Power and particle transport in NBI vs ECRH plasmas

Profiles Topical Group, May 2021

Authors:
O. P. Ford, M. Beurskens, S. Bozhenkov, S. Lazerson

Contributors:
L, Vanó, H. Smith, Y. Turkin, P. McNeely, N. Rust, D. Hartmann, A Langenberg, D. Zhang, N. Pablant[2],
G. Fuchert, E. Pasch, T. Kremeyer, C. Beidler, S. Bannmann, V.Perseo,
(... Interferometry, Diamagnetic Loop, ECRH ...)

*: Max-Planck Institut für Plasmaphysik, Greifswald, Germany
2: PPPL

...

Background:
- Gas fuelled ECRH dischages:
  - Flat density profiles
  - T_i clamped at 1.5keV because:
    1) Poor coupling at low collisionality,
    2) Turbulence and stiff profiles
    3) Te/Ti exacerbates turbulence
  - Low and flat impurity densities

- Pellets:
  - Core fuelling --> peaked density profiles
  - Turbulence supression. Q_i reduced to *O(*neoclassical*)*
    --> Highest observed T_i

Great but.... Only seen *after* rapid pellets. Can steady state pellets give peaked density?
If not, what can we do?

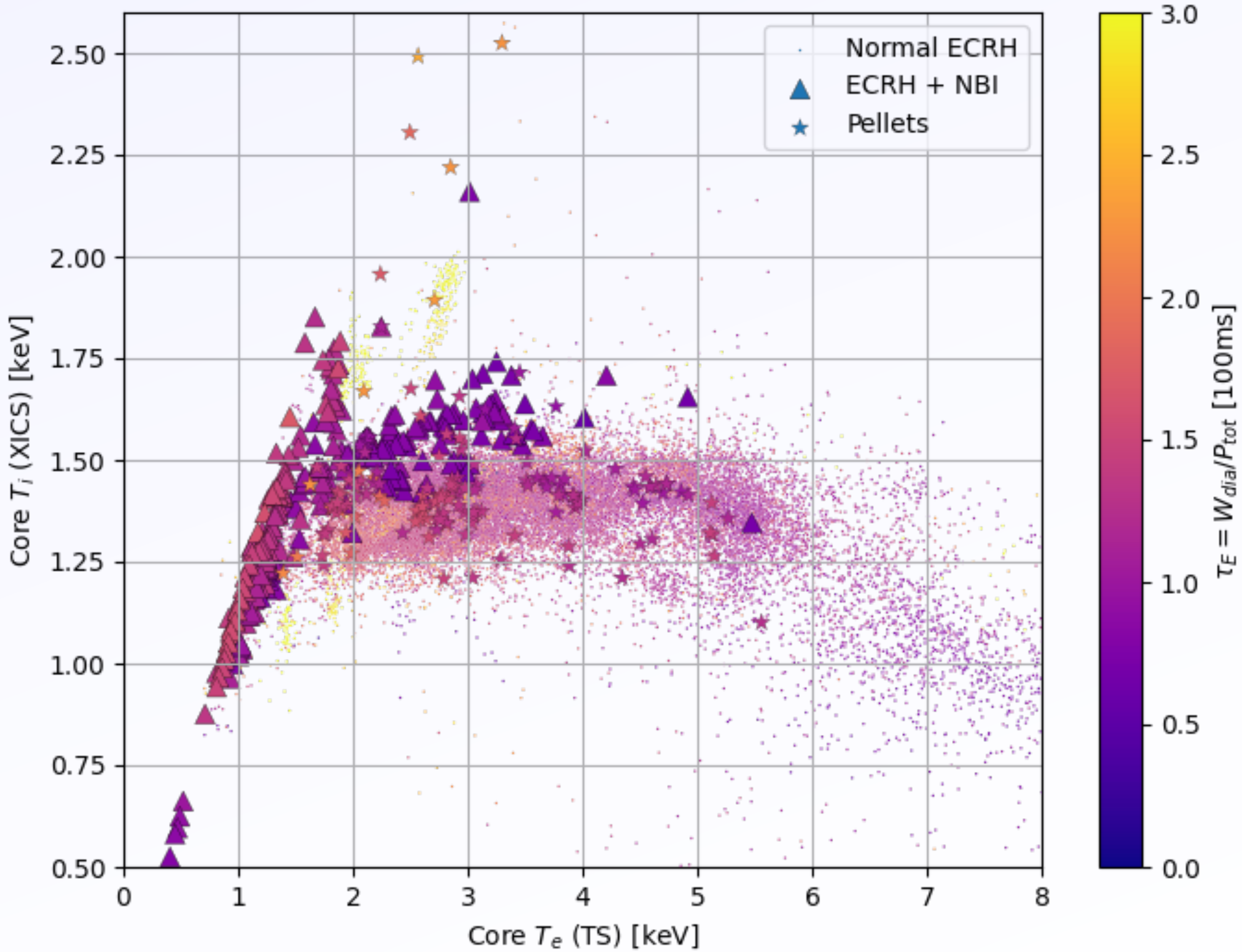
NBI gives continuous core fuelling and ion heating. Can NBI provide a route to improved performance (higher T_i)?

Note: I focus here on high T_i, not β, so I am ignoring T_e 'performance'.

Global view

How does global T_i look?

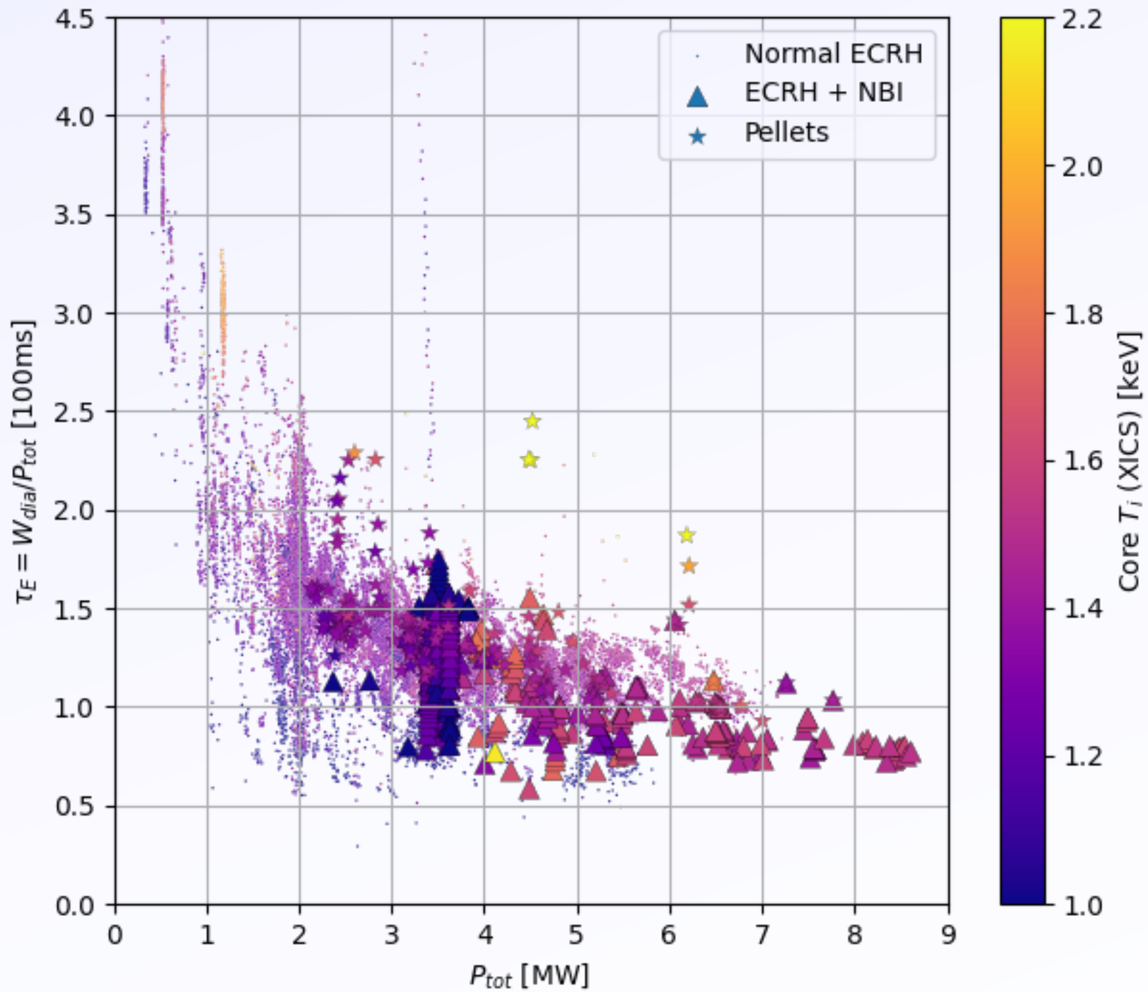
- Most shots are ECRH + NBI.
- T_i still around clamping limit, maybe slightly higher but generally not as high as post-pellets plasmas.
- Some of the highest T_i are at lower T_e.



Global view

Global confinement generally lower for NBI compared to ECRH due to lower efficiency of NBI heating physics:

1) Significant fast-ion loss fraction >> ECRH stray radiation
2) Power deposition profile much broader



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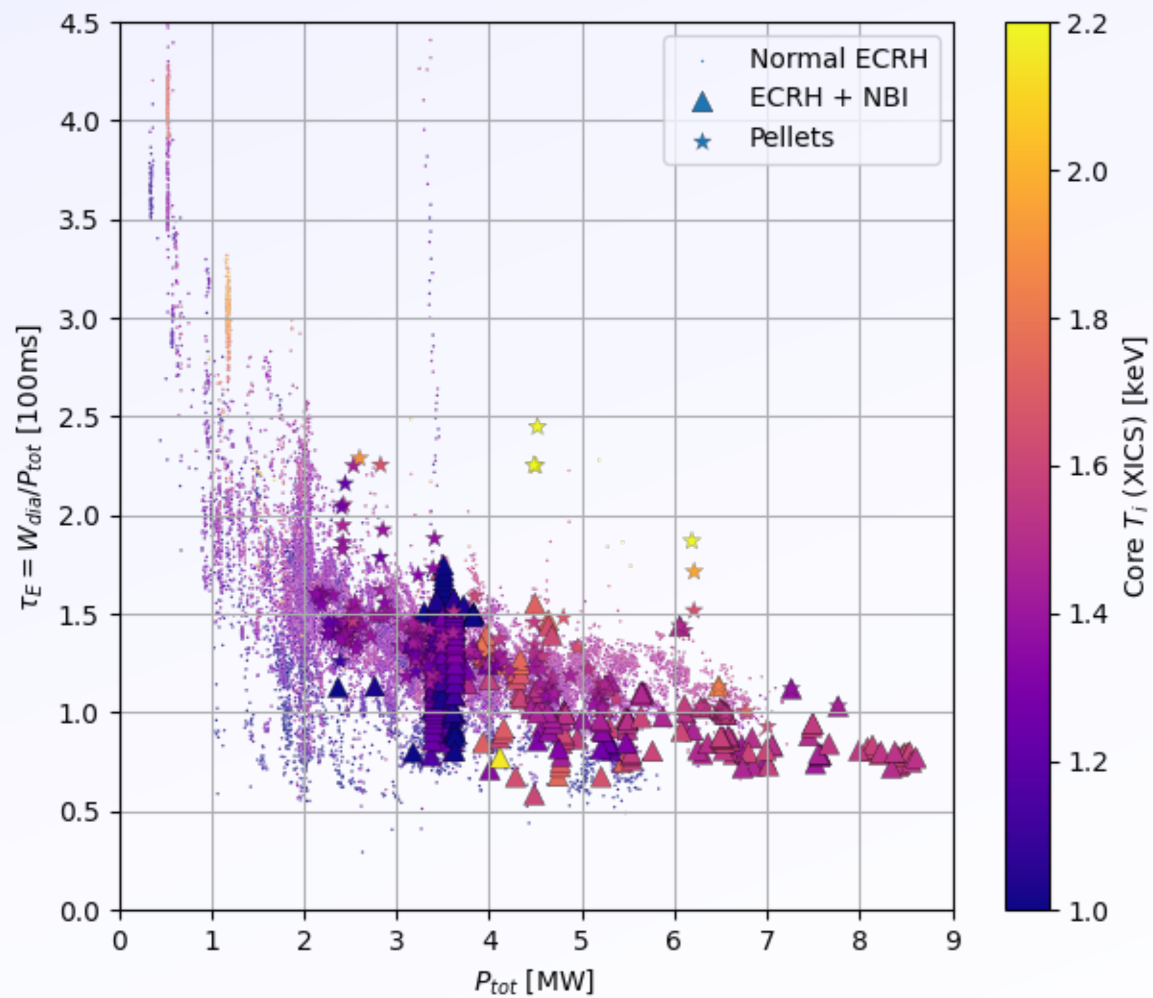

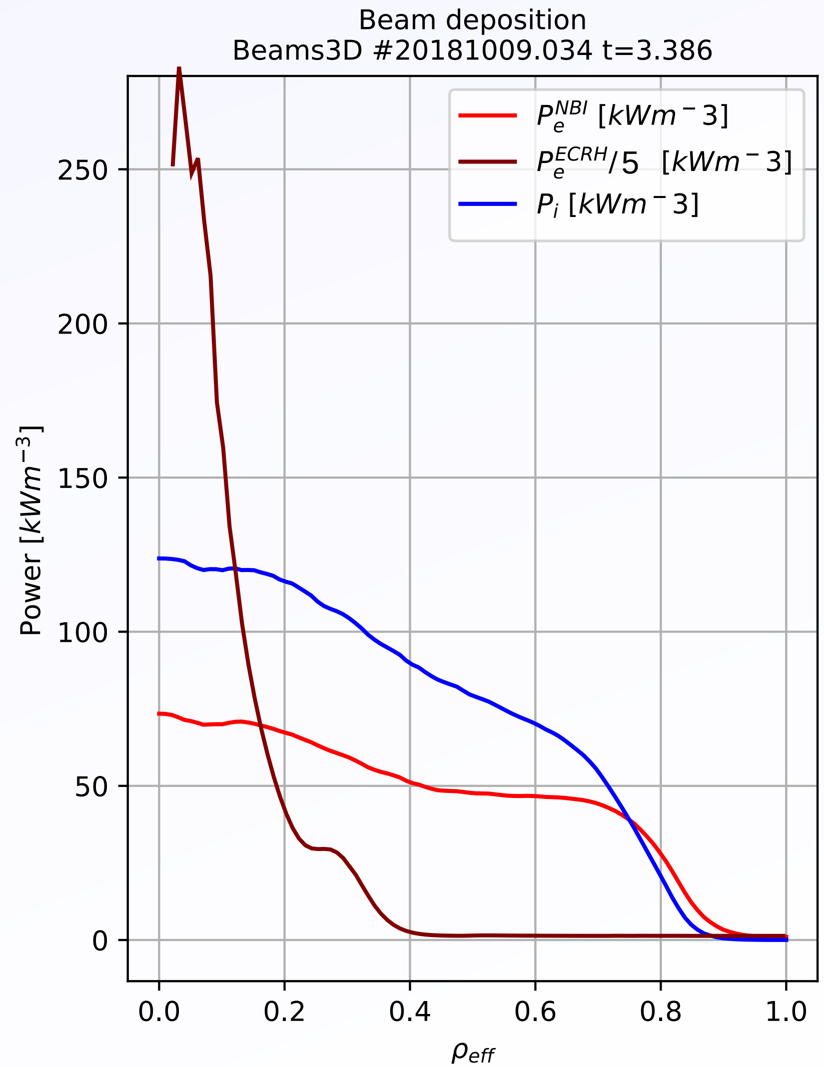

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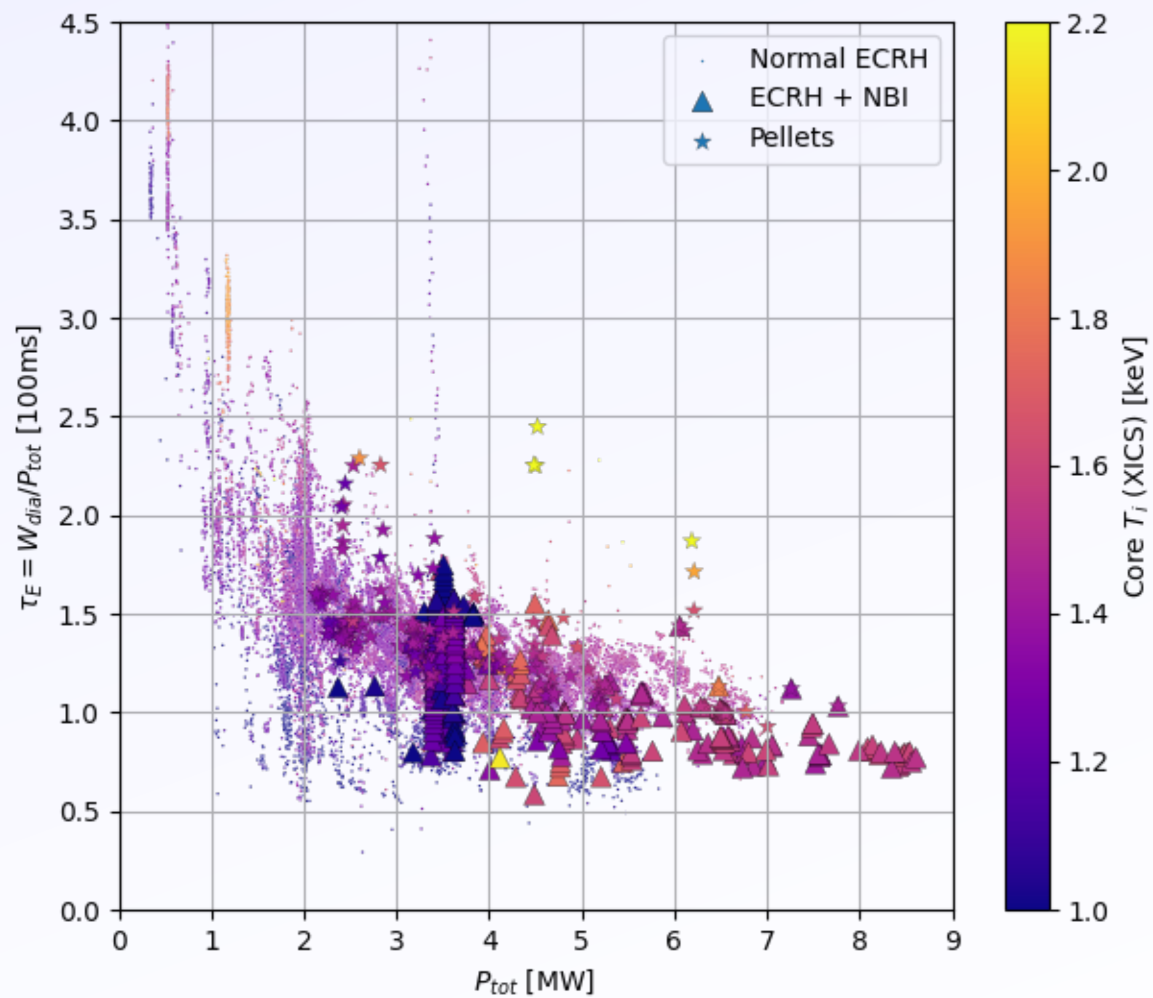

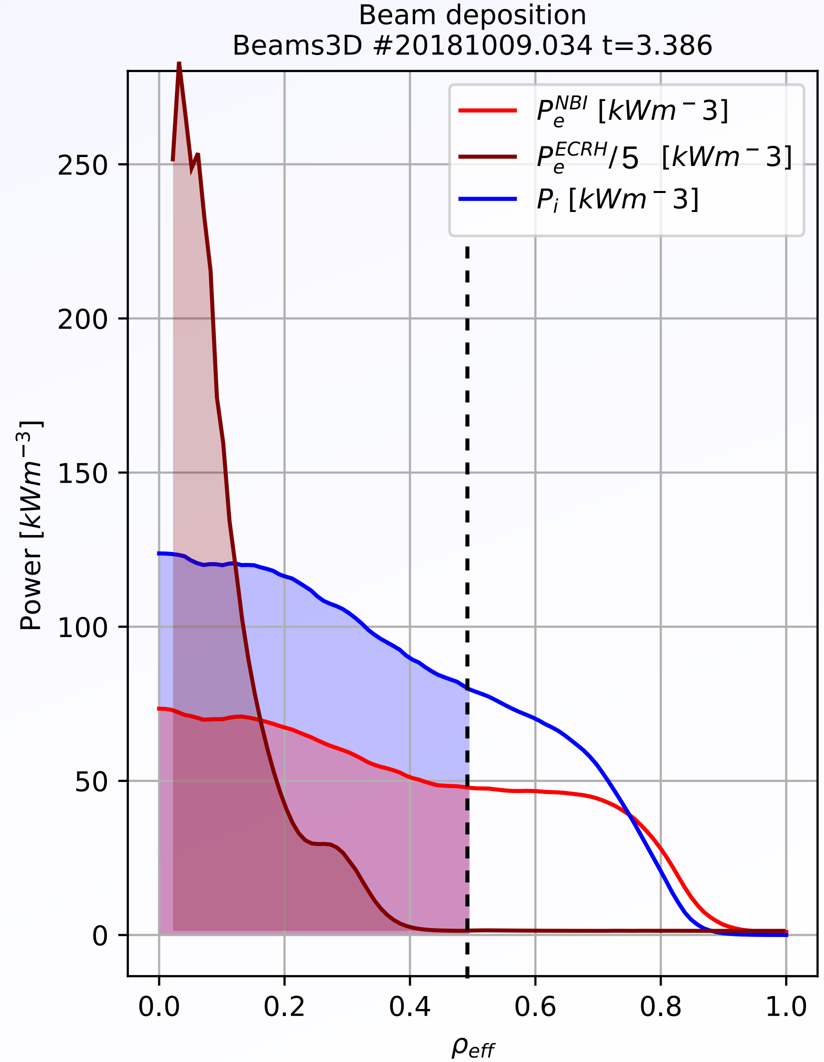

Confinement vs Transport

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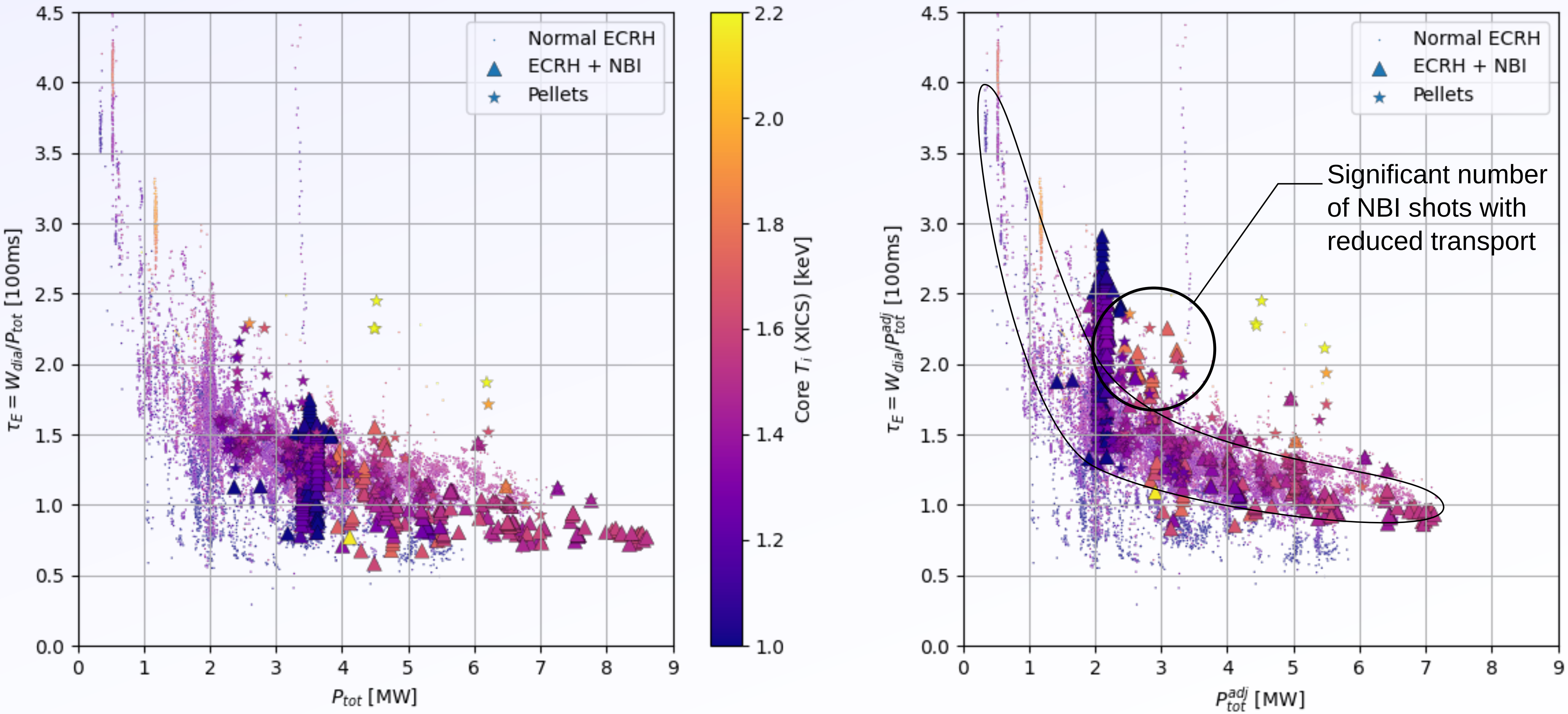
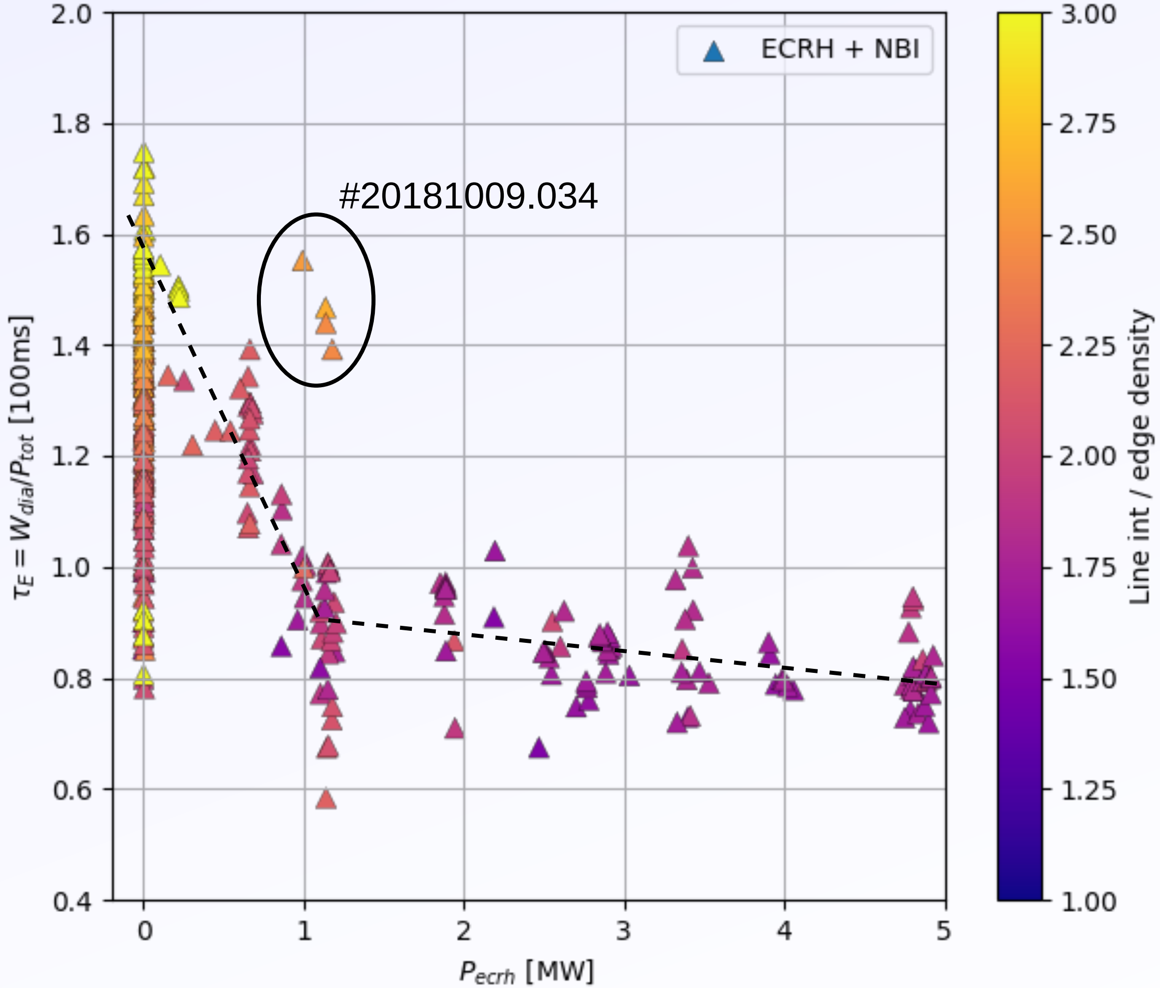
To consider *transport* rather than *confinement*, examine adjust to e.g. $P_{total} = P_{ECRH} + 60\% \, P_{NBI}$:



Confinement vs Transport

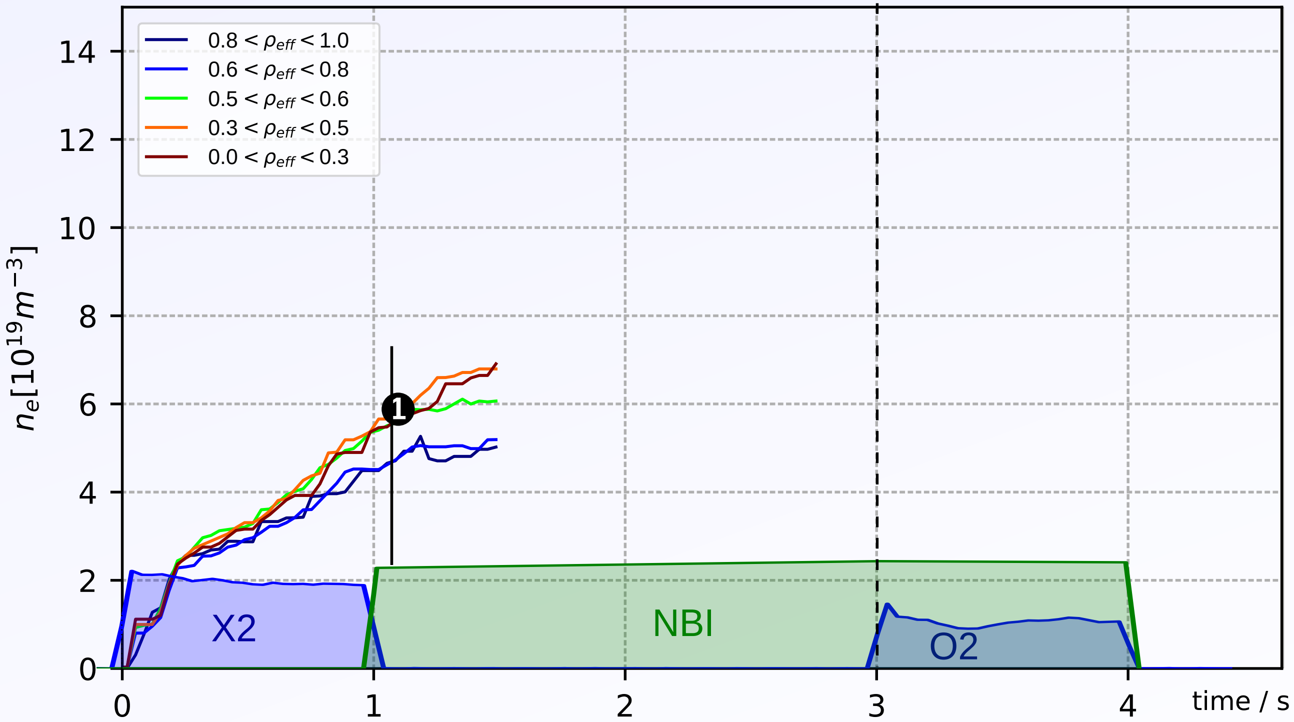
Within the NBI shots, ECRH >= 1MW quickly degrades performance.
ECRH < 1MW shots show some density peaking.

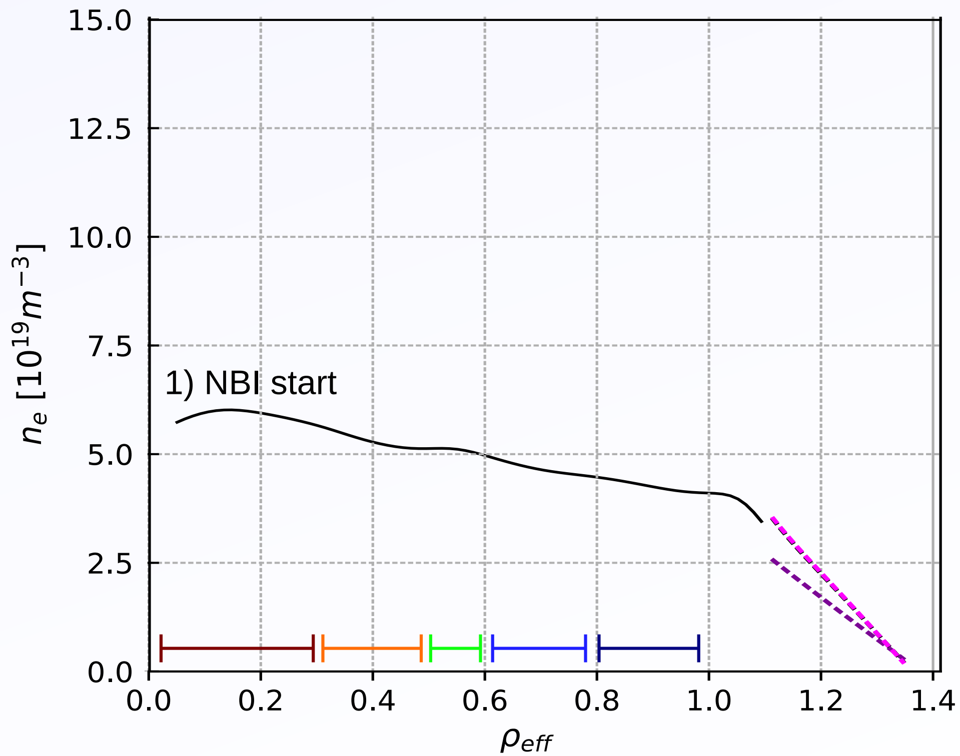


Pure NBI

- Pure NBI discharges show core density and impurity peaking (*almost* all of the time!).
- Strong density rise occurs
  - $\rho_{eff} < 0.5$.
  - $t > t_{onset}$, which varies over 1 - 2s after NBI in different shots. No apparent correlation of t_{onset} with external events.

Binned Thomson Scattering n_e (no fitting):





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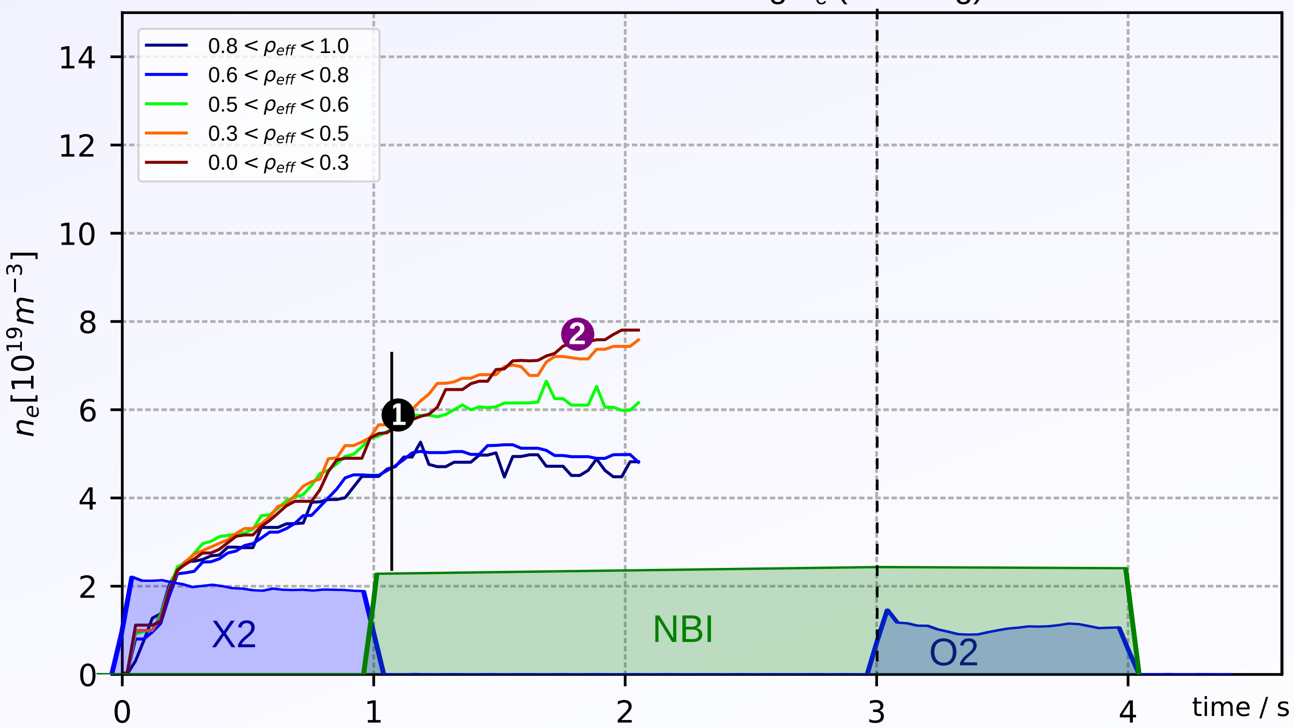

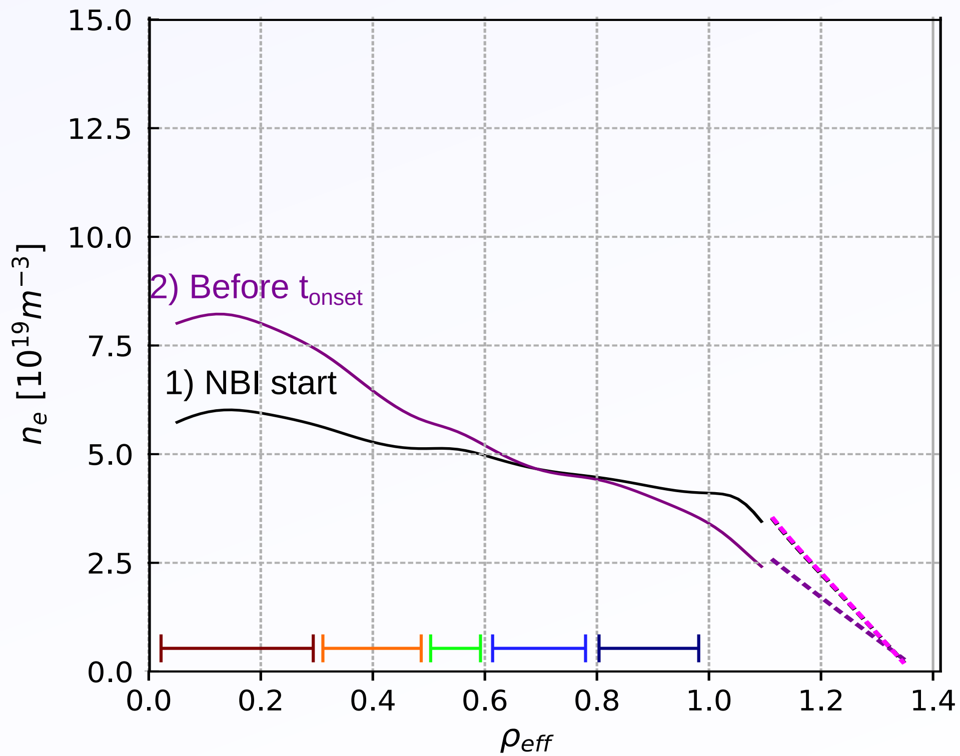

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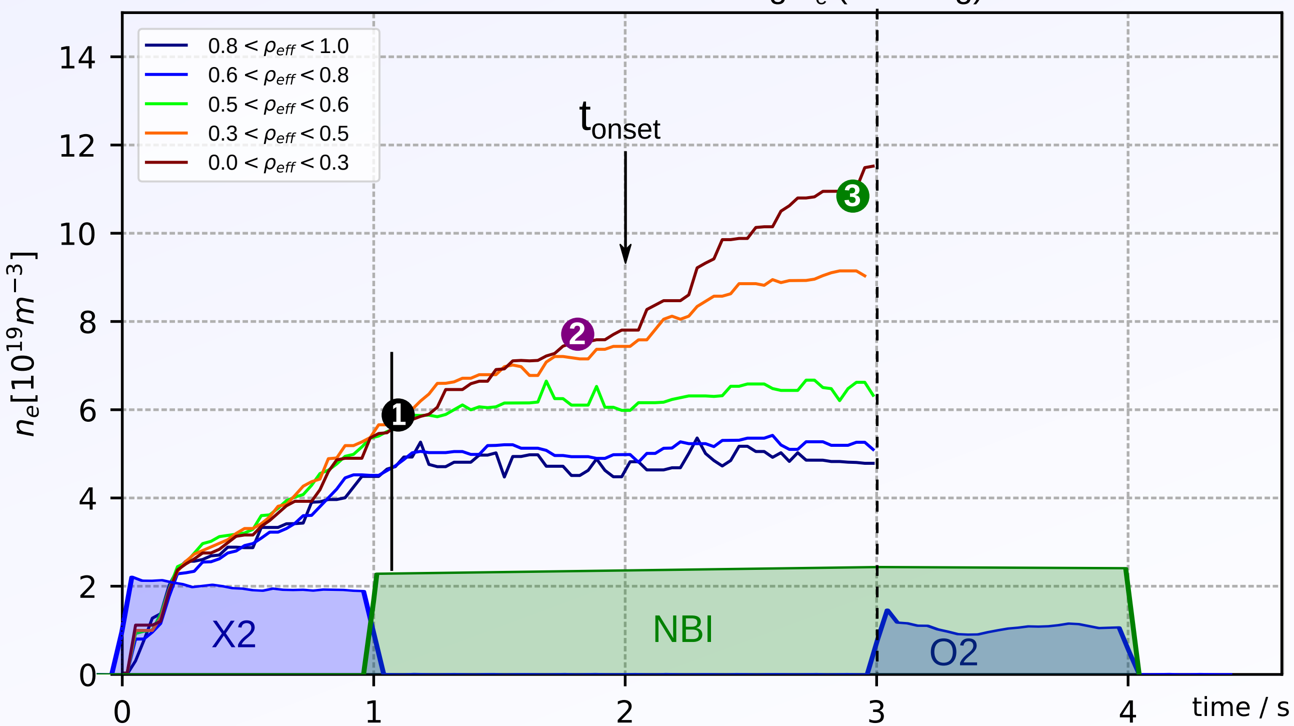

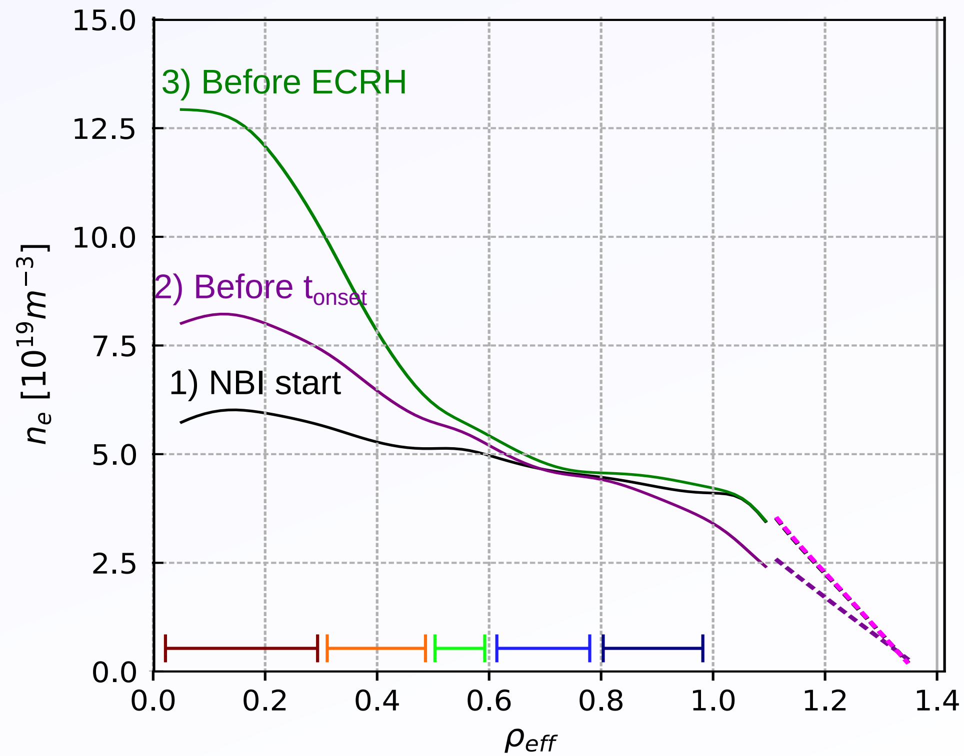

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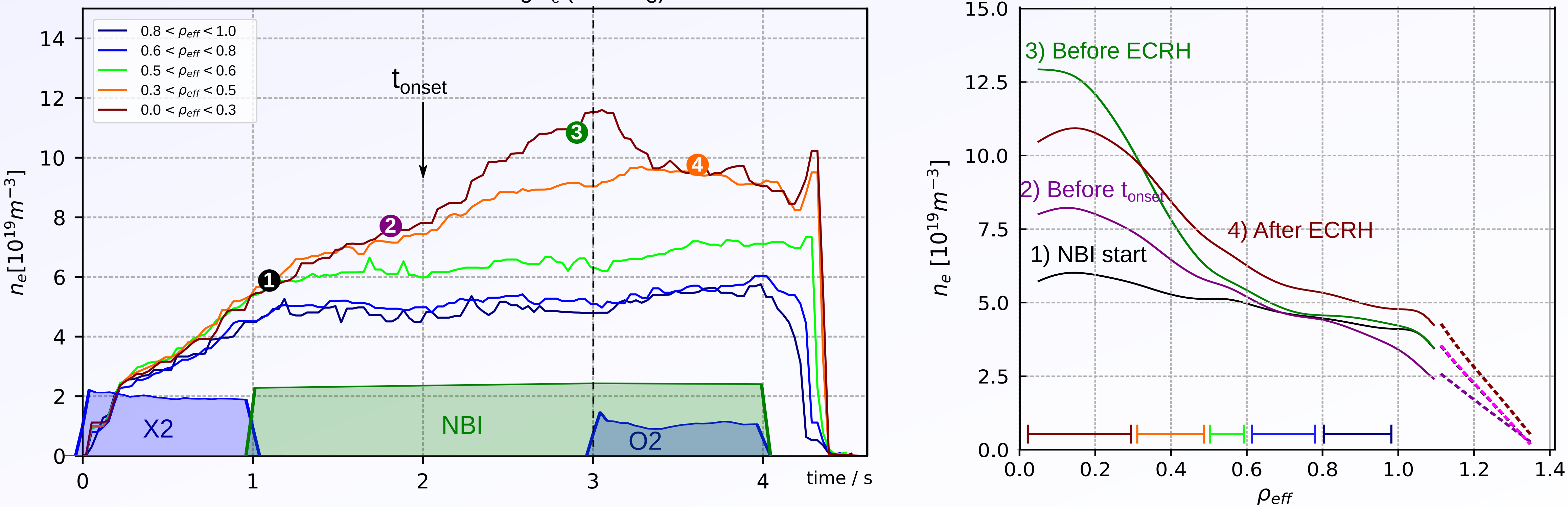

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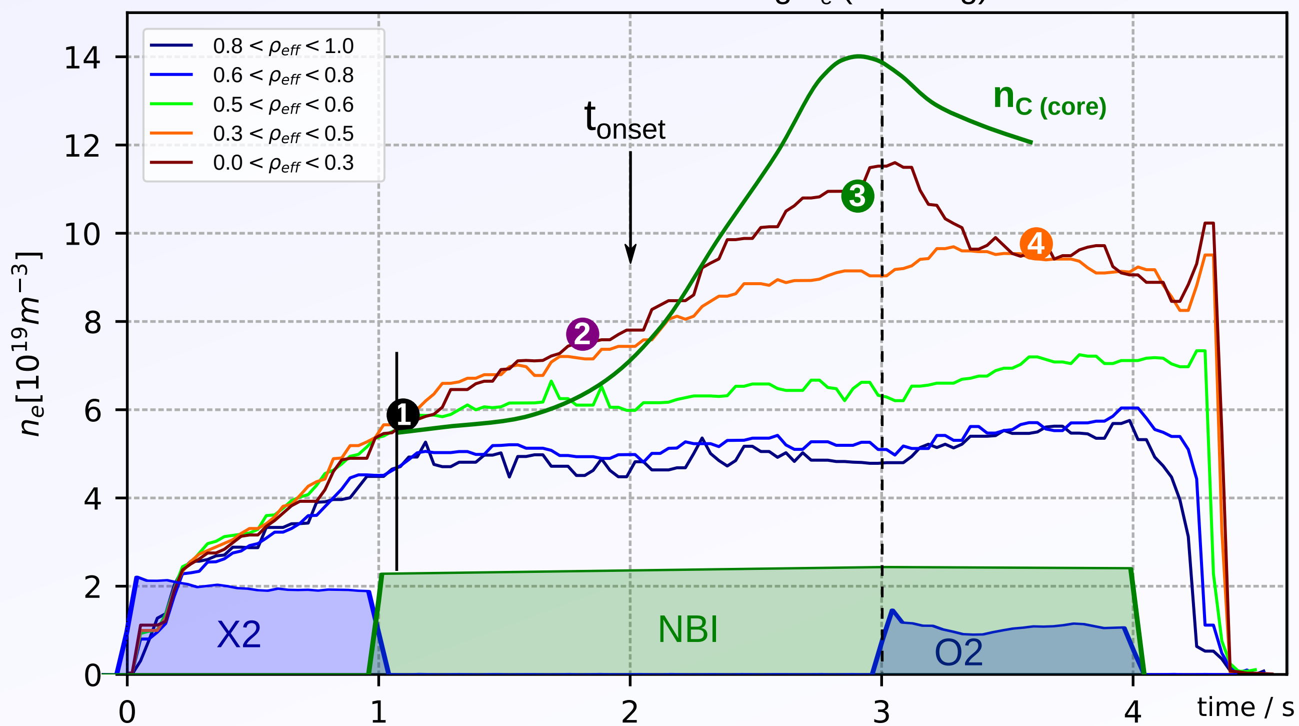
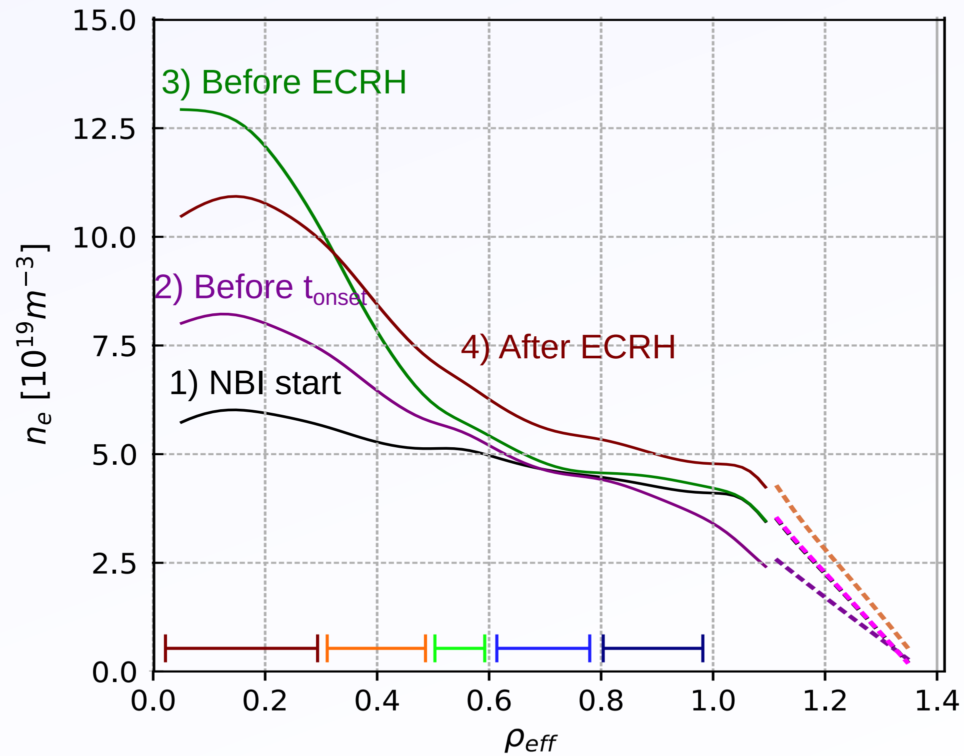


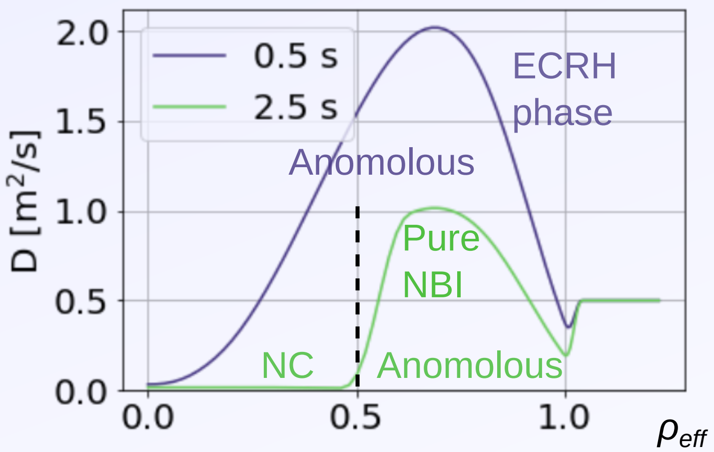


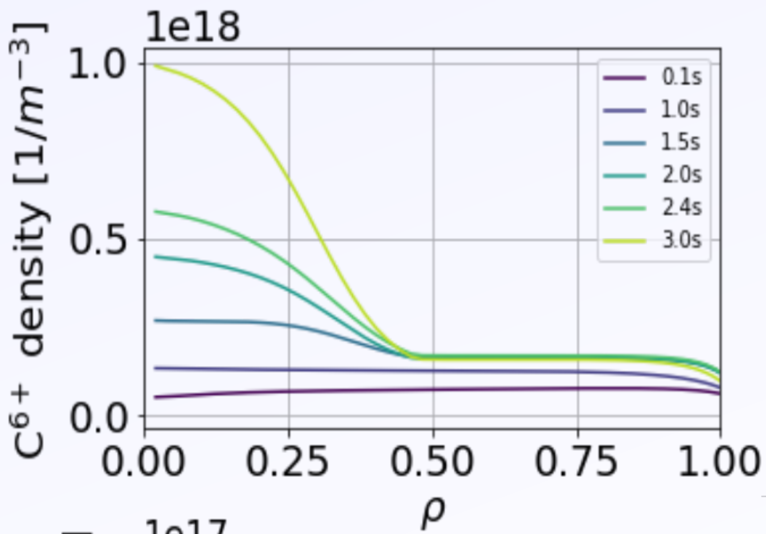
Pure NBI

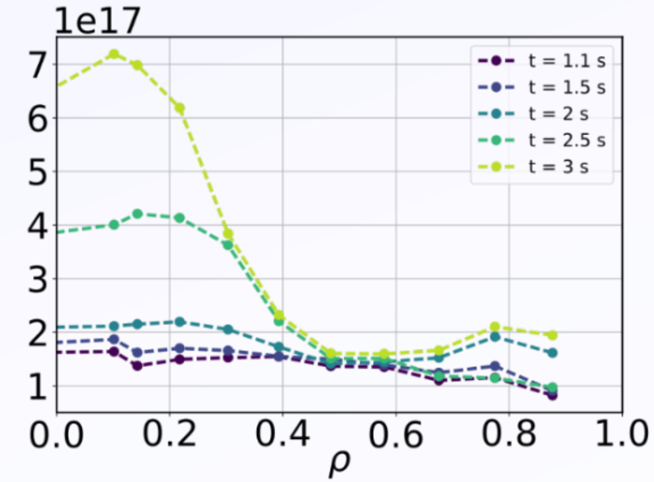
Carbon peaking consistent with neoclassical transport for $\rho < 0.5$ and some turbulent diffusion for $\rho > 0.5$.
STRAHL simulations [L Vanó]:

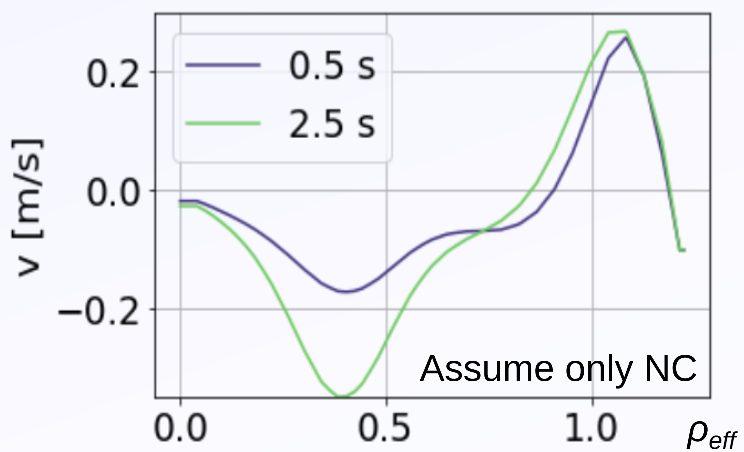
Simulation

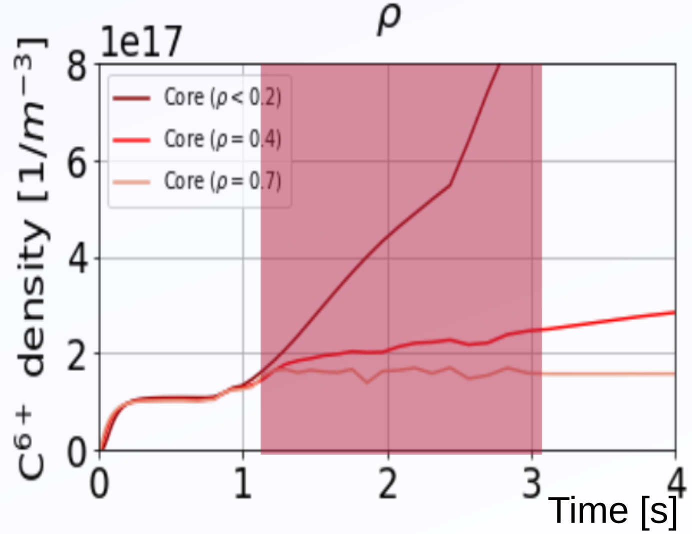
Experiment

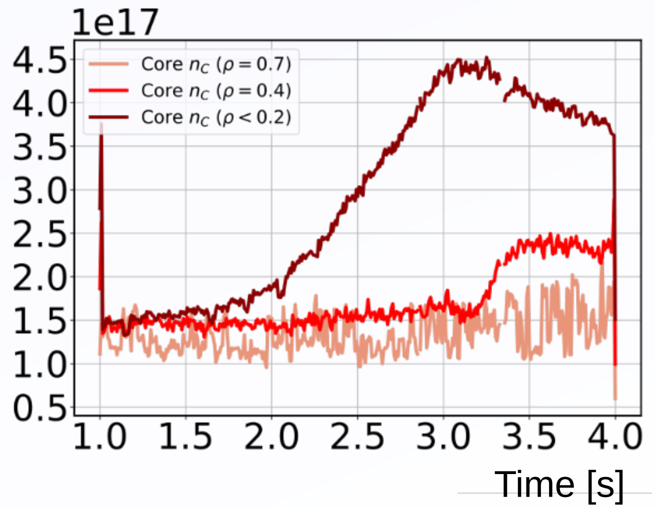












Peaking (supressed turbulent diffusion) starts at same onset time of accelerated core electron density peaking (t=2.2s)

Pure NBI - particle transport

Particle balance:
- Source rate from Beams 3D. Roughly agrees with ADAS beam stopping. No Halo diffusion but not significant.
- NC particle fluxes calculated using NEOTRANSP. Robust to uncertainties: Profiles, Te-Ti, Zeff, Er --> no more than ±20%.
- Ignore gas fuelling and recycling --> Maybe invalid for rho > 0.7

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NC particle flux insignificant.
Density rises at fuelling rate.
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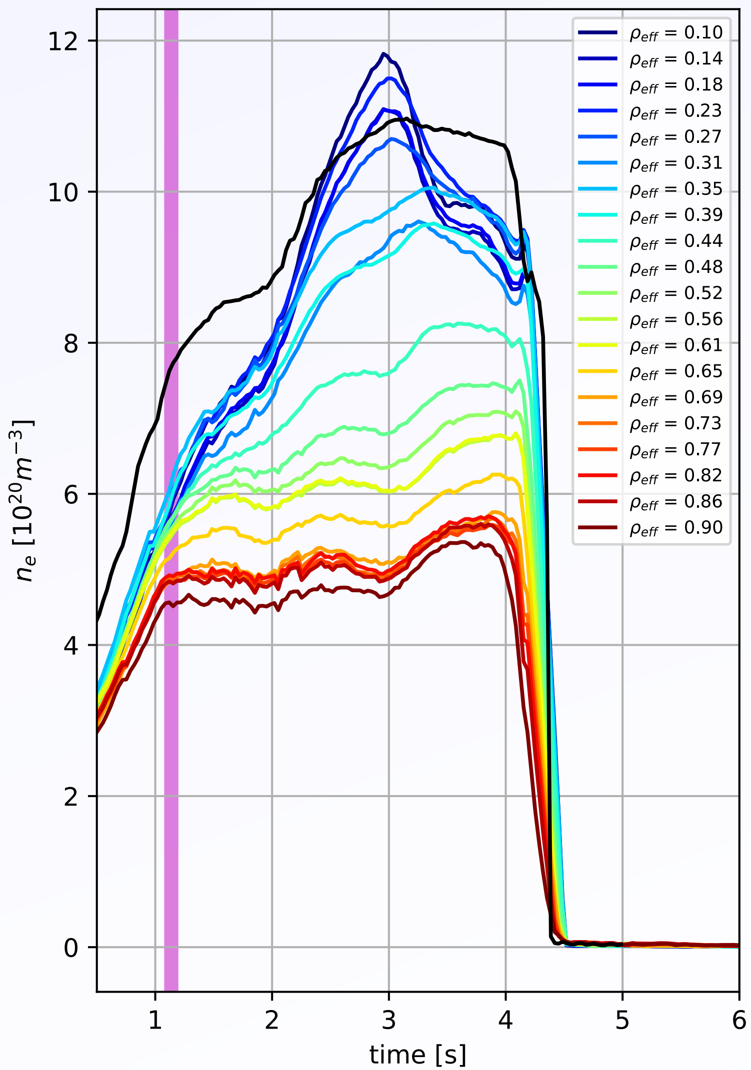

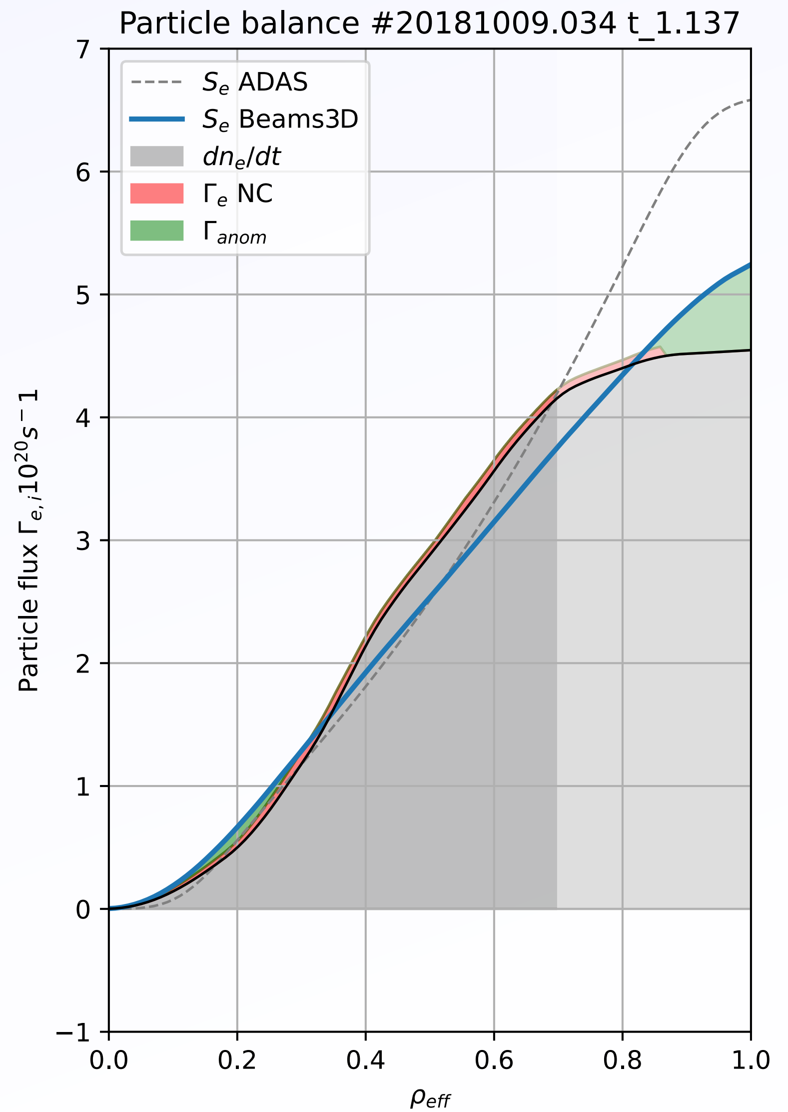

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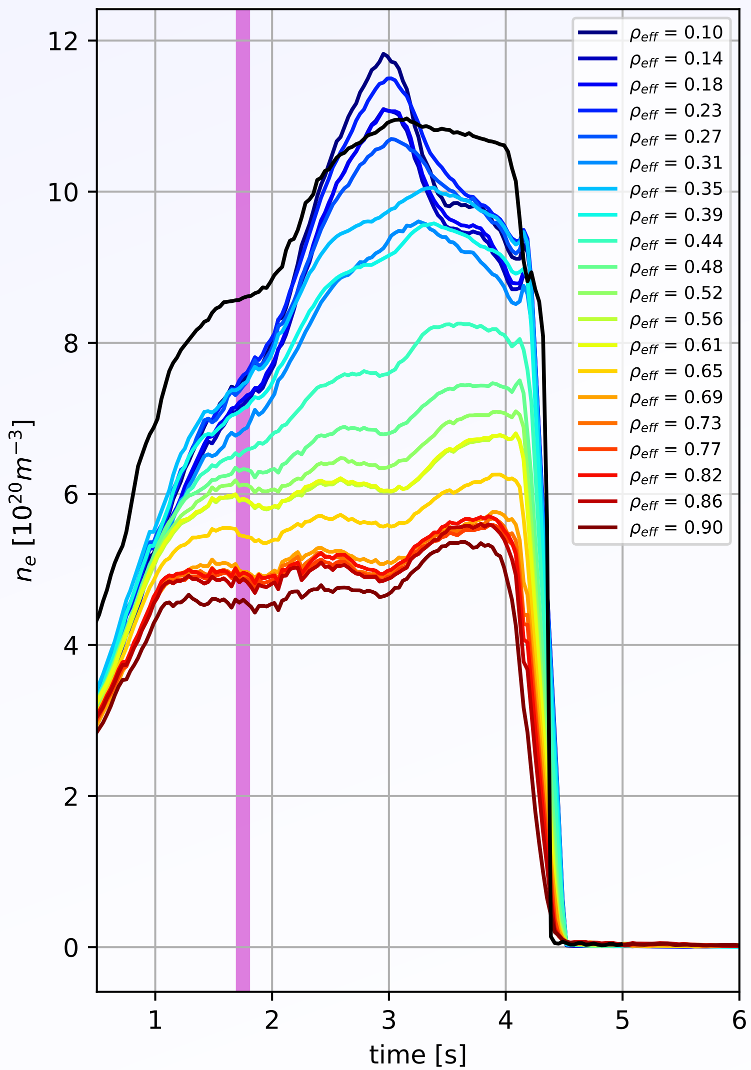

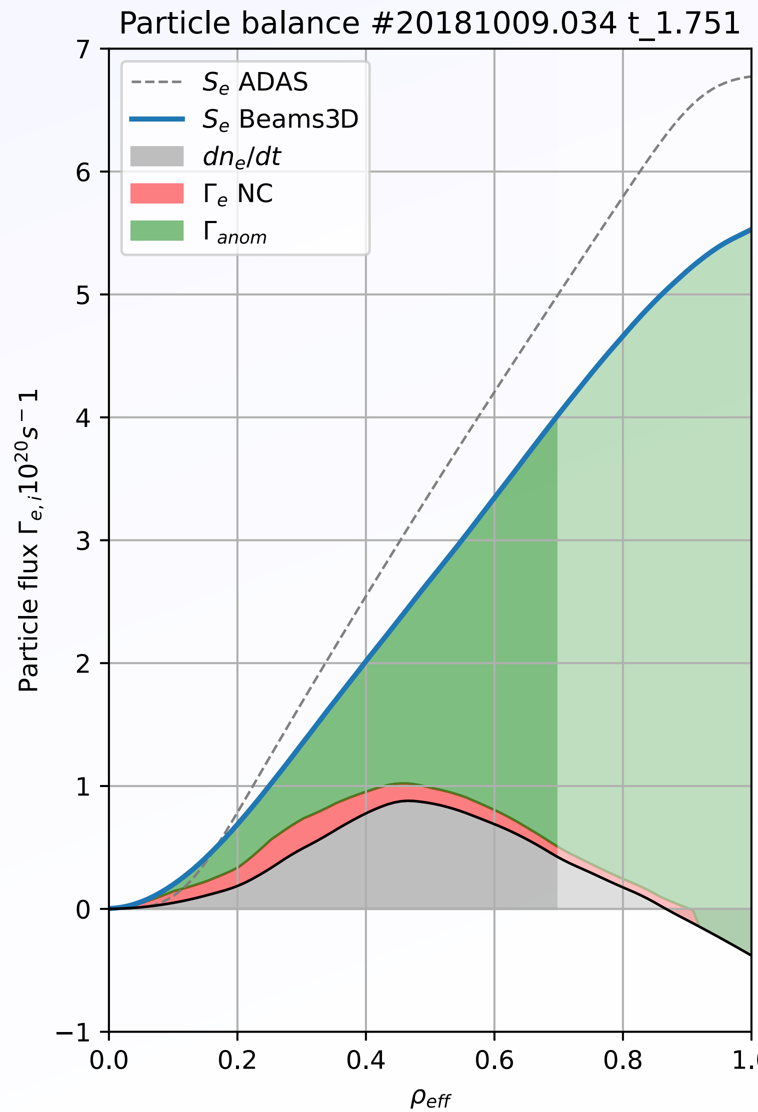

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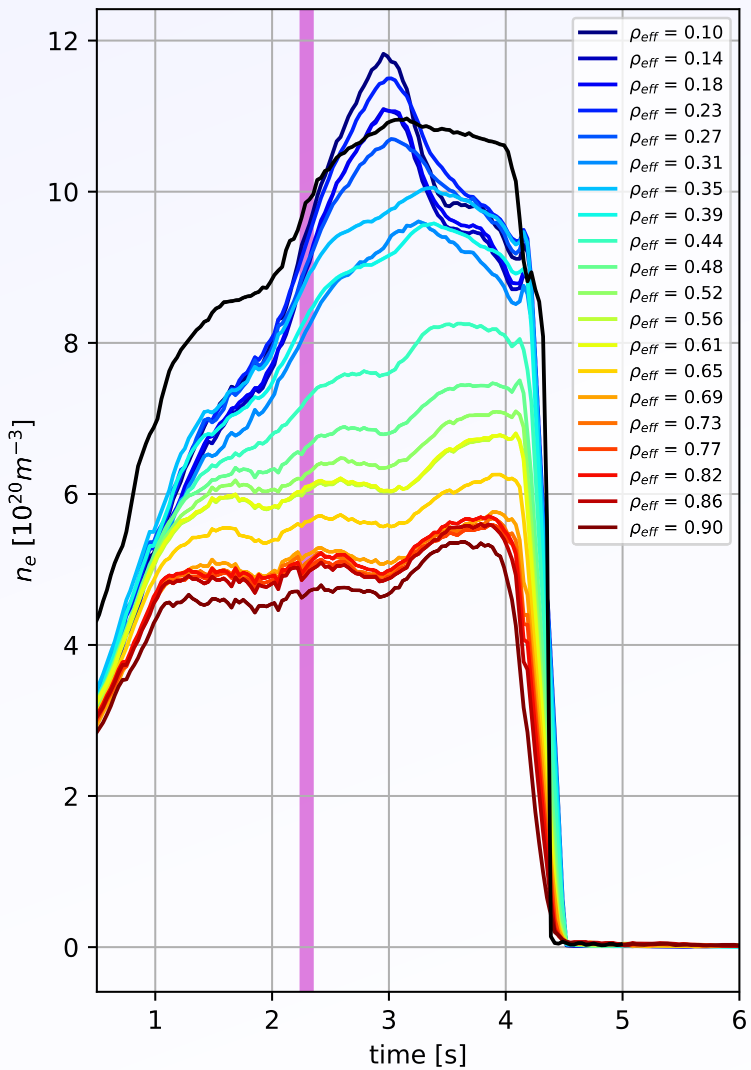

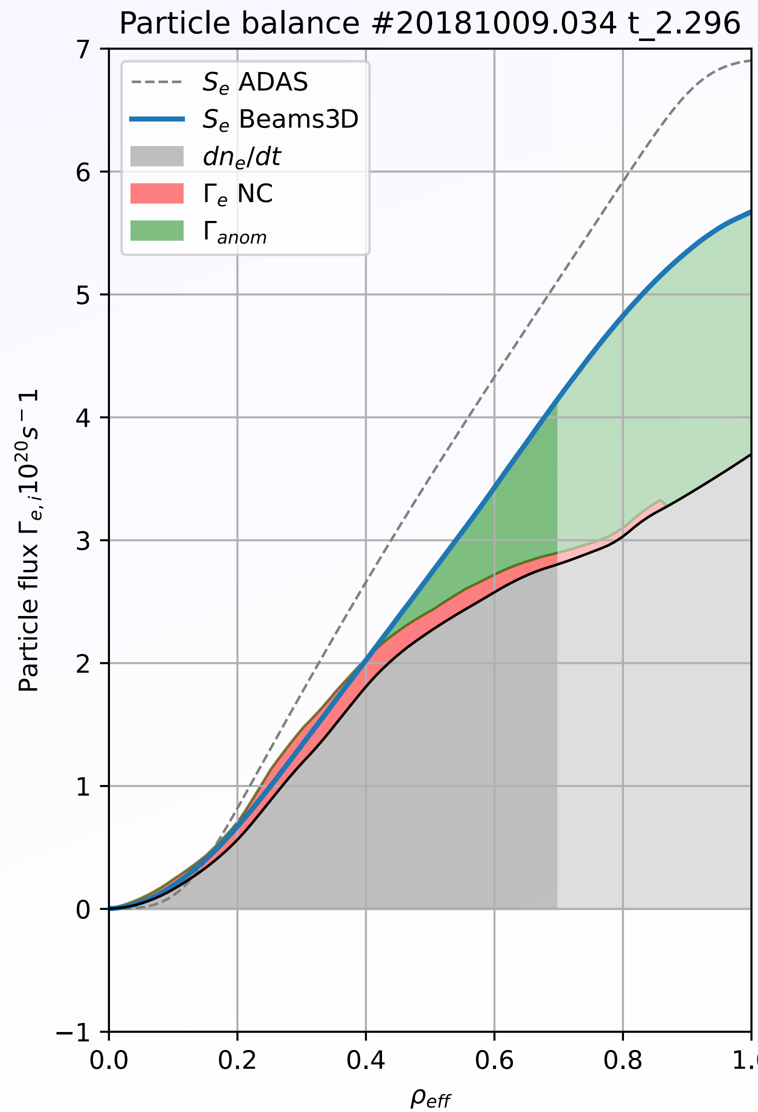

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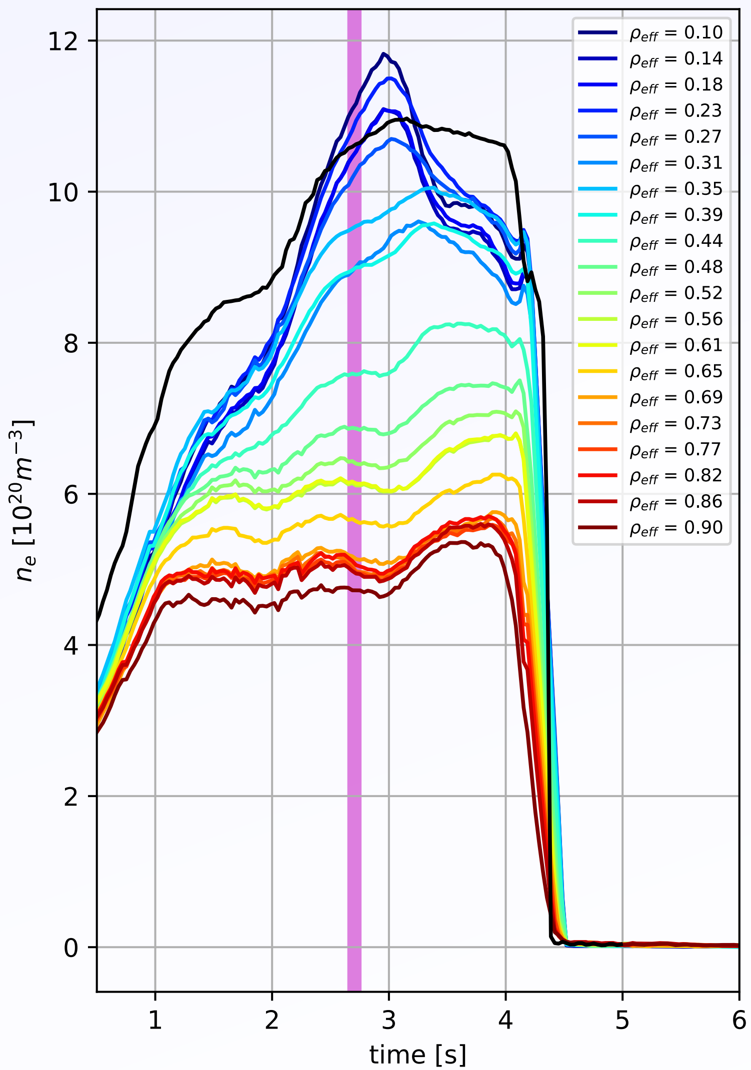

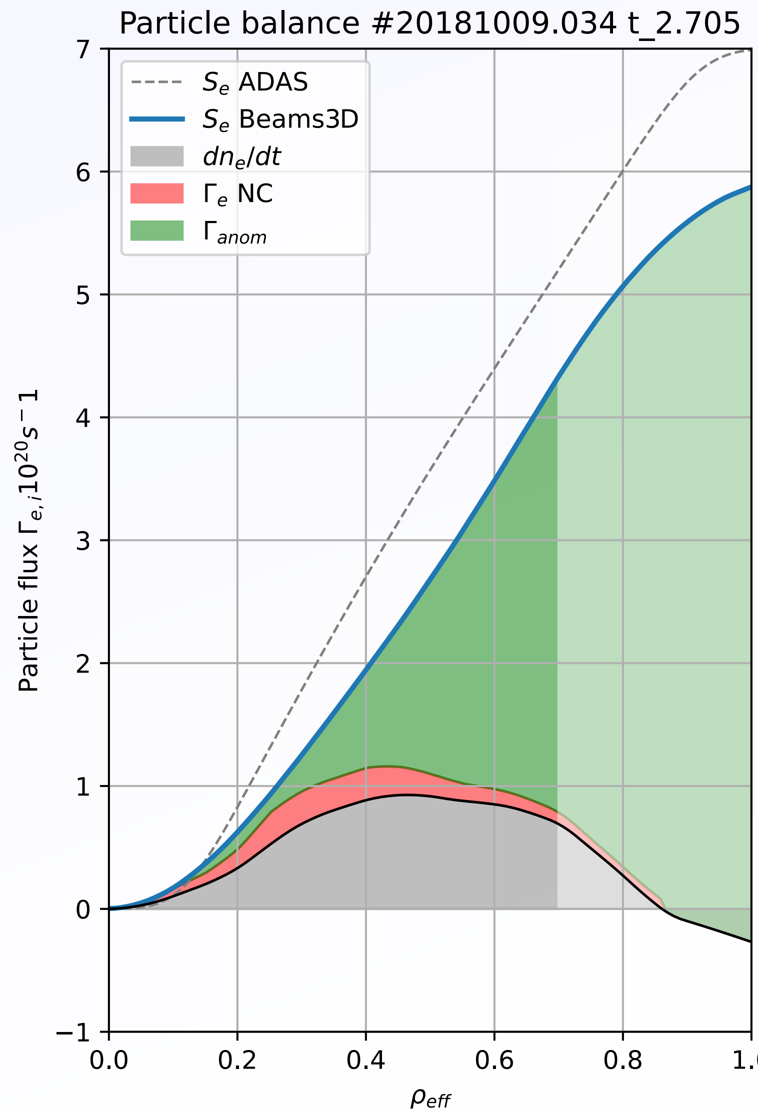

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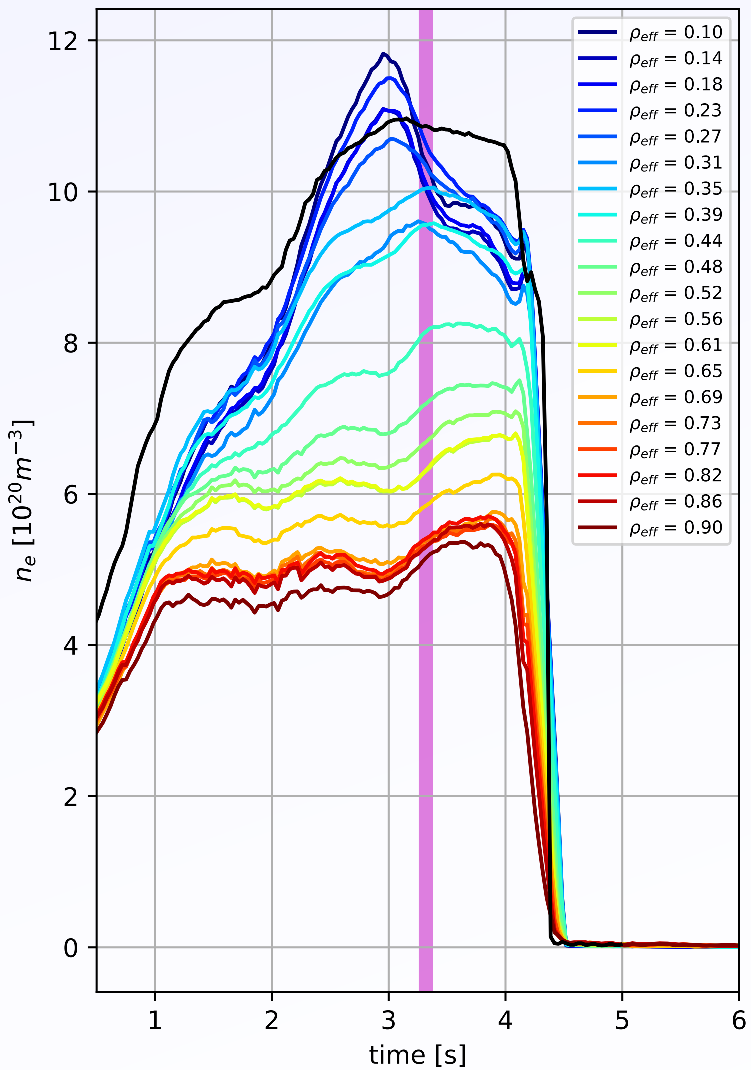
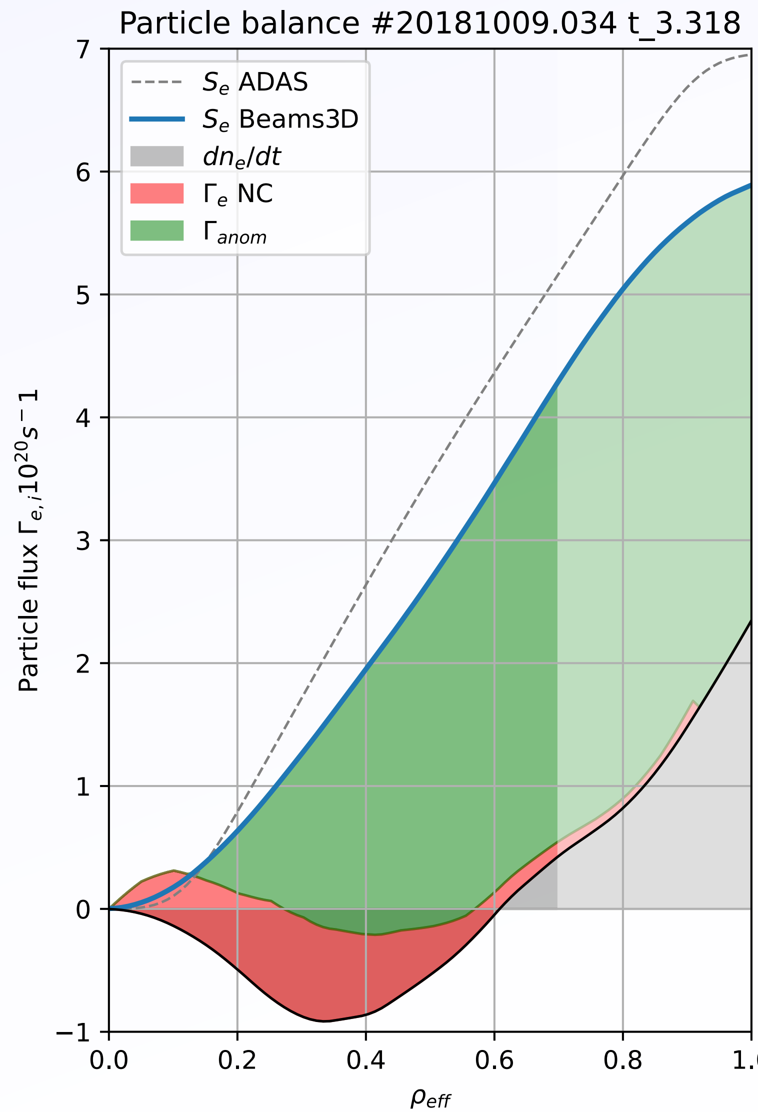
- Strong increase in both NC and anomolous
- Flush out of particles in very core





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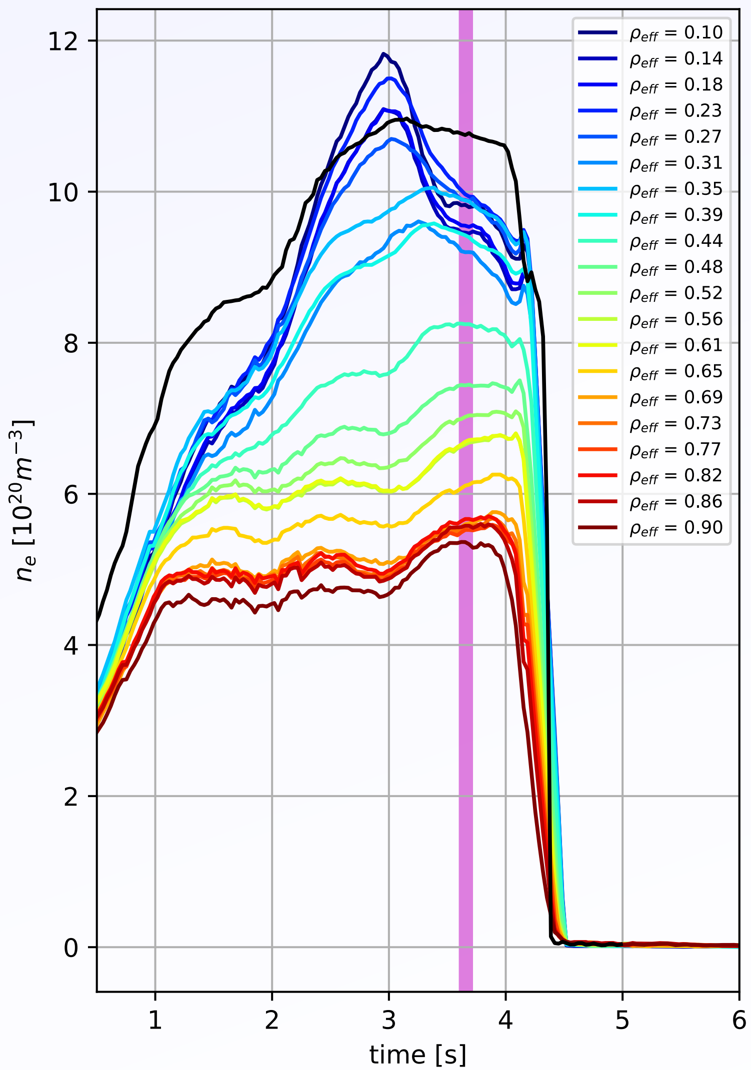
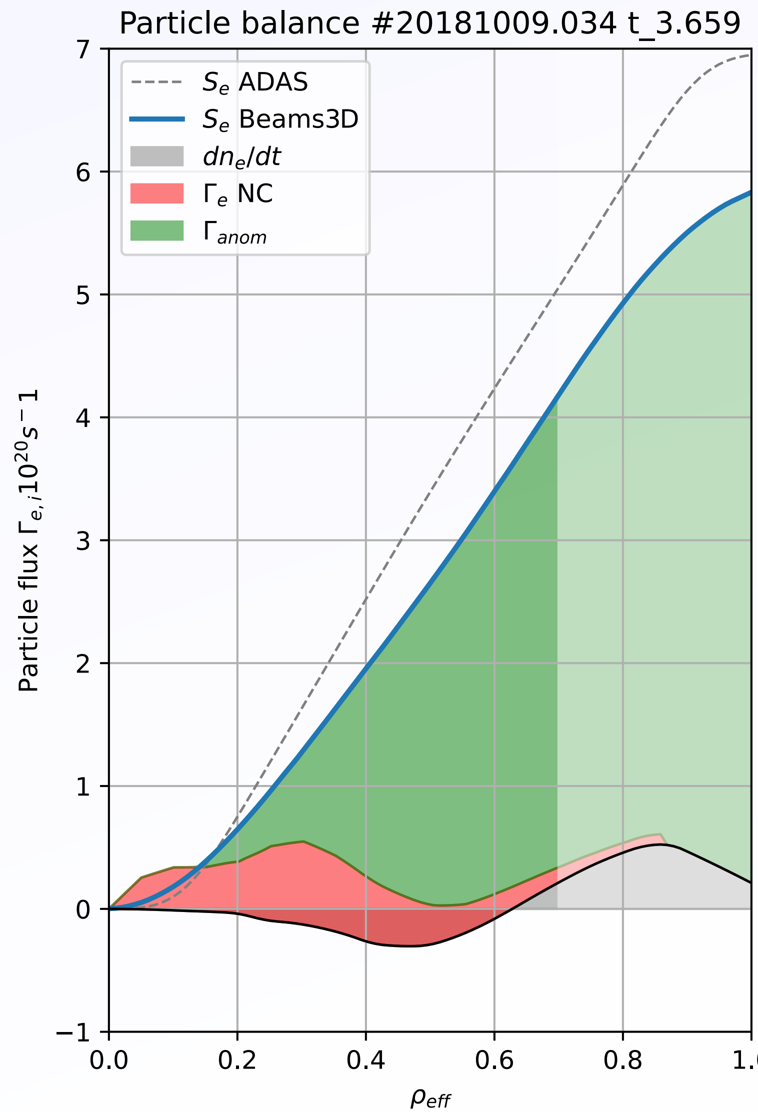
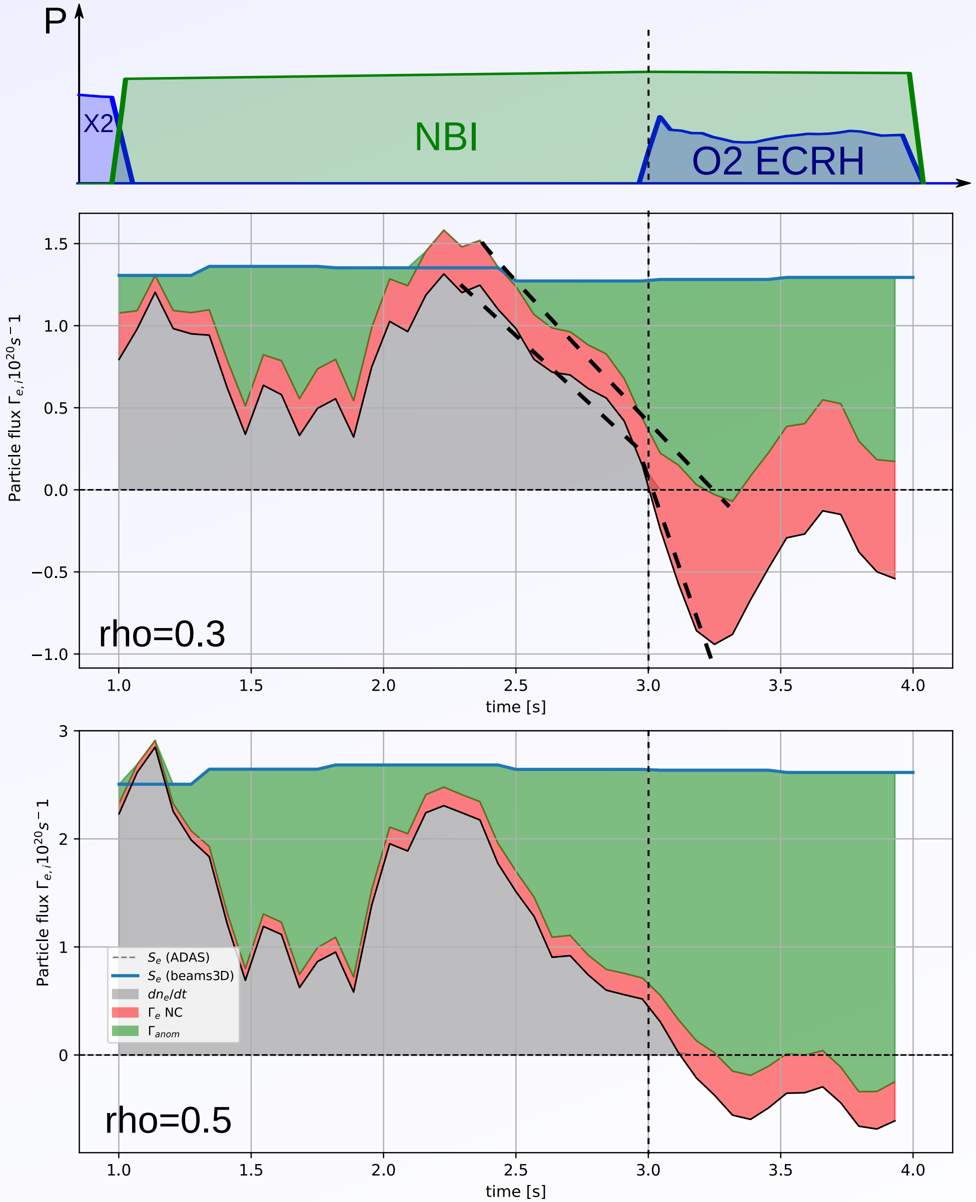
6) Density stabilises with balance of NC and anomolous in core. Strong anomolous at mid-radius to edge.



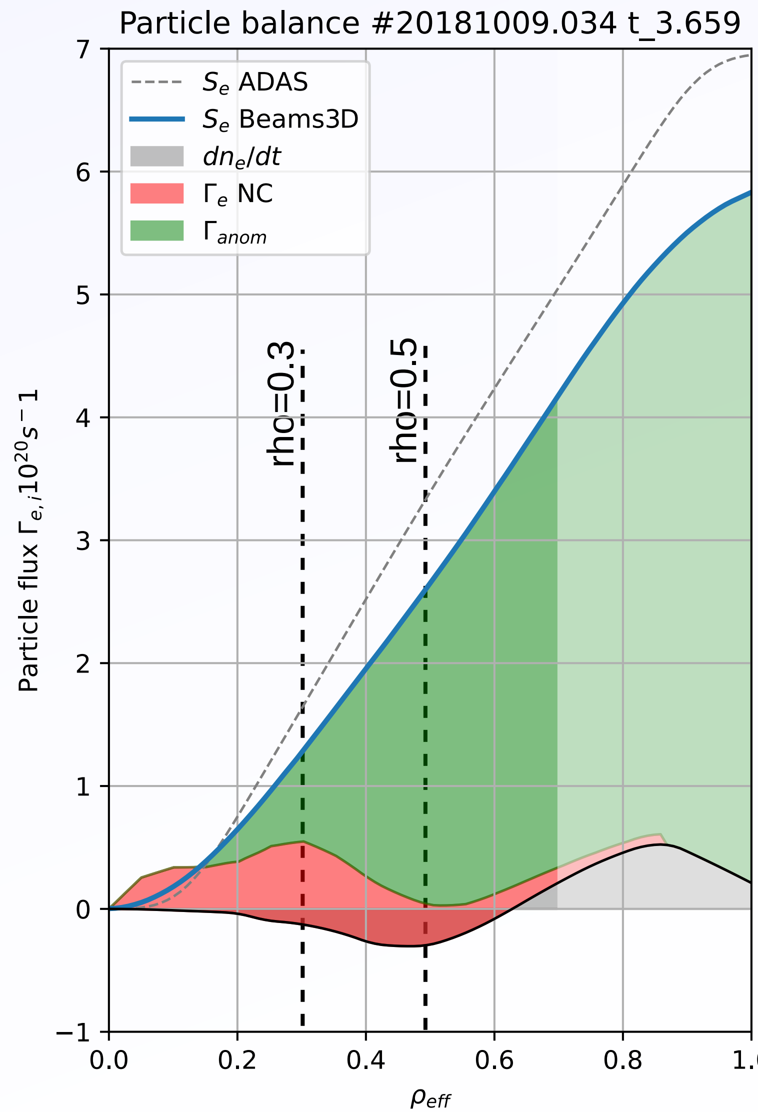


Pure NBI - particle transport

Particle balance temporal evolution:



At ECRH switch on, core d^2n_e/dt^2 is consistent with increase of NC flux.
i.e. new dn_e/dt matches Γ_{NC} with existing anomolous flux trajectory.
---> how quickly should turbulence react to profiles?



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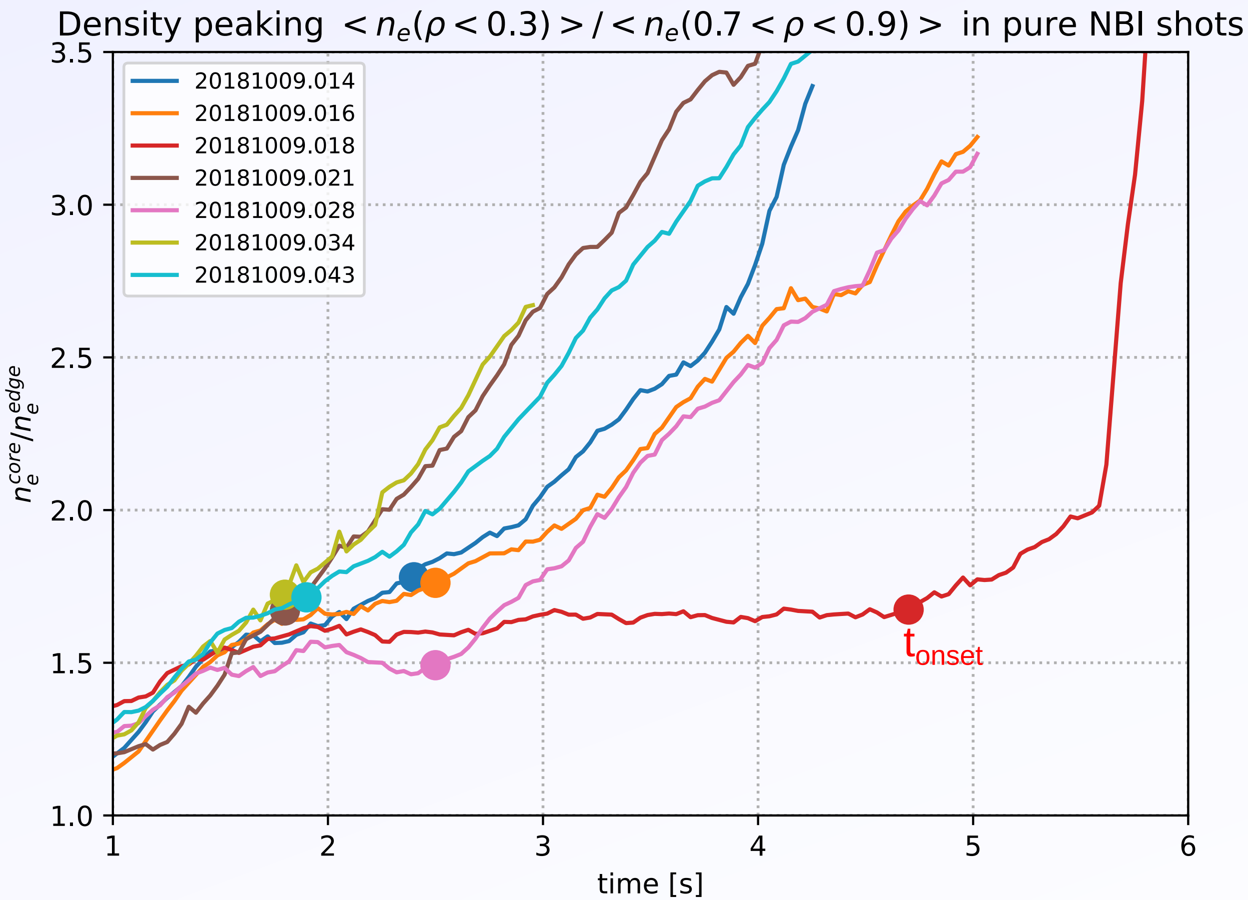
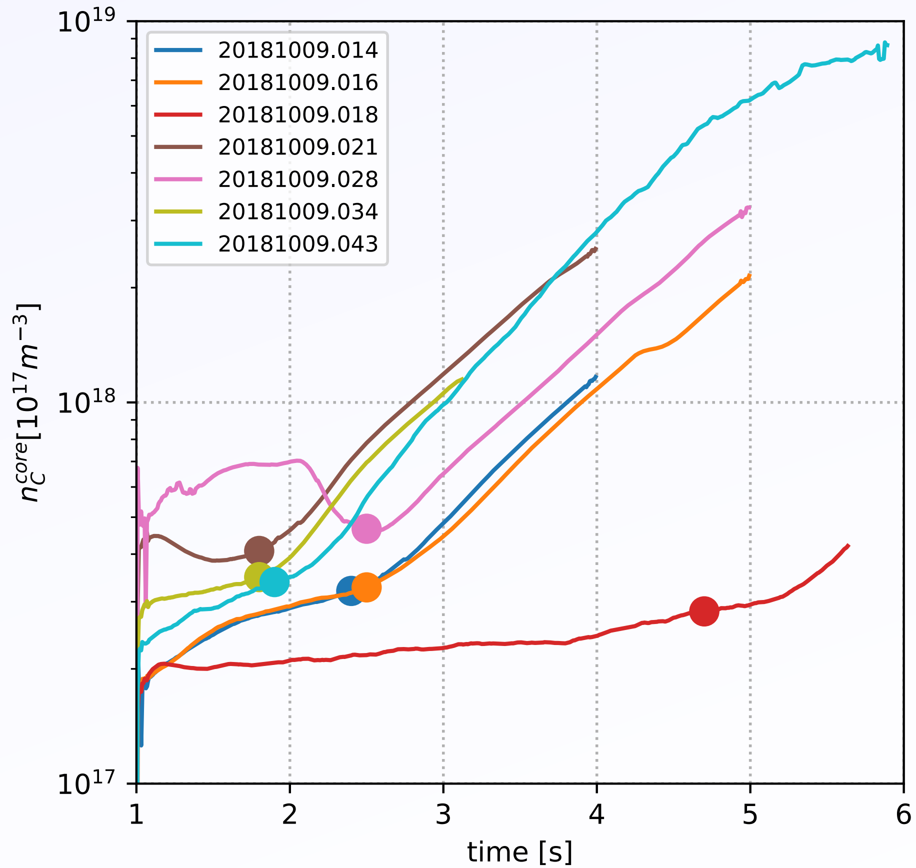
The particle transport change appears in almost all NBI shots with P_{ECRH} < 1MW, at different on-set times.
In some cases hard to see in n_e, but very obvious in log(n_C) and almost coincident in time.





No change on any other signals at edge (T_e, T_i, H_α, P_{rad})
In some cases ne rises a little at all radii, in others the edge doesn't change.
Most consistent parameter at t_{onset} is a/L_n = 0.8 ± 0.05, but this relies heavily the single red point (#018)

Pure NBI - Species power balance

For power balance of individual species, we require the collisional power transfer P_{ei}:

$$P_{e-i} \approx 38 \cdot n_e^2 \cdot \frac{(T_e - T_i)}{T_e^{3/2}} \cdot \frac{Z}{A} \left[\frac{kW}{m^3} \right]$$

At $n_e \sim 10^{20}$ m^{-3} and T ~1keV and integrating to mid radius:

$P_{e\text{-}i}$ ~ 2.6 MW for every 100eV difference between Te and Ti.

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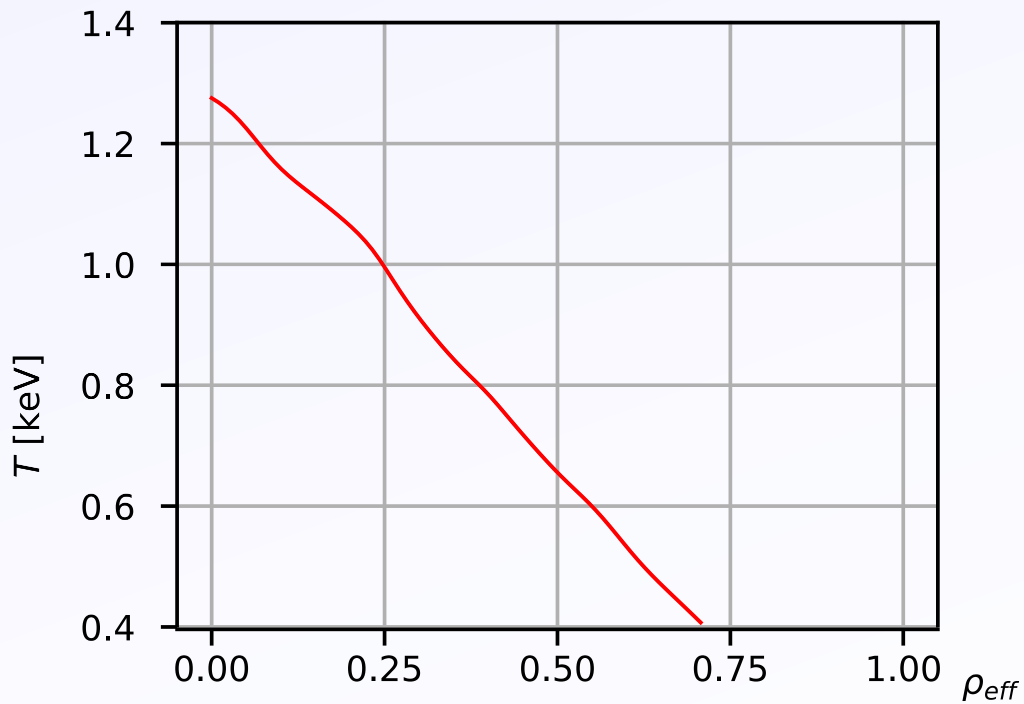

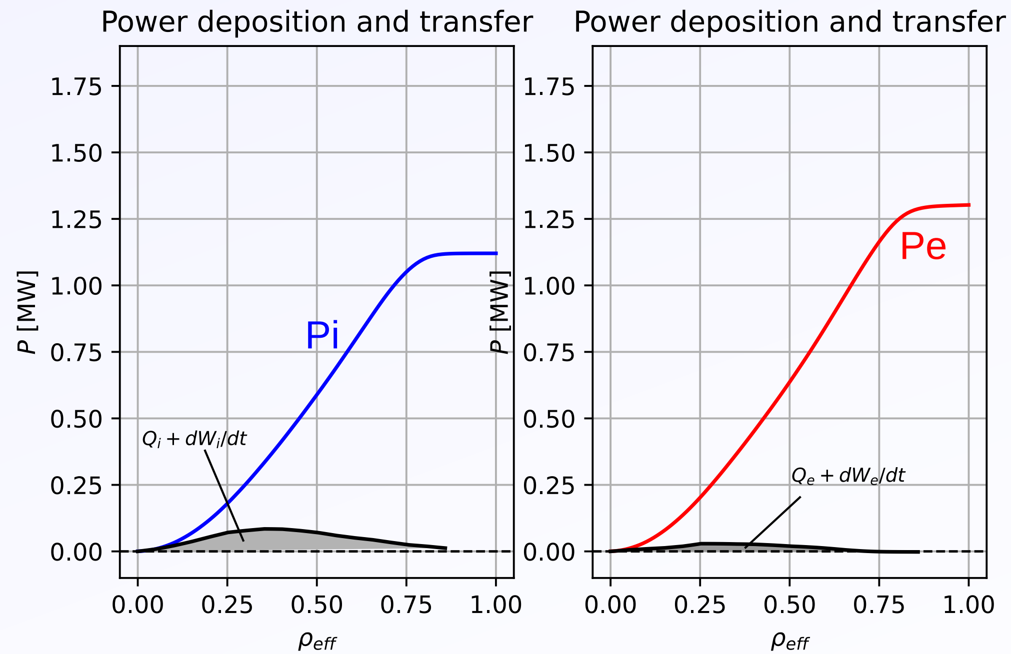

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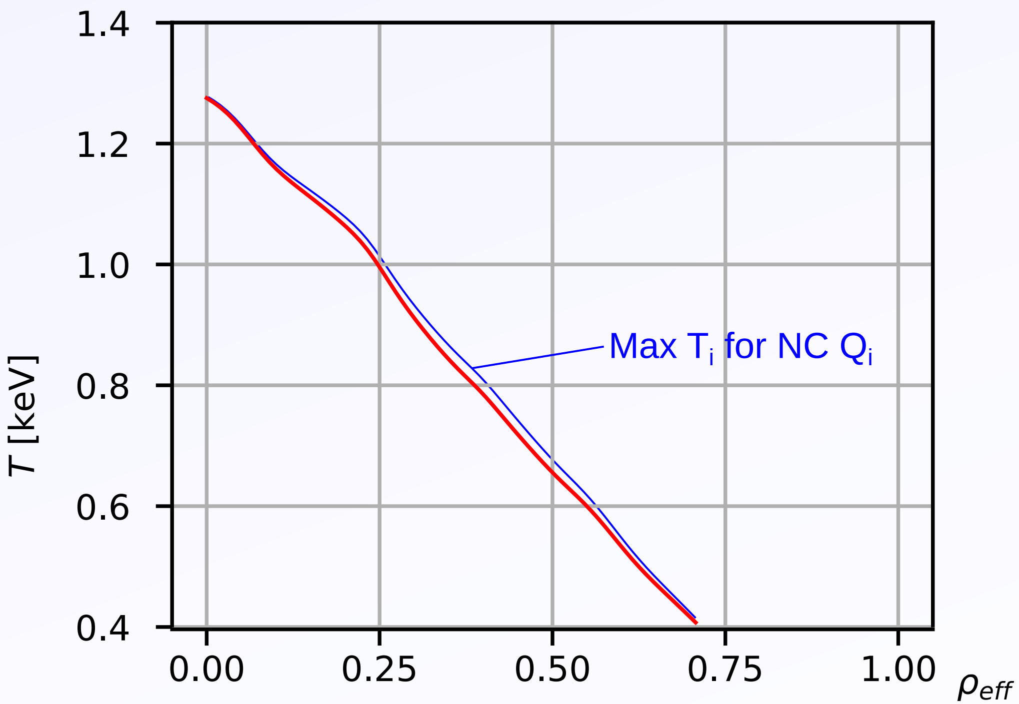

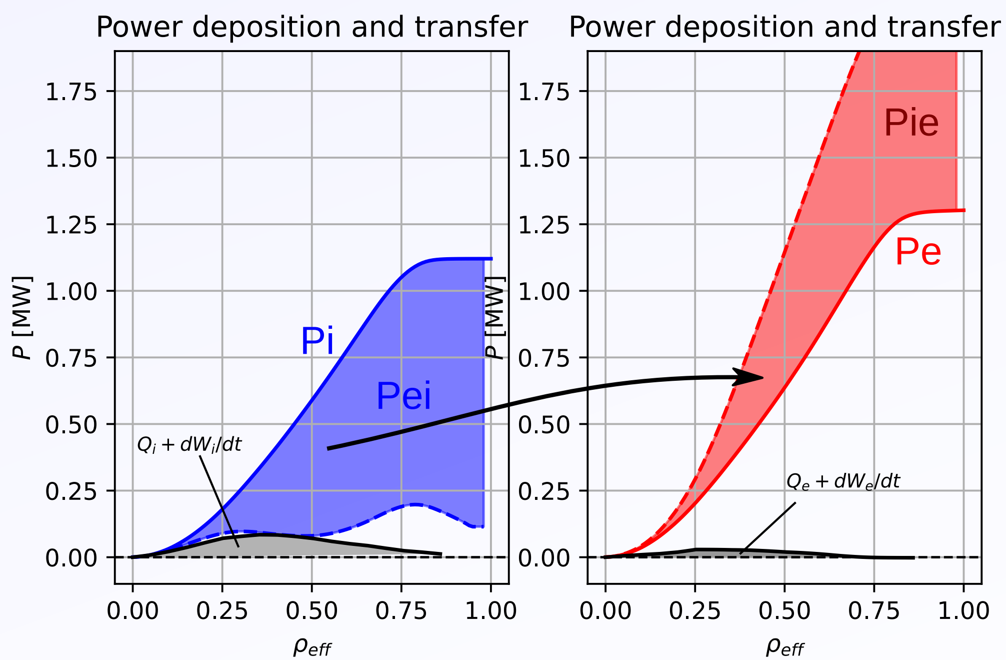

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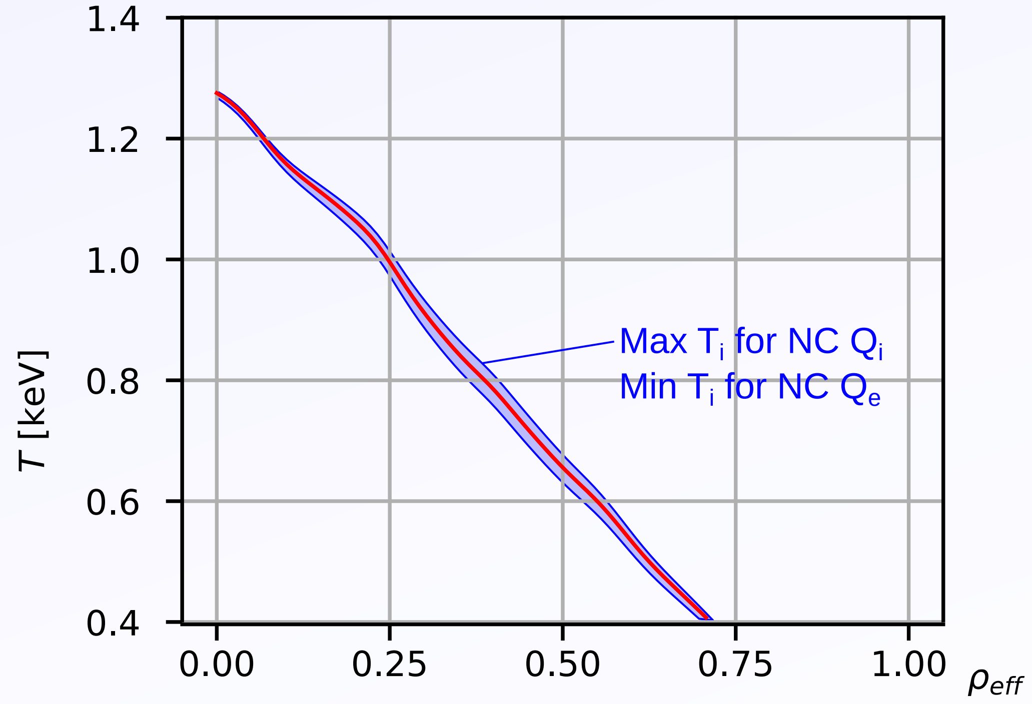

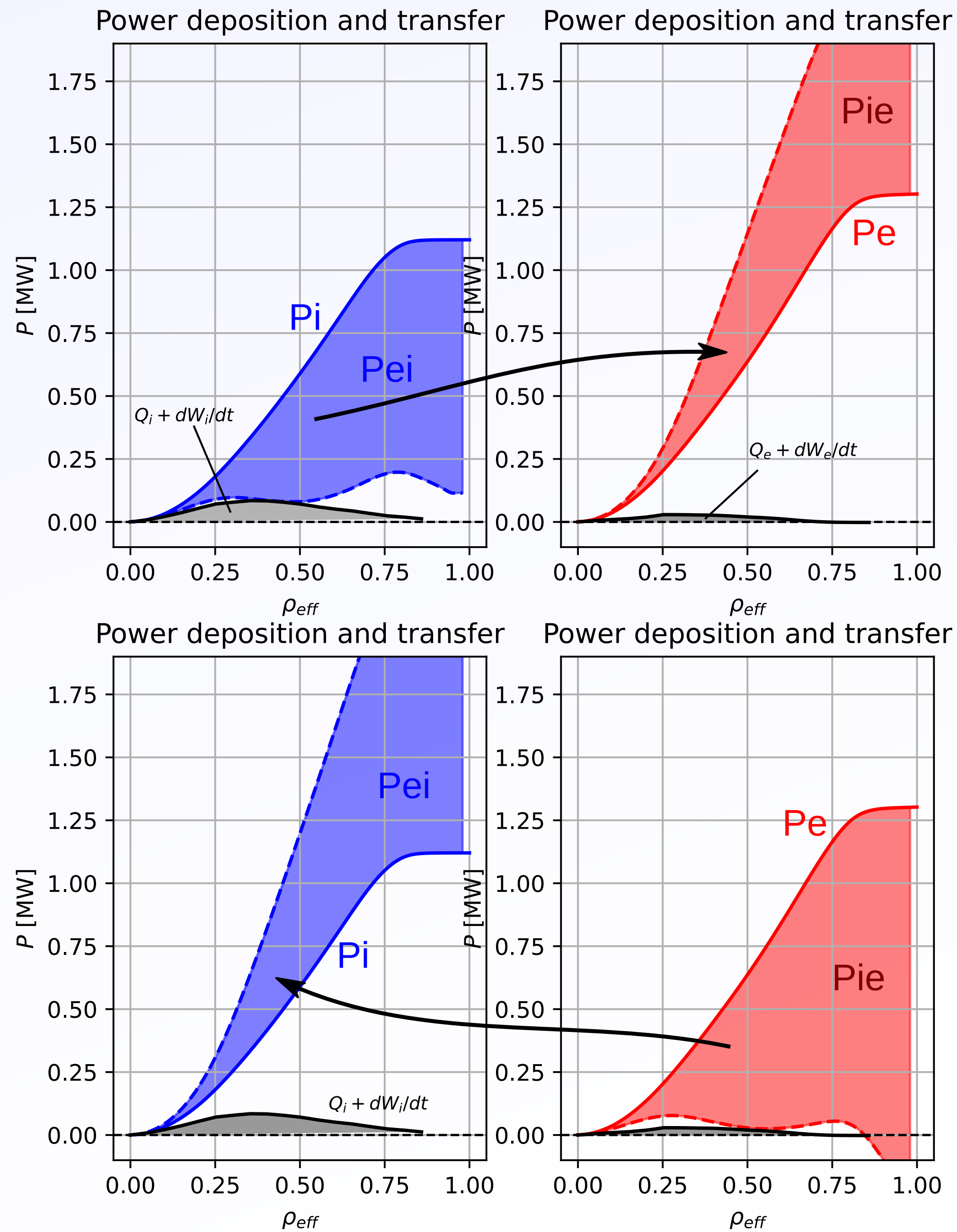

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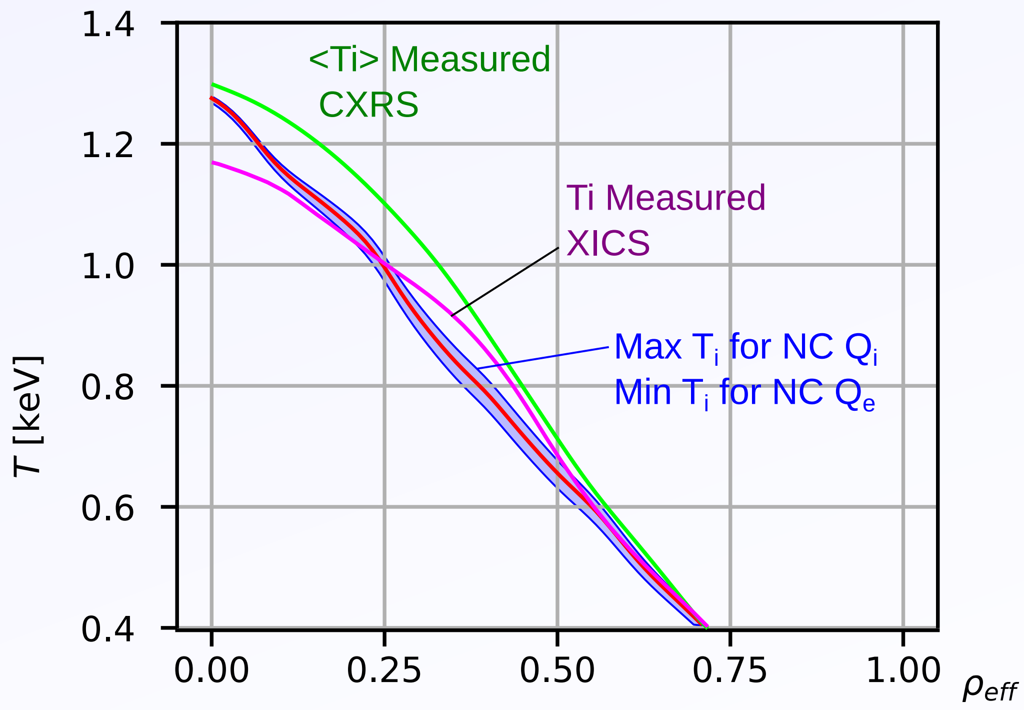
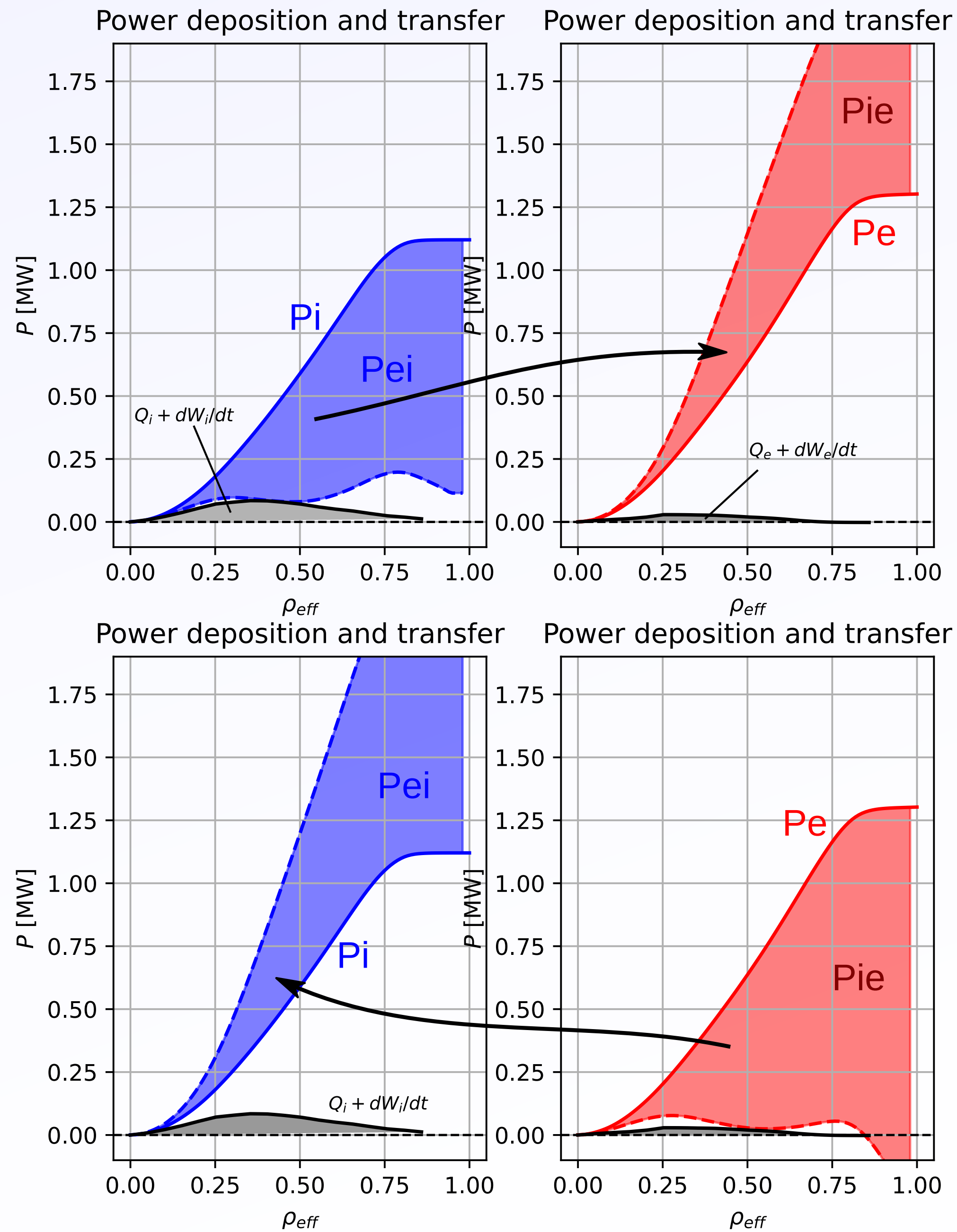
$$p_{e-i} \approx 38 \cdot n_e^2 \cdot \frac{(T_e - T_i)}{T_e^{3/2}} \cdot \frac{Z}{A} \left[\frac{kW}{m^3} \right]$$

At $n_e \sim 10^{20}$ m^{-3} and T ~1keV and integrating to mid radius:

$P_{e\text{-}i}$ ~ 2.6 MW for every 100eV difference between Te and Ti.

Only ~ 0.5MW is available from NBI at mid radius, so





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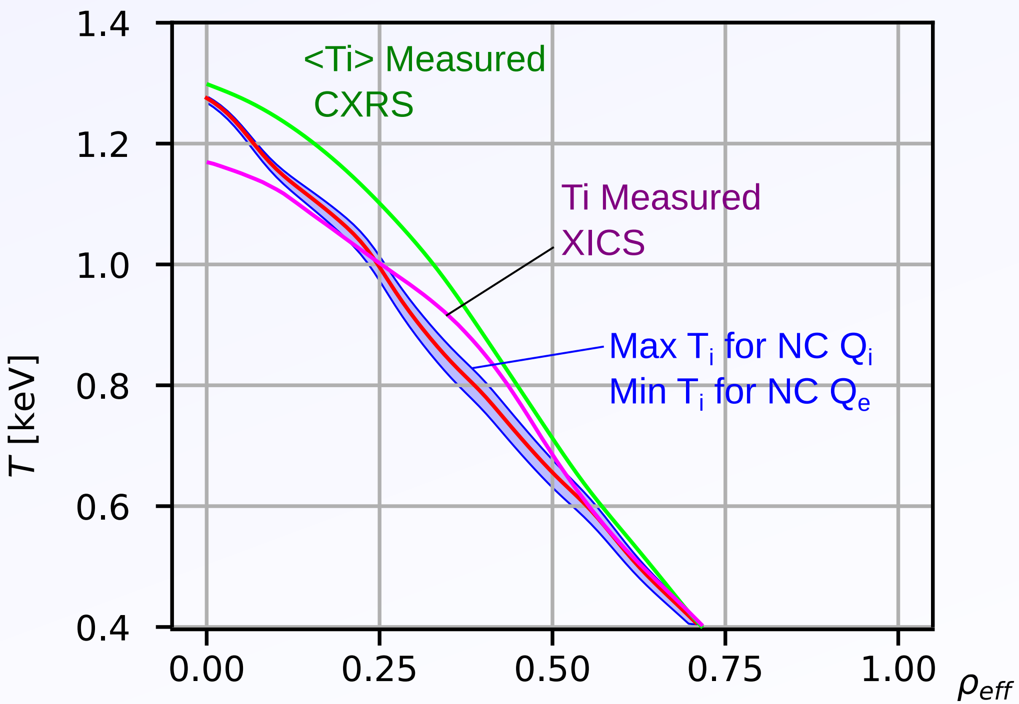
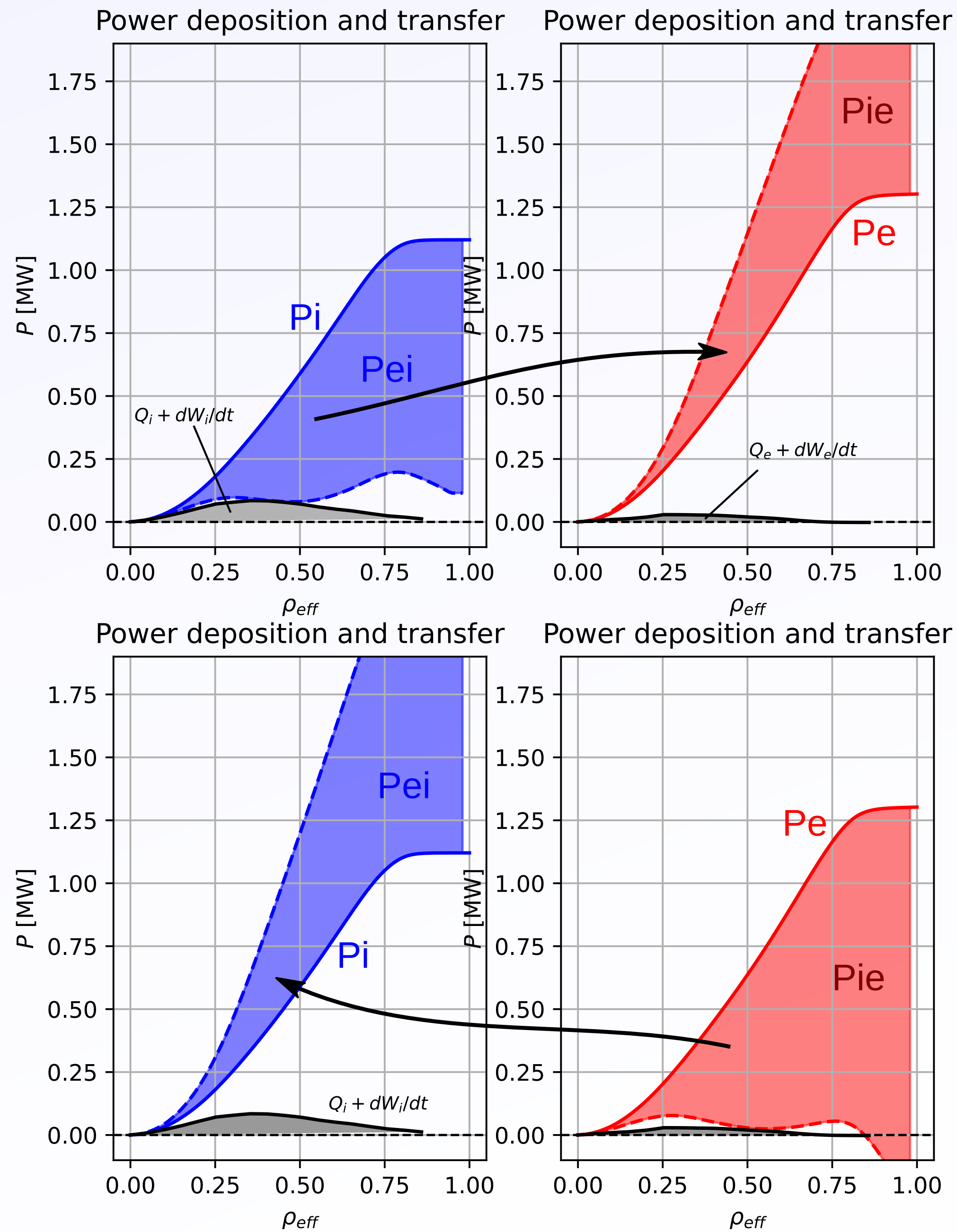


Assumptions like $T_e = T_i$ ***are*** assumptions about P_{ei} and lead to Q_e and Q_i values that ***are not experimental quantities!***



Te, Ti, Tz profiles during peaking

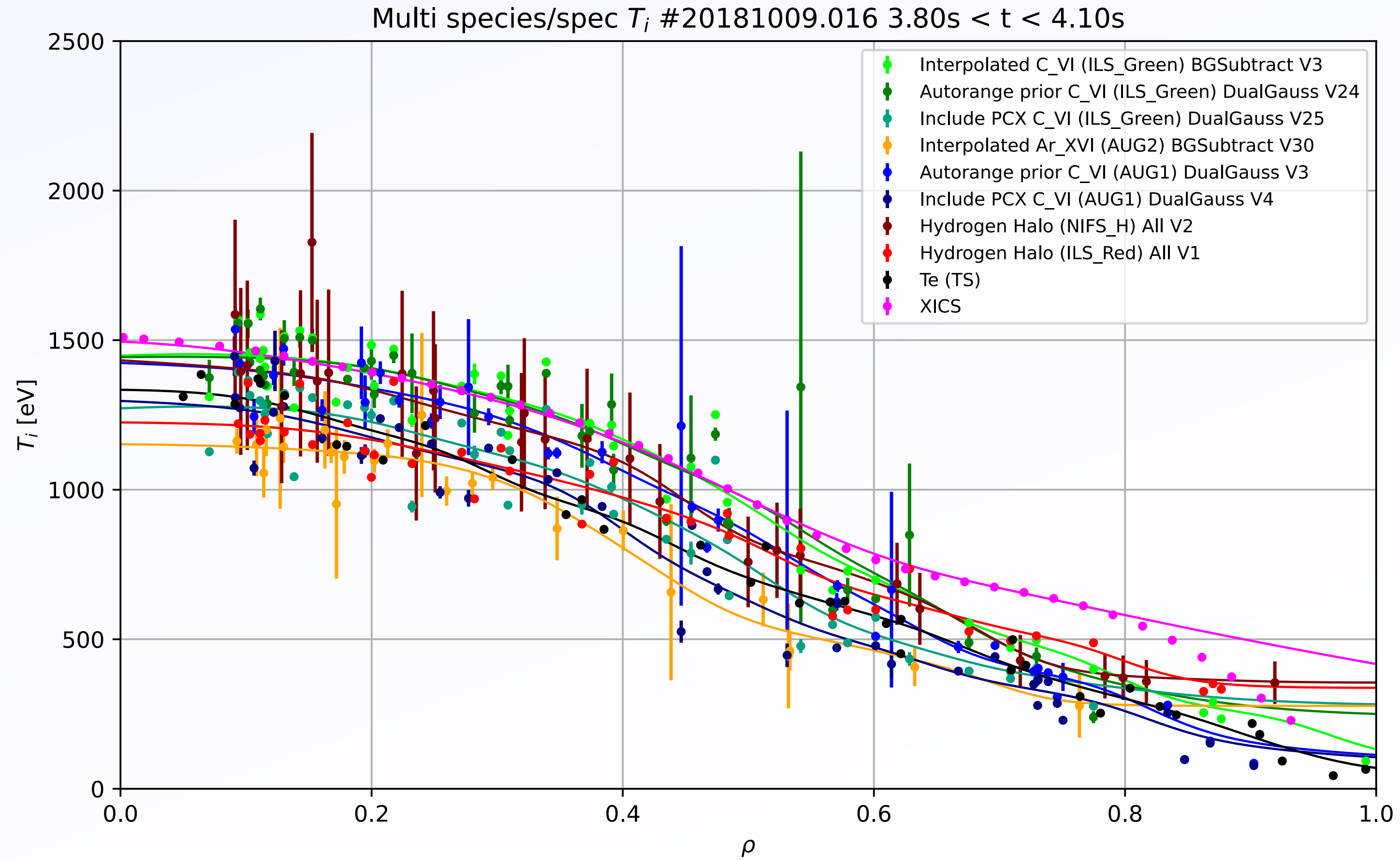
Can we recover P_{ei} by clever diagnostic analysis now we know $|T_i - T_e|$ should be < ~50eV

Temperature profiles available:

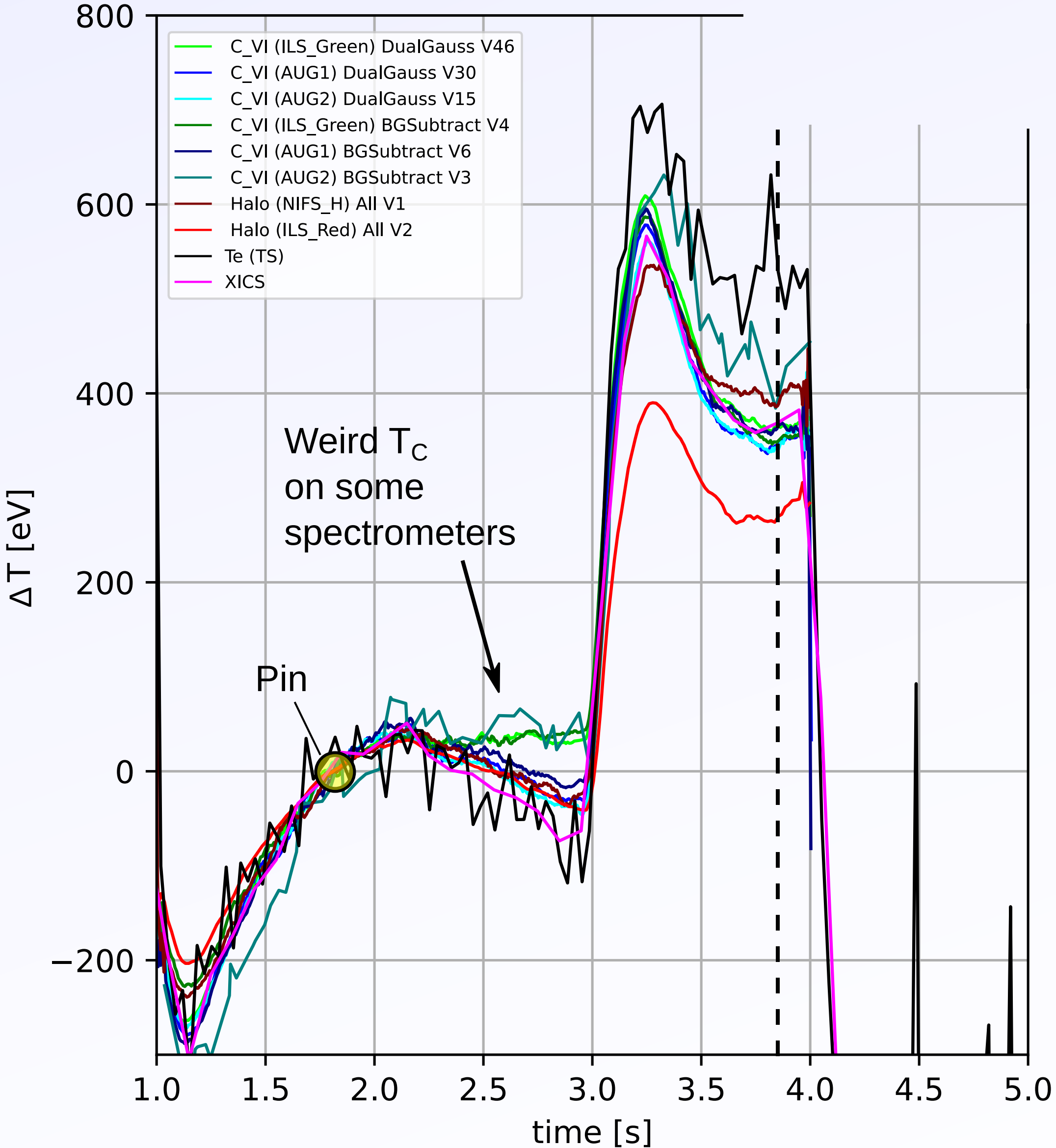
- Thomson scattering Te.
- XICS Argon Tz
- XICS Te
- CXRS Hydrogen (Halo) Ti
- CXRS Carbon Tz
- CXRS Argon Tz (in 1 shot)

(All CXRS profiles corrected for fine structure, Zeeman and instrument function. Various methods to correct for PCX)

Generally these are mess of systematic errors:



T_e, T_i, T_z profiles



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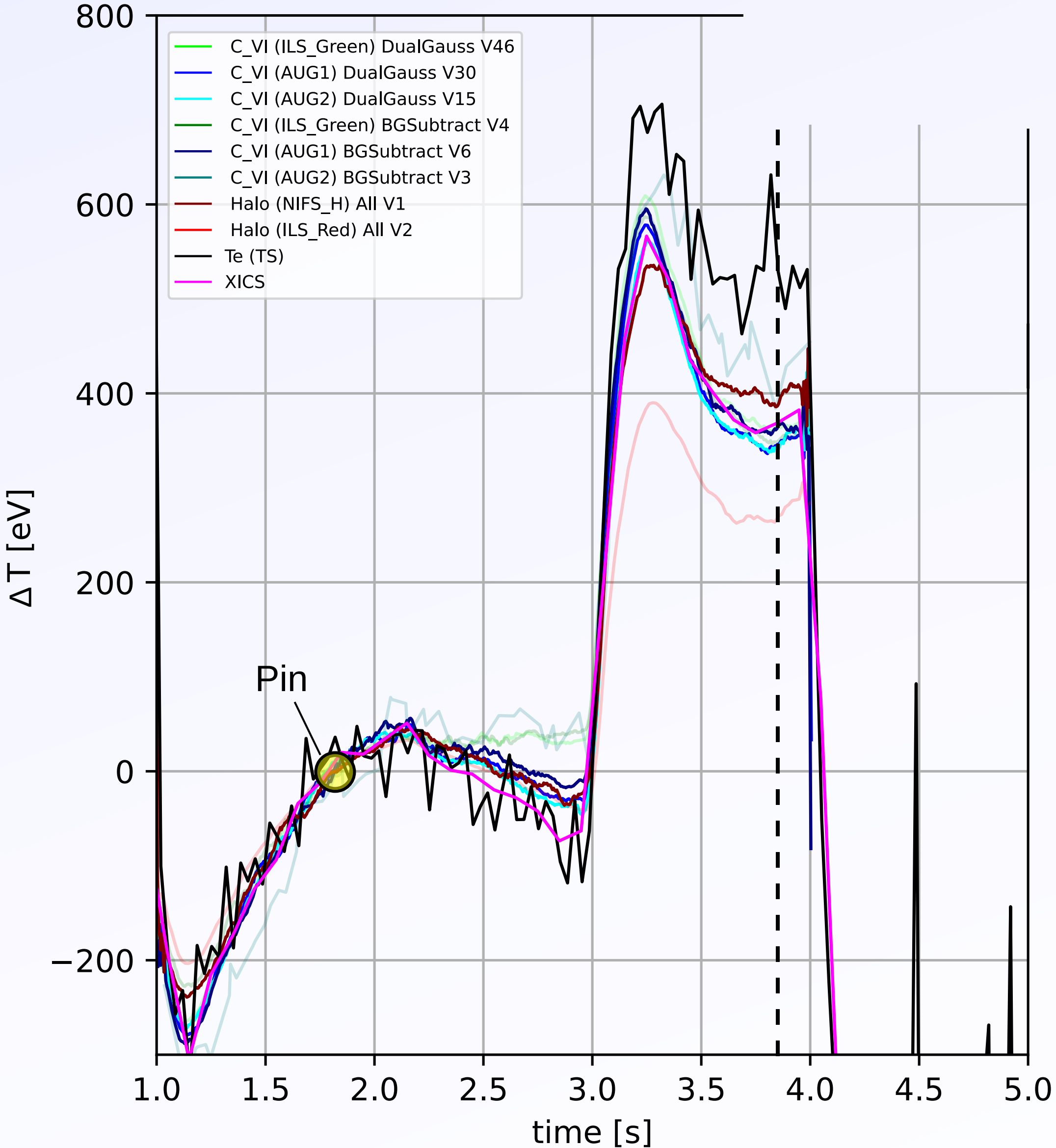

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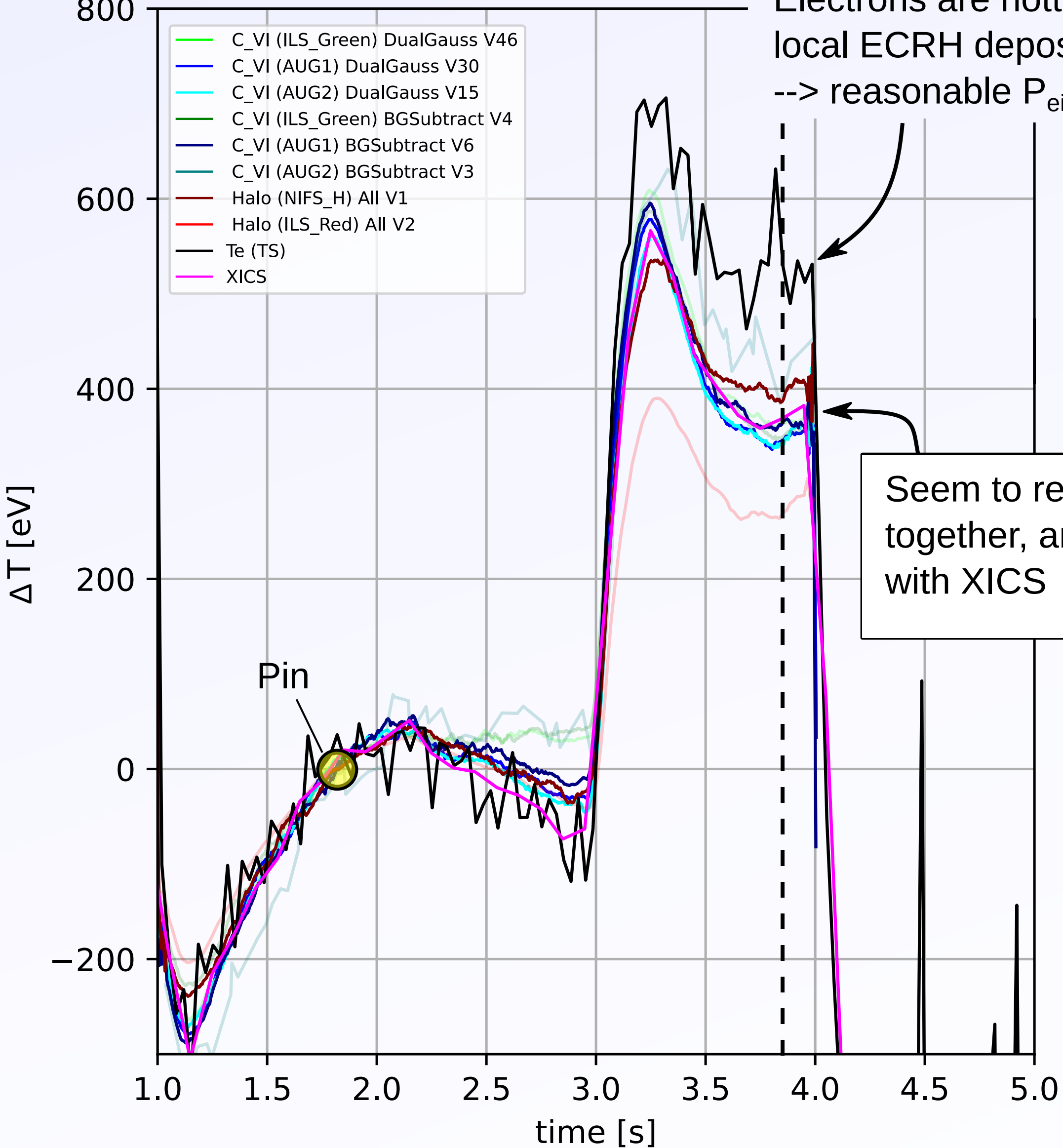
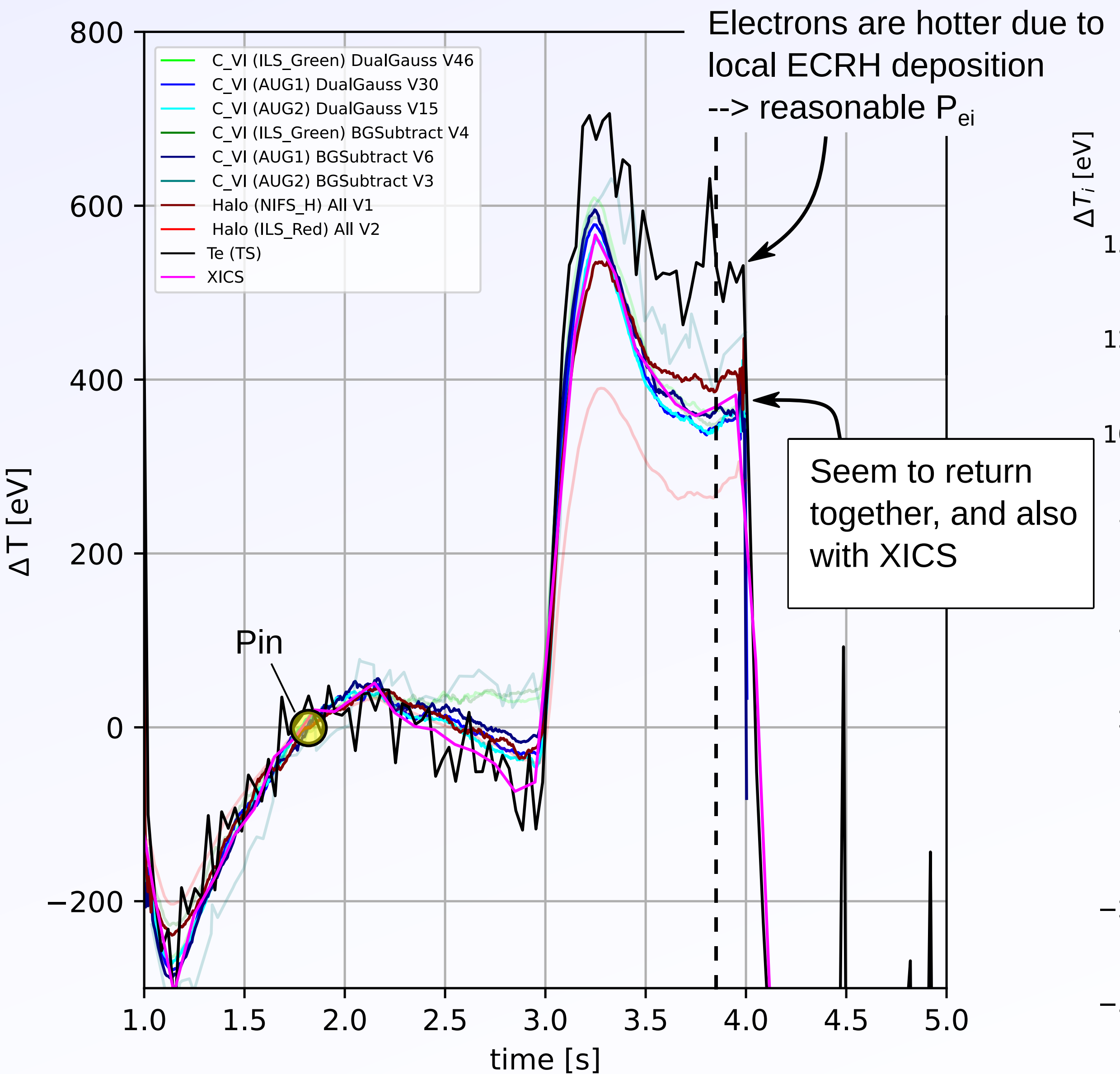
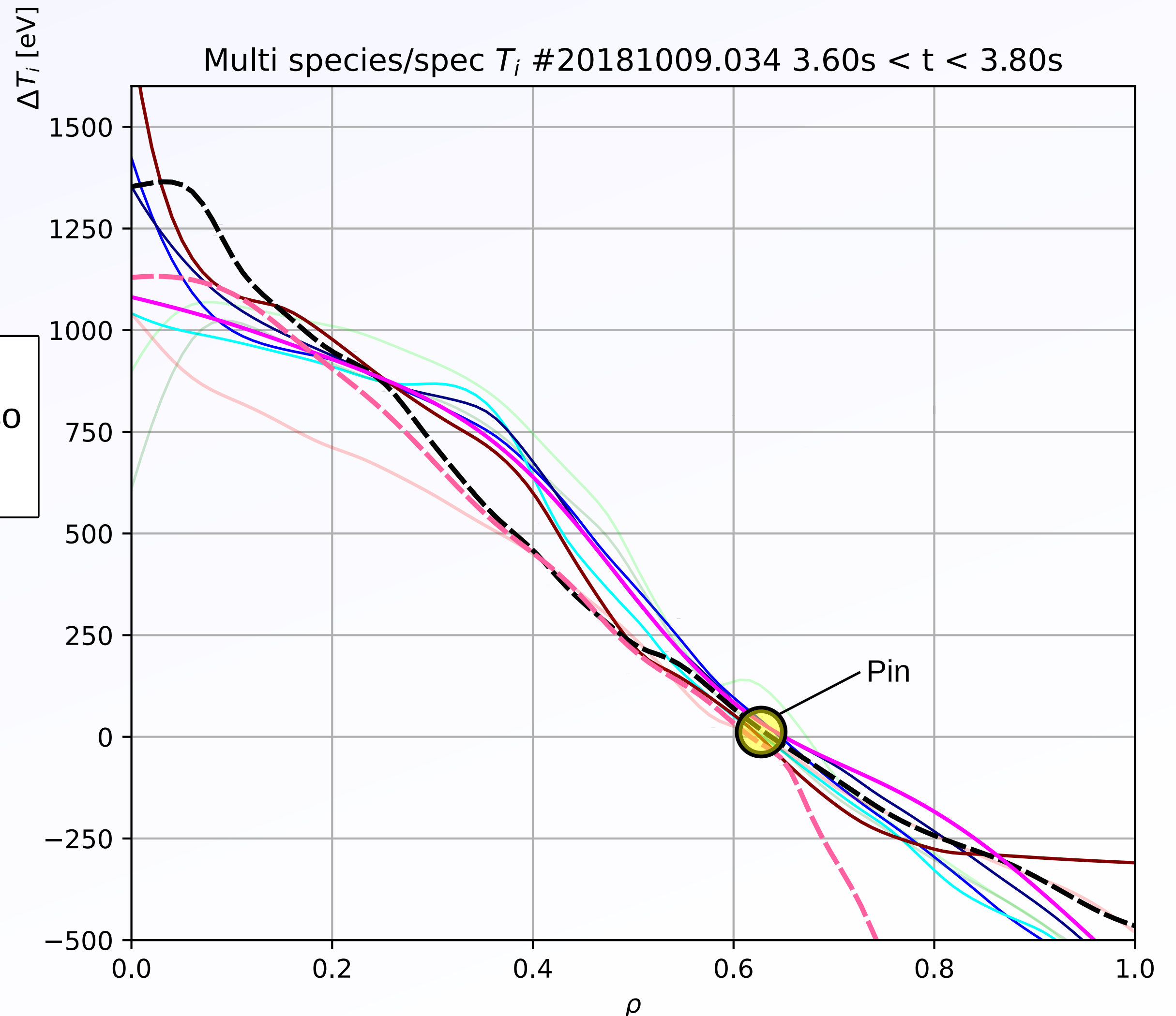


Electrons are hotter due to local ECRH deposition --> reasonable P_{ei}

Seem to return together, and also with XICS

T_e, T_i, T_z profiles





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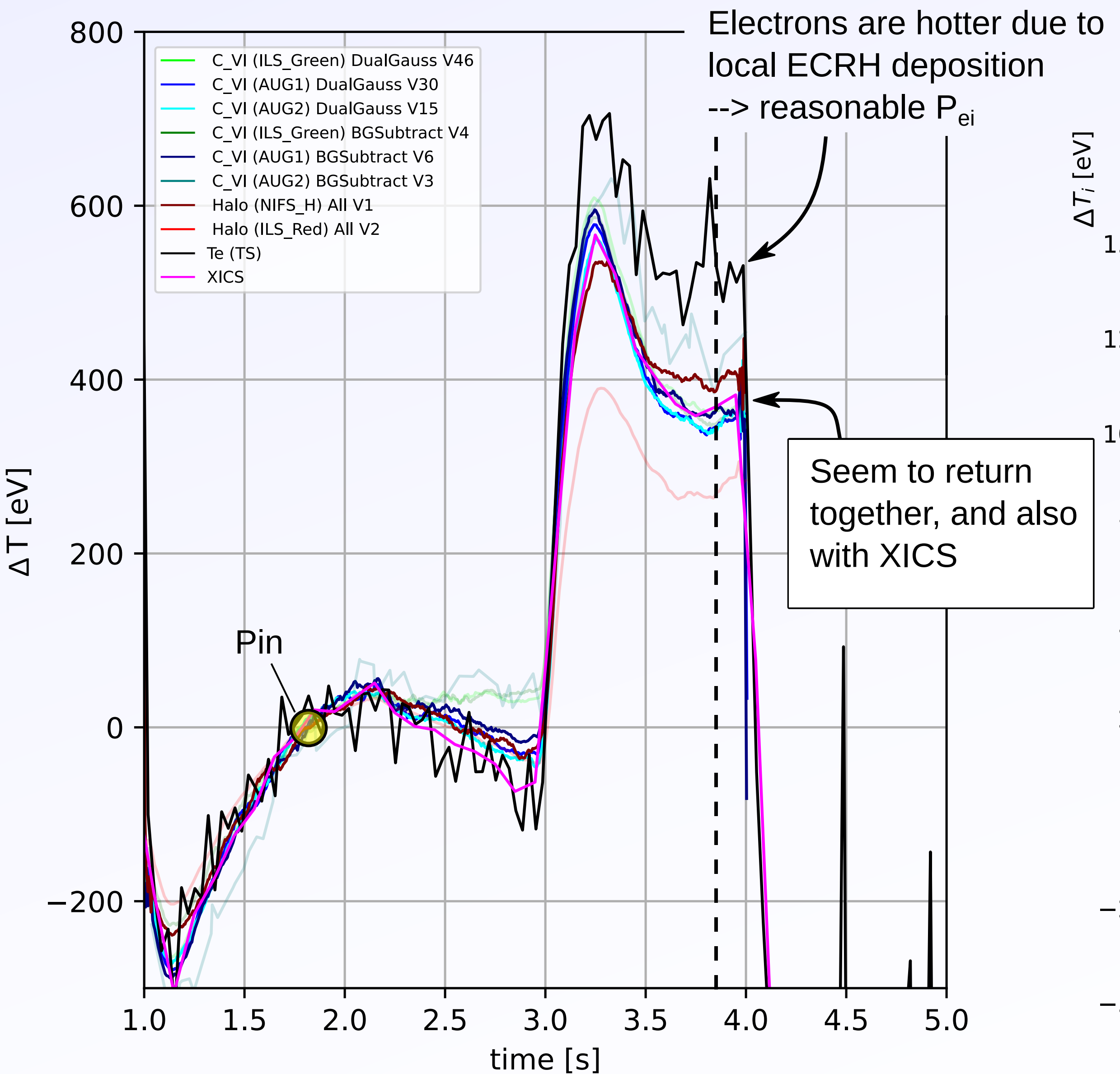
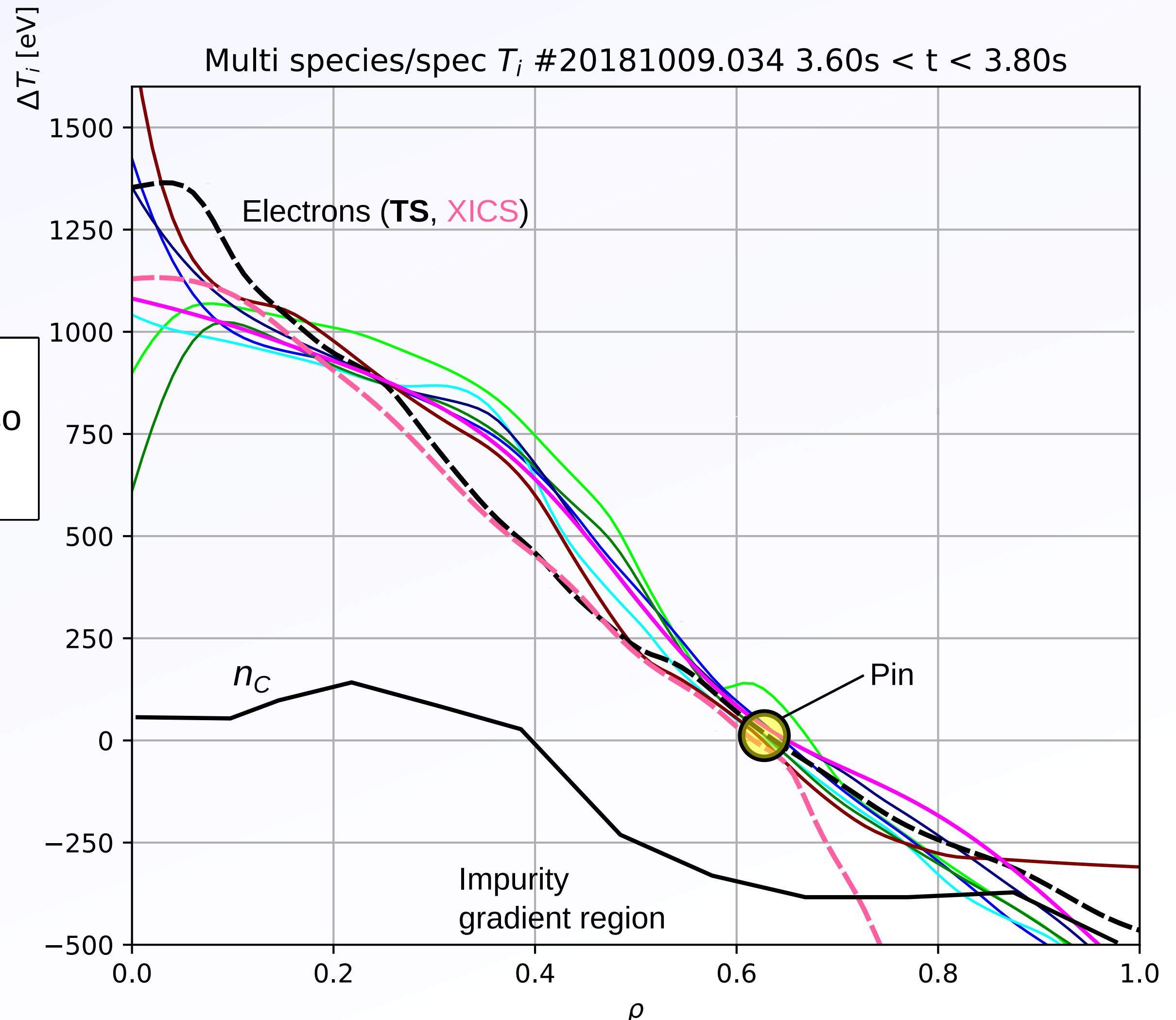
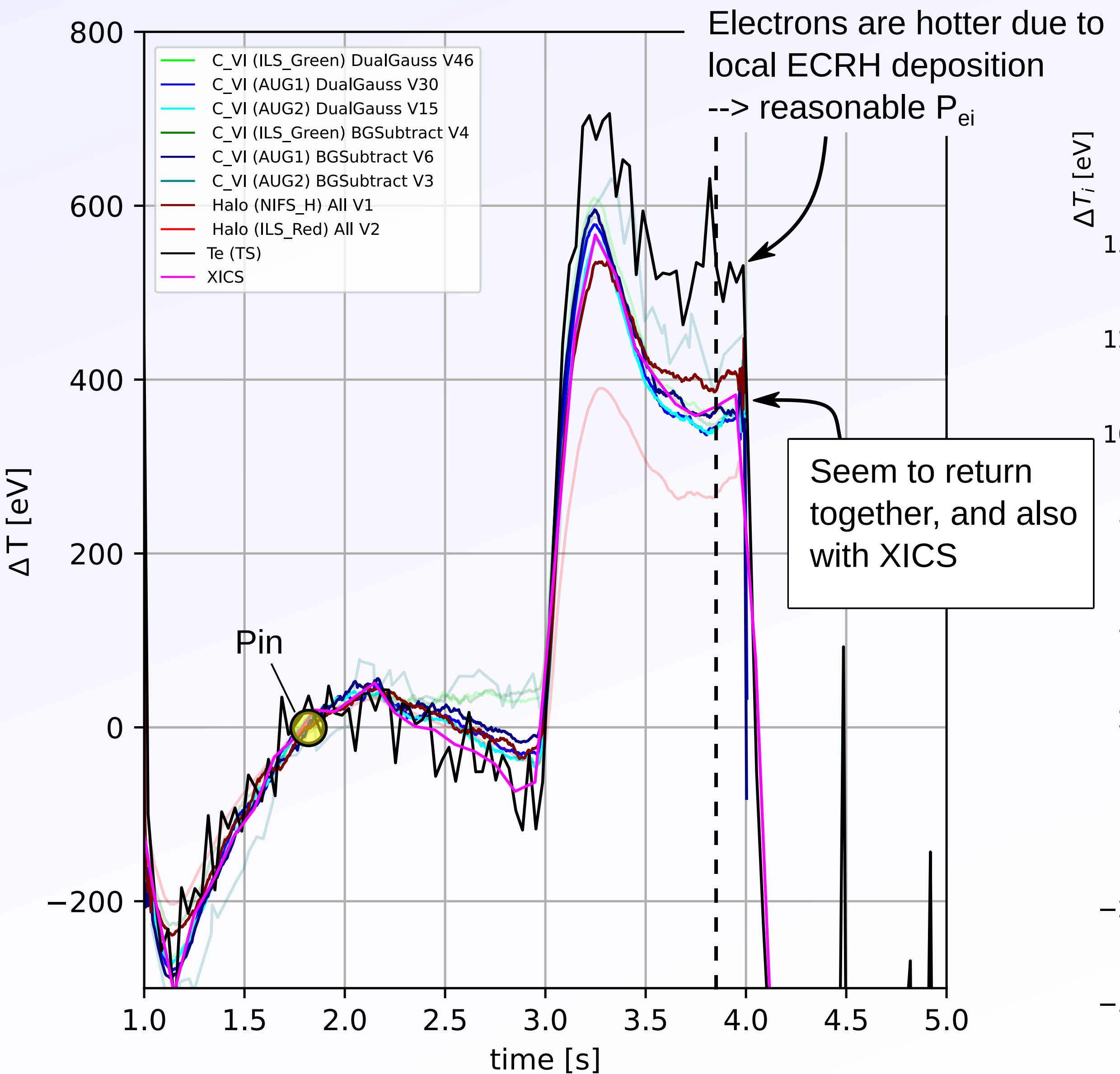
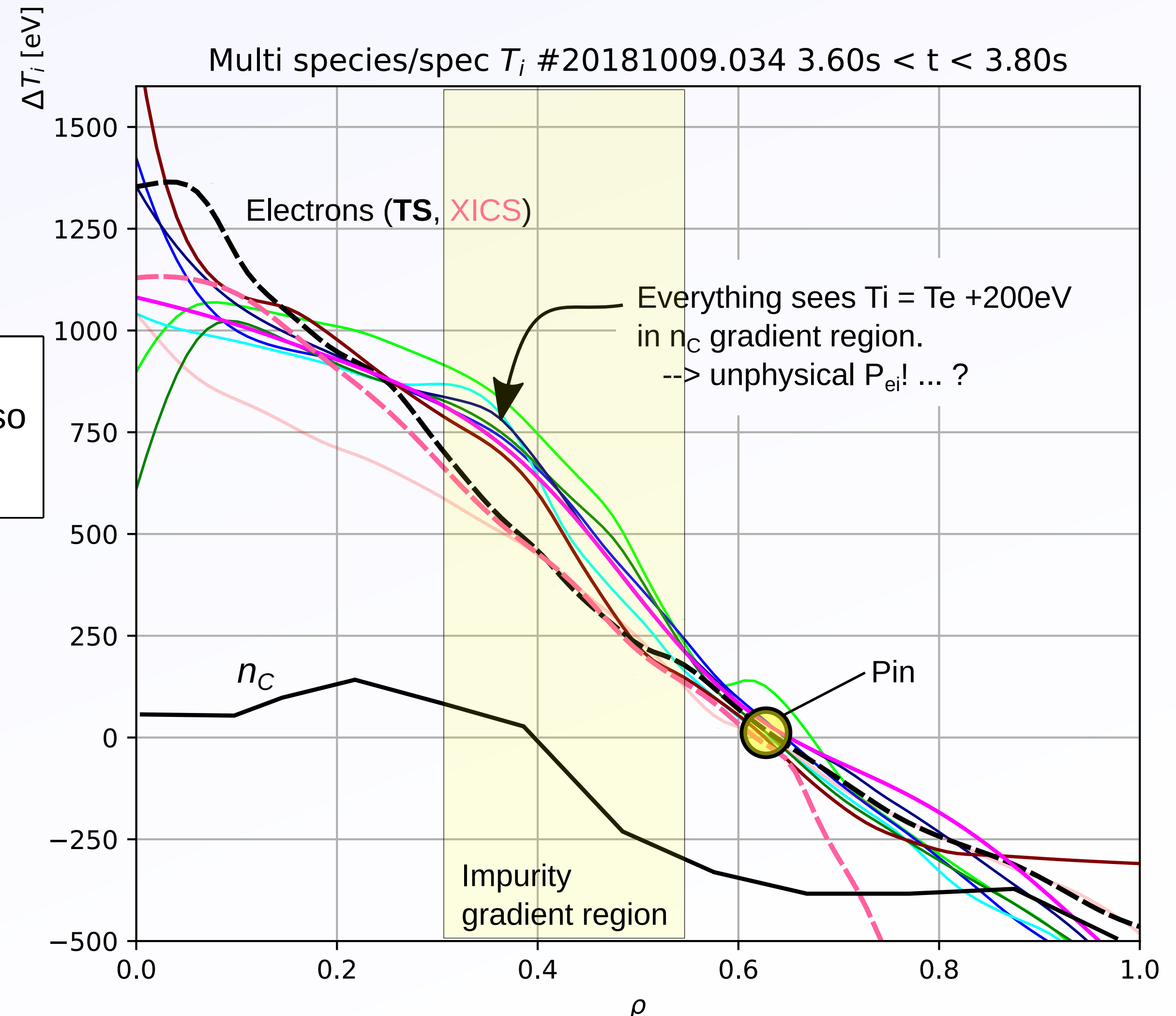




T_e, T_i, T_z profiles

It *seems* like the T_z becomes much higher near very steep gradients.





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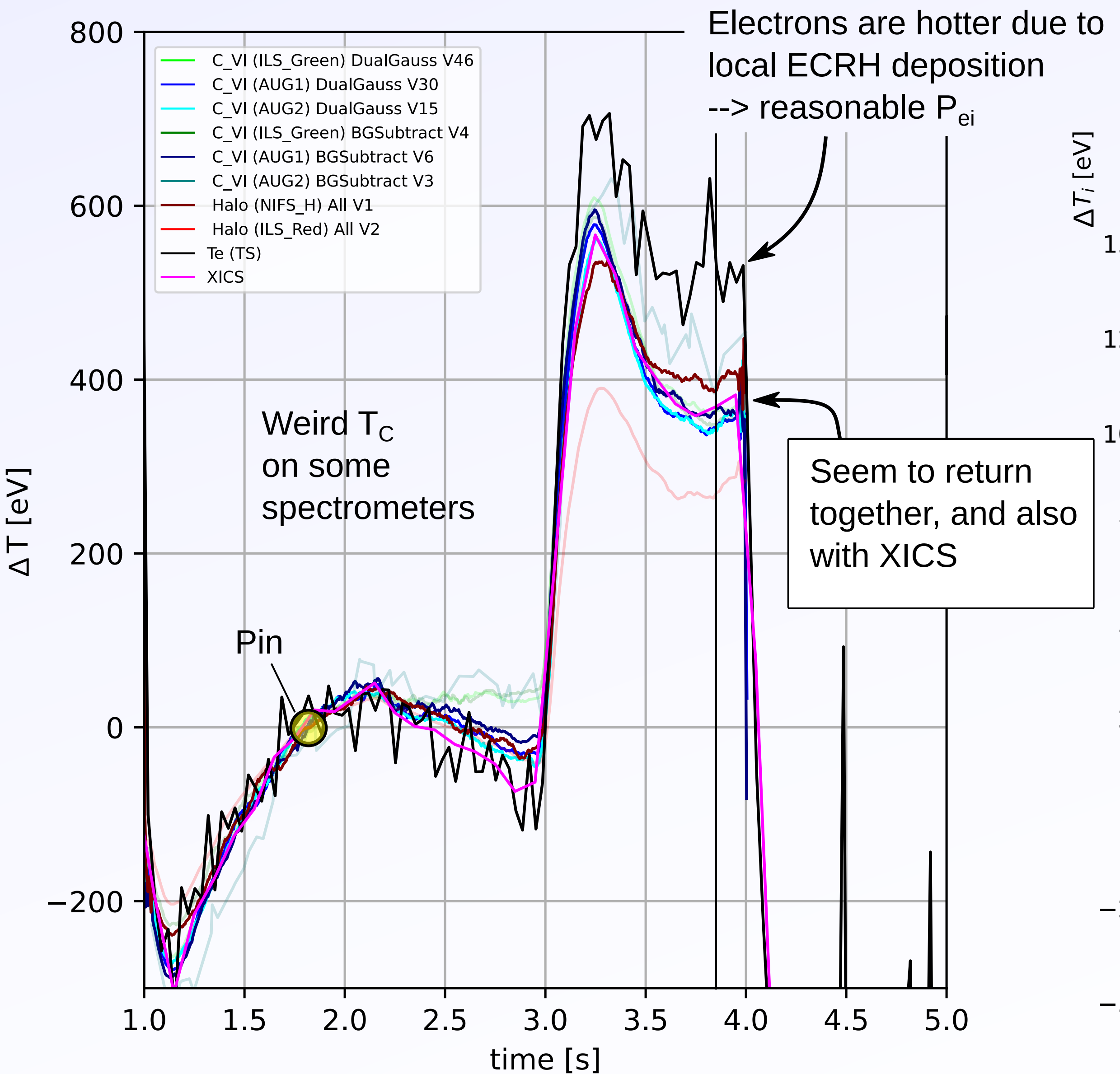
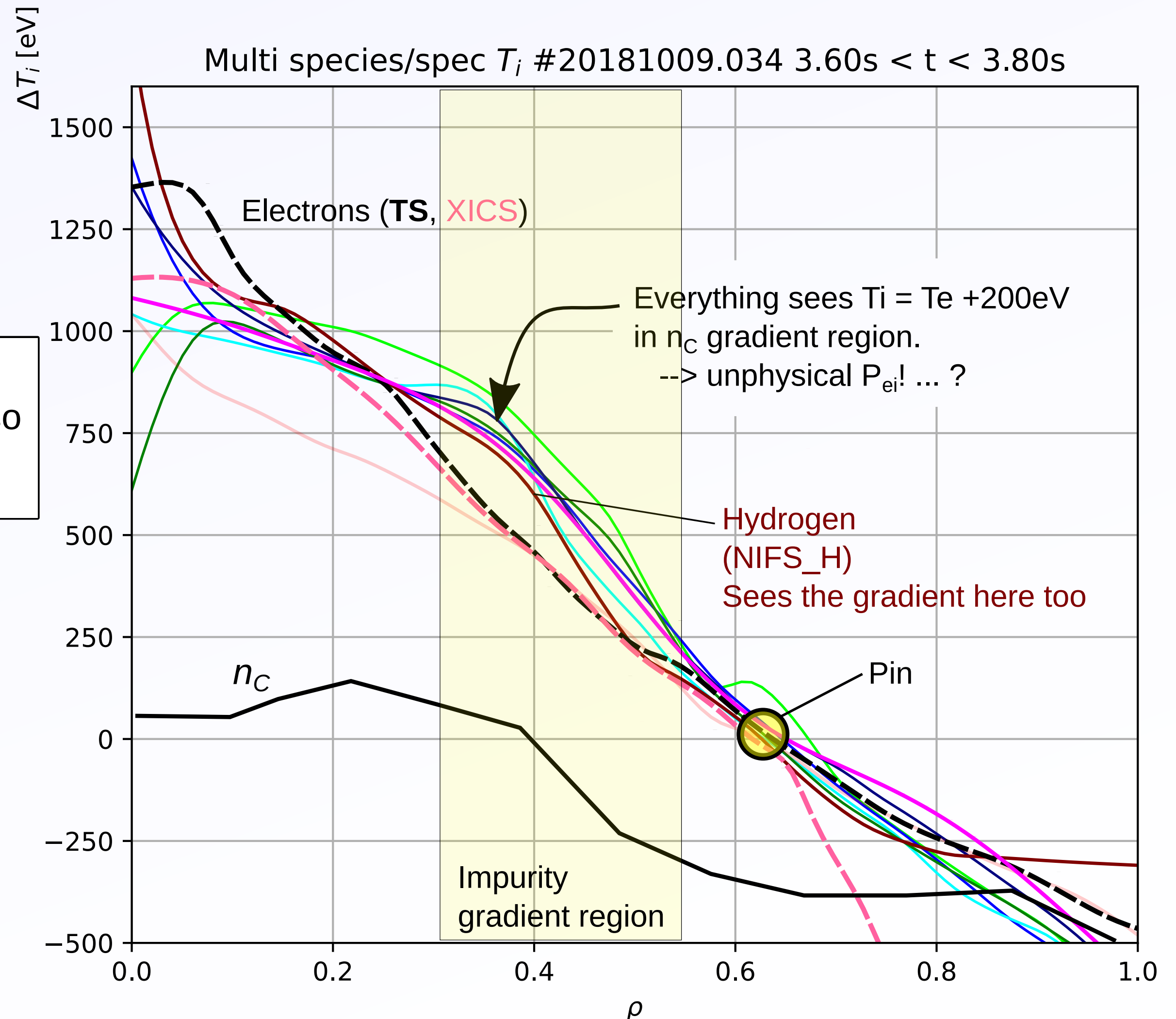




Pure NBI - Species power balance

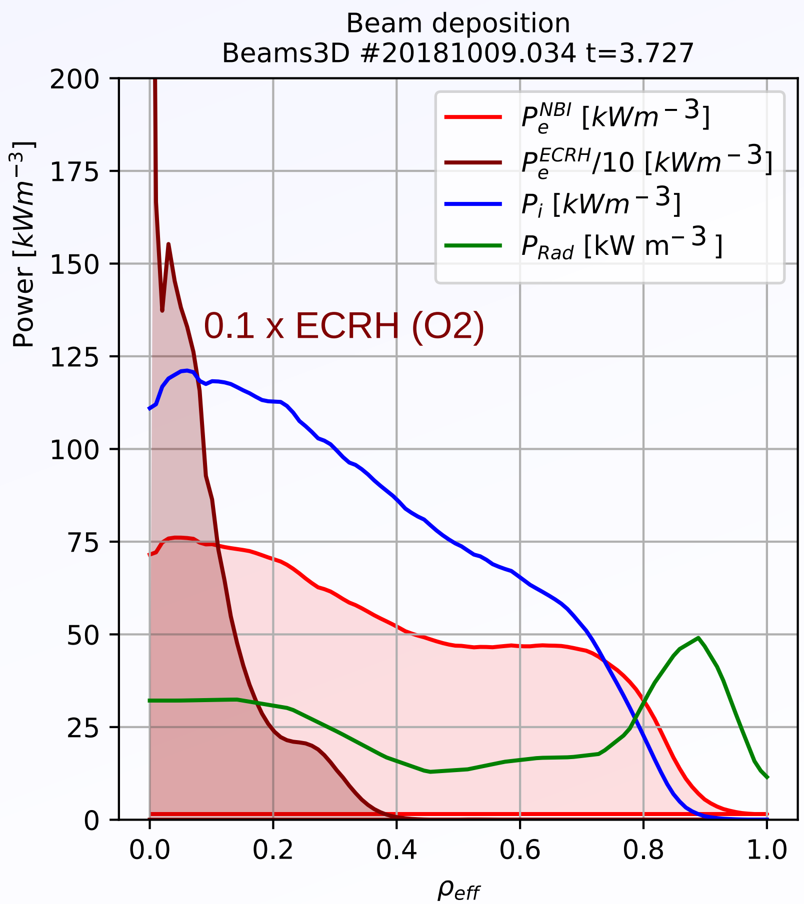
So what can we say?

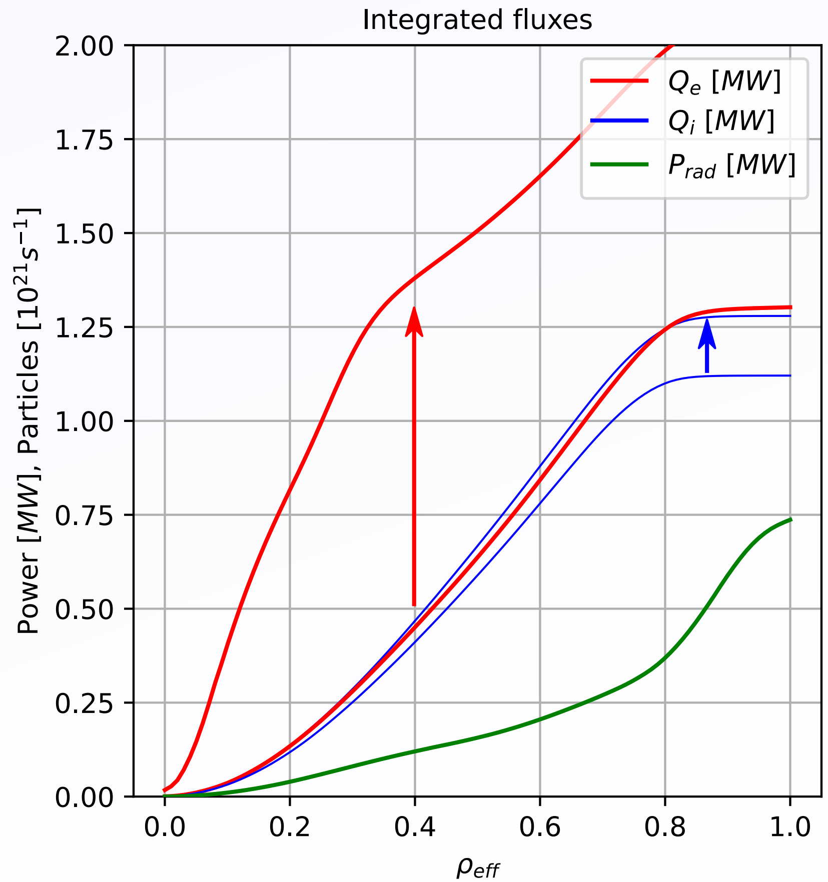
- There are no believable cases where $T_i < T_e$, so we probably do not have neoclassical electrons.
  (This would fit with post-pellets plasmas, where we have near beoclassical ions but still very anomolous electrons)
- The ions could easily be completely neoclassical.
- There is no good reason to assume $T_i = T_e$. Any small differences in the heat transport would lead to differences building up radially until P_{ei} compensates it. To assume this, one would need to propose some mechanism to expect an exact $Q_e = Q_e^{NBI} + Q_e^{ECRH}$ and $Q_i = Q_i^{NBI}$ balance.

During the pure NBI phase, only 1.2MW of total power is available by ρ=0.5, so we can have max 45eV difference.

In the NBI+ECRH phase we get an additional 1MW of O2 ECRH power and can easily now have higher T_e in $\rho < 0.2$.

And in fact, the data tells us this...

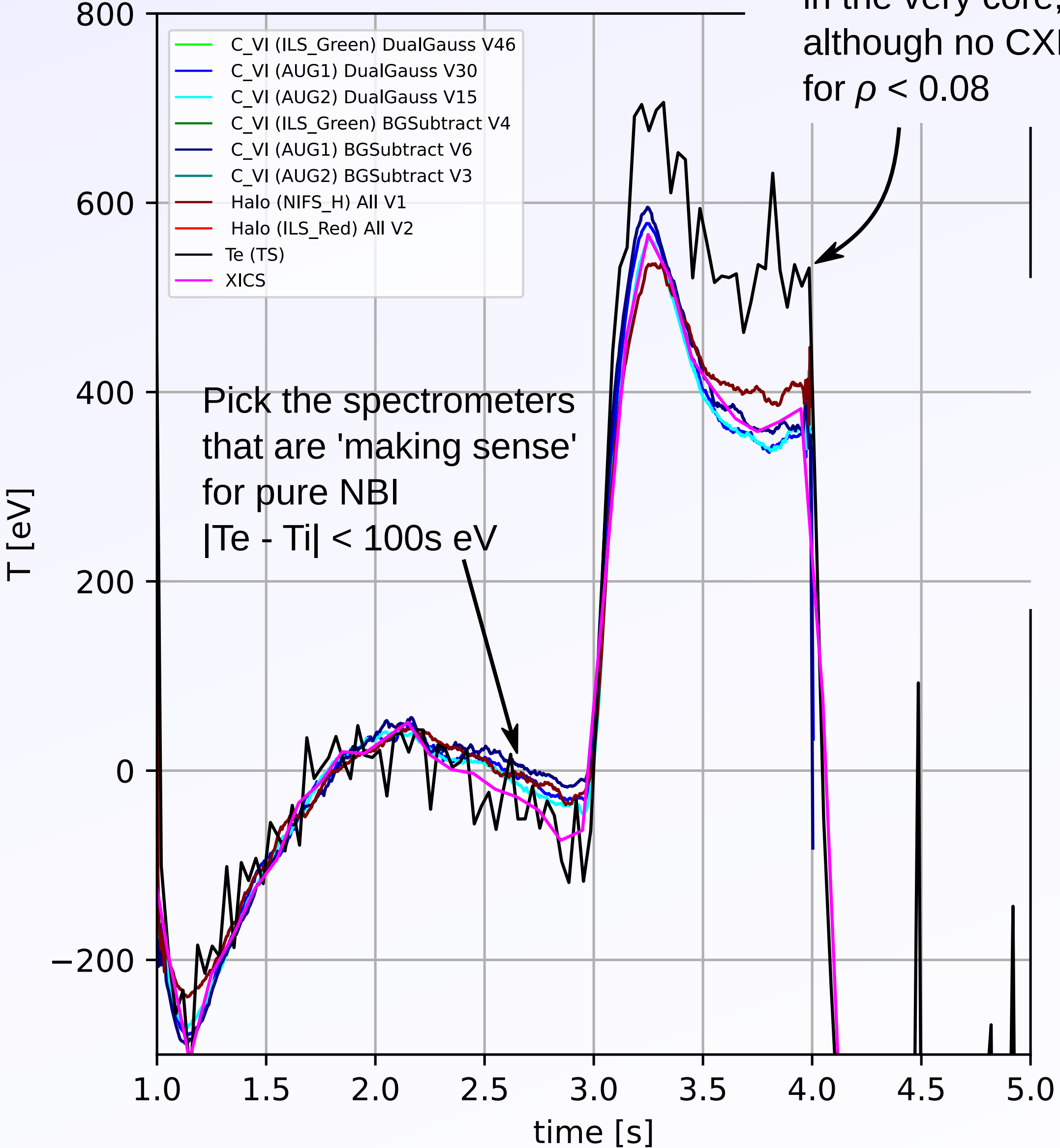


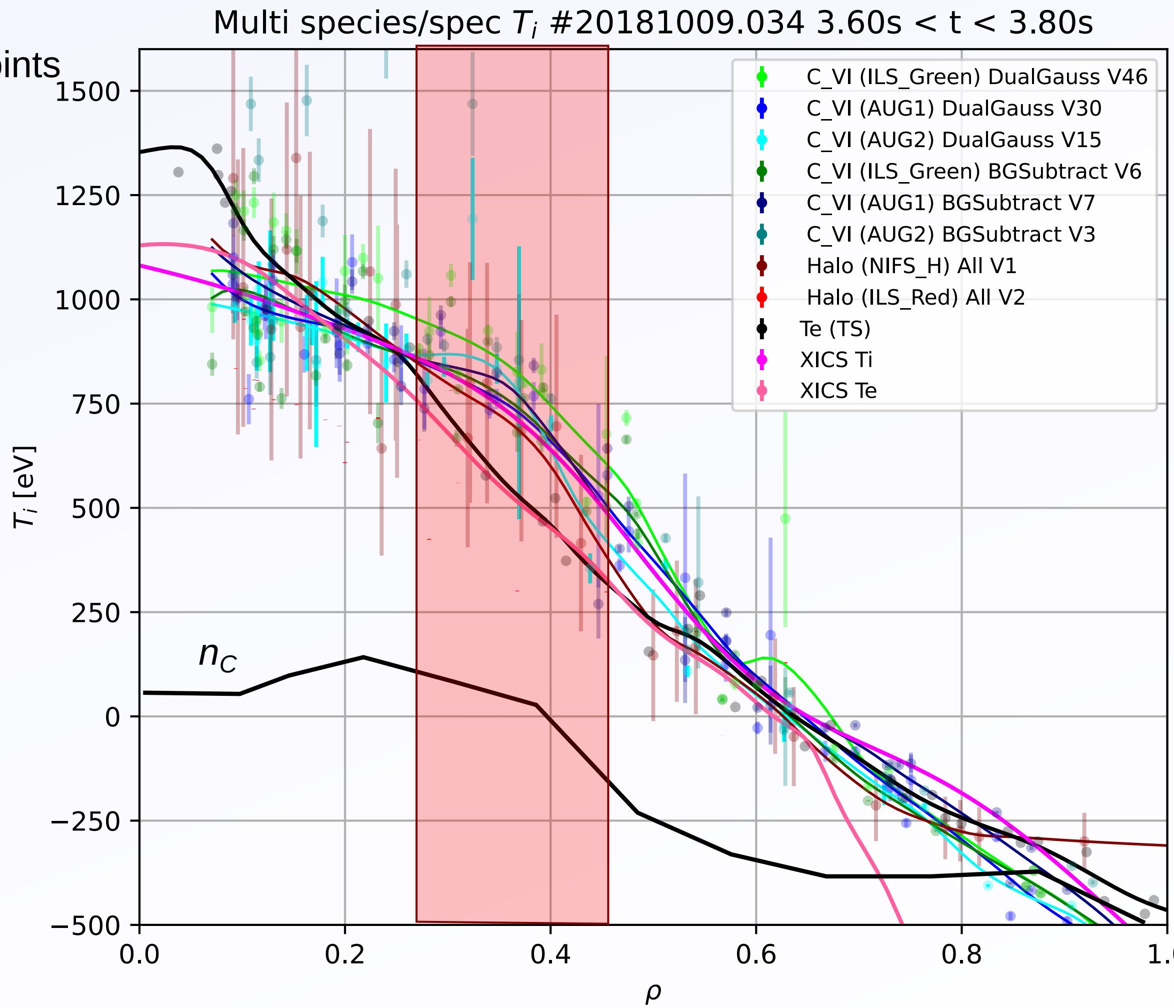


Pure NBI - Species power balance

Examining the pinned measurement time traces again:

Definitely have $T_e > T_i$ in the very core, although no CXRS points for $\rho < 0.08$

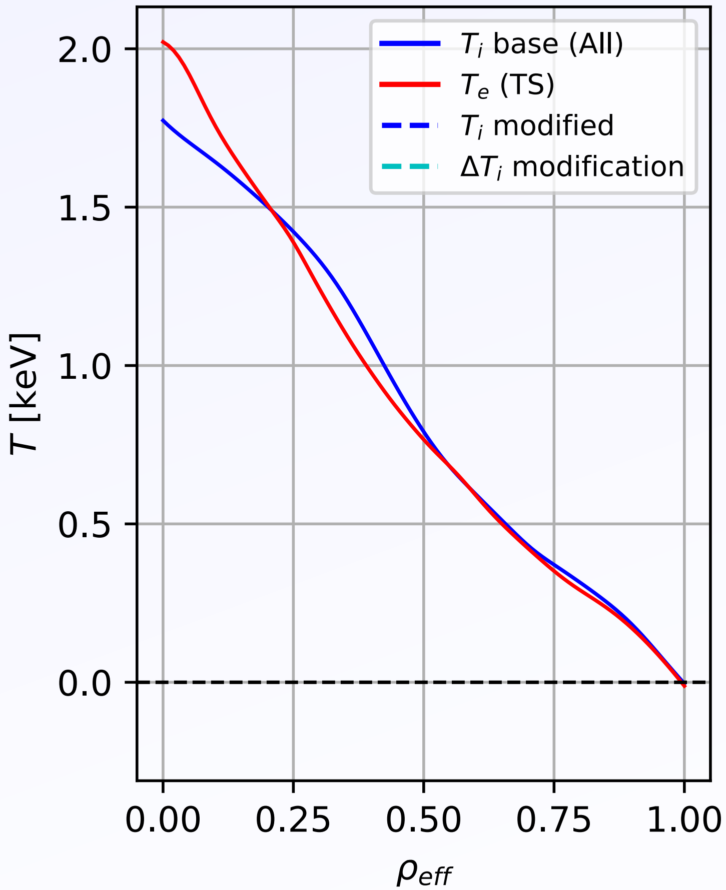




We're looking for an issue that effects both types of spectroscopy (CXRS + XICS), or something spatial (e.g. equilibrium).
So we might 'mistrust' the gradient region where $T_i >> T_e$

Pure NBI - Species power balance

We can go back to the original data (no pinning, no adjustment) and just average everything:
all Carbon CXRS + hydrogen Halo + XICS argon.



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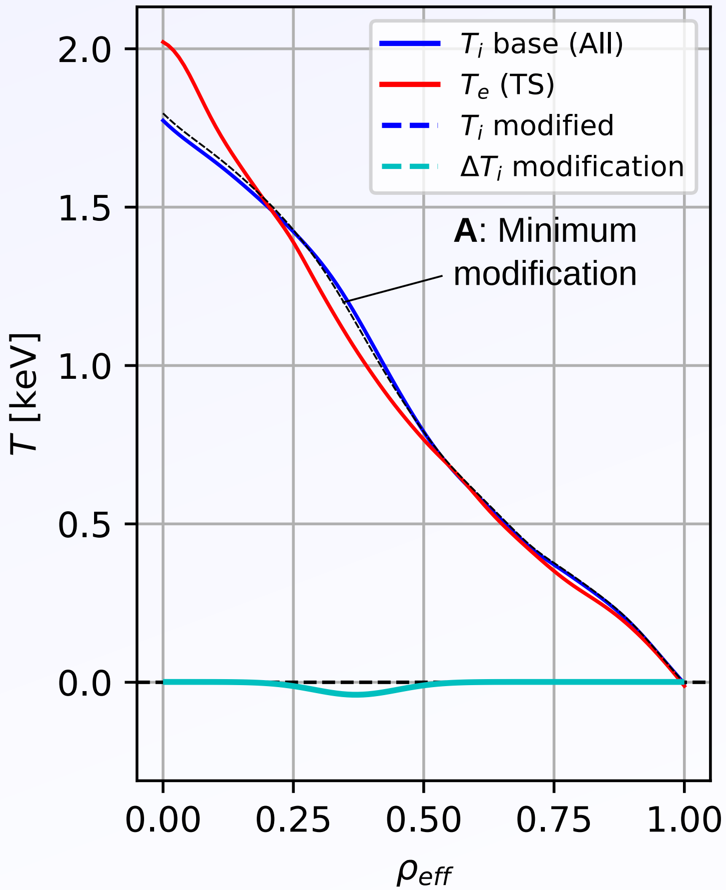

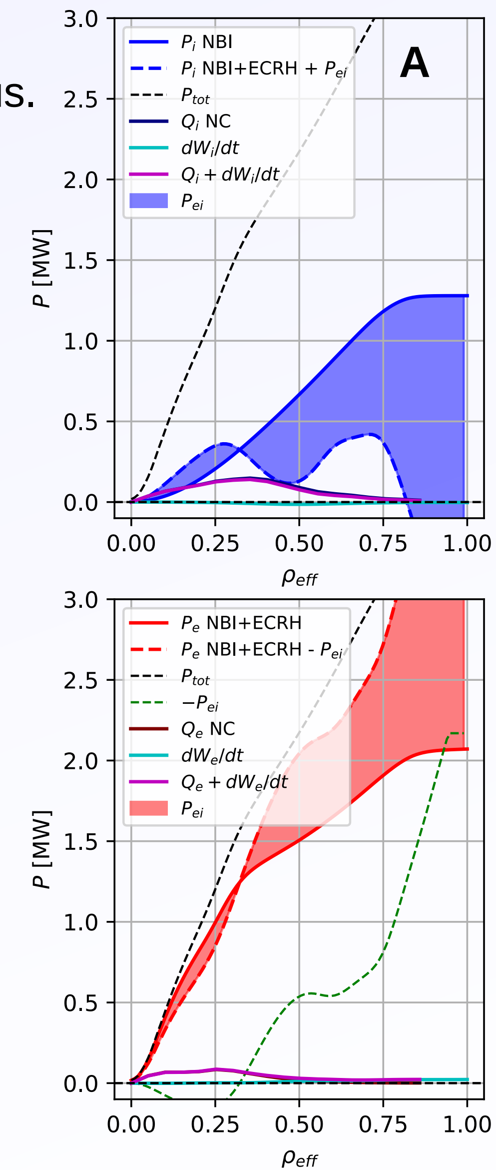

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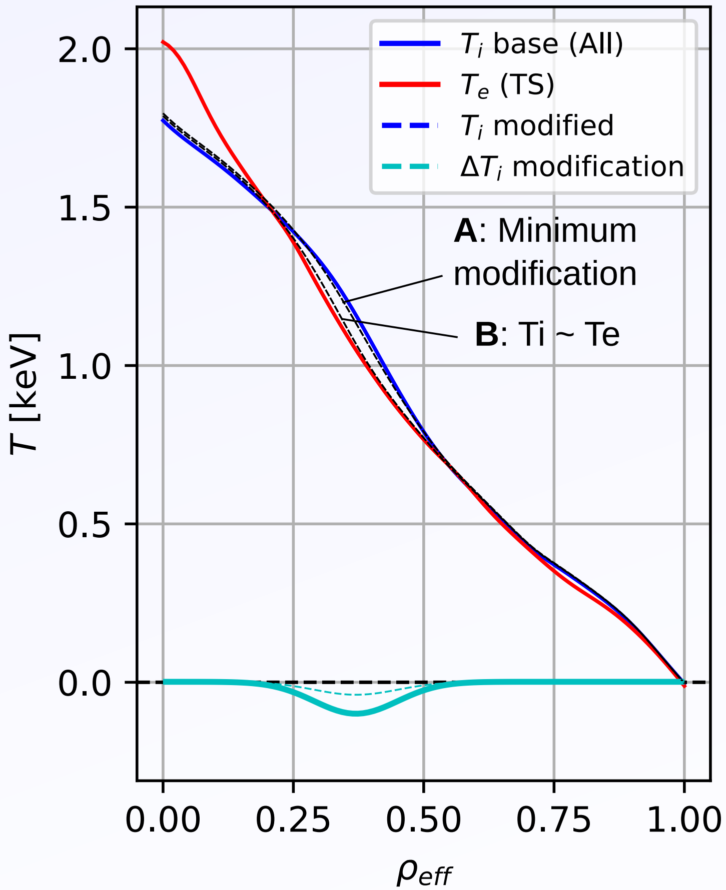

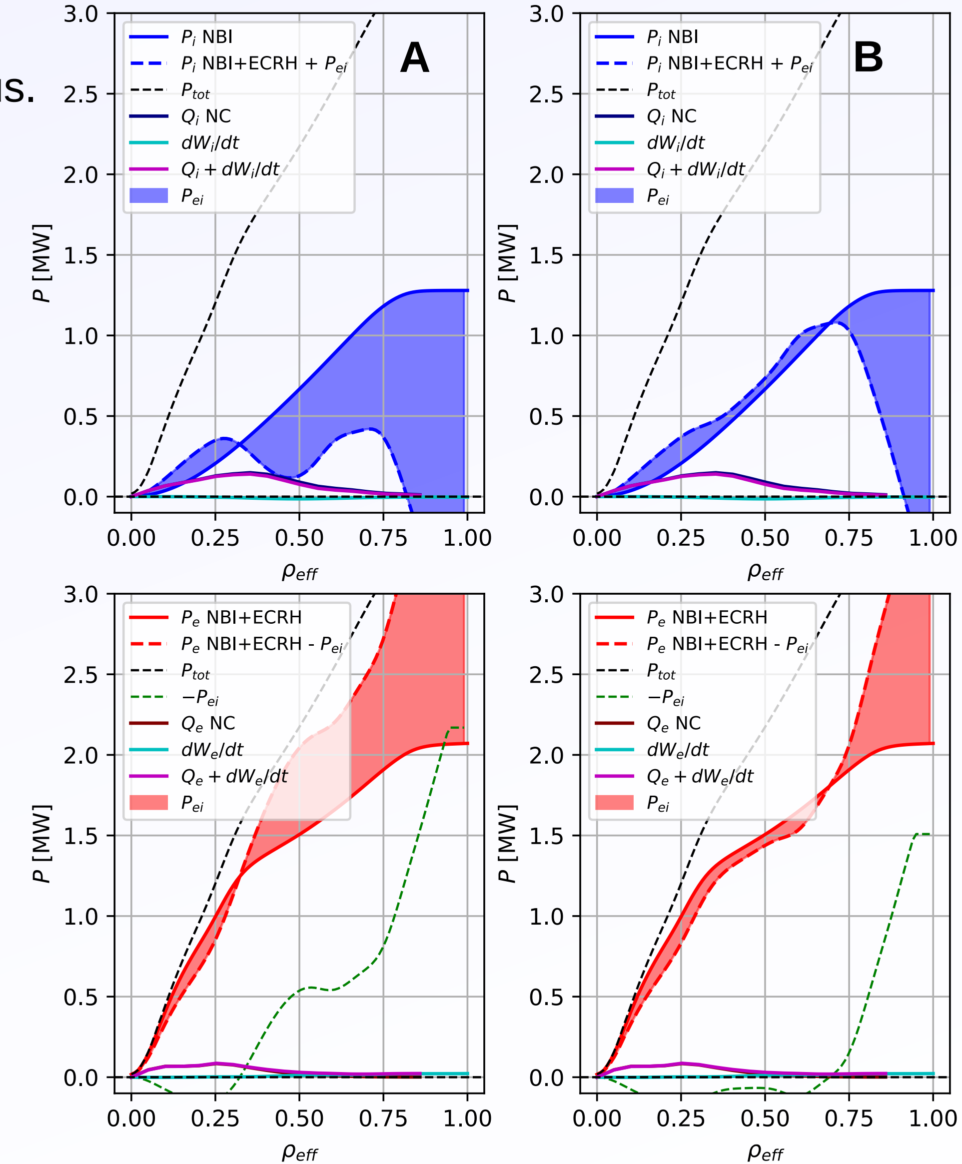

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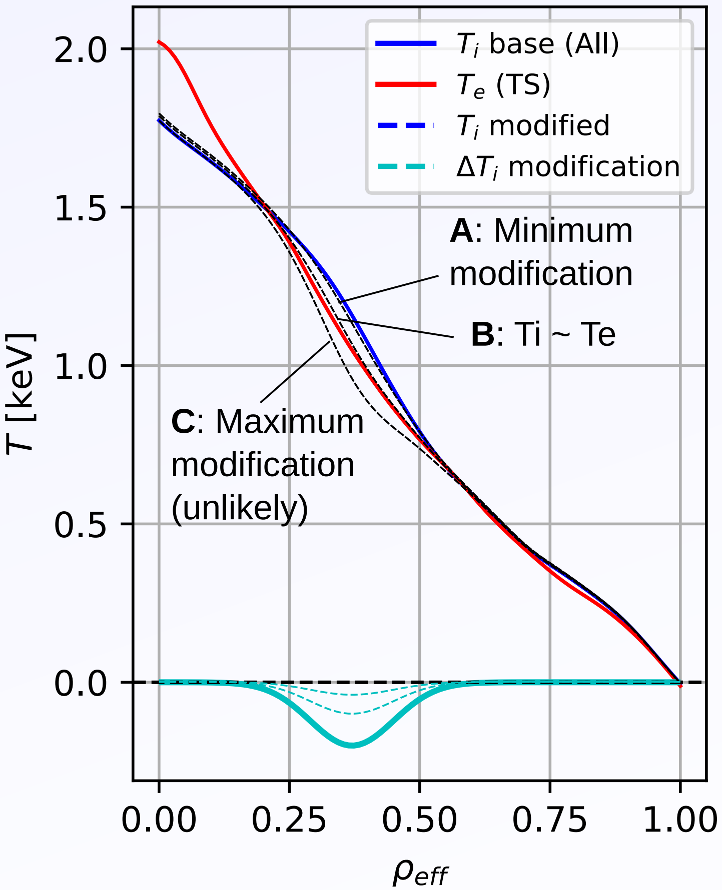

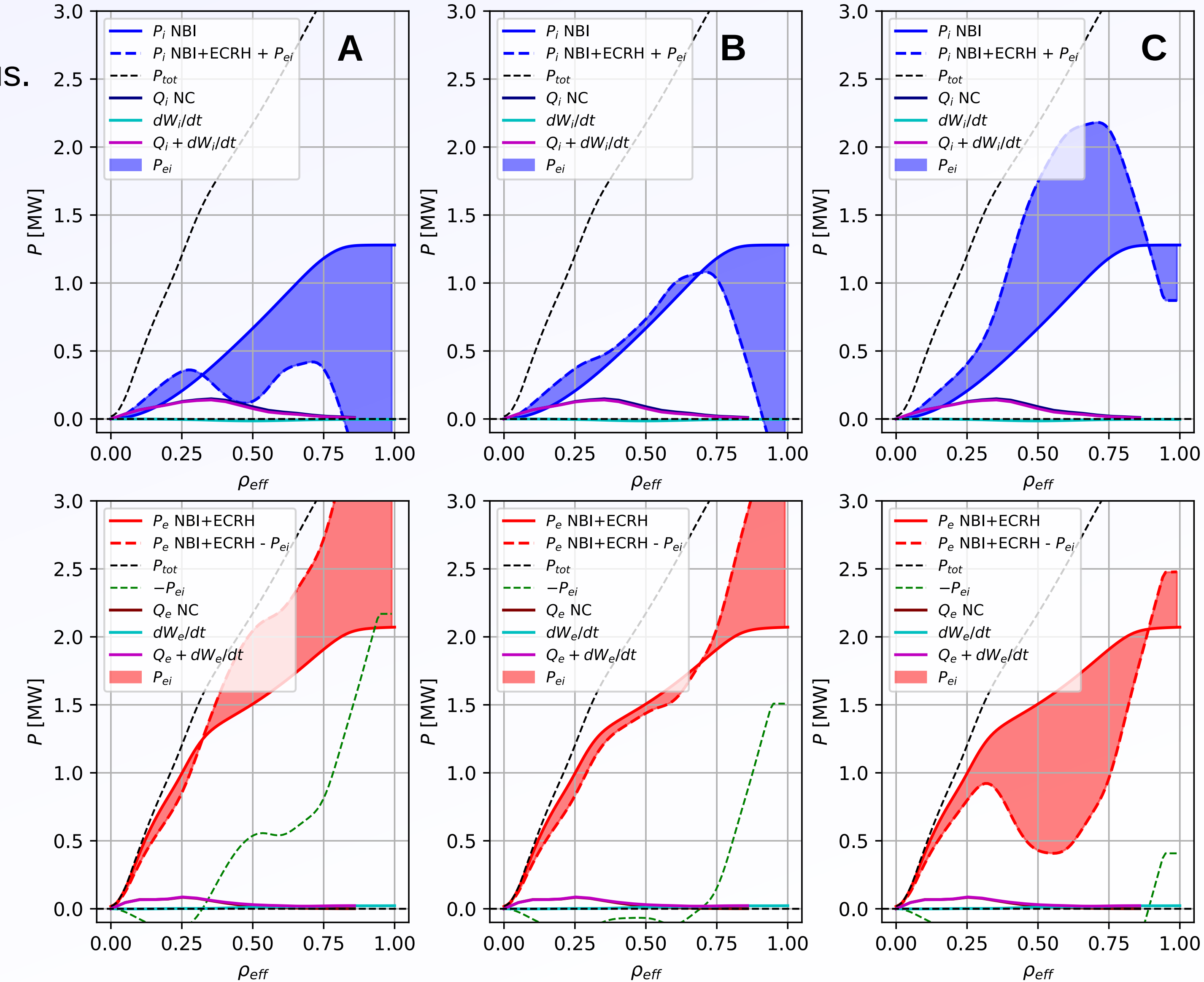

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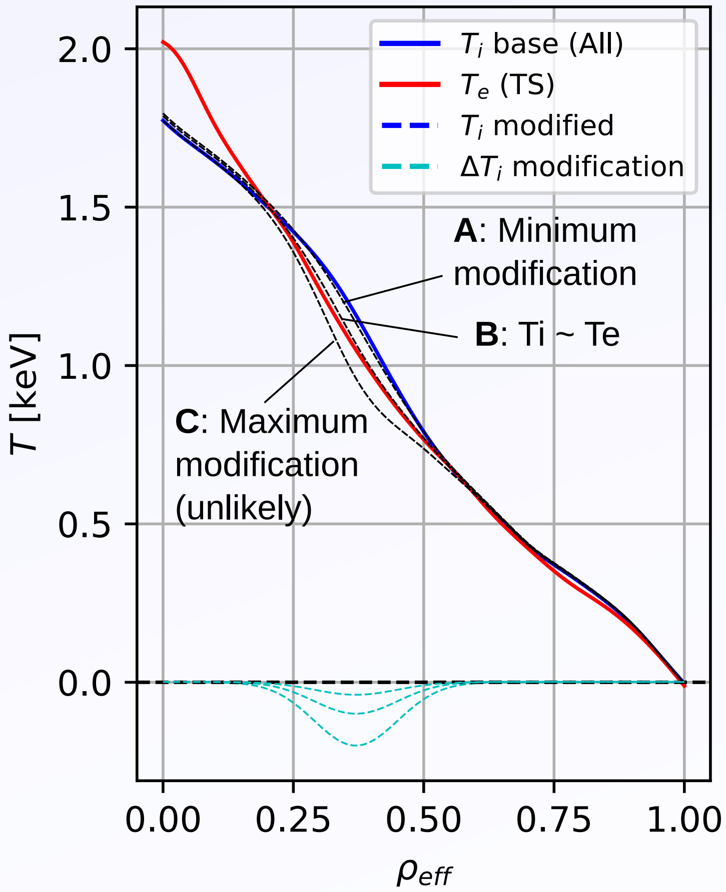
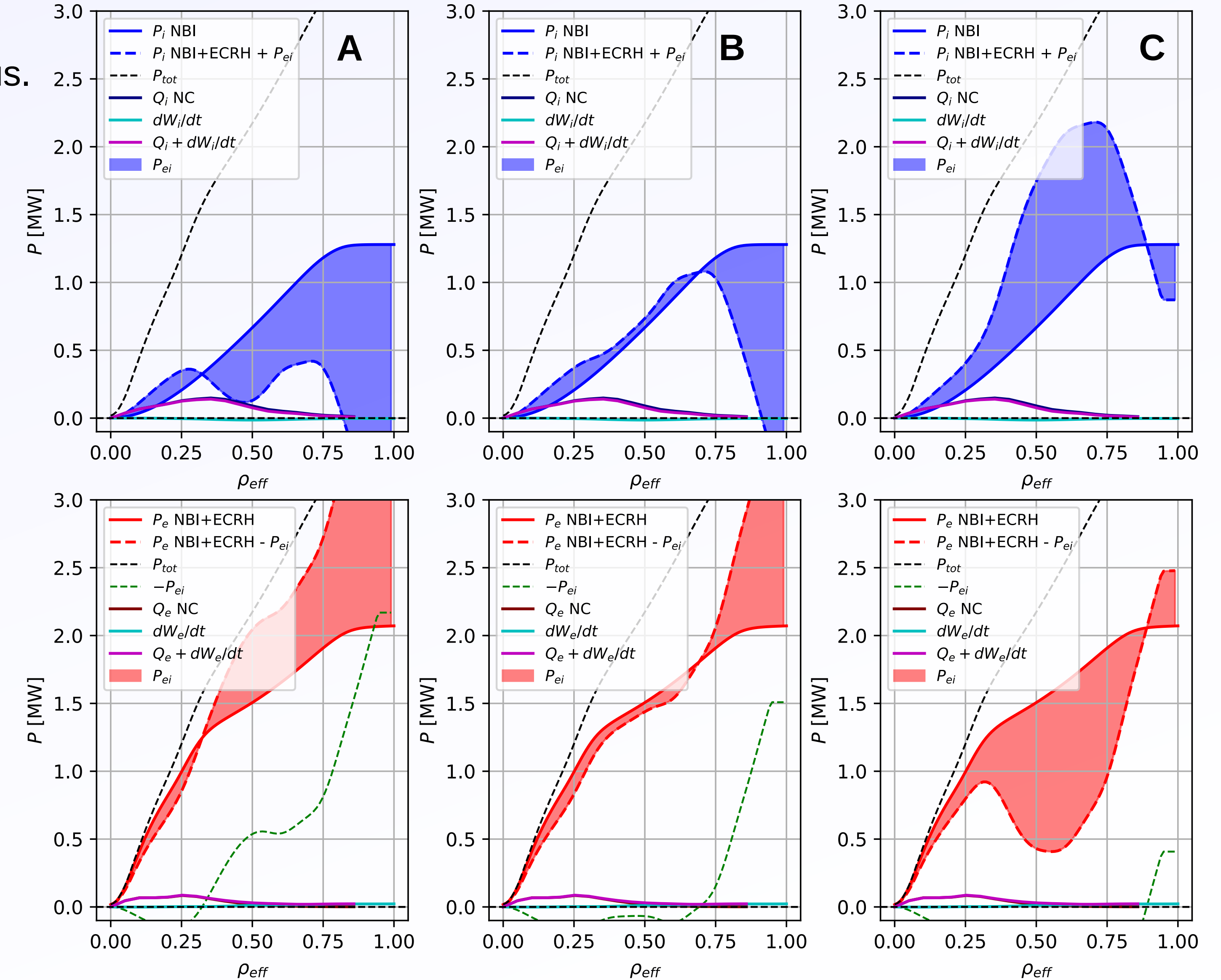
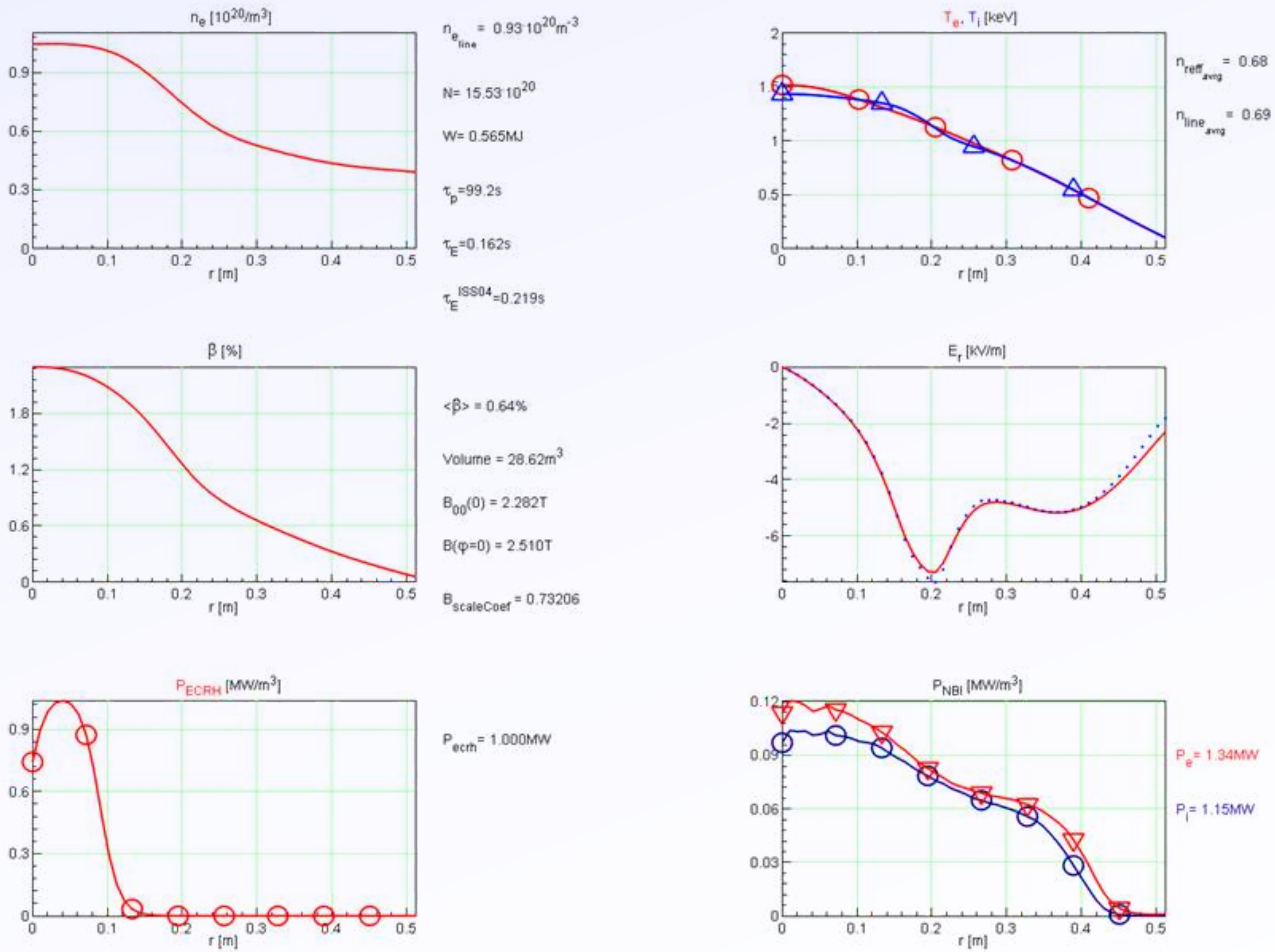




Pure NBI - Species power balance

- We can construct this situation in NTSS:

[Beurskens]



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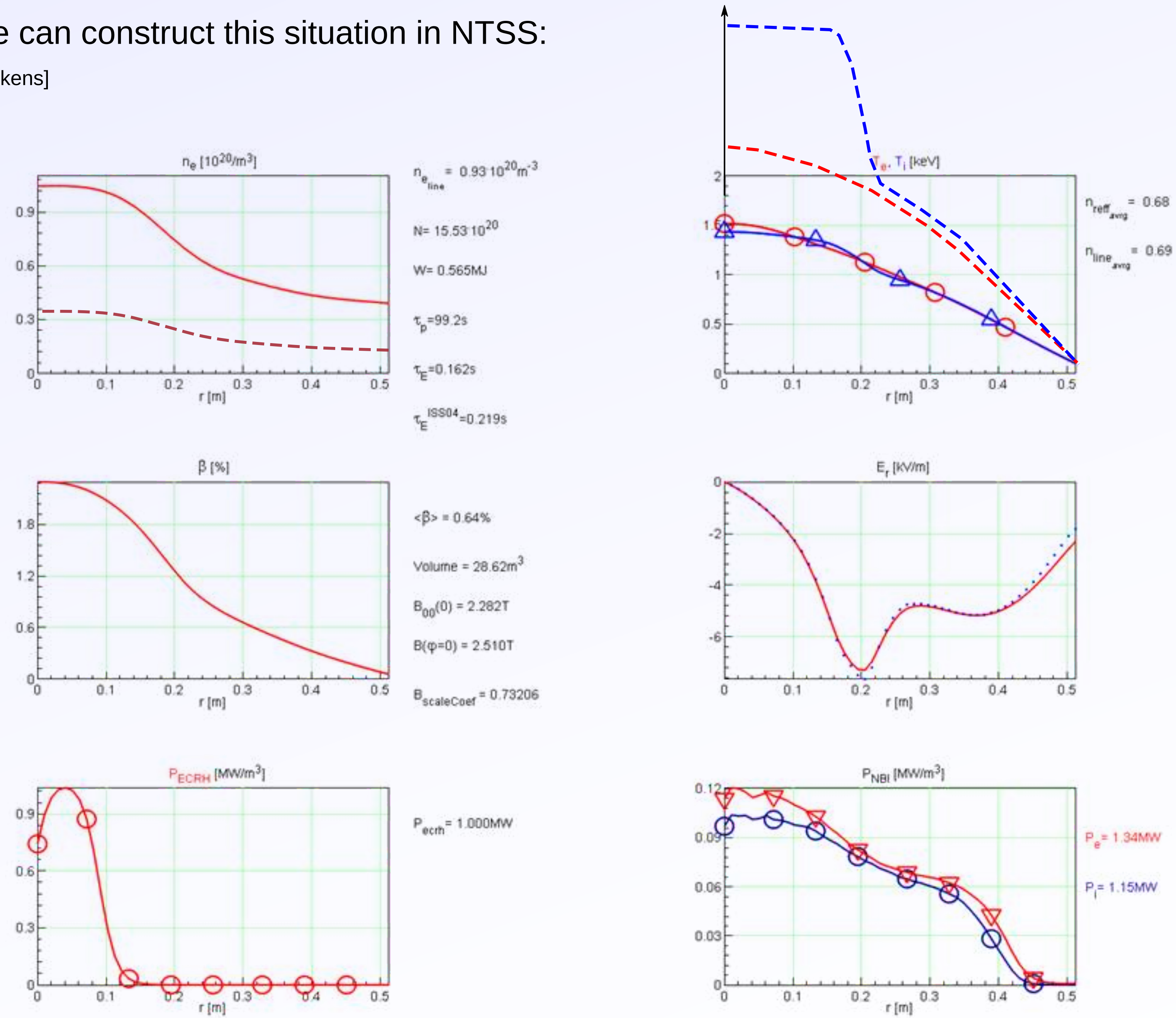


At low density such a barrier would be very significant, but we would not get the a/L_{ne} required to create it.

Pure NBI - Species power balance

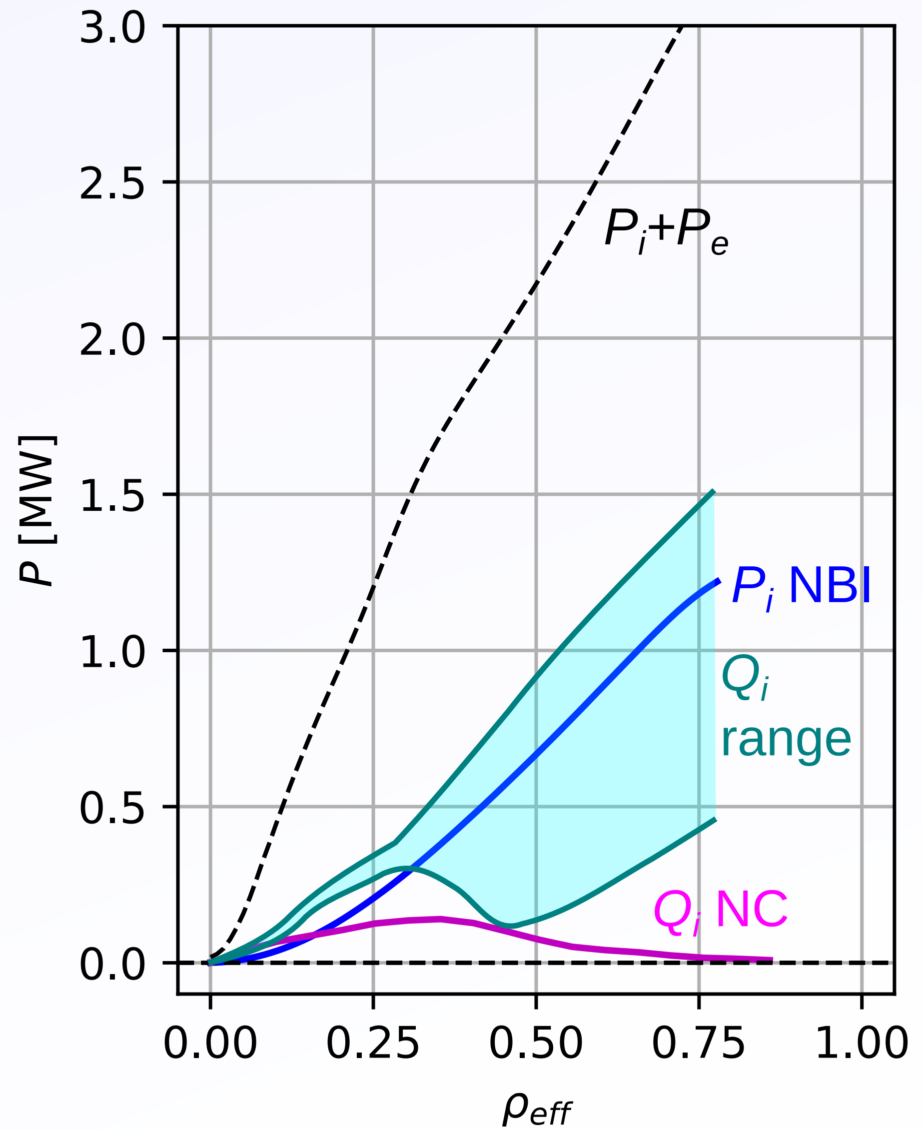
- Intermediate conclusions from profile analysis:
  1) We can not separate Q_i and Q_e at high collisionality without improvements to the CXRS, XICS and TS analysis!
     It needs ~50eV accuracy, which is hard (but not impossible).

  2) Q_i at ρ = 0.5 is somewhere between NC value and Q_i^{NBI}.
     It is unlikely to have taken a large fraction of the ECRH power.

  3) Fully supressed ion turbulence barrier is very possible at ρ =0.5,
     conincident with the apparent particle transport barrier.

     However, this is not useful, since all power is transferred to electrons, so that $T_i = T_e$.

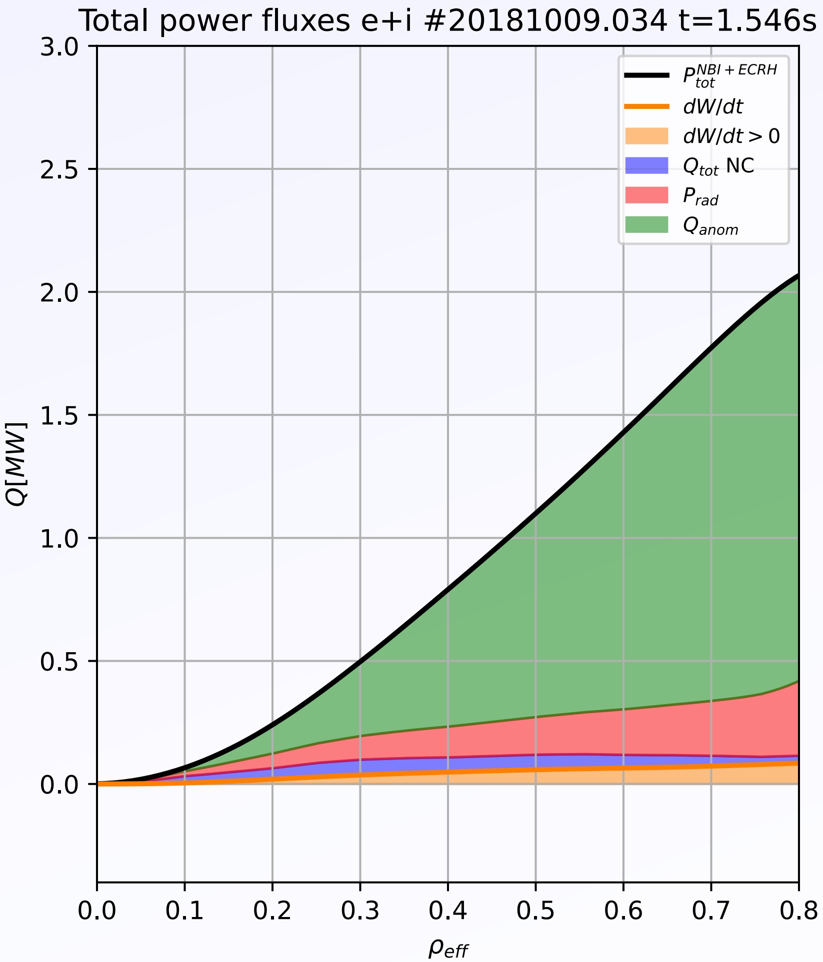
--> In high collisionality plasmas, the species with fastest heat transport completely determines both temperatures and stored energy.

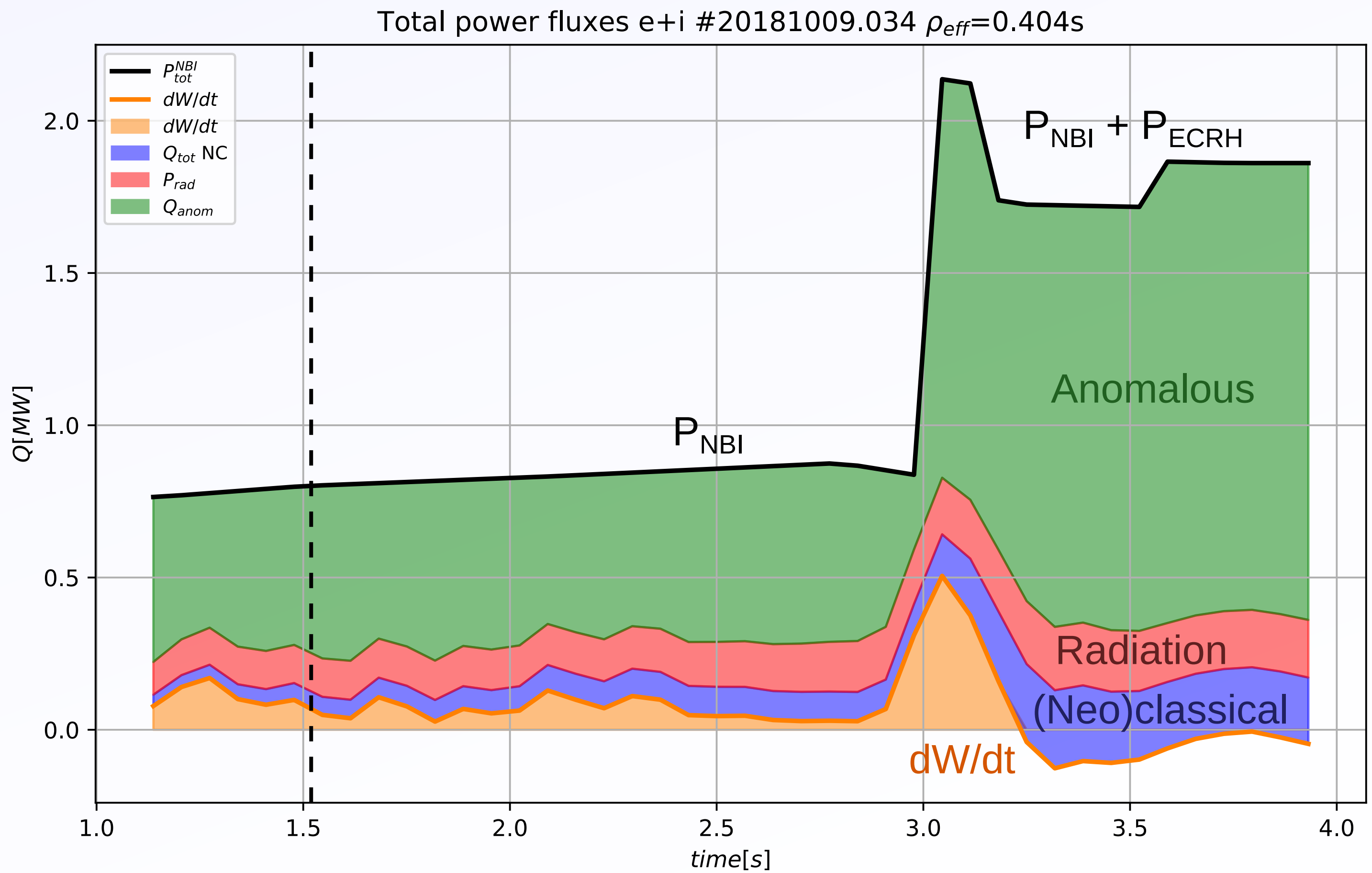


Total power balance

We can ignore P_{ei} and examine the balance of Q_{total}:

- Dominated by anomolous transport at all time points for ρ >= 0.3.
- Both radiation and (neo)classical transport are small but significant (classical ~ 20% x neoclassical).
- Significant increase in anomolous transport with ECRH.
- Possibly a very weak sign of very small temporary decrease in heat transport coincident with particles.





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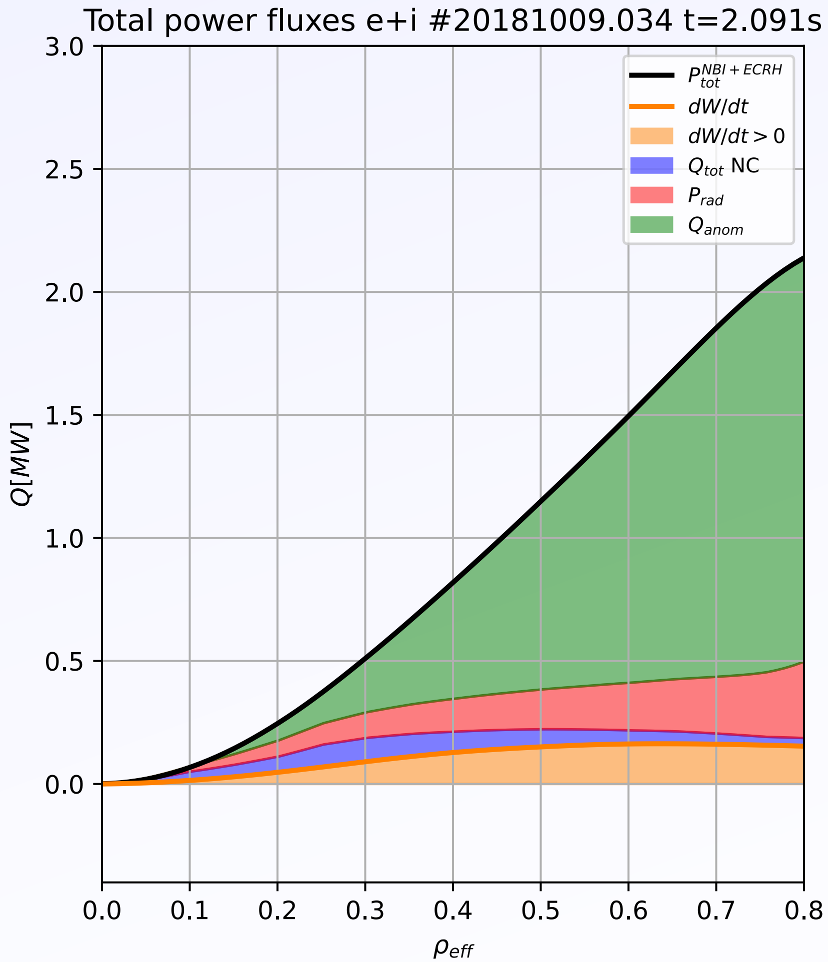

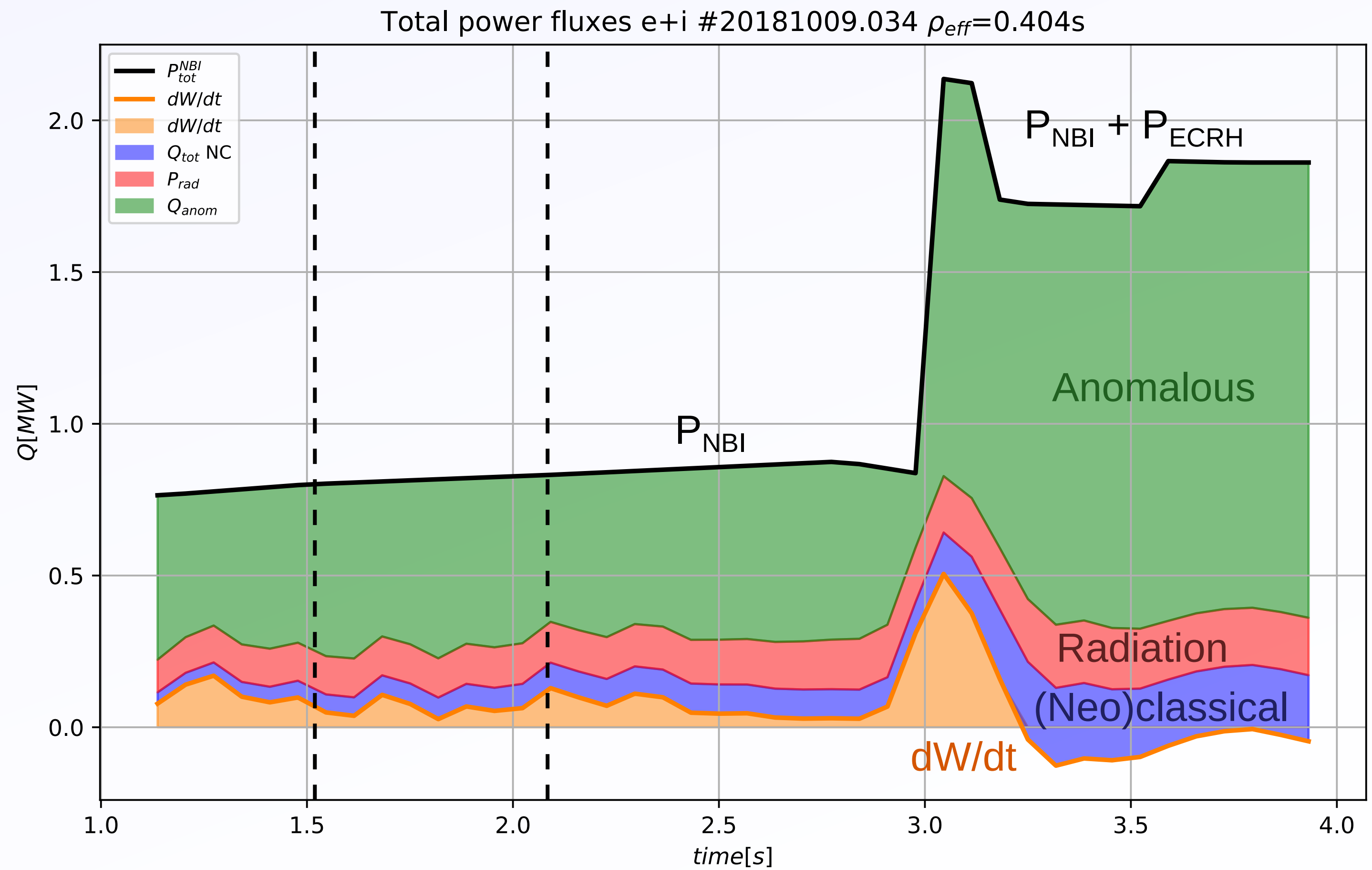

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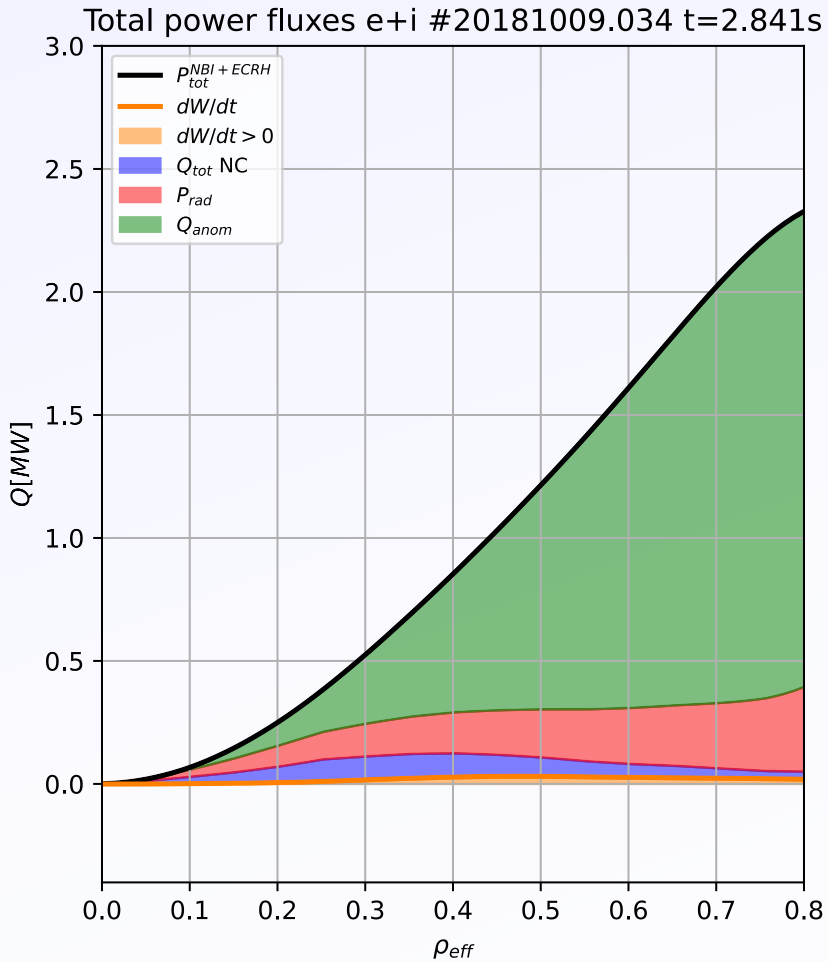

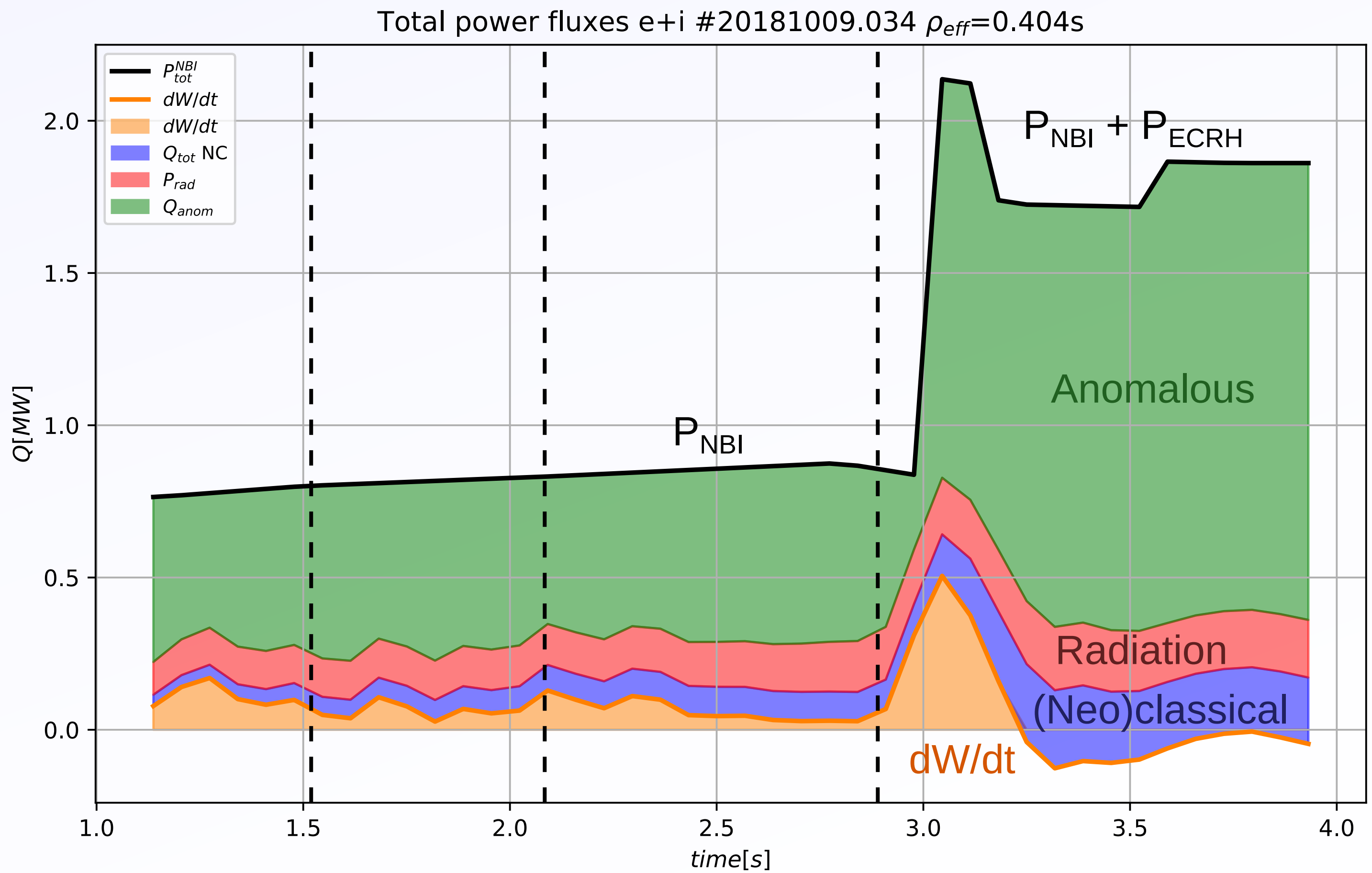

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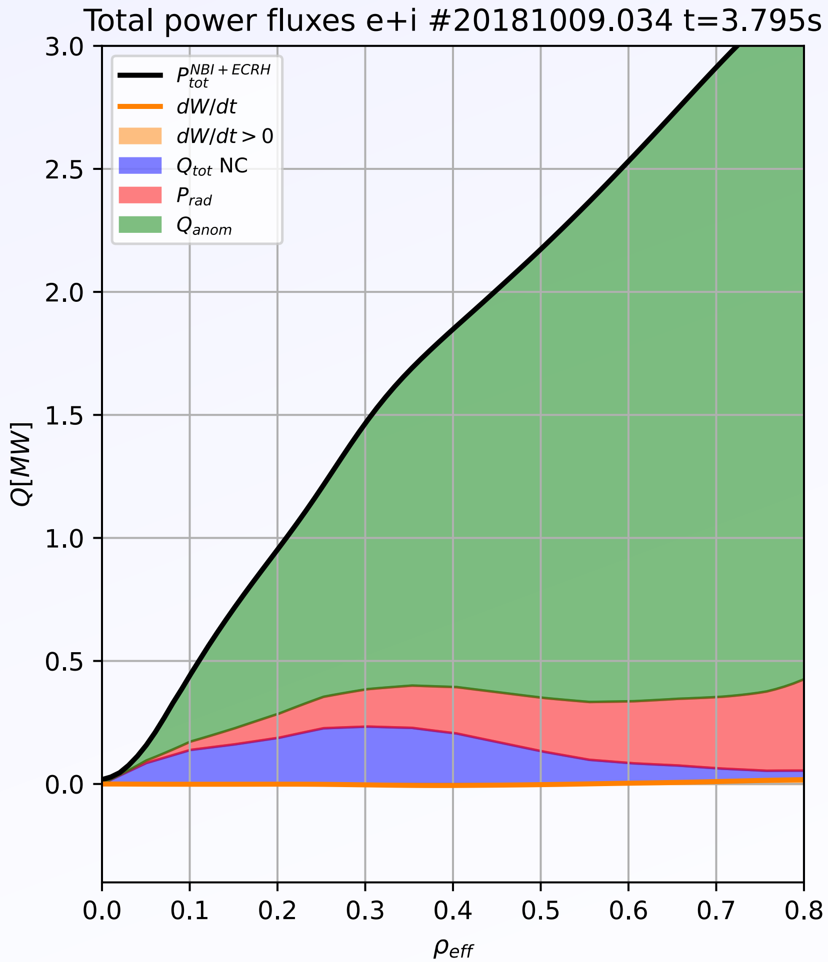
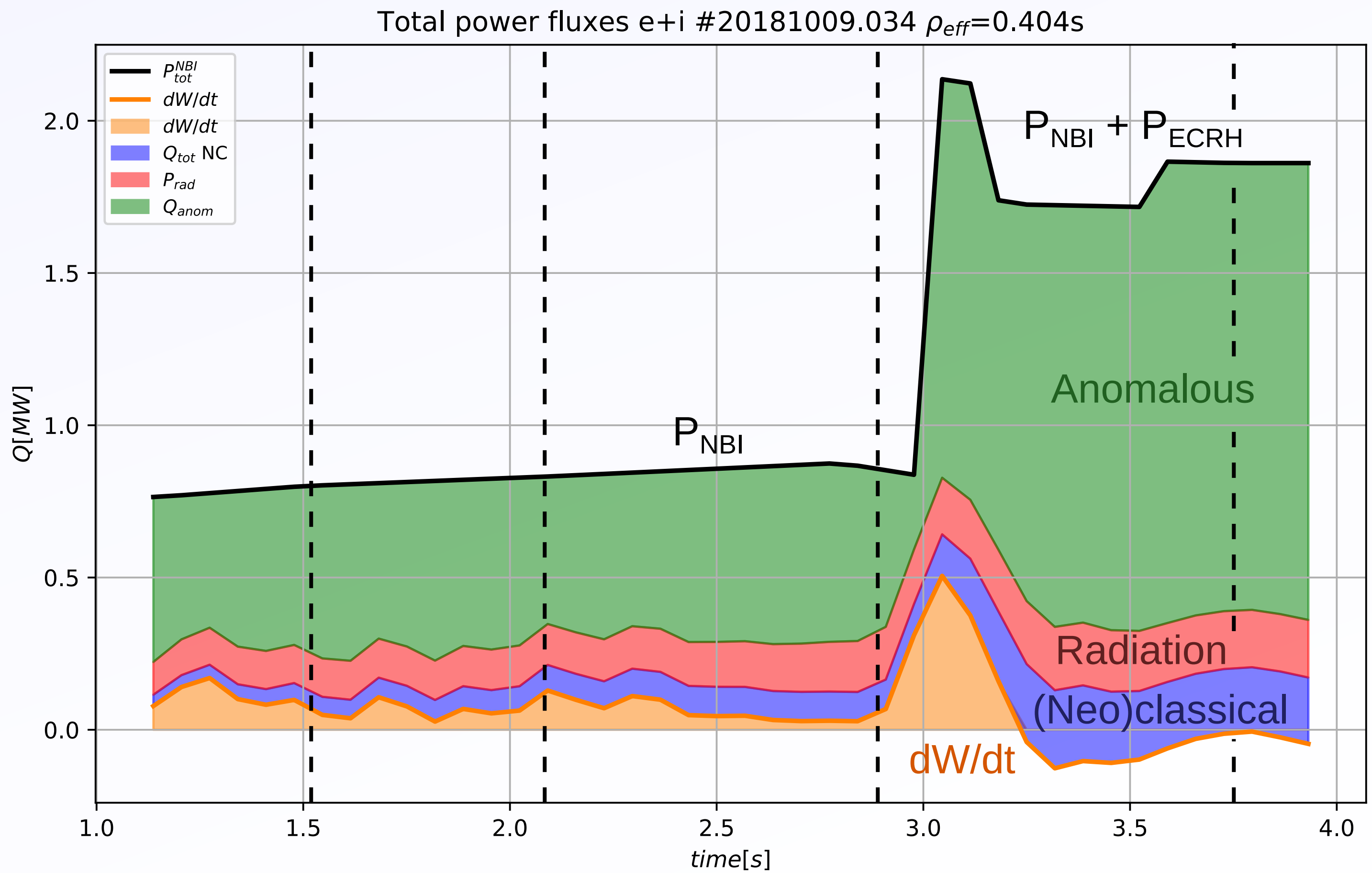
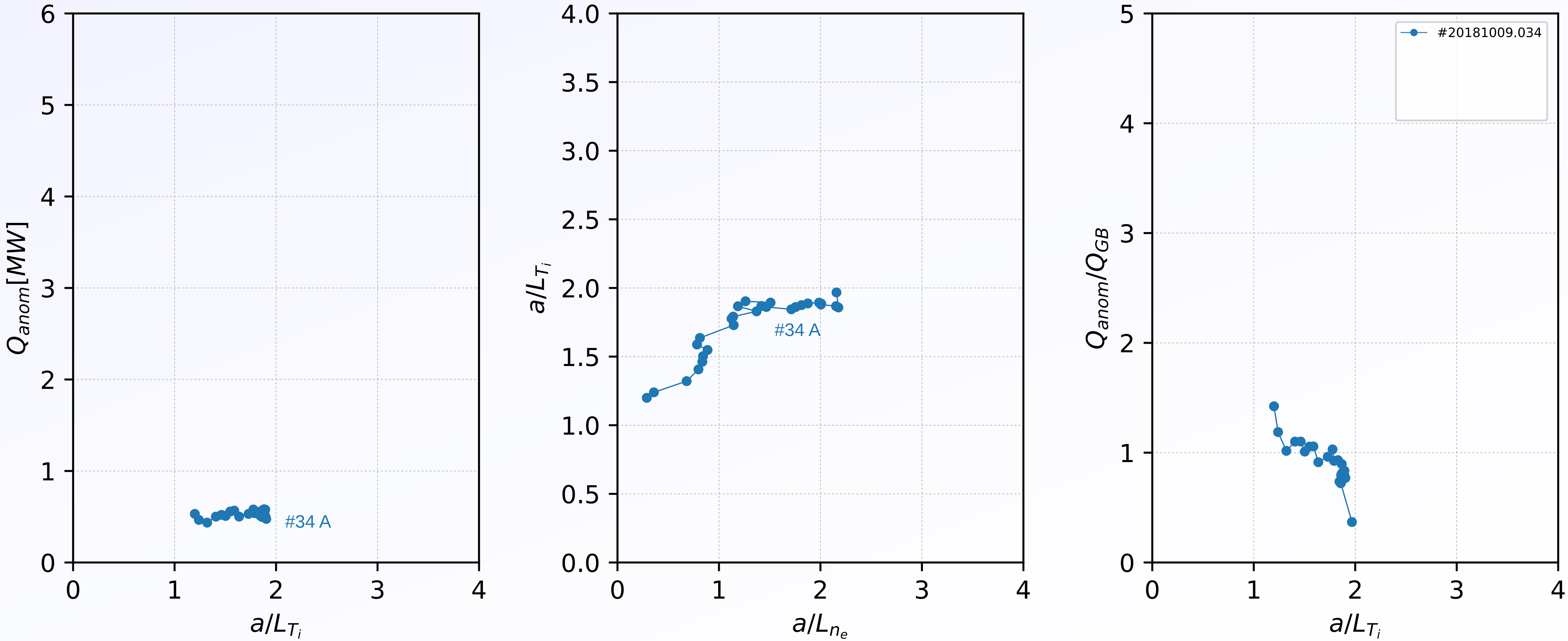




Total power flux

Over multiple shots, a pattern emerges:

#34: **A)** Pure NBI phase builds up density gradient.



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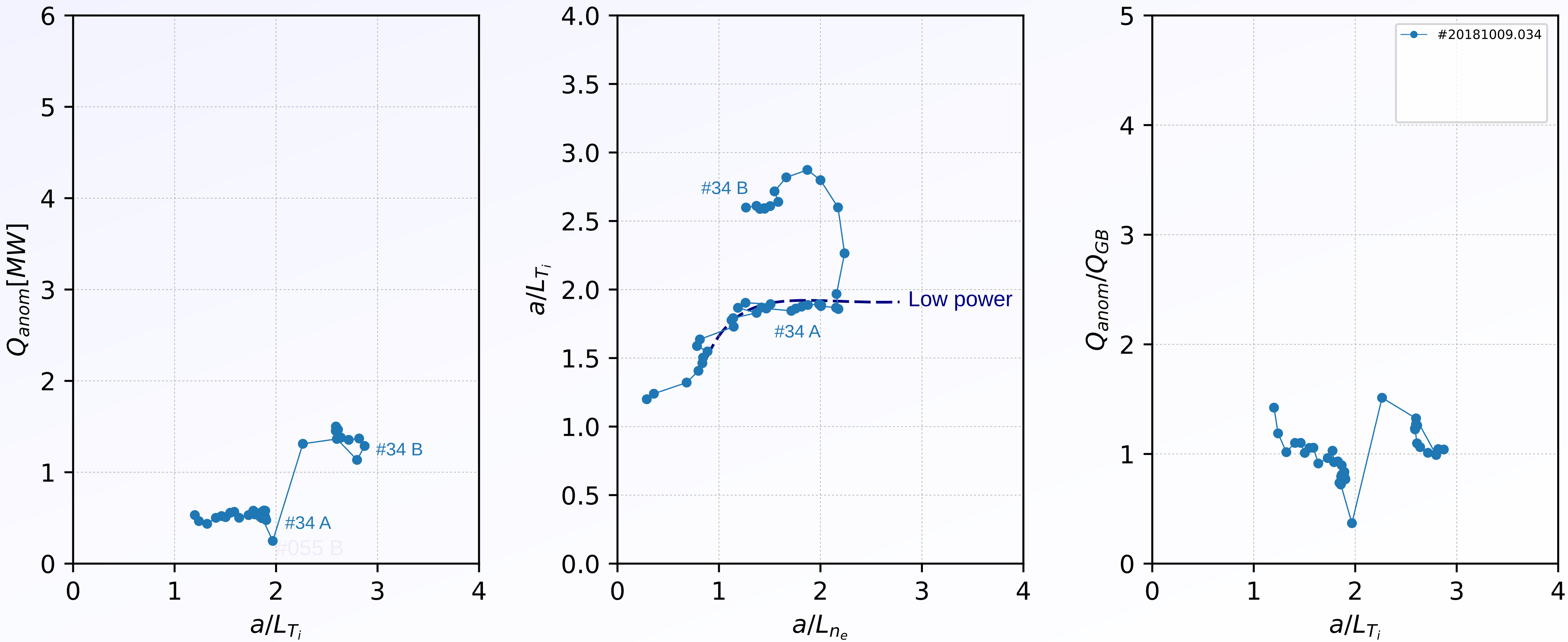

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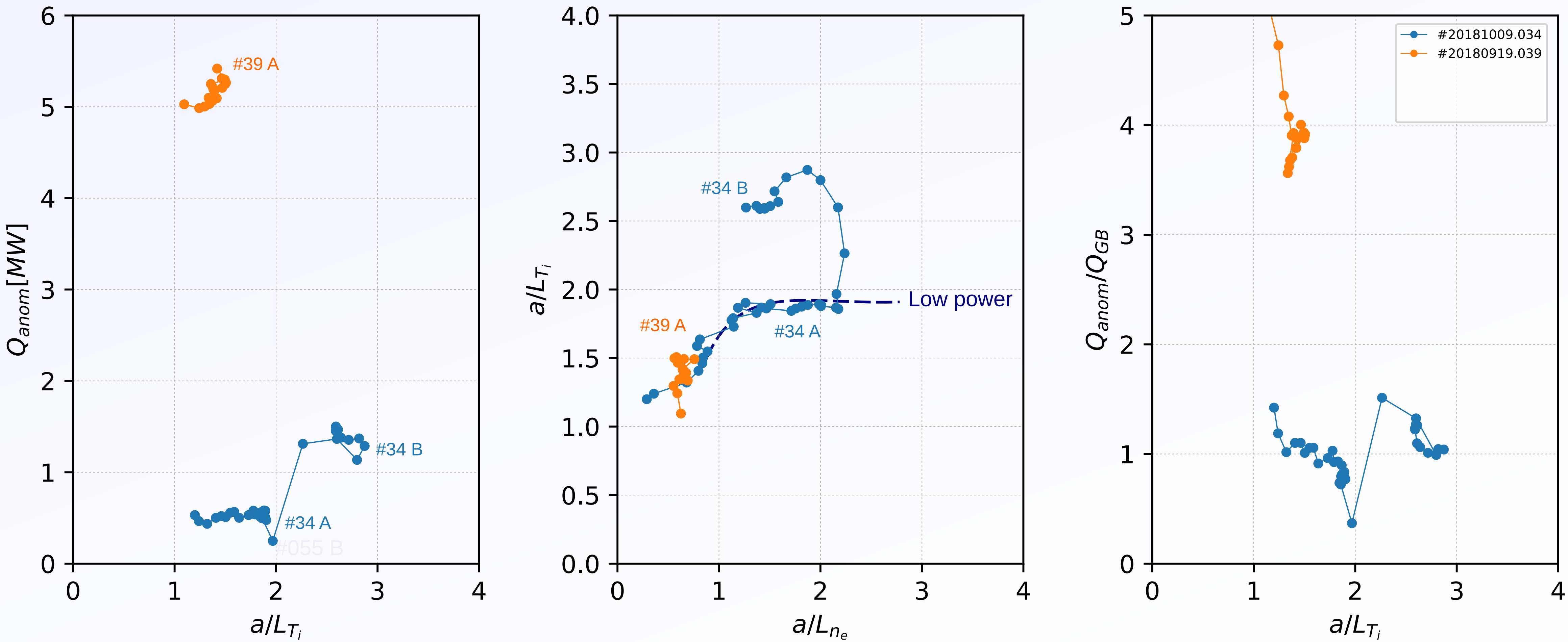

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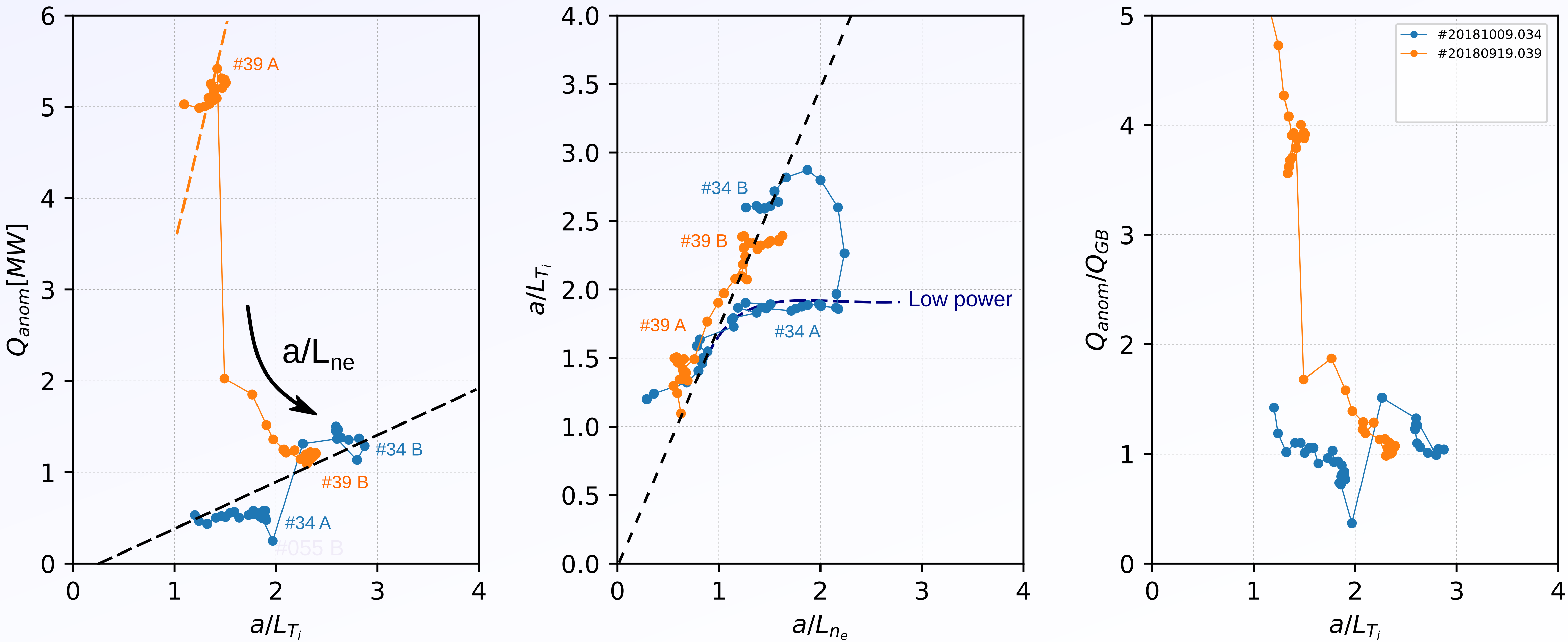

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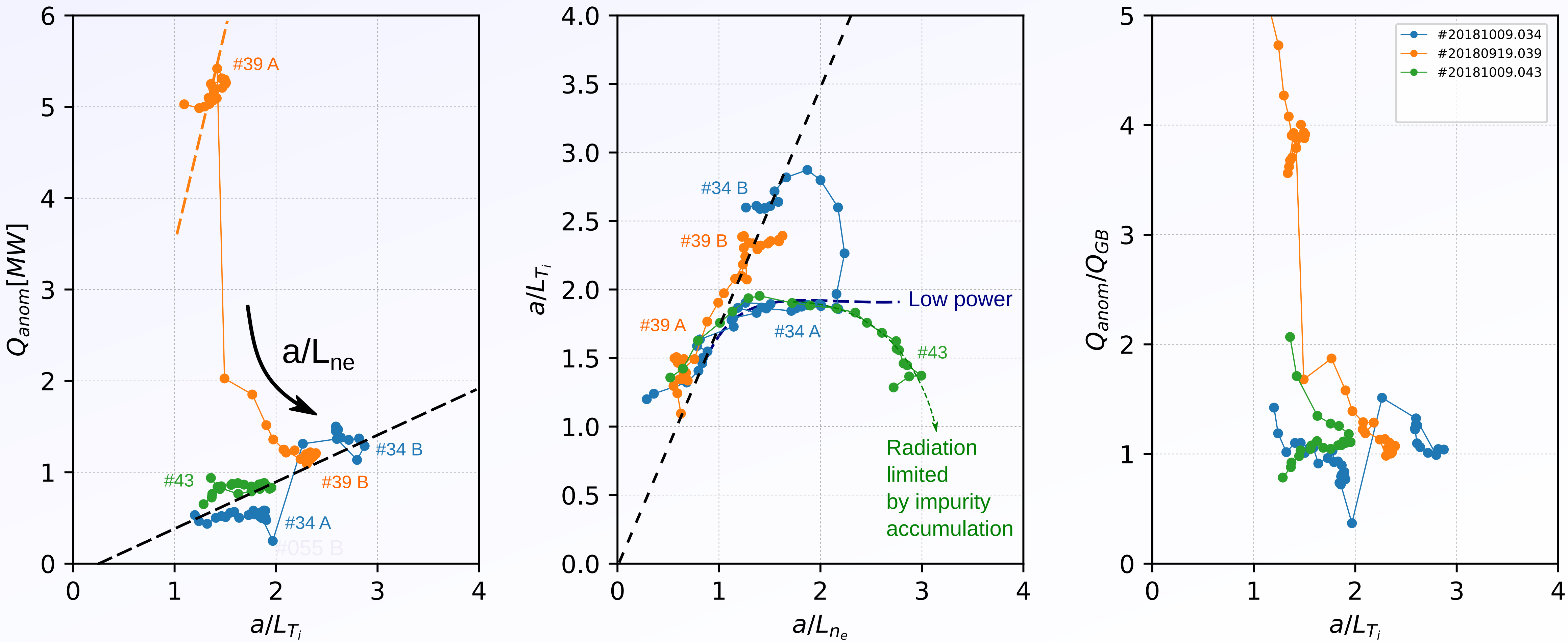
#43: Pure NBI - density gradient builds but power is low, so gyro-Bohm like transport alone limits ∇Ti.



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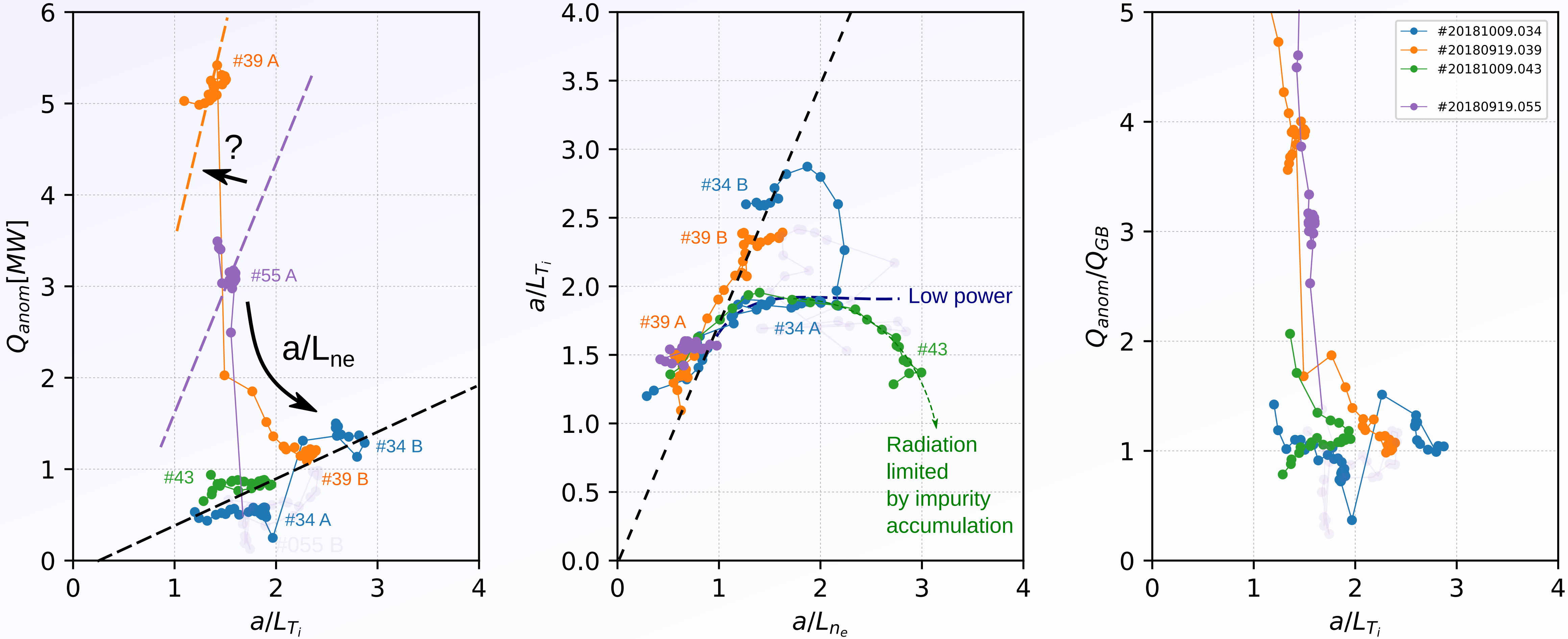

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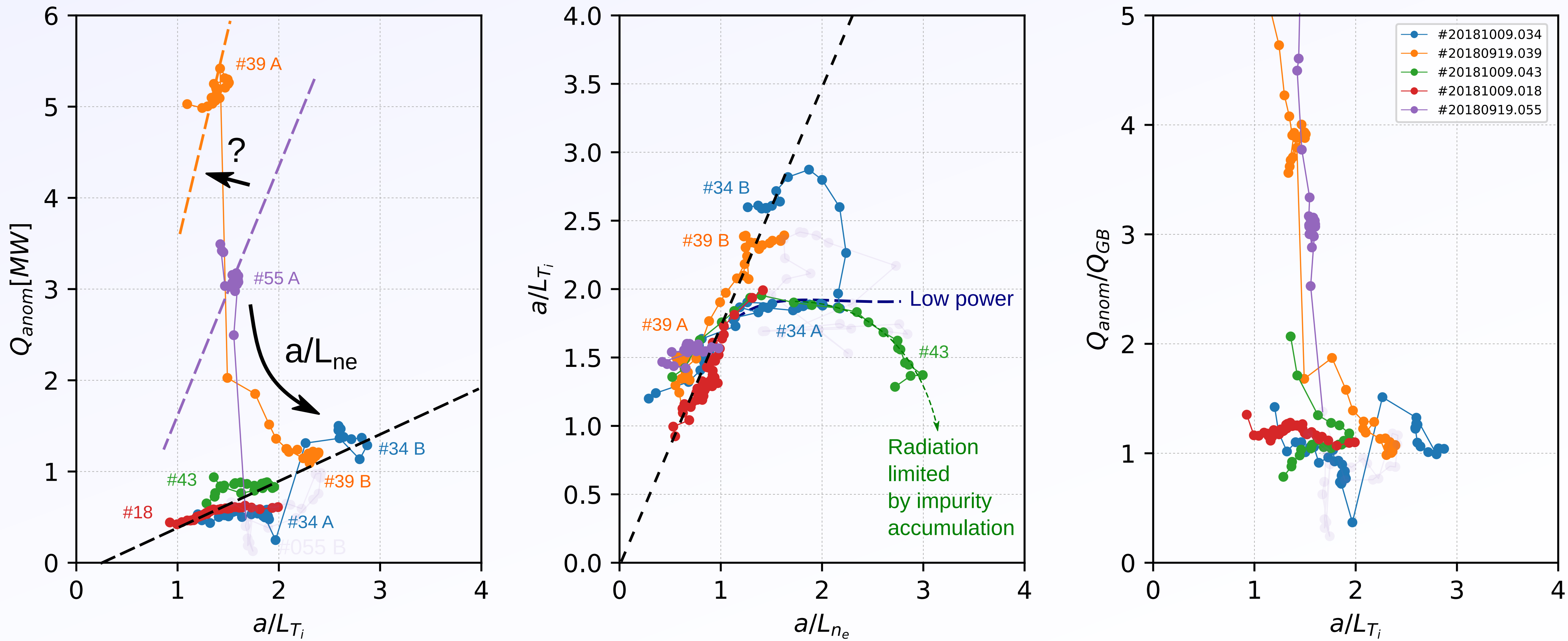
- #18: Pure NBI. Density gradient builds up late and power is not added.



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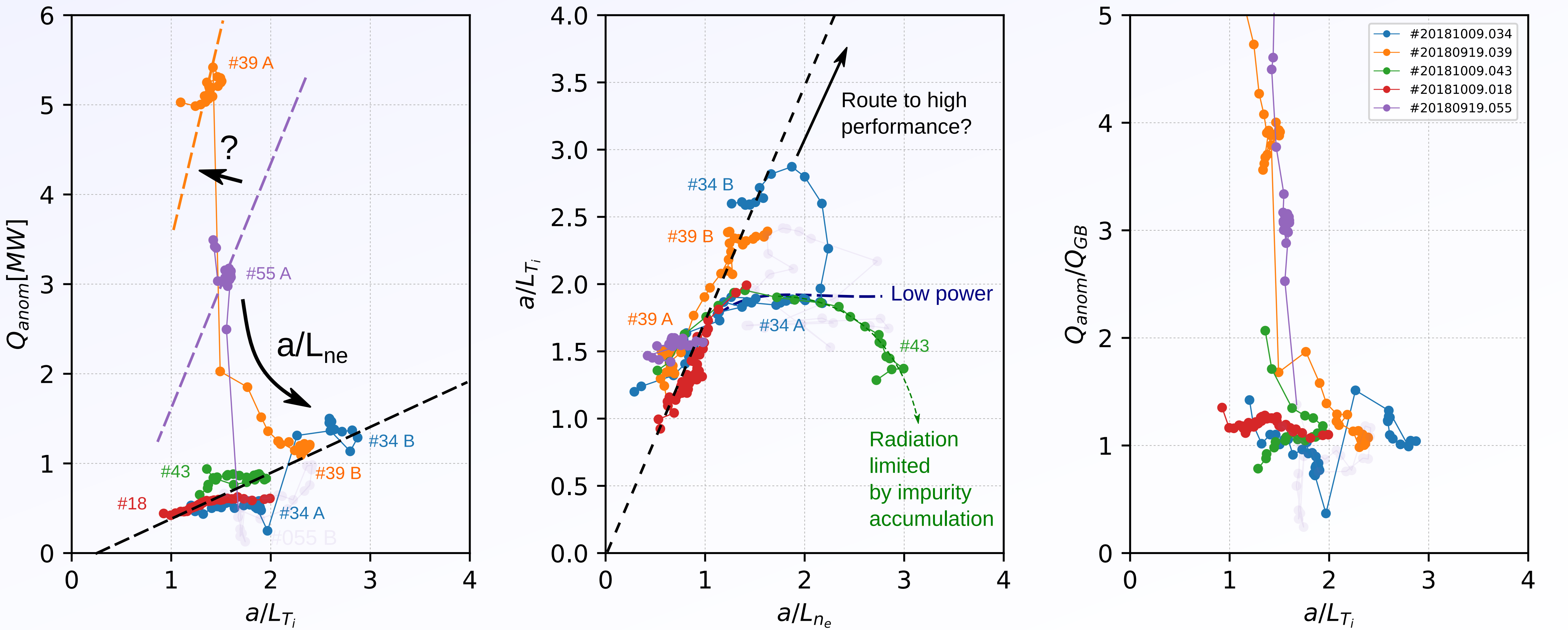
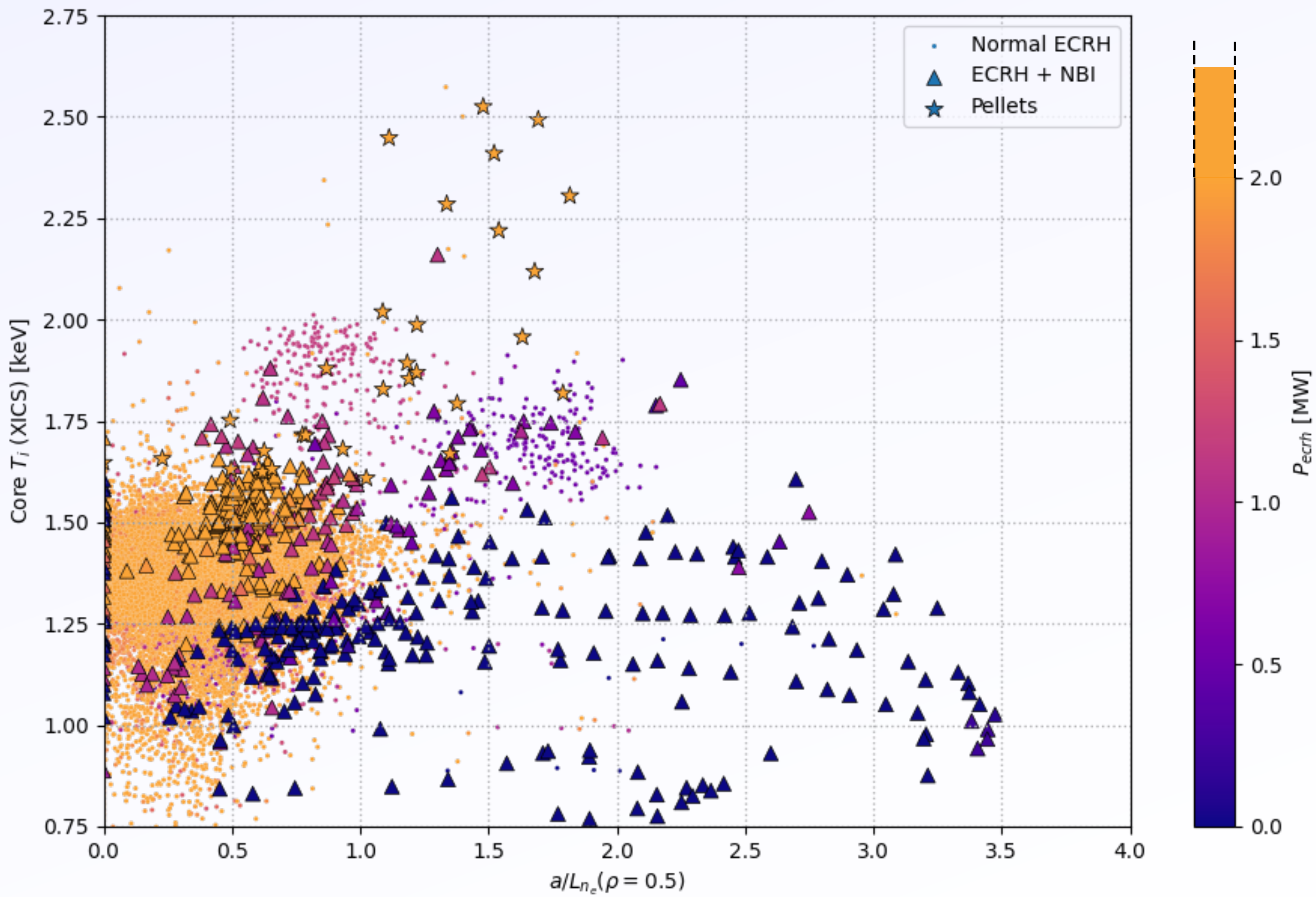


Confinement vs density gradient

This can also be seen in the global view:



Confinement vs density gradient

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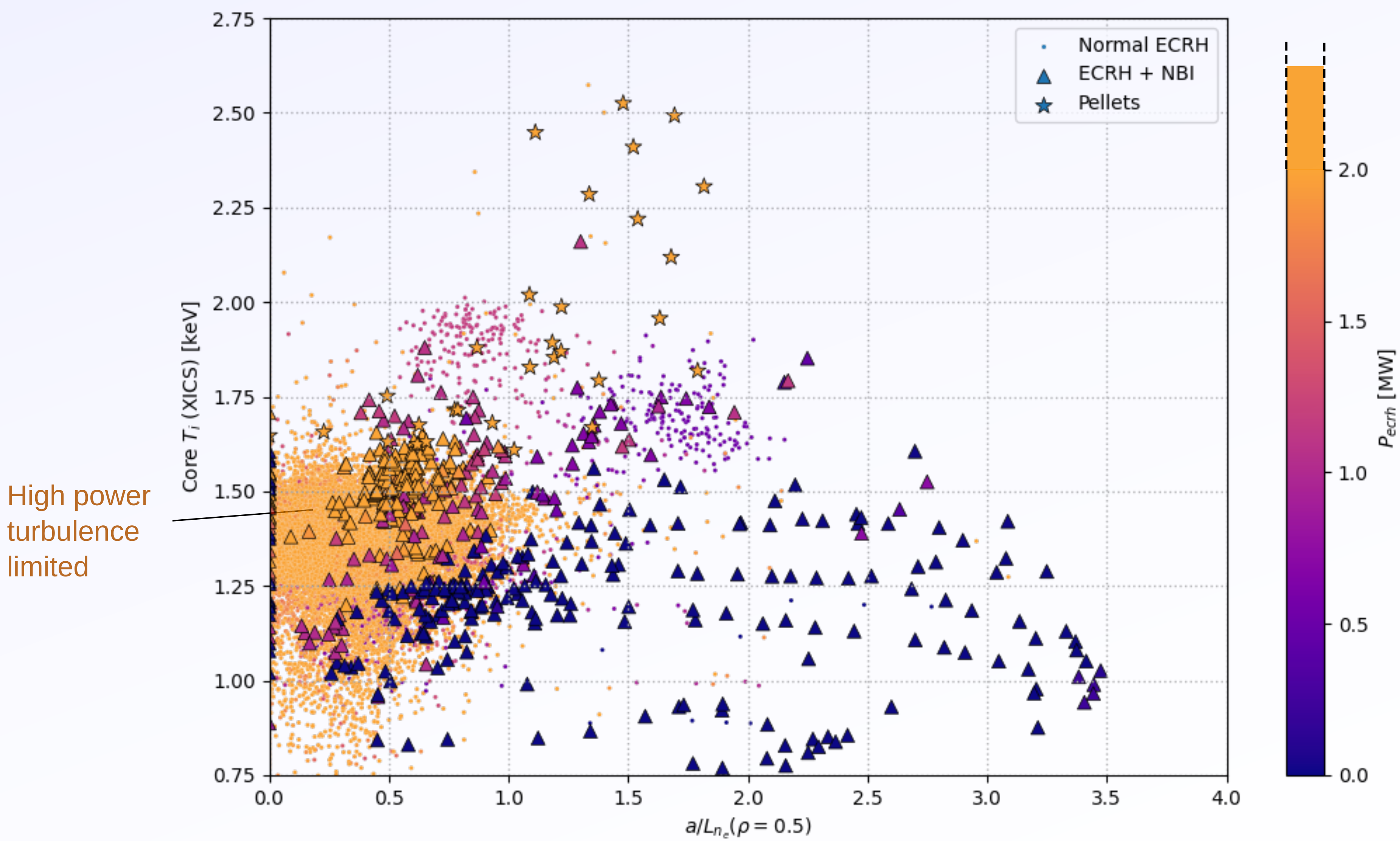

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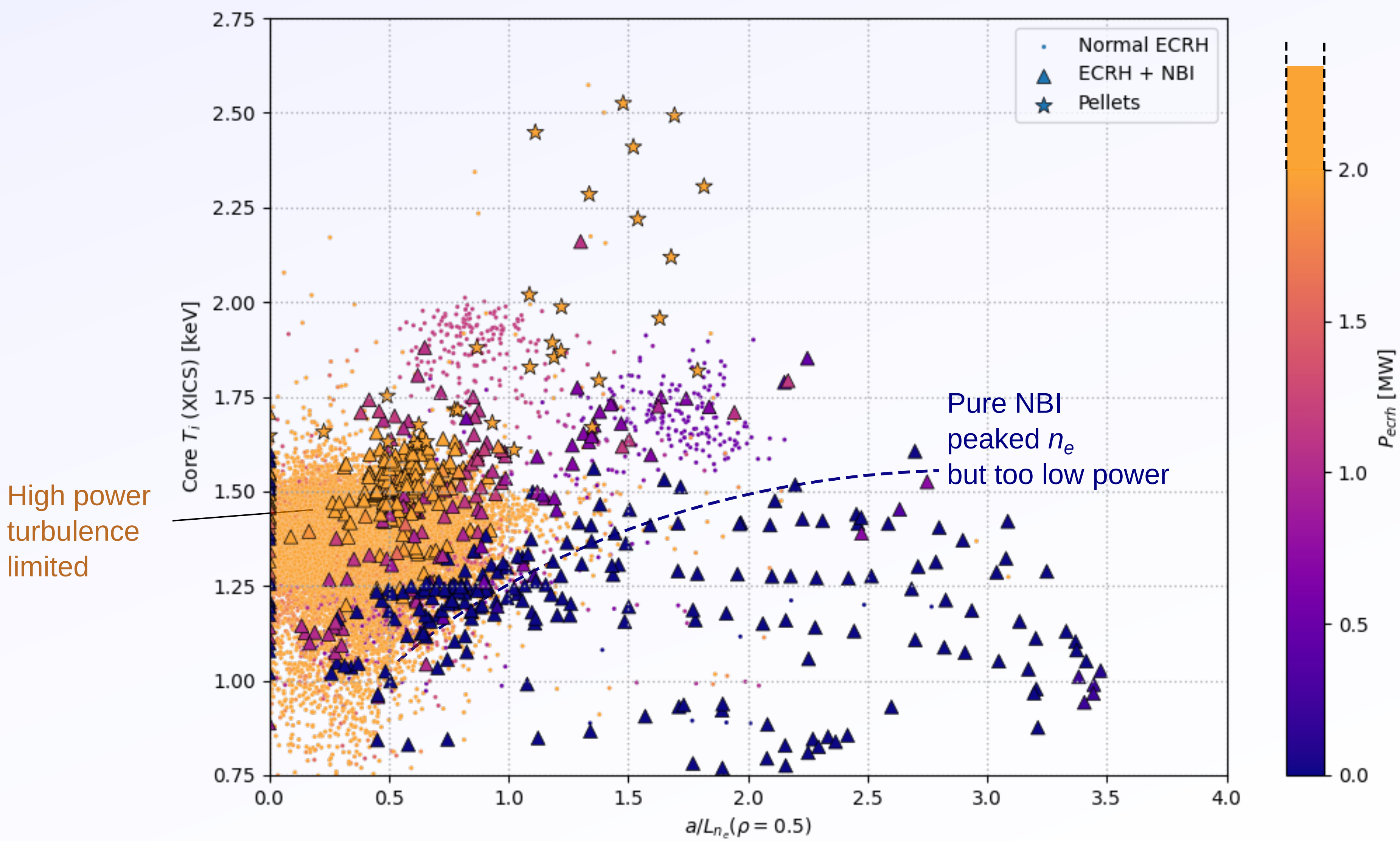

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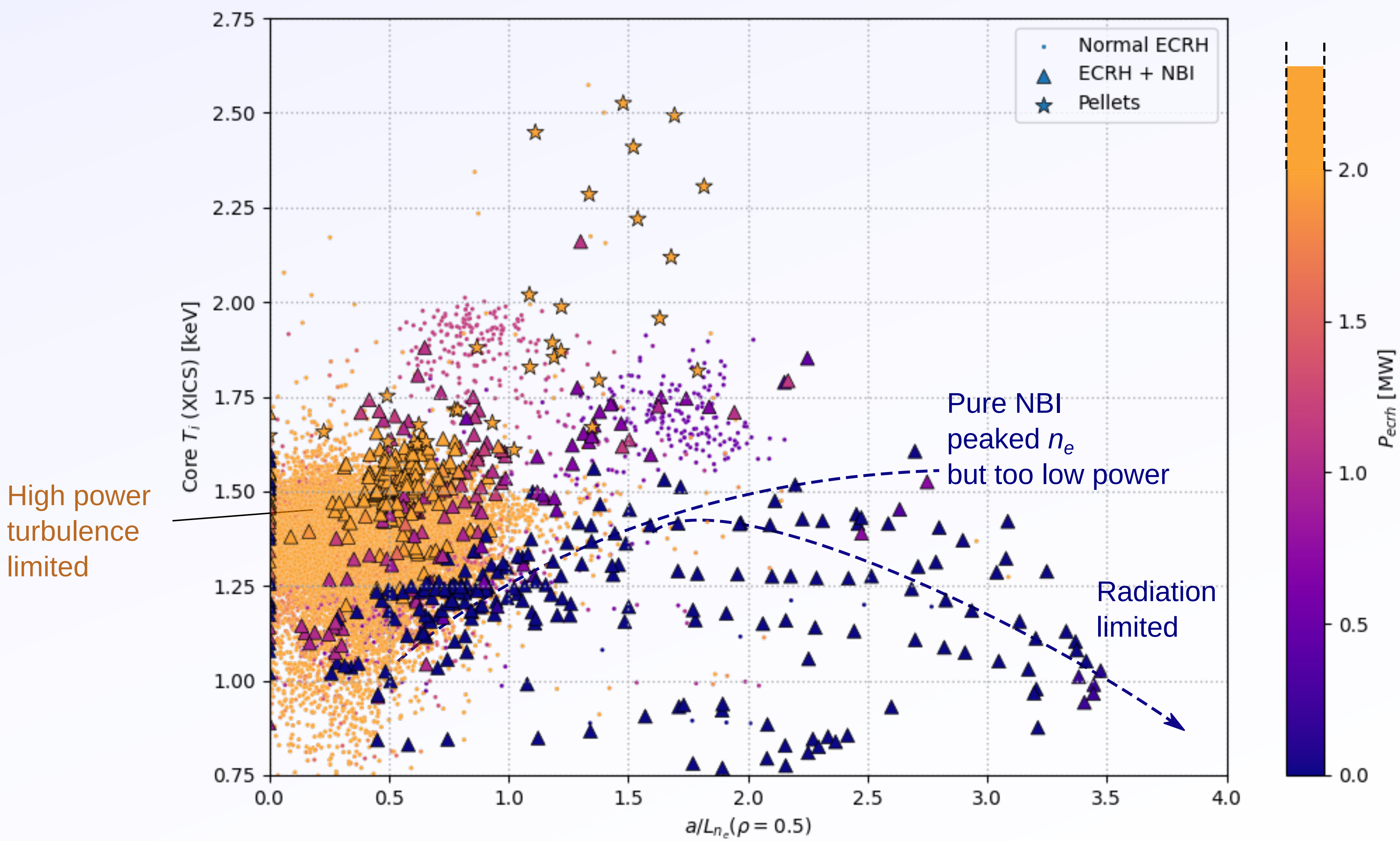
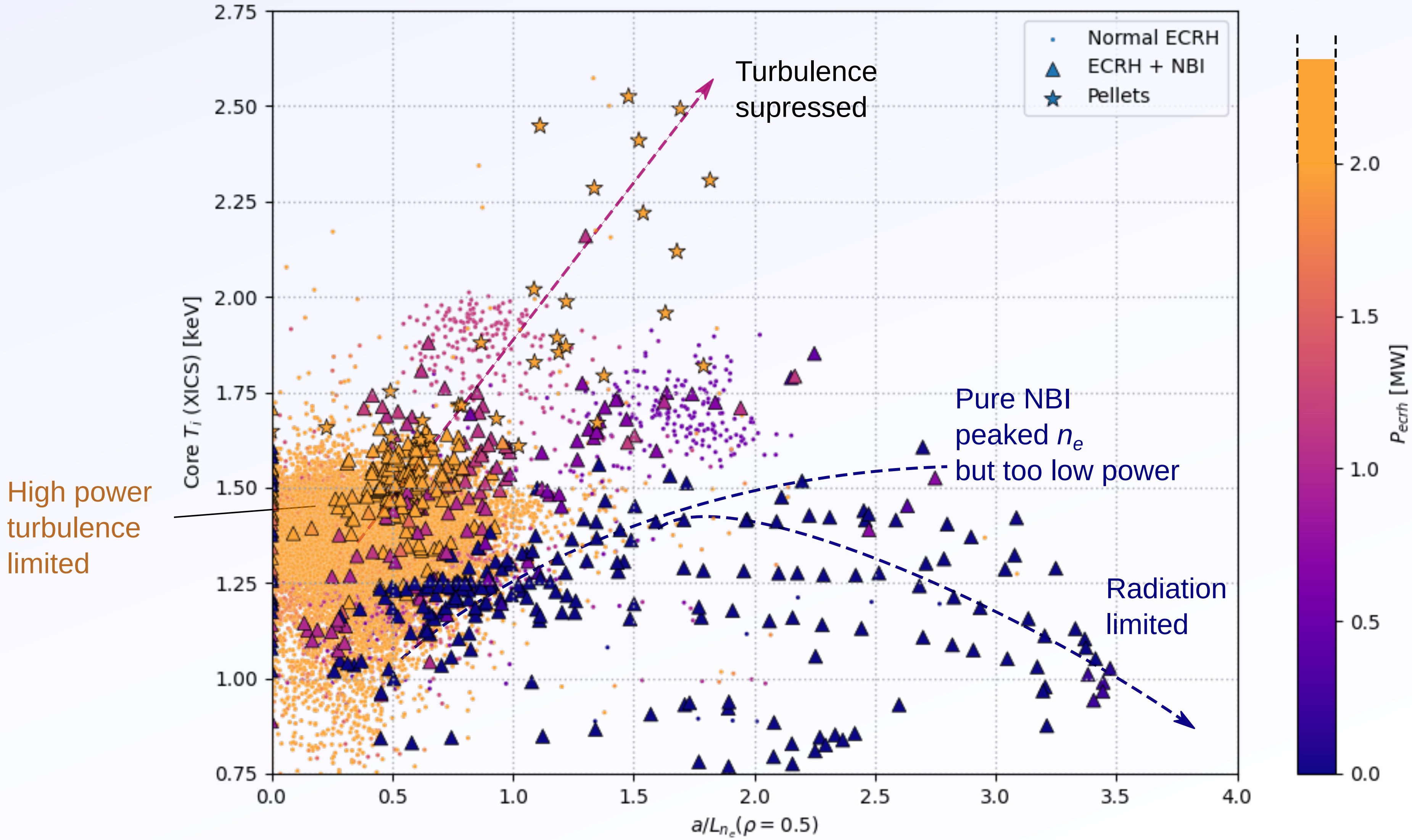


Confinement vs density gradient

This can also be seen in the global view:
- All higher a/L_{ne} discharges with a little ECRH move up towards post-pellets HP plasmas.



Confinement vs density gradient

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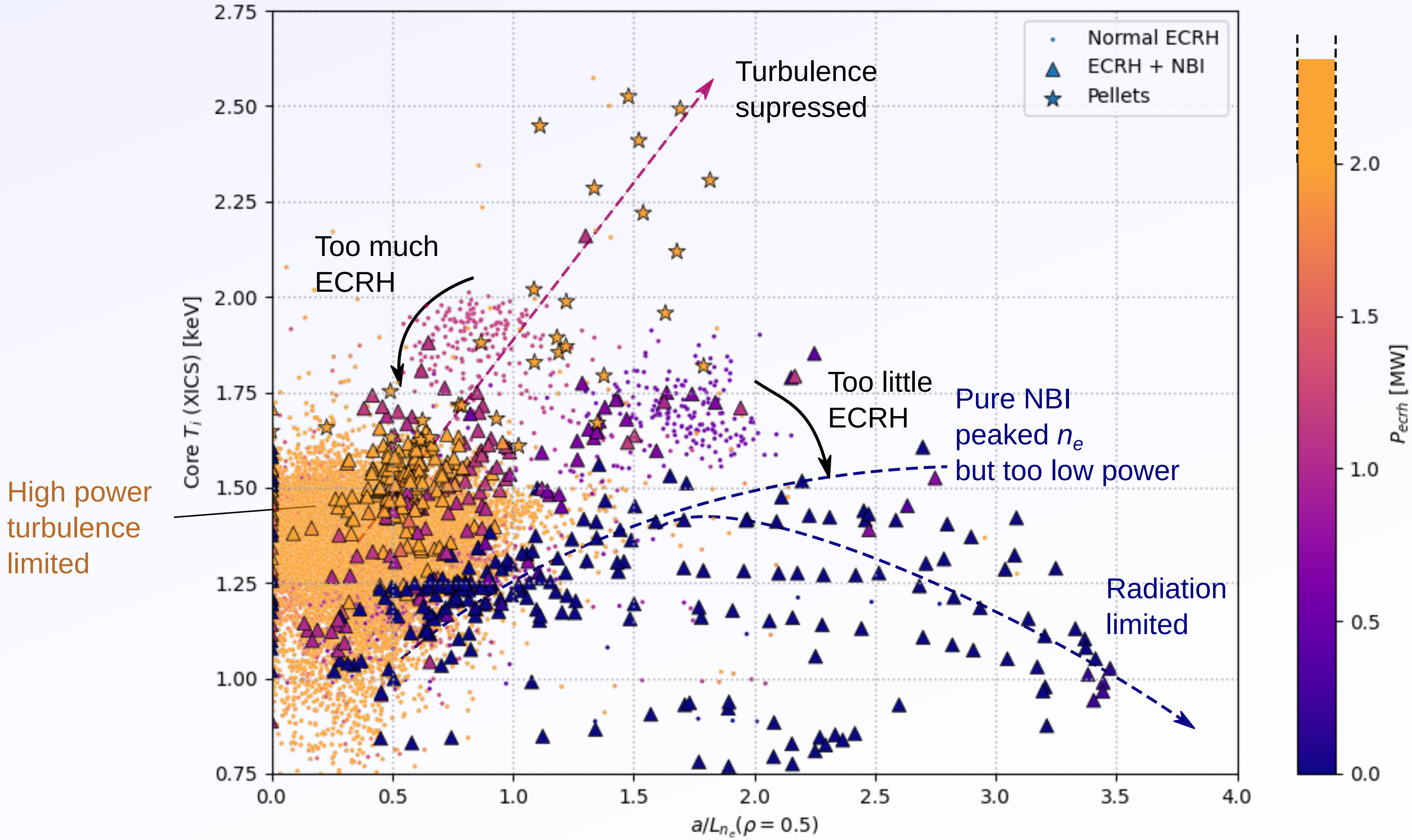
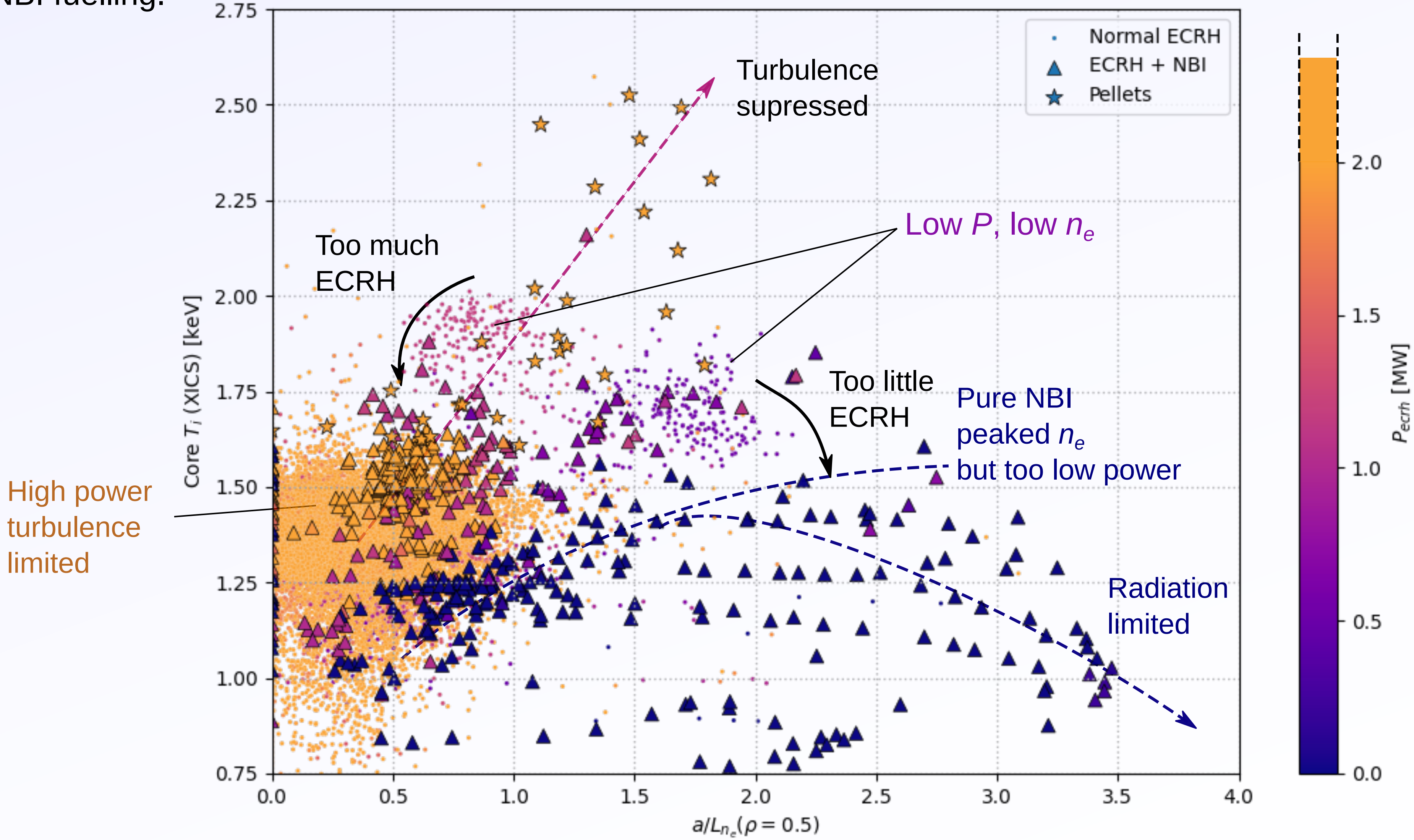


Confinement vs density gradient

This can also be seen in the global view:

- All higher a/L_{ne} discharges with a little ECRH move up towards post-pellets HP plasmas.
- Low P, low n_e shots without NBI show the same behaviour - denisty peaking most likely a transport effect and not from NBI fuelling.



Summary

Particle transport (in pure NBI only):
- Low net particle flux initially gives slow rise of core density.
- At a/L_{ne} ~ 0.8 anomolous particle flux at/inside rho=0.5 reduces dramatically --> density peaking + impurity accumulation.

Heat transport:
- Heat transport at low a/L_{ne} is consistent with high stiffness in ECRH-only plasmas.
- Heat transport at high a/L_{ne} is consistent with gyro-Bohm scaling.
- Pure NBI plasmas are limited by the input power --> More power initially gives higher Ti.
- In pure NBI plasmas, the radiation from impurity accumulation eventually kills the plasma.
- Too much power (at least with ECRH > ~1.2MW) reduces a/L_{ne} and heat transport degrades dramatically.
- There could be a strong Q_i barrier at mid-radius... interesting, but probably not very useful.
  --> Should we invest resources to measure it?

General:
- It *might* be possible to slowly increase the NBI and ECRH power together, such that $\eta_i = (a/L_{Ti} / a/L_{ne}) \sim 1.75$ is maintained and to follow this path *towards* the post-pellet plasma performance.

- Is it most critically important to understand when the extra ECRH power decreases a/L_{ne}.
  --> Study the turbulent particle transport!

Open questions

- What causes the low particle flux at $\rho < 0.5$ in (some) NBI discharges? Is this really density gradient?

- Is there really an ITB in Qi? (Although we probably shouldn't care)

- Why does high ECRH increase the core particle flux?

- What is the 'right amount' of ECRH to flush out impurities and control density rise?
  - If the ECRH needed to control impurities is already enough to lower *a/Lne*, then we cannot win.

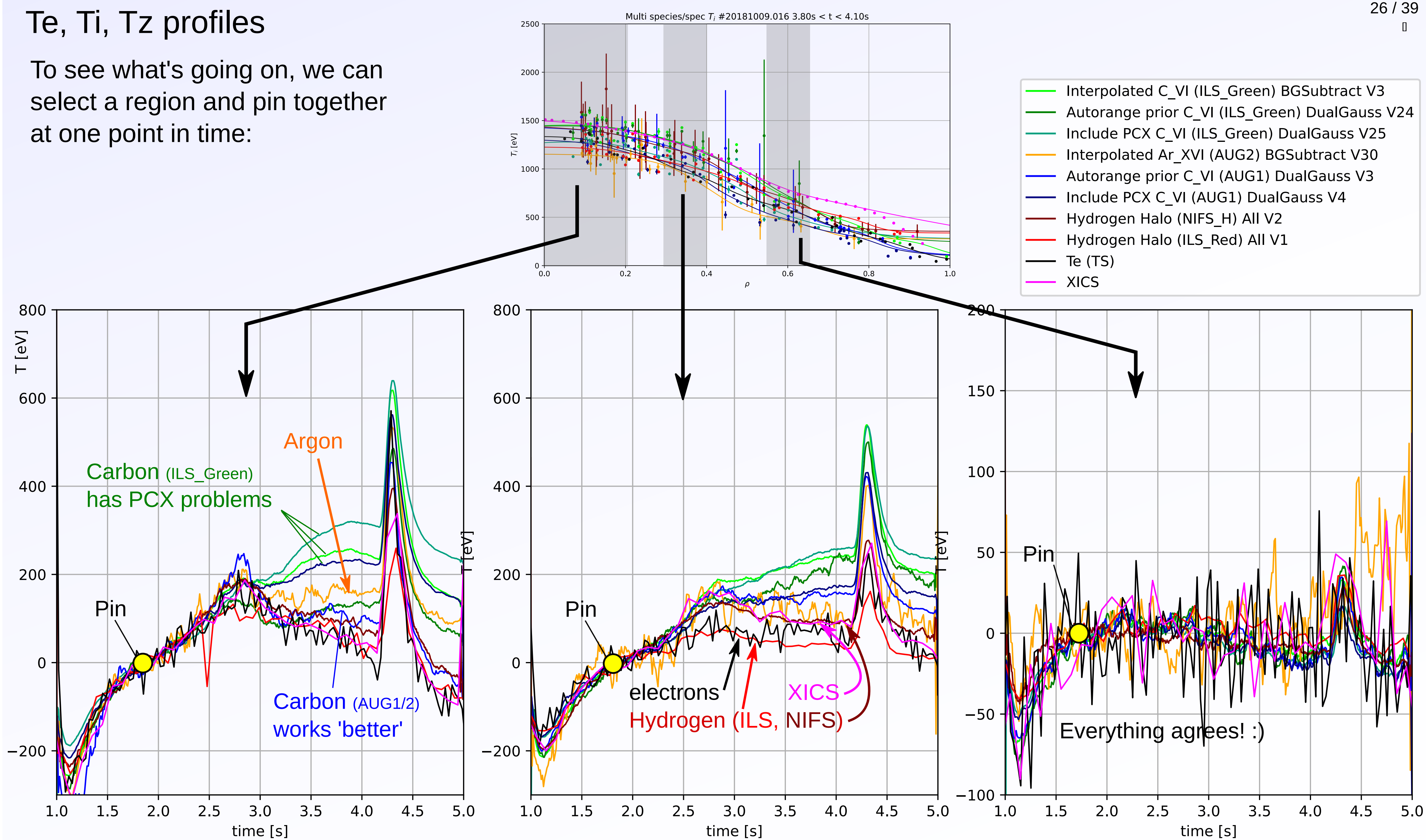
- What happens when we add more NBI?
  - If the particle fluxes do not increase: Add more ECRH, but this ok, because density gradient will remain. Great!
  - If particles fluxes increase: No way to add power without losing density gradient.

Study other things: beam current, momentum .... etc

Experiments for OP2:
Fine ECRH power steps at several NBI power steps to empirically map:
- Density peaking and flattening with ECRH
- Impurity explusion
- Profile stiffness at higher ECRH power and behaviour on the border.

Te, Ti, Tz profiles

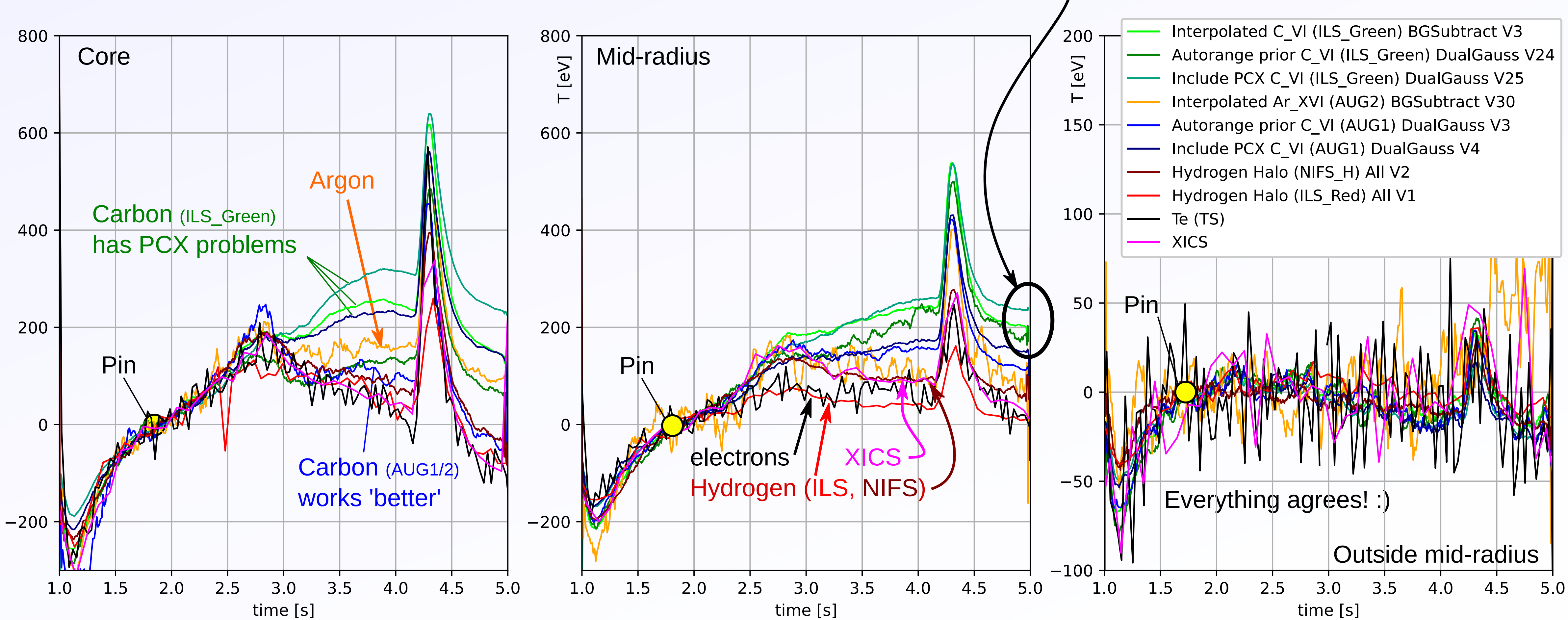
To see what's going on, we can select a region and pin together at one point in time:



Te, Ti, Tz profiles

Generally visible:

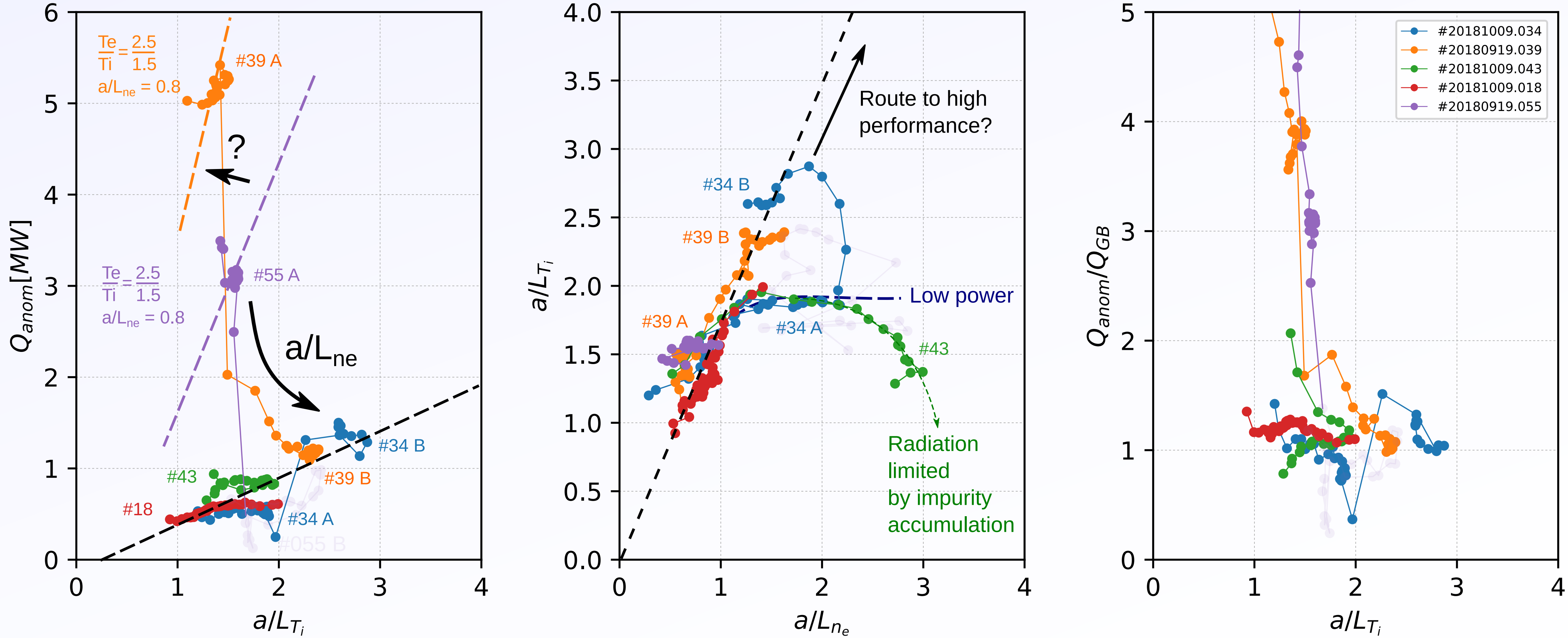
- Behaviour of T_e and T_i (hydrogen) mostly agree --> Expected as (Ti-Te) > ±50eV will lead to P_{ei} >> available power.
- All temperatues agree outside gradient region, and in the one case where peaking does not occur (#20181009.018)
- XICS Tz in very core seems to agree with Te,Ti, but maybe shows similar higher Ti in steepest gradient region near mid-radius.
- Passive CX .... is a big complication, but the doesn't quite seem to fit.
  e.g. one would expect the interpolated subtraction to work near end of NBI.



Total power flux

Over multiple shots, a pattern emerges:

- #34: **A)** Pure NBI phase builds up density gradient. **B)** ECRH is added to take advantage, a/L_{ne} drops only a little.
- #39: **A)** Initially high ECRH. **B)** Power step down to 1MW, density gradient develops, temperature gradient develops.
- #43: Pure NBI - density gradient builds but power is low, so gyro-Bohm like transport alone limits ∇Ti.
- #55: Initially high ECRH like #39 but for some reason same Te, Ti, n_e at less power...?
- #18: Pure NBI. Density gradient builds up late and power is not added.



...

...

Total power balance

We can ignore P_{ei} and examine the balance of Q_{total}:

- Dominated by anomolous transport at all time points for $\rho >= 0.3$.
- Both radiation and (neo)classical transport are small but significant (classical ~ 20% x neoclassical).
- Significant increase in anomolous transport with ECRH.
- Possibly a very weak sign of very small temporary decrease in heat transport coincident with particles.