Max-Planck-Institut für Plasmaphysik

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

O. P. Ford, S. Bannmann, M. Beurskens, S. Bozhenkov, T. Romba, T. Stange, M. Wappl

A. Alonso, C. Beidler, H. Braune, K.J. Brunner, G. Fuchert, D. Hartmann, J. Knauer, A. Langenberg, H.P. Laqua, S. Lazerson, S. Marsen, P. McNeely, N. Pablant, E. Pasch, V. Perseo, N. Rust, H. Smith, D. Zhang

24th International Stellarator Heliotron Workshop, Hiroshima, Japan

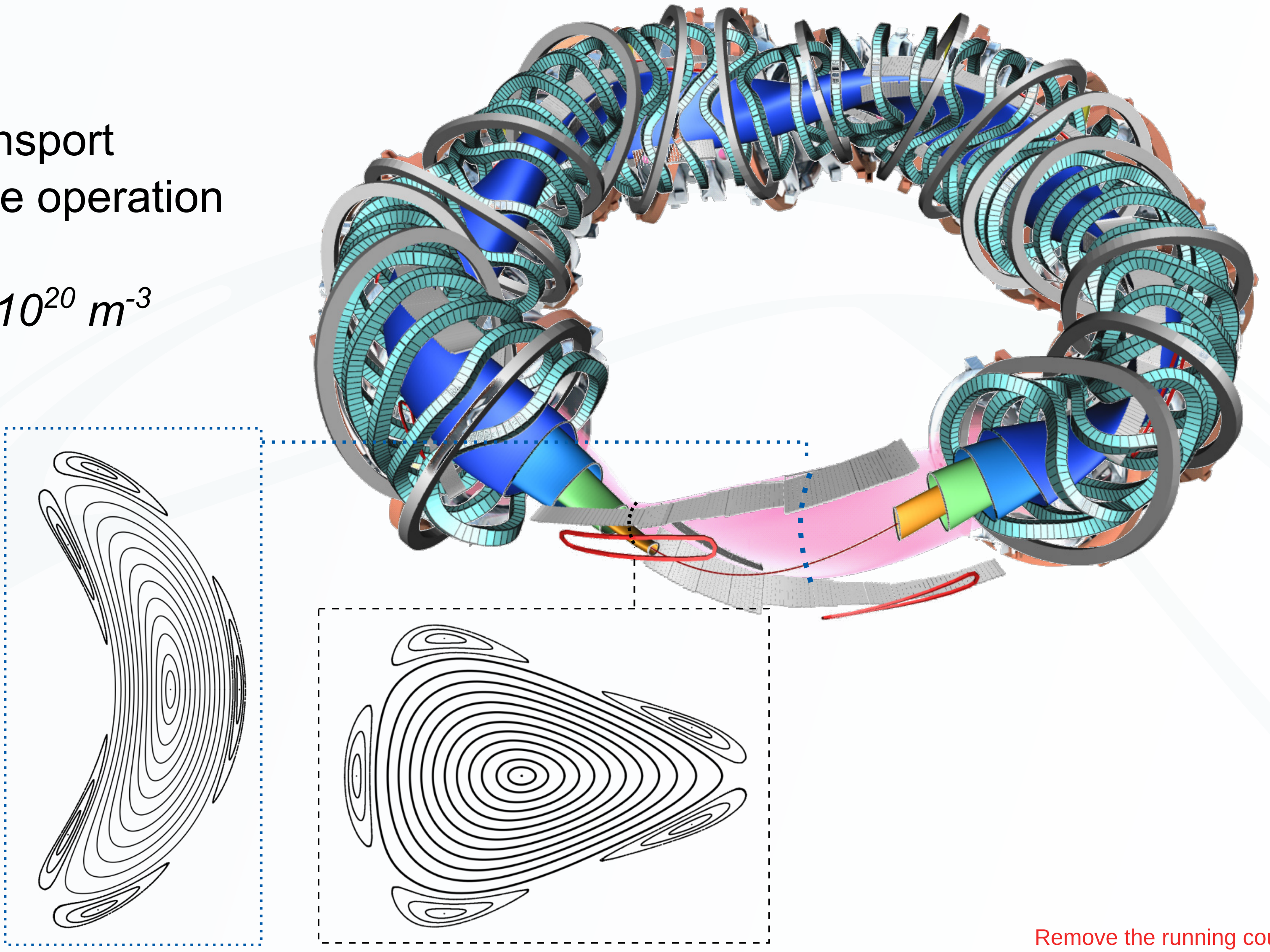
The Wendelstein 7-X Stellarator

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

Those are not OP2.2 values, i.e. 2024



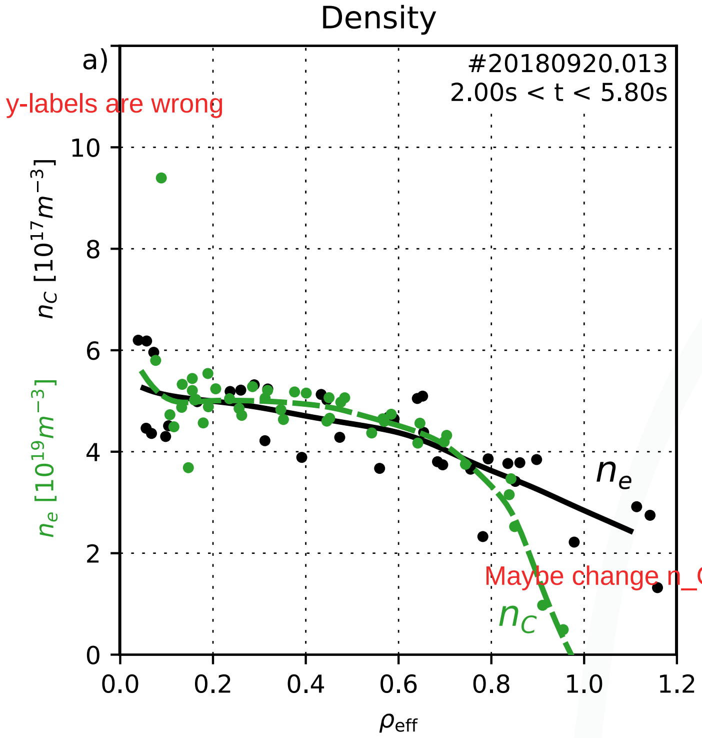
Remove the running count

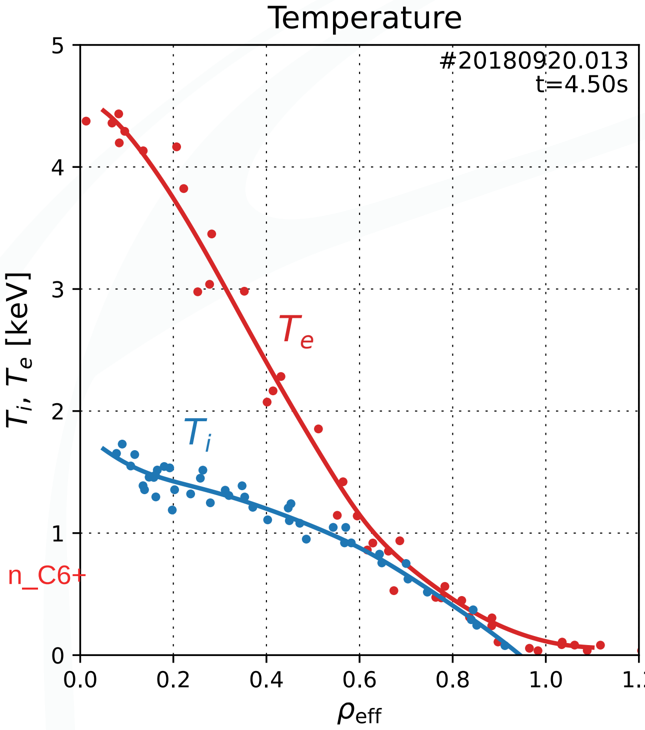
Gas-fuelled ECRH discharges

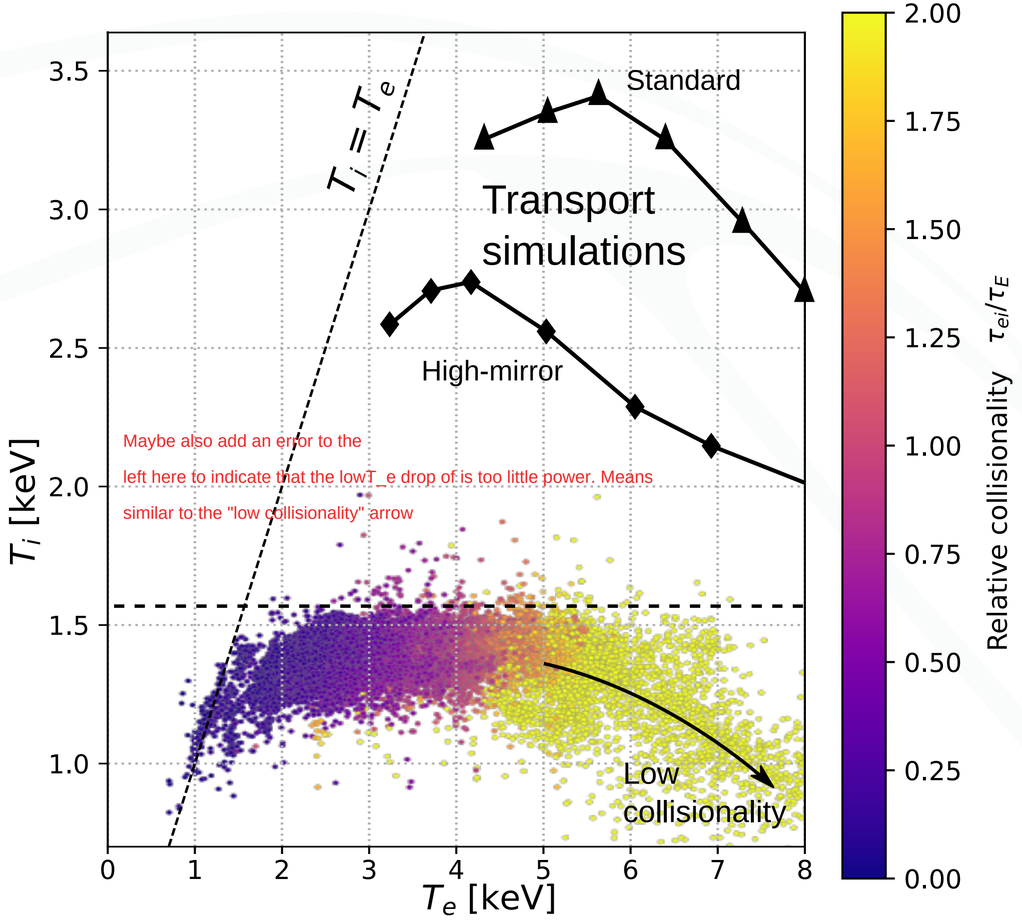
Typical scenario for long pulse, divertor experiments, parameter scans etc:
- Gas/recycling fuelled. - Continuous ECRH heated.

Isn't ECRH heated saying "heating" twice :P

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





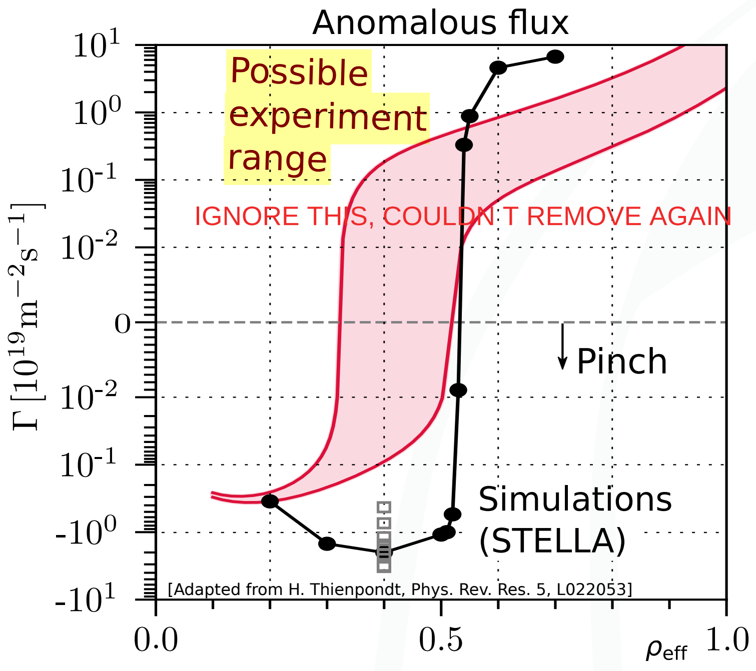


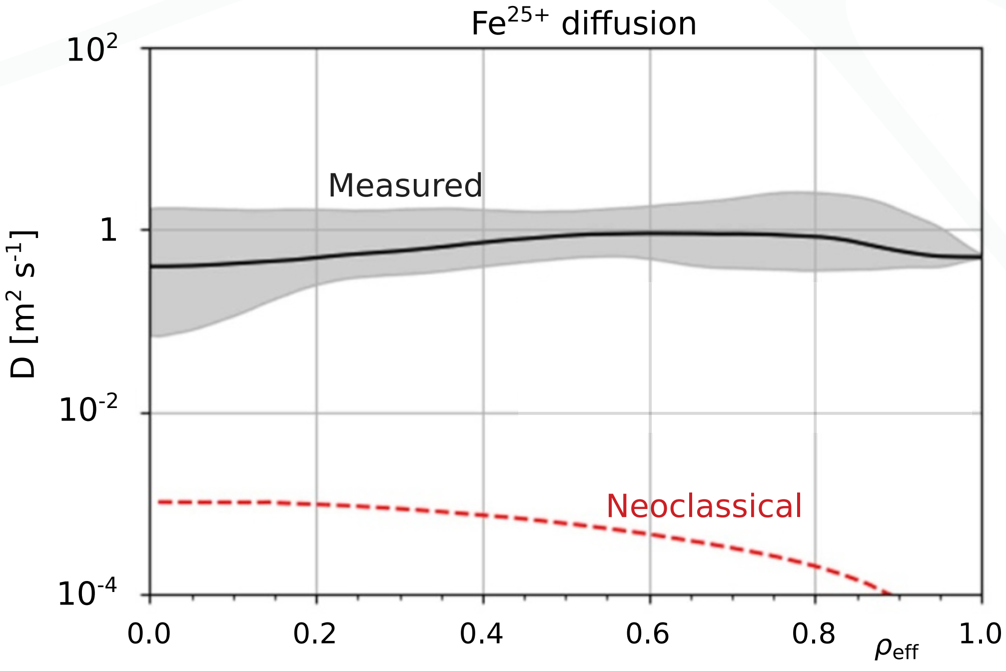
Gas-fuelled ECRH discharges

Main ions:
Neoclassics --> hollow,   Experiment = flat
- Requires requires anomalous pinch inside r/a < 0.5.
- Pinch is seen in some new gyrokinetic simulations in the *roughly* the right place.
  [Thienpondt, Phys. Rev. Res. **5**, L022053 (2023)]
- but large quantitive differences
  (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)]



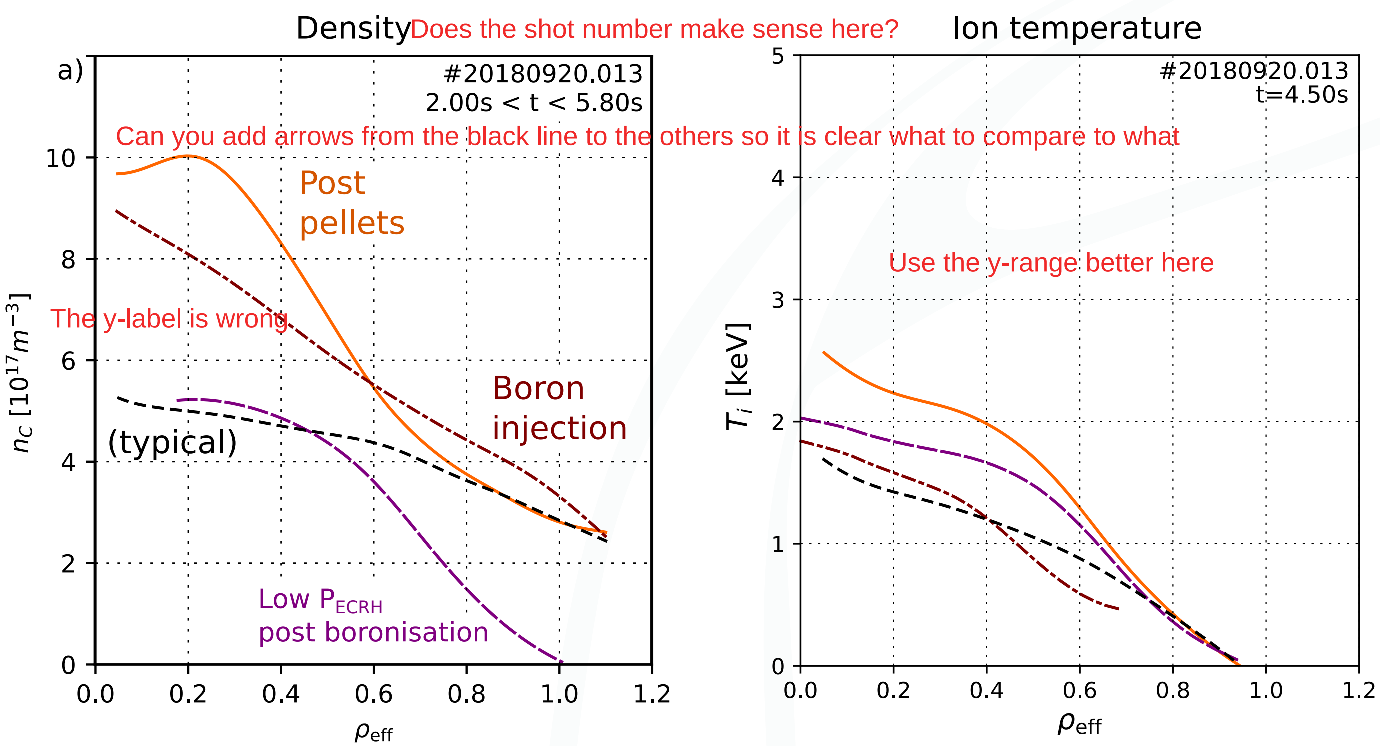


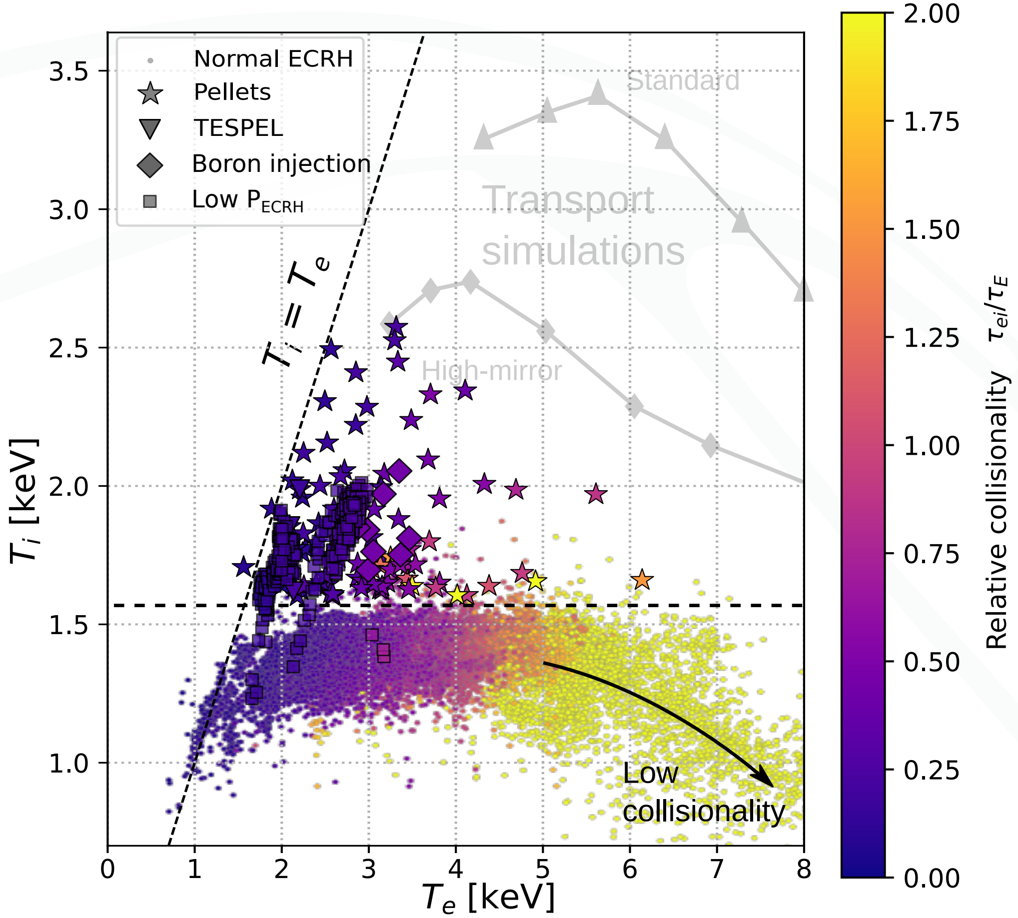
Reduced turbulent transport scenarios

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)*



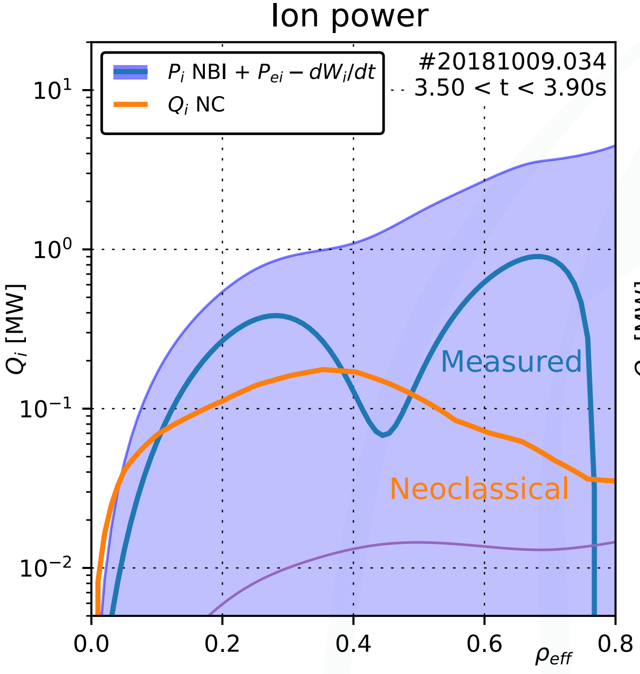


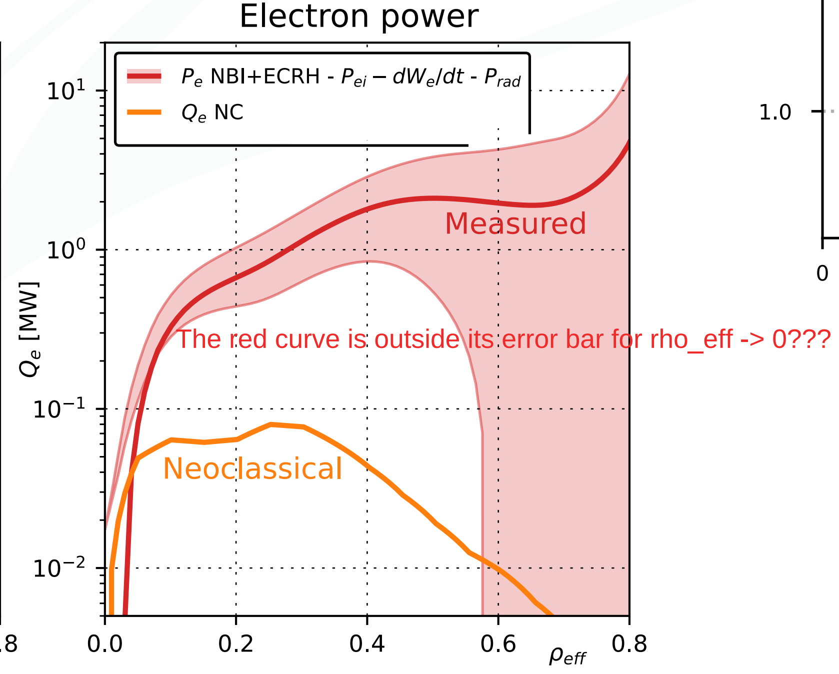
NBI (±ECRH) Scenarios

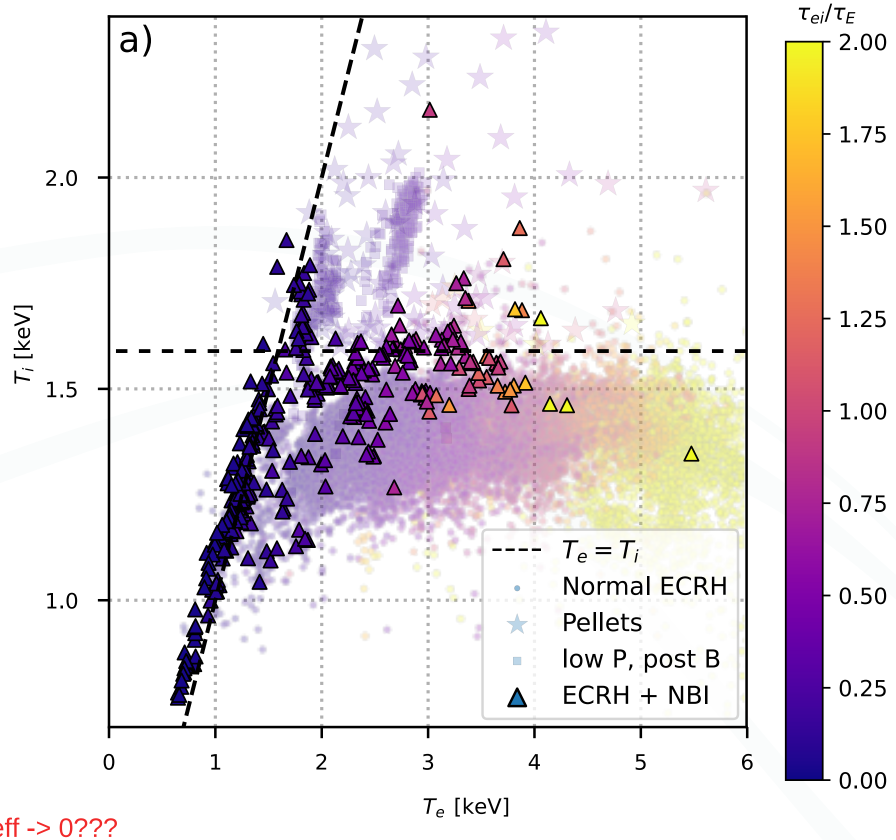
- NBI also *sometimes* gives density gradients.
- Is the turbulent transport reduced compared to ECRH?
  - Not immediately clear from T_i - some above $T_i > 1.5$
    --> we need to look at transport coefficients.

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

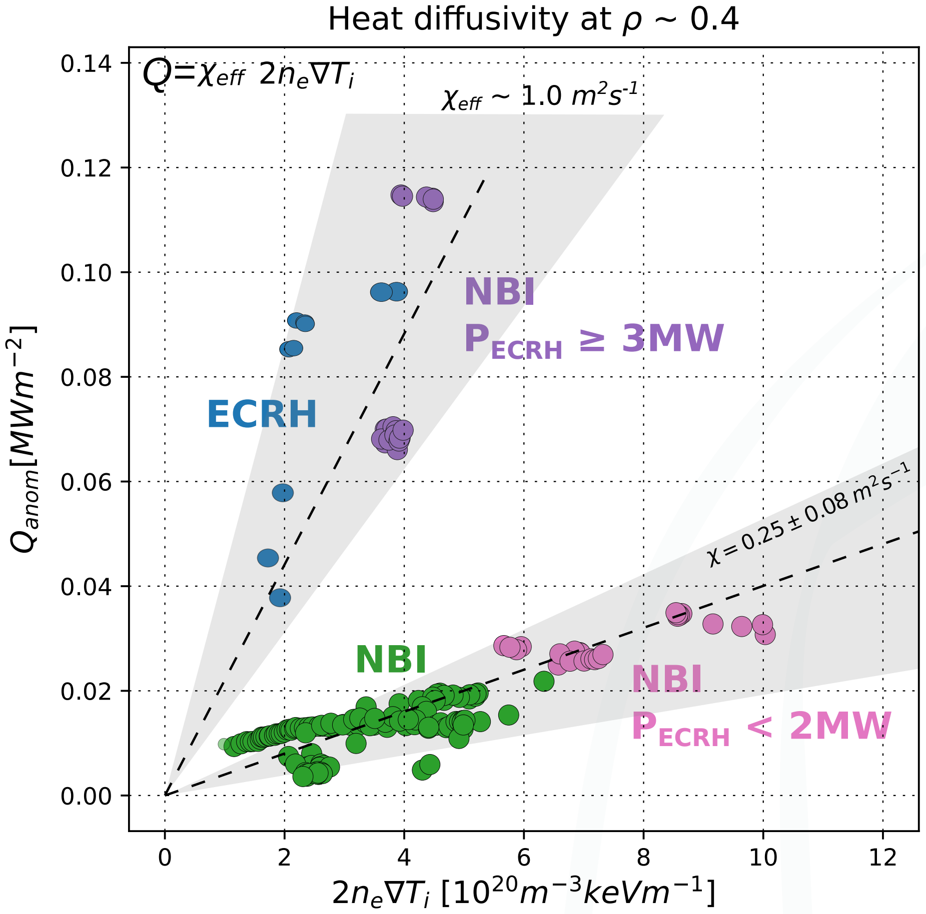


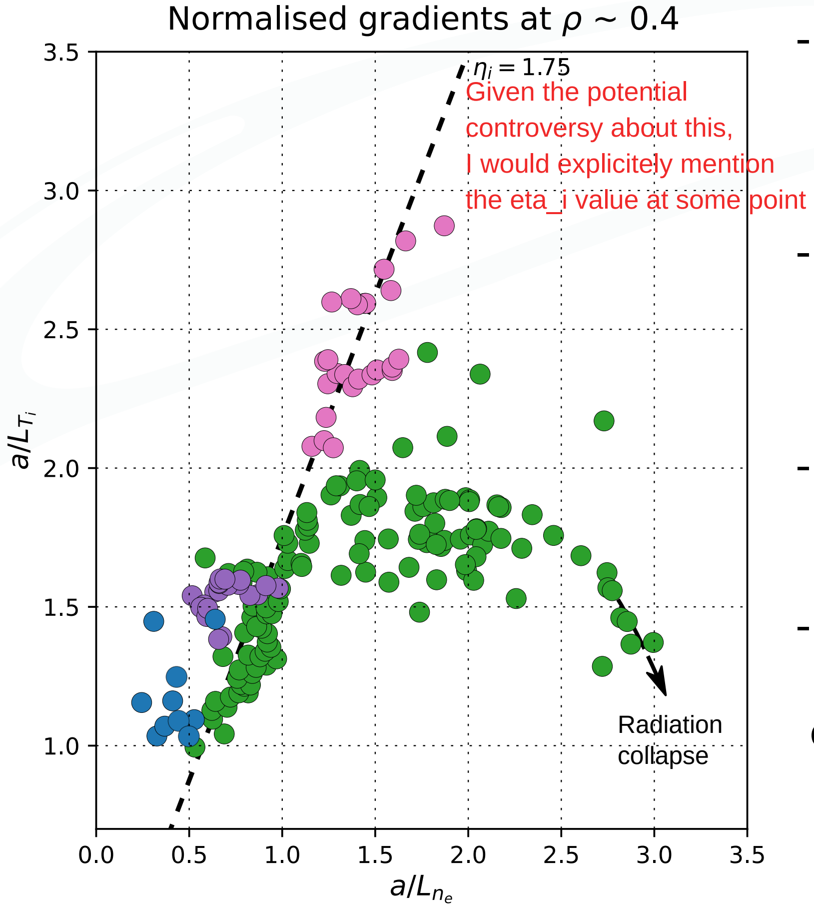




NBI (±ECRH) - Anomalous heat diffusivity

- 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: $\chi_{eff} \sim 0.25\ m^2s^{-1}$



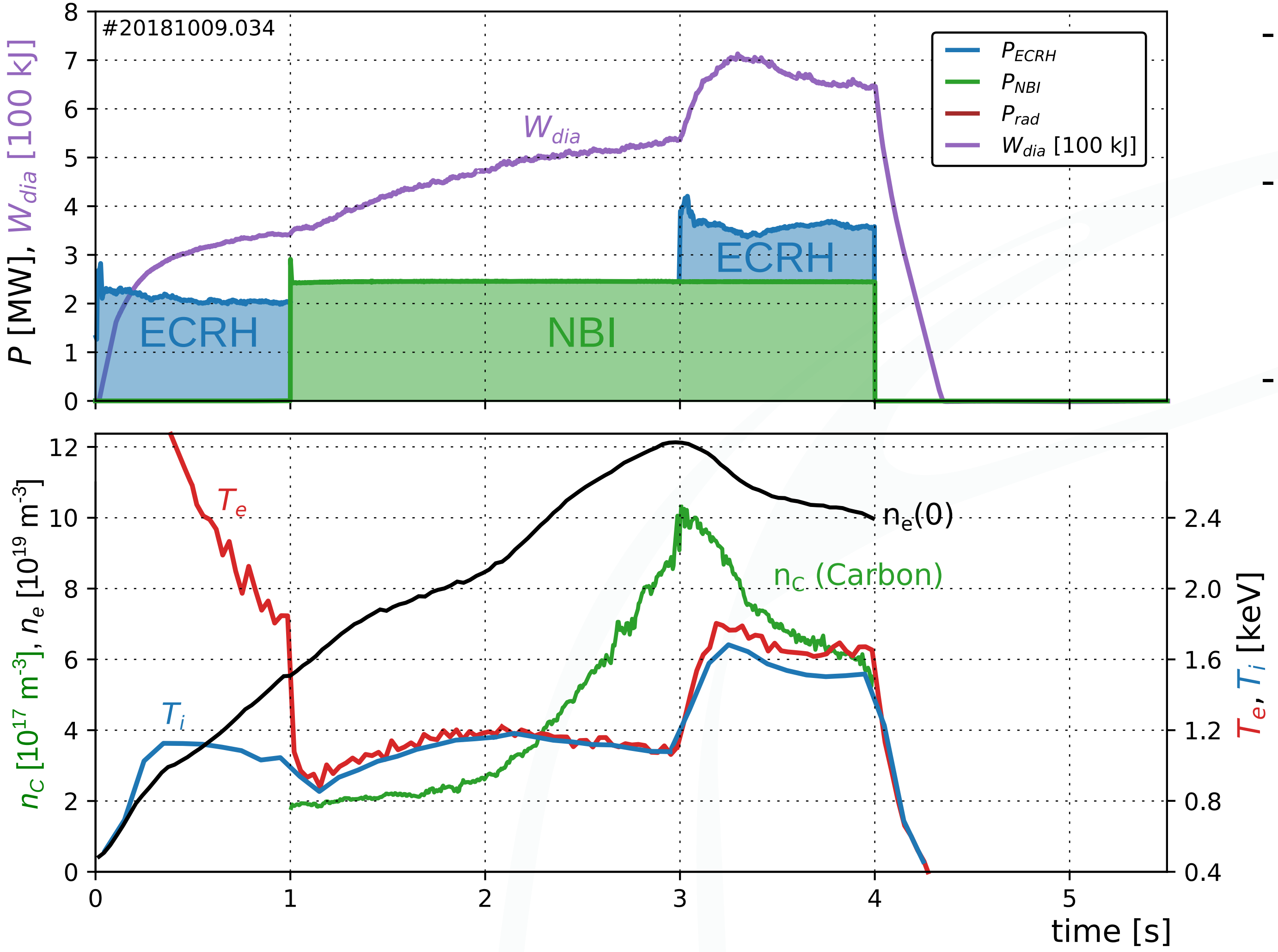


- Pure NBI has reduced χ_{eff}, but much broader power deposition results in similar ∇T_i. (and T_{i0})
- Mixed NBI with low PECRH maintain $\chi_{eff} \sim 0.25$ and exploit it for higher ∇T_i.
- All plasmas with $a/L_{ne} > 1.0$ have lower χ_{eff}.
- Without additional ECRH, NBI plasmas can undergo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

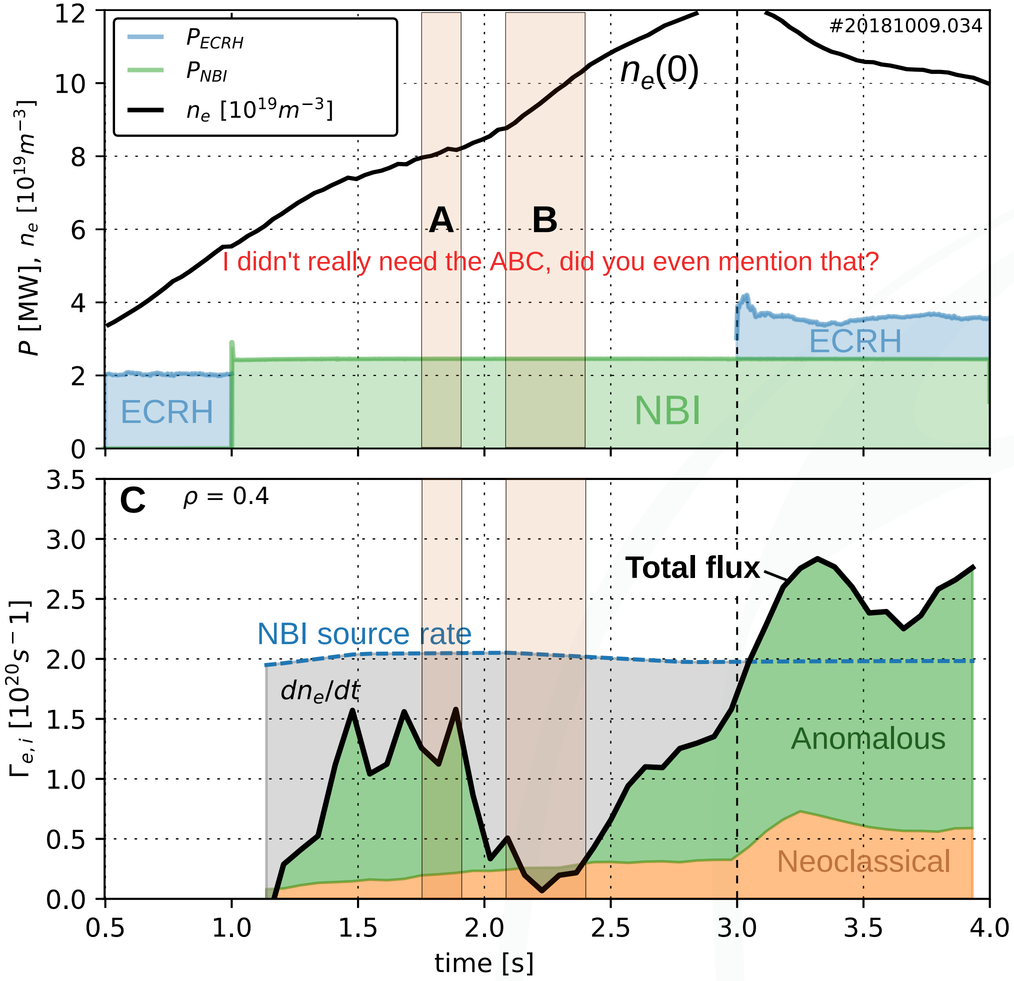
[O. Ford Nucl. Fus. 64 086067 (2024)]

Pure NBI - Particle flux

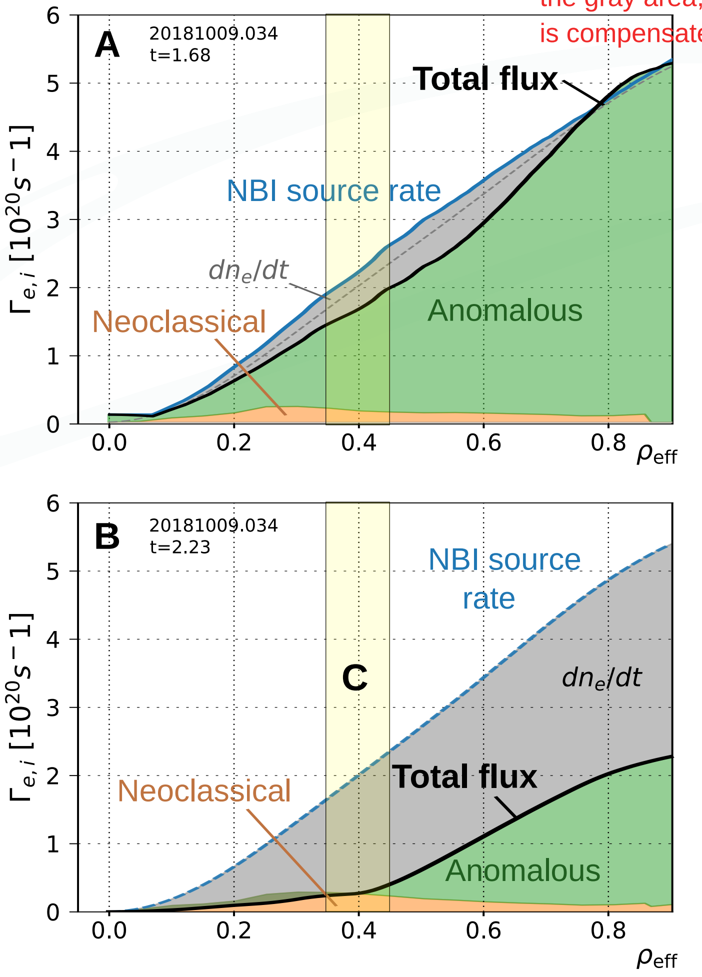
I don't like the "opposite to ECRH case" here as, while the flux might be in the other direction, the underlying transport might just be the same. Using "opposite" feels like it indicates that there is a change in transport - which we can not really say, right?

- 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.

To me, based on the explanation you gave in the rehearsal, it was not clear what the actual change in transport is. This is the gray area, right? Maybe phrase it that "most of the NBI fueling is compensated by an anomalous flux" or so.



I didn't really need the ABC, did you even mention that?



- 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)]

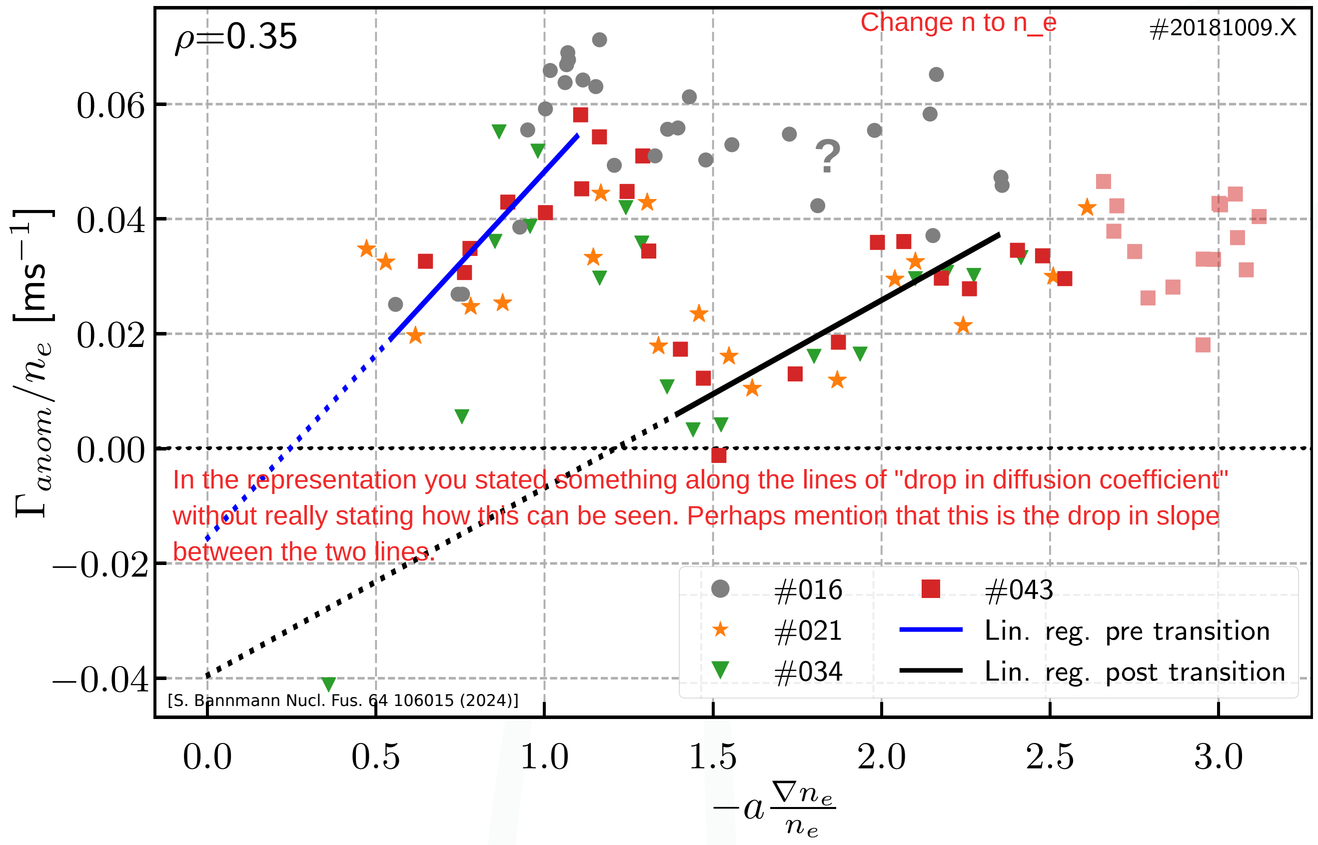
Pure NBI - Particle transport

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

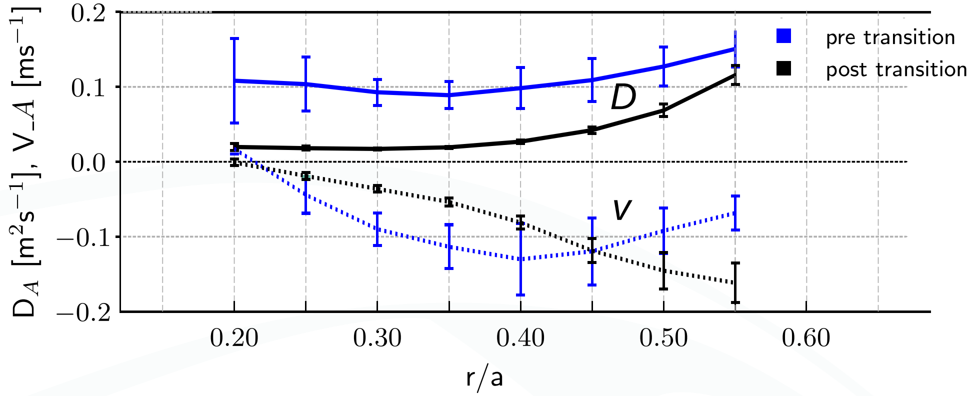
∇n_e is changing. What is just an 'expected' reponse to this?
--> Decompose into diffusive *D* and convective *v*.
- Indicates two phases of ~consistent *v, D,* with significant drop of *D* at a/L_n ~ 1.3.

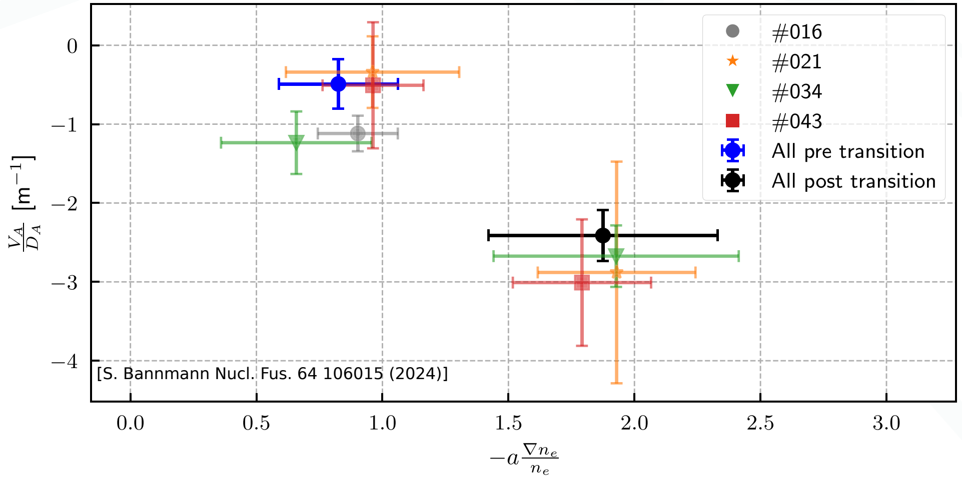
$$\frac{\Gamma_{anom}}{n} = -D_A \frac{\nabla n}{n} + V_A$$

Looks super weirdly formatted
Be consistent between "anom" and "A"
Change n to n_e



In the representation you stated something along the lines of "drop in diffusion coefficient" without really stating how this can be seen. Perhaps mention that this is the drop in slope between the two lines.

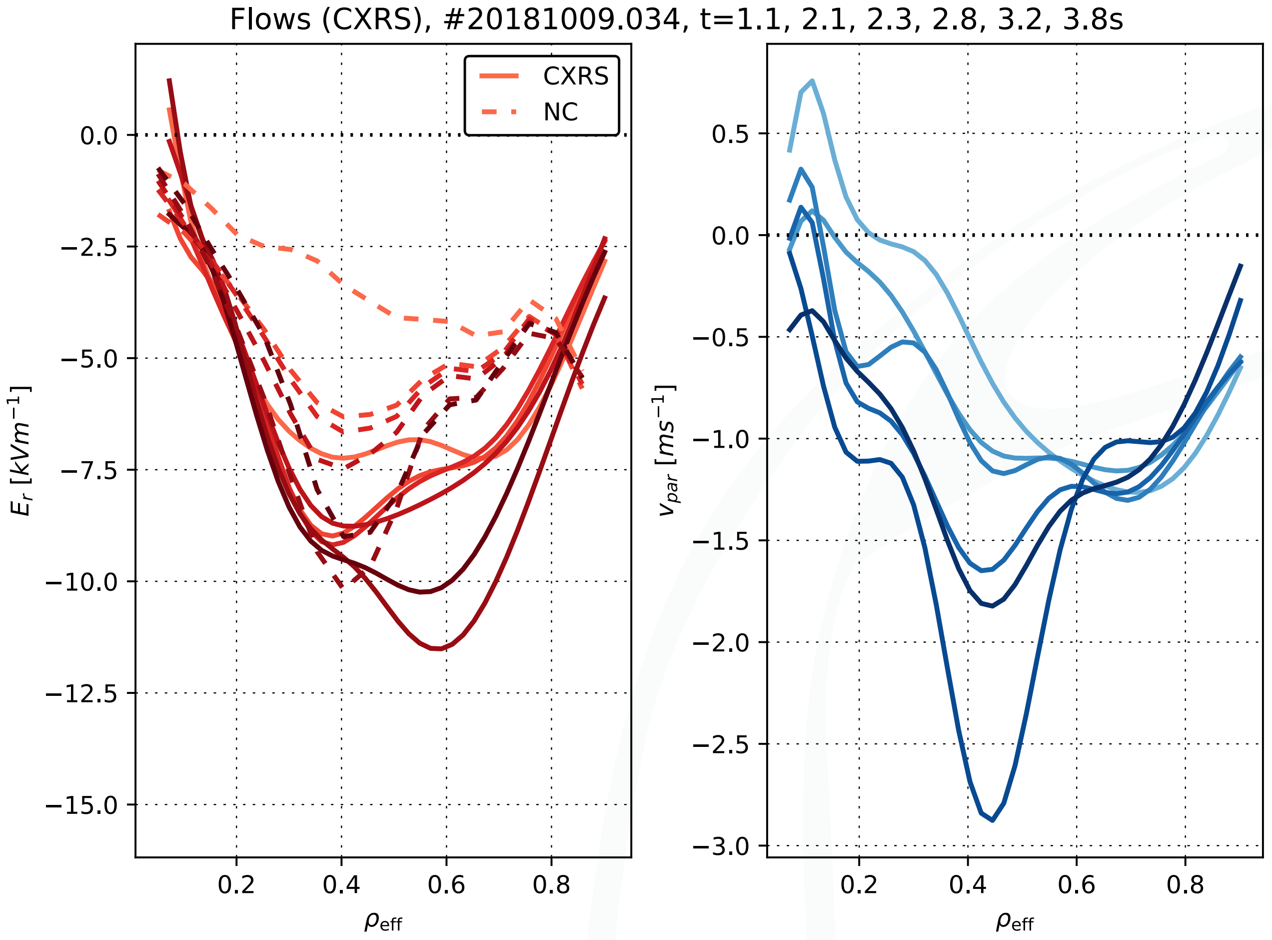


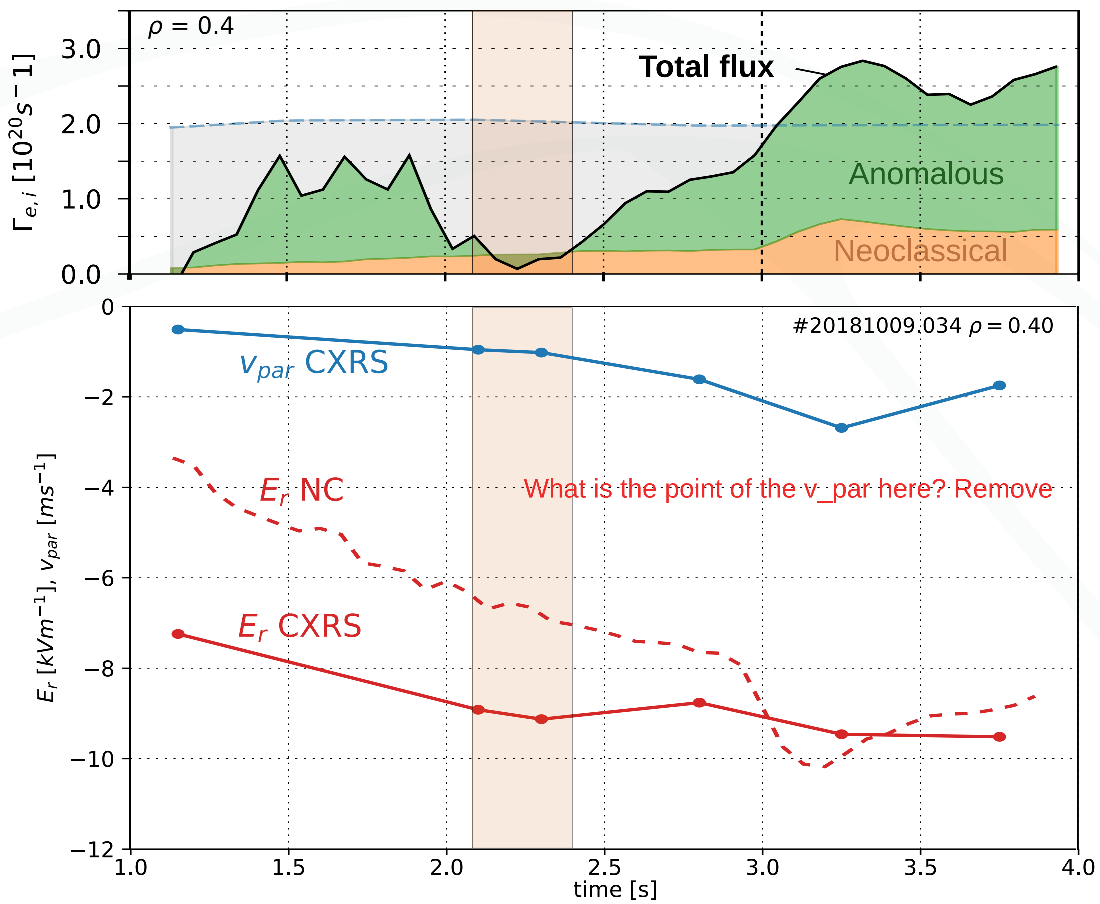


- Threshold not yet reproduced in modelling. (Range not covered by original STELLA study [H. Thienpondt, Phys. Rev. Res. 5, L022053 (2023)])

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)

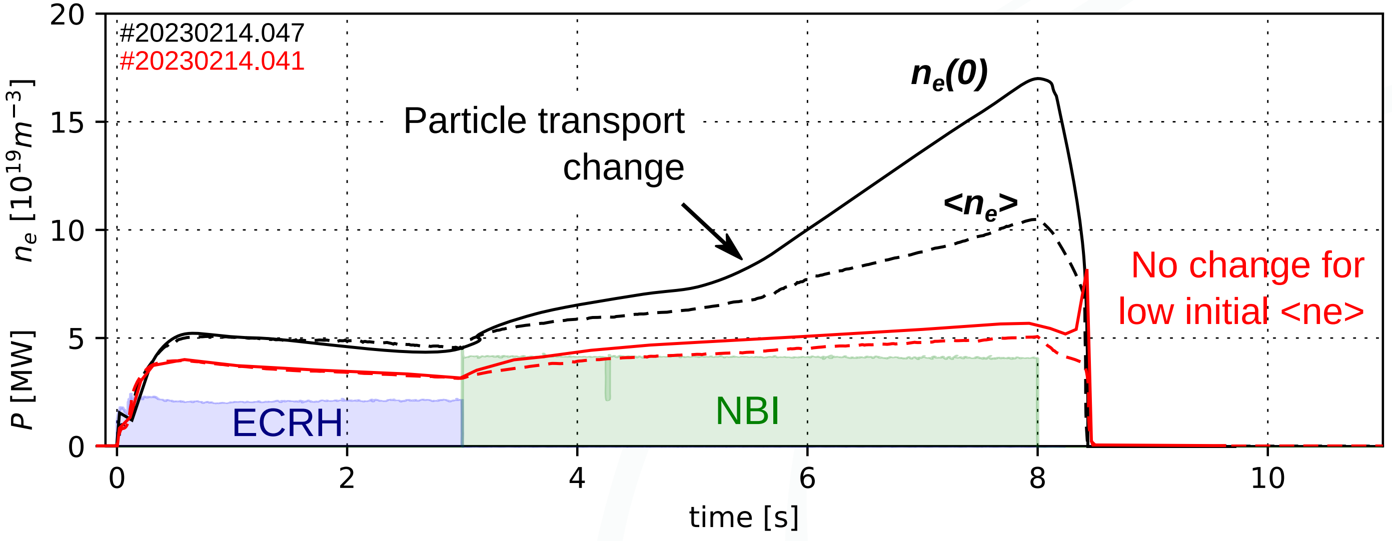


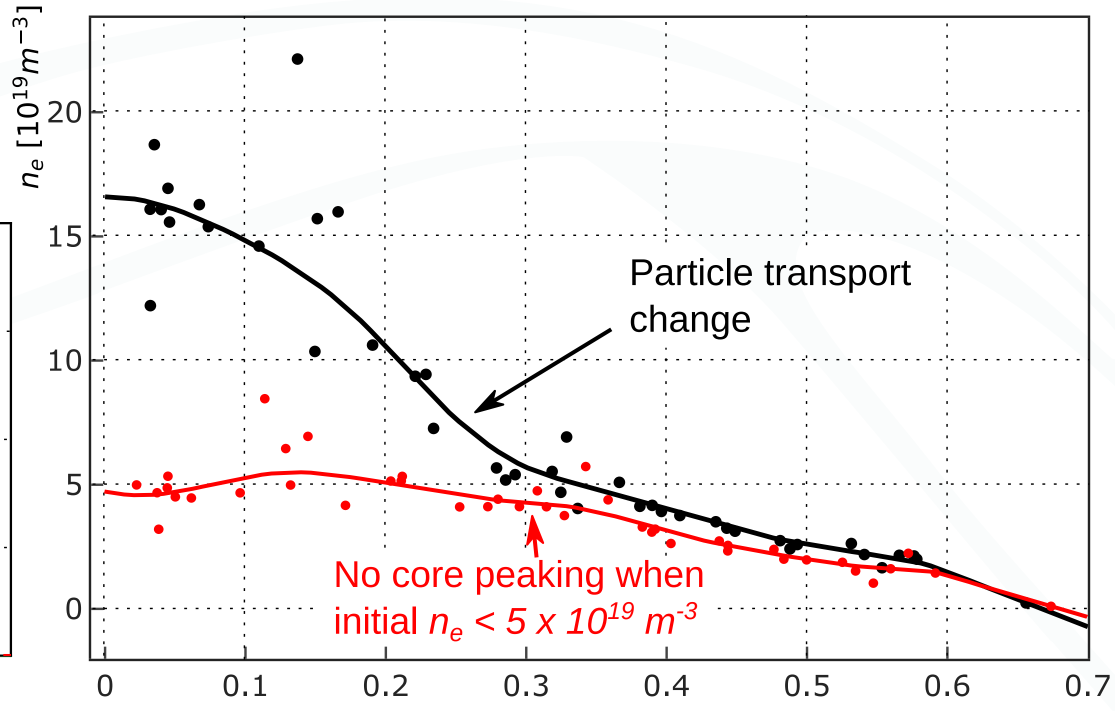


OP2.1 (2023) campaign

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:



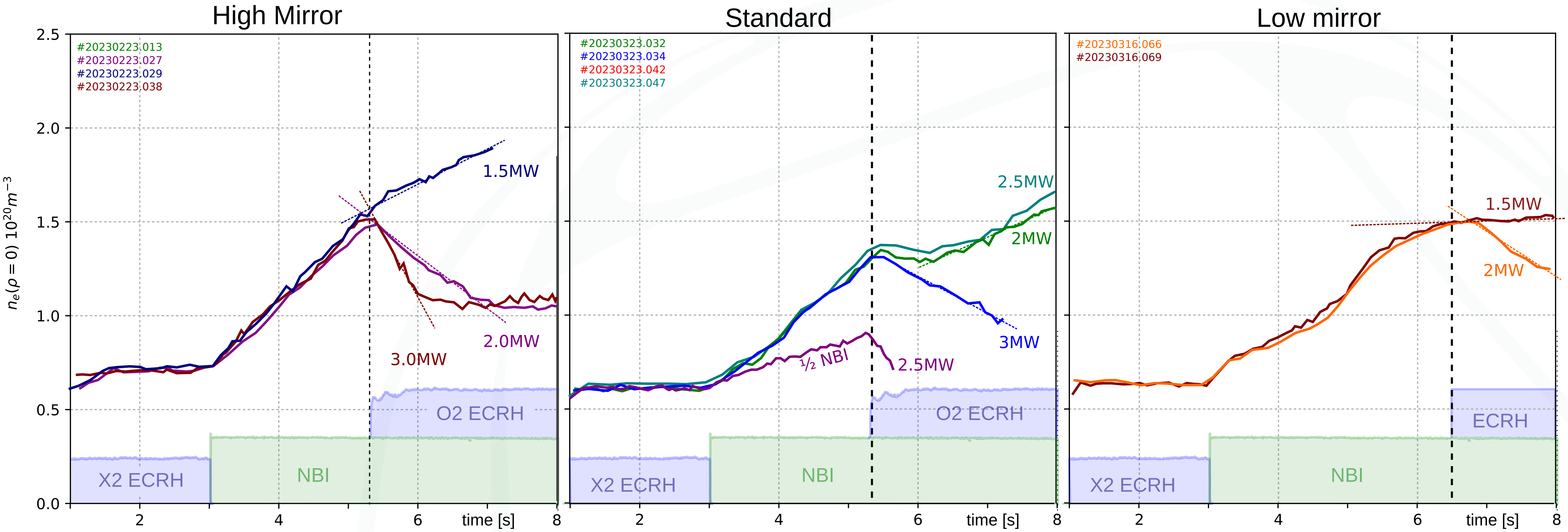


ECRH power and configuration scans

In the 2022/3 campaign:

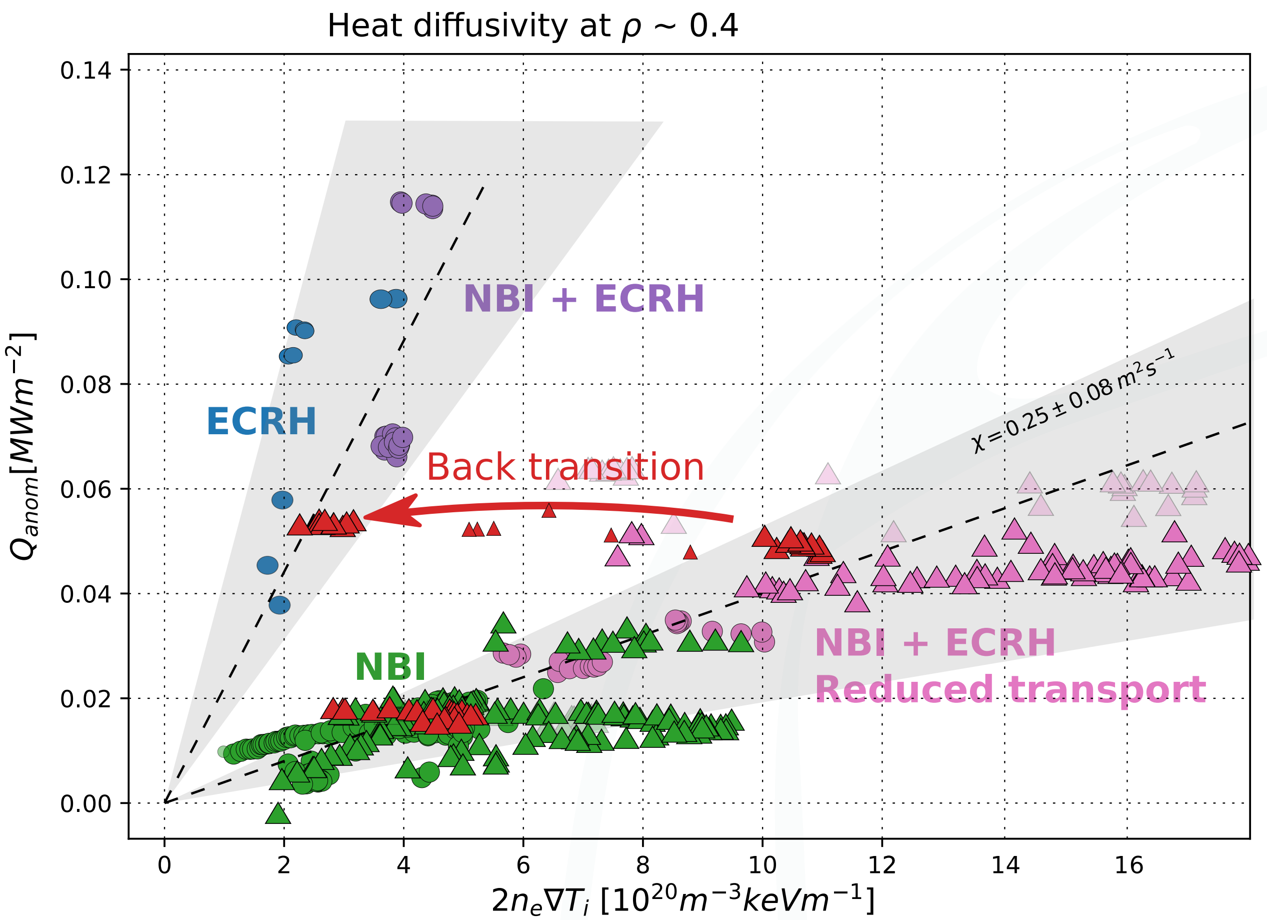
3) Scans of ECRH power at fixed reintroduction time - varying pump-out effect.

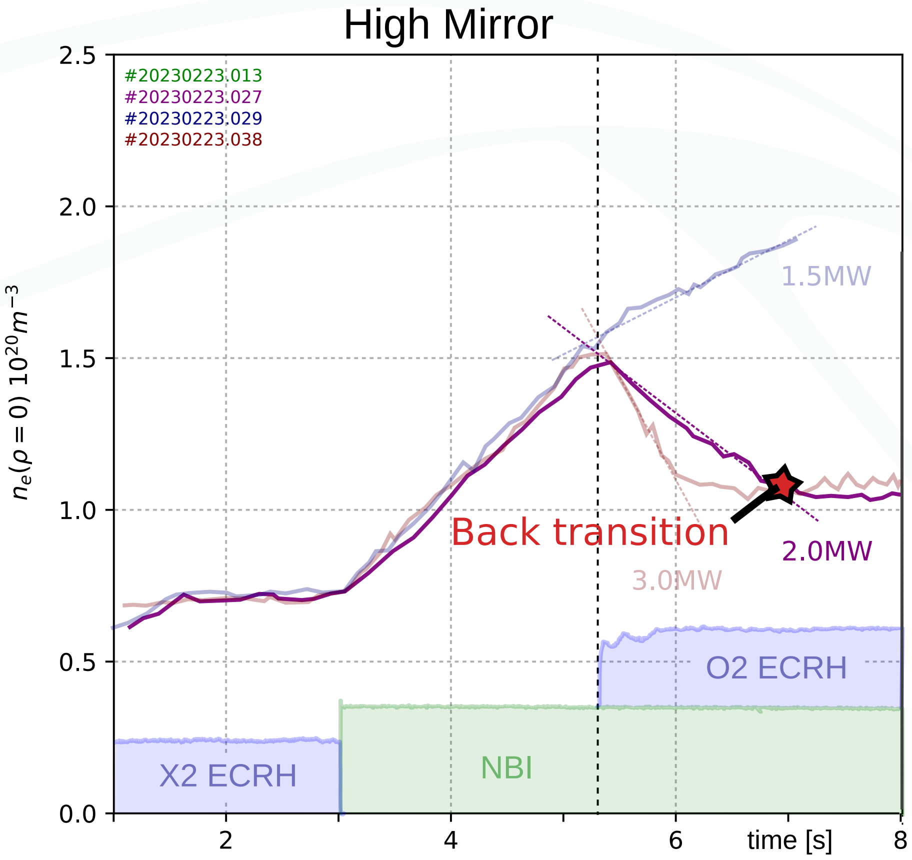
4) (Low - mid - high) -mirror configurations:
- Density rise in NBI phase almost identical.
- Different pump-out effect of ECRH



Balancing ECRH power

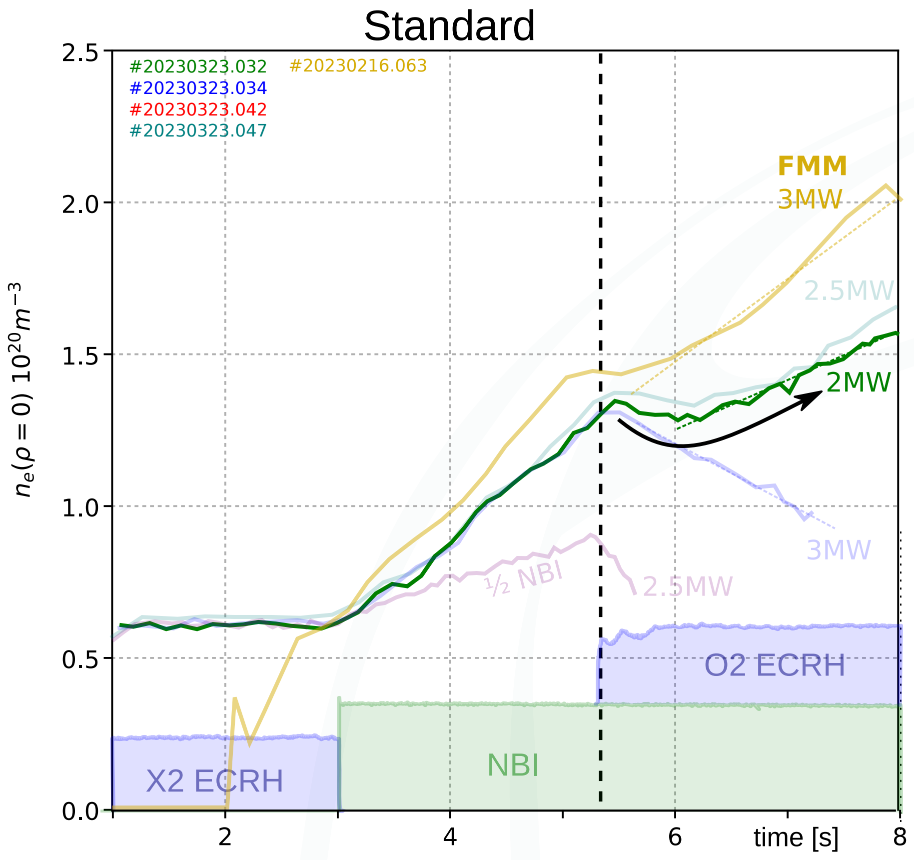
2023 experiments pushed to higher ECRH power to take advantage of reduced heat diffusivity
- χ_{eff} ~ 0.25 maintained despite x2 higher Q_{anom}. (as high as some turbulent ECRH-only shots)
- Spontaneous back-transition to high transport observed as ECRH reduces density gradient.





ECRH control

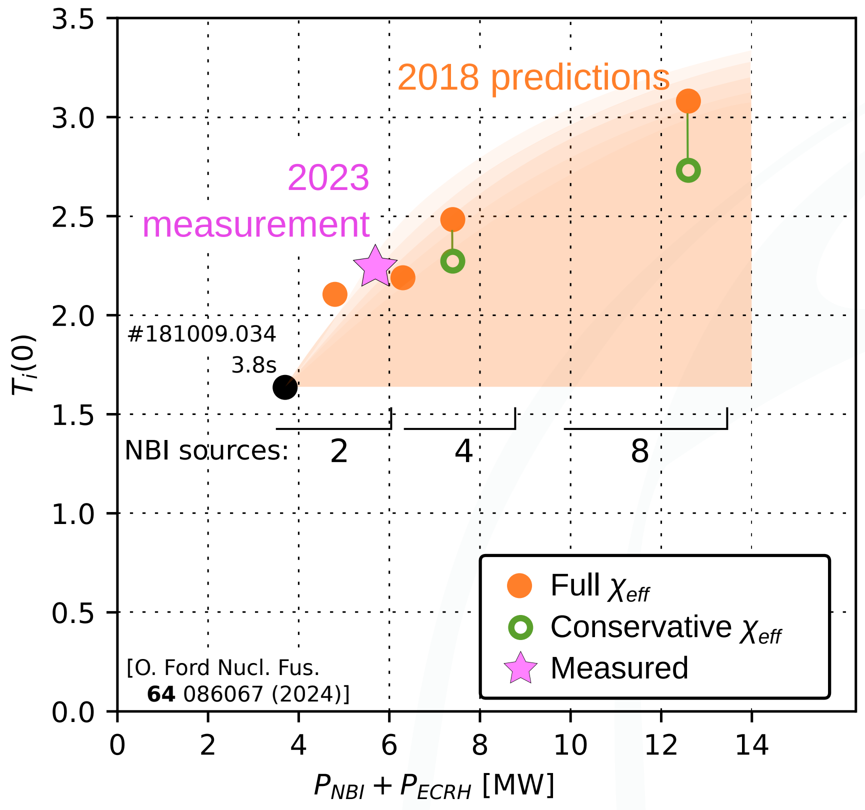
Challenge: Needs dynamic active control of ECRH level:
- Too much --> Loss of density gradient --> back-transition
- Too little --> Too high density, low P/n, impurity accumulation --> radiation collapse.

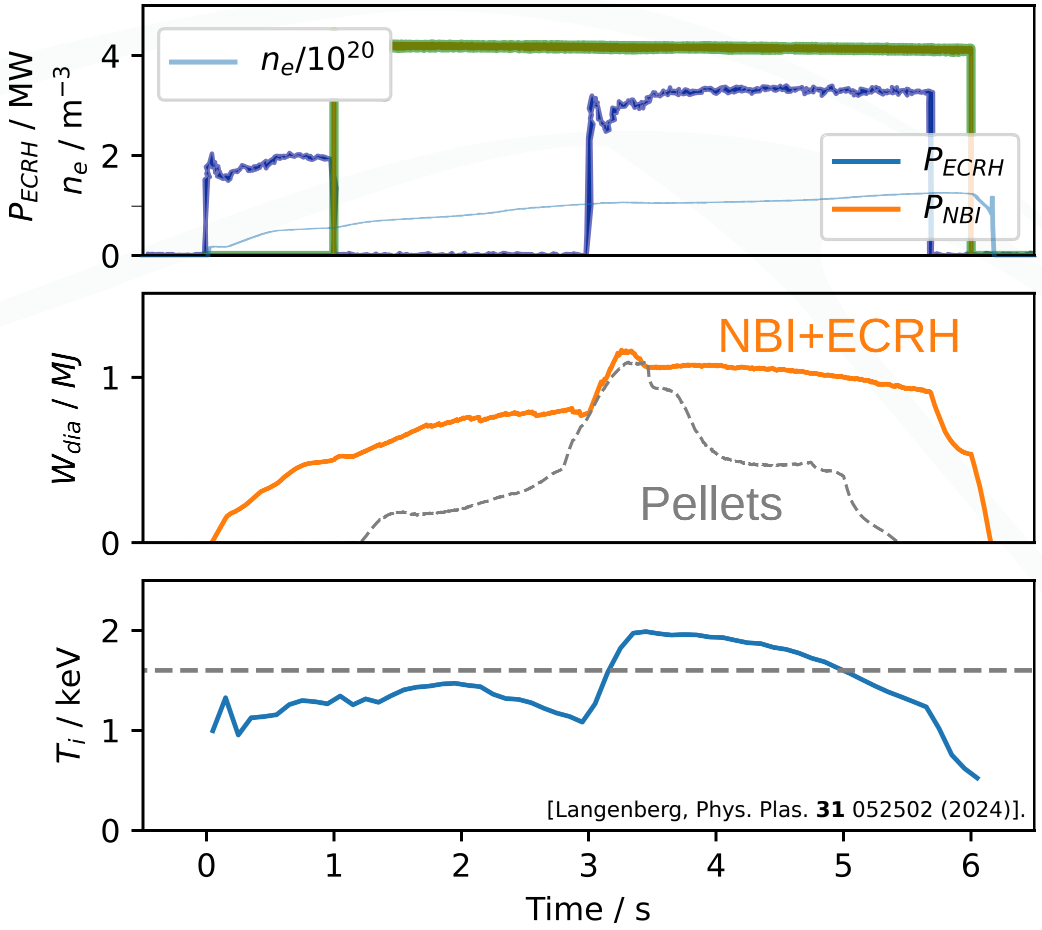


Achieved performance

- 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 at $a/L_{n_e} \sim 1.3$ during pure NBI, leading to accelerated peaking. Impurity transport is fully neoclassical from this point on. As a shameless self plug, you can reference me here

- 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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Some text

Most interesting part of the whole presentation. I'm still trying to grasp this breathtaking content