Max-Planck-Institut für Plasmaphysik

Particle and energy transport of the improved confinement NBI scenario at W7-X

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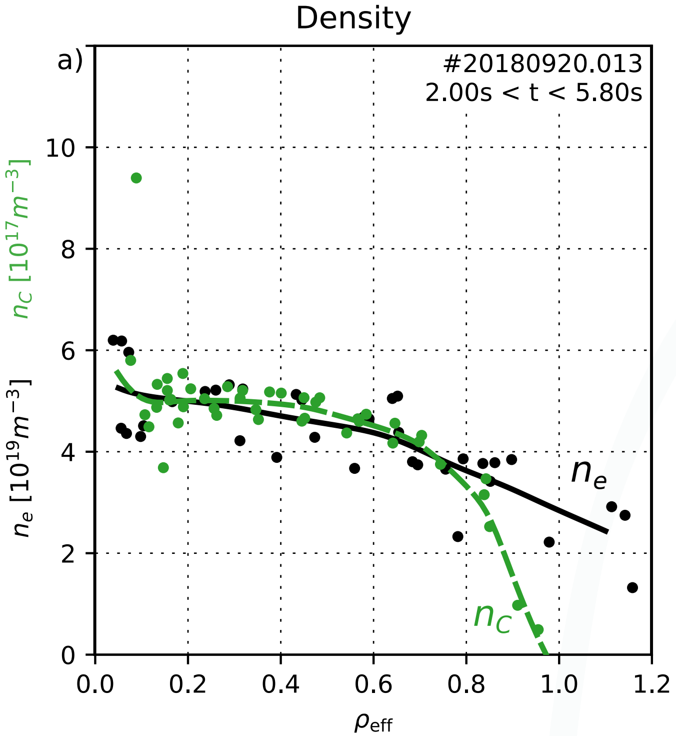
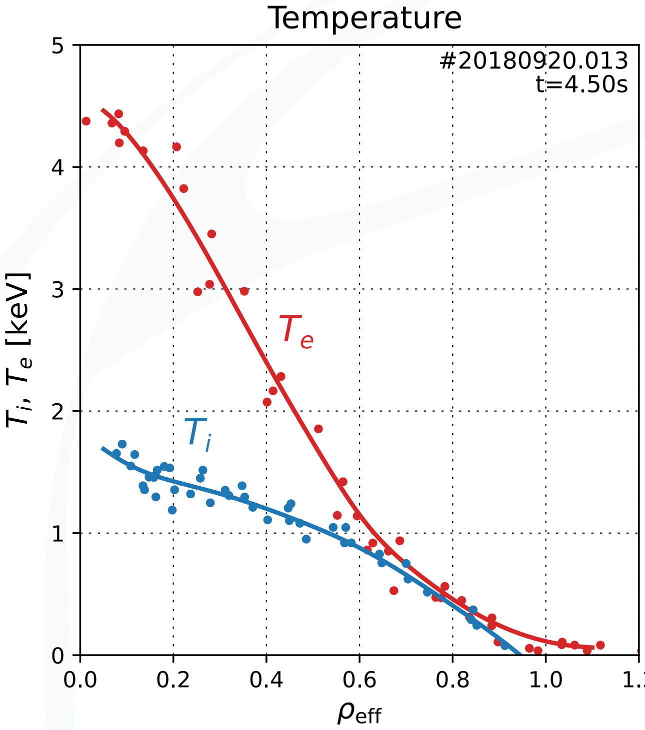
24th International Stellarator Heliotron Workshop, Hiroshima, Japan

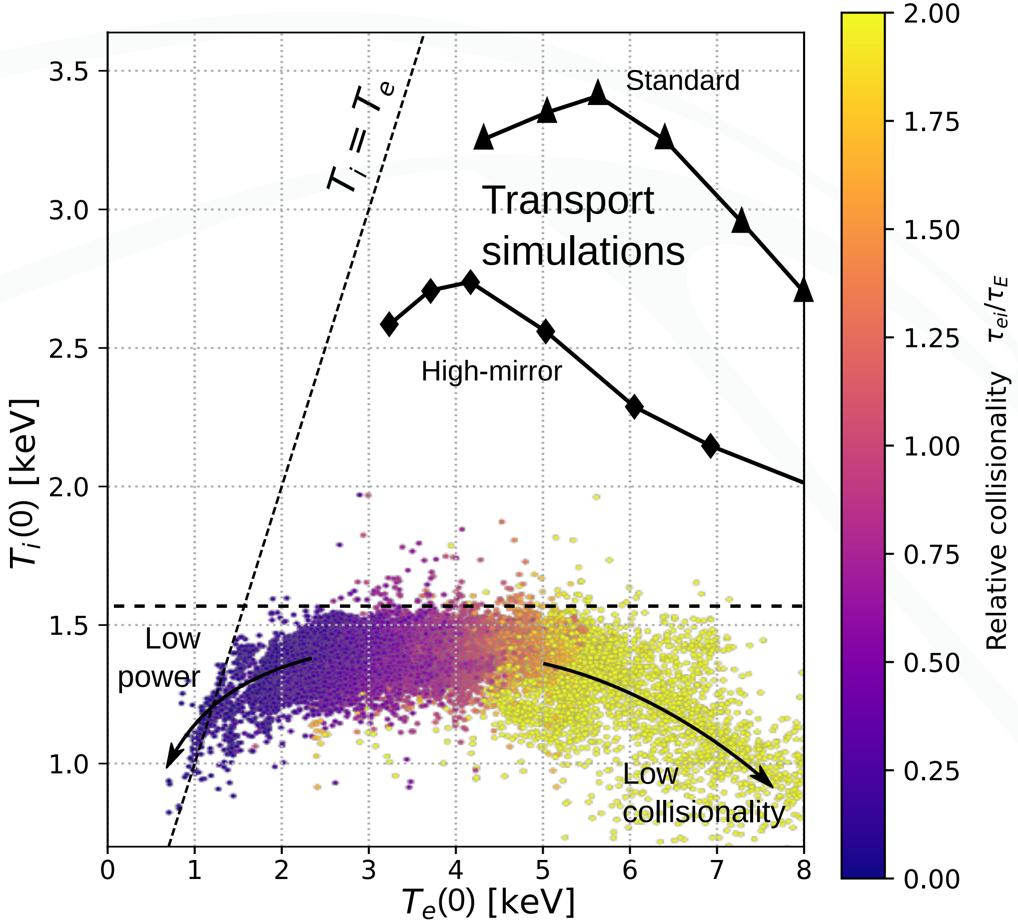
Gas-fuelled ECRH discharges

In W7-X, typical scenario for long pulse, divertor experiments, parameter scans etc [as shown in talk by D. Gradic].
- Gas/recycling fuelled. - Continuous ECRH.

Result:
- Steady-state
- Flat n_e profiles
- Low, flat impurity density profiles
- Core $T_i \leq$ 1.5keV --> Turbulence dominates e + i heat fluxes.







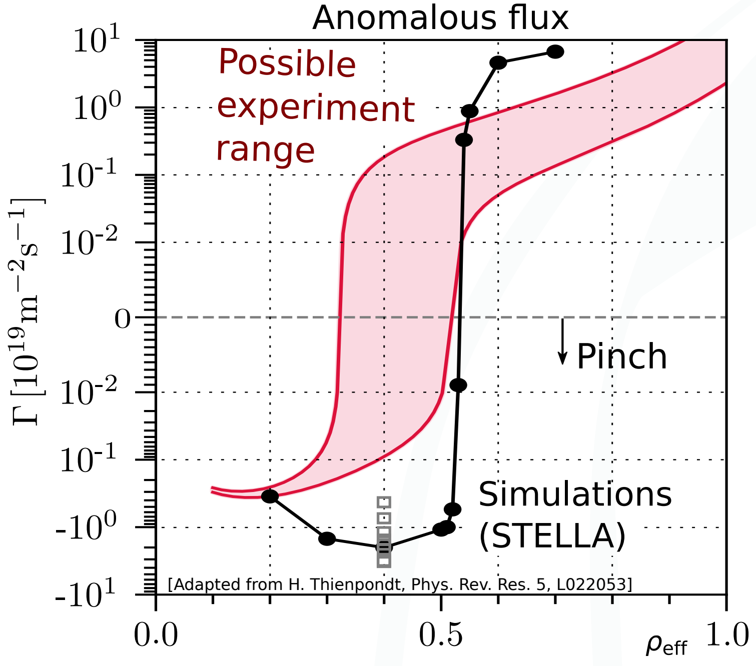
Gas-fuelled ECRH discharges

Main ions:

Neoclassics --> hollow,   Experiment = flat

- Requires anomalous pinch inside $\rho < 0.5$.
- Pinch is seen in gyrokinetic simulations in *roughly* the right place.

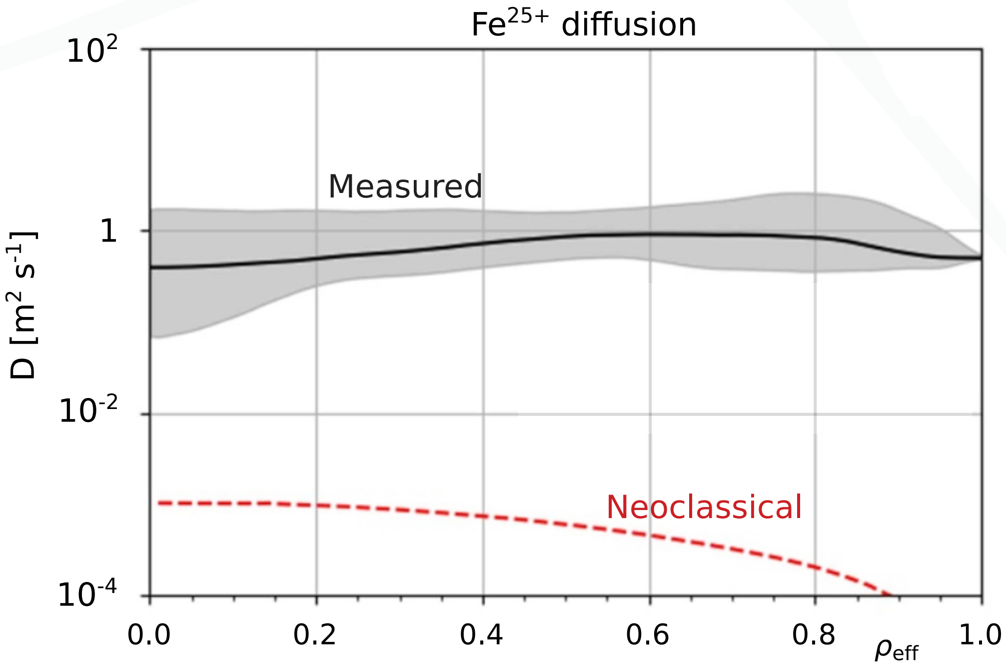
  [Thienpondt, Phys. Rev. Res. **5**, L022053 (2023)]
- but large quantitative differences and comparison is Difficult without measured neutral fuelling profile.



Impurities:

- Neoclassics --> peaked, Experiment = flat

  Require strong anomalous diffusion to flatten the profile ($D > 0.1\mathrm{m}^2\mathrm{s}^{-1}$).   [T. Romba PPCF **65** 075011 (2023)]
- Measured *v, D* in LBO injections show strong anomalous diffusion   [Swee Nucl. Fus. **64** 086062 (2024), B. Geiger Nucl. Fus. **59** 046009 (2019)]
- Gyrokinetic predictions of D ~ $O(1)$ $\mathrm{m}^2\mathrm{s}^{-1}$ from TEM+ITG turbulence. [García-Regaña JPP'21]



Reduced turbulent transport scenarios

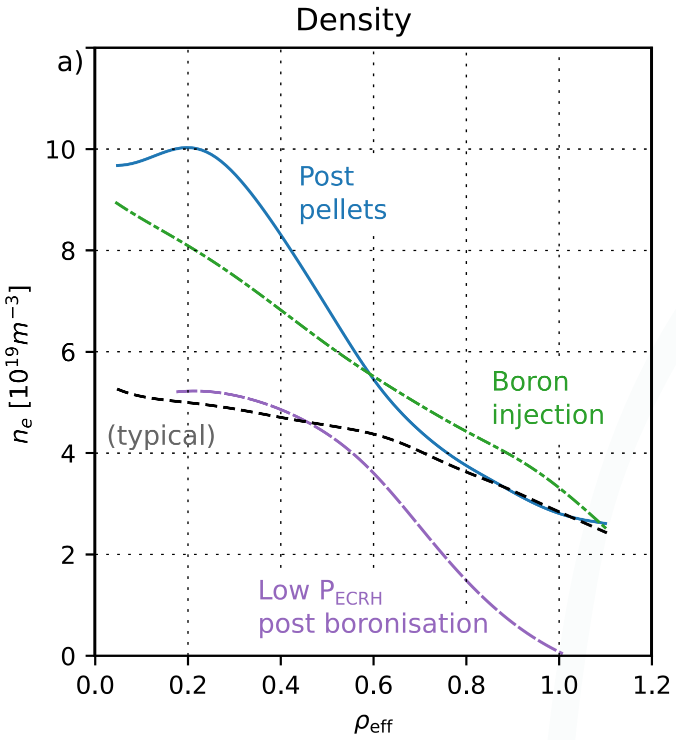
ECRH + gas --> Turbulence dominated heat and main ion and impurity particle transport.

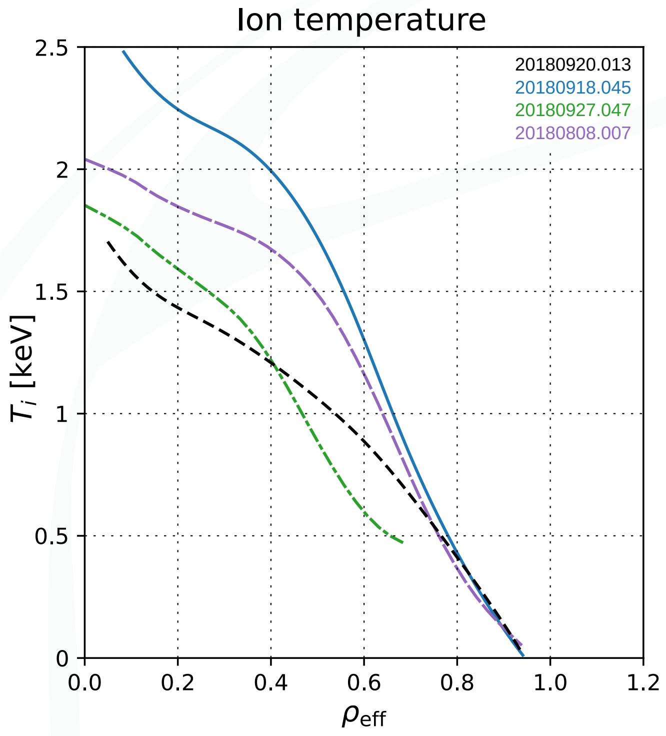
Various plasma scenarios show effects of reduced turbulence:

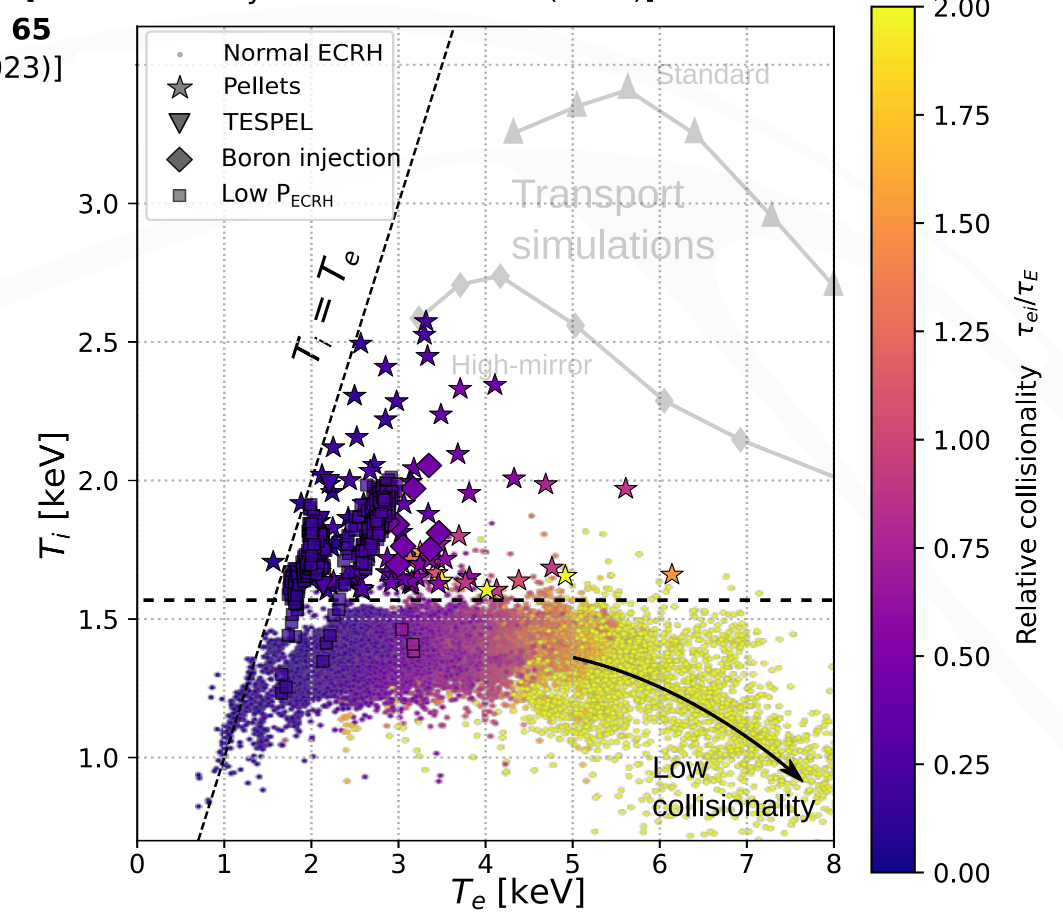
- After pellets --> peaked n_e, peaked n_z --> neoclassical Q_i --> T_i > 1.5keV [S. Bozhenkov Nucl. Fusion **60** 066011 (2020)]
- Impurity pellets, boron injection --> peaked n_e --> T_i > 1.5 keV [R. Lunsford Phys. Plas. **28** 082506 (2021)]
- Some low power ECRH --> Spontaneous peaked n_e, n_Z [Zhang PPCF **65** 105006 (2023)]

∇n_e --> ITG suppression [Xanthopoulos, PRL **125** 075001 (2020)]

--> reduced χ_i --> higher ∇T_i *(poster by M. Wappl, today)*

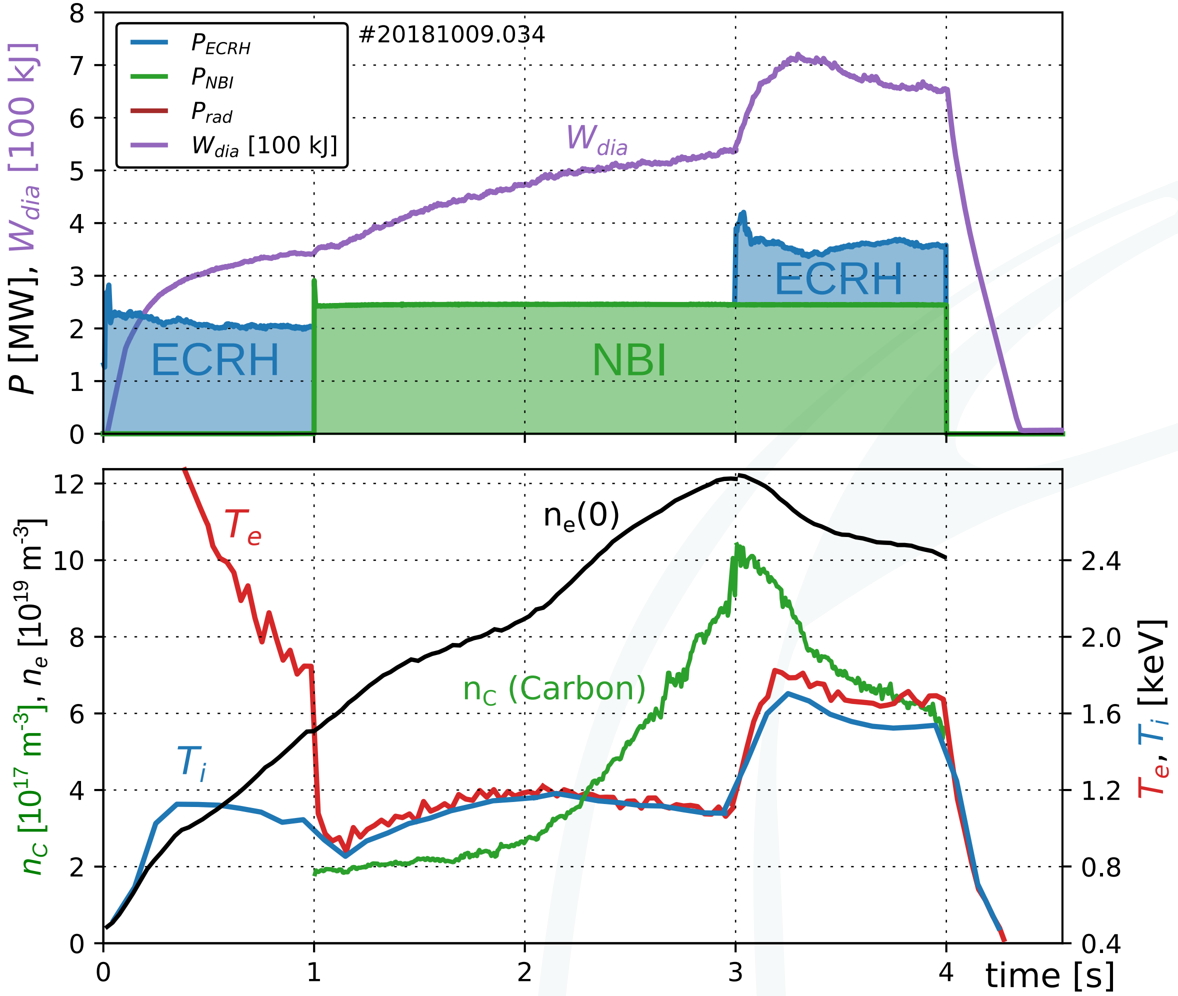


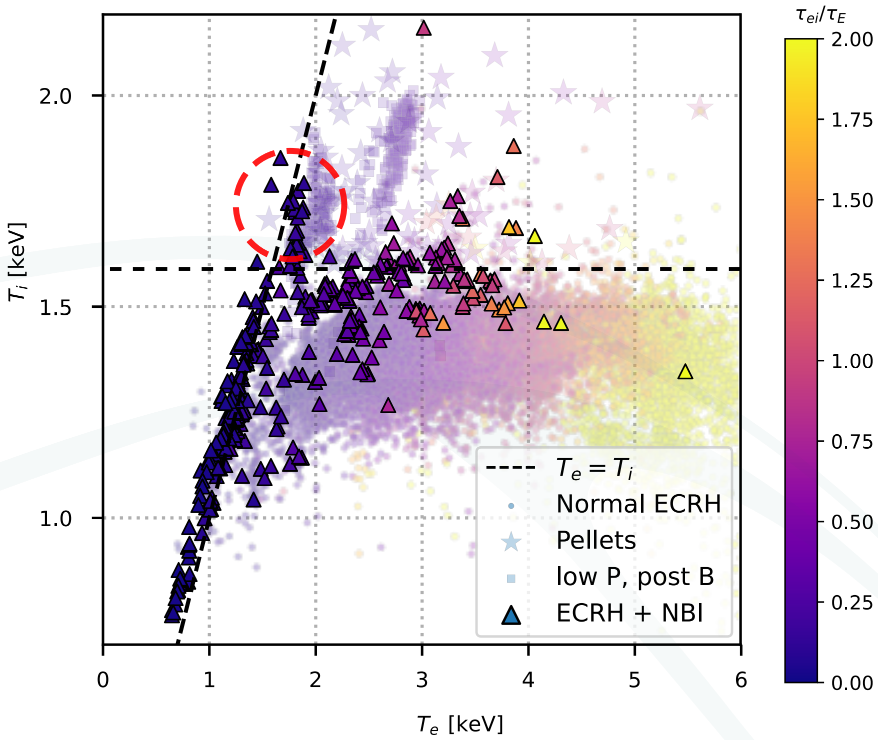




NBI + ECRH reintroduction scenario

- NBI *sometimes* gives density gradients. In some cases cleary $T_i > 1.5$
- Strong density peaking during pure NBI but low T_i.
- Higher T_i after reintroduction of ECRH.





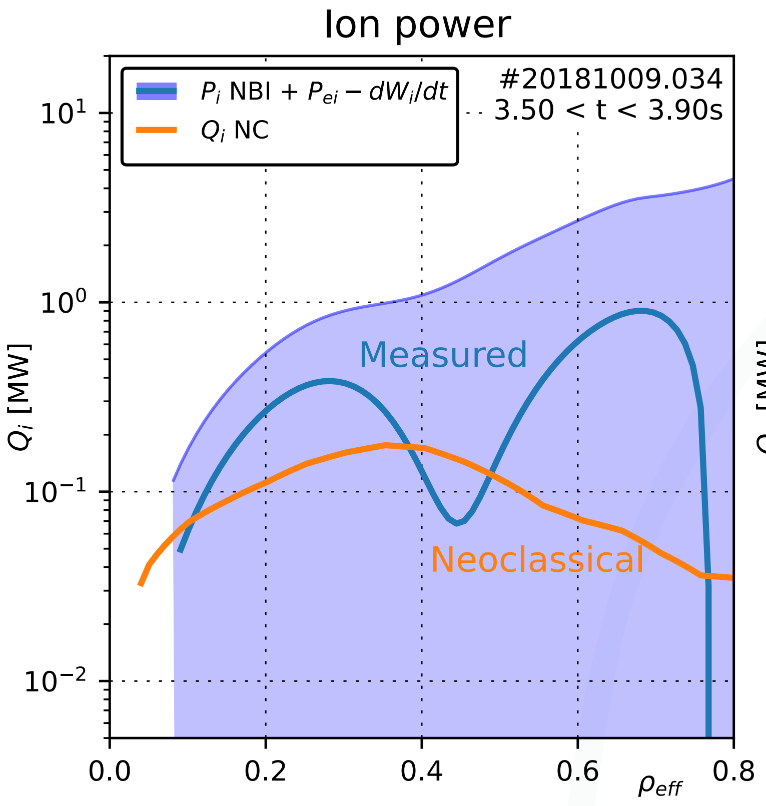
- Impurities accumulate from the middle of NBI phase, almost entirely determined by neoclassical transport.
  [T.Romba Nucl. Fus. **63** 076023 (2023)] (talk by T. Romba - Monday)

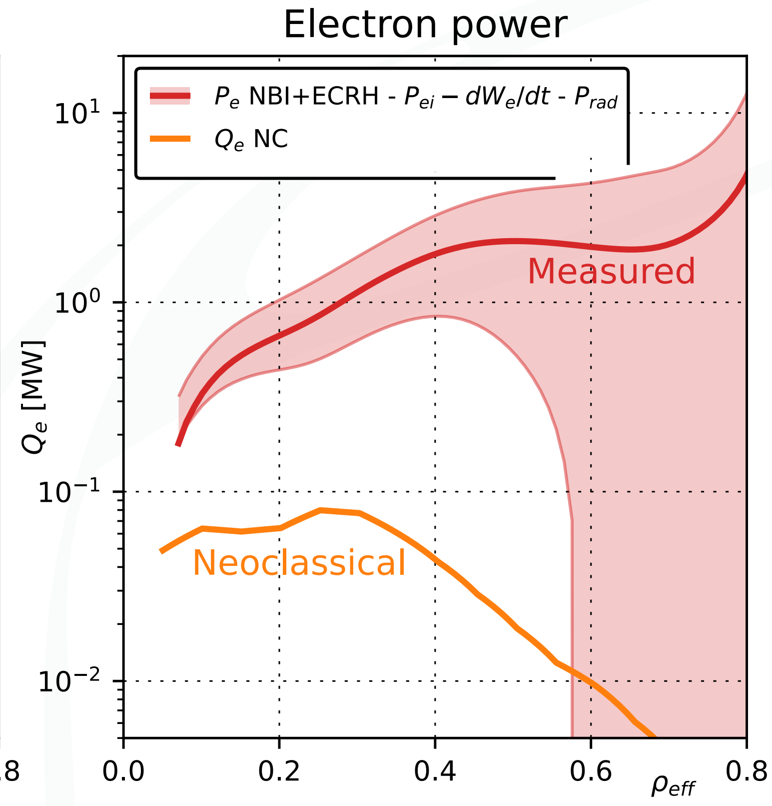
- Reintroduced ECRH stops density peaking or reduces it, and flushes out impurities.

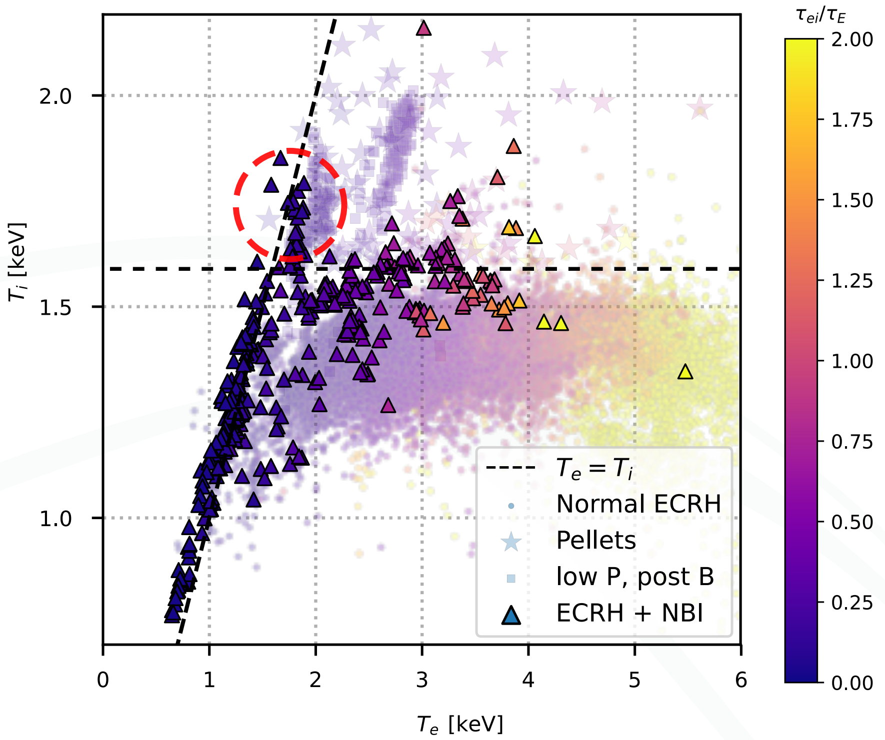
[O. Ford Nucl. Fus. 64 086067 (2024)]

Electron/ion energy fluxes in NBI plasmas

Energy fluxes:
- Pure NBI: Not possible to separate Q_i, Q_e due to high collisionality and similar heating effect of NBI - $P_e \sim P_i$.
- Some NBI+ECRH plasmas hint at **possibility** of Q_i near neoclassical levels, e.g.:



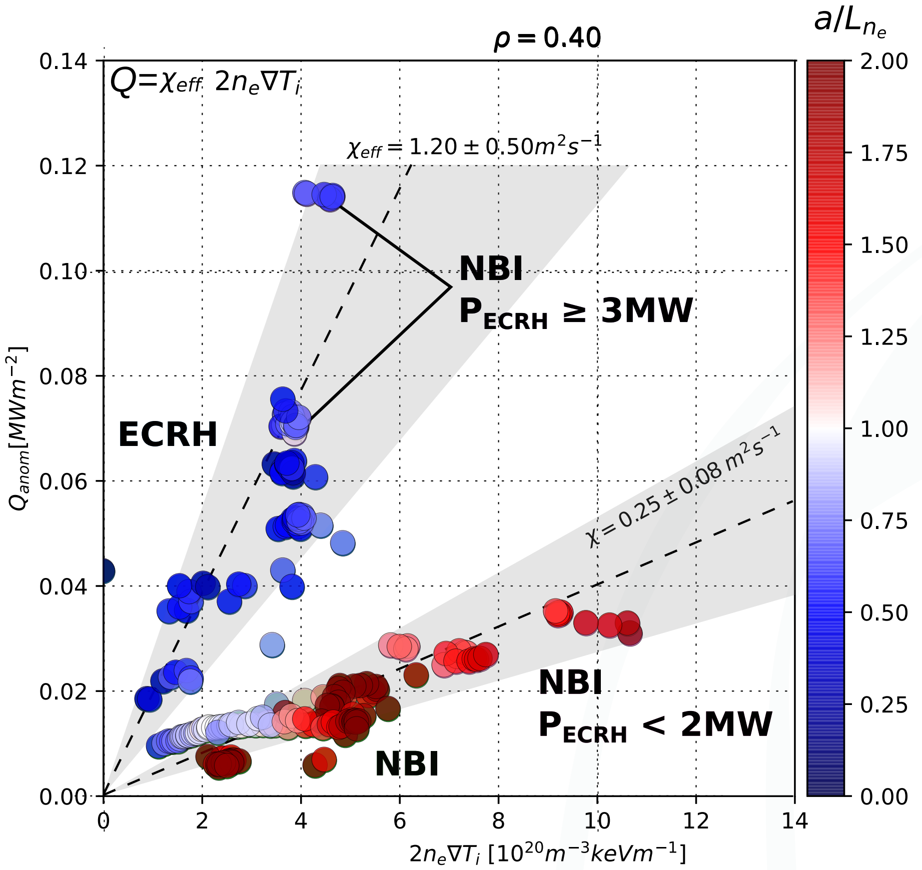


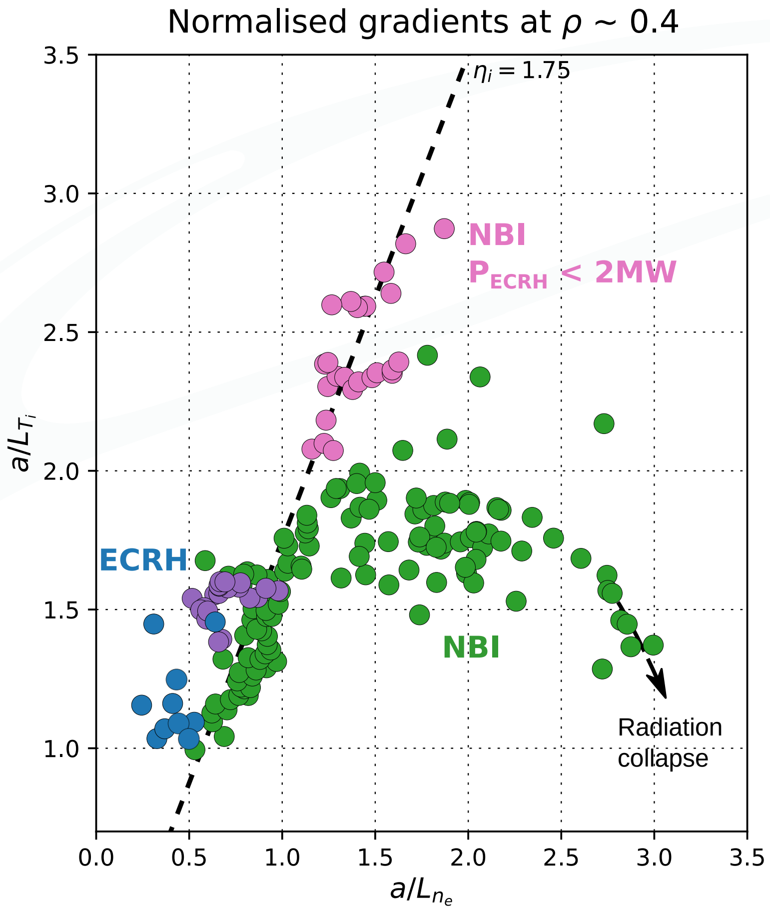


[O. Ford Nucl. Fus. 64 086067 (2024)]
[D. Carralero et al. Nucl. Fus. 61 096015 (2021)]

NBI (±ECRH) - Anomalous heat diffusivity

- Not possible to separate Q_i, Q_e due to high collisionality and similar heating effect of NBI - $P_e \sim P_i$.
- Looking at combined χ_{eff} in gradient region ($\rho \sim 0.4$) reveals two branches:
    Dominant ECRH: $\chi_{eff} \sim 1\ m^2s^{-1}$ as in pure ECRH scenarios [M. Beurskens, Nucl. Fus. 61 116072 (2021)].
    Dominant NBI: $\chi_{eff} \sim 0.25\ m^2s^{-1}$

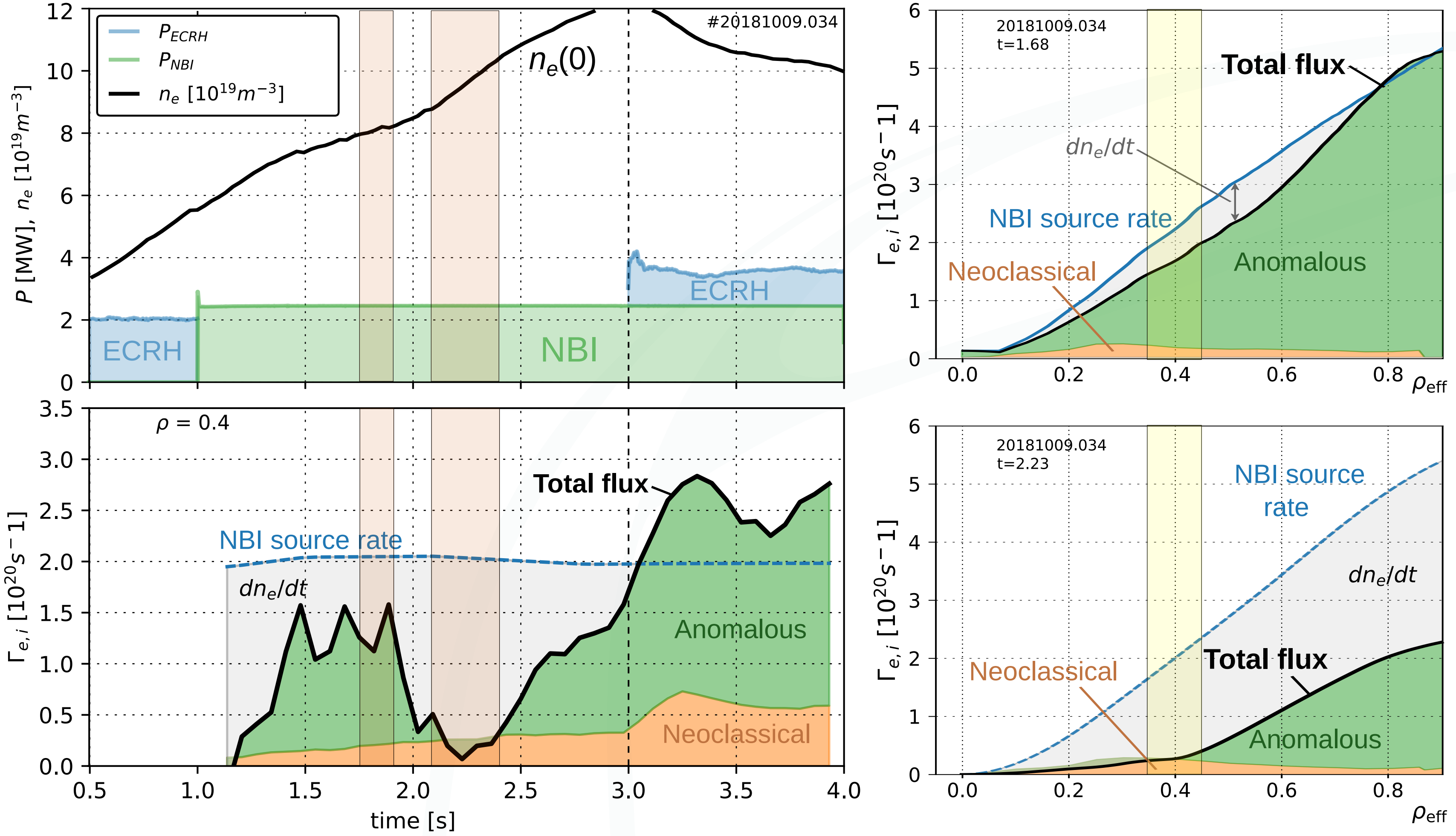




[O. Ford Nucl. Fus. 64 086067 (2024)]
[D. Carralero et al. Nucl. Fus. 61 096015 (2021)]

Pure NBI - Particle flux

- Particle balance during pure NBI phase shows:
  - Initially significant **outward** anomalous flux (opposite direction to ECRH case) --> slow n_e rise.
  - Sudden drop in particle flux with no external changes --> fast n_e rise.



- Drops to apparently neoclassical flux level.

- Increases again shortly afterwards.

- Increases again at ECRH reinroduction, reducing n_e a little.

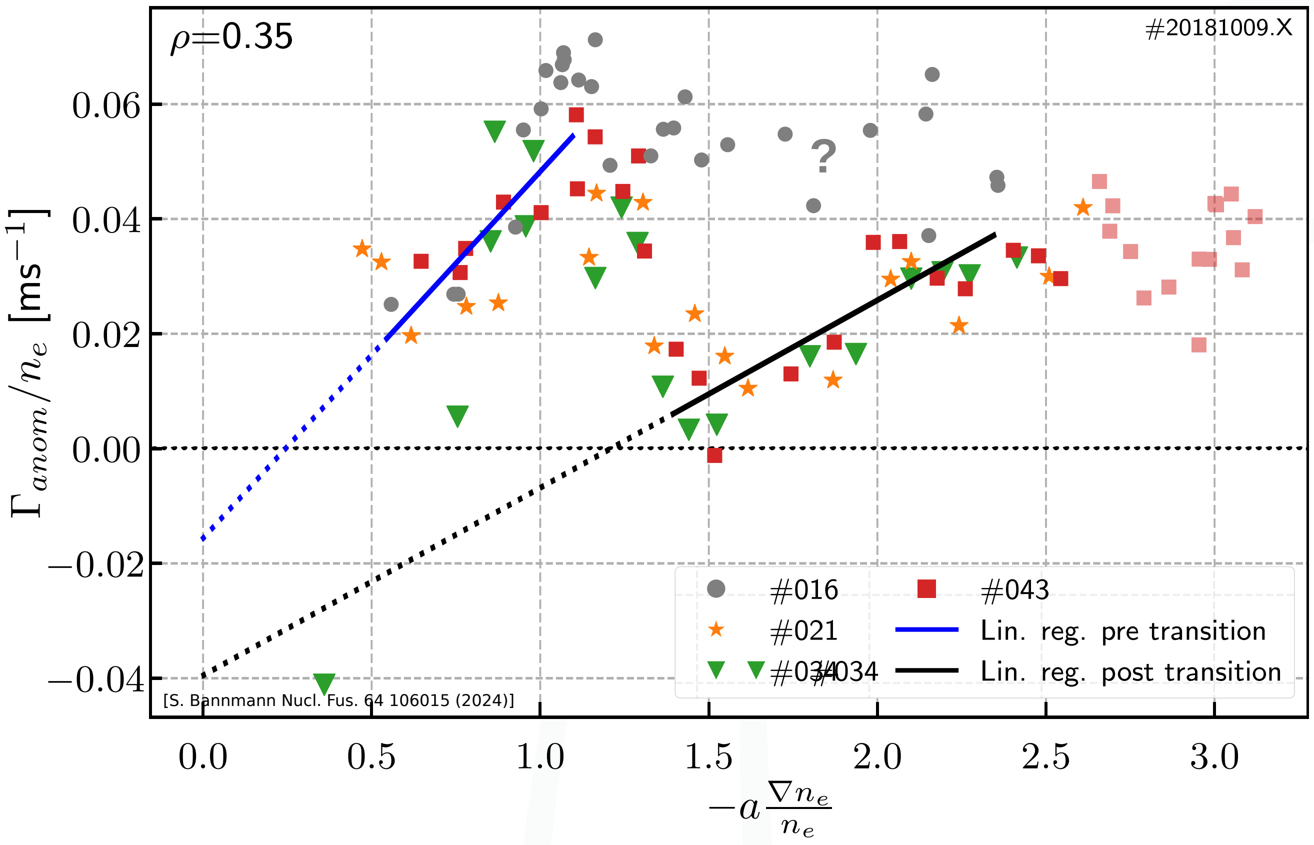
[O. Ford Nucl. Fus. 64 086067 (2024)]

Pure NBI - Particle transport

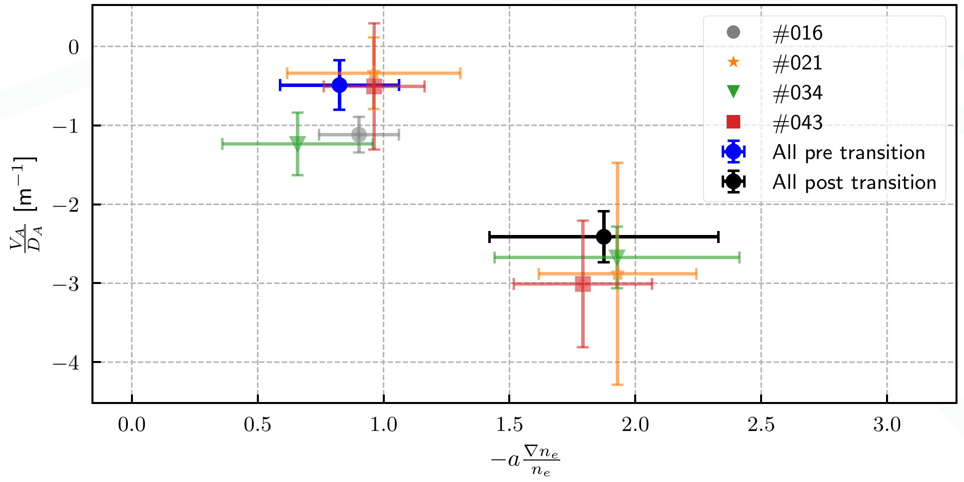
[S. Bannmann Nucl. Fus. 64 106015 (2024)]

∇n_e is changing. What is just an 'expected' reponse to this?
--> Decompose into diffusive *D* and convective *v*.

$$\frac{\Gamma_{\text{anom}}}{n_e} = -D \frac{\nabla n_e}{n_e} + V$$



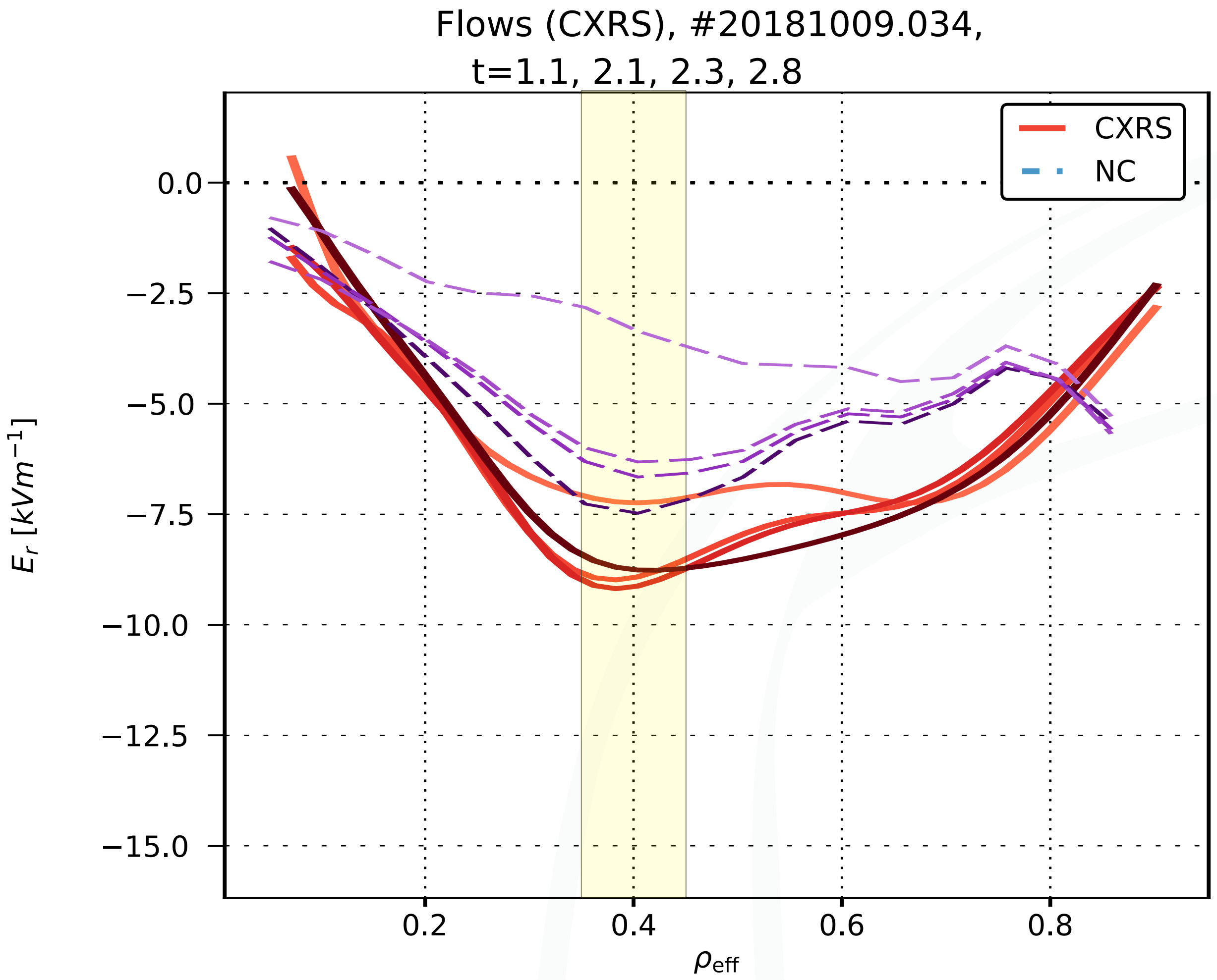
- Indicates two phases of ~consistent *v*, *D* with significant drop of *D* at a/L_n ~ 1.3.
- *v/D* ratio increases by factor ~ x5 leading to strong peaking.

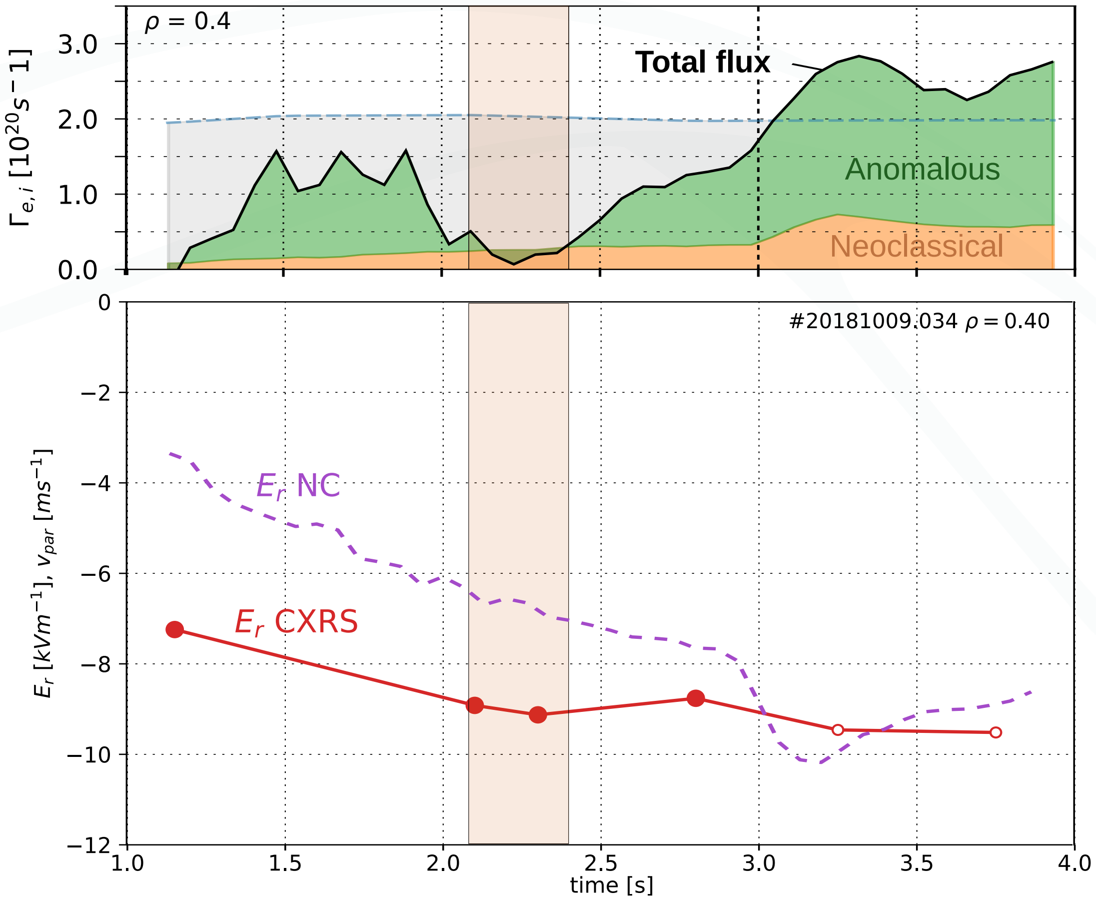


- Threshold not yet seen in modelling. (Range not covered by STELLA study [H. Thienpondt, Phys. Rev. Res. 5, L022053 (2023)])

Pure NBI - Radial Electric Field

- E_r or shear can affect anomalous transport and often change strongly in W7-X. (e.g. Ion vs Electorn root).
- NBI discharges all ion root with no significant E_r changes at onset time (measured or NC).

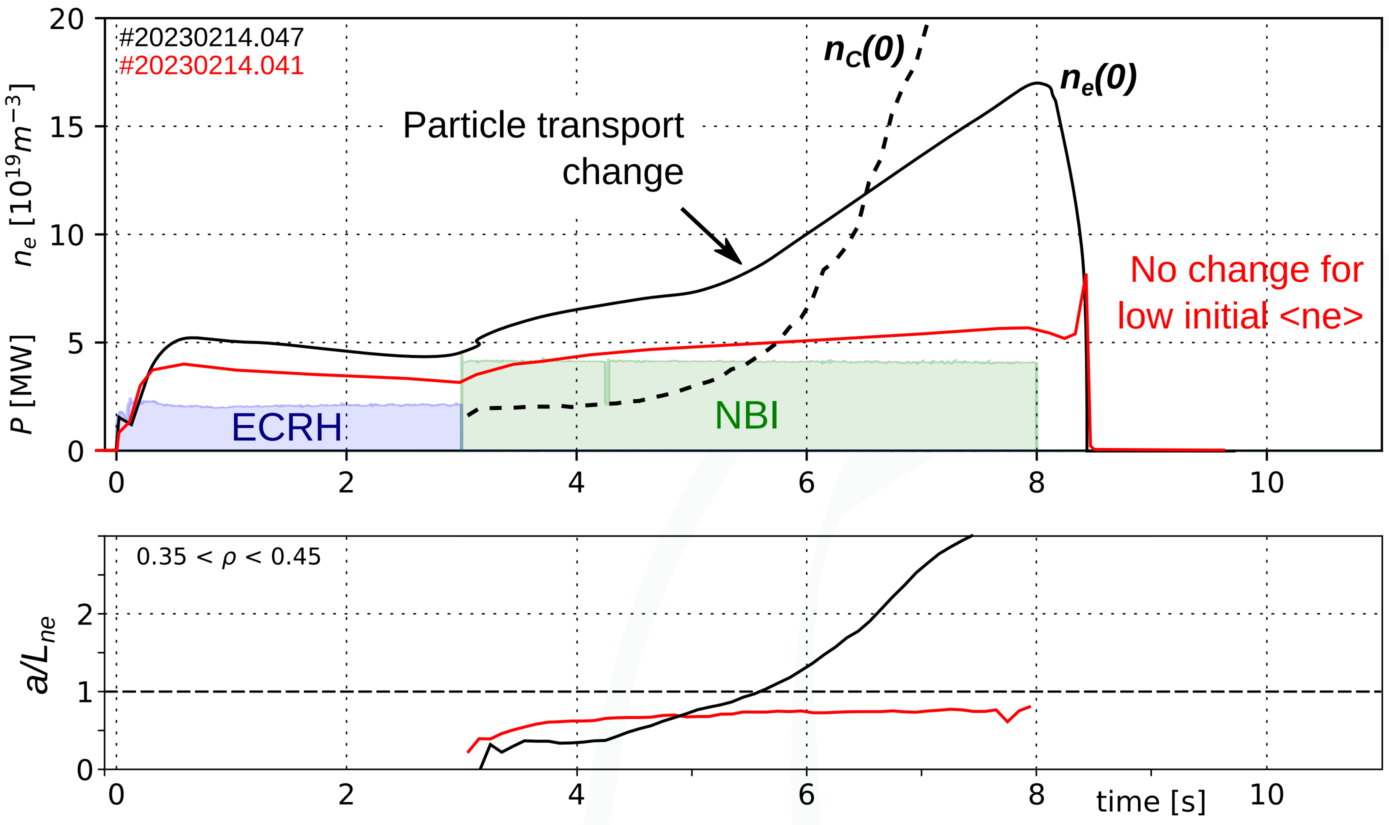


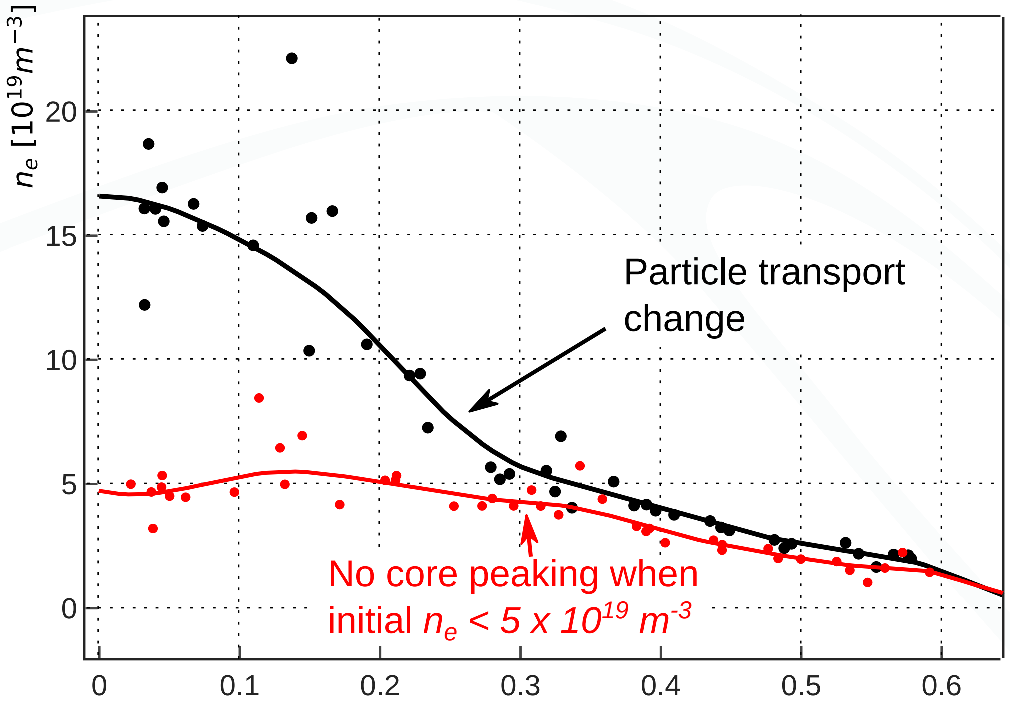


OP2.1 (2023) campaign

In the 2022/3 campaign:

1) Reintroduction scenario repeated multiple time in multiple magnetic configuration.
2) Confirmation of threshold behaviour - NBI with low initial density never shows strong peaking:



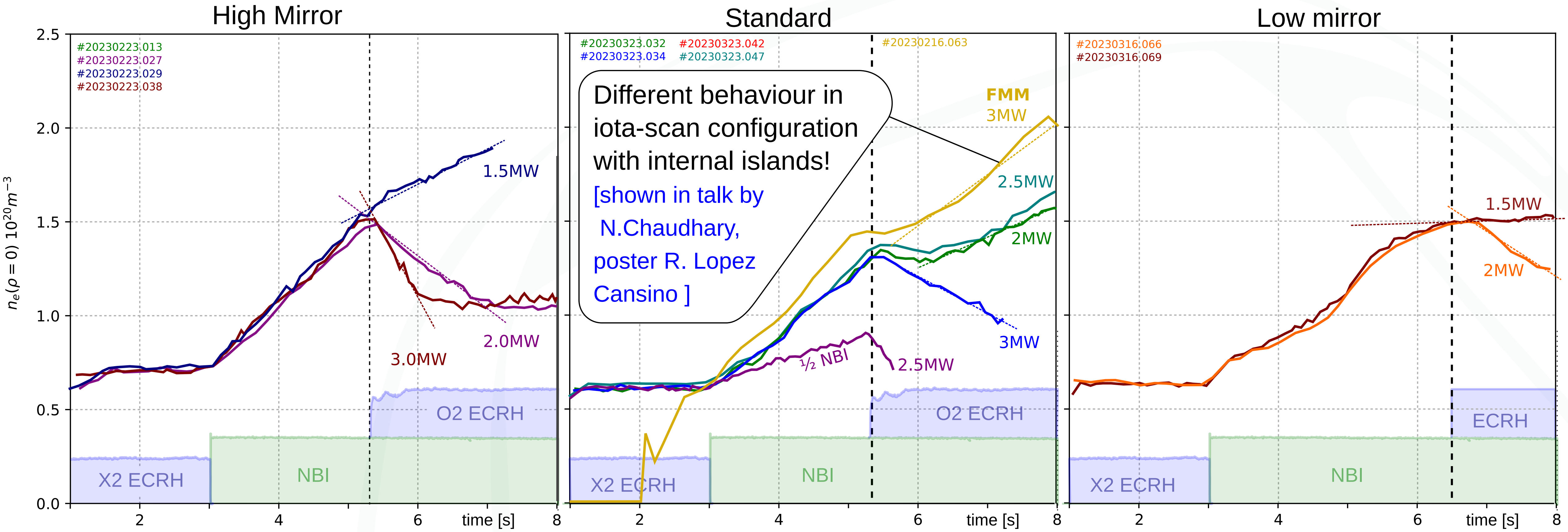


ECRH power and configuration scans

In the 2022/3 campaign:

3) Scans of ECRH power at fixed reintroduction time - varying pump-out effect.

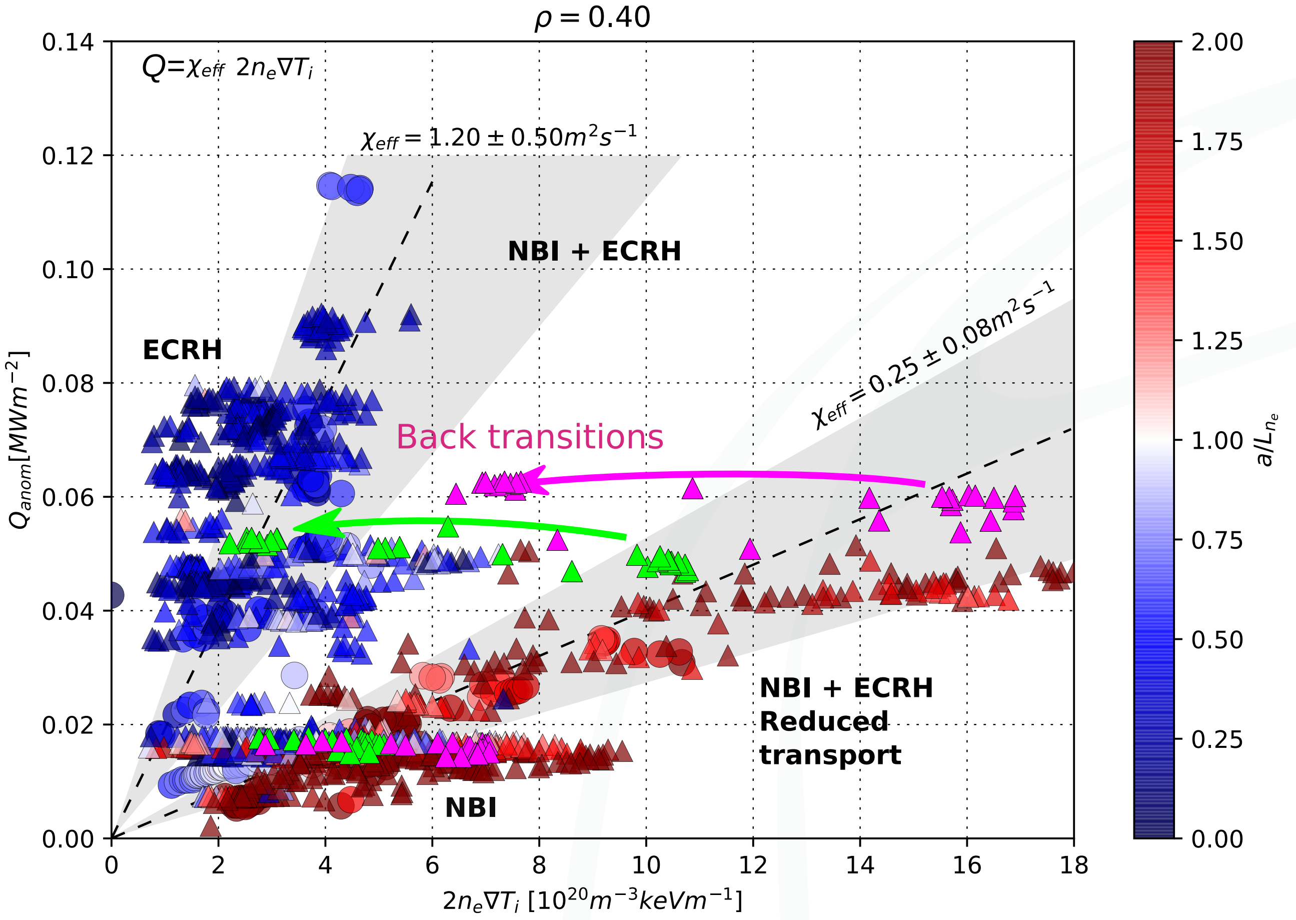
4) (Low - mid - high) -mirror configurations: - Density rise in NBI phase almost identical.
- Different pump-out effect of ECRH

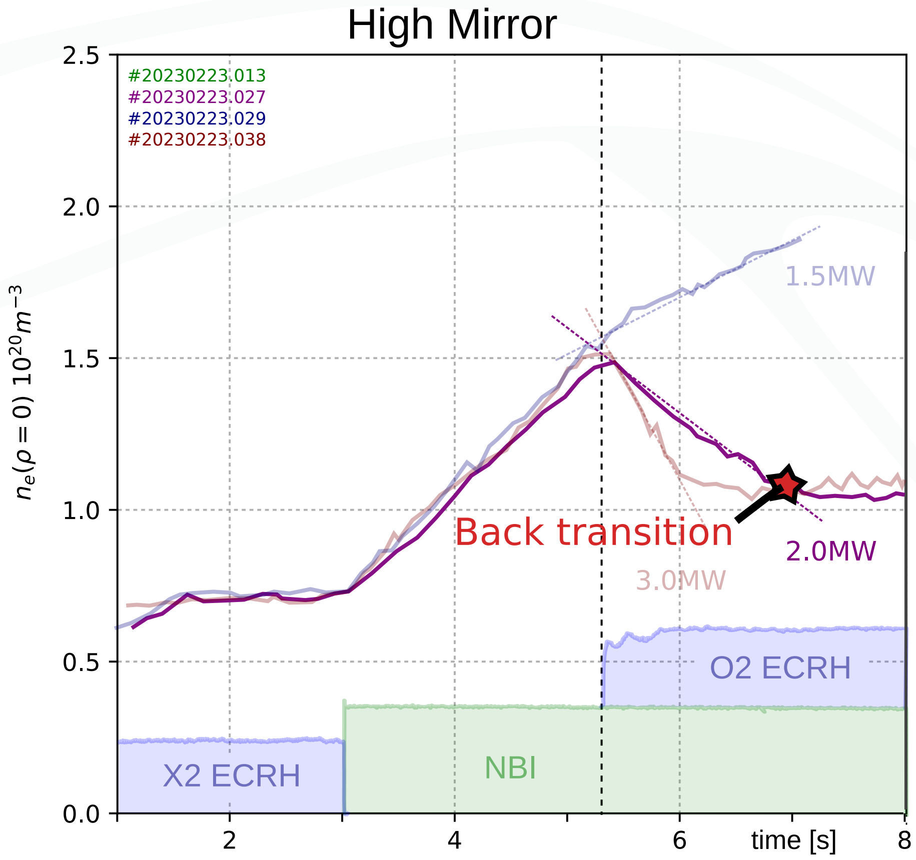


Balancing ECRH power

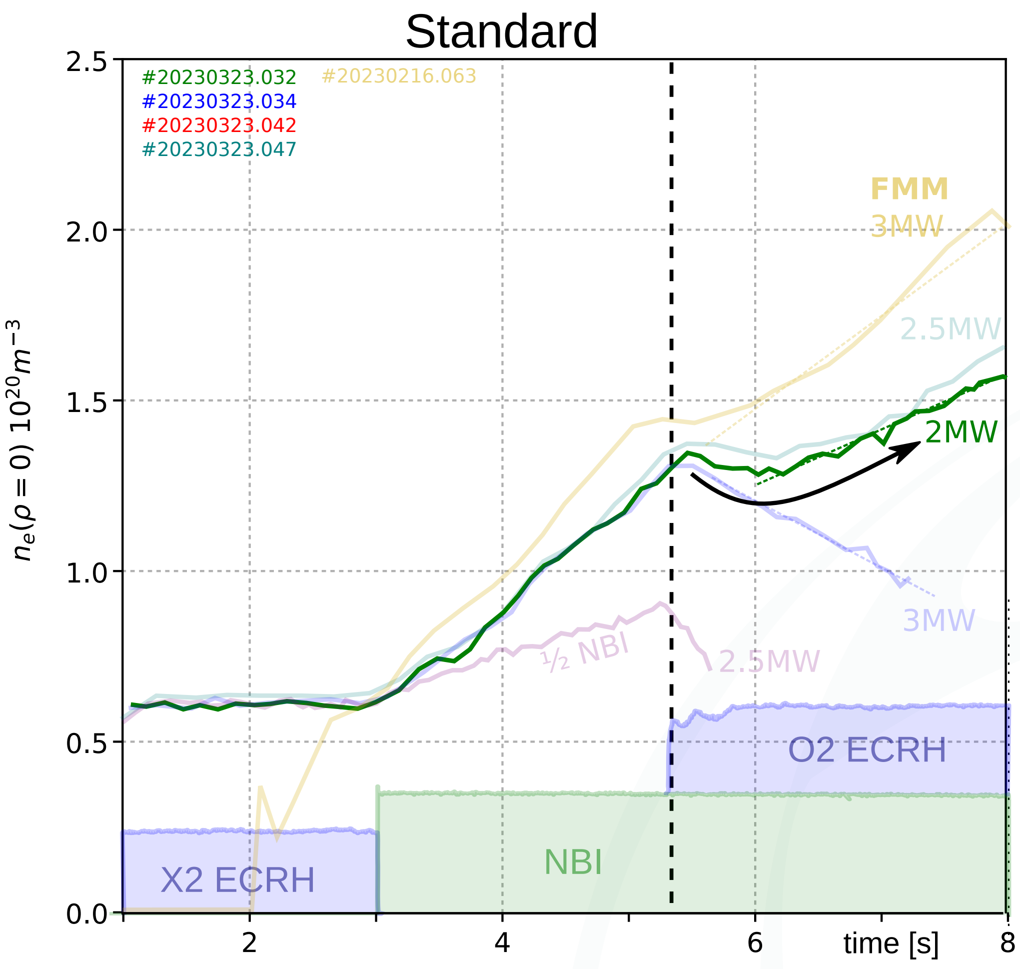
2023 experiments pushed to higher ECRH power to take advantage of reduced heat diffusivity

- χ_{eff} ~ 0.25 m^2s^{-1} maintained despite x2 higher Q_{anom}. (as high as some turbulent ECRH-only shots)
- Spontaneous back-transition to high transport observed as ECRH reduces density gradient.





ECRH control



Challenge: Needs to carefully control of ECRH level:

- Too much --> Loss of density gradient
  --> back-transition

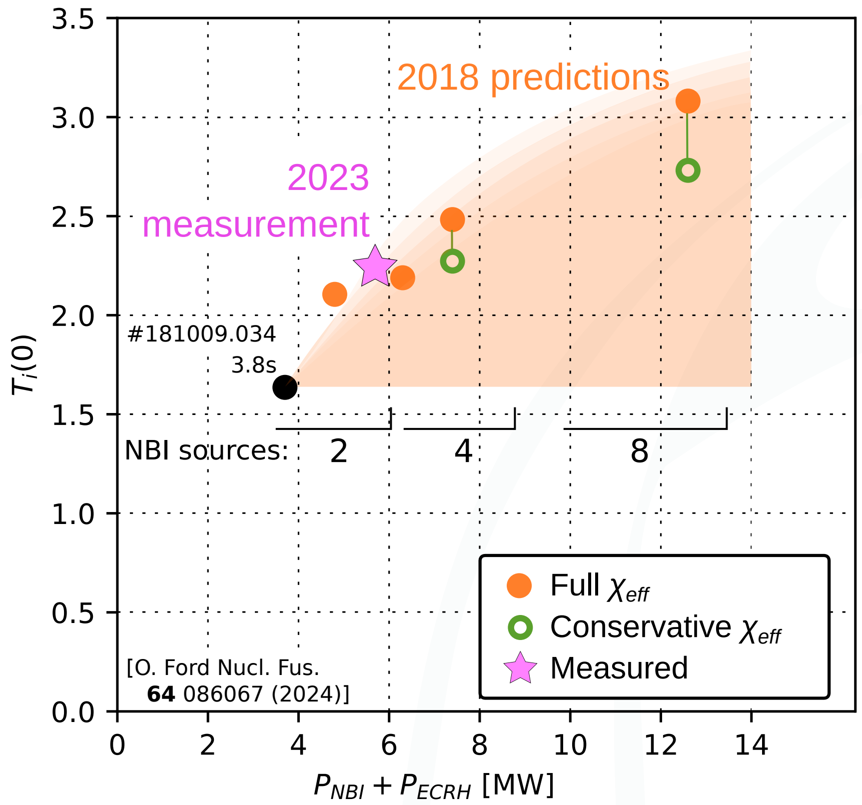
- Too little --> Too high density, low P/n, impurity accumulation
  --> radiation collapse.

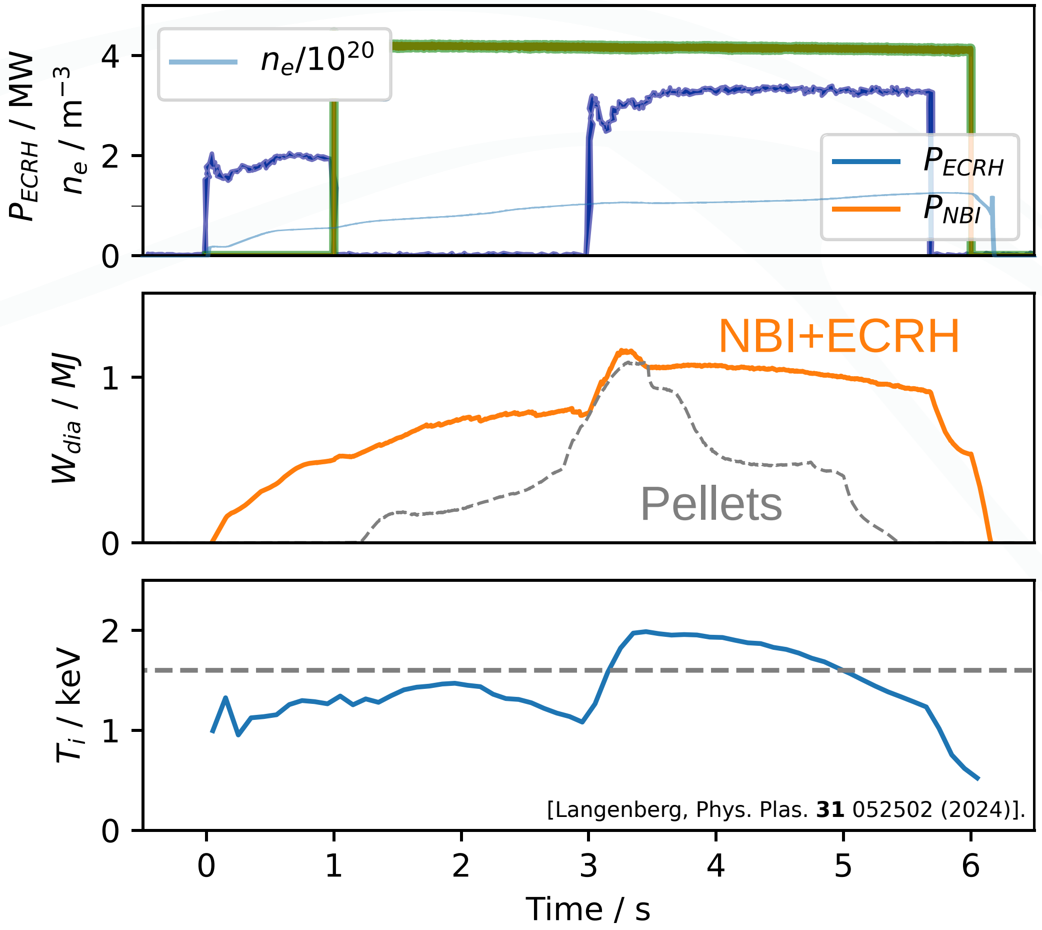
For feedback control we would need real-time electron density profile and real-time control of ECRH power.

Achieved performance

- Predictions made from 2018 data using transport simulation (NTSS) - First point matched in 2023!

- Highest ECRH power in FMM configuration still does not flush out density --> Higher n_e --> high W_{dia}
  --> Matches record stored energy (W_{dia}) for W7-X, but for $t >> \tau_E$ [Langenberg, Phys. Plas. **31** 052502 (2024)].





Summary

- ECRH+Gas fuelling: Turbulence dominated heat transport, main ion and impurity transport.

- Various scenarios with peaked density profile --> reduced heat transport.

- Dominant NBI plasmas show $\chi_{eff} \sim 0.25\ m^2 s^{-1}$, 4 times lower than dominant ECRH when $a/L_{ne} > 1$.

- D_{anom} of main ions drops spontaneously at $a/L_{ne} \sim 1.3$ during pure NBI, leading to accelerated peaking. Impurity transport is fully neoclassical from this point on.

- Reduced heat diffusivity can be exploided by reintroducing a low ECRH power at high a/L_n.

- Reintroduction scenario reproduced and refined in 2023 expeiments.
    - Extend to ECRH power, giving higher ∇T_i and core T_i well above 1.5 keV.
    - Density pump-out by too-high ECRH leads to back-transition to high χ_{eff}.
    - NTSS simulations of predicted doubling of ECRH power well matched by experiment.
    - Record level of stored energy (marginally above pellets experiments) held for > 2s.

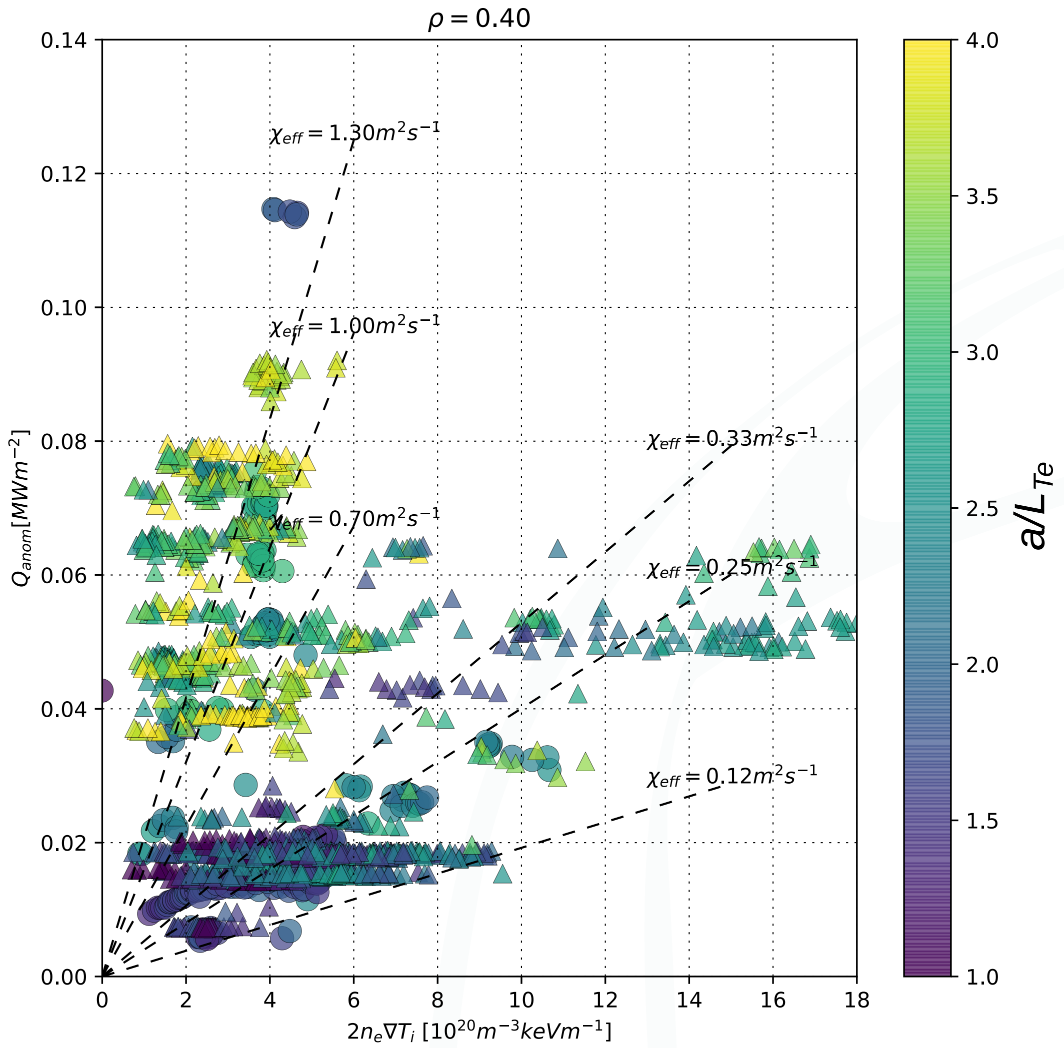
    - Density profile appears to affect transport stronger than magnetic configuration in W7-X

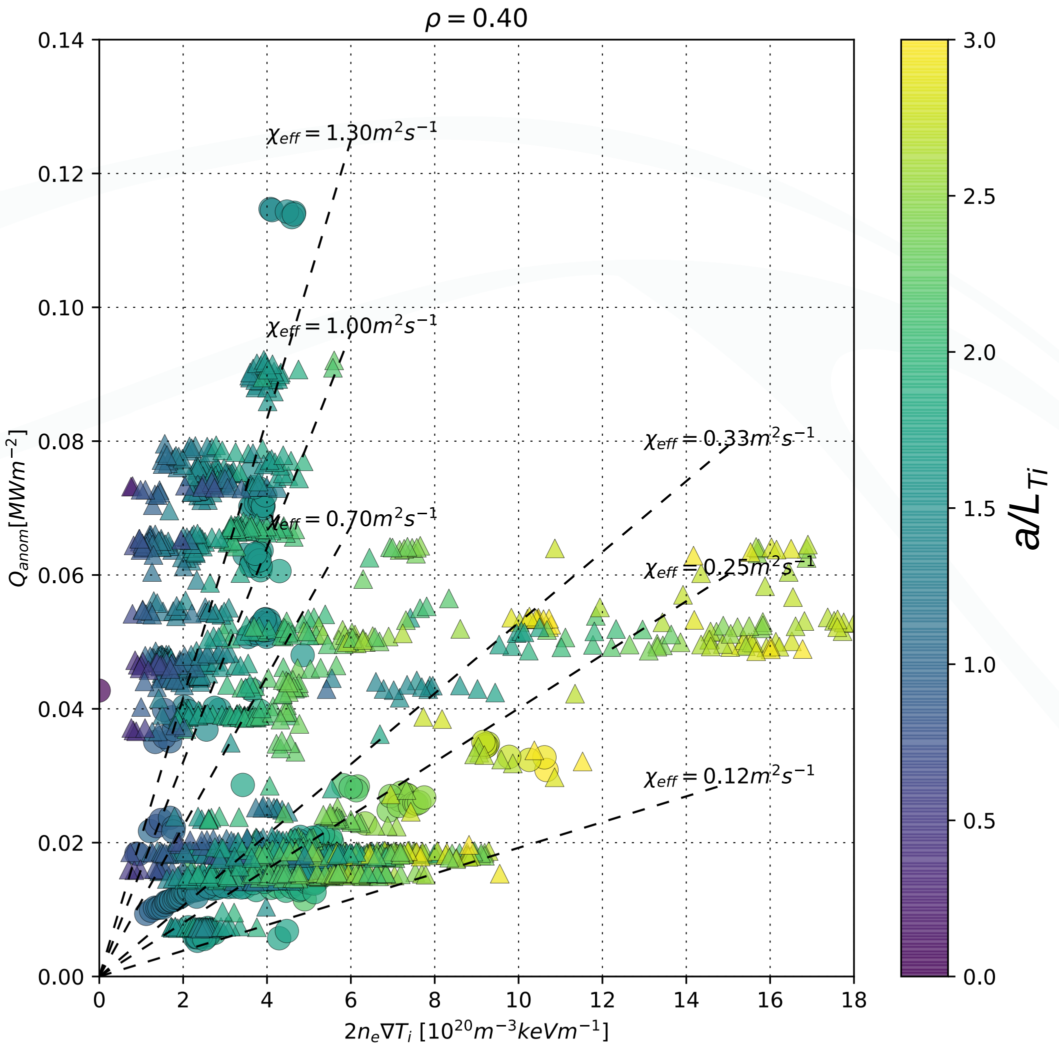
--> Predicting particle transport critical to performance optimisation.

Diffusivity vs temperature gradients

gr

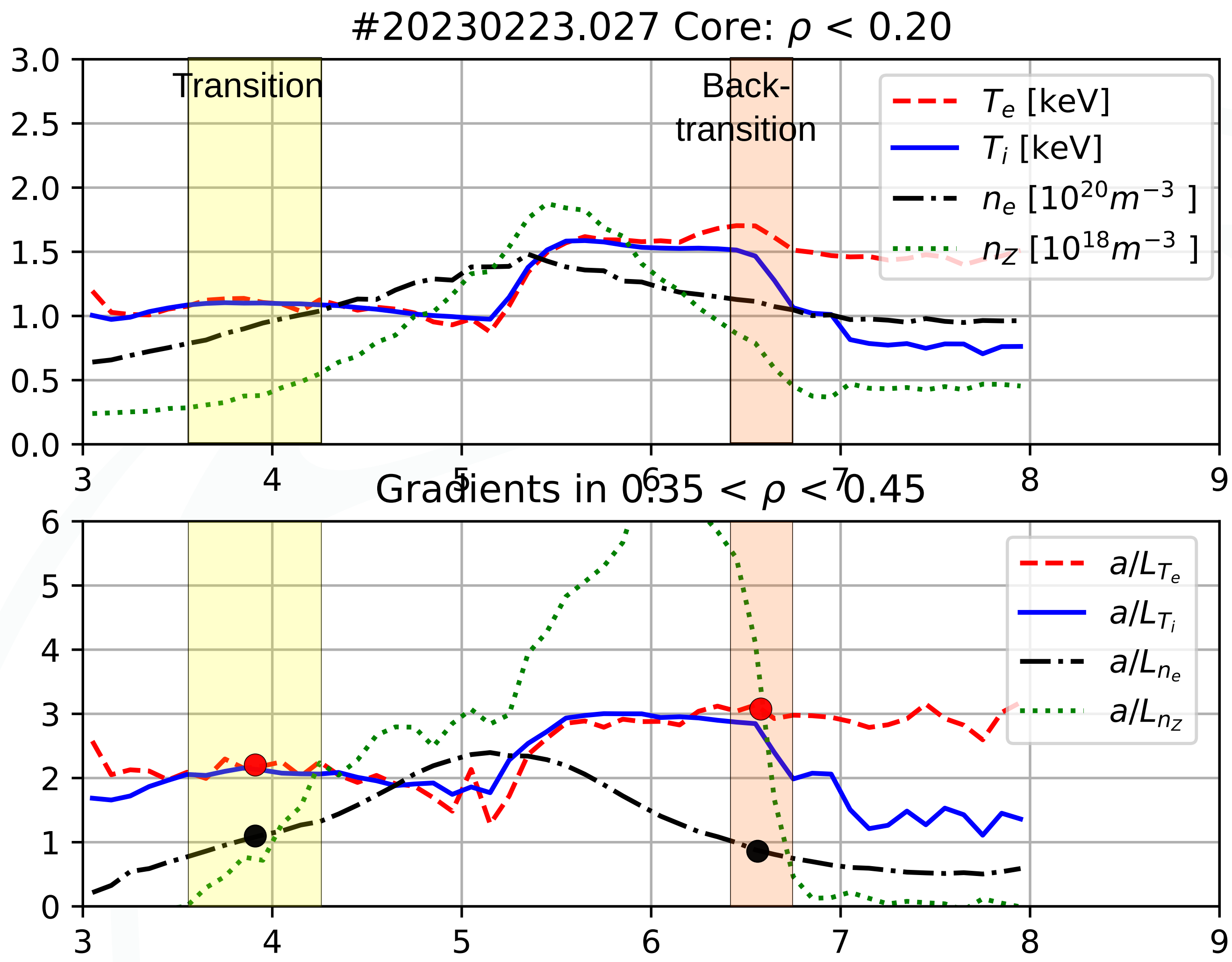
No obvious dependence of χ_{eff} on a/L_{Te} - at least not clear as a/L_n. (a/L_{T_i} is the dependant variable)





Back transition at different a/L_T?

OP2.3 back-transitions allow examination of threshold location in a/LT vs a/LN space:



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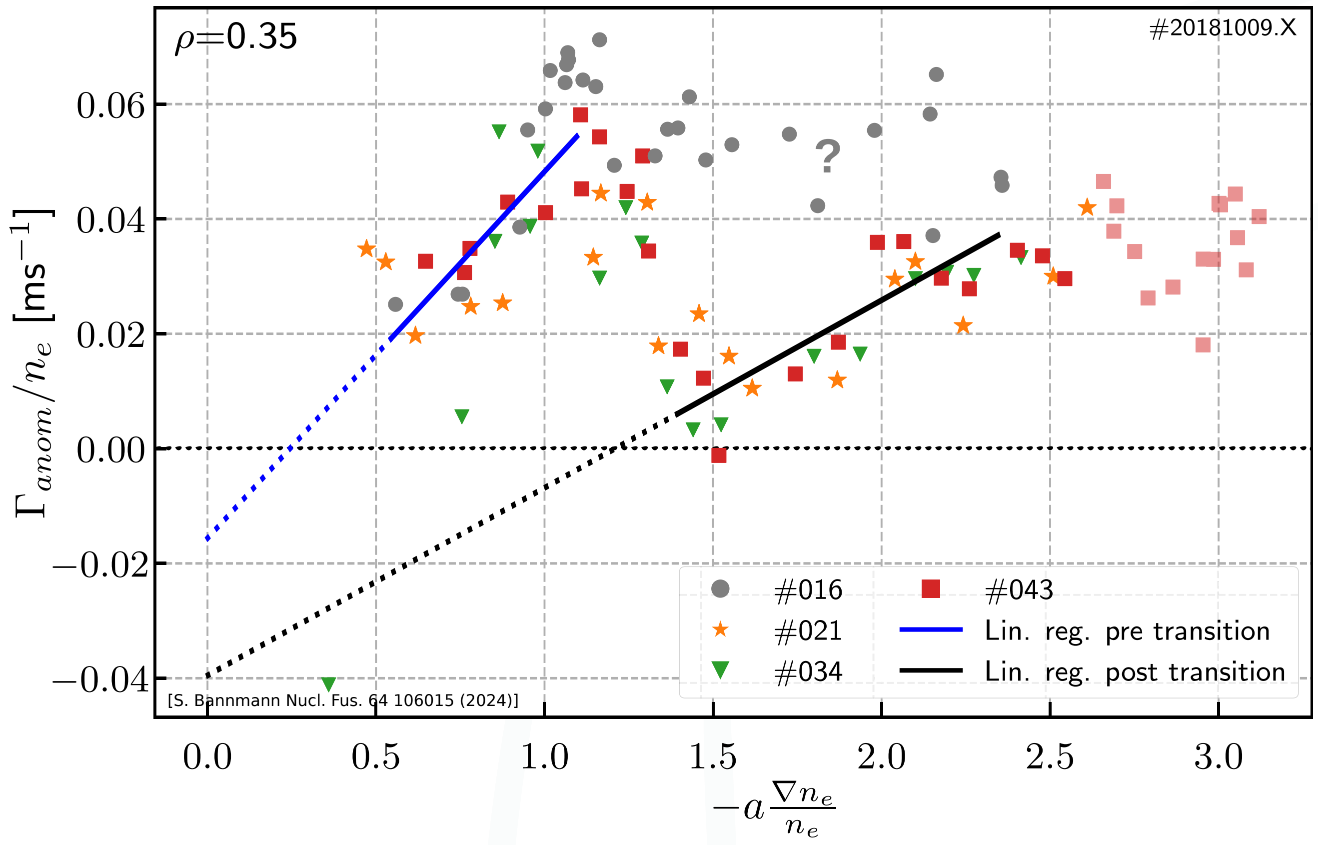
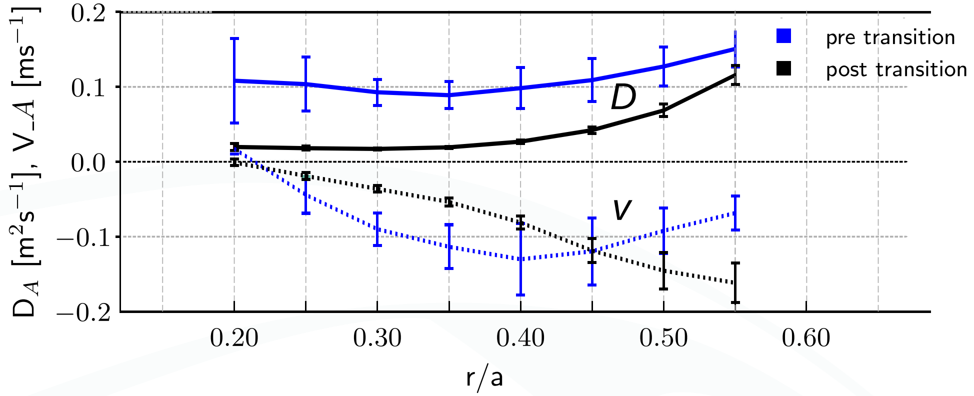
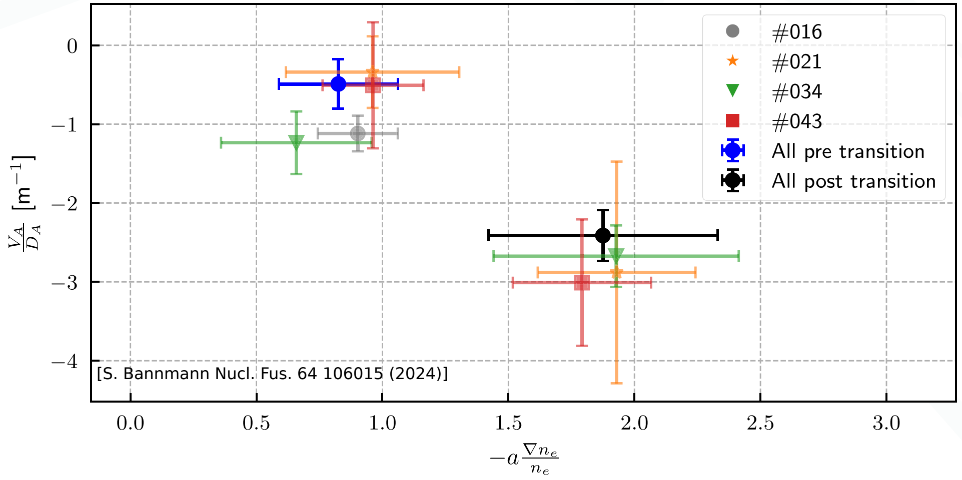
$$\frac{\Gamma_{anom}}{n} = -D_A \frac{\nabla n}{n} + V_A$$

[S. Bannmann Nucl. Fus. 64 106015 (2024)]







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port

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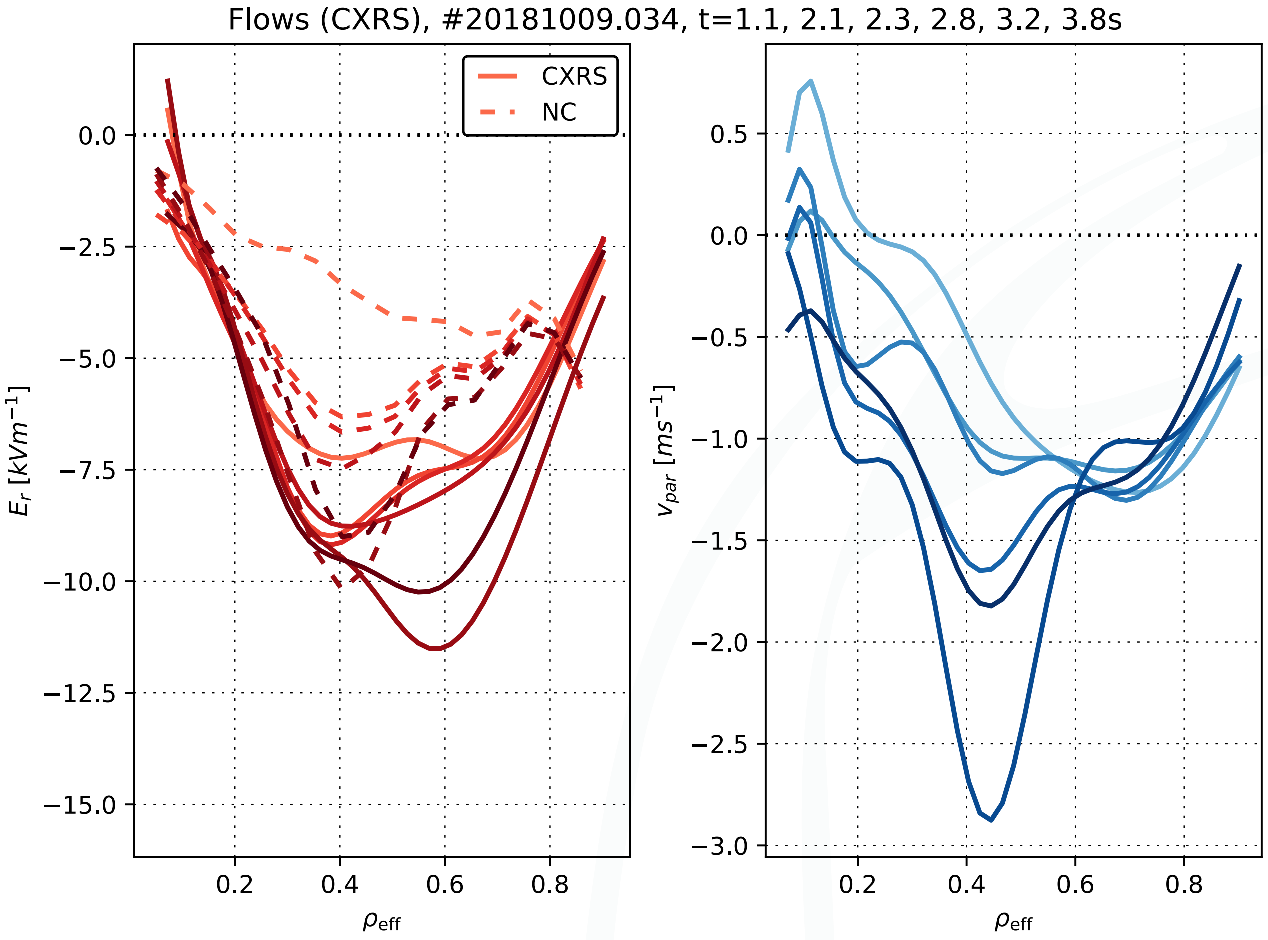
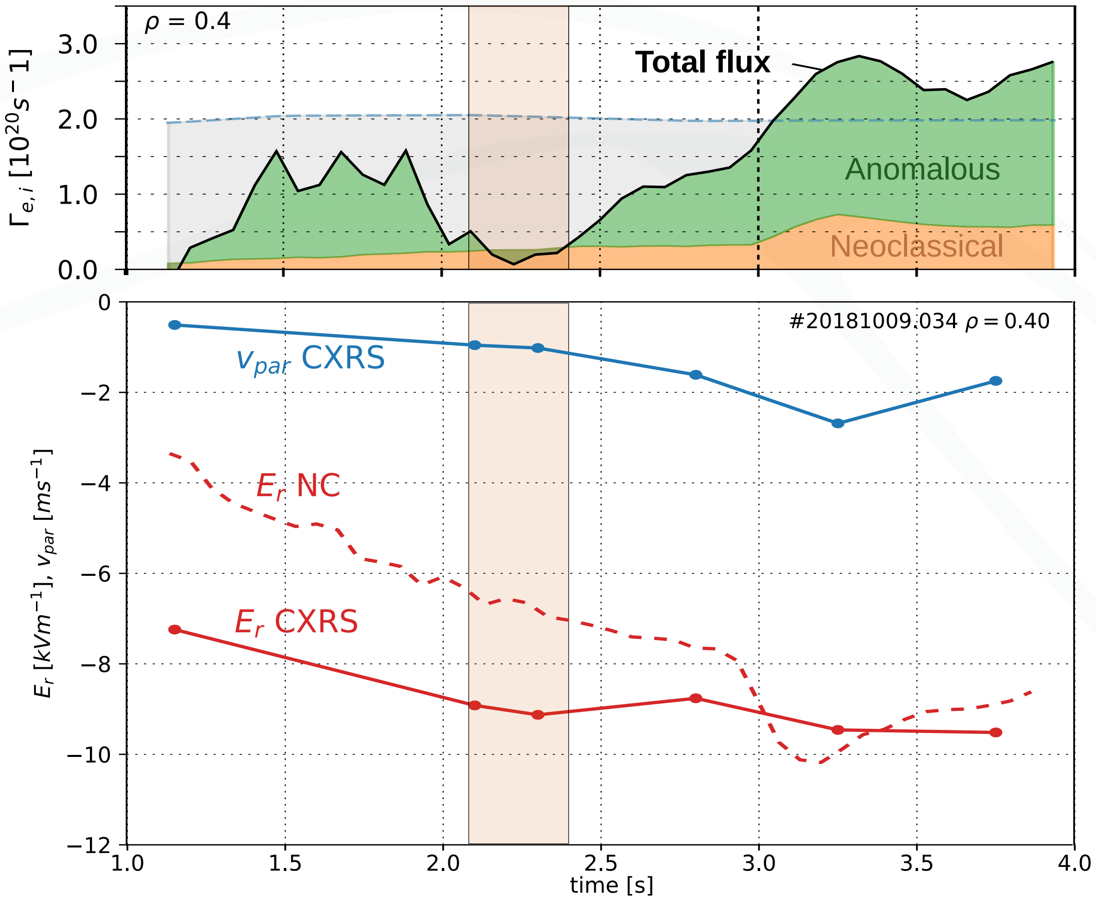


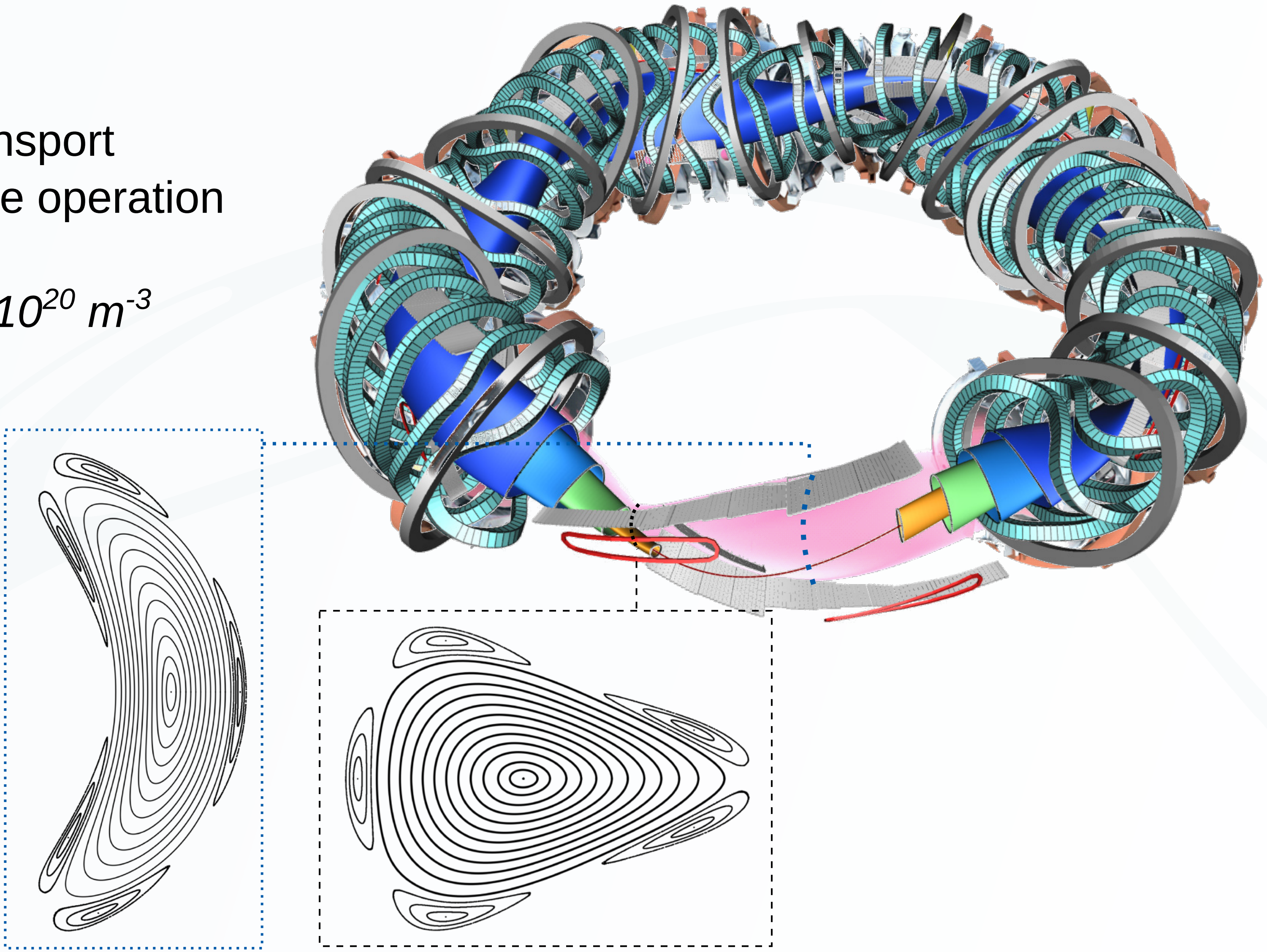


The Wendelstein 7-X Stellarator

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

	2024	2026+
pulse	200s	30 min
ECRH	7.5MW	10 MW
NBI	2.6MW	5.2MW
ICRH	-	1.5MW



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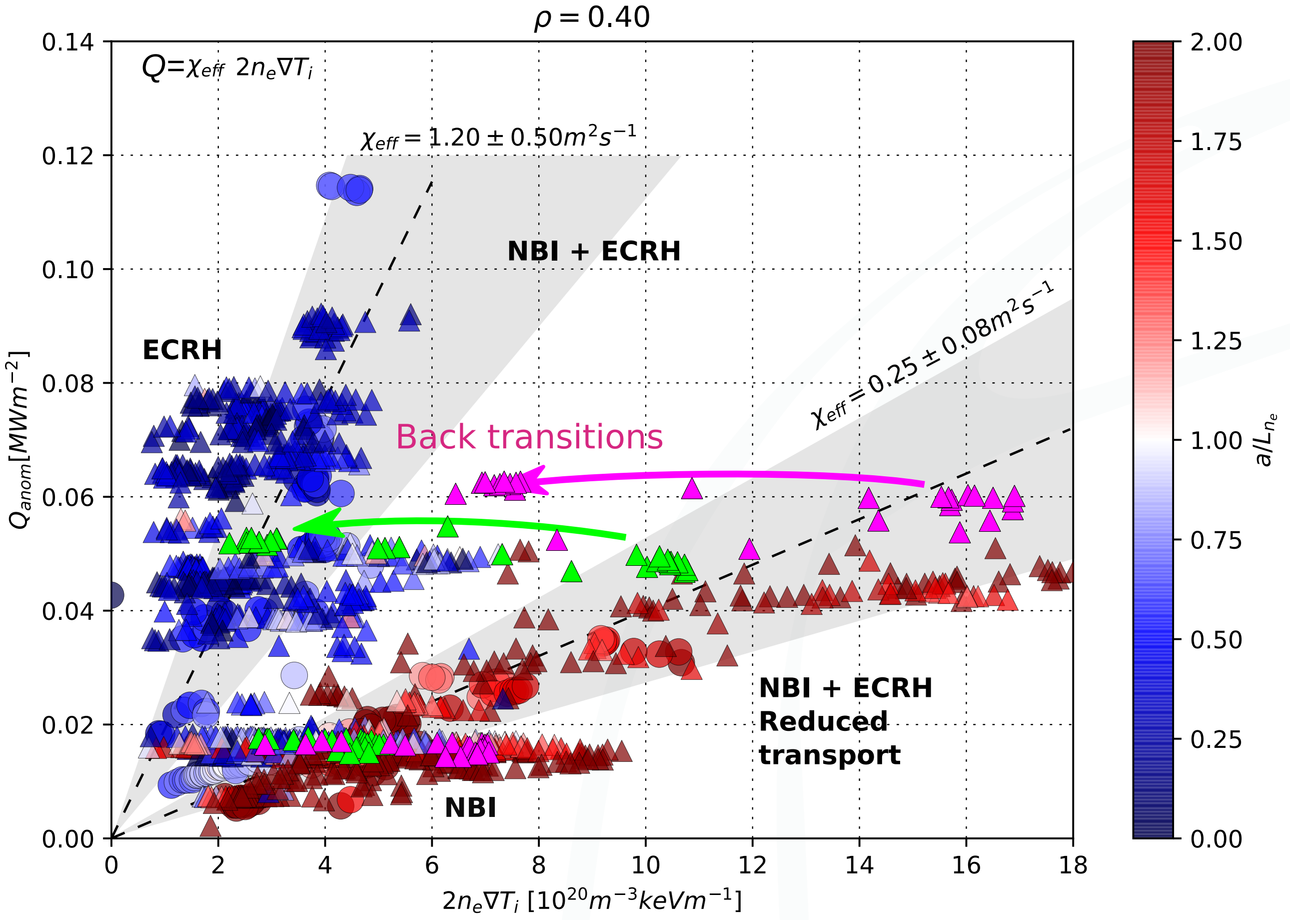

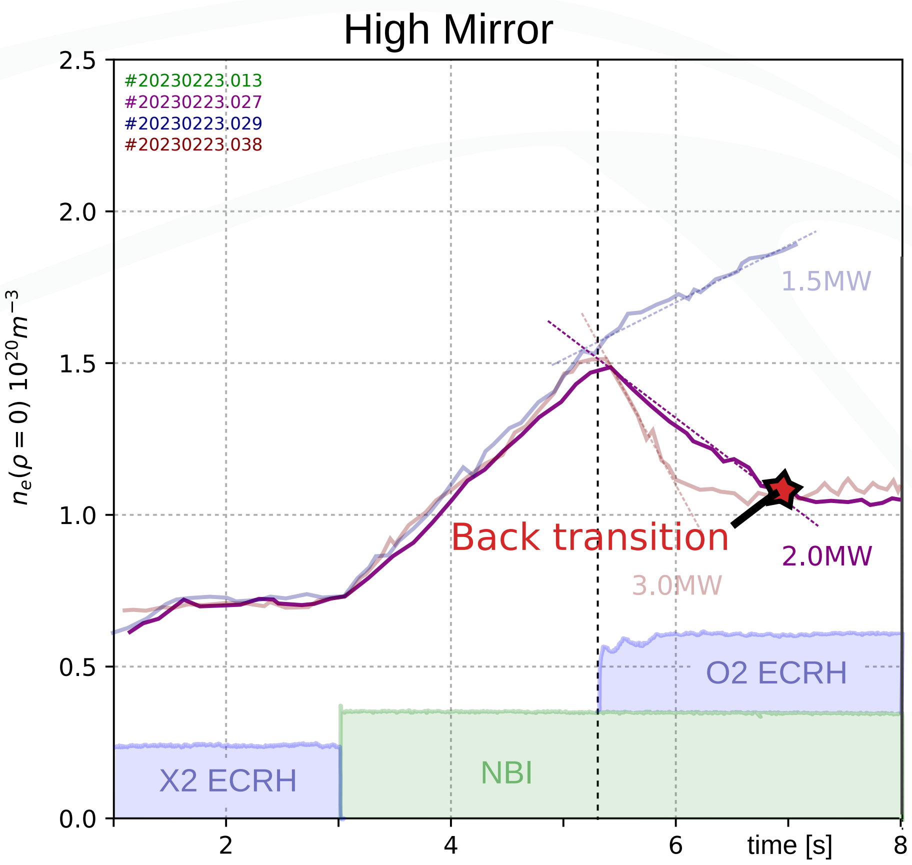

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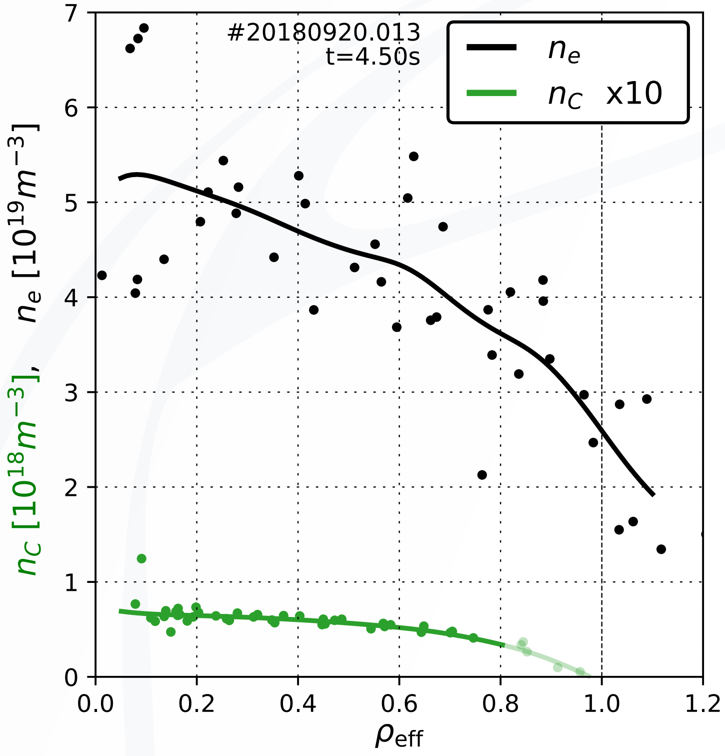
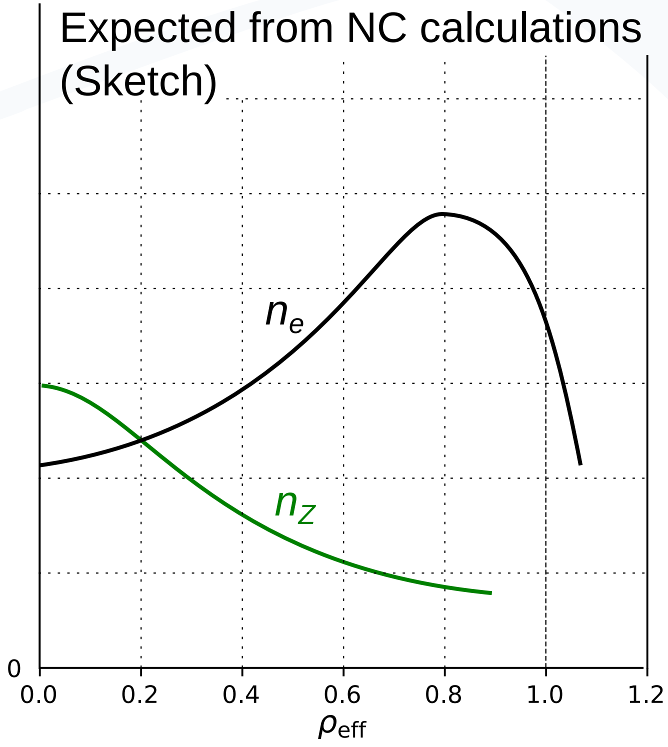
Some text

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]*
- Flat impurity profiles despite neoclassical pinch:
  High turbulent impurity diffusion shown by LBO injection experiments *[B. Geiger et al 2019 Nucl. Fus. 59 046009]*



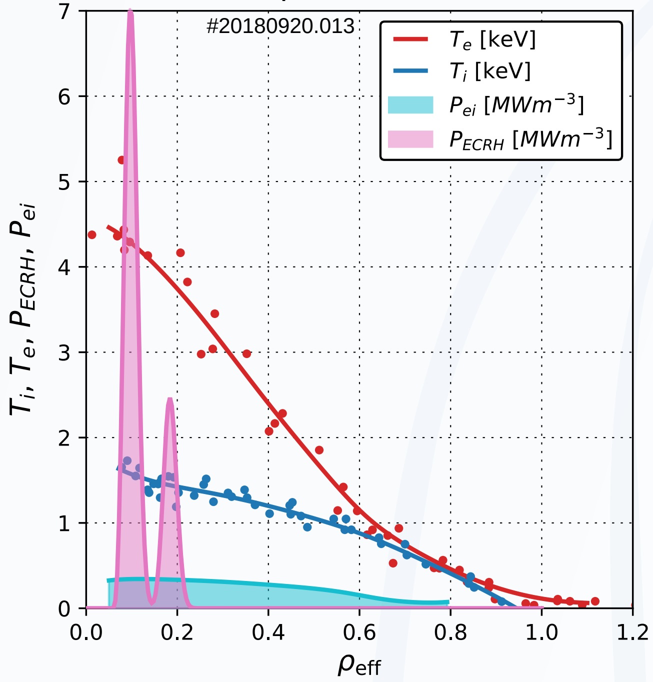


Ion temperature clamping

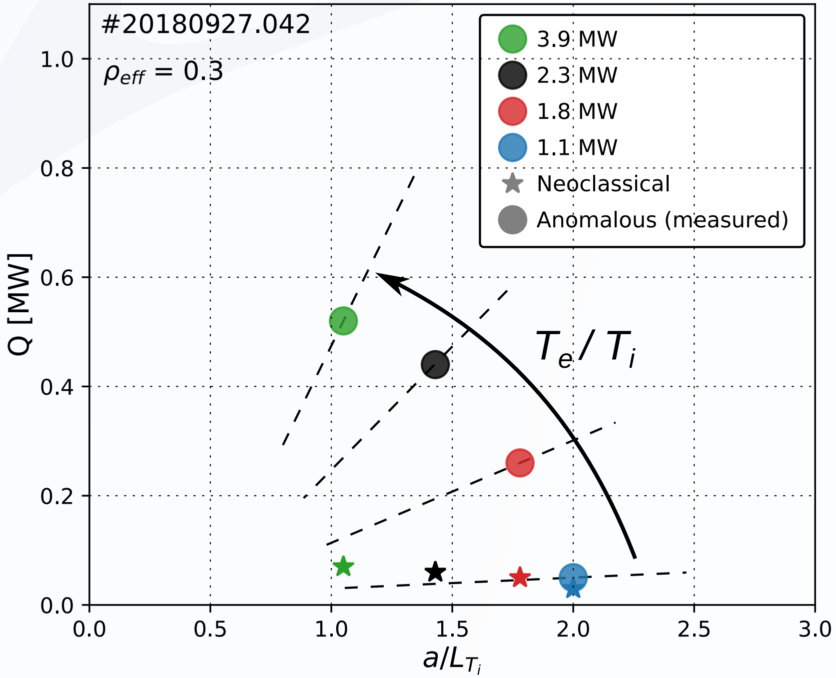
Ion temperature clamping explained by combination of effects: [Beurskens et al. Nucl Fus 2021 (submitted), IAEA 2021]
- Collisional coupling gives broad ion heating profile
- Strong profiles stiffness observed in turbulence
- Increasing ITG turbulence with T_e / T_i exacerbates stiffness with increasing P_{ECRH}.
  supported by linear growth rate from ITG simulations *[A. Zocco, J. Plasma Phys 2017]*

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

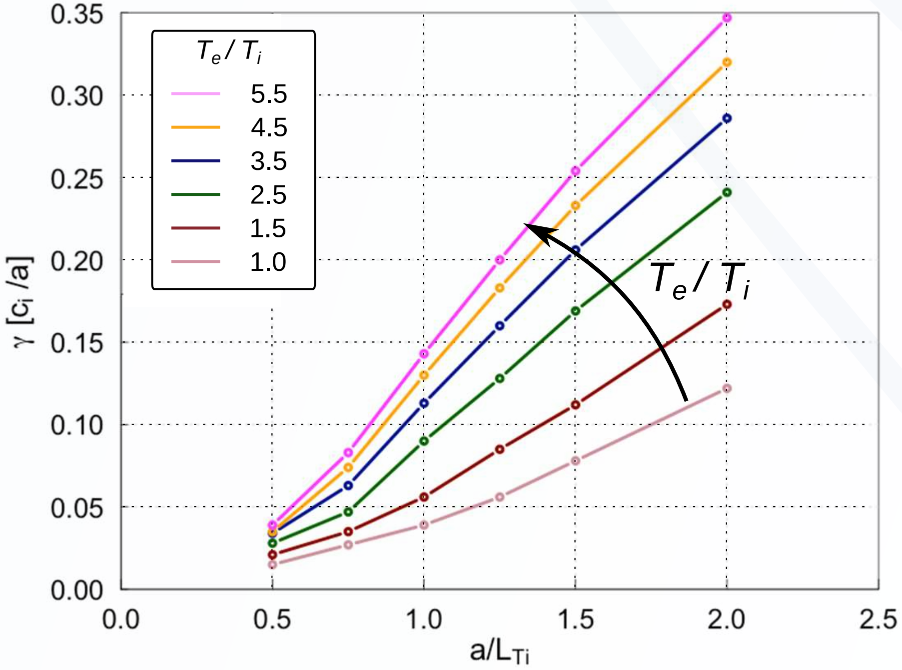
Power deposition and transfer



Power flux vs temperature gradient



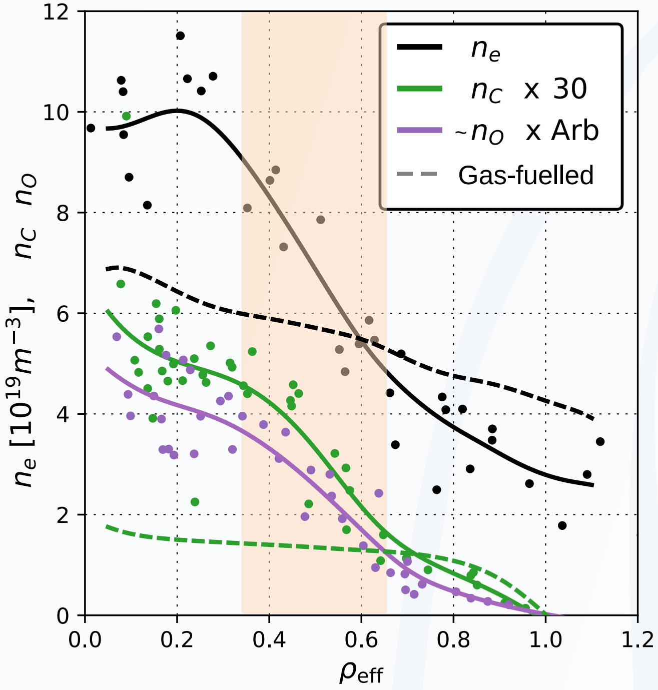
Linear growth rates. ITG simulations.

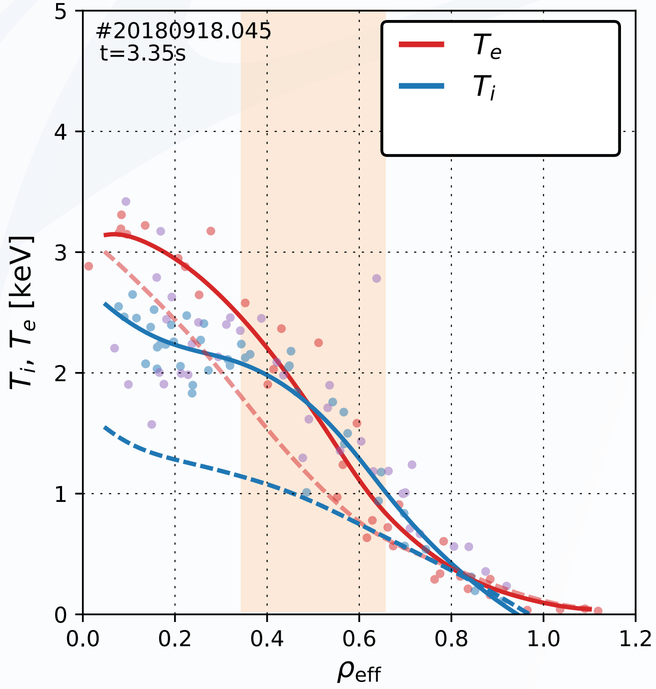


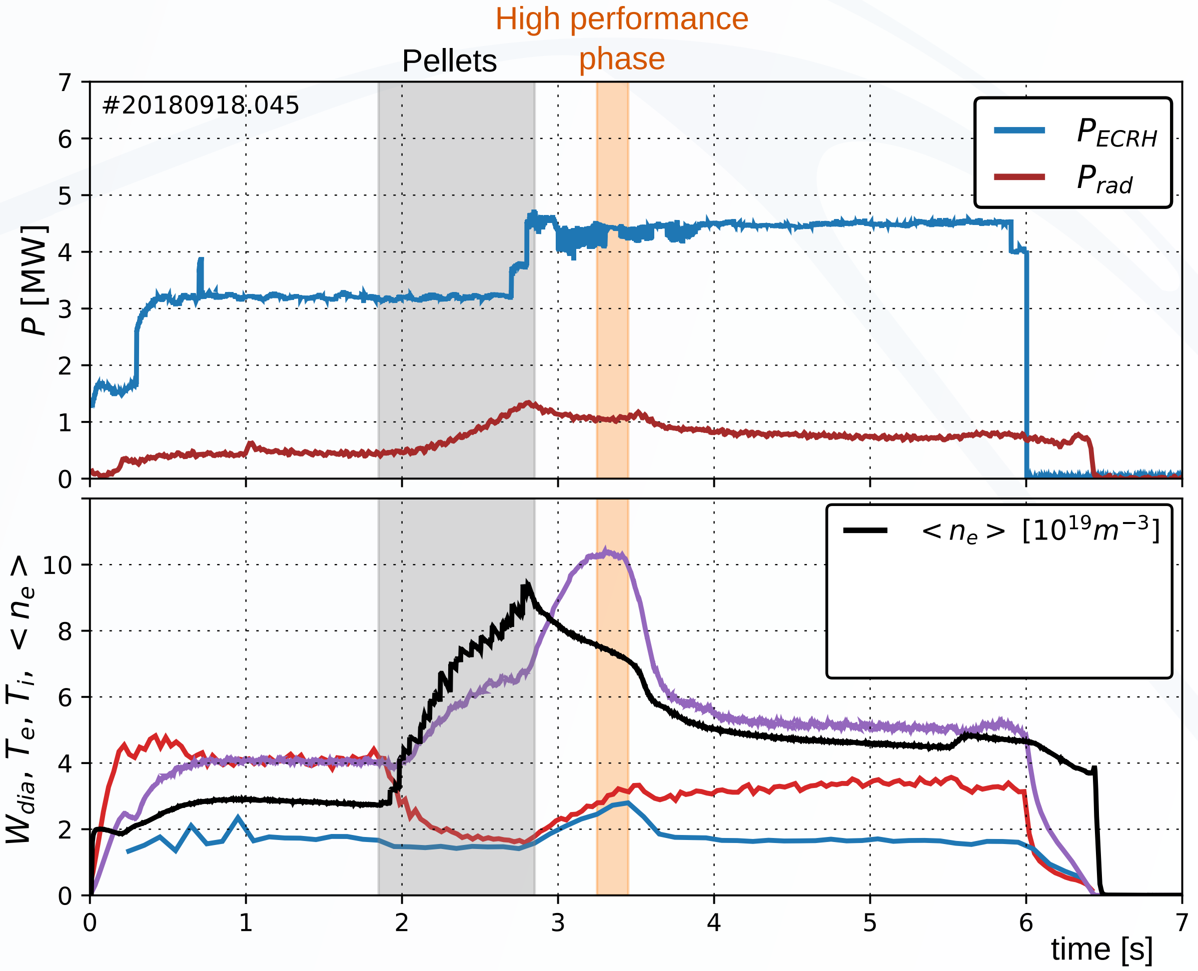
Post-pellet turbulence suppression

Steep density profiles after rapid series of hydrogen ice pellets.

- High confinement $T_i = T_e$ phase builds slowly ~5 τ_E after end of pellets.
- 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)



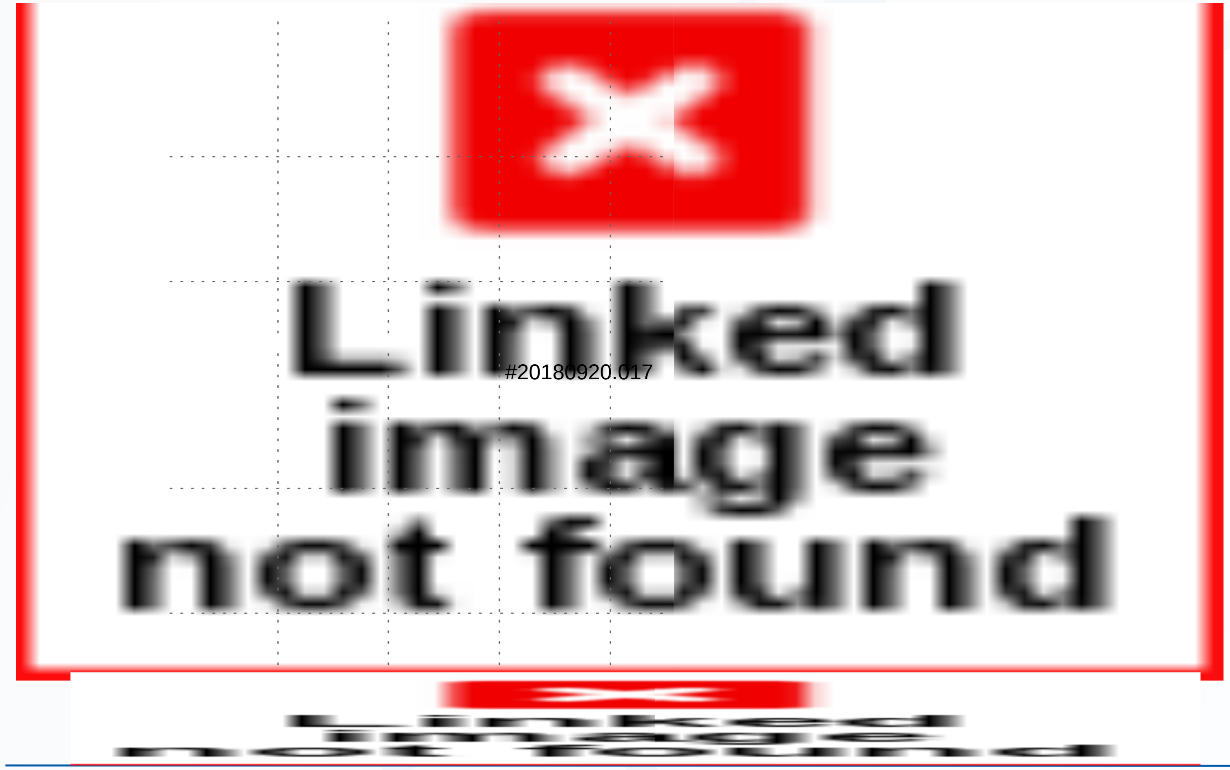




Post-pellet turbulence suppression

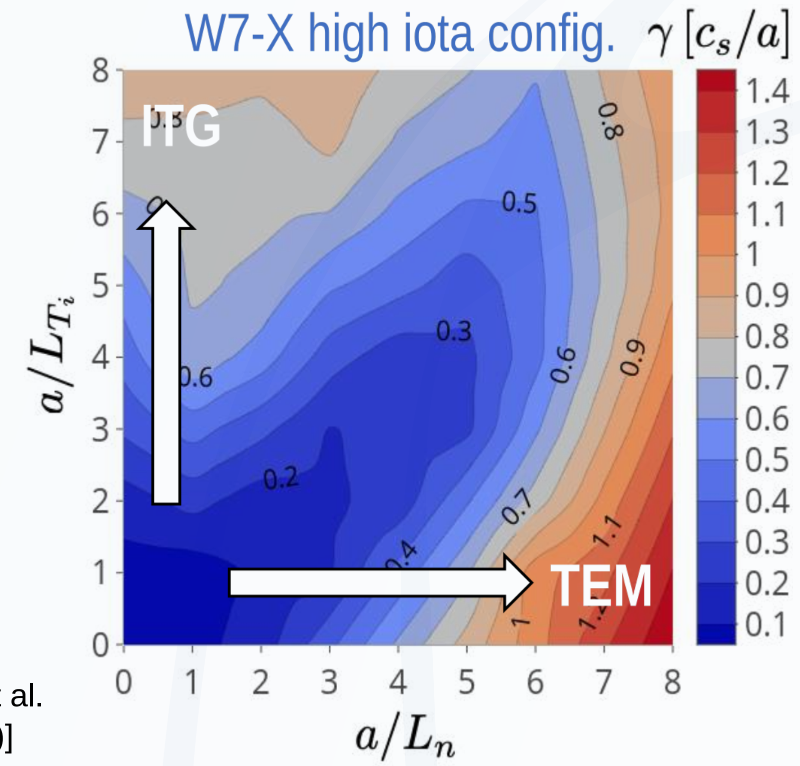
- Ion heat transport reduced to order of neoclassical level.
- Electron heat transport significantly reduced.

Typical gas-fuelled plasma   Post-pellets plasma



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)]
  - 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]

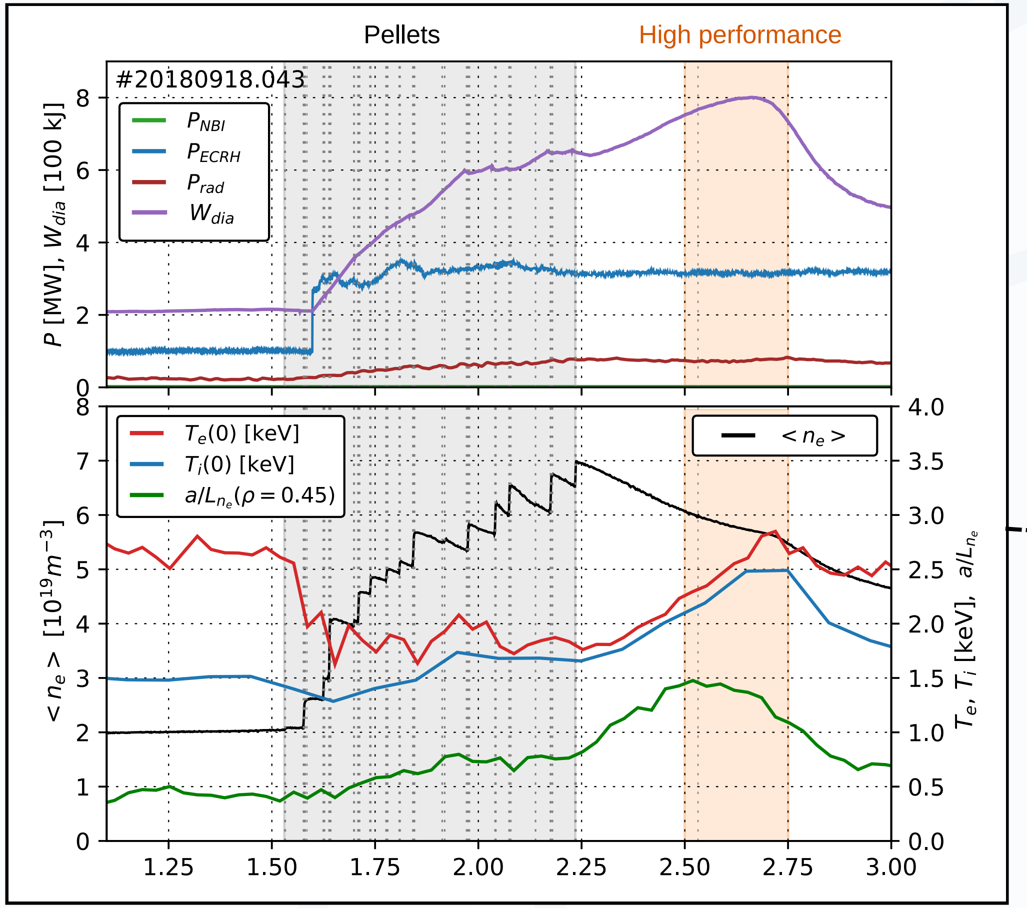


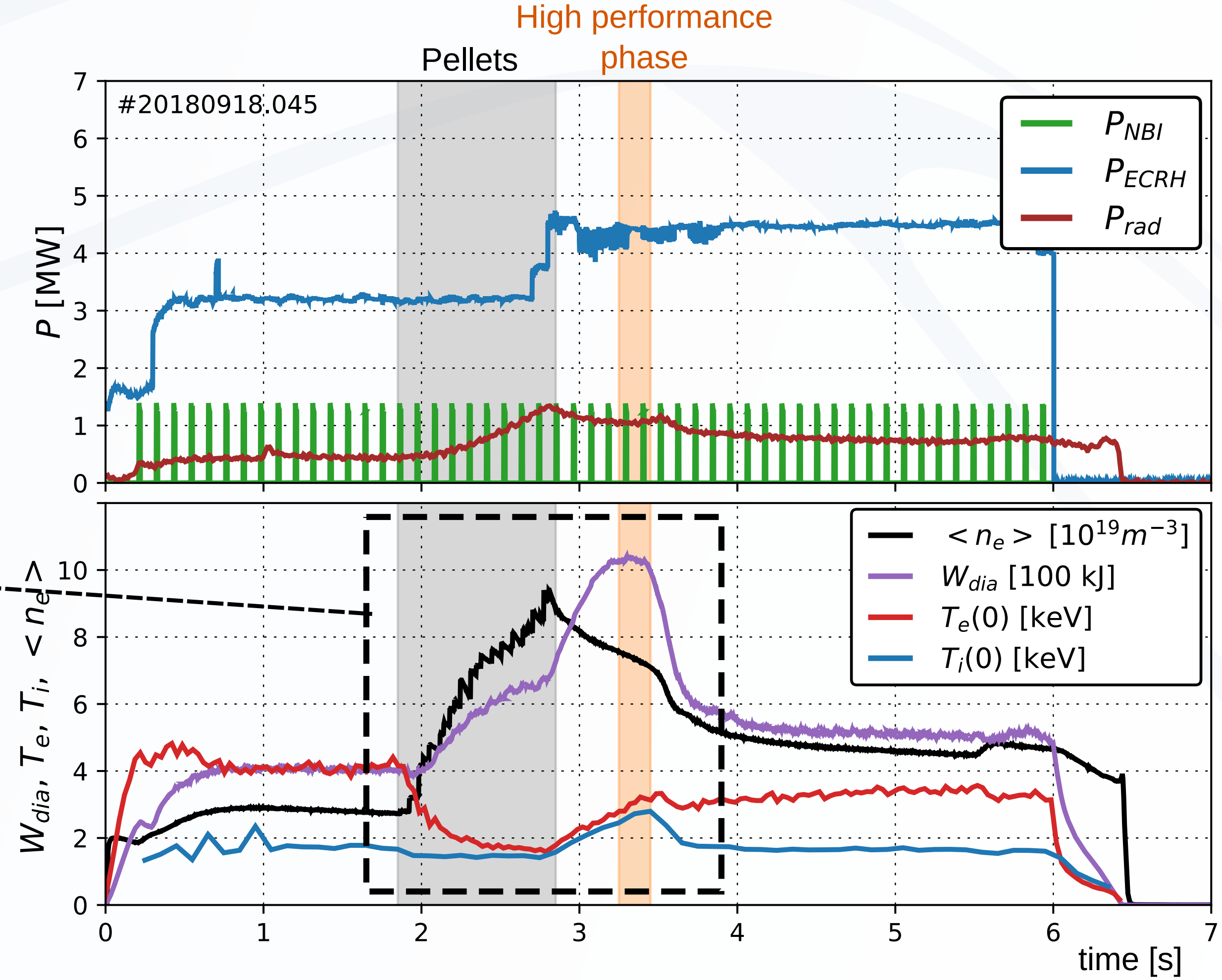
[J. A. Alcusón et al. PPCF 21 (2020)]

[P. Xanthopoulos et. al. PRL 2021]

Post-pellet turbulence suppression

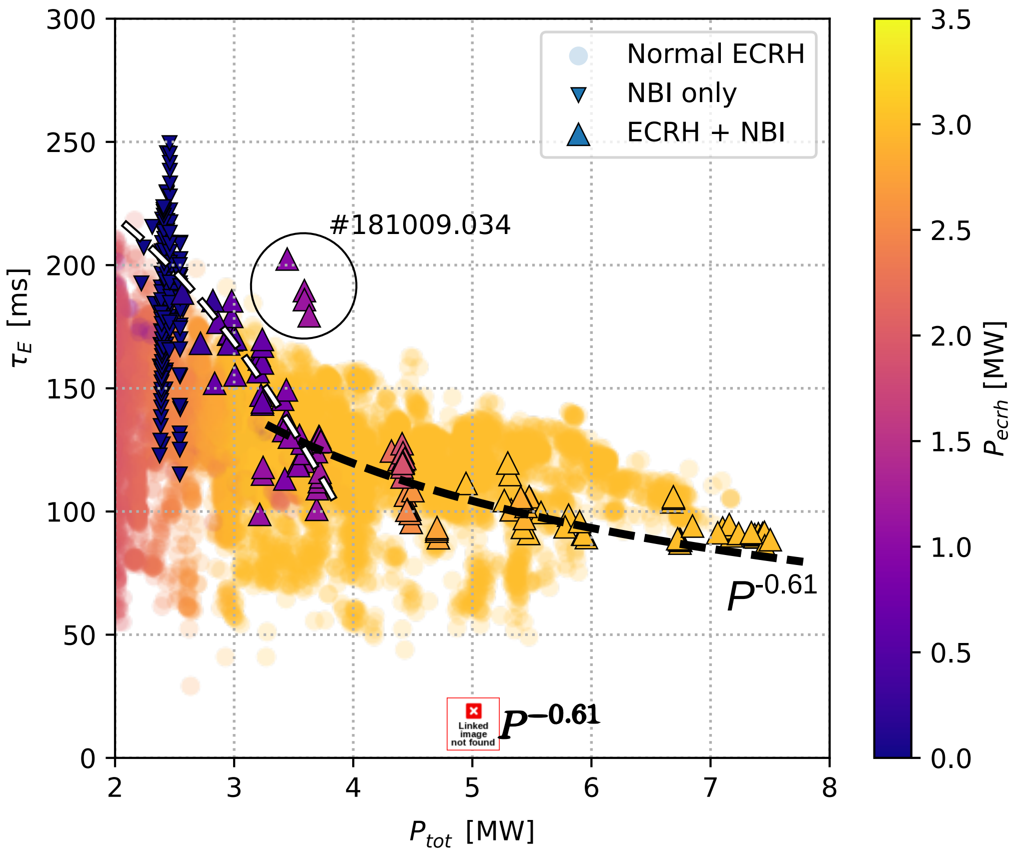
- Steady-state pellet injector next campaign to investigate ability to maintain high performance phase *during* pellets.
- So far, density gradient only observed after injection of last pellet.

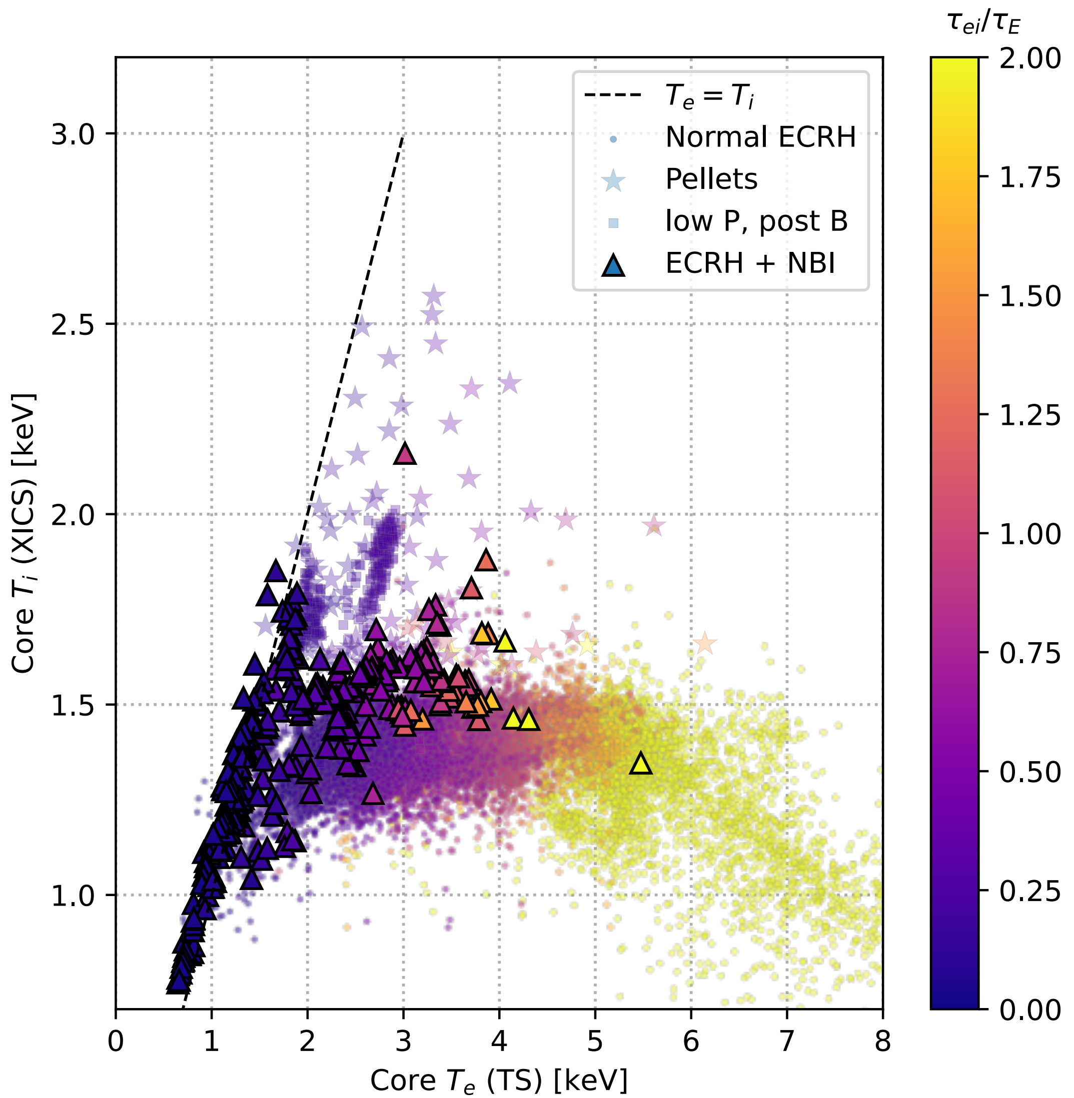




NBI : ECRH ratio

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





Energy transport: Total fluxes

- High collisionality leads to large P_{ei} with small O(~10eV) differences in T_e, 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.
- Total energy fluxes are anomalous dominated at all times but (neo)classical fluxes + radiation loss not insignificant.
- Anomalous fluxes increase with ECRH addition.