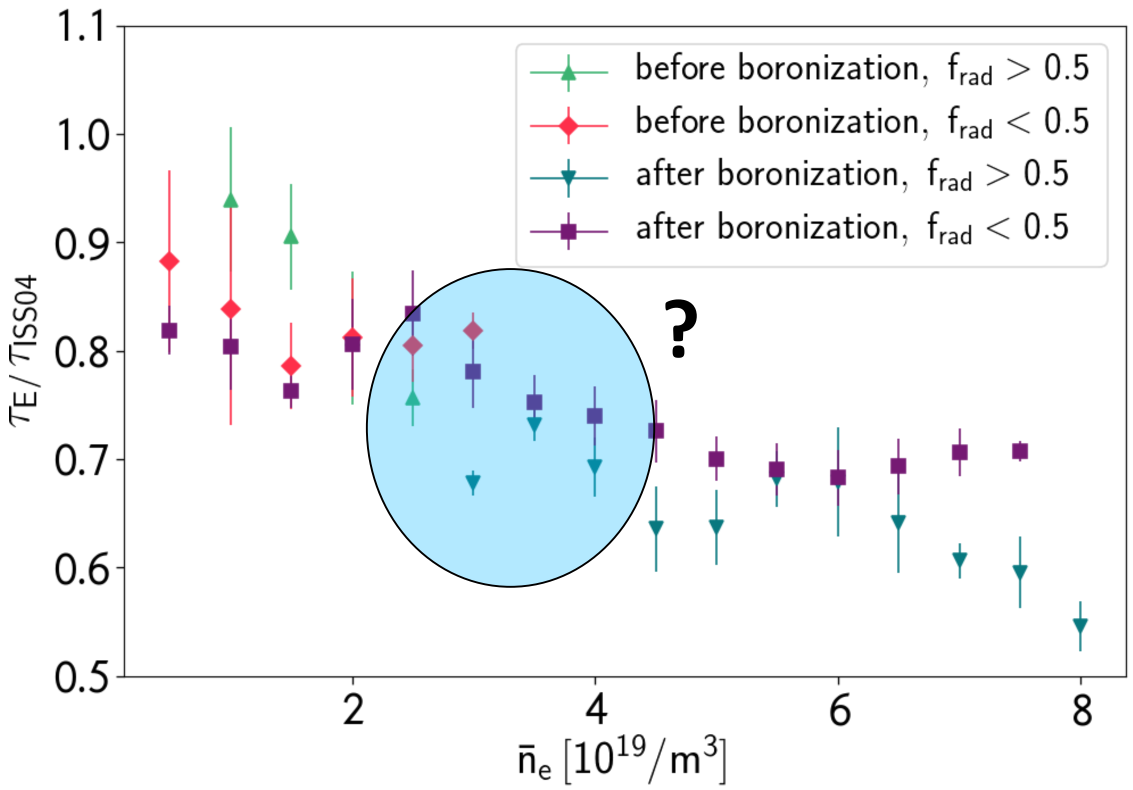
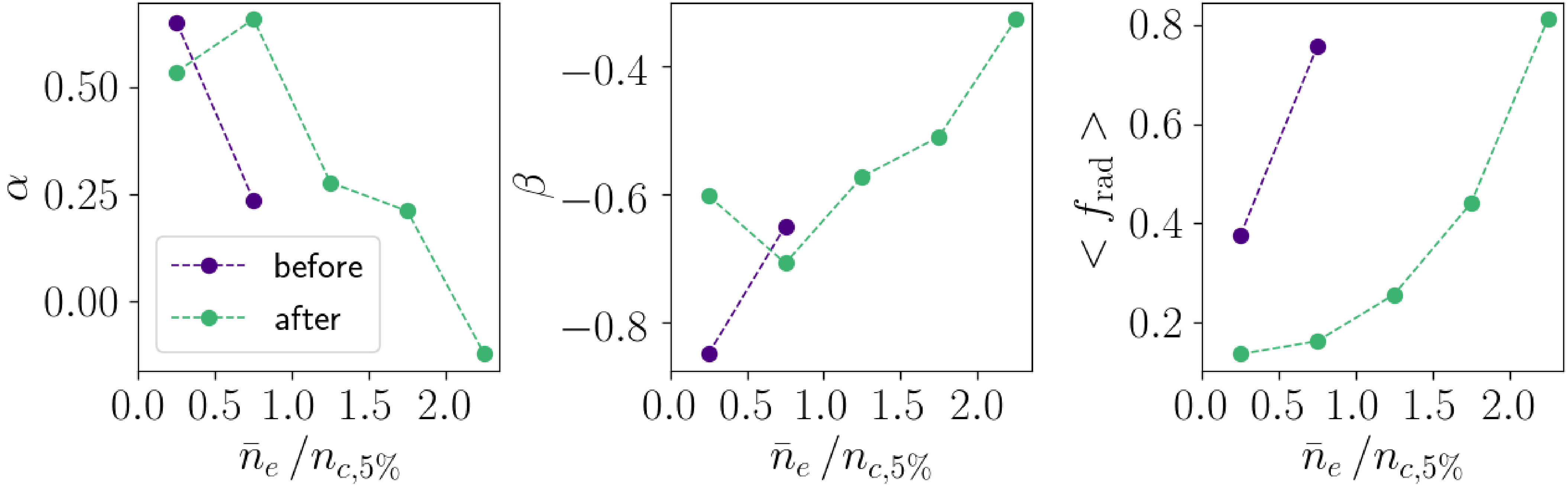


# Energy confinement close to $n_c$

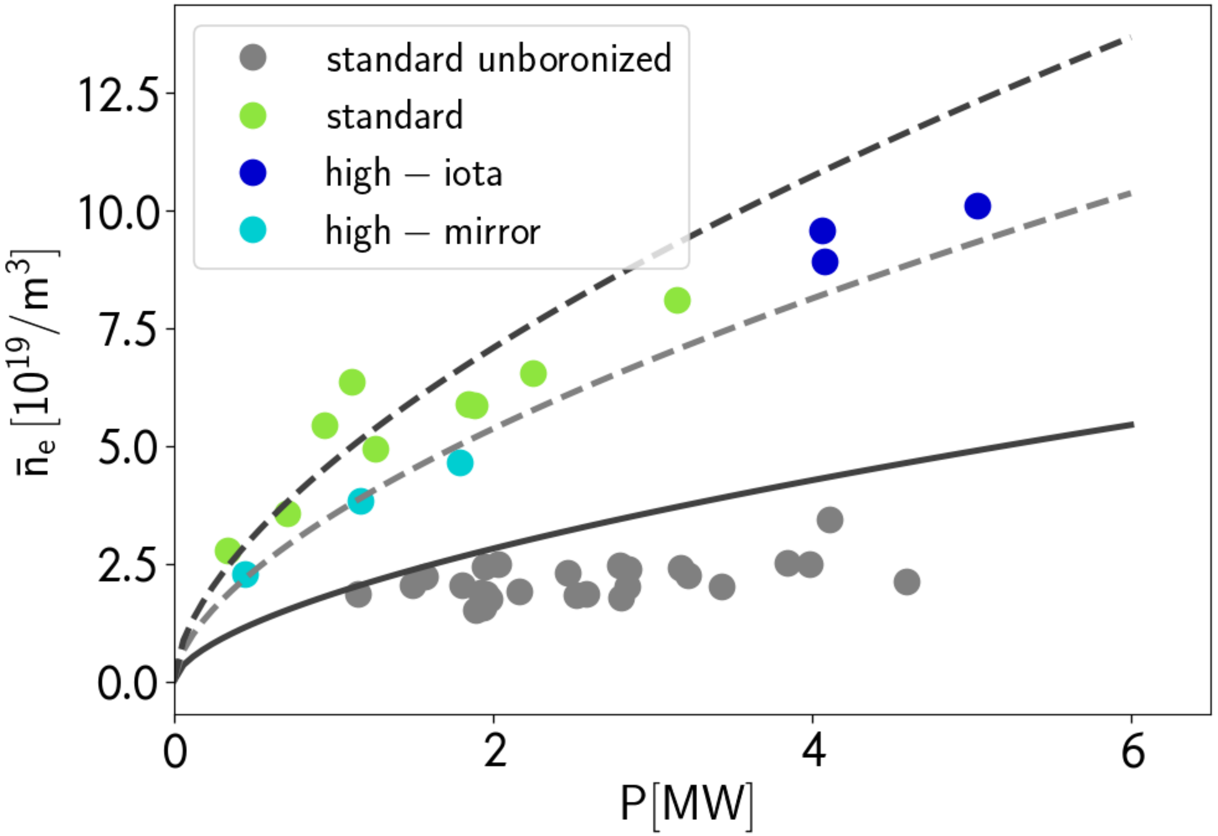
- Before boronization, the density scaling becomes weaker above ~$0.5 \cdot n_{c,5\%}$
- After boronization, the density scaling becomes weaker above ~$1.0 \cdot n_{c,5\%}$
- $f_{rad}$ increases with $n_e/n_c$
- As it was shown before, high densities as such are not an issue



# Summary and conclusion

**Energy confinement time in W7-X**

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

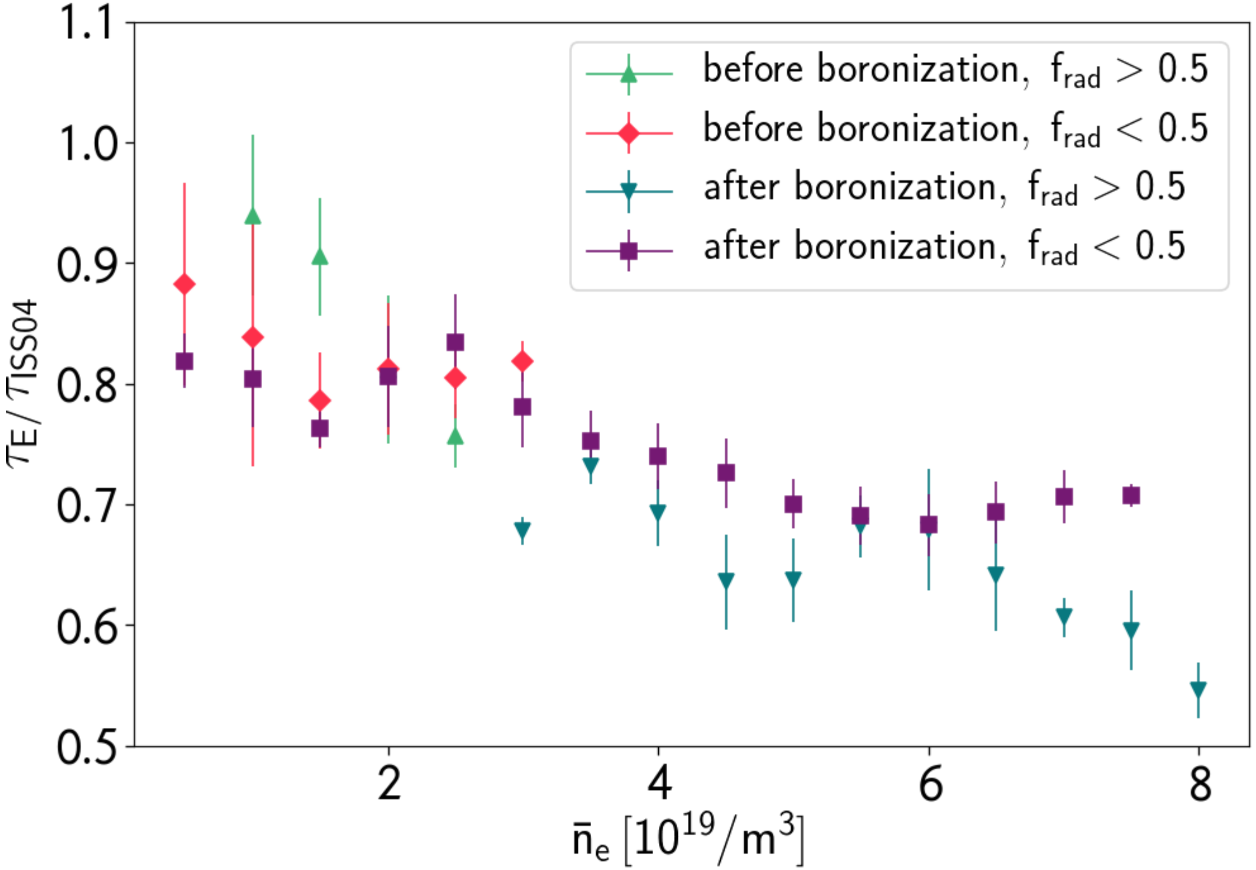



$$\bar{n}_c = c \cdot \frac{P_{\text{heat}}^{0.6}}{f_{\text{imp}}^{0.4}}$$

# 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.