Turbulence reduced high performance scenarios in Wendelstein 7-X, on the path to a steady state reactor

O. P. Ford, M. Beurskens, S. Bozhenkov, S. Lazerson

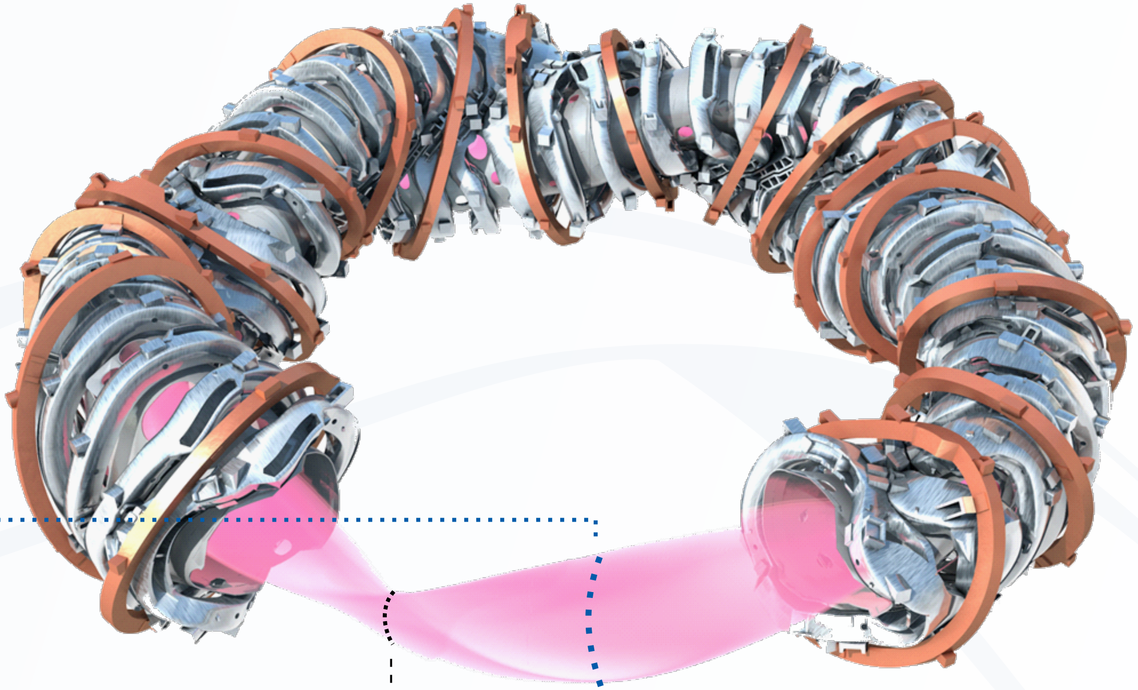
J. Alcusón, A. Alonso, S. Bannmann, C. Beidler, H. Braune, K.J. Brunner, G. Fuchert, D. Hartmann, J. Knauer, T. Kremeyer, A. Langenberg, H.P. Laqua, S. Marsen, P. McNeely, N. Pablant, E. Pasch, V. Perseo, N. Rust, E.R. Scott, H. Smith, T. Stange, Y. Turkin, L. Vanó, P. Xanthopoulos, D. Zhang

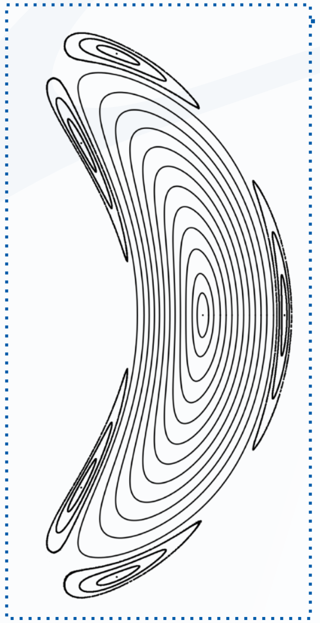
47th EPS Plasma Physics conference, 2020/1, Sitges, Spain

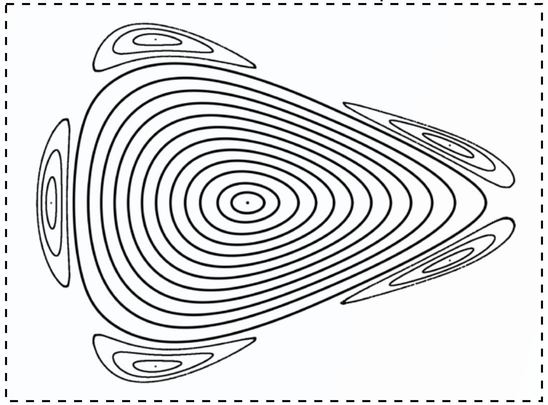
The Wendelstein 7-X Stellarator

Wendelstein 7-X:
- 5 period helixcal axis stellarator
- Optimised to reduce neoclassical transport
- Designed to demonstrate steady-state operation with continuous ECRH heating.
- Operation at high density: $n_e \sim 1.8 \times 10^{20}\ m^{-3}$

R_0	5.5 m	
a	0.5 m	
V	30 m^3	
B_0	⩽ 3 T	
ι_a $(\sim q_{95}^{-1})$	5/6 ... 5/4	
	2018	2023+
pulse	100s	30 min
ECRH	7.5MW	10 MW
NBI	2.6MW	5.2MW
ICRH	-	1.5MW





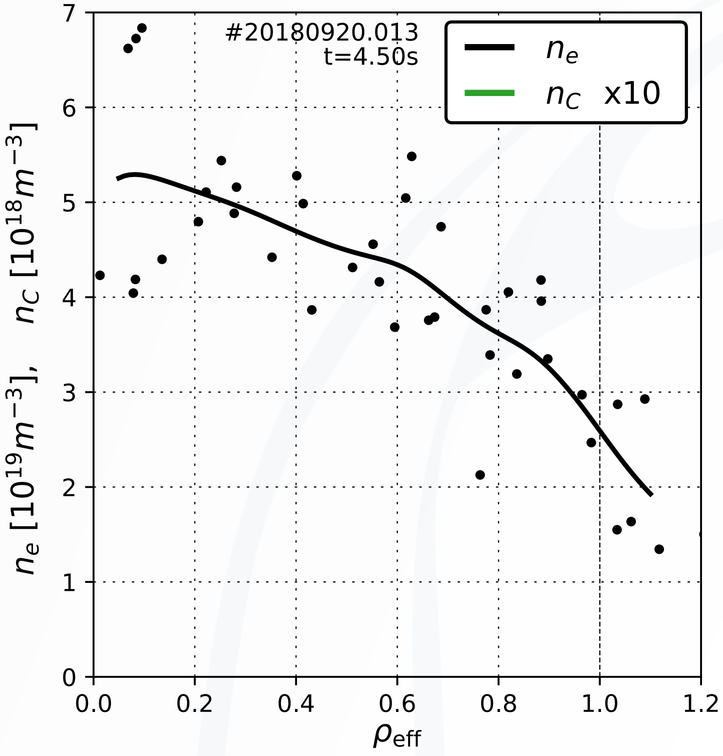


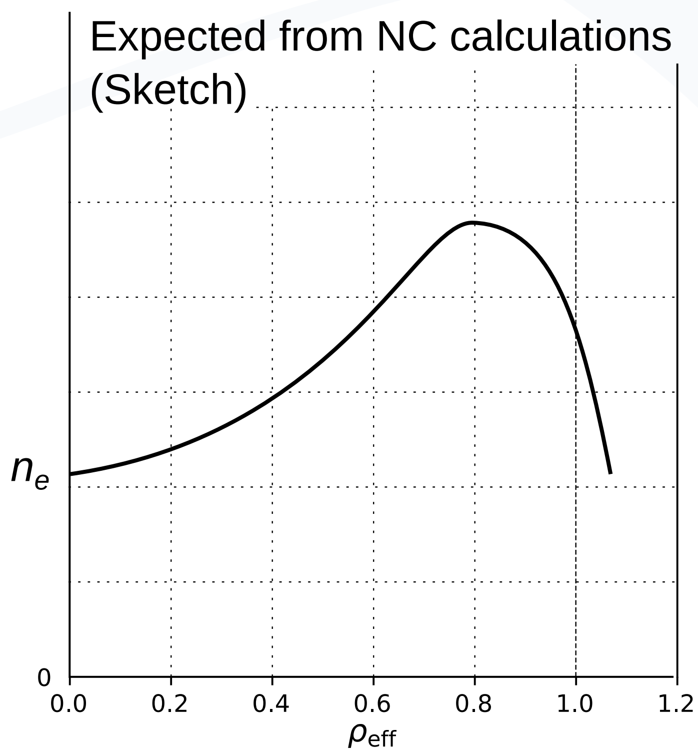
Gas-fuelled ECRH discharges

Typical discharges from last campaign (2018):

- On-axis X2 ECRH heating 2 - 6MW; $\langle n_e \rangle$ ~ 1 to 10 x 10^{19}. Gas/recycling fuelled.
- Flat or slightly peaked density profiles despite outward neoclassical thermo-diffusion:

  An anomalous pinch required to counteract [C D Beidler et al 2018 PPCF 60 105008]





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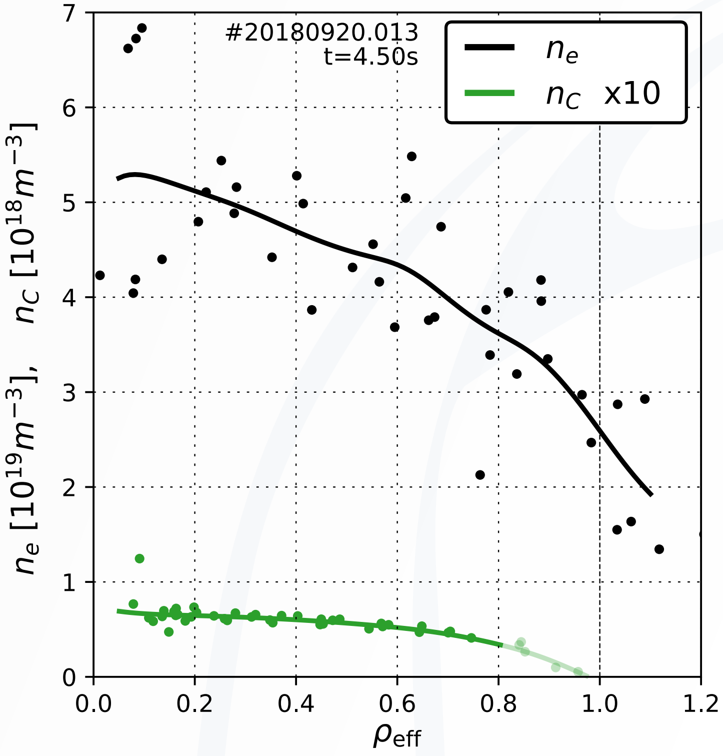
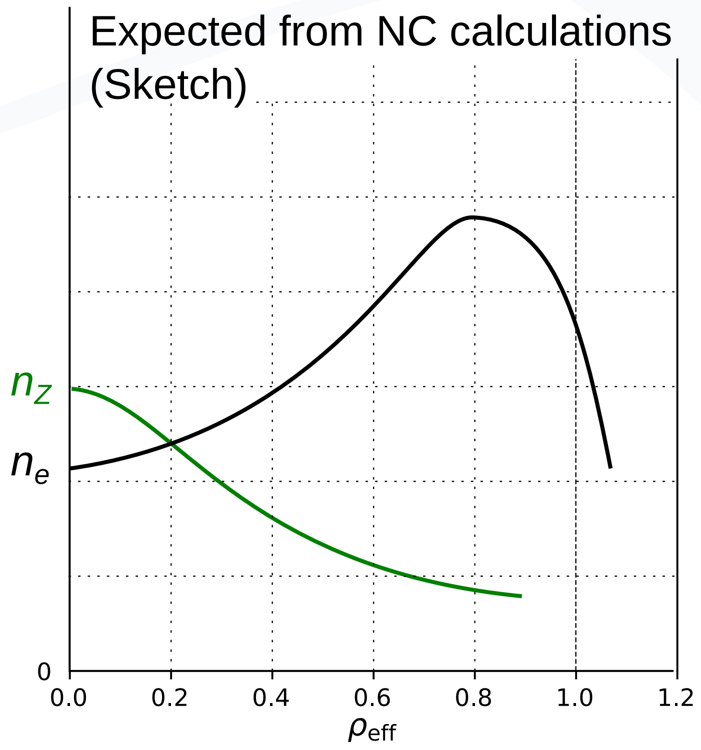
  An anomalous pinch required to counteract *[C D Beidler et al 2018 PPCF 60 105008]*
- Flat impurity profiles despite neoclassical pinch:
  High turbulent impurity diffusion shown by LBO injection experiments *[B. Geiger et al 2019 Nucl. Fus. 59 046009]*





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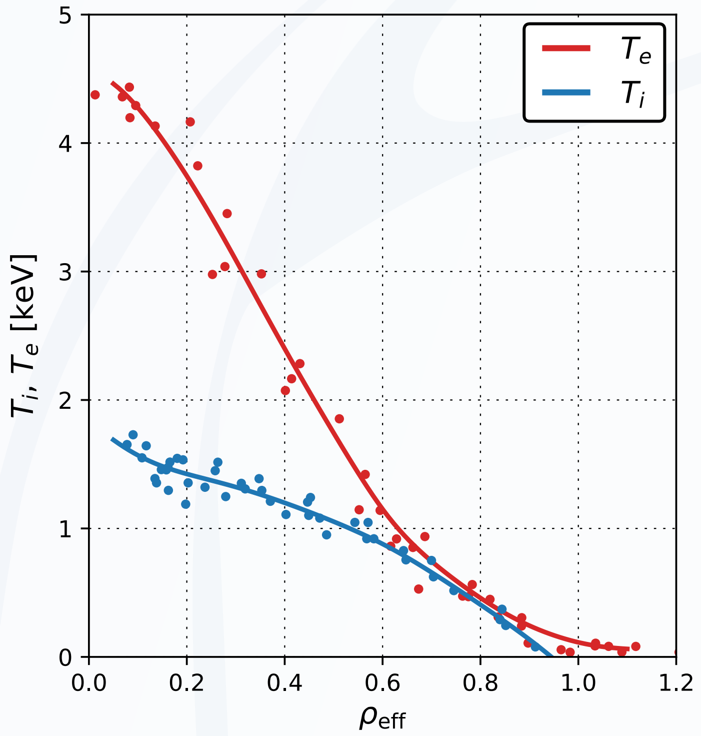

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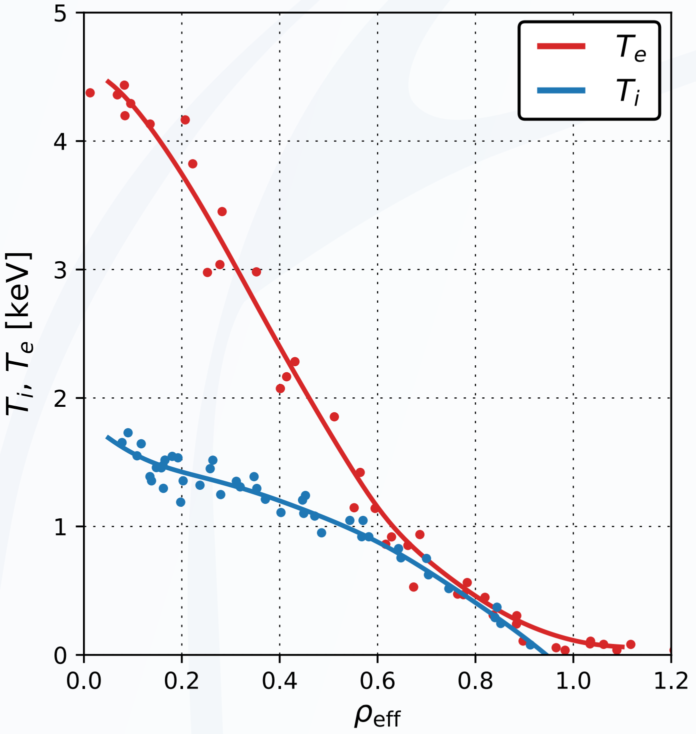

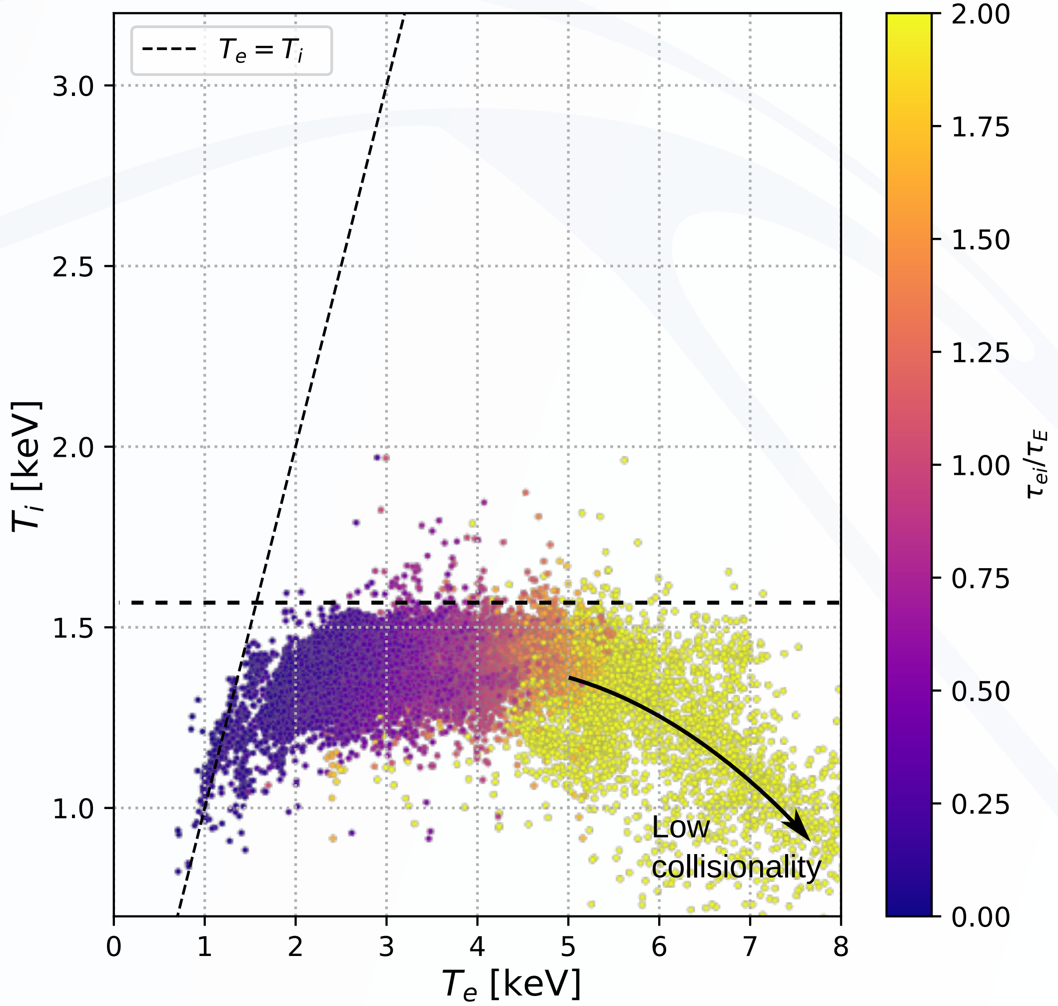

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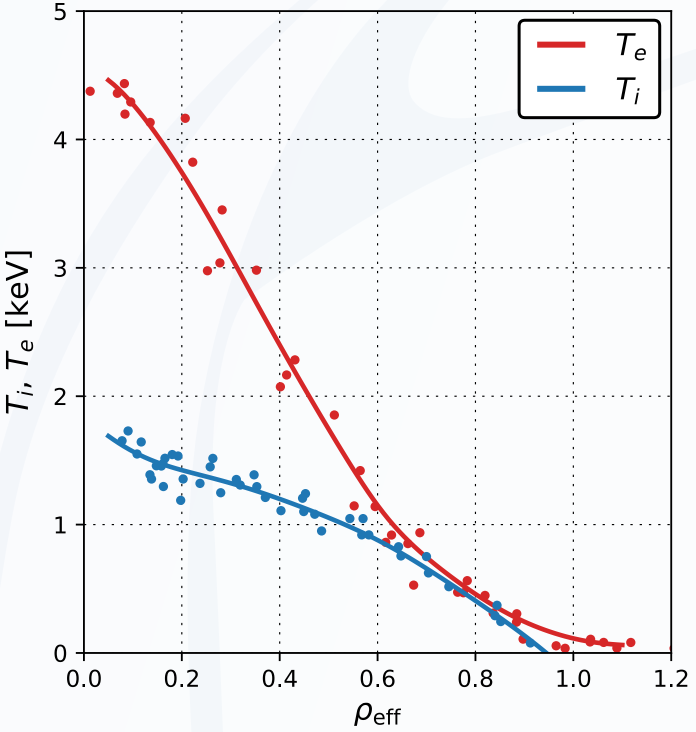
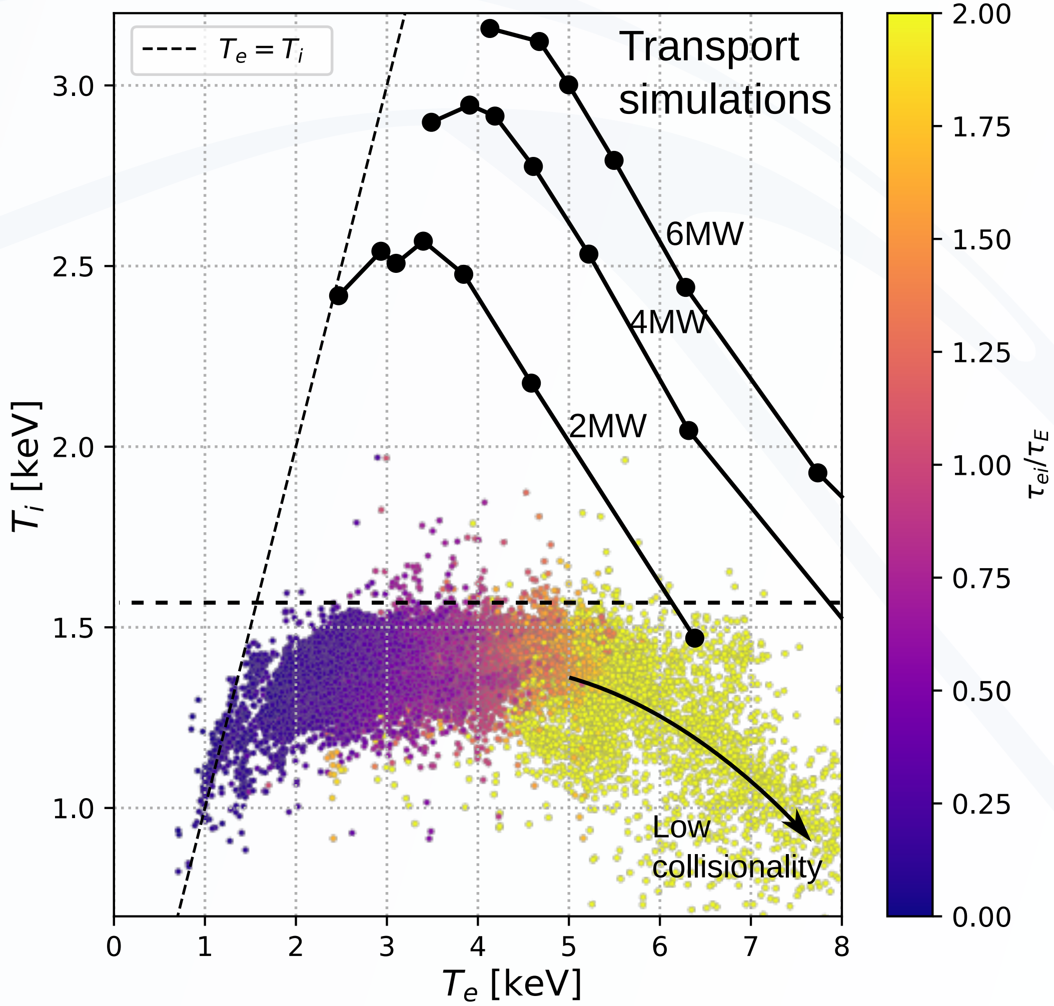
- Simulations with neoclassical and moderate turbulent transport predict T_i ~ 3keV for P_{ECRH} = 6MW.

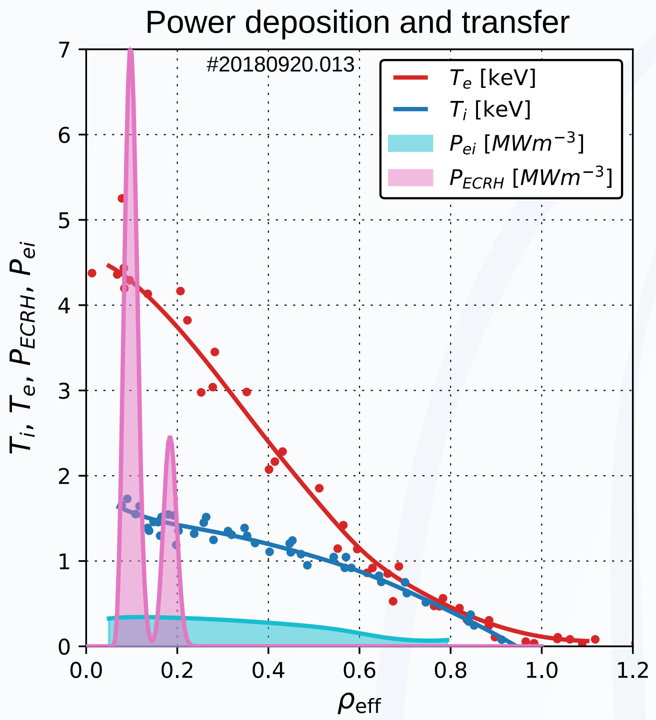




Ion temperature clamping

Ion temperature clamping explained by combination of effects: [Beurskens et al. Nucl Fus 2021 (submitted), IAEA 2021]

- Collisional coupling gives broad ion heating profile



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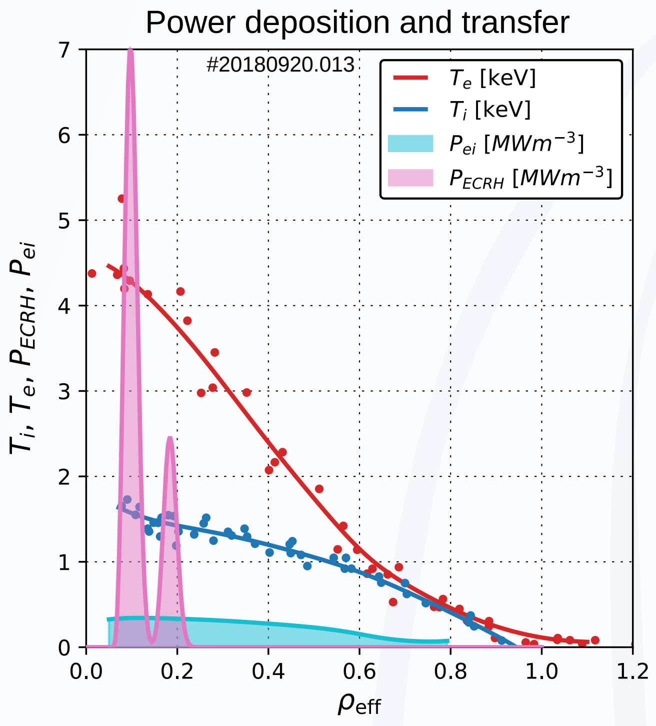

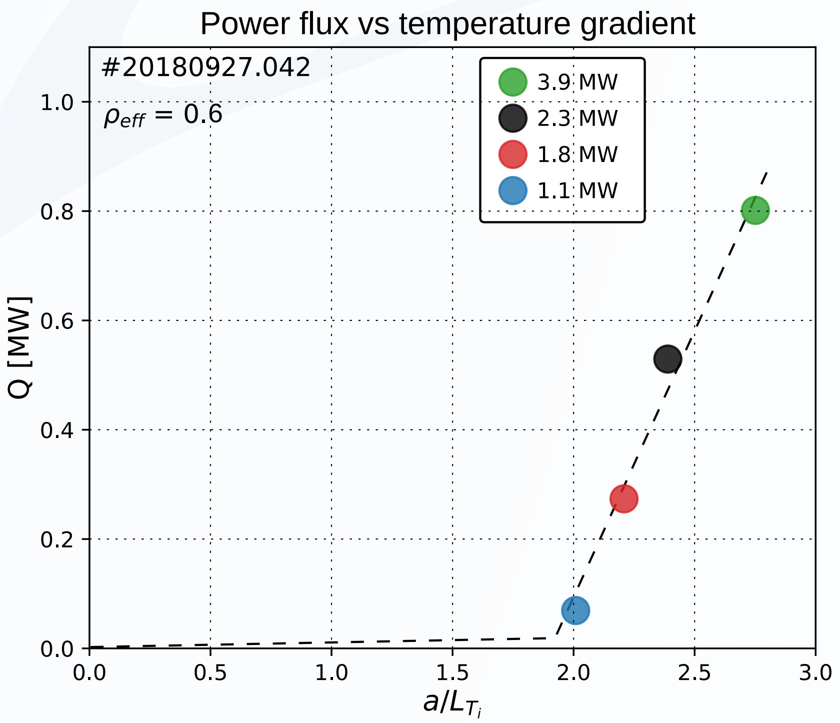

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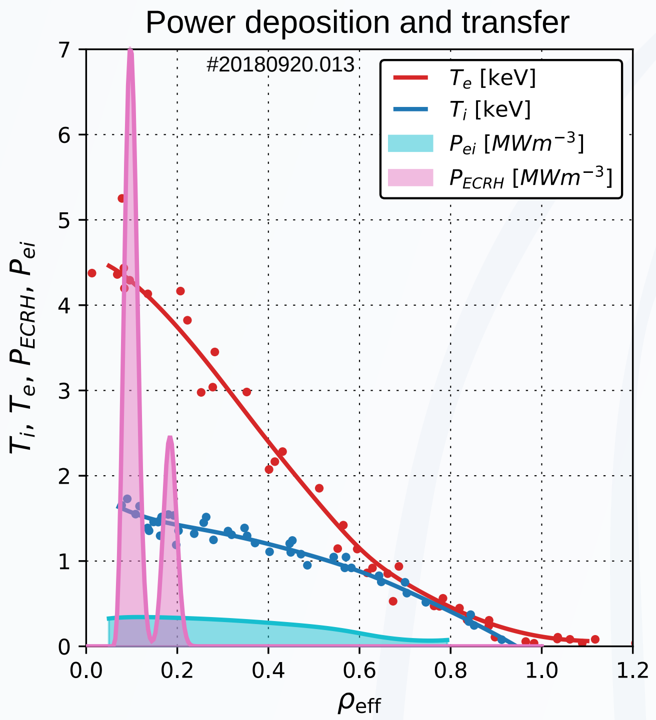

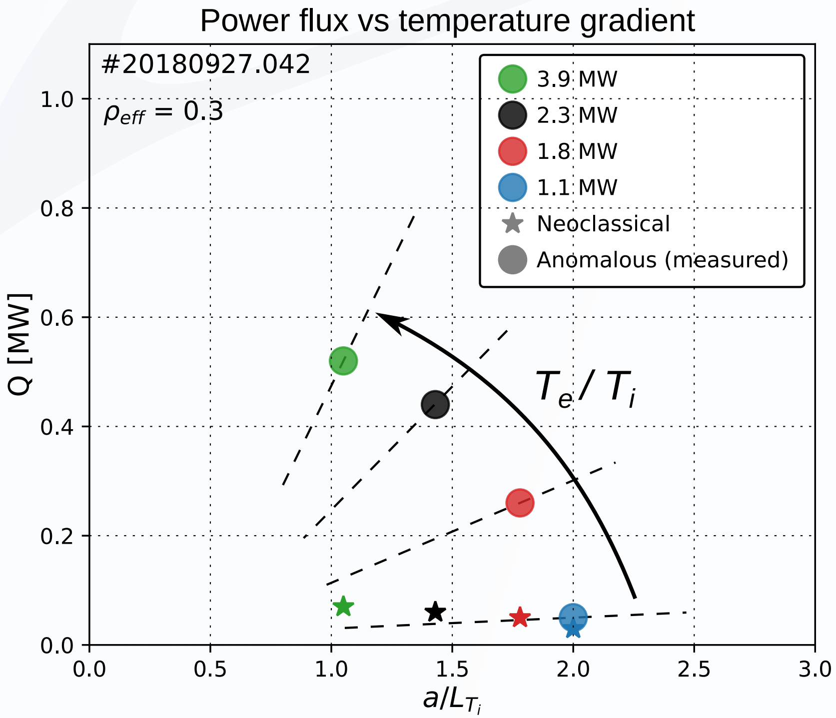

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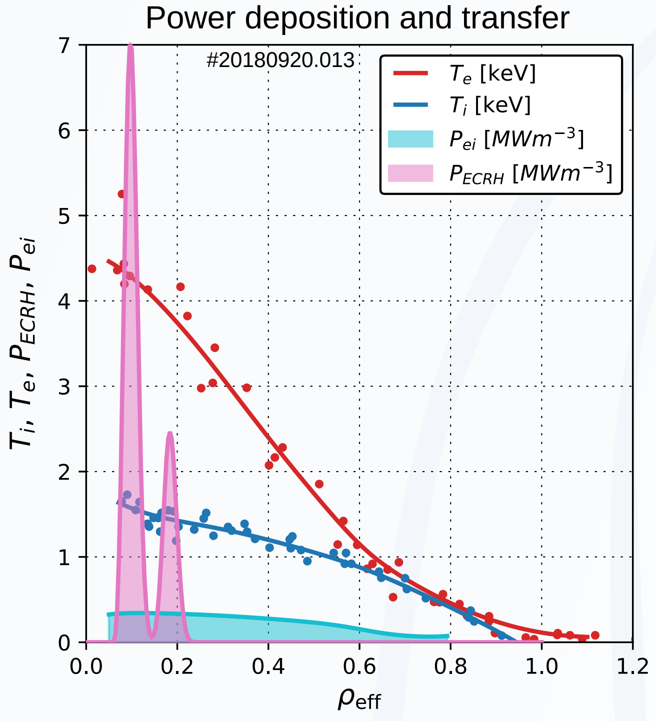
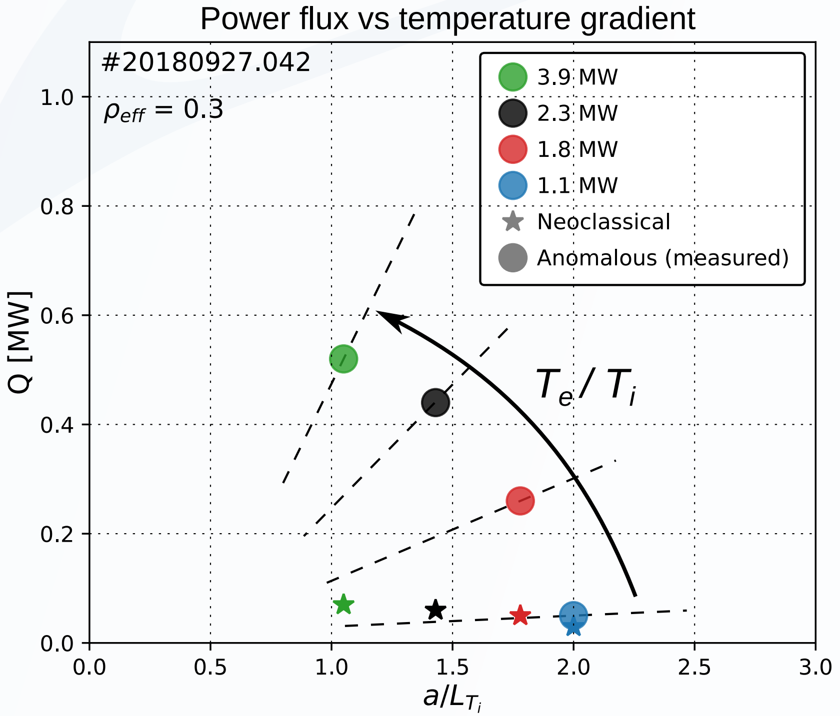
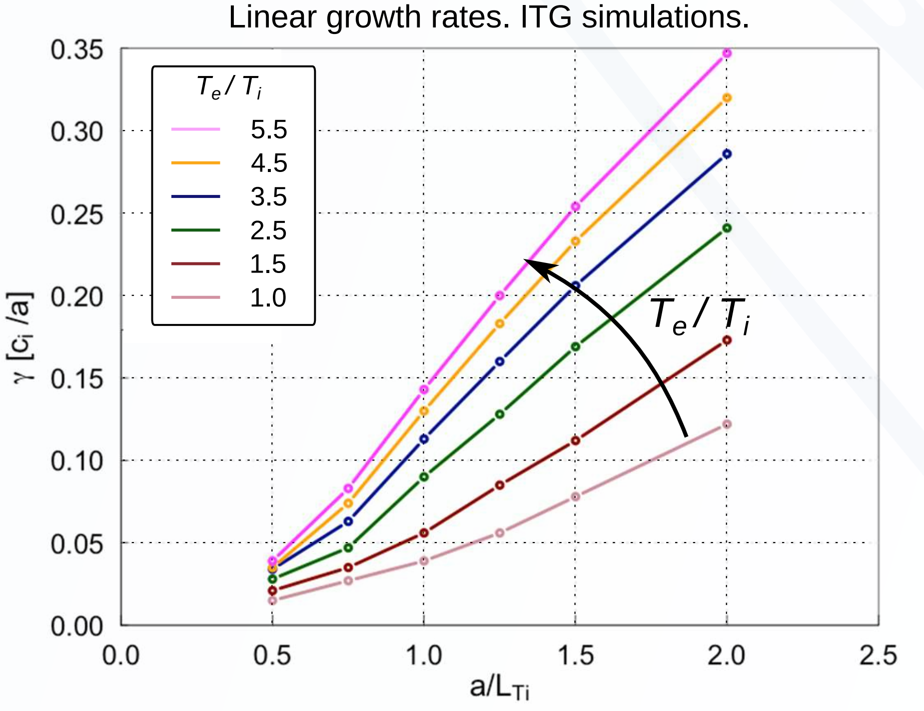
  supported by linear growth rate from ITG simulations *[A. Zocco, J. Plasma Phys 2017]*

---> Typical gas fuelled ECRH W7-X plasmas ITG turbulence dominated

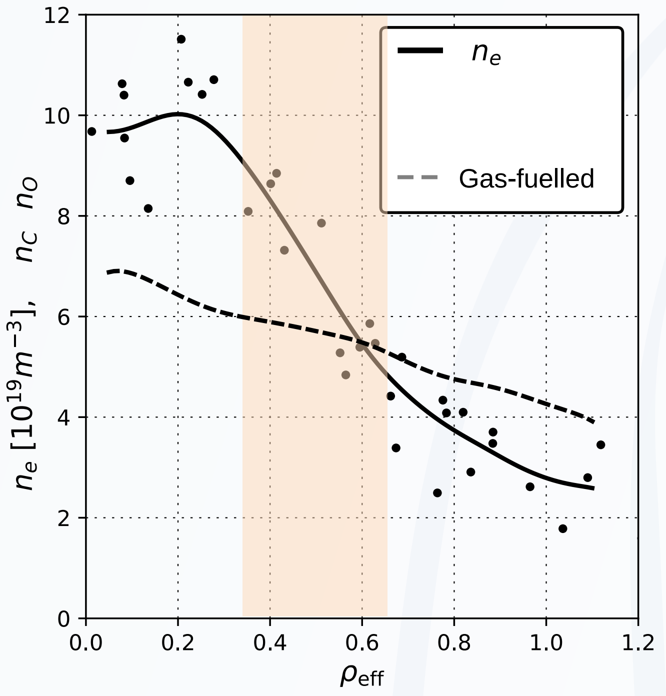


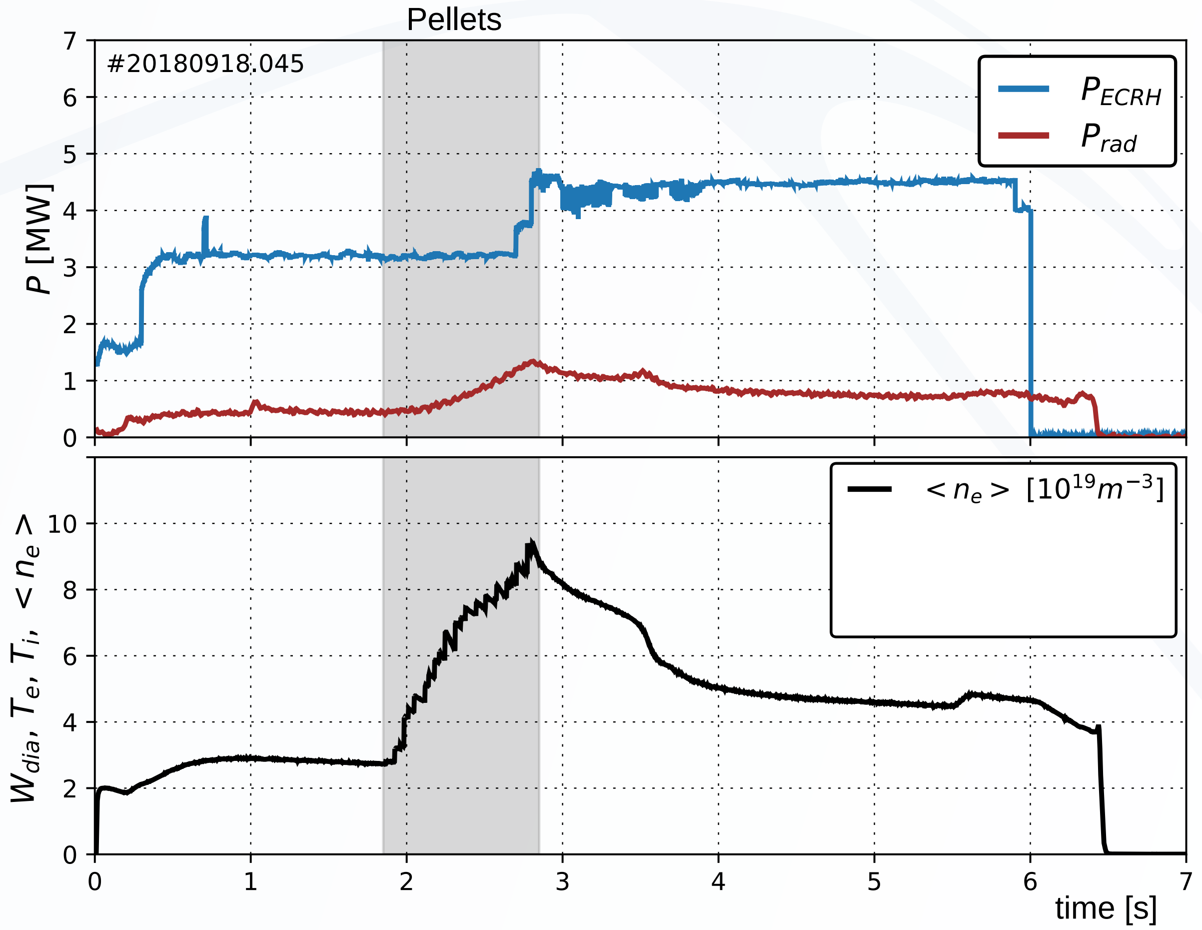




Post-pellet turbulence suppression

Steep density profiles after rapid series of hydrogen ice pellets.





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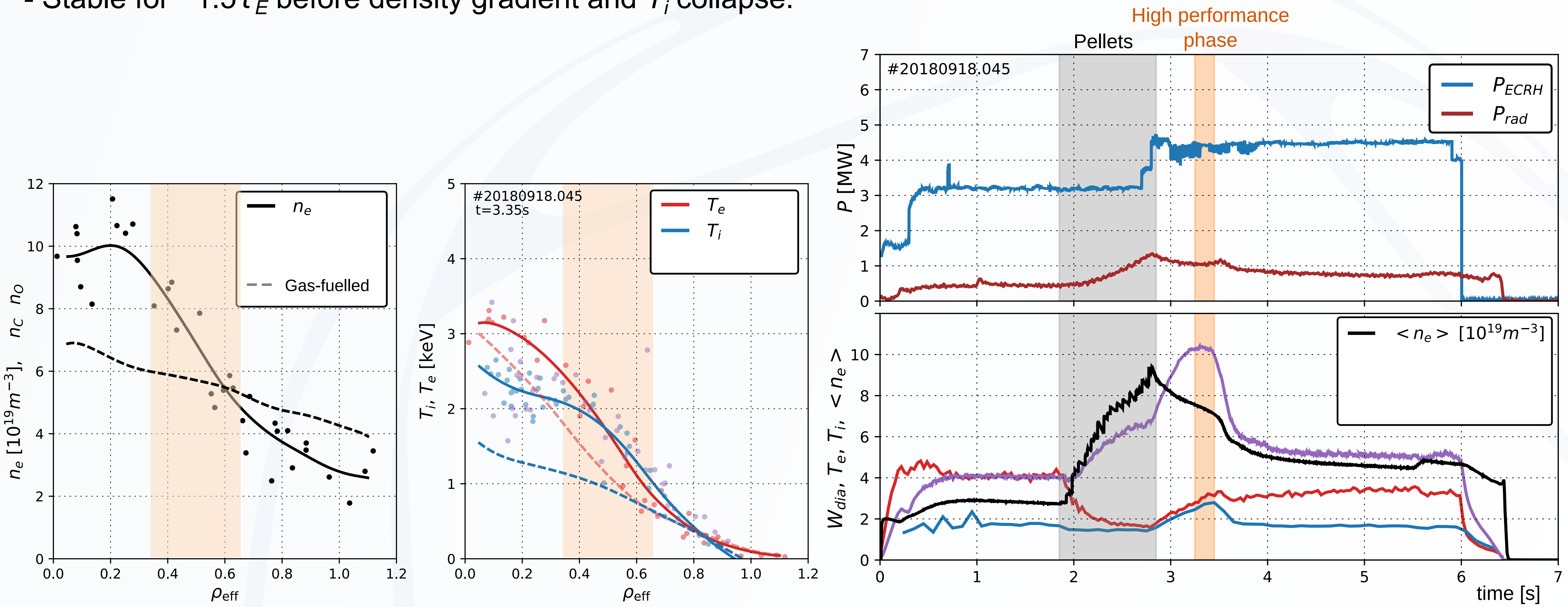

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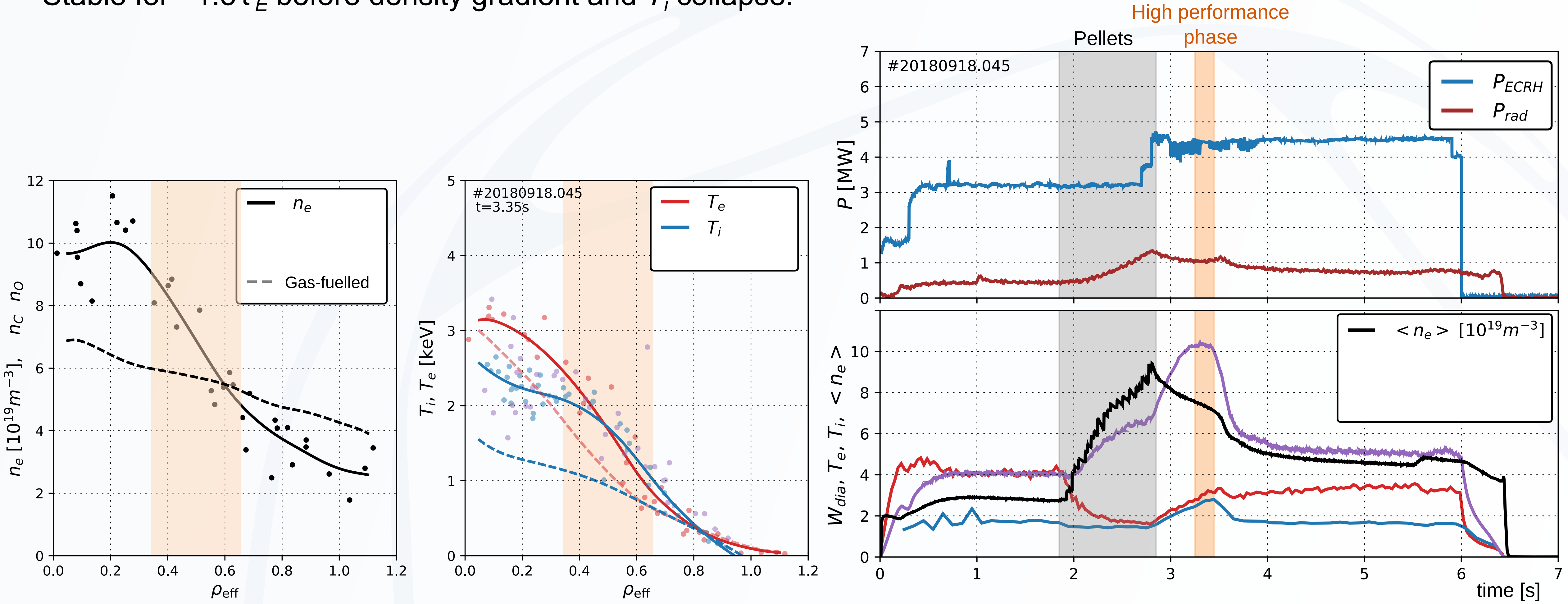

Post-pellet turbulence suppression

Wendelstein 7-X
IPP

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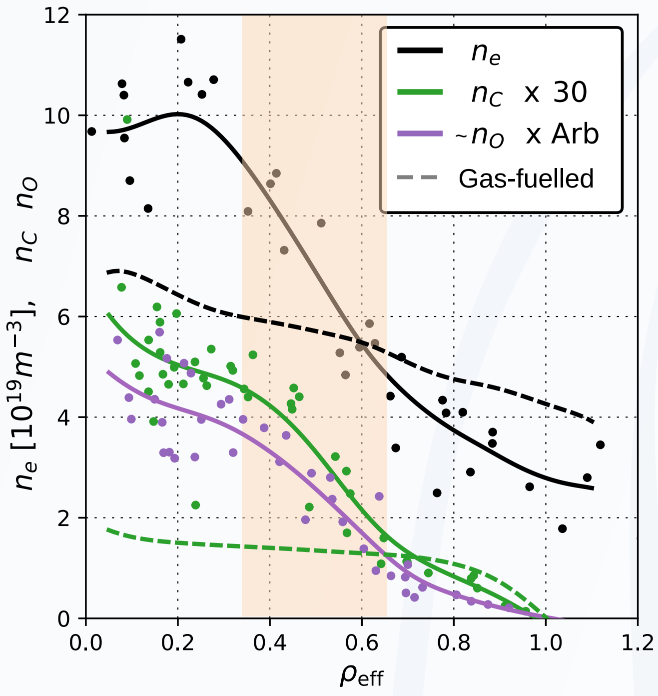
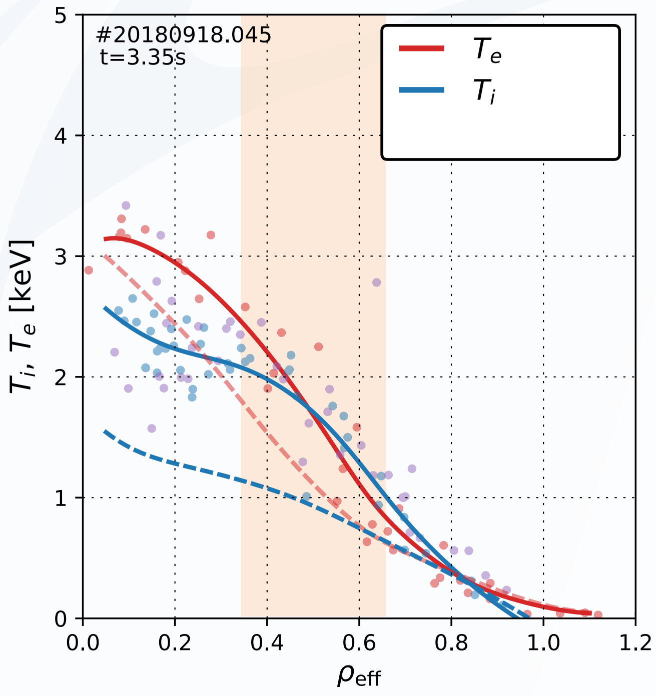
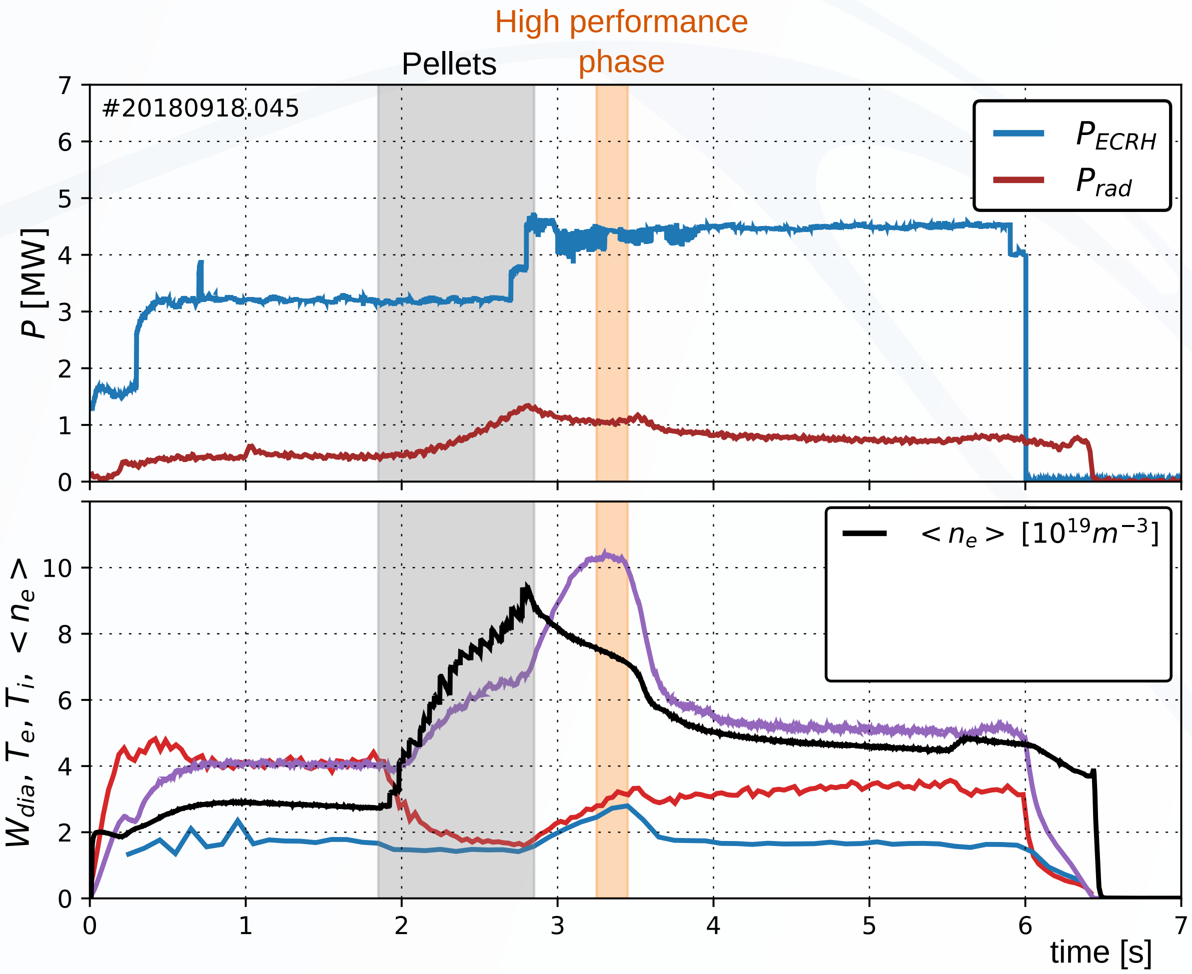
- Stable for ~1.5τ_E before density gradient and T_i collapse.
- Peaking of impurities observed consistent with reduced turbulence, but n_C still < 1% (Z_{Eff} < 1.5)







Post-pellet turbulence suppression

- Ion heat transport reduced to order of neoclassical level.
- Electron heat transport significantly reduced.

Typical gas-fuelled plasma

Post-pellets plasma

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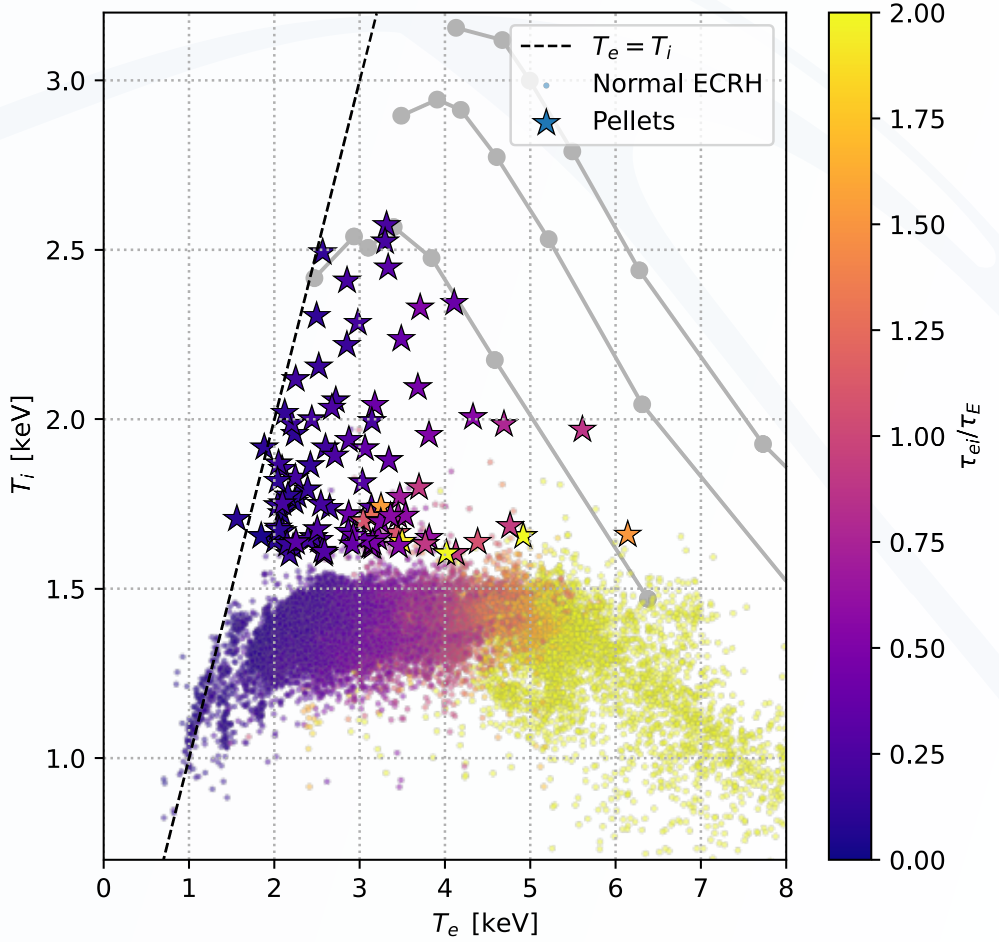

Post-pellet turbulence suppression

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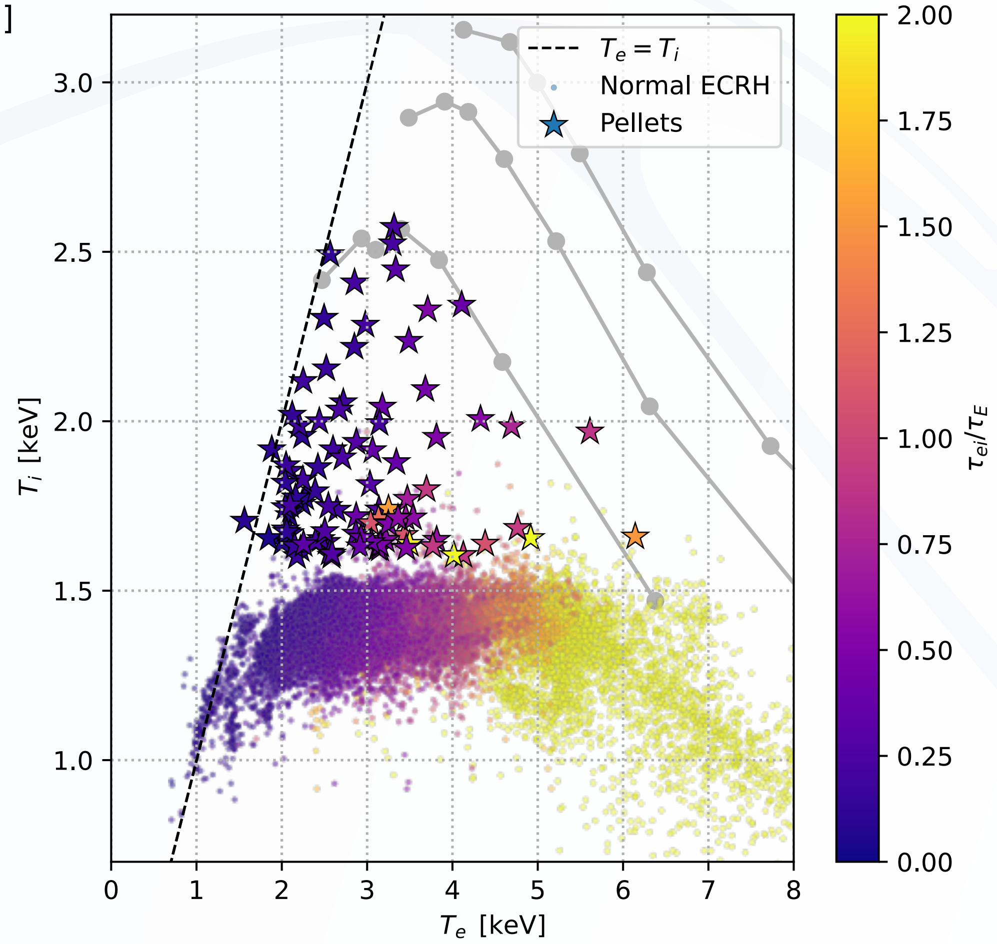
- Central T_i raised significantly above clamping limit.
- Sufficient to demonstrate NC optimisation of W7-X [Beidler et al. Nature, 2021]
- Record stellarator $n\ T\ \tau_E$ *[Pedersen et al. PPCF 61 (2019)]*

Typical gas-fuelled plasma | Post-pellets plasma



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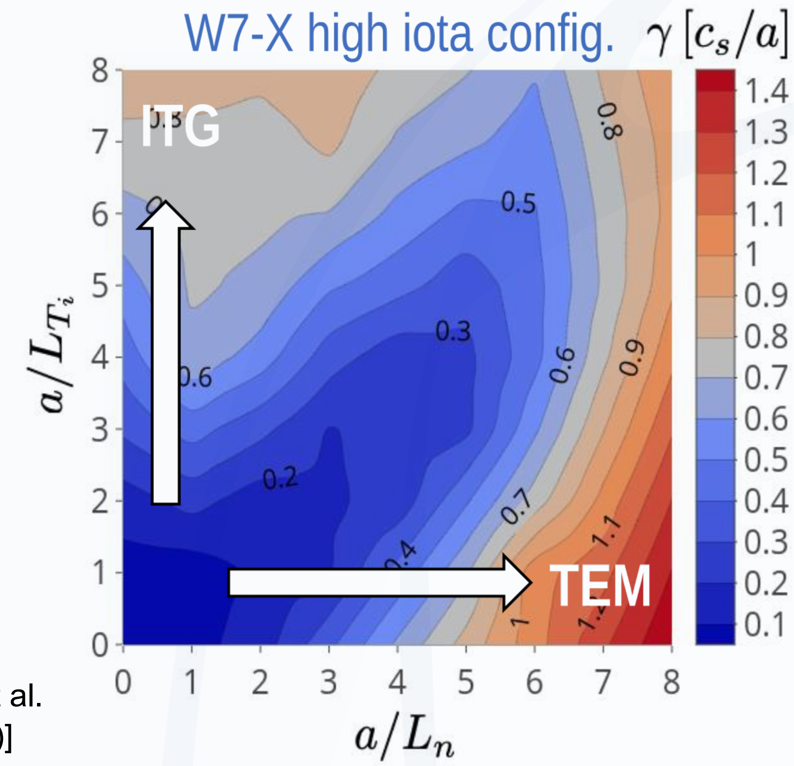

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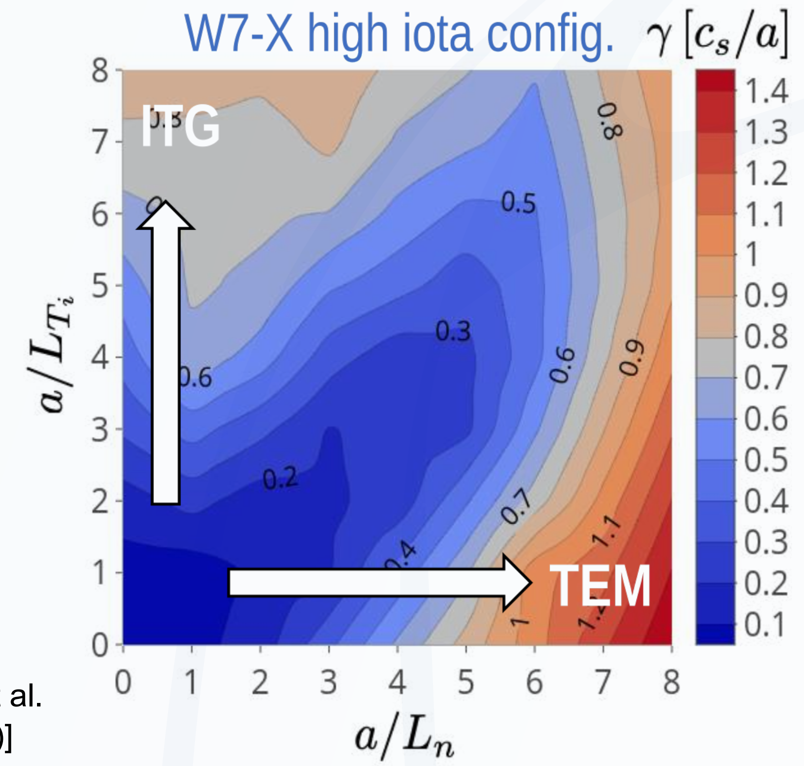
  - 'Stability valley' around a/Ln_e ~ a/LT_i [J. A. Alcusón et al. PPCF 21 (2020)]
  - Non-linear simulations show transistion of from ITG to iTEM during post-pellet phase. [P. Xanthopoulos et. al. PRL 2021]
  - Reduction in fluctuation levels seen by PCI [Z. Huang, this conference], Doppler reflectometer [T. Estrada et al., Nucl. Fus. 2021] and even in SOL Beam Emission Spectroscopy [L. Édes, this conference]



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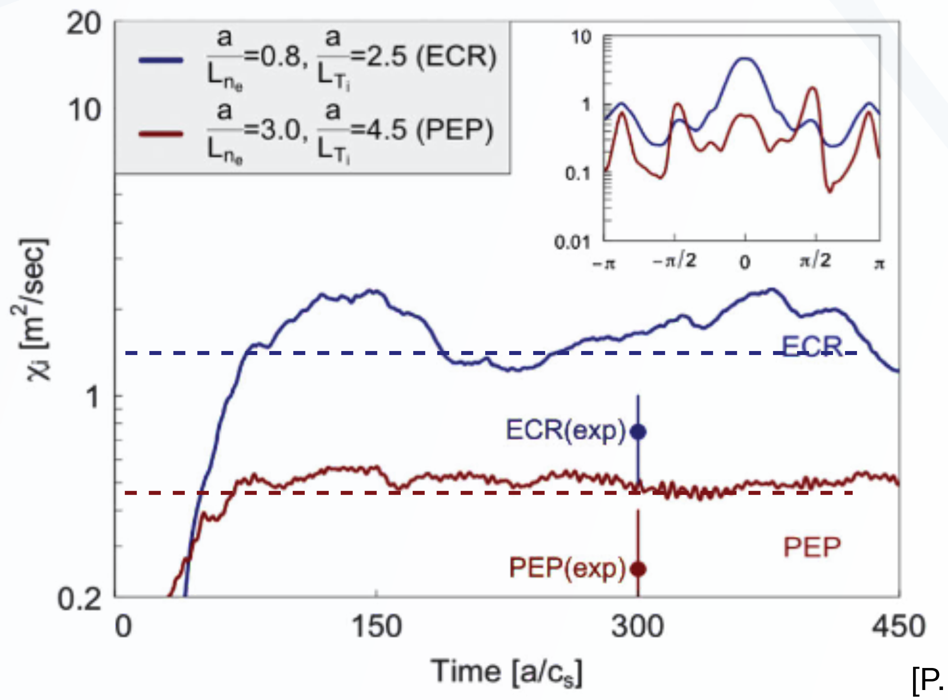

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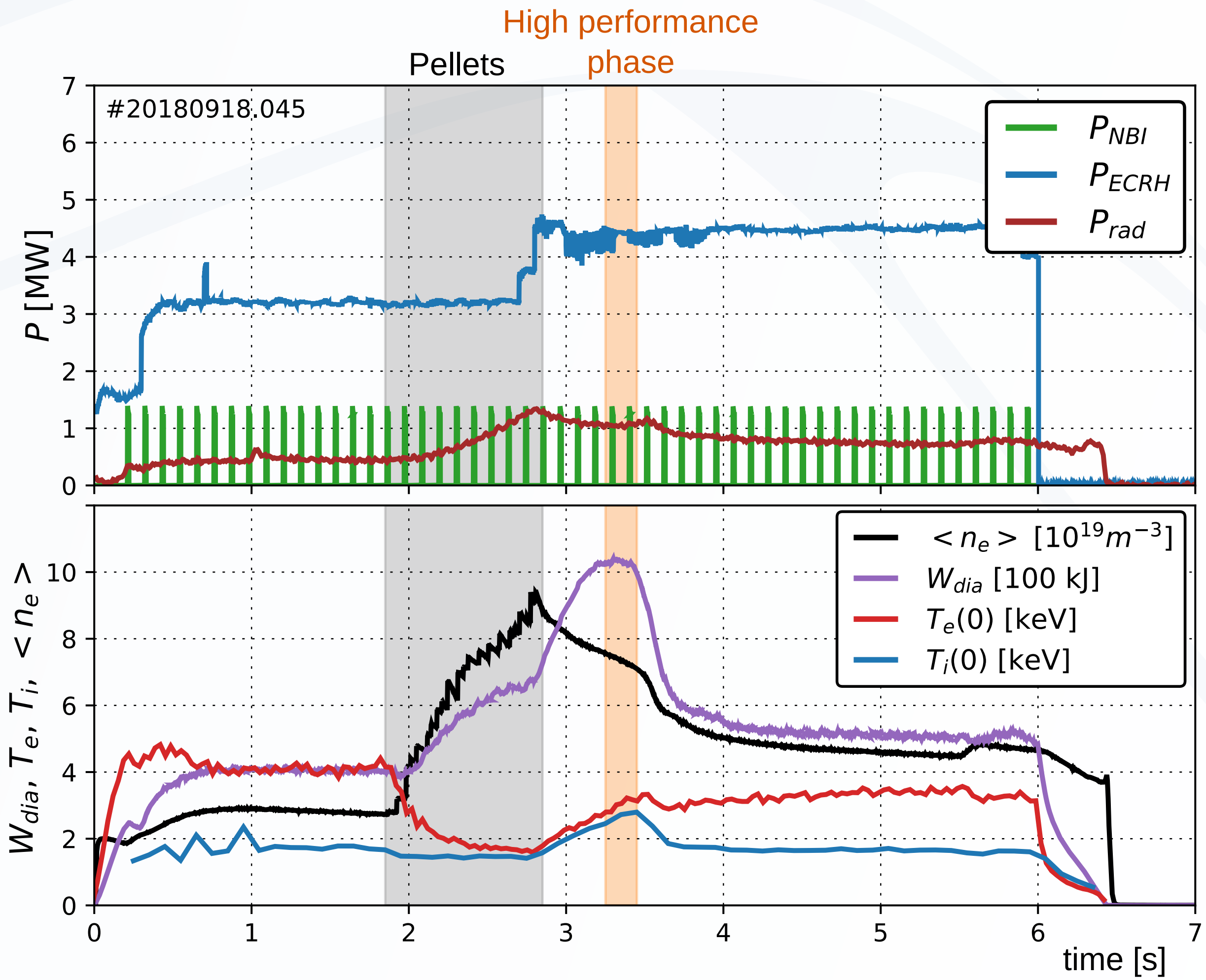
Post-pellet turbulence suppression

- Steady-state pellet injector next campaign to investigate ability to maintain high performance phase *during* pellets.



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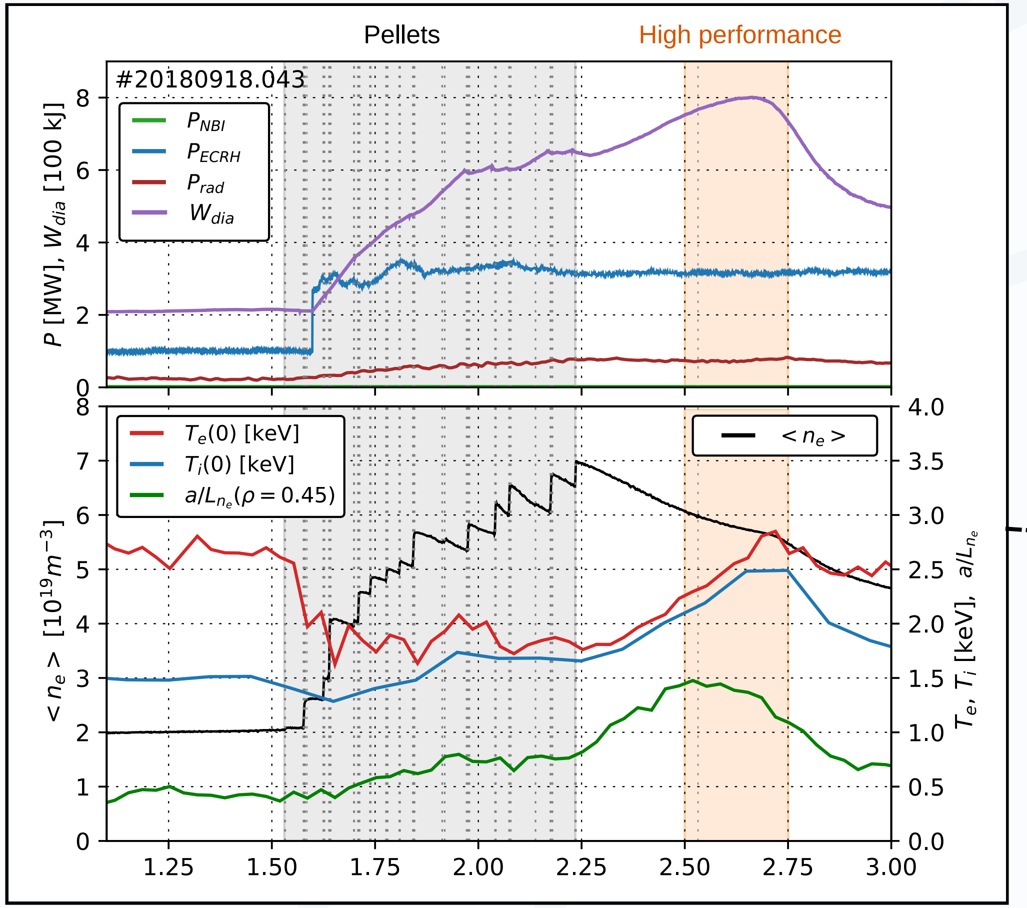
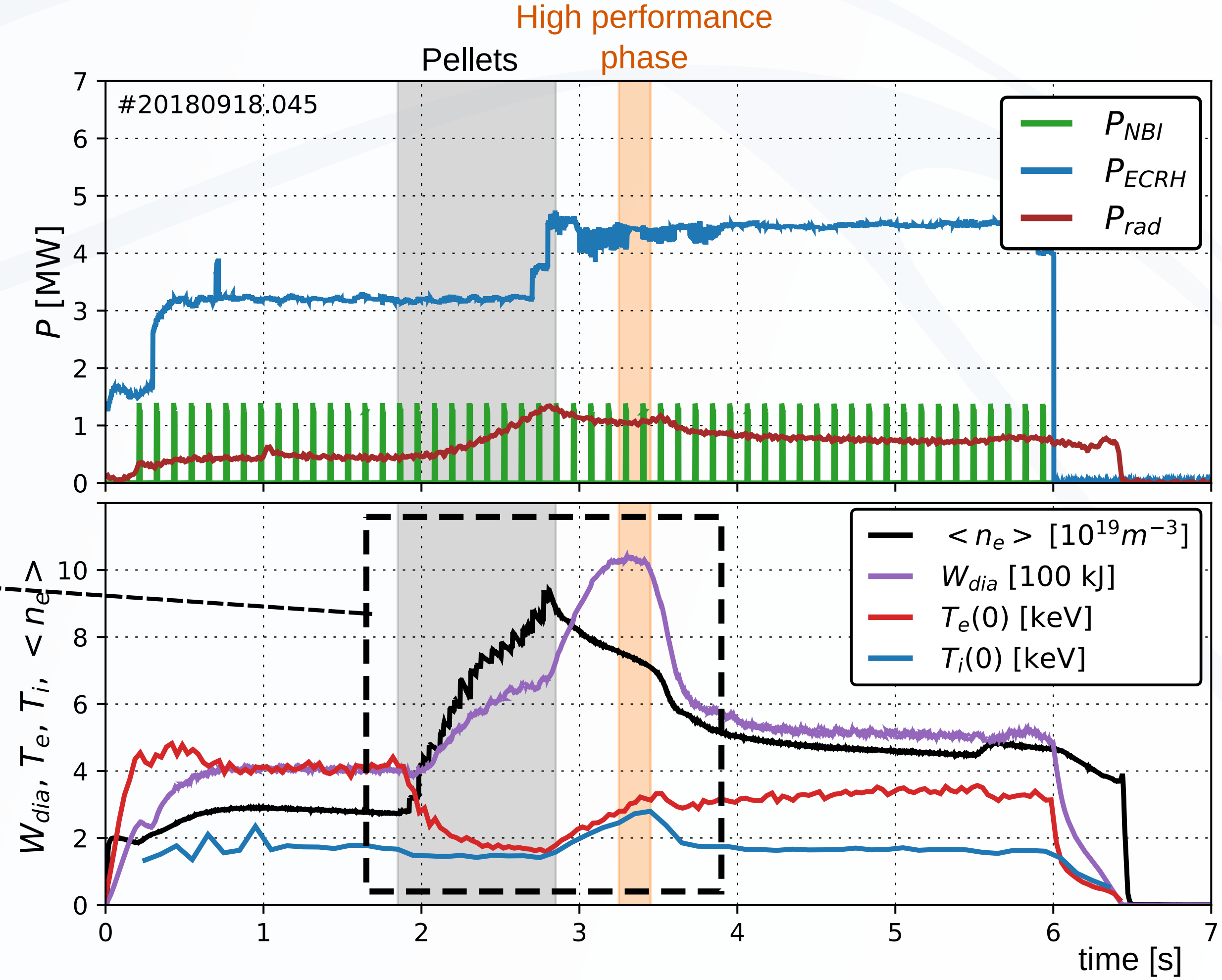
- So far, density gradient only observed after injection of last pellet.





Density gradient turbulence suppression

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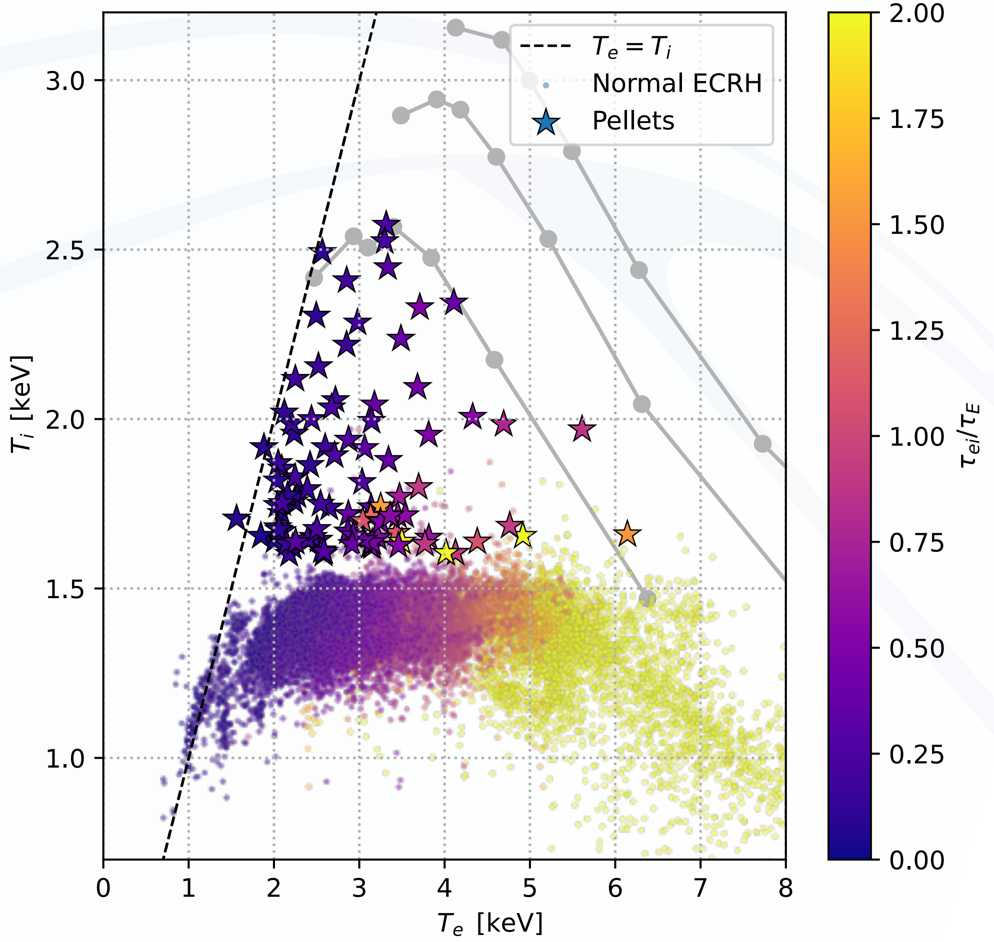

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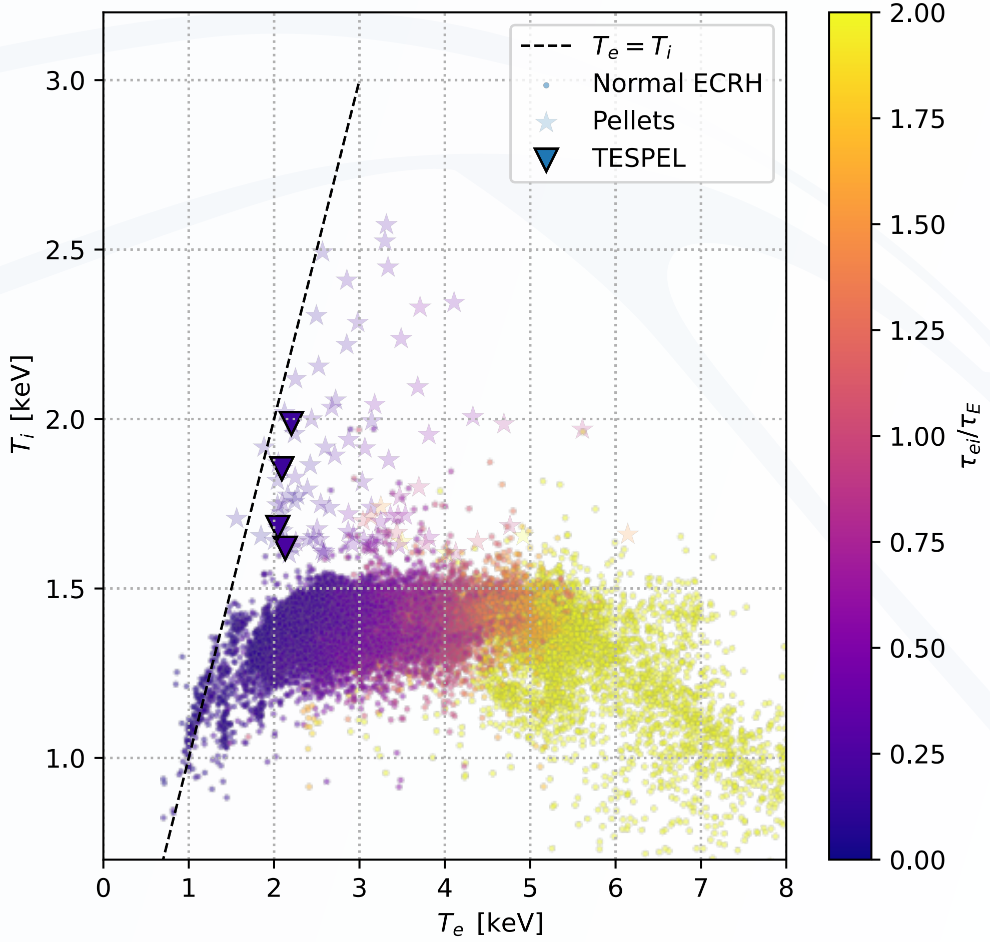

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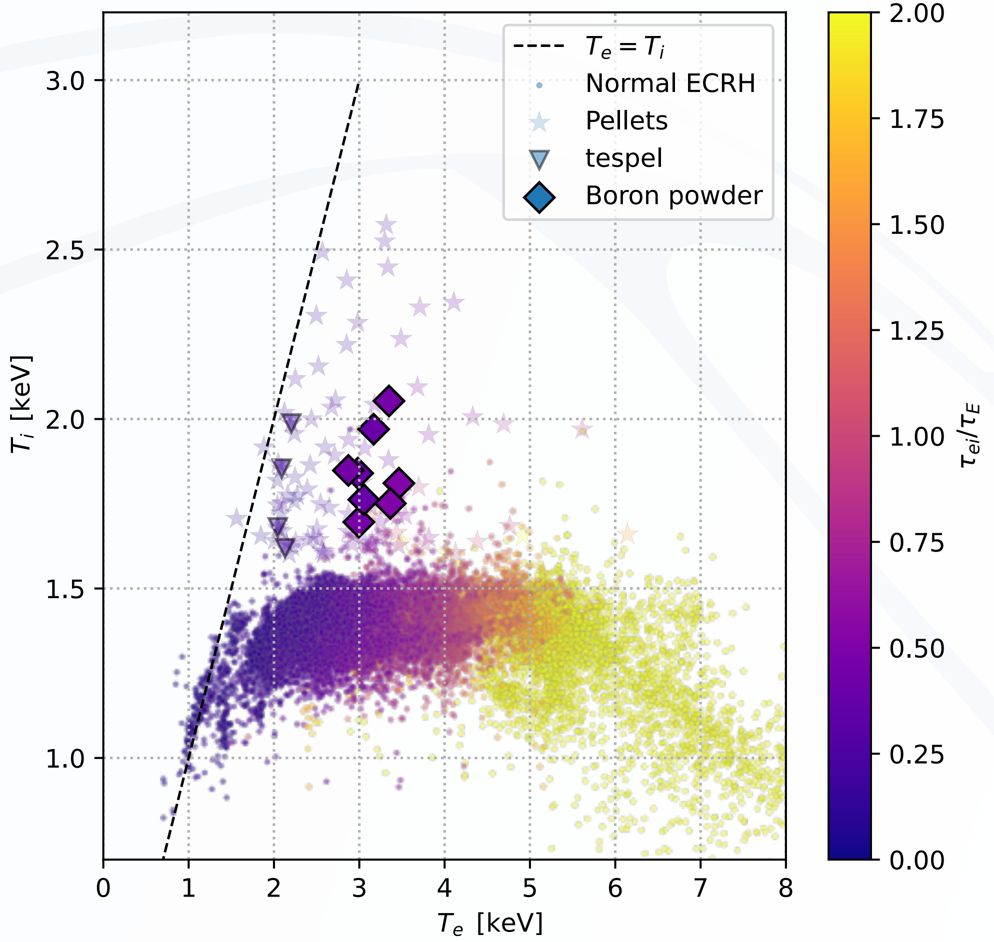

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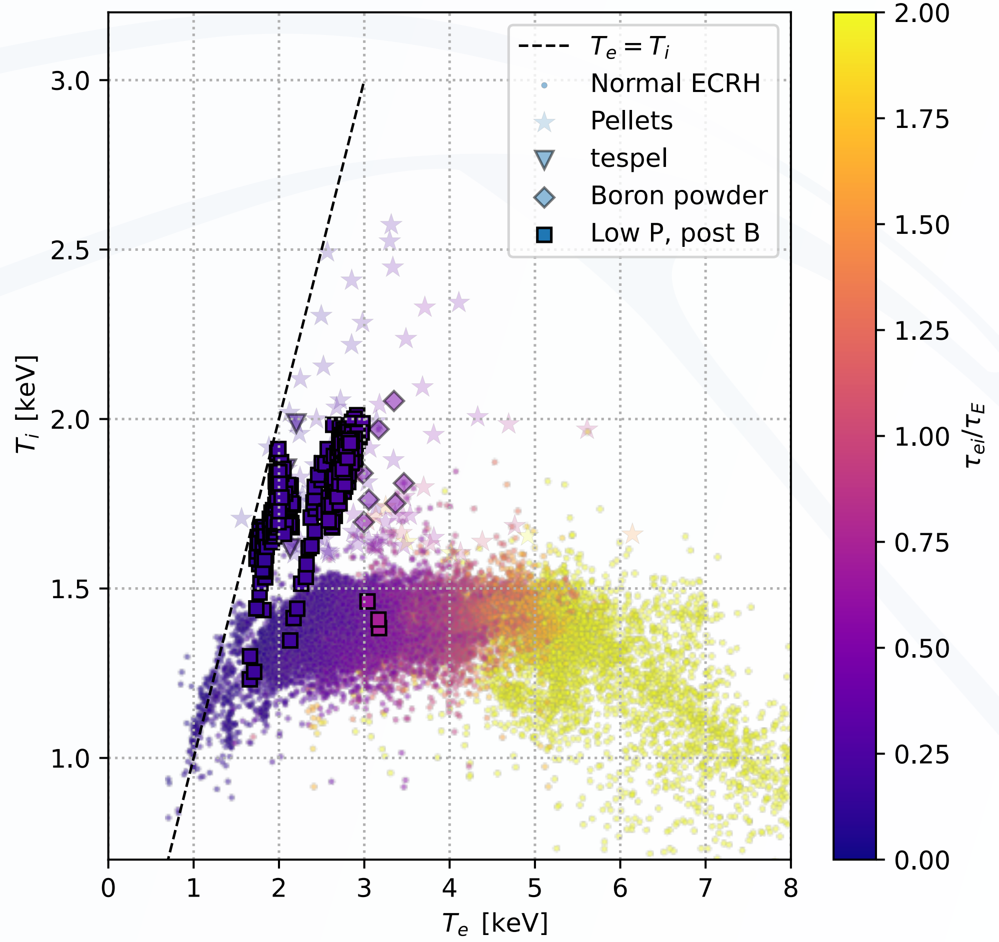

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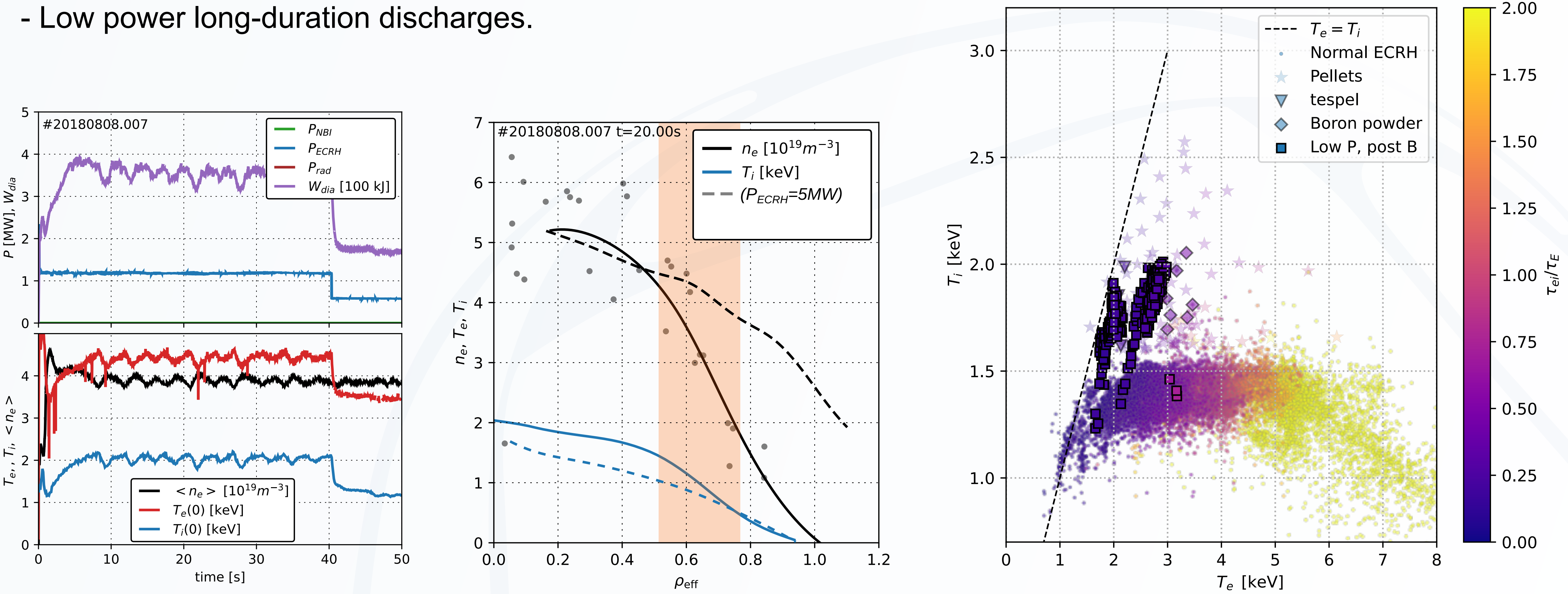

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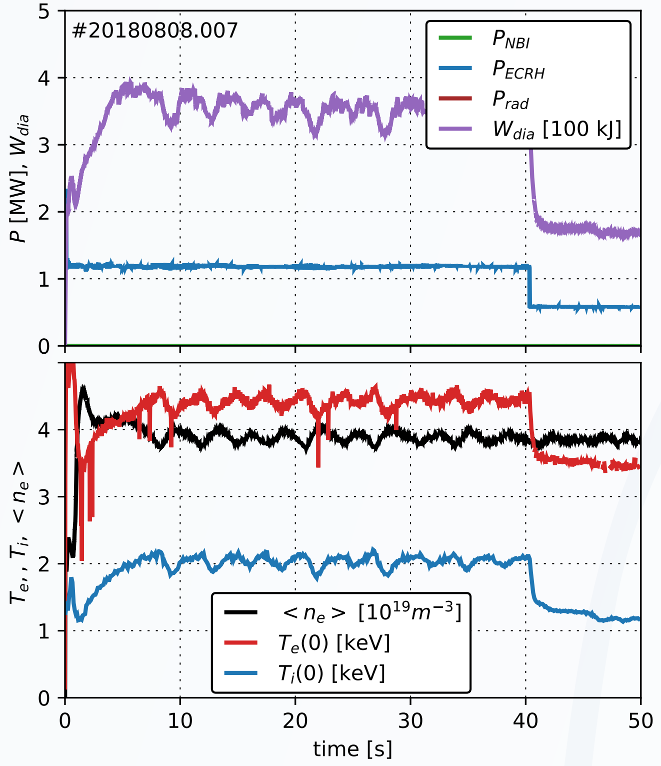
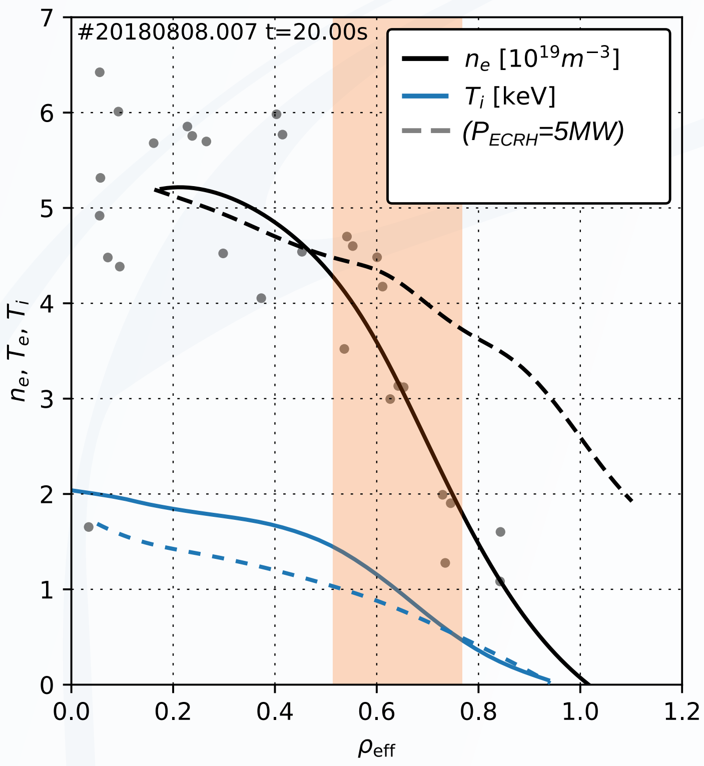
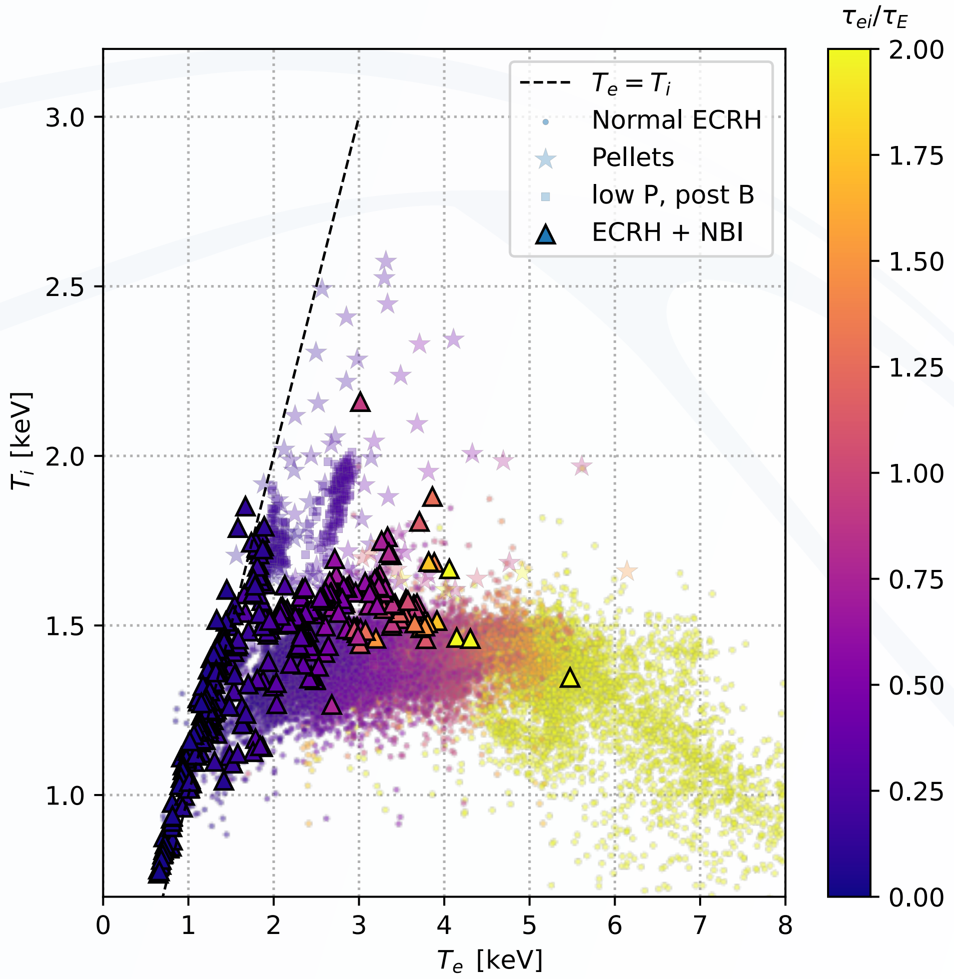
  ... NBI core fuelling?

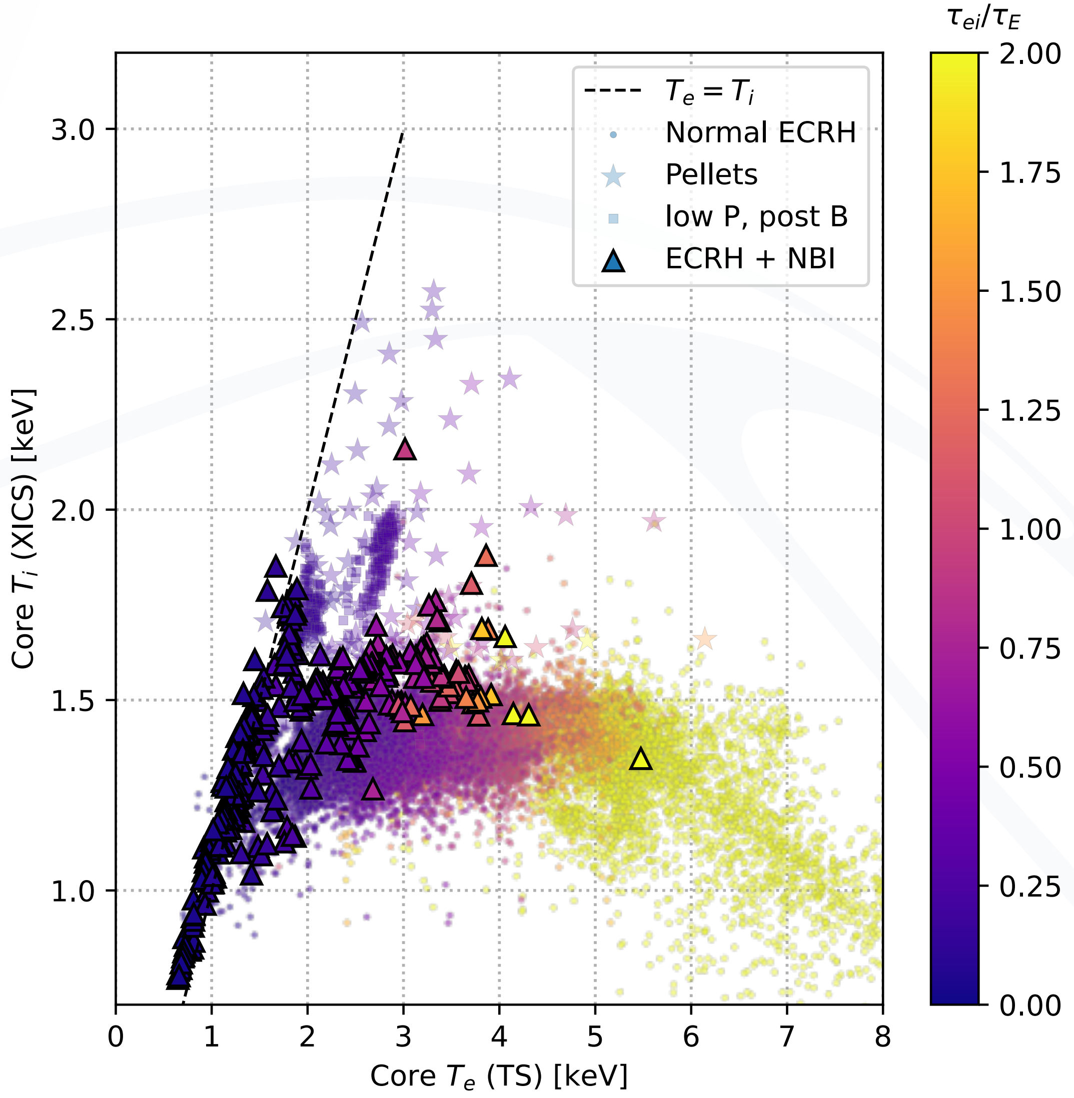






NBI : ECRH ratio

- NBI mostly supplementary to moderate-high ECRH power.



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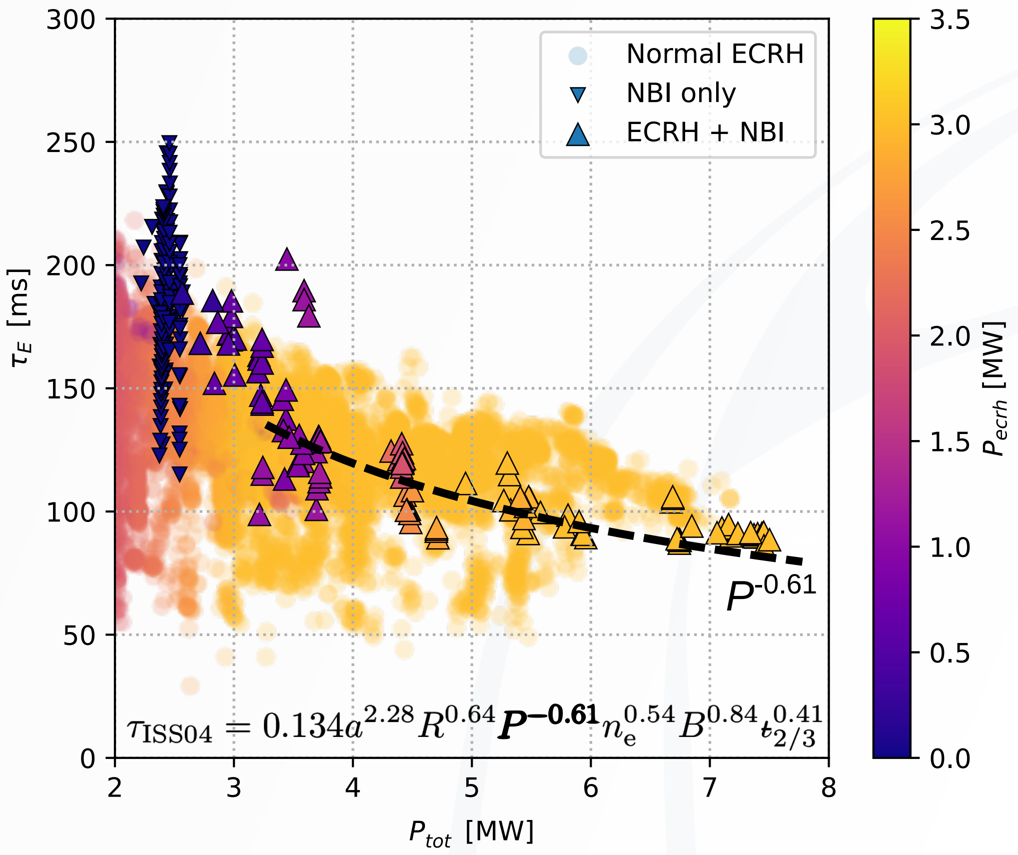

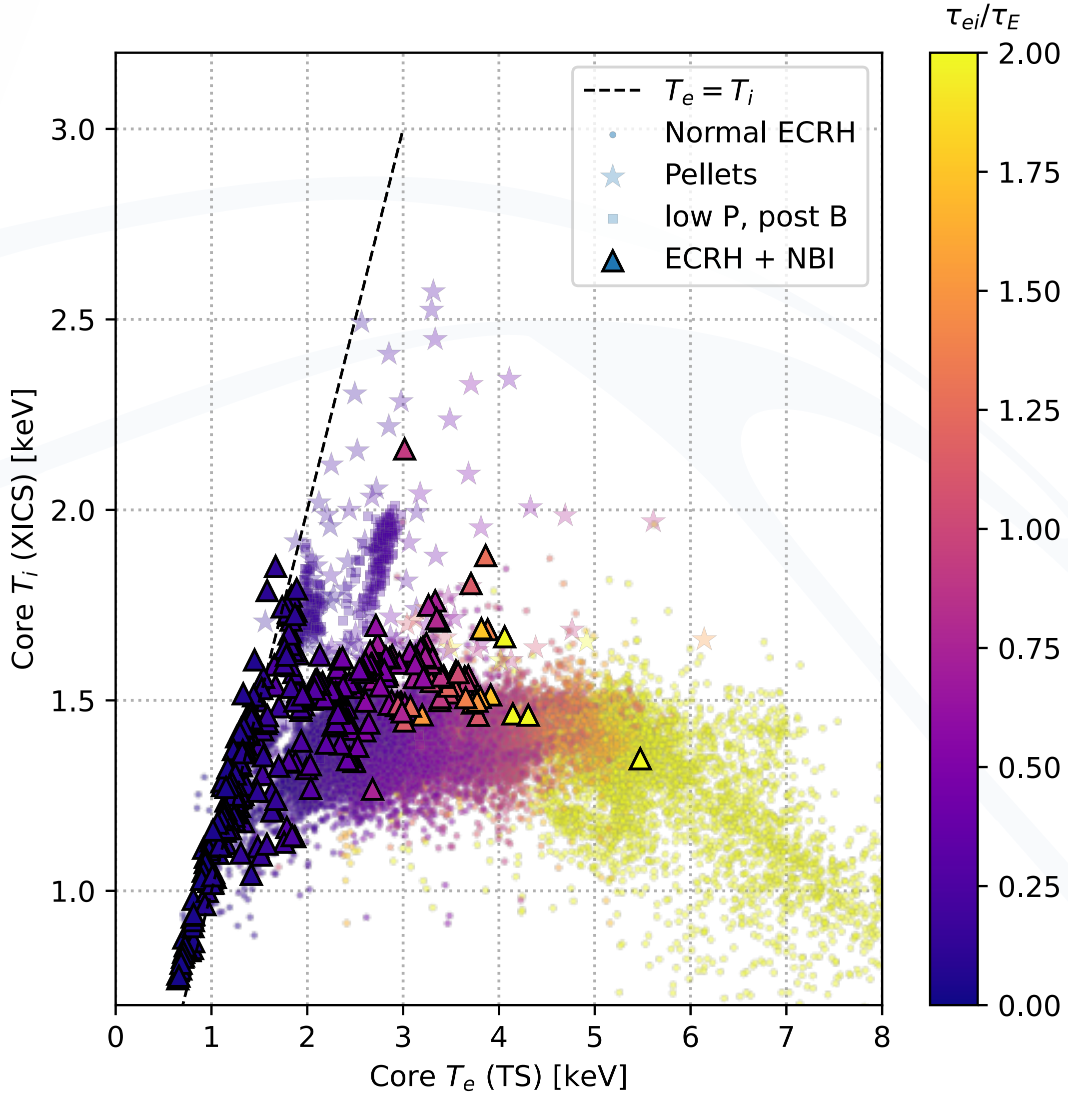

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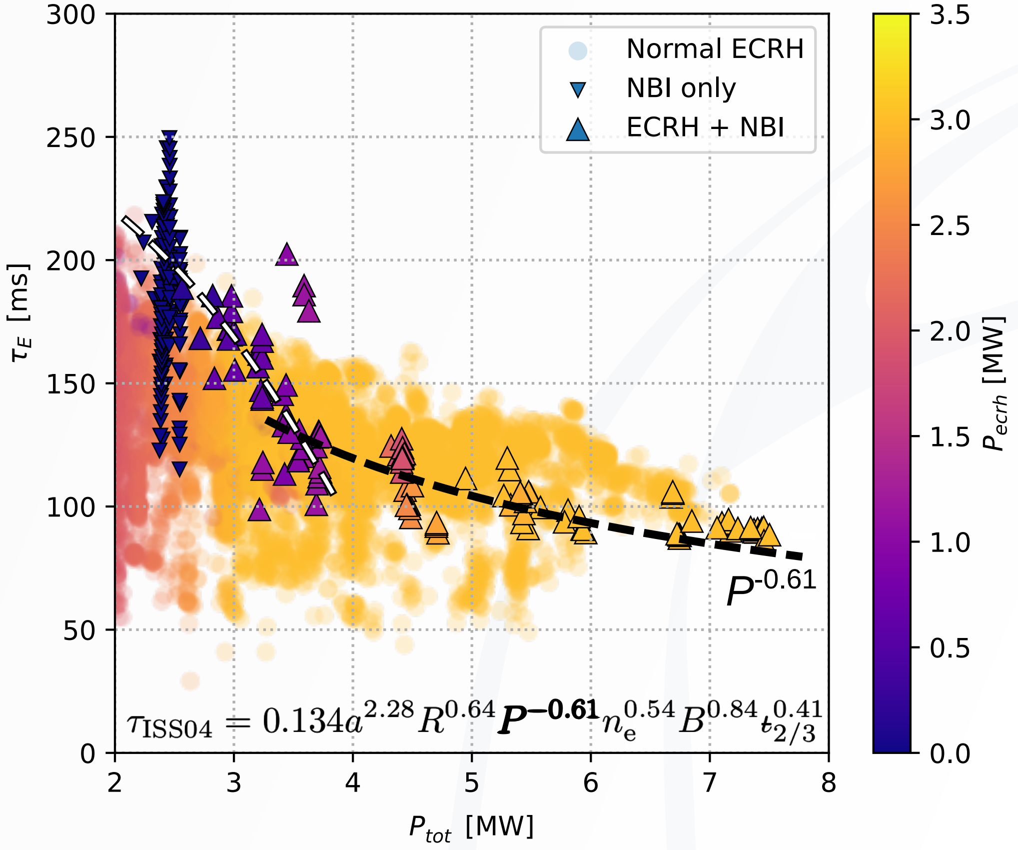

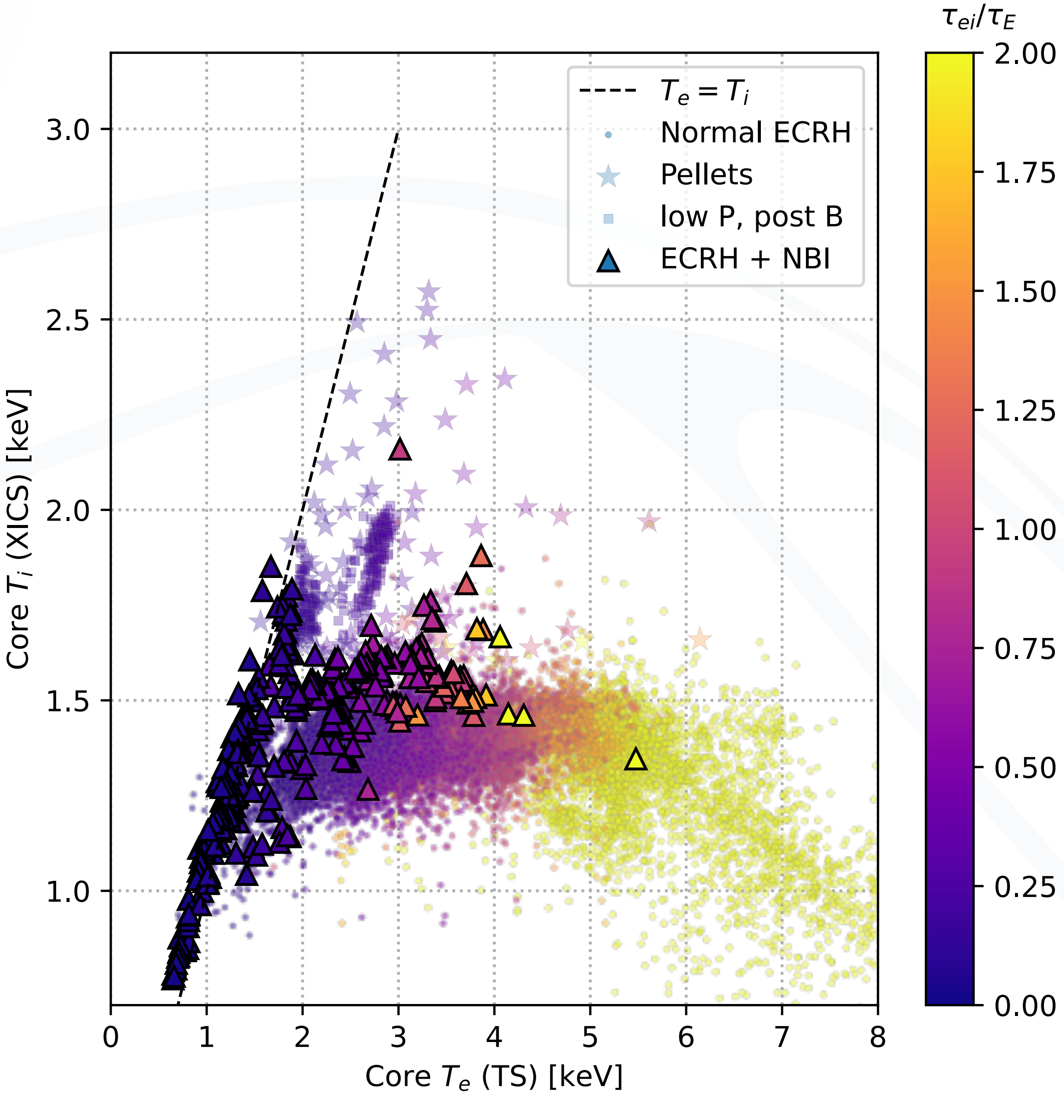

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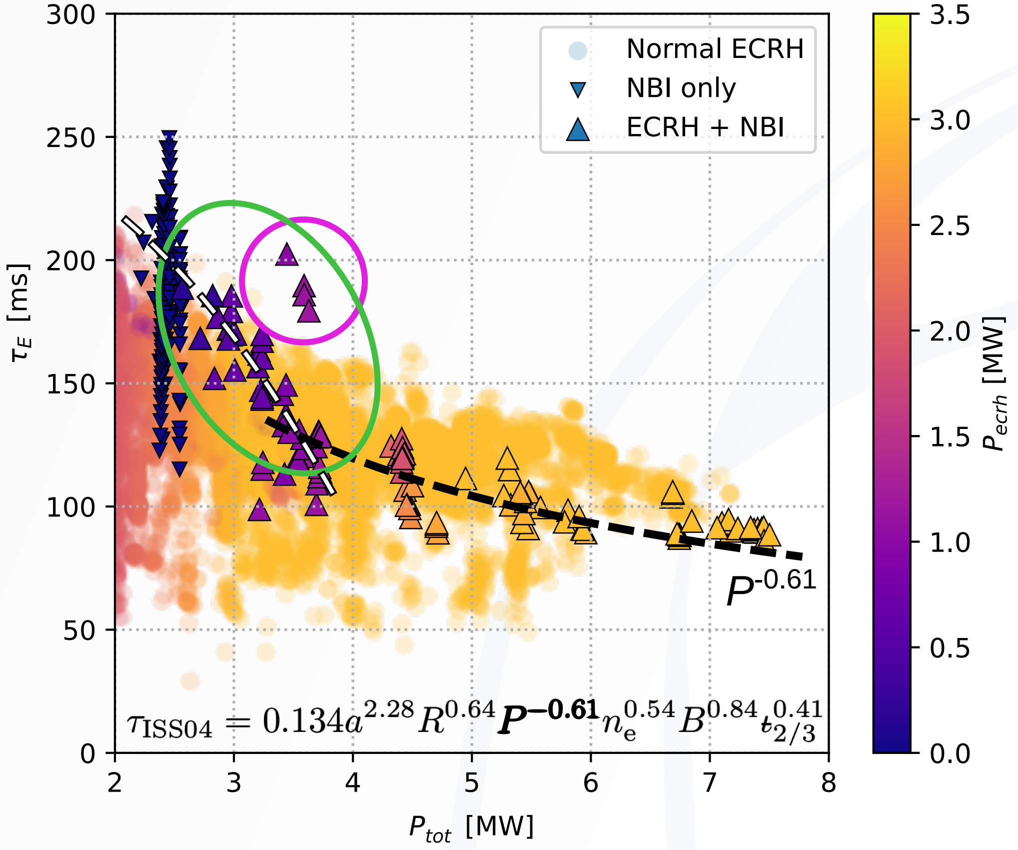
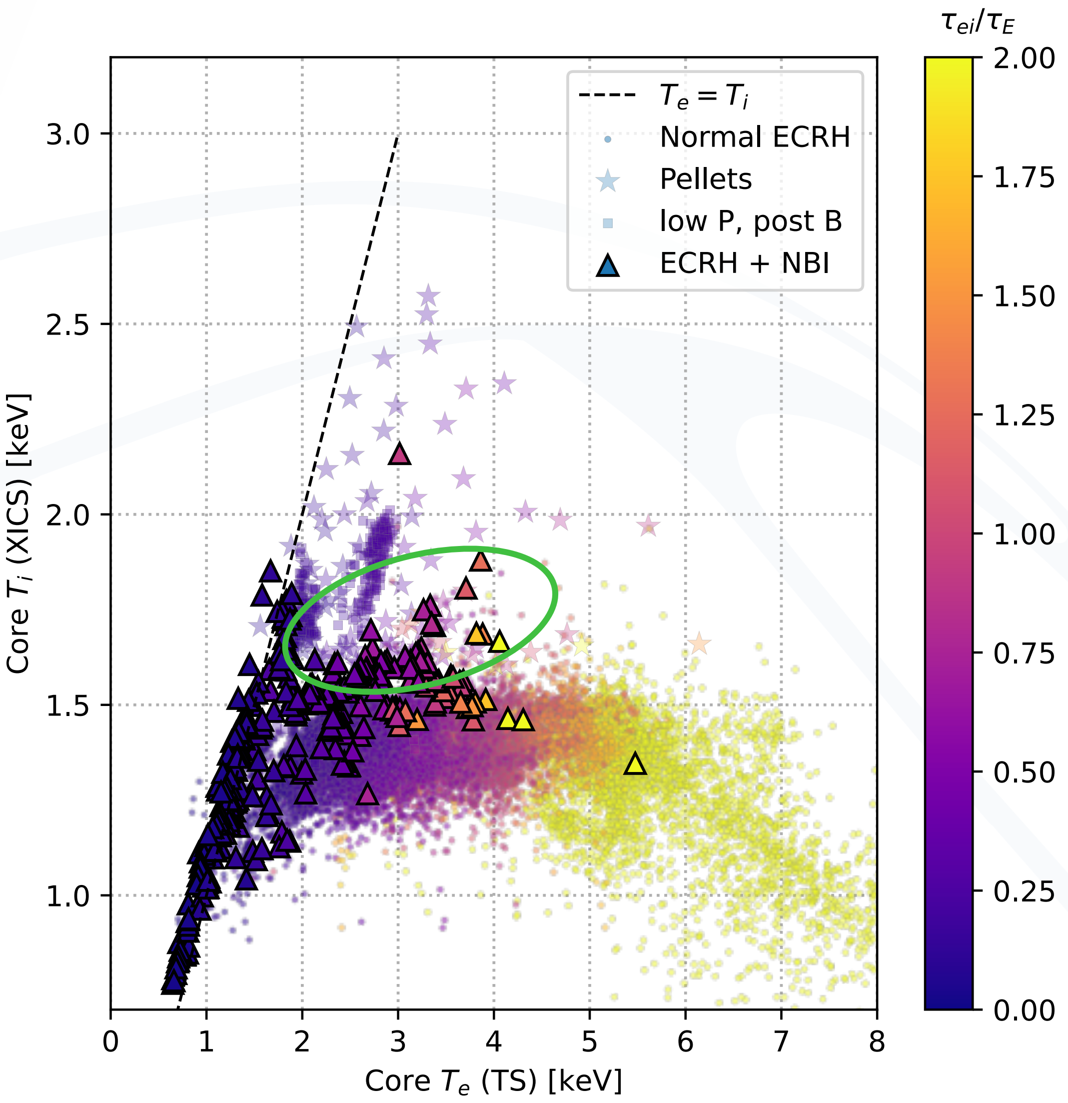
- Highest stationary T_i above clamping with NBI + 1MW ECRH.

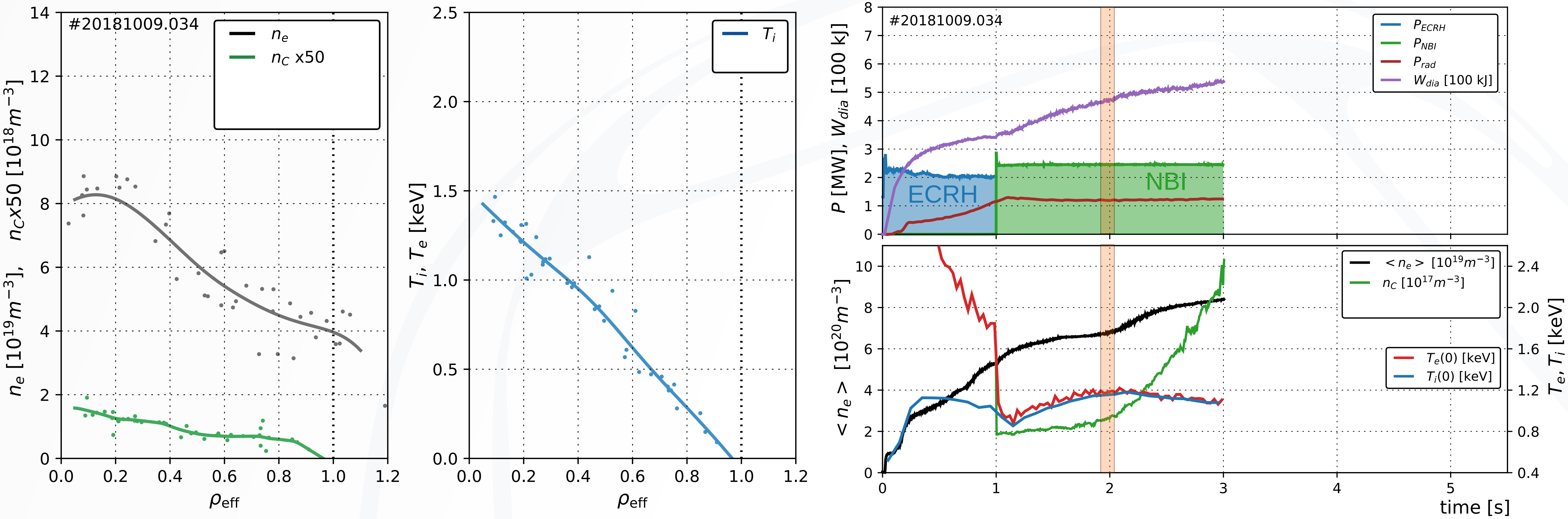




Mixed heating experiments

1: ECRH startup, switch to NBI only. Initial NBI phase shows moderate density peaking.

2: Density rise in $\rho < 0.5$ accelerates.



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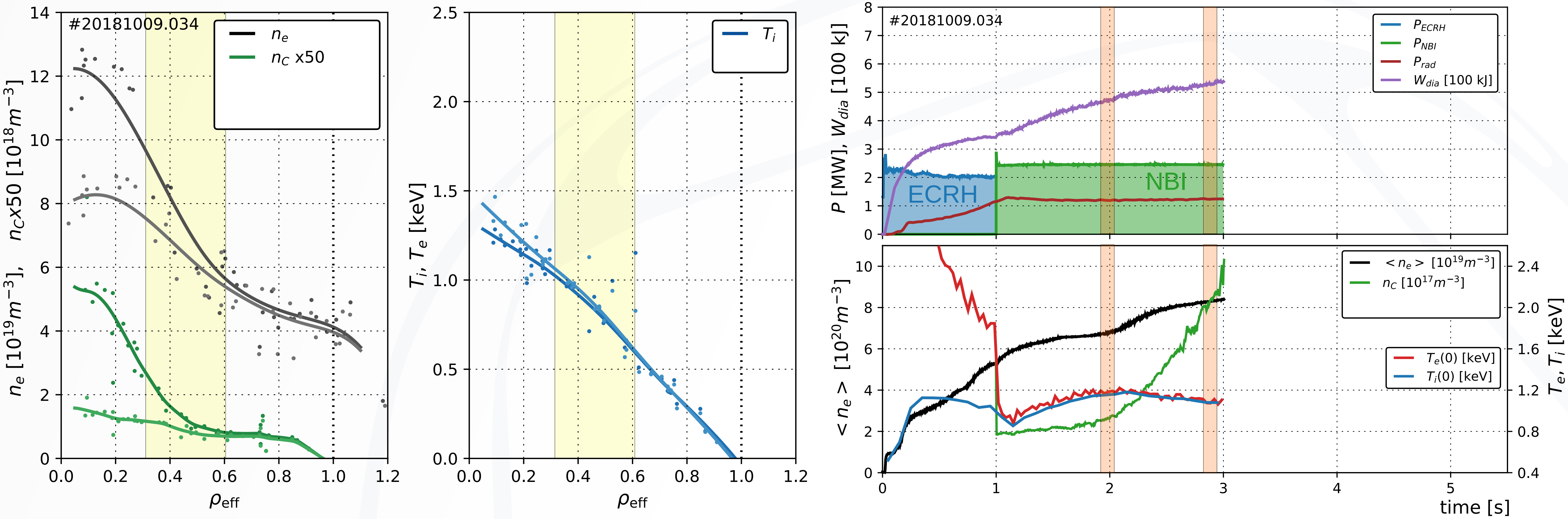

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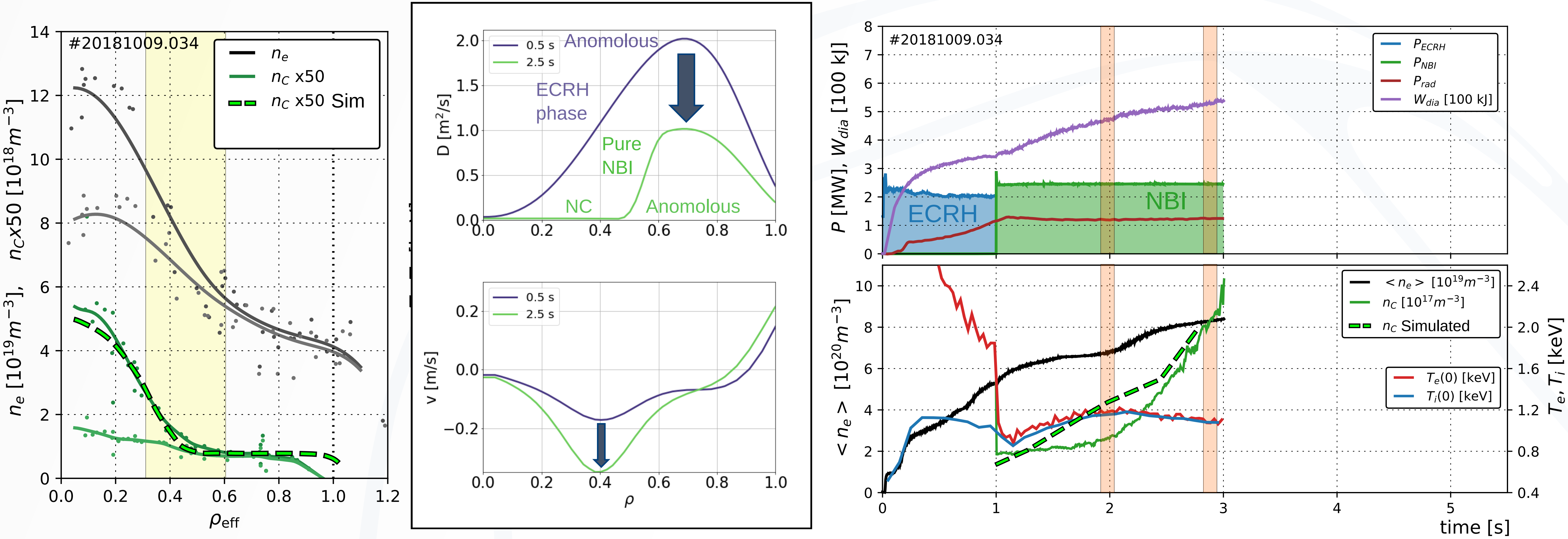

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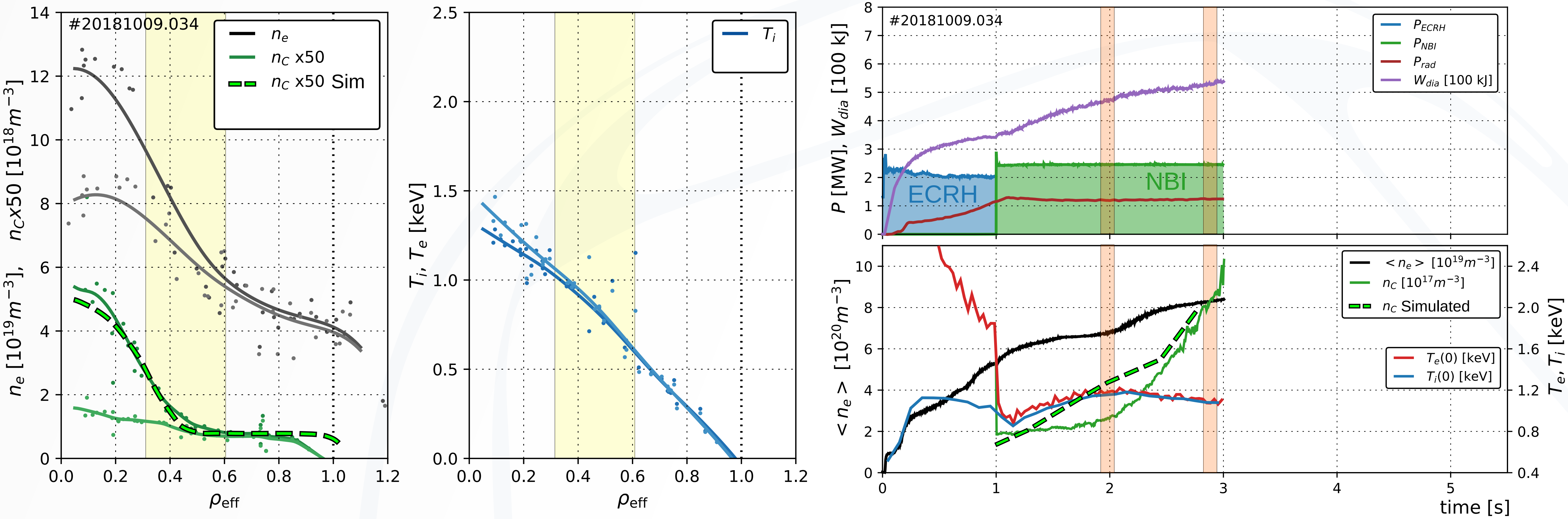

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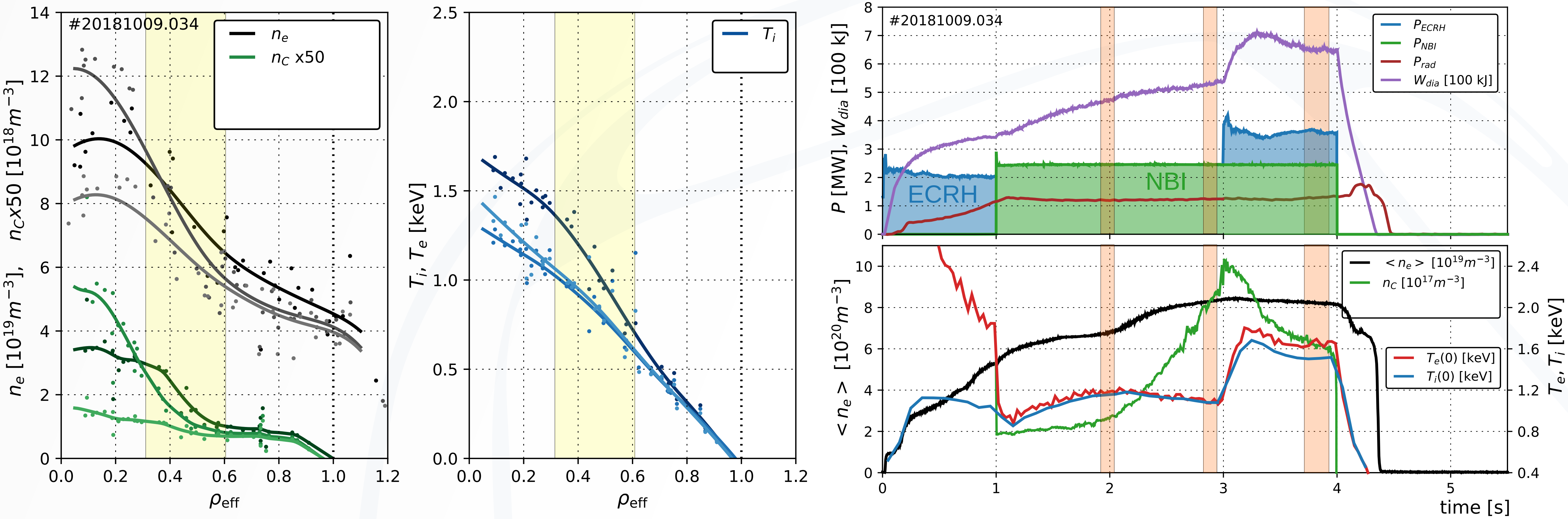

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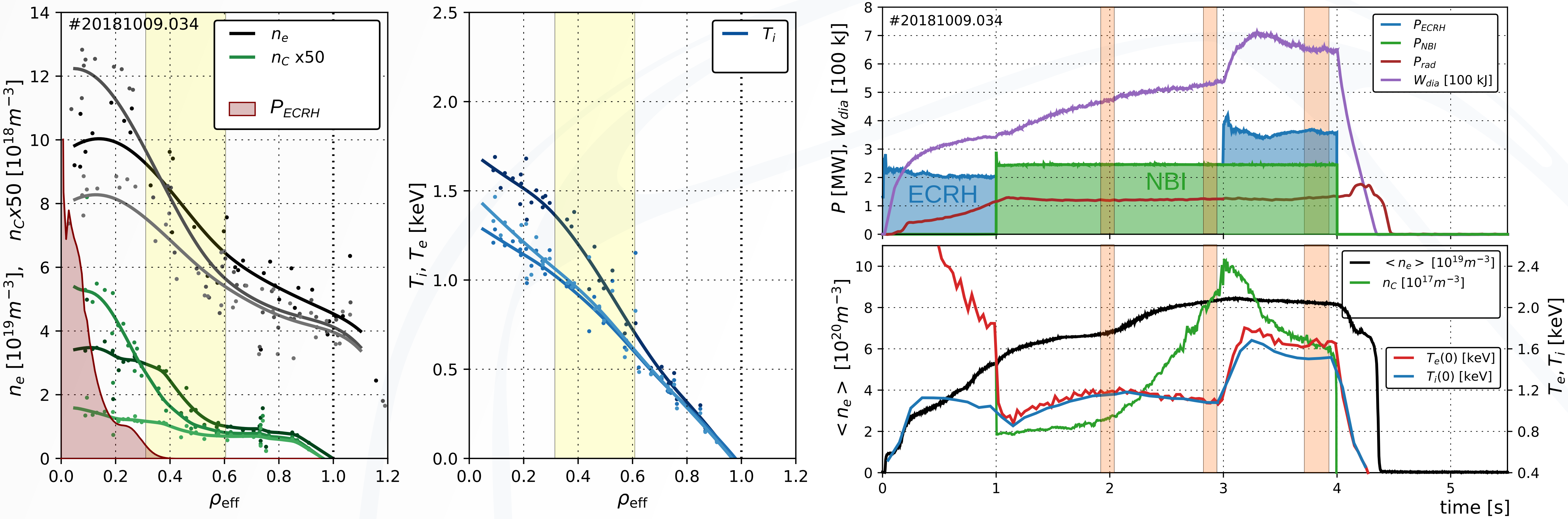
3: Add 1MW O2-mode ECRH raises temperature, slightly reduces density peaking and flattens impurity profile in deposition region.



Electron/ion particle transport

- Particle flux reduces to neoclassical level inside mid-radius at onset of peaking.
  --> indicates strong suppression of turbulent flux in plasma core.
- Anomalous particle flux increases again as density gradient builds.
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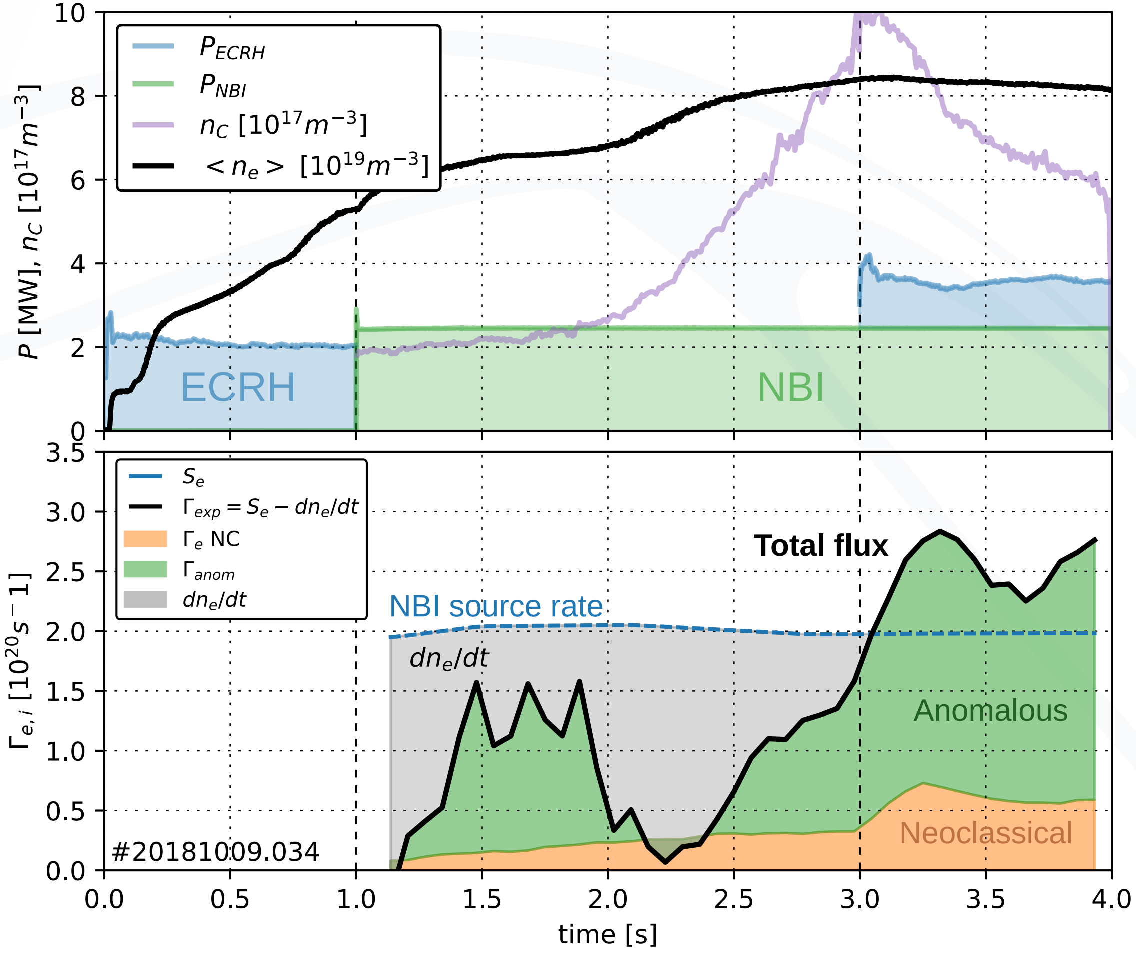

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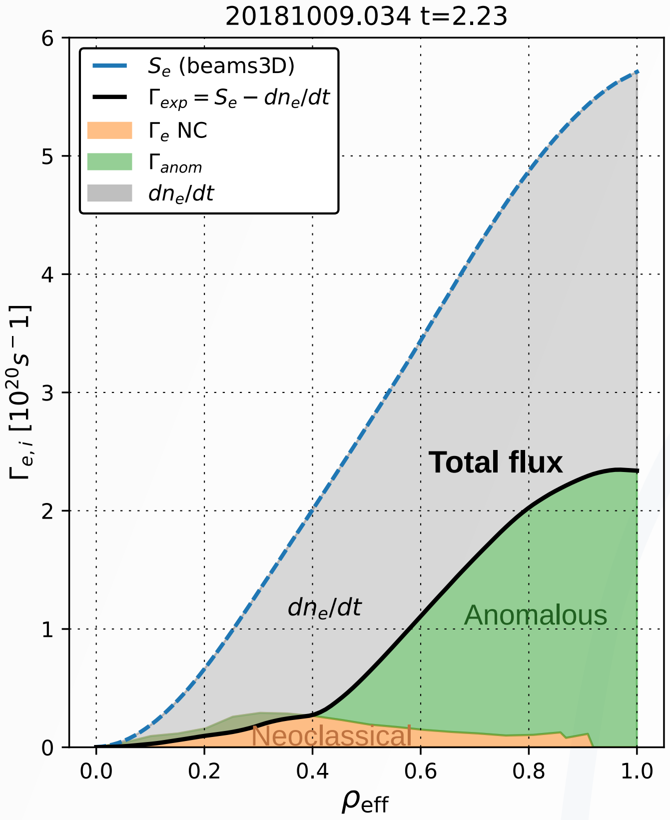

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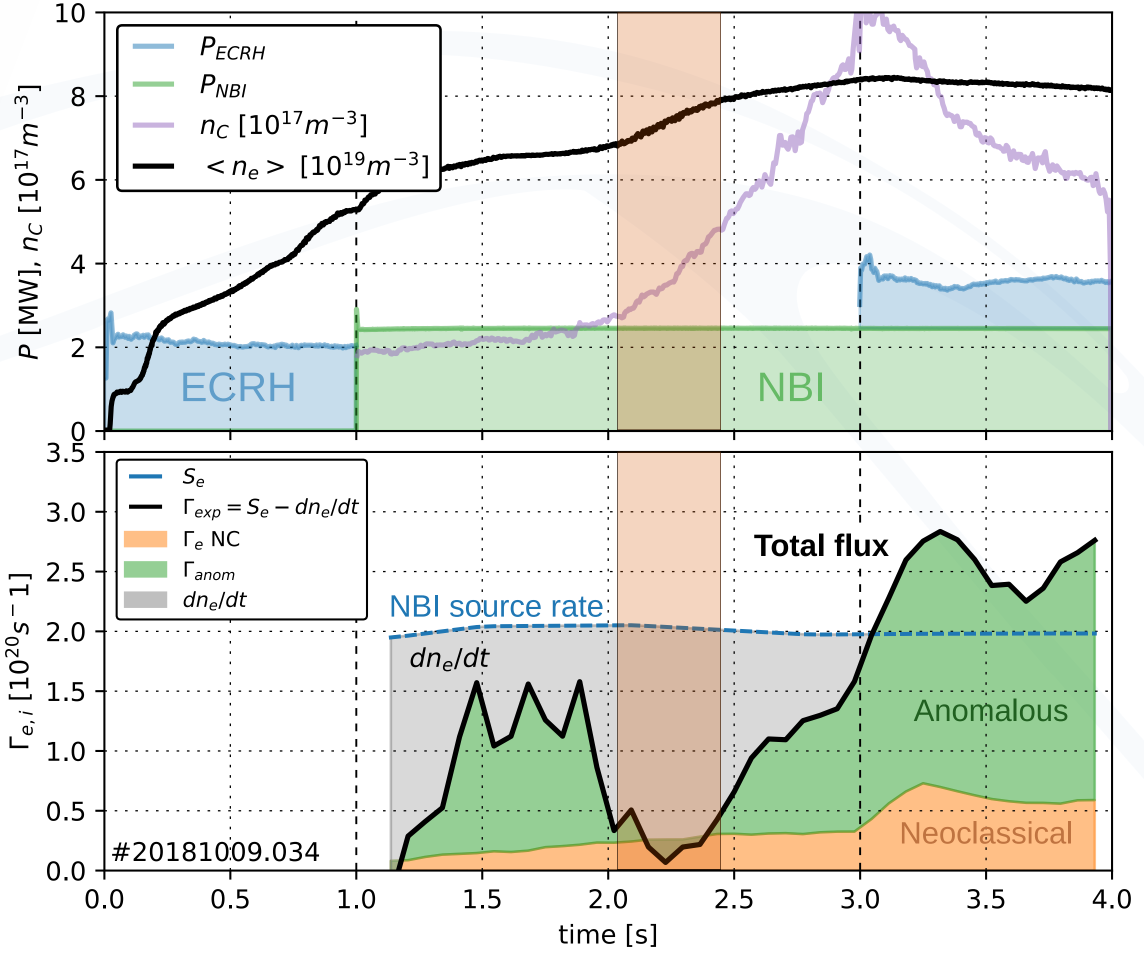

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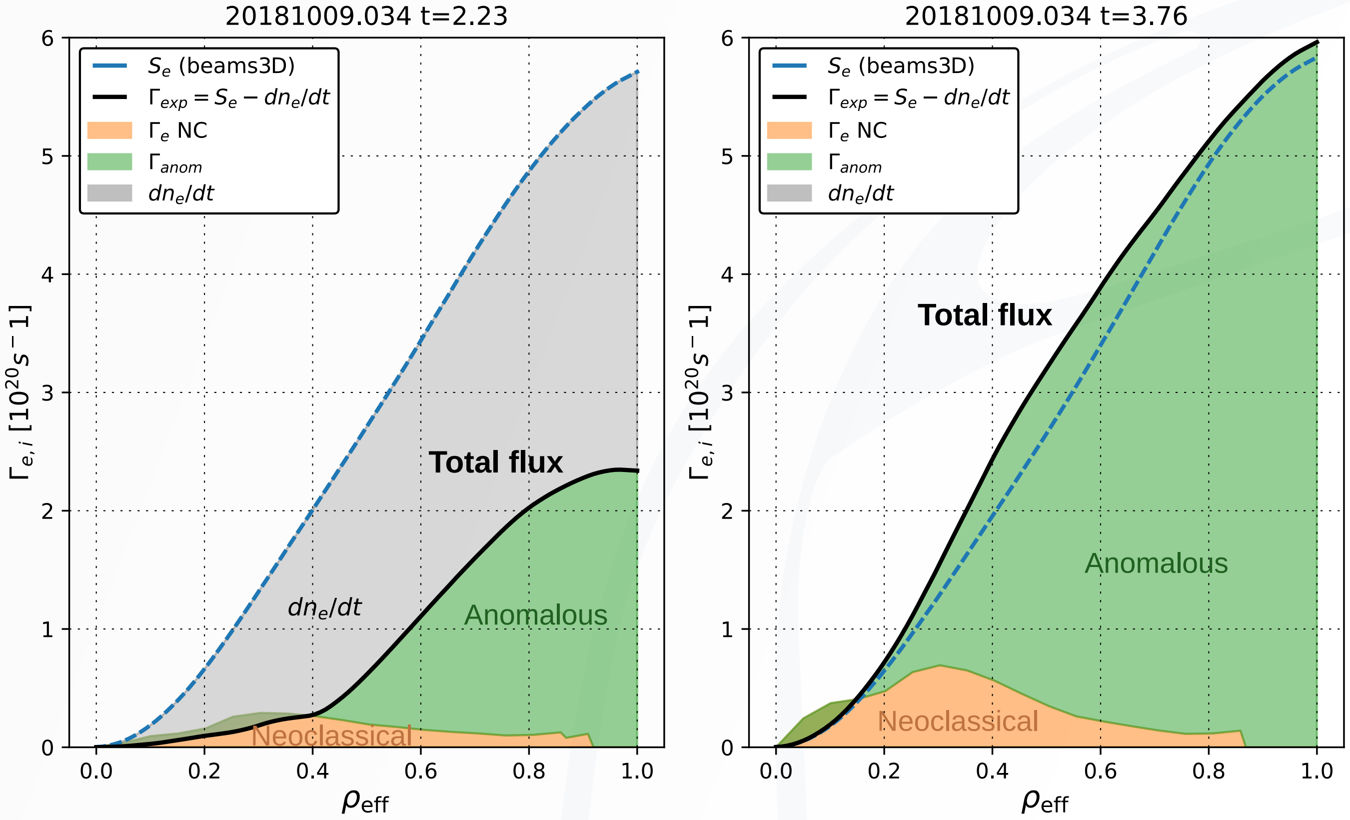

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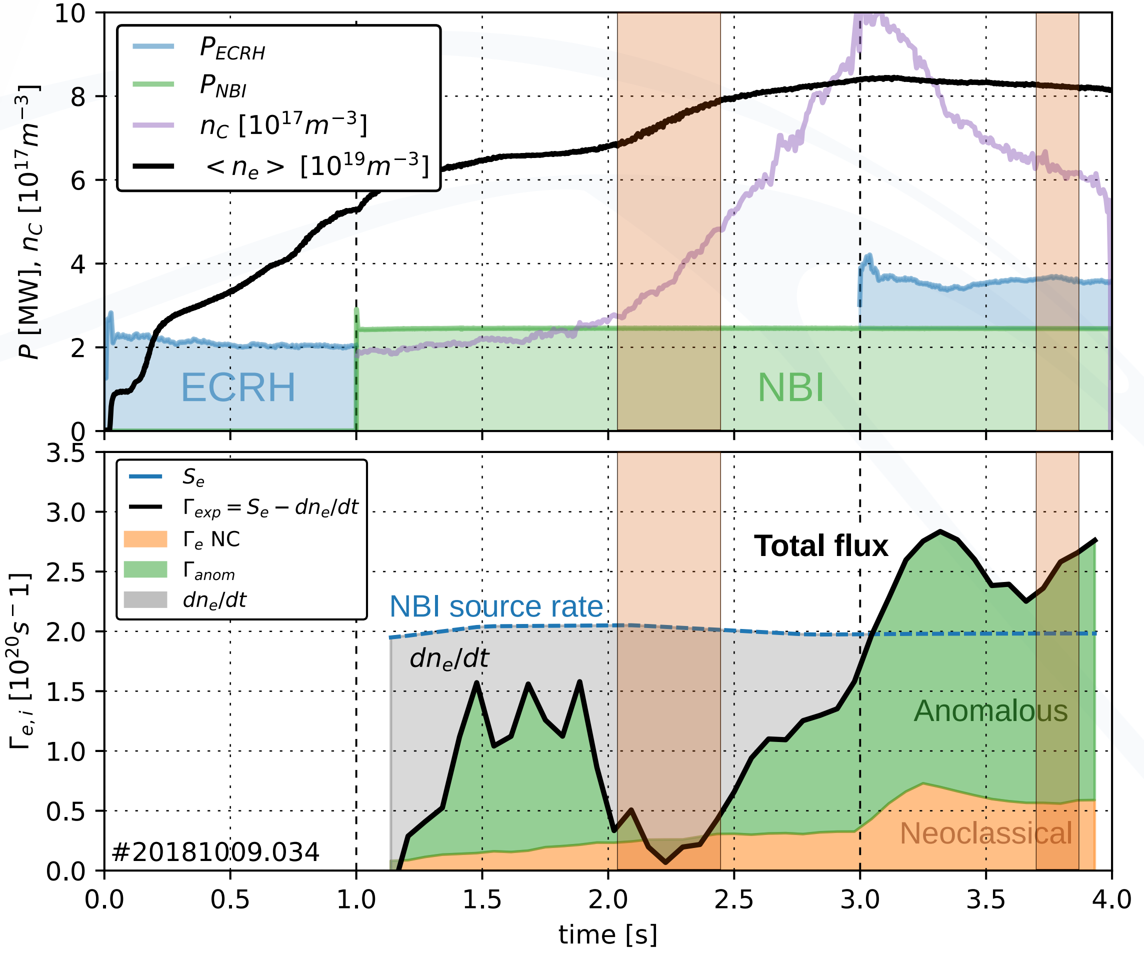

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- High collisionality leads to large P_{ei} with small O(~10eV) differences in T_e, T_i profiles.
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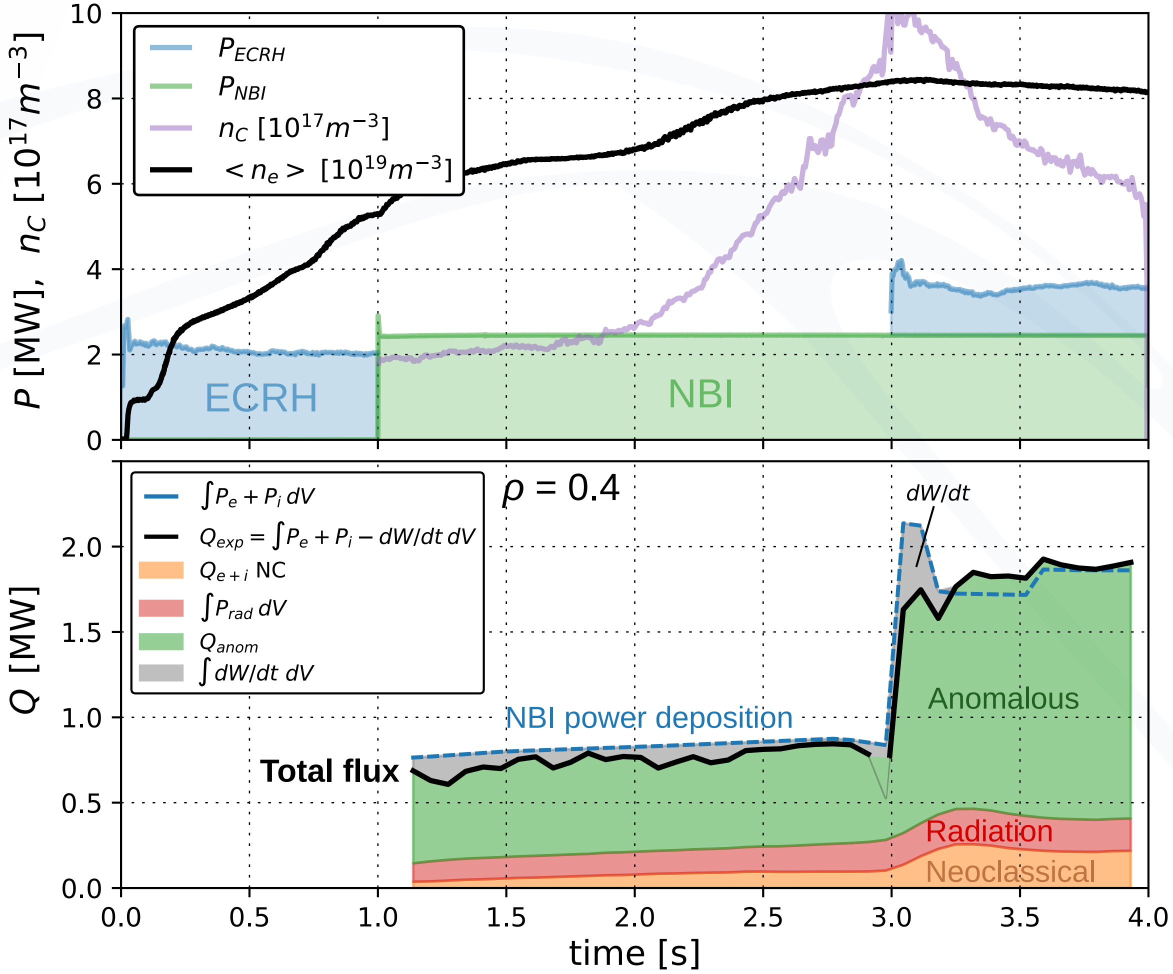

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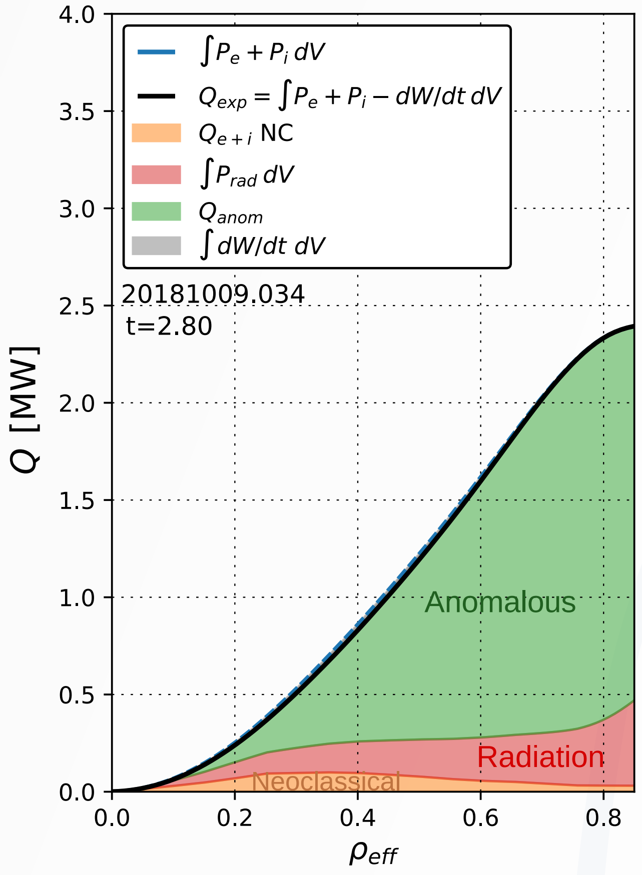

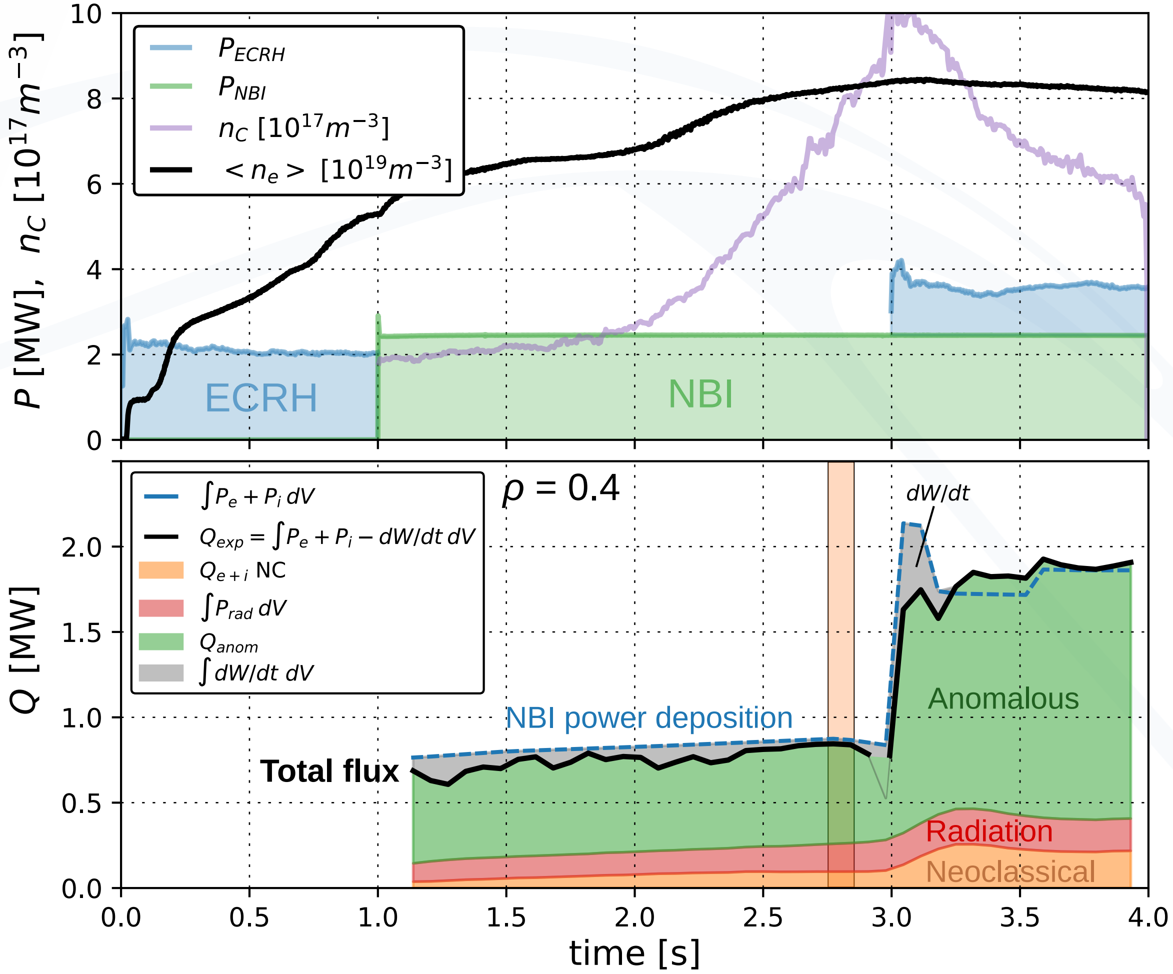

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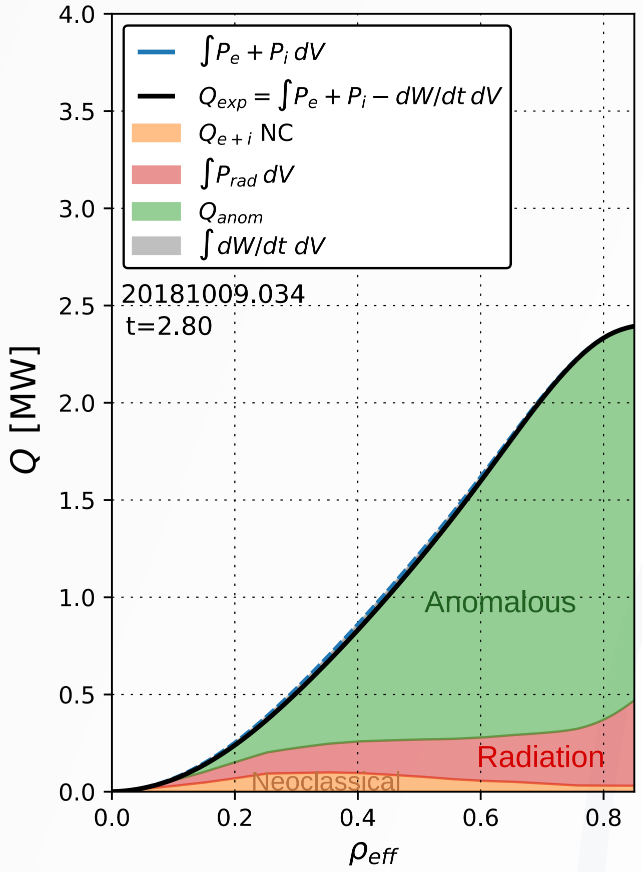
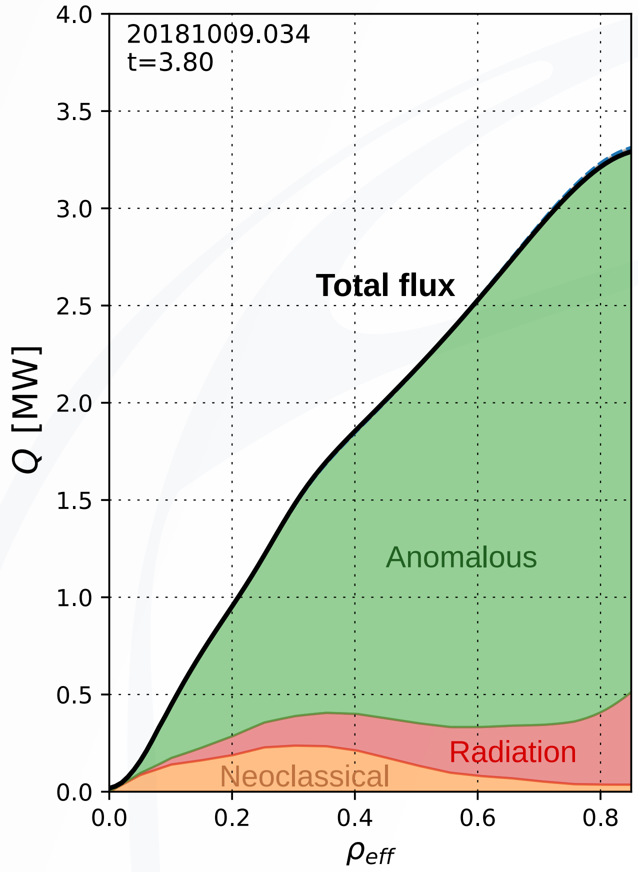
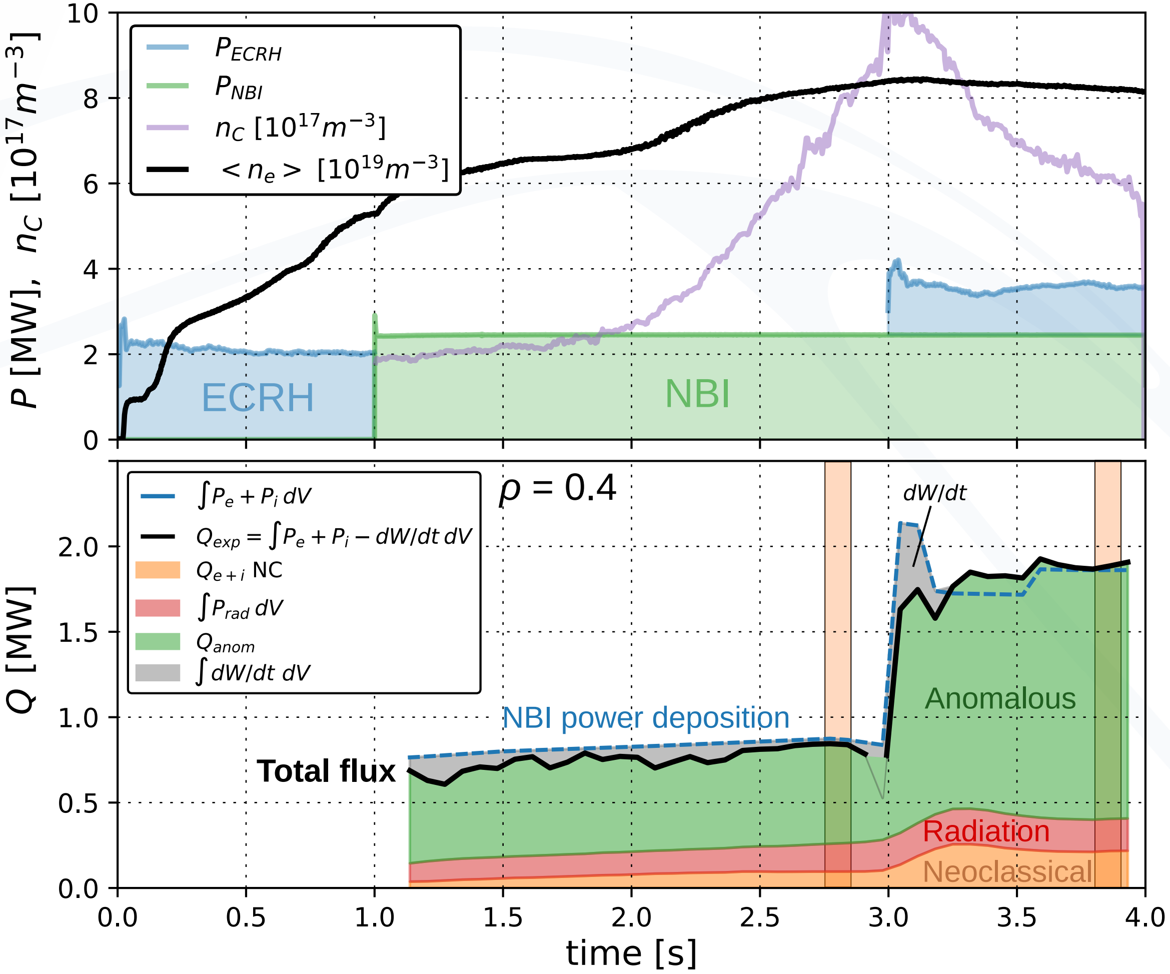
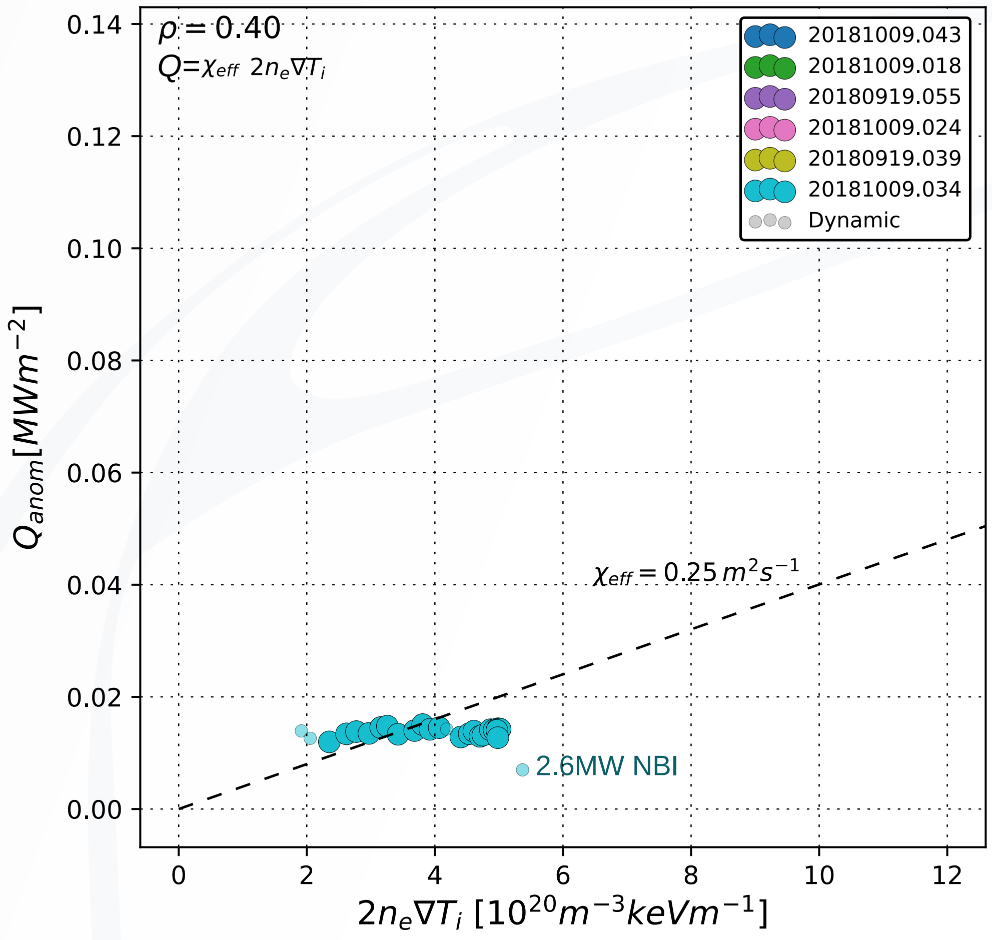


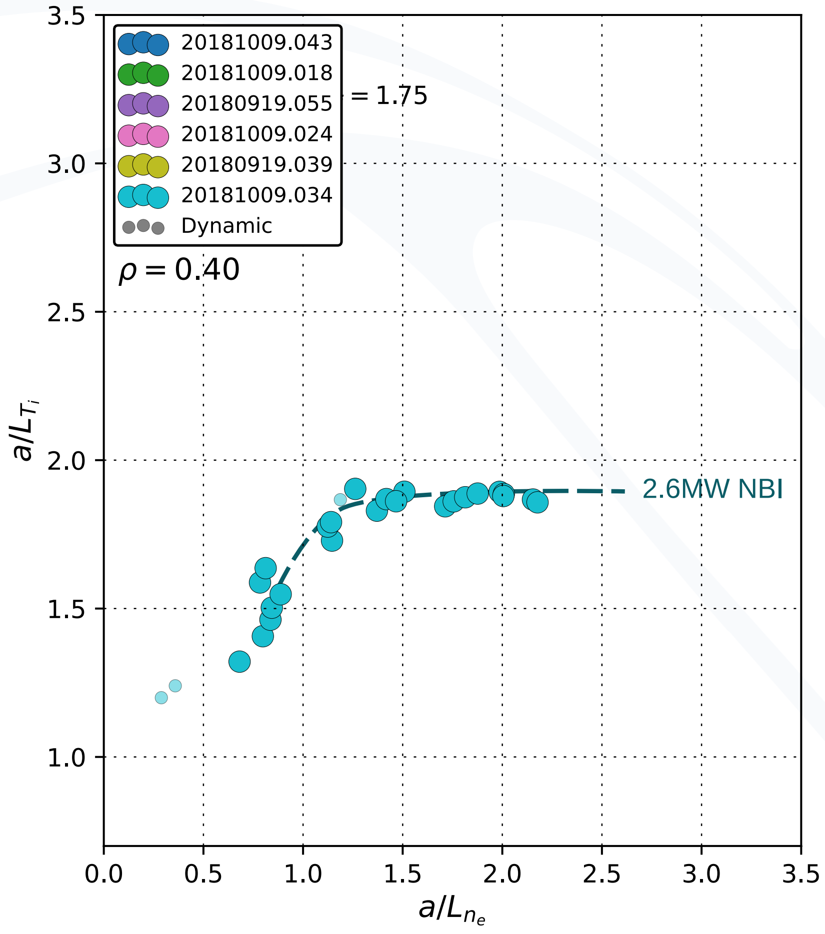




Routes to high confinement

- Density gradient builds during pure NBI phase. $T_{e,i}$ gradients limited by 2.6MW input power.





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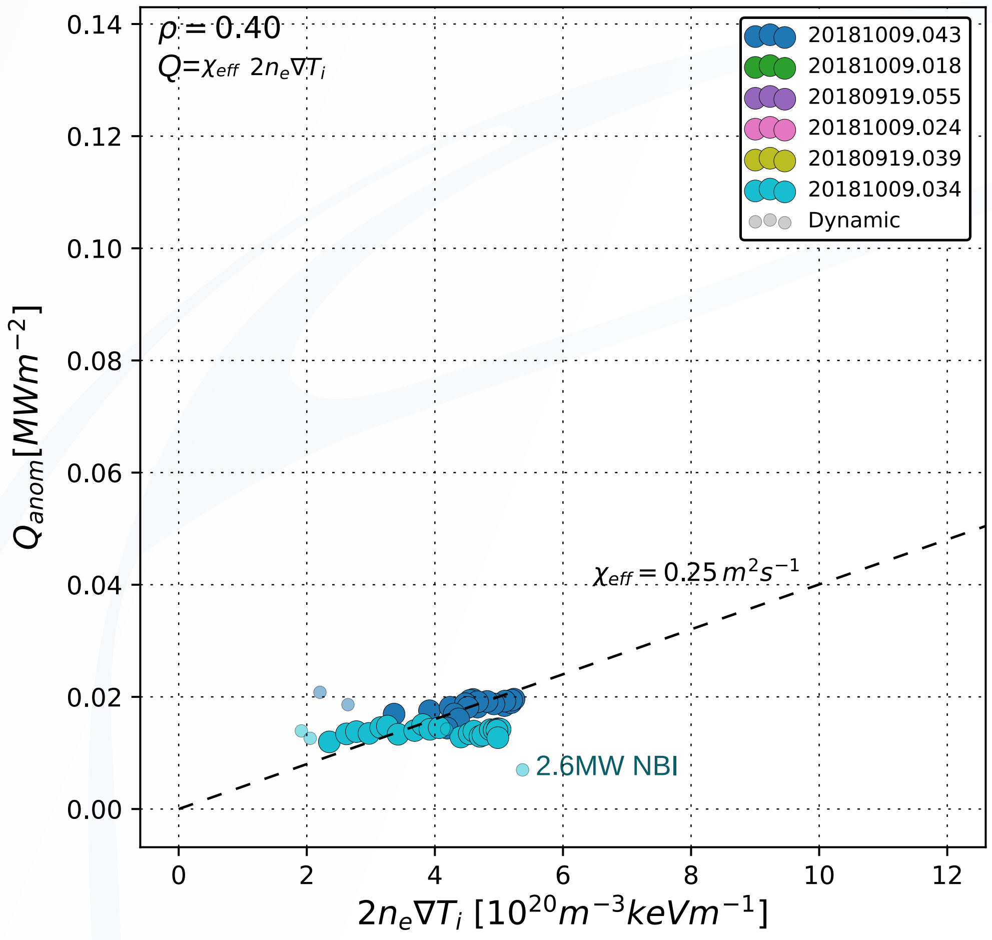

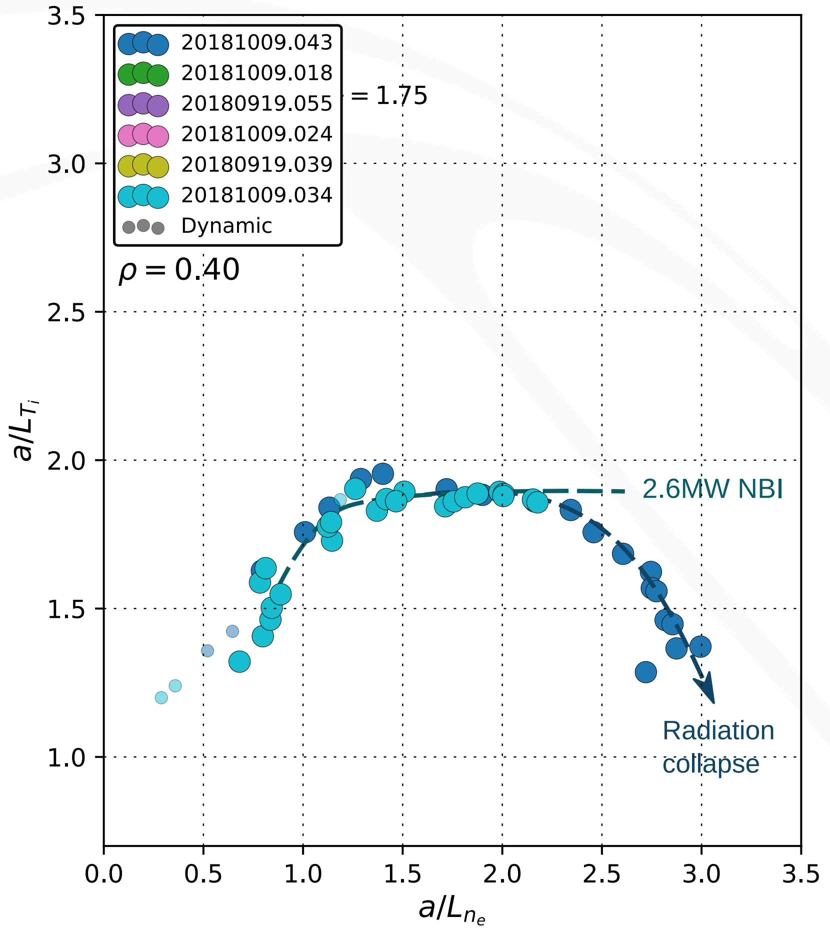

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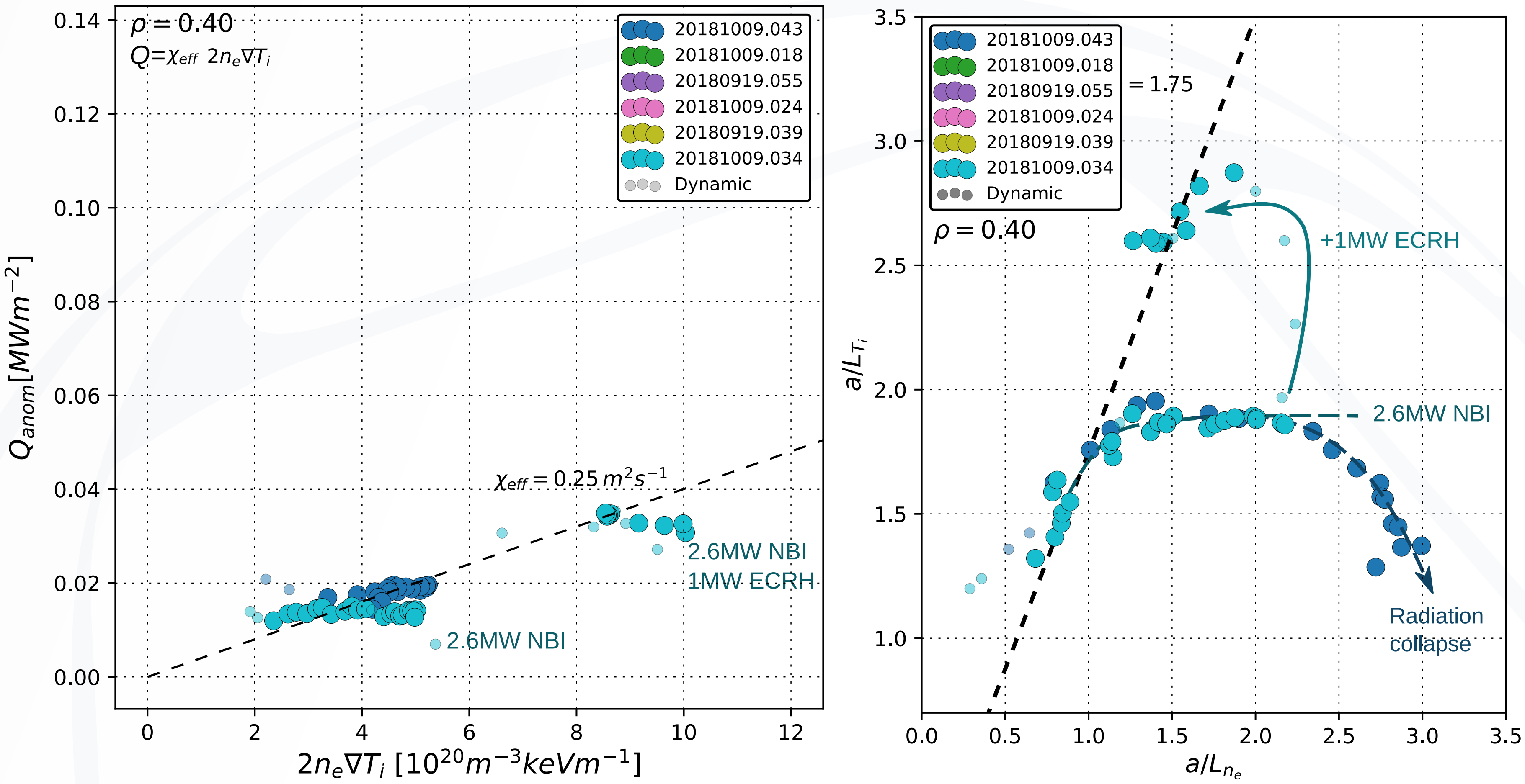

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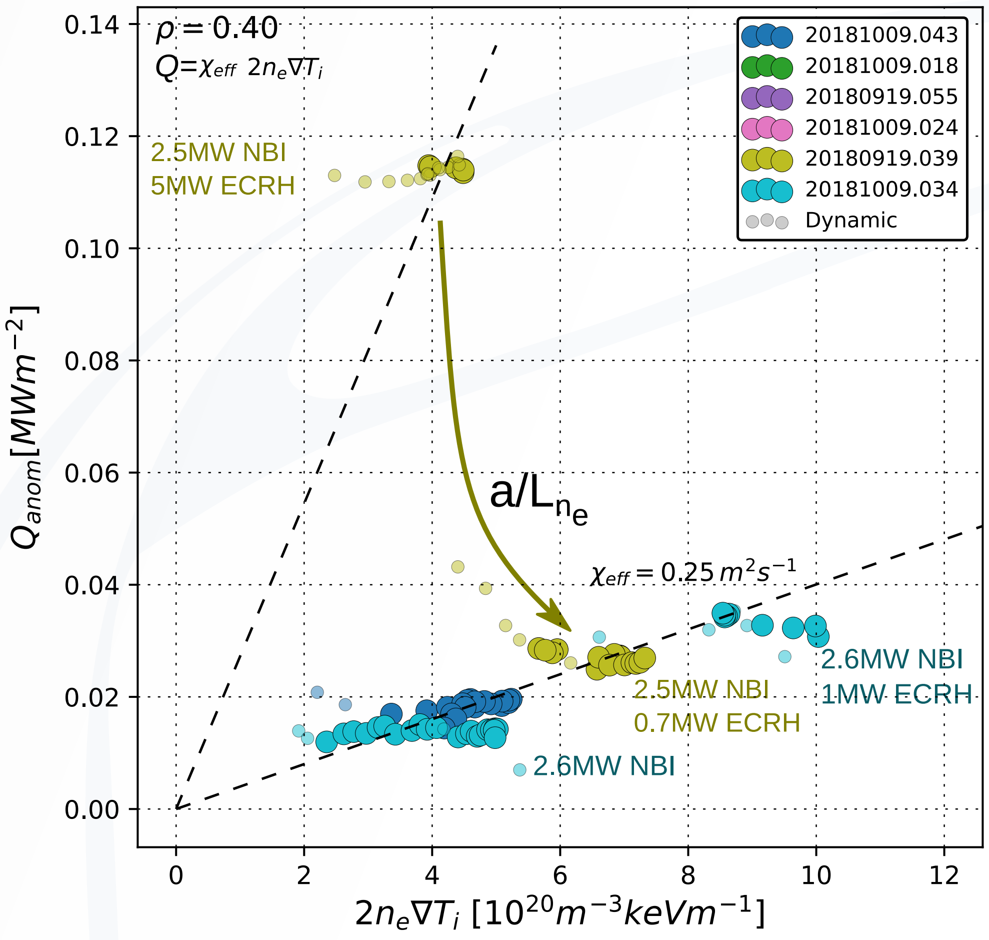

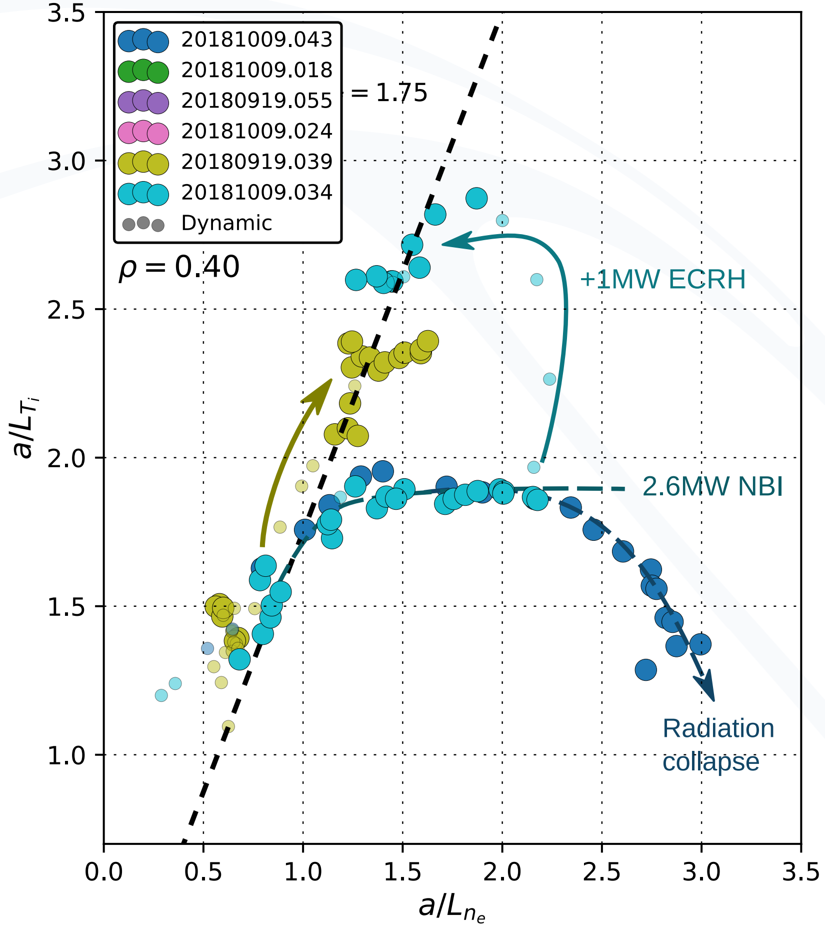

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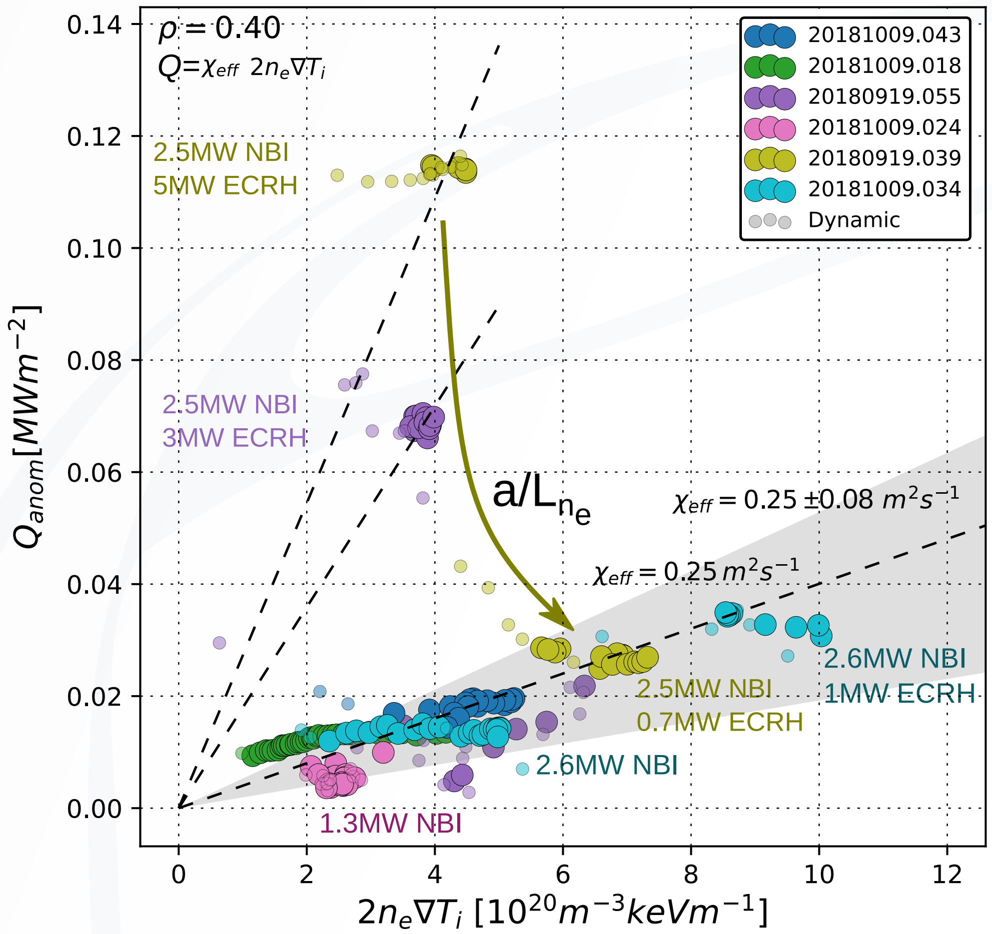

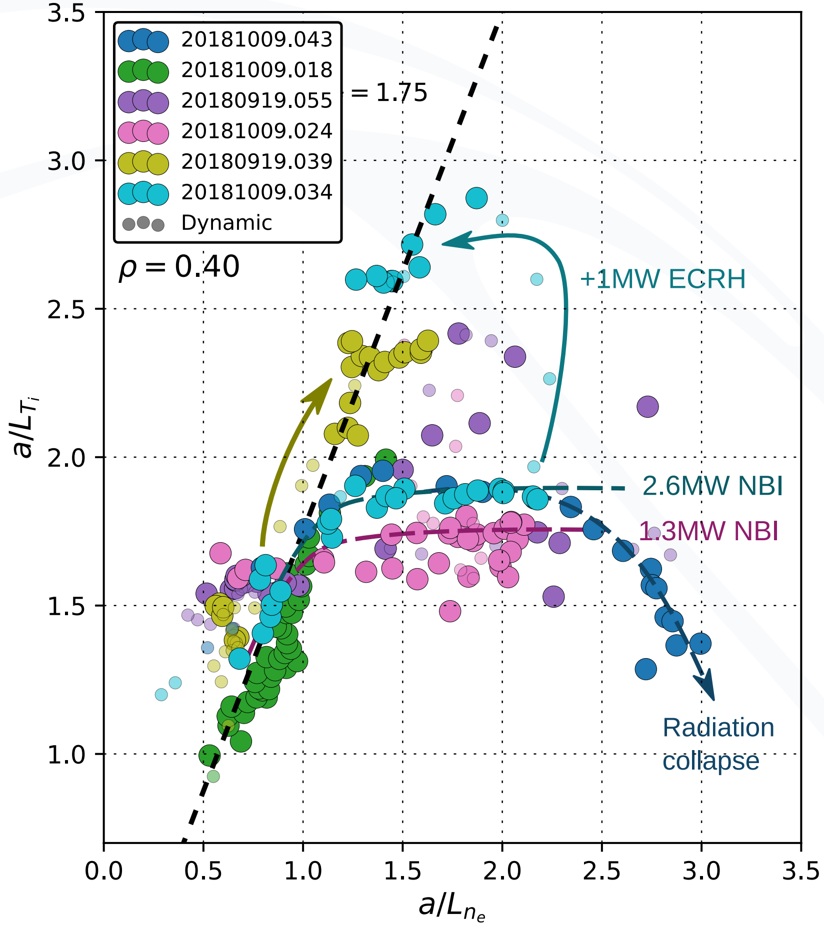

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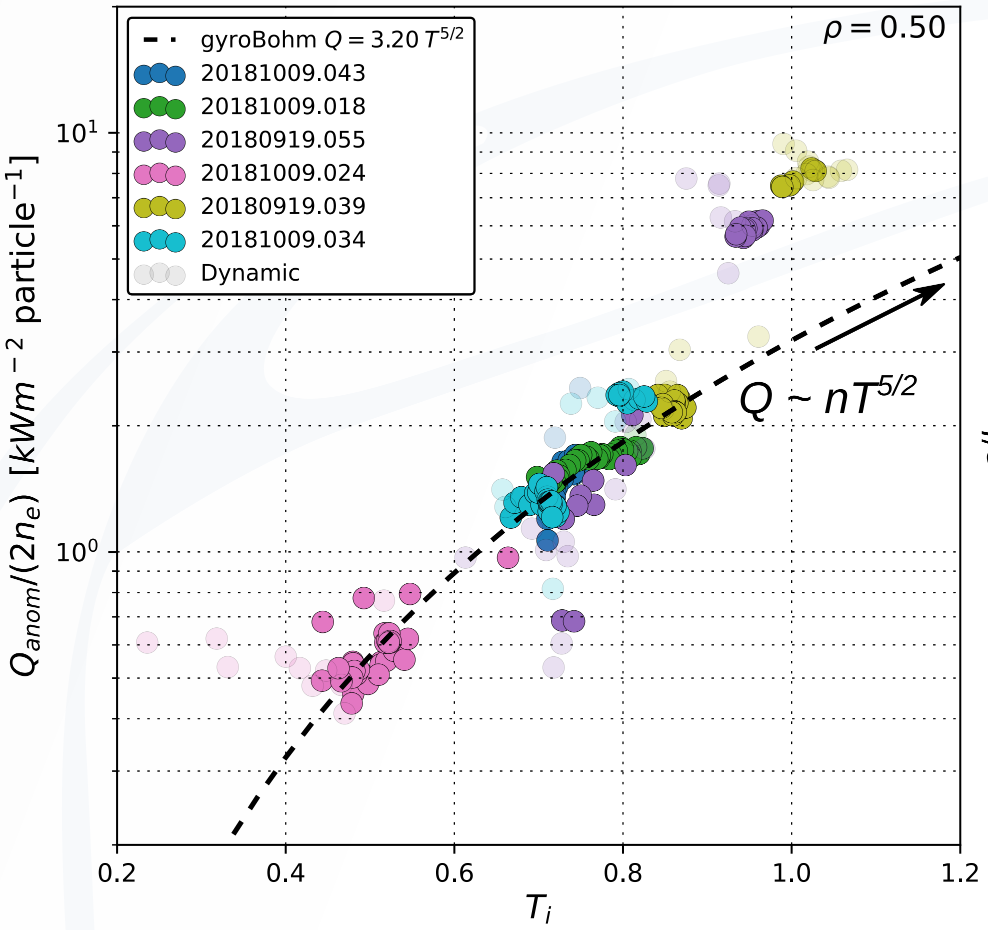

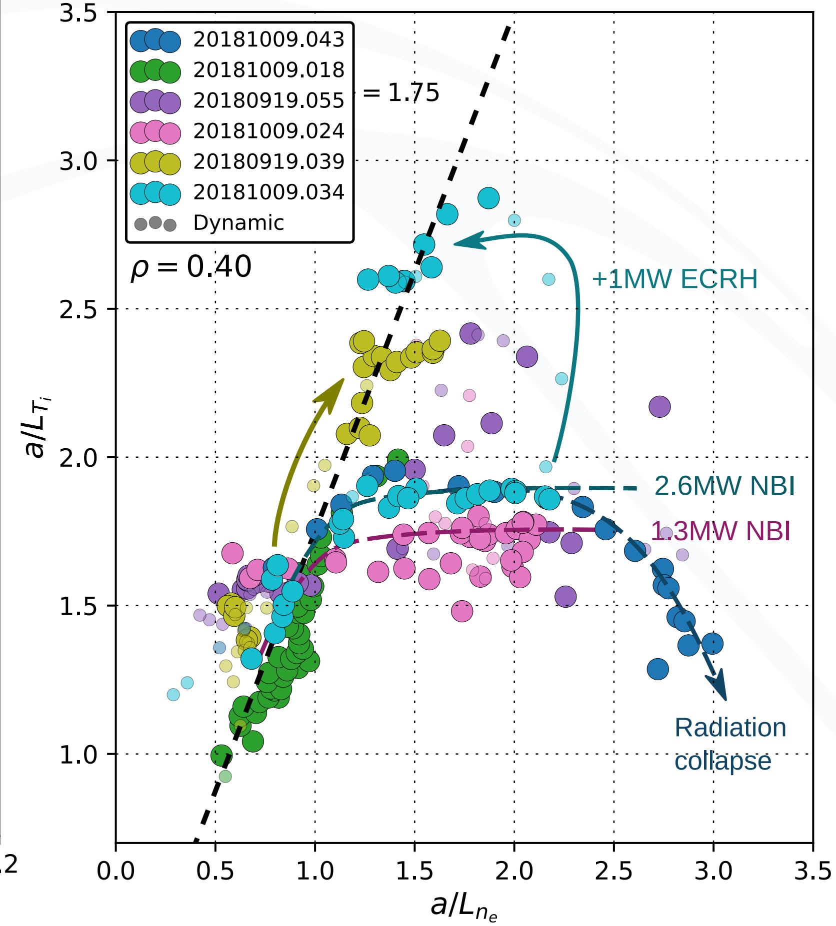

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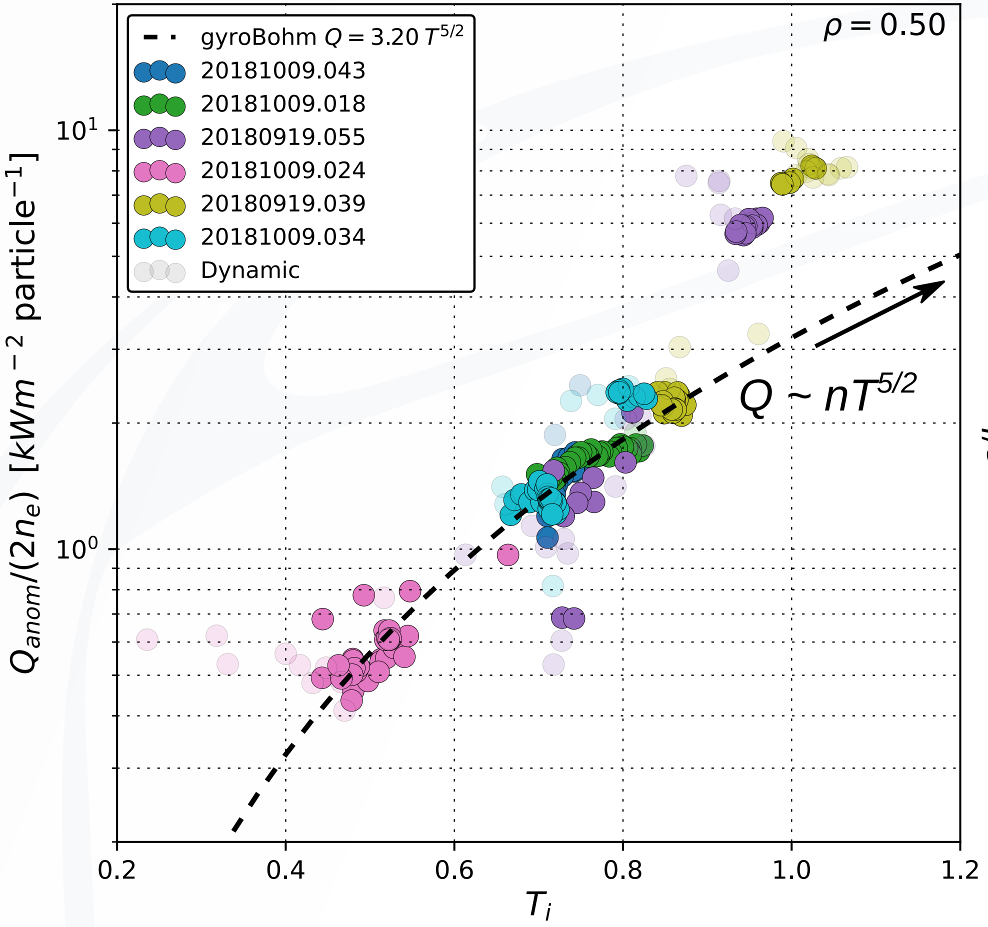
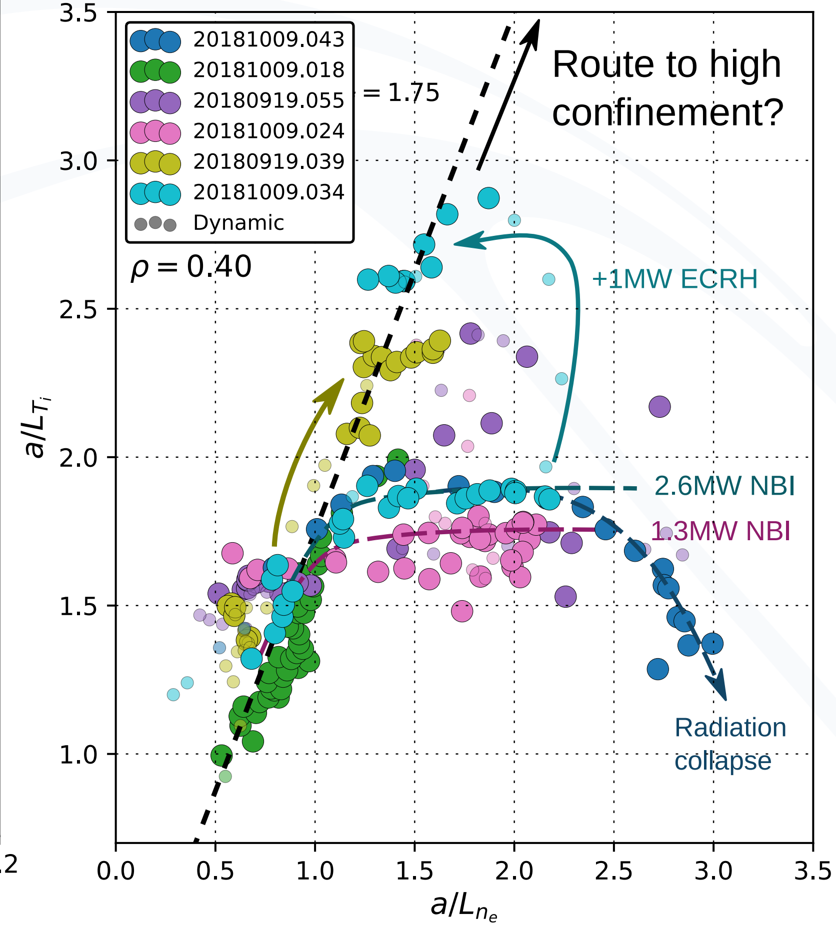
- If density gradient can be maintained, additional NBI power may lead to high n_e, high T_i plasmas.





Routes to high confinement

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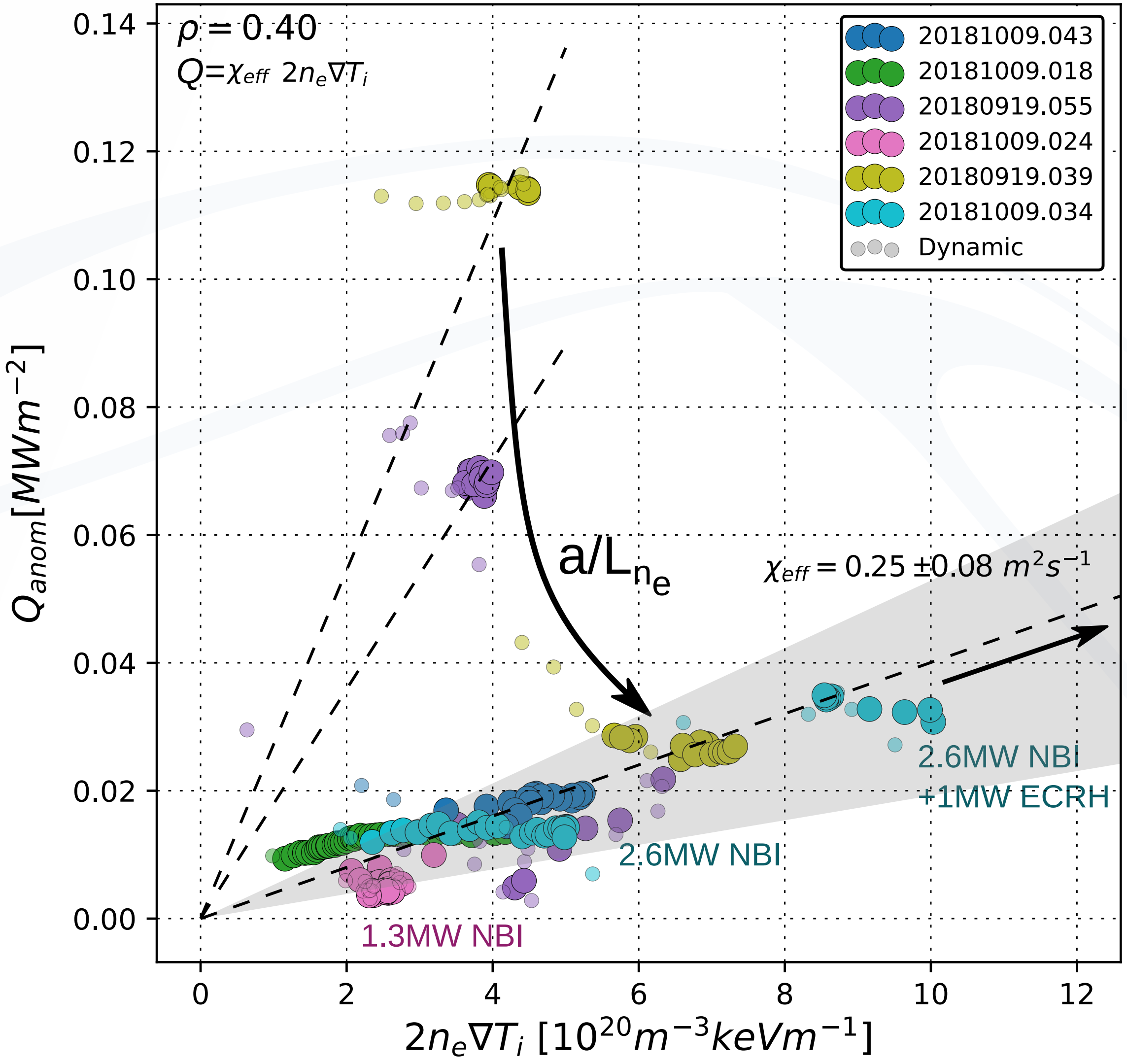

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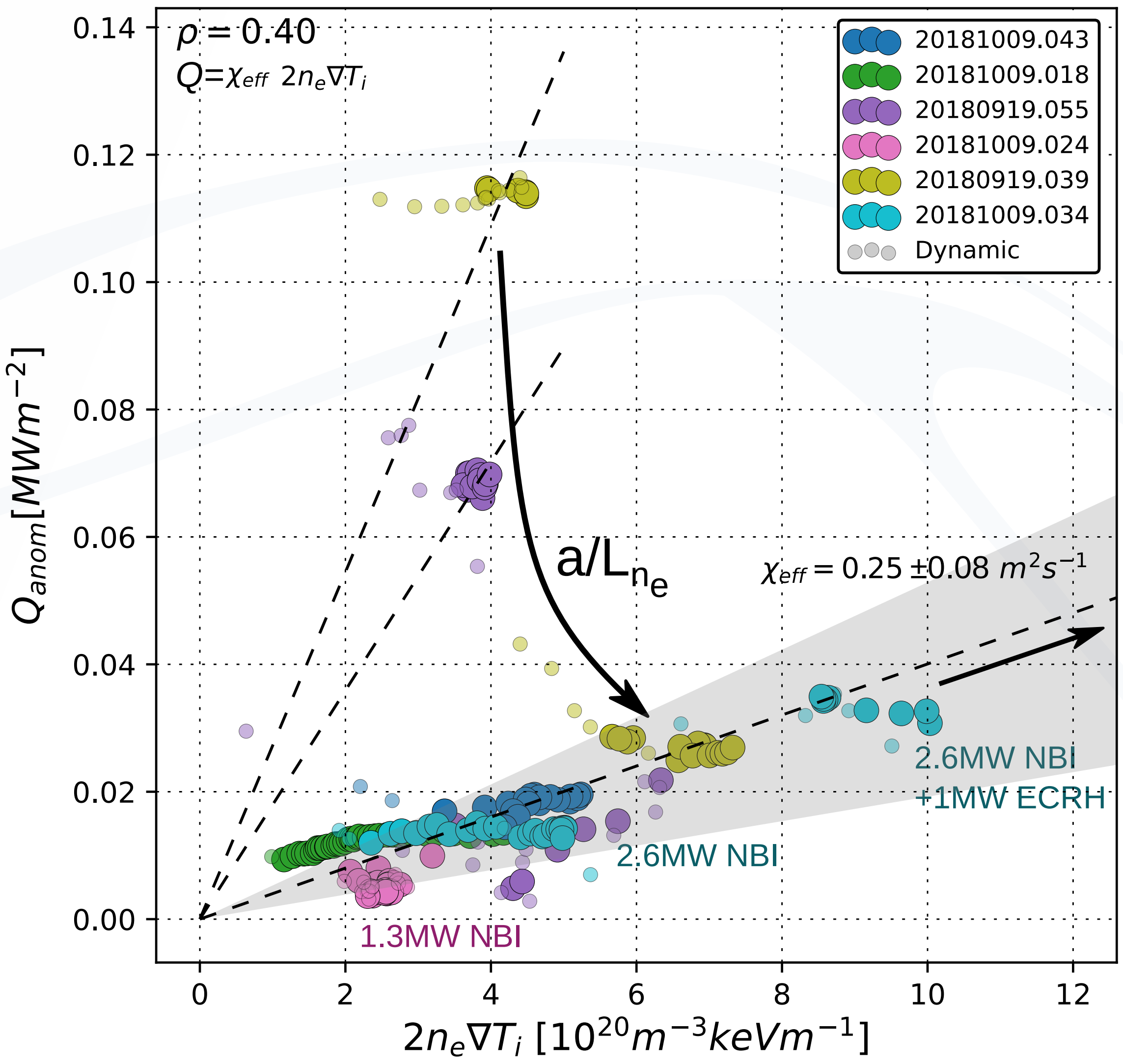

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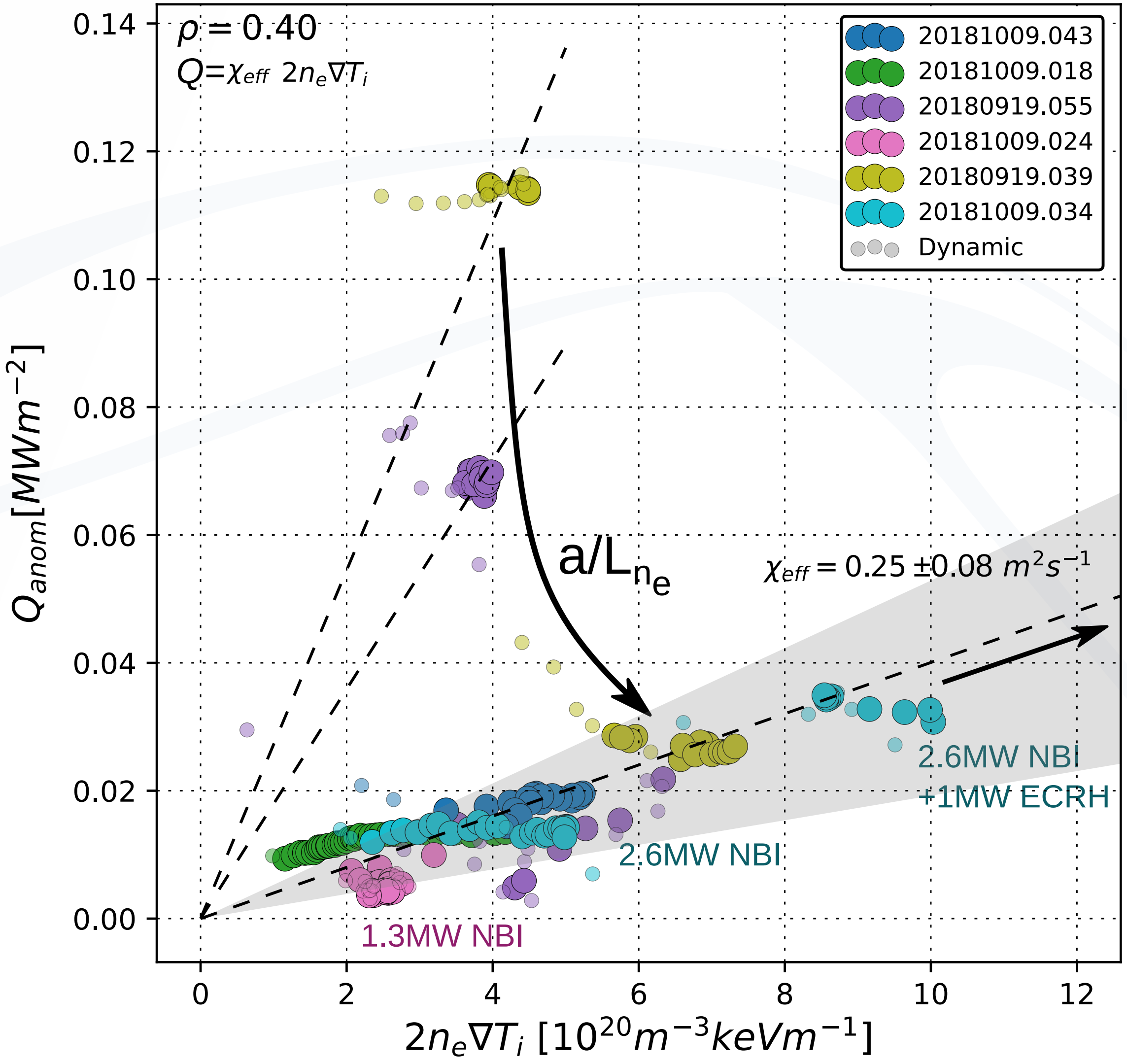
Open questions for 2022/3 campaign:
- Increase NBI power. What happens to a/Ln_e?
- Why does a/Ln_e decrease with ECRH?
- Can sufficient a/Ln_e be maintained while flushing out impurities?



Summary and outlook

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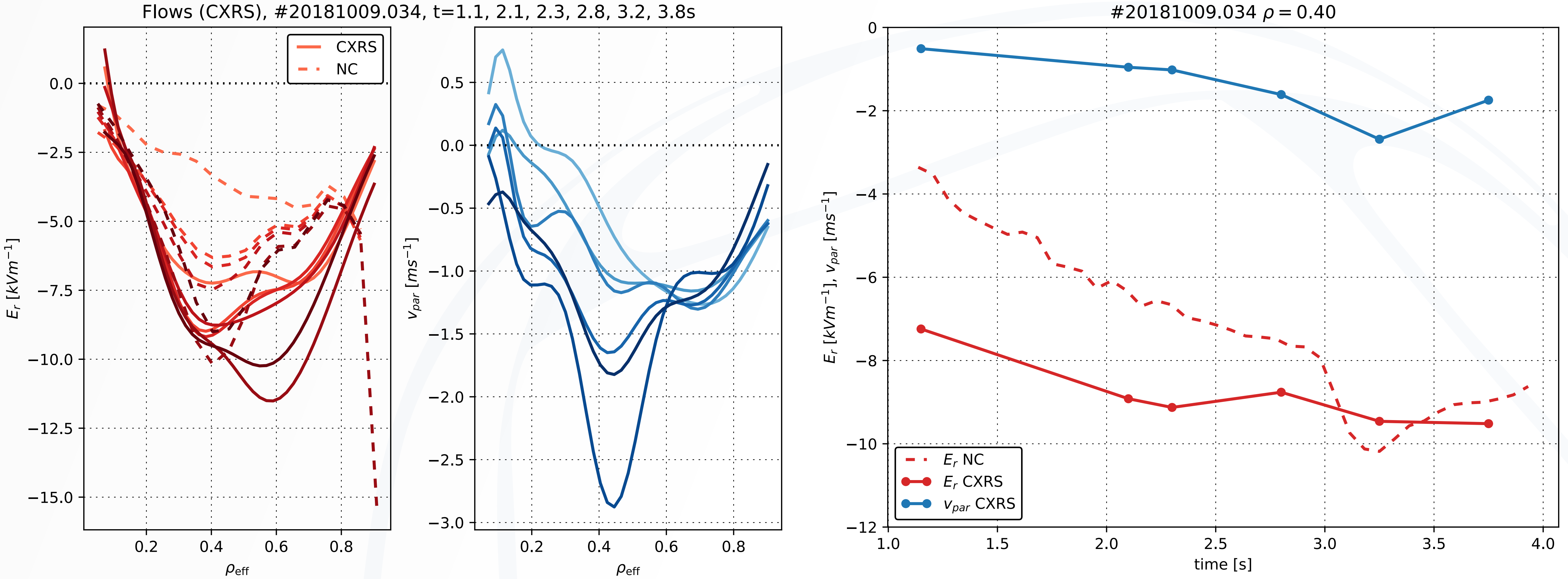
Upgrades for the 2023 campaign:

- Steady state pellet injection - Explore pellets scenarios more.
- 2x NBI power - Determine fuelling vs heating scaling.
- Divertor cryo-pumps - Possibly 3x pumping speed. May help reduce edge n_e and increase gradients.
- Additional ECRH+NBI power - expand range to search for L-H transition.
- ICRH (commisioning)*[K. Crombé, this conference]* - explore ITG stabilisation by fast ions *[N. Bonanomi et al, Nucl. Fusion 58 (2018) 056025]*

Radial Electric Field

- E_r affects NC transport and can play a strong role in global transport changes, especially at low collisionality. $T_e >> T_i$ --> 'Electron root'
- NBI discharges all ion root with no significant E_r changes at onset time (measured or NC)



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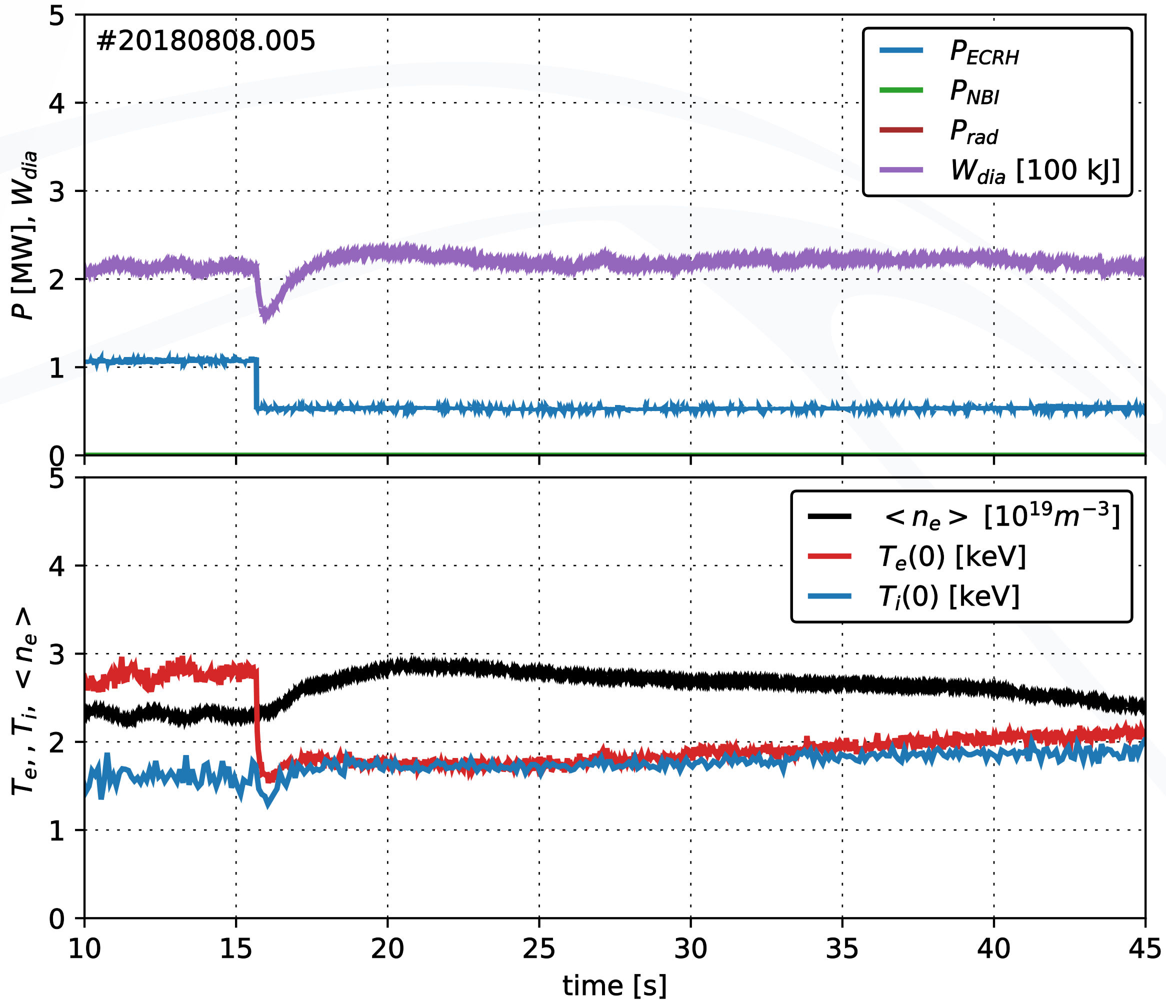

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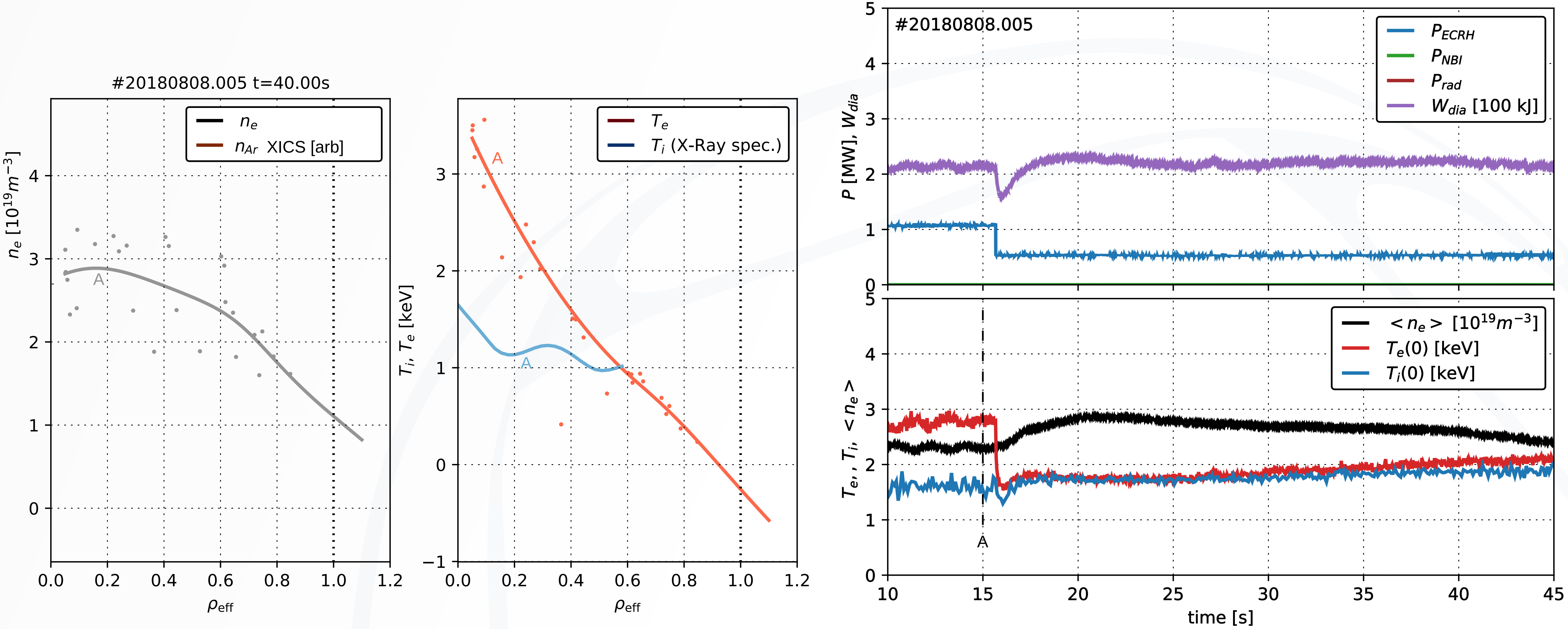

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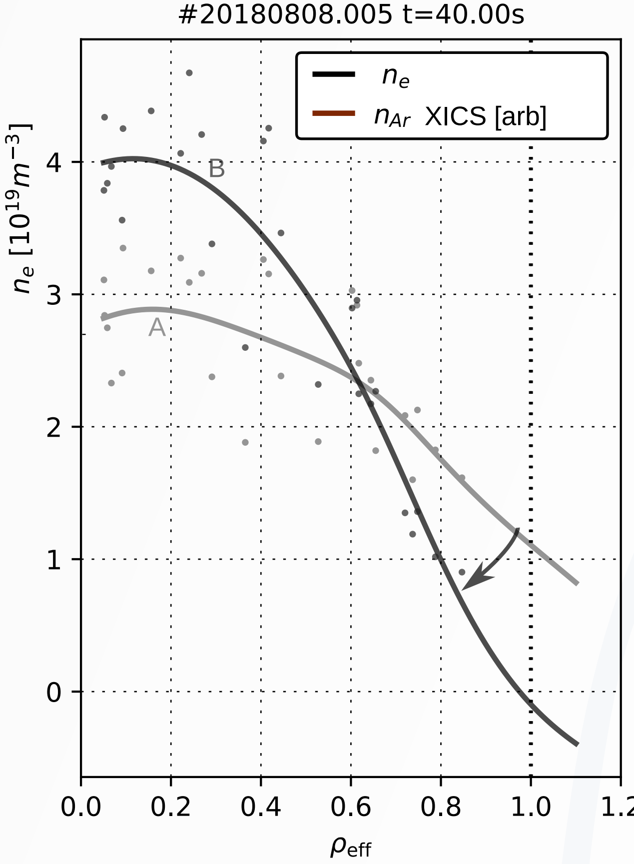

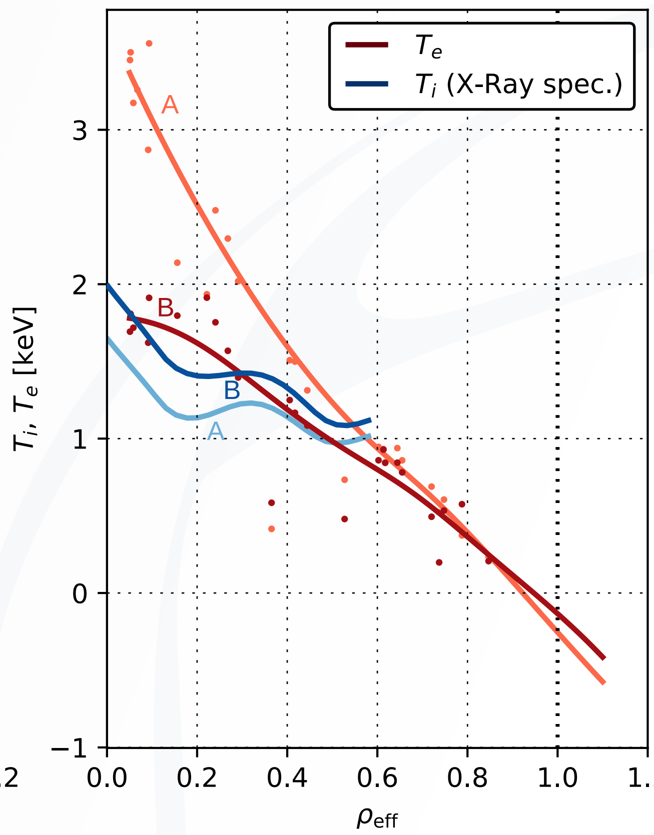

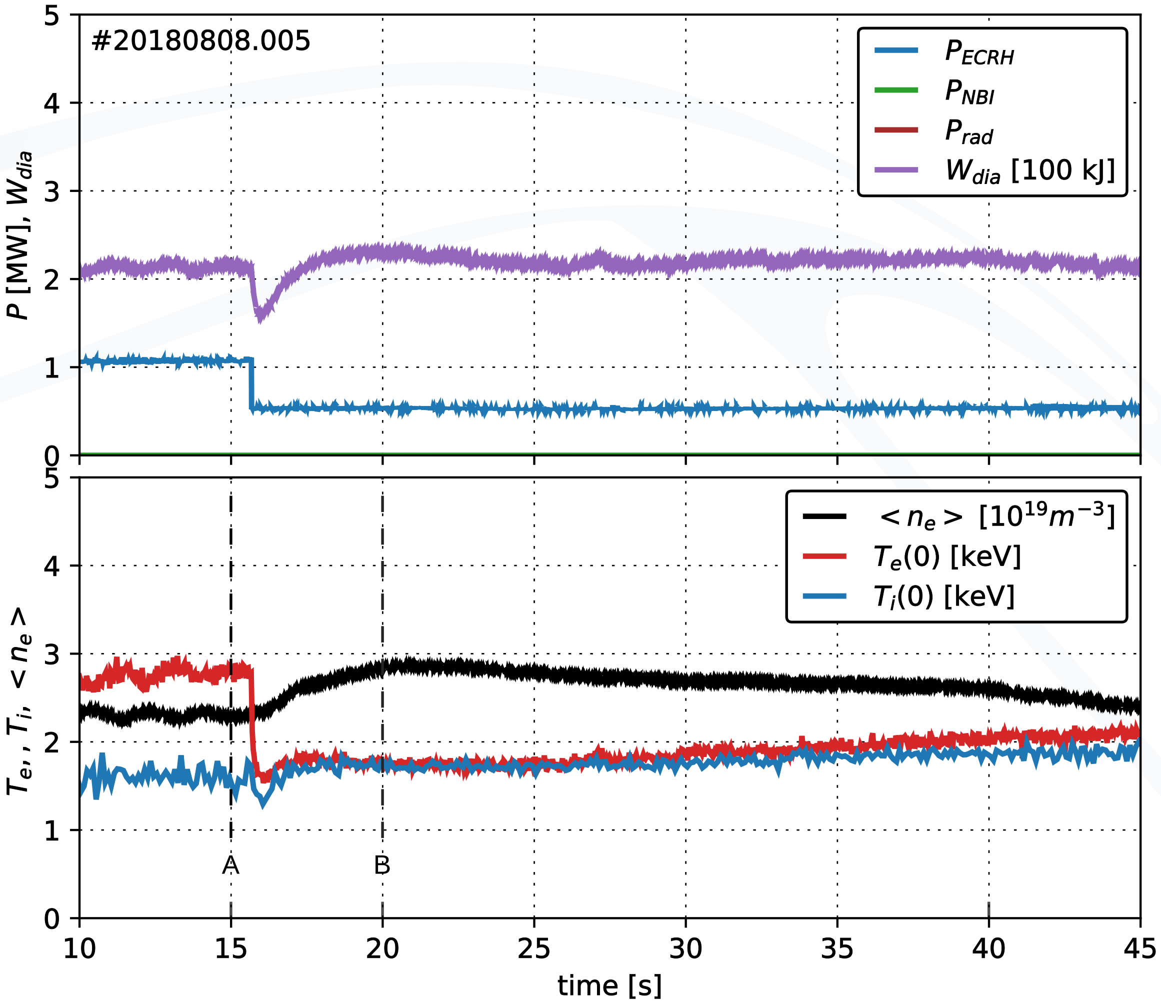

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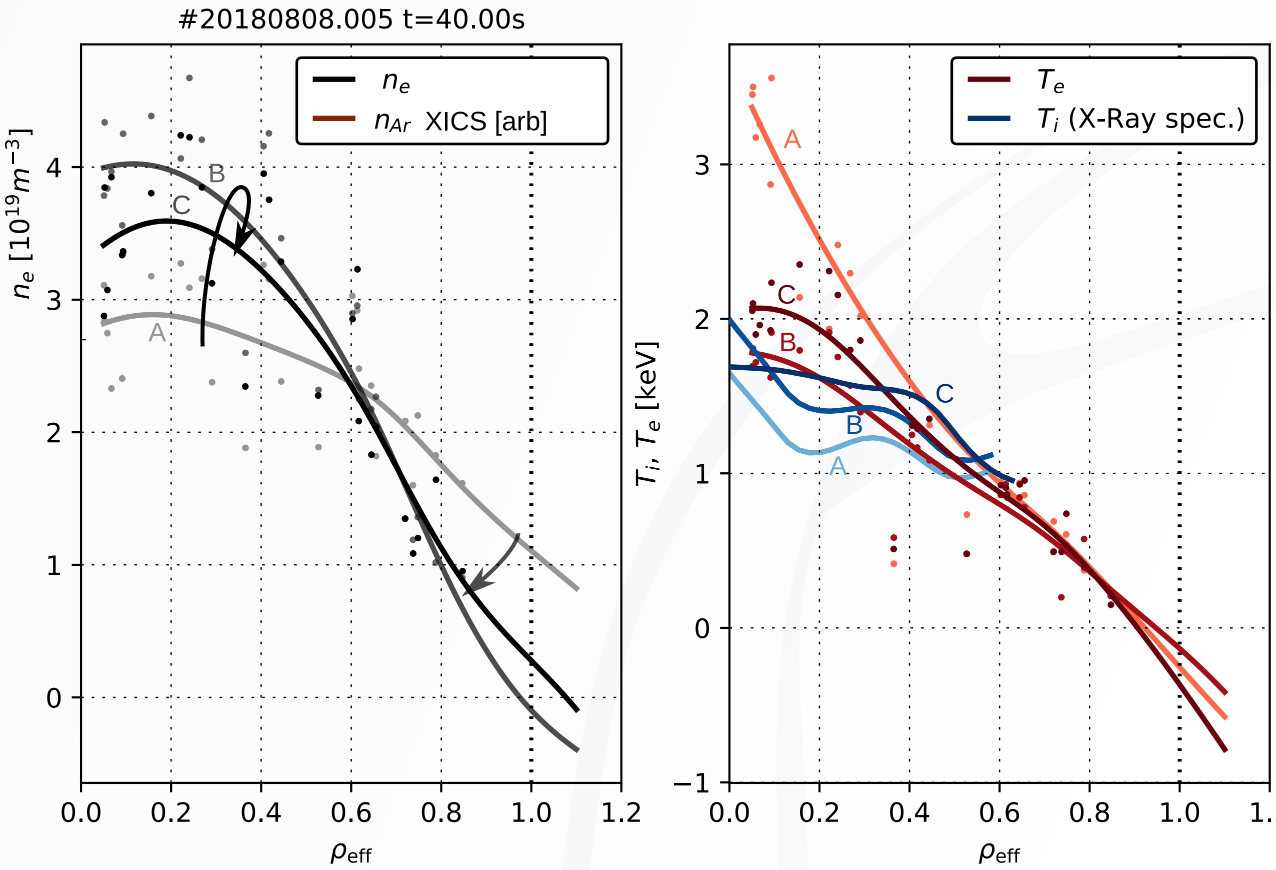

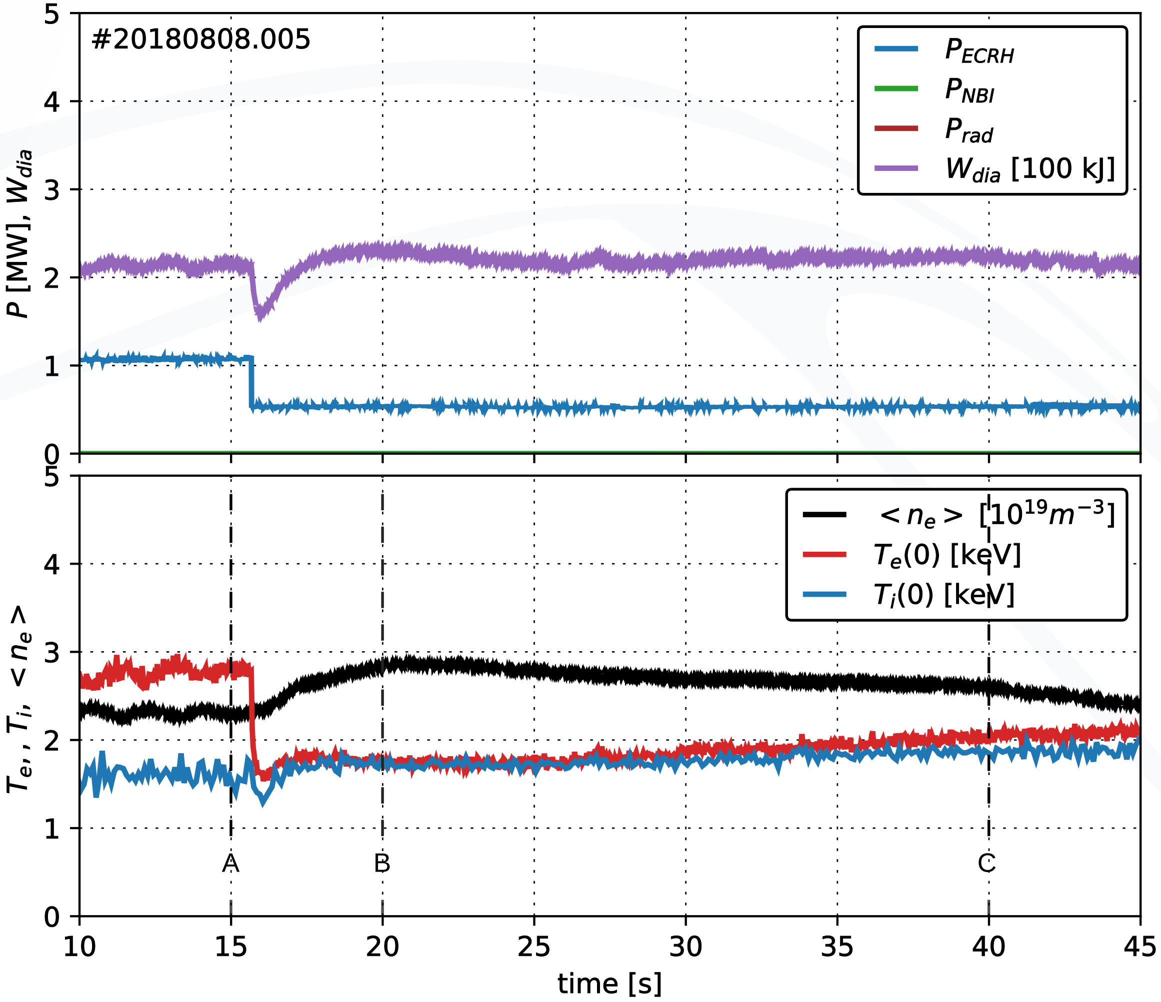

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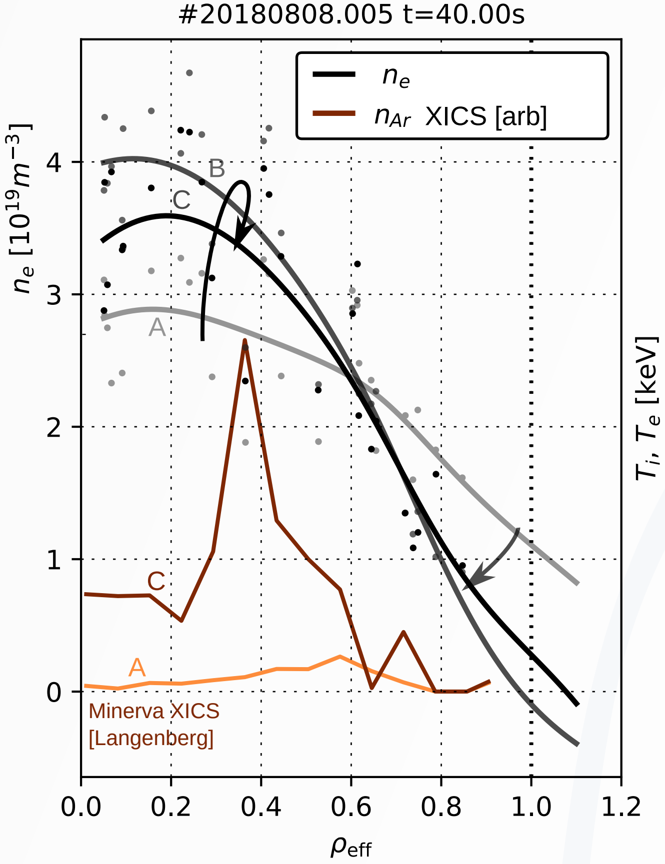
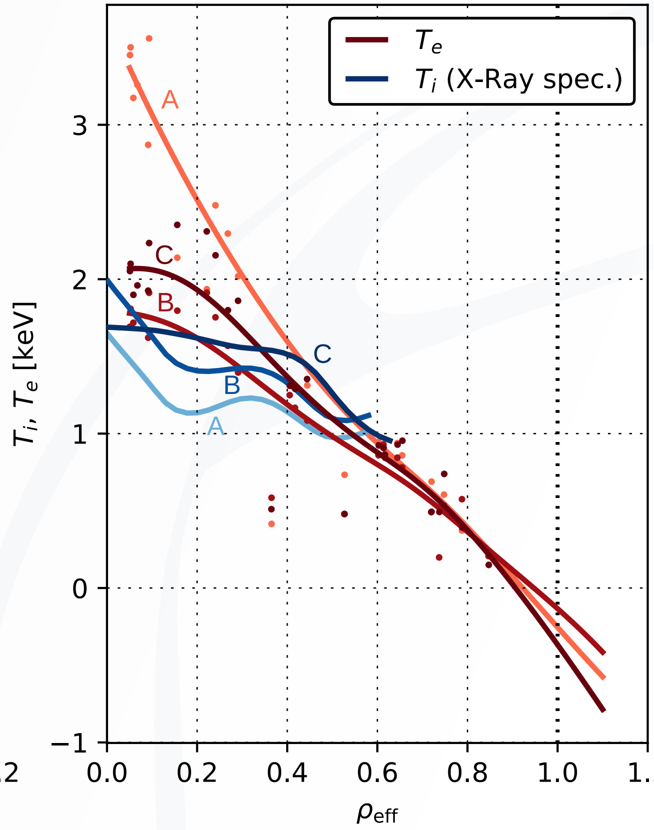
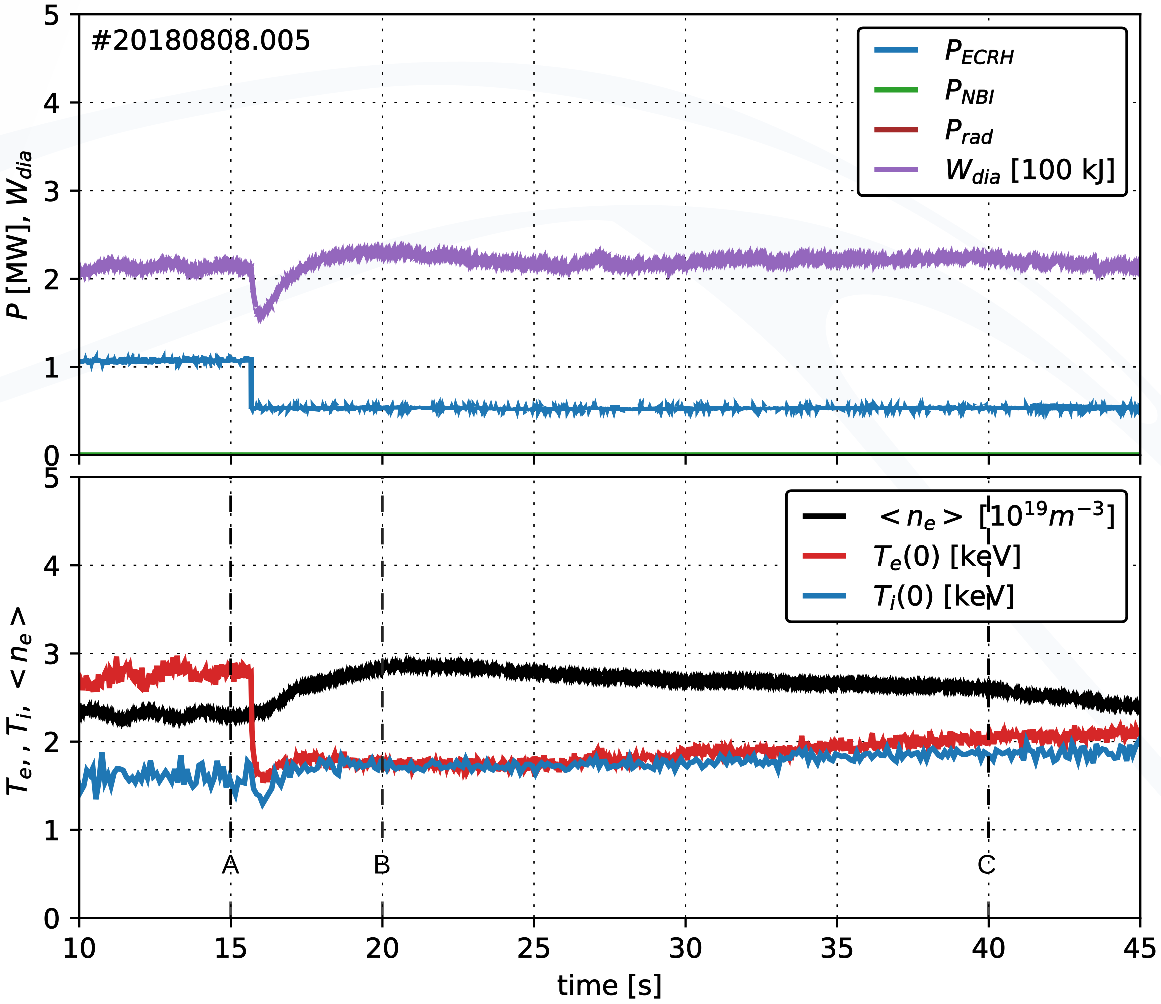
- XICS: n_{Ar16+} increases. Need STRAHL runs to separate T_e.

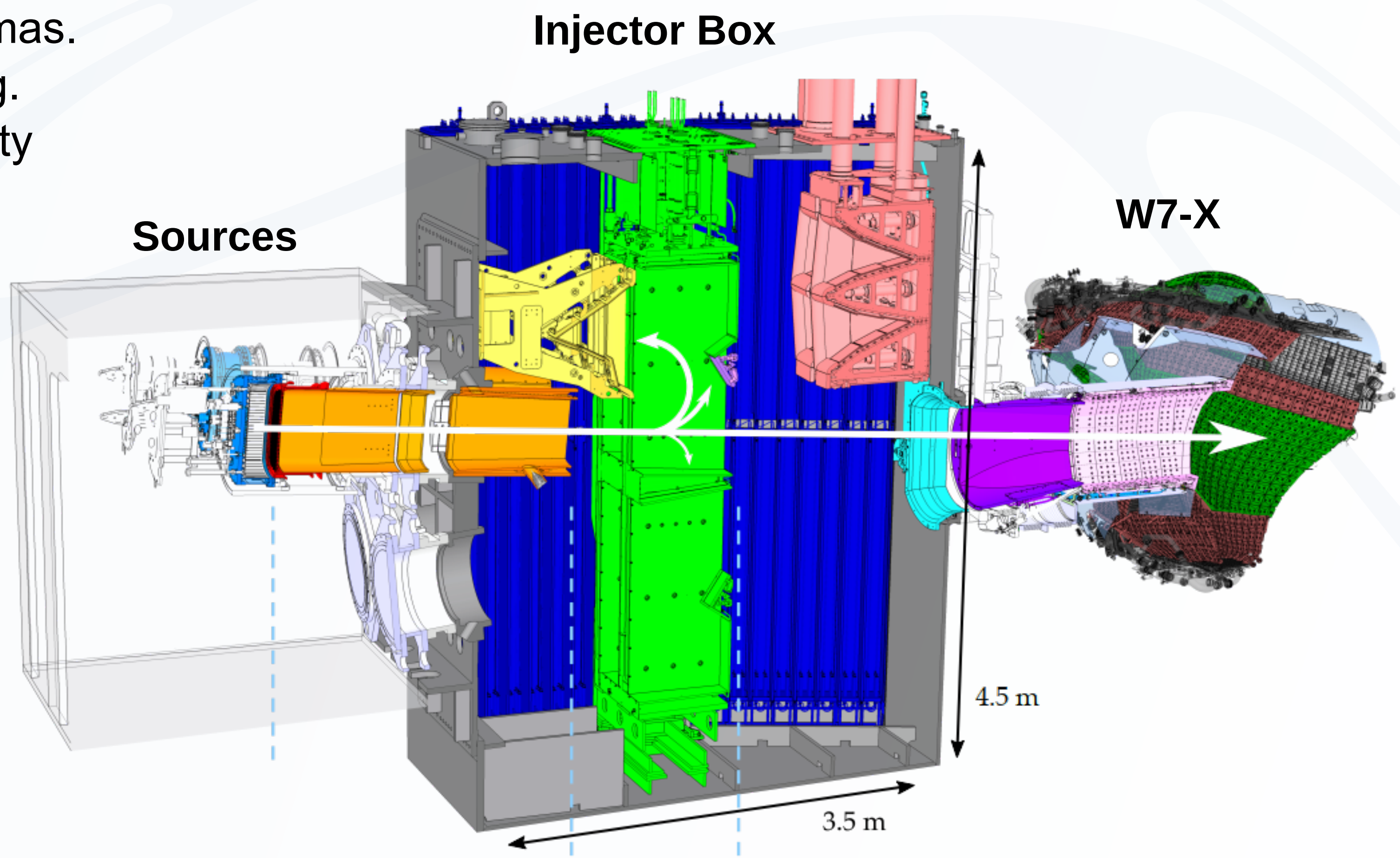






Neutral Beam Injection

- In the last campaign, the W7-X NBI system was comissioned
  - 2x 2.5MW radial sources of H injection at ~55kV (2x 1.3MW thermalised power)
  - Core fuelling even in high density plasmas.
  - Similar level of ion and electron heating.
  - Can fuelling provide steady-state density peaking with T_i above clamping limit?

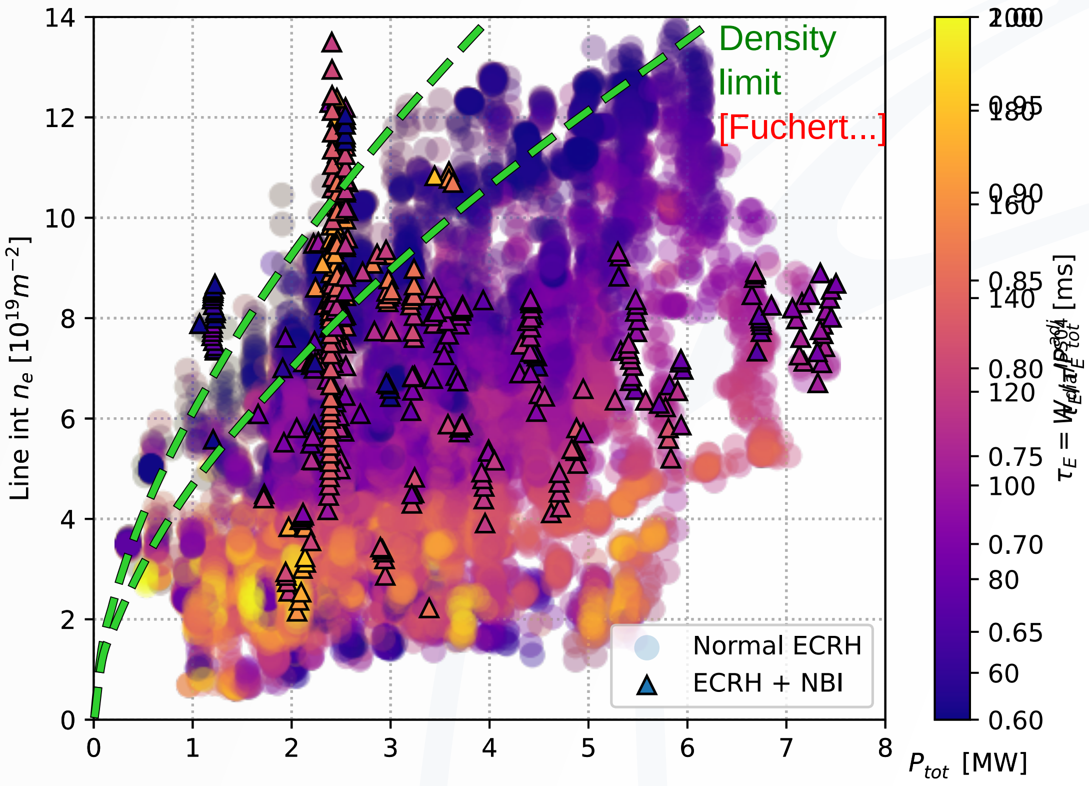


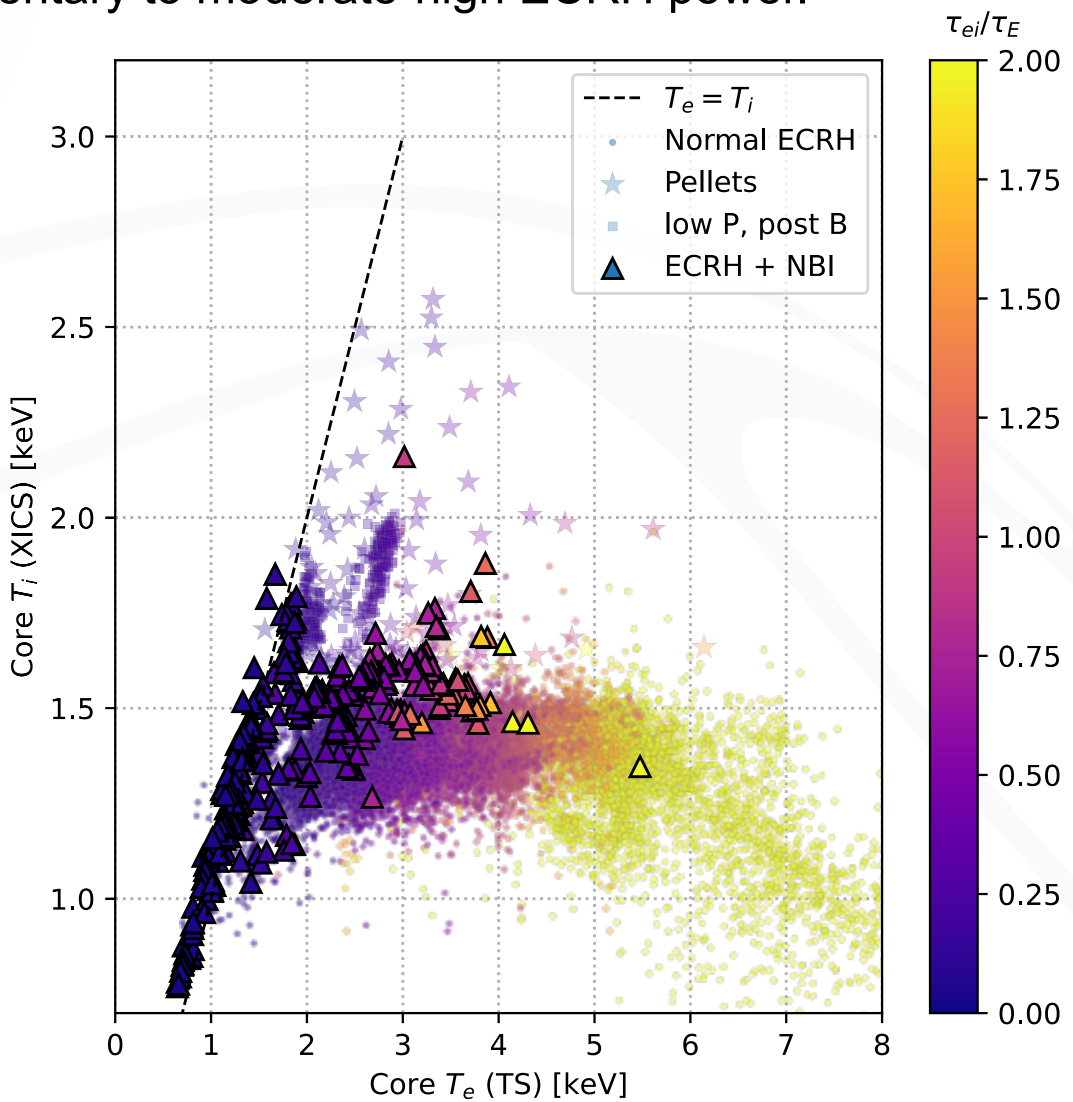
Neutral Beam Injection: Confinement

- NBI startup not possible on W7-X. Most beam injection is supplmentary to moderate-high ECRH power.
- Operation above ECRH radiative density limit [Fuchert...]
- Degradation with n_e relative to ISS04 stellarator scaling reduced.

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

- $\mathrm{T_i}$ typically at only slightly above the Ti clamping limit.



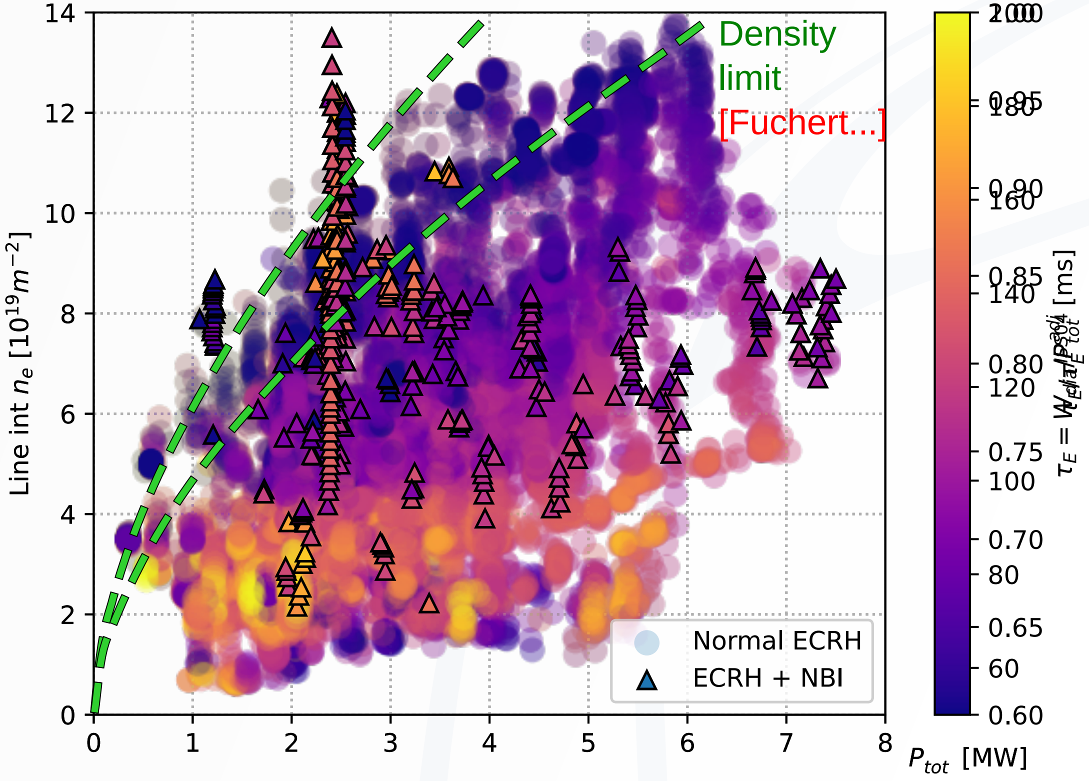


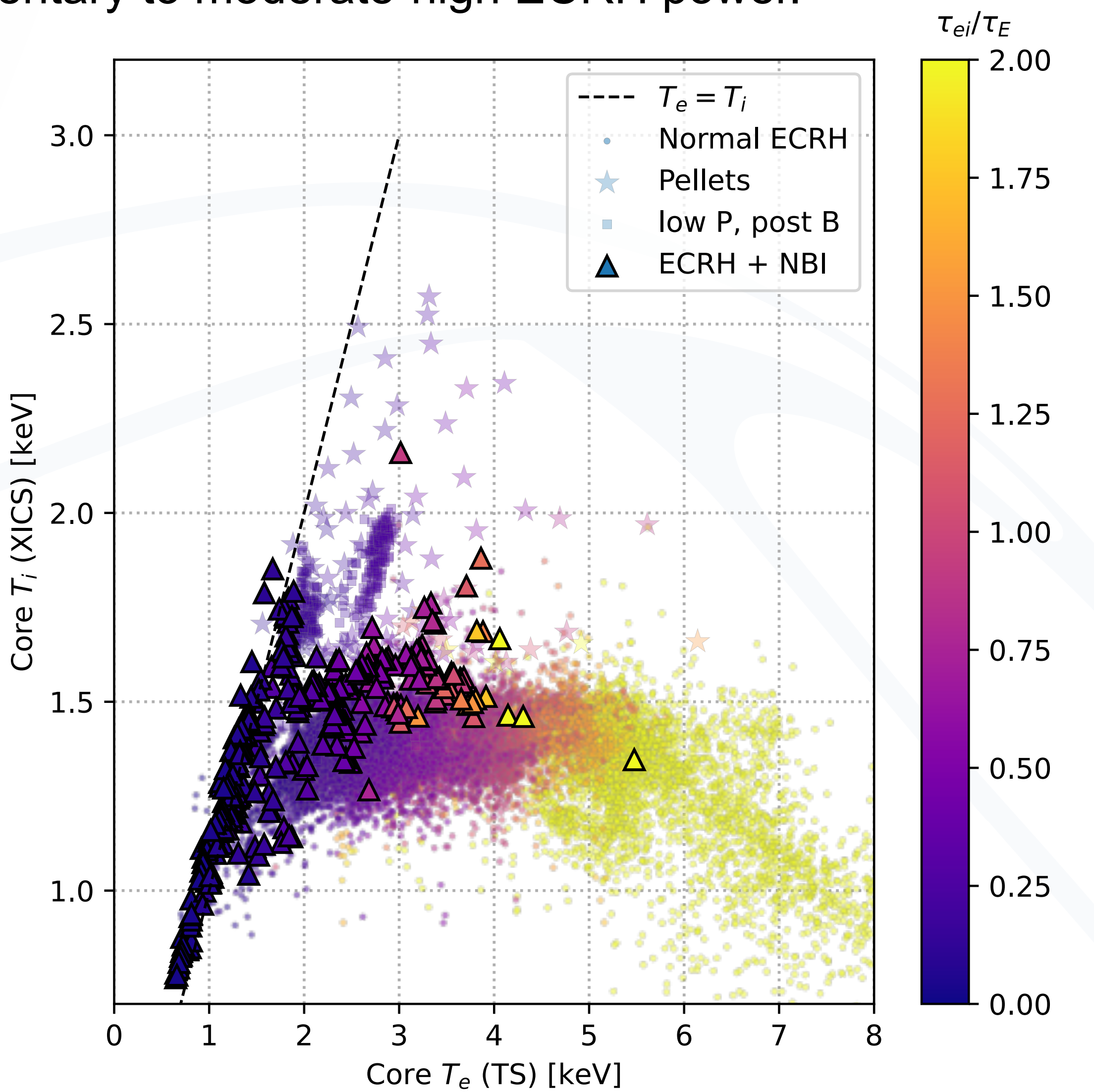
Neutral Beam Injection: Confinement

- NBI startup not possible on W7-X. Most beam injection is supplmentary to moderate-high ECRH power.
- Operation above ECRH radiative density limit [Fuchert...]
- Degradation with n_e relative to ISS04 stellarator scaling reduced.

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

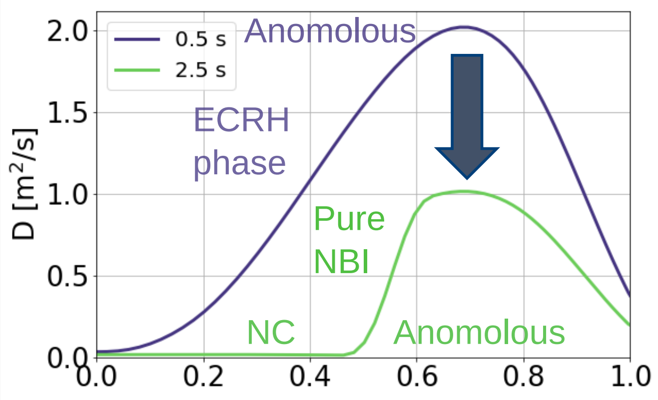
- T_i typically at only slightly above the Ti clamping limit.

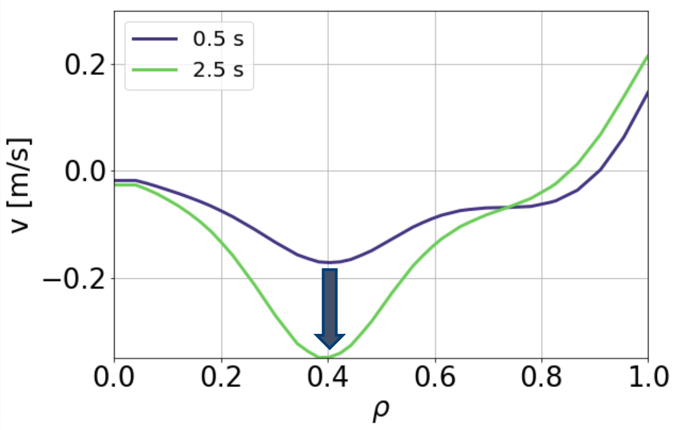


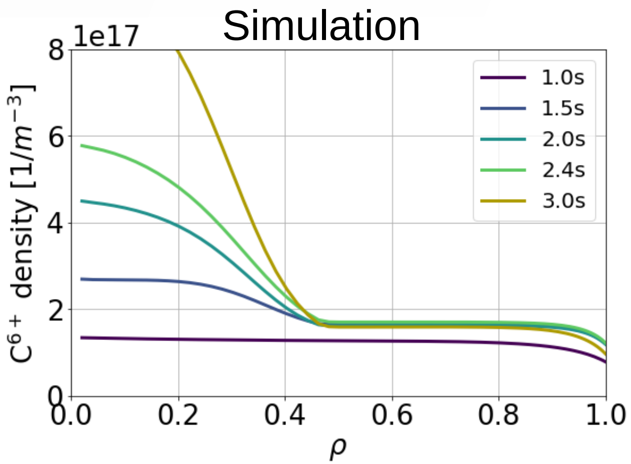


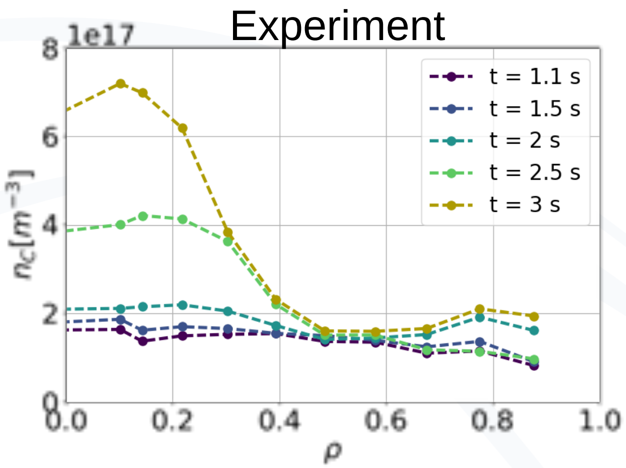
NBI only impurity pinch

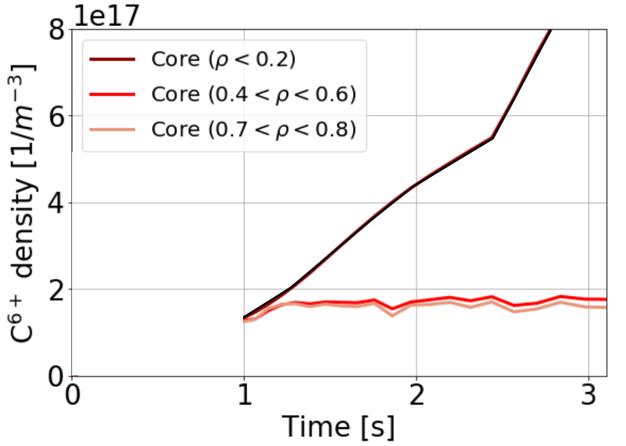
- STRAHL simulations assuming neoclassical transport coefficients inside ρ = 0.5 during NBI only phase give similar qualitative beahviour and profiles. Quantitatively too rapid rise rate and too early.
- Behaviour consistent with strong reduction of turbulence in density peaking region after given onset time.

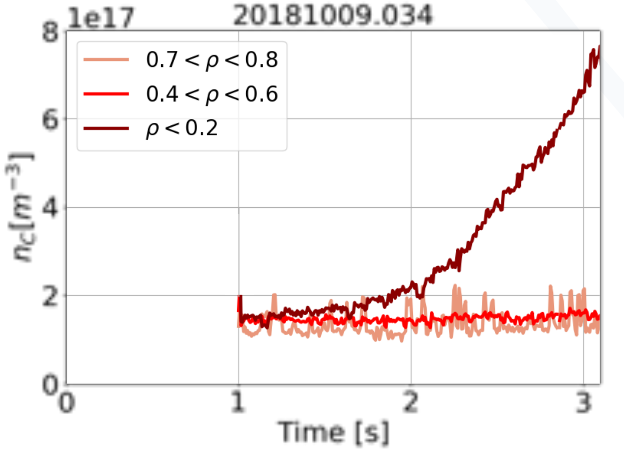






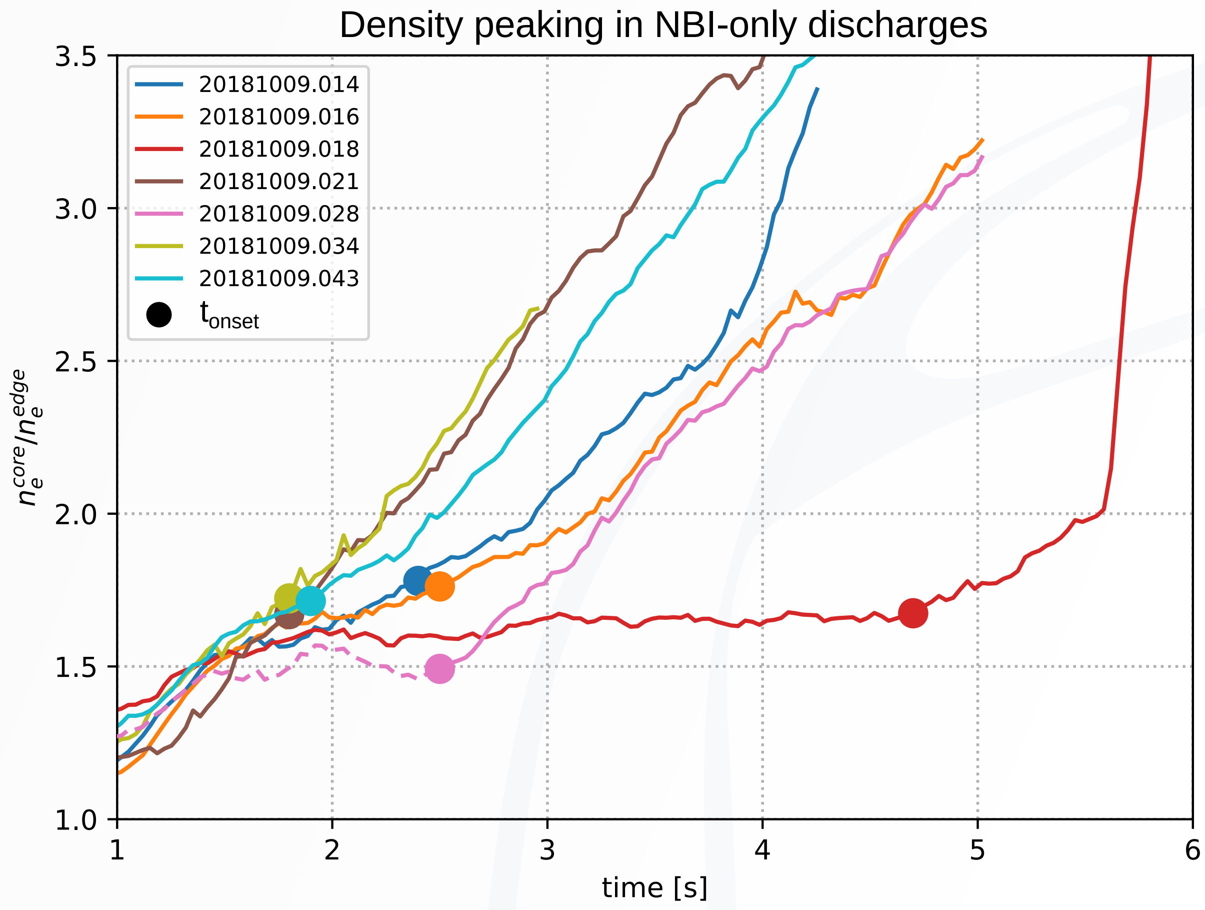


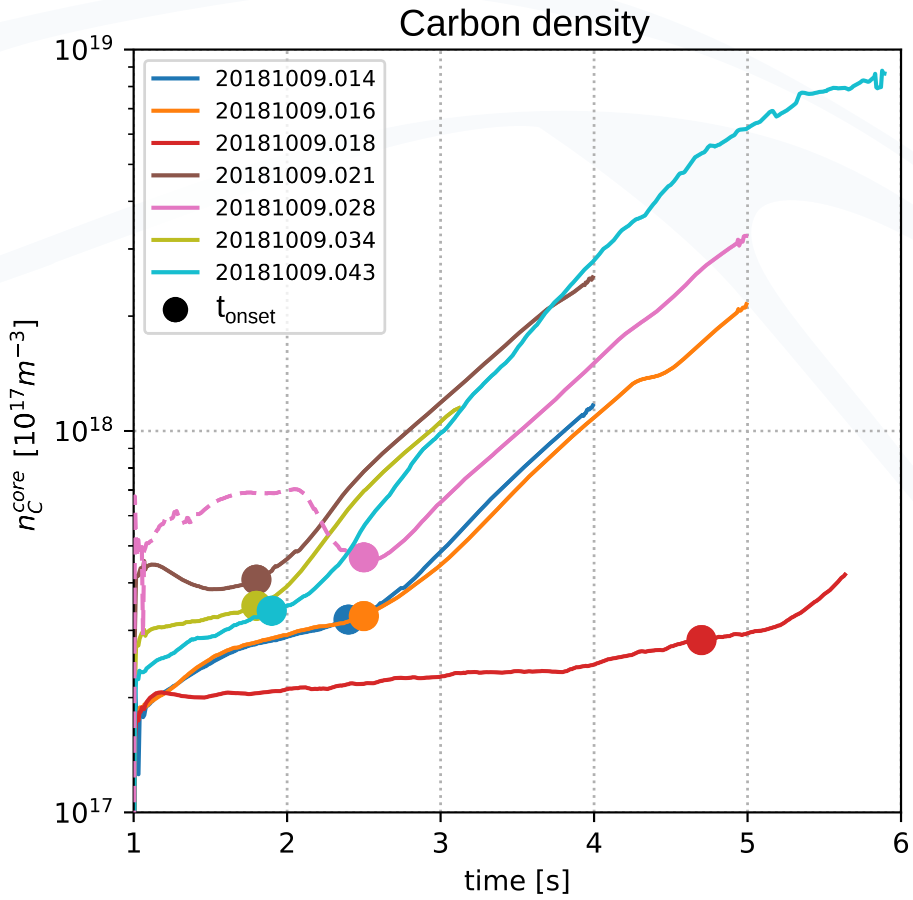




Electron/ion particle transport

- The onset time of the reduced particle and impurity anomalous fluxes varies between shots.
- No external events, no changes observed at plasma edge.
- Onset appears to occurs when *a/Ln*$_e$ reaches ~0.85 *(tentative)*

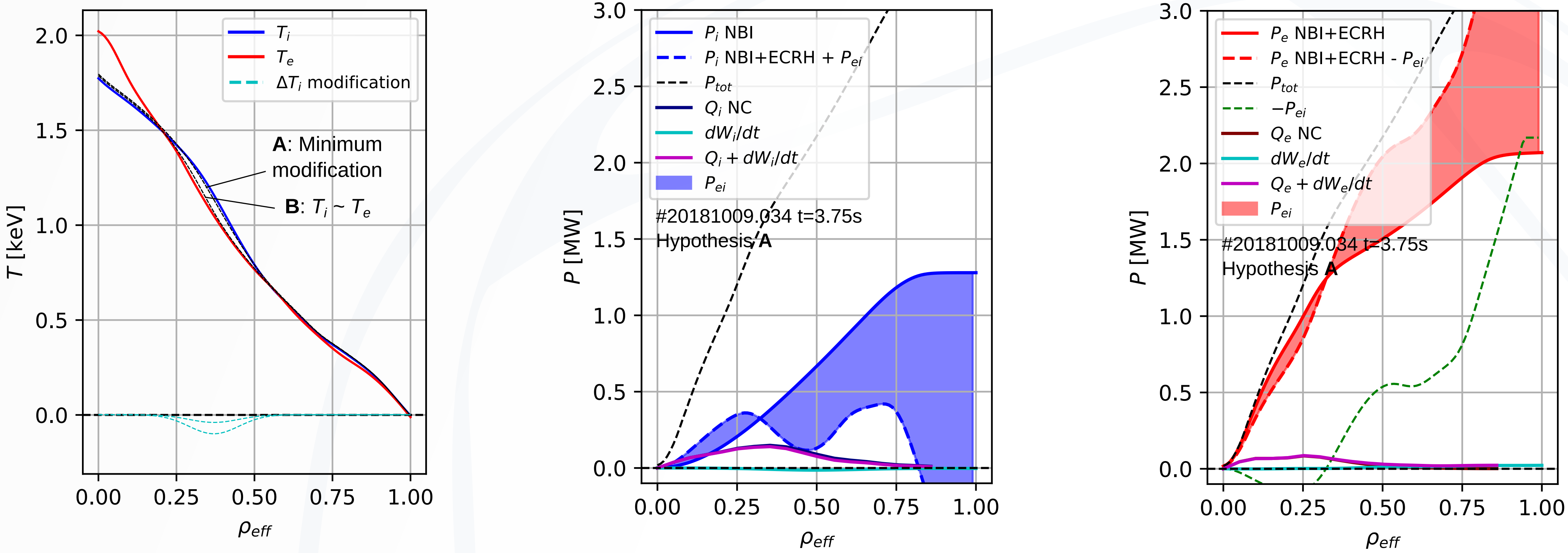




Energy transport: Species separation

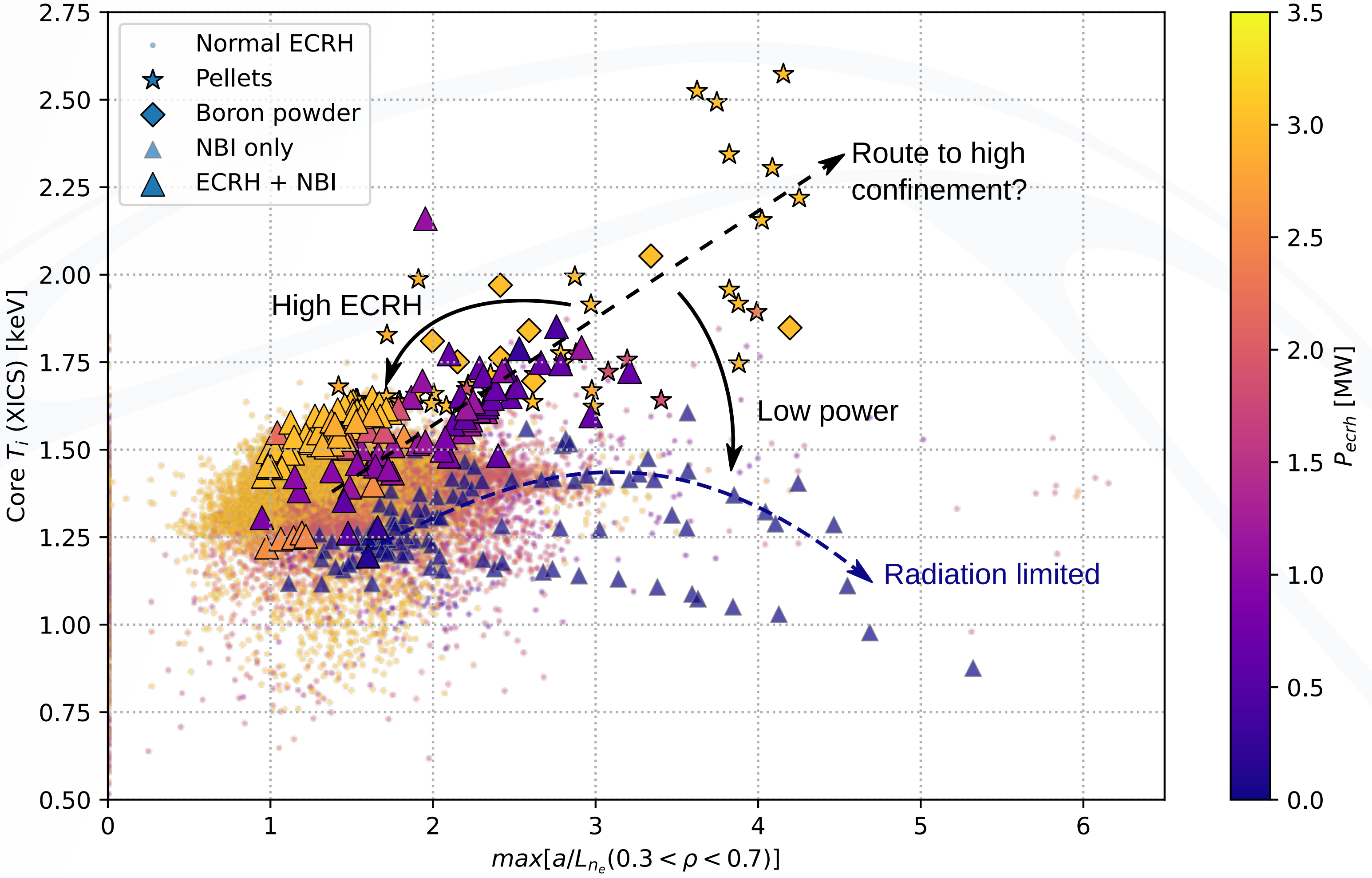
- Separation of ion and electron energy fluxes requires determination of power exchange term.
- At high collisionality ($n_e \sim 10^{20}$), this requires $O(10\text{eV})$ accruacy of (T_e - T_i) profile, which has not yet been achieved.
- Best effort analysis for highest T_i gives range from: **A)** large Q_e with Q_i~Q_i^{NC} to **B)** Q_i ~ Q_e >> Q^{NC}.
- $Q_e >> Q_i \sim Q_{NC}$ would be consistent with with post-pellets experiments.
- However, neoclassical electron energy fluxes *not* supported by measurements.

    --> Next campaign: Improvements in Ti profiles + heat wave measurements.



Routes to high confinement

- Dependence on density gradient and ECRH power clear in global picture.
- Need to find balance of NBI and ECRH:
  - Too little ECRH:
    - Low total power
    - Impurity accumulation
  - Too much ECRH:
    - Density peaking reduced
    - Return to ITG dominated plasmas with clamped T_i.



Open questions for 2022/3 campaign:
- Increase NBI power. What happens to a/Ln_e?
- Why does a/Ln_e decrease with ECRH?
- Can sufficient a/Ln_e be maintained while flushing out impurities?