Ion heating and thermal confinement: NBI / ICRH routes to high performance (T_i)?

TG Profiles / TG Confinement / E3 Retreat

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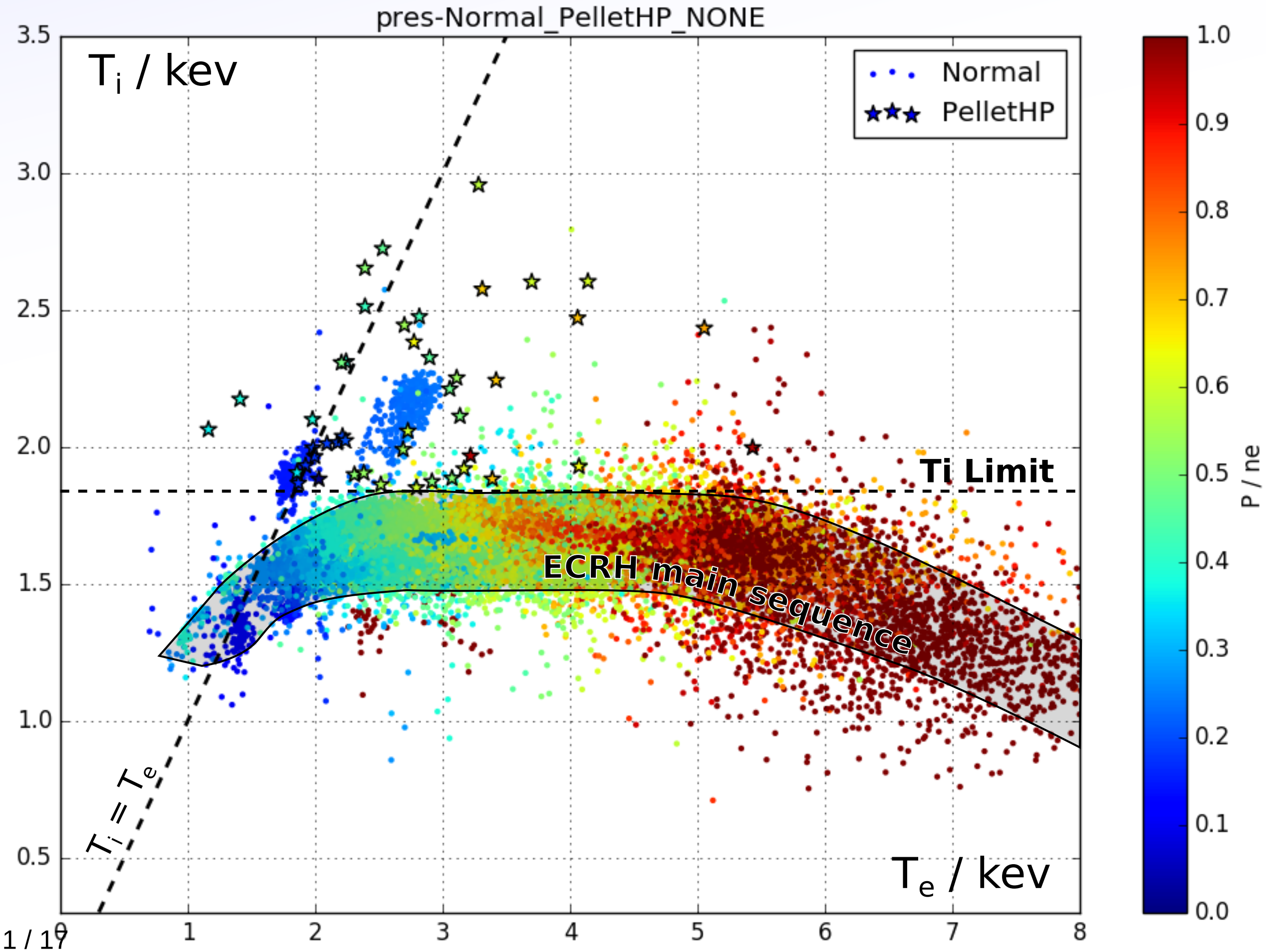
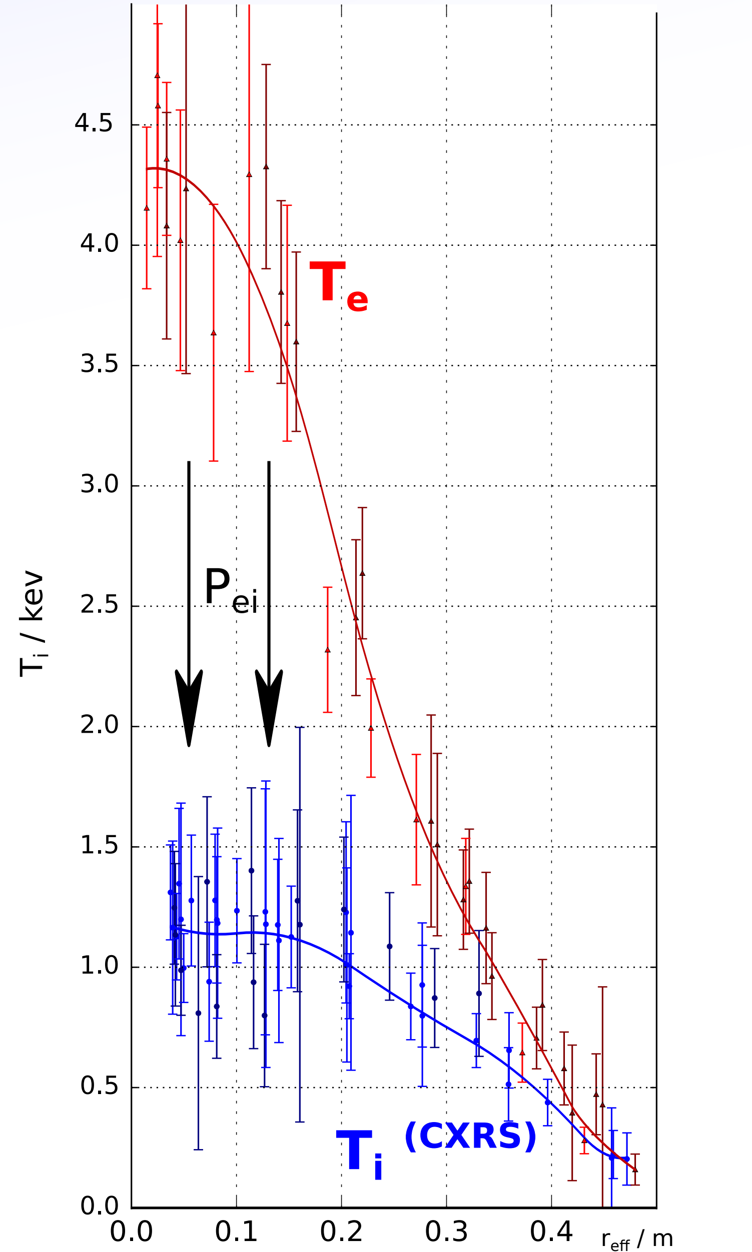
Ti profile resilience: ECRH

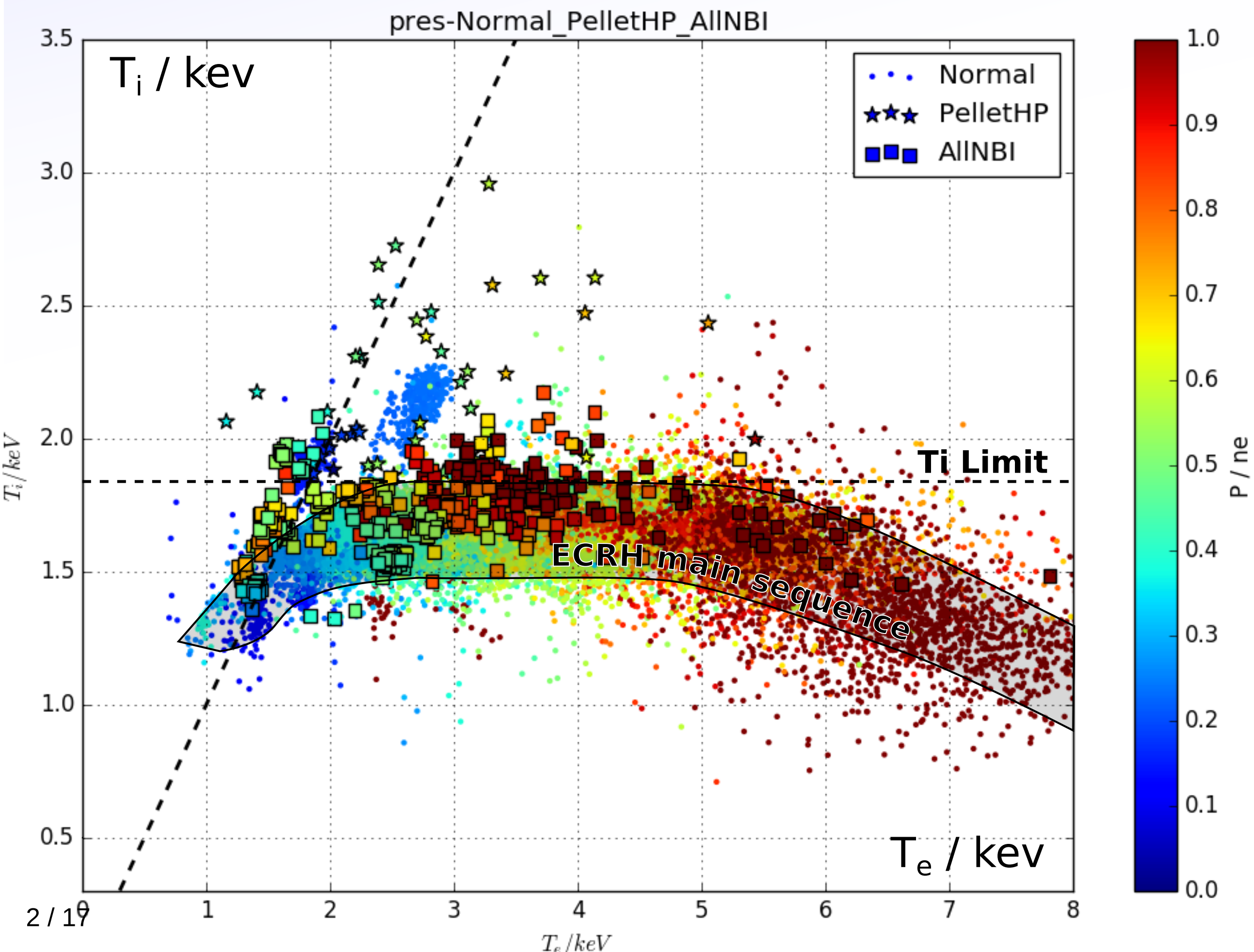
- Core Ti usually within same range and profile gradients similar regardless of P_{ECRH} and electron-ion coupling.
- Leads to effective Ti limit ~ 1.8keV (XICS)
- Exceptions:
  1) High-Performance pellet discharges
  2) Some particular low P_{ECRH} cases.

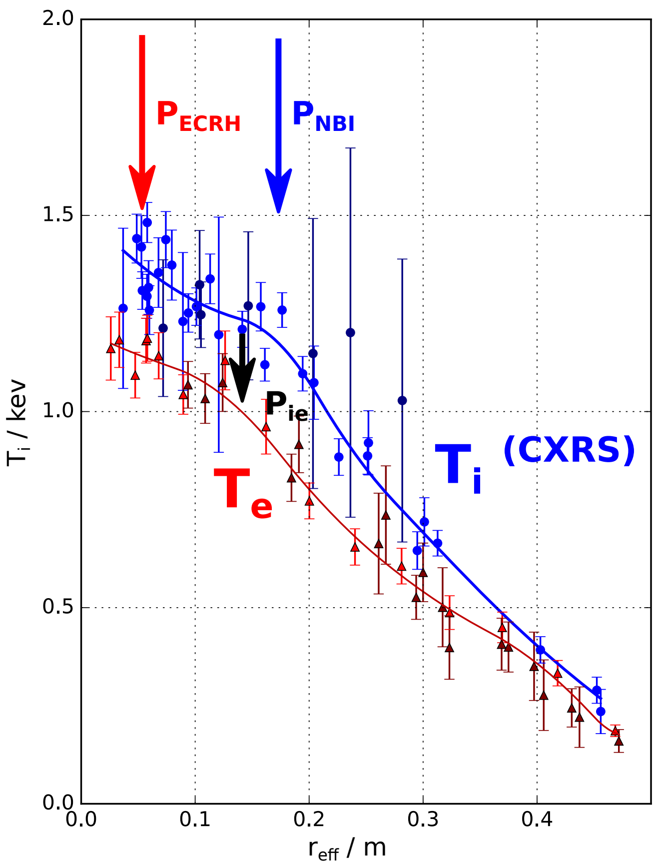




Ti profile resilience: NBI

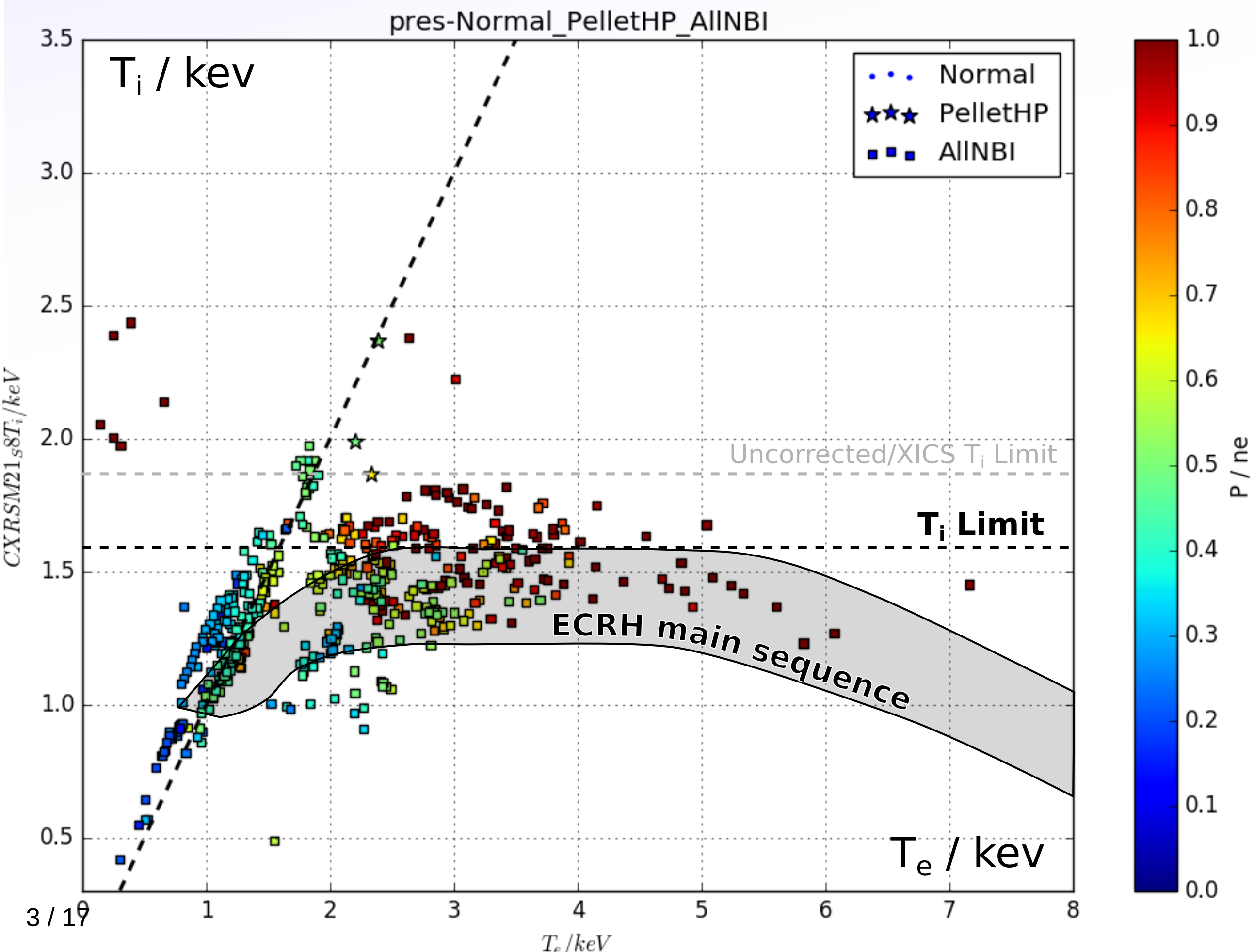
- NBI does typically not raise Ti significantly in normal ECRH plasmas, despite significant direct ion heating (>50%).
- Consistent with the existence of a critical Ti gradient.
- NBI also shows some exceptions. For detail, look at CXRS Ti...





XICS --> CXRS

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



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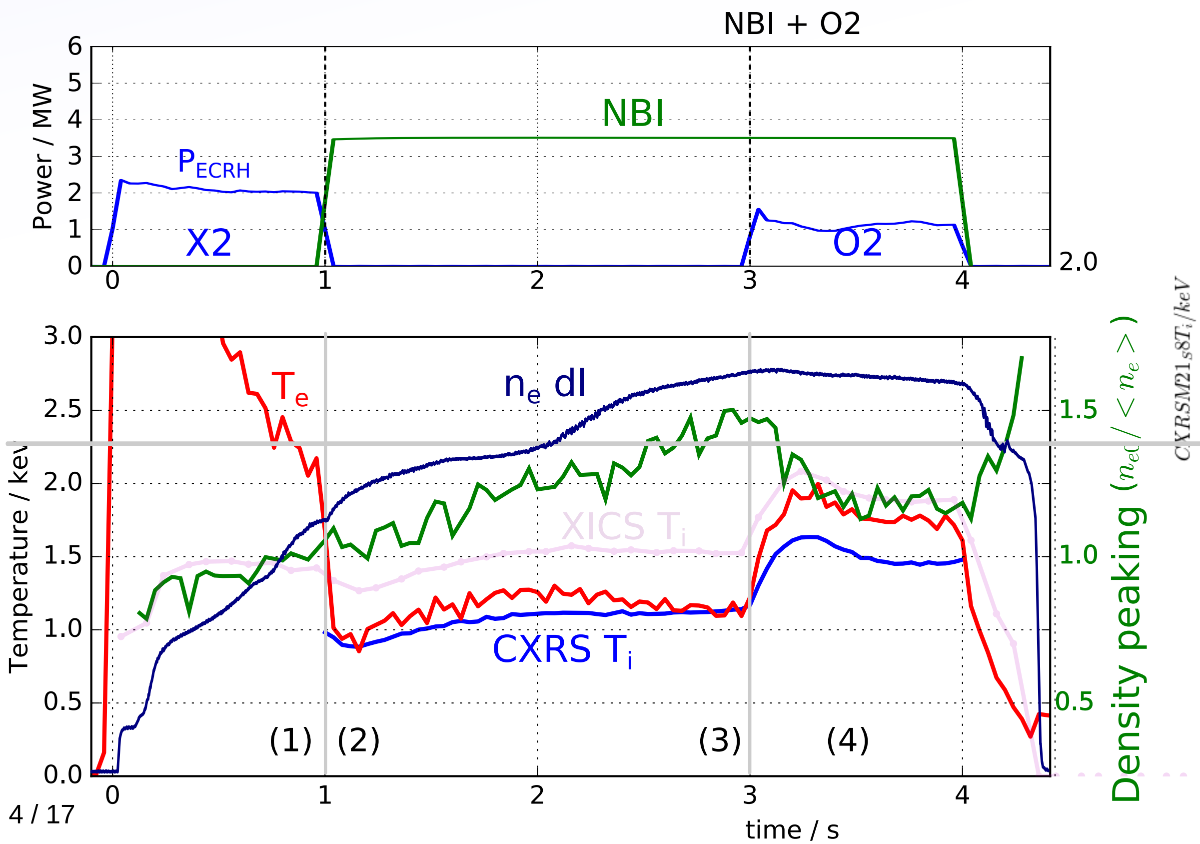
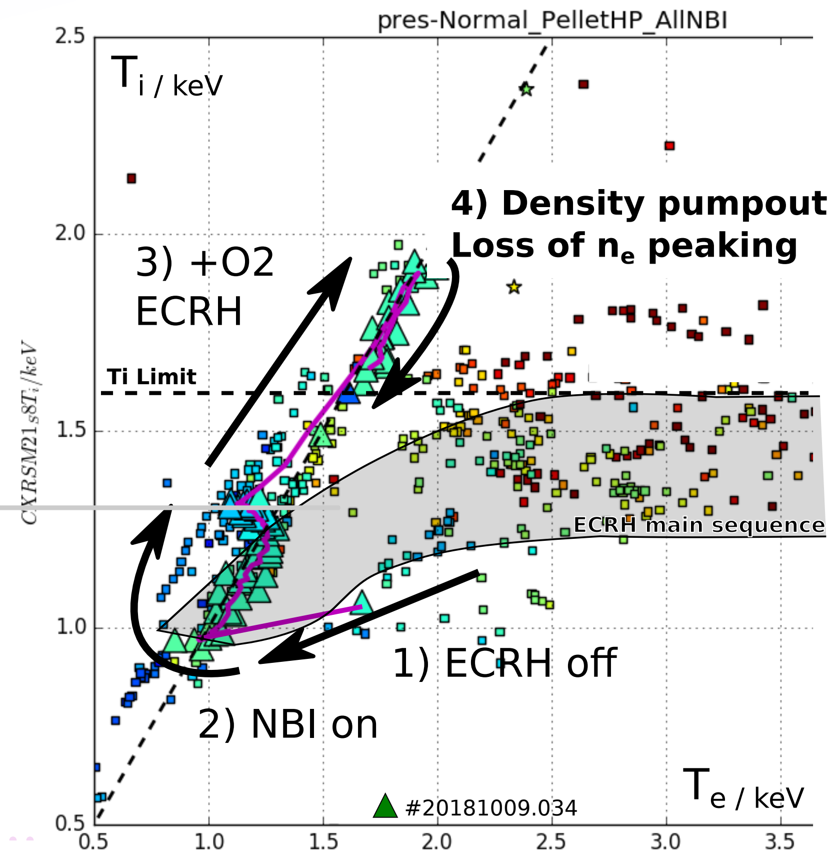
Case 1: NBI + O2

- Observed that NBI created peaked density profiles (similar to high-performance pellets) with steadily increasing density.

(S62/olfo_012): Can we use low power ECRH to control density level/peaking, expel impurities and increase T_e??

- Core density drops after O2 reintroduction.
(Also see explusion of Carbon)





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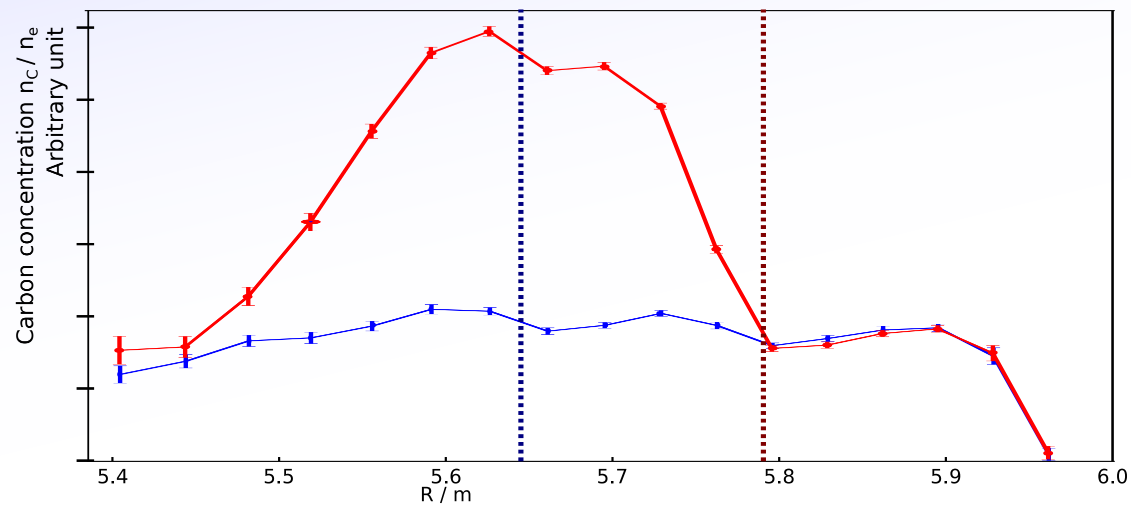
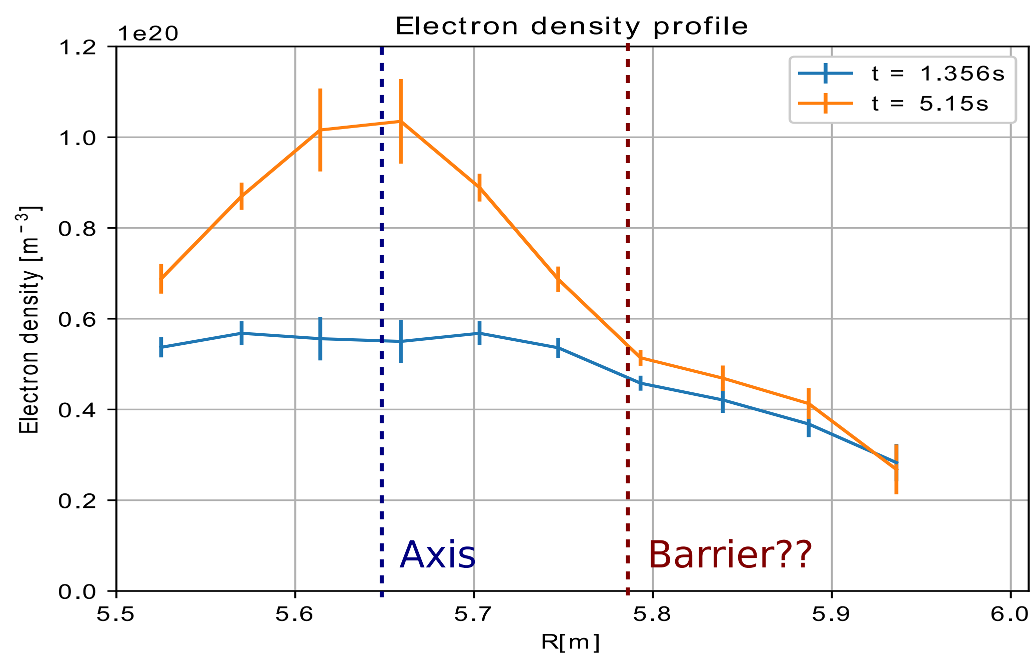
S. Äkäslompolo

Beam deposition (T.W.C.Neelis)

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

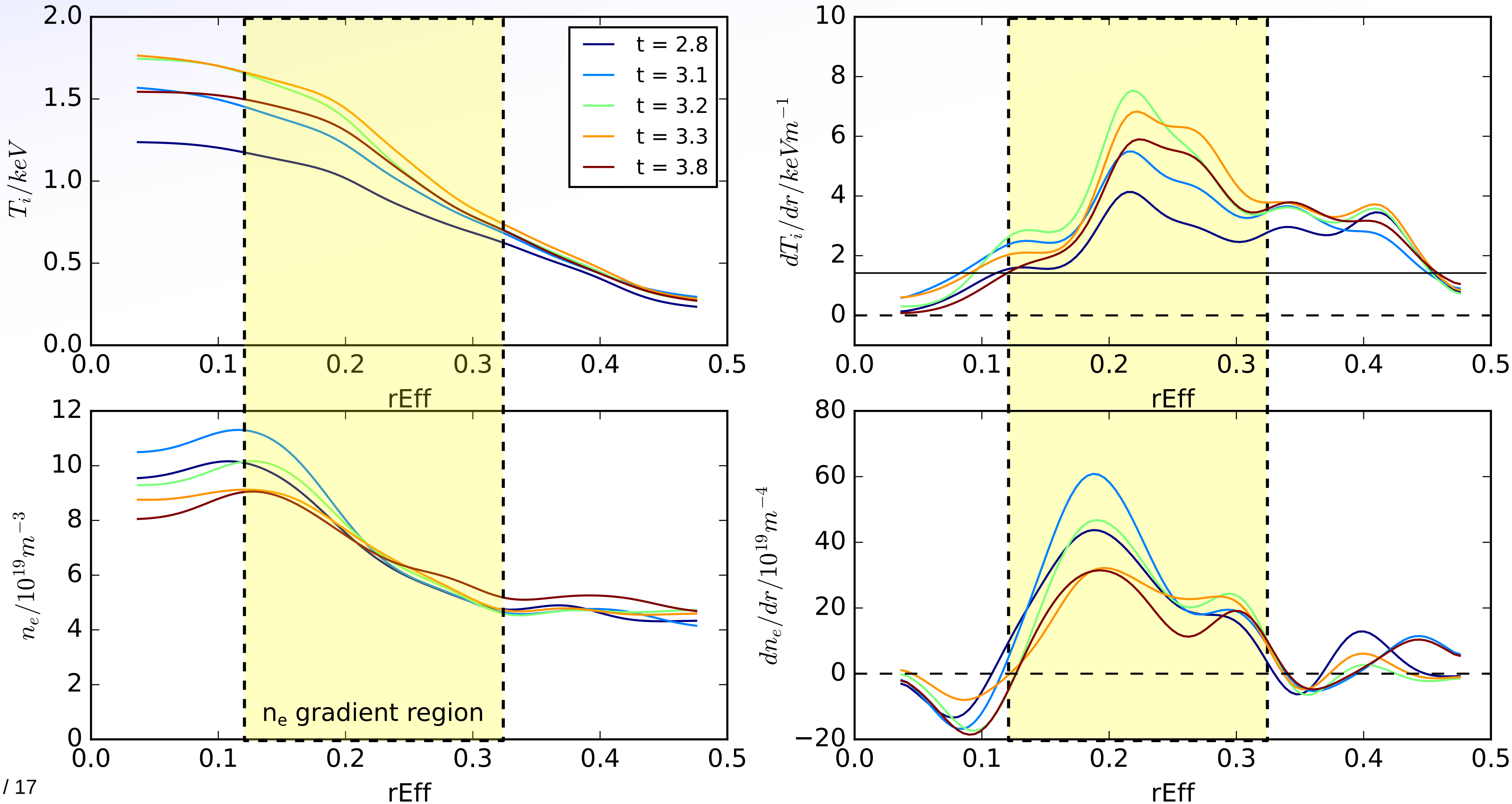




Profiles

Start looking at exactly where steeper Ti / density gradients are.
High resolution CXRS mode (all optics, all spectrometers). 6 point spline fit:

NBI+O2:



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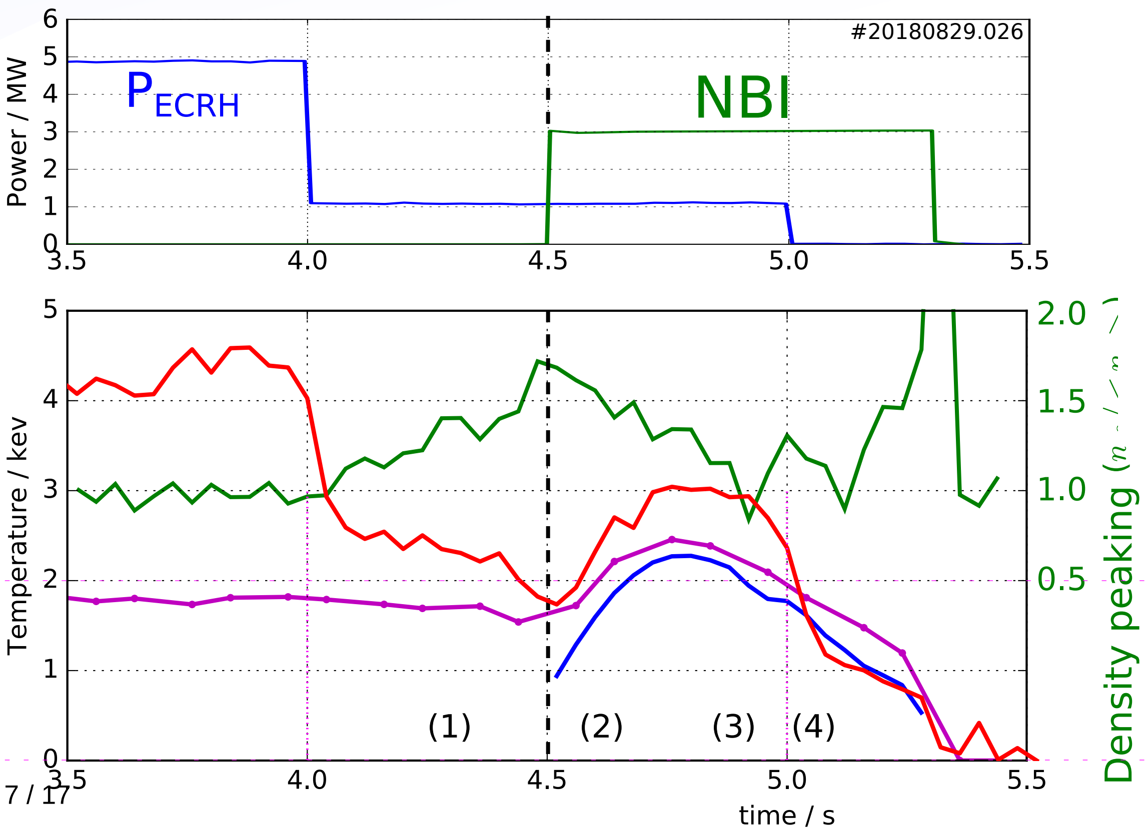
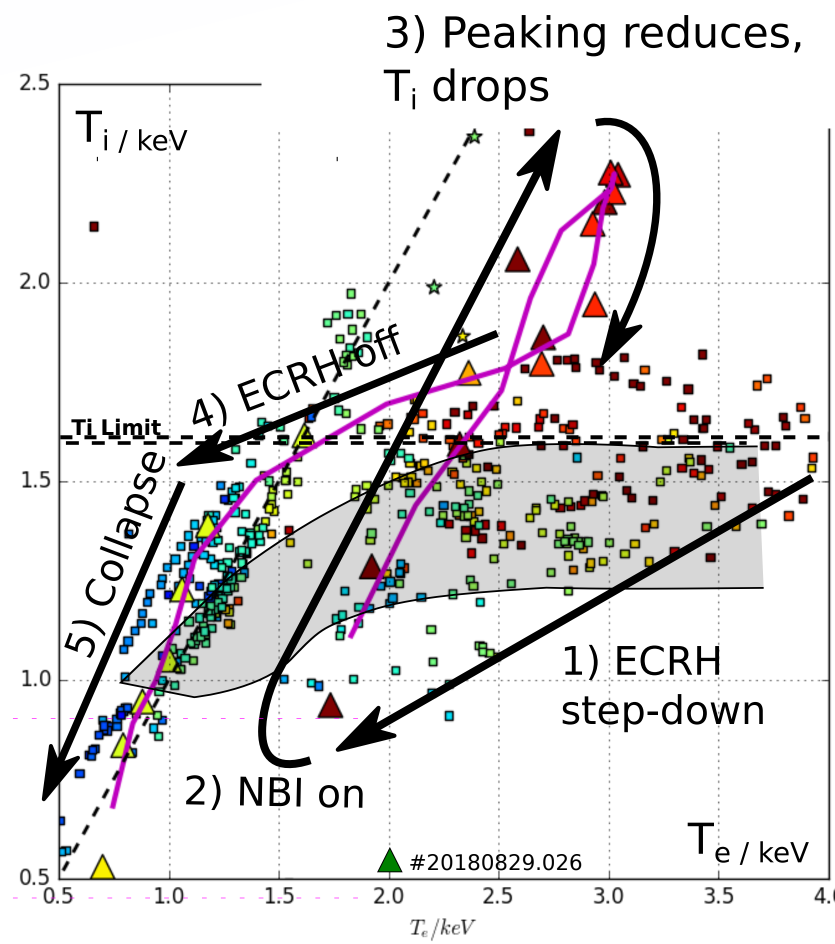
Case 2: NBI into collapse

- 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.
- Like pellets, state is transient and retreats back towards normal maximum.

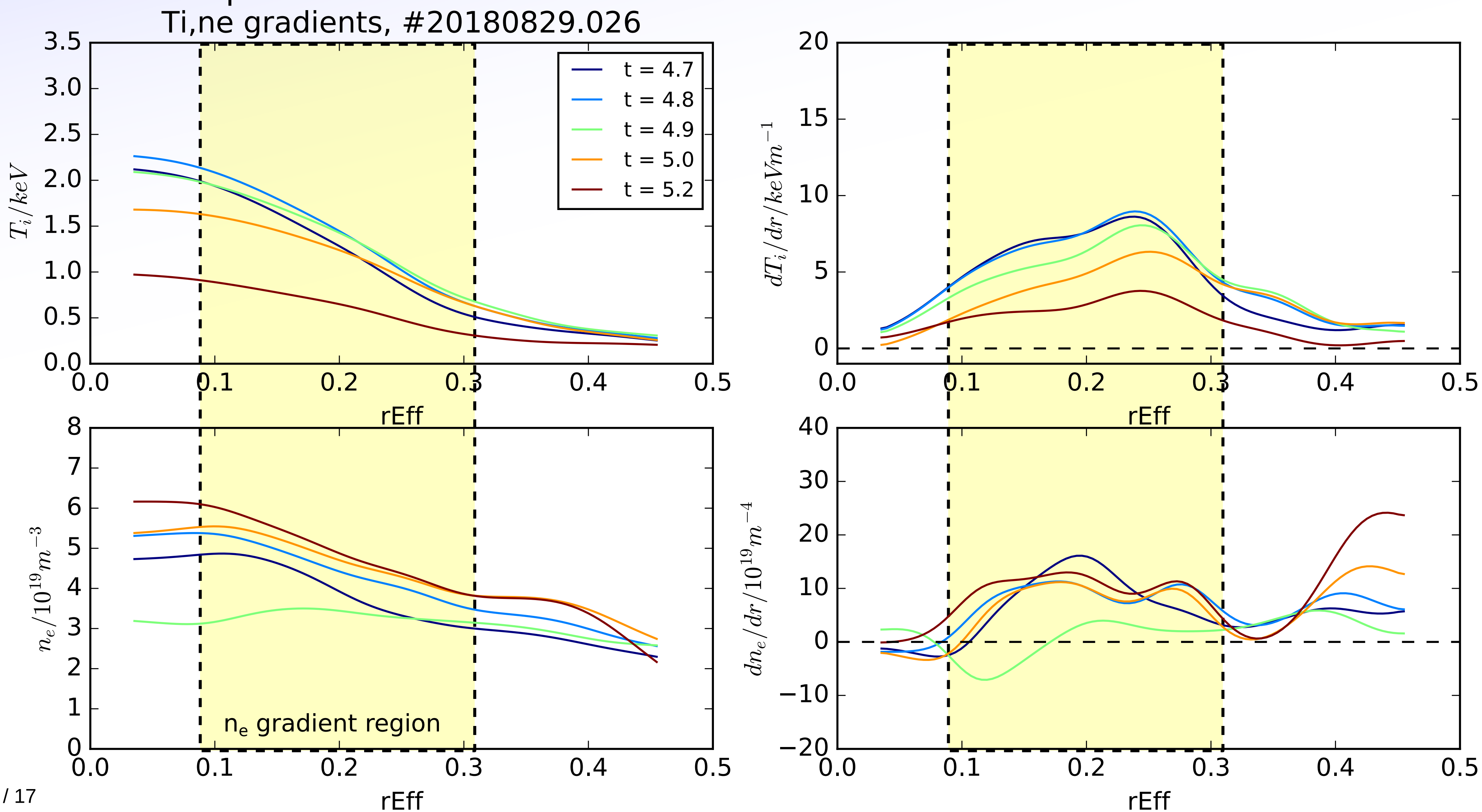




Profiles

Start looking at exactly where steeper Ti / density gradients are.

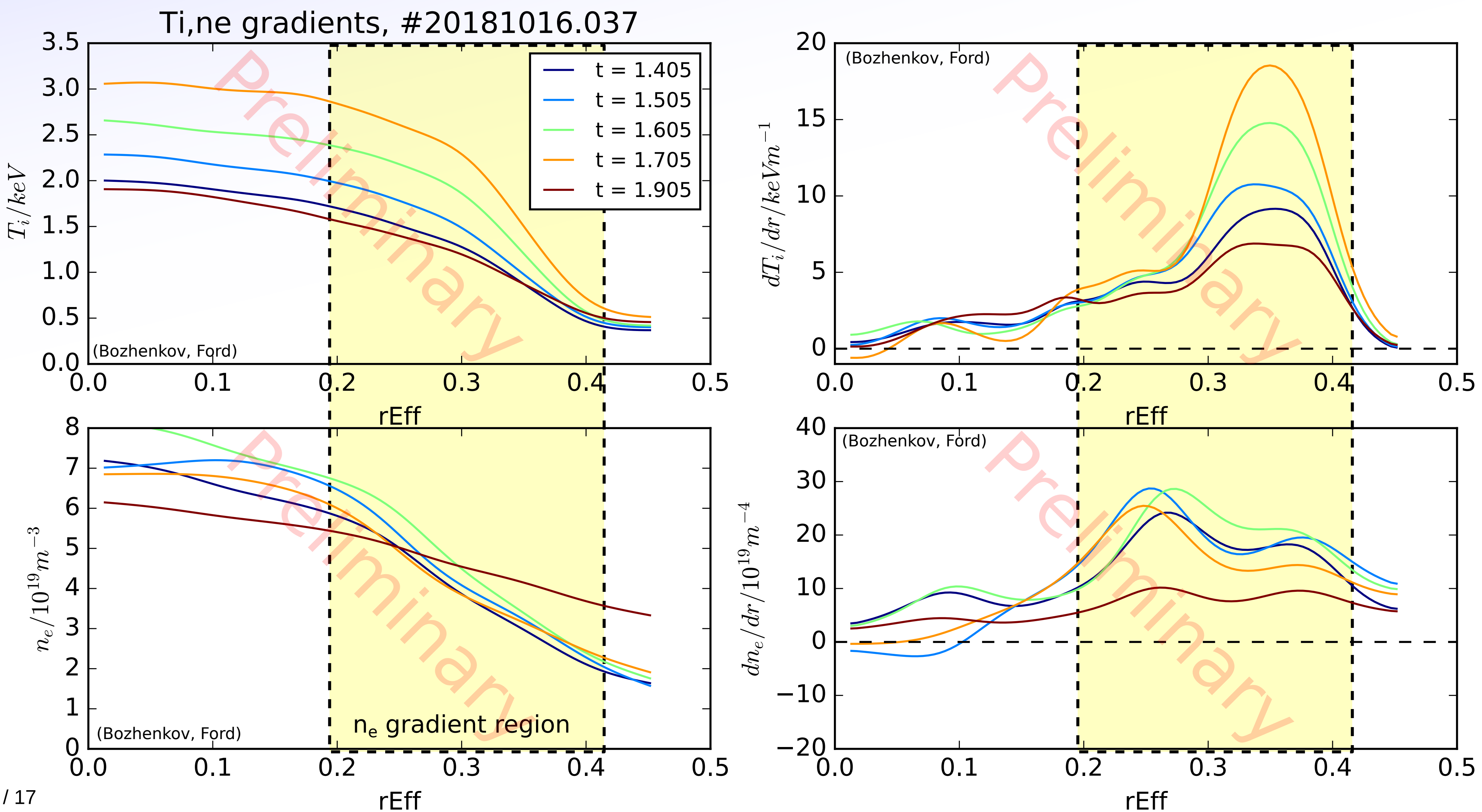
NBI into collapse:



Profiles - Pellets (boz_010)

Start looking at exactly where steeper Ti / density gradients are.
High resolution CXRS mode (all optics, all spectrometers). 6 point spline fit:

Pellets: (NBI blips only) ** This one is very mapping-sensitive, needs examination **



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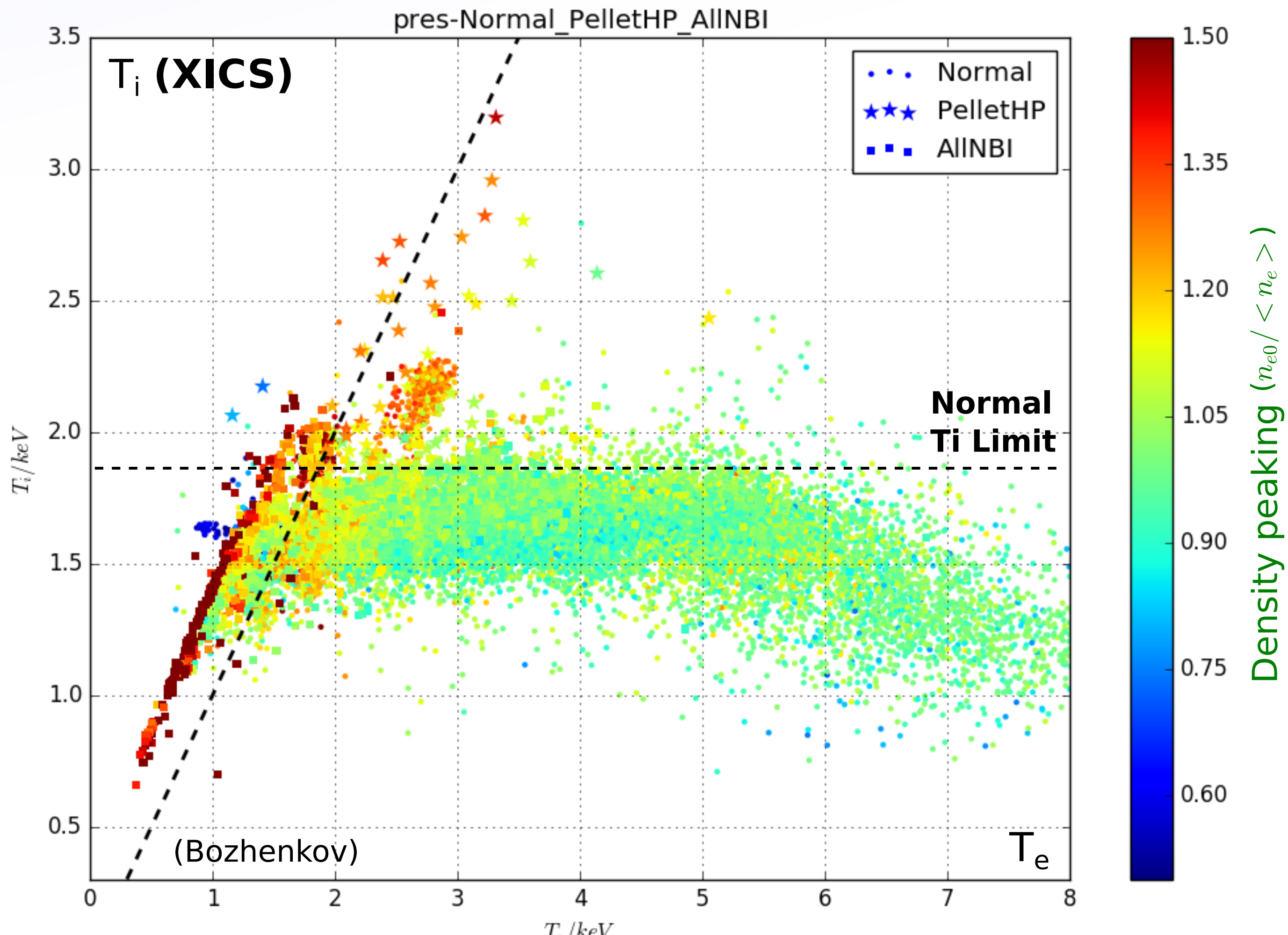
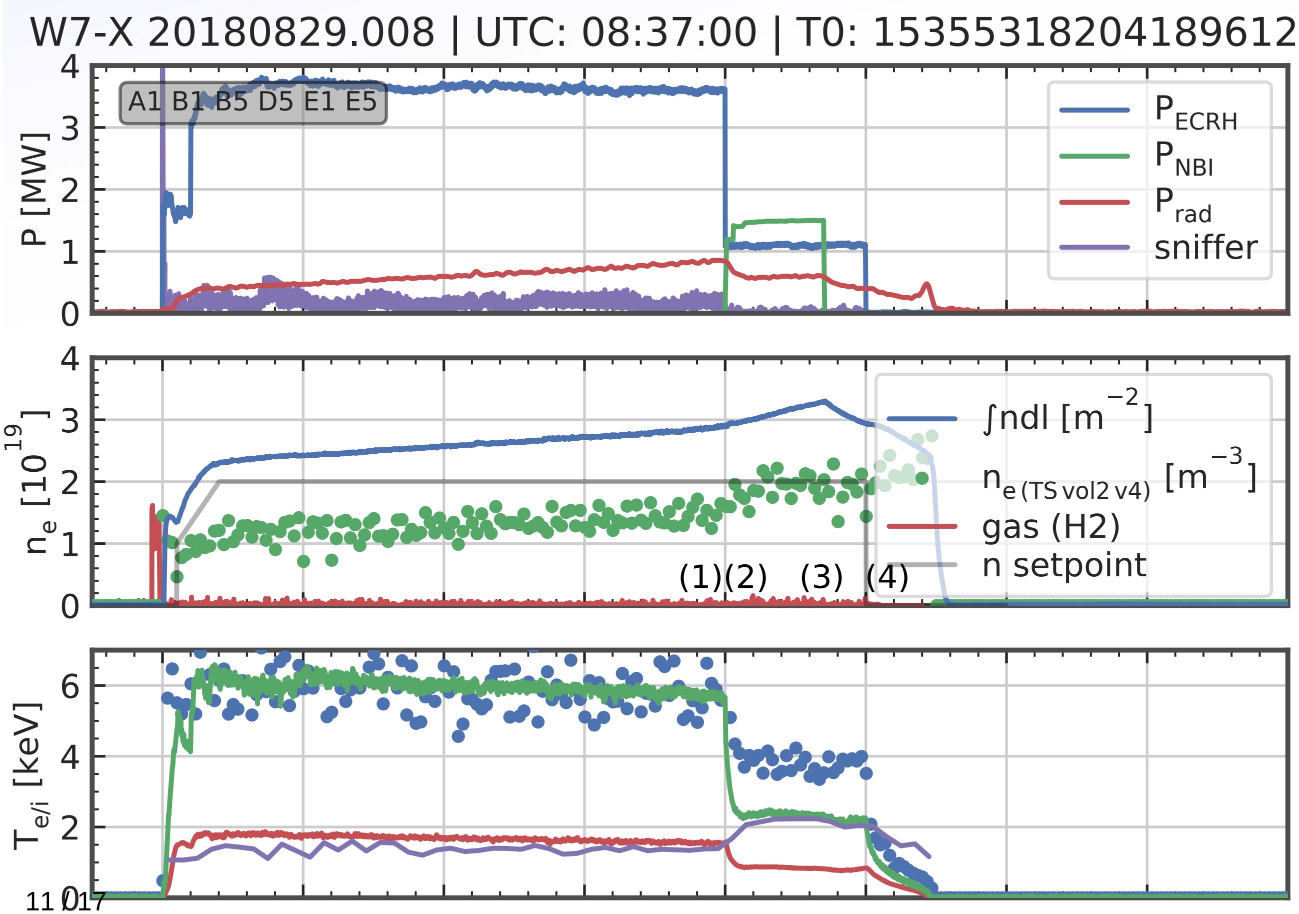
Density Peaking

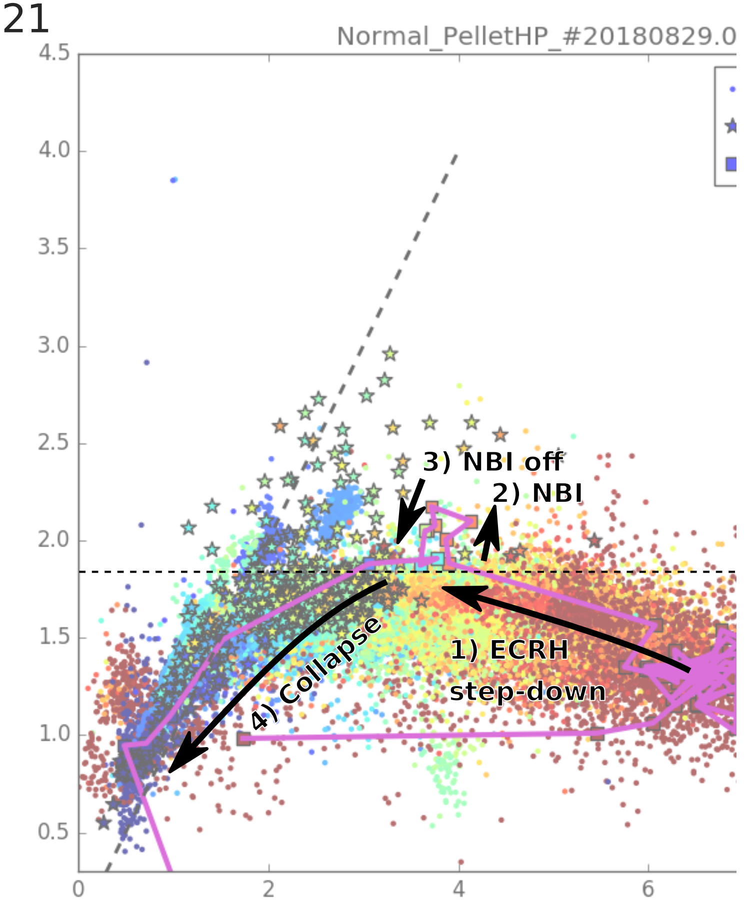
- Density peaking is common to all cases of high(er) Ti / reduced transport:
- Currently seen in:
    1) High performance pellets shots
    2) High ΔTi NBI
    3) Spontaneous slowly rising cases in ECRH
    4) Some TESPEL cases.



Density Peaking

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





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ICRH stabilization of turbulence?

[Y. Kazakov]

Experiments on JET have shown ICRH plasmas with steeper gradients/lower heat flux:

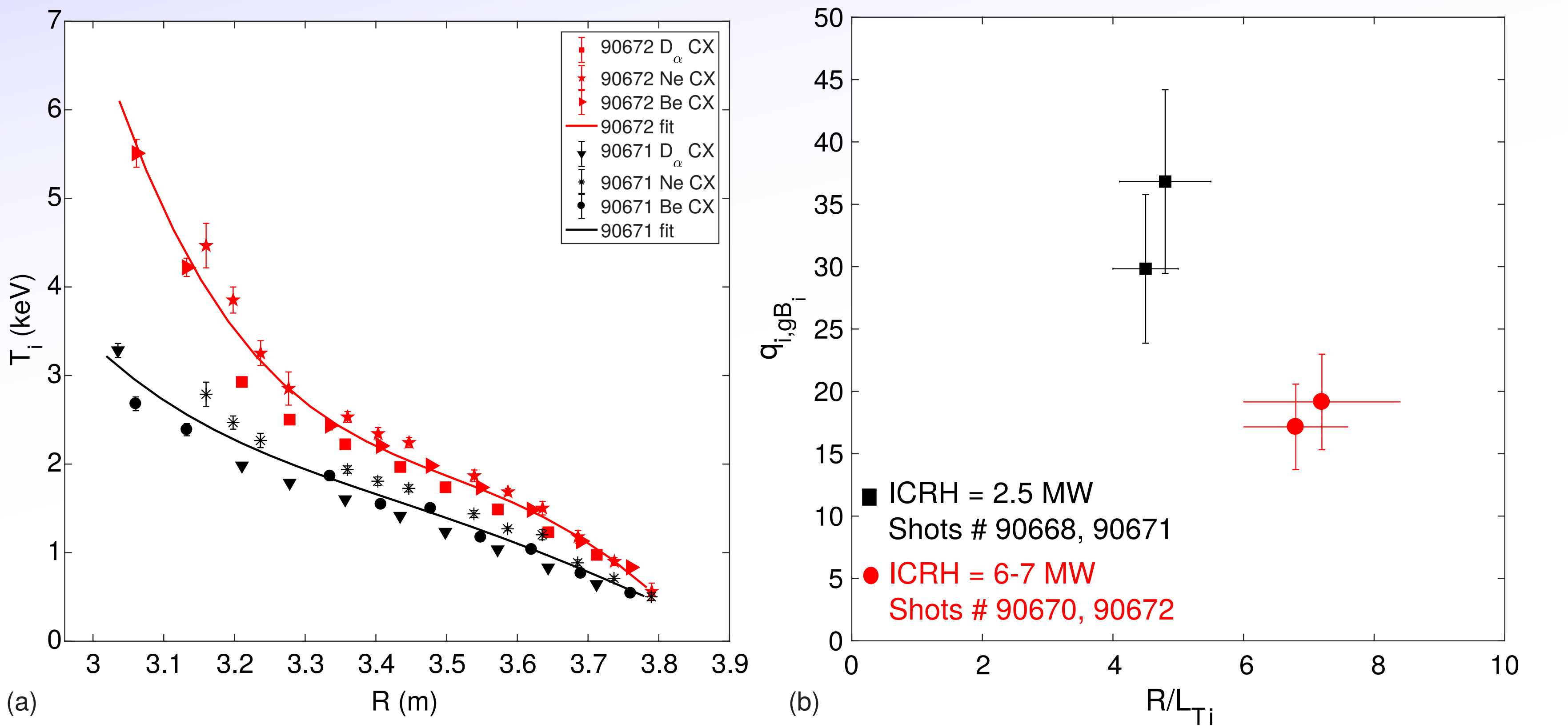

Figure 2. (a) Comparison between the Ti profile of discharges n. 90671 (2.6 MW of ICRH, black points and line) and n. 90672 (7 MW of ICRH, red points and line). (b) q i,gB (R/L Ti) at ρ tor = 0.25 of discharges with low ICRH power (2.6 MW, discharges n. 90668 and n. 90671) and of discharges with high ICRH power (6–7 MW, discharges n. 90670 and n. 90672).
[N. Bonanomi et al, Nucl. Fusion **58** (2018) 056025]

"Gyrokinetic simulations indicate that ITG (ion temperature gradient) turbulence stabilization induced by the presence of high-energetic ^{3}He ions is the key mechanism in order to explain the experimental observations."

How do we increase T_i?

We need to diversify the tools and try to learn how to control turbulence.

Possible actuators:

1) Density profile control

1) Pellets **2) NBI** 3) Seeding?

2) Turbulence optimised magnetic configurations.

3) ITG Stabilisation with ICRH

- Somewhat hypothetical, well theotically grounded and observed in some machines.

4) Transport barriers: i.e. 'H-mode might happen'

- No solid basis for expectation but L-H mostly comes with higher P_{tot}.
- Consider H-Mode compatibility with #1.

- NBI will probably be a critical tool for testing/investigating high Ti in future campaigns.

- NBI could provide a fine and reproducible control of density peaking and core fueling rate for turbulence and high performance experiments.

- Majority of tokamaks achieve high performance with NBI (Also W7-AS, LHD)

Options/upgrades:

- 100/72kV injection? (OP1.2b - fuelled slightly faster than heating)
  - 'Balanced injection in D' - How should we configure power supplies?
- Deuterium? (More power, shoot longer, higher energy injection, isotope effect?)
- All 8 sources?
- Helium injection?
- Other ideas?

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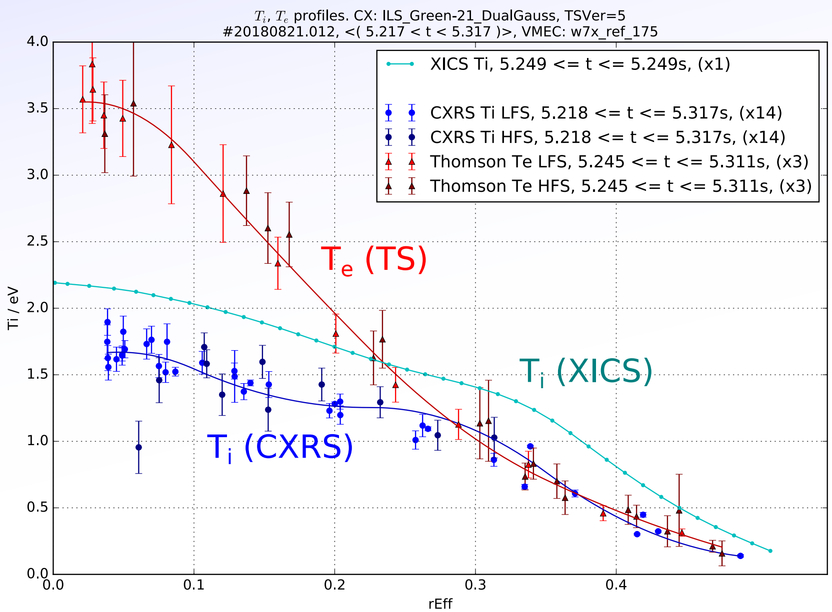
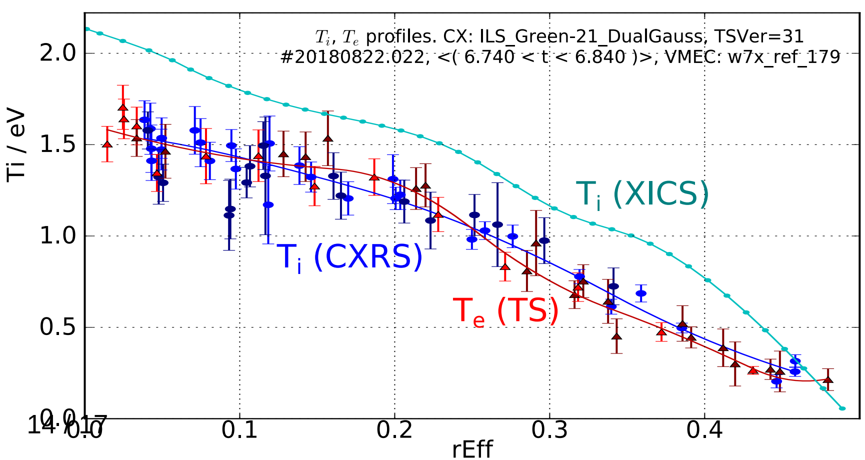
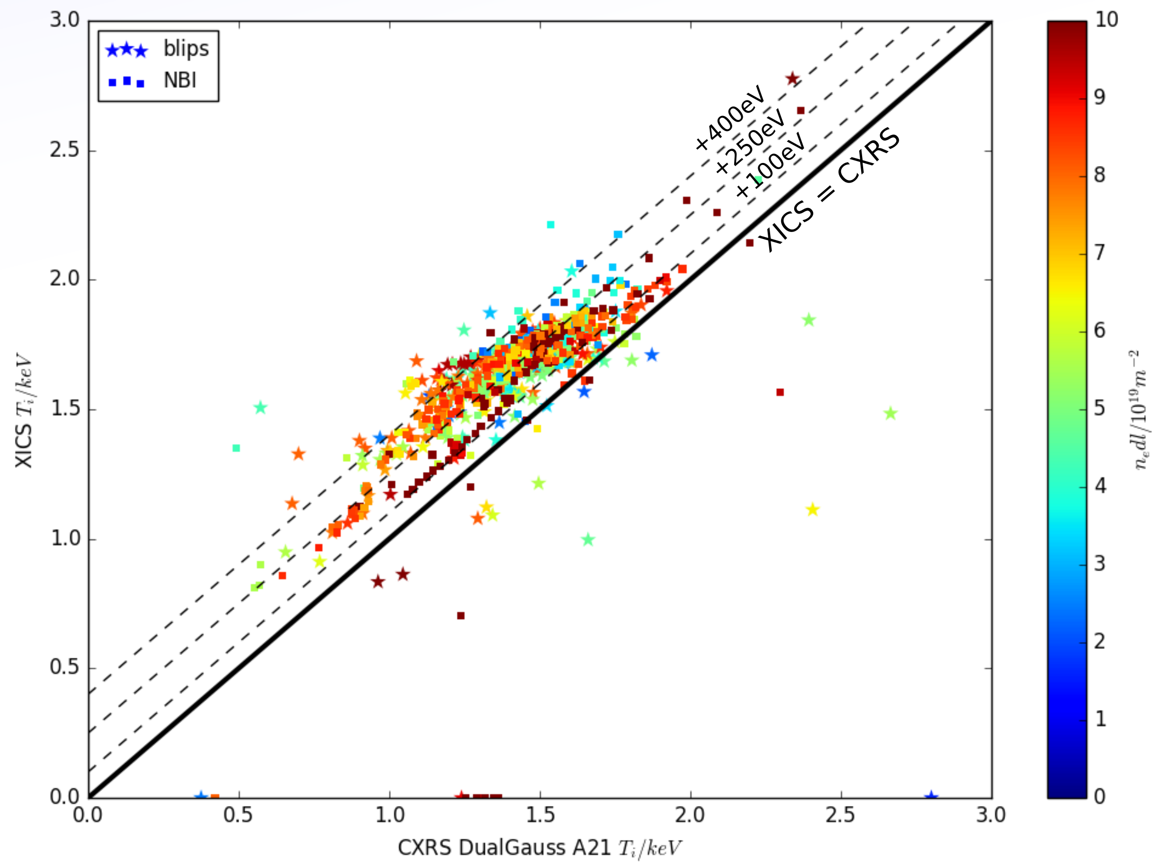
XICS --> CXRS

- 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 presentation)







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P_{ECRH} Upgrade

From the observed experimental evidence, upgrades to P_{ECRH} and associated higher n_e will not access higher T_i:

Plot Ti vbs (ne, PECRH)

- There *are* other good reasons to increase P_{ECRH} - e.g. to hope to find an H-mode, but increasing *nTt* is not one of them.

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What's next and open questions.

- Scaling - we know where we go with ECRH + higier density, if nothing magic happens.

Ways out:

1) Magic: H-mode might happen, but no basis for expectation. Most tokamaks with NBI.
2) Pellets: Pellets most likely non-stationary. Badly controlled.
3) ICRH might also stabilise ITG. (Somewhat hypothetical, well theotical grounded and observed elsewhere)
4) Turbulence optimised magnetic configurations.
5) Something with the NBI:
   - Majority (all?) tokamaks achieve high performance with NBI (Also W7-AS, LHD)

Operational question for OP2.1:

- Can we increase power while maintaining sufficient density peaking??
- Will more NBI help?
  a) More power without ECRH pump-out.
  b) More core fuelling to compensate ECRH pump-out
- Control beam deposition with beam energy and component fraction (neutraliser/source pressure??)
- Can we refine NBI into ECRH step-down plasma recipe to be reproducible? and refine?
  - reach higher Ti?
  - Hold Ti = 2.5keV for longer?
- NBI into pellets high-performance discharges.
  - Does it stop the pellets HP?
  - Can we get steeper ne gradient this way, or steep across more of the radius?
- We need to find an H-mode!

- NBI will probably be a critical tool for testing/investigating high Ti in future campaigns.

- NBI could provide a fine and reproducible control of density peaking and core fueling rate for turbulence and high performance experiments.