Max-Planck-Institut für Plasmaphysik

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

(Modified for impurity topical group 17.06.21)

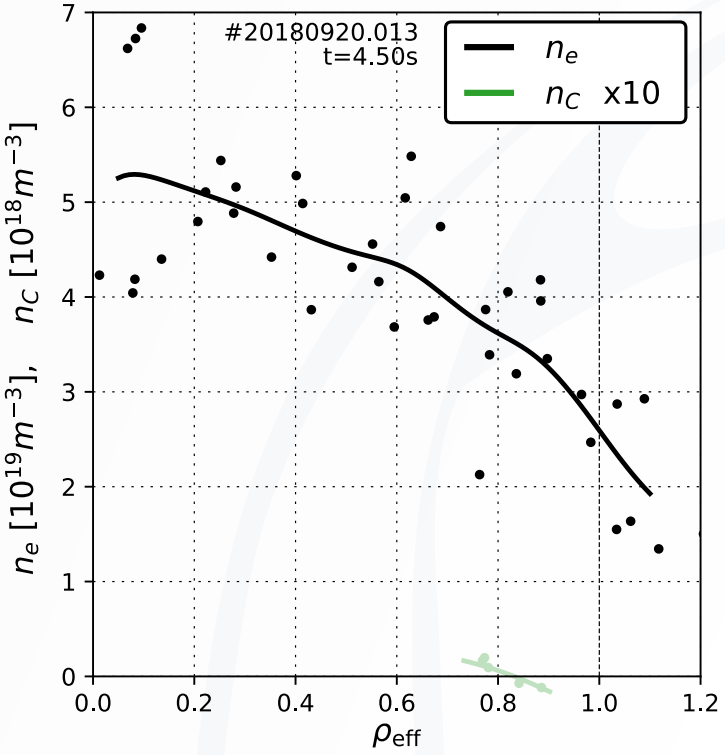
O. P. Ford, M. Beurskens, S. Bozhenkov, S. Lazerson

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

Gas-fuelled ECRH discharges

Typical discharges from last campaign (2018):
- On-axis X2 ECRH heating 2 - 6MW; $\langle n_e \rangle \sim 1$ to 10 x 10^{19}. Gas/recycling fuelled.
- Flat or slightly peaked density profiles



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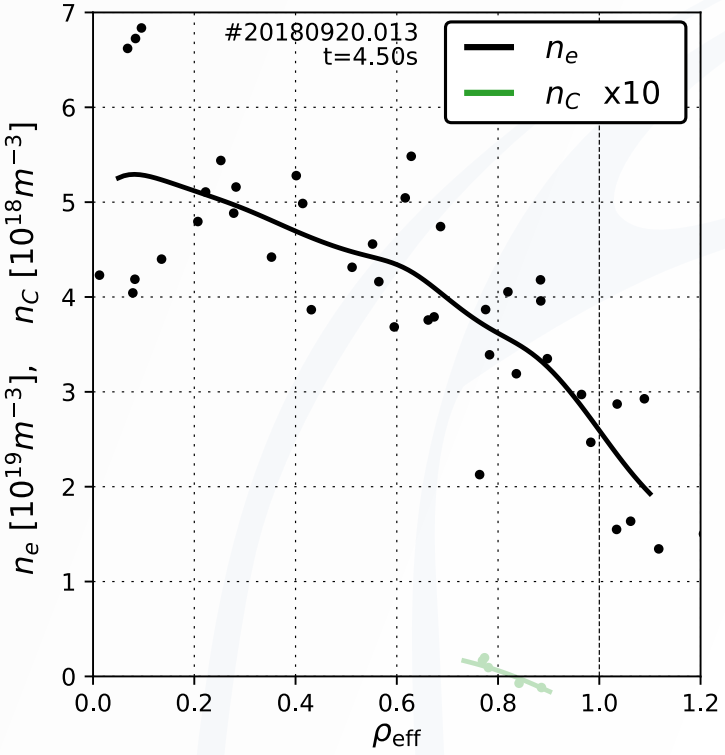
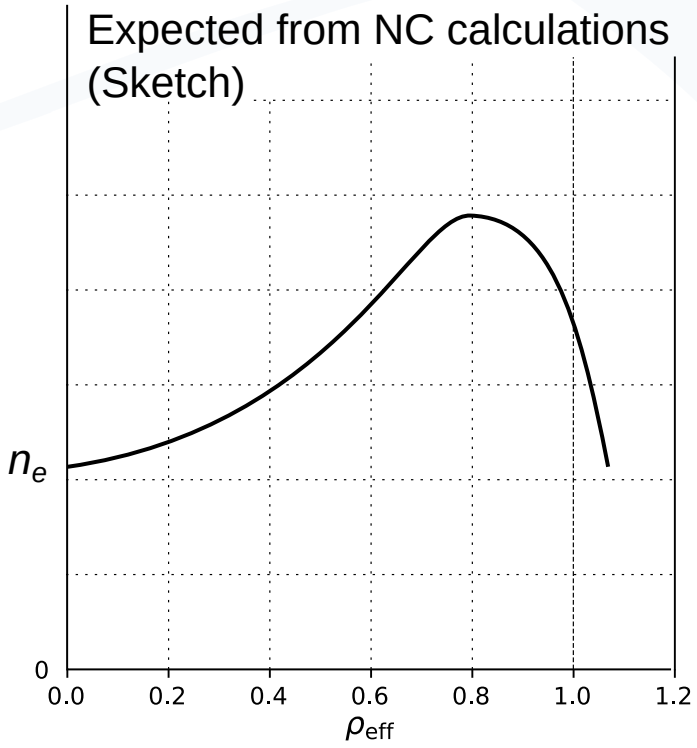
  An anomalous pinch required to counteract *[C D Beidler et al 2018 PPCF 60 105008]*





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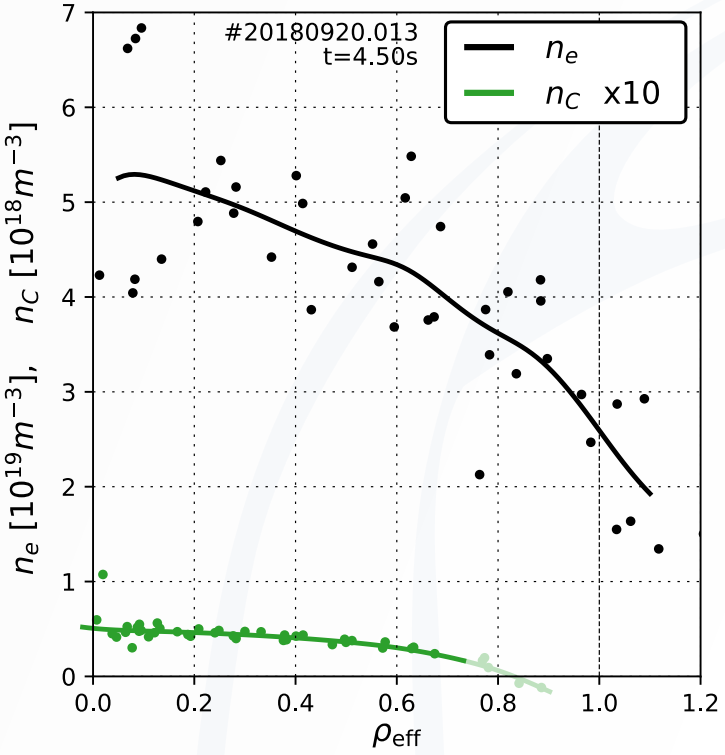
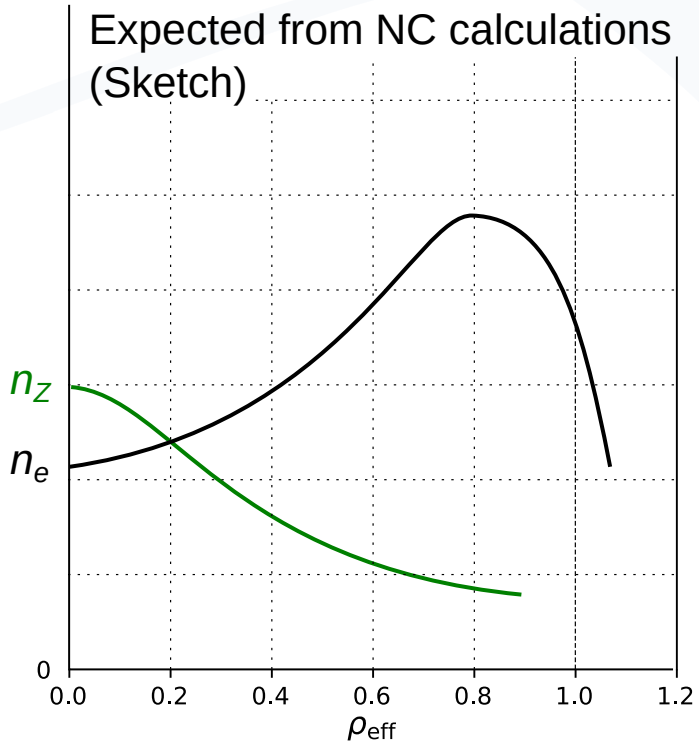
  An anomalous pinch required to counteract *[C D Beidler et al 2018 PPCF 60 105008]*
- Flat impurity profiles despite neoclassical pinch:
  High turbulent impurity diffusion shown by LBO injection experiments *[B. Geiger et al 2019 Nucl. Fus. 59 046009]*





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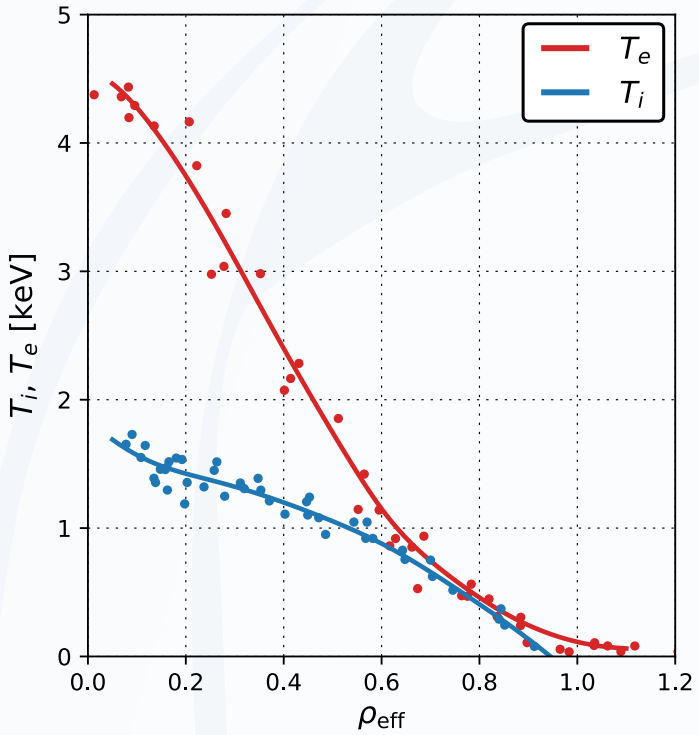

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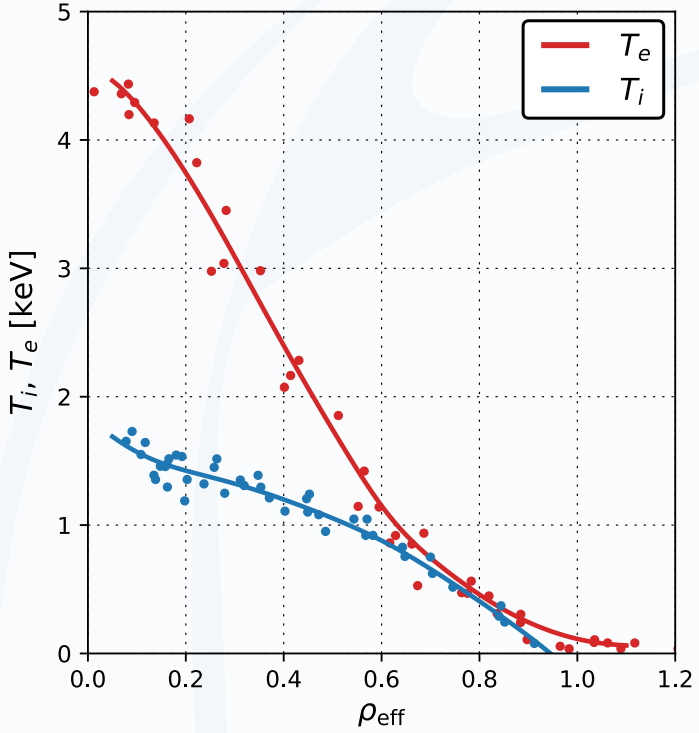

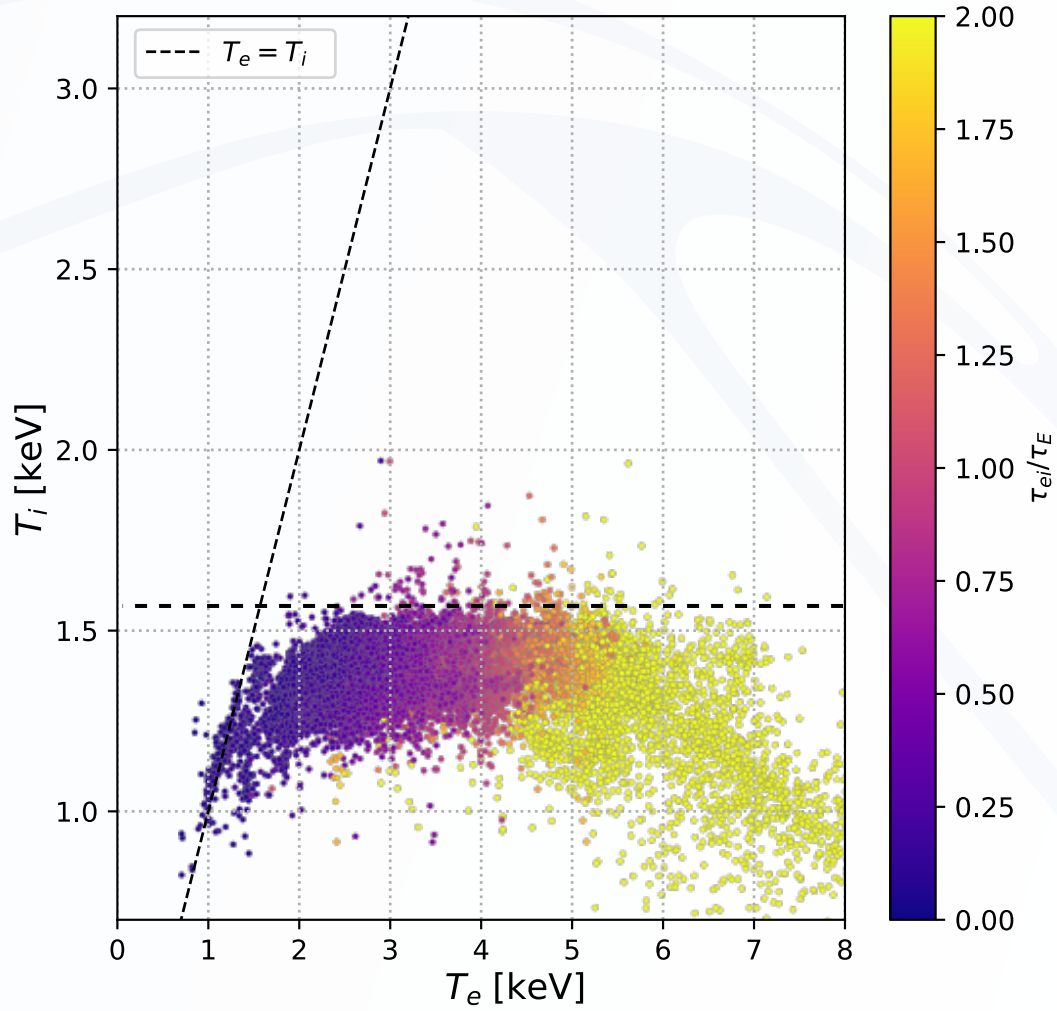

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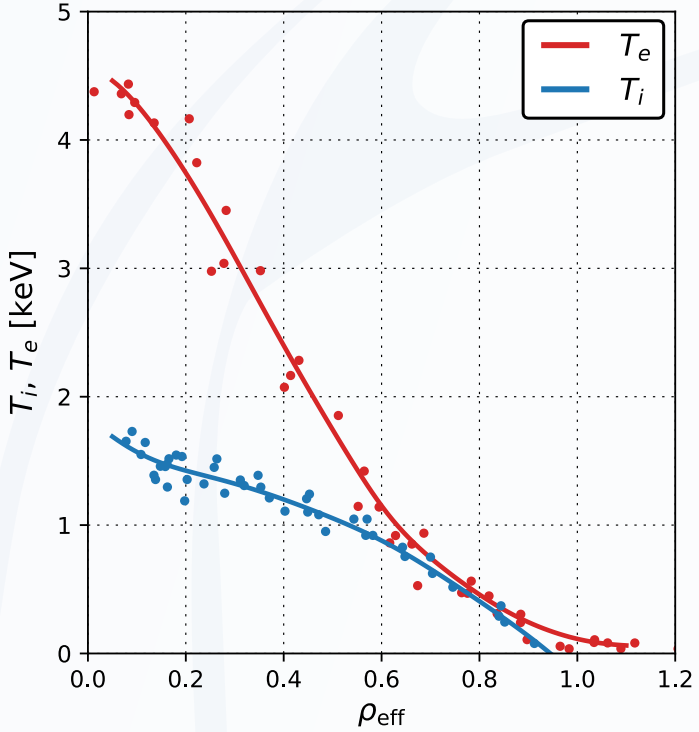

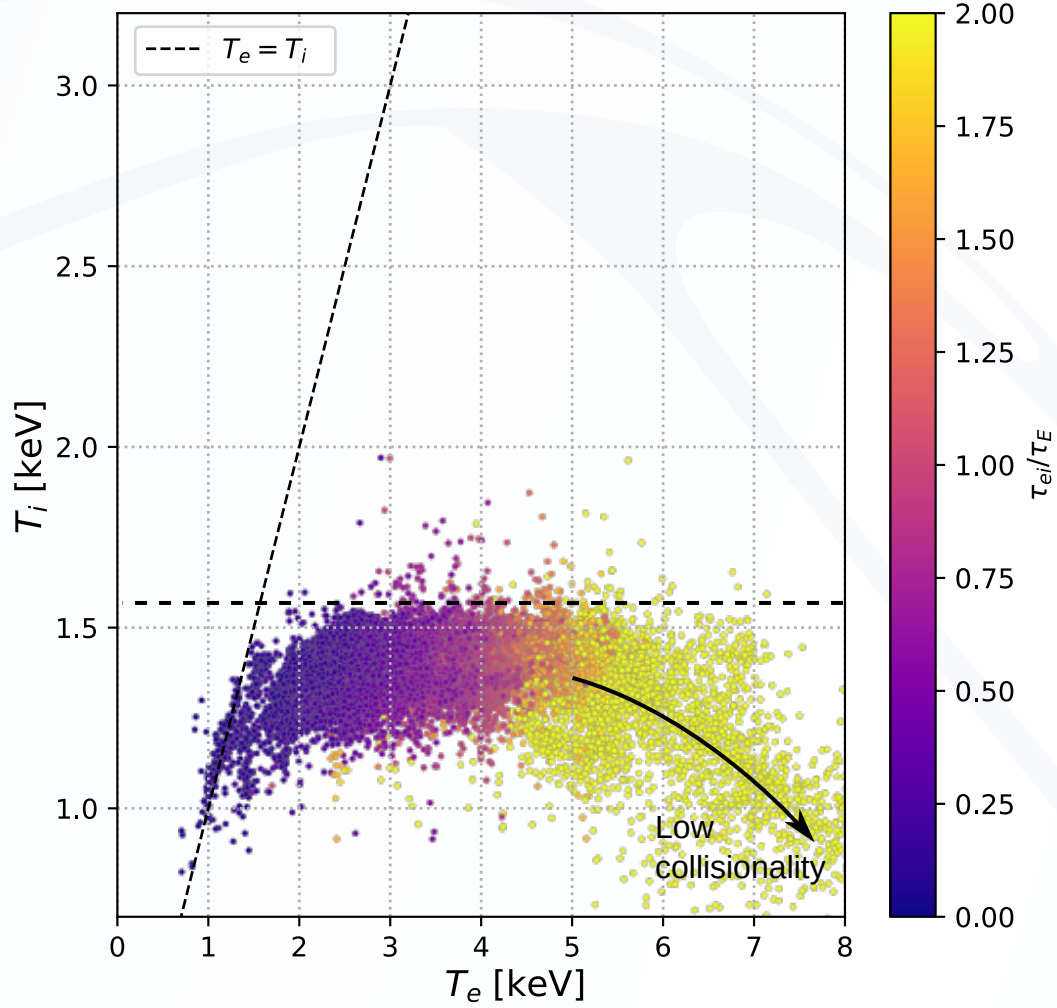

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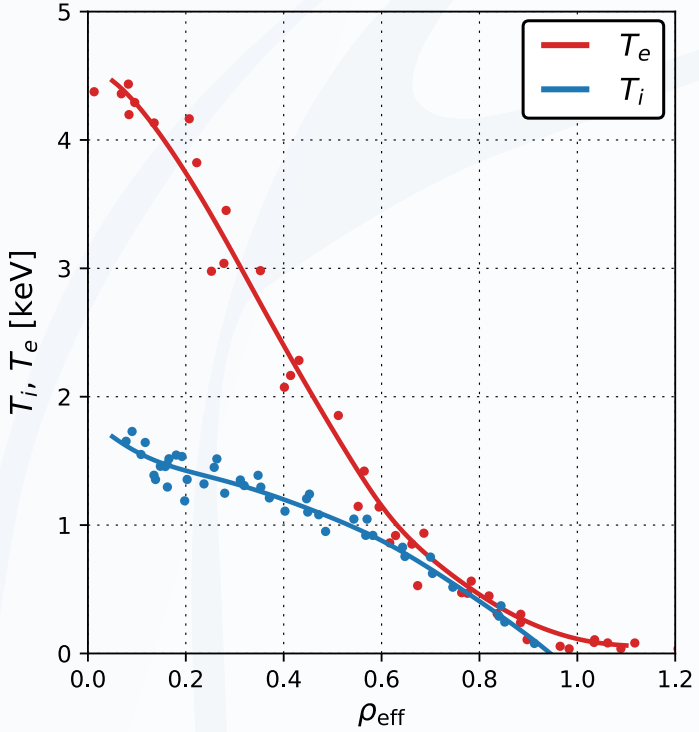
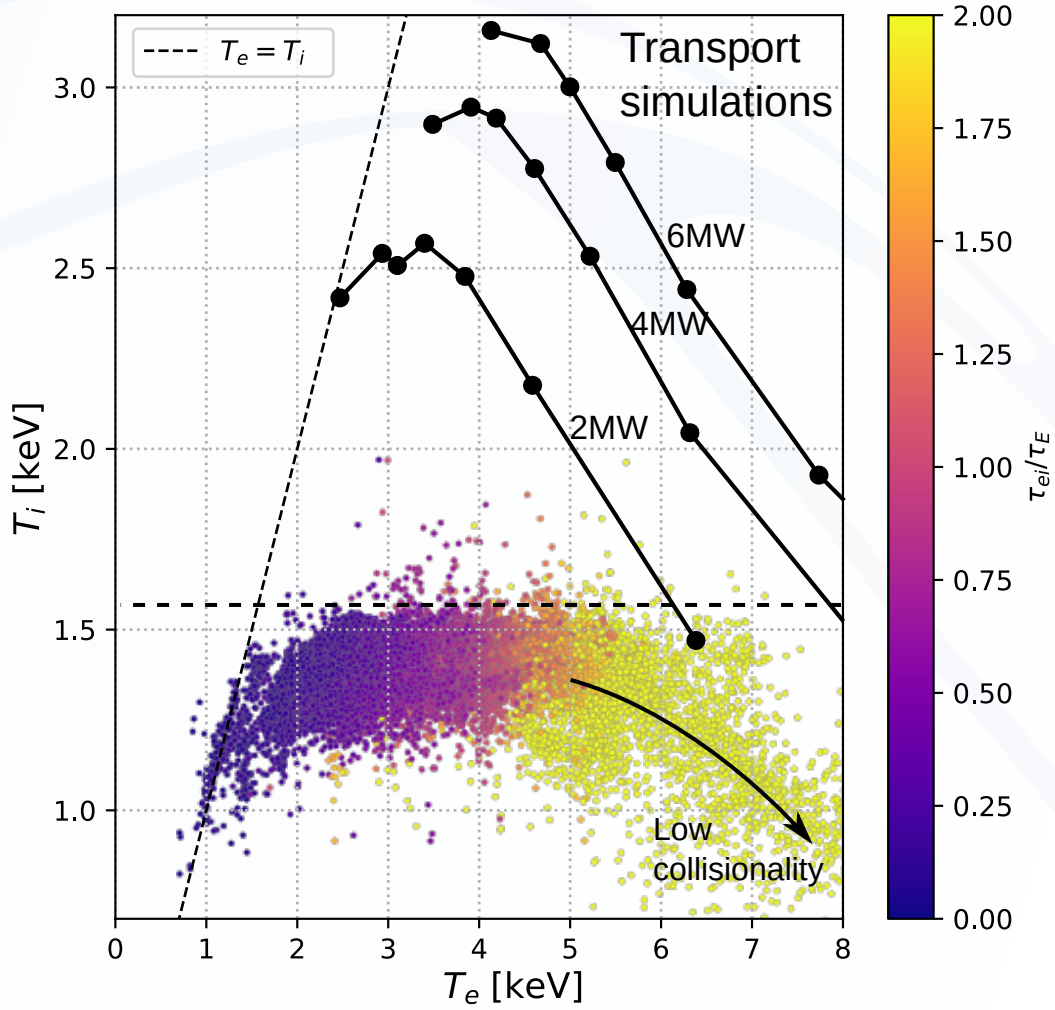
- Simulations with neoclassical and moderate turbulent transport predict T_i ~ 3keV for P_{ECRH} = 6MW.





Post-pellet turbulence suppression

- Theoretical undestanding:
  - Density gradient strongly stabilises ITG. W7-X resilient to TEM due to optimisation [Proll et. al. PRL 2012].
  - 'Stability valley' around $a/Ln_e \sim a/LT_i$ [J. A. Alcusón et al. PPCF 21 (2020)]

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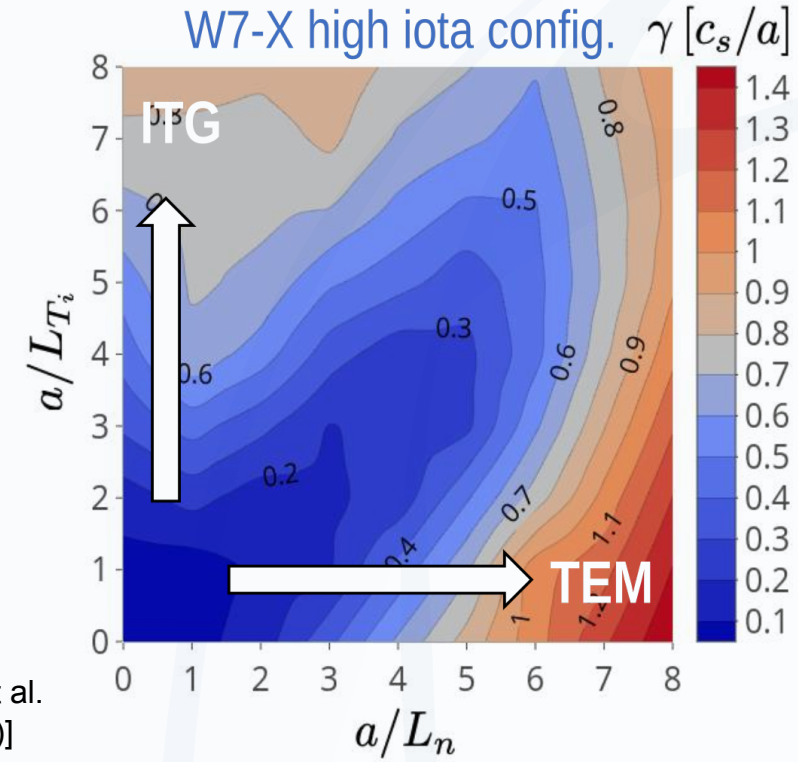
  - 'Stability valley' around $a/Ln_e \sim a/LT_i$ [J. A. Alcusón et al. PPCF 21 (2020)]
  - Non-linear simulations show transistion of from ITG to iTEM during post-pellet phase. [P. Xanthopoulos et. al. PRL 2021]
  - Reduction in fluctuation levels seen by PCI [Z. Huang, this conference] and Doppler reflectometer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



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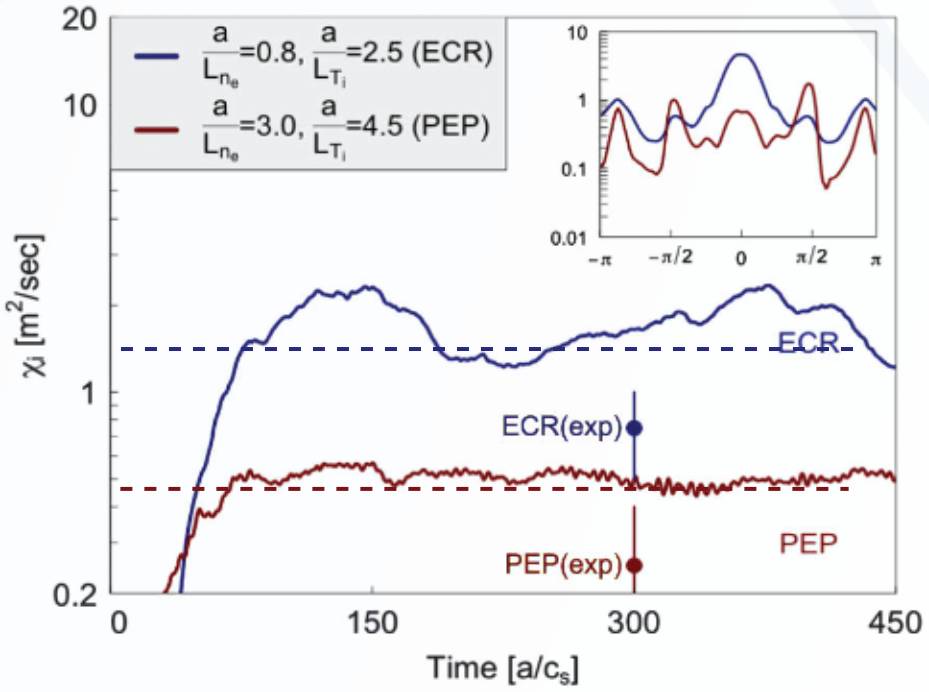

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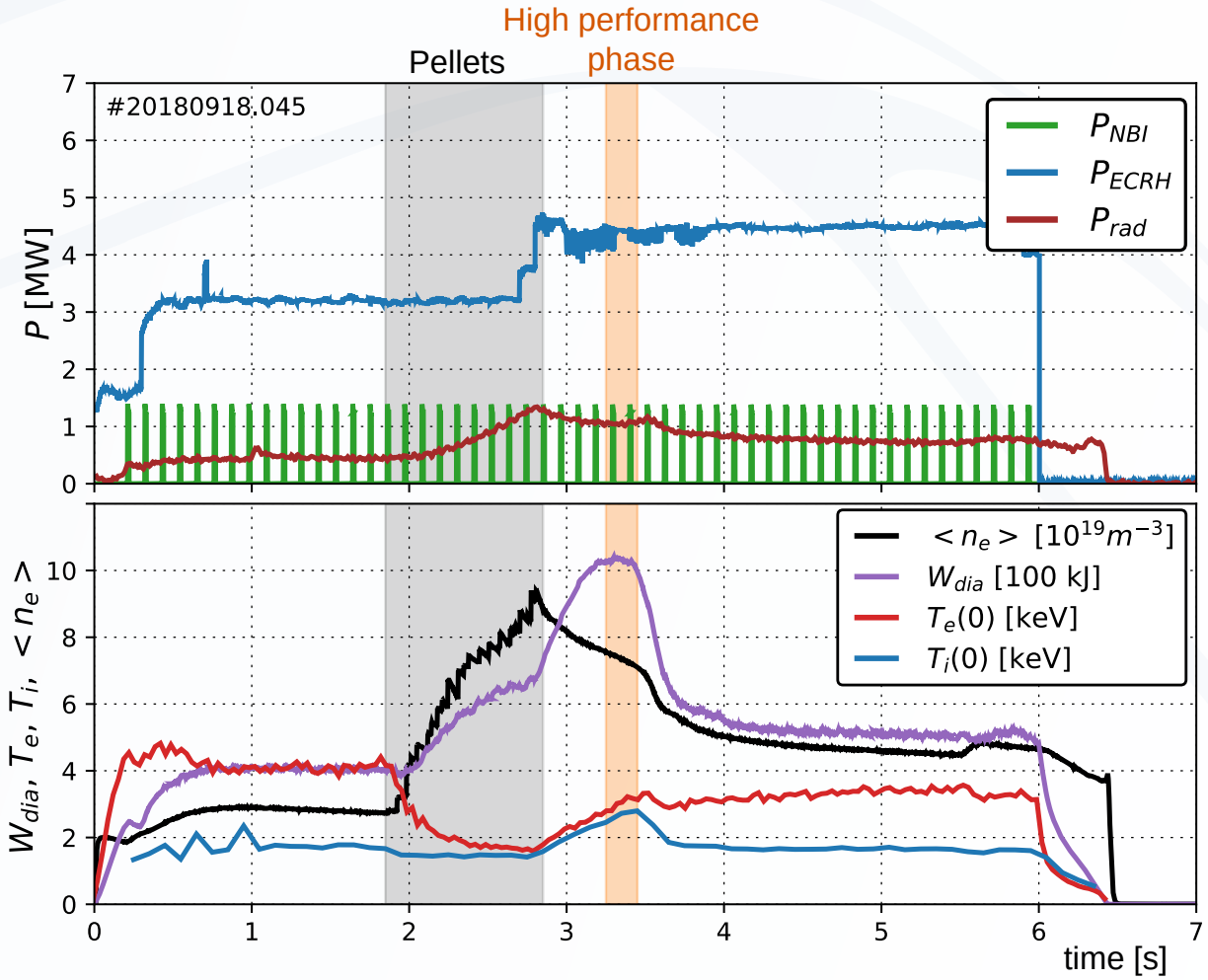

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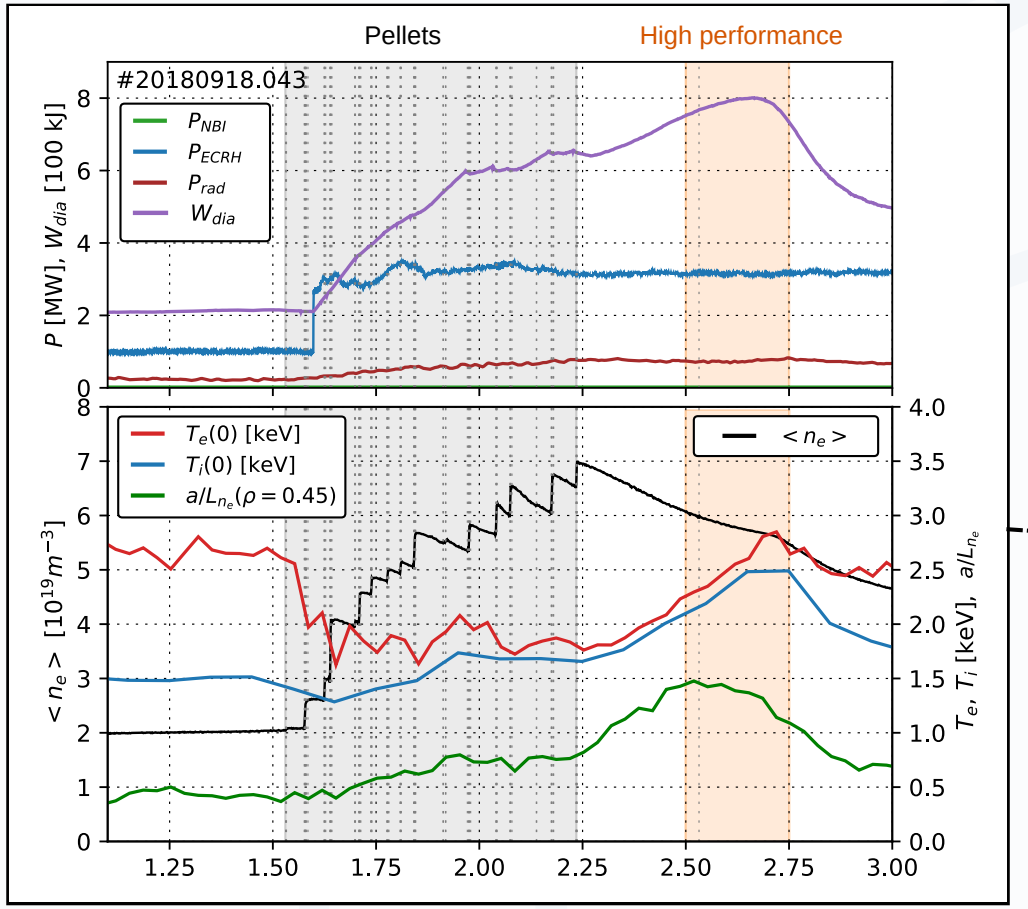
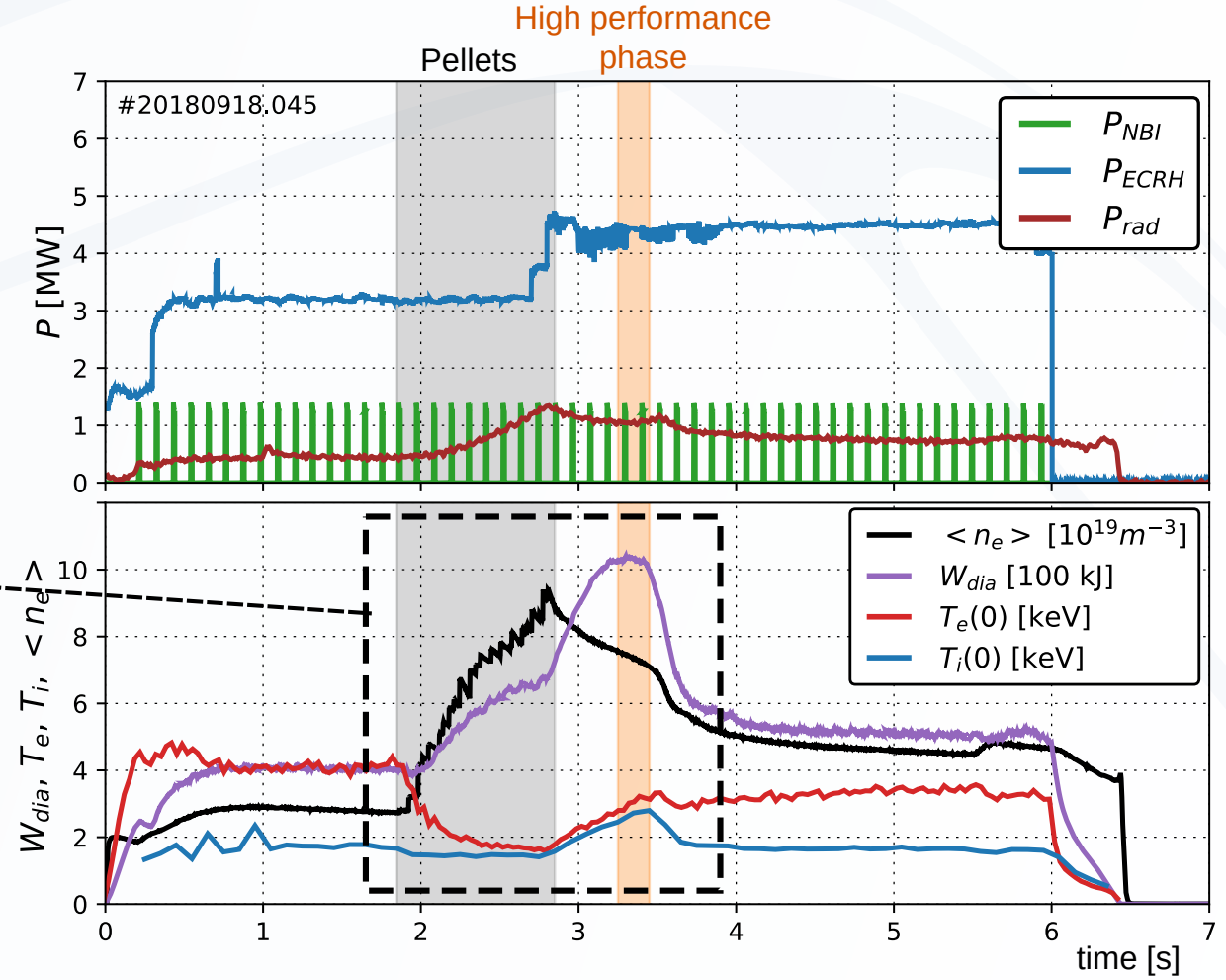
- So far, density gradient only observed after injection of last pellet.





Density gradient turbulence suppression

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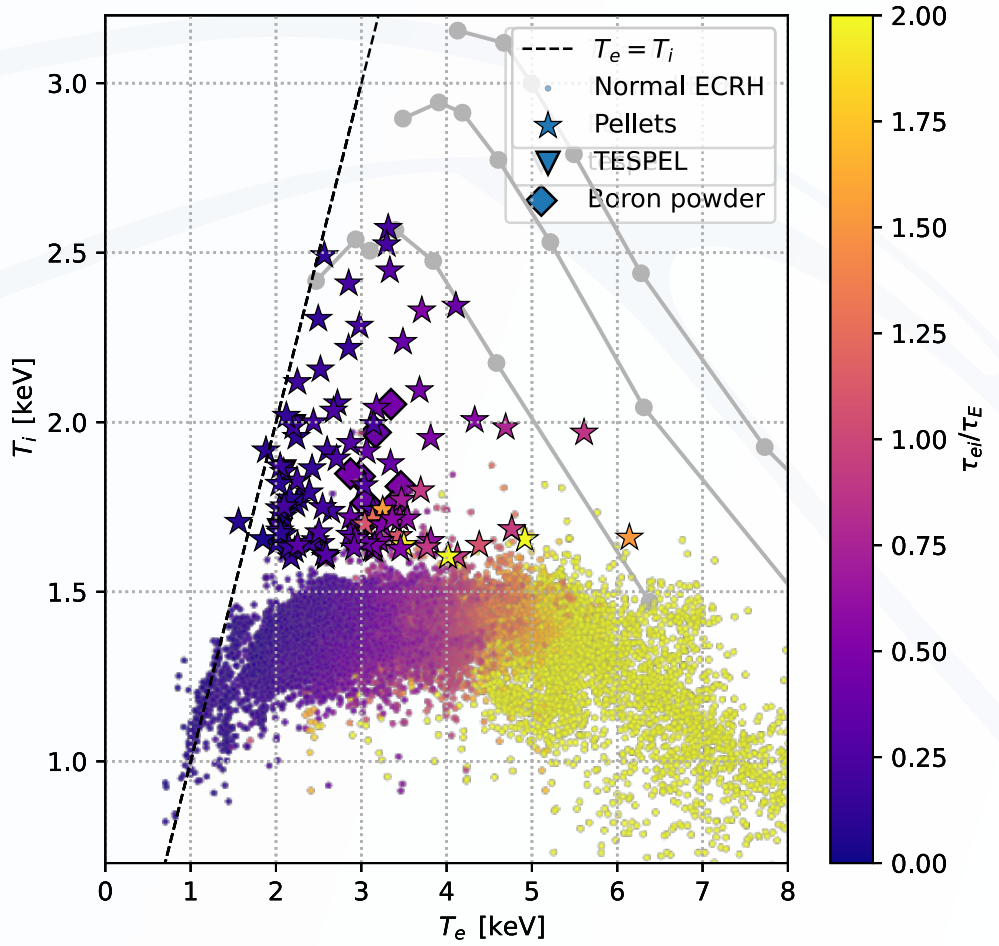

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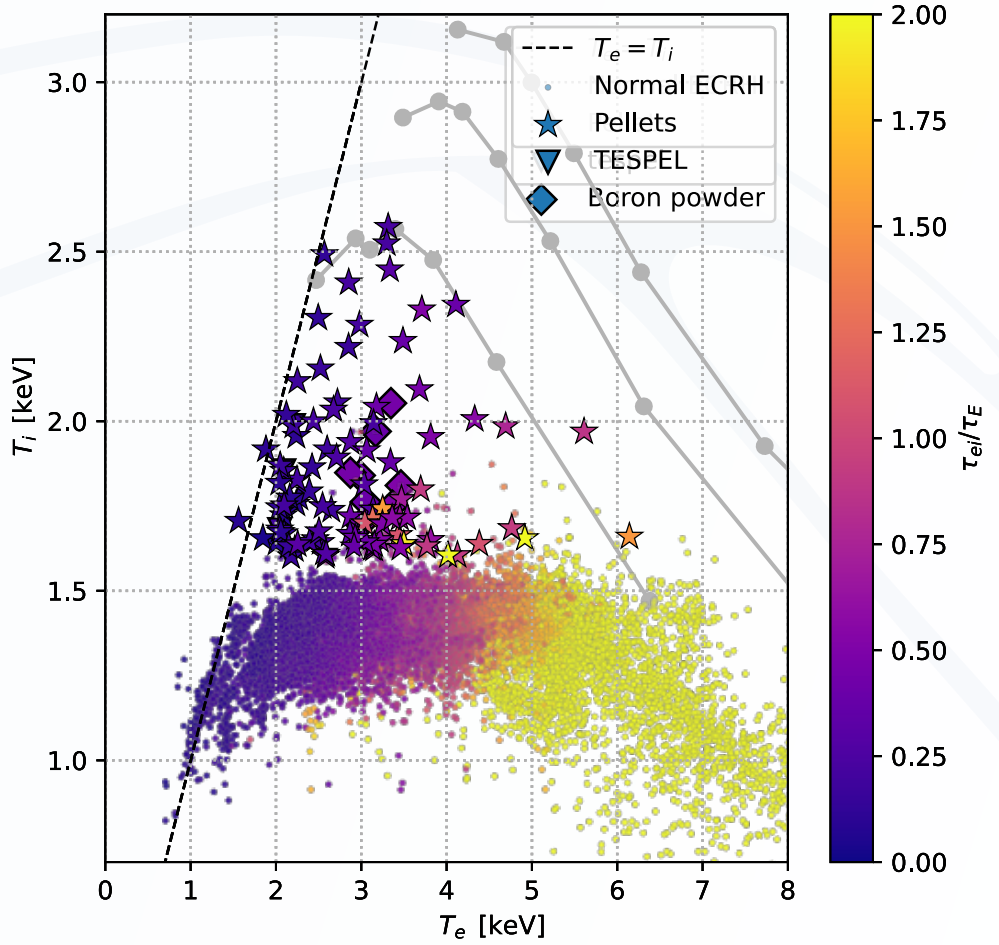

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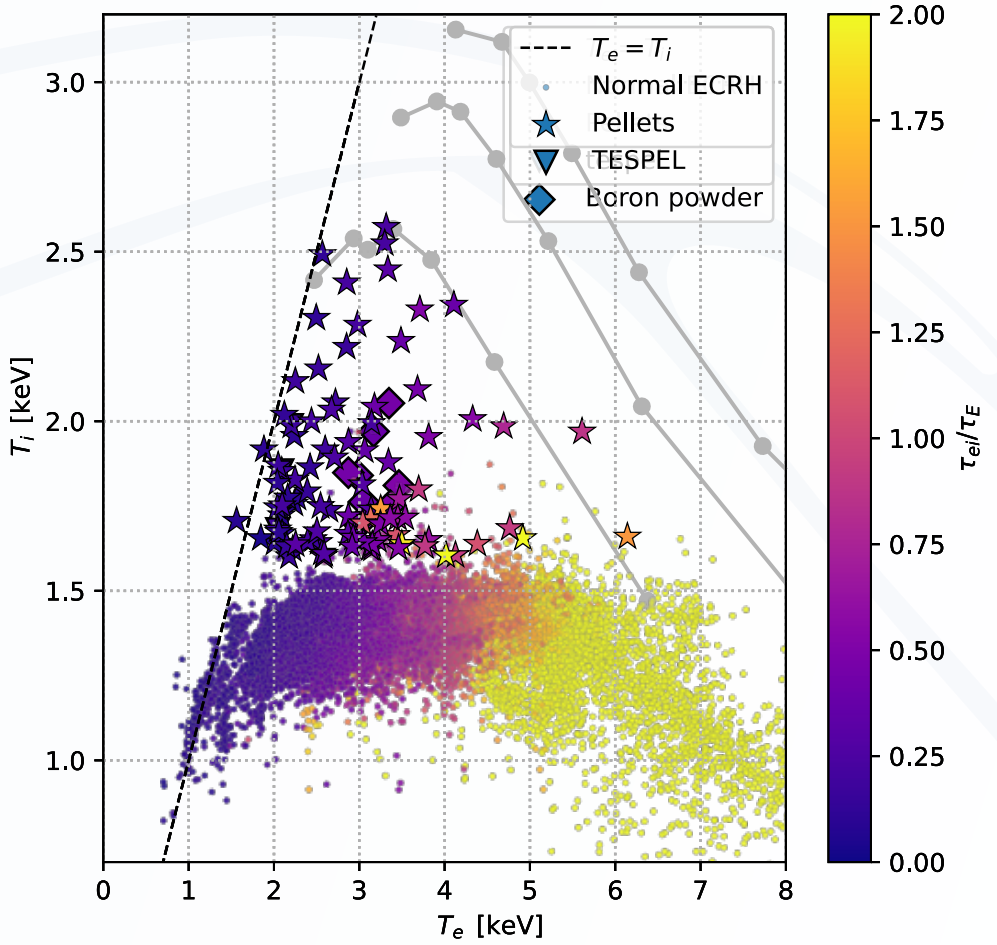

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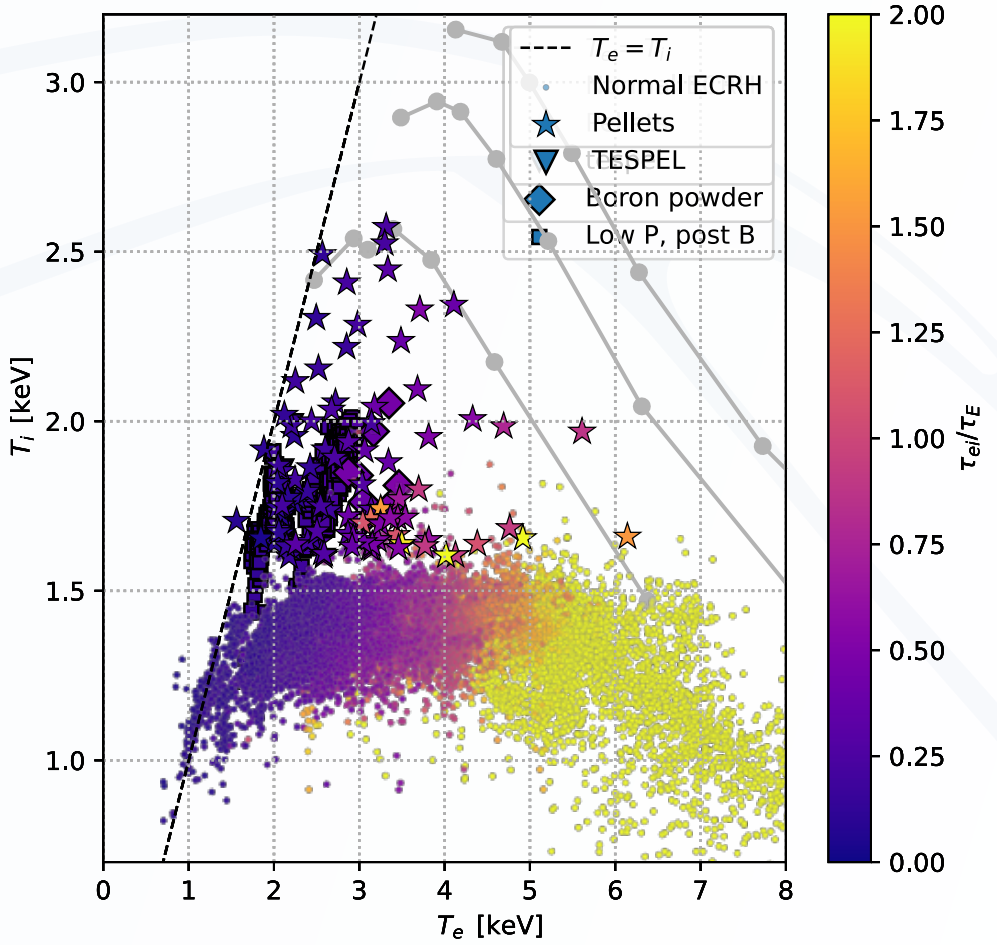

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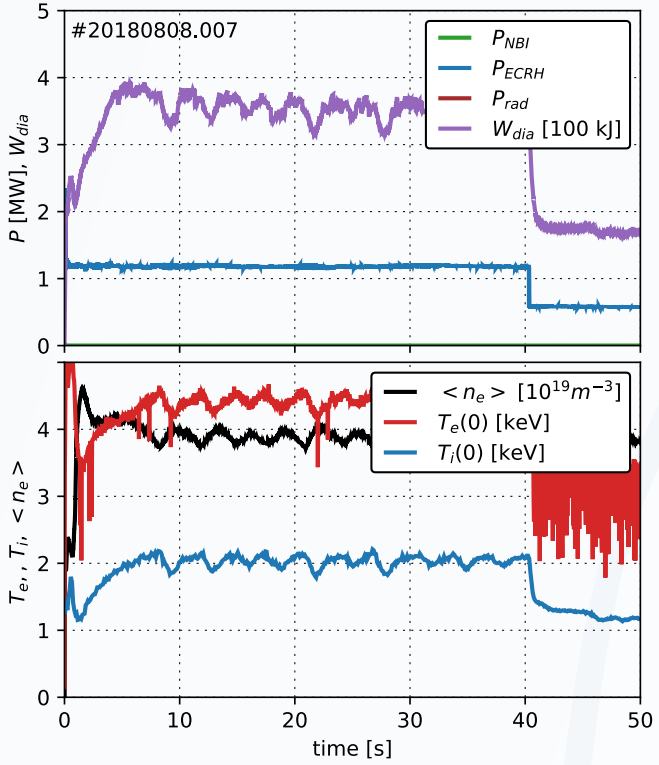

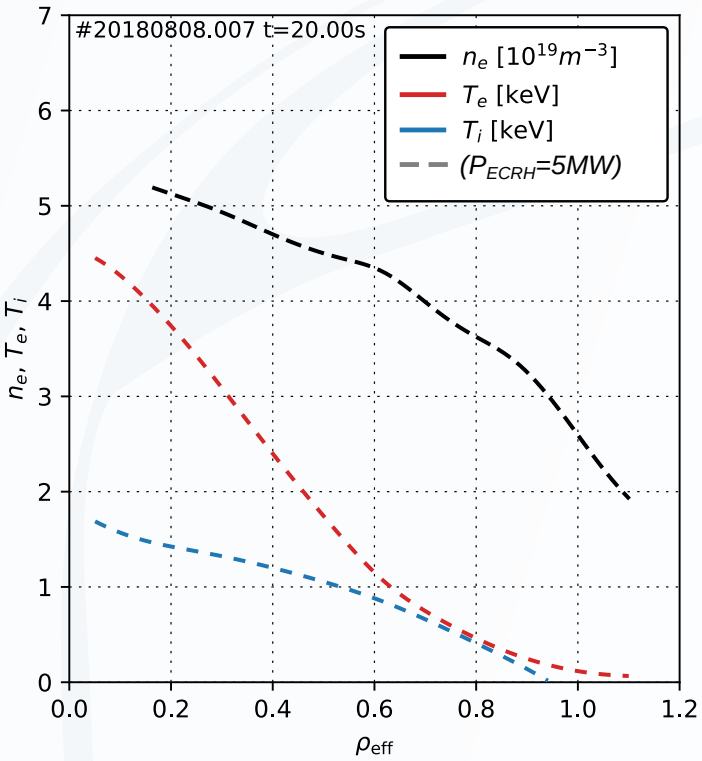

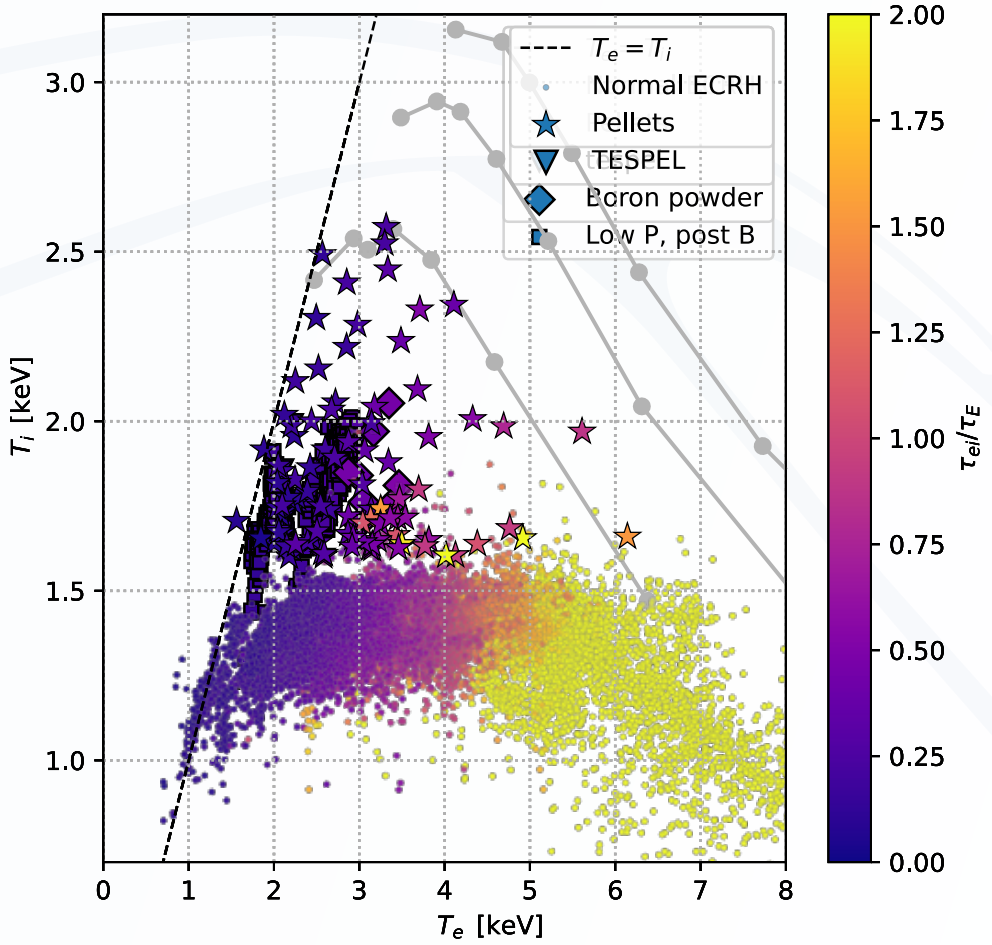

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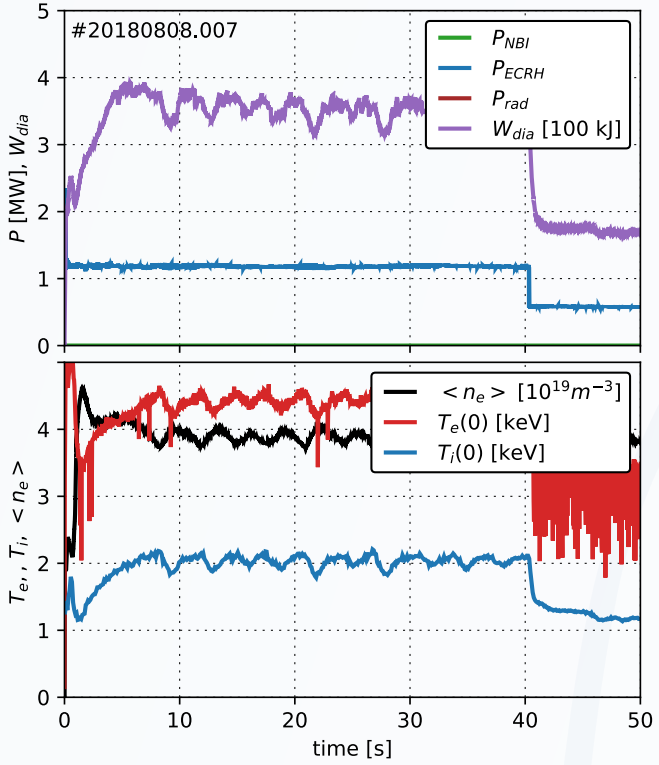

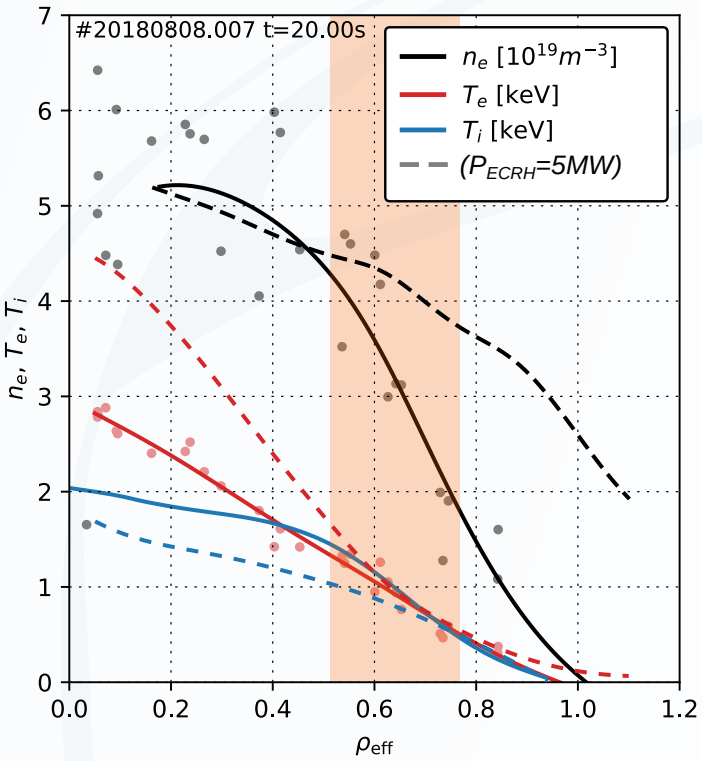

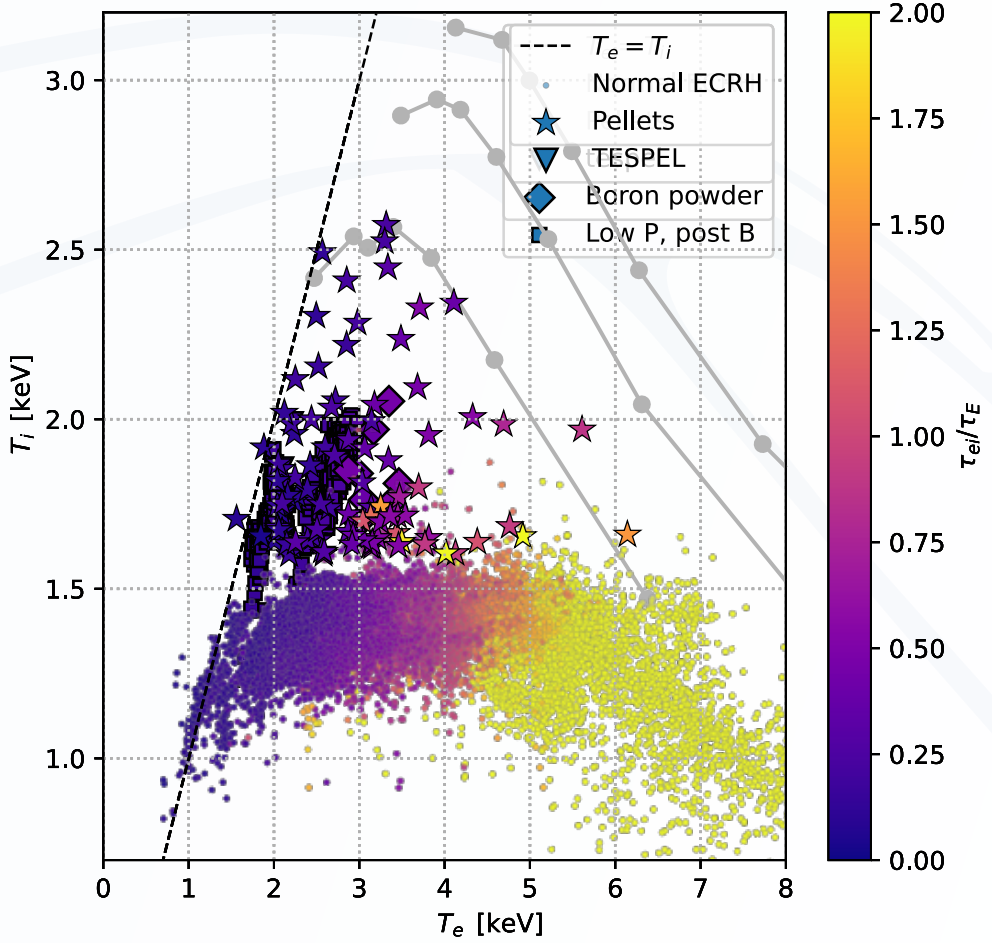

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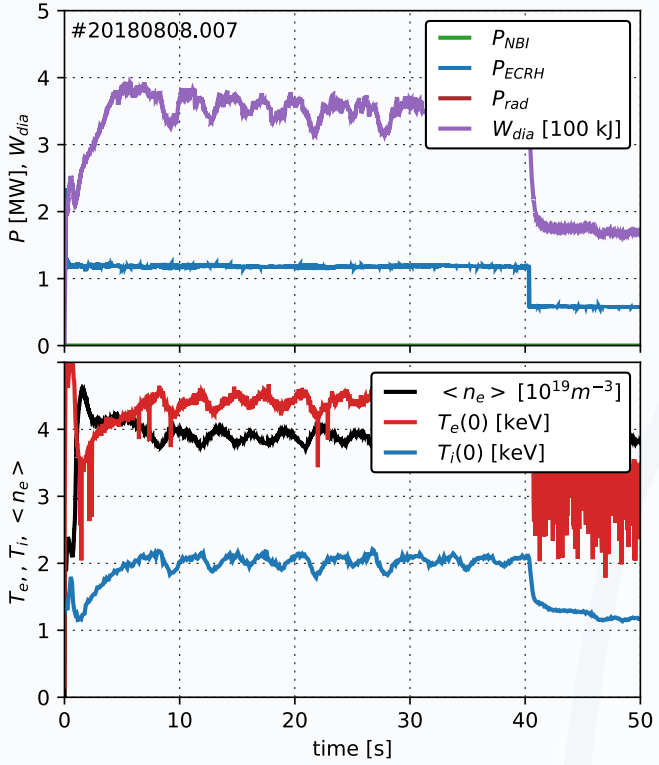
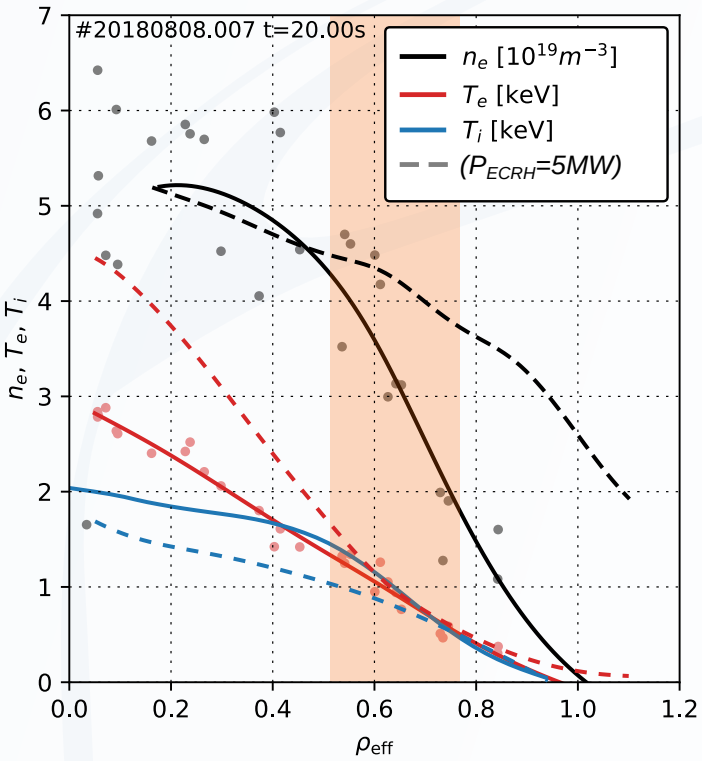
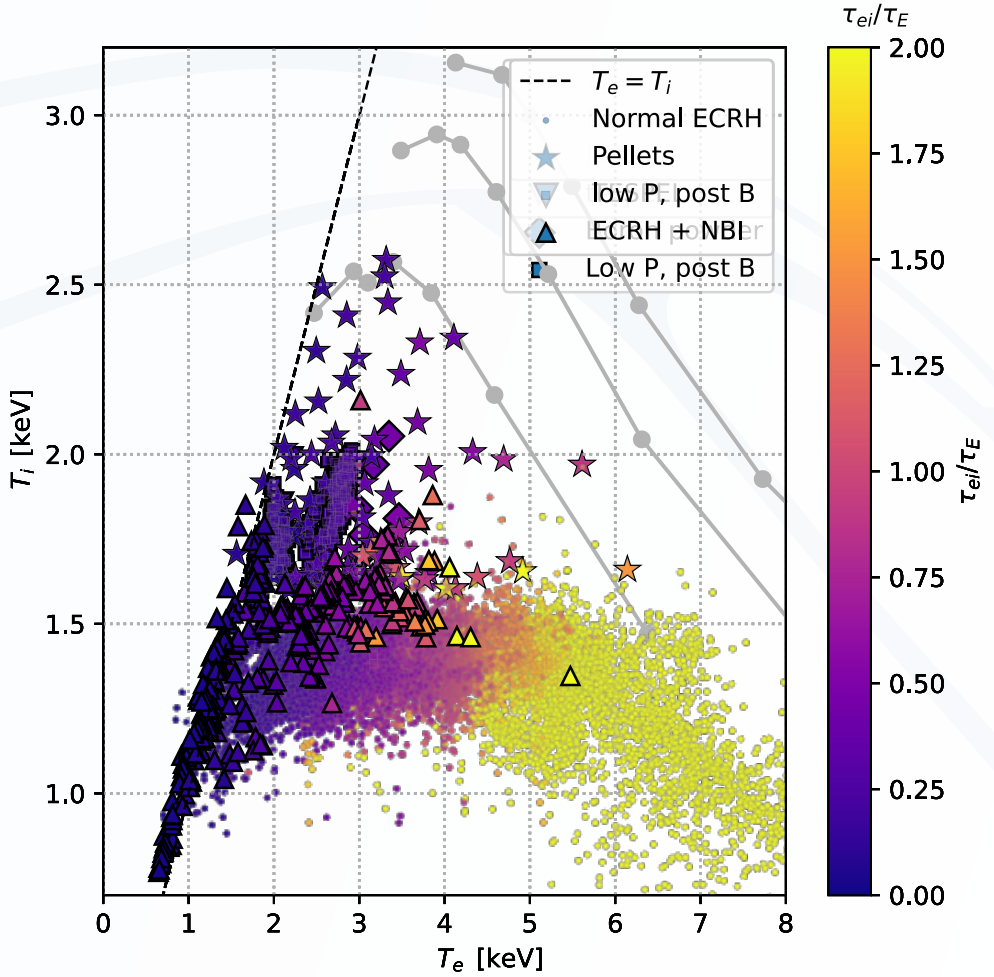
  ... NBI core fuelling?







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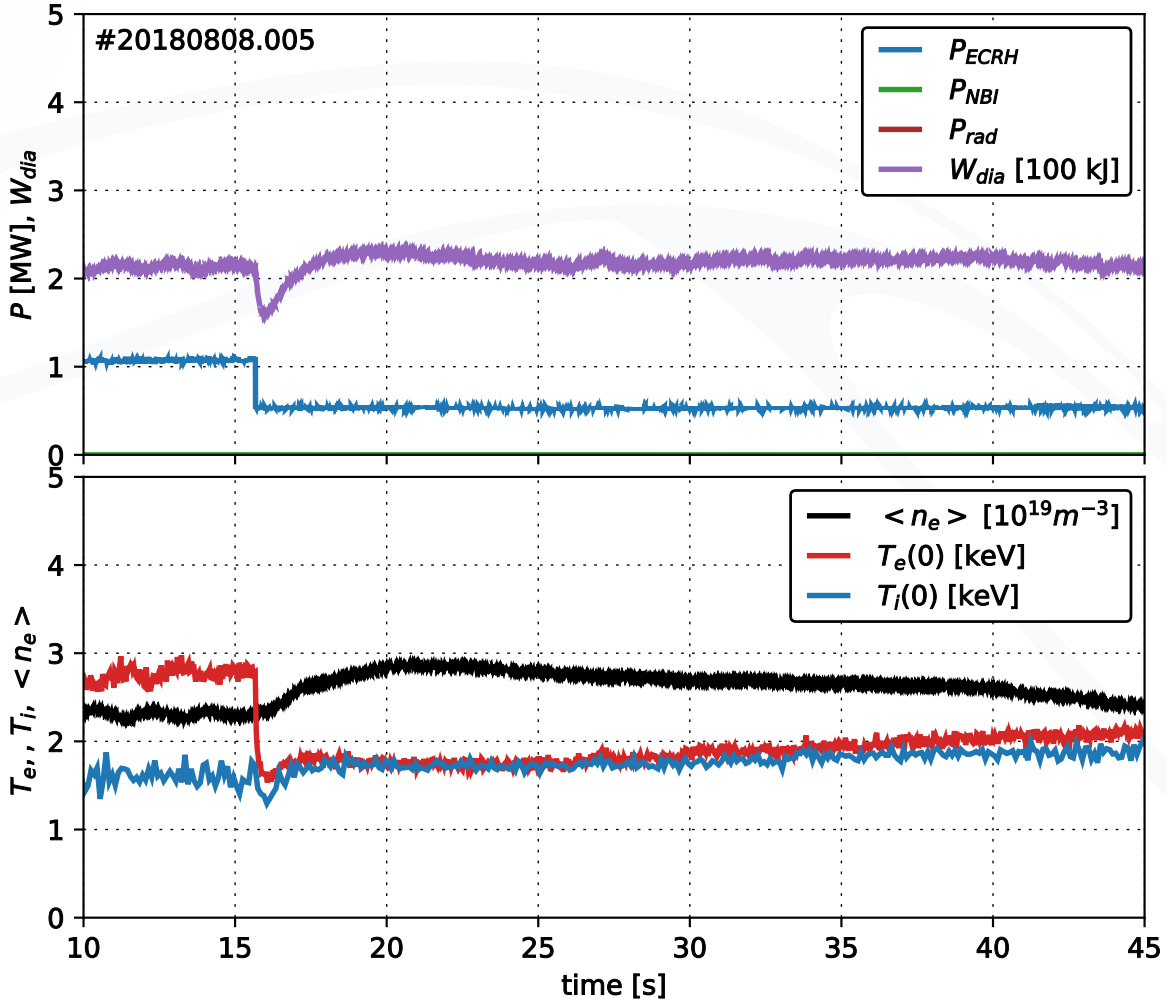

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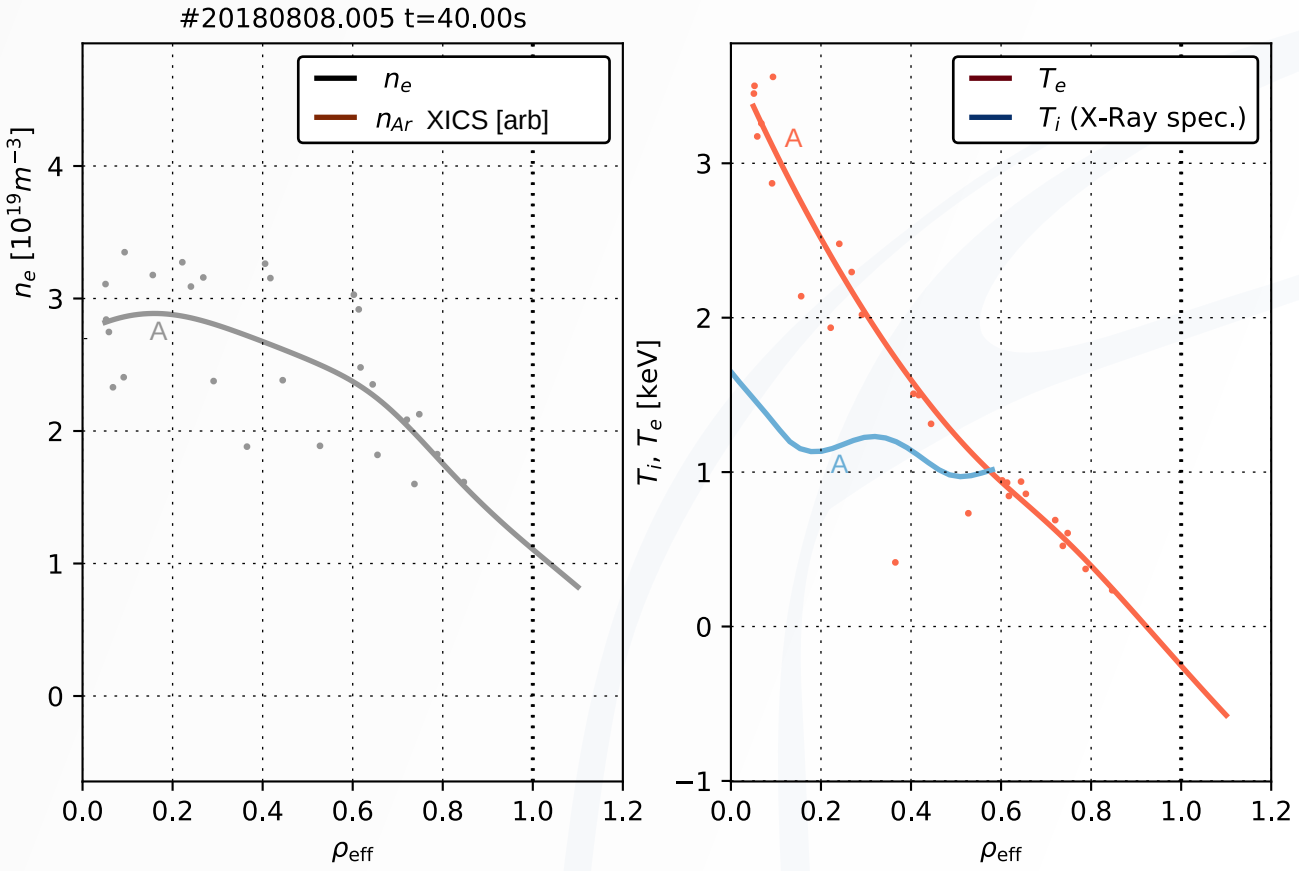

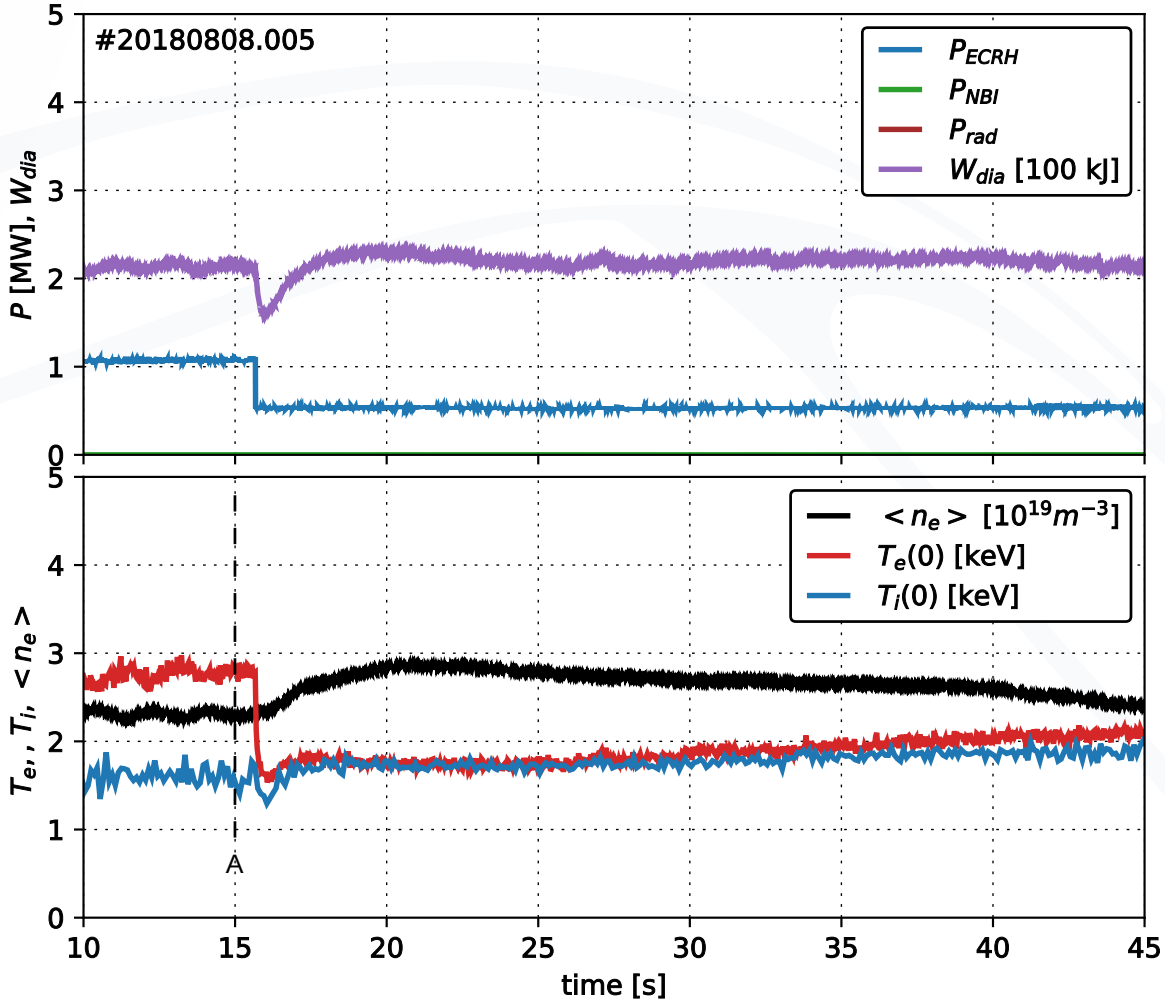

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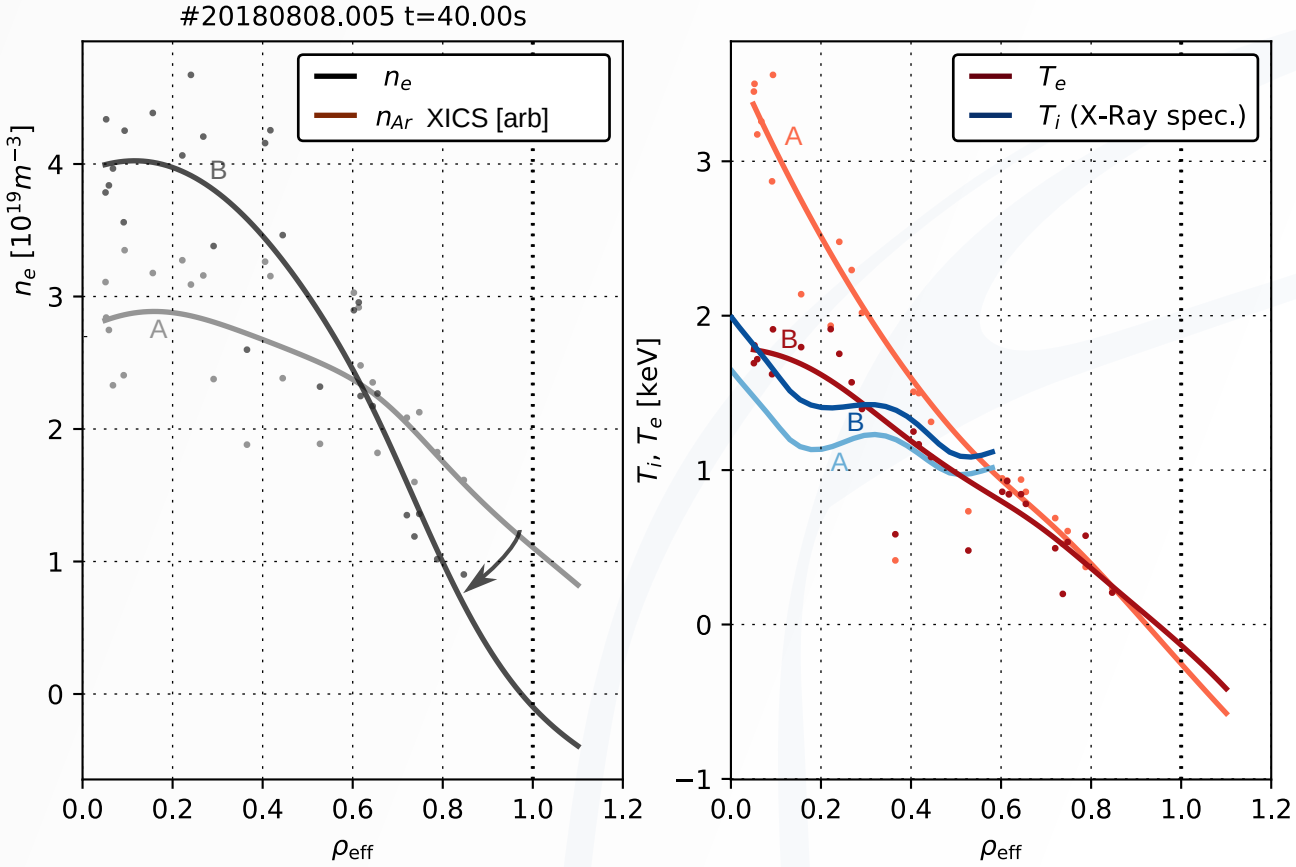

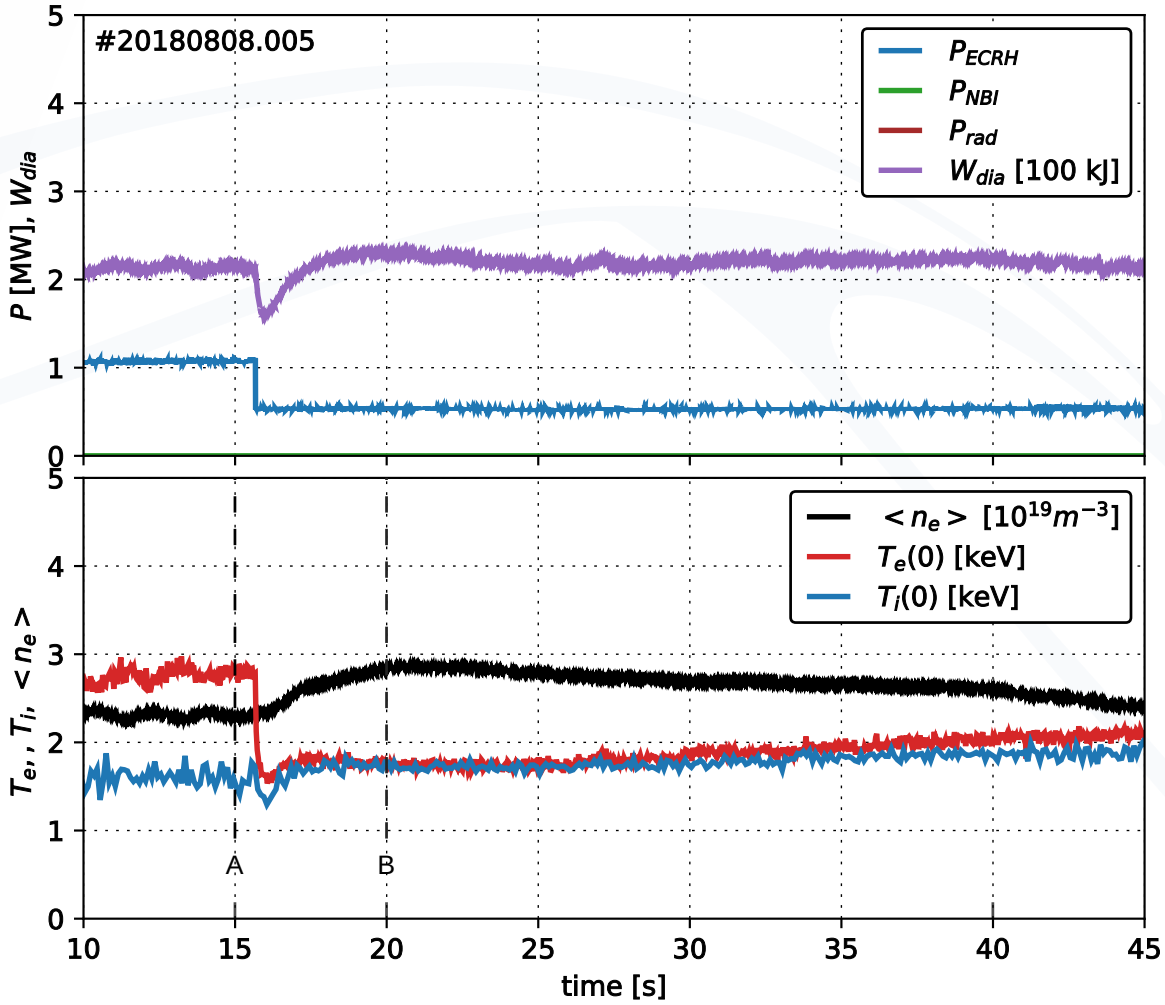

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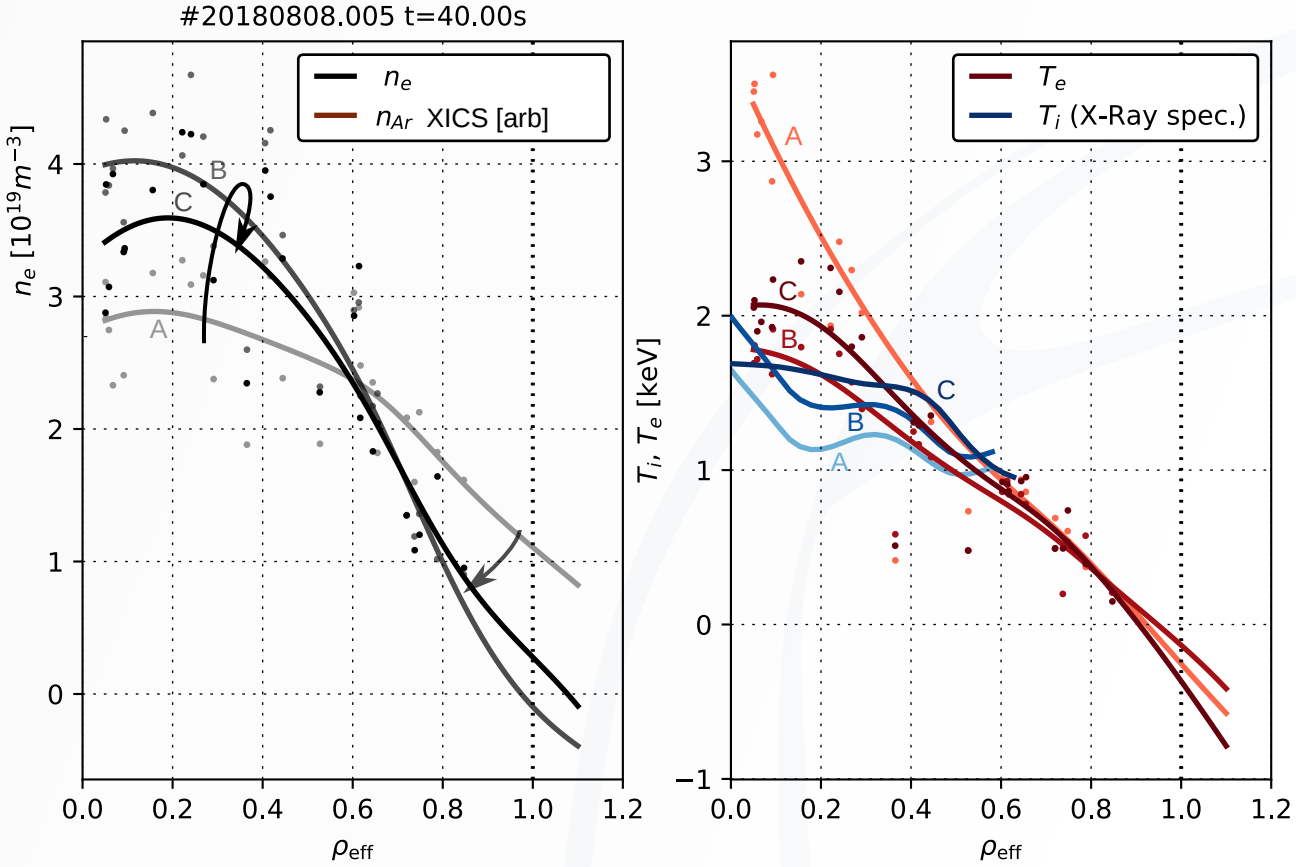

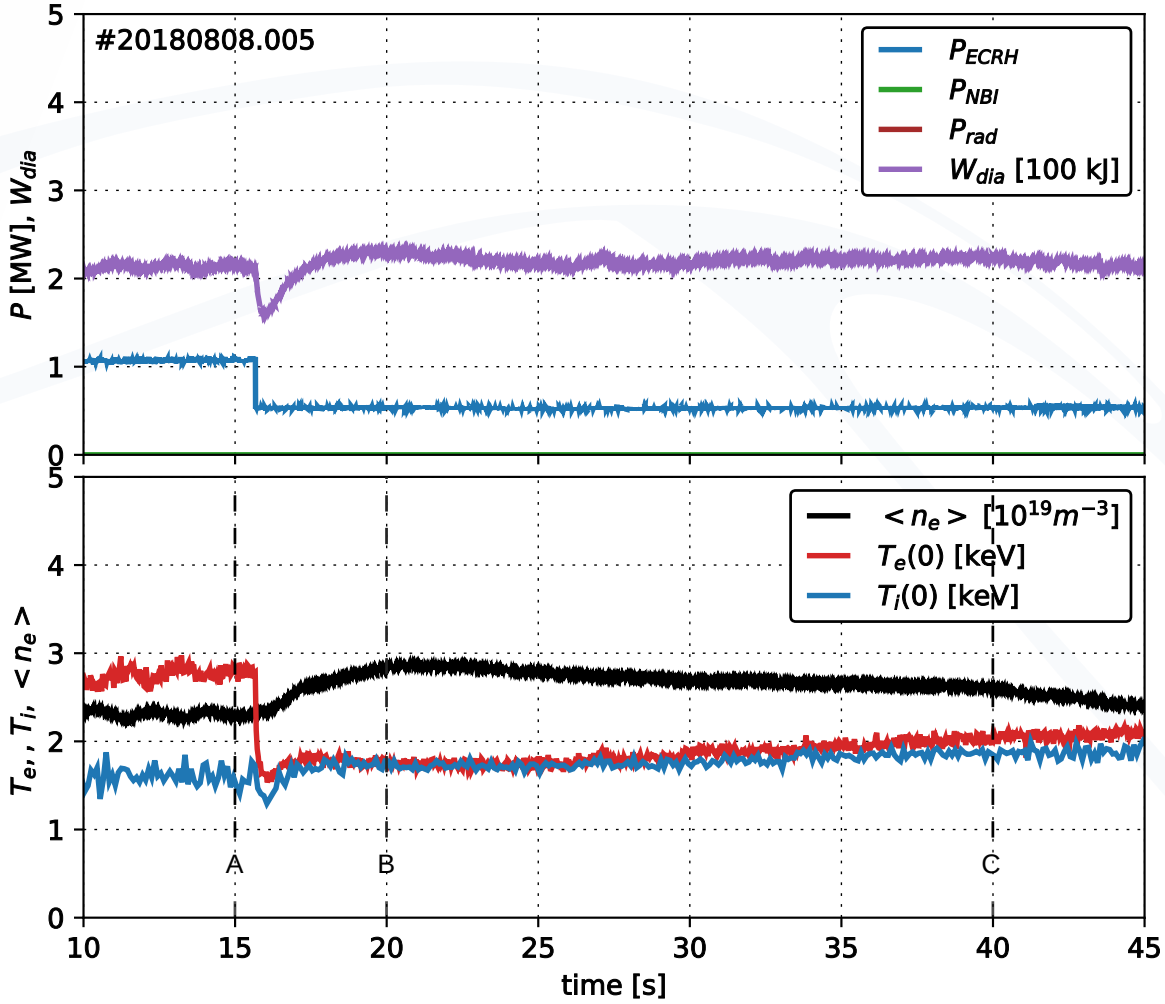

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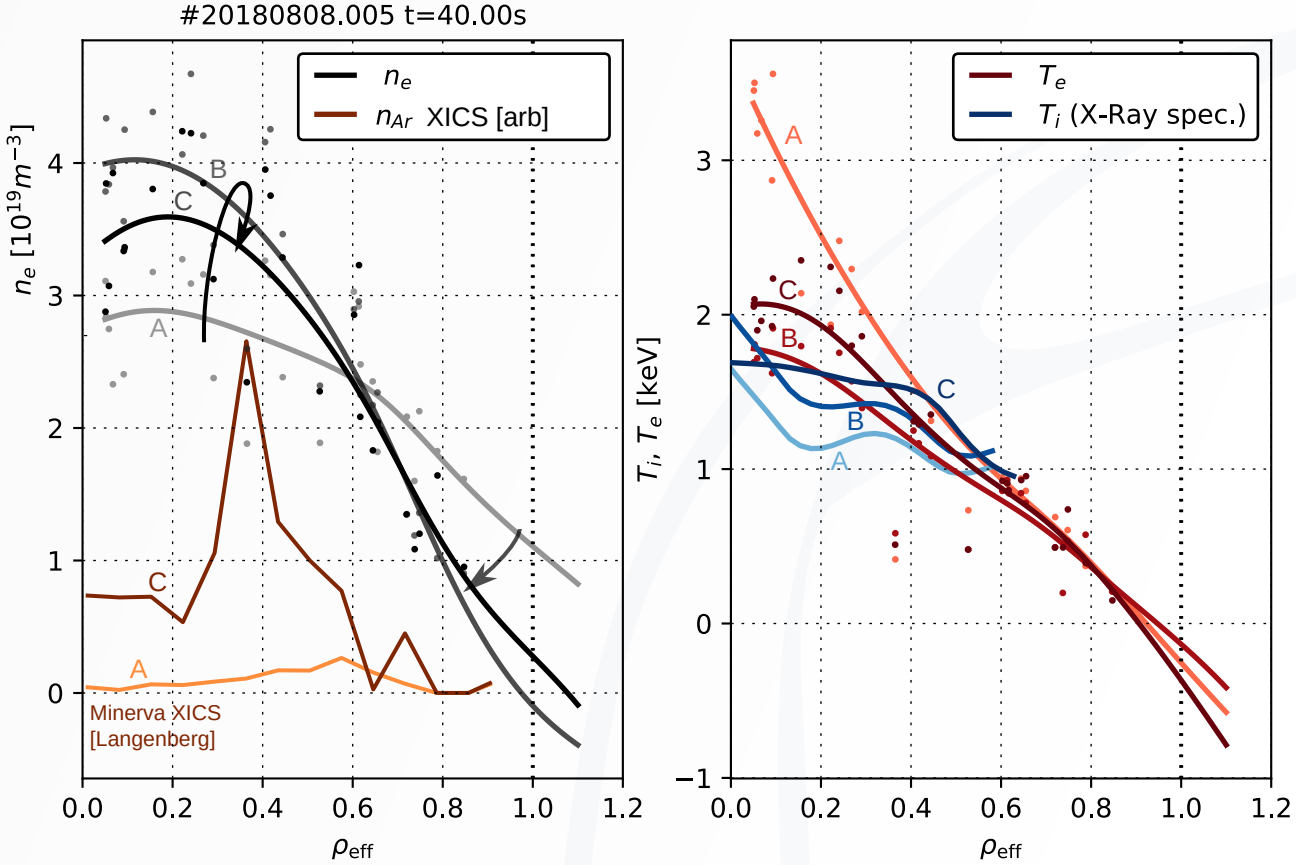
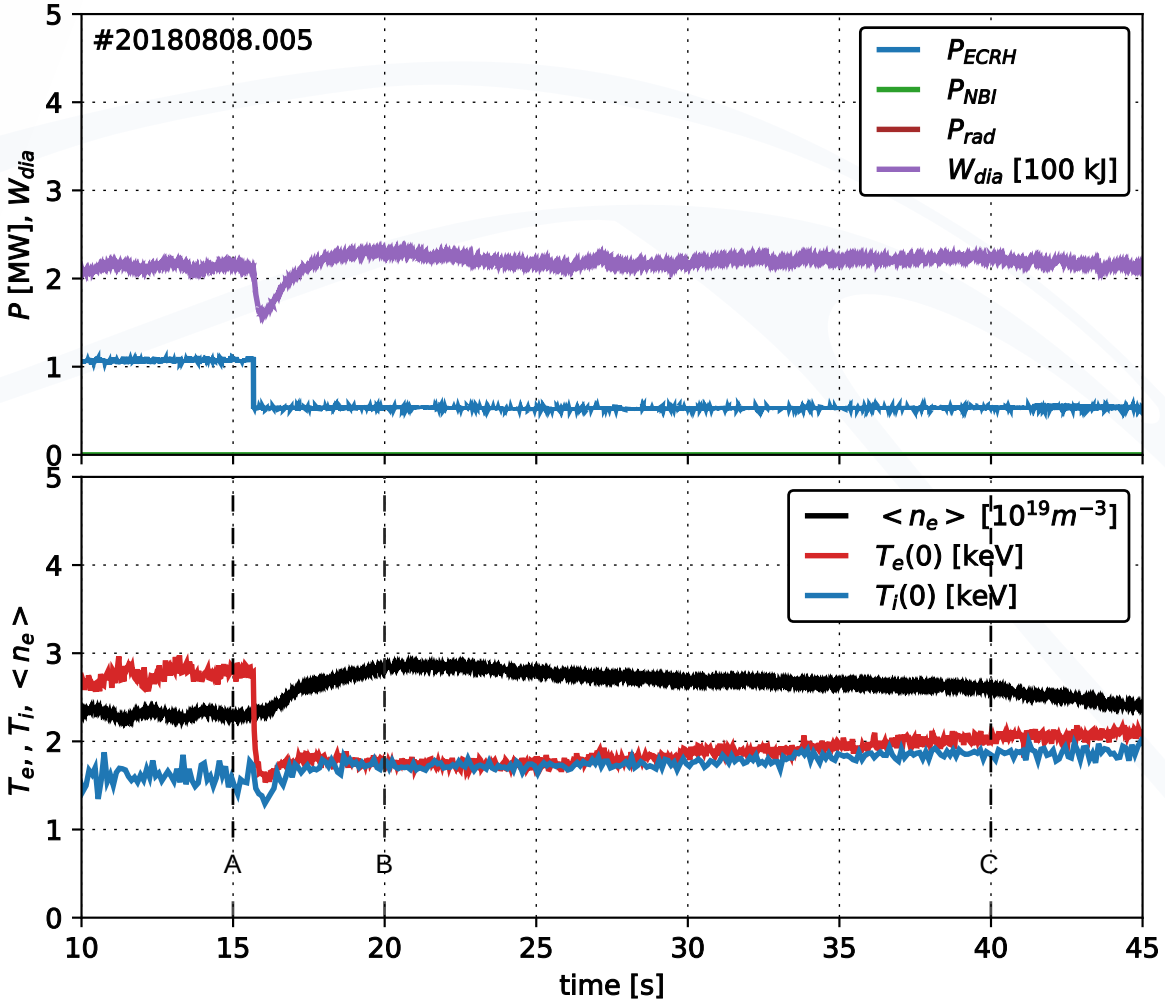
- XICS: n_{Ar16+} increases. Need STRAHL runs to separate T_e.





Fast impurity pinch?

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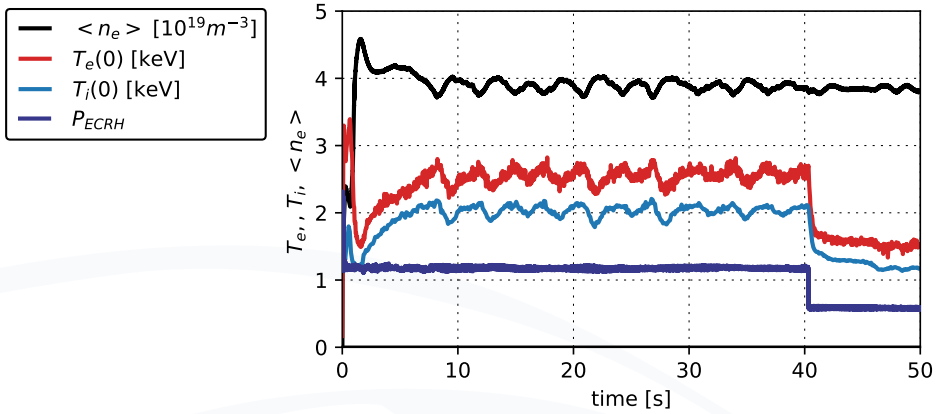

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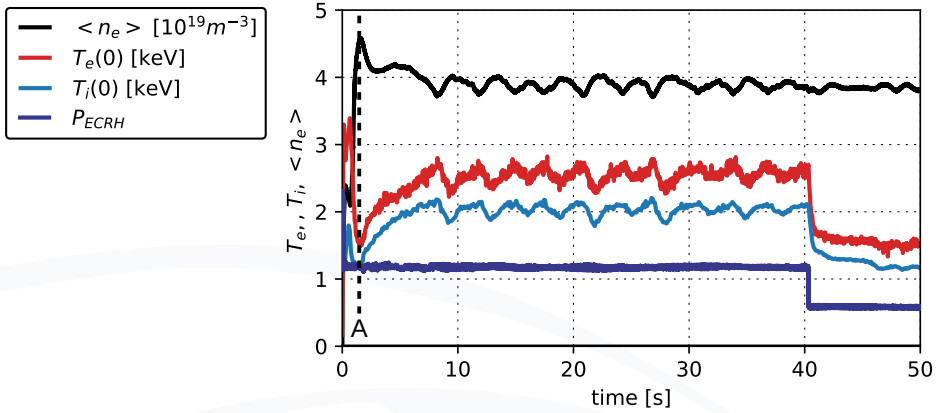

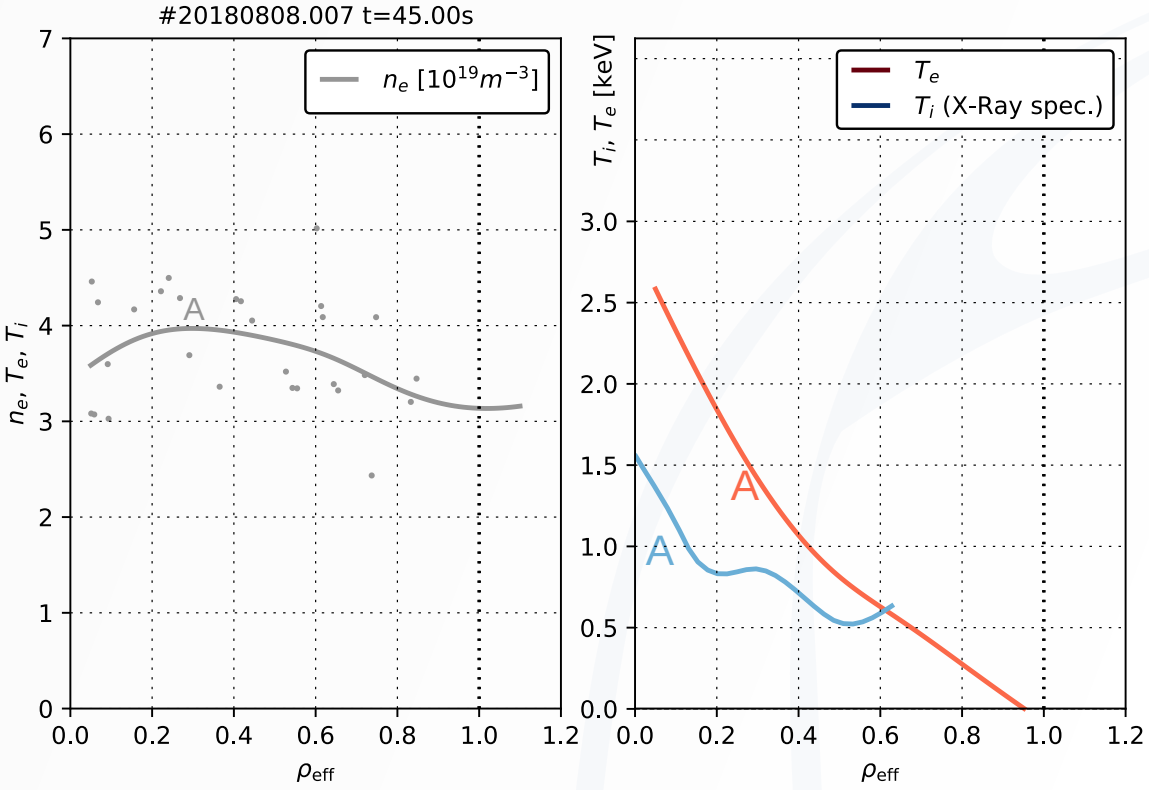

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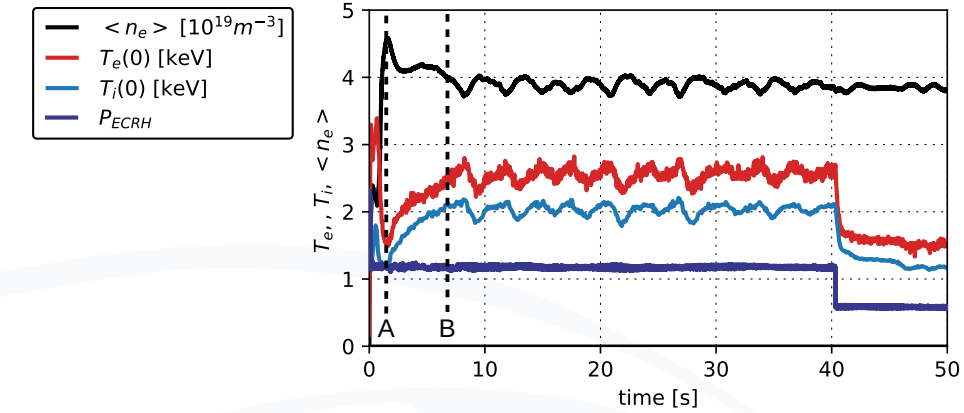
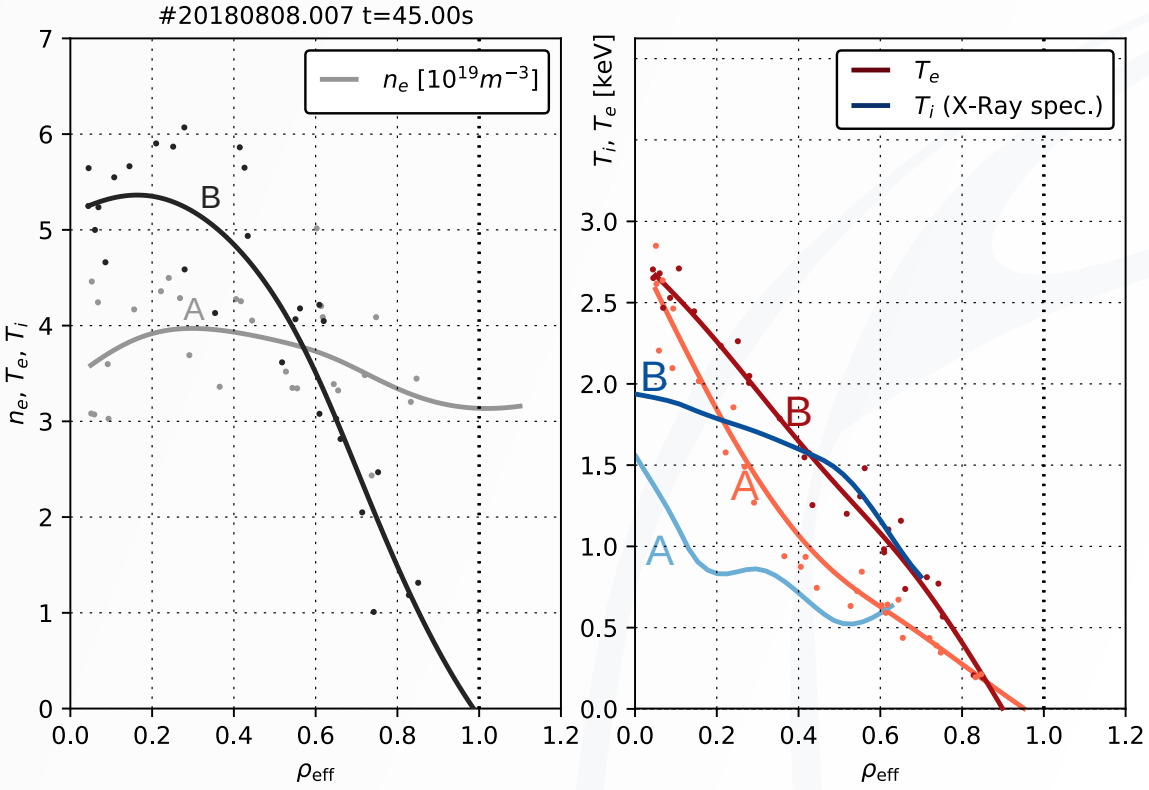
- Electron density peaks and T_i rises over first 6 seconds.
- n_e and T_i oscillate slightly due to small gas puffs.





Fast impurity pinch?

- 180808.007: Starts with 1MW ECRH but has density gradient.
- Electron density peaks and T_i rises over first 6 seconds.
- n_e and T_i oscillate slightly due to small gas puffs.
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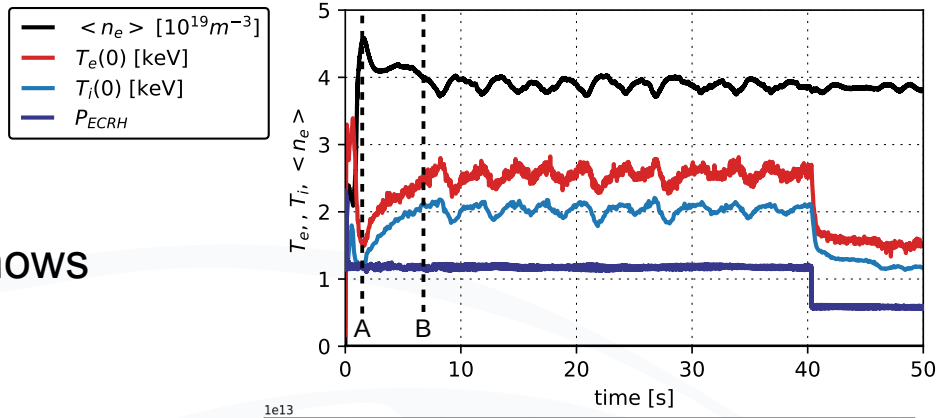

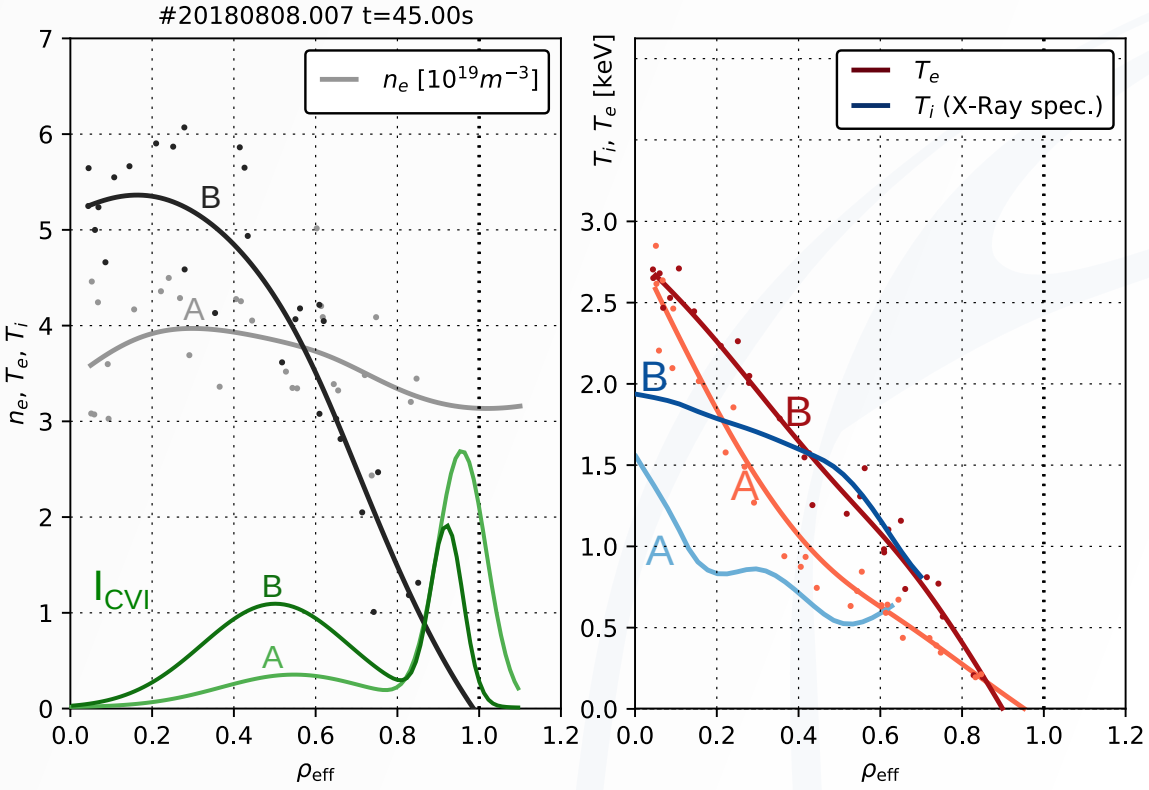

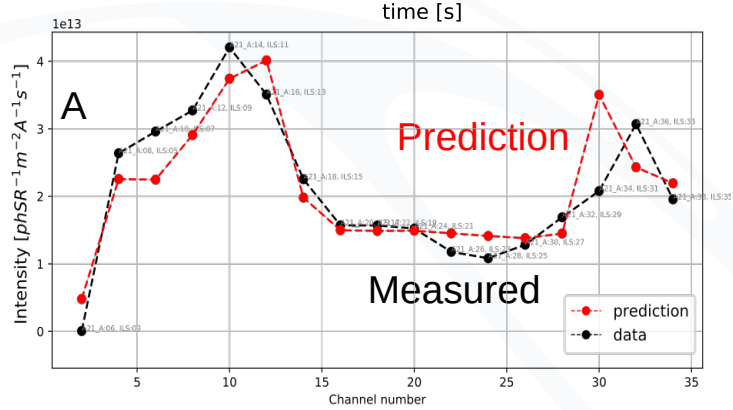

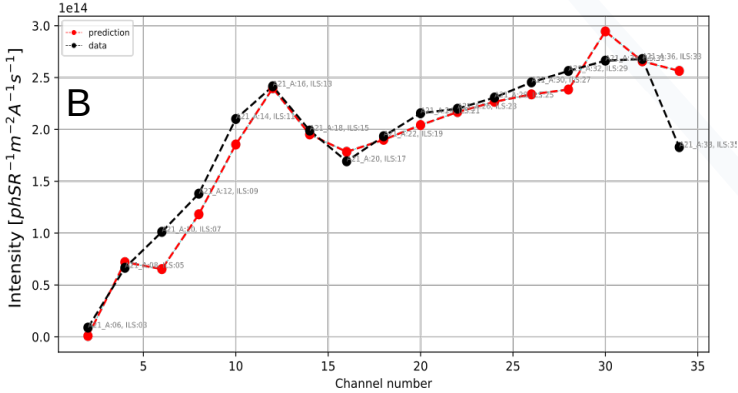

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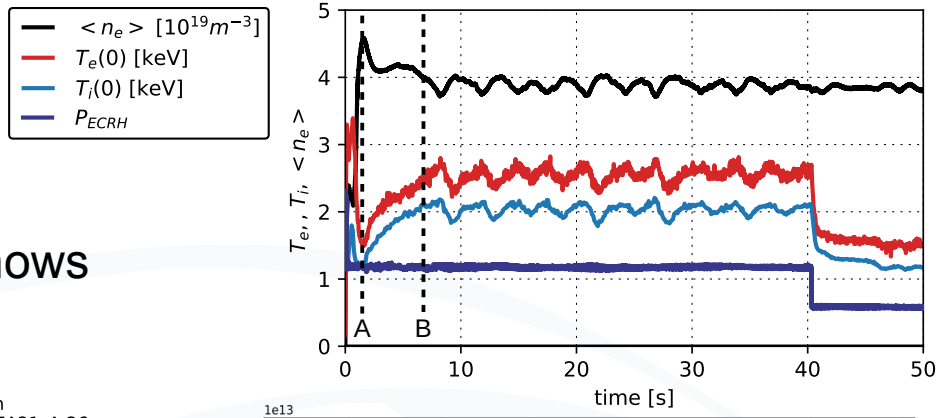
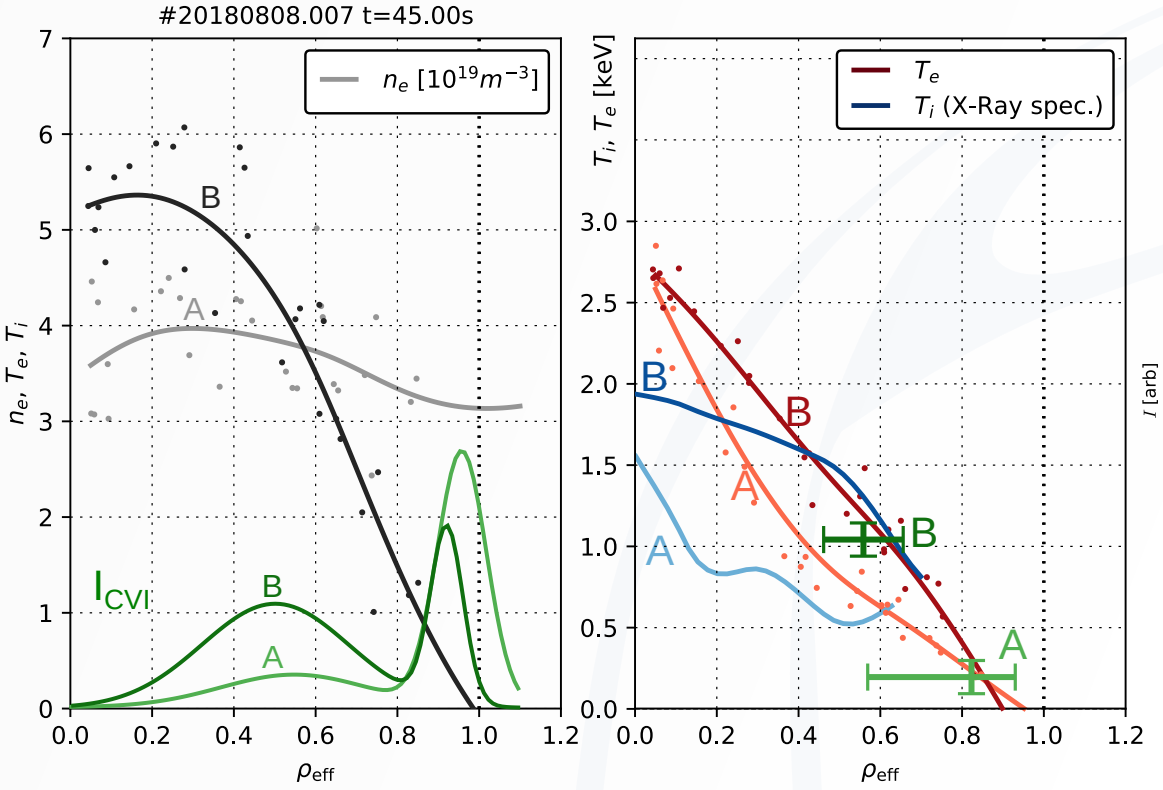
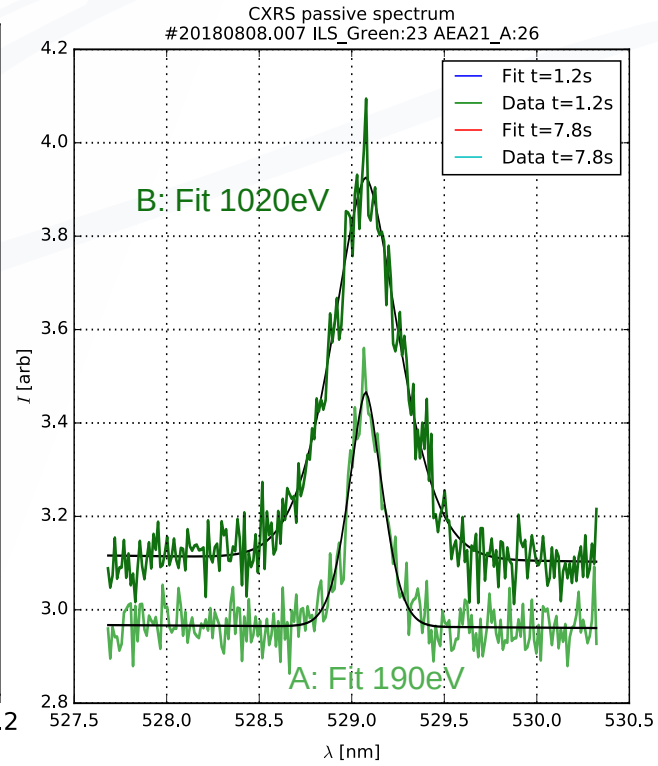
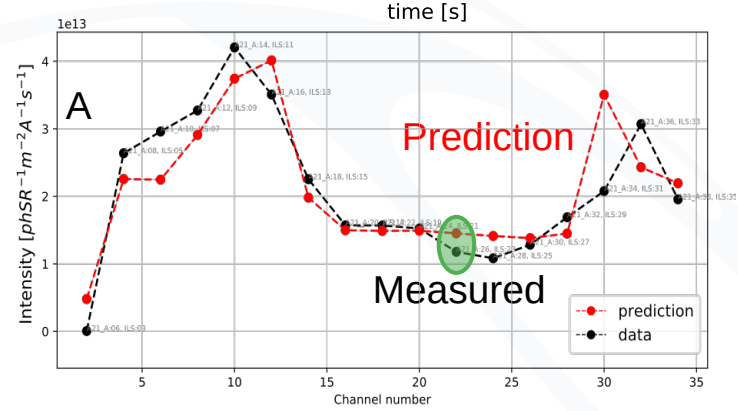
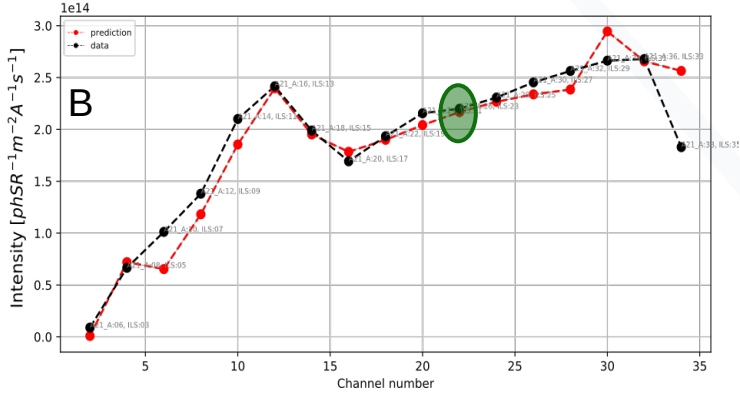




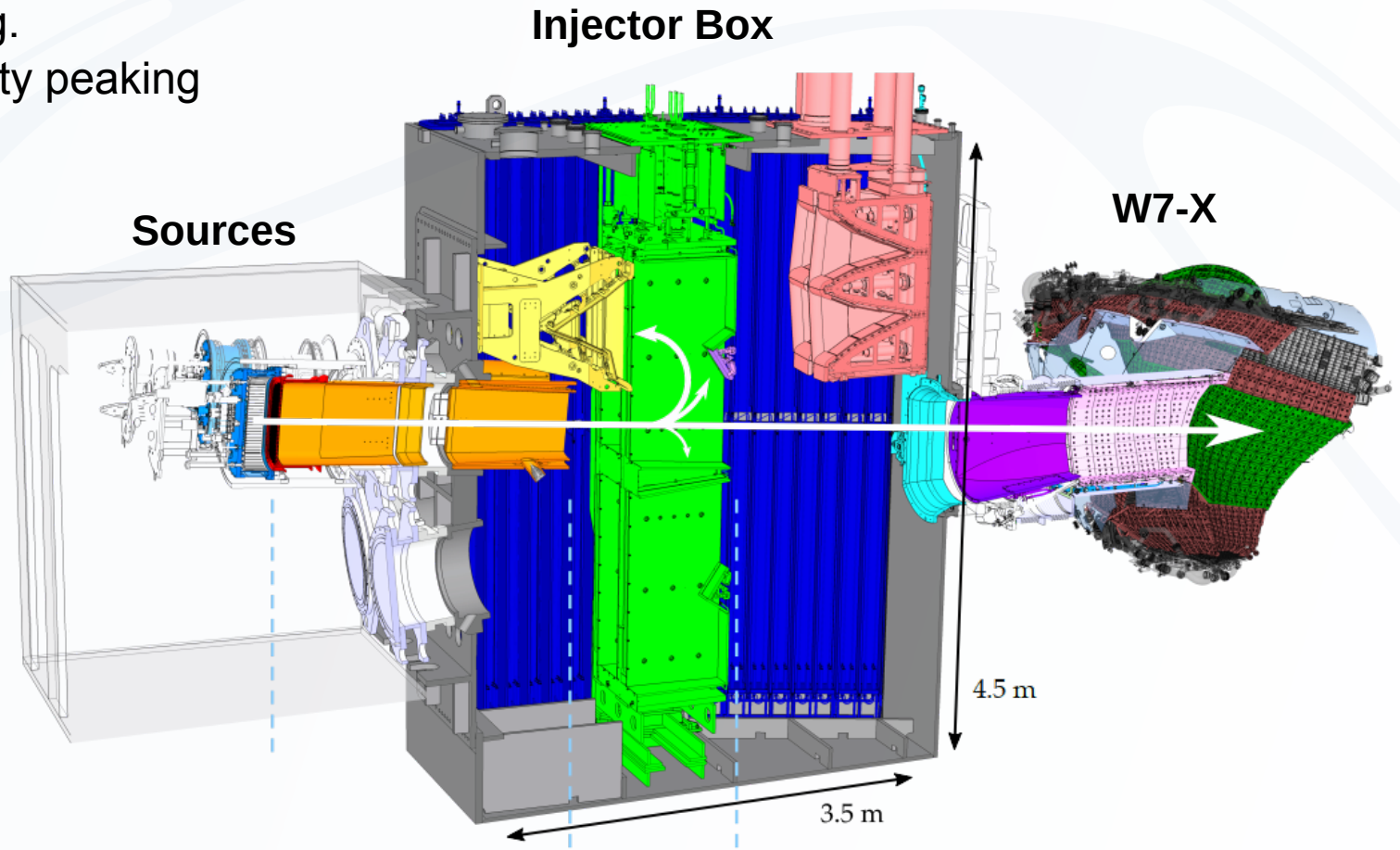






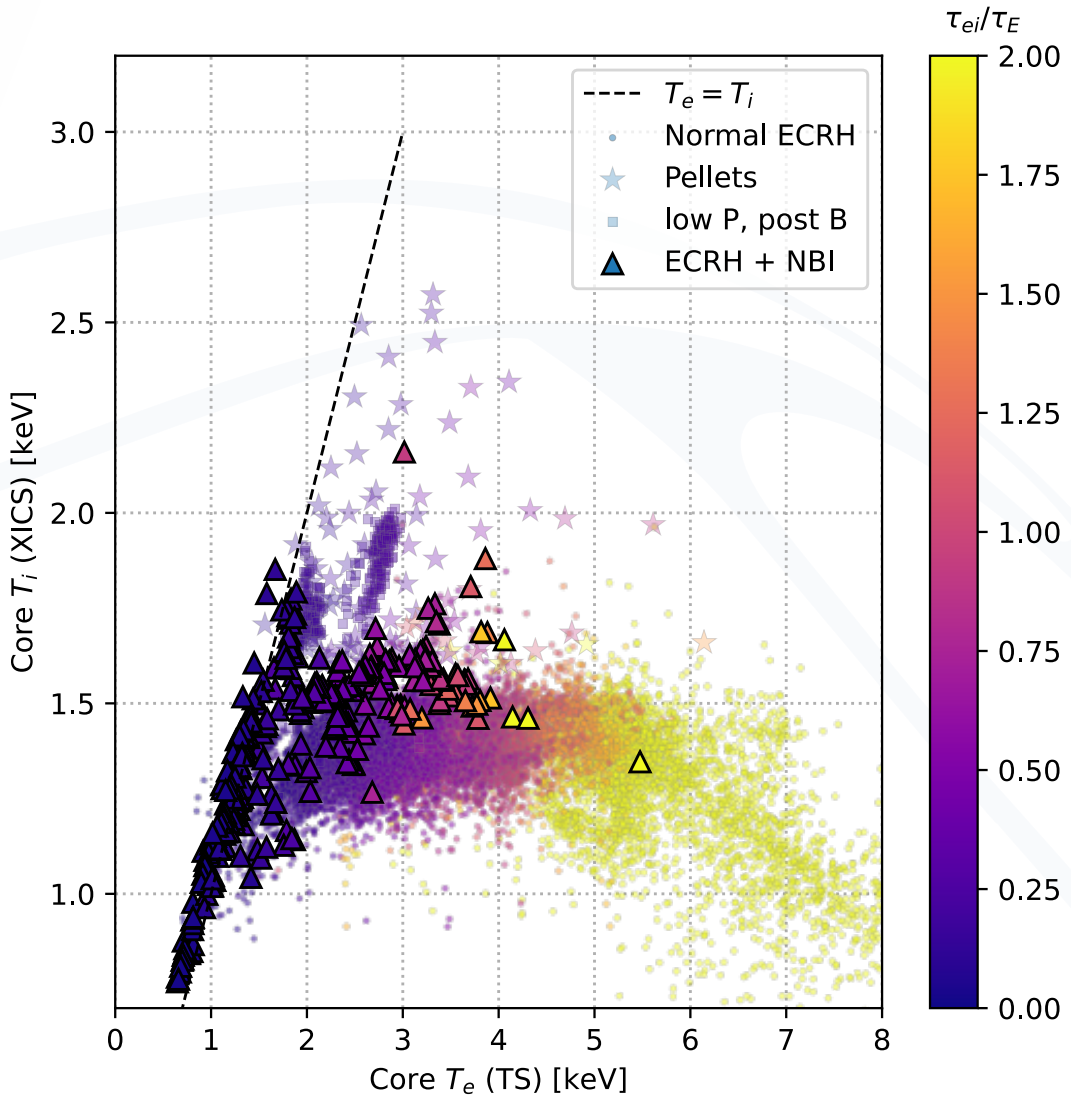
Neutral Beam Injection

- In the last campaign, the W7-X NBI system was comissioned
  - 2x 2.5MW radial sources of H injection at ~55kV
  - 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?



NBI : ECRH ratio

- NBI mostly supplementary to moderate-high ECRH power.



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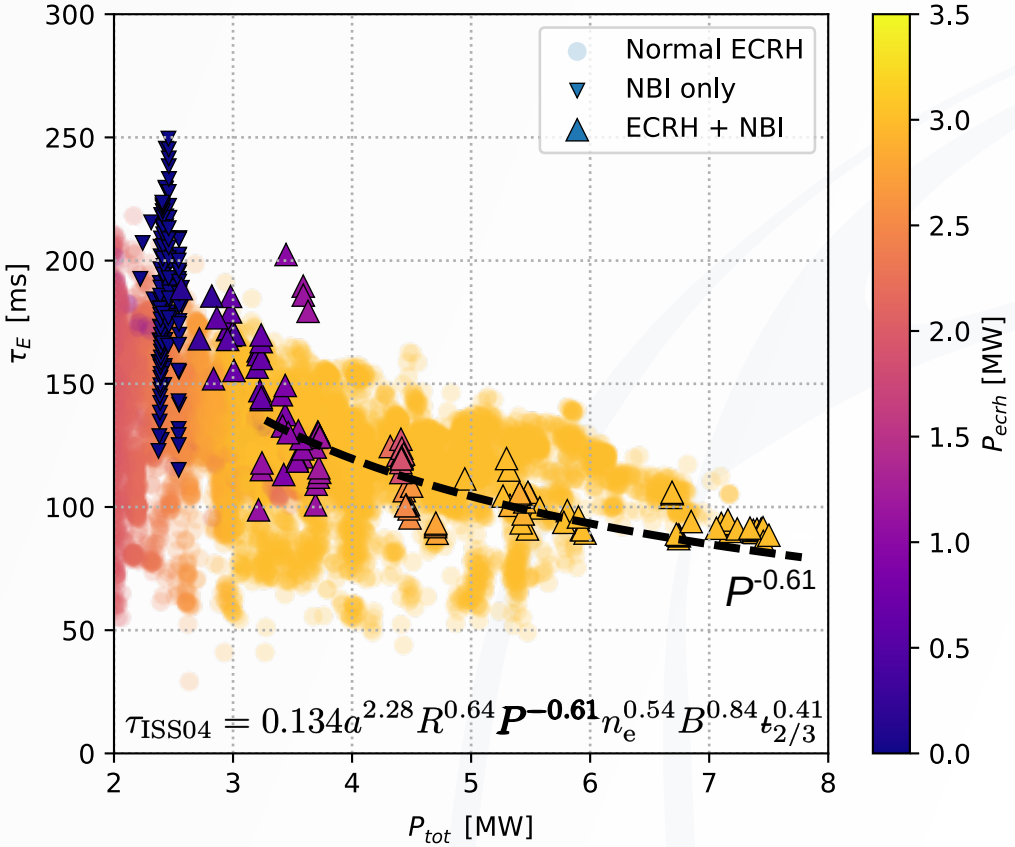
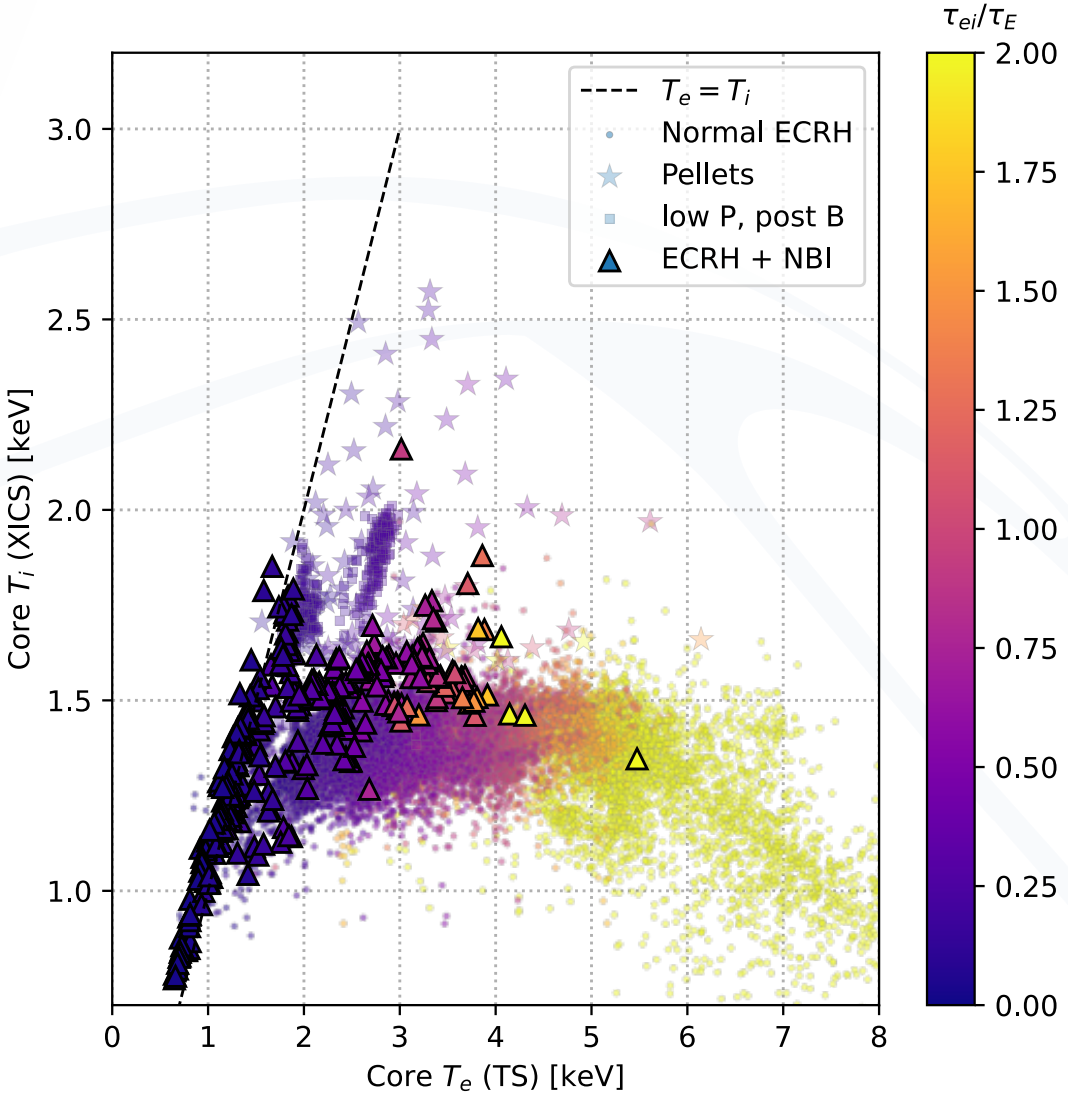
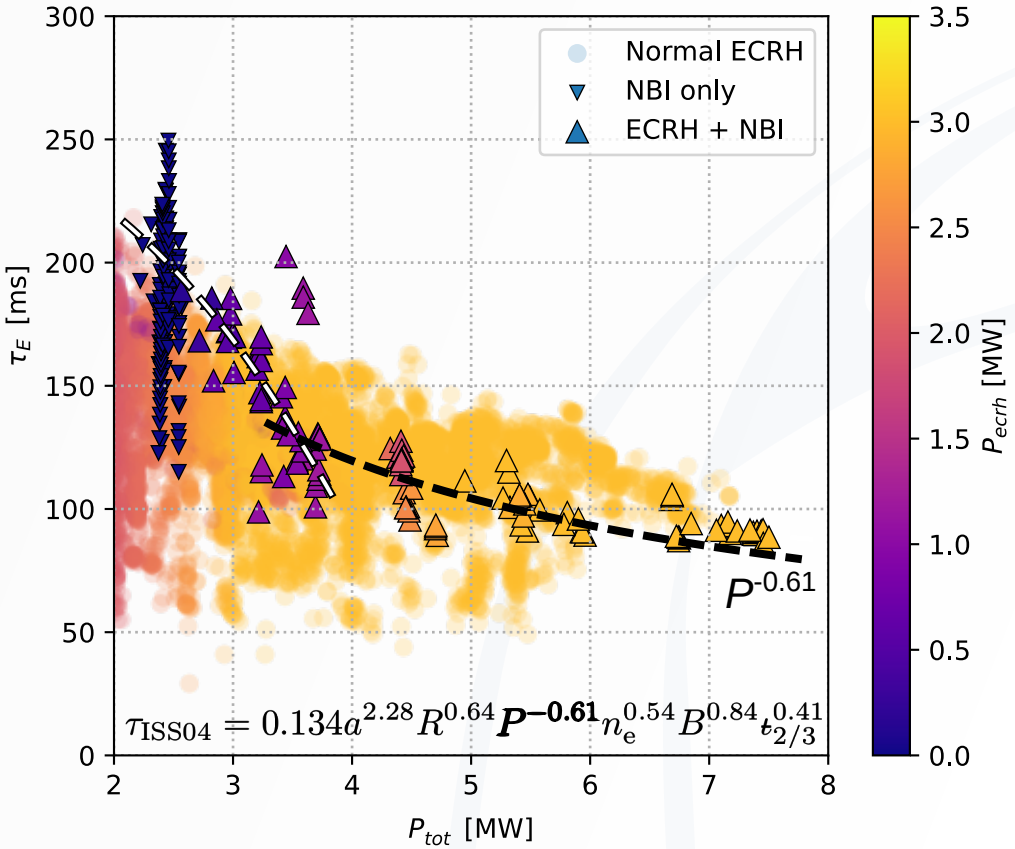
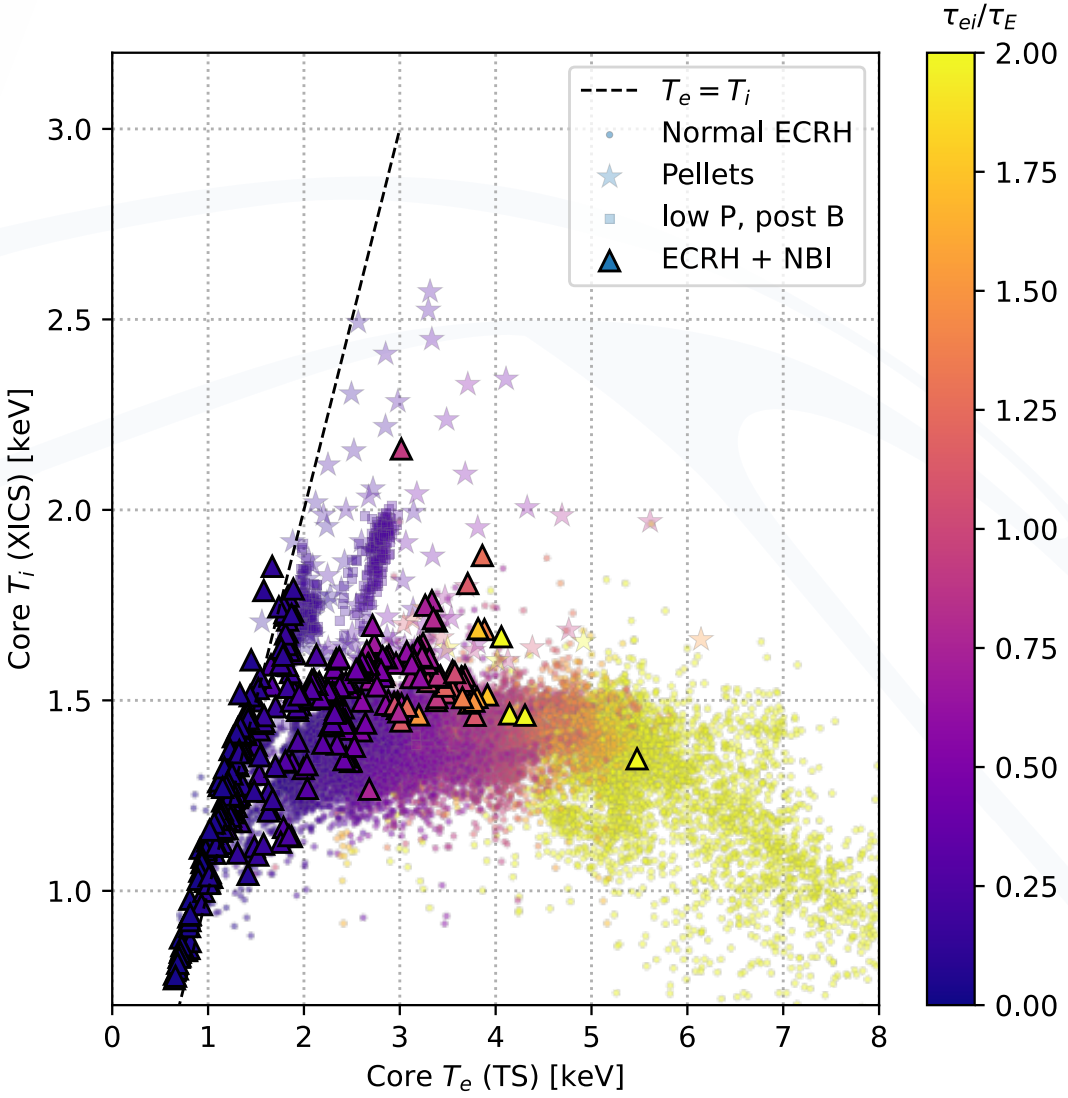




NBI : ECRH ratio

- NBI mostly supplementary to moderate-high ECRH power.
- Highest τ_E plasmas at zero or low ECRH power.
- Scaling changes around P_{ECRH} ~ 1MW





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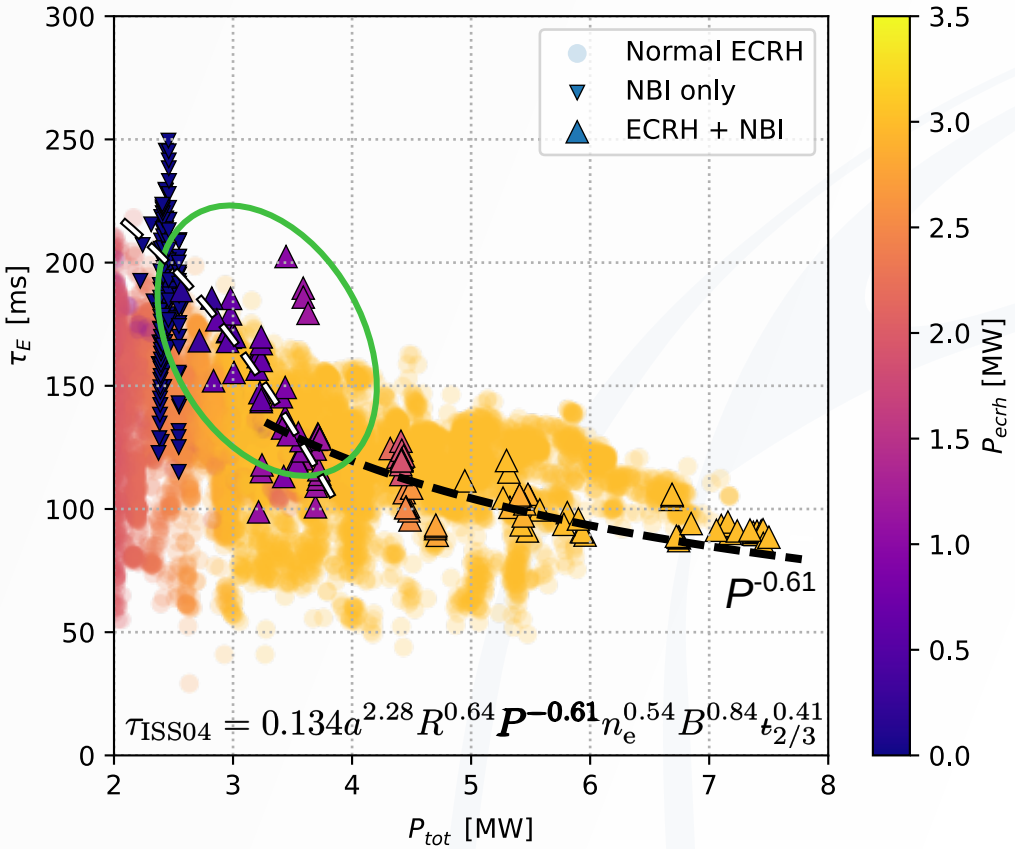

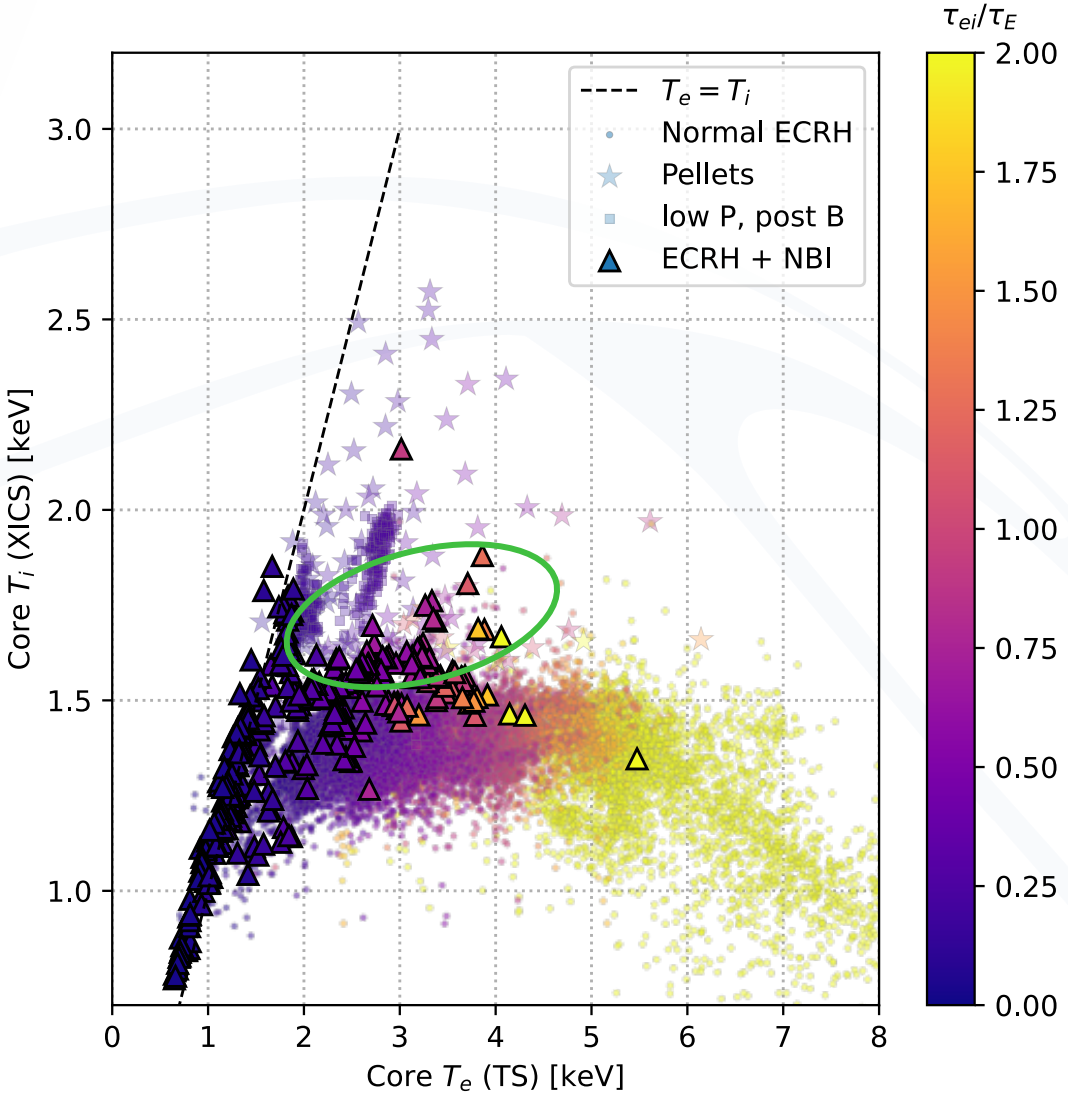

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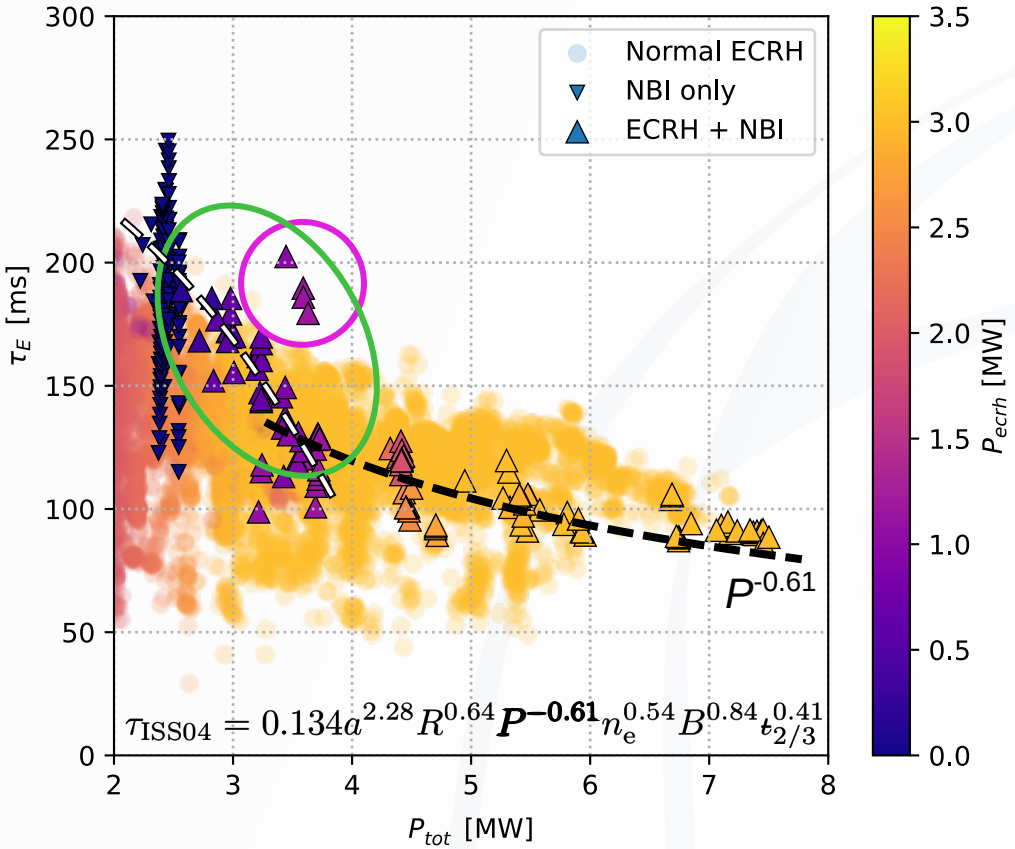
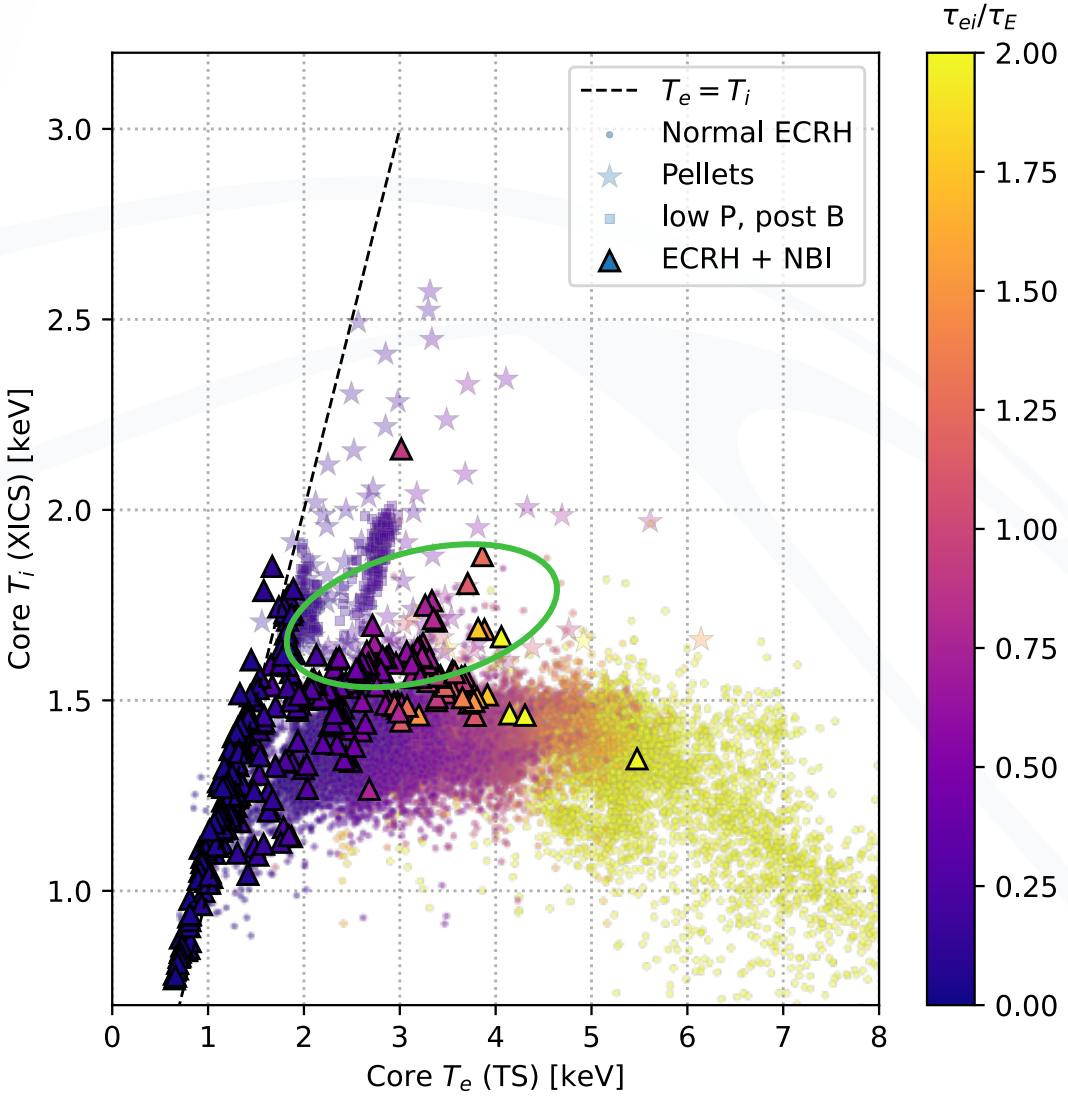
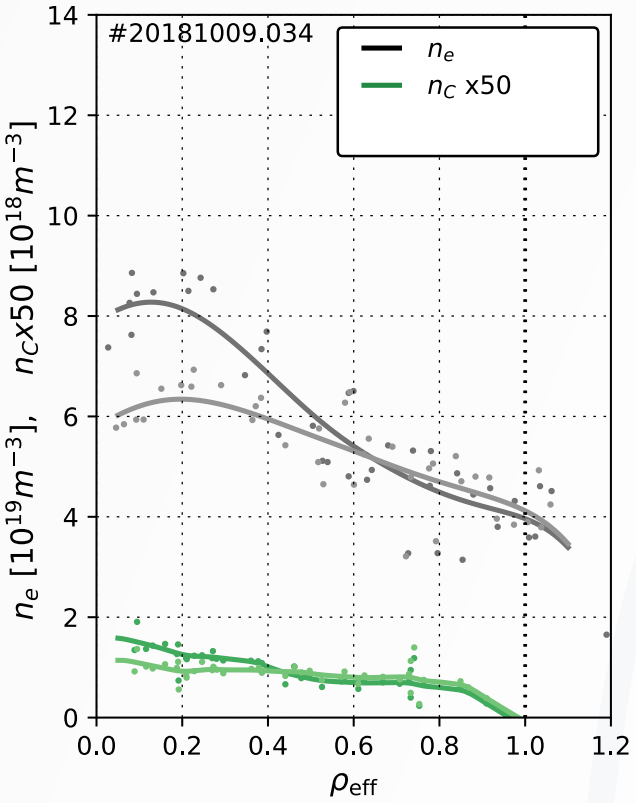
- Highest stationary T_i above clamping with NBI + 1MW ECRH.

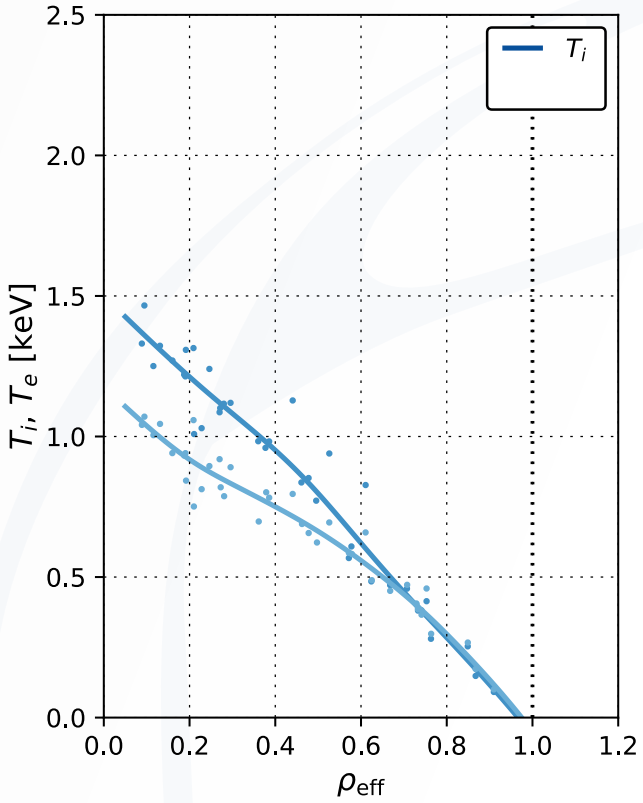


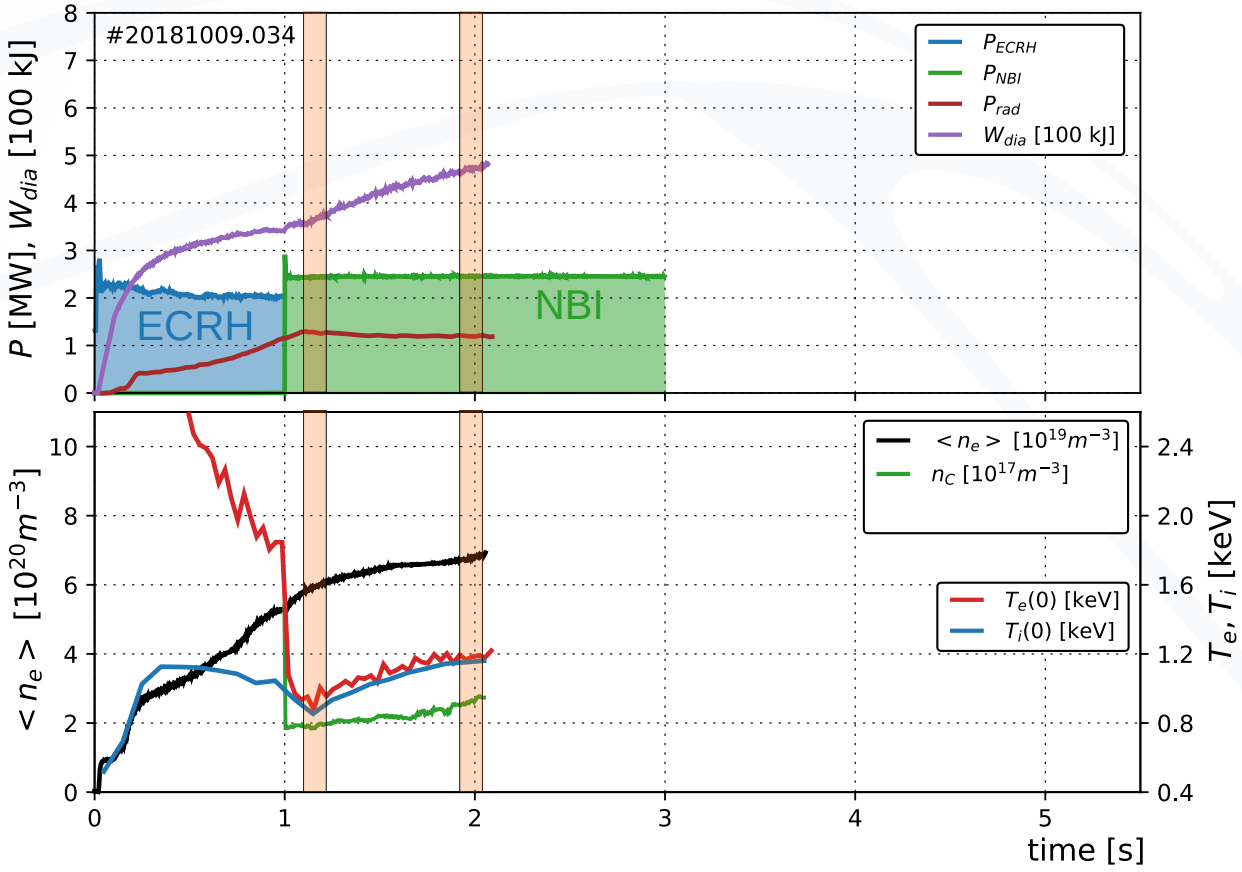


Mixed heating experiments

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







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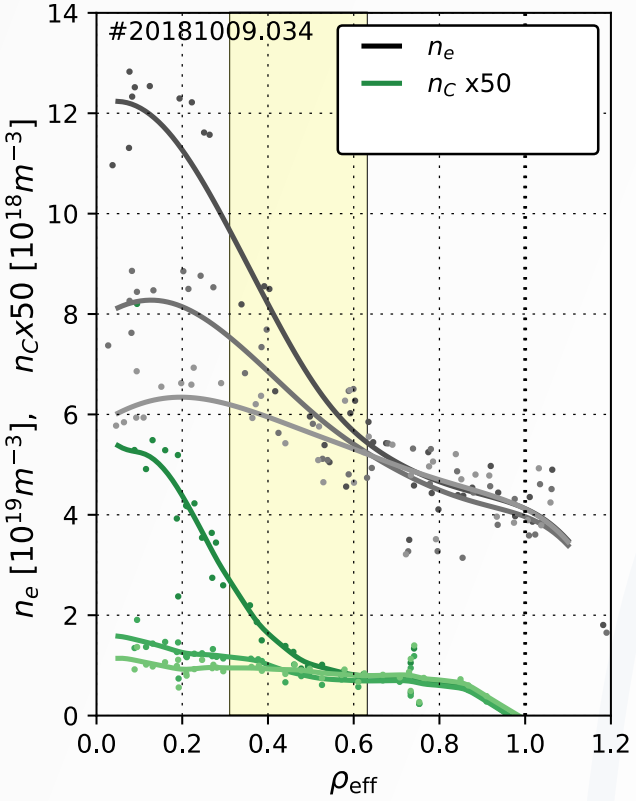

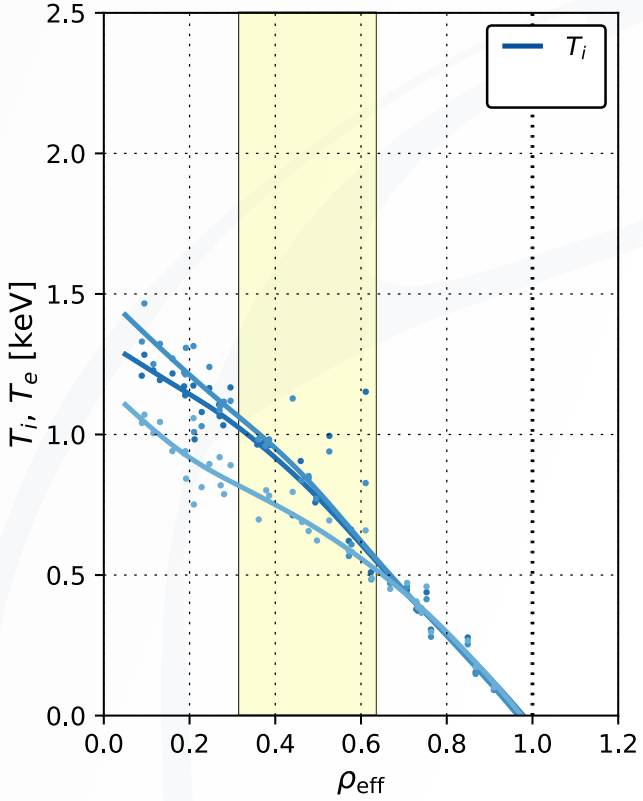

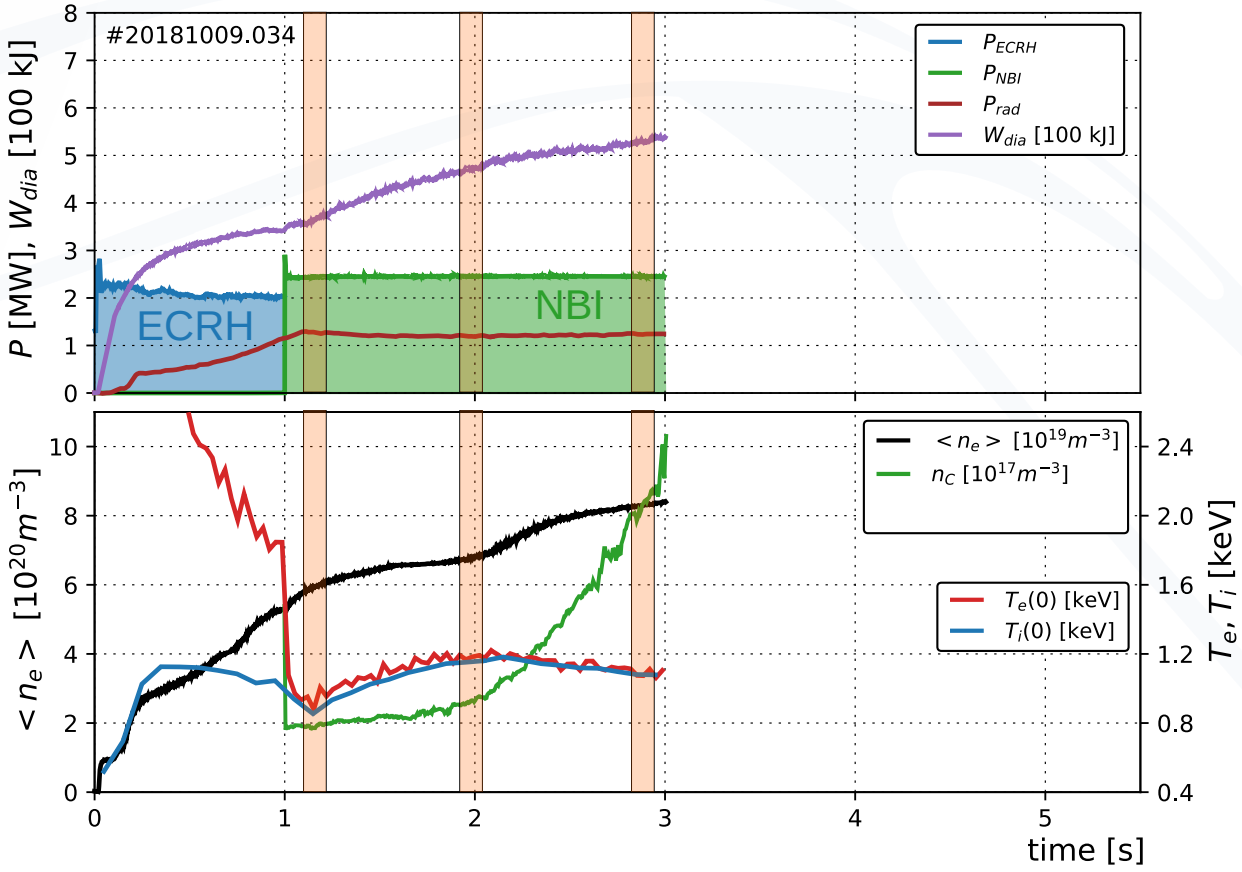

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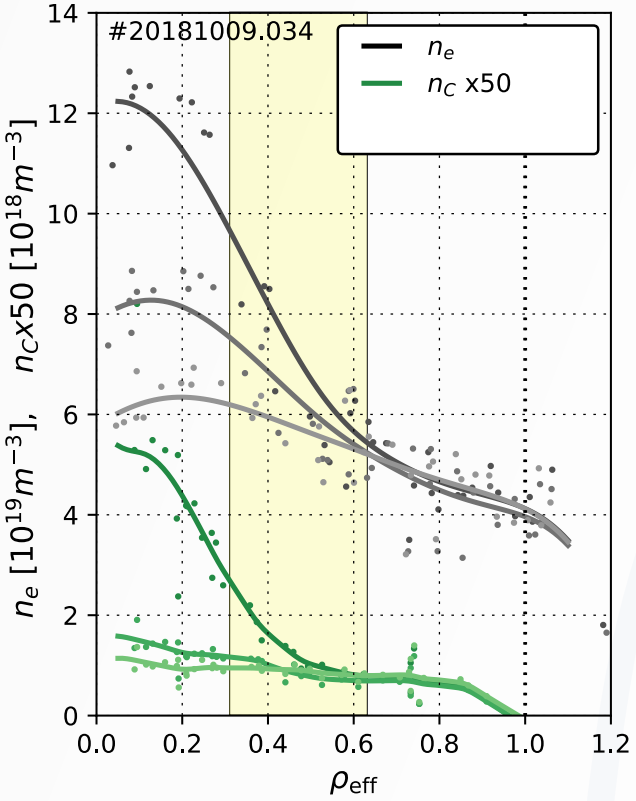

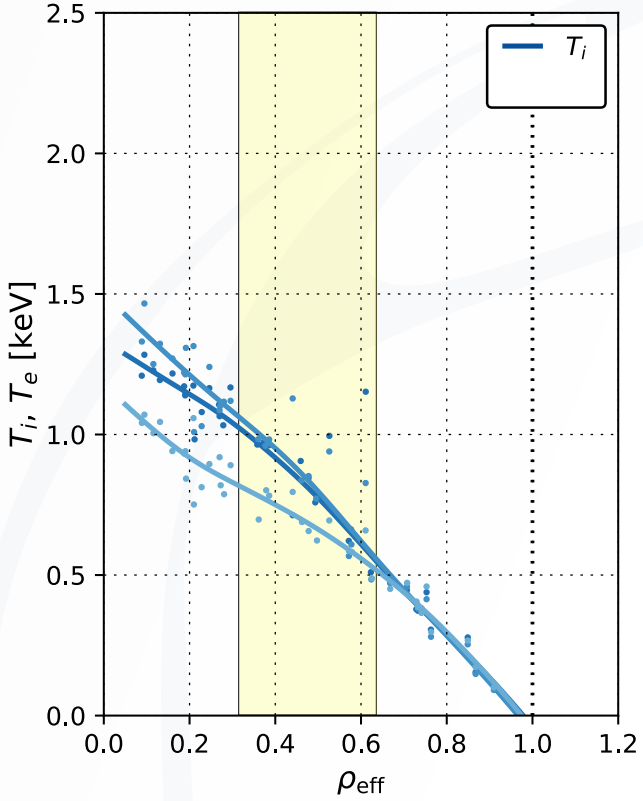

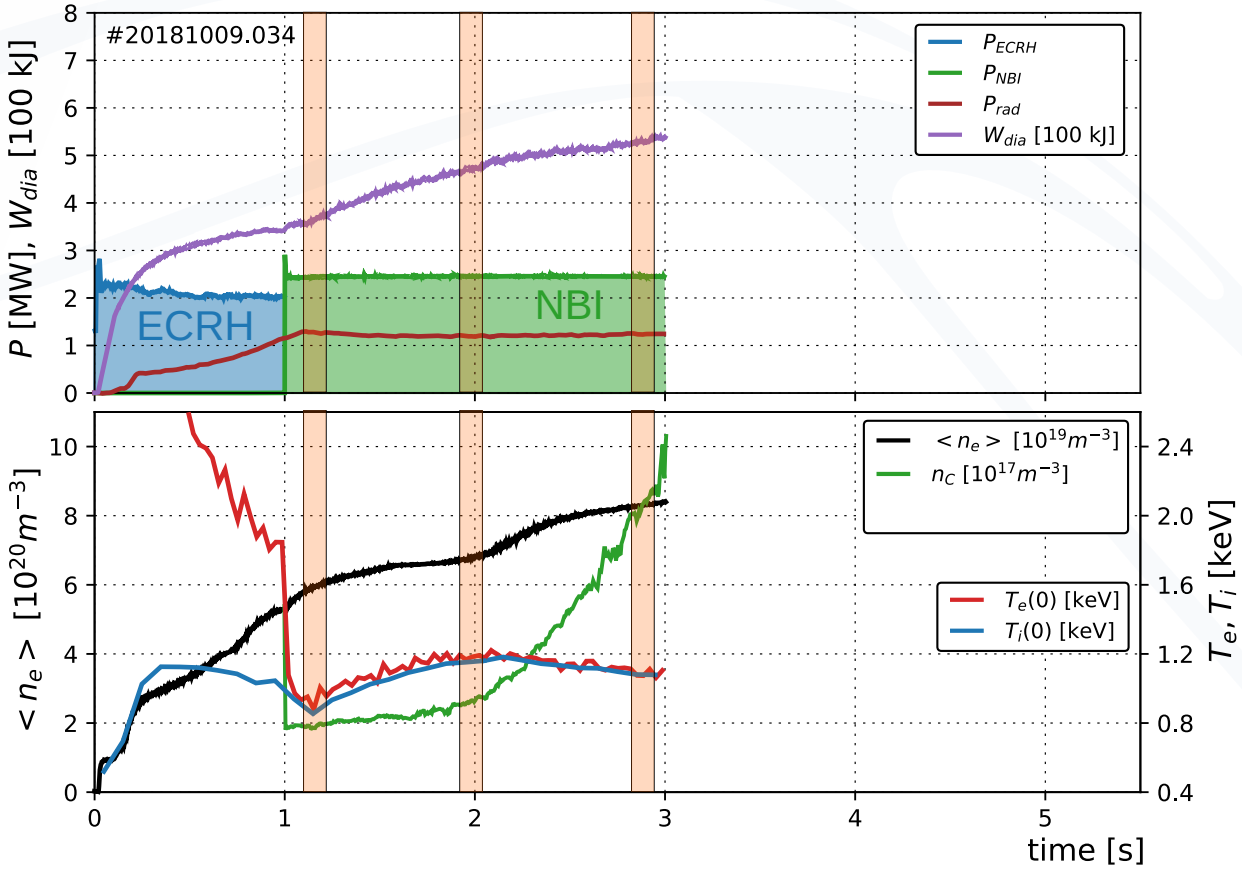

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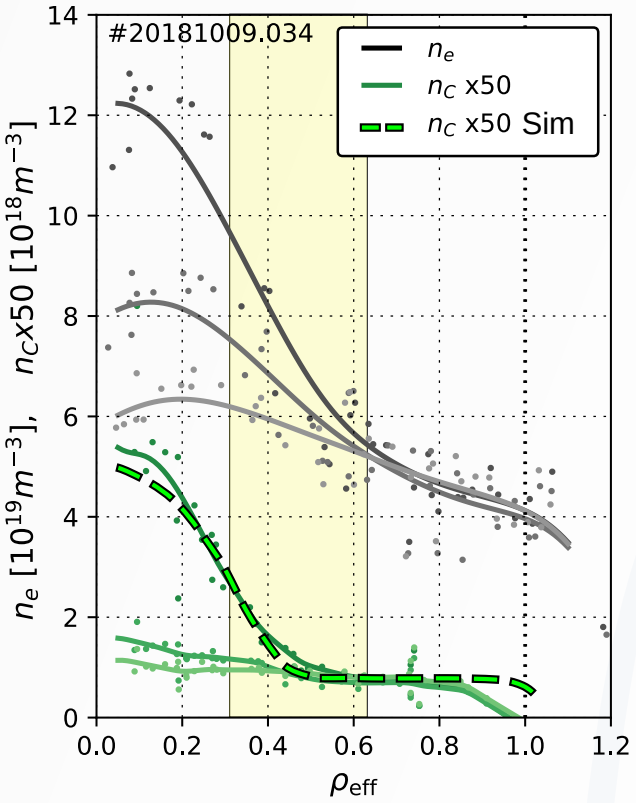

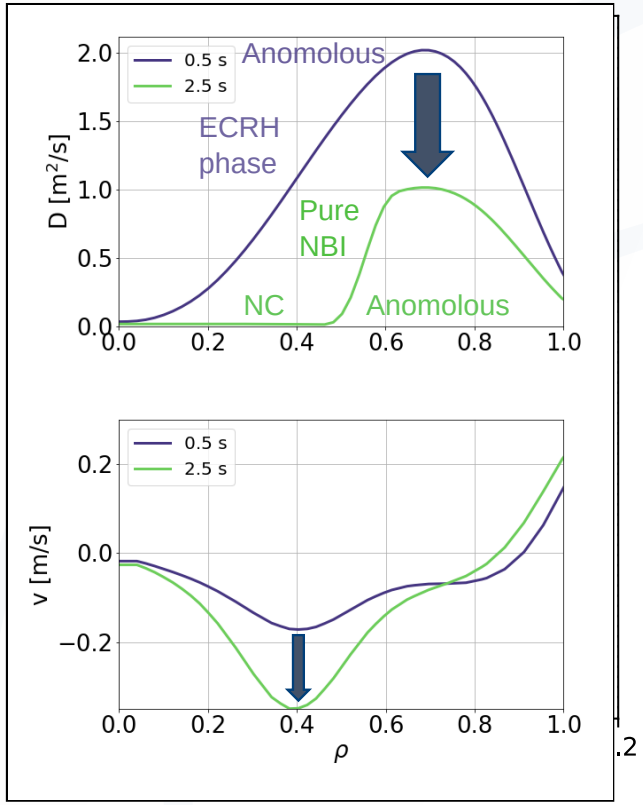

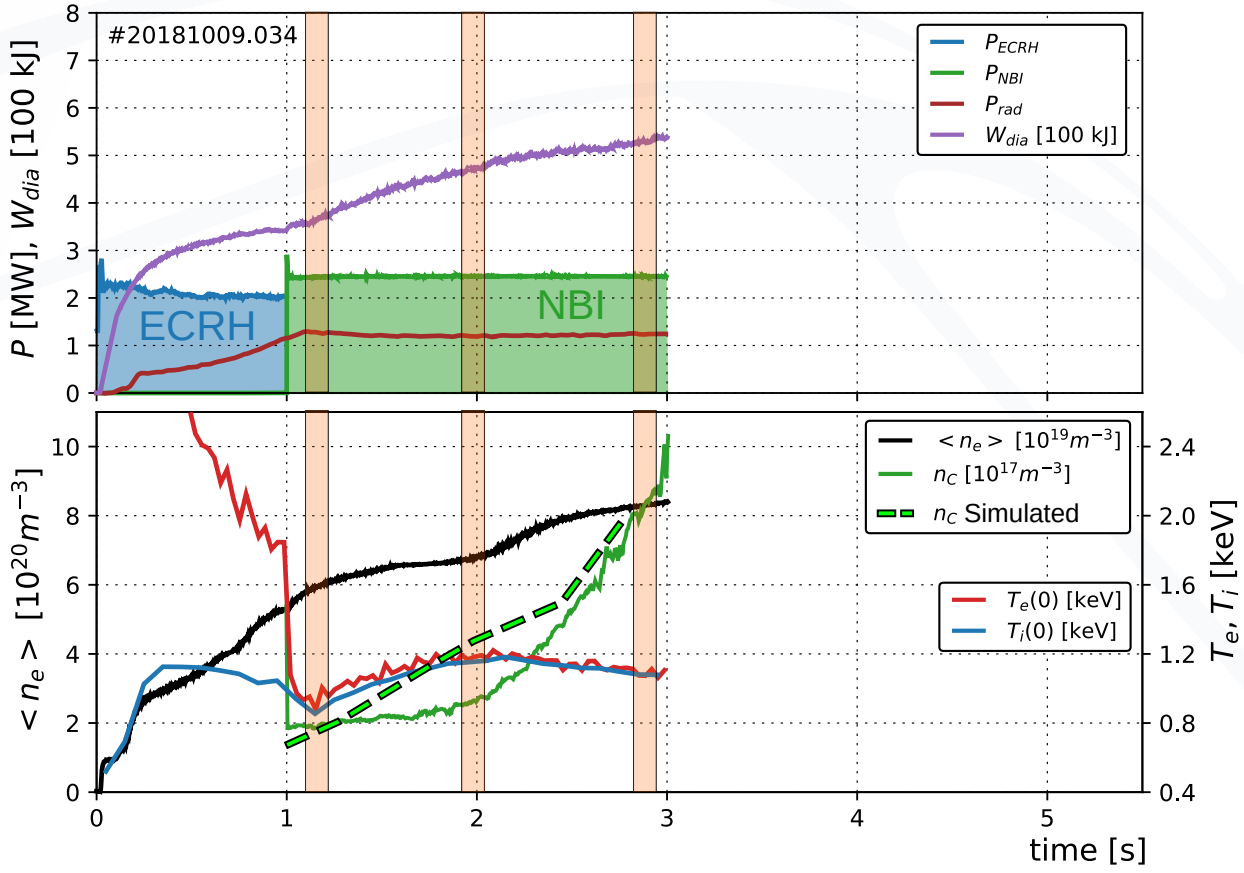

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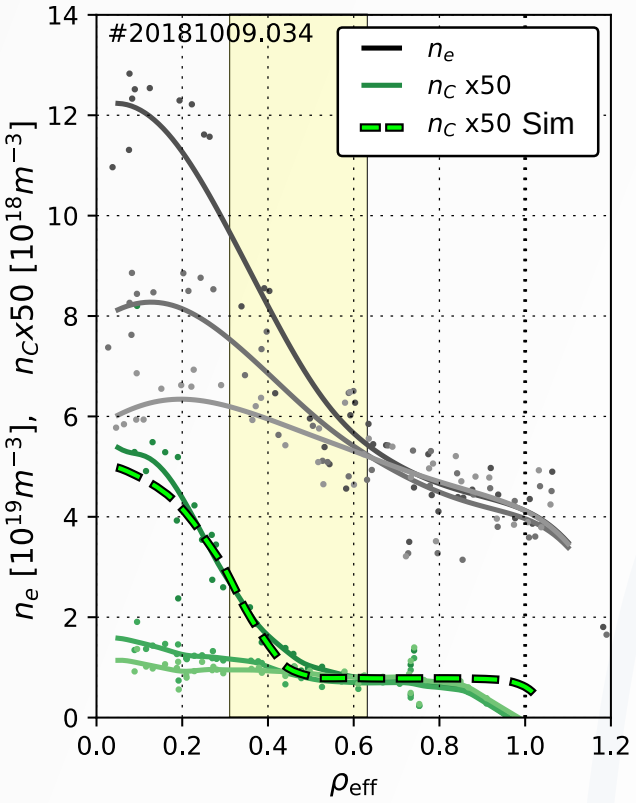

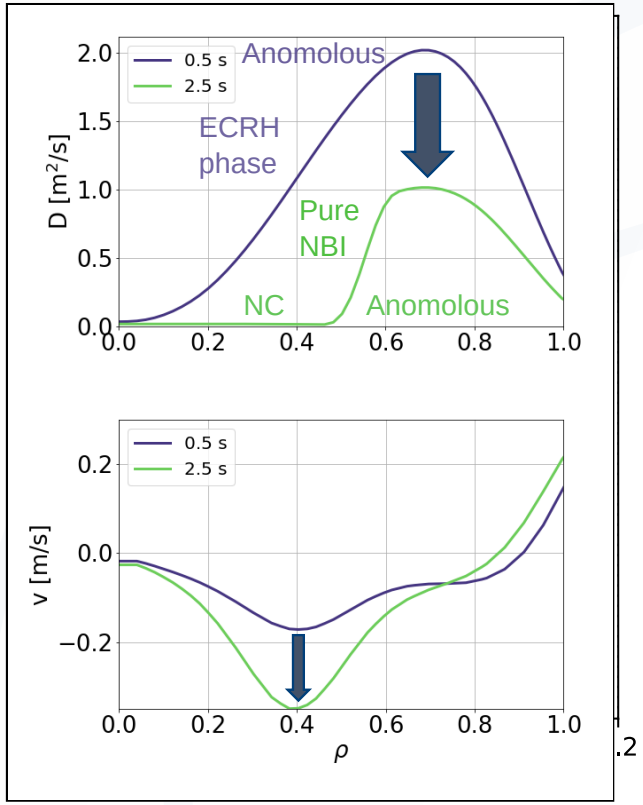

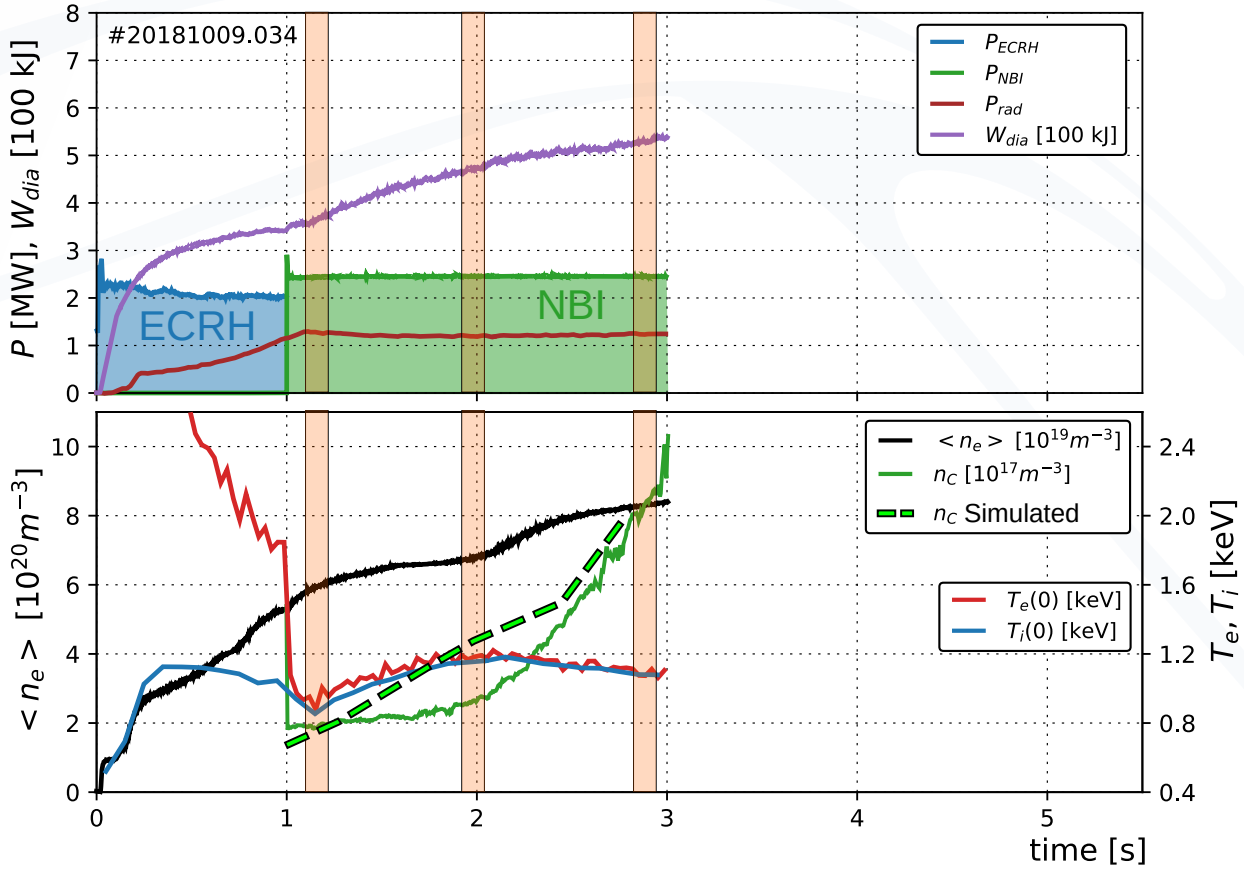

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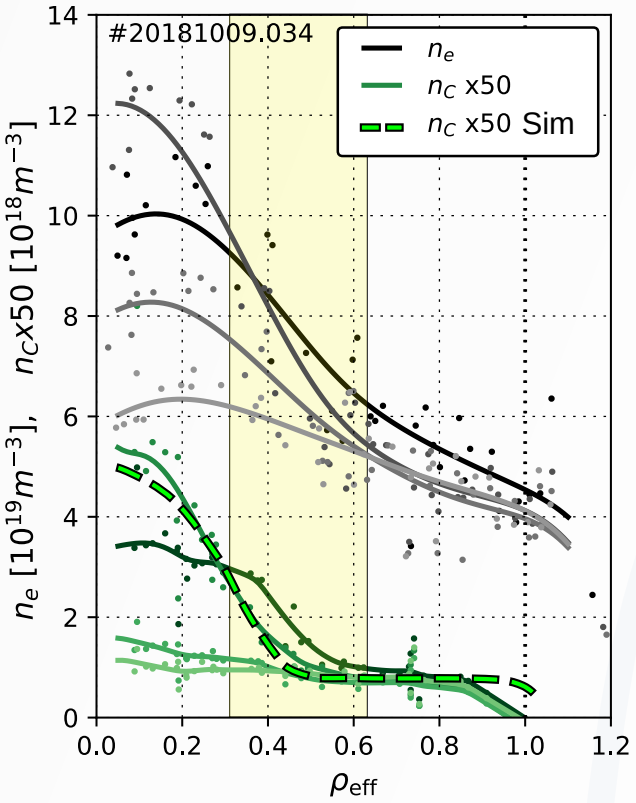

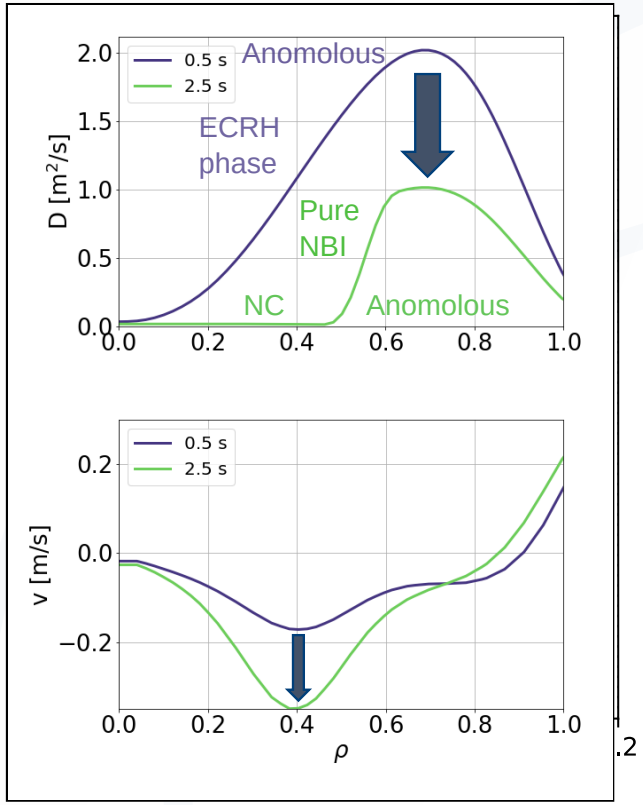

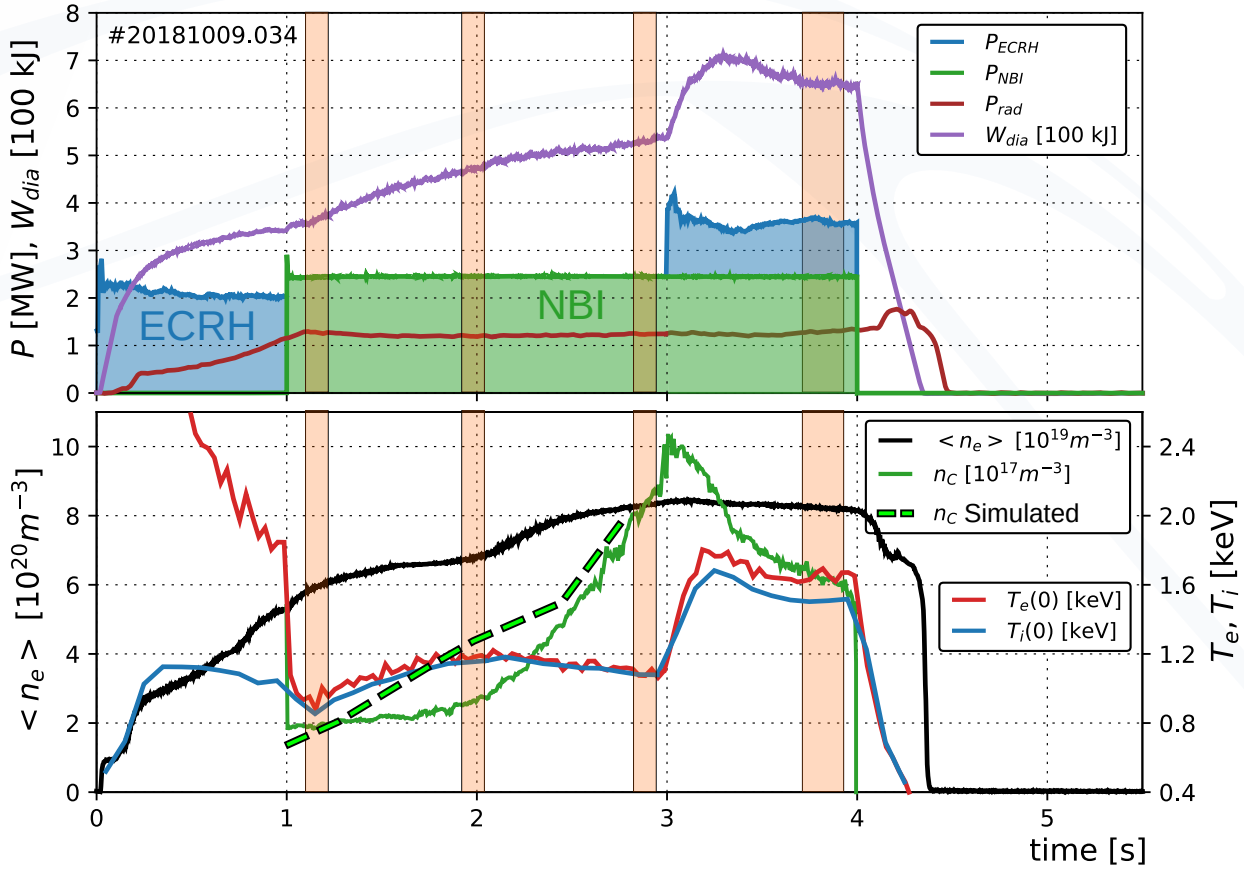

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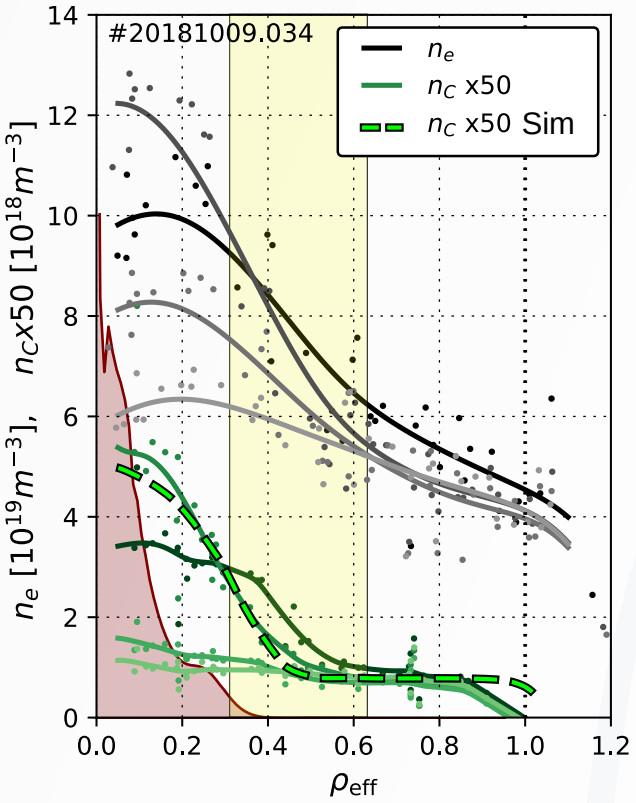
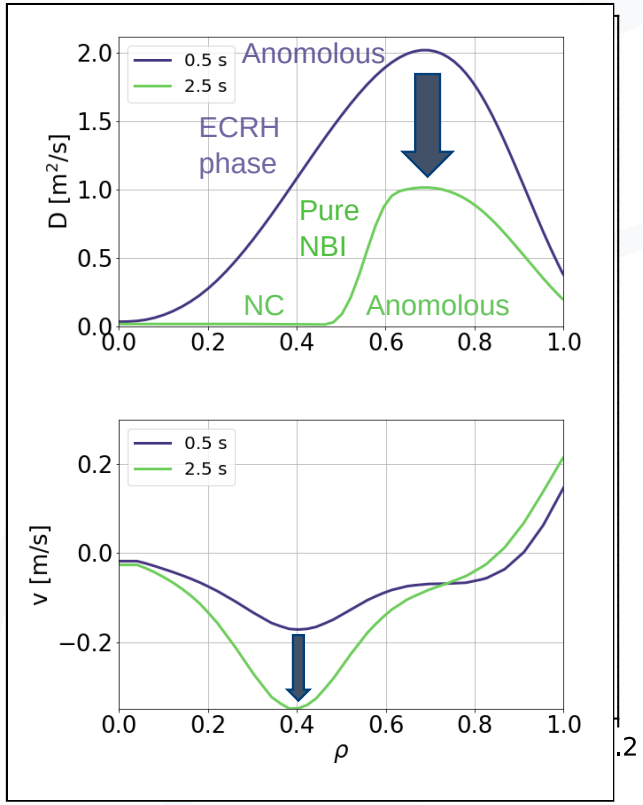
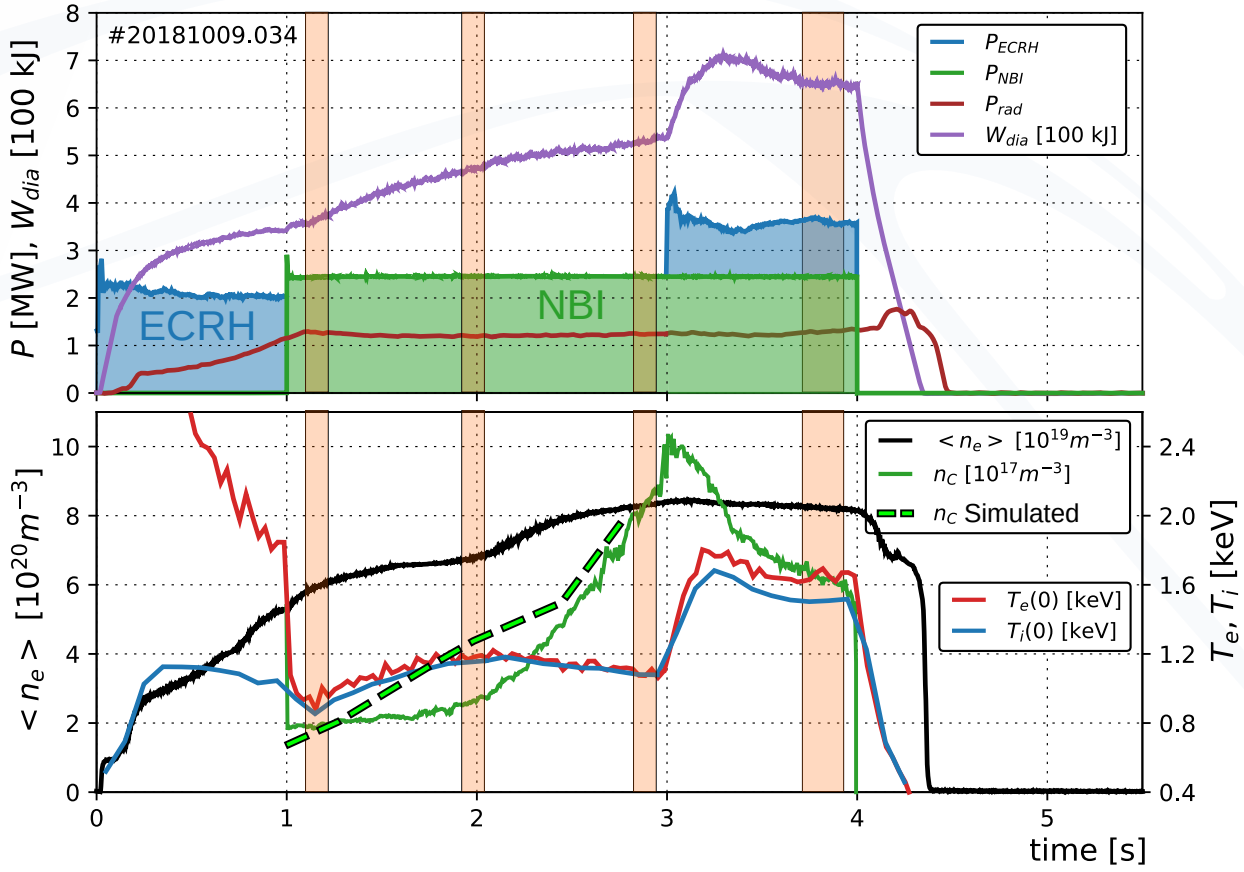
3: Add 1MW O2-mode ECRH raises temperature, slightly reduces density peaking and flattens impurity profile in deposition region.

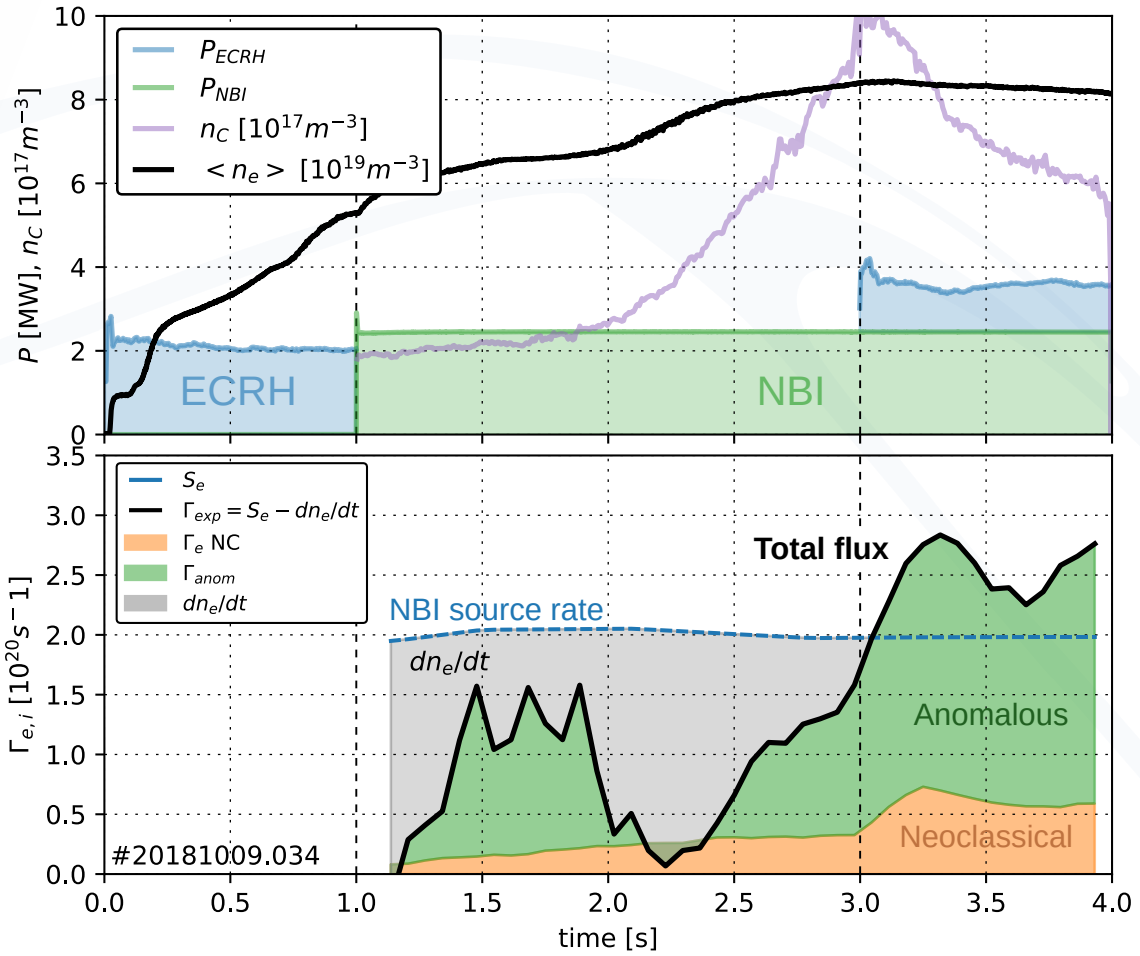






Electron/ion particle transport

- 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.
- Both neoclassical and anomalous increase with addition of ECRH, which stops density rise.



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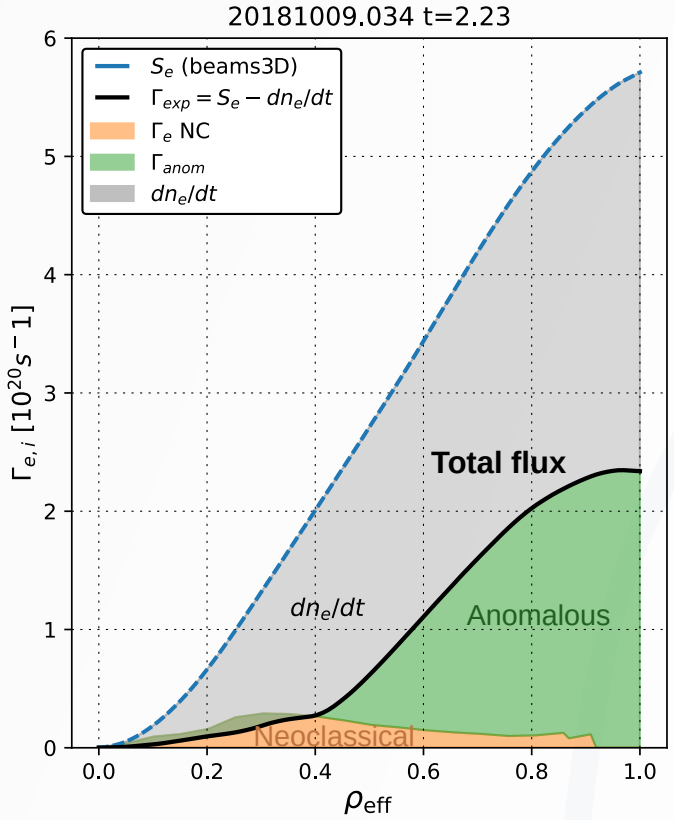

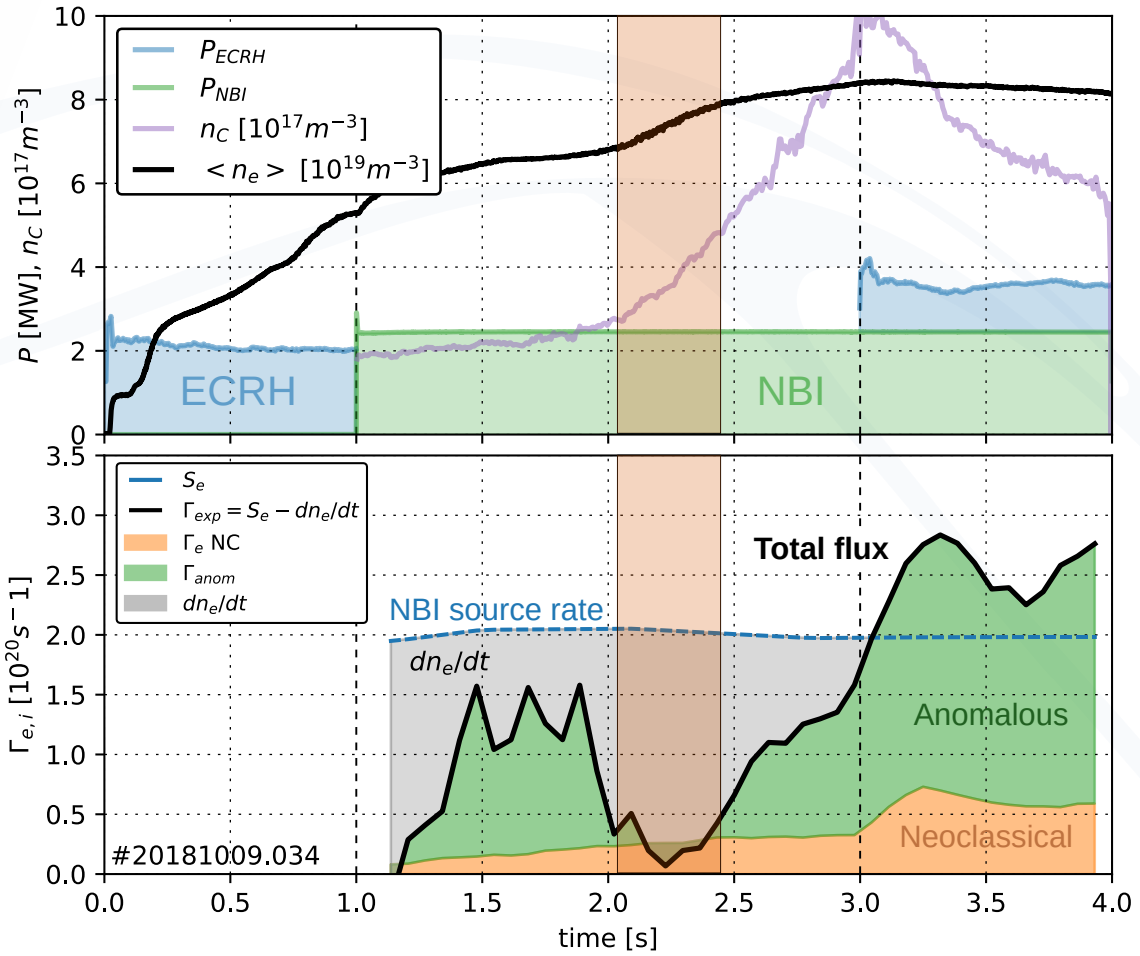

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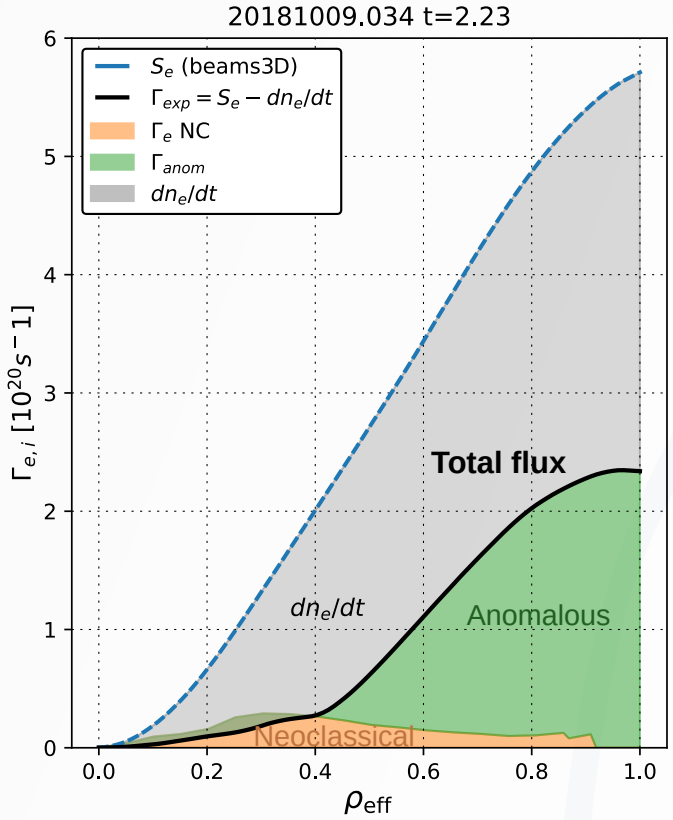

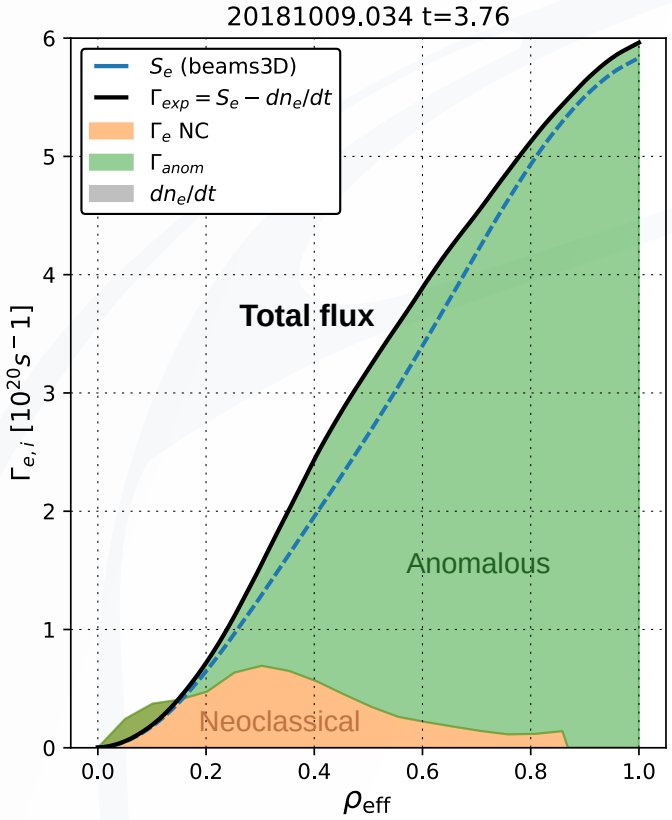

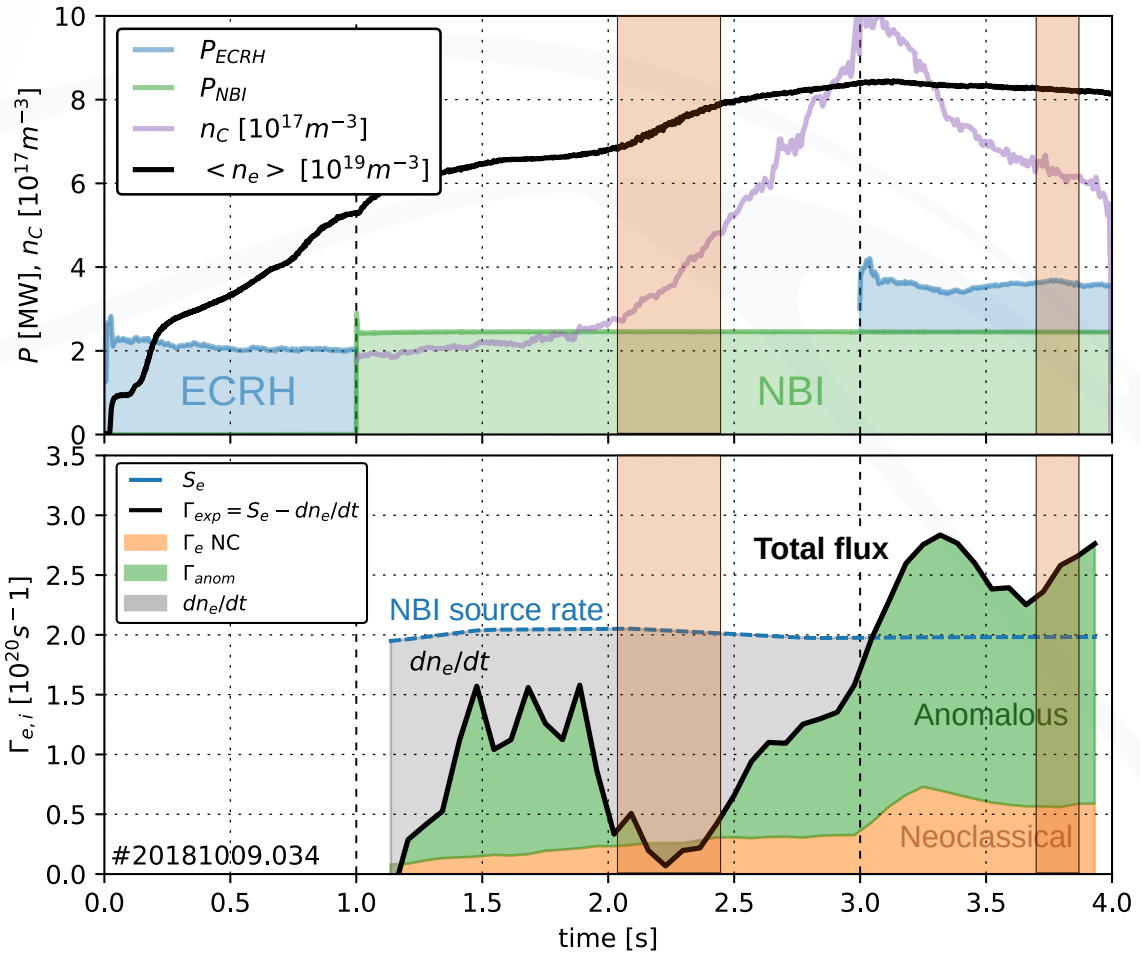

Energy transport: Total fluxes

- High collisionality leads to large P_{ei} with small O(~10eV) differences in Te, T_i profiles.
- Data shows $Q_e >> Q_e^{NC}$ but could support $Q_i \sim Q_i^{NC}$. However, $Q_e \sim Q_i >> Q^{NC}$ also possible within uncertainty.

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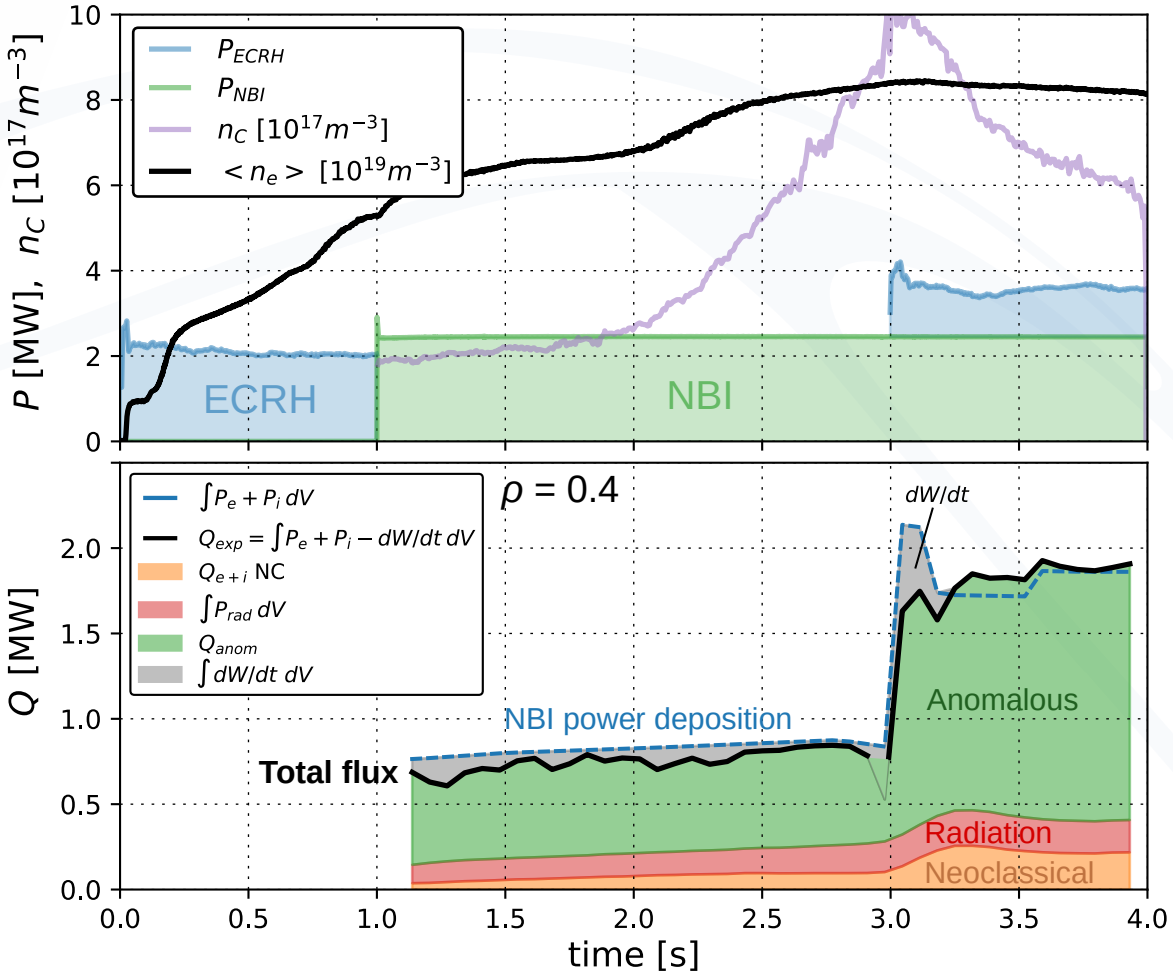

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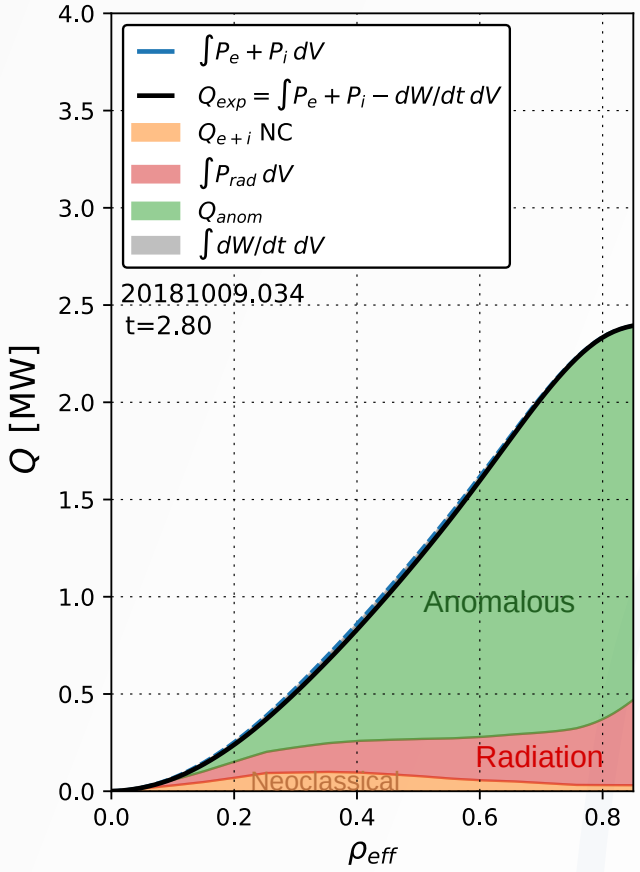

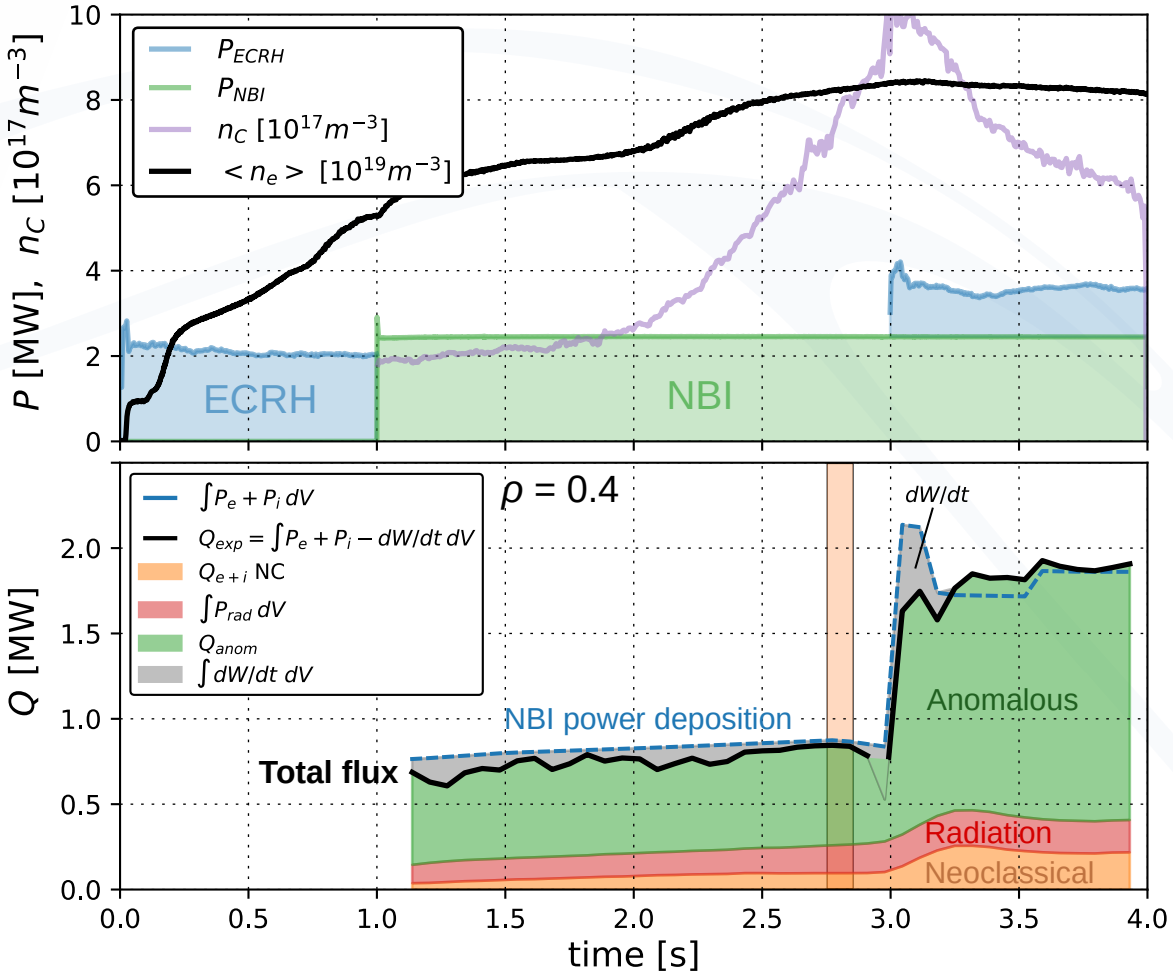

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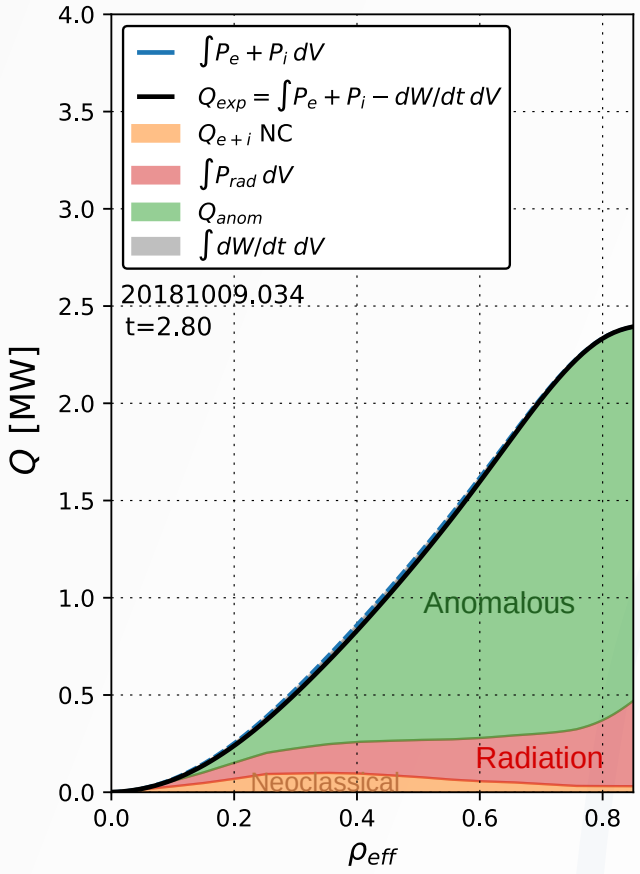

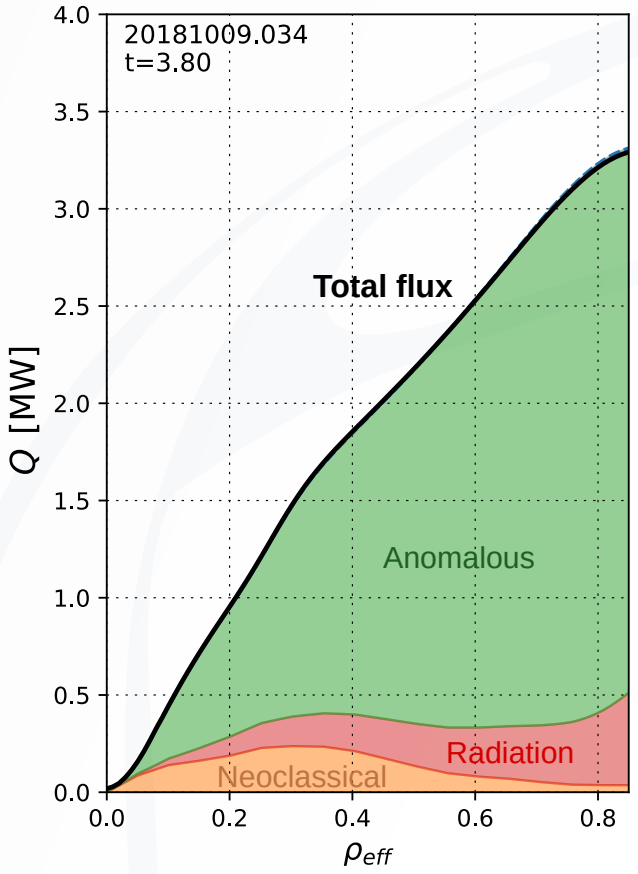

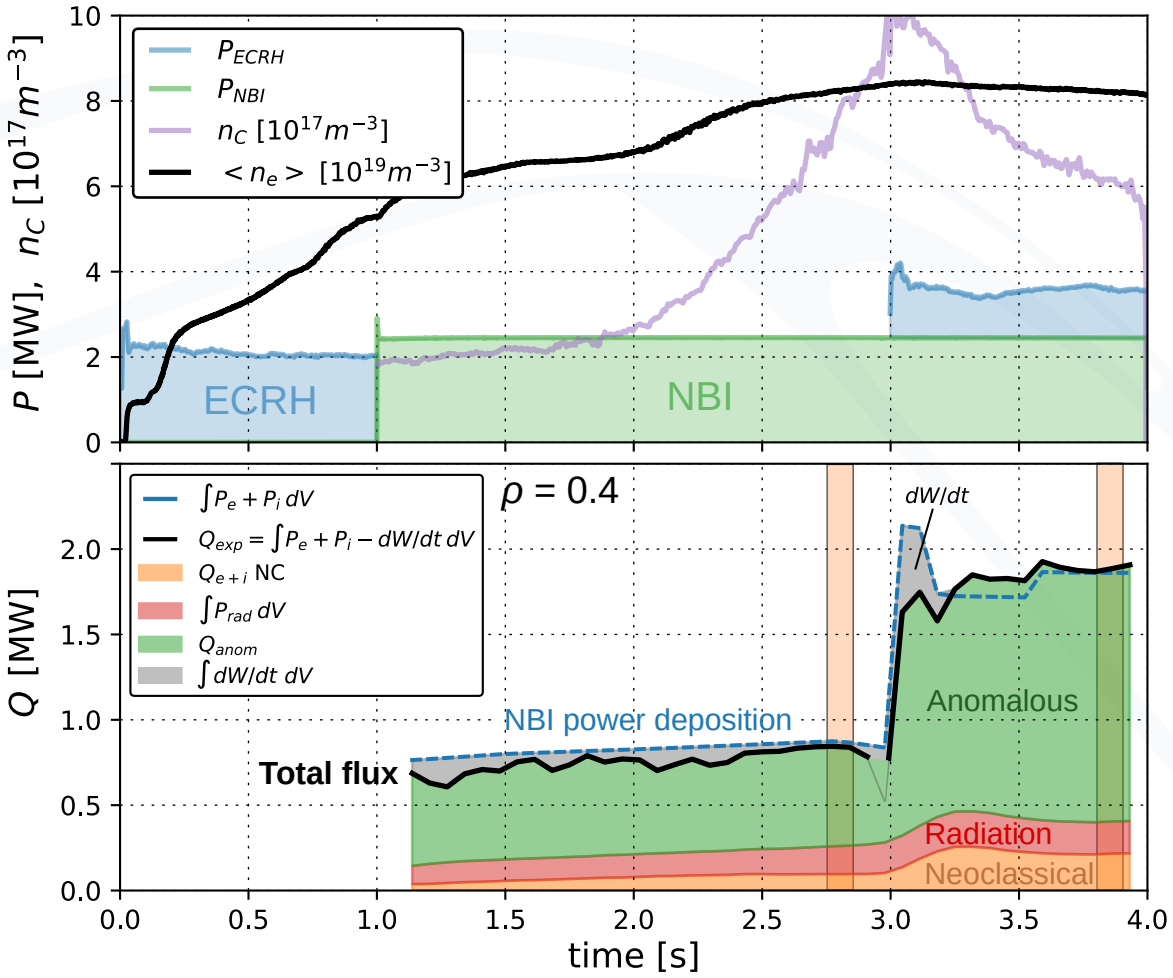

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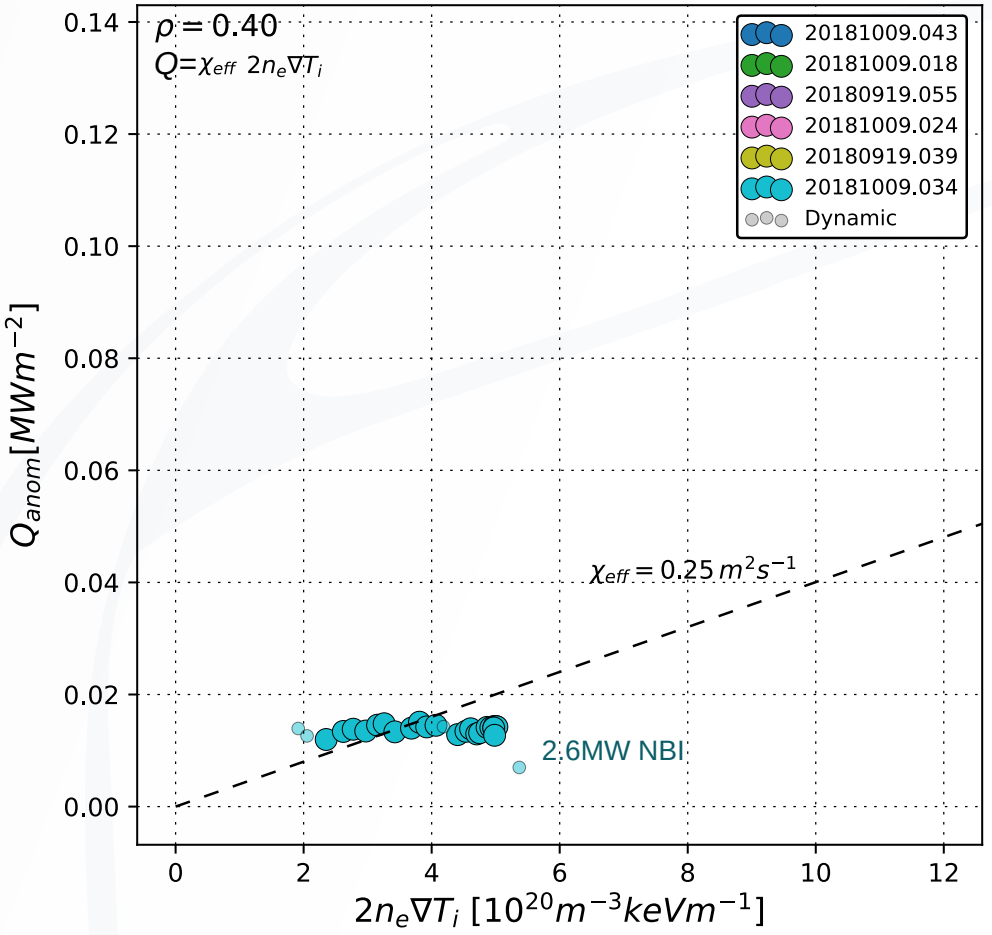

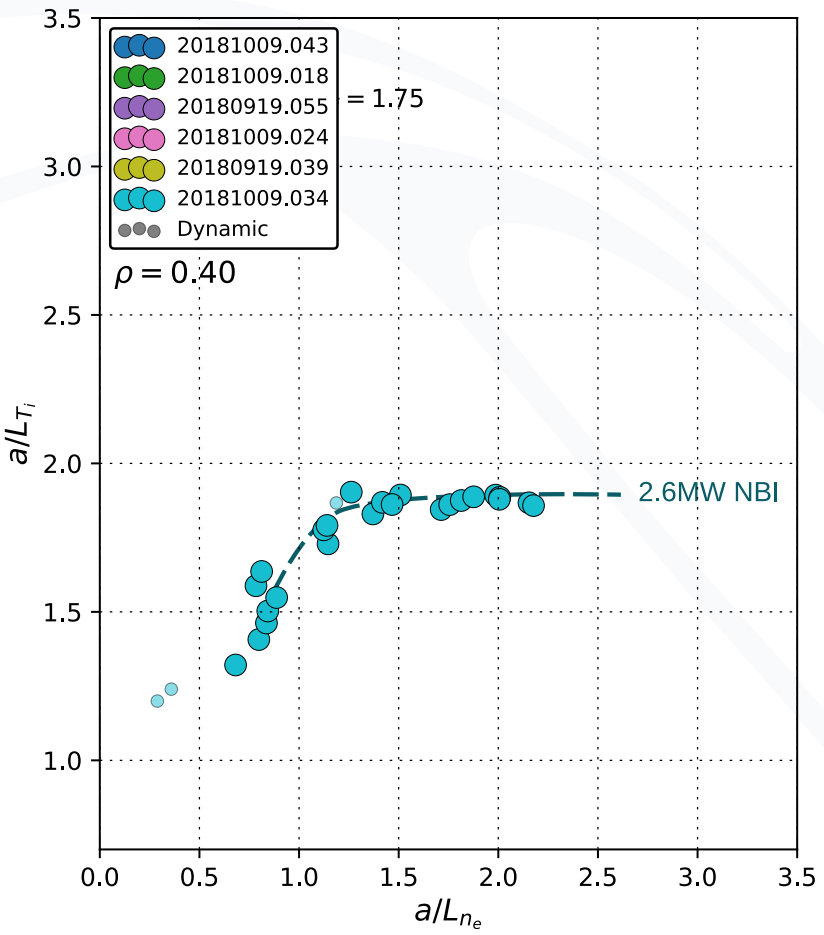

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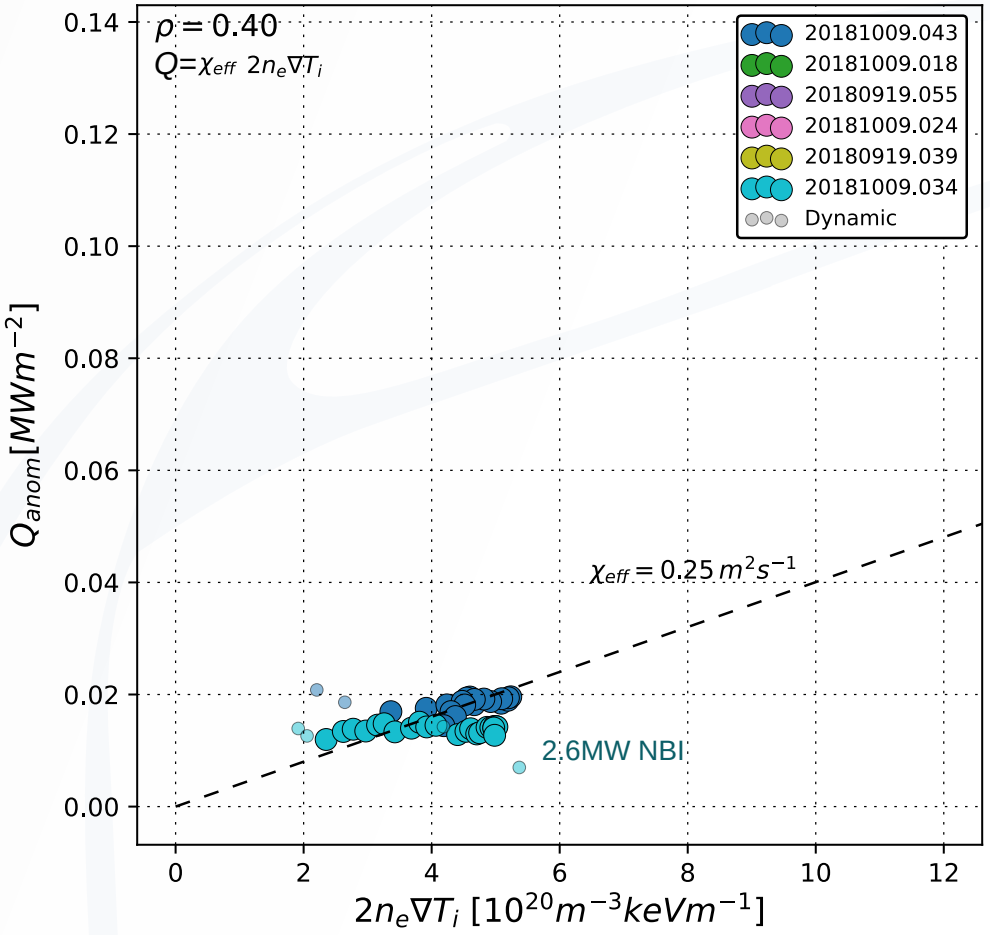

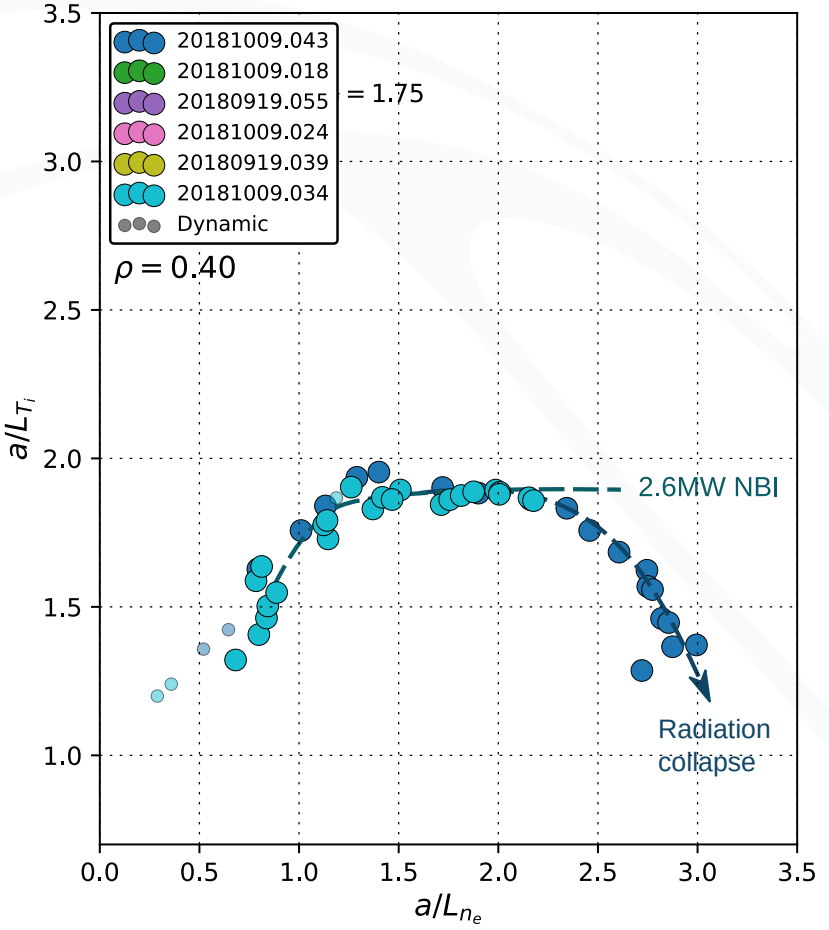

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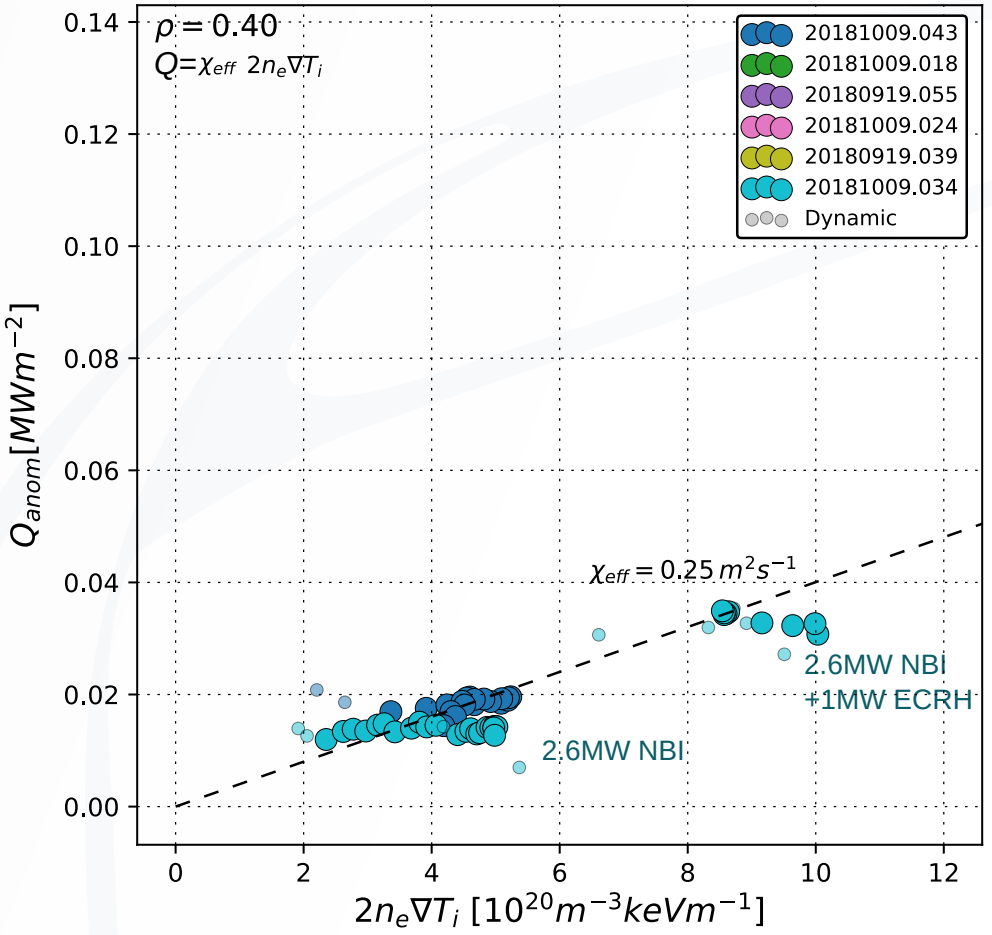

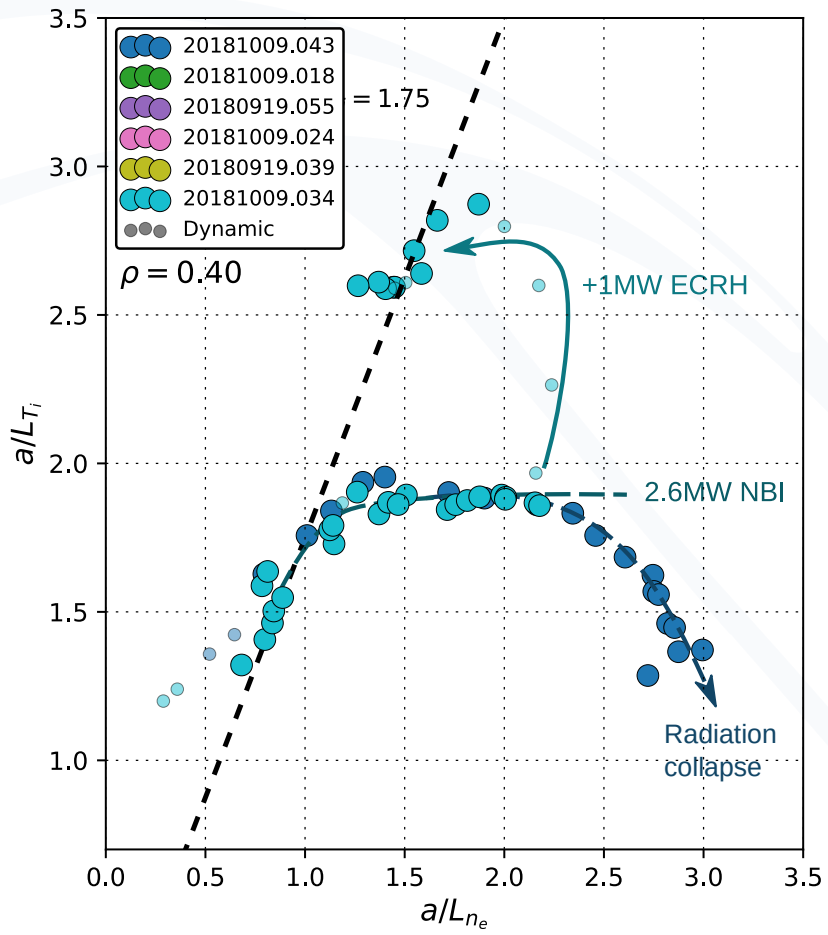

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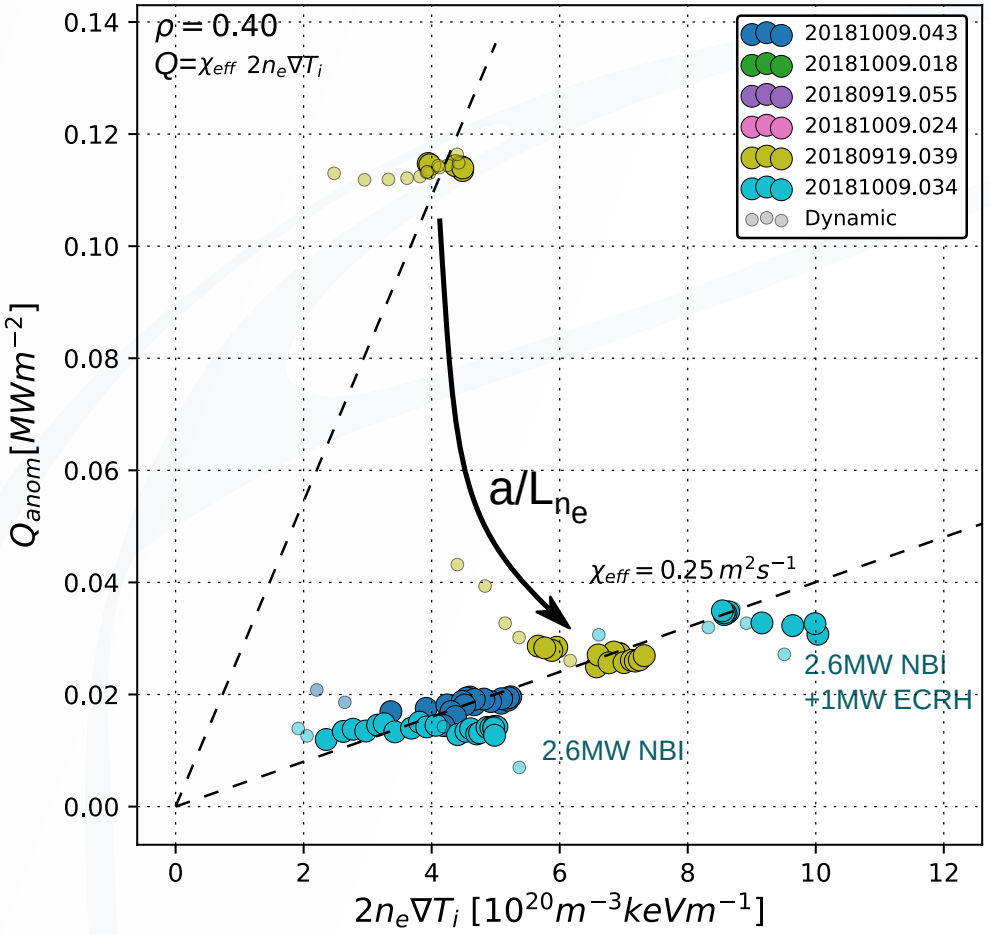

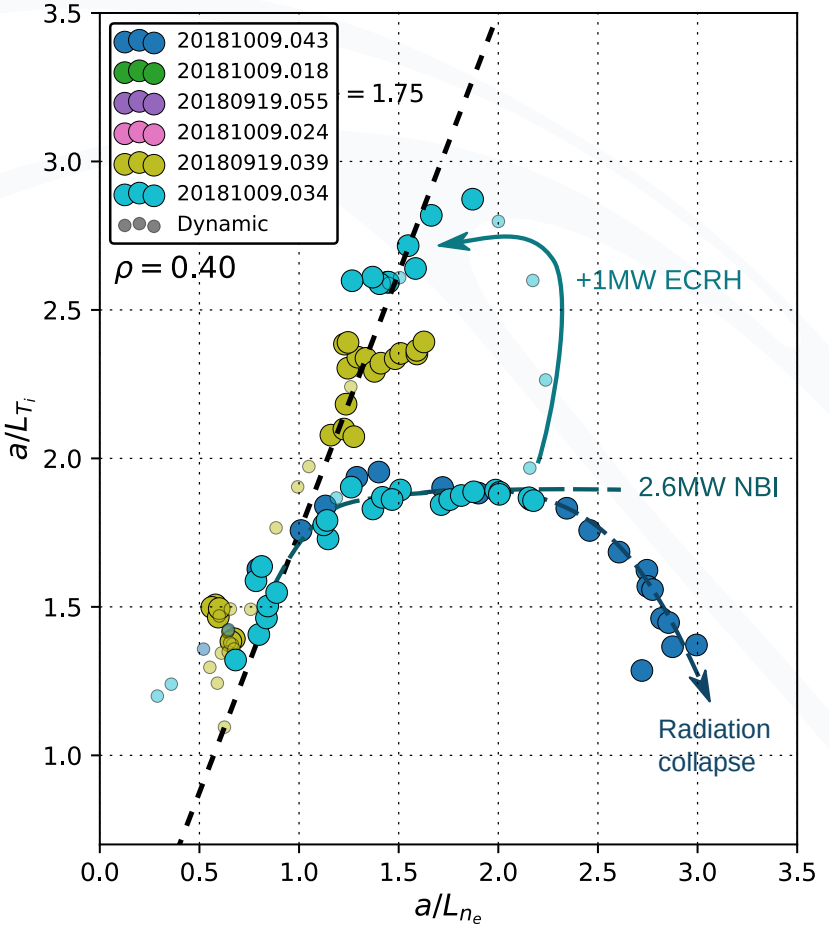

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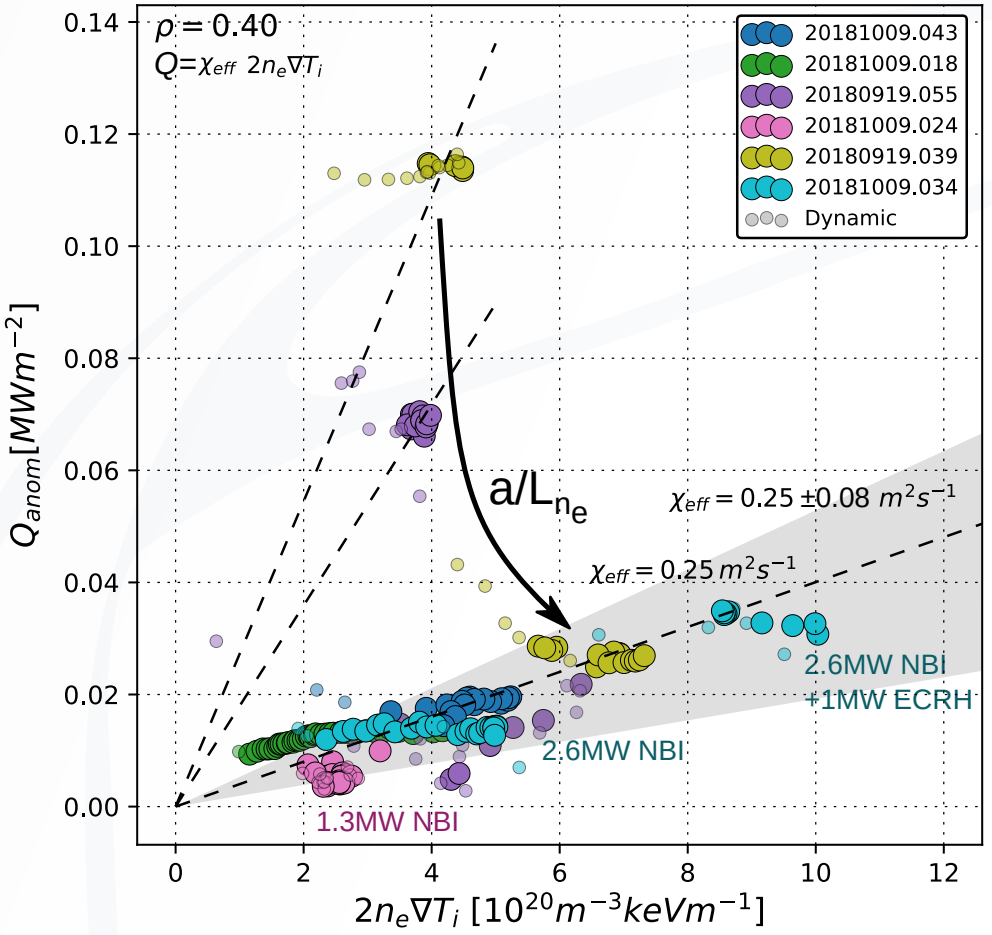

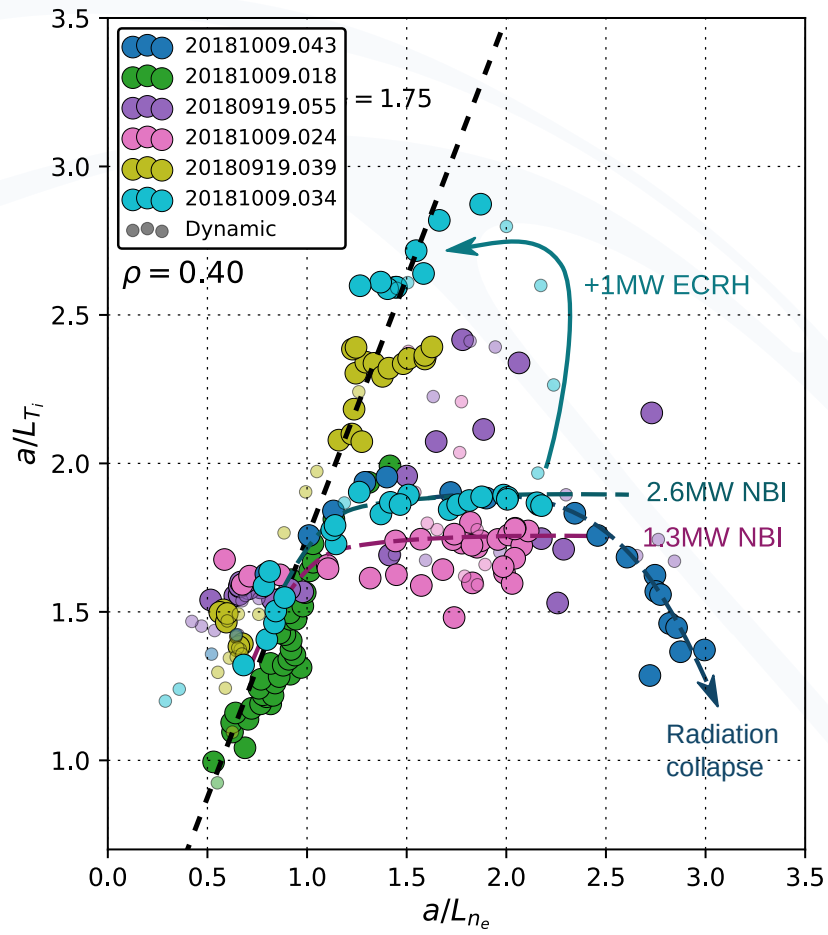

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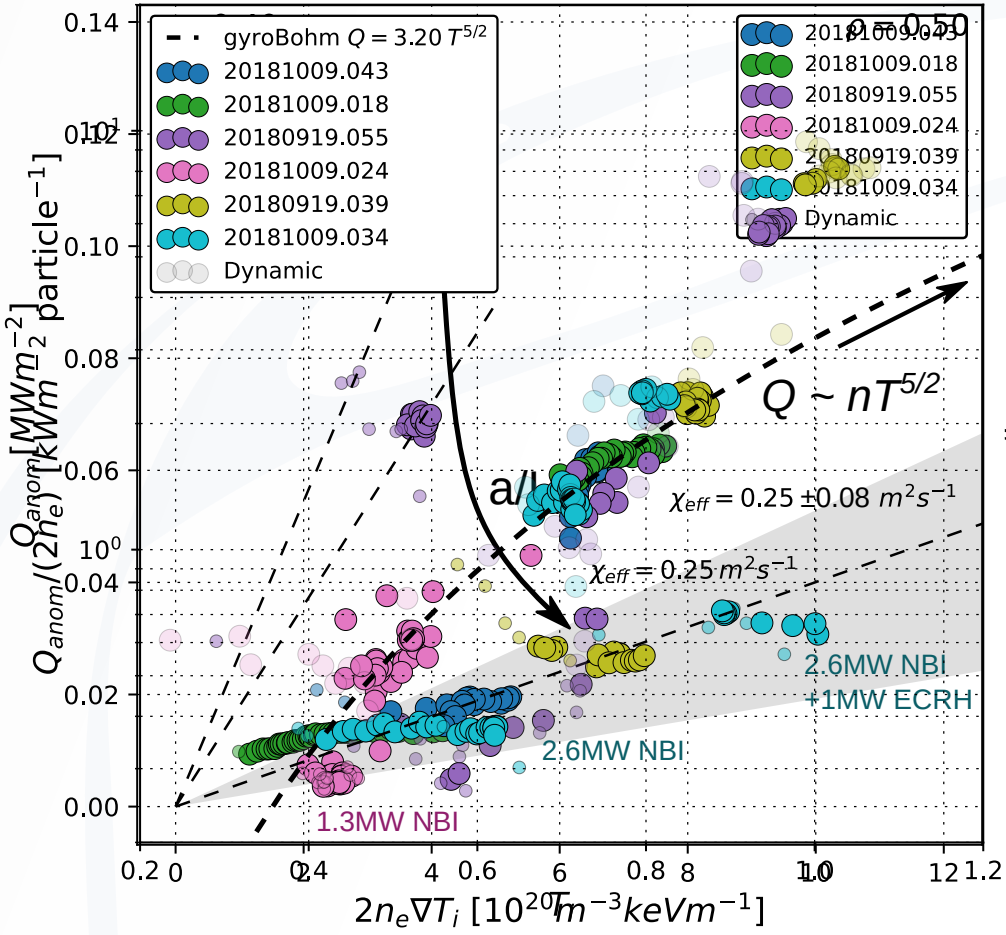

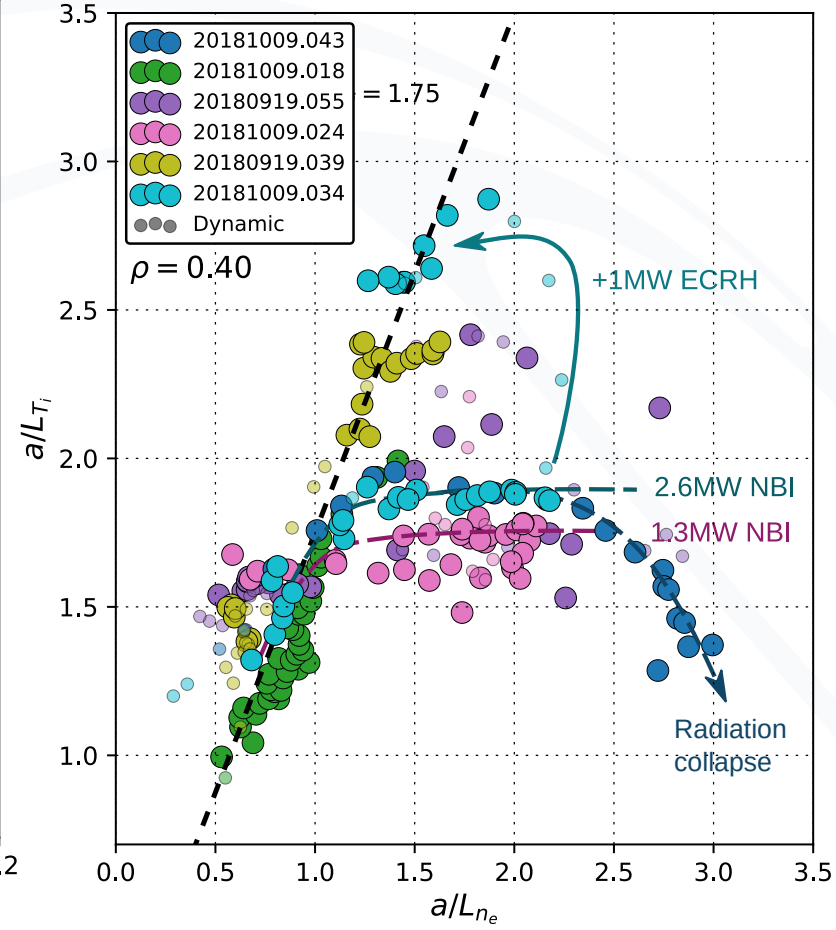

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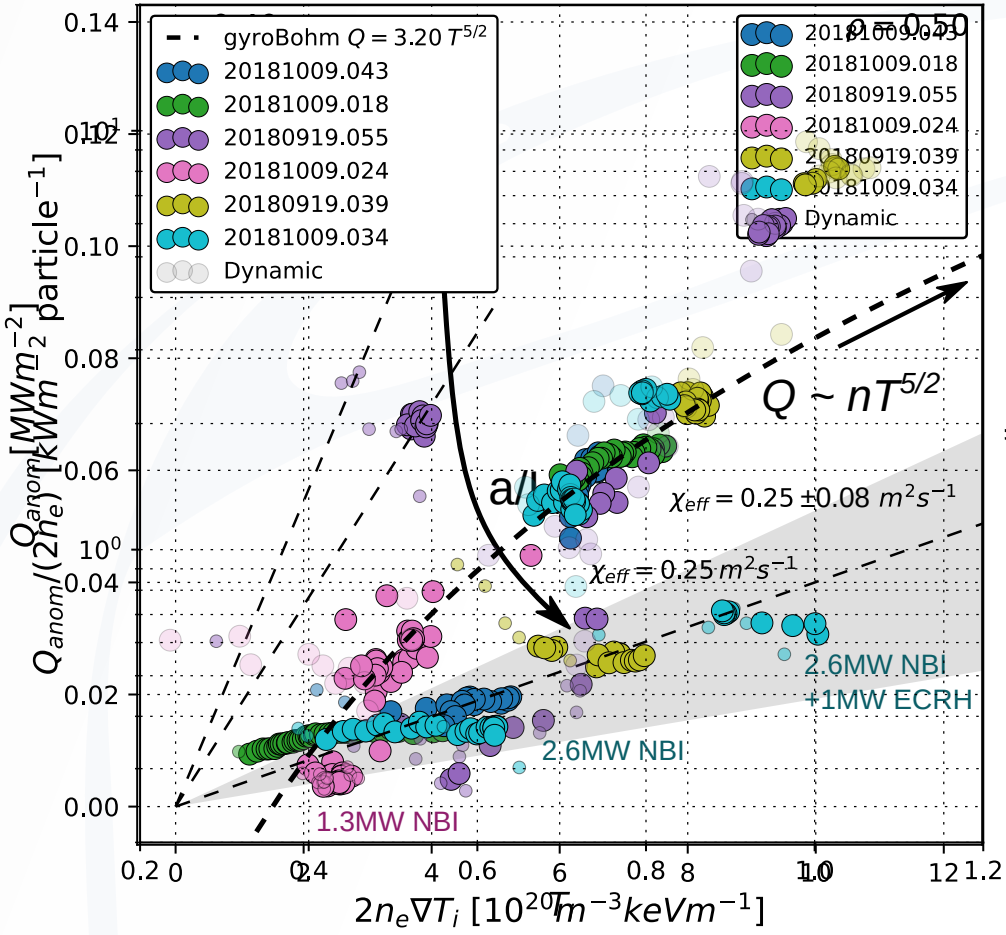
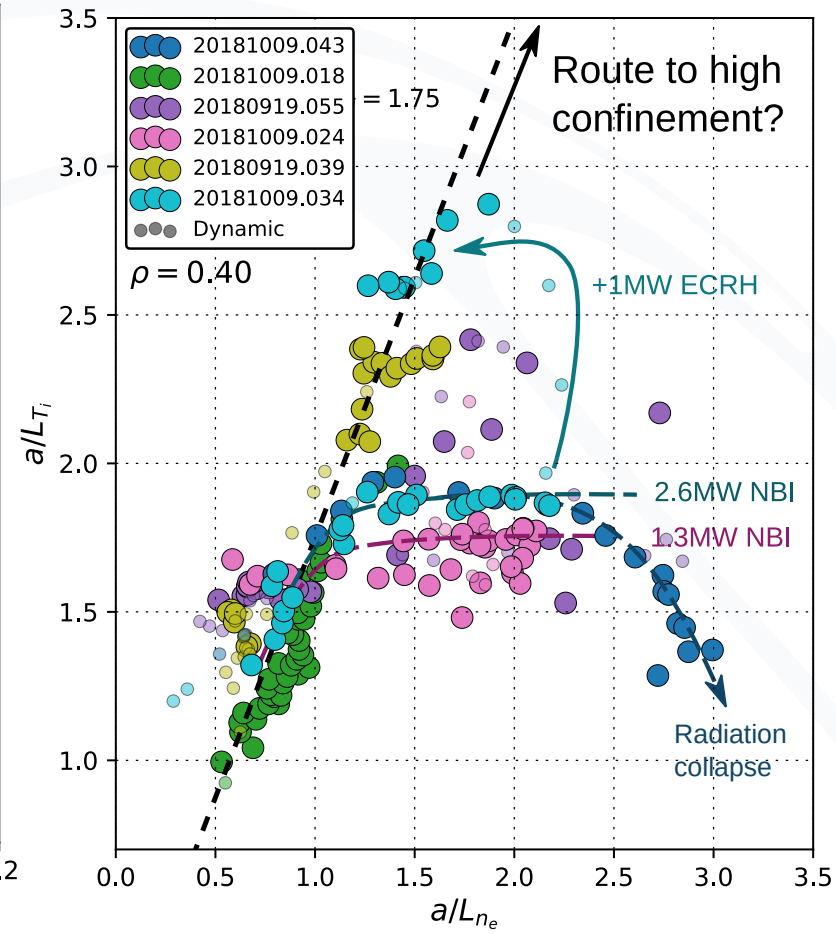
- If density gradient can be maintained, additional NBI power may lead to high n_e, high T_i plasmas.





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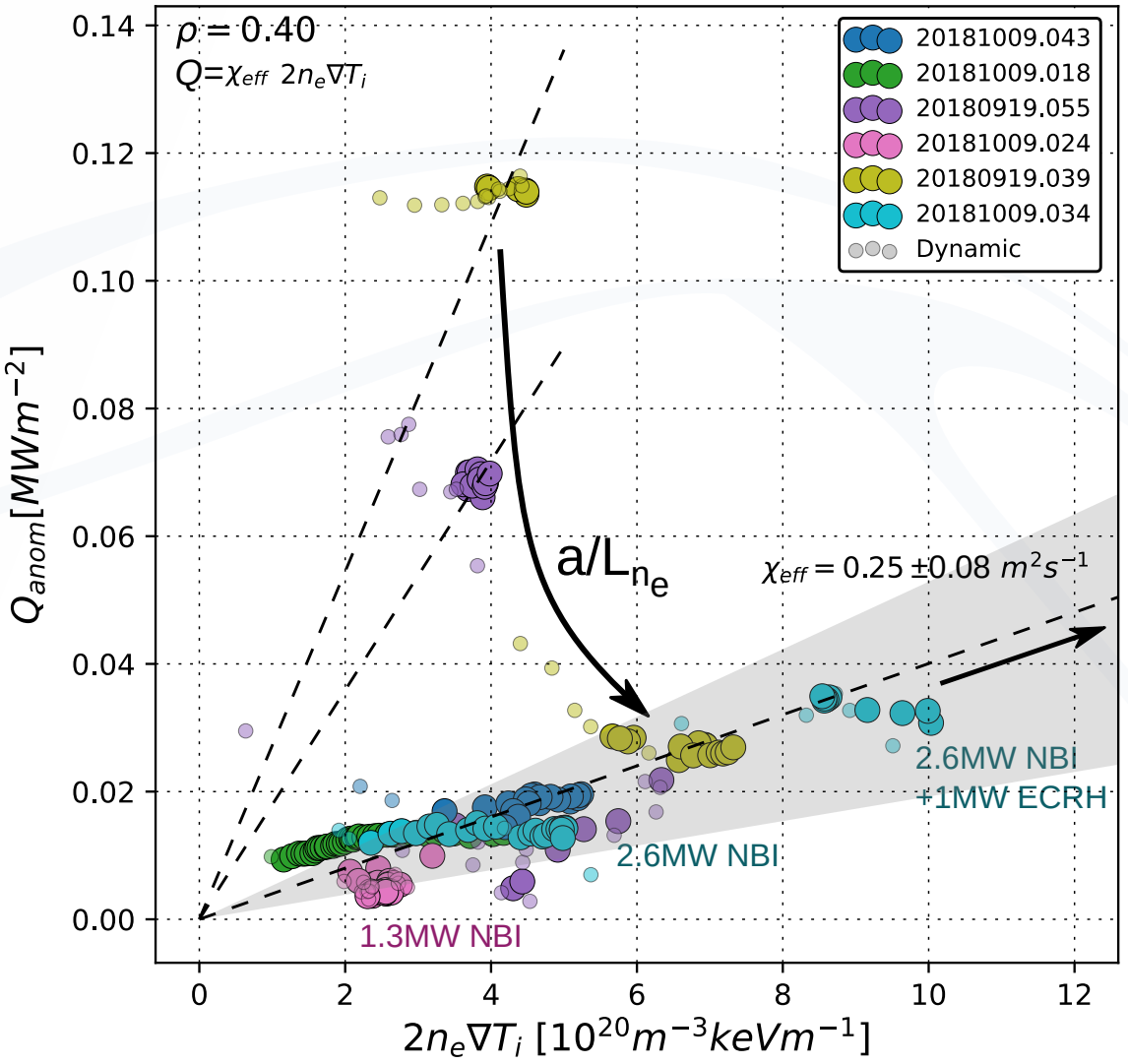

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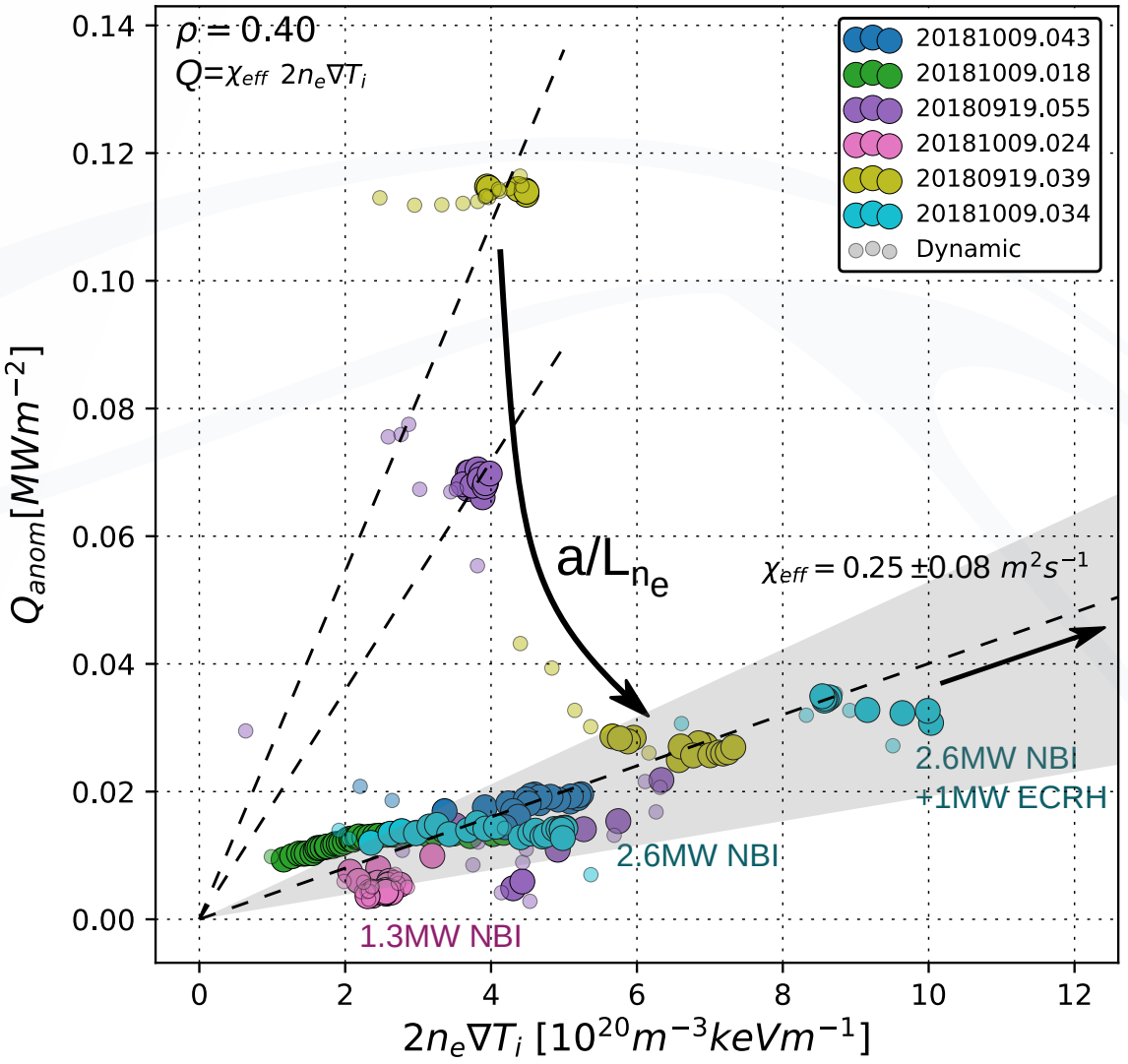

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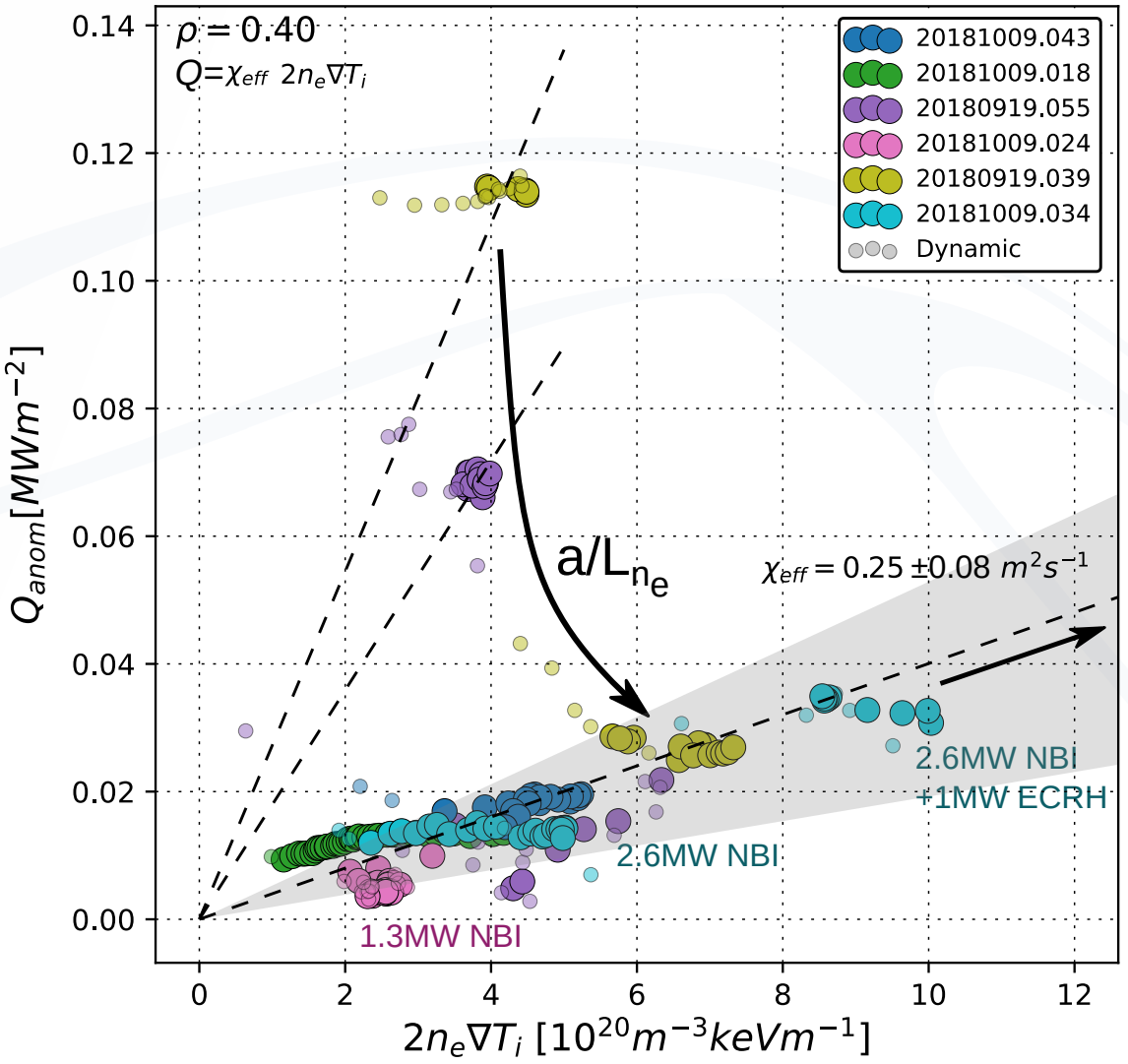
Open questions for 2022/3 campaign:
- Increase NBI power. What happens to a/Ln_e?
- Why does a/Ln_e decrease with ECRH?
- Can sufficient a/Ln_e be maintained while flushing out impurities?



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) - explore ITG stabilisation by fast ions *[N. Bonanomi et al, Nucl. Fusion 58 (2018) 056025]*

20181011.012 - Fe XXIV measurements

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  AUG1 = 529nm: C^{VI}, same as primary spectrometer)
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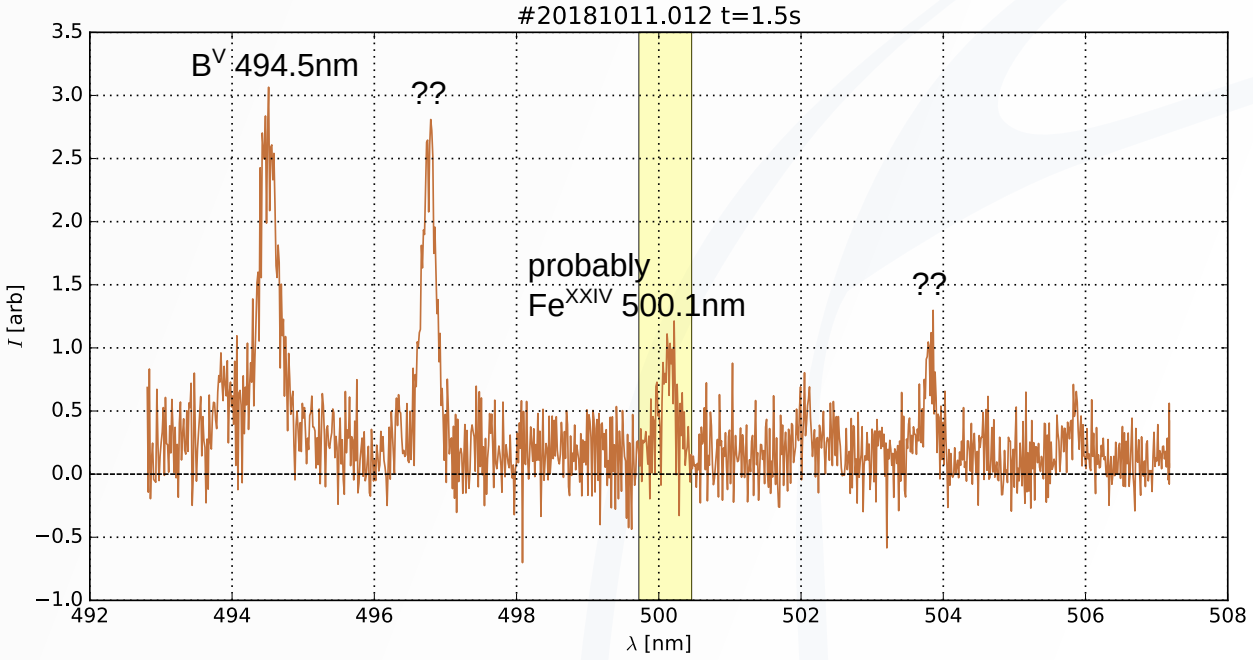

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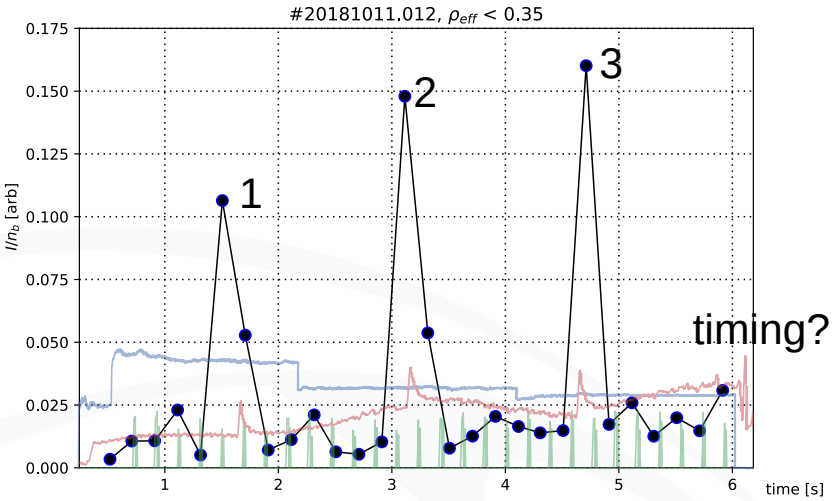

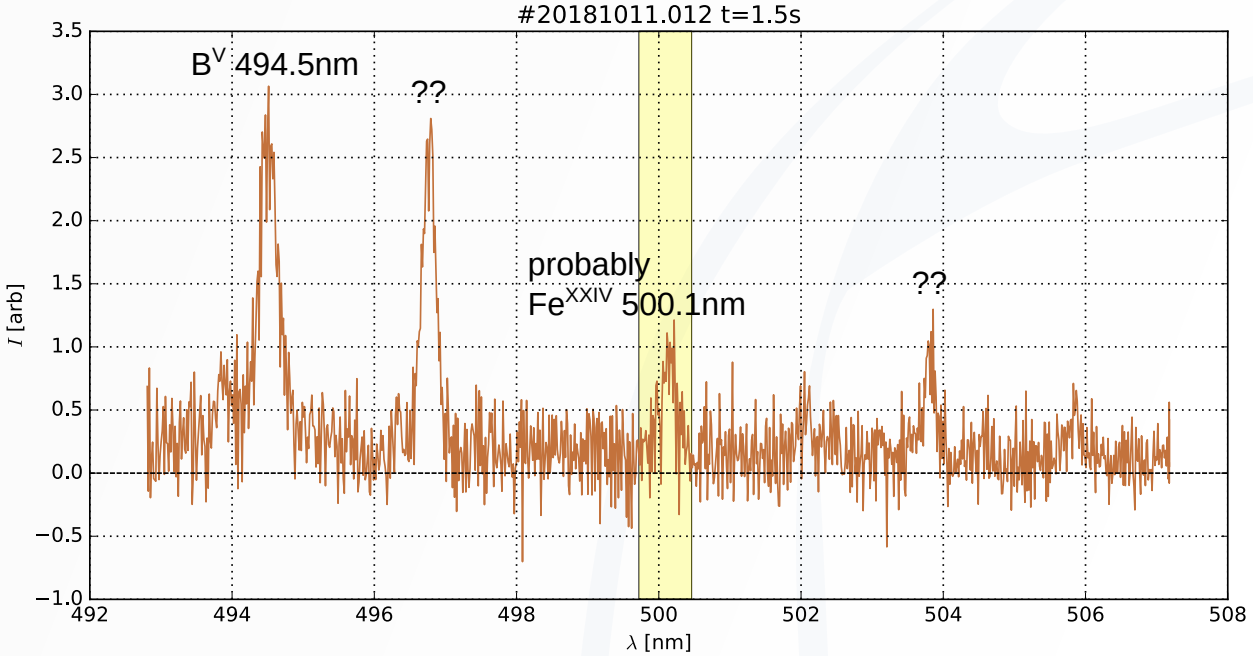

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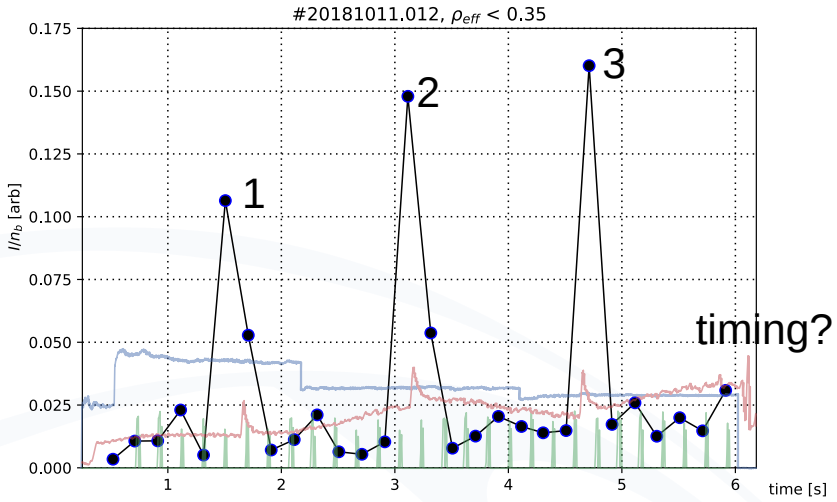
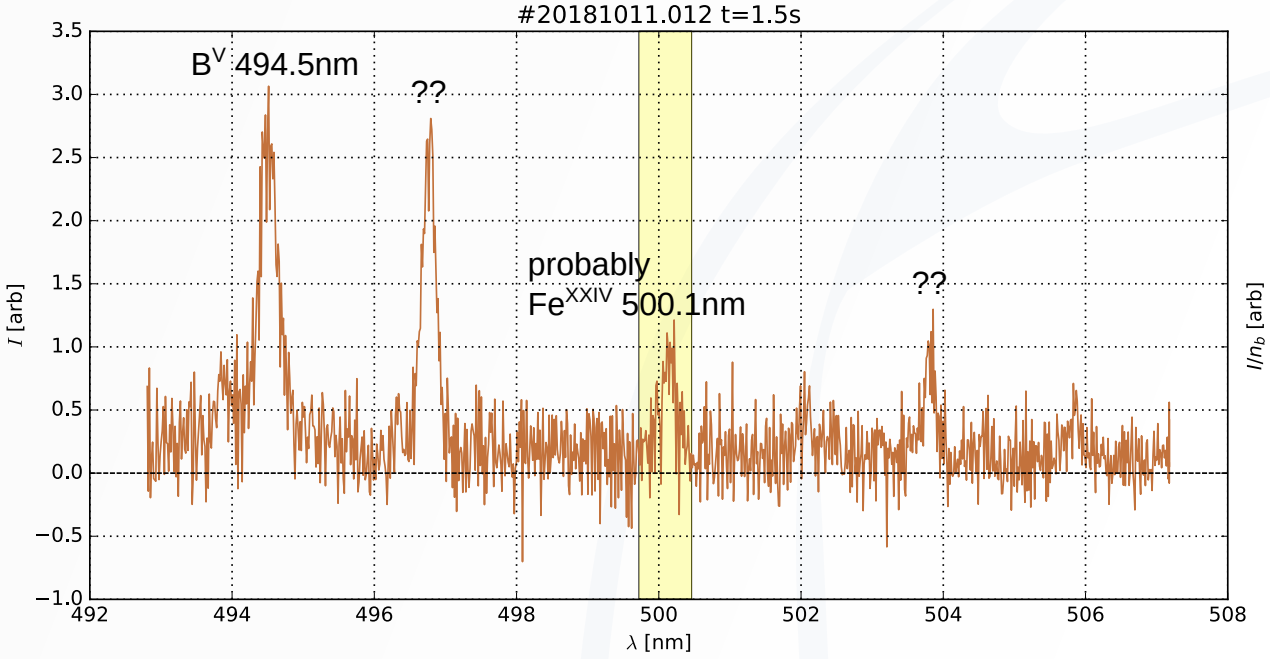
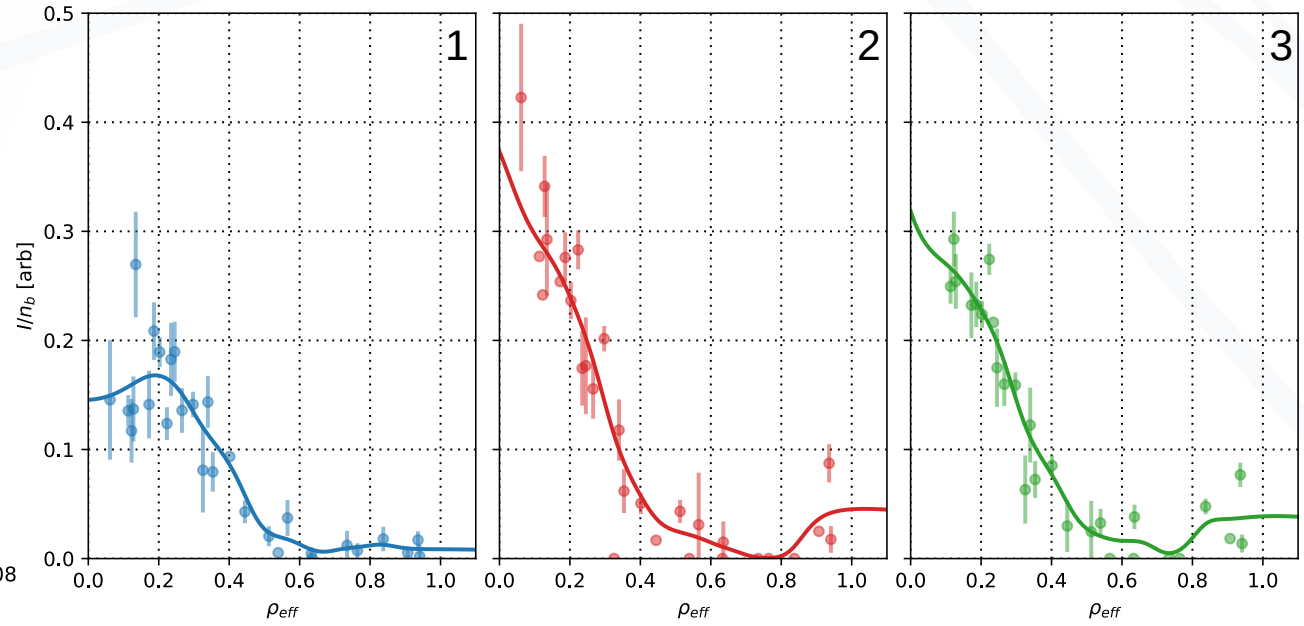
  - Parent state density (Fe^{24+}) dependant on T_e (like Ar^{16+} etc in XICS)
  - Might be other shots with Fe^{XXIII} 544.5nm (for n_{Fe23+})

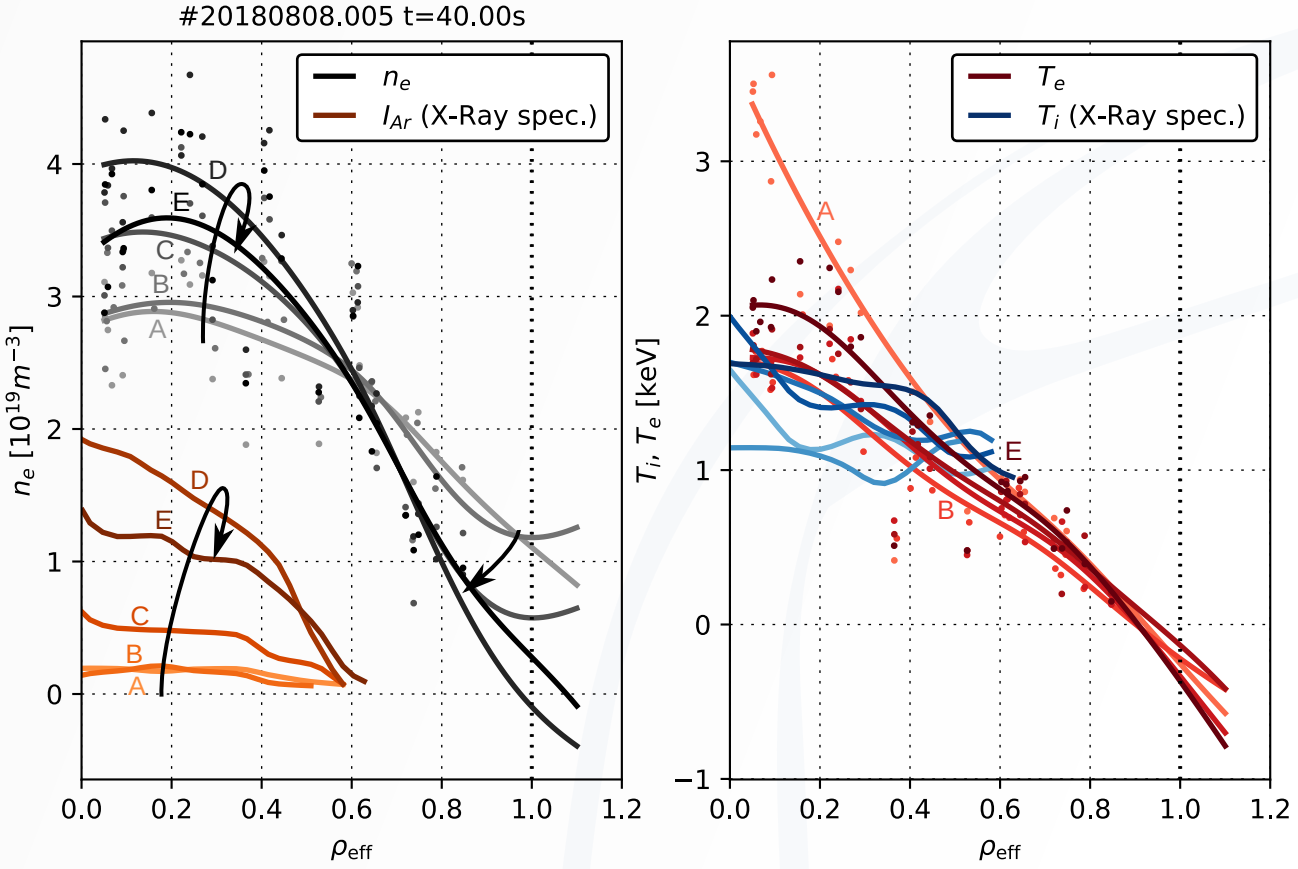


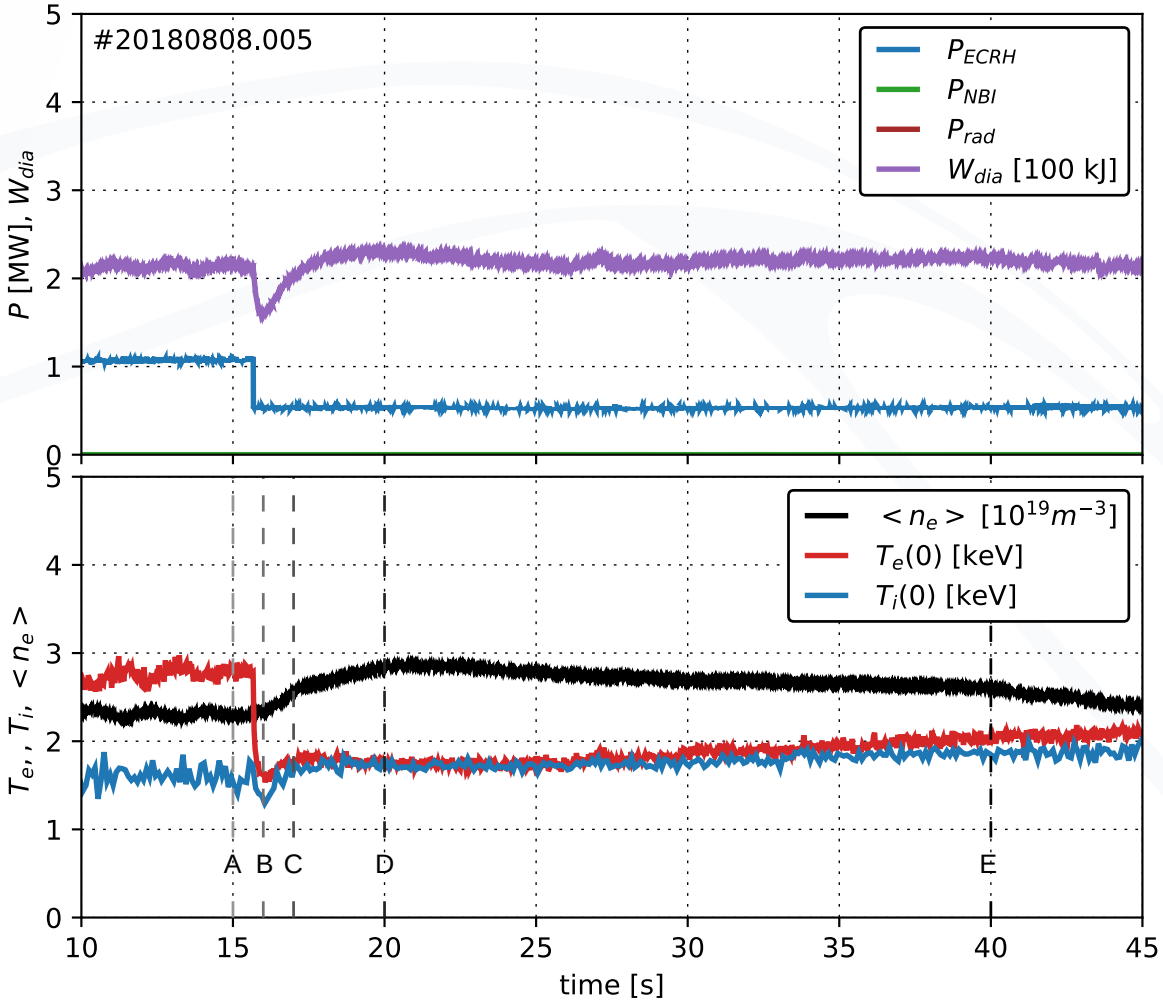




Density gradient turbulence suppression

- 180808.005: Drop from 1MW to 0.5MW ECRH. T_e Drops to ~T_i,
- Electron and argon densities peak over ~seconds.
- T_i increases over ~10s seconds as n_e decreases slightly.



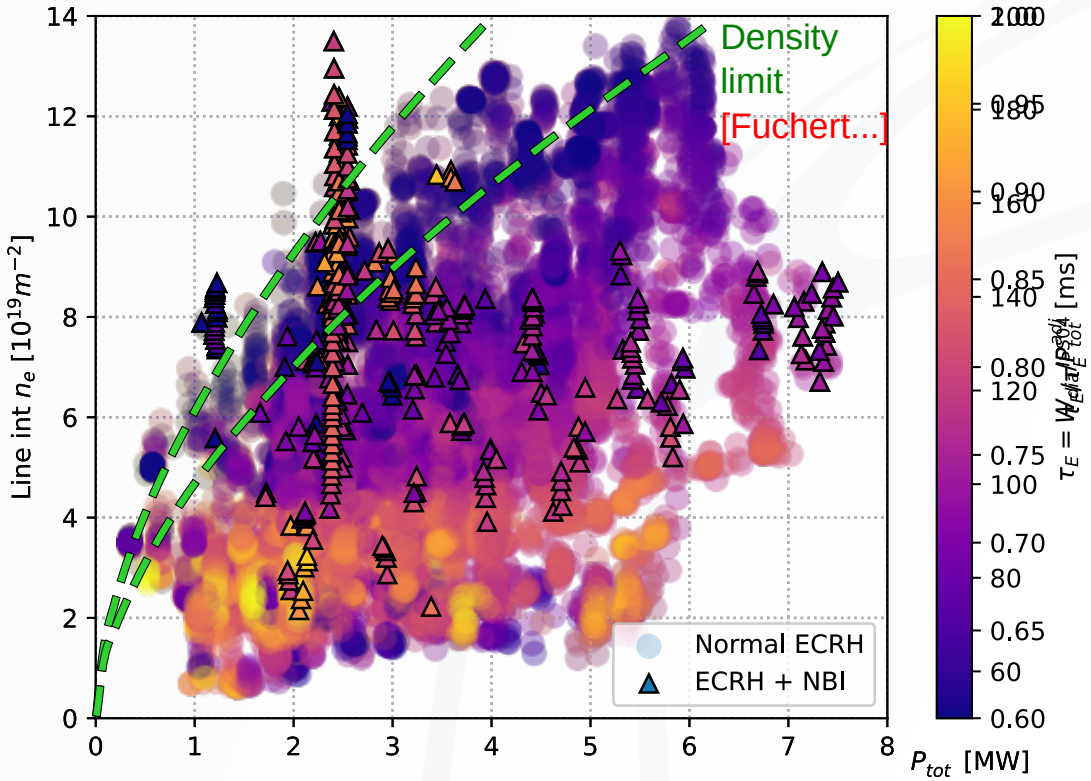


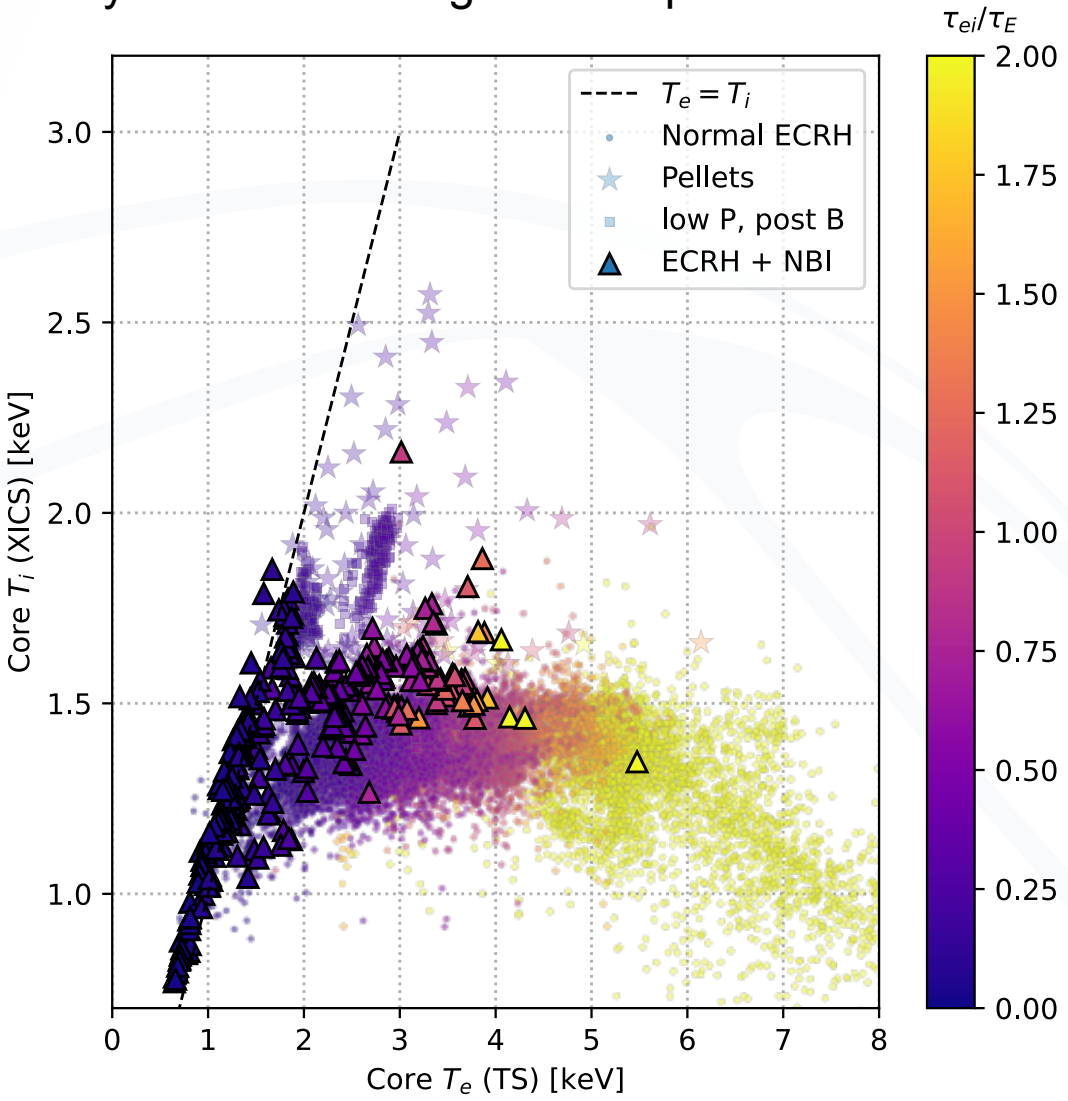
Neutral Beam Injection: Confinement

- 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.

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

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





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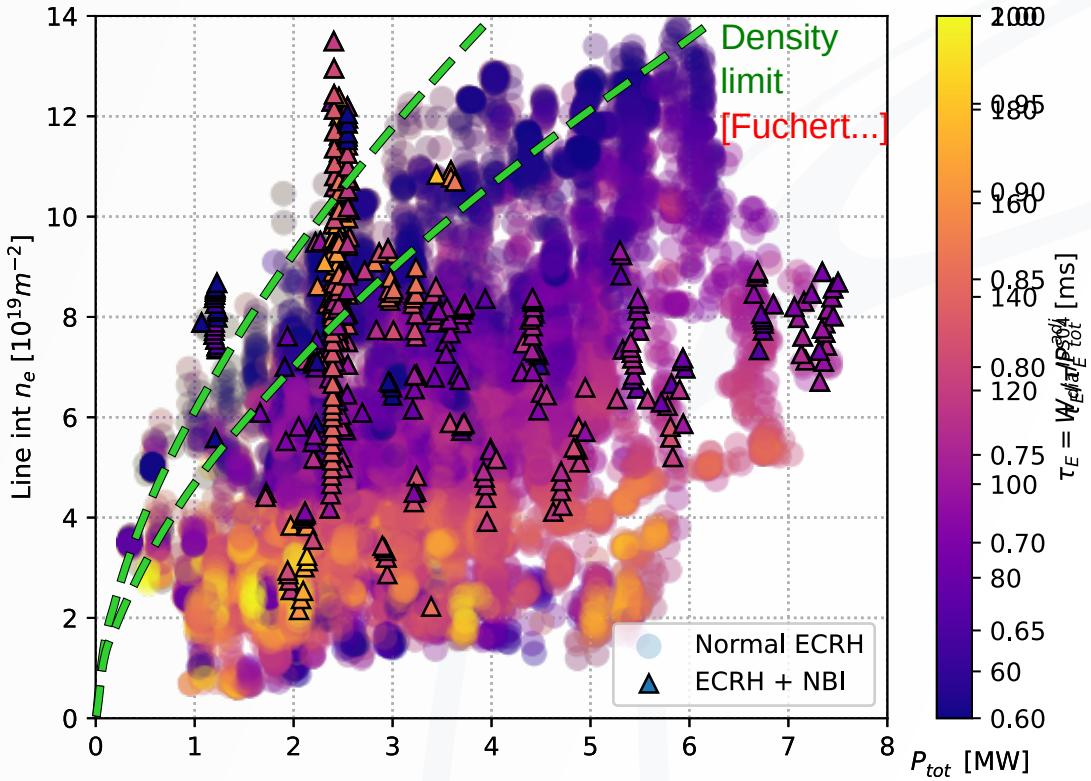
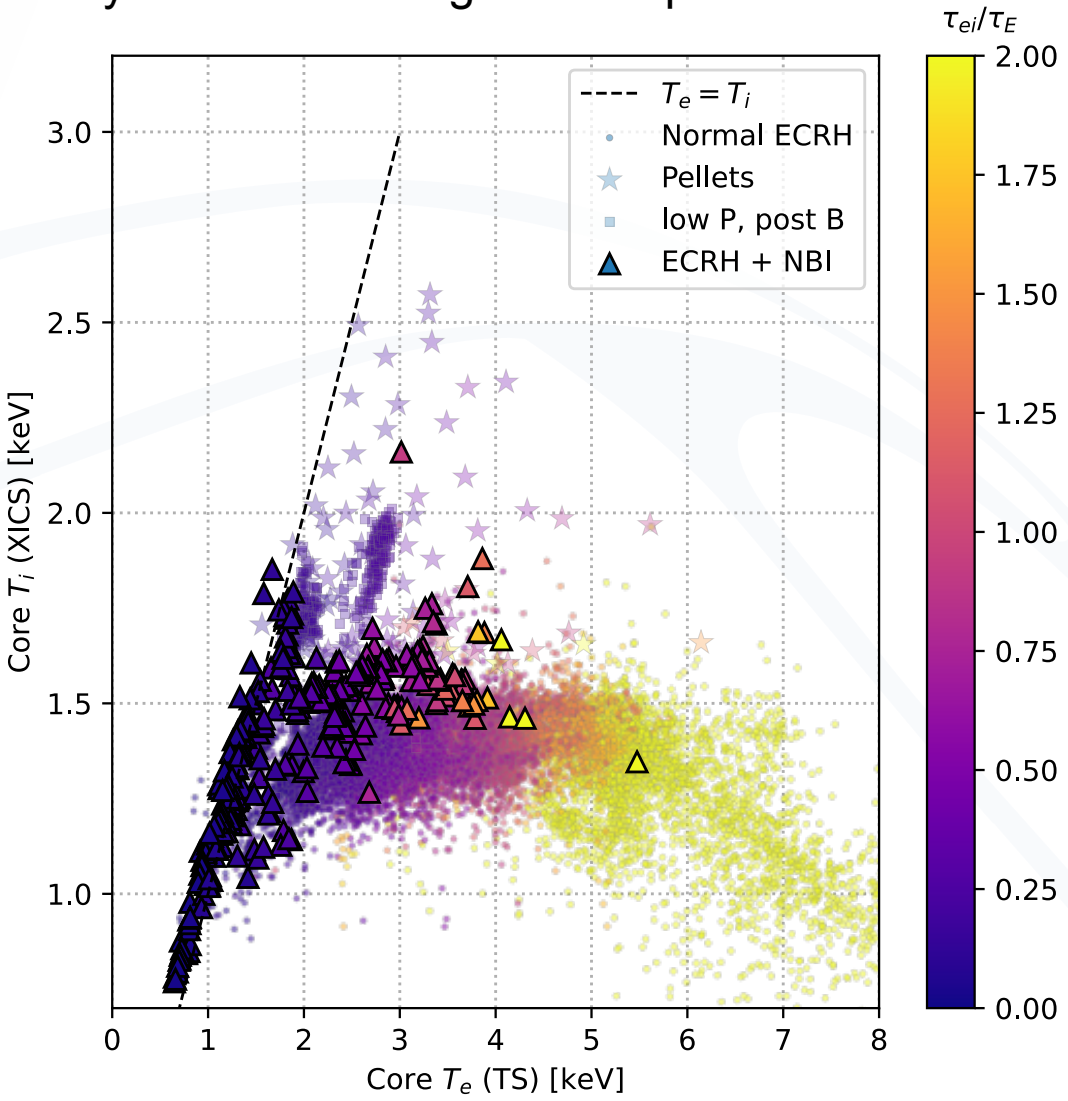
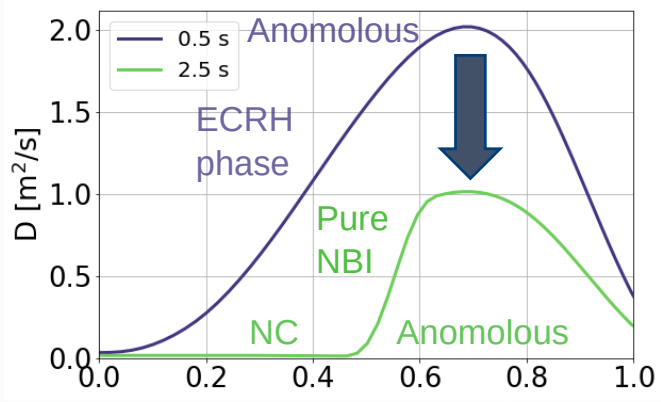
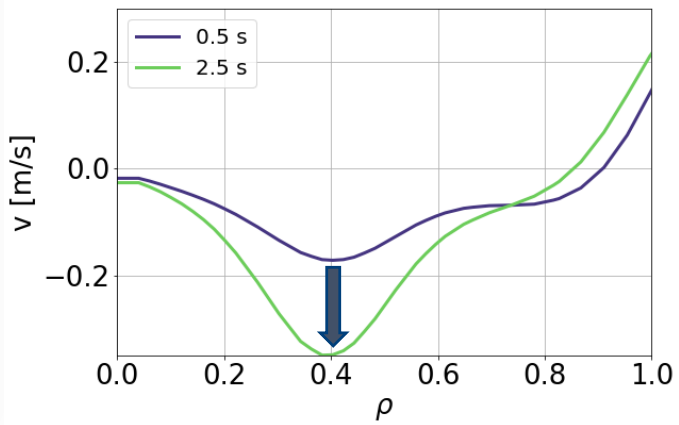




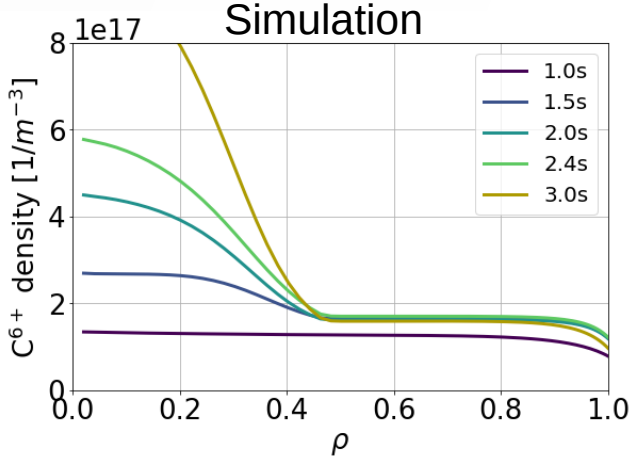
NBI only impurity pinch

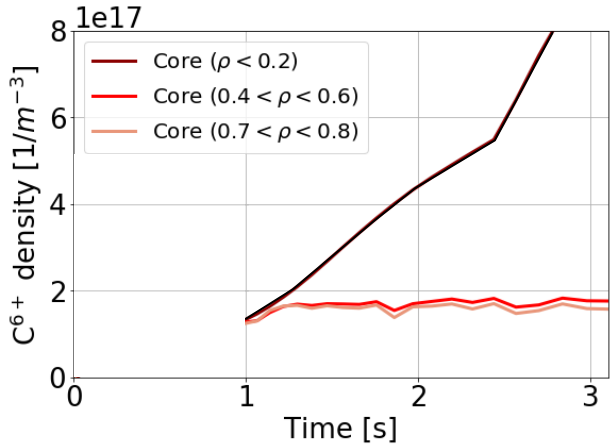
- STRAHL simulations assuming neoclassical transport coefficients inside ρ = 0.5 during NBI only phase give similar qualitative beahviour and profiles. Quantitatively too rapid rise rate and too early.
- Behaviour consistent with strong reduction of turbulence in density peaking region after given onset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



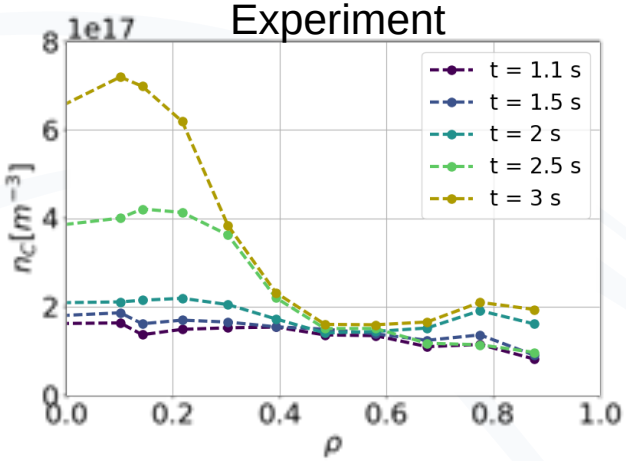


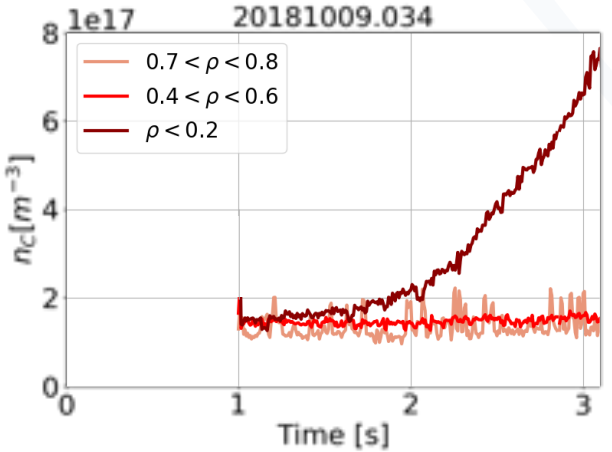
Simulation





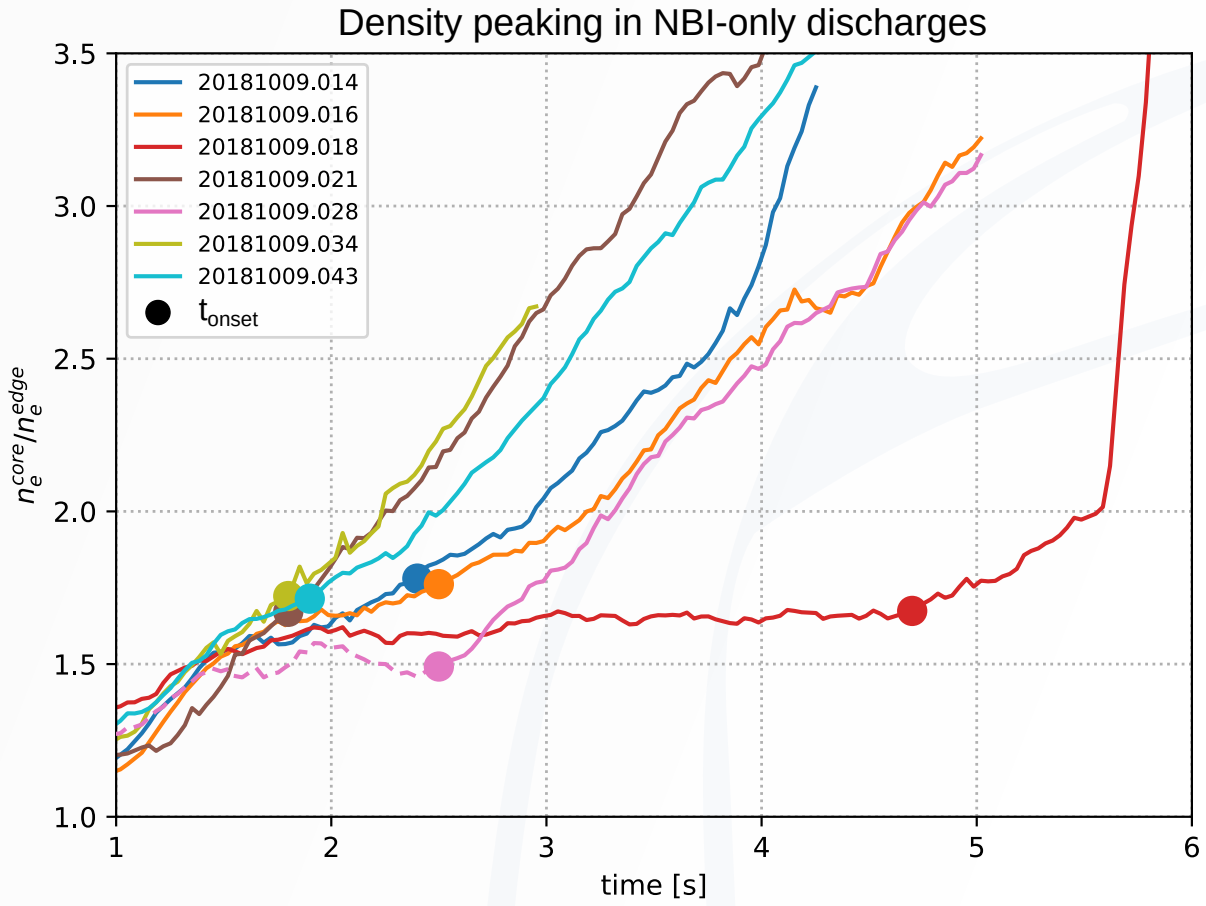
Experiment

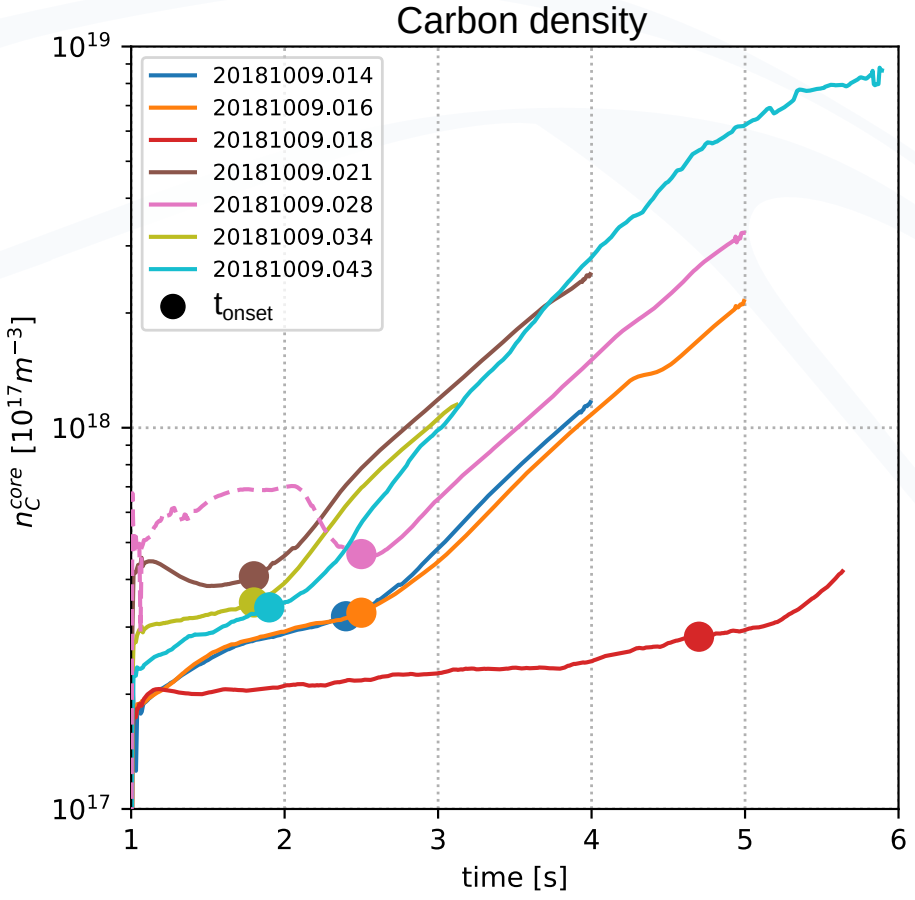




Electron/ion particle transport

- 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)*

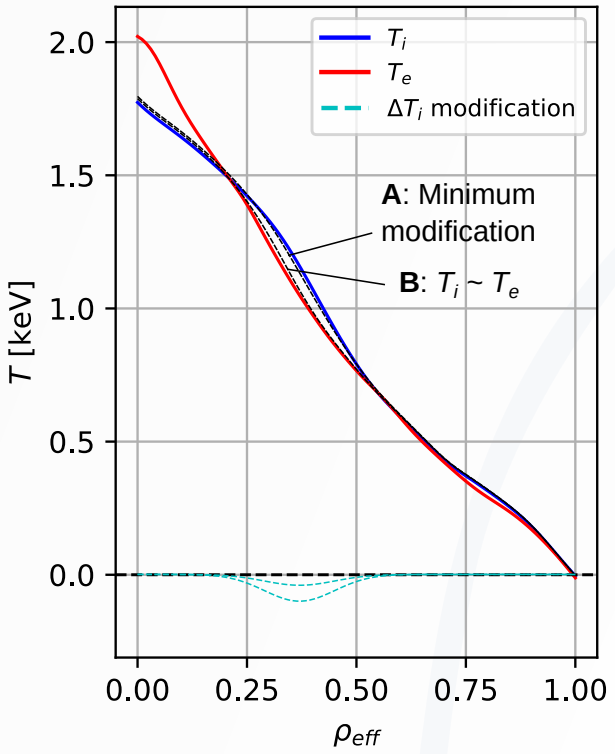


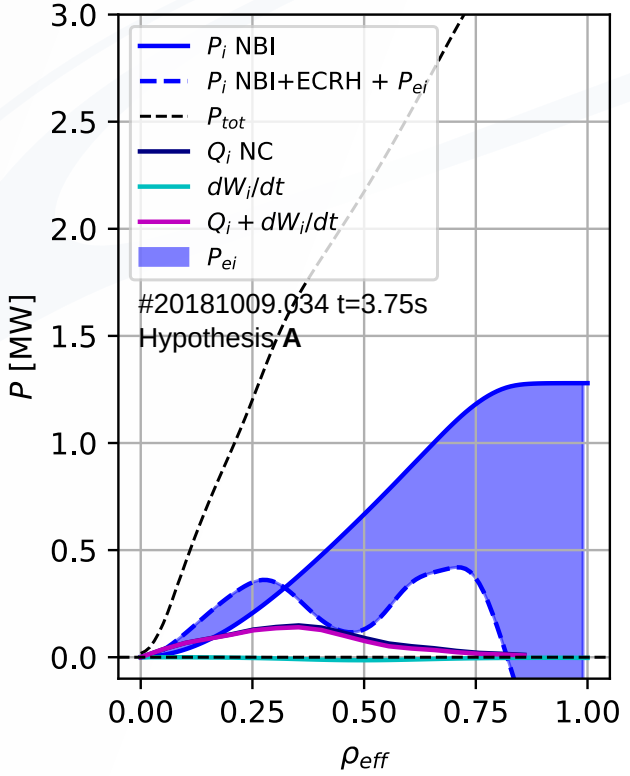


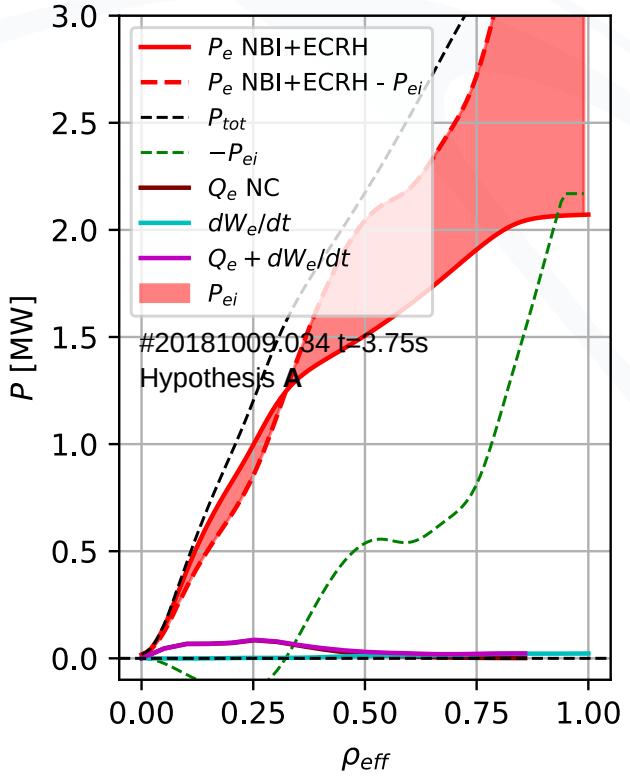
Energy transport: Species separation

- Separation of ion and electron energy fluxes requires determination of power exchange term.
- At high collisionality (n_e ~ 10^{20}), this requires *O(*10eV*)* 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 ~ Q_{NC} would be consistent with with post-pellets experiments.
- However, neoclassical electron energy fluxes *not* supported by measurements.

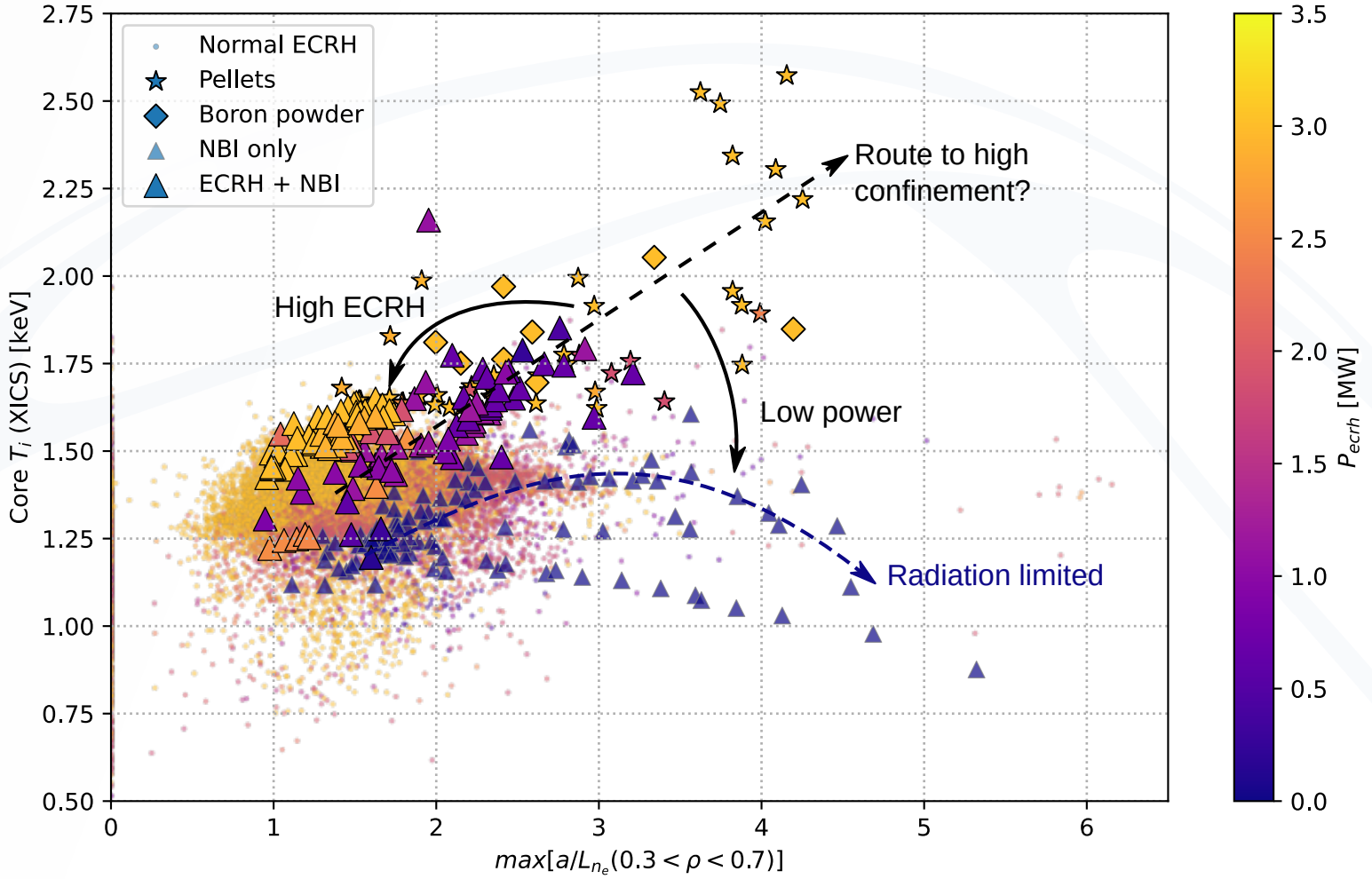
  --> Next campaign: Improvements in Ti profiles + heat wave measurements.







Routes to high confinment

- 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?