Ion heating and thermal confinement: Routes to higher T_i

W7-X Workshop 2019

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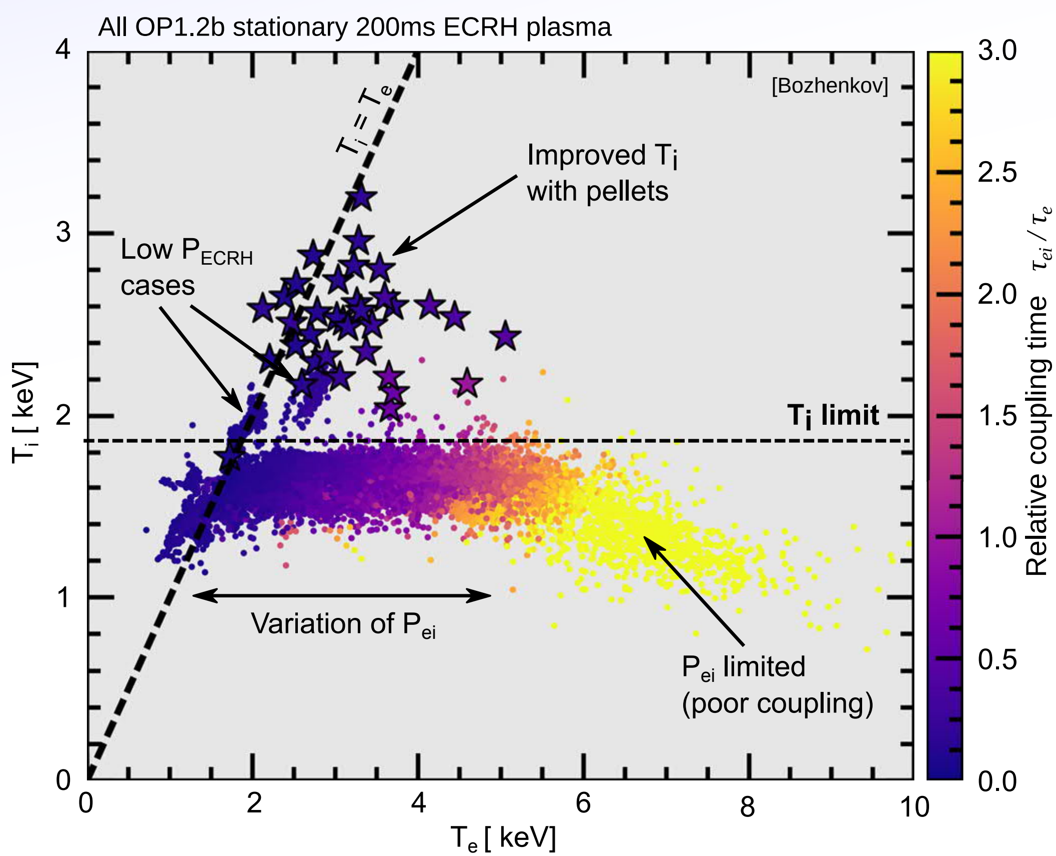
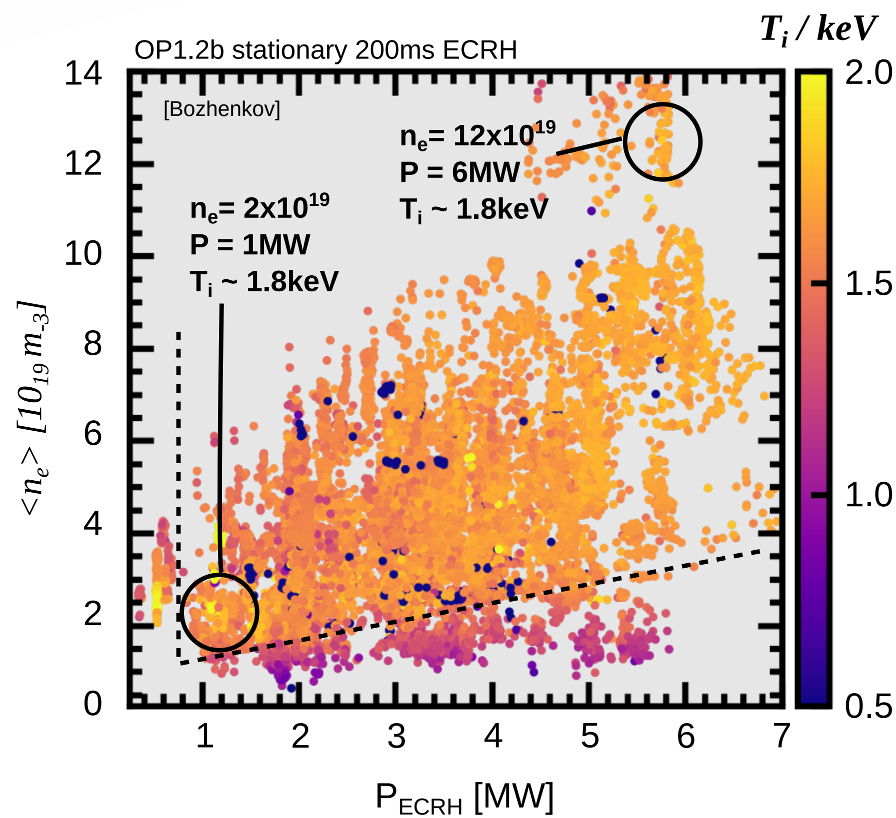
T_i profile resilience: ECRH

- Core T_i stays within same range and with similar gradients regardless of P_{ei} / electron-ion coupling.
- Effective T_i limit ~ 1.9 keV XICS (1.6keV CXRS)
- Exceptions:
    1) High-Performance pellet discharges
    2) Some particular low P_{ECRH} cases.





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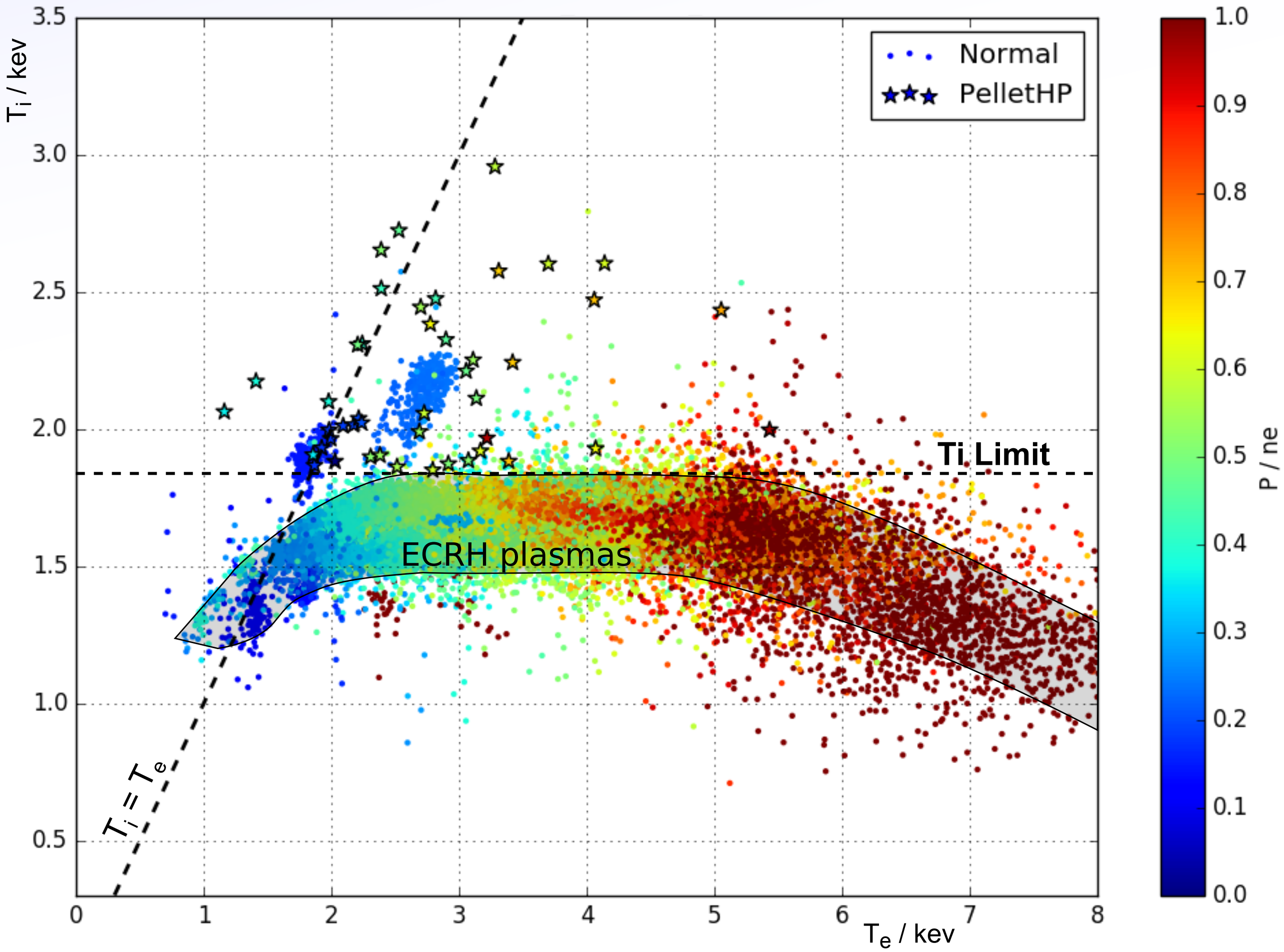
T_i profile resilience: Non-stationary

- Core T_i stays within same range and with similar gradients regardless of P_{ei} / electron-ion coupling.
- Effective T_i limit ~ 1.9 keV XICS (1.6keV CXRS)
- Exceptions:
    1) High-Performance pellet discharges
    2) Some particular low P_{ECRH} cases.
- All ECRH plasmas, including 'non-stationary': A little noisier, but no significant change.



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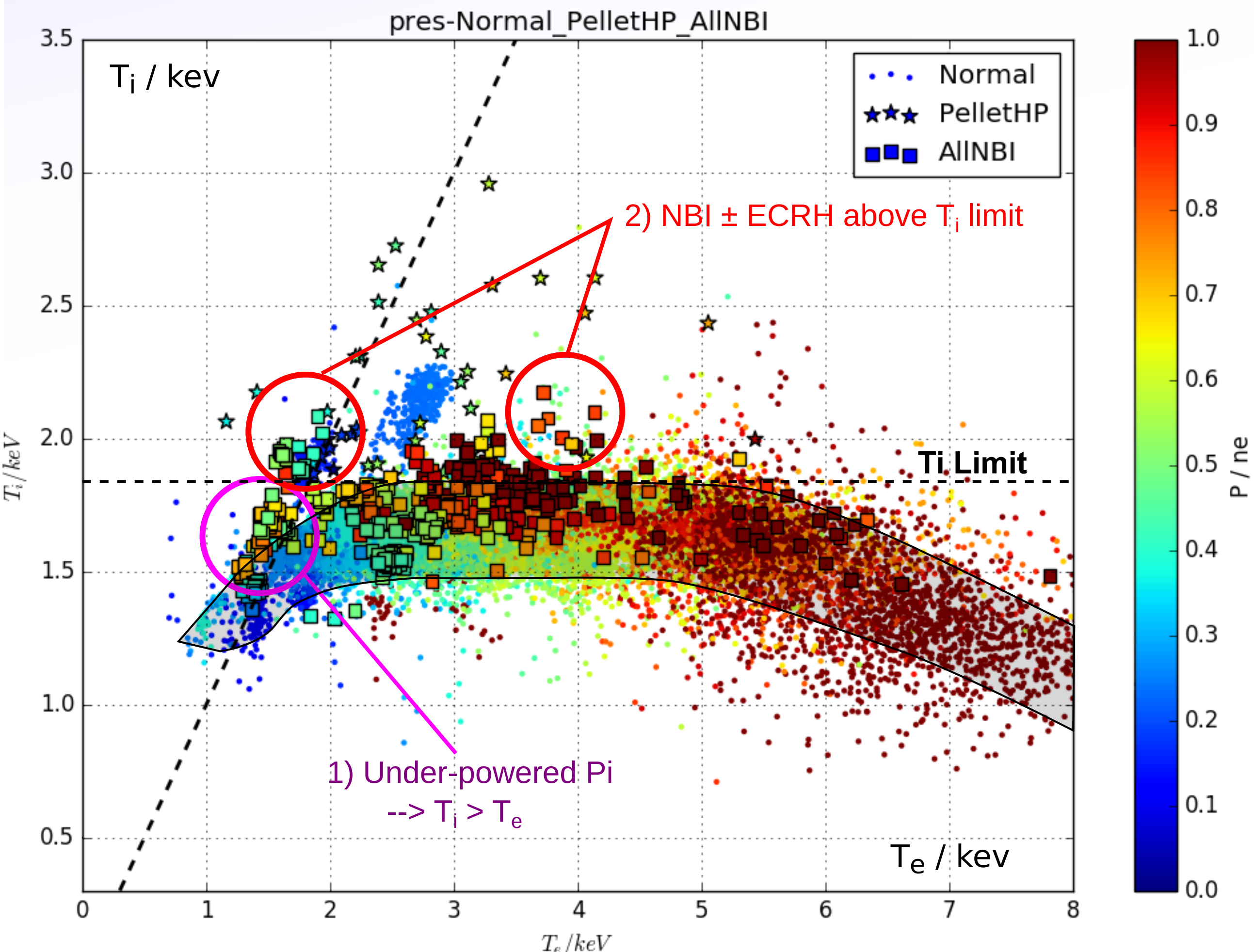
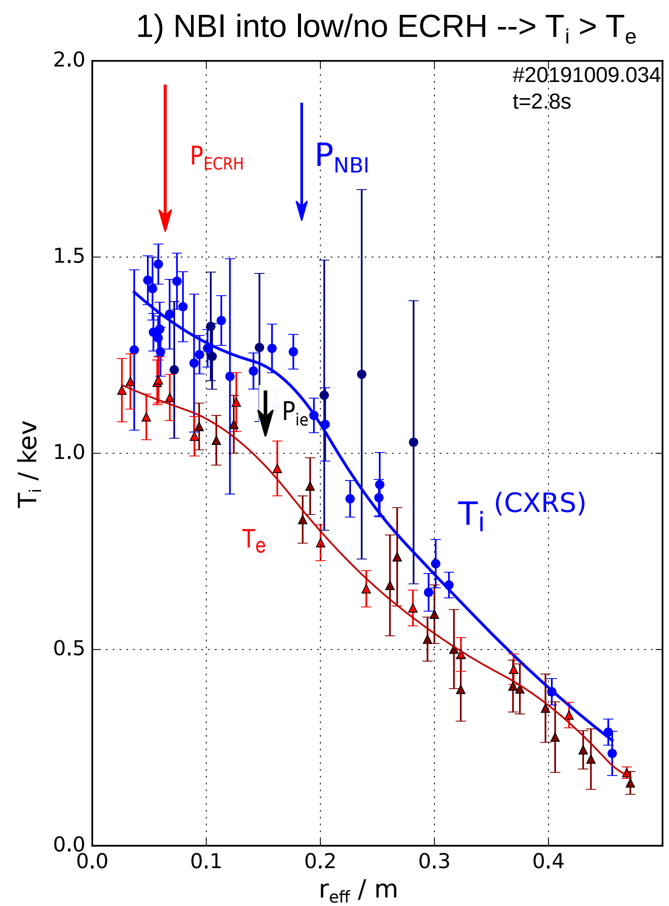
T_i profile resilience: NBI

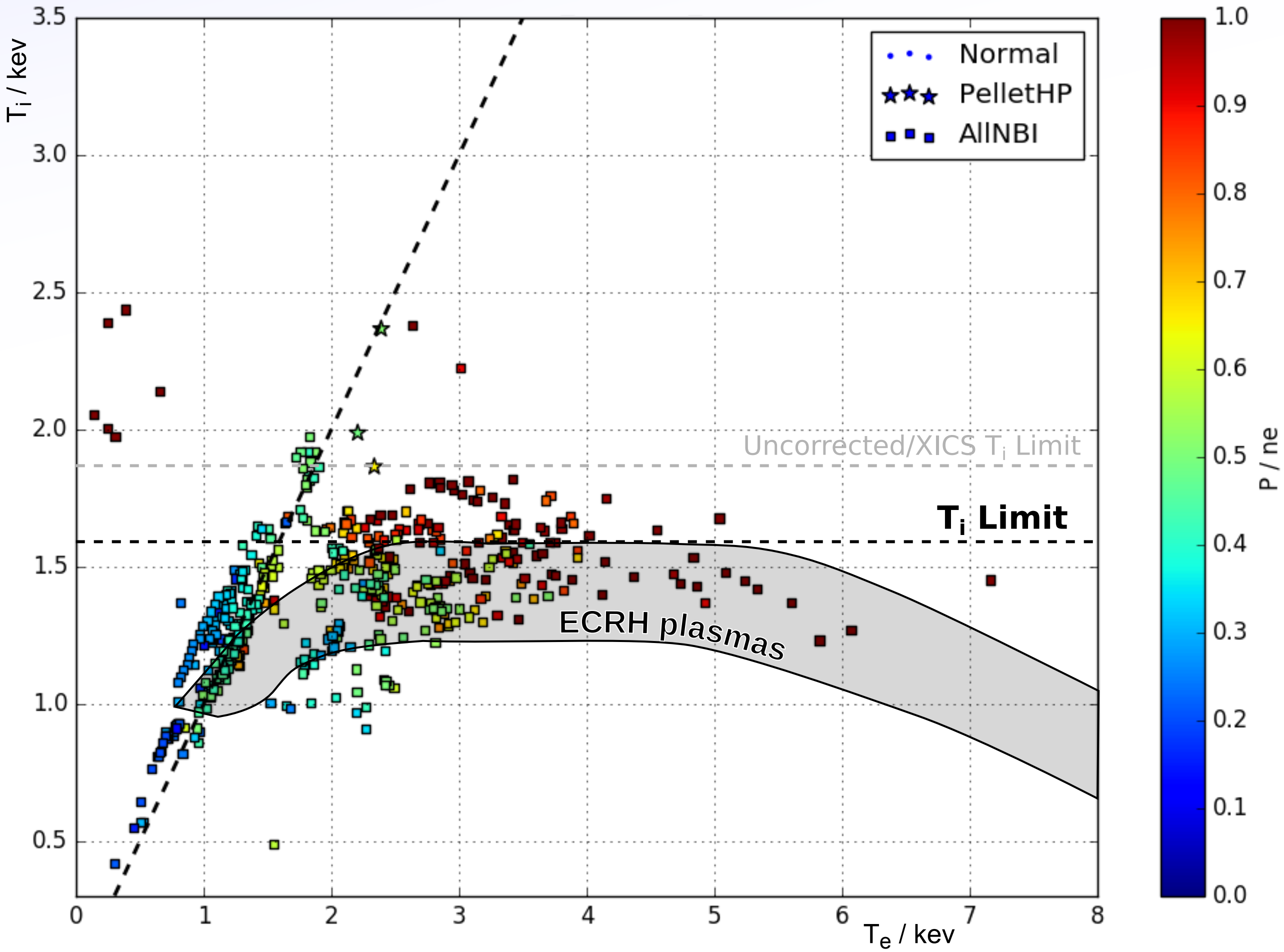
- NBI adds signficant direct ion heating (> 50%) but does not raise $T_{i.}$
- Consistent with the existence of a critical T_i gradient.
- Exceptions:
    1) 'Under powered' plasmas: Little/no ECRH, so T_i below limit.
    2) Some specific cases - look at CXRS for detail.





XICS --> CXRS

- CXRS gives higher resolution data, but only with NBI (~200 shots)
- Trend is less obvious, but CXRS profiles don't change the situation.



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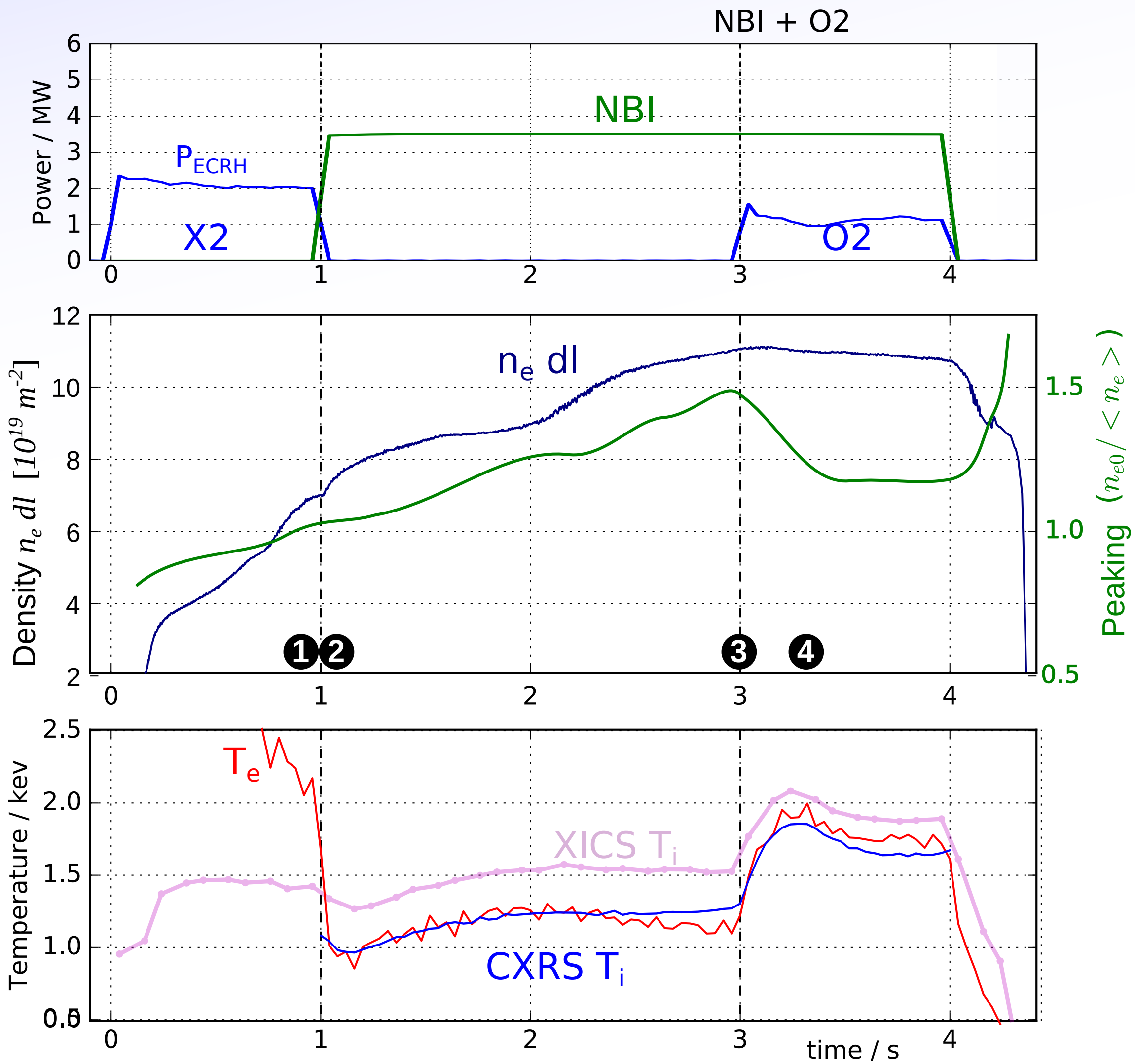
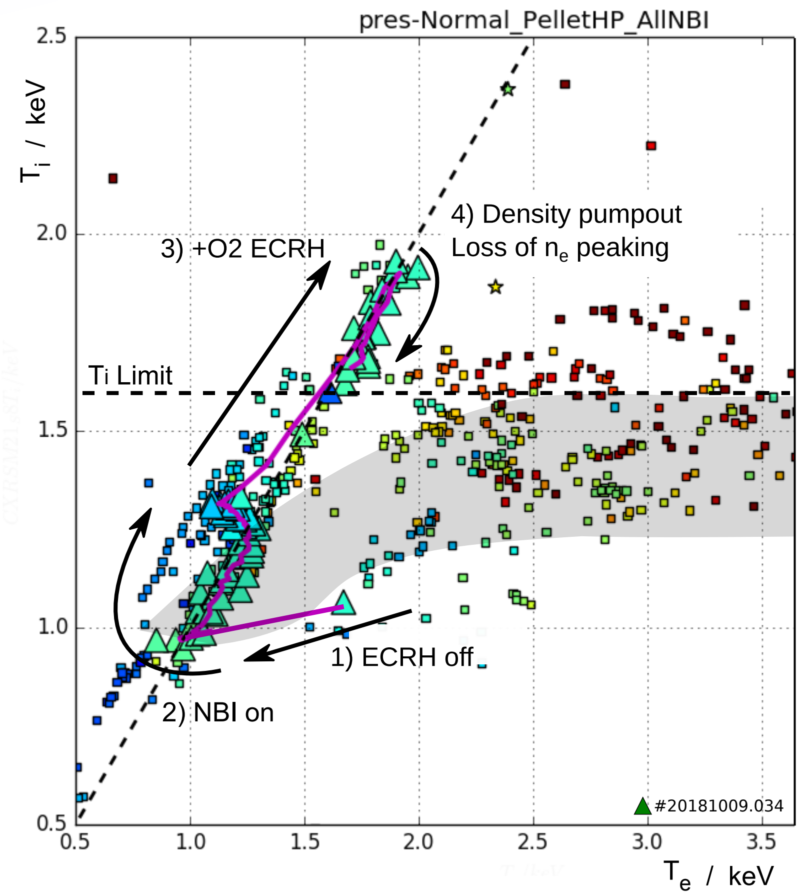
Case 1: NBI + O2

- NBI creates peaked density profiles with steadily increasing density and impurities.
- We can use low power ECRH to control density level, expel impurities and increase T_e. (S62/olfo_012)
- Core density drops after O2 reintroduction and C is partially expelled (See talk N. Tamura)
- ECRH kills otherwise stable peaked density - T_i drops back below limit.





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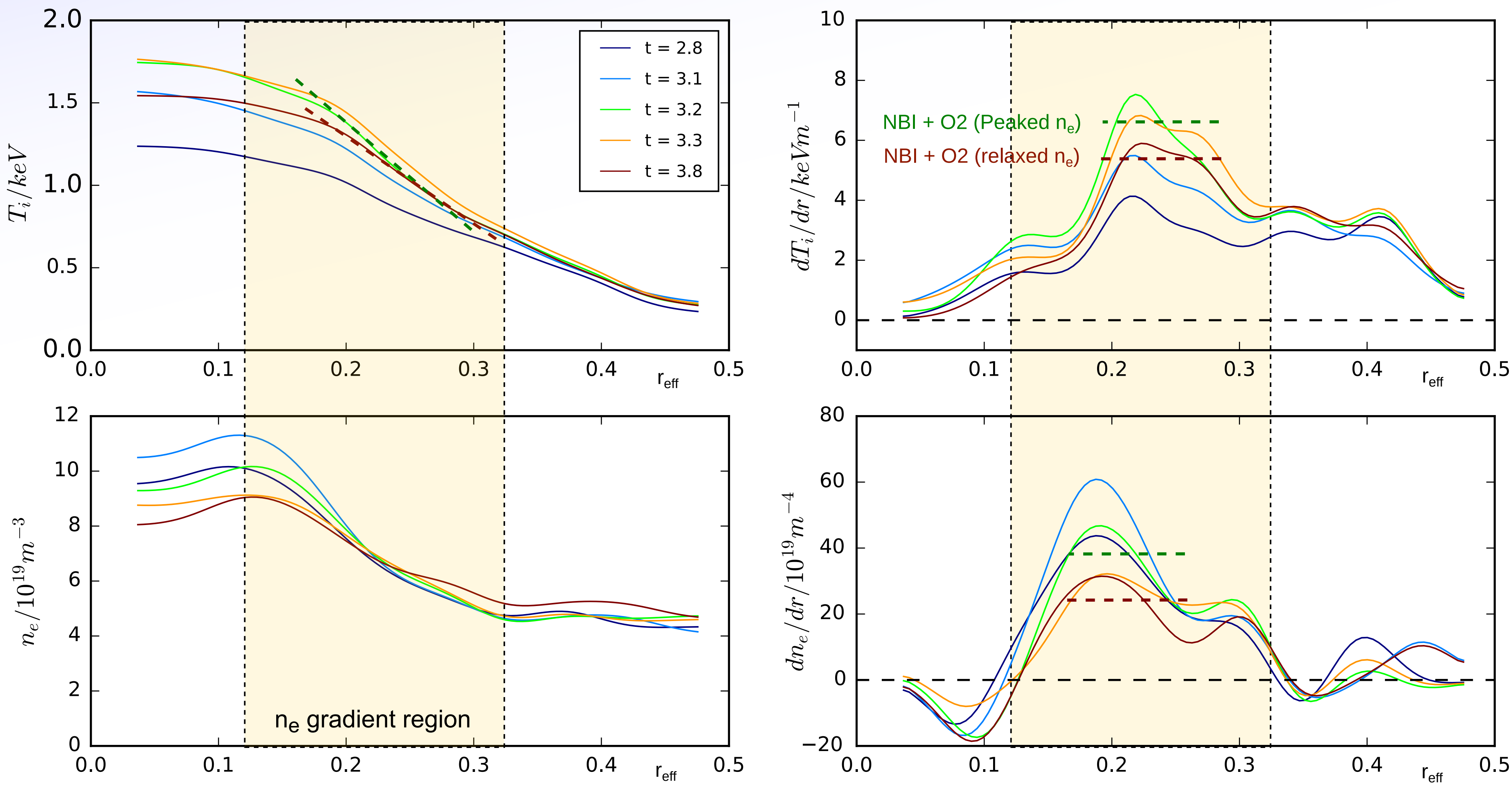
Case 1: NBI + O2 - Profiles

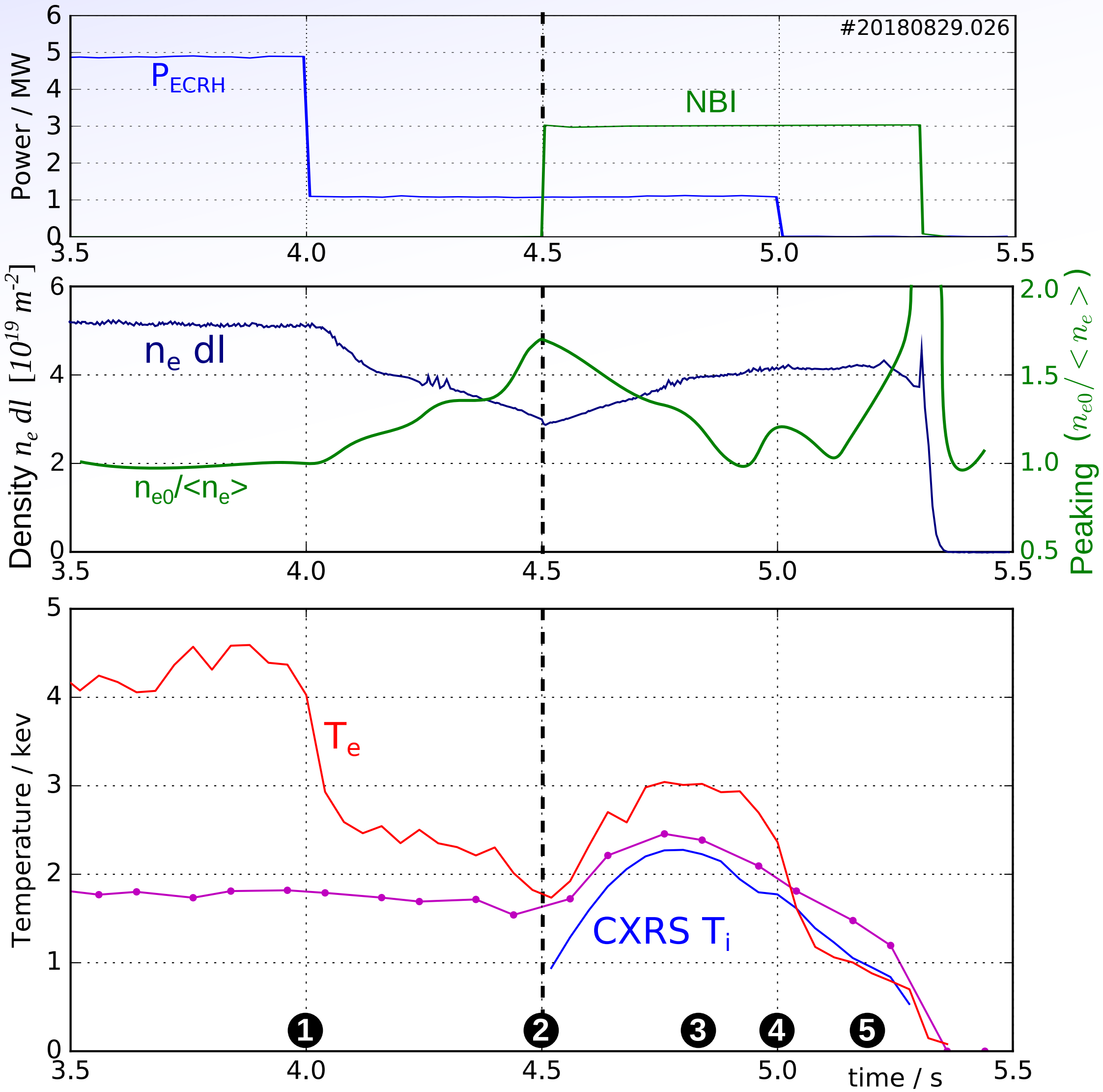
From CXRS data we can see where T_i gradients are comapred to n_e.

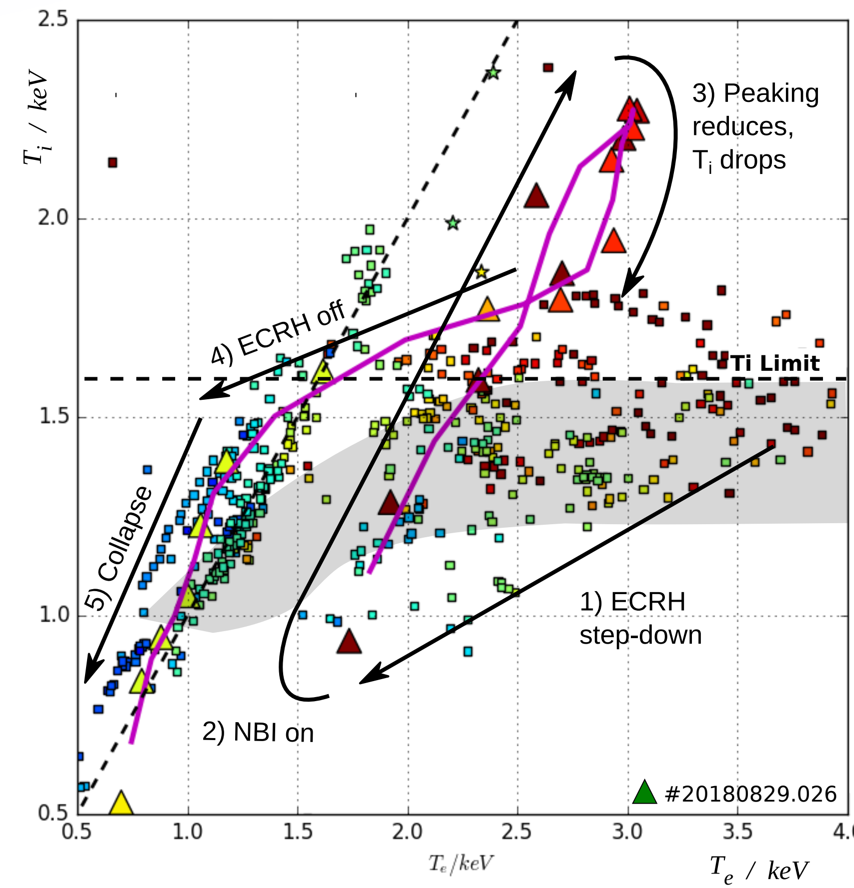
- Coincidence of gradients would support turbulence picture (see talk A. von Stechow)
- Matches approximately in r_{eff} - needs *careful* examination of n_e profile data.
- T_i response delayed in time to n_e.



Case 2: NBI into collapse

- Observed that NBI after ECRH step-down can rise T_i.
- Extreme effect when NBI starts at plasma collapse, which also generates a peaked density profile.
- State is transient and retreats back towards normal maximum (as pellets)





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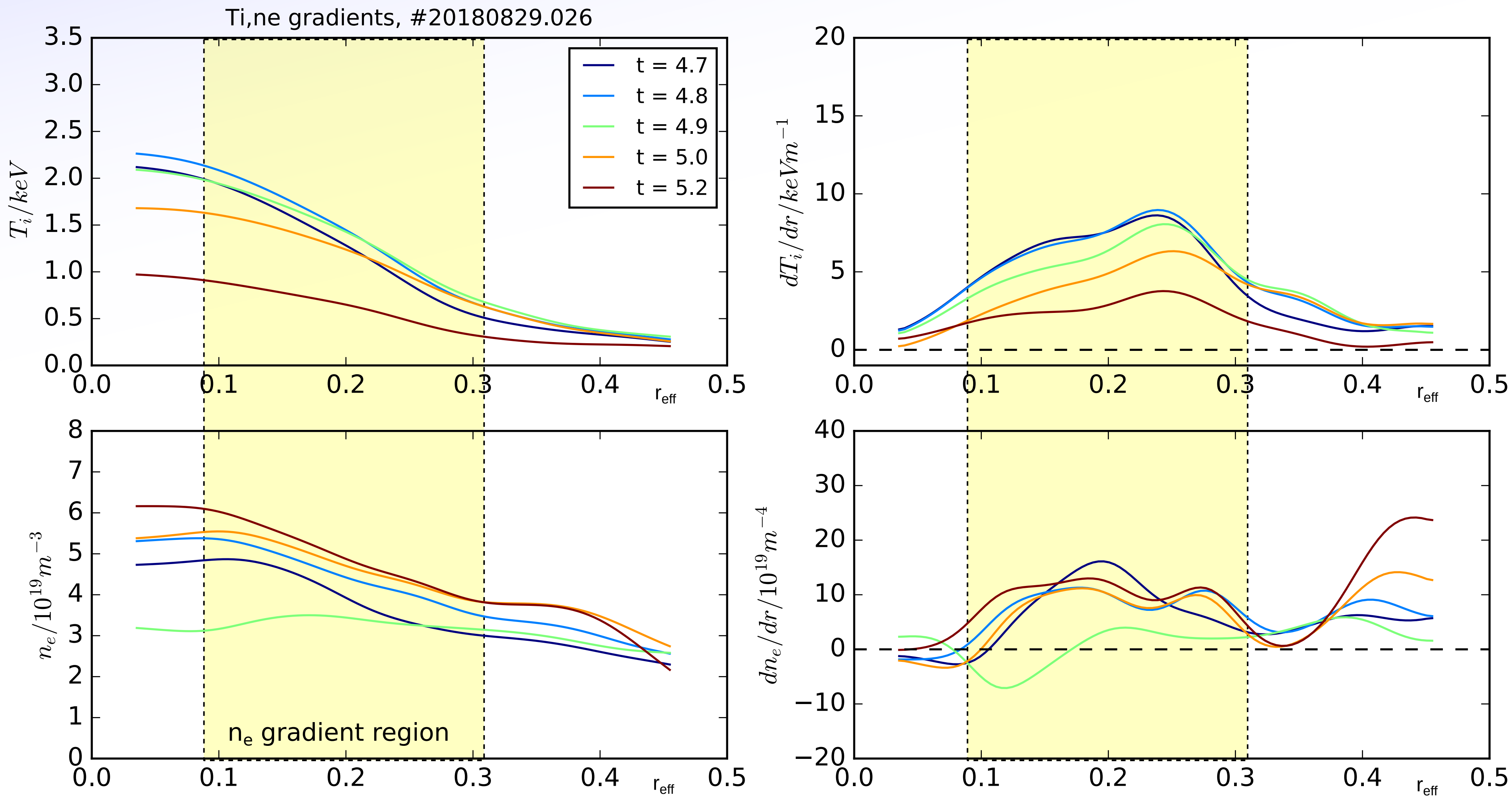
Profiles - NBI into collapse

From CXRS data we can see where T_i gradients are comapred to n_e.

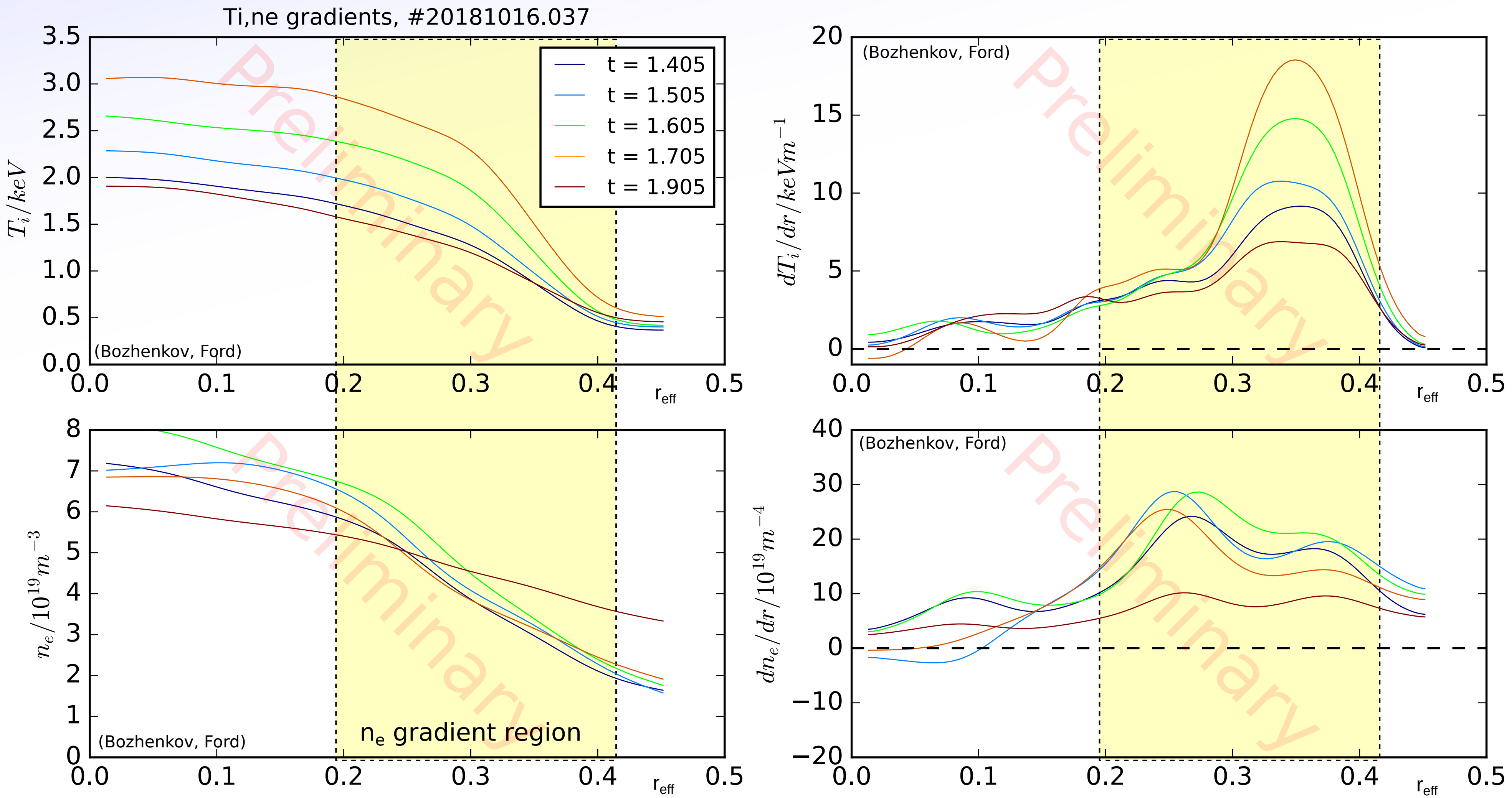
- Coincidence of gradients would support turbulence picture (see. von Stechow)

n_e profiles only marginally able to support idea.



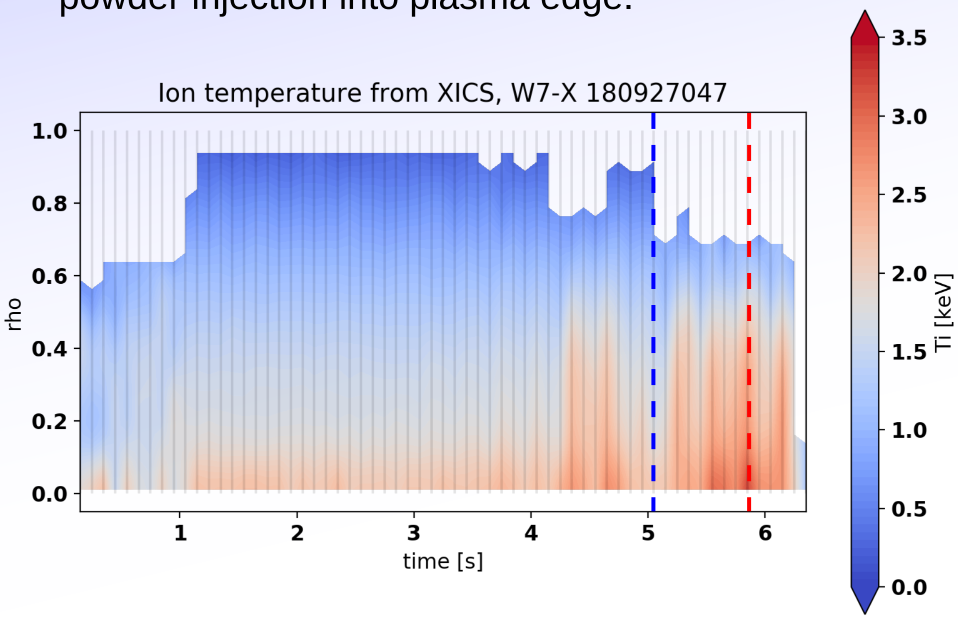
Profiles - Pellets (boz_010)

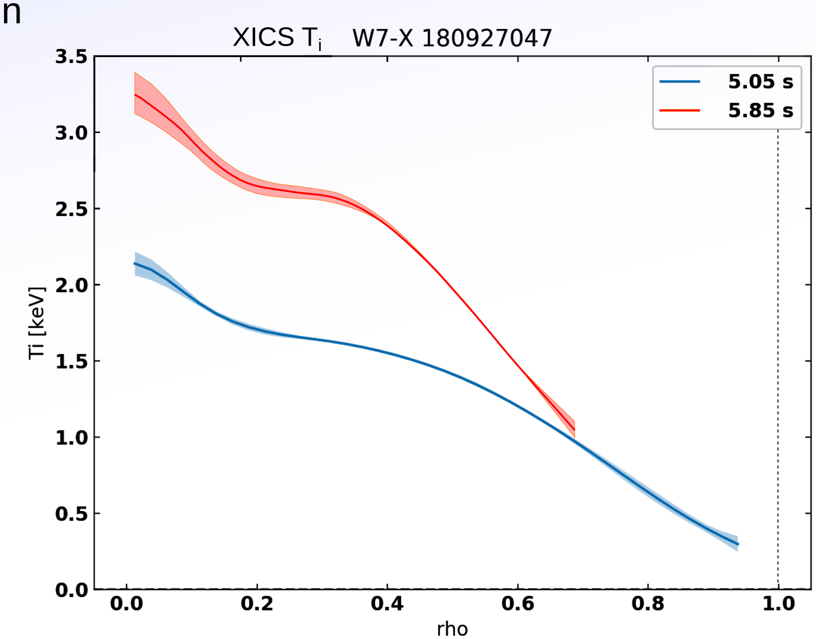
From CXRS data we can see where T_i gradients are comapred to n_e.
- Conincidence of gradients would support turbulence picture (see. von Stechow)
- n_e gradient region appears wider.



Boron powder injection

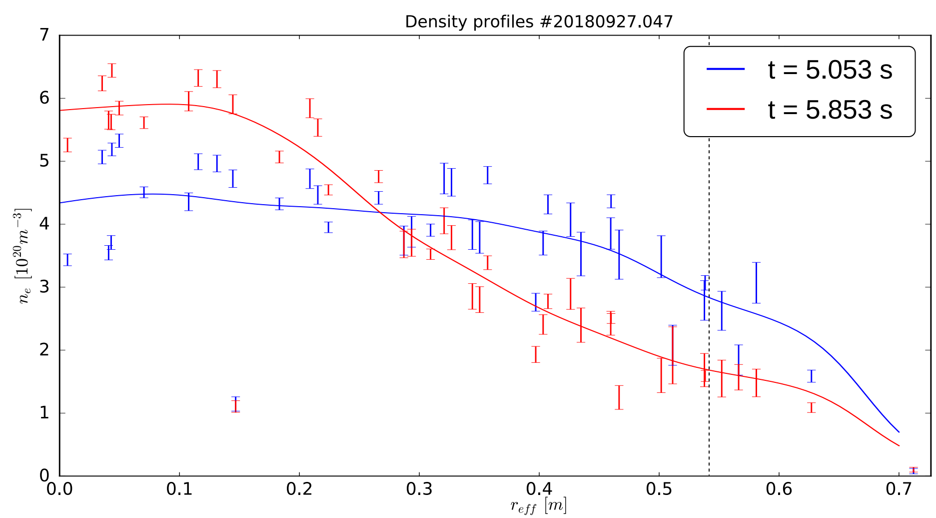
- Higher Ti also observed in one shot with very strong boron powder injection into plasma edge.





- Steepening of n_e gradient by reduction of edge n_e.

- Should consider if strong edge seeding could be used to control edge n_e.



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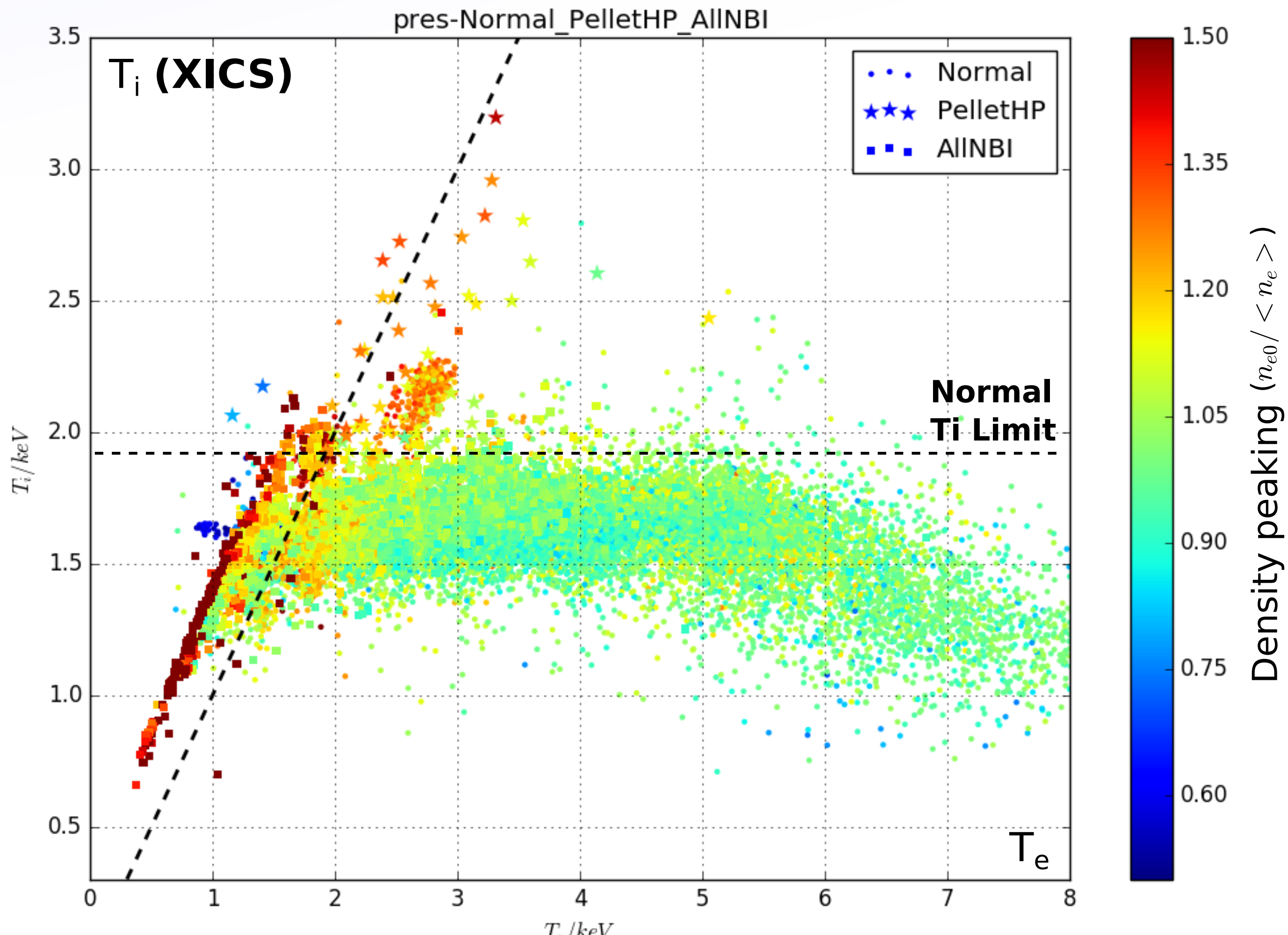
Density Peaking

- Density peaking is common to all observed cases of T_i > 1.9keV XICS.
- Currently seen in:
  1) High performance pellets shots
  2) NBI
  3) Spontaneous slowly rising cases in ECRH
  4) Boron powder dropper.
  5) Some TESPEL cases.



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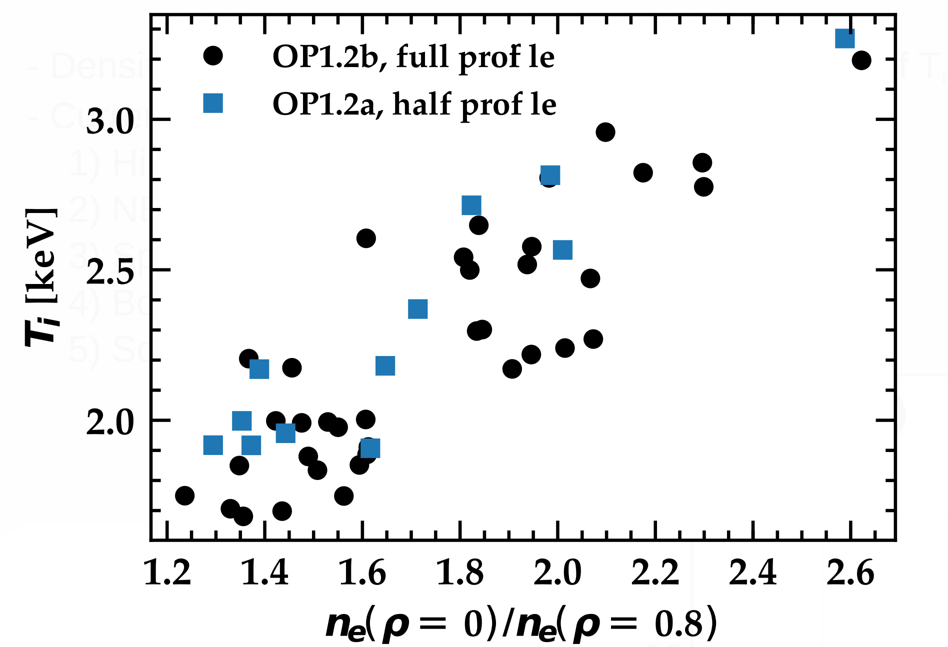
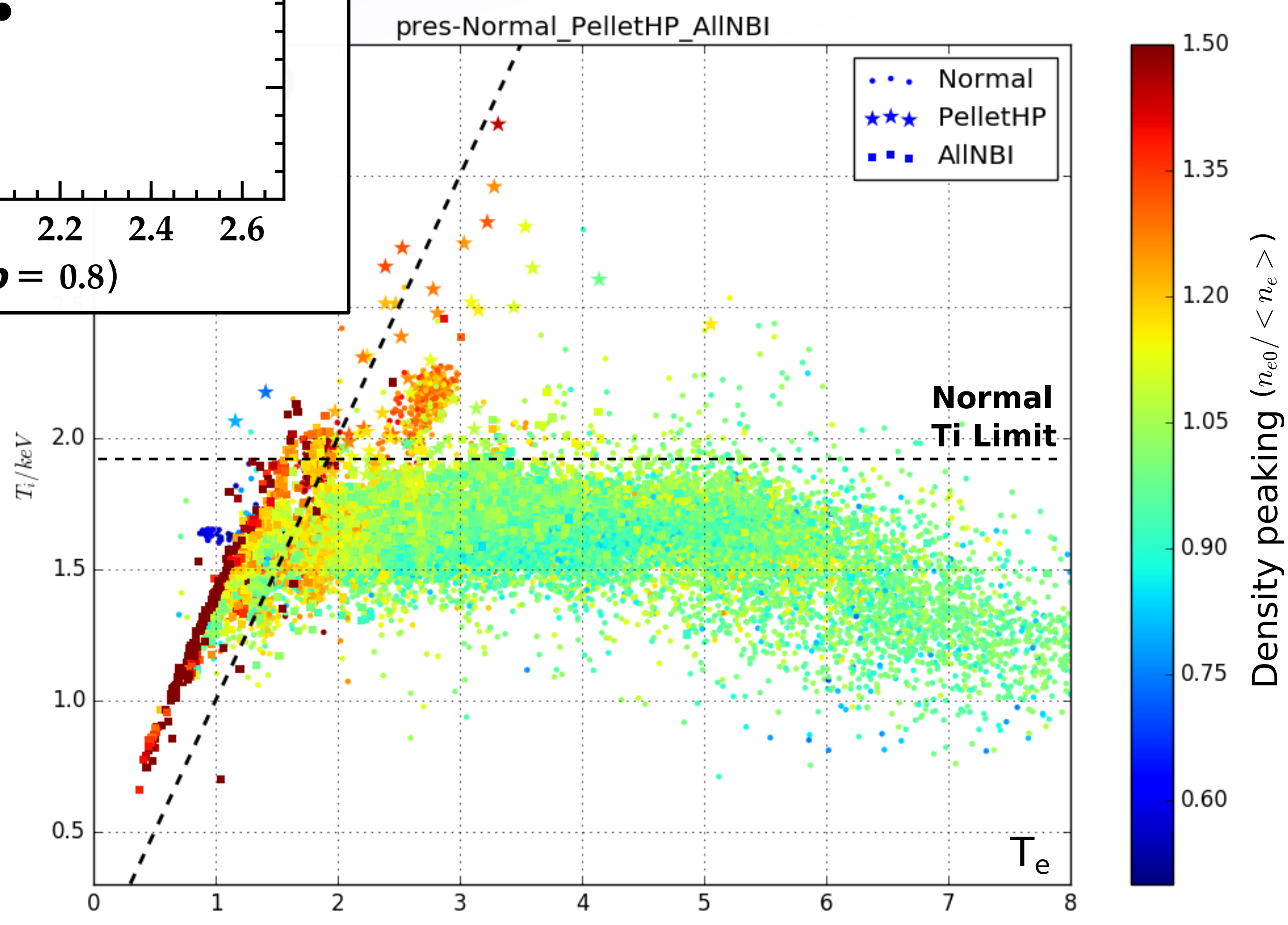
Density Peaking

$>$ 1.9keV XICS.

Correlation of best performance with peaking factor:





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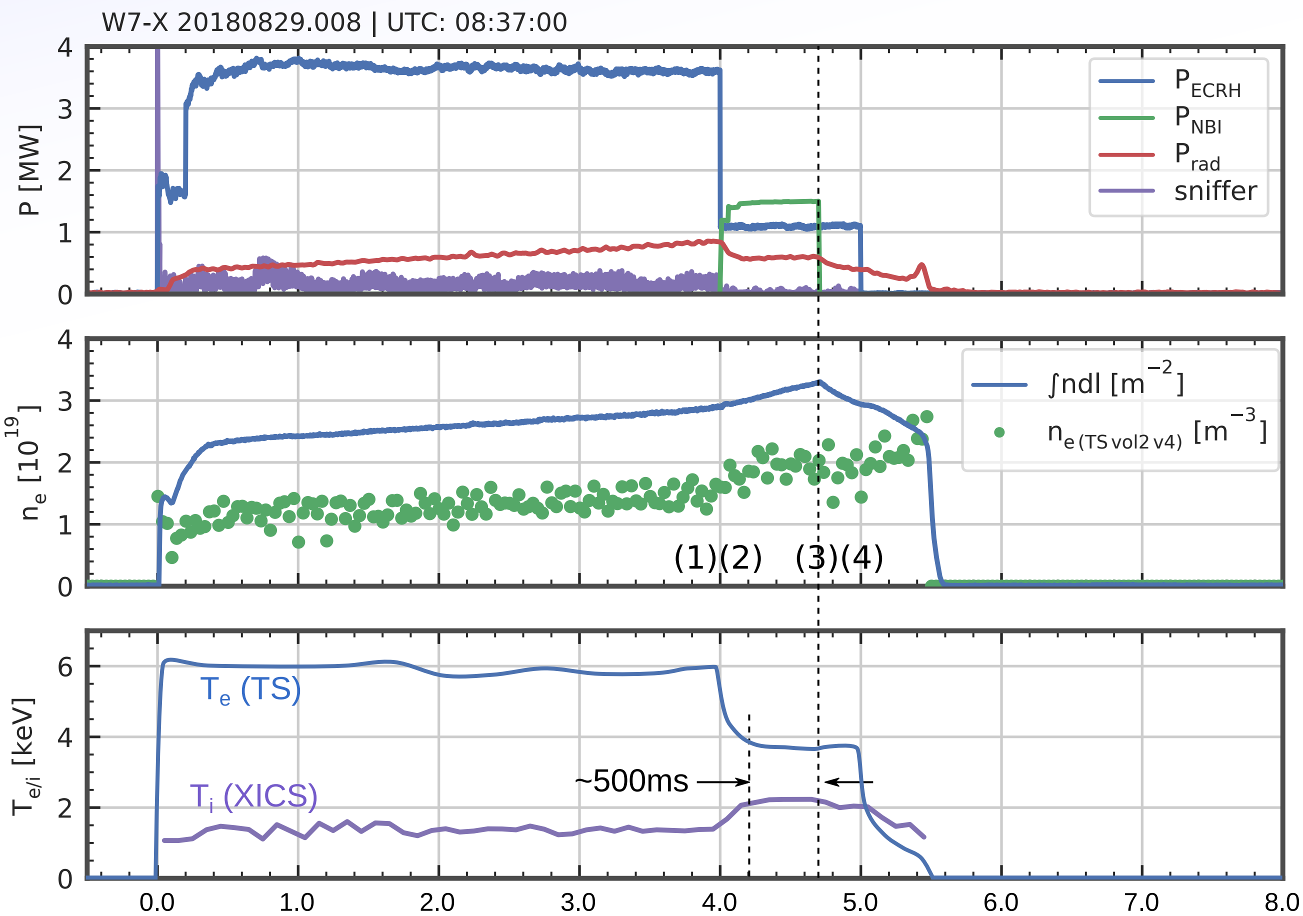
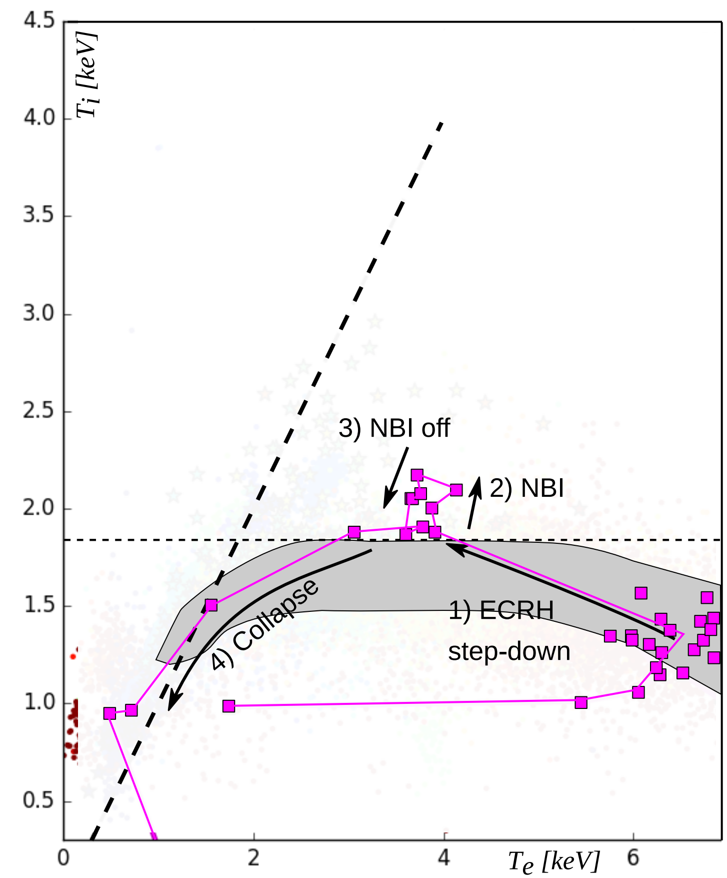
Stationary(ish) cases

- Can we maintain sufficient density peaking?
- Cases so far have all been transient, but there are some almost stationary/stable cases, albeit with low power.

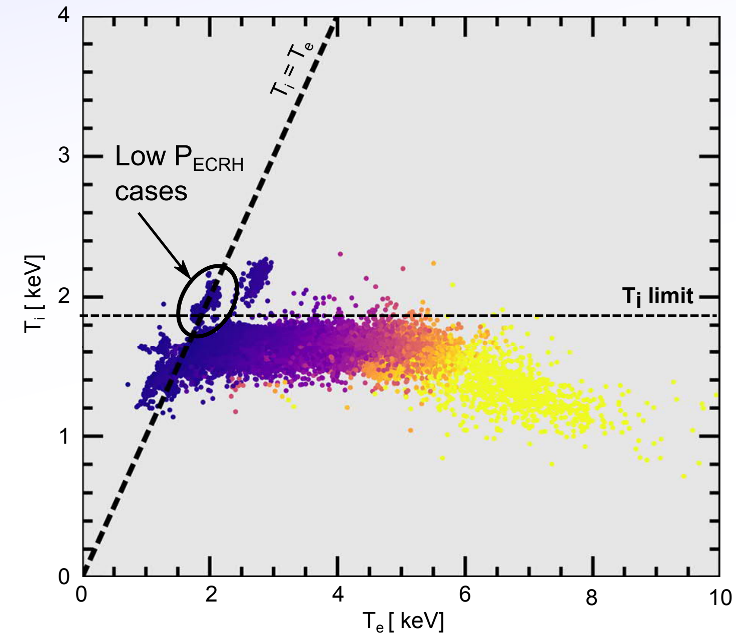
NBI at low ECRH:
(but with slowly rising core density)

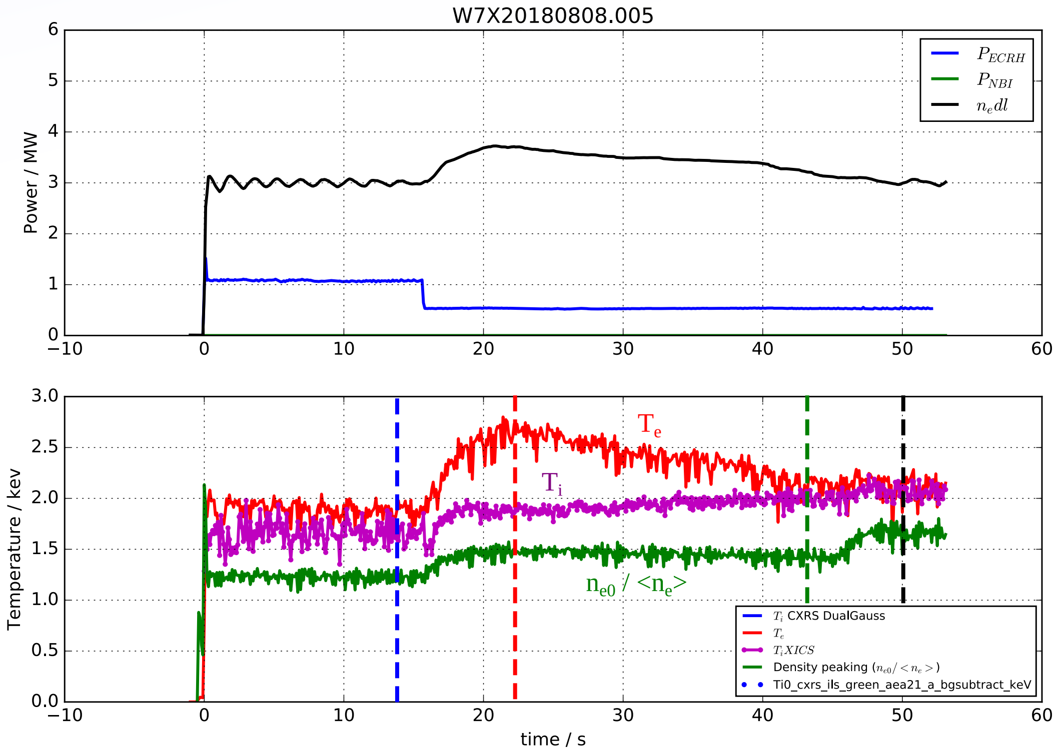


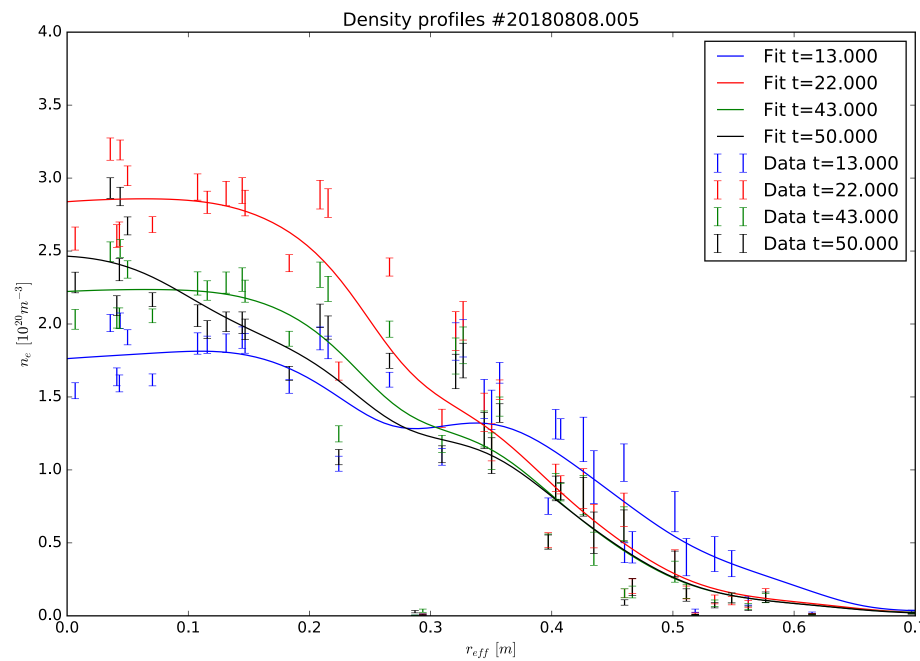


Stationary cases

The two low-power ECRH cases from the main database:
- Immediately after boronisation.
- Low edge density leads to steep gradient.
- Very stationary: ~ x10s seconds
- Low ECRH power --> low recycling







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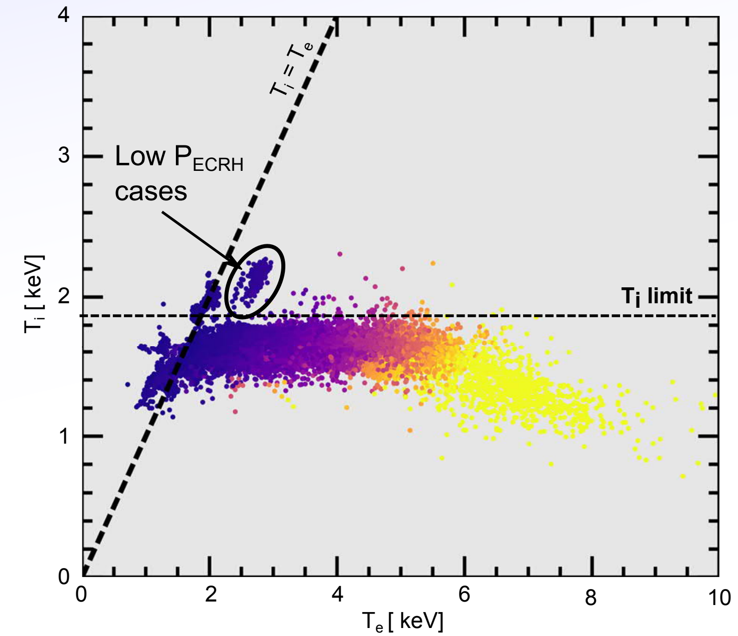
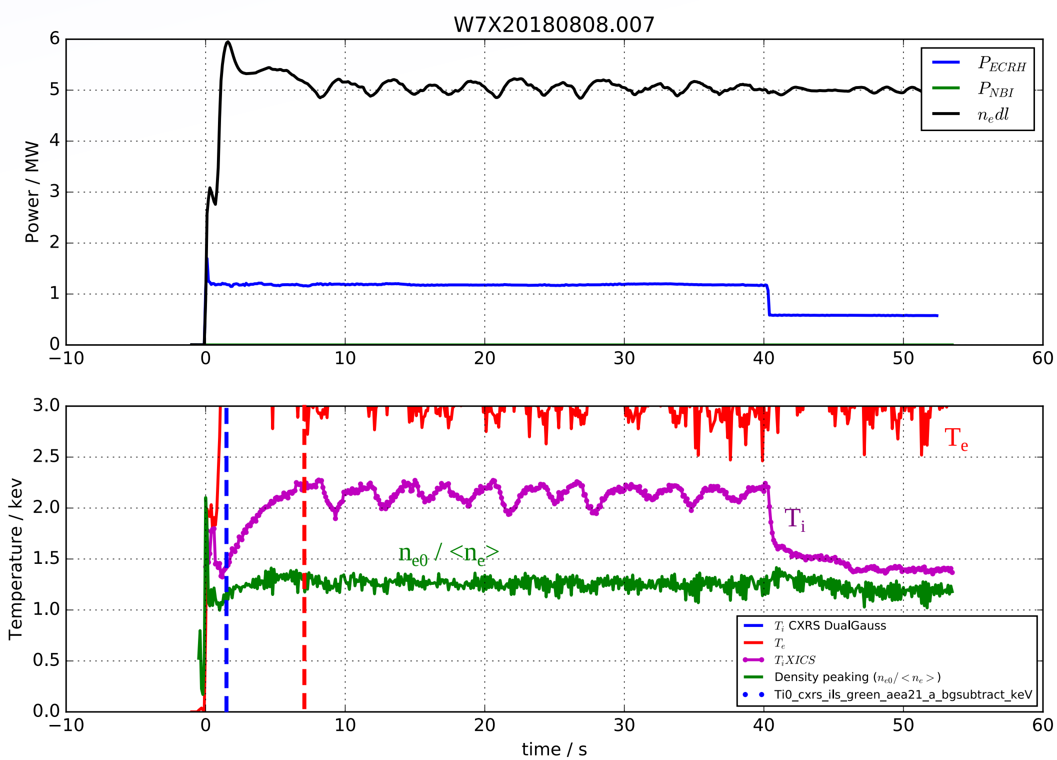
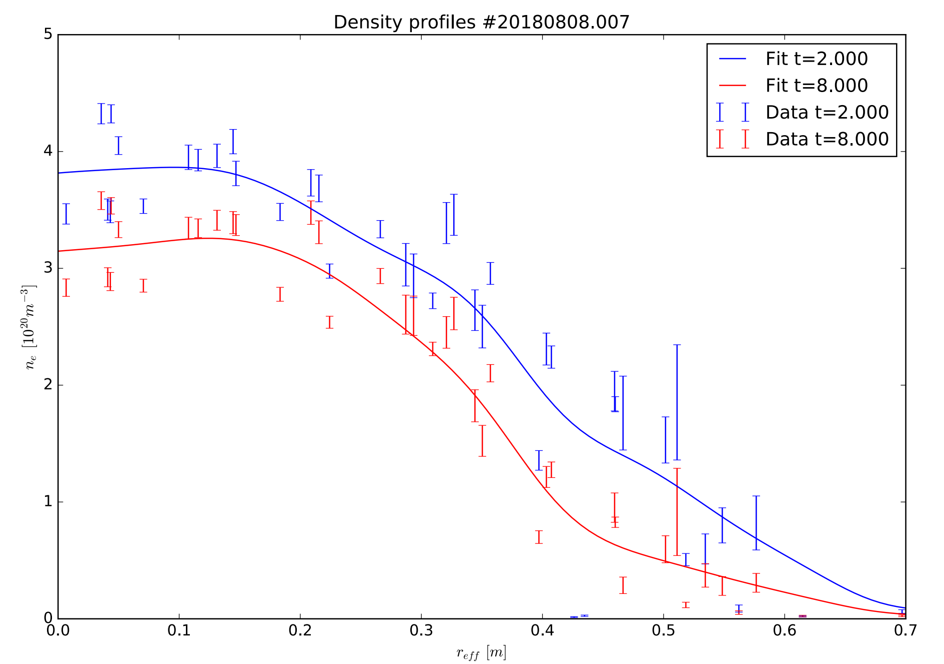
Stationary cases

The two low-power ECRH cases from the main database:

- Immediately after boronisation.
- Low edge density leads to steep gradient.
- Very stationary: ~ 30s seconds
- Low ECRH power --> low recycling
- Density control (modulation) seen in T_i.







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Routes to T_i > 1.6keV

- Ti will remain at 1.6keV in gas-fuelled ECRH plasmas, regardless of increase in P_{tot} or n_e.
- To improve it, we need to diversify our approach.

Possible routes:

1) Density profile control

1) Pellets 2) NBI 3) Edge impurity seeding?

2) Turbulence optimised magnetic configurations.

3) ITG Stabilisation with ICRH

4) Transport barriers: i.e. 'H-mode might happen' - No observation yet, but L-H usually comes with higher power.

Only #1 has been shown so far, so...

Density profile diagnosis/control may be critical to high beta operation.

We should start to examine:

1) How does n_e gradient affect achievable Ti --> TG Turbulence.
   - We see various cases with very different n_e/T_i profiles but same qualitative effect.
2) Is the n_e profile sufficiently well diagnosed for the necessary gradient calculation?
3) How can we actuate the density profile?
4) Can this be done in steady-state?
5) Is this compatible with other steady-state requirements? (e.g. detachment, impurity control)

Performance of stationary ECRH plasmas

- no or very weak configuration dependence
- mainly consistent with the ISS04-scaling (can be below, see *G. Fuchert*)
- **hardly any dependence for the ion temperature**

Scaling-up

Given the ISS04 scaling one can roughly see what parameters we can achieve with more heating power, assuming the same plasma regime (note, that the ion temperature is fixed):

$$\tau \sim n^{1/2} \cdot P^{-1/2}, n_{max} \sim P^{1/2}$$

$$W_{dia} = P \cdot \tau \sim n^{1/2} \cdot P^{1/2} \leq P^{3/4}$$

$$n \cdot T_i \cdot \tau \sim n \cdot \tau \sim n^{3/2} P^{-1/2} \leq P^{1/4}$$

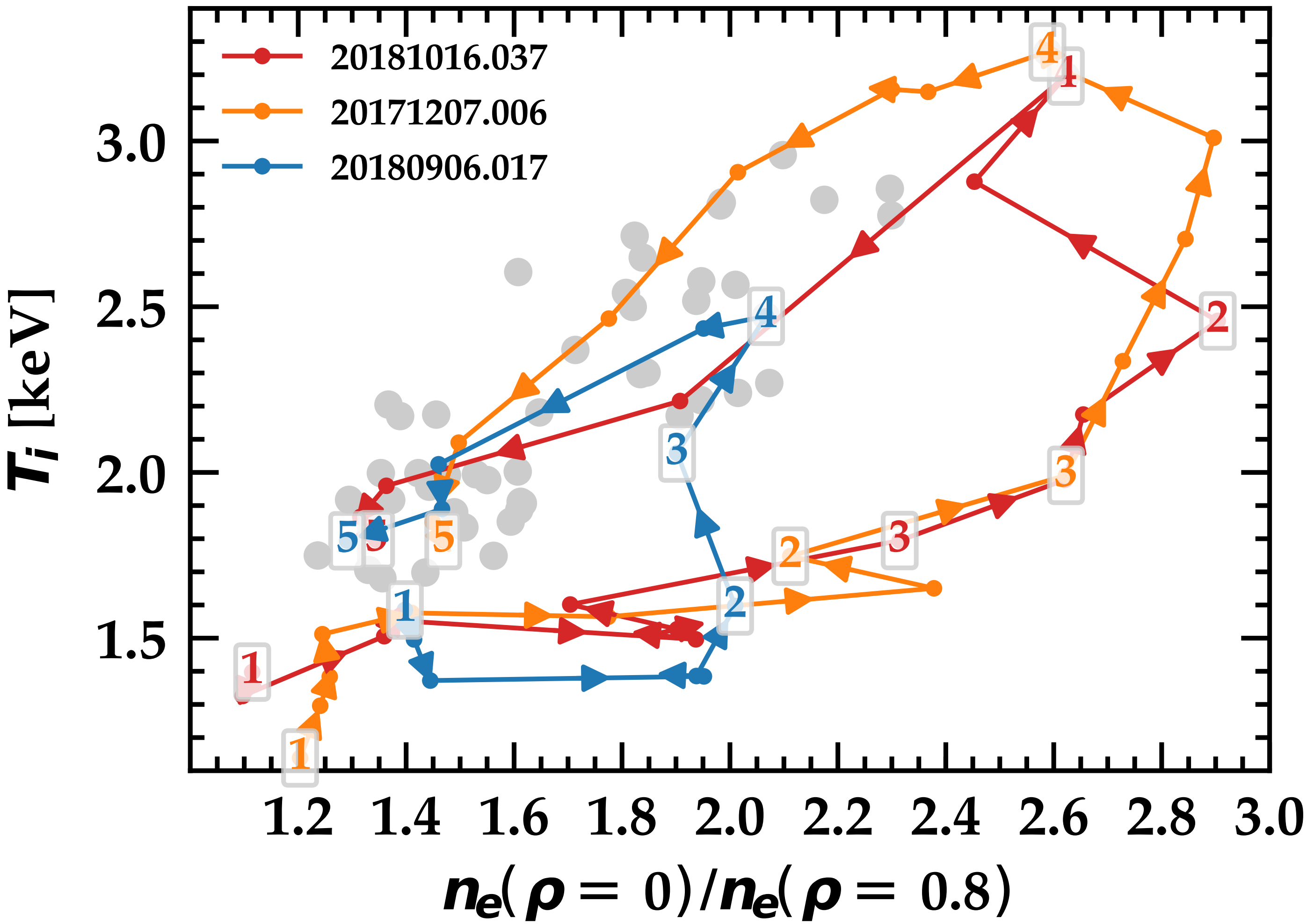
But, we have almost reached the O2-limit (1.5 vs 1.8), i.e. from certain point the density will be fixed:

$$\tau \sim P^{-1/2}, n_{max} = n_{limit}$$

$$W_{dia} = P \cdot \tau \sim P^{1/2}$$

$$n \cdot T_i \cdot \tau \sim n \cdot \tau \sim P^{-1/2}$$

Pellet trajectories



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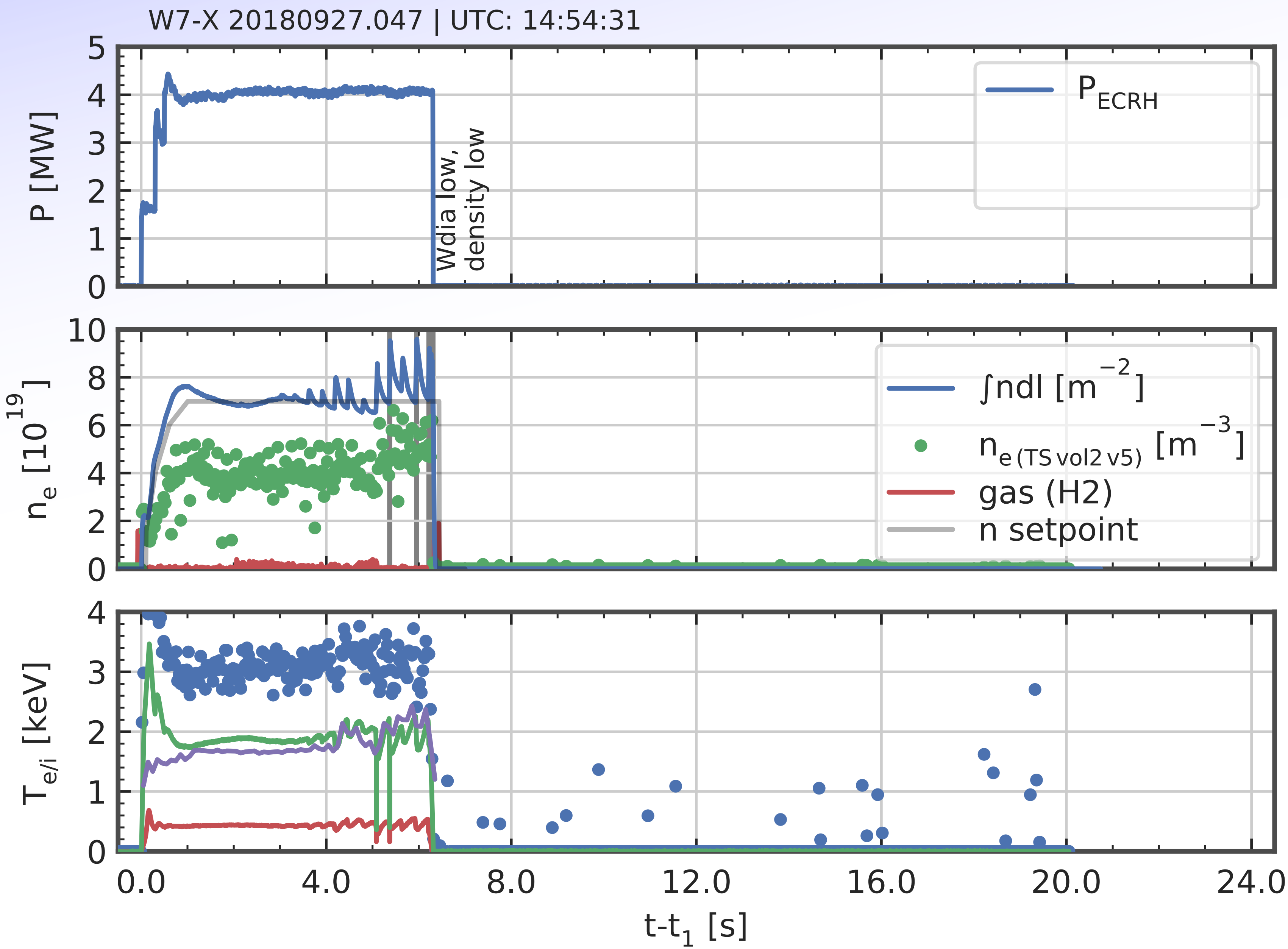
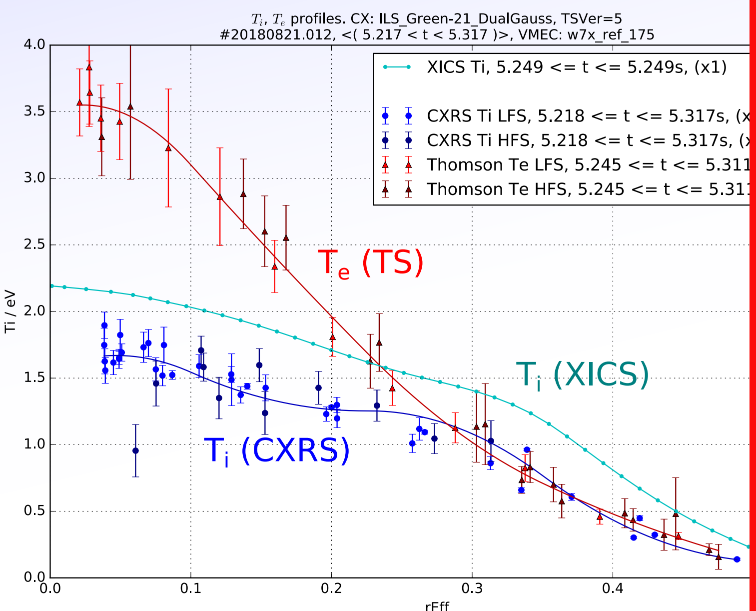
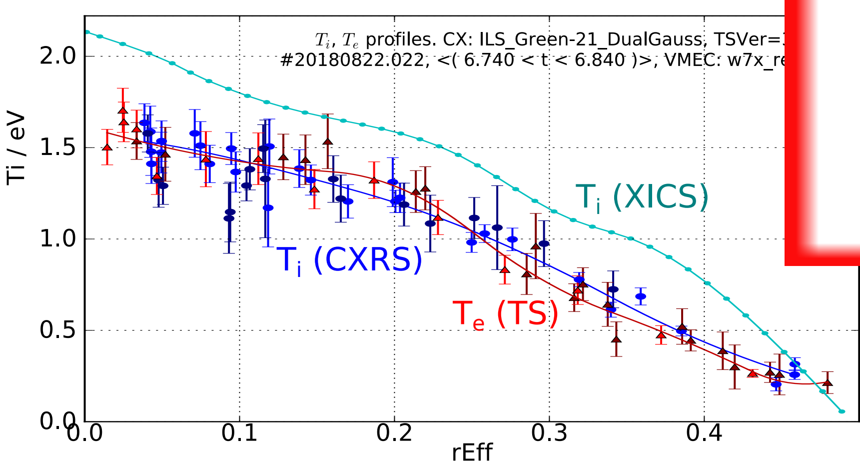
Boron powder injection



XICS --> CXRS

- CXRS gives higher resolution data, but only where NBI is on (~200 shots)
- To compare the two, we need to adjust for ~250±150eV higher core XICS T_i values:
(More on this in a later presentati[...]





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Beam deposition (T.W.C.Neelis)

Measured beam deposition
(ignoring Halo CX broadening)
may partly explain central peaking: