



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

TG Profiles / TG Confinement / E3 Retreat

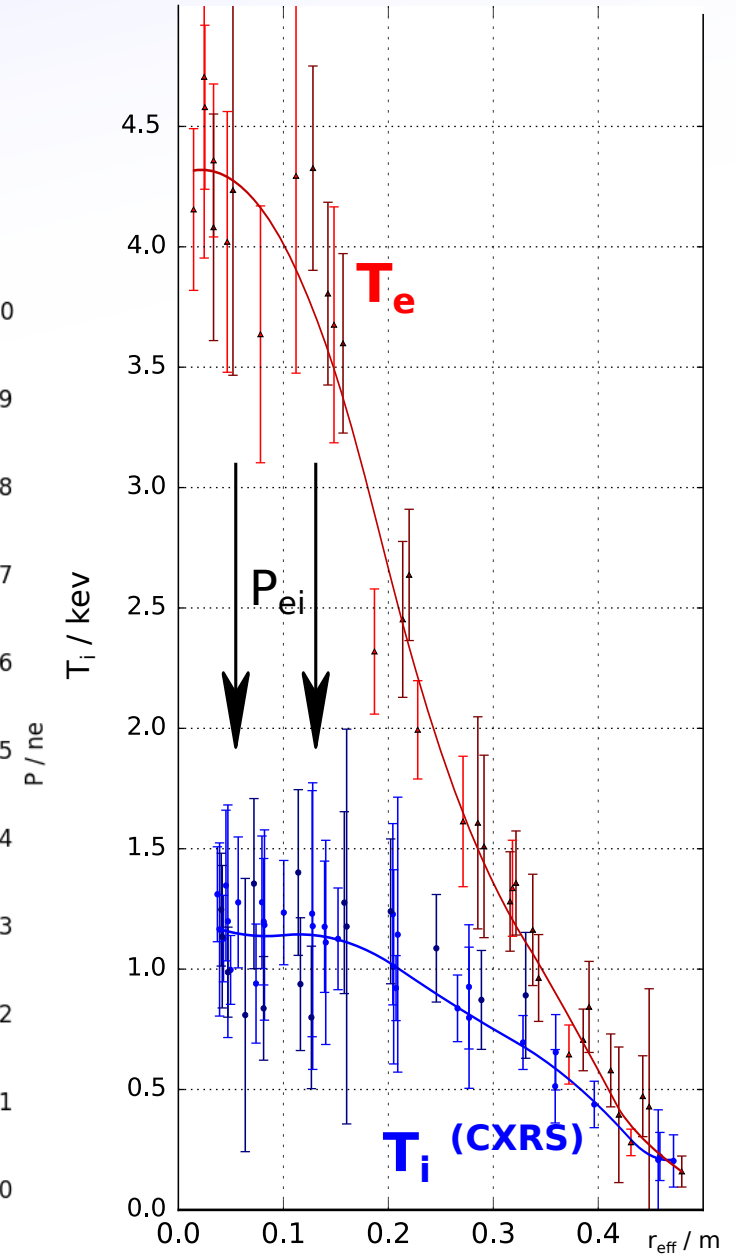
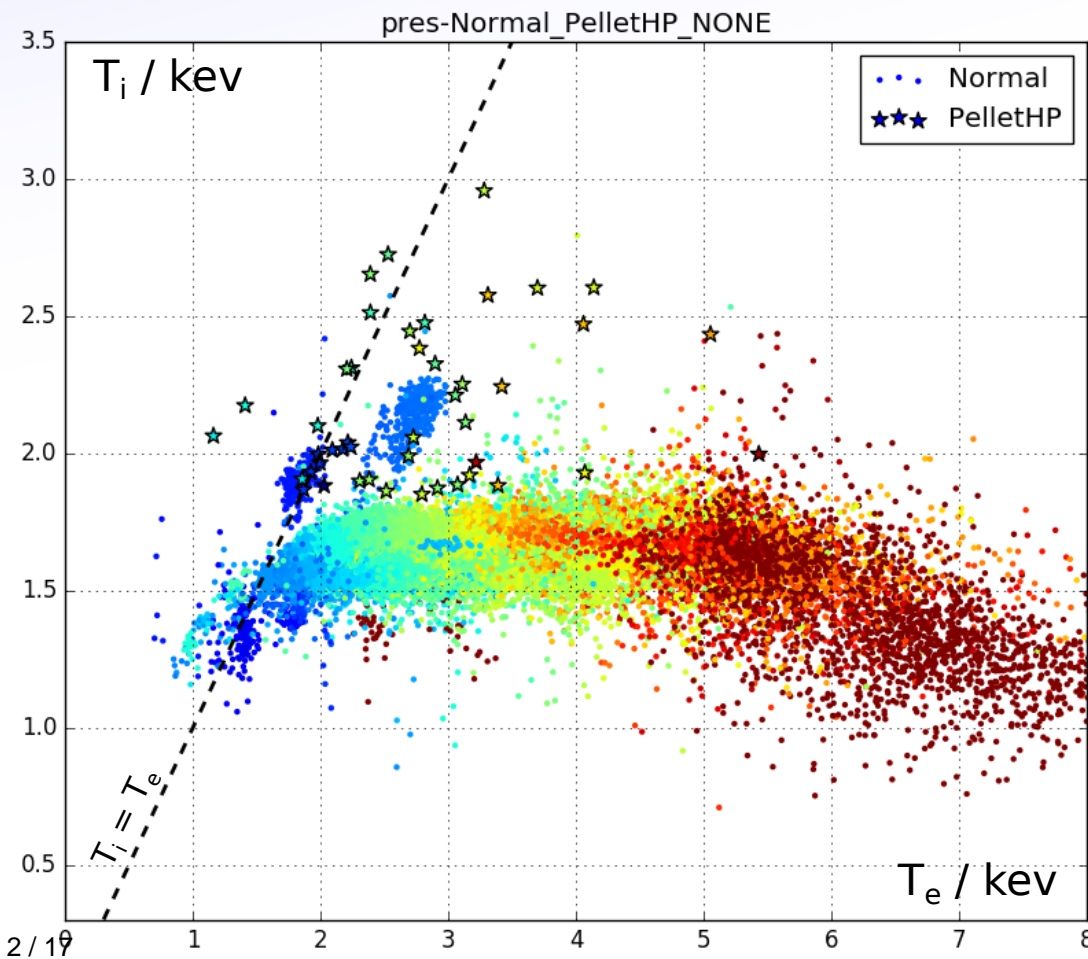
O. P. Ford¹, S. Bozhenkov¹, M. Beurskens¹,
Y. Kazakov², S. Lazerson², N. Pablant², R. Wolf¹

1: Max-Planck Institut für Plasmaphysik, Greifswald, Germany

2: PPPL, NJ, US

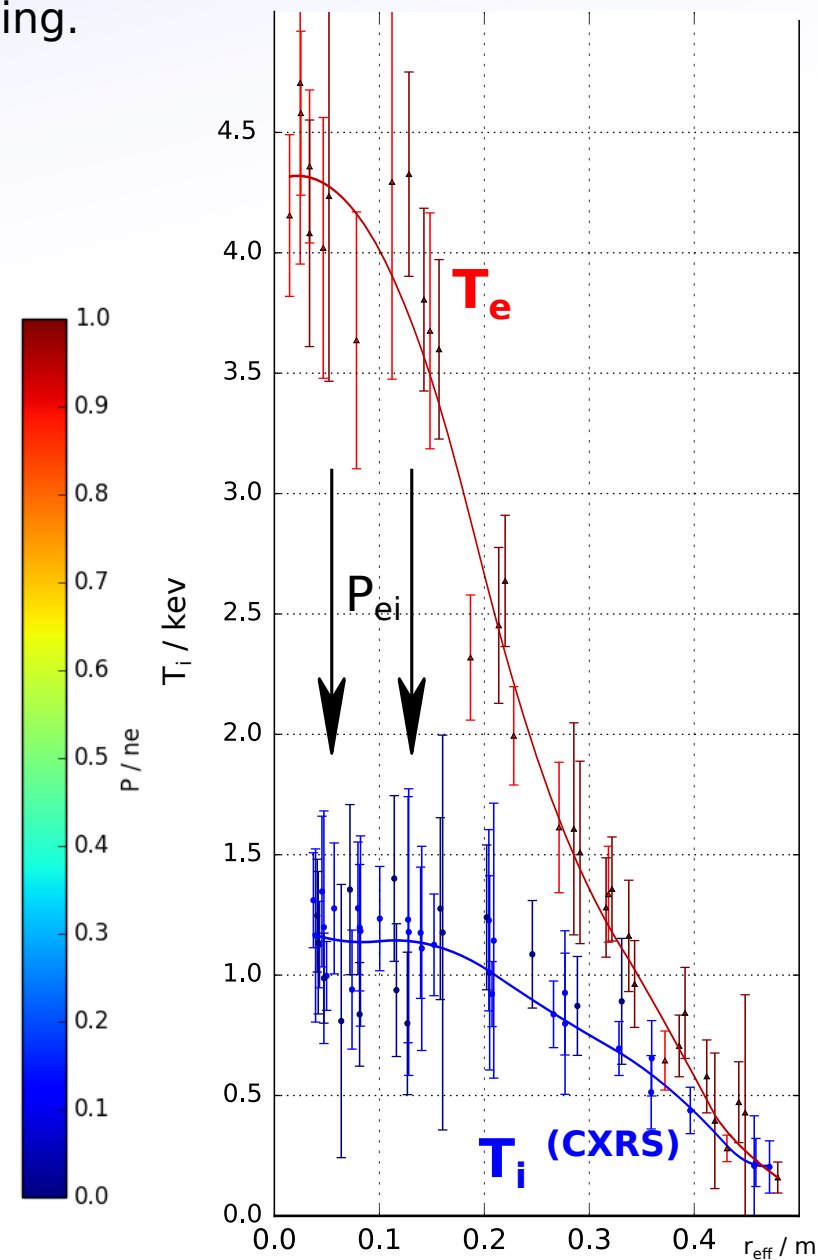
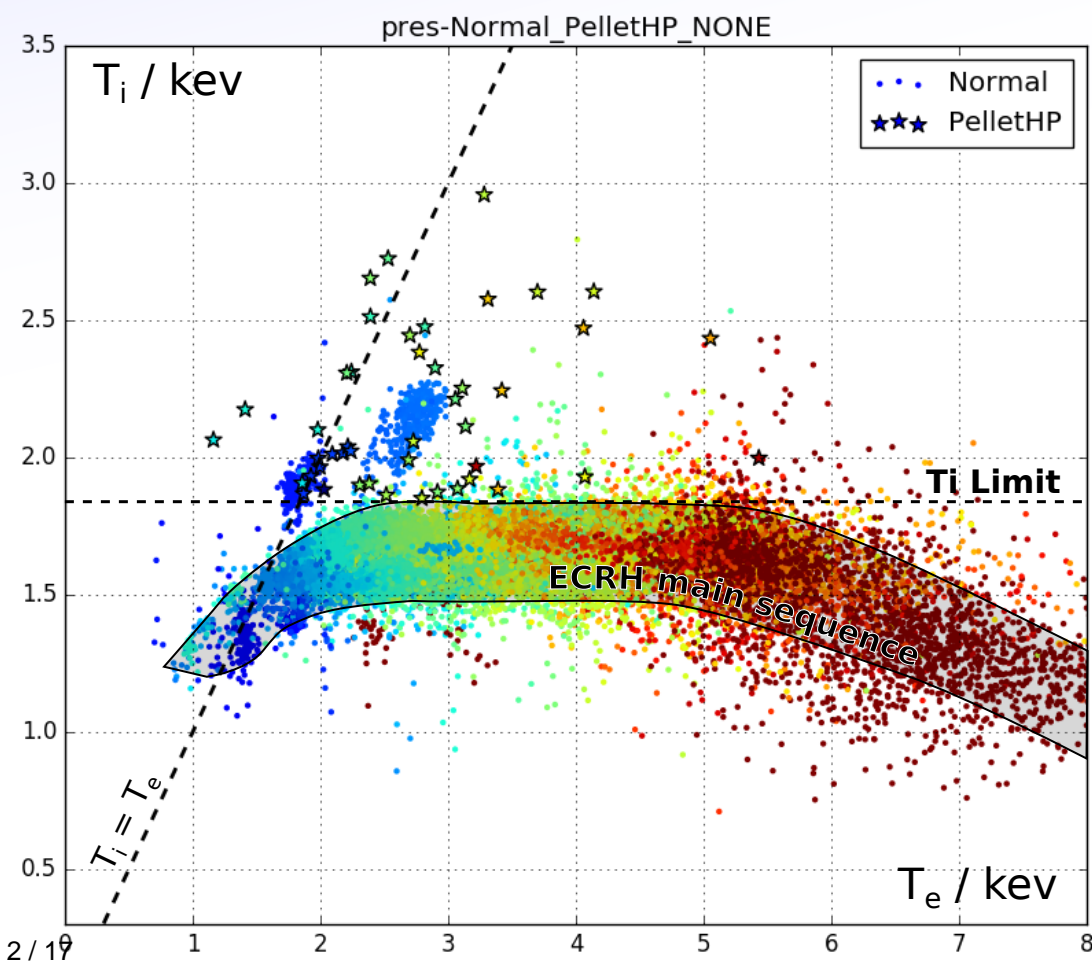
Ti profile resilience: ECRH

- Core Ti usually within same range and profile gradients similar regardless of P_{ECRH} and electron-ion coupling.
- Leads to effective Ti limit $\sim 1.8\text{keV}$ (XICS)



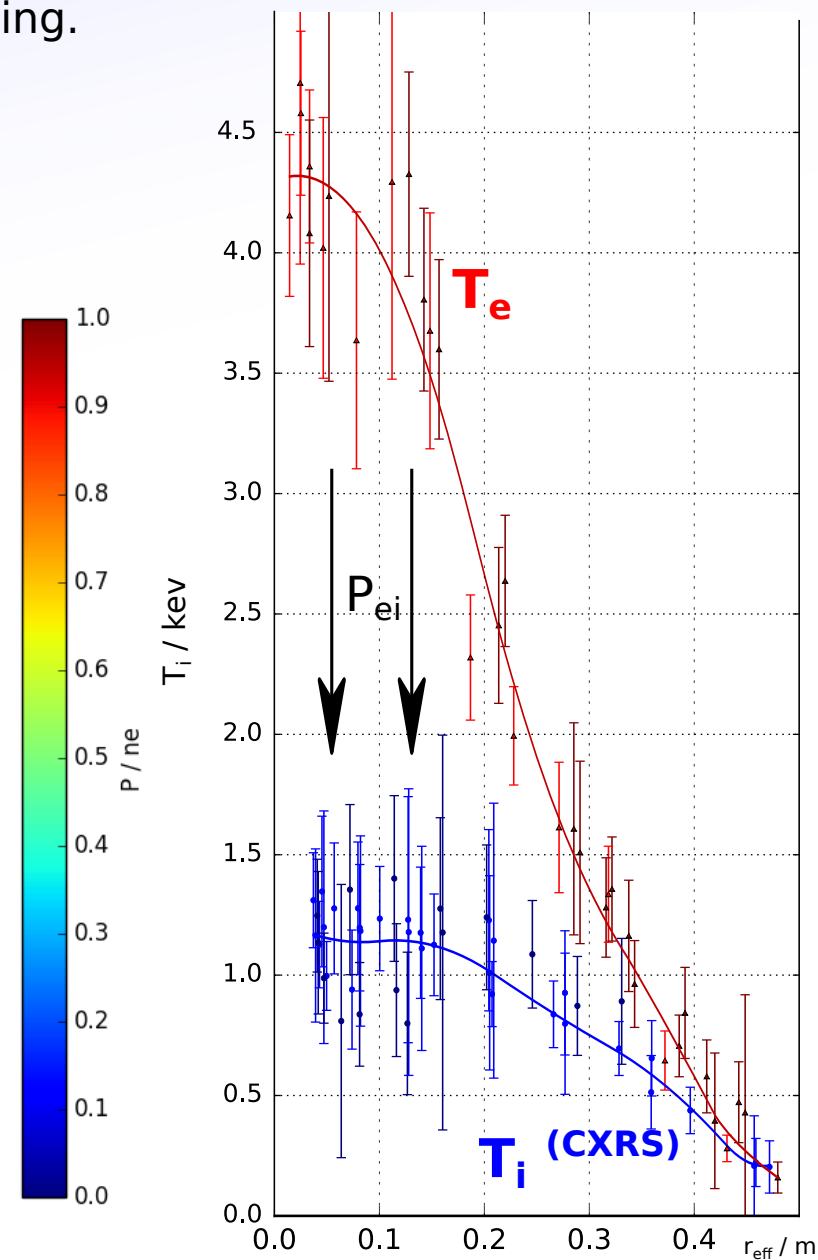
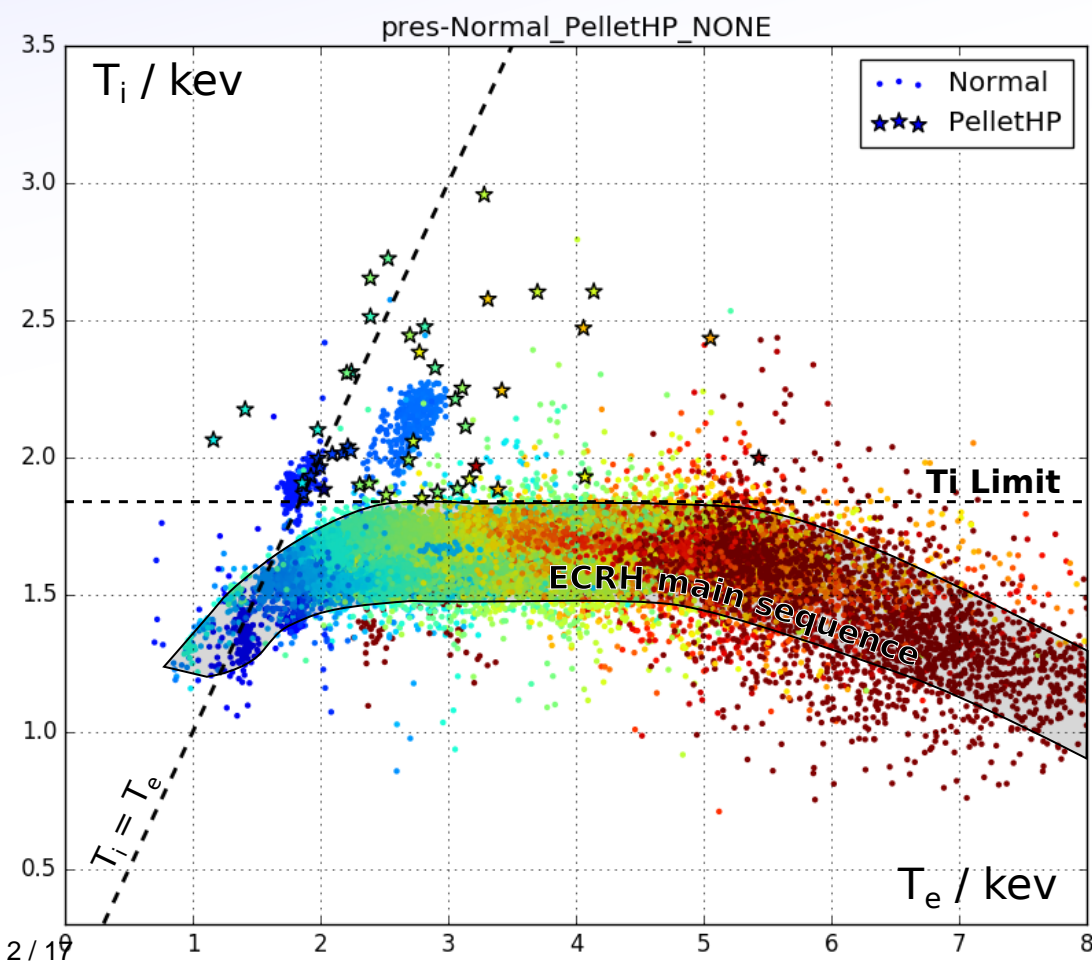
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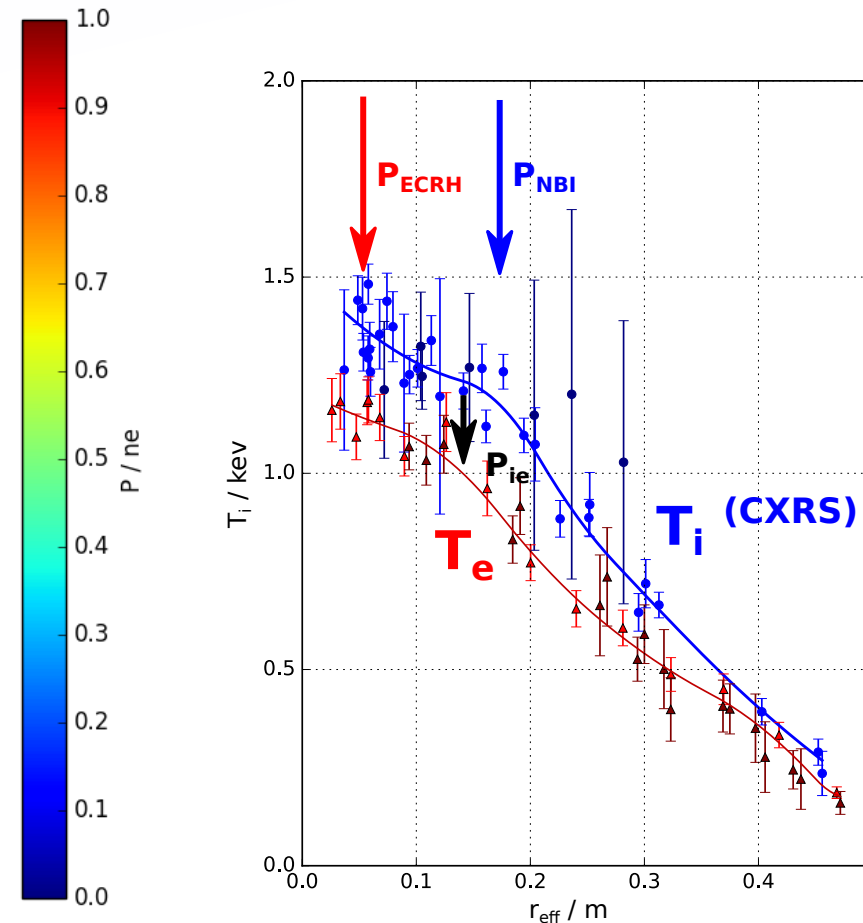
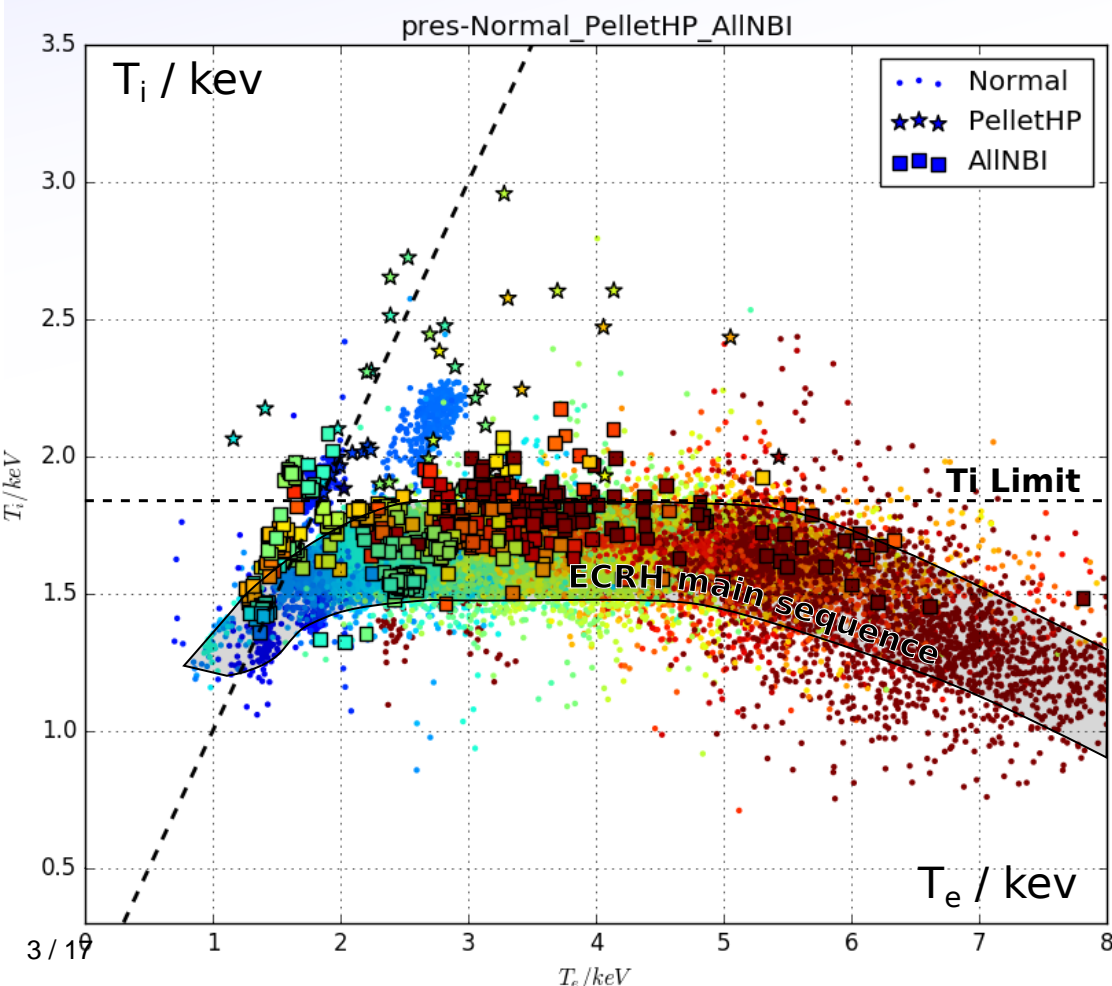
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- Leads to effective Ti limit $\sim 1.8\text{keV}$ (XICS)
- Exceptions:
 - 1) High-Performance pellet discharges
 - 2) Some particular low P_{ECRH} cases.



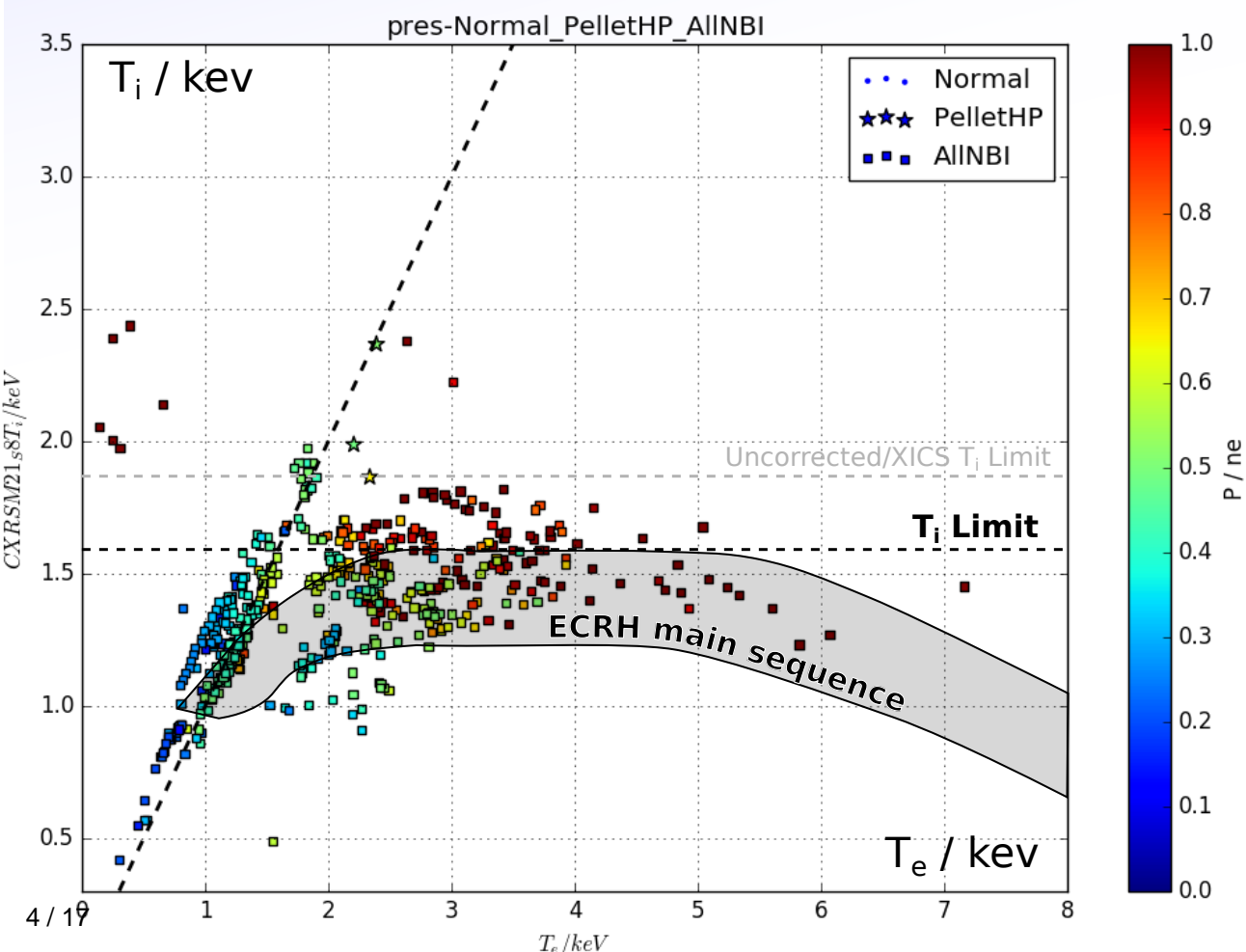
Ti profile resilience: NBI

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



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 .

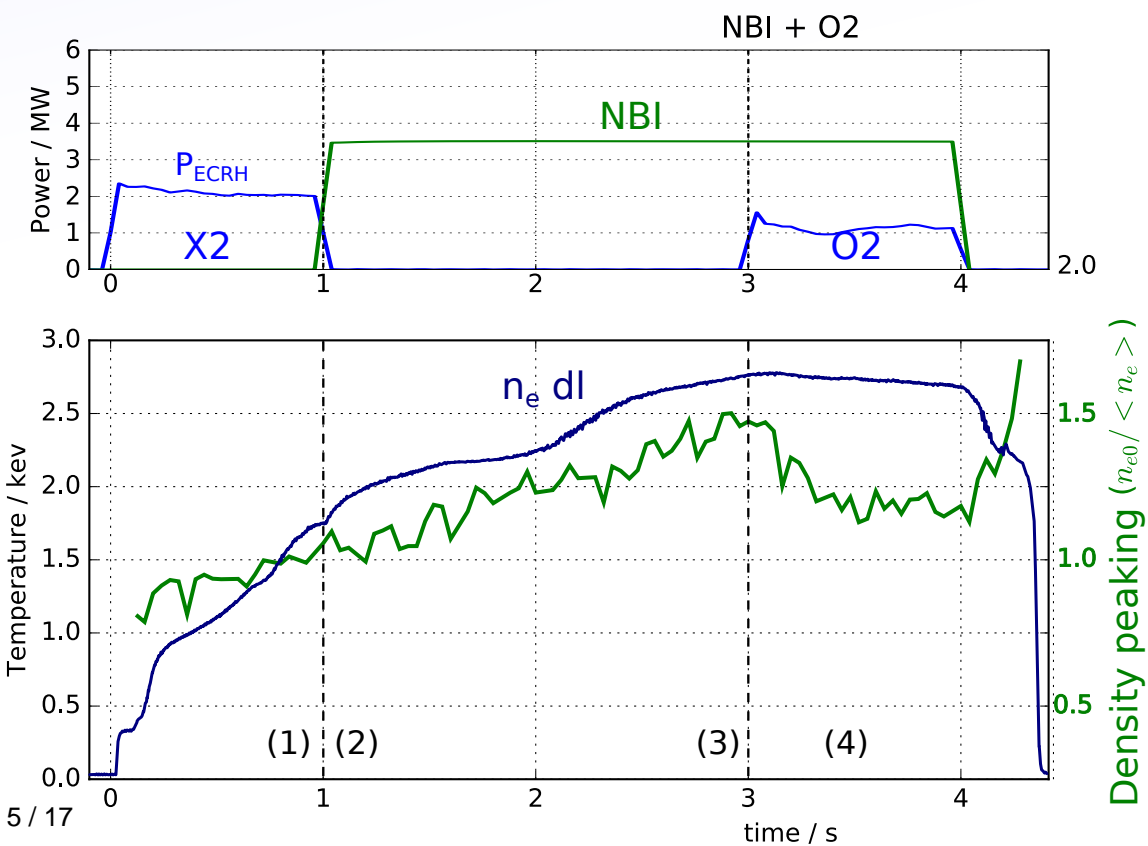


Case 1: NBI + O2

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

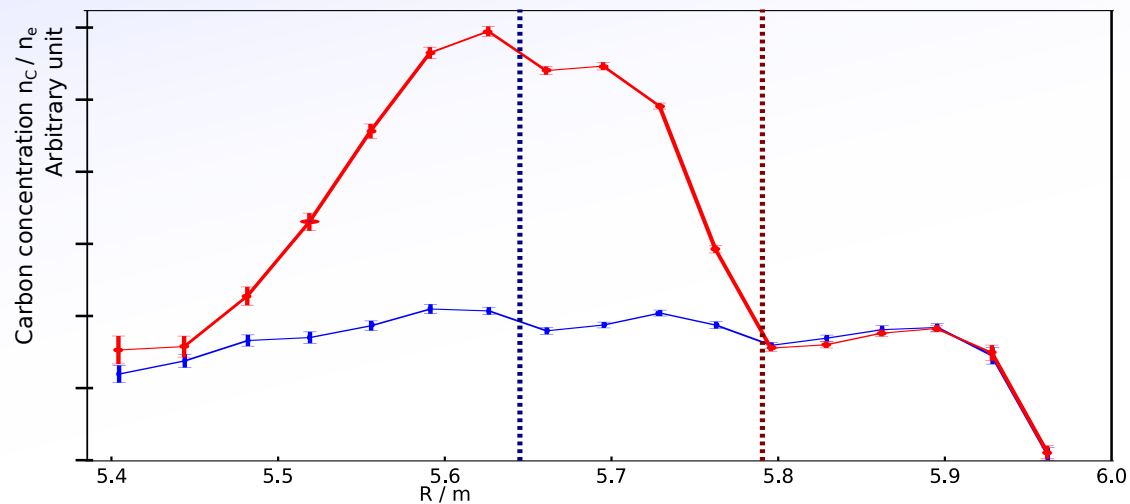
(S62/olfo_012): Can we use low power ECRH to control density level/peaking, expel impurities and increase T_e ??

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

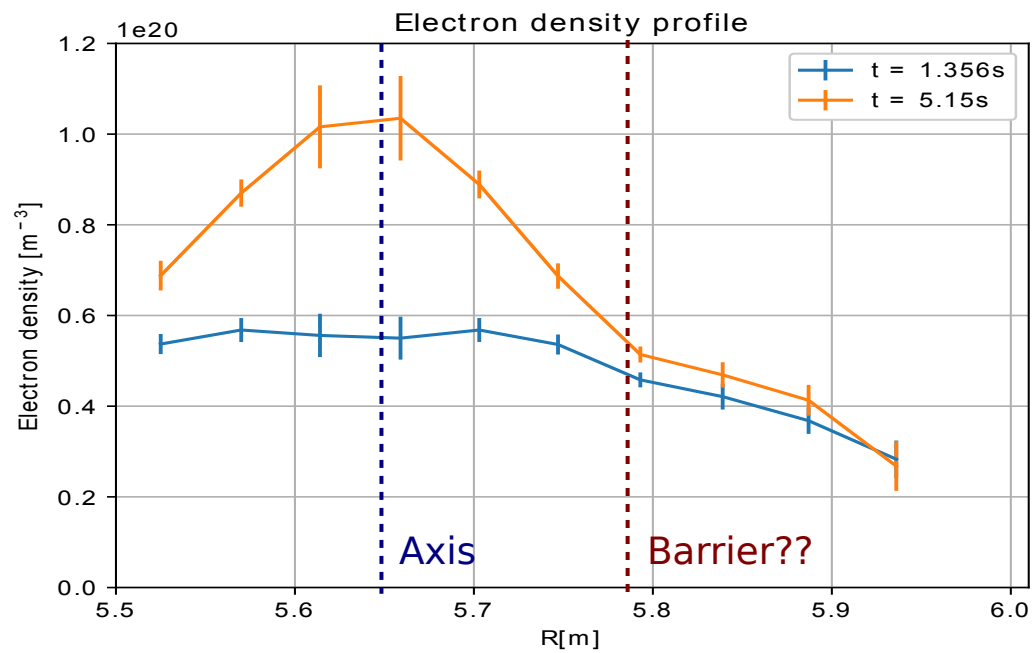
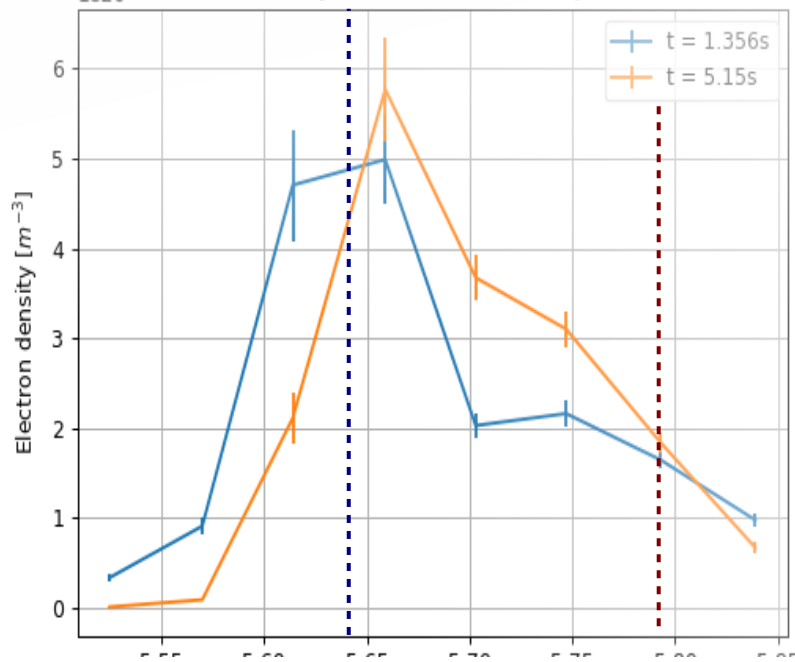


Beam deposition (T.W.C.Neelis)

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



Electron density increase/Particle deposition rate

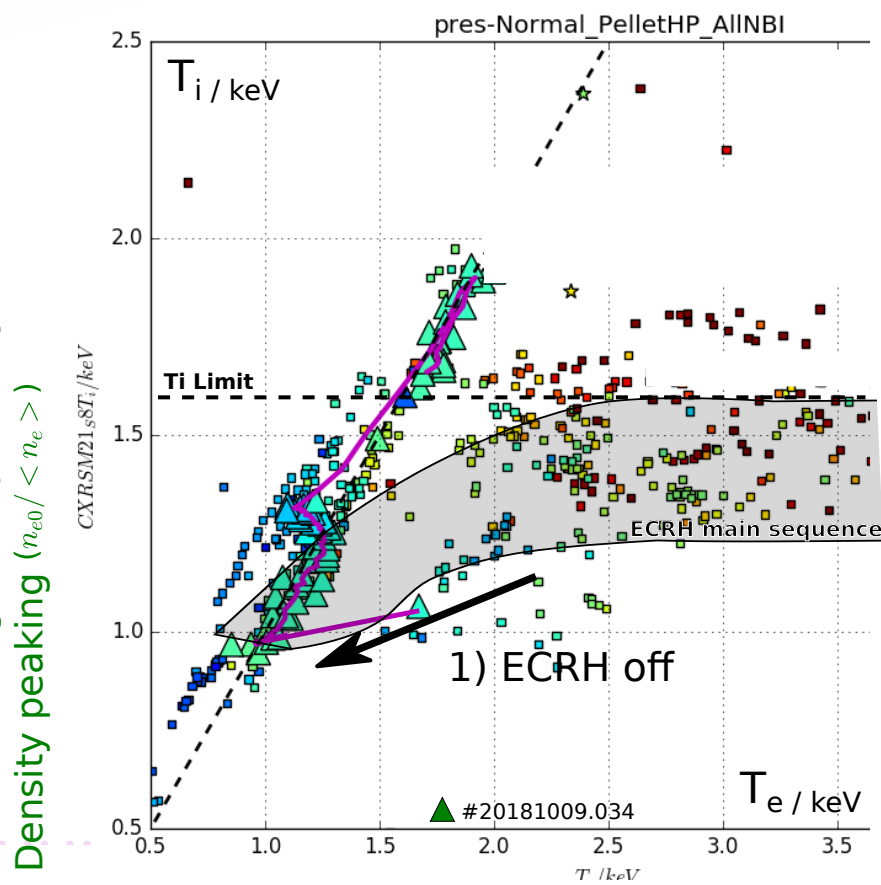
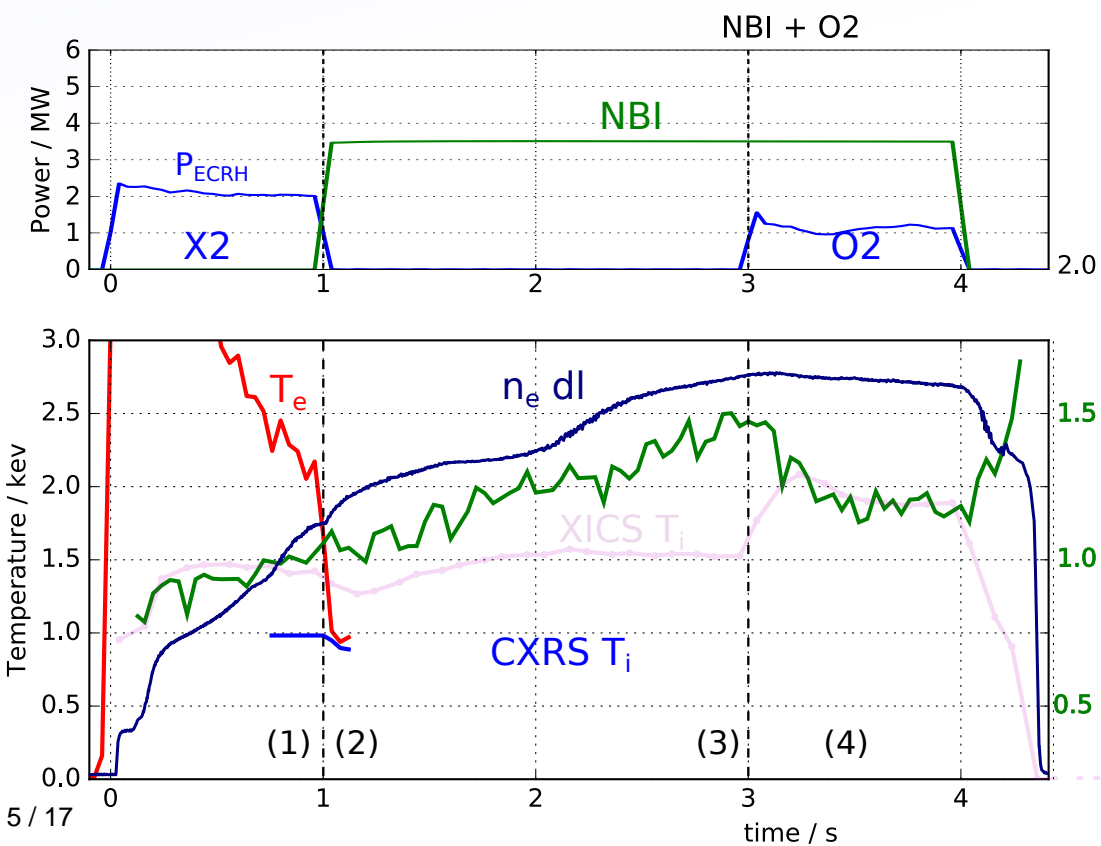


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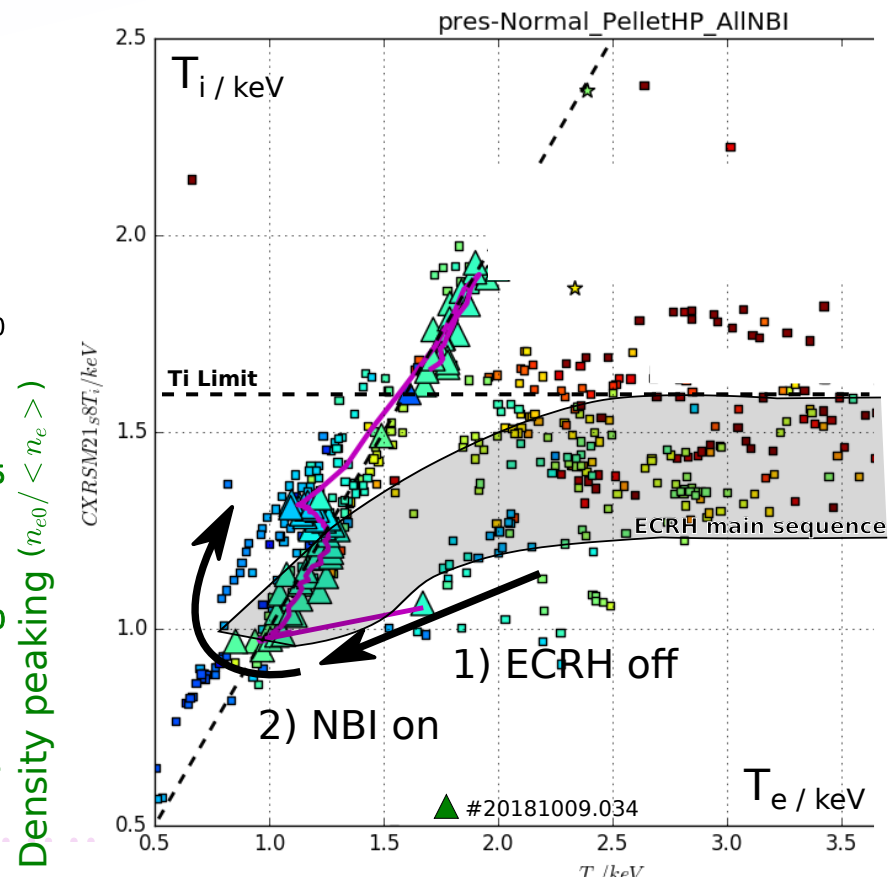
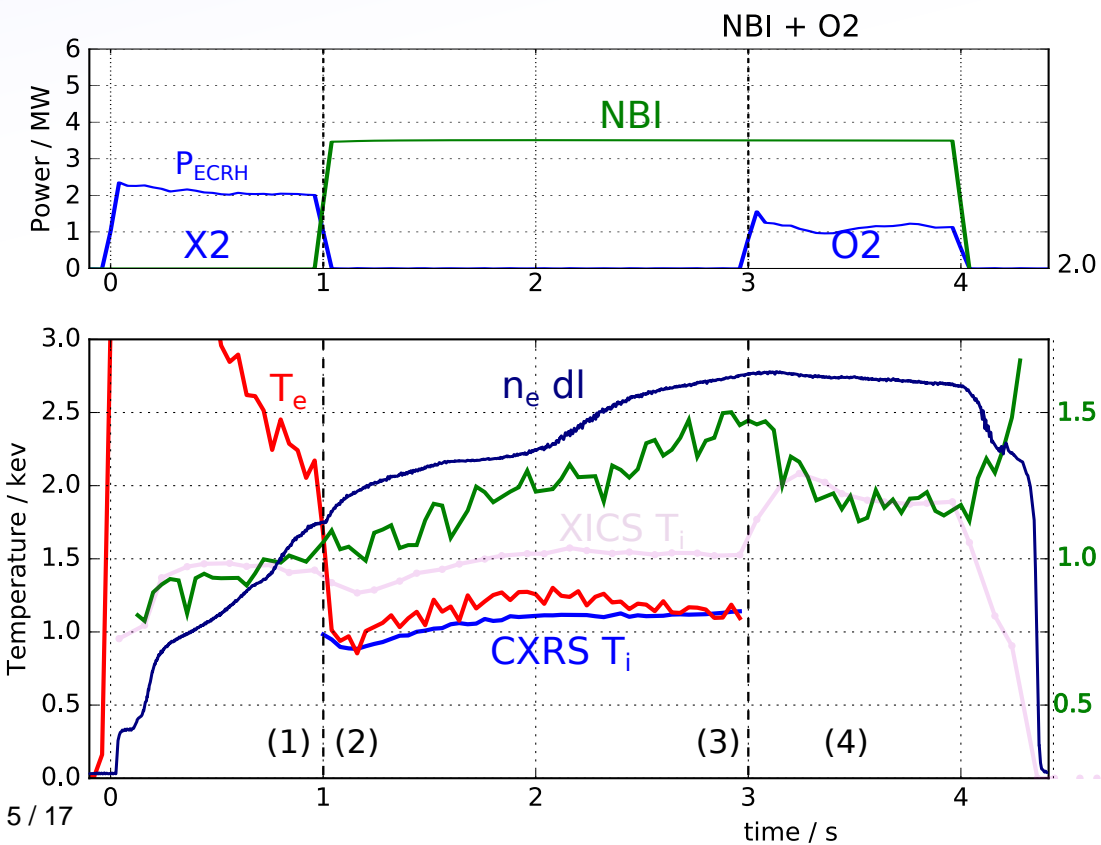


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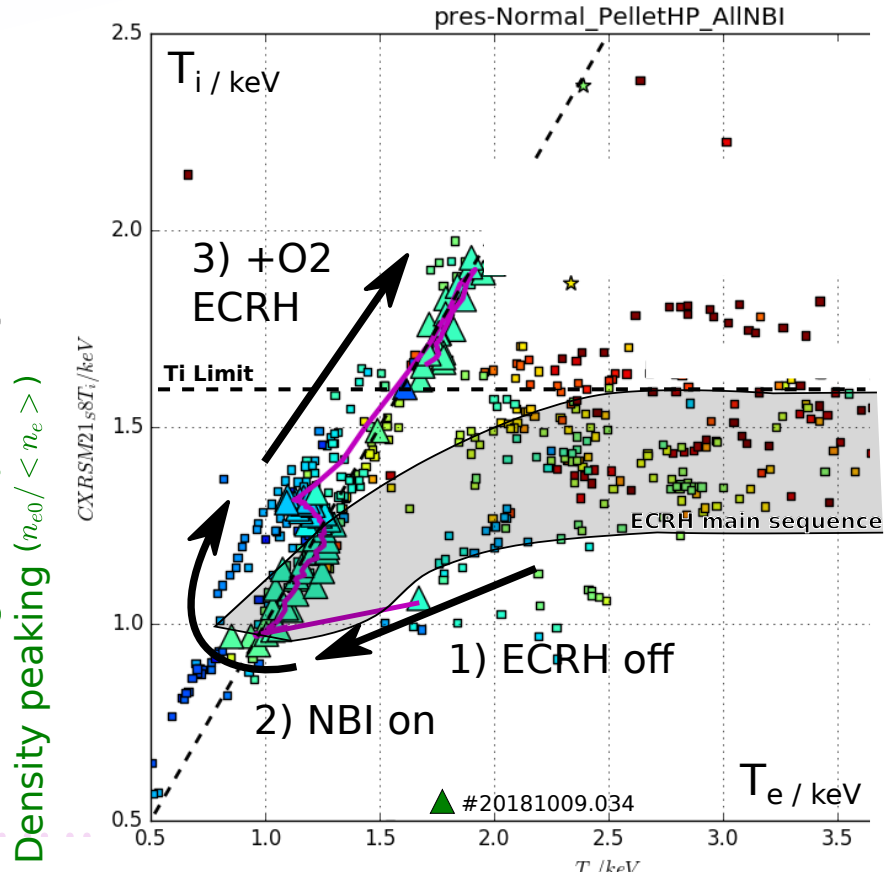
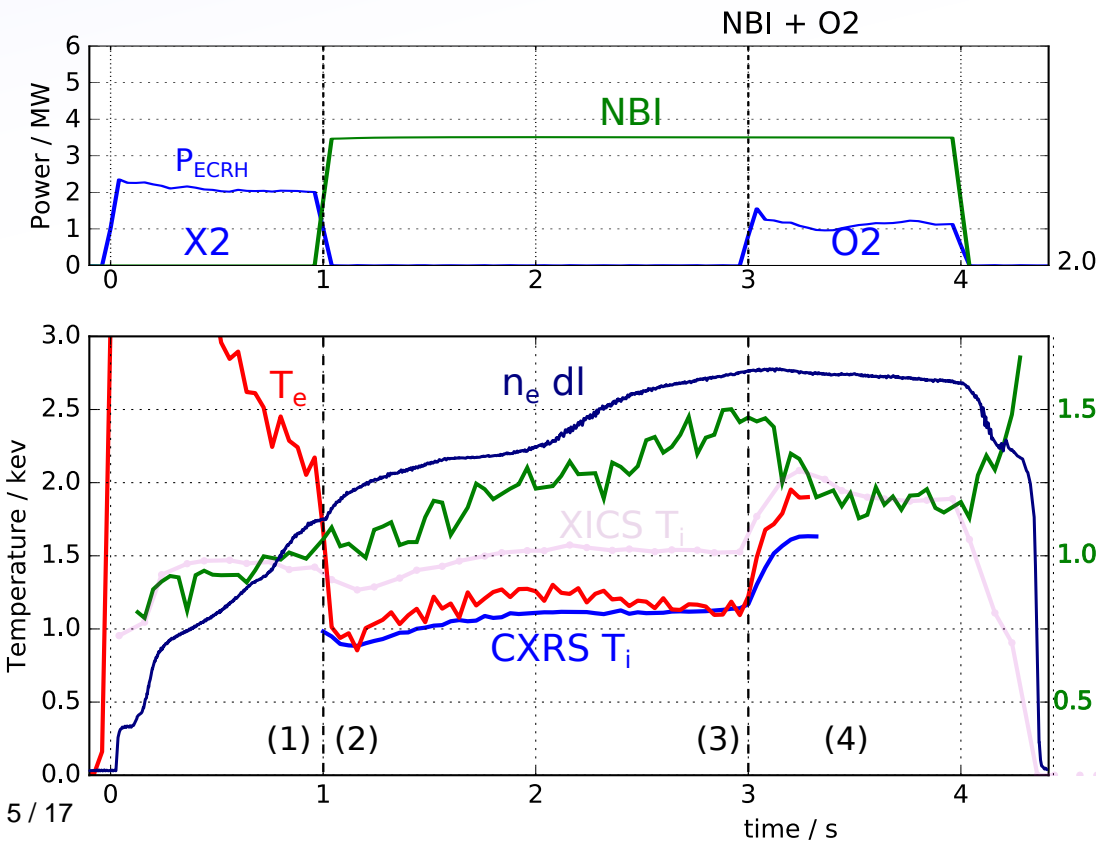


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Density peaking ($n_{e0} / < n_e >$)

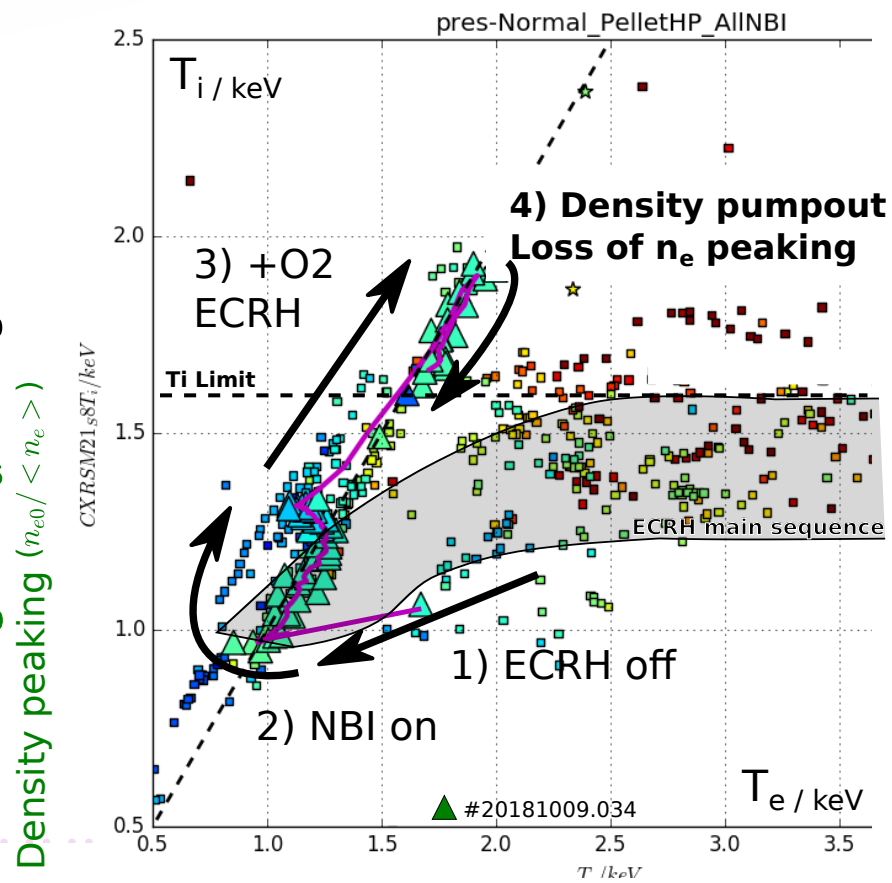
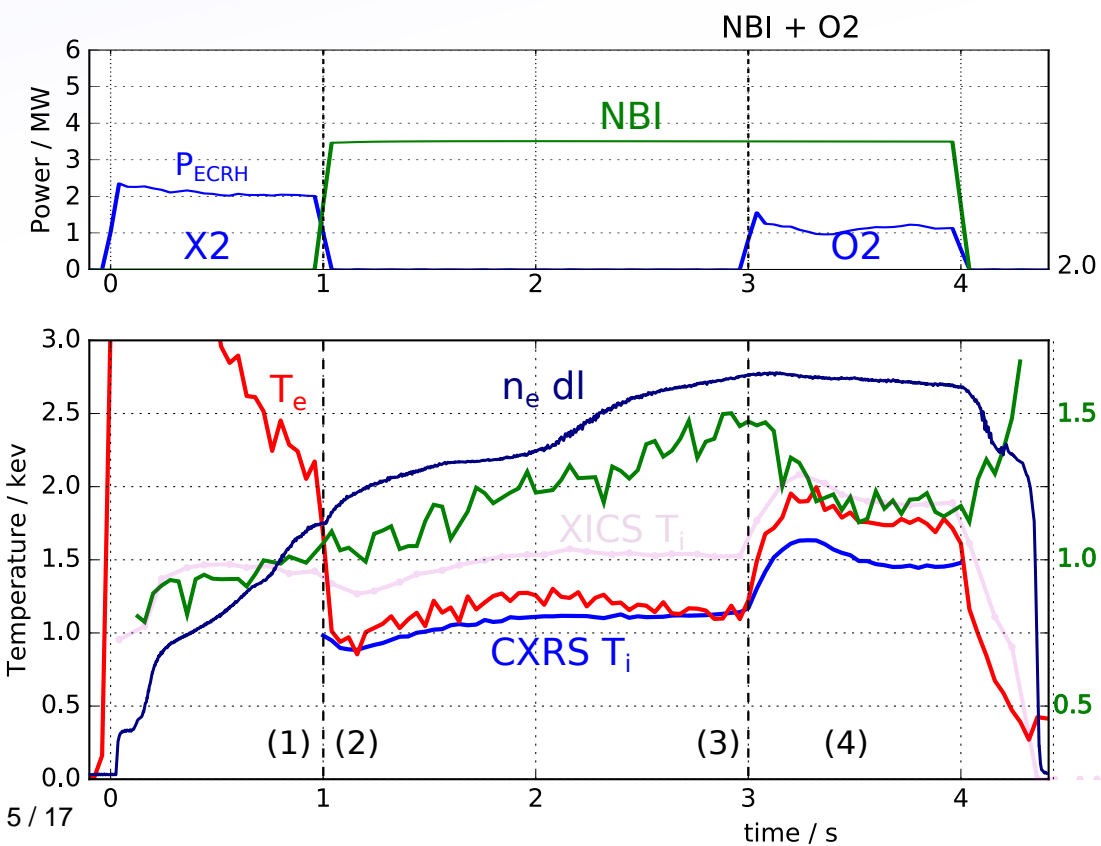


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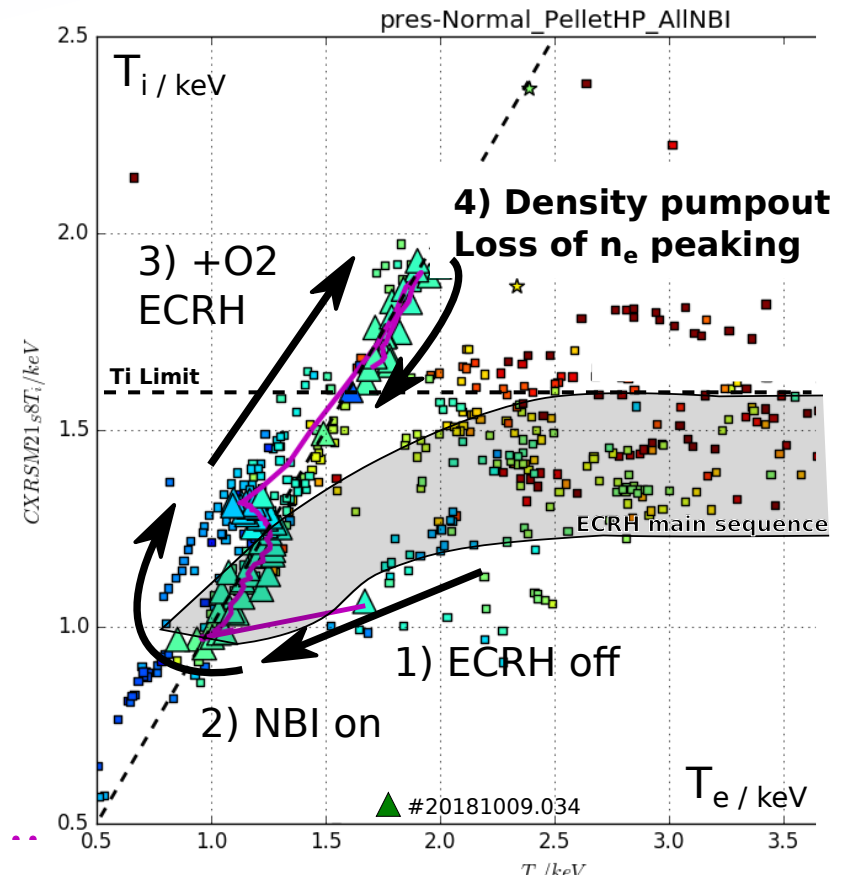
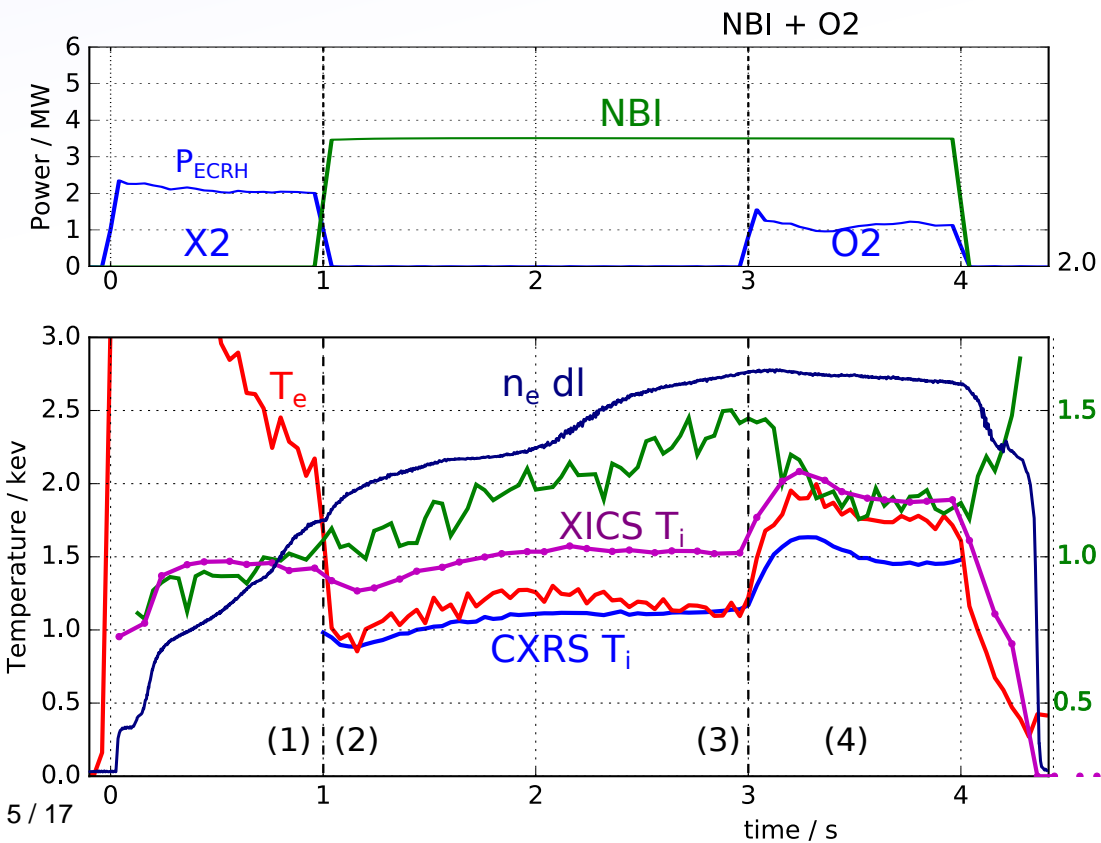


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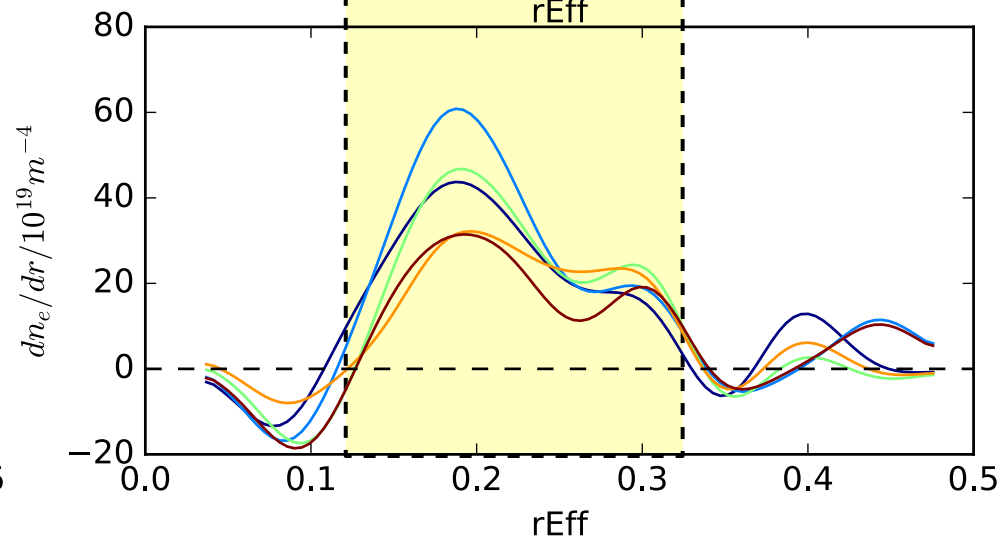
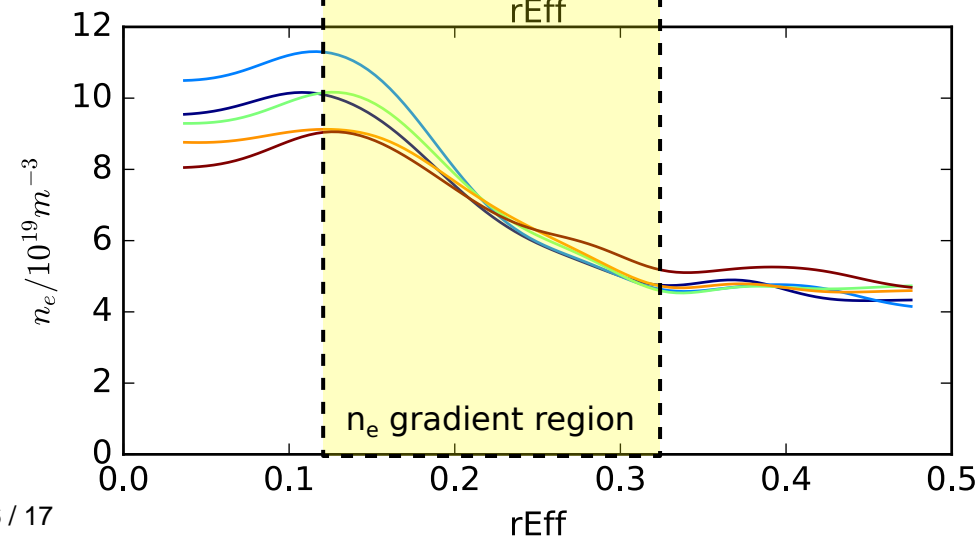
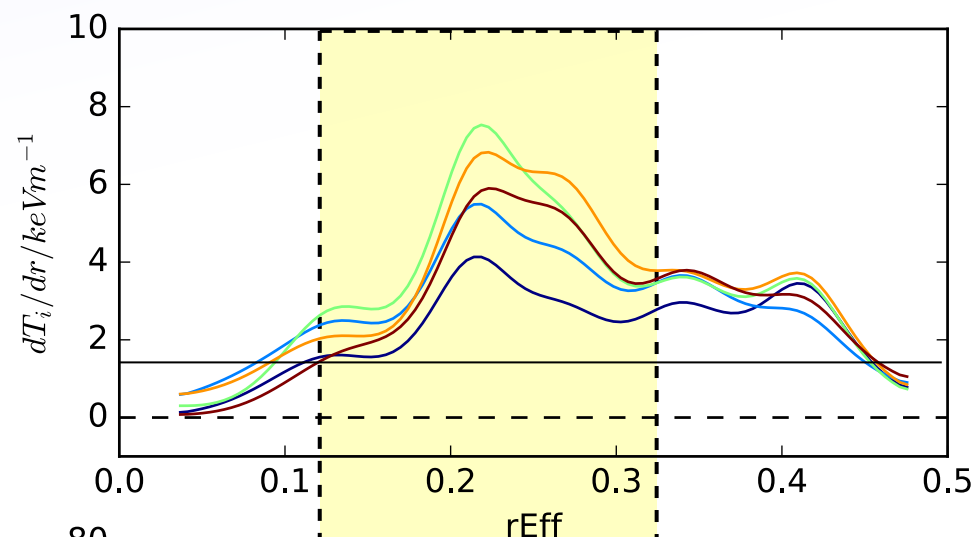
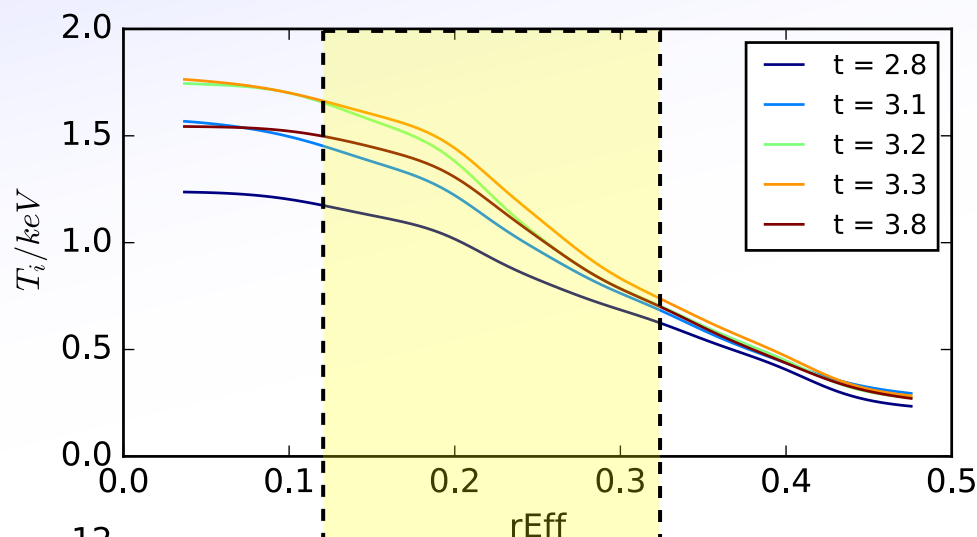
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Profiles

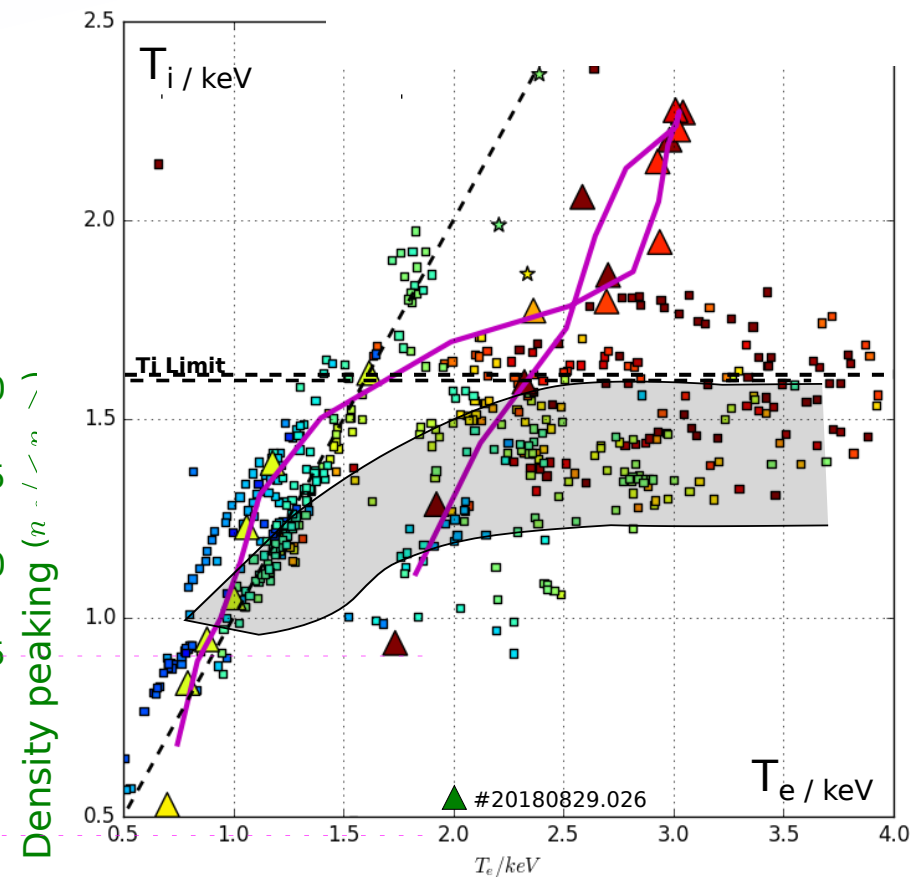
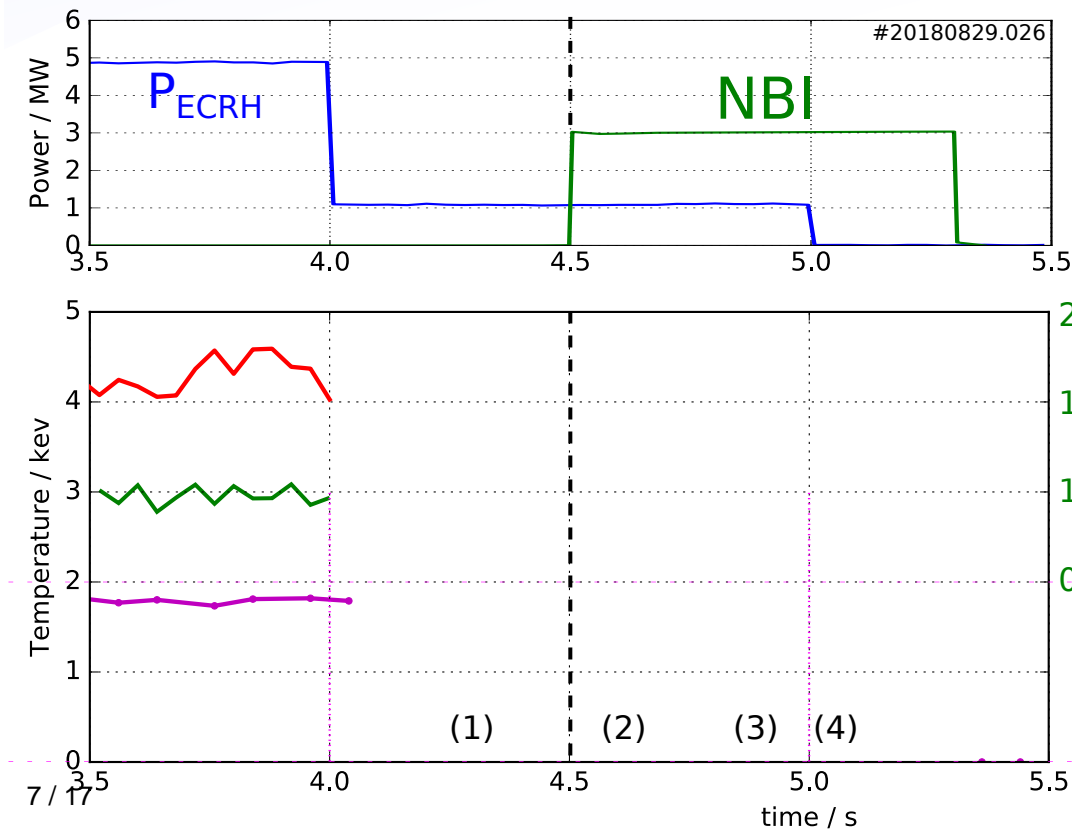
Start looking at exactly where steeper T_i / density gradients are.
High resolution CXRS mode (all optics, all spectrometers). 6 point spline fit:

NBI+O2:



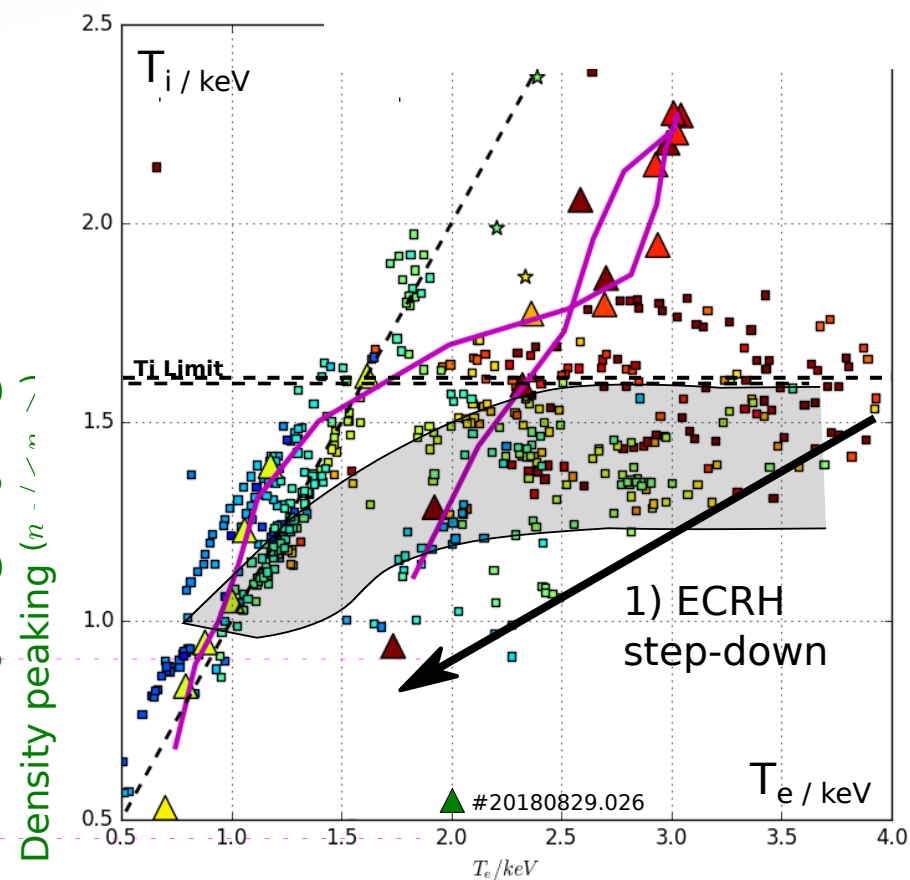
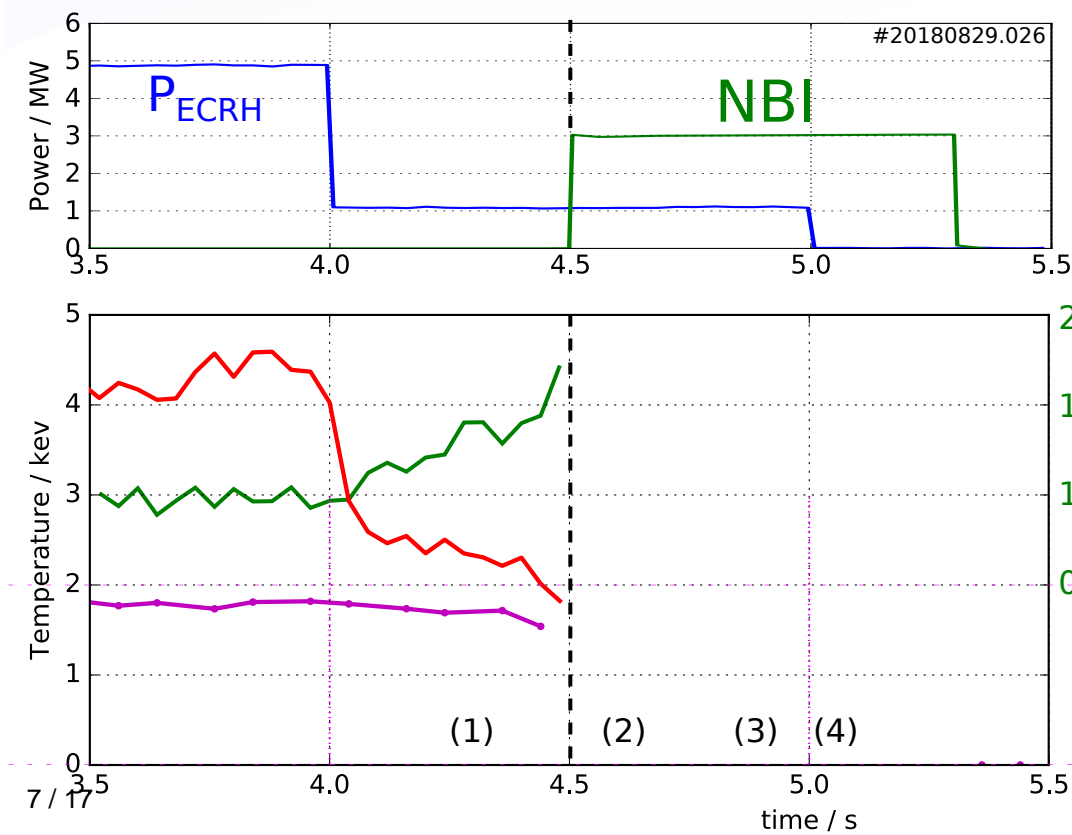
Case 2: NBI into collapse

- 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.



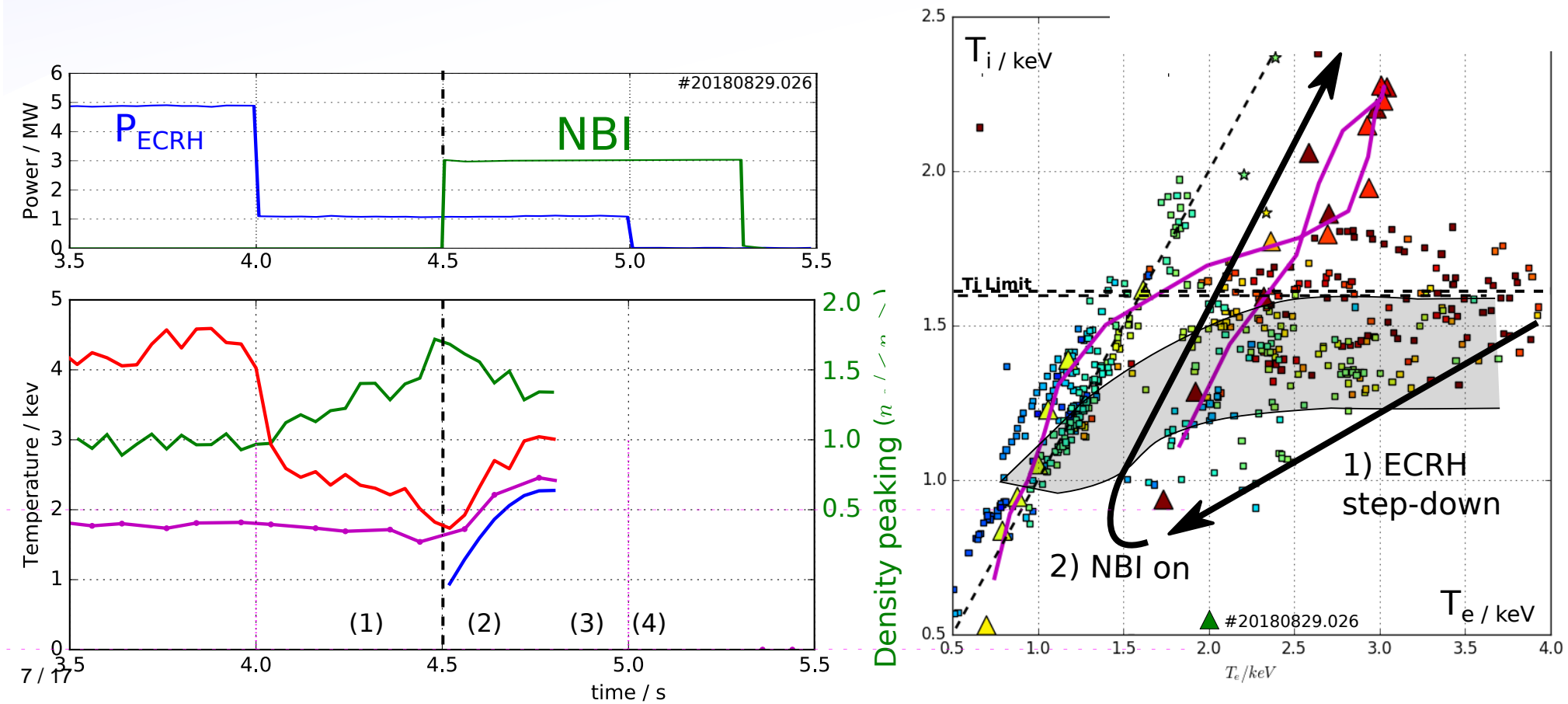
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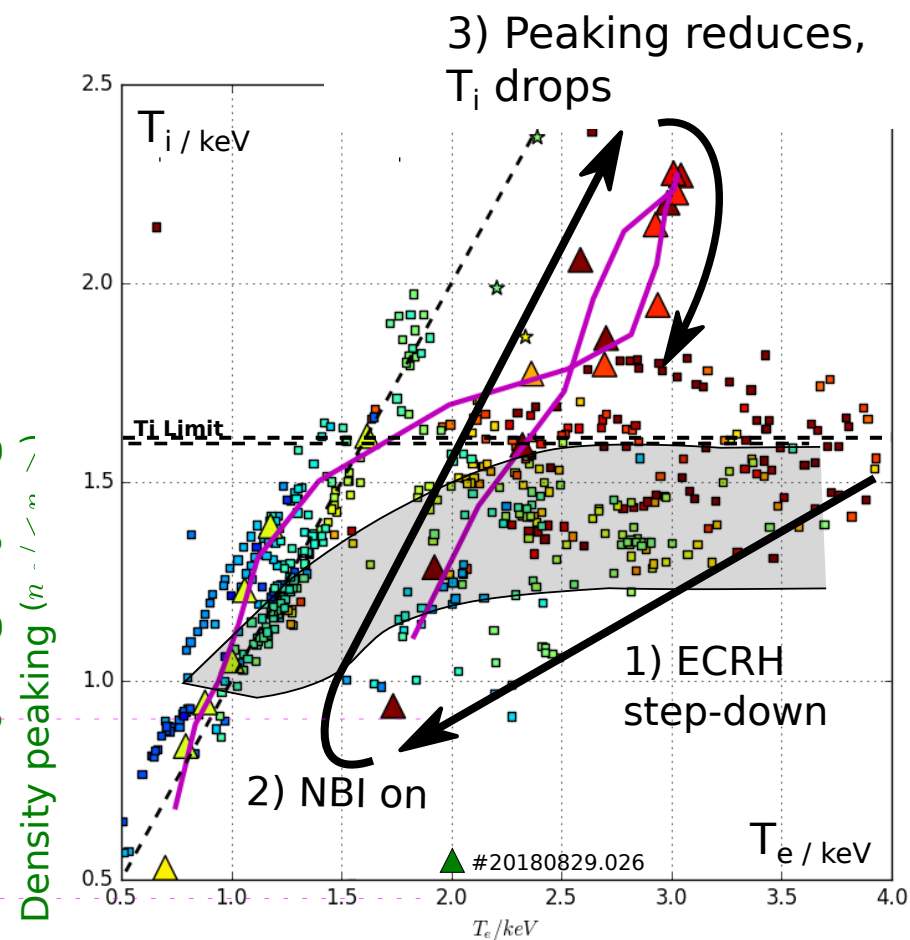
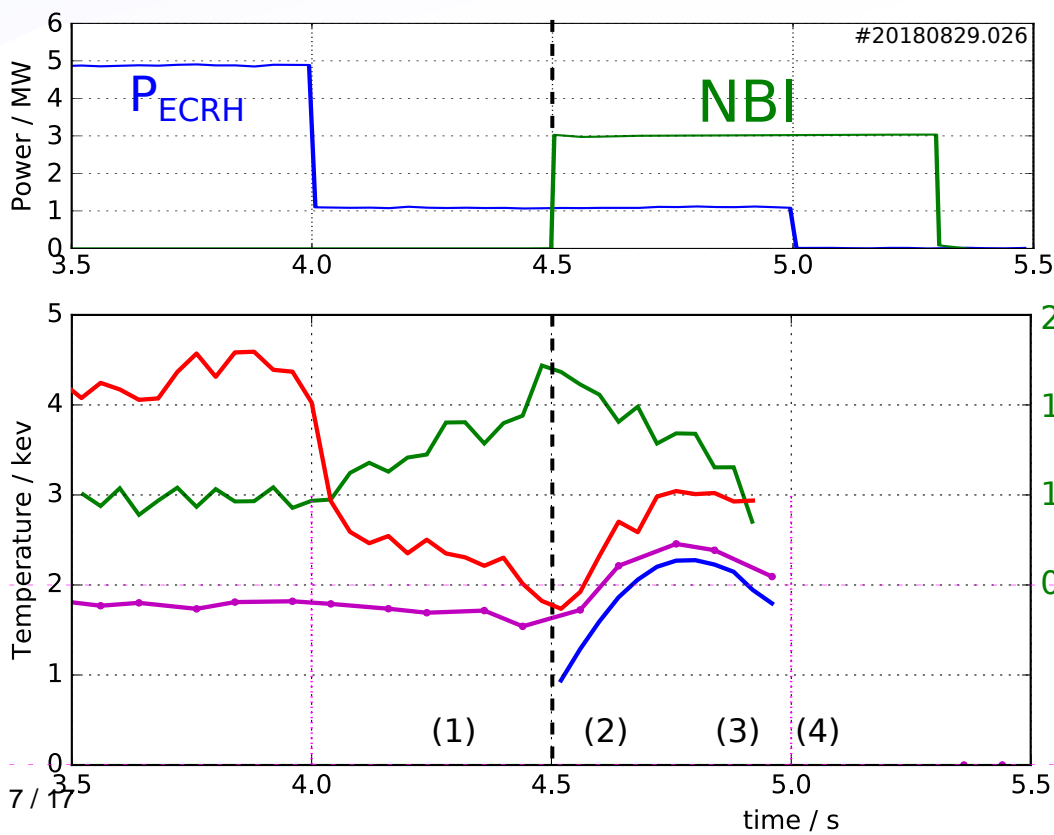
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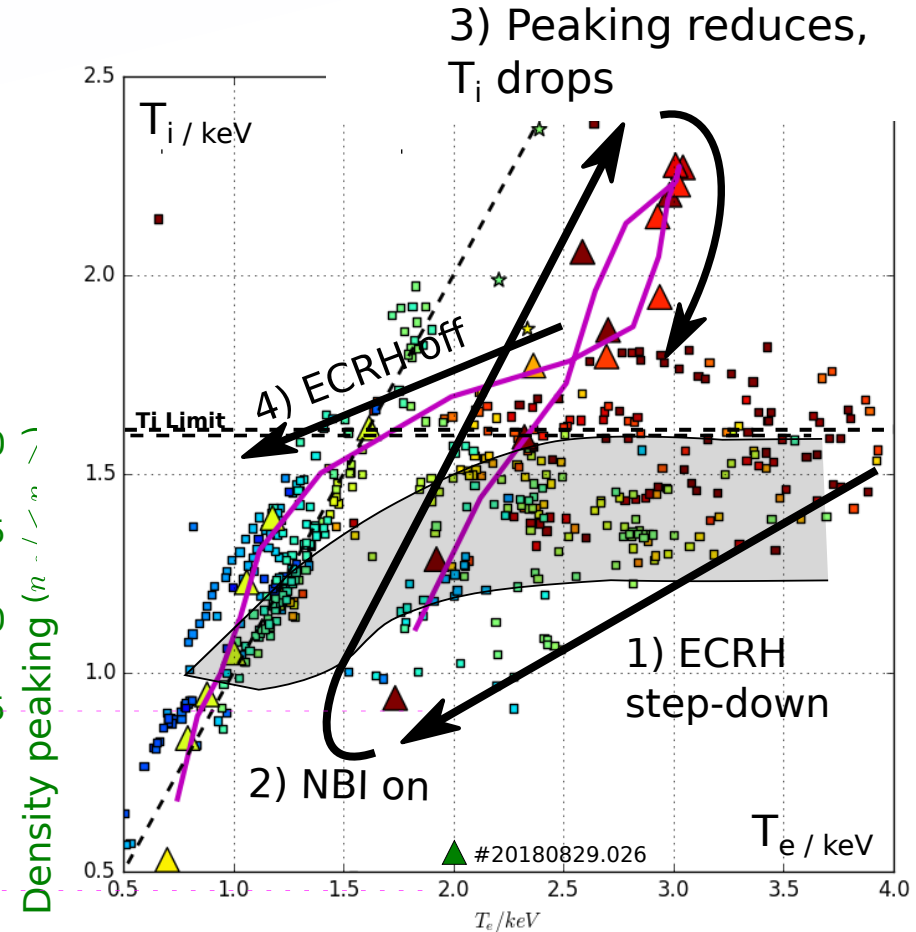
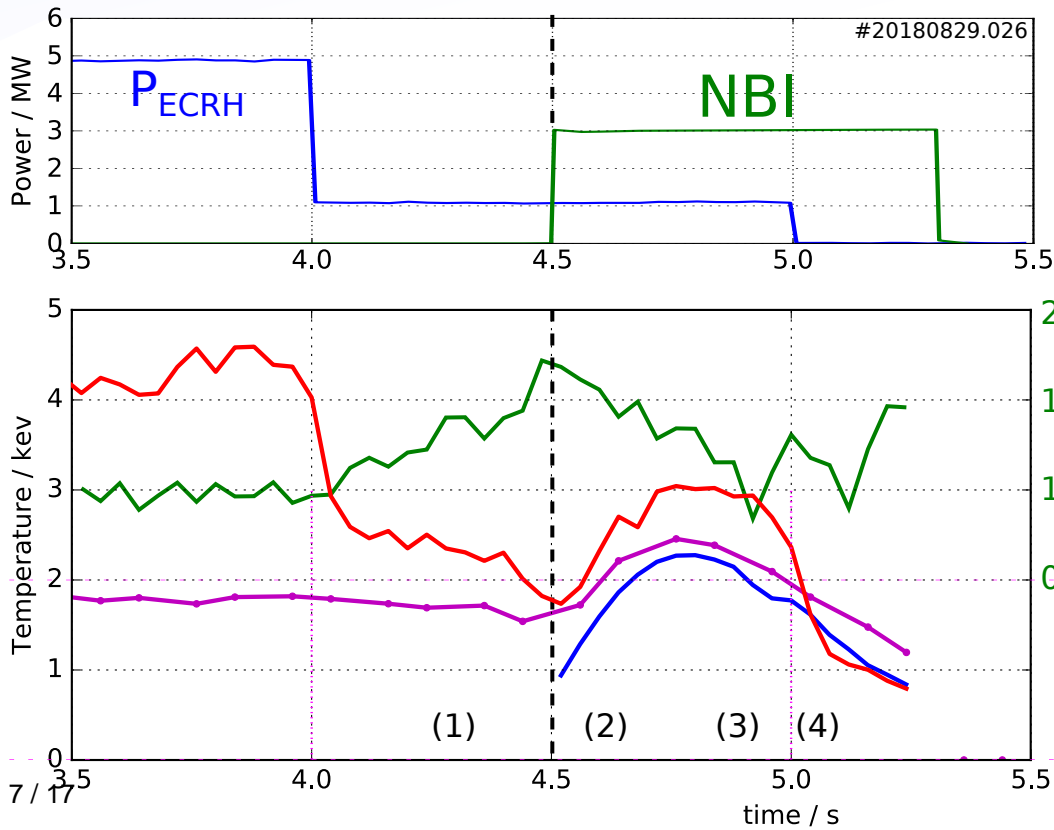
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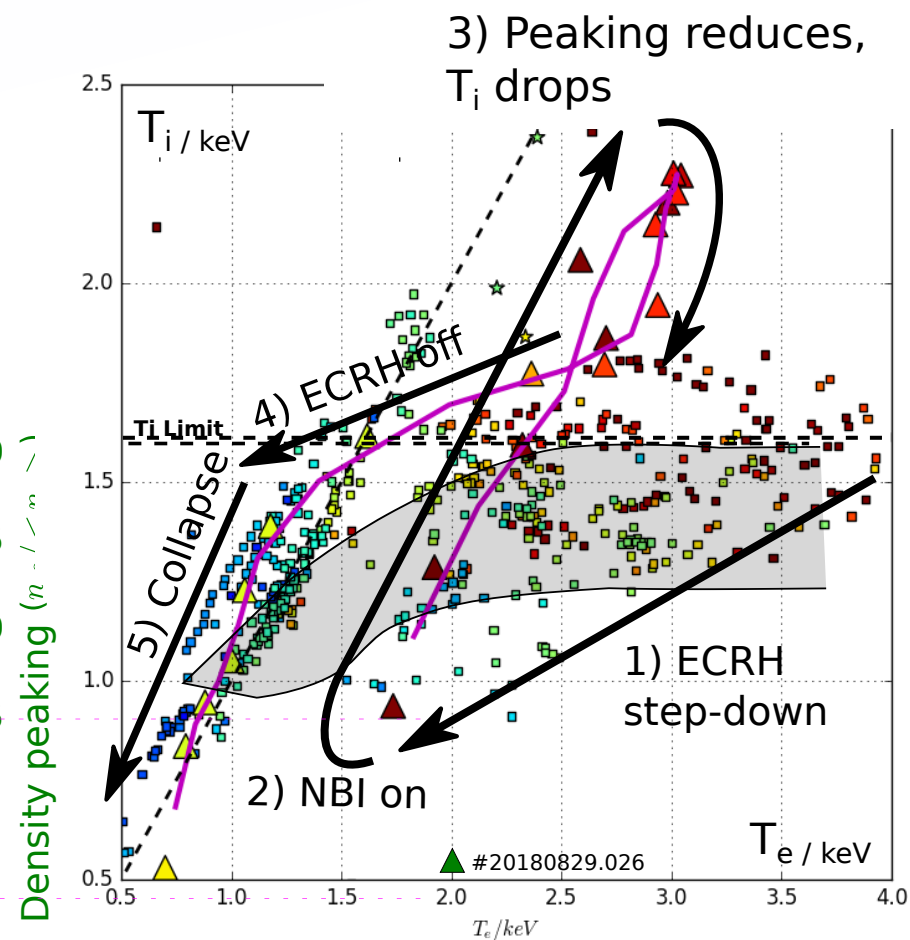
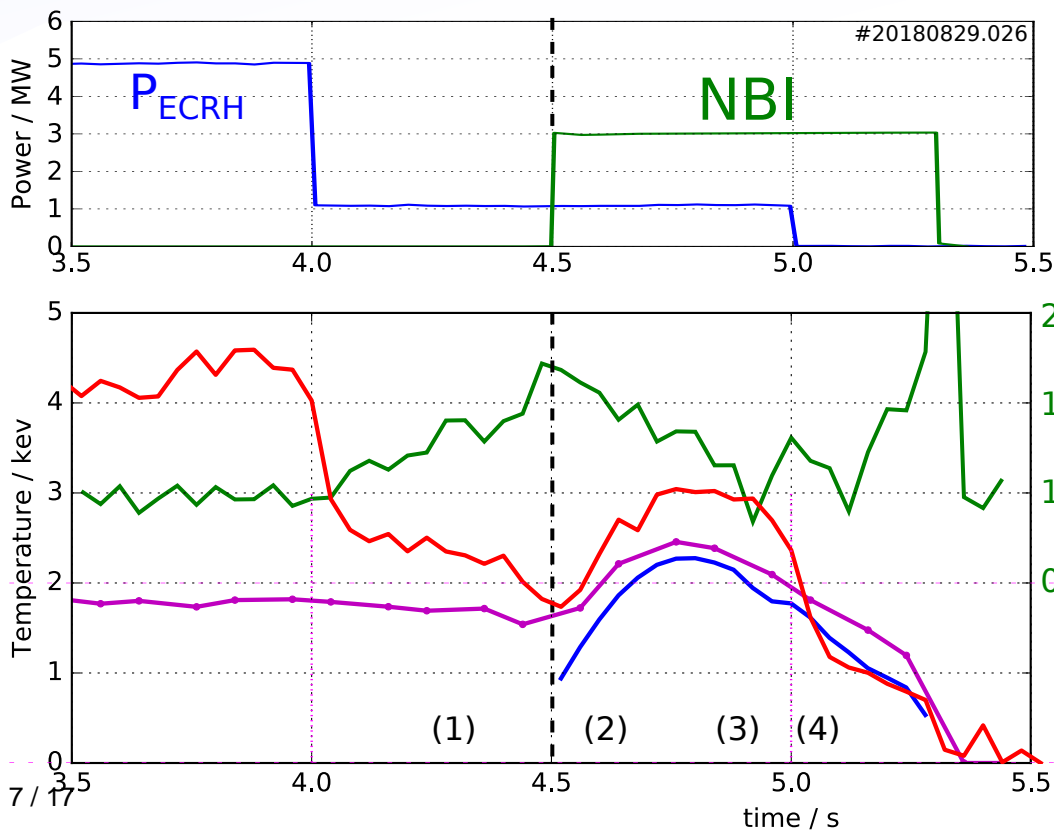
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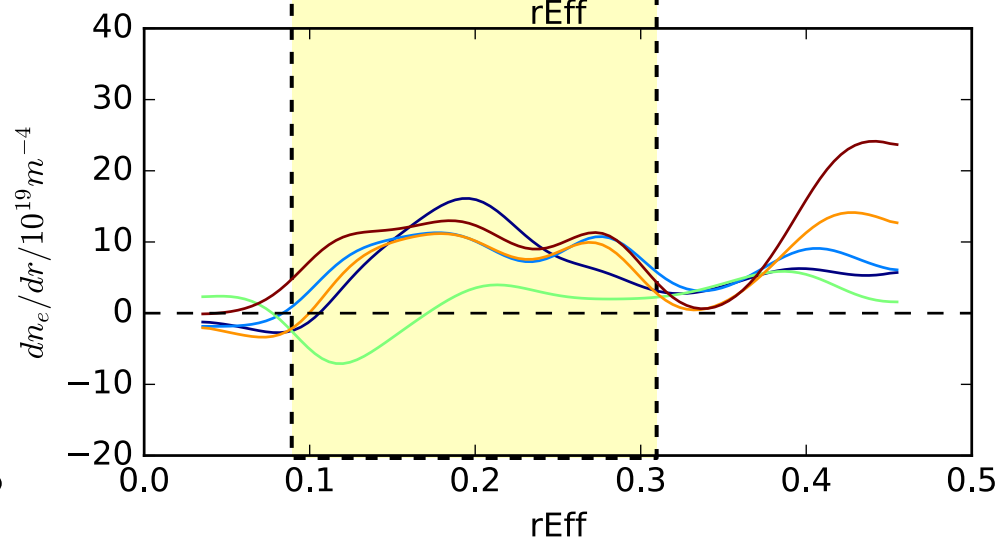
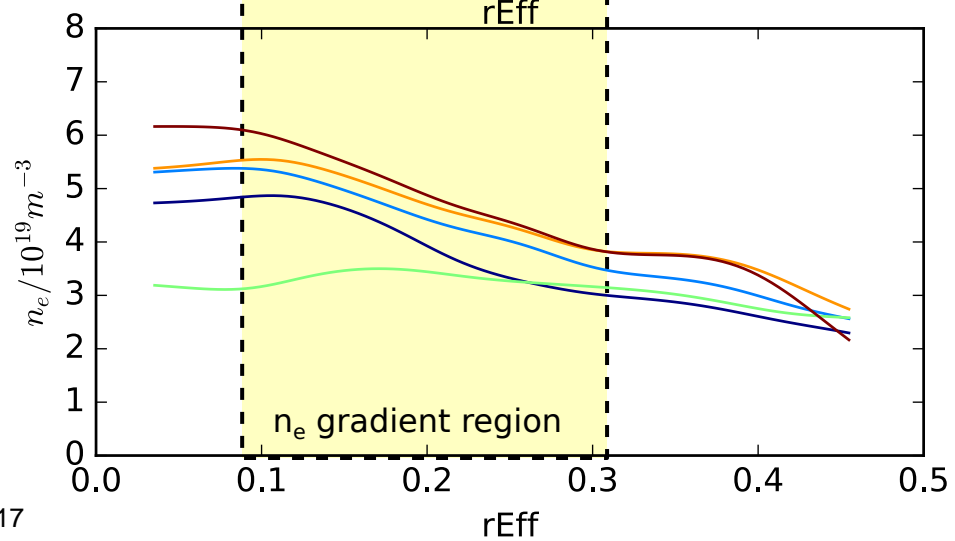
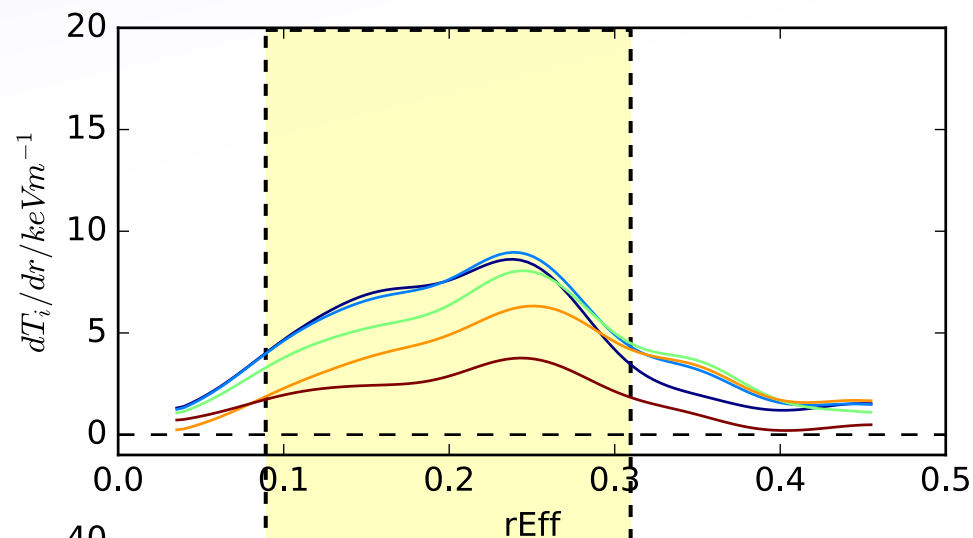
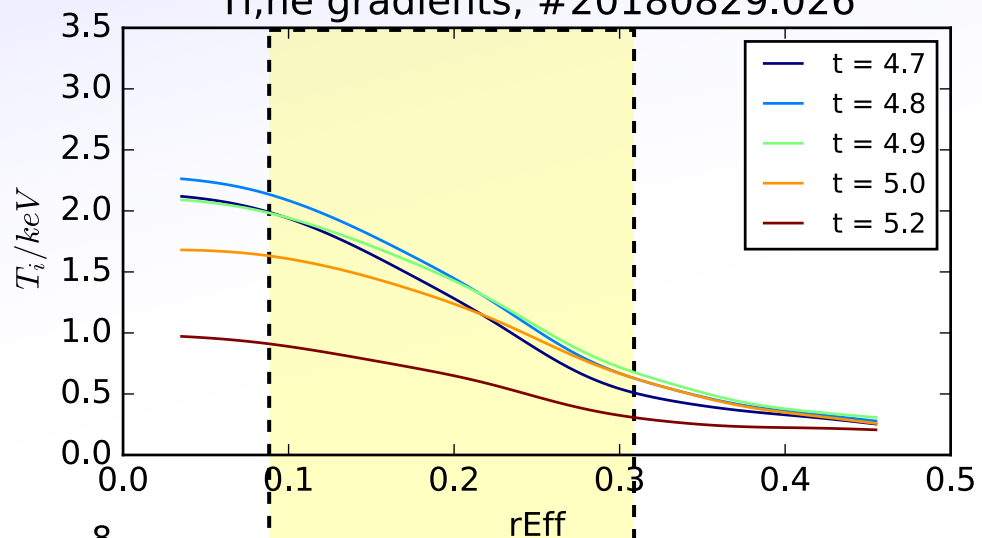


Profiles

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

NBI into collapse:

T_i, n_e gradients, #20180829.026



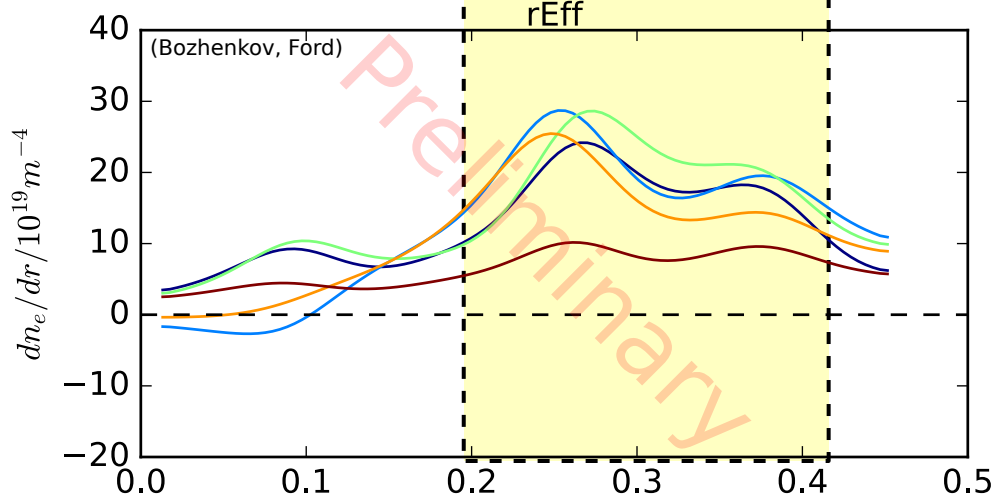
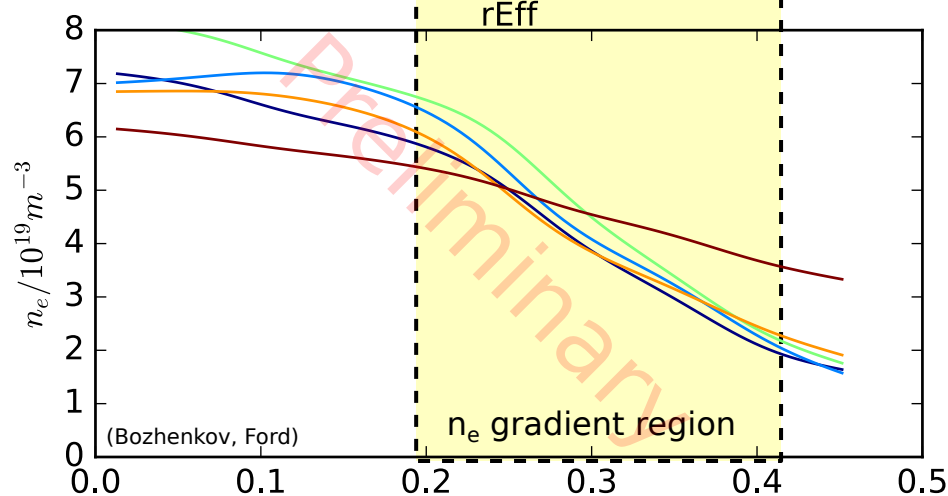
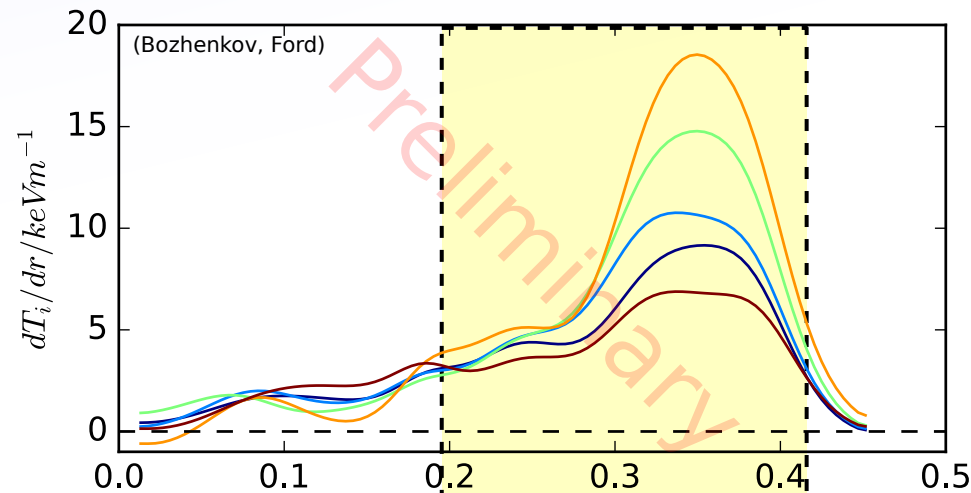
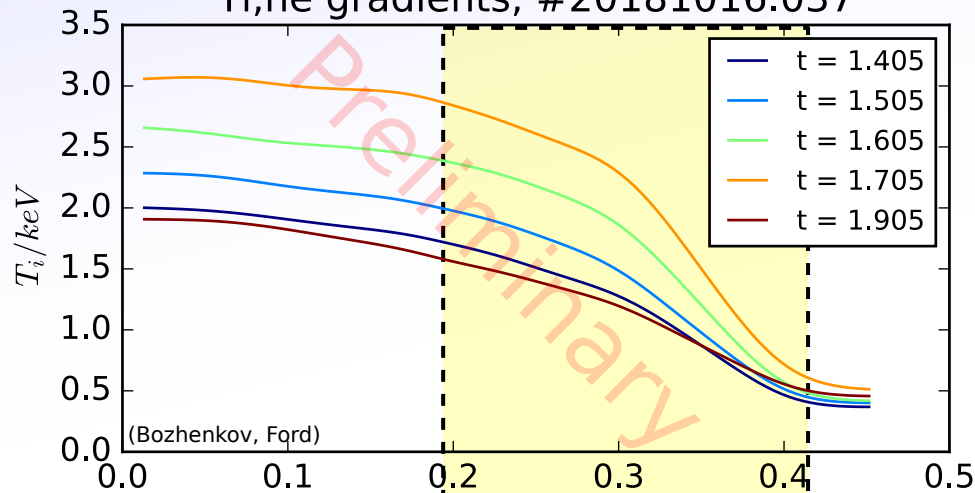


Profiles - Pellets (boz_010)

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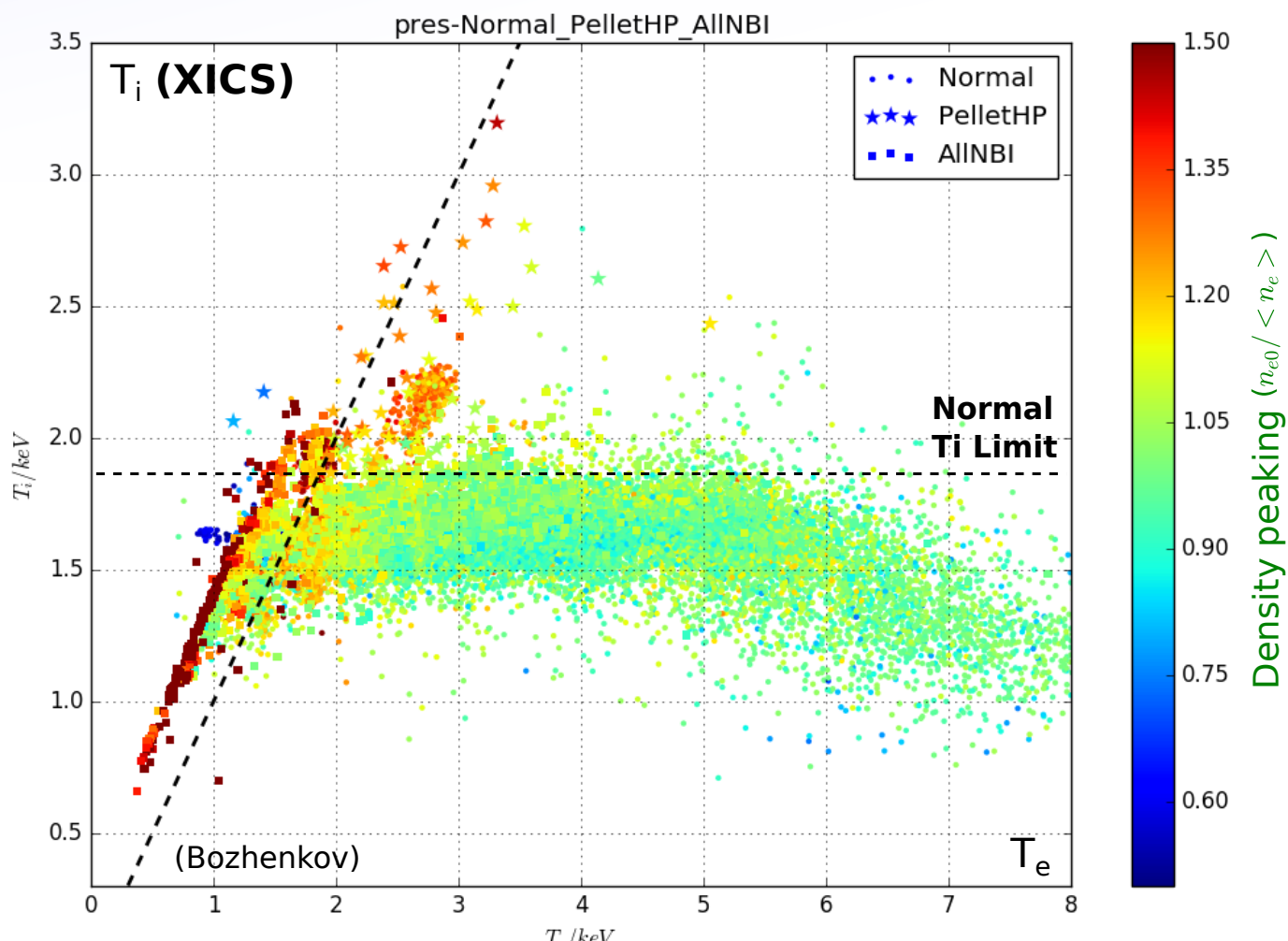
Pellets: (NBI blips only) **** This one is very mapping-sensitive, needs examination ****

Ti,ne gradients, #20181016.037



Density Peaking

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

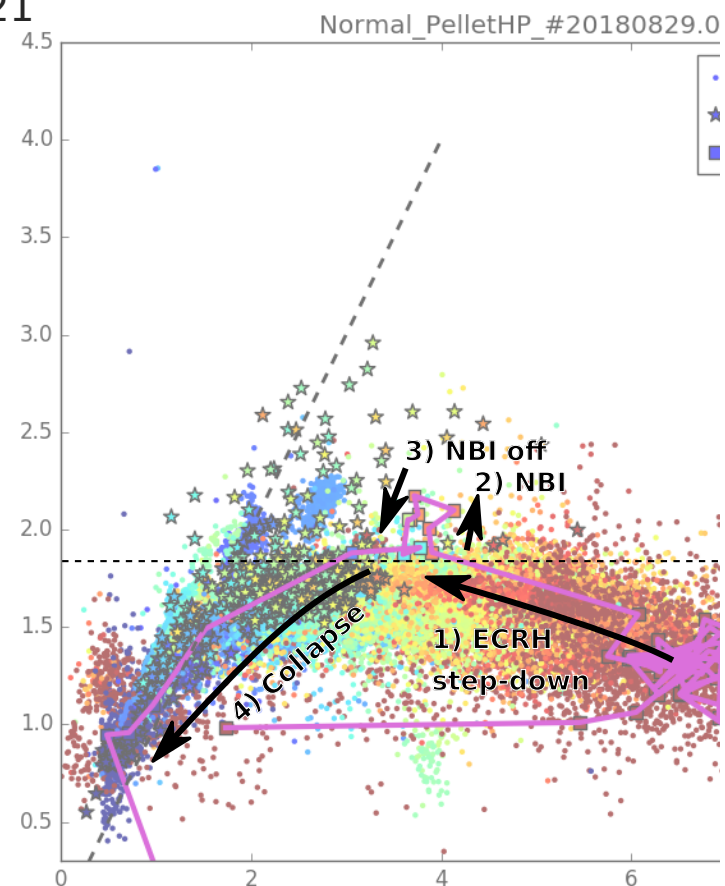
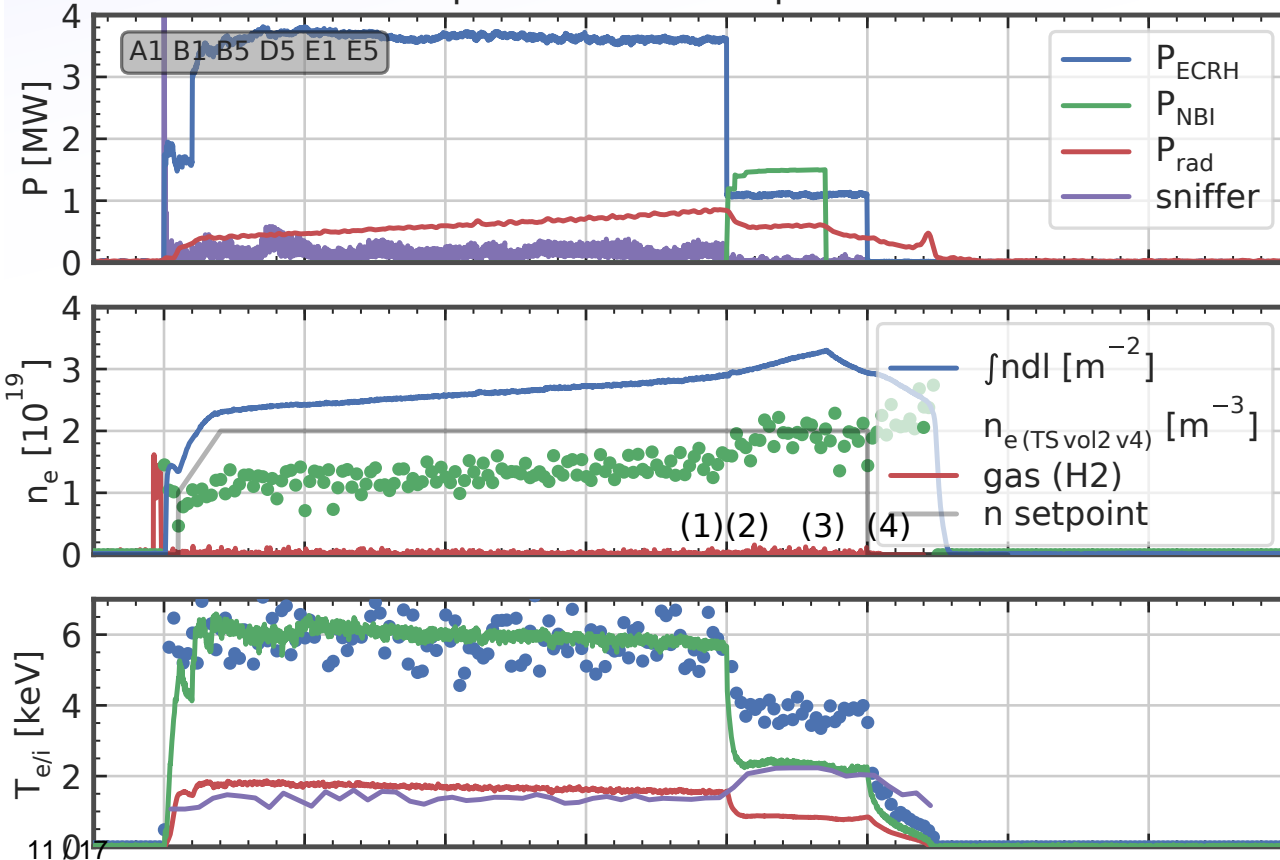




Density Peaking

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

W7-X 20180829.008 | UTC: 08:37:00 | T0: 1535531820418961221



ICRH stabilization of turbulence?

[Y. Kazakov]

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

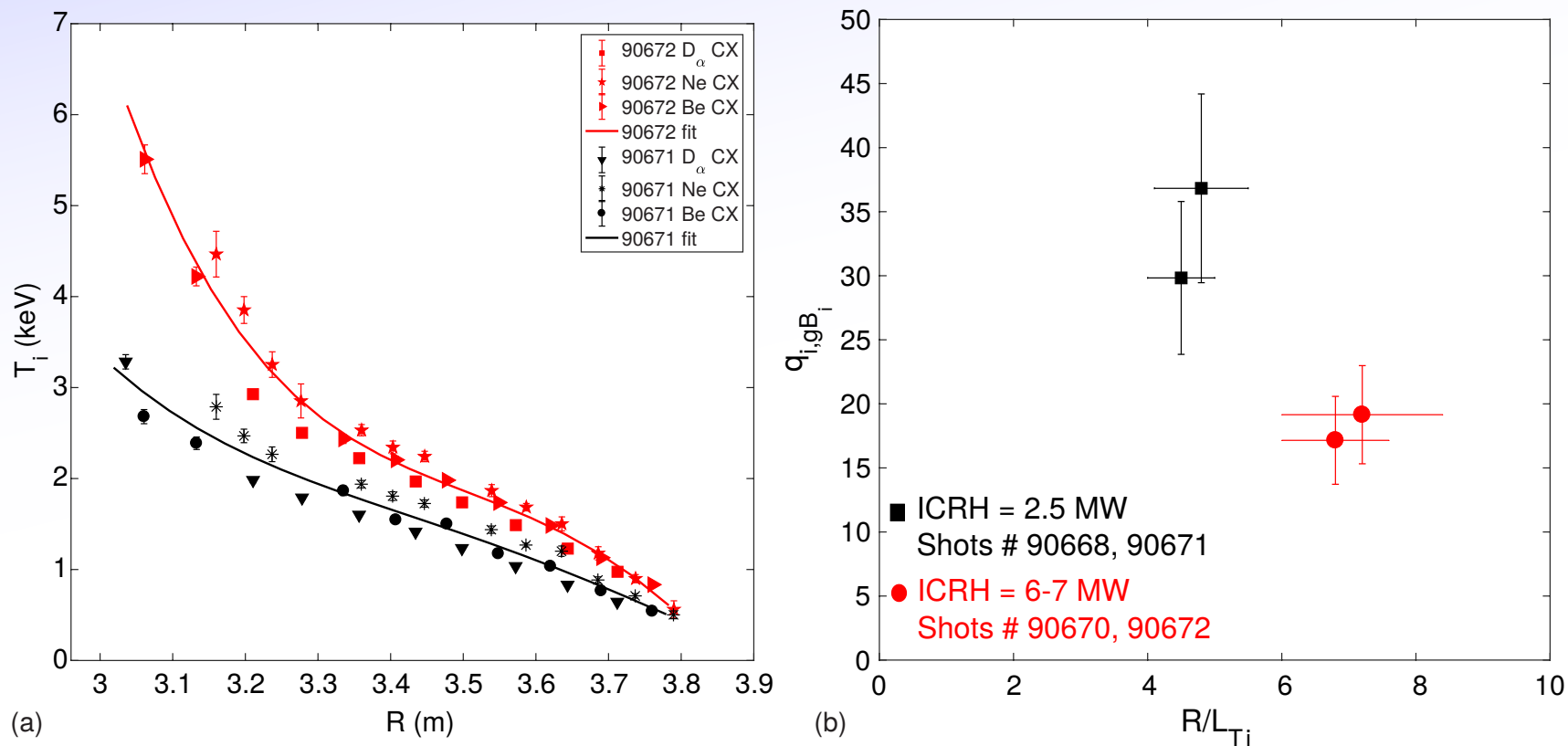


Figure 2. (a) Comparison between the T_i profile of discharges n. 90671 (2.6 MW of ICRH, black points and line) and n. 90672 (7 MW of ICRH, red points and line). (b) q_{i,gB_i} (R/L_{T_i}) at $\rho_{tor} = 0.25$ of discharges with low ICRH power (2.6 MW, discharges n. 90668 and n. 90671) and of discharges 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 ^3He 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 theoretically 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.



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- NBI will probably be a critical tool for testing/investigating high T_i 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)



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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?)

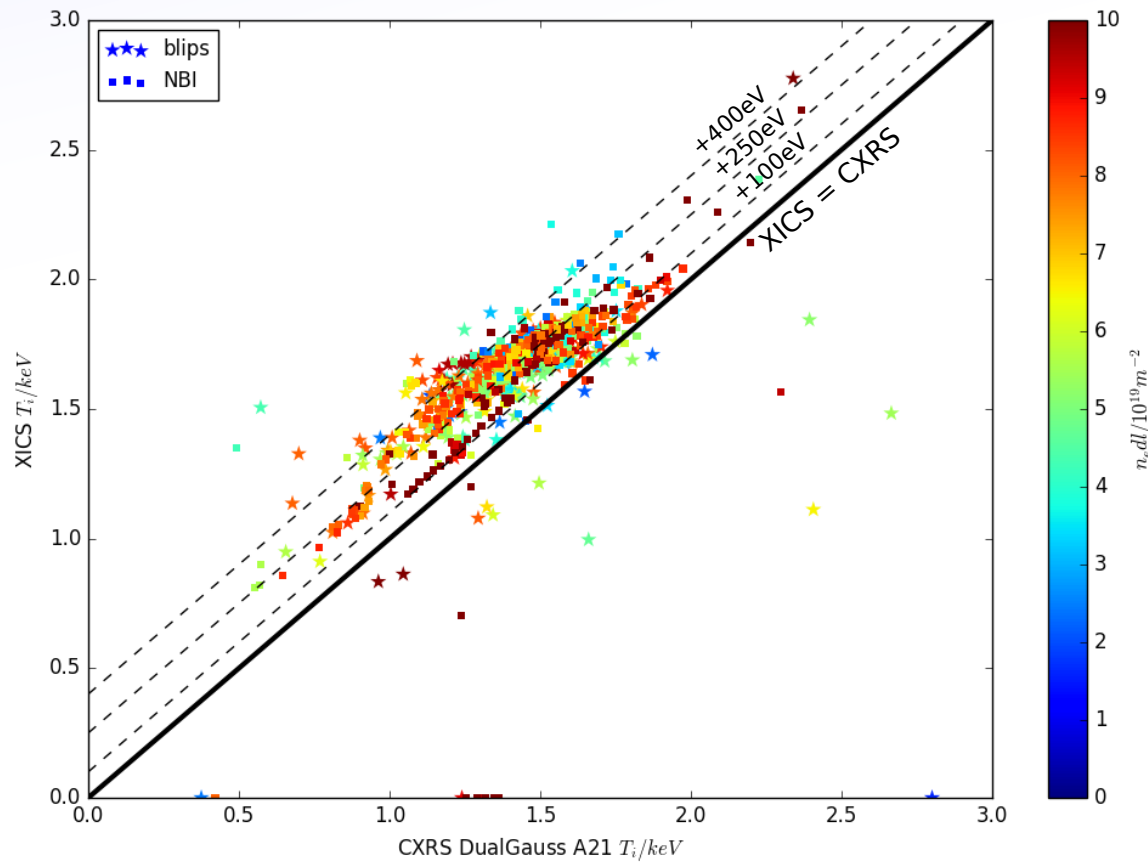
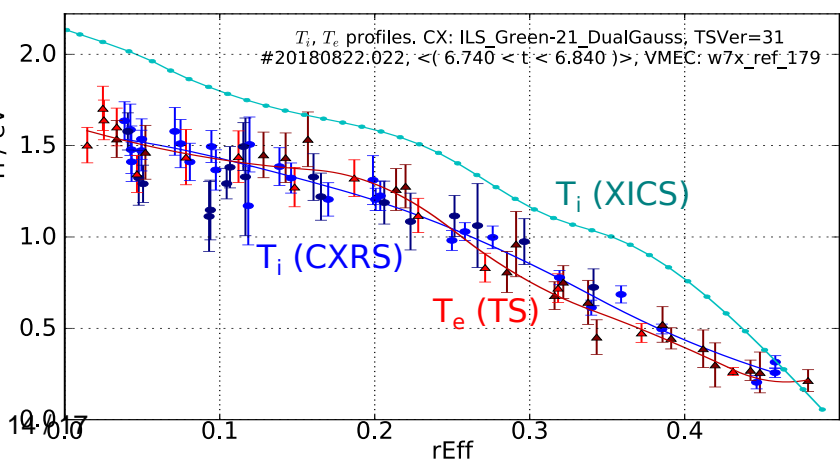
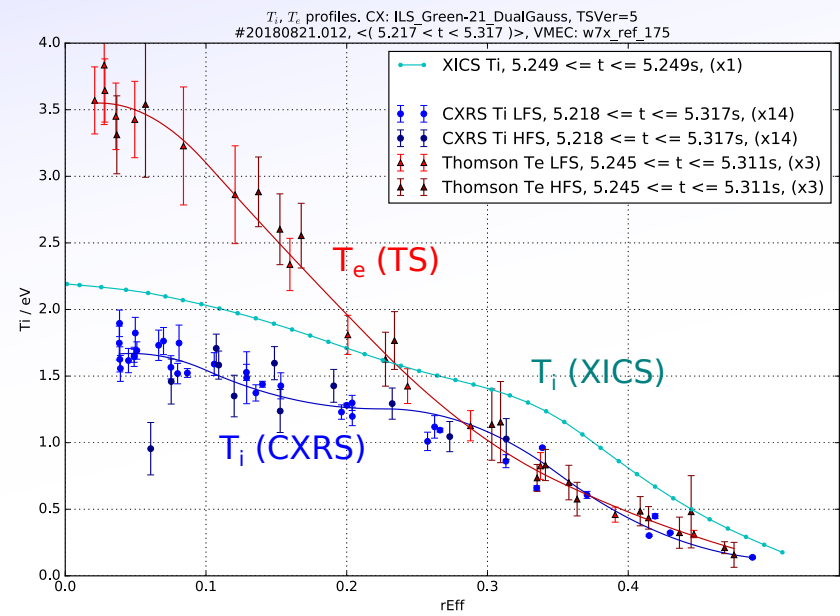
- All 8 sources?

- Helium injection?



XICS --> CXRS

- CXRS gives higher resolution data, but only where NBI is on (~200 shots)
- To compare the two, we need to adjust for $\sim 250 \pm 150 \text{ eV}$ higher core XICS T_i values: (More on this in a later presentation)





P_{ECRH} Upgrade

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

Plot T_i vbs (n_e , P_{ECRH})

- 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.



What's next and open questions.

- Scaling - we know where we go with ECRH + higher 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 theoretical 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 T_i ?
 - Hold $T_i = 2.5\text{keV}$ for longer?
 - **NBI will probably be a critical tool for testing/investigating high T_i in future campaigns.**
 - **NBI could provide a fine and reproducible control of density peaking and core fuelling rate for turbulence and high performance experiments.**
- Does it stop the pellets HP?
Can we get steeper ne gradient this way, or steep across more of the radius?