Combined NBI+ECRH heating and impurity handling

Presented by Oliver Ford on behalf of the W7-X Team

W7X Program Workshop. 7th September 2022

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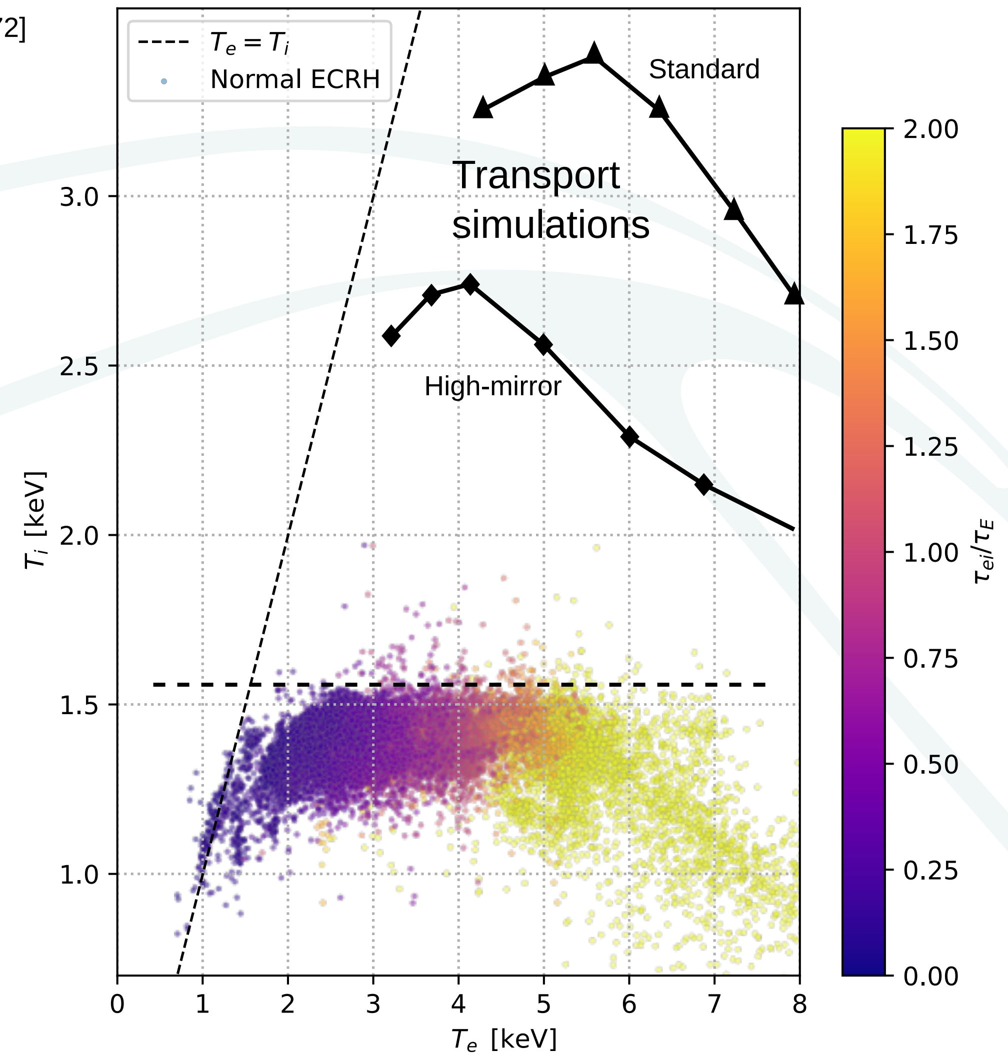
Ti clamping in OP1.2b

In OP1.2, most plasmas were dominated by strong turbulence, limiting T_i < *1.5keV*.

Three effects were found to be responsible: [M.N.A. Beurskens et al 2021 Nucl. Fusion 61 116072]



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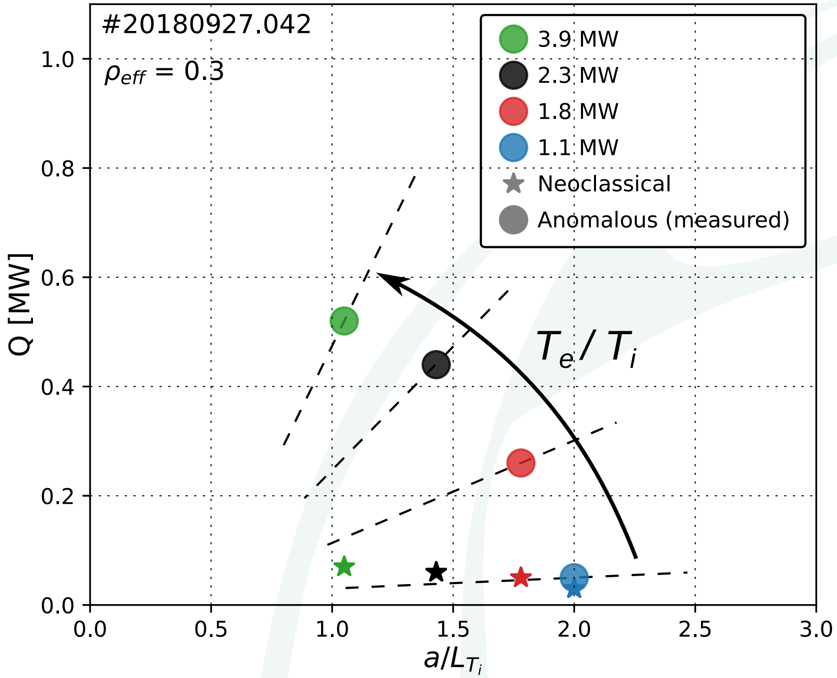
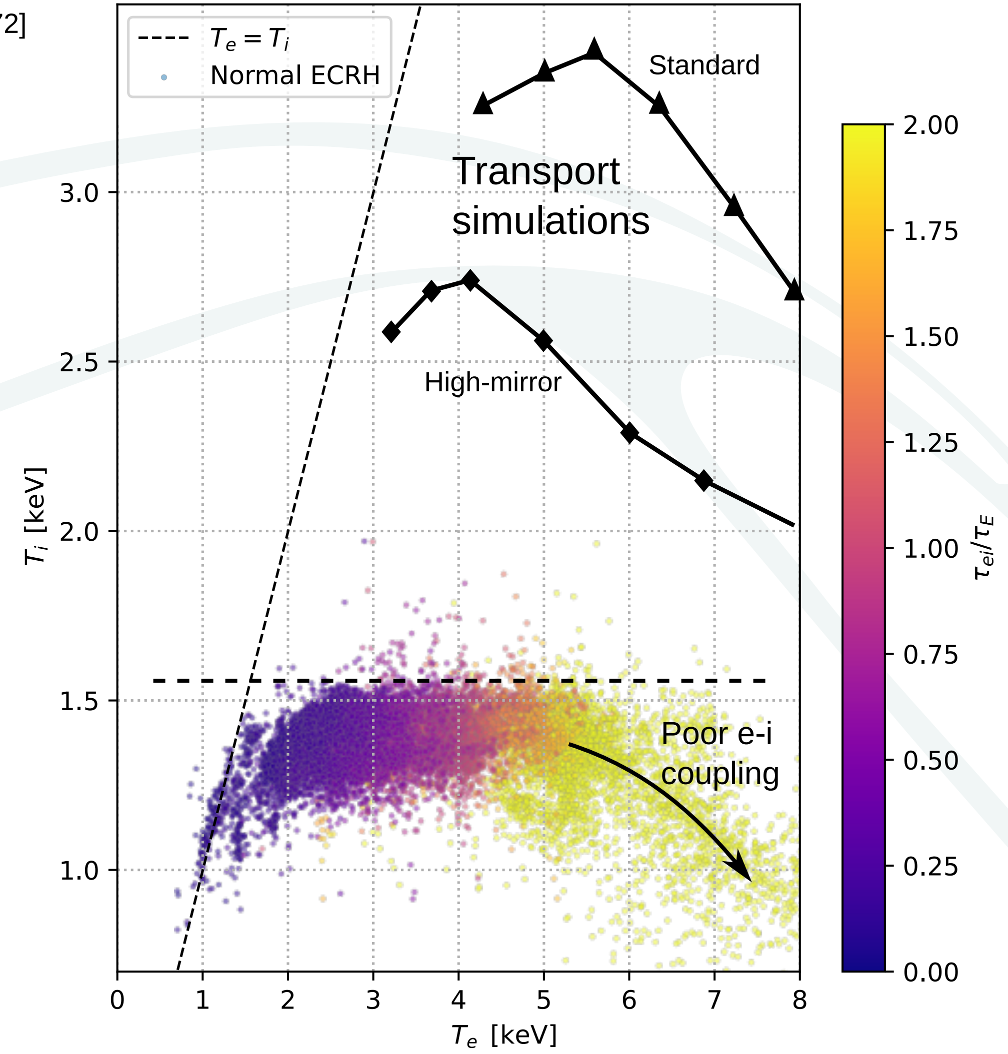
1) Poor collisional coupling to ions at large (T_e - T_i).
2) Strong profile 'stiffness' due to ITG turbulence.
3) Increase in ITG with T_e / T_i exacerbates stiffness.





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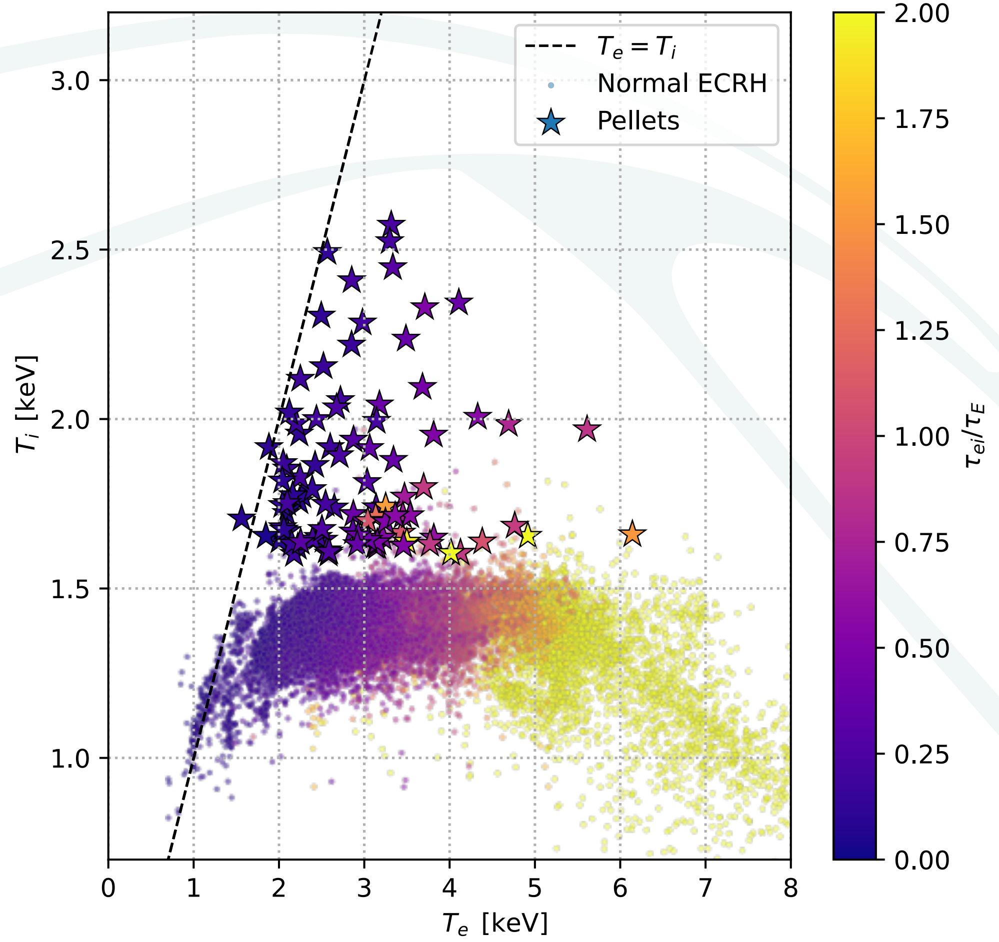

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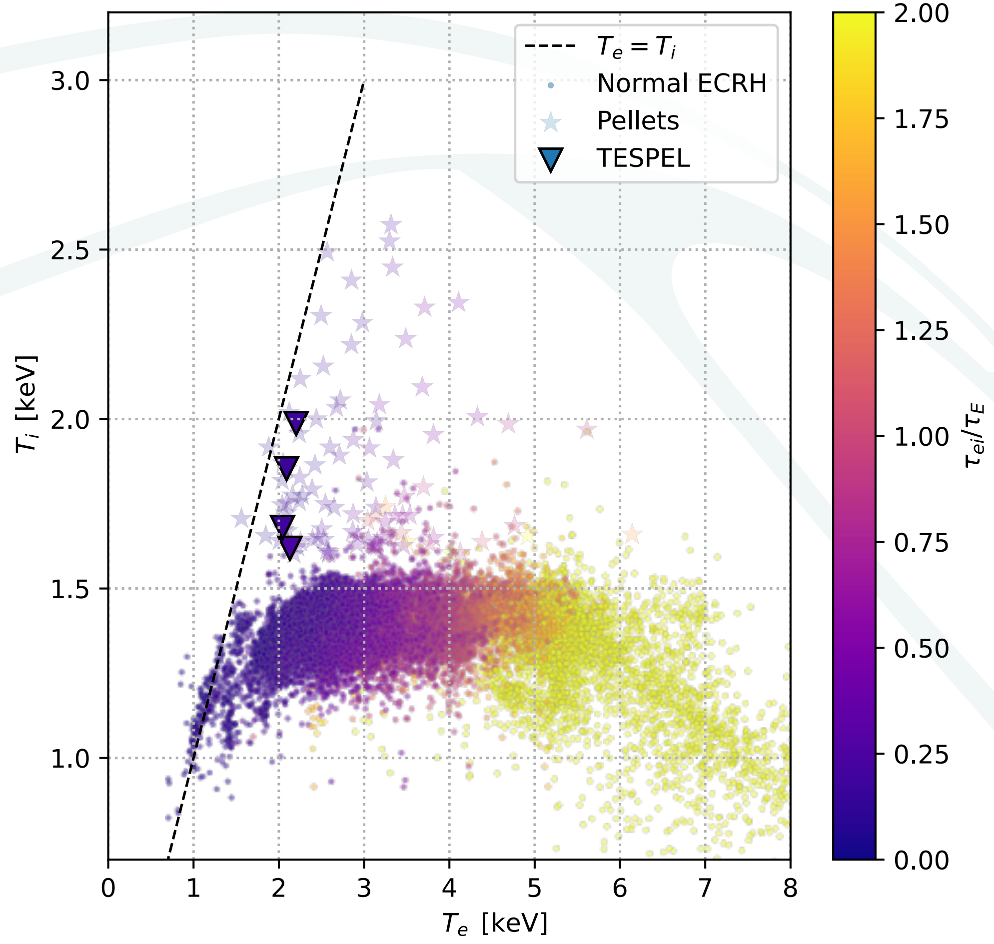

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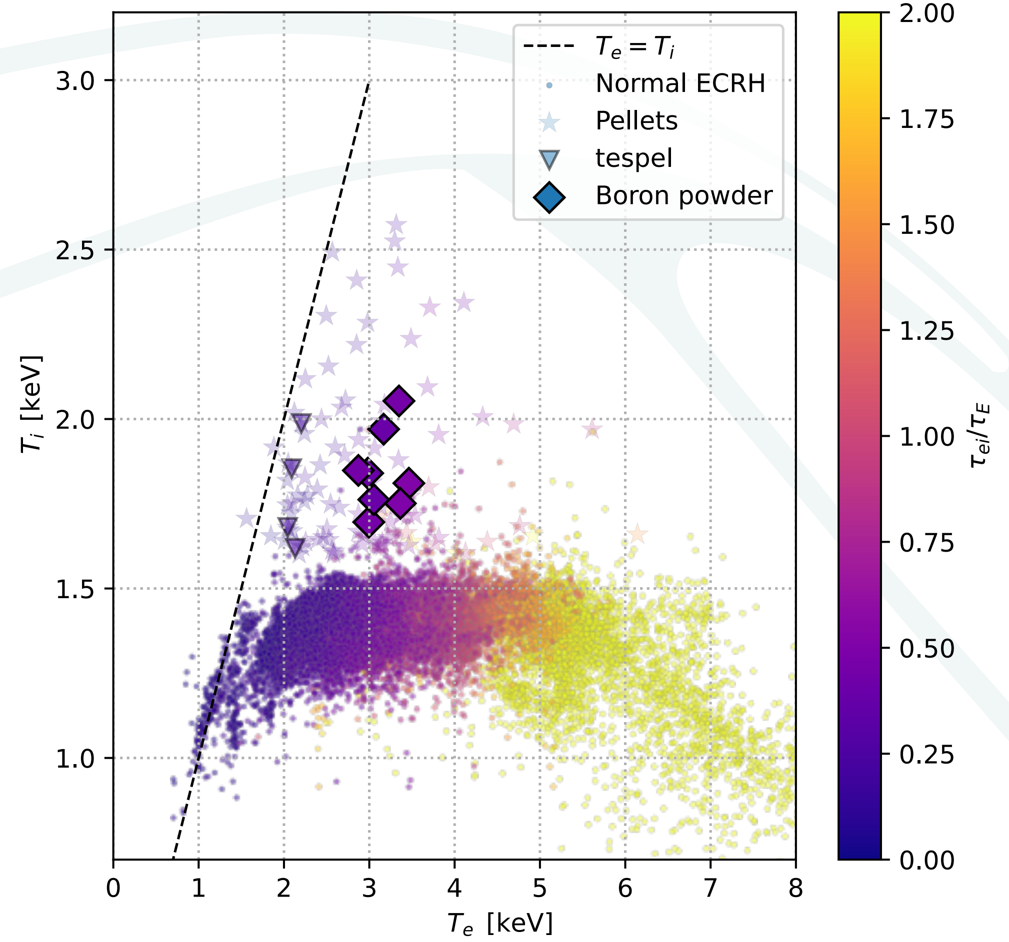

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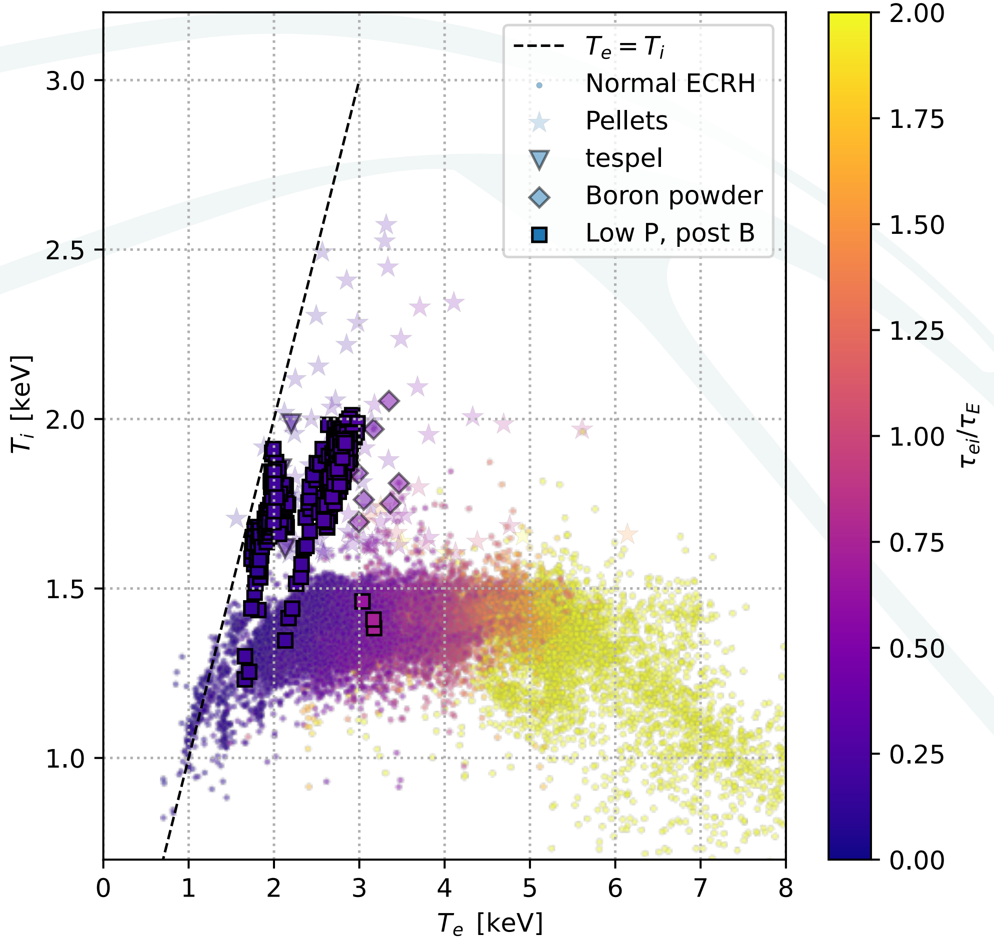

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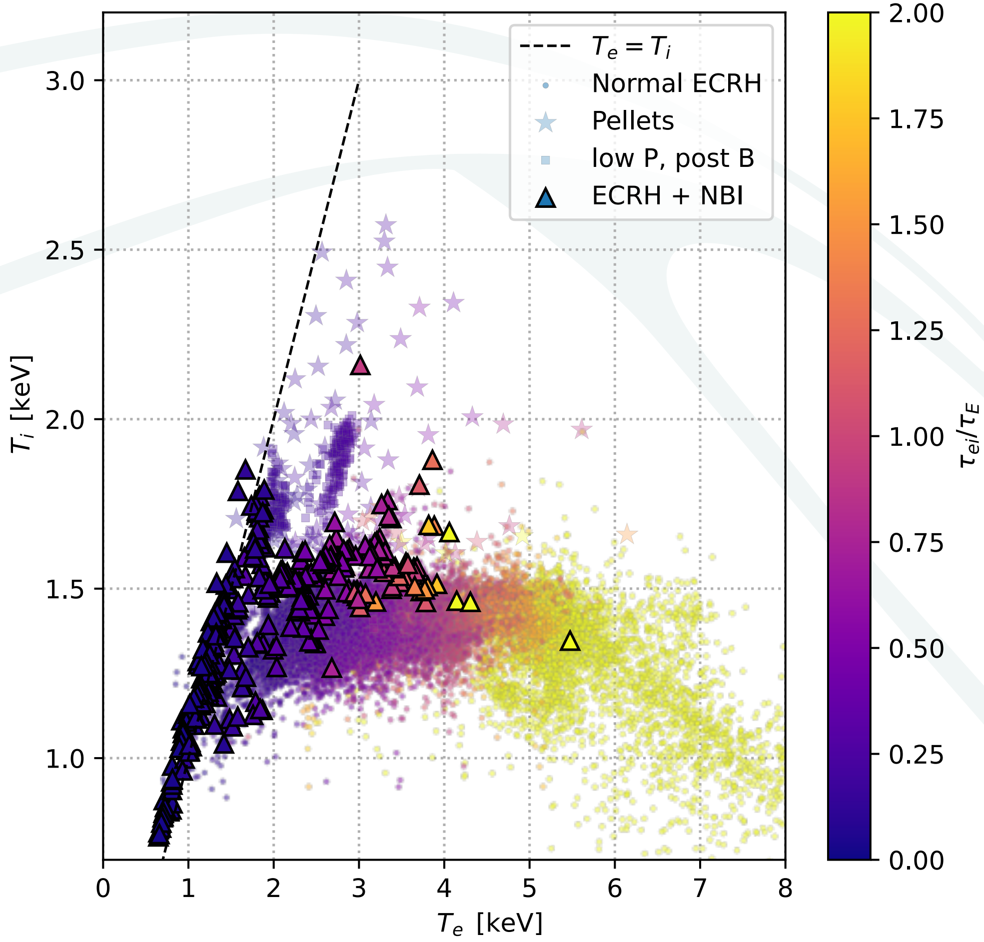

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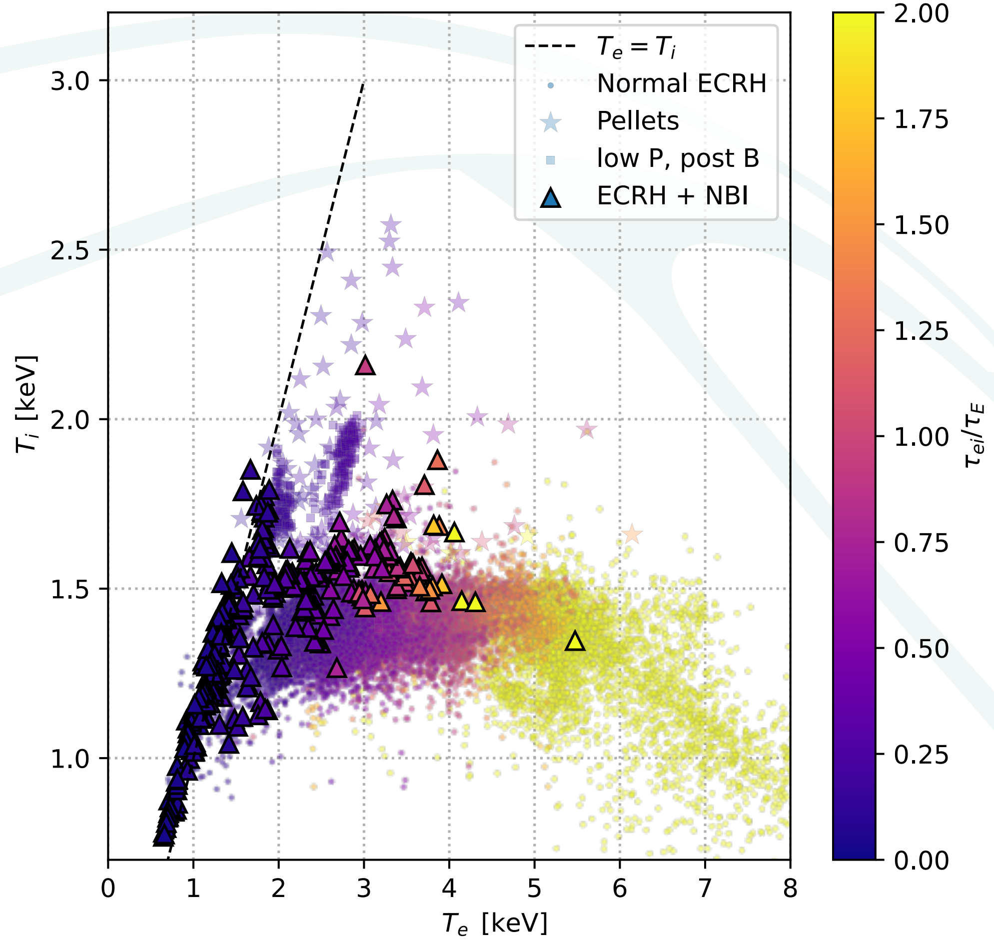
Evidence of turbulence reduction from:
- Reduced heat transport and T_i > 1.5kV.
- Reduced impurity transport and some accumulation.
- Reduced fluctuation levels.

Cause most likely related to either ∇n_e or T_e/T_i.

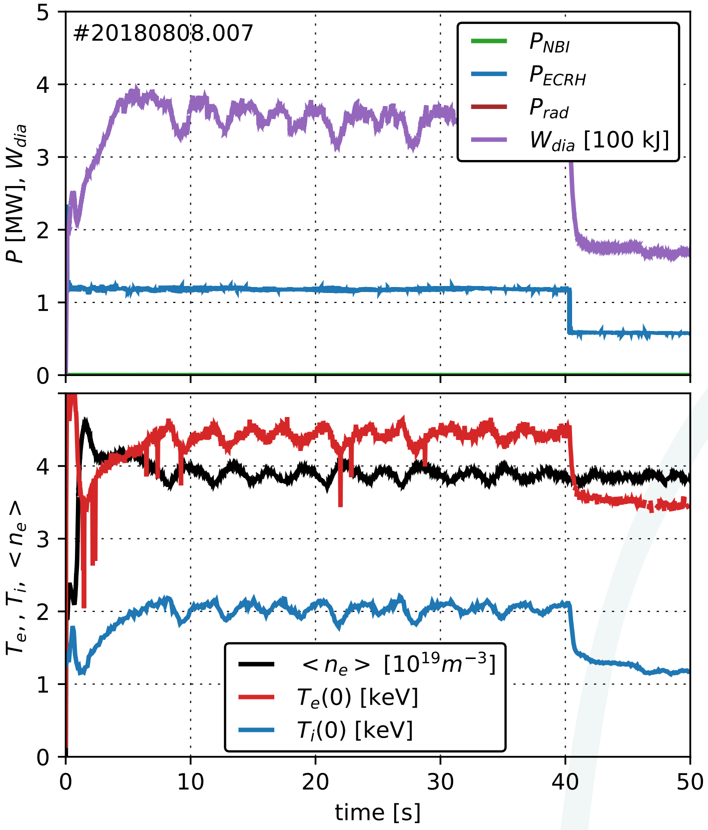
Candidates for:
T1D1: *High plasmas performance in order of seconds.*
T1D2: *Avoidance of impurity accumulation*

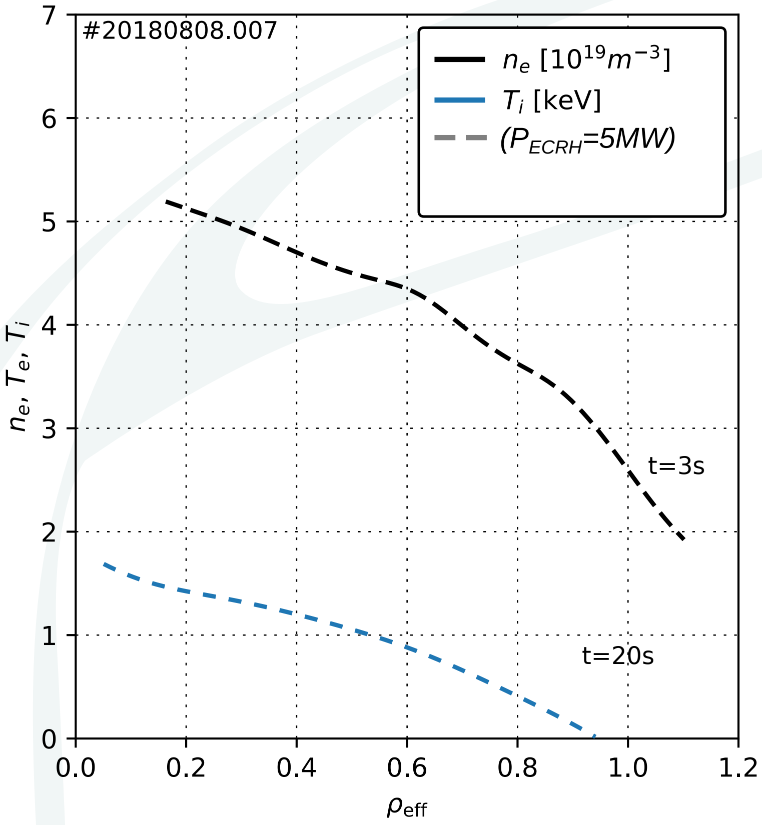
However, data was limited and the scenarios barely explored.



Low P/post-B improved performance.

Background:
- Immediately post-boronisation at low-power.
- Very slow (~5 seconds) spontaneous decrease of edge density while core remains high.
- Increase in edge T_i gradient roughly consistent with edge density gradient.
- Indications of impurity peaking from bolometry and passive spectroscopy.





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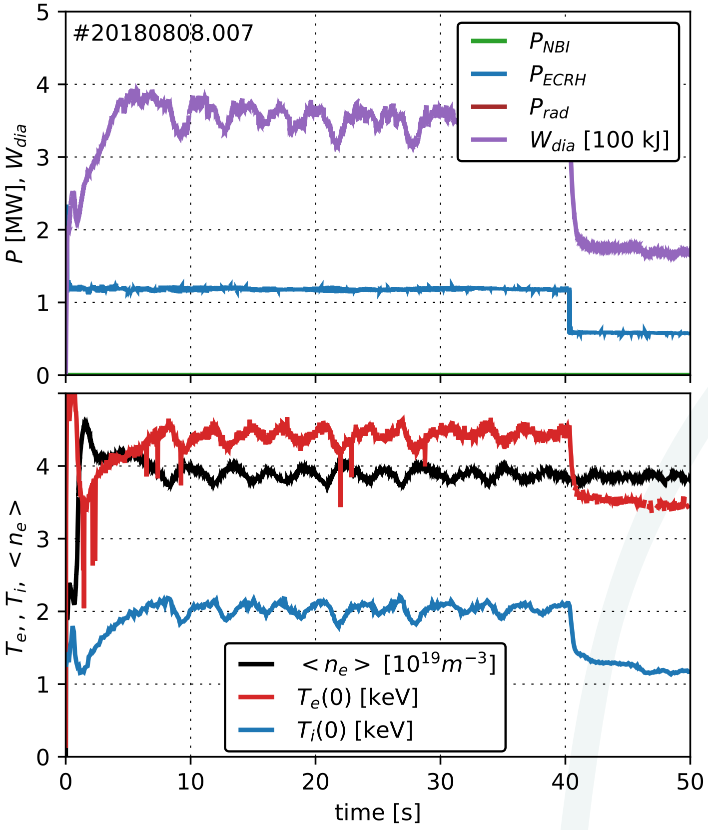

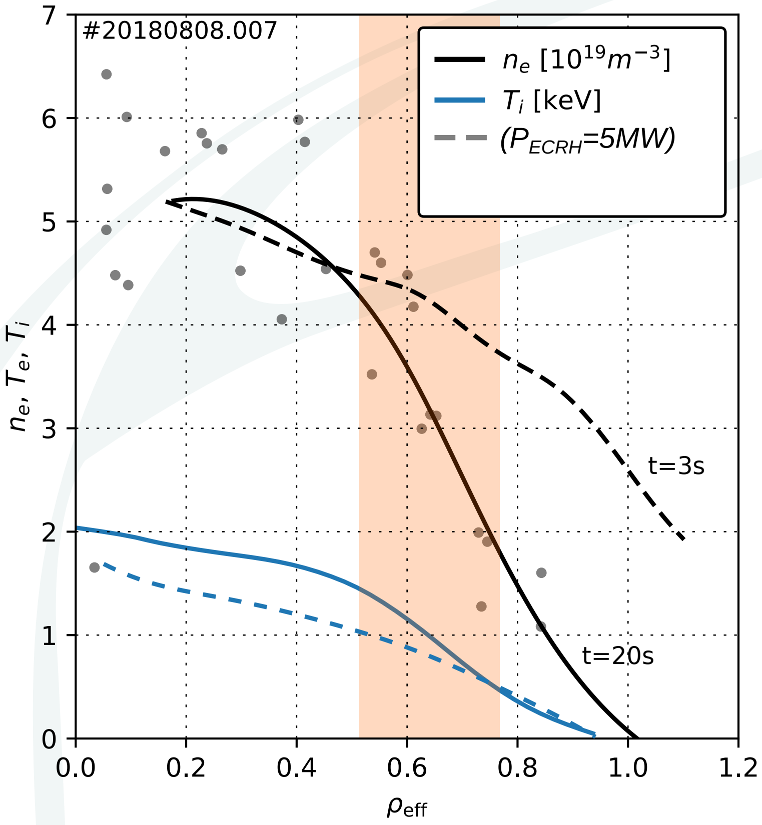

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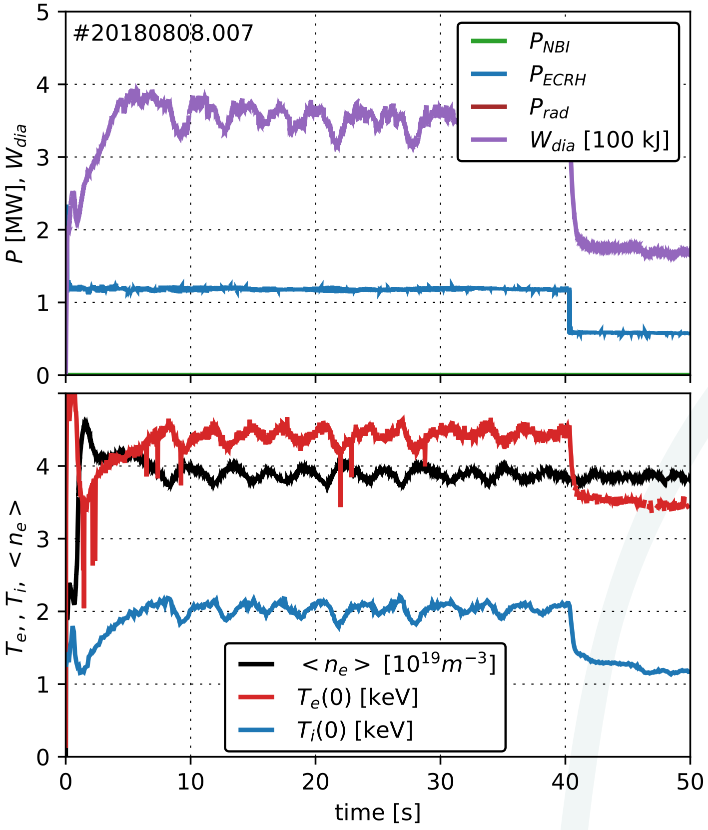

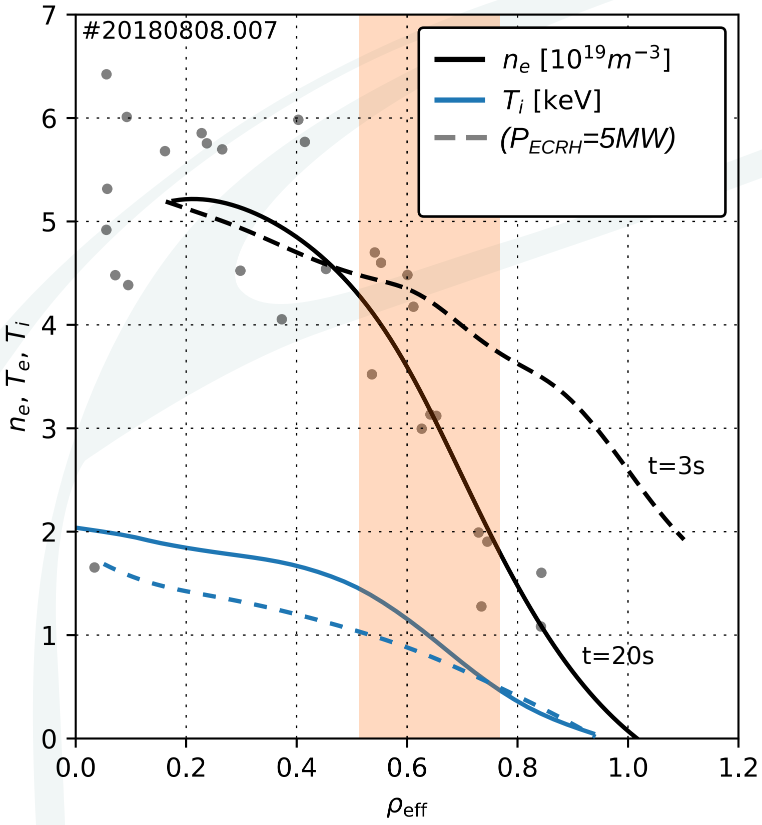

- Good candidate for steady state as already seen for 35s.
- Might not scale to high power.

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- Core profile diagnostics: CXRS Ti with NBI blips and improved Thomson scattering.
- Edge diagnostics: Alkali beam, reciprocating probe.
- Turbulent fluctuations: PCI, Reflectometer
- Impurity transport measurements (details later...)

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II: - Repeat in different magnetic configurations.
- Repeat with different gas settings, maybe add NBI.

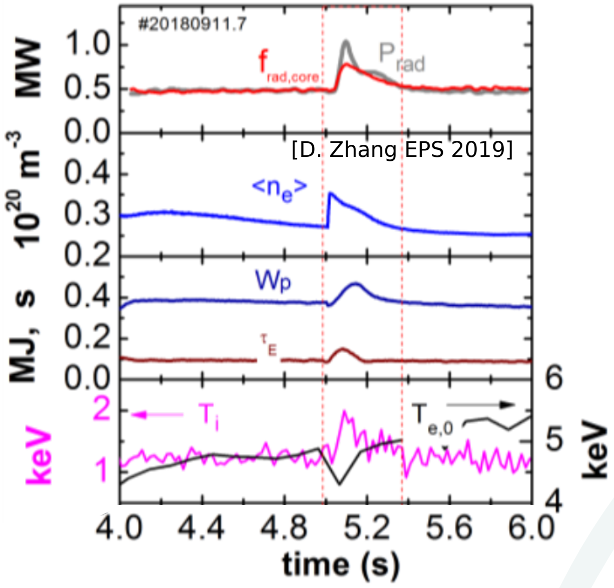
Analysis/results:

- Clear measurement of turbulence reduction from fluctuation measurements.
- Limits of scenario in power, density, boron condition etc.
- Full power+particle balance for transport assesment.
- Impurity transport.
- Understanding of edge density reduction mechanism.

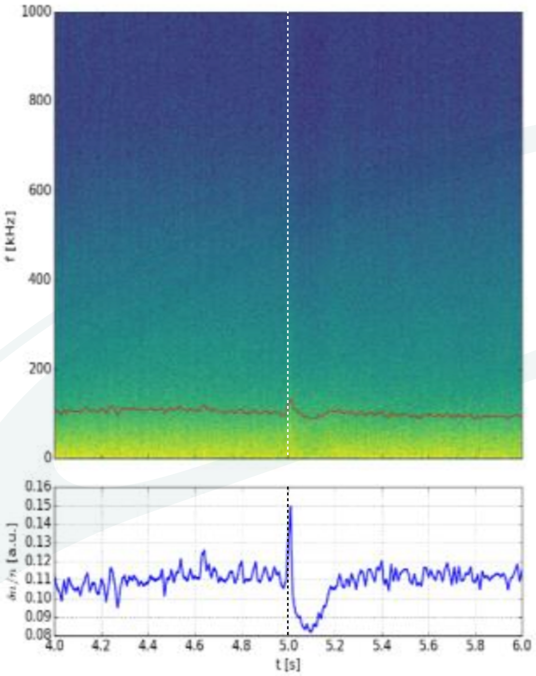
Improved performance by impurity injection

Reduced turbulence was seen due to TESPEL impurity injection...

Improved T_i, W_{dia} due to TESPEL



Reduced fluctuations (PCI) after TESPEL



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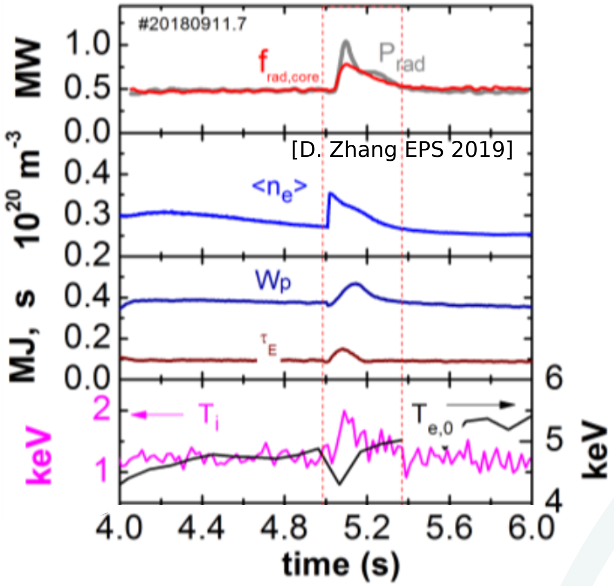

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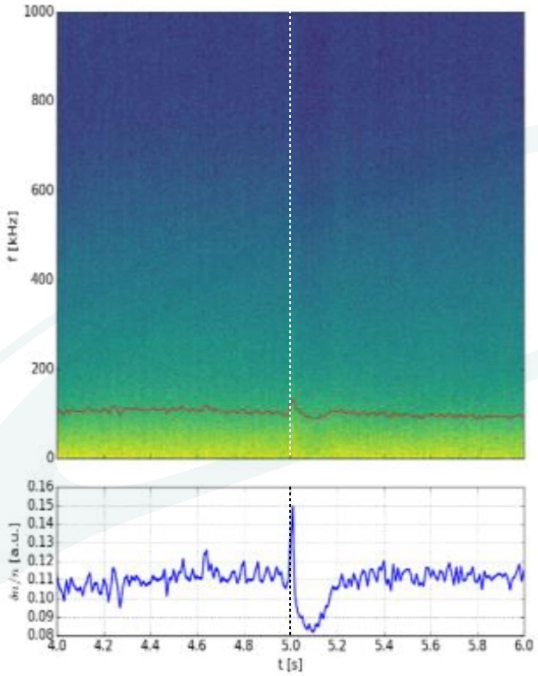

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- Examine differences with pellets induced turbulence supression.

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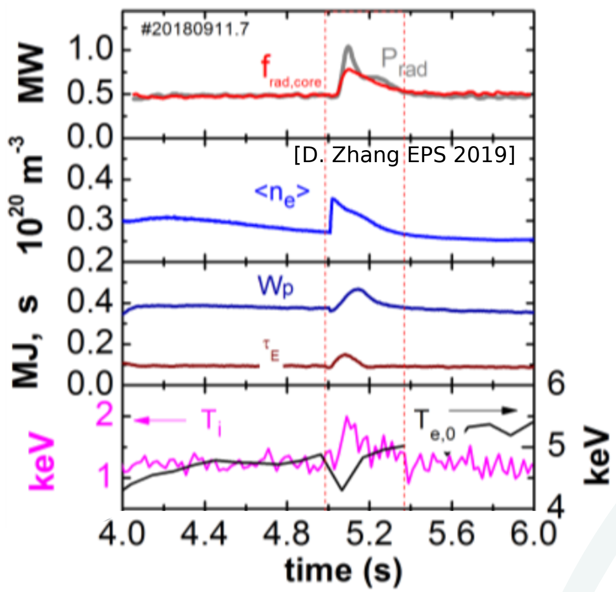

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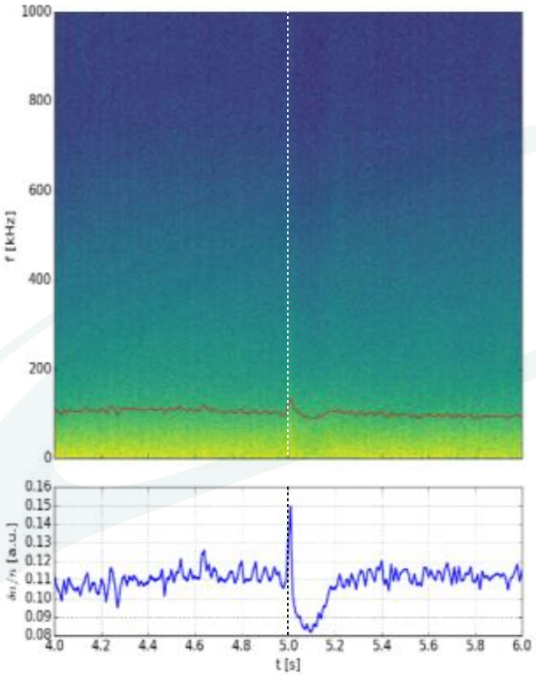
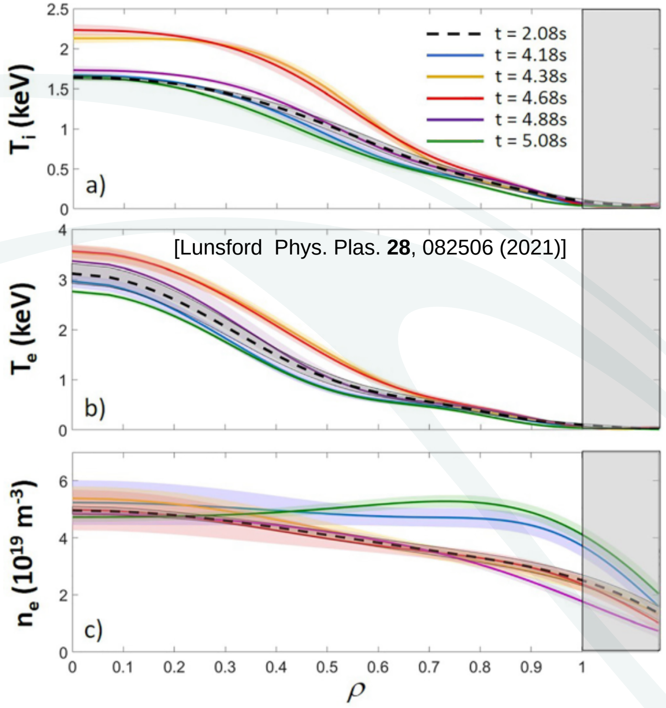


Improved Ti with boron dropper



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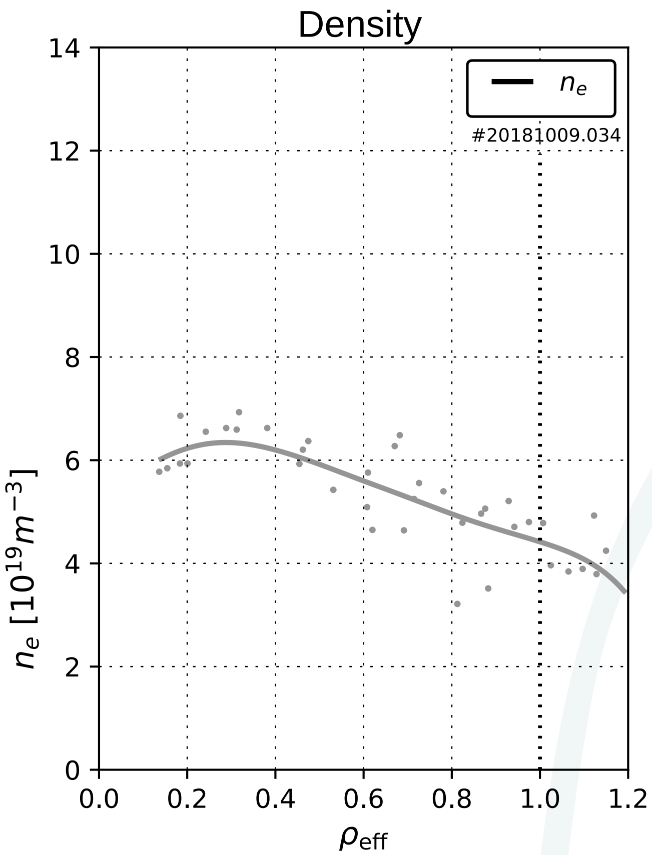
- Examine differences with pellets induced turbulence supression.

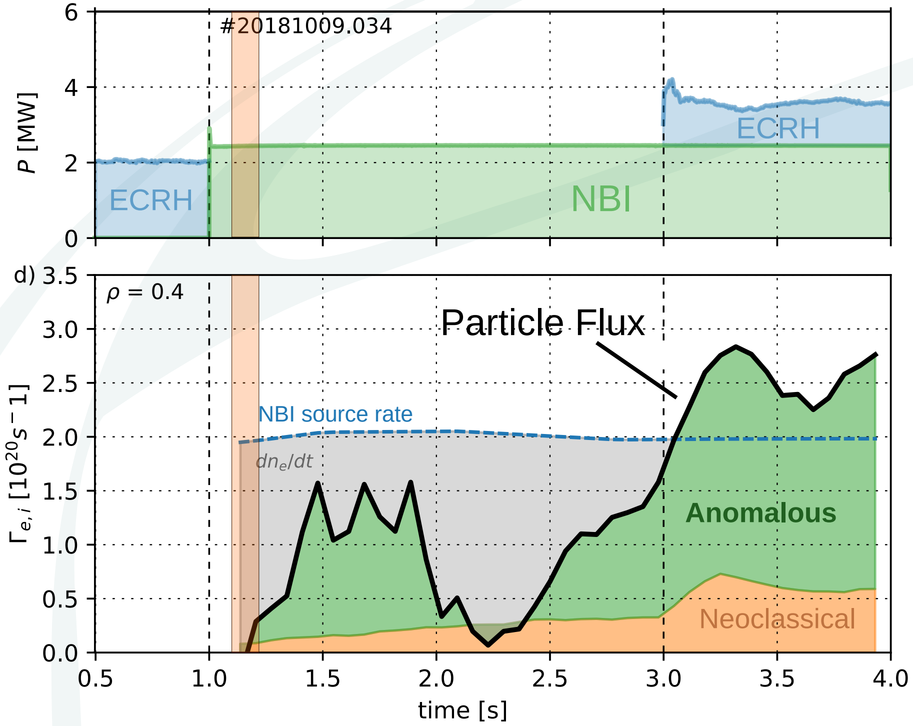
- Repeat boron powder experiments with carefully controlled injection rate and full diagnostics.
- Investigate impurity, size and background density depedence of TESPEL injections.

NBI + ECRH: Density peaking

Background:

- Pure NBI plasmas in OP1.2 showed strong density peaking.





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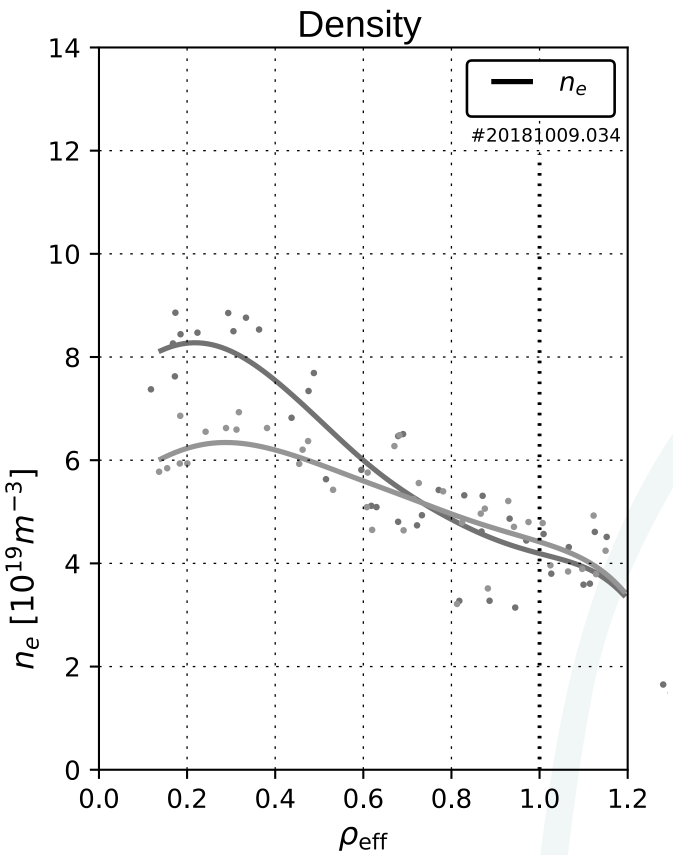

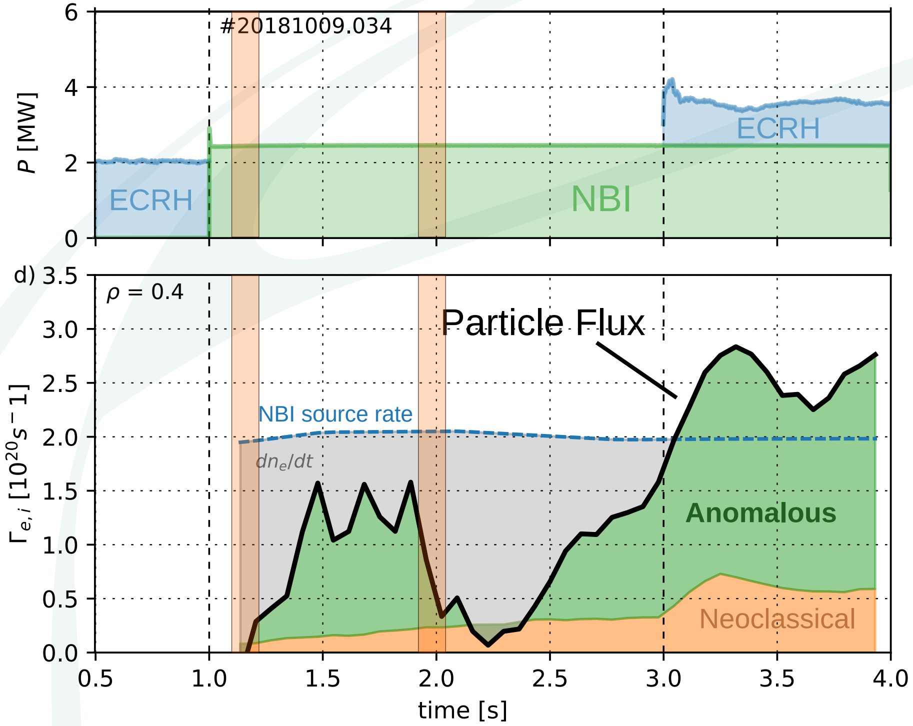

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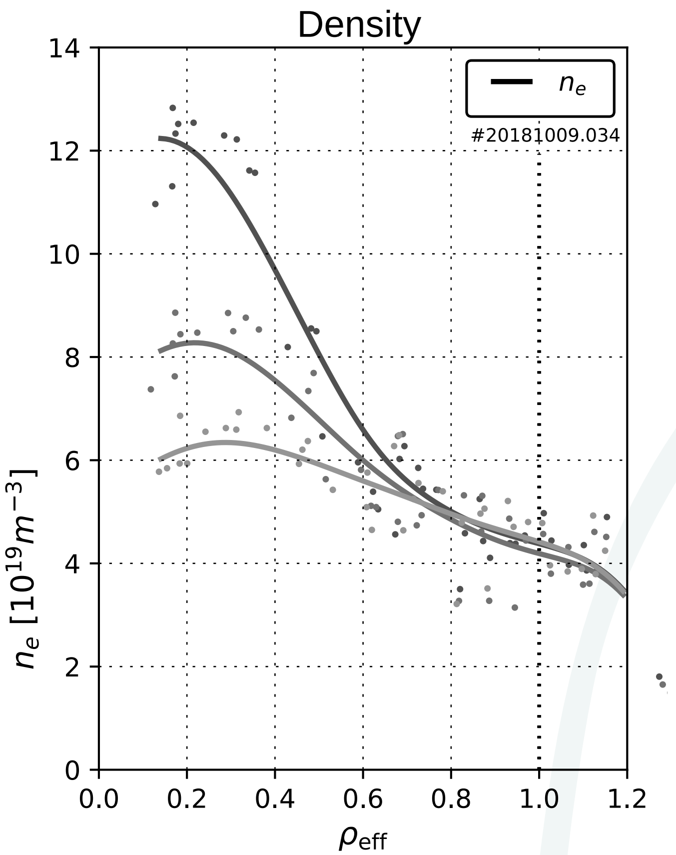

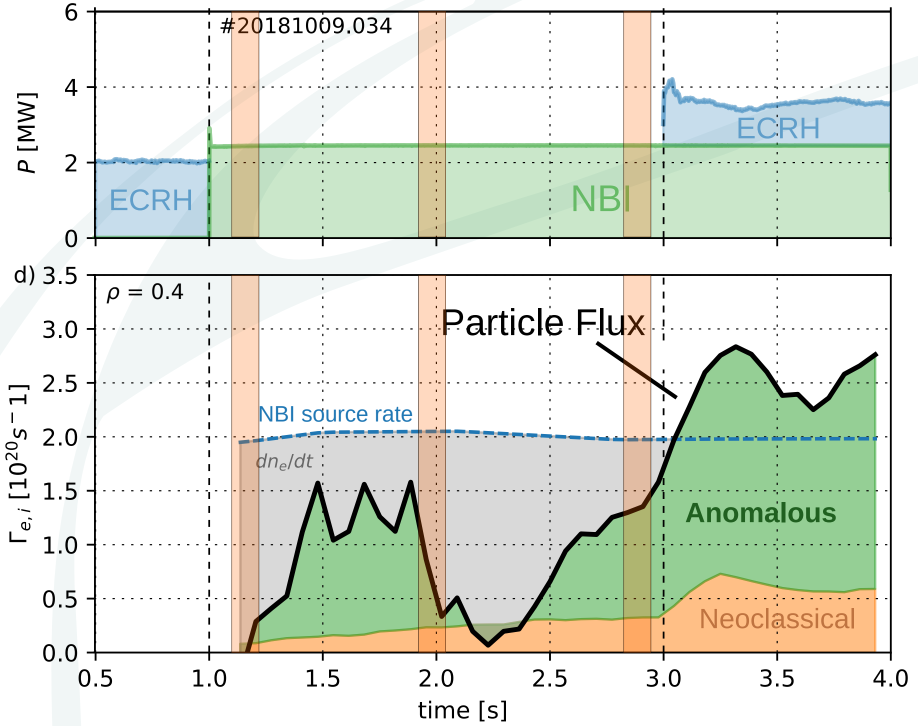

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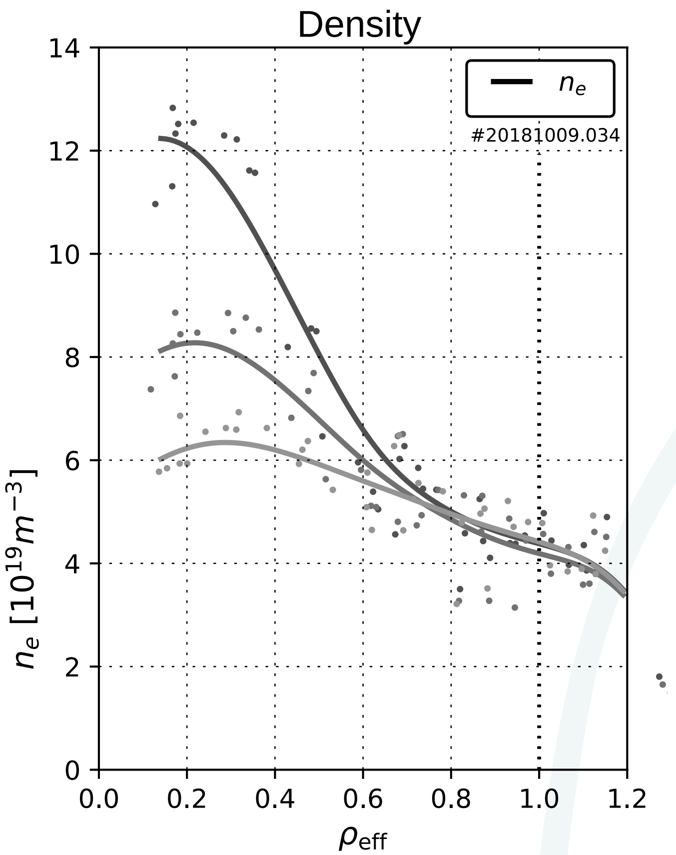

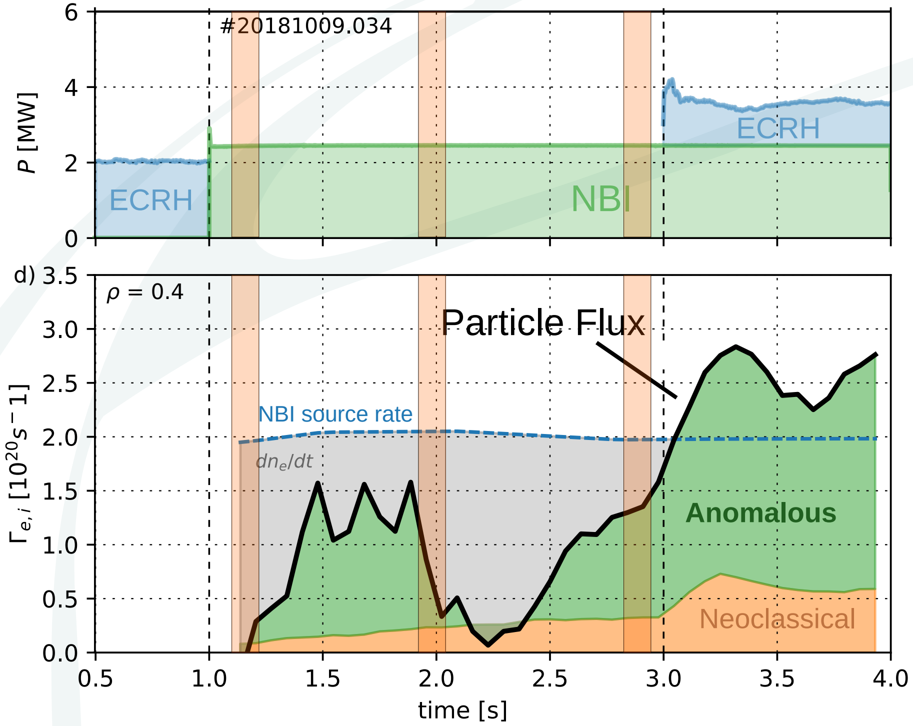

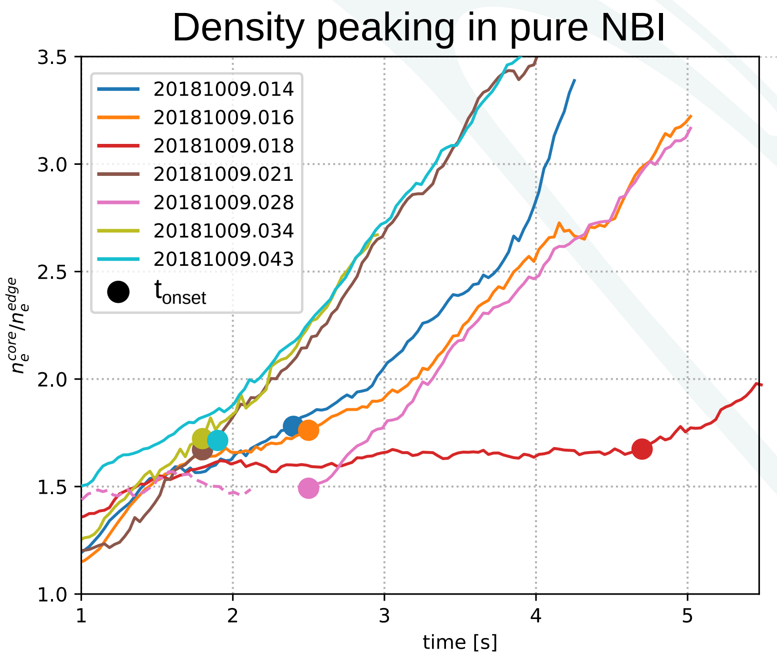

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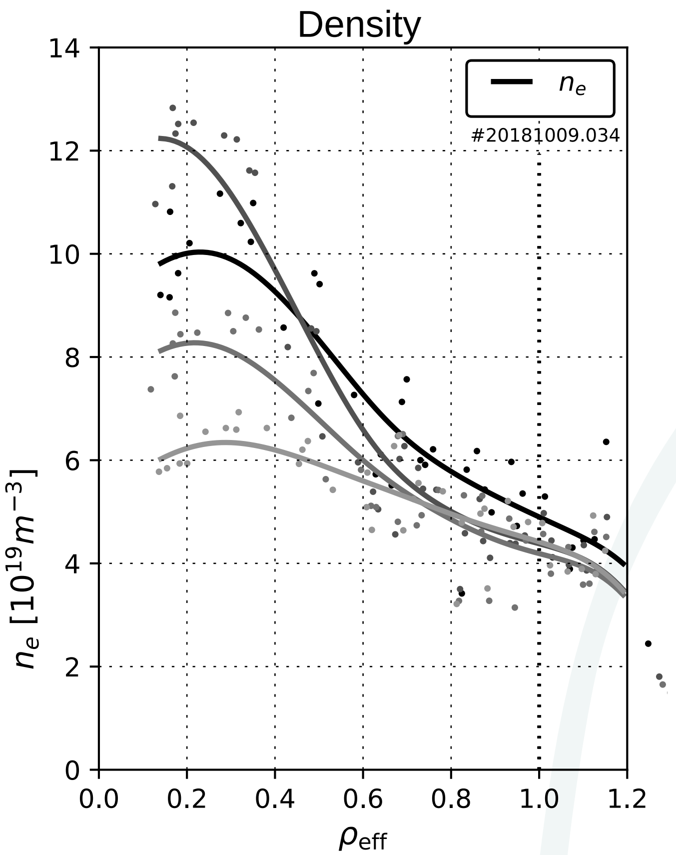
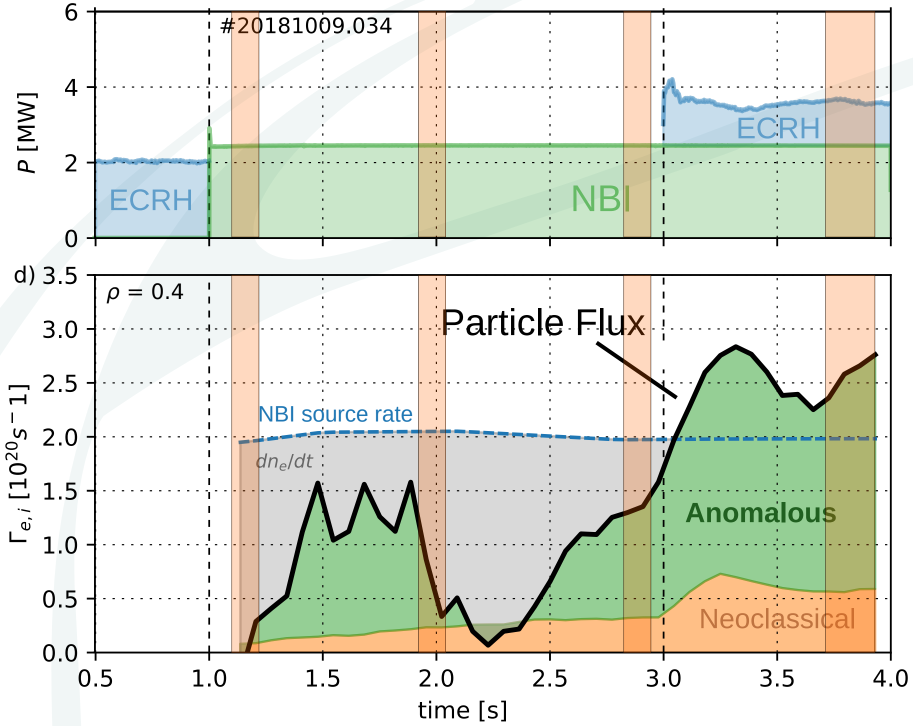
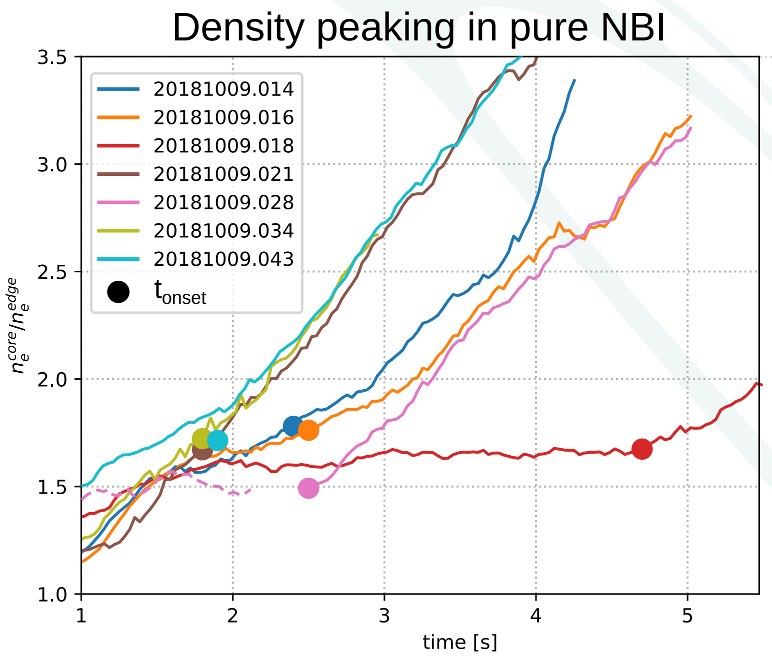
- In some cases with no ECRH, strong outward flux reduces spontaneously, leading to strong density peaking inside mid-radius.
- Reintroduction of ECRH slightly reduces peaking.







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Analysis/results:

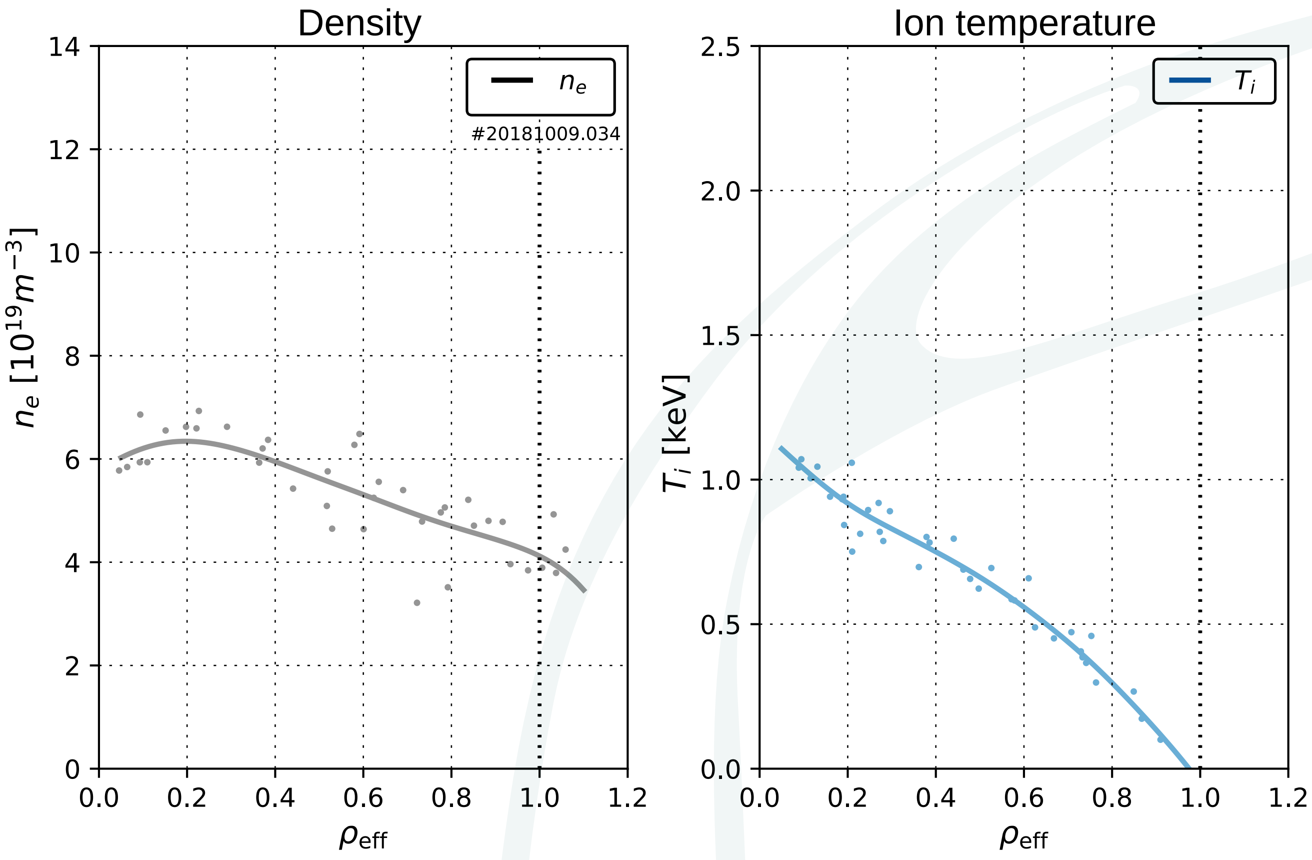
- Documentation of density peaking vs initial density and other initial conditions.
- Main ion particle flux and ideally transport coefficients throughout NBI phase.
- Determination of mechanism of particle flux reduction.

--> Eventually: Prediction capability of density profiles in NBI discharges.

NBI + ECRH: Heat transport

Background:

- Steep density gradients lead to ~4x lower heat diffusivity than in high ECRH.
- Low ECRH power (< 1MW) does not significantly increase anomalous diffusivity, so allows increase in T_i.



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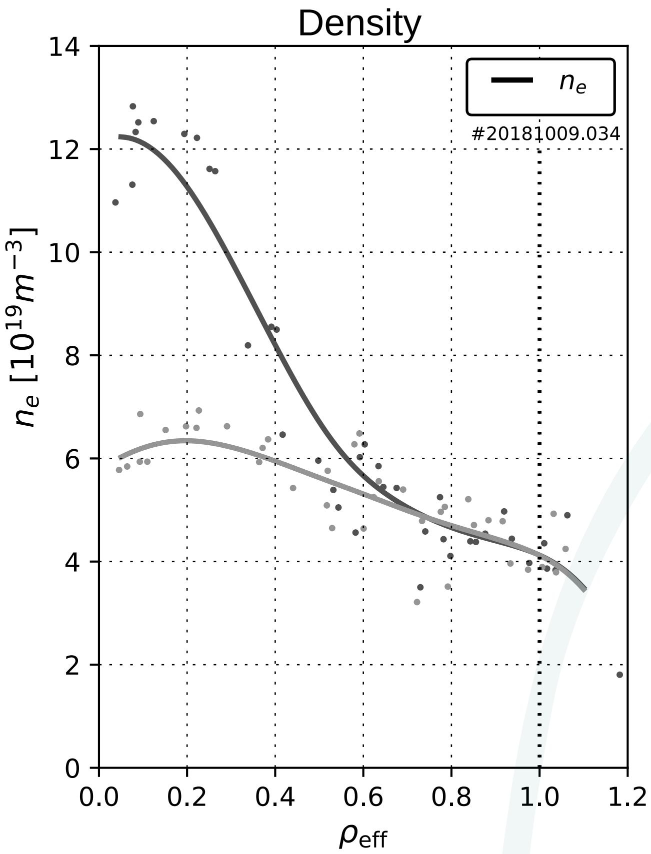

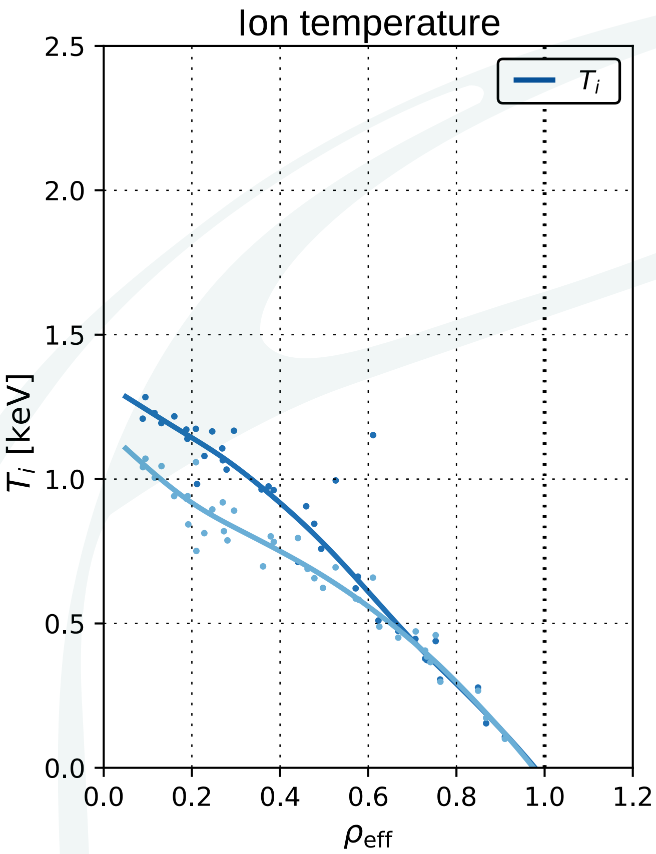

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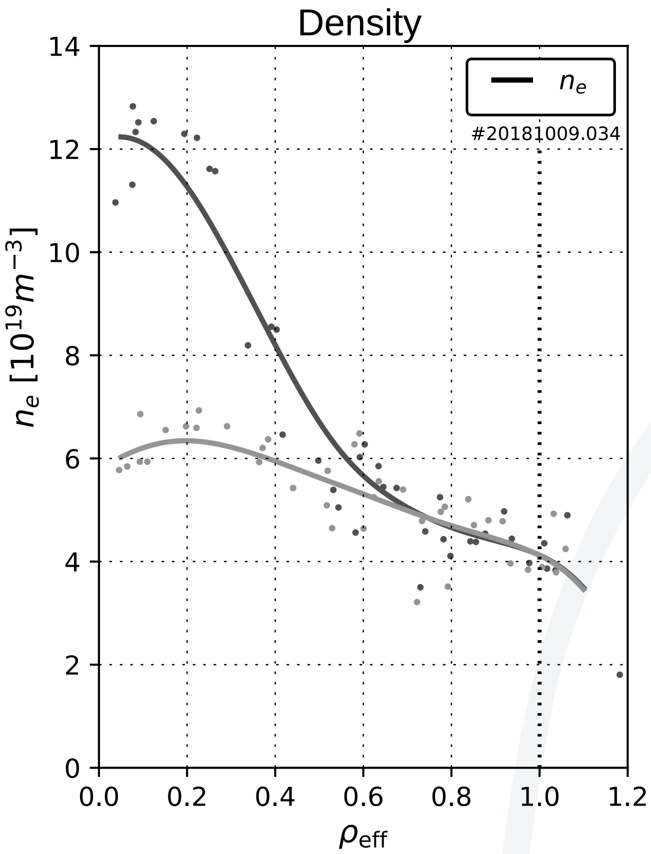

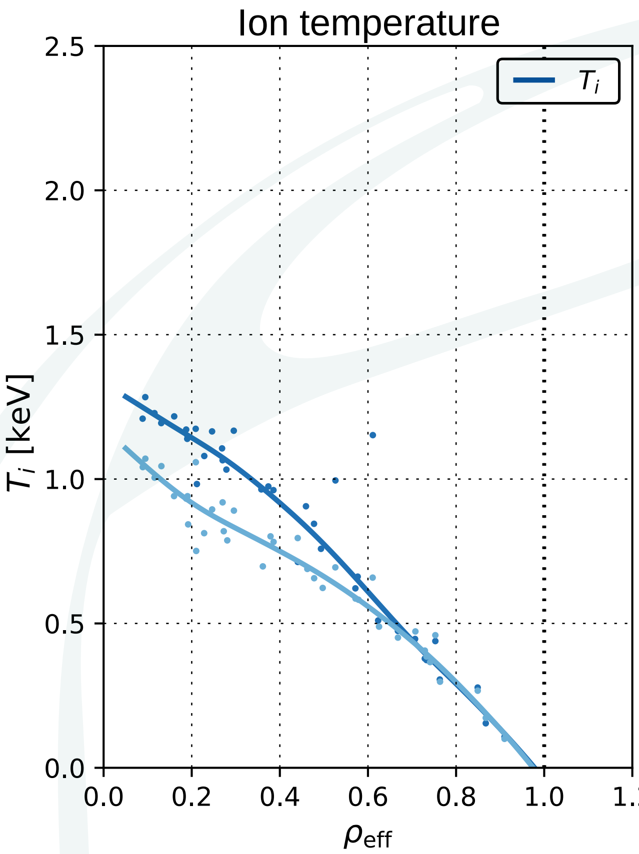

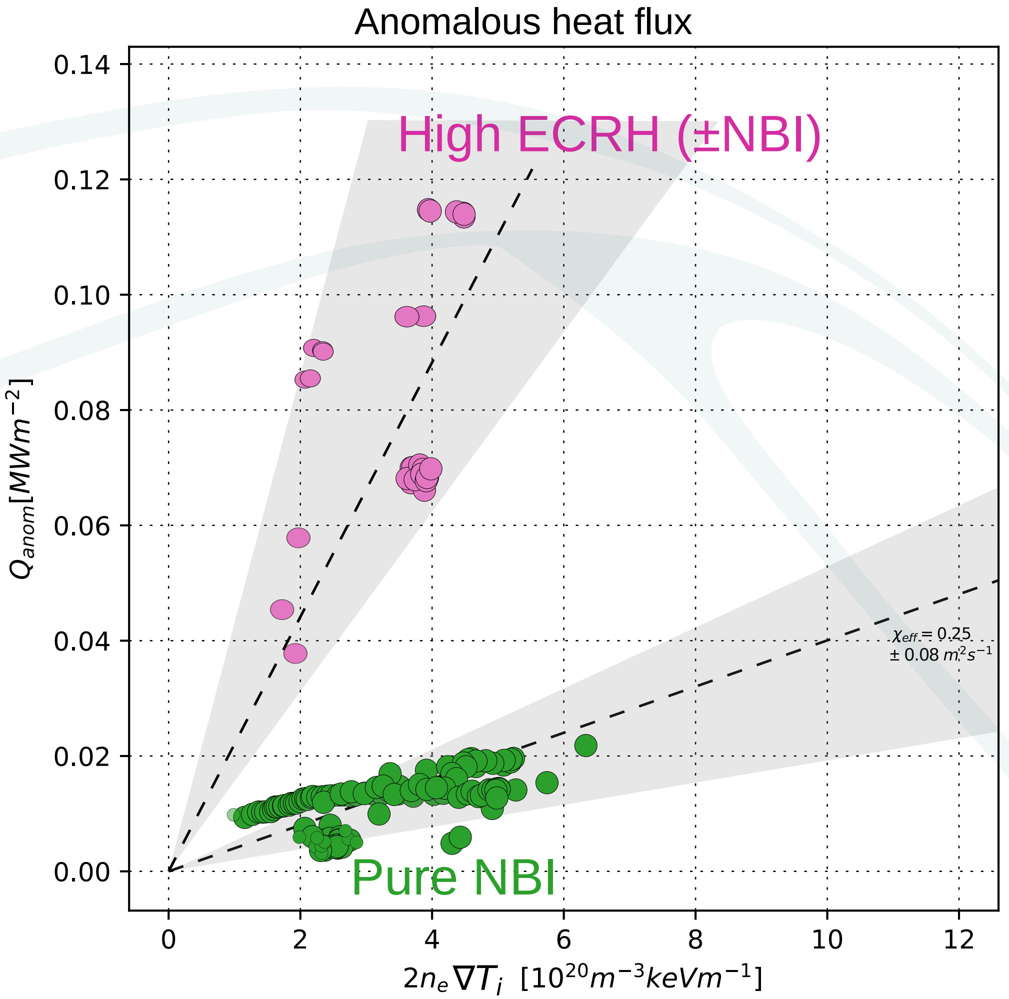

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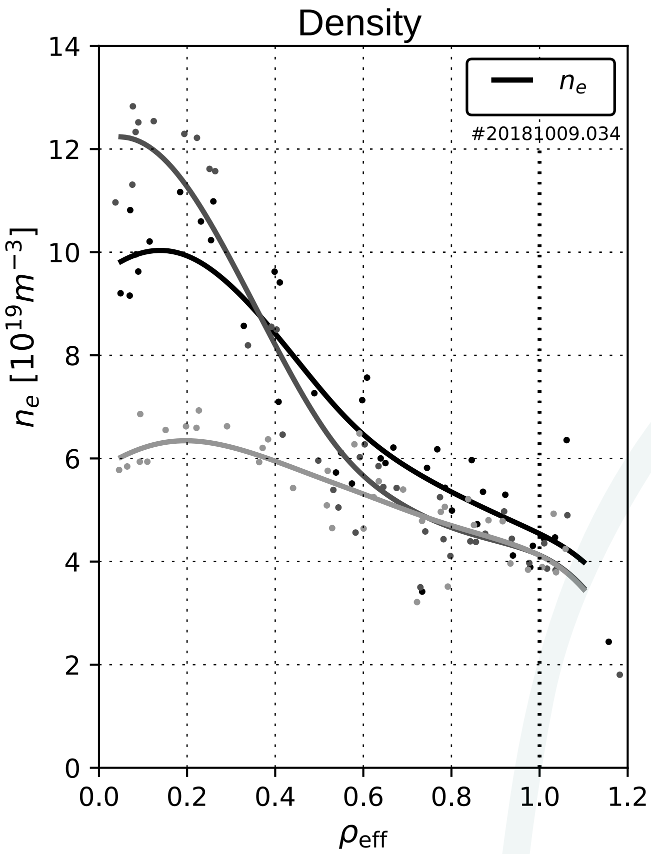

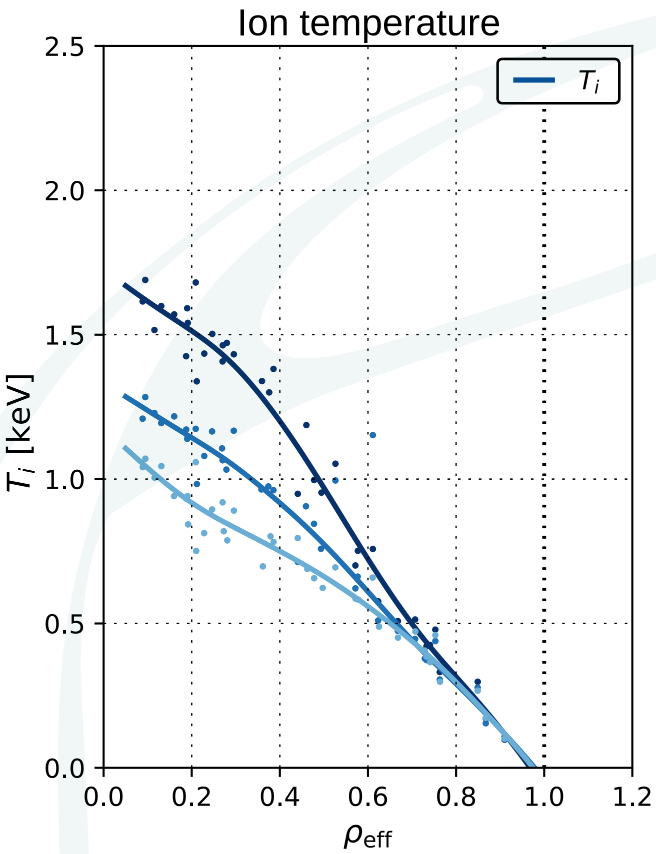

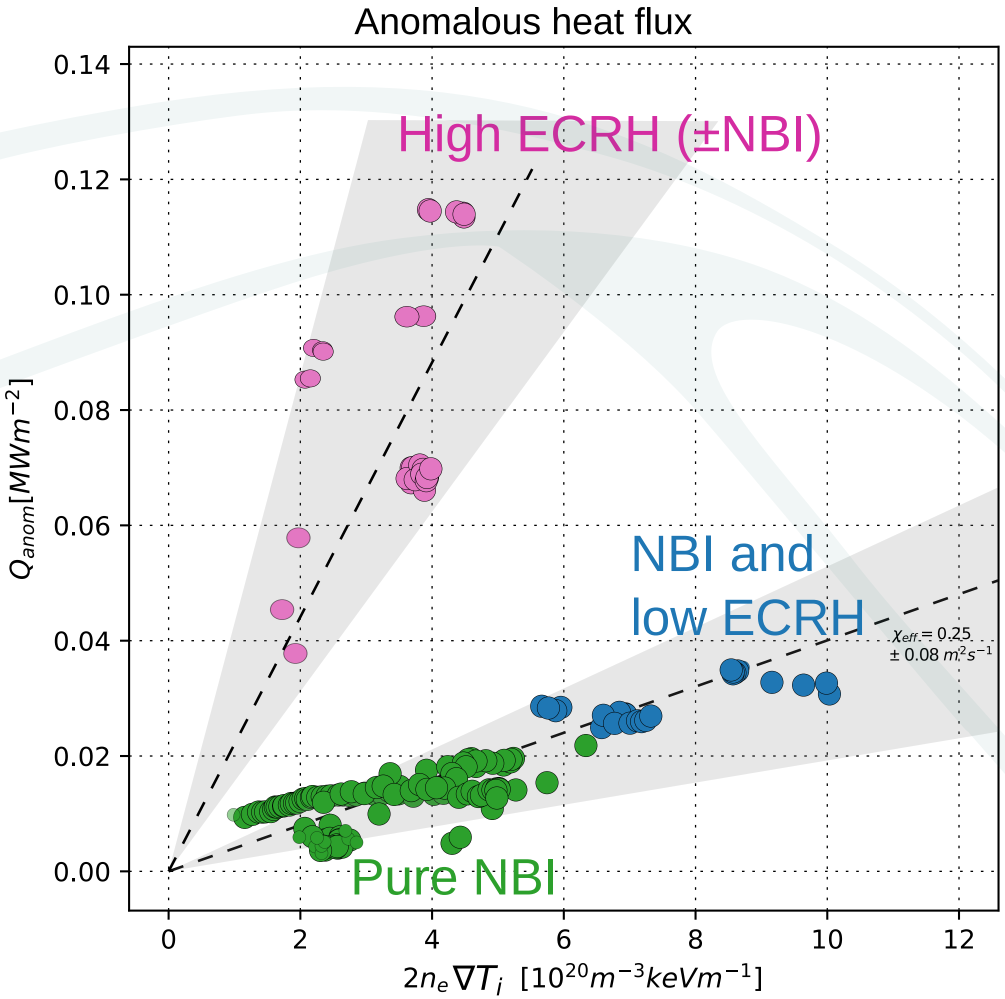

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- Approach from higher and lower ECRH plasmas.

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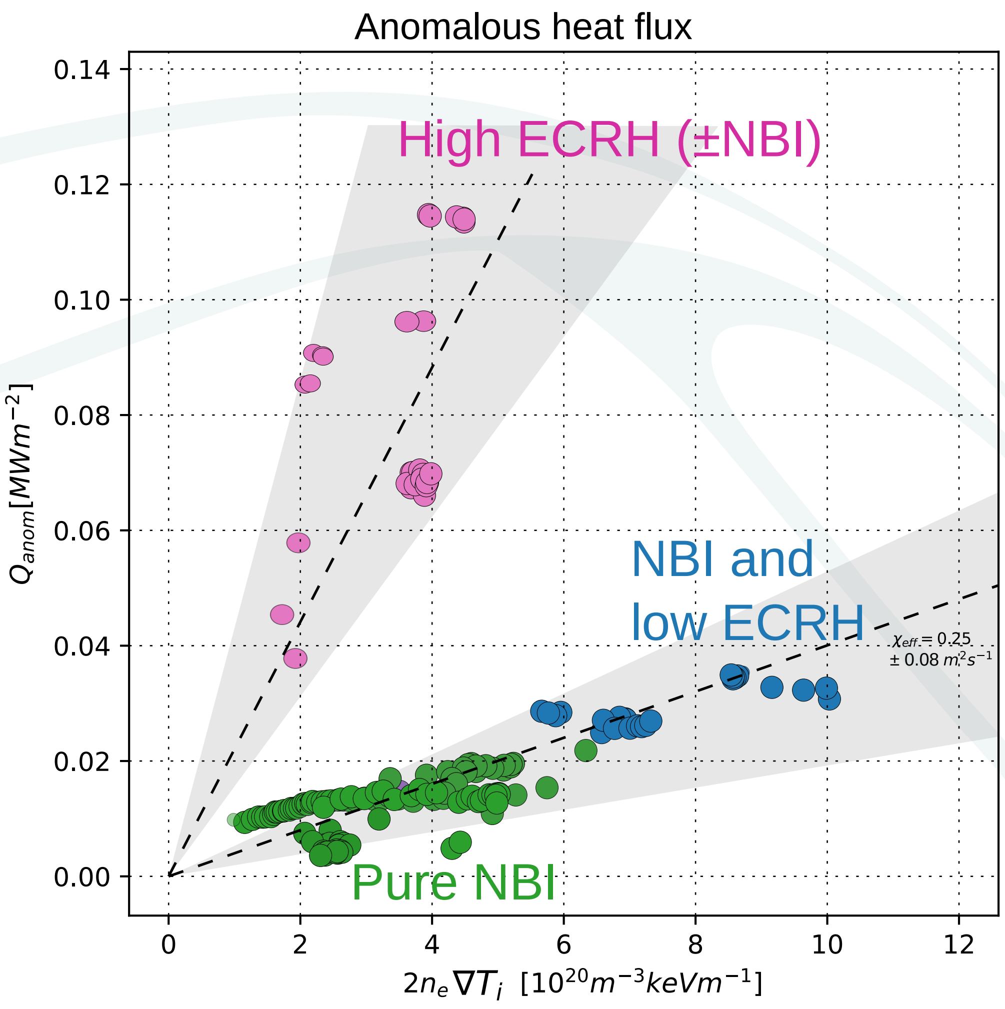
- Compare global confinement of NBI/ECRH balance with similar series already performed at LHD.



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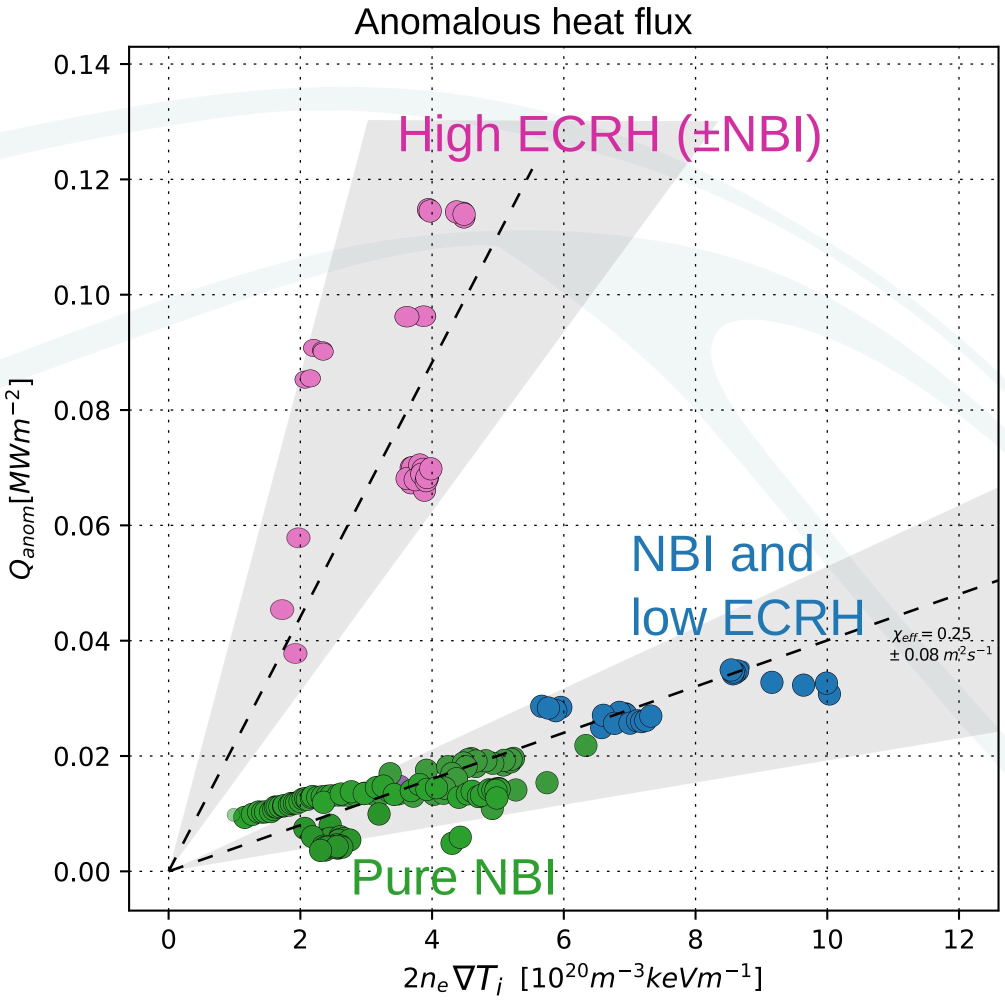
Analysis/results:

- Precise dependence of heat diffusivity on density gradient.
- Assesment of the generality and scaling of the scenario.
- An optimised NBI/ECRH scenario for use in later studies, e.g. impurity transport, turbulence, detachment compatibility etc...

With 4 NBI sources, *might* give access to up to $T_i = 2.5keV$.



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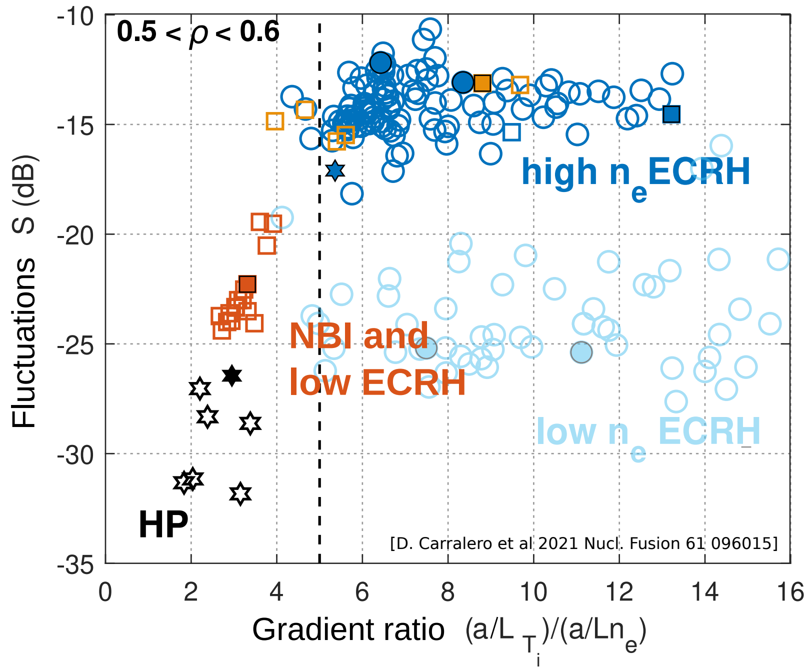
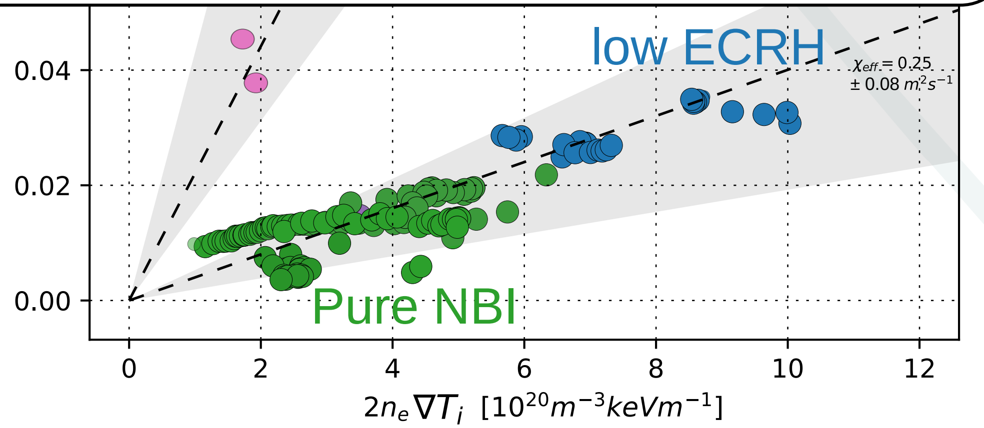
- Turbulent fluctuation measurements for in all scenarios for turbulence studies --> see talk by A. von Stechow

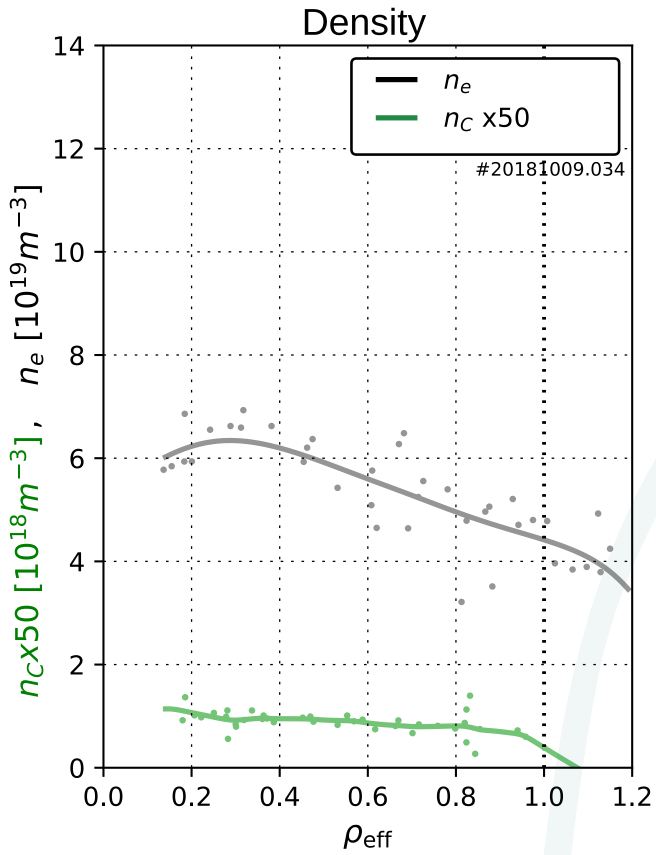


Turbulent fluctuations from Doppler reflectometer reduced in NBI+low ECRH compared to equivalent ECRH



Pure NBI: Impurity transport

Background:



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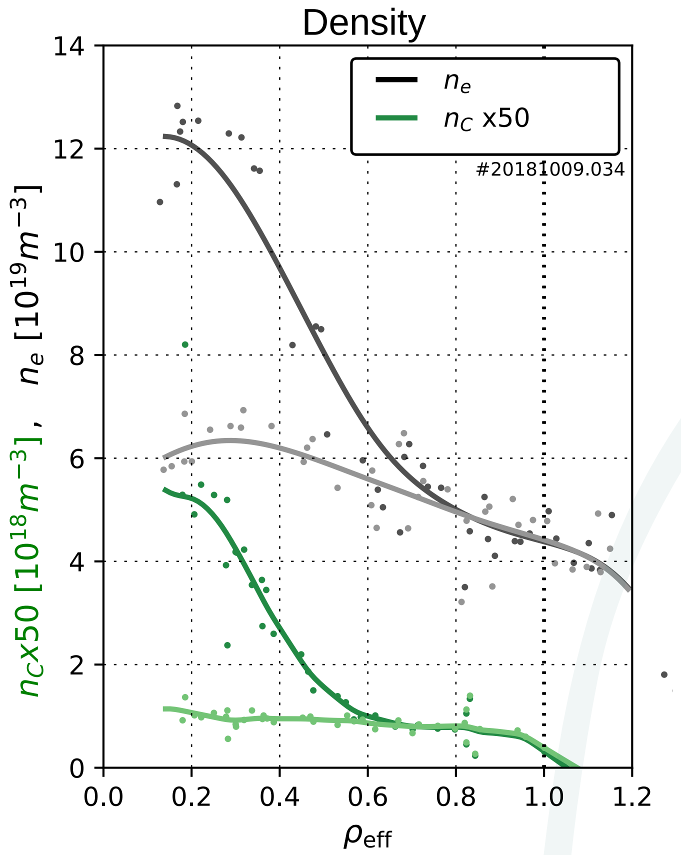

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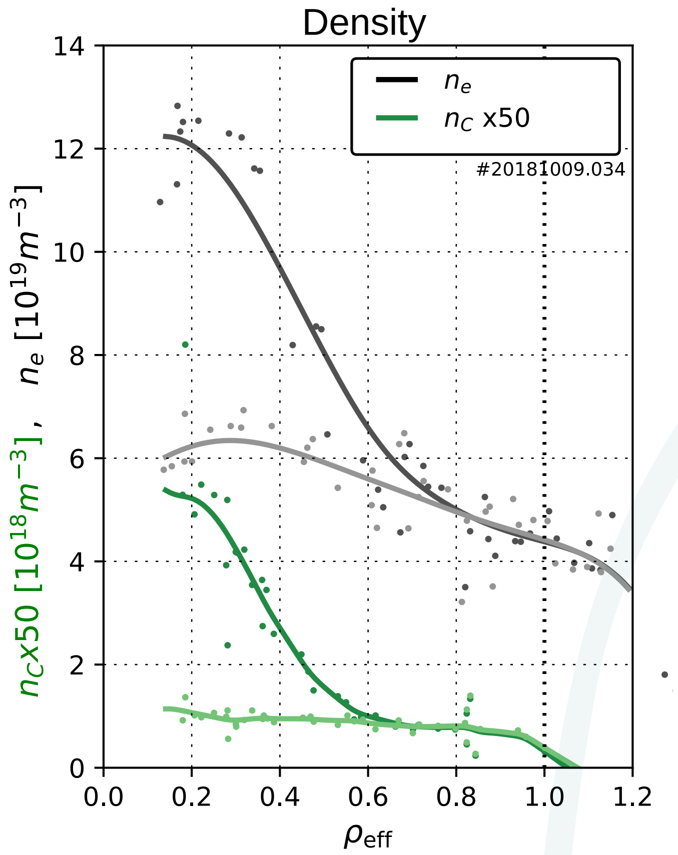

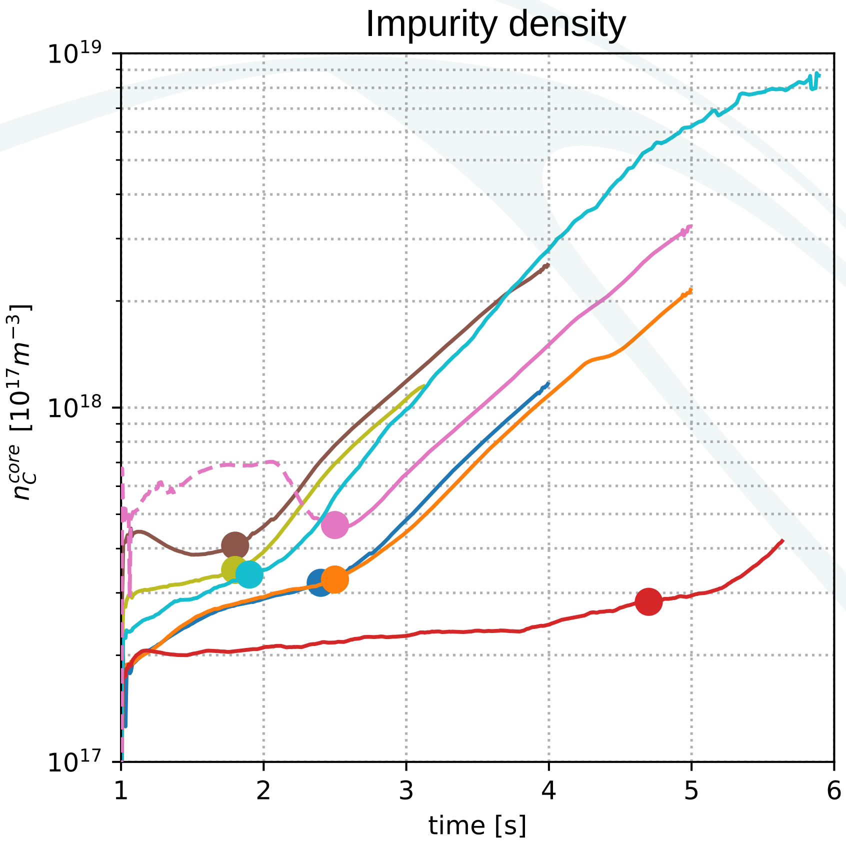

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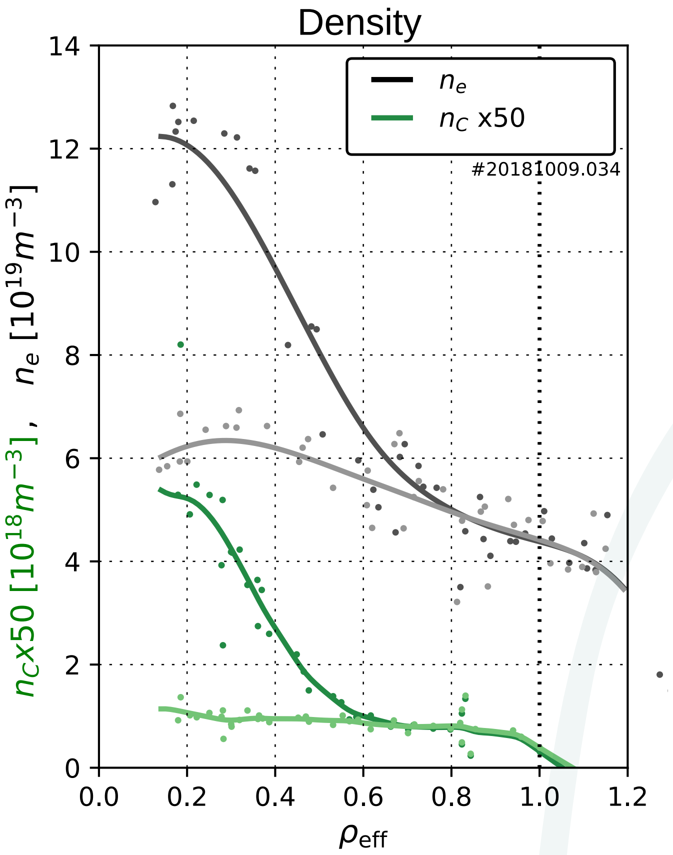

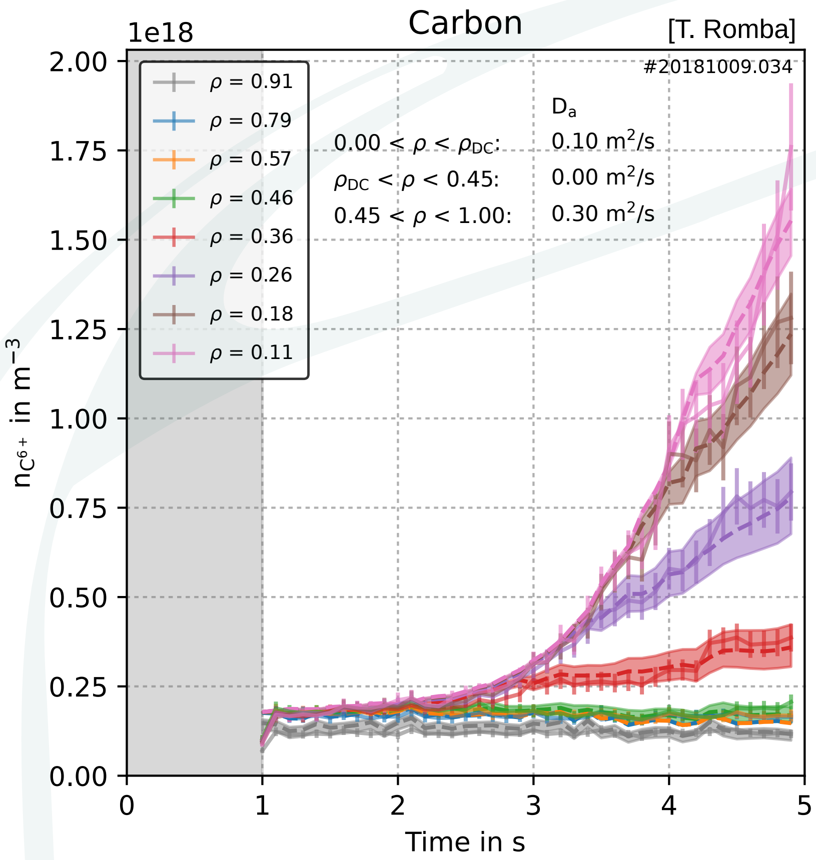

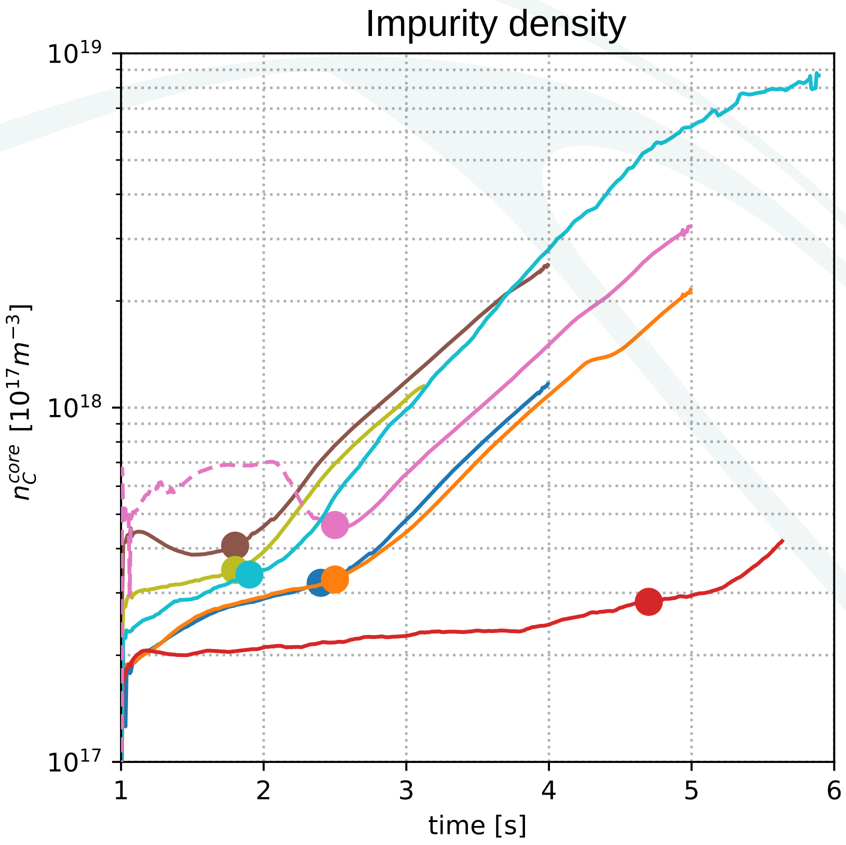

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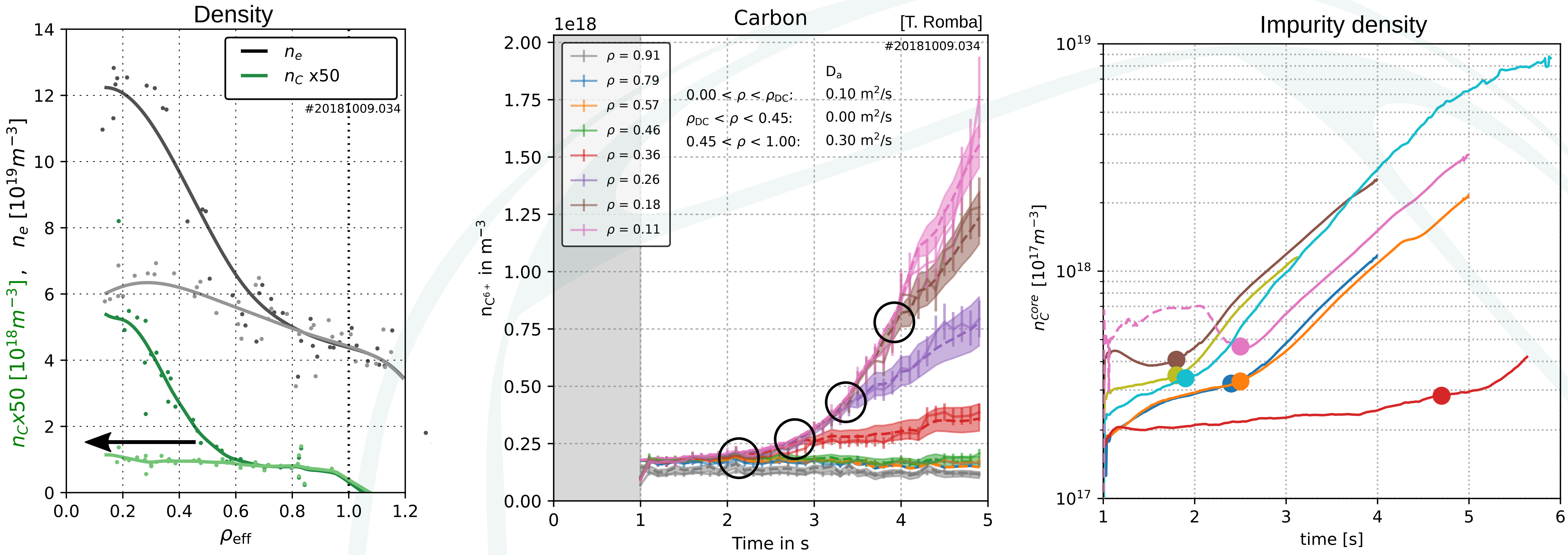

ECRH pump-out

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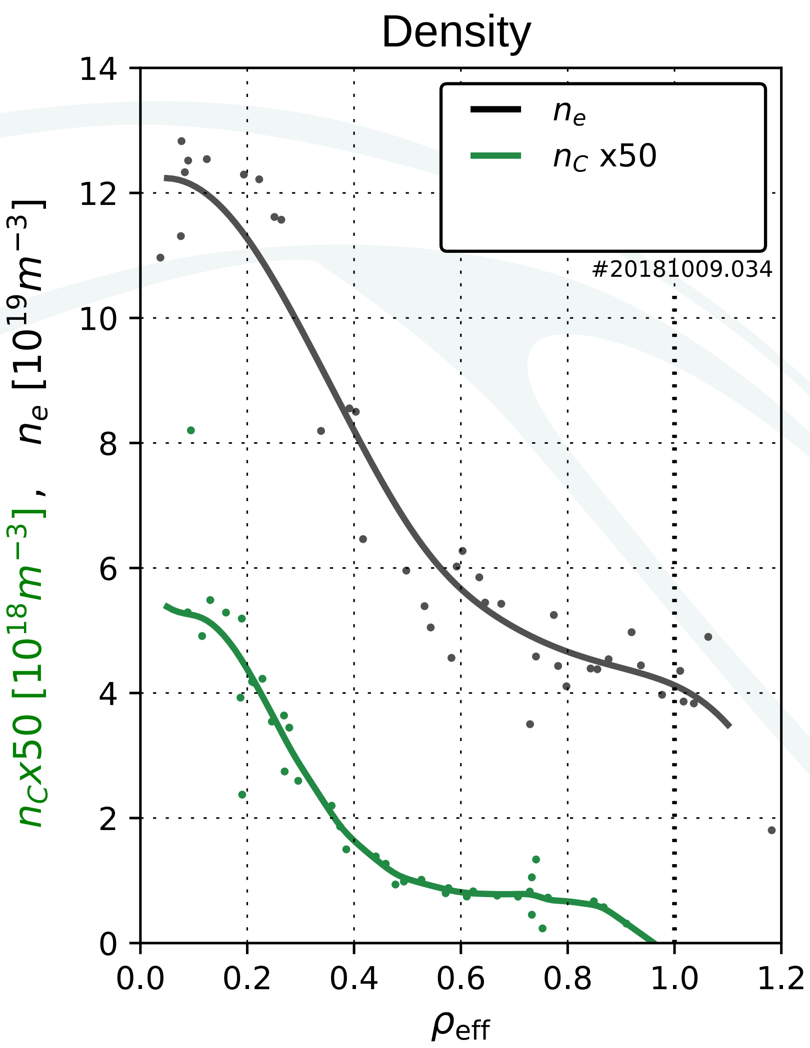

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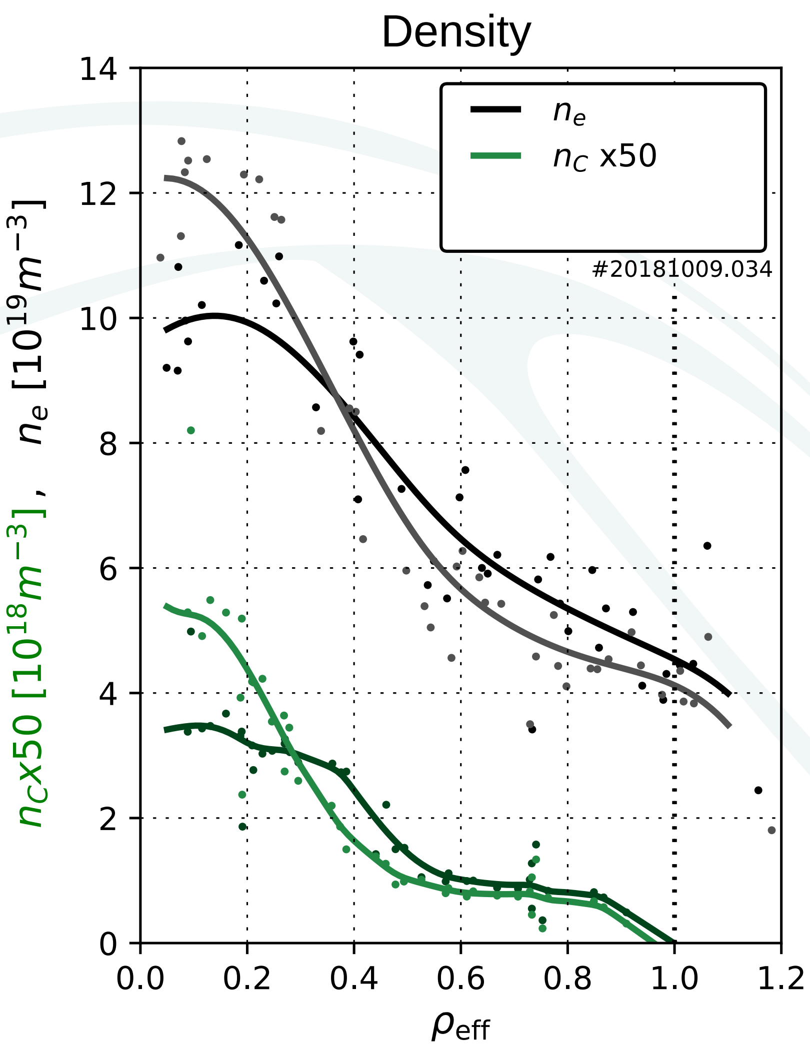

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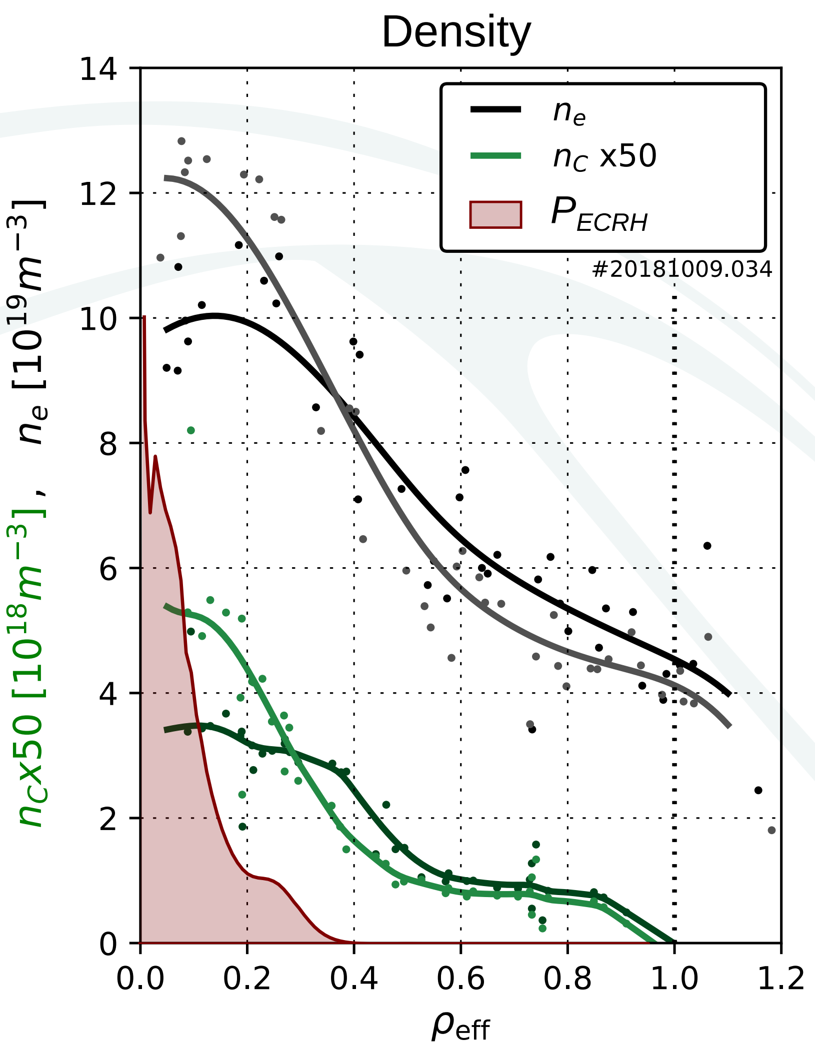

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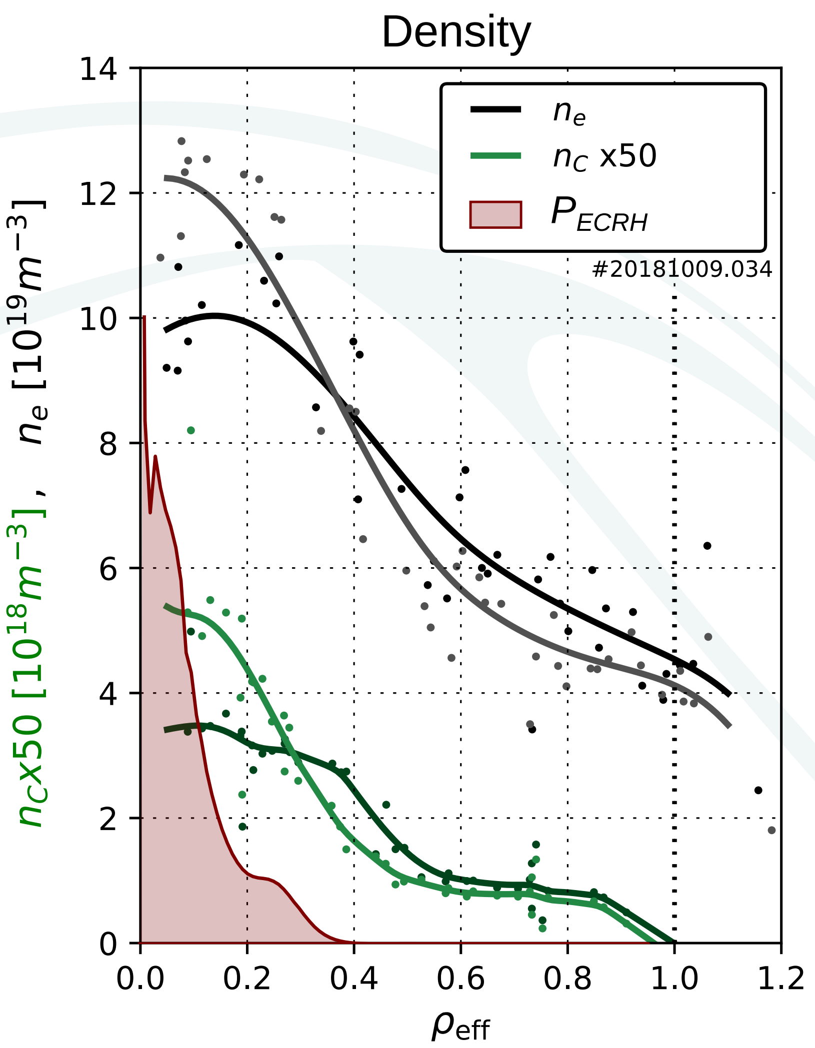

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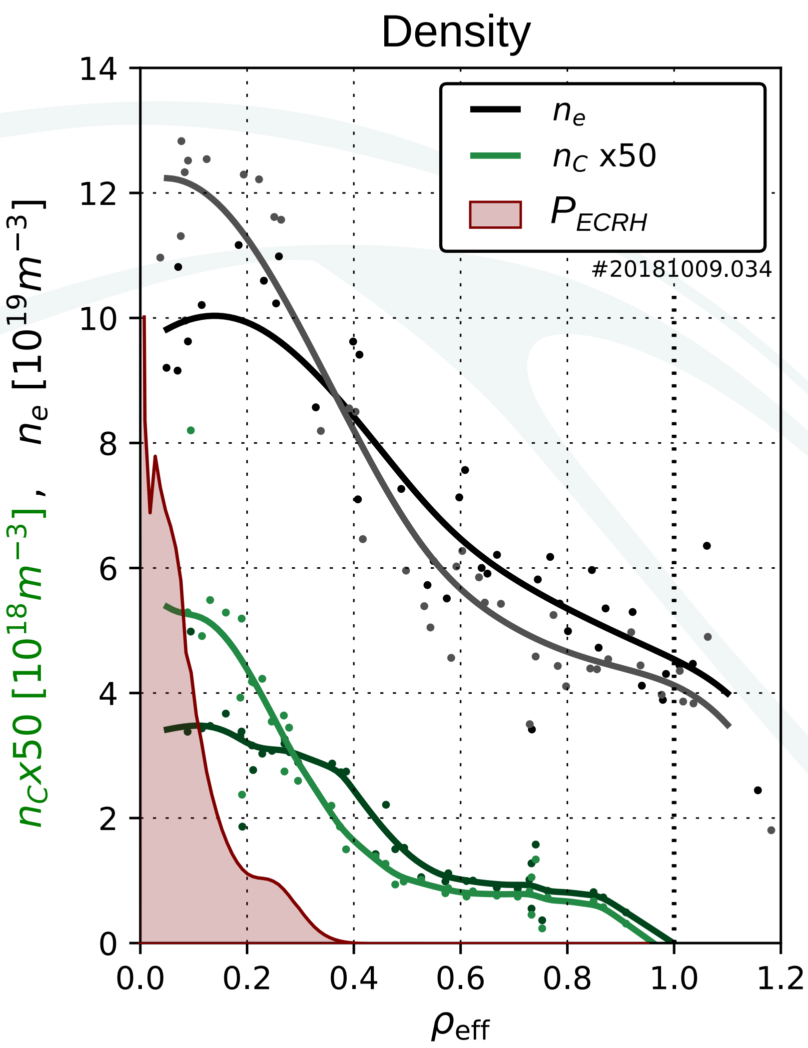
II: - Vary duty cycle and lengths of short ECRH pulses.
- Investigate effect of sawtooth crashes driven with ECCD.

- Add LBO/TESPEL impurity injections at the different ECRH settings to determine impurity transport coefficients. (and measure with high speed impurity diagnostics)

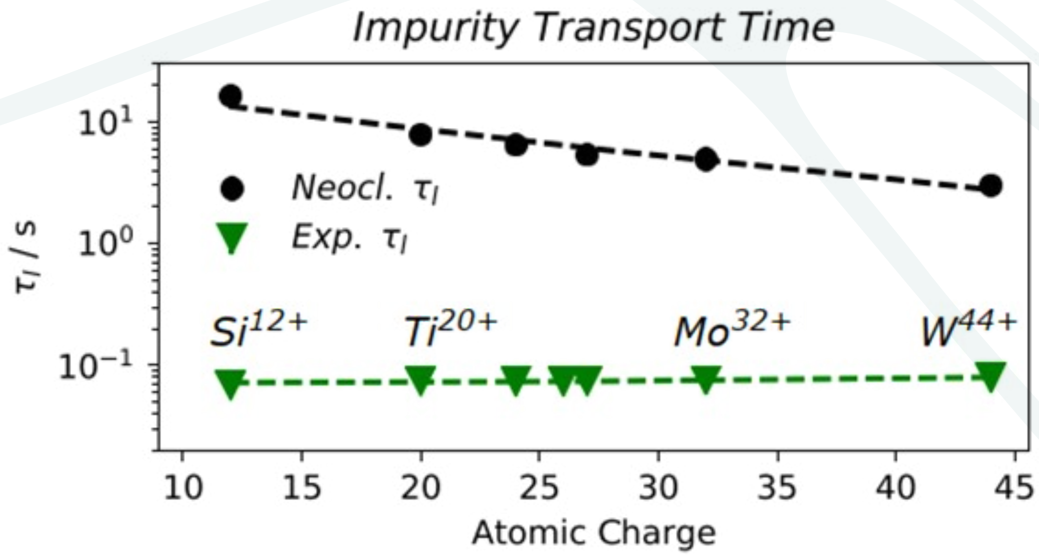
- Attempt 'pump-out' with ICRH 3-ion scheme.



Z-dependence in turbulence reduced scenarios

Background:

- In turbuence dominated ECRH scenarios, Z-dependence of impurity transport is weak.
- Turbulence reduced scenarios allow examination of neoclassical *f(Z)* expectation, with a view to predicting W-accumulation in high-T_i scenarios.



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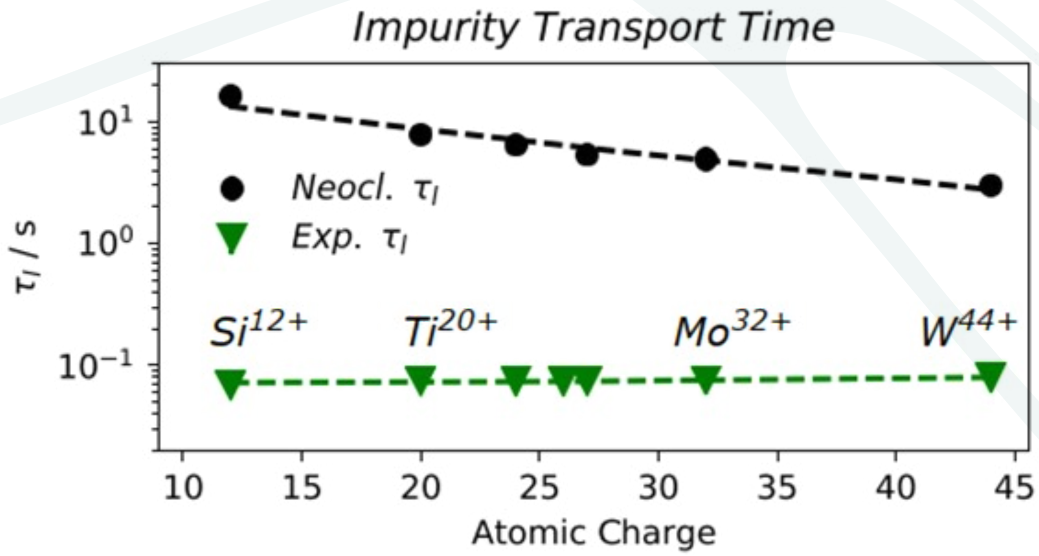

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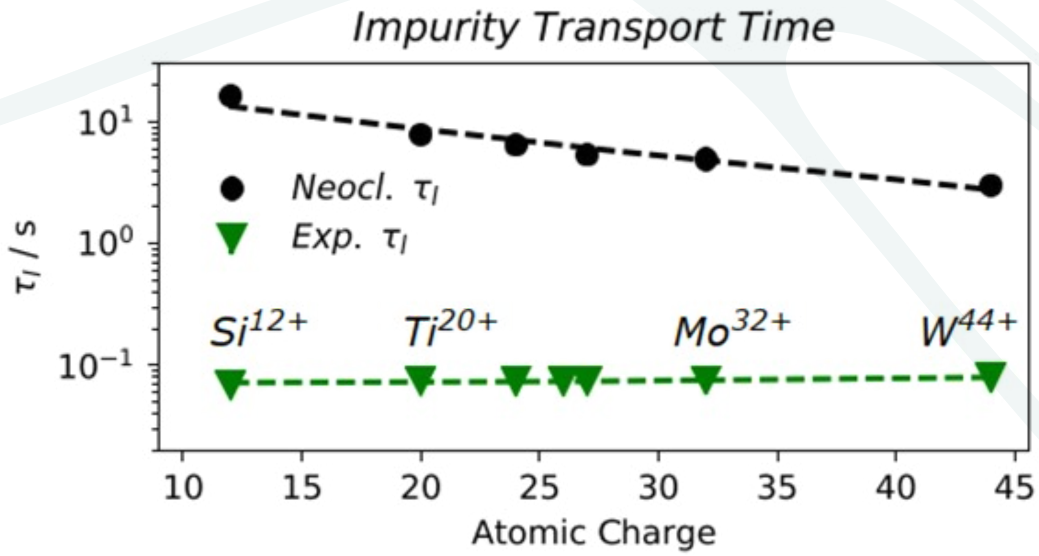
Plan:

I: - Perform LBO, TESPEL injections of wide range of Z in turbulence reduced NBI+ECRH.

II: - Simultaneous injections of multi-species per TESPEL.

- Examine radiation asymetries after injections.
- Compare similar LBO injections in different scenarios.
- Find maximum LBO injection to induce plasma collapse.



Analysis/results:
- Time-dependant analysis of injections to delivery transport coefficients.
- Database of transport coefficients for range of Z in major candidate scenarios.

Summary

Investigations in the specific plasma scenarios:
- Pure NBI
- NBI + low ECRH
- Post-boronisation, low ECRH power
- Mass impurity injection (LBO, TESPEL, Boron dropper)

Physics studies in each scenario:
- Main ion particle transport --> Density peaking --> Density profile control
  +
- Heat transport --> Reduced turbulence --> Optimised performance

  --> **T1D1:** *High plasmas performance in order of seconds.*

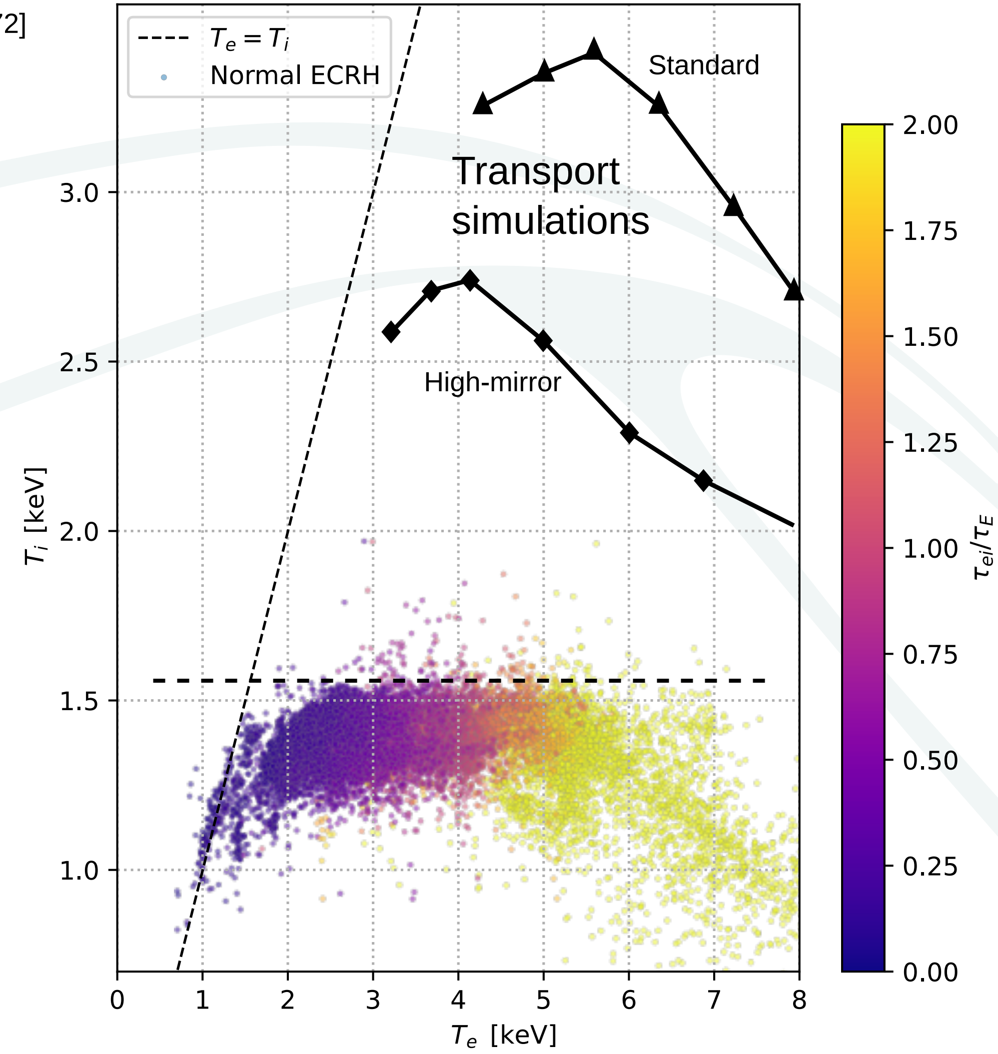
- Impurity transport --> Impurity accumulation --> Radiation control

  --> **T1D2:** *Avoidance of impurity accumulation*

Ti clamping in OP1.2b

In OP1.2, most plasmas were dominated by strong turbulence, limiting T_i < *1.5keV*.

Three effects were found to be responsible: [M.N.A. Beurskens et al 2021 Nucl. Fusion 61 116072]



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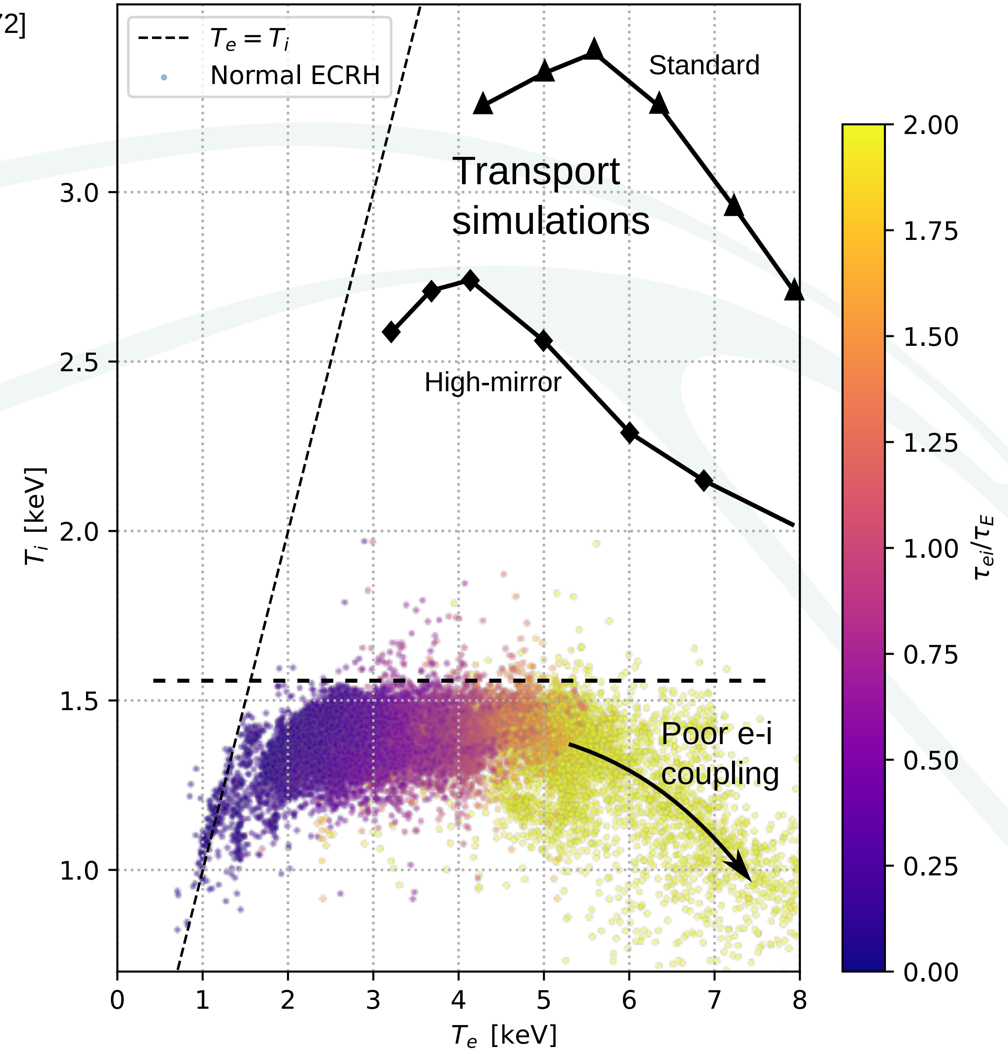

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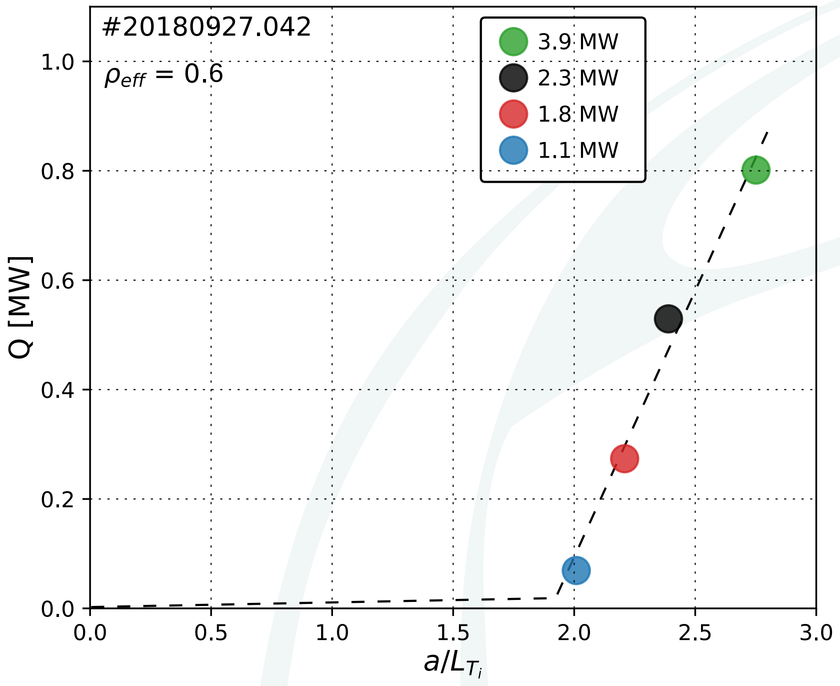

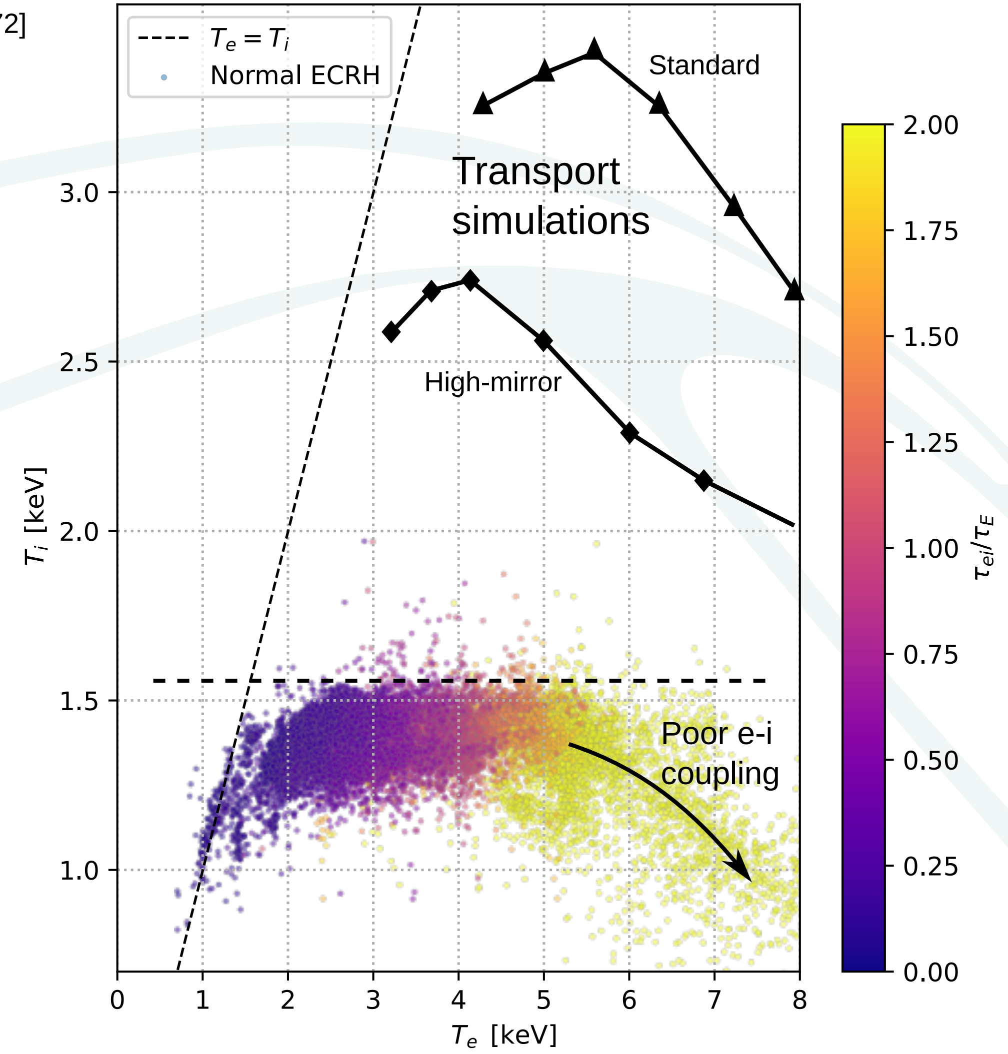

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2) Strong profile 'stiffness' due to ITG turbulence.
3) Increase in ITG with T_e/T_i exacerbates stiffness.