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

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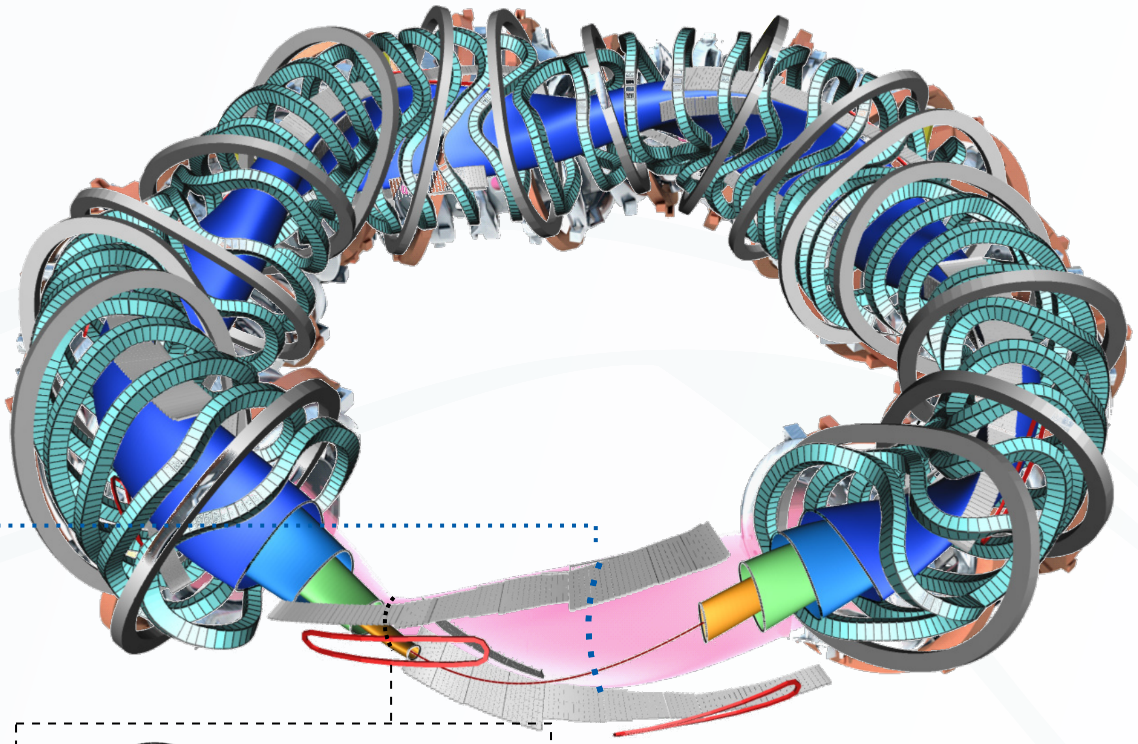
24th International Stellarator Heliotron Workshop, Hiroshima, Japan

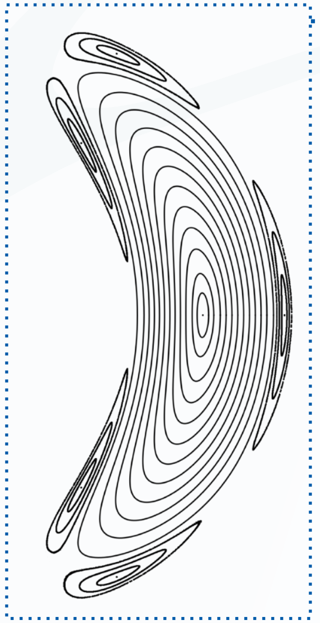
The Wendelstein 7-X Stellarator

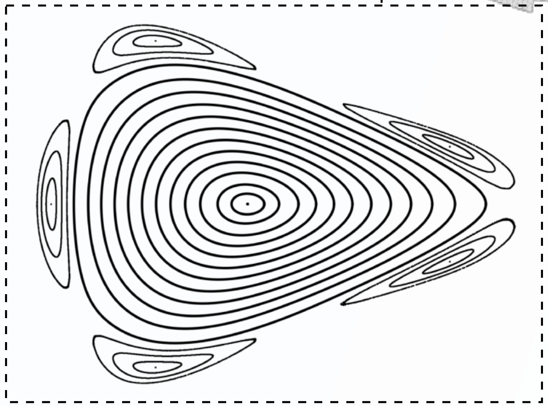
Wendelstein 7-X:
- 5 period helixcal axis stellarator
- Optimised to reduce neoclassical transport
- Designed to demonstrate steady-state operation with continuous ECRH heating.
- Operation at high density: $n_e \sim 1.8 \times 10^{20}\ m^{-3}$

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



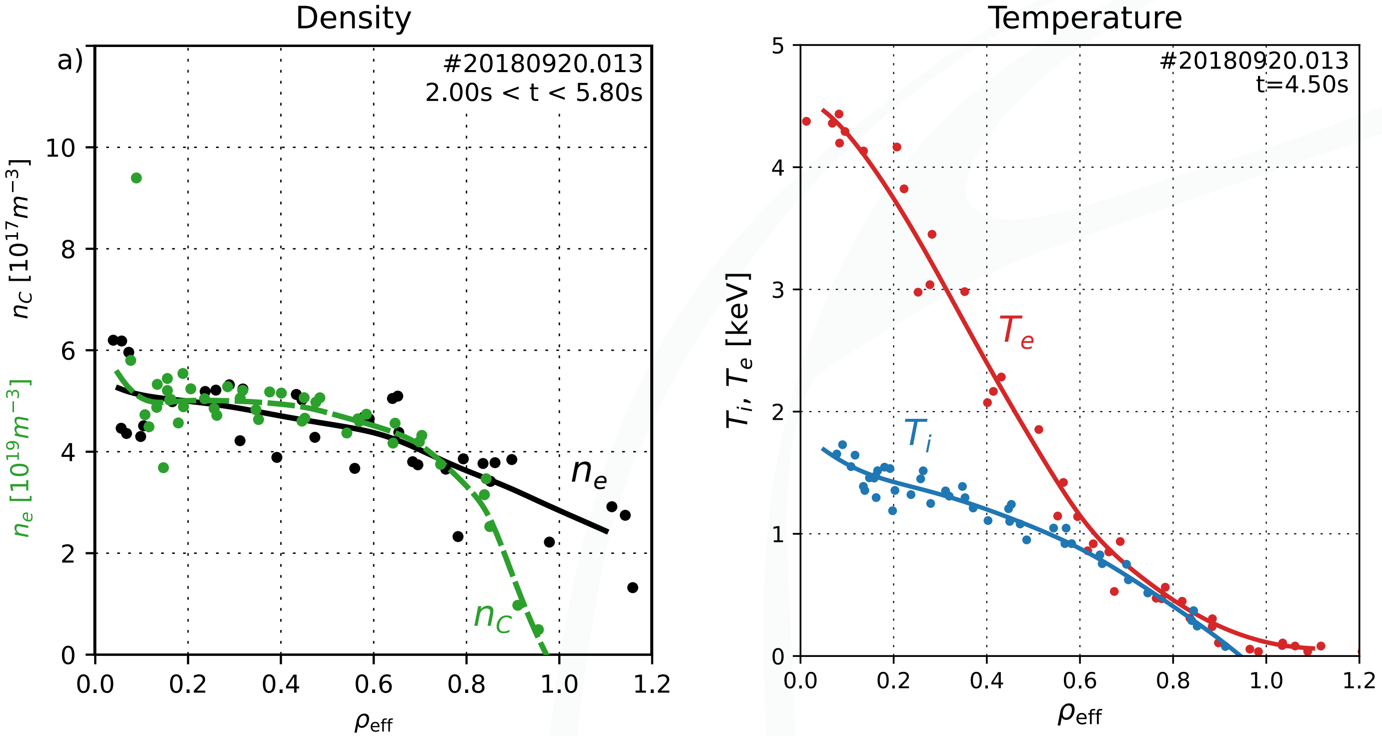


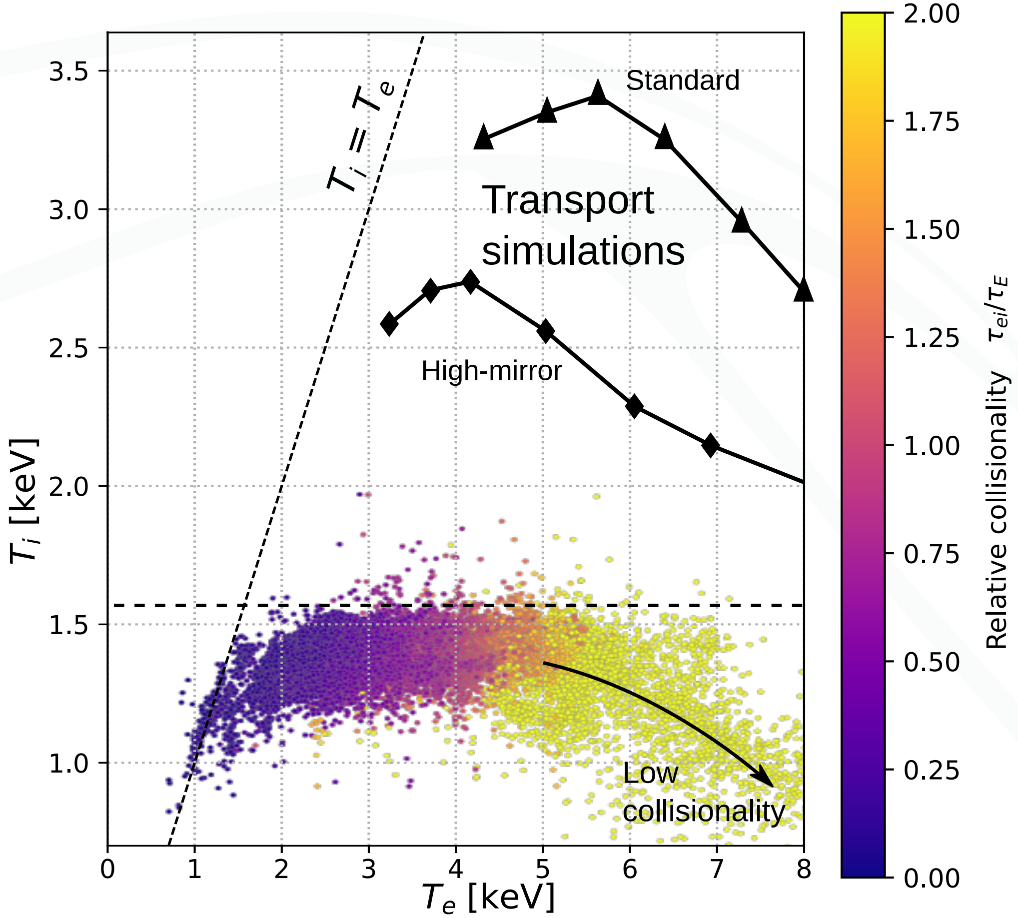


Gas-fuelled ECRH discharges

Typical scenario for long pulse, divertor experiments, parameter scans etc:
- Gas/recycling fuelled.
- Continuous ECRH heated.

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 requires core anomalous pinch.
- Pinch is seen in some new gyrokinetic simulations in the roughly the right place.

  [Thienpondt, Phys. Rev. Res. **5**, L022053 (2023)]
- No quantitive match
  (Difficult without measured neutral fuelling profile)

Impurities:

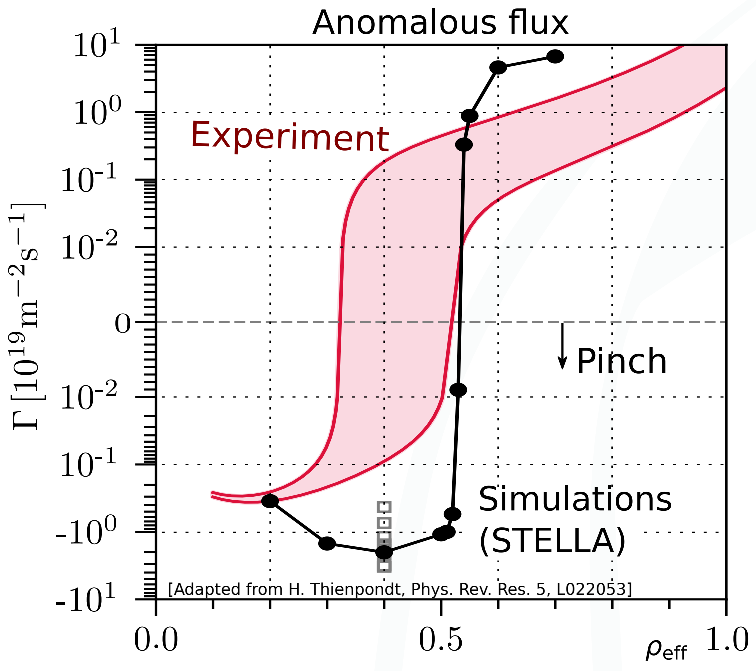
Neoclassics --> peaked, Experiment = flat

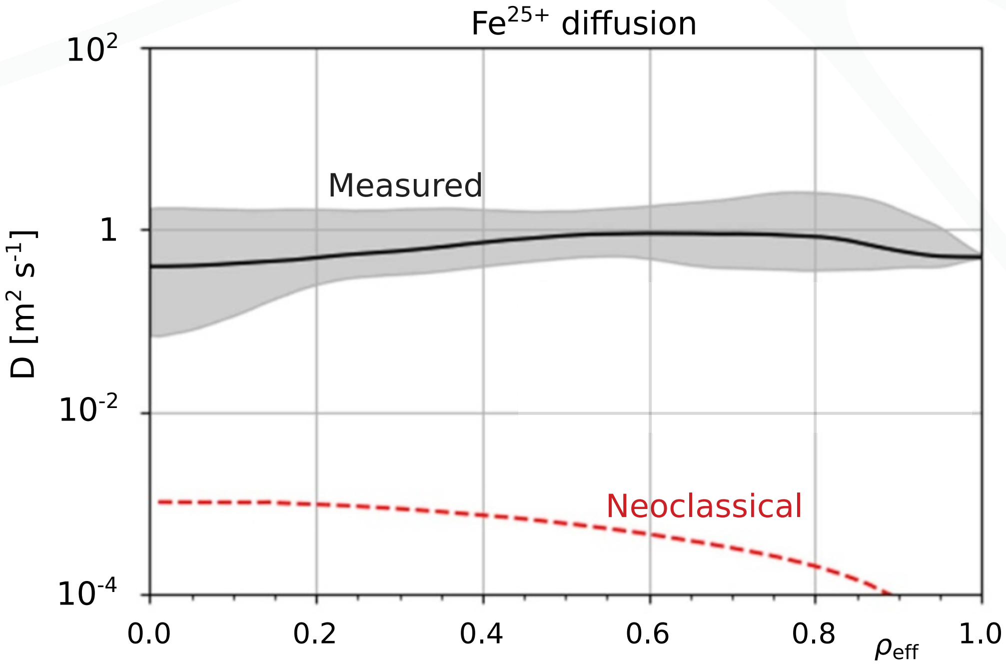
Require strong anomalous flux to flatten (D >> $0.1 m^2 s^{-1}$) .

[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)]





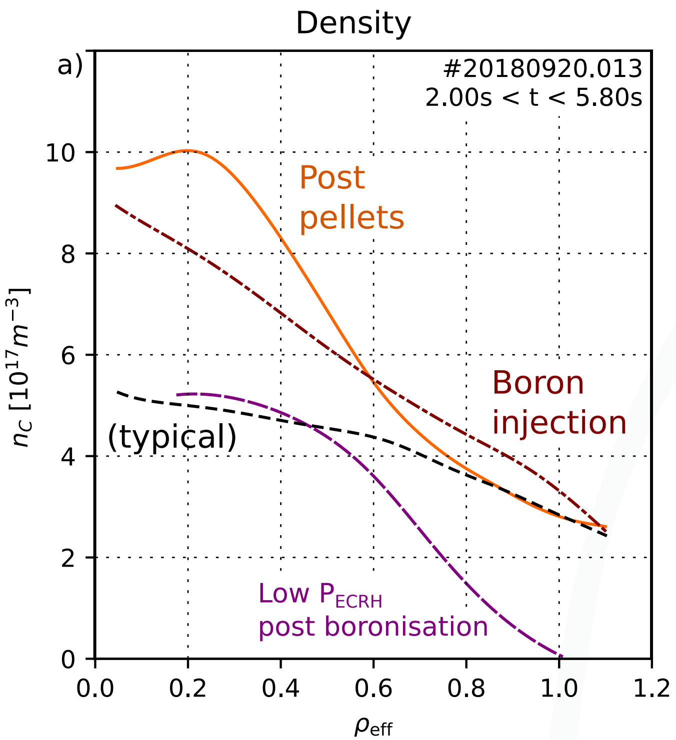
Reduced turbulent transport scenarios

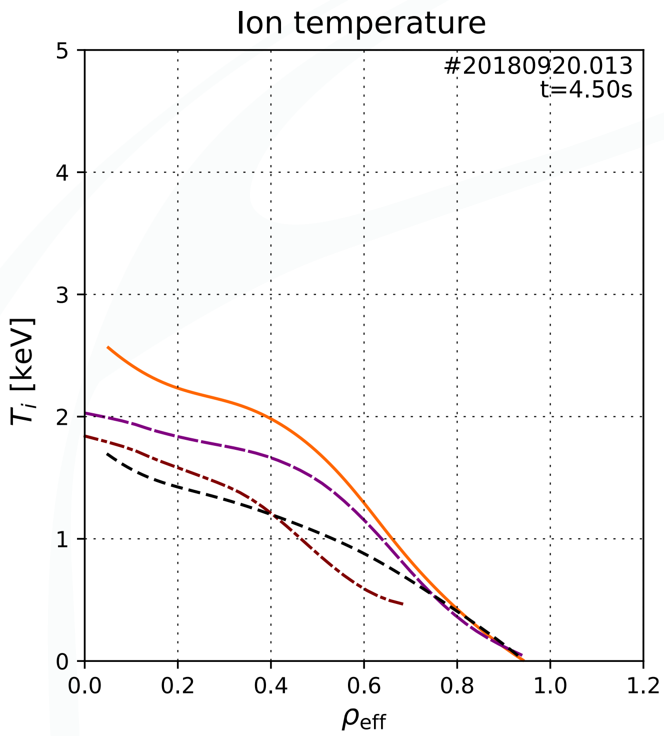
Varous plasma scenarios show effects of reduced turbulence:

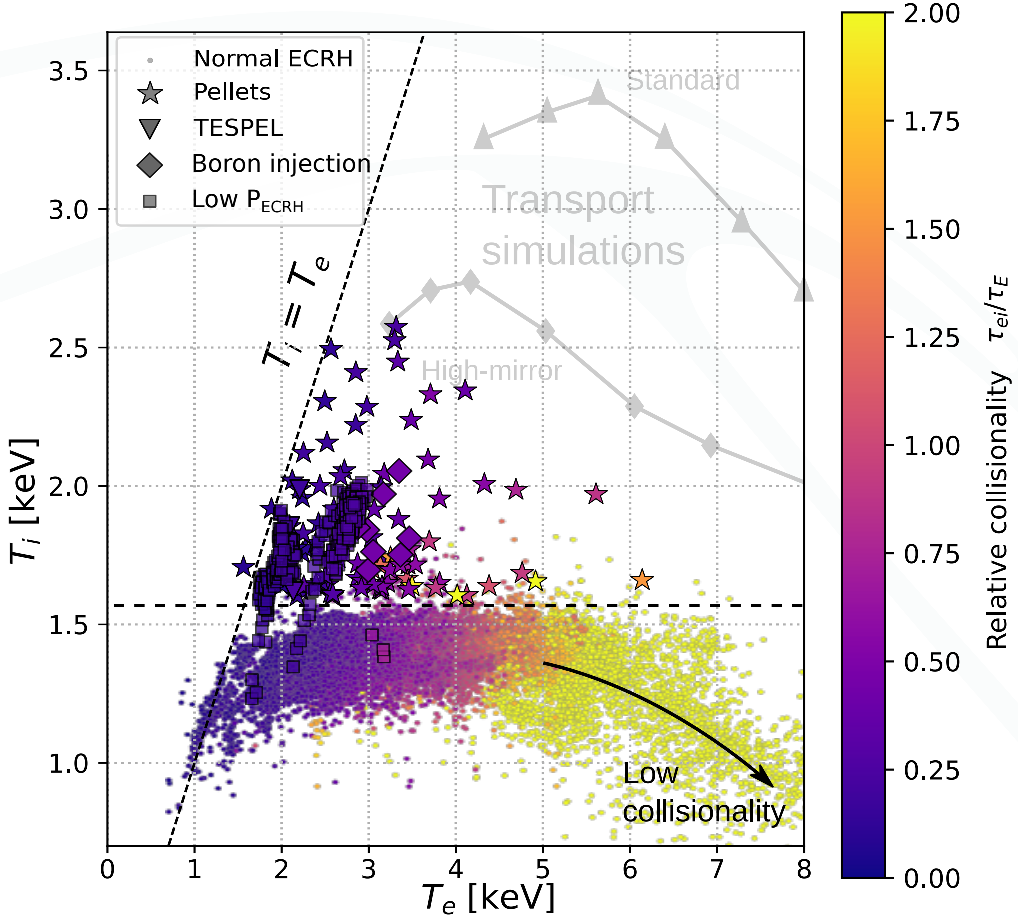
- After pellets --> peaked n_e, peaked n_z --> neoclassical Q_i --> T_i > 1.5keV [S. Bozhenkov Nucl. Fusion **60** 066011 (2020)]
- Impurity pellets, boron injection --> peaked n_e --> T_i > 1.5 keV [R. Lunsford Phys. Plas. **28** 082506 (2021)]
- Some low power ECRH --> Spontaneous peaked n_e, n_Z [D.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

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

--> Reduced χ_i --> Higher ∇T_i *(see Poster M. Wappl)*





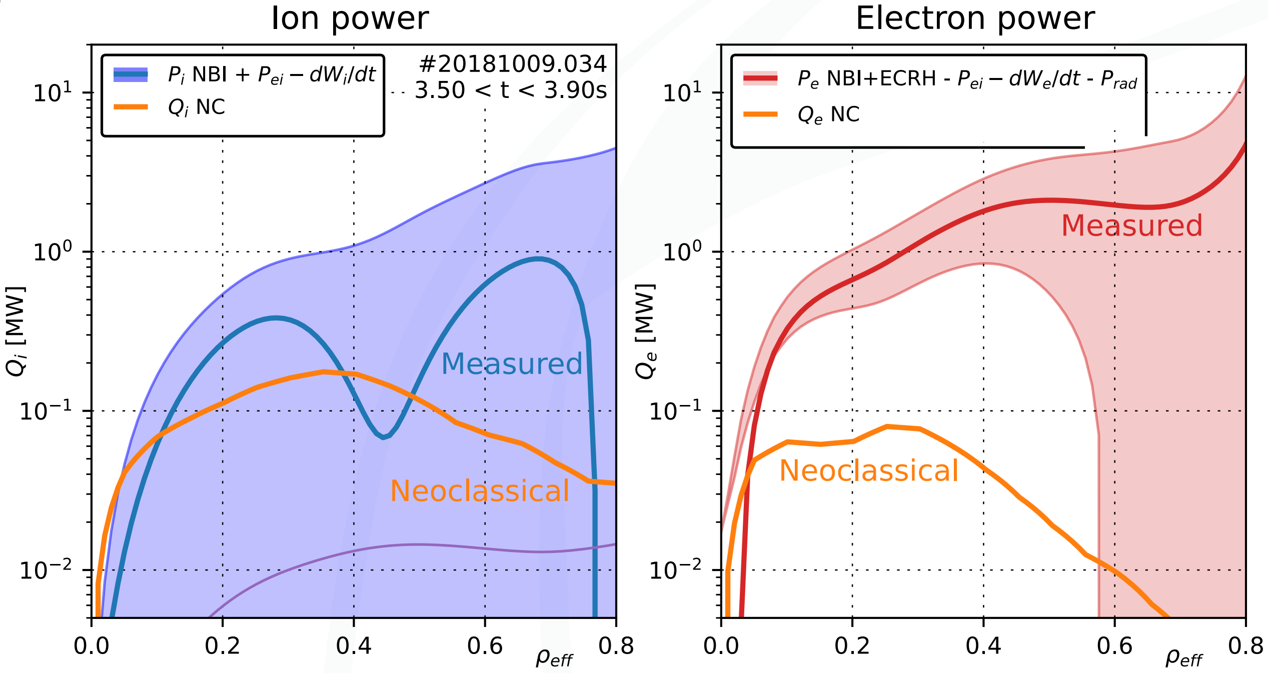


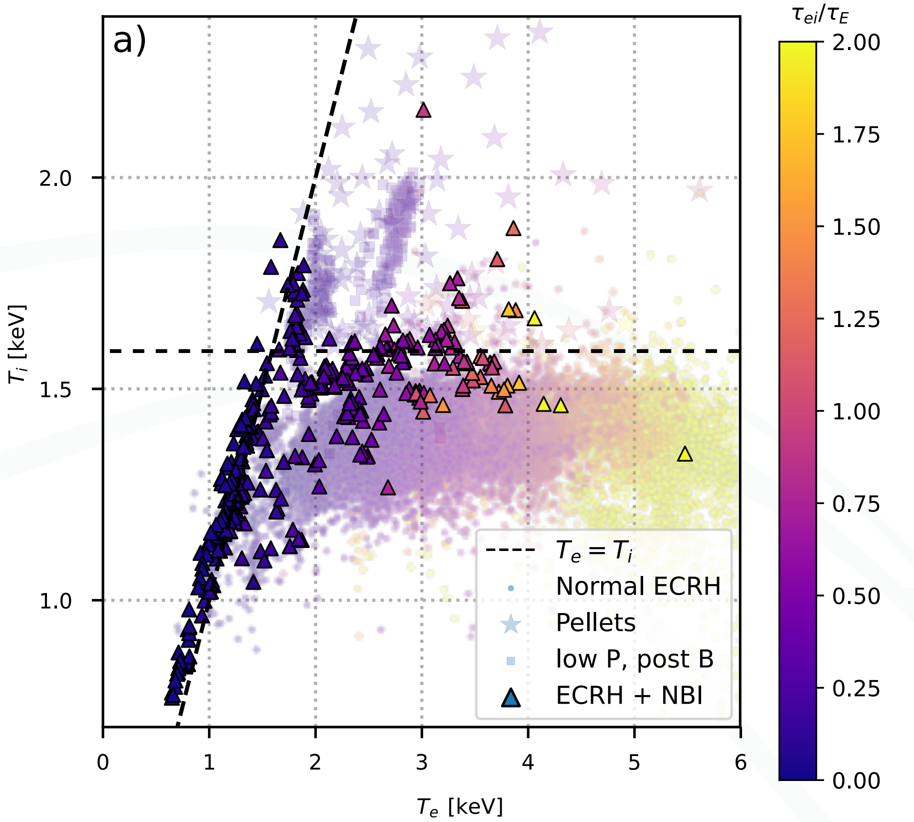
NBI (±ECRH) Scenarios

- NBI also *sometimes* gives density gradients.
- Is the turbulent transport reduced compared to ECRH?
  - Not immediately clear from T_i - some above $T_i > 1.5$
    --> we need to look at transport coefficients.

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.:

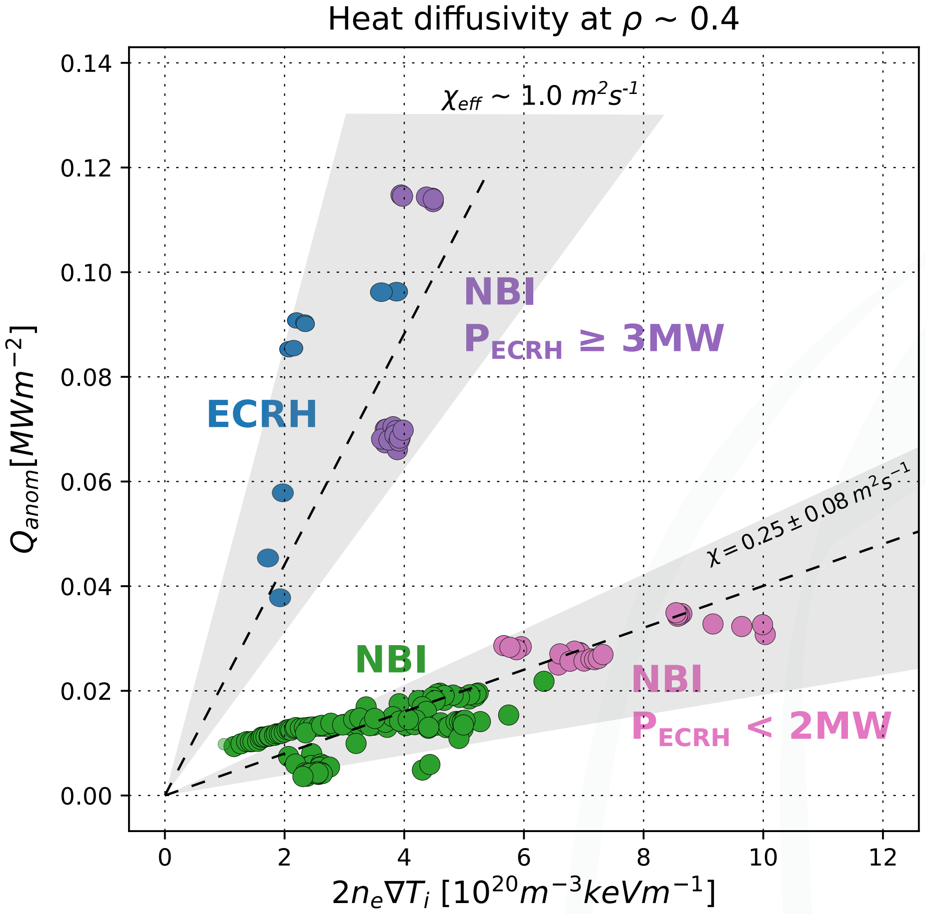
NBI 3MW
ECRH 1MW

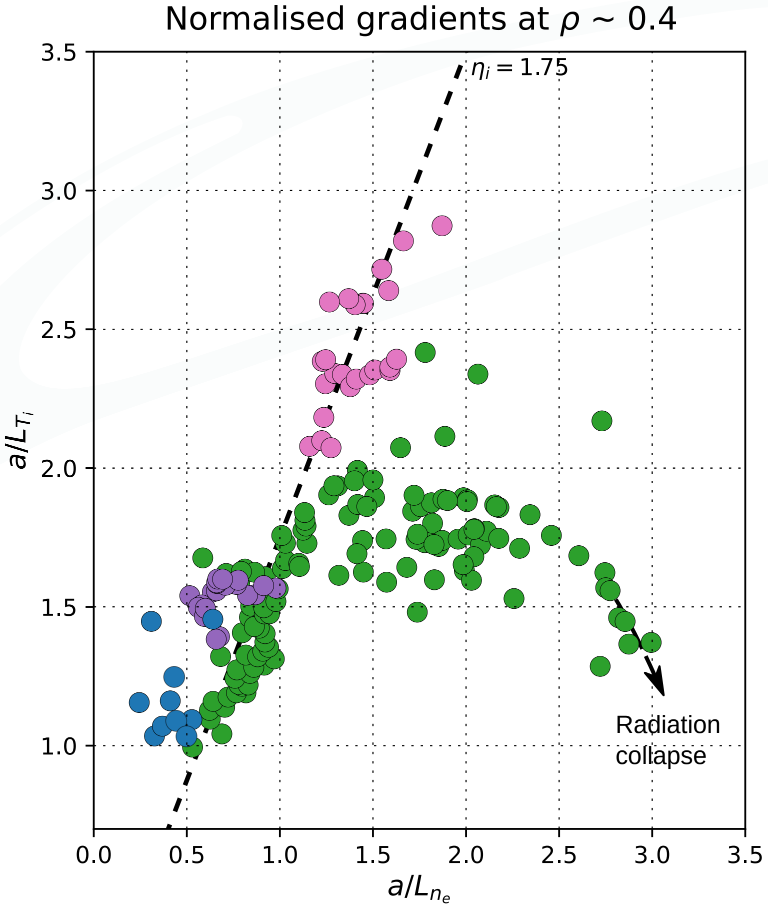




NBI (±ECRH) - Anomalous heat diffusivity

- Not possible to separate Q_i, Q_e due to high collisionality and similar heating effect of NBI - $P_e \sim P_i$.
- Look 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: $\chi_{eff} \sim 0.25\ m^2s^{-1}$



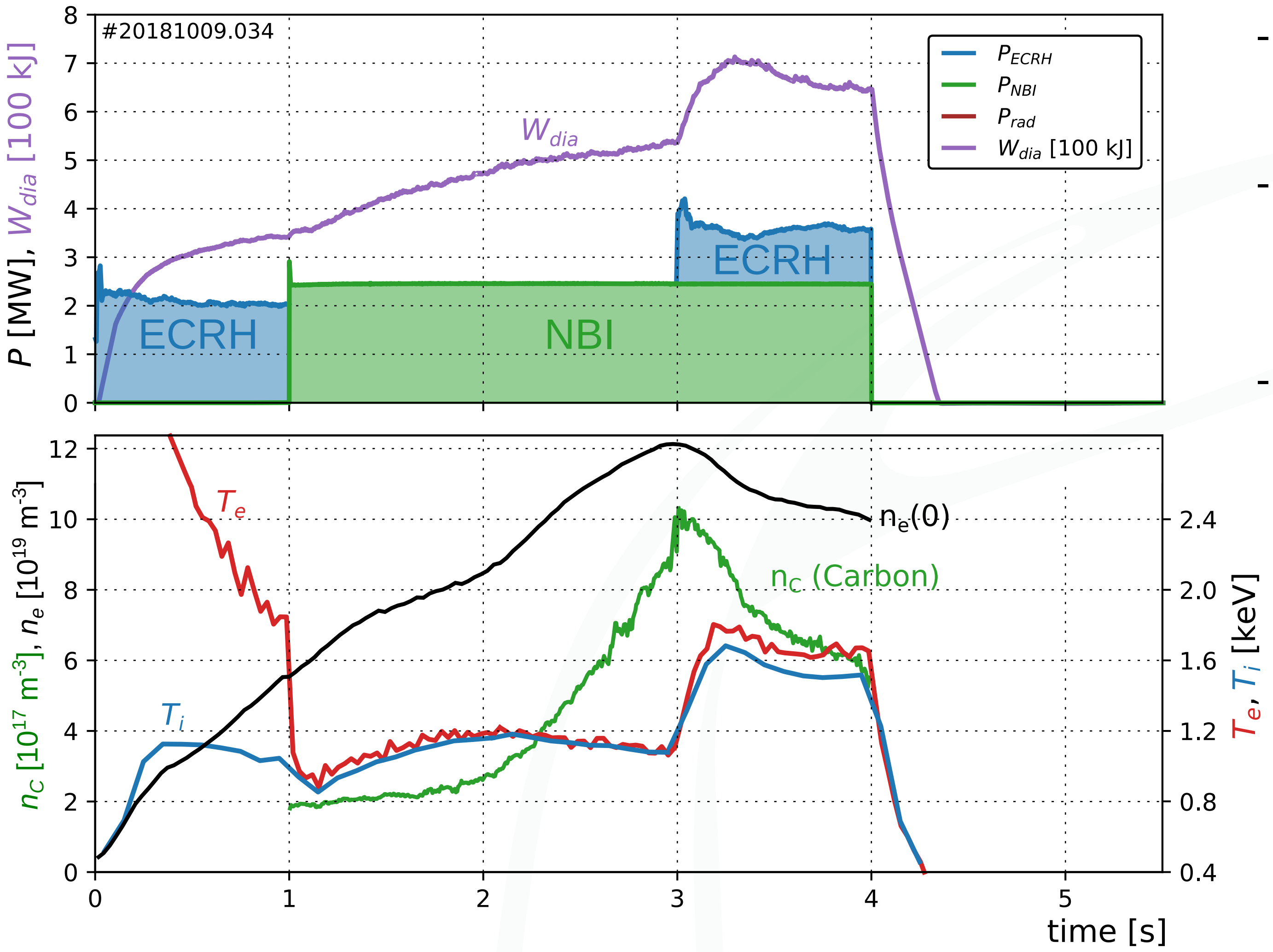


- Pure NBI has reduced χ_{eff}, but much broader power deposition results in similar ∇T_i. (and T_{i0})
- Mixed NBI with low PECRH maintain $\chi_{eff} \sim 0.25$ and exploit it for higher ∇T_i.
- All plasmas with $a/L_{ne} > 1.0$ have lower χ_{eff}.
- Without additional ECRH, NBI plasmas can undergo radiation collapse.

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

NBI + ECRH reintroduction

- Density gradient builds up in pure NBI phase, which is exploited with reintroduction of O2 ECRH at high ne.



- Density peaking accelerates at a given time after switch to pure NBI --> Particle transport changes.

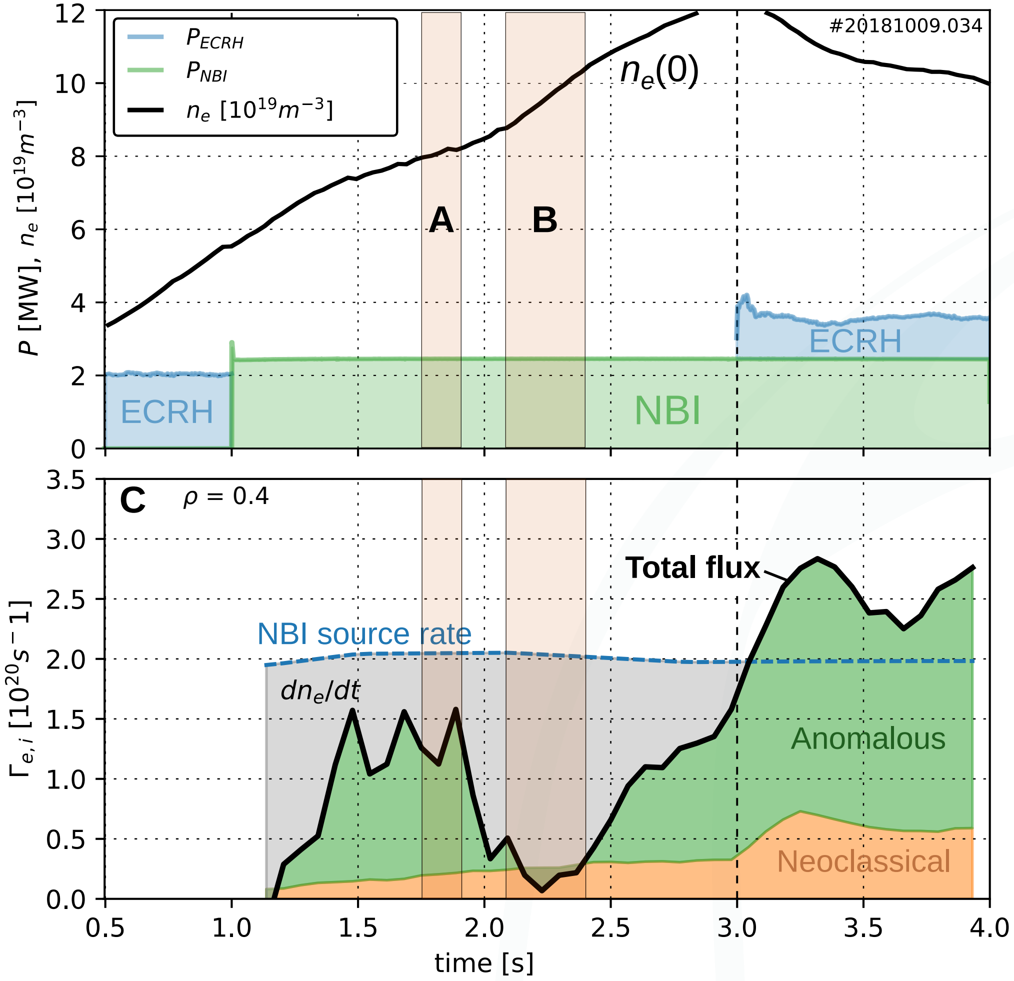
- Impurities accumulate from this time, almost entirely determined by neoclassical transport. [T.Romba Nucl. Fus. **63** 076023 (2023)] (see talk by T. Romba)

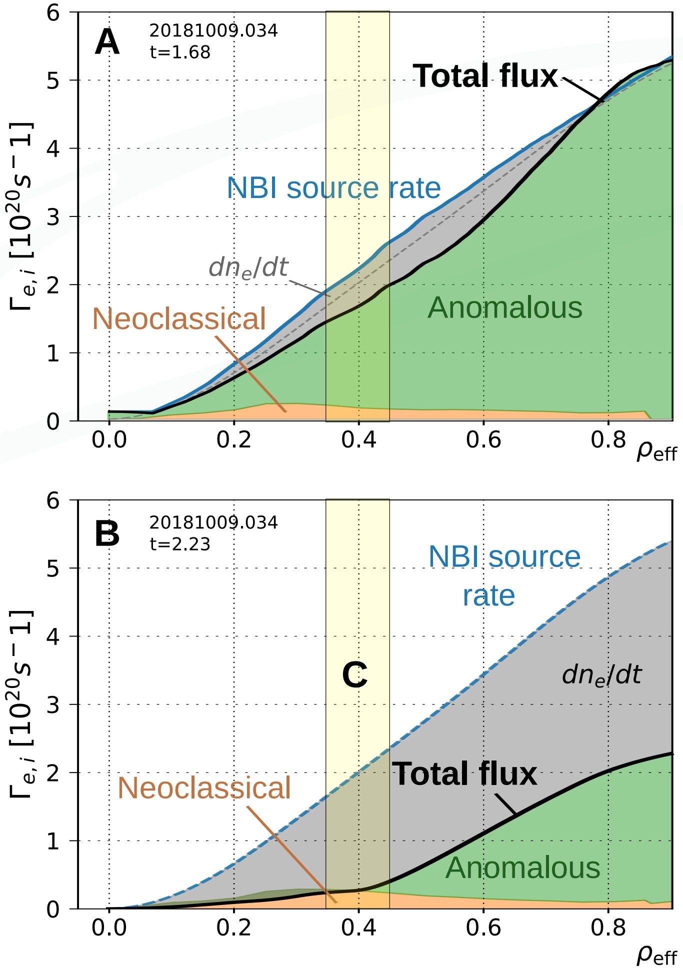
- Reintroduced ECRH stops density peaking or reduces it, and flushes out impurities.

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

Pure NBI - Particle flux

- Particle balance during pure NBI phase shows:
  - Initially significant **outward** anomalous flux (opposite 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.

  Really no tubulent flux??

- Increases again shortly afterwards.

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

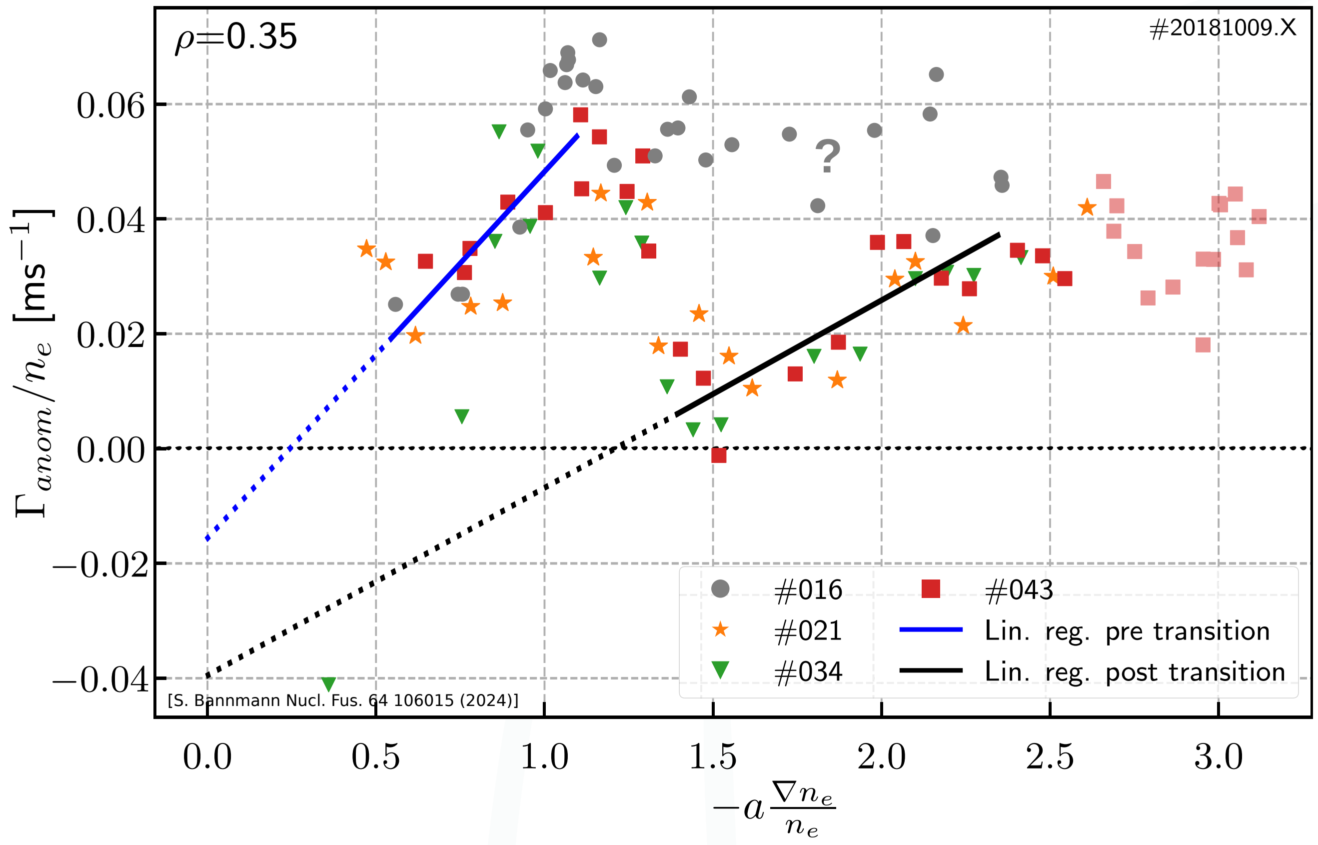
[O. Ford Nucl. Fus. 64 086067 (2024)]

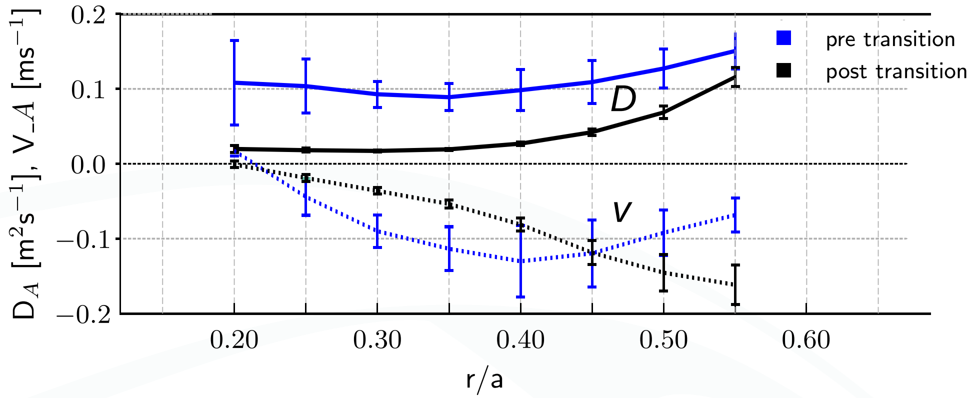
Pure NBI - Particle transport

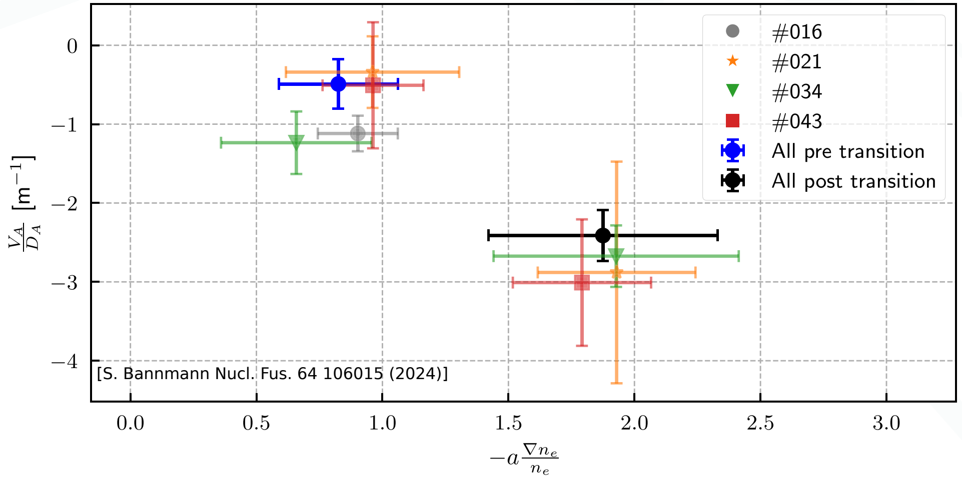
[S. Bannmann Nucl. Fus. 64 106015 (2024)]

∇n_e is changing. What is just an 'expected' reponse to this?
--> Decompose into diffusive *D* and convective *v*.
- Indicates two phases of ~consistent *v, D,* with significant drop of *D* at a/L_n ~ 1.3.

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



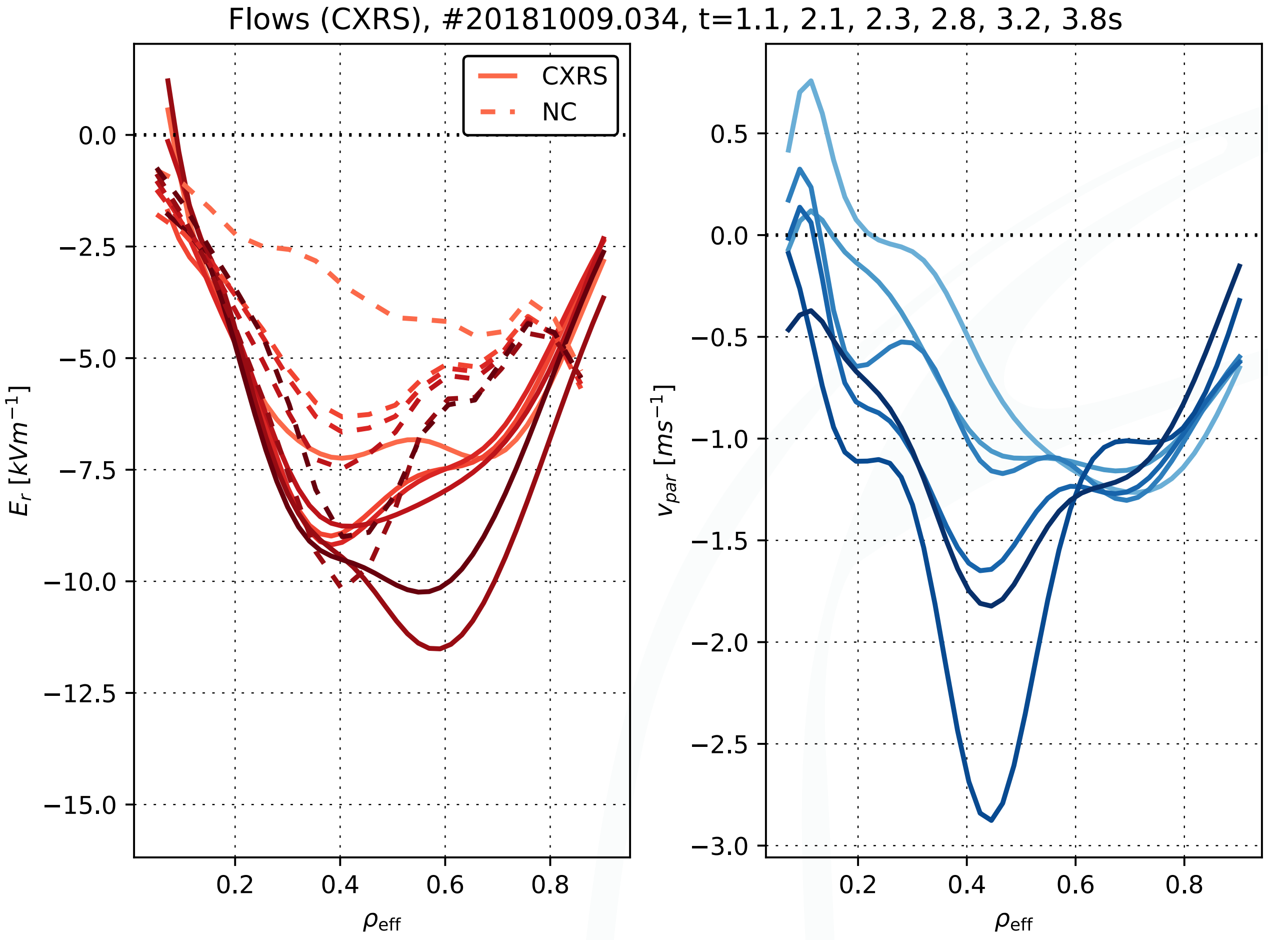


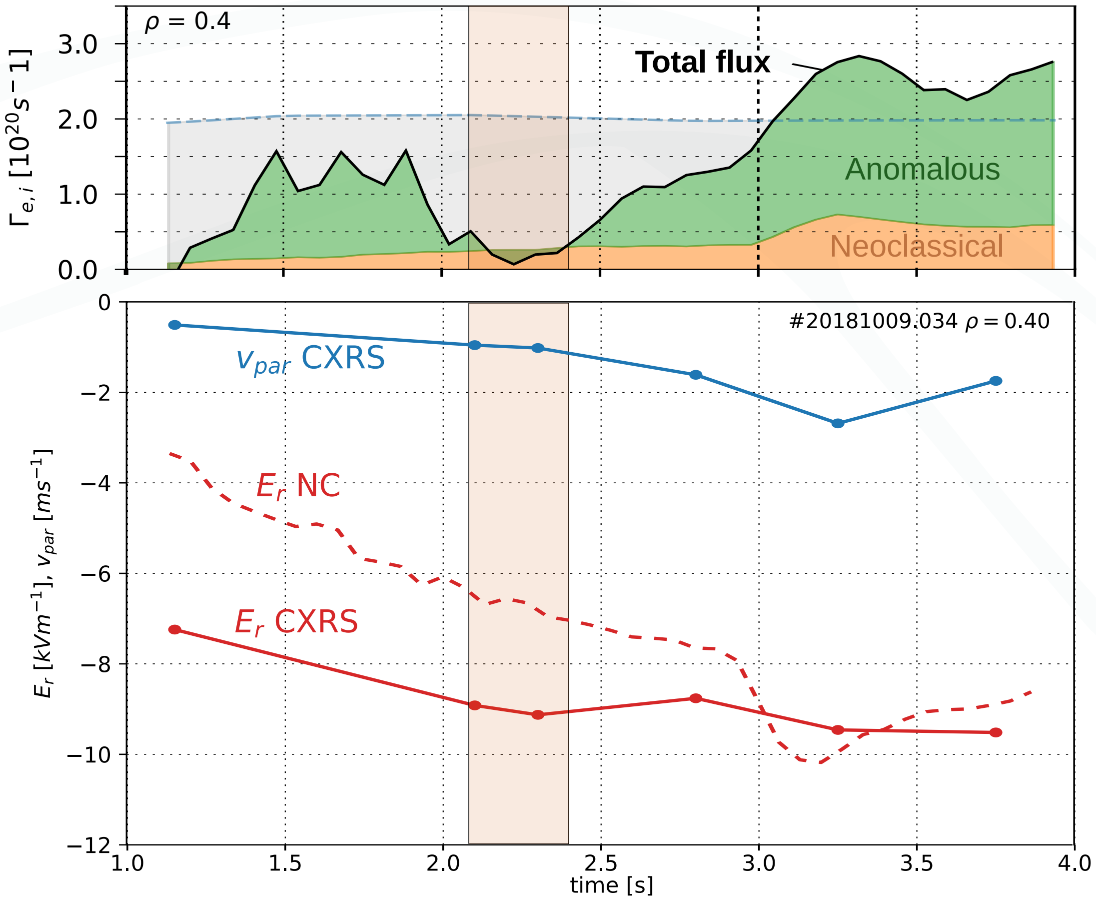


- Threshold not yet reproduced in modelling.
(Range not covered by original STELLA study
[H. Thienpondt, Phys. Rev. Res. 5, L022053 (2023)])

Pure NBI - Radial Electric Field

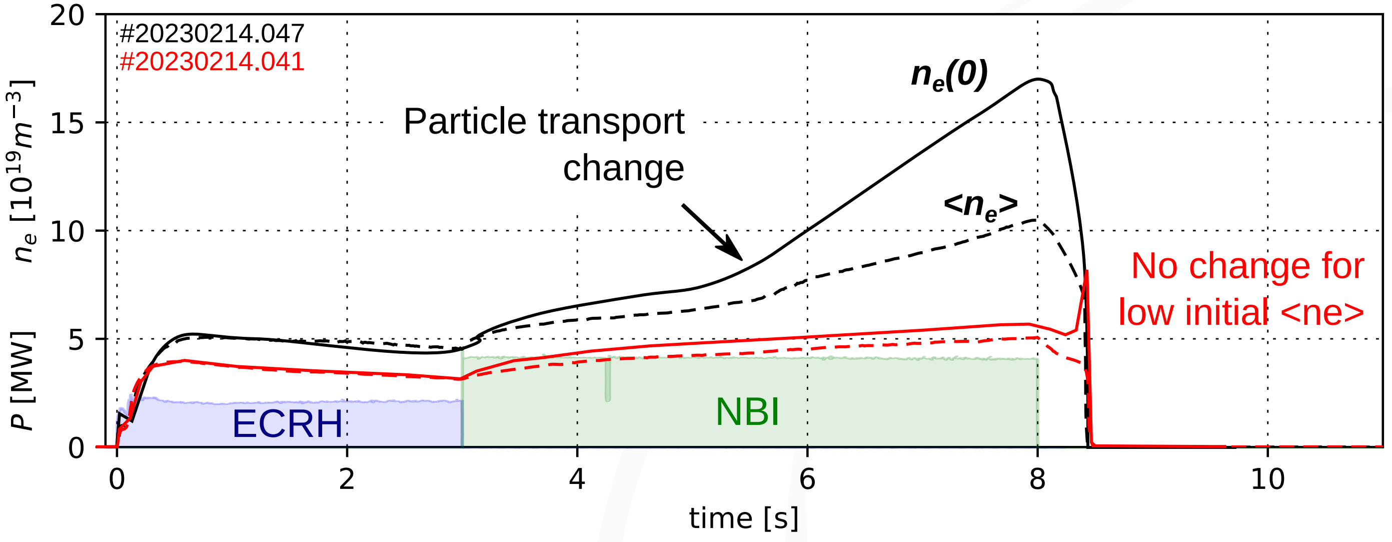
- E_r affects NC transport and can play a strong role in global transport changes, especially at low collisionality.
  $T_e >> T_i$ --> 'Electron root'
- NBI discharges all ion root with no significant E_r changes at onset time (measured or NC)

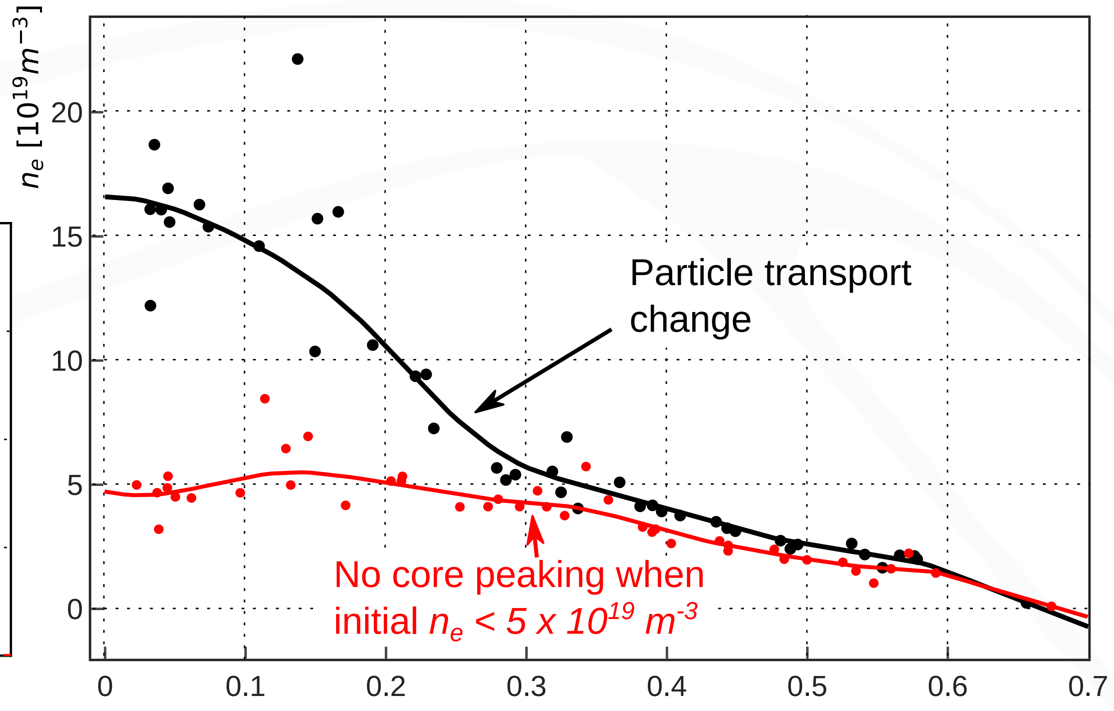




OP2.1 (2023) campaign

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:



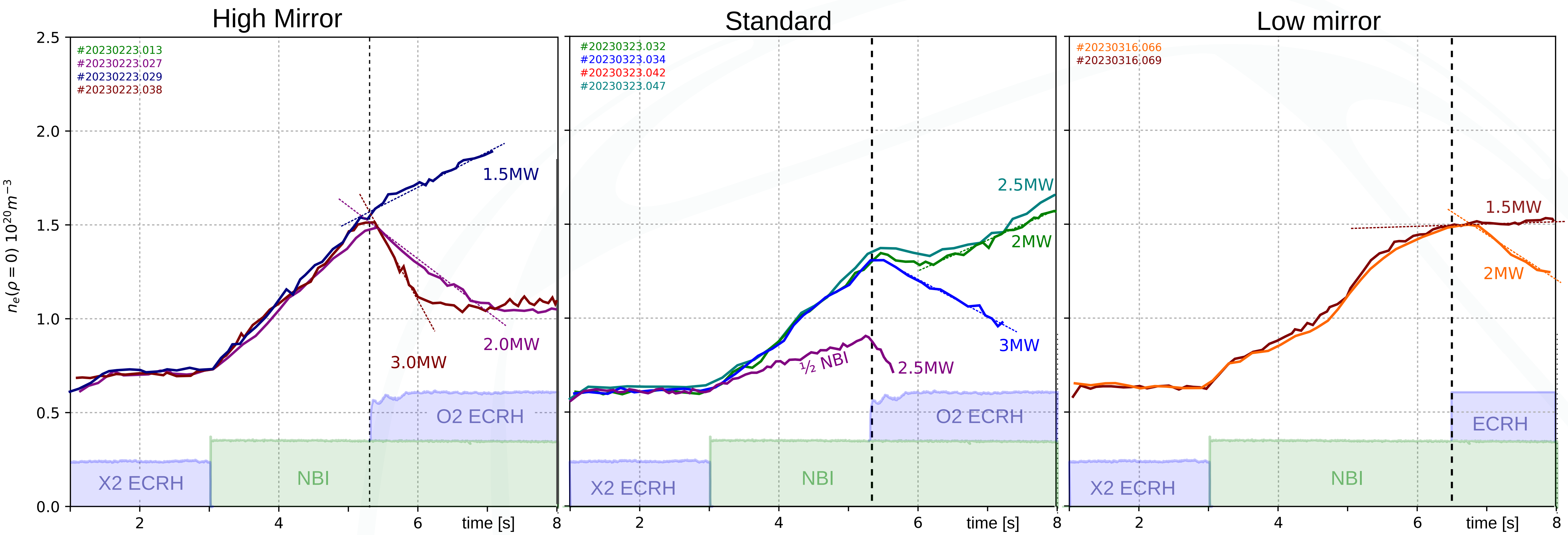


ECRH power and configuration scans

In the 2022/3 campaign:

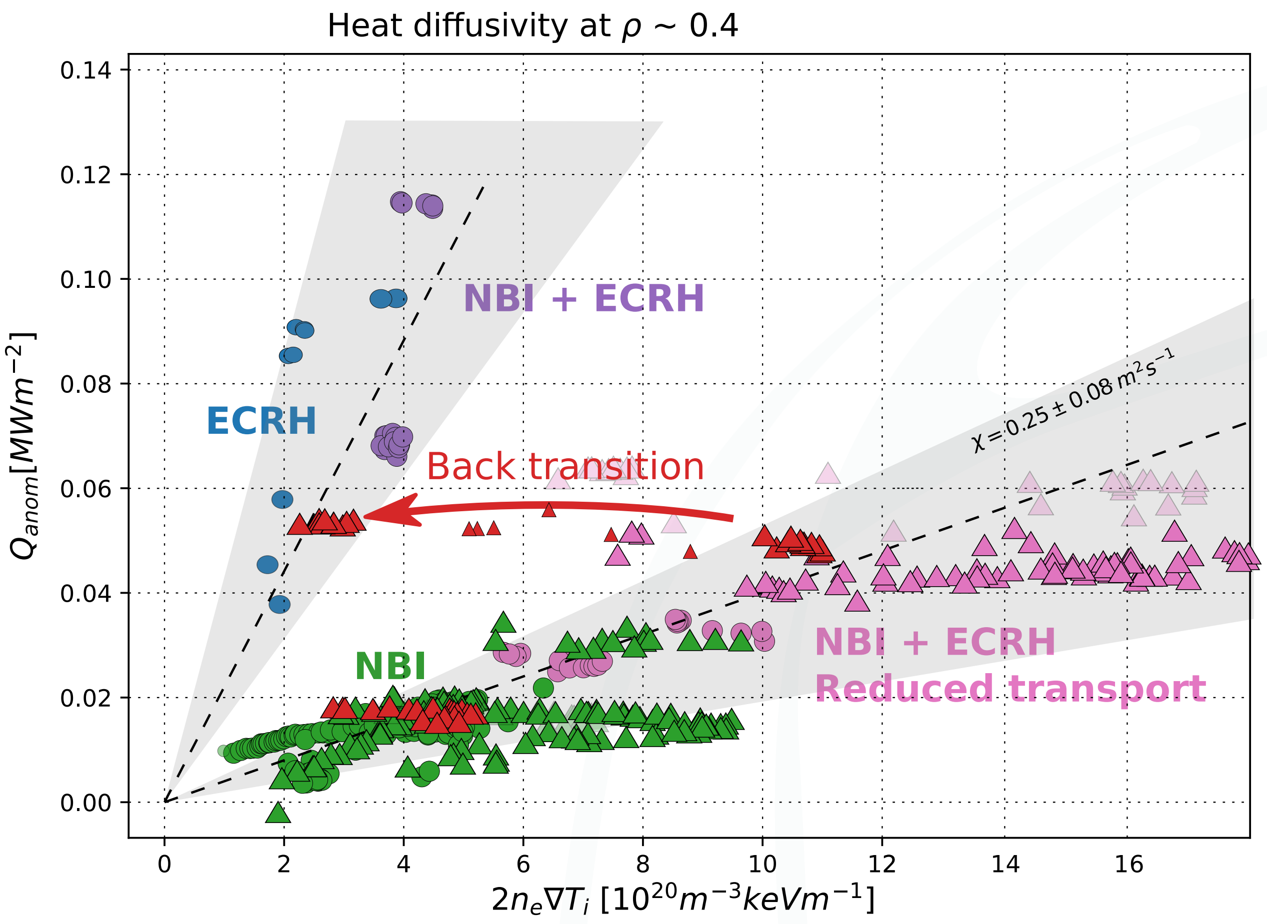
3) Scans of ECRH power at fixed reintroduction time - varying pump-out effect.

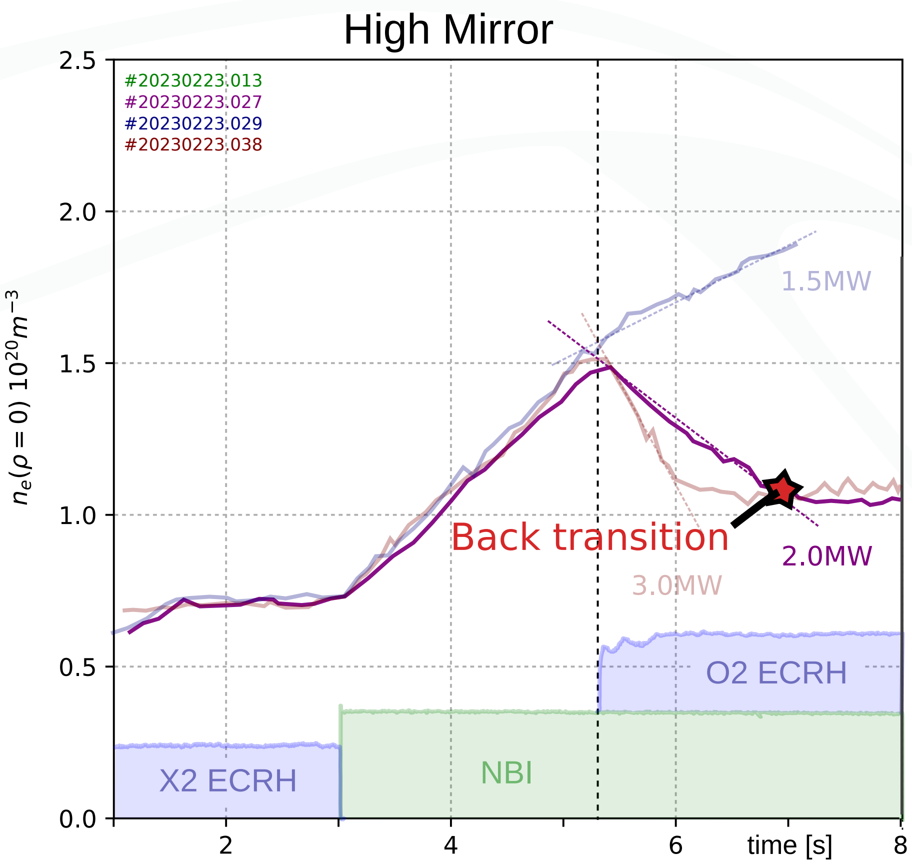
4) (Low - mid - high) -mirror configurations: - Density rise in NBI phase almost identical.
- Different pump-out effect of ECRH



Balancing ECRH power

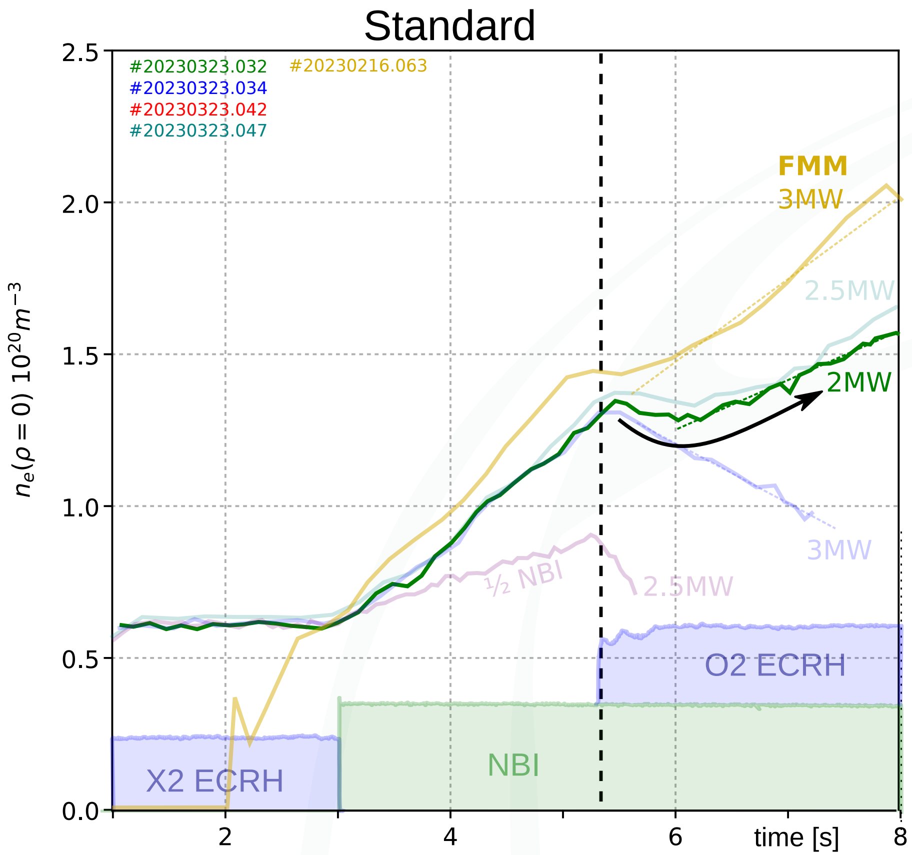
2023 experiments pushed to higher ECRH power to take advantage of reduced heat diffusivity
- $\chi_{eff} \sim 0.25$ maintained despite x2 higher Q_{anom}. (as high as some turbulent ECRH-only shots)
- Spontaneous back-transition to high transport observed as ECRH reduces density gradient.





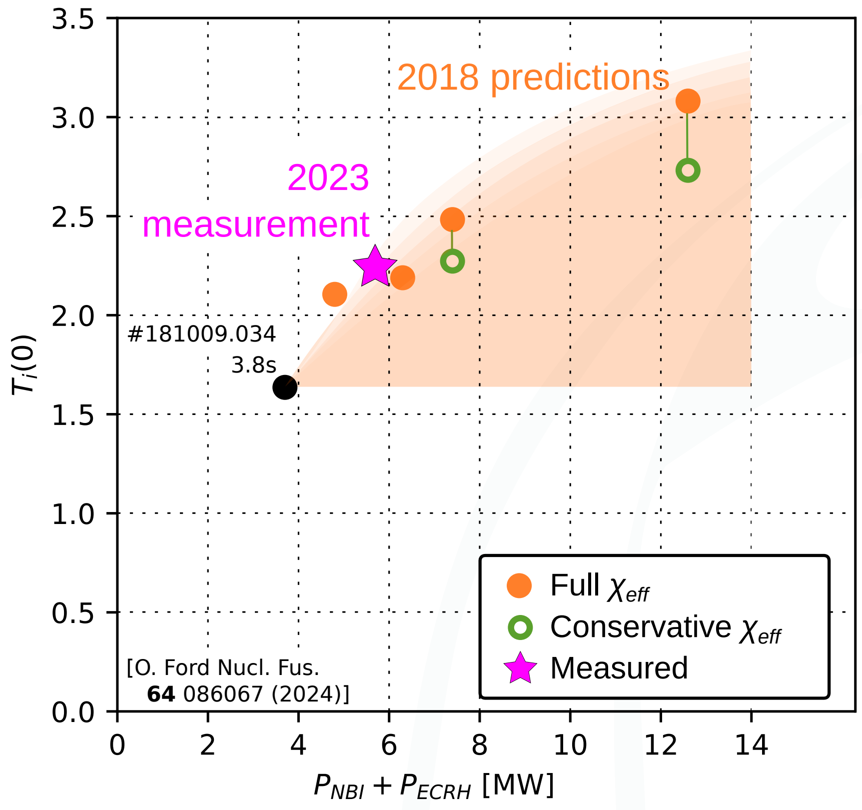
ECRH control

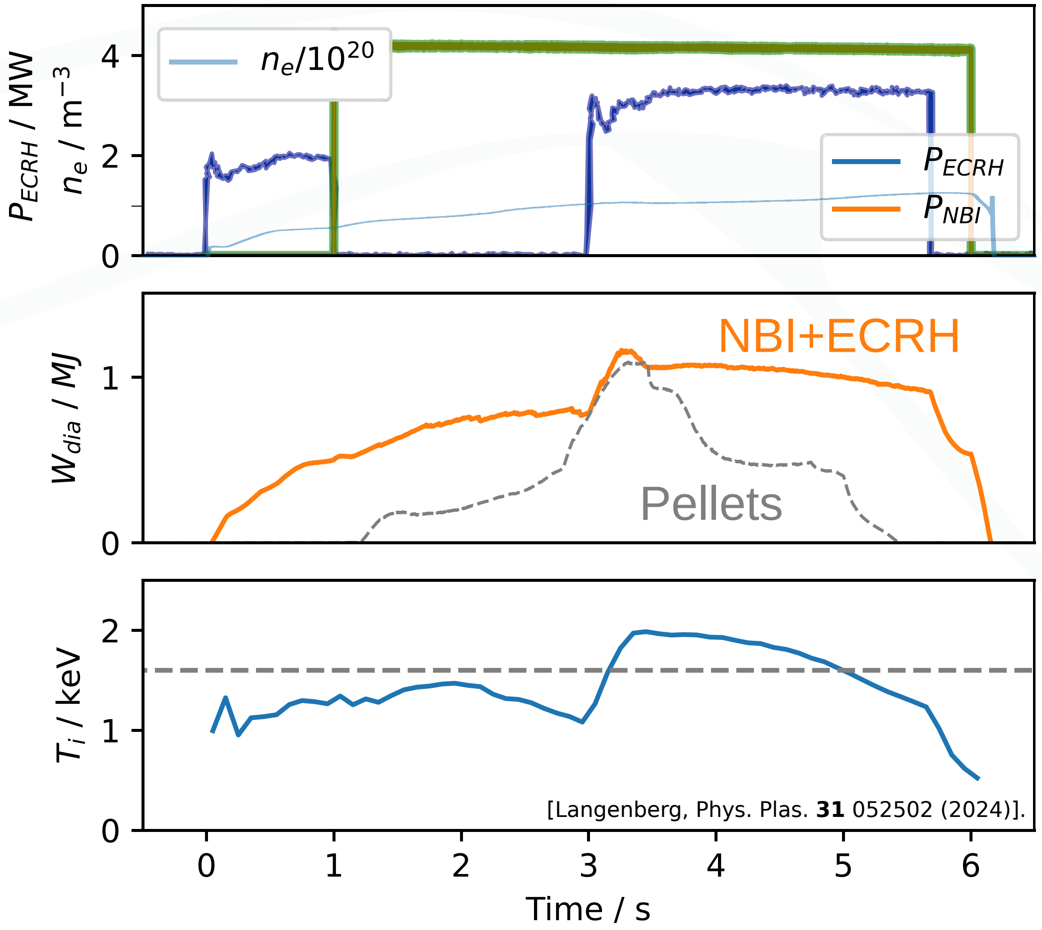
Challenge: Needs dynamic active control of ECRH level:
- Too much --> Loss of density gradient --> back-transition
- Too little --> Too high density, low P/n, impurity accumulation --> radiation collapse.



Achieved performance

- Predictions made from 2018 data using transport simulation (NTSS) - First point matched in 2023!
- Highest ECRH power in FMM configuration still does 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 scenarious 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.

- D_{anom} of main ions drops spontaneously 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 predicated doubling of ECRH power well matched by experiment.

    - Record level of stored energy (marginally above pellets experiments) held for > 2s.

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