OP1.2 NBI analysis status and physics results

Eurofusion fast-ions workshop 2021

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2: Aalto University, Espoo, Finland
3: Princeton Plasma Physics Laboratory, Princeton, US

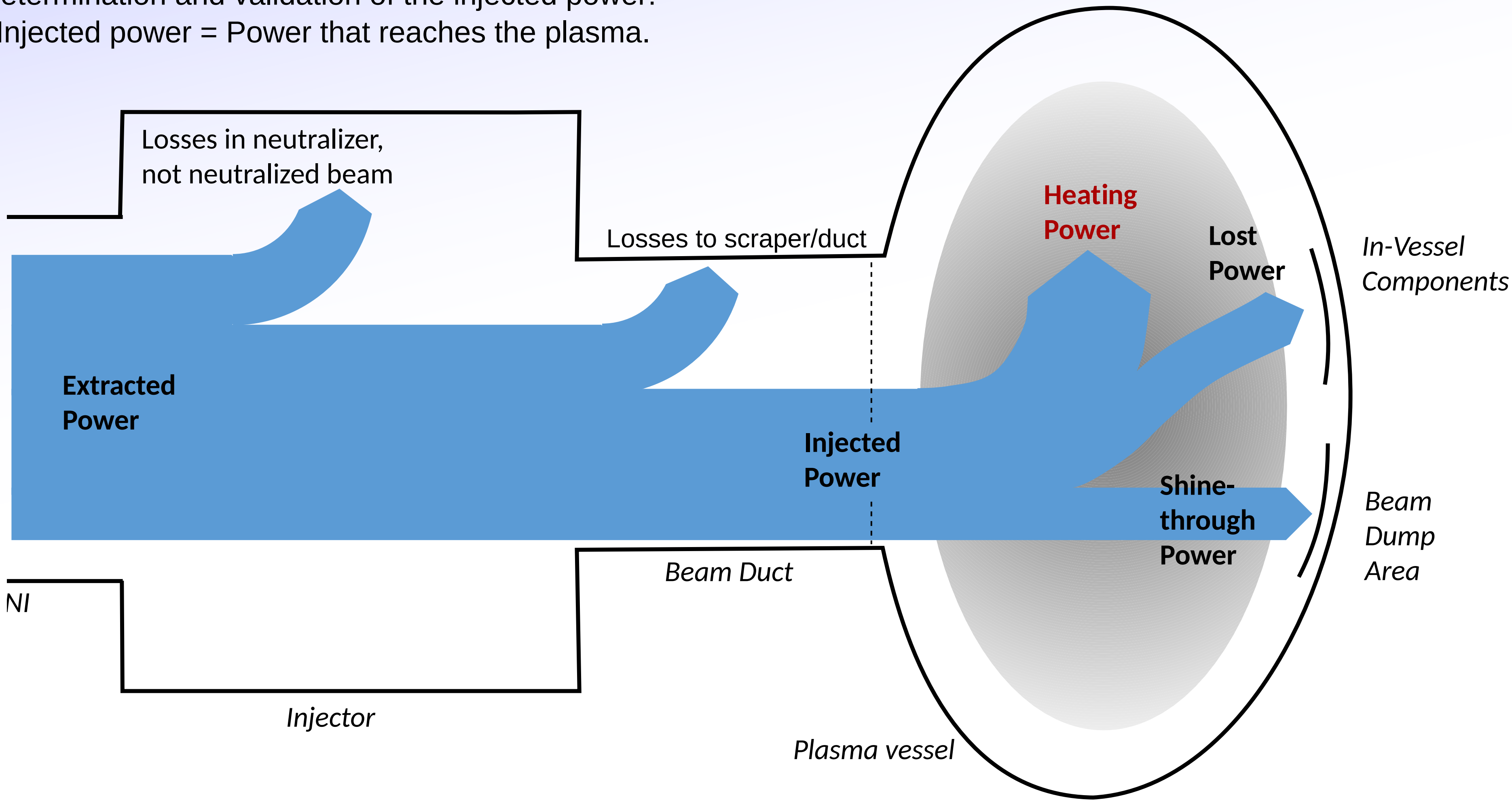
Outline:

1) Status report

2) Observational results from OP1.2

Injected Power

Determination and validation of the injected power:
Injected power = Power that reaches the plasma.



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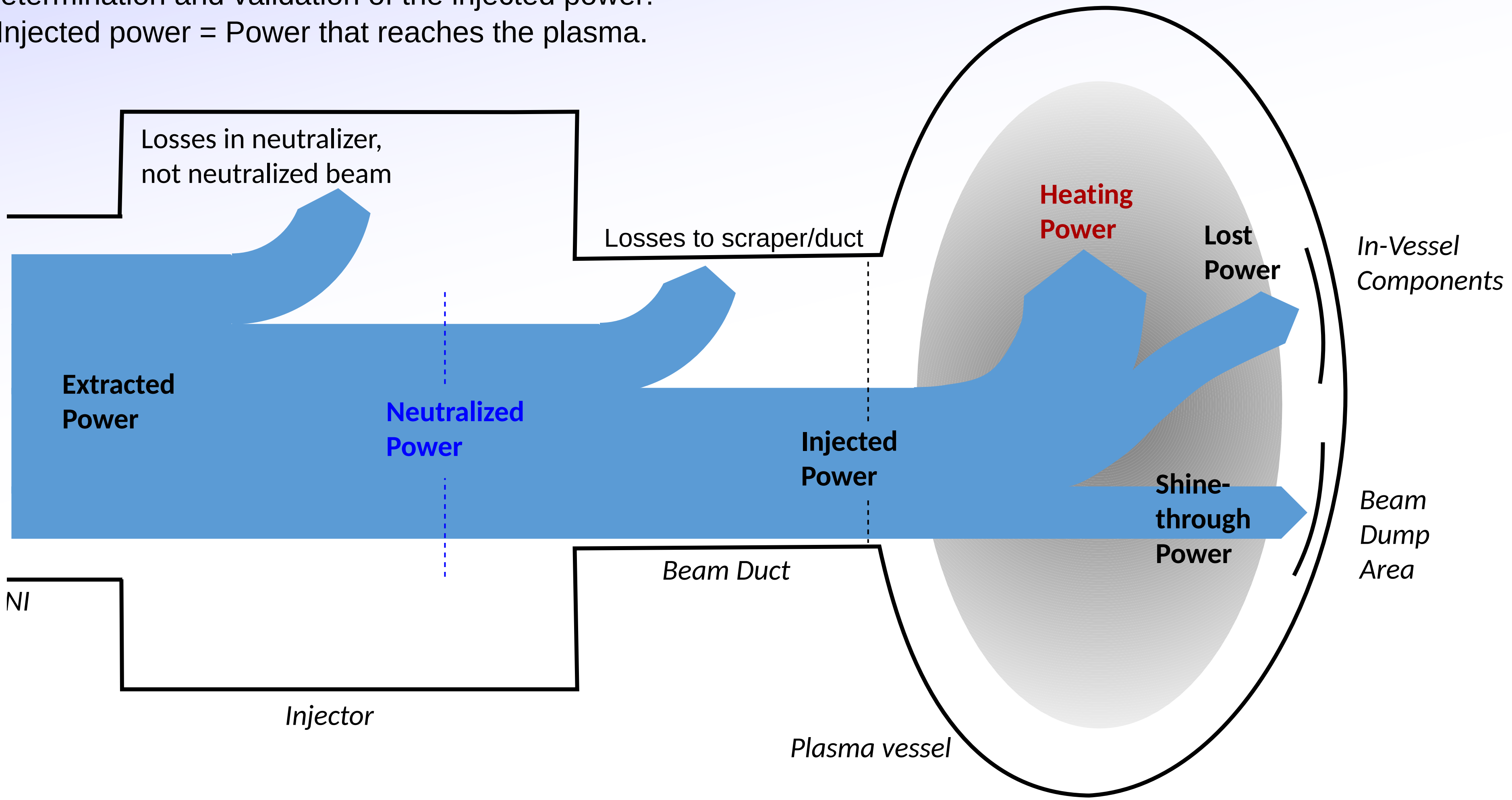

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We can measure:
Calorimeter --> Neutralised power for non-plasma shots

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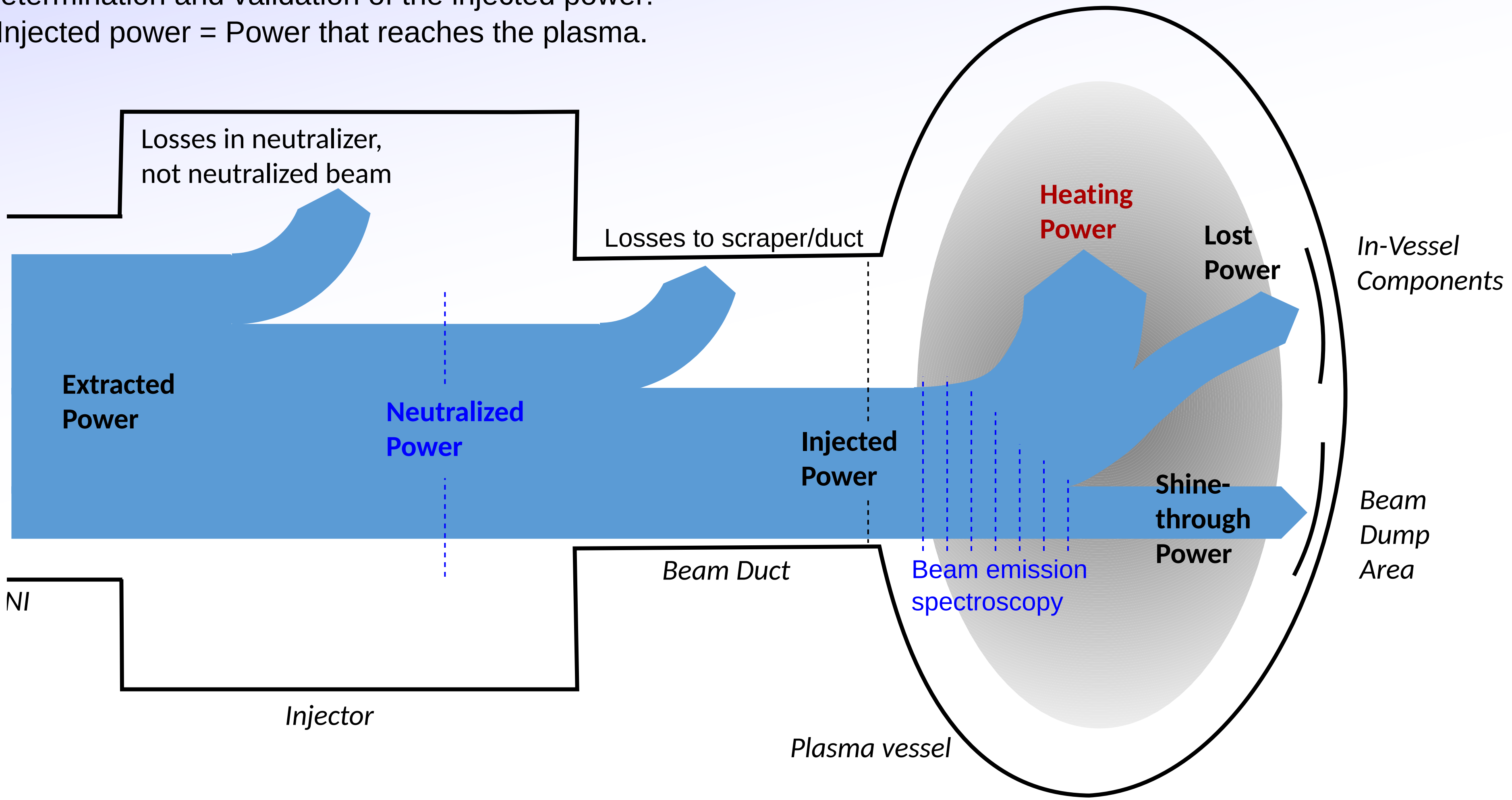
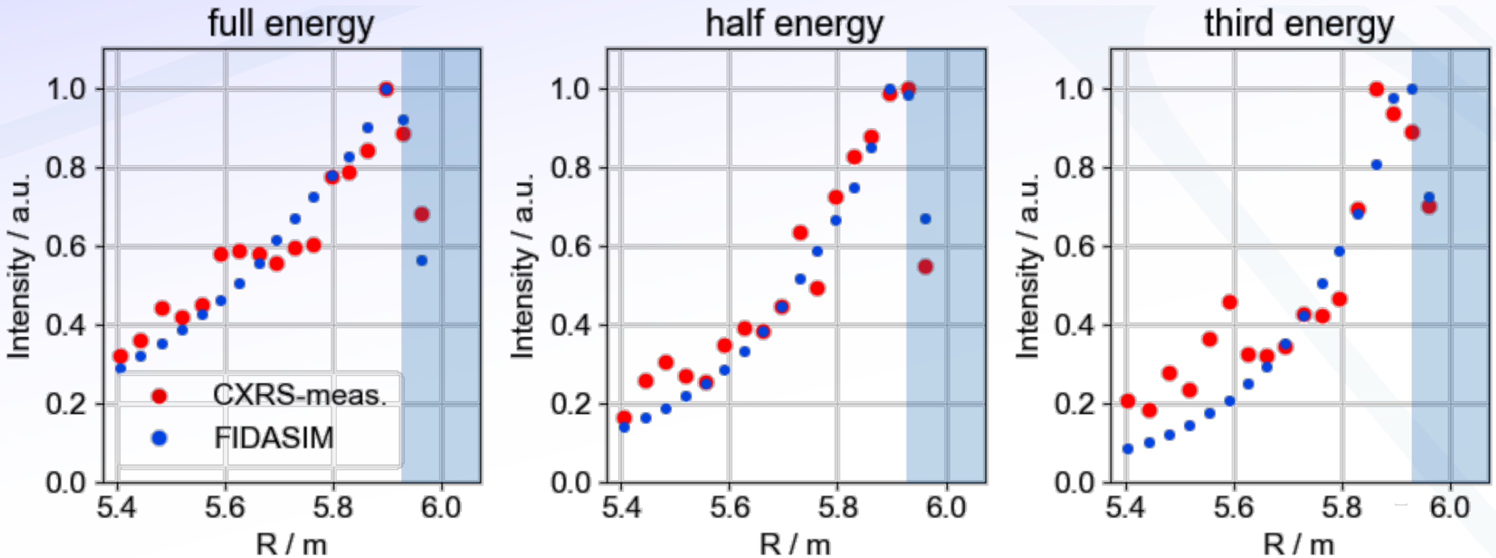


We want: **Heating power** = Power passed to thermal electron/ion population in the plasma.
We can measure:

- **Calorimeter** --> Neutralised power for non-plasma shots
- **Beam emission spectroscopy** --> Profile of power remaining in the beam.

Injected Power

P. Poloskei - Simulation of BES spectrum with FIDASim --> Match input power to absolute spectrum



[A. Spanier, "Performance of the first neutral beam injector at the Wendelstein 7-X stellarator", https://doi.org/10.1016/j.fusengdes.2020.112115]

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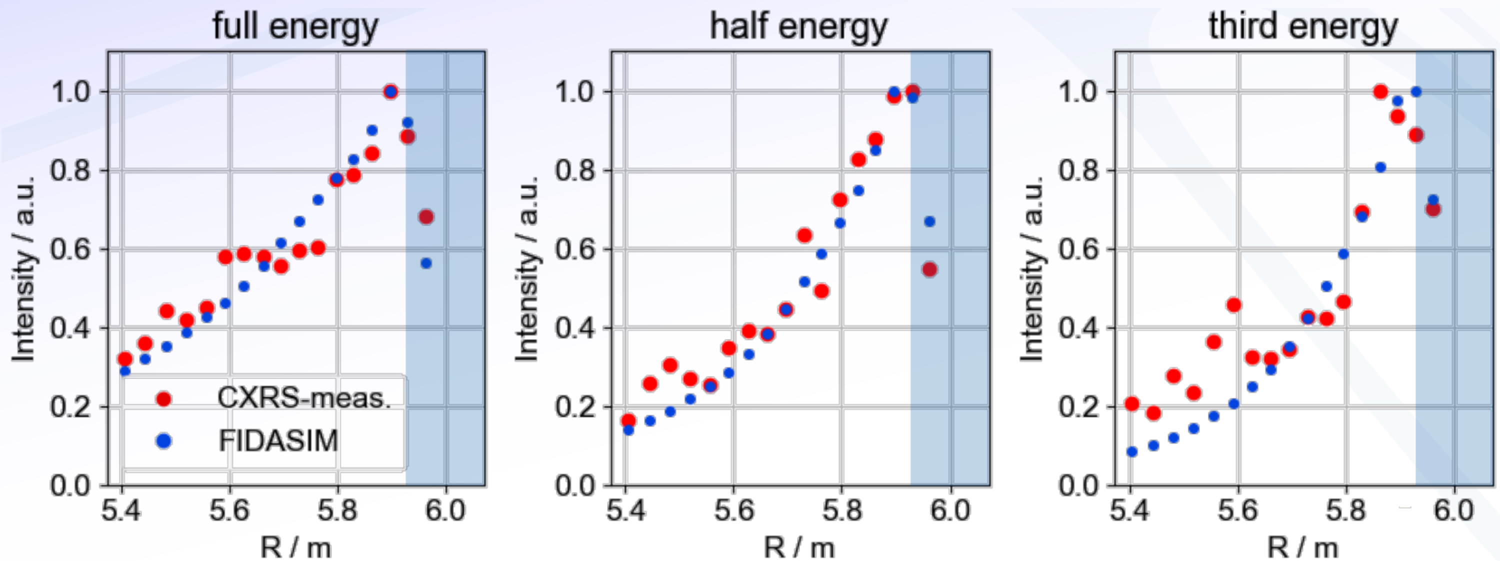


A. Spanier - Analysis of calorimetry in NBI box, subtracting shinethrough from calorimetry of beam dump.

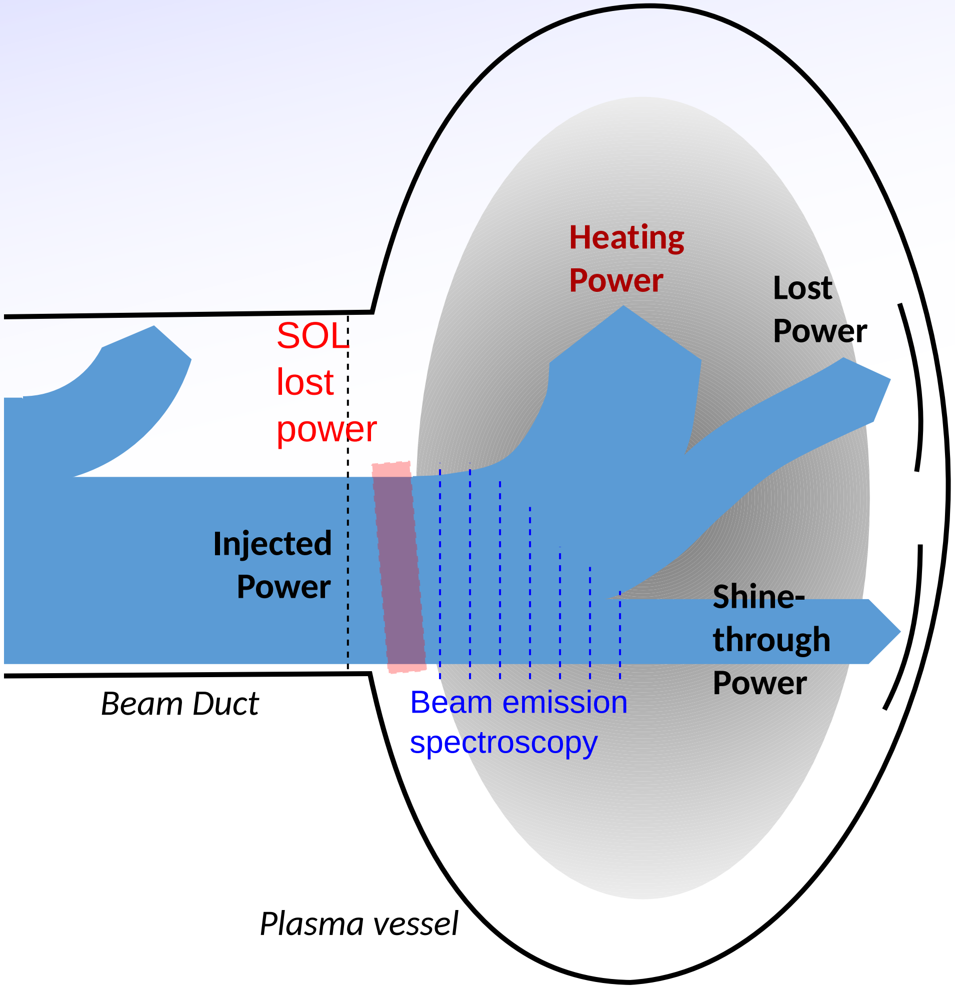
	20180823/037		20181009/016*		
	Flat density (ECRH)		Peak density (Pure NBI)		
E_0 / keV	48.0		54.6		
Neutral fractions	0.32/0.61/0.07		0.3/0.5/0.2		
	Calorimetry	Beam emission	Calorimetry	Beam emission	
P_{torus} / MW	2.7	2.6	3.1	2.8	
P_{dump} / MW	0.29	0.26	0.21	0.34[1]	0.16[2]
P_{NBI} / MW	**2.41 ± 0.24**	**2.34 ± 0.23**	**2.89 ± 0.29**	**2.55 ± 0.26**	

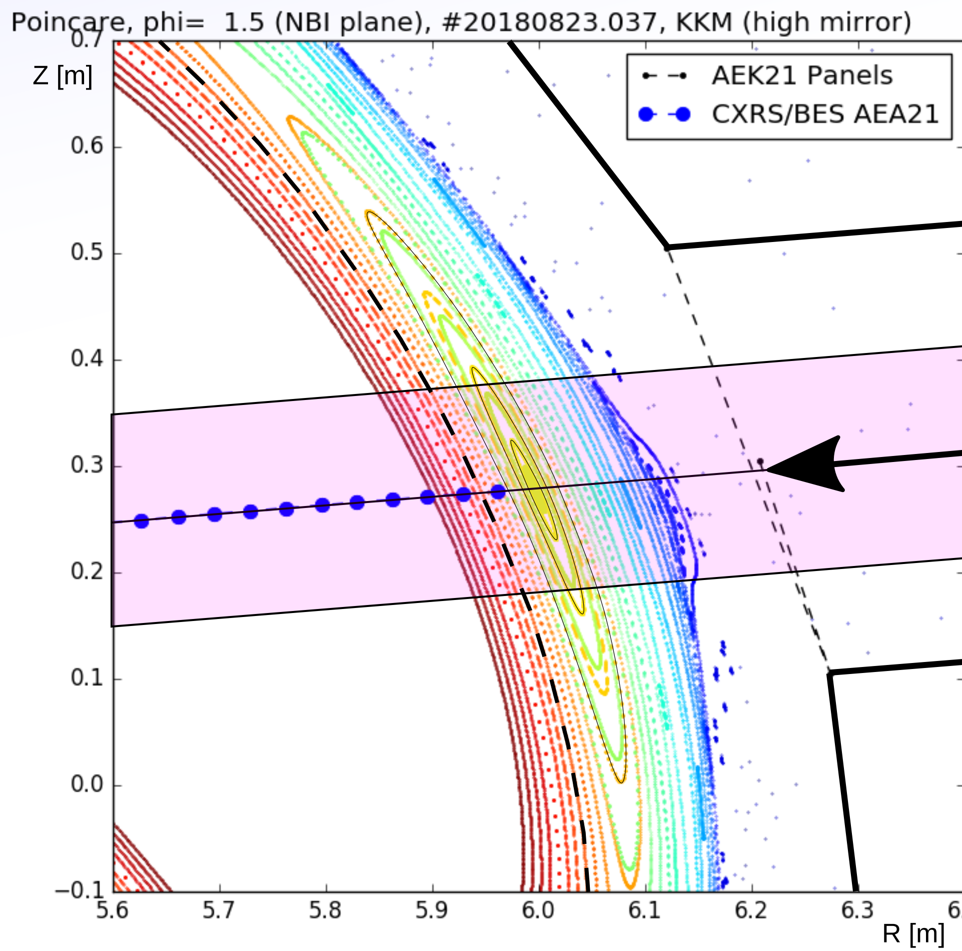
[1]: Flat n_e
[2]: Peaked n_e

[A. Spanier, "Performance of the first neutral beam injector at the Wendelstein 7-X stellarator", https://doi.org/10.1016/j.fusengdes.2020.112115]

Scrape-off layer lost power

One remaining question:
How much power is lost in the SOL?



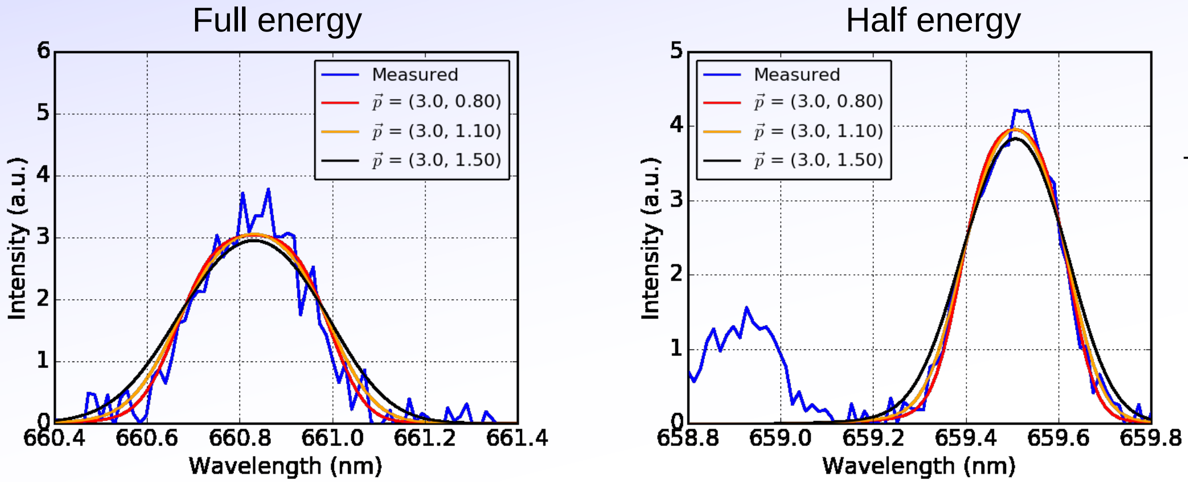


[Poloskei]: Assuming min/max n_e and T_e = 100eV across 5cm of island --> 2 - 12% of beam power lost in the SOL.

[16]

Beam divergence / duct loses

S. Äkäslompolo - BBNBI Modelling of beam source and port. Comparison with:
- Divergence measurements in the source (neutraliser spectroscopy)



→ Beamlet divergence
~ 1.0° ± 0.2°

[S. Äkäslompolo, "Validating the ASCOT modelling of NBI fast ions in Wendelstein 7-X stellarator" , https://doi.org/10.1088/1748-0221/14/10/C10012]

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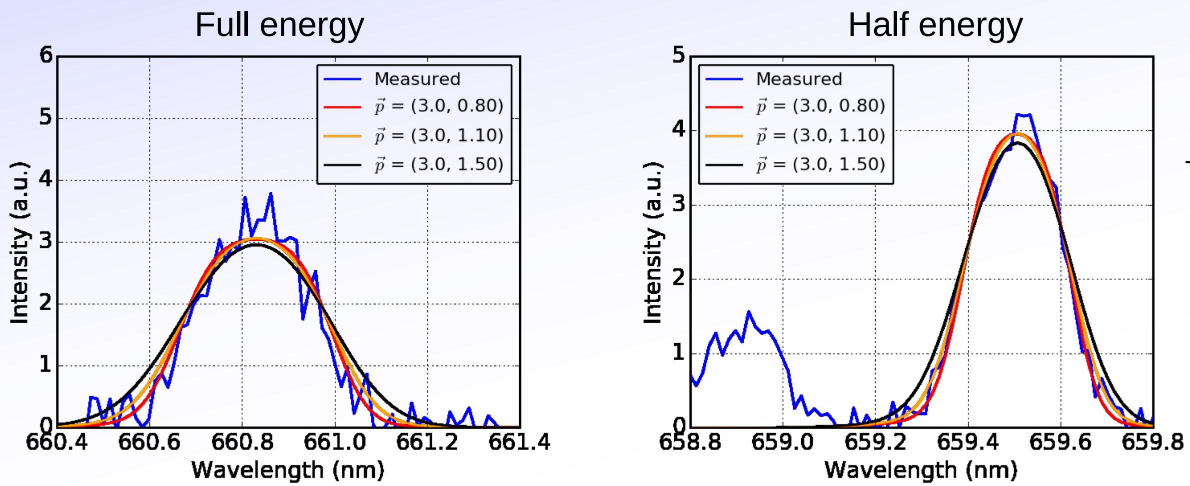

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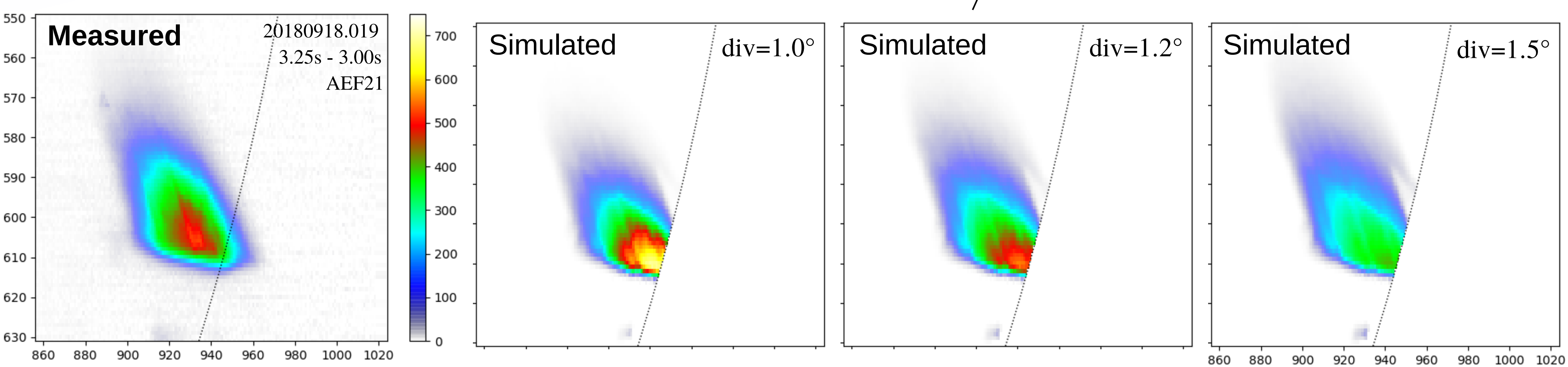

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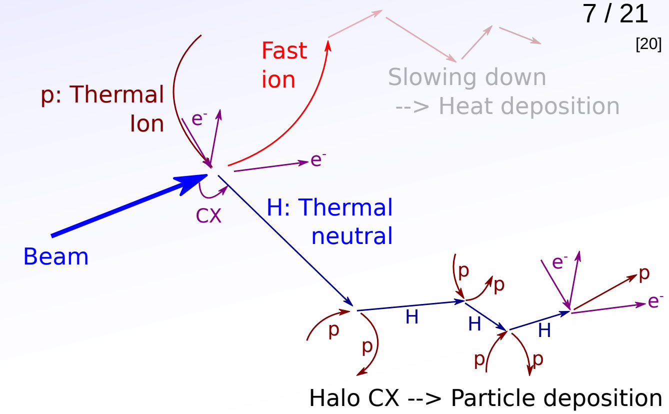
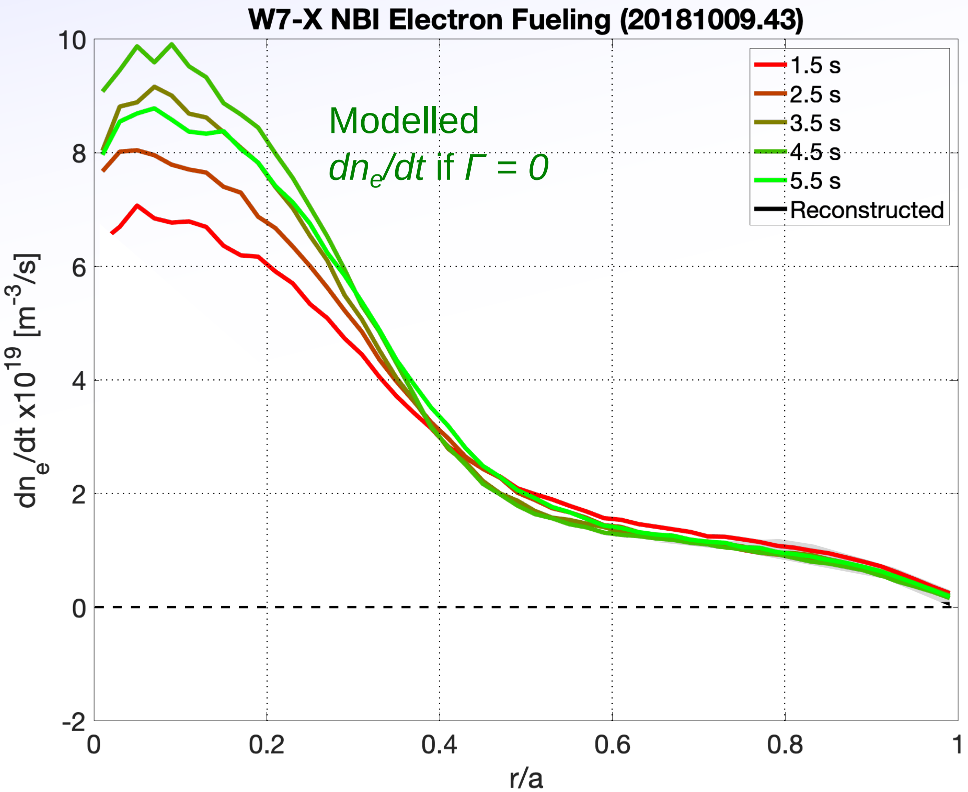
Particle deposition



For particle transport in NBI discharges, we need the particle source profile.
Electrons (dn_e/dt) come roughly from:

~50% Beam ionisation
~50% Halo ionisation



[S. Lazerson]:
Analysis of pure NBI peaked density shots.

Beam attenuation from BEAMS3D MC beam model (decay length validated against BES measurements).

Approximation: **Assume no halo transport.**

[S. Lazerson, "Validation of the BEAMS3D neutral beam deposition model on Wendelstein 7-X", https://doi.org/10.1088/1741-4326/ab8e61]
[S. Lazerson, "Modeling and measurement of energetic particle slowing down on Wendelstein 7-X", *(in preparation)*]

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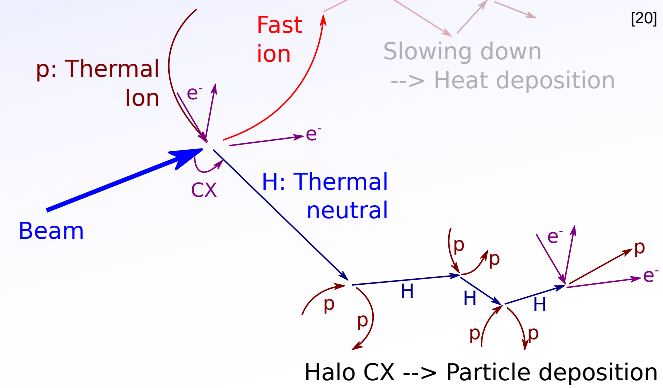

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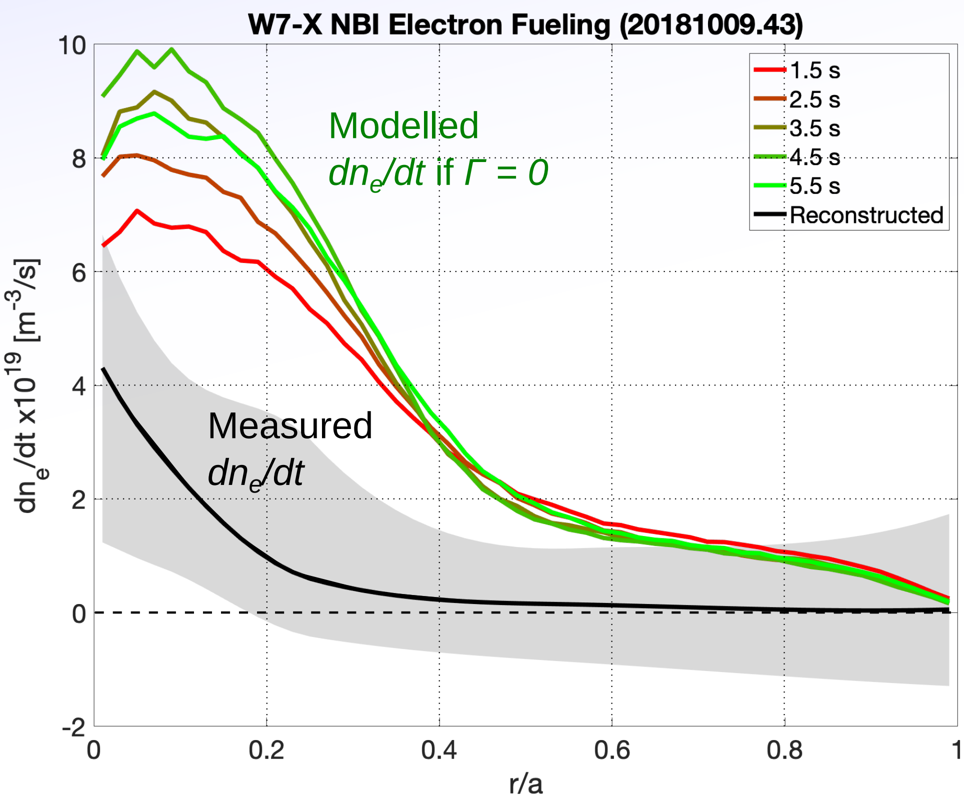

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If there were no particle transport how would n_e grow?
(*D, v, Er* --> *Γ = 0*, infinite confinement time)

2 - 10x faster than observed, so:
Density peaking not simply due to beam fuelling,
but a transport effect.
(more on this later)

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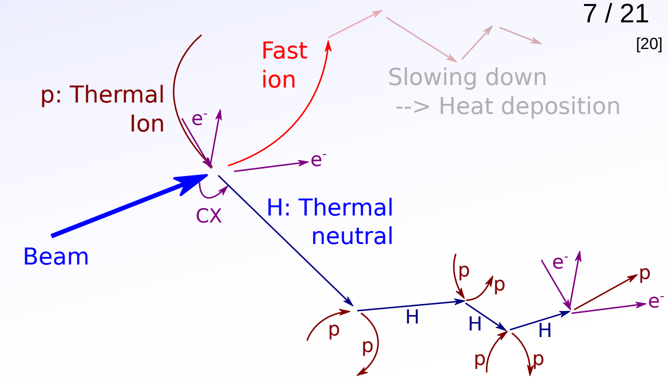

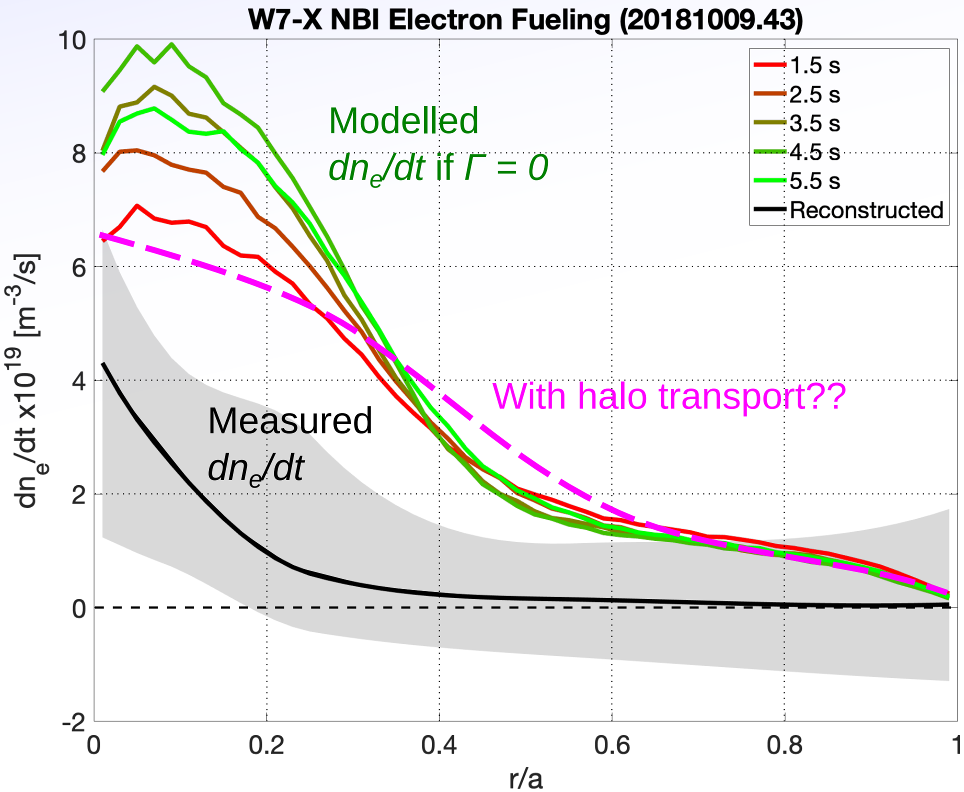

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Halo transport will broaden the deposition by up to Δρ ~0.2. Some fraction will be lost at the edge and amplitude will reduce due to volume effect --> Halo transport must be accounted for source profiles.

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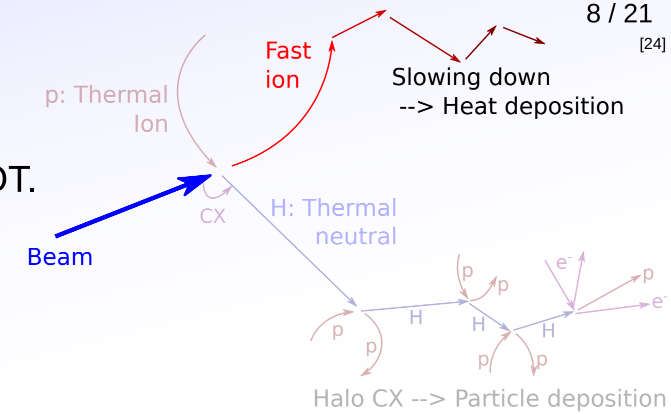
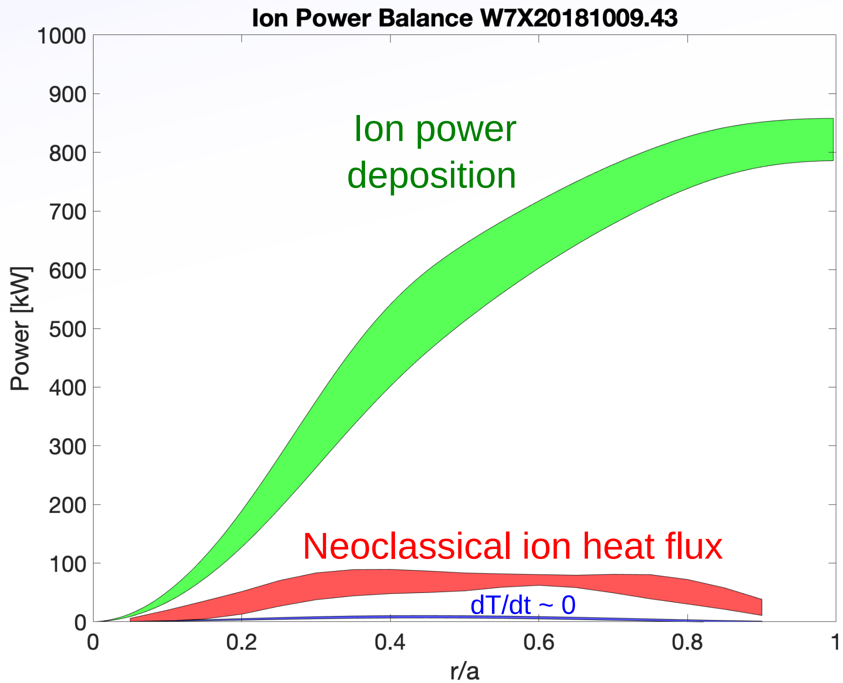
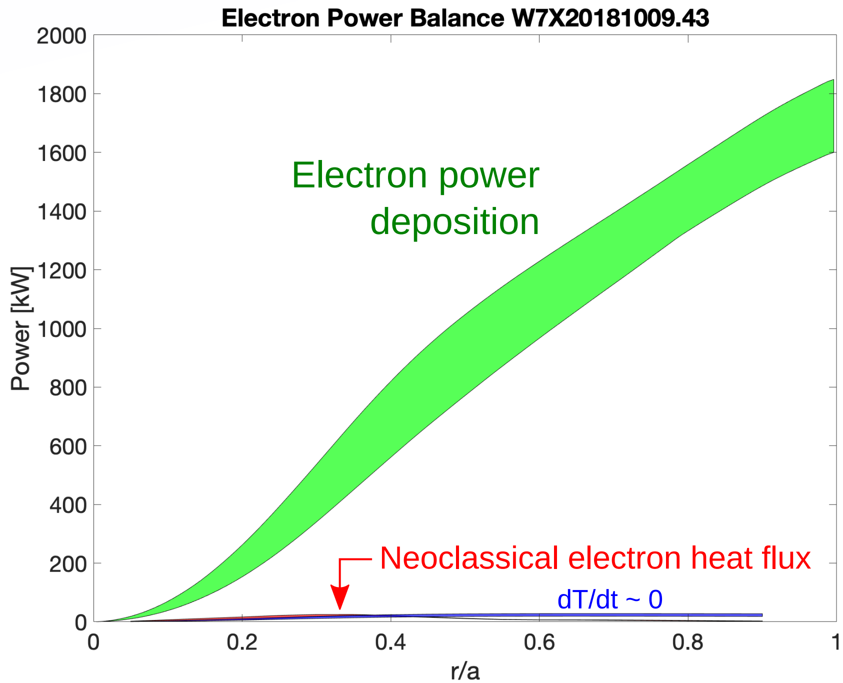
Heat/power deposition



Energy 'deposited' into electrons and ions by fast ions until they slow down.
[S. Lazerson]: MC modelling of fast ion orbits and collisions by BEAMS3D/ASCOT.

e.g. for pure NBI discharge:





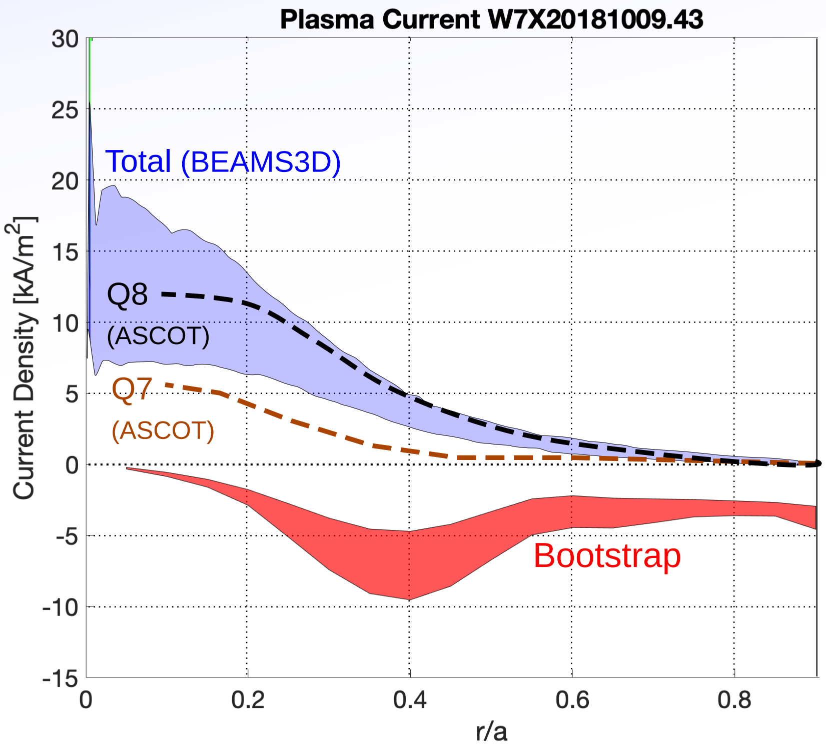
Indicates anomalous heat transport is dominant for both ion and electron channels.

[S. Lazerson, "Modeling and measurement of energetic particle slowing down on Wendelstein 7-X", *(in preparation)*]

Neutral beam current drive

NBI current drive calculations by
- BEAMS3D [Lazerson]
- ASCOT [Rust]

--> Reasonable agreement



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[N.Rust,]

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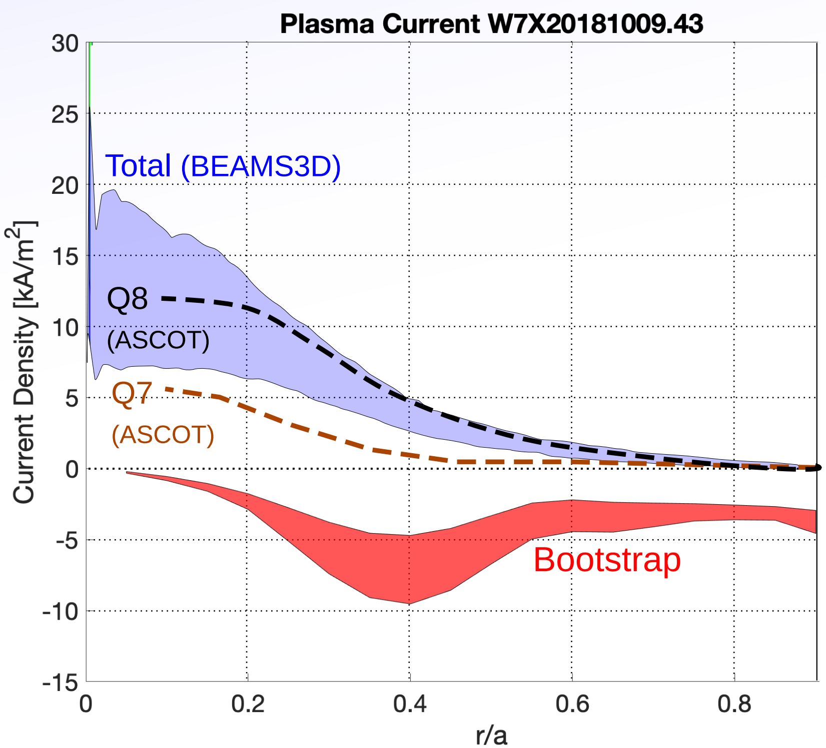
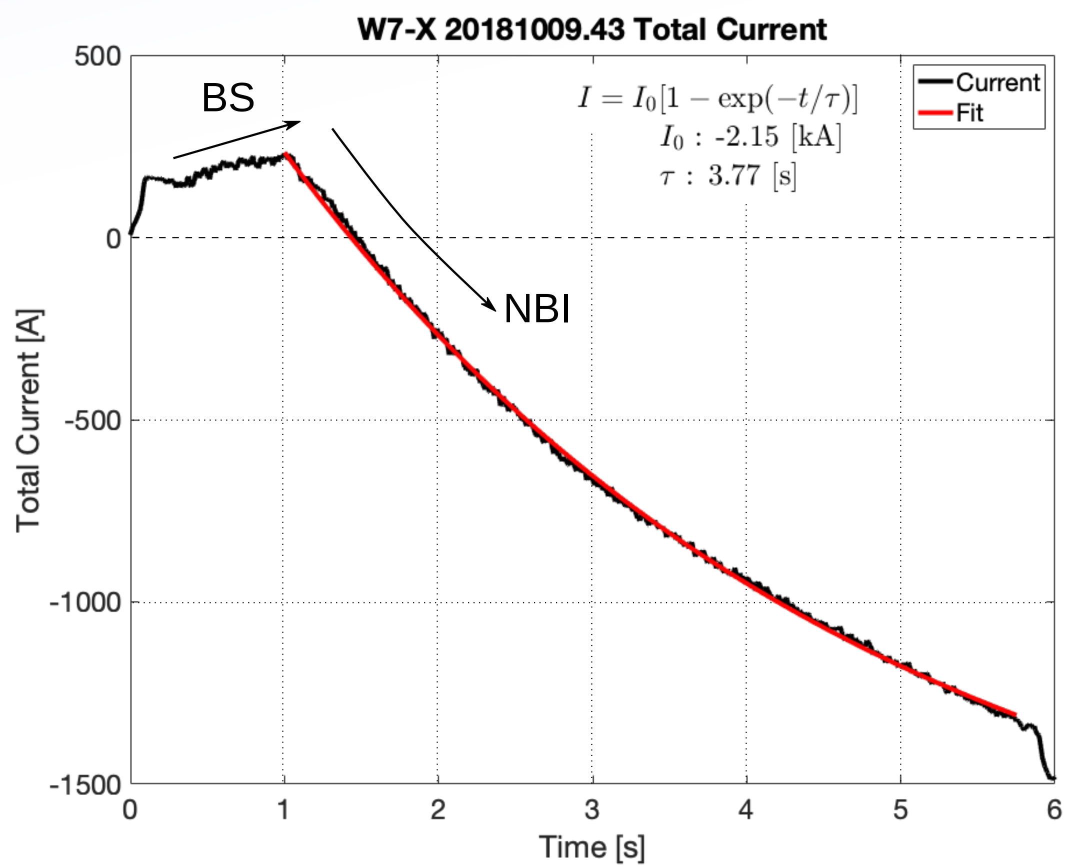
Direction opposite and larger than boostrap as predicted.

Experimental current appears smaller than simulated --> work ongoing to model more precisely.





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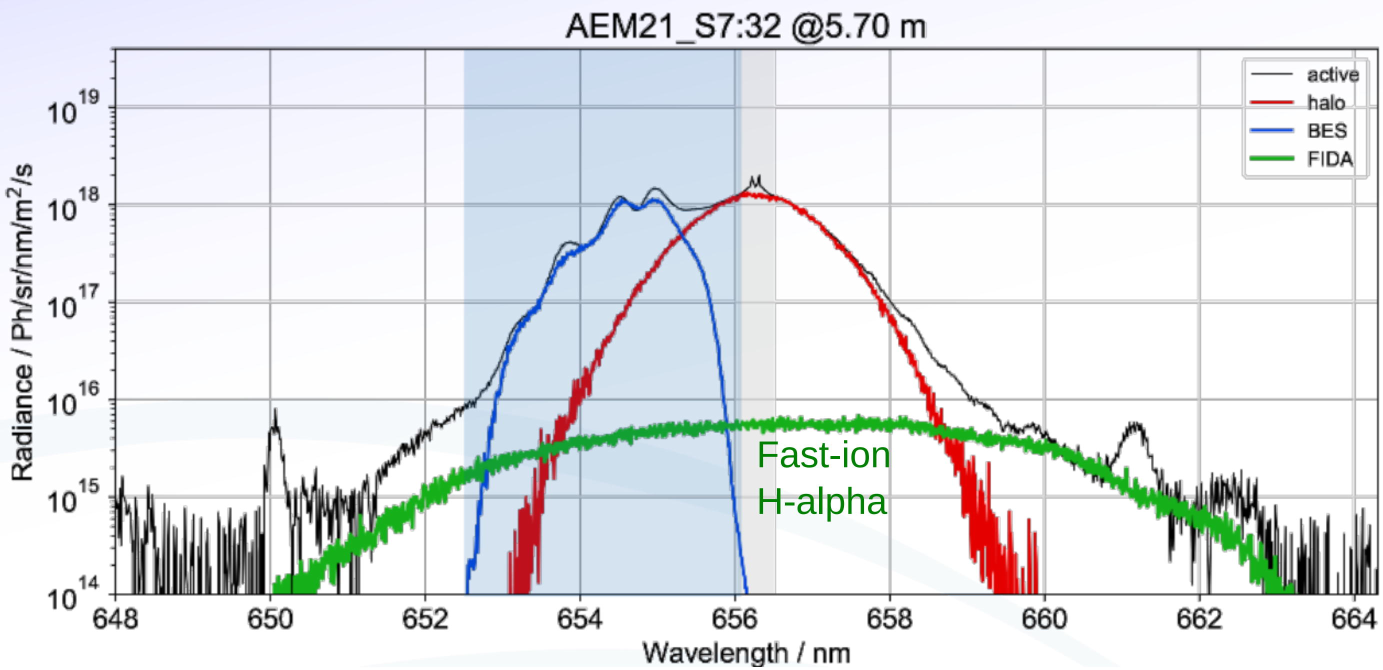
[N.Rust,]

Fast ion distribution

With unknown transport, validation of the heating profiles only possible through validation of the fast ions:
- Fast ion losses - Infrared wall measurements and FILD measurements.
- Fast ion distribution - CTS and FIDA measurements.



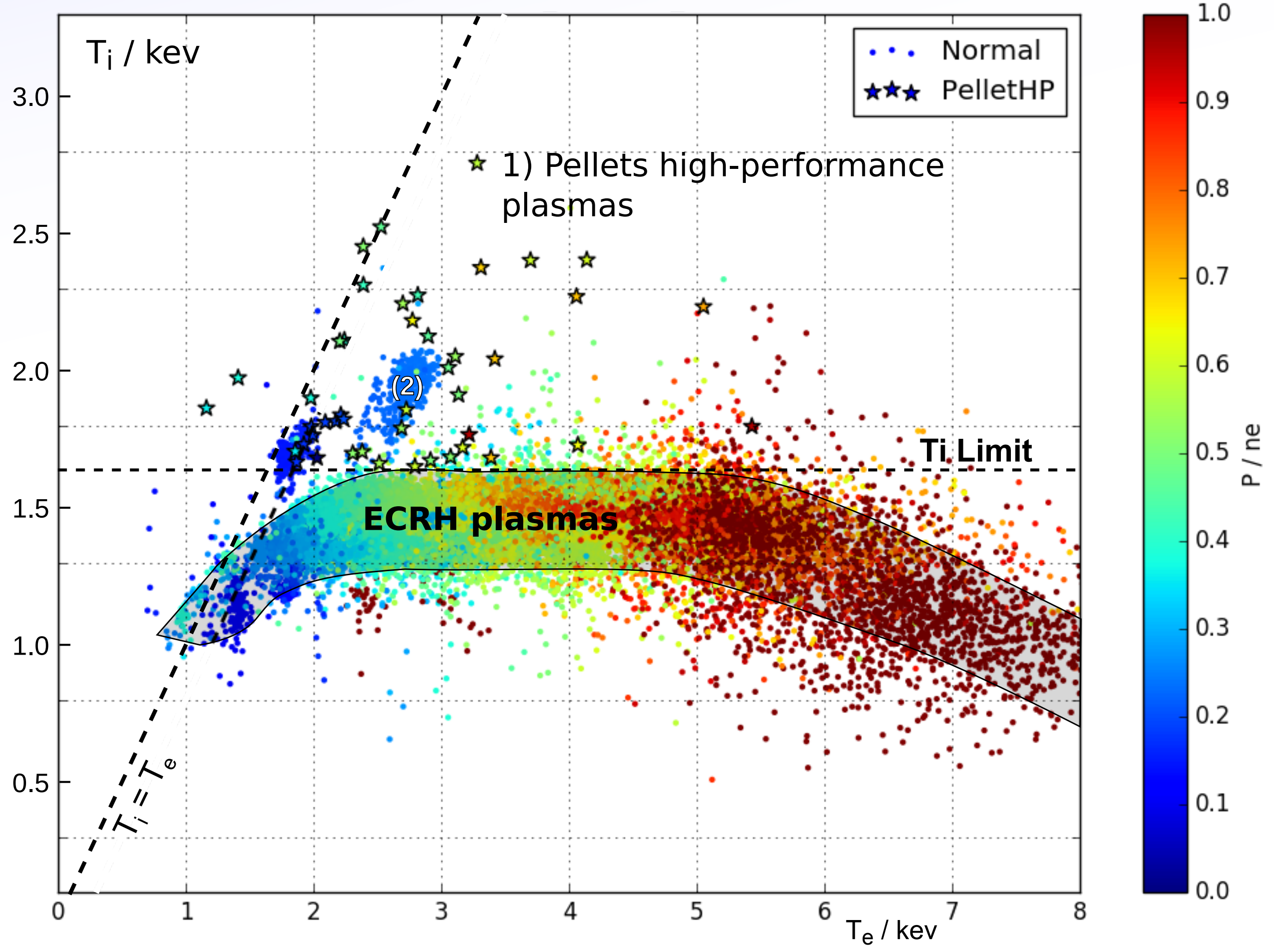
FIDA results already collected during OP1.2 --> Last talk today by P. Poloskei.

1) Status report

2) Observational results from OP1.2

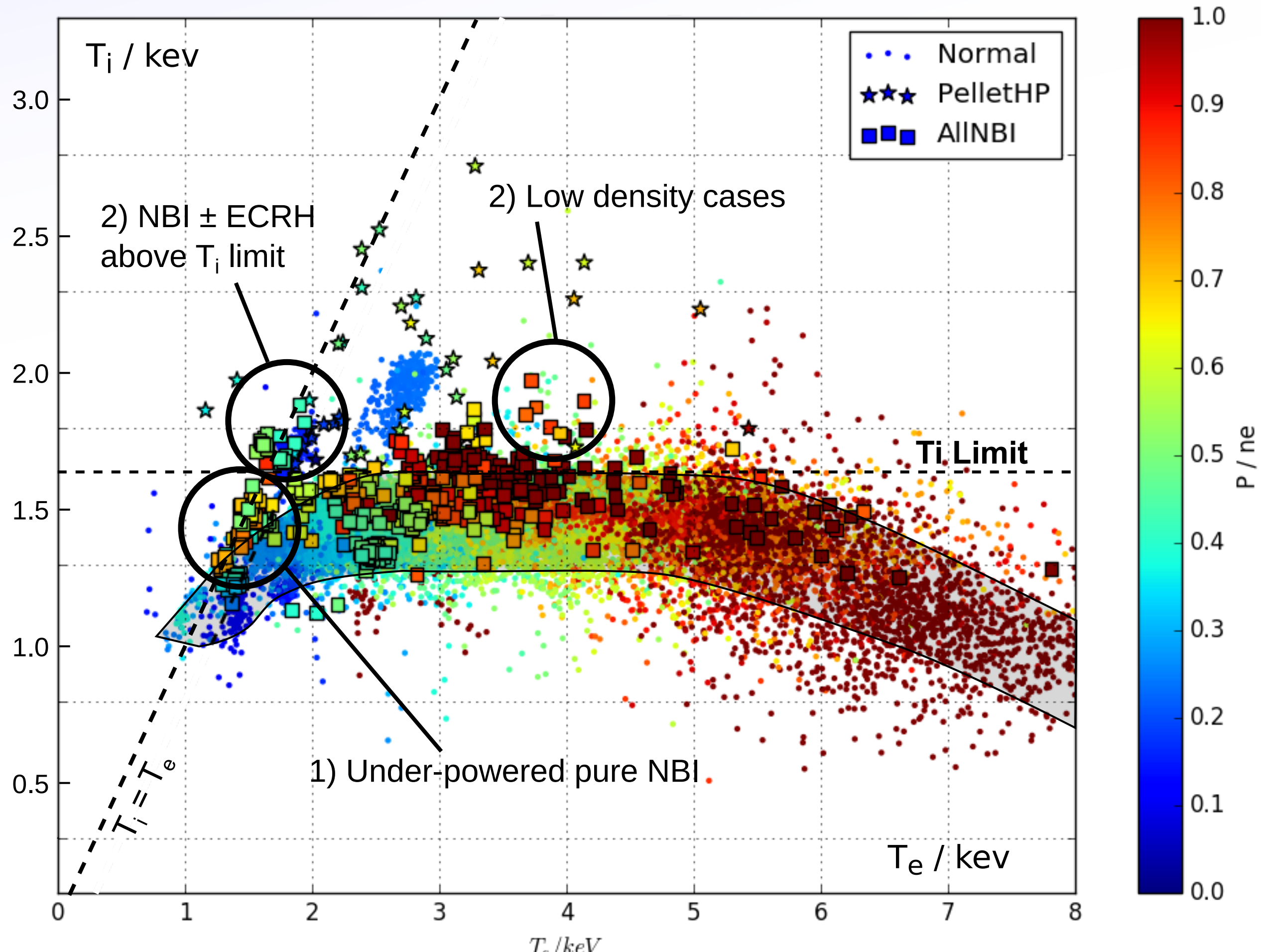
T_i profile 'clamping' in W7-X

- Core T_i stays within same range and with similar gradients regardless of P_{ei} / electron-ion coupling.
- Effective T_i limit ~ 1.6 keV
- Exceptions:
    1) High-Performance pellet discharges
    2) Low density post-boronisation shots.



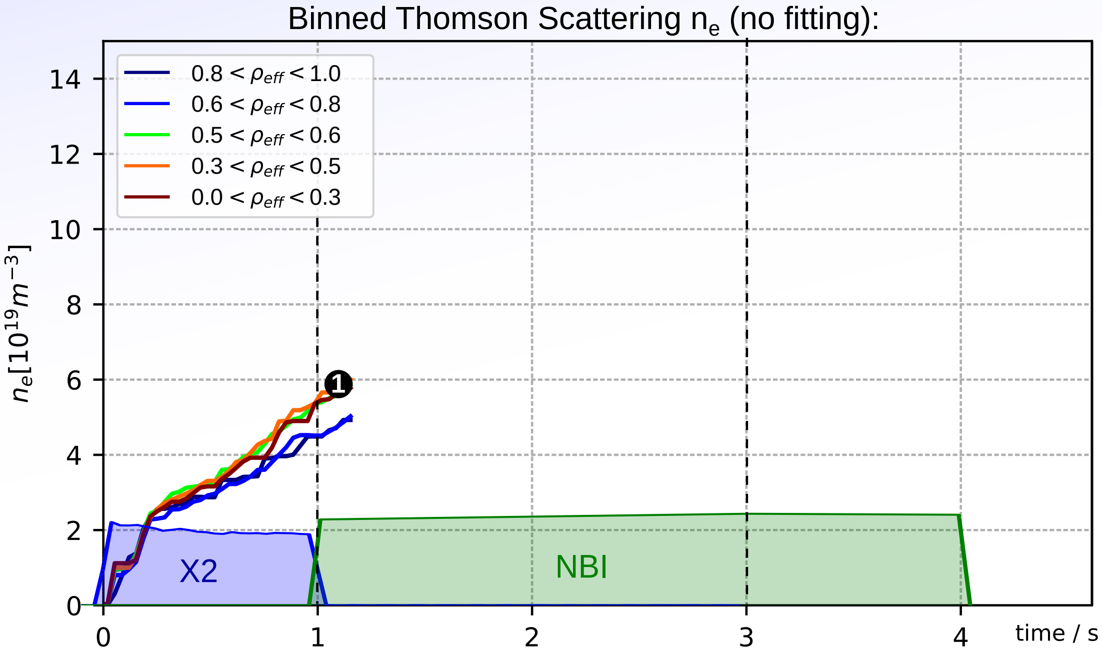
T_i profile resilience: NBI

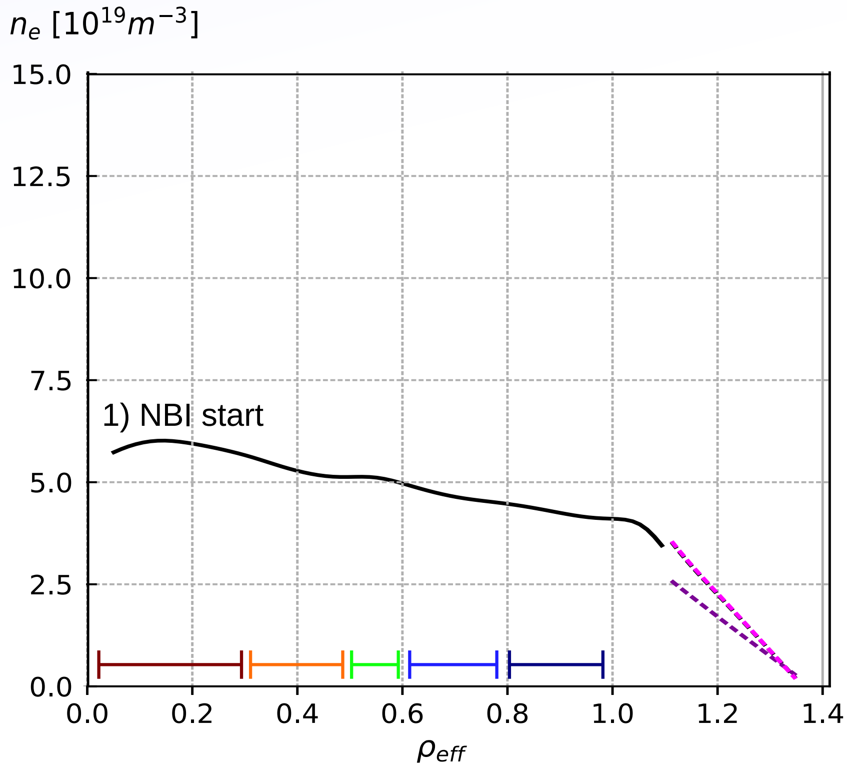
- NBI adds signficant direct ion heating (> 50%) but still does not raise T_i.
- Consistent with the existence of a critical T_i gradient.
- Exceptions:
  1) 'Under powered' plasmas: No ECRH, so T_i below limit.
  2) Low-density cases ECRH step-down cases.
  3) NBI peaked density + ECRH



Pure NBI density peaking

- Pure NBI discharges show core density peaking.
- Density rise is less than NBI fuelling rate and core peaking accelerates at a specific radius and time:
  - $\rho_{eff} < 0.5$.
  - $t > t_{onset}$, which varies over 1 - 2s after NBI in different shots. No apparent correlation of t_{onset} with external events.





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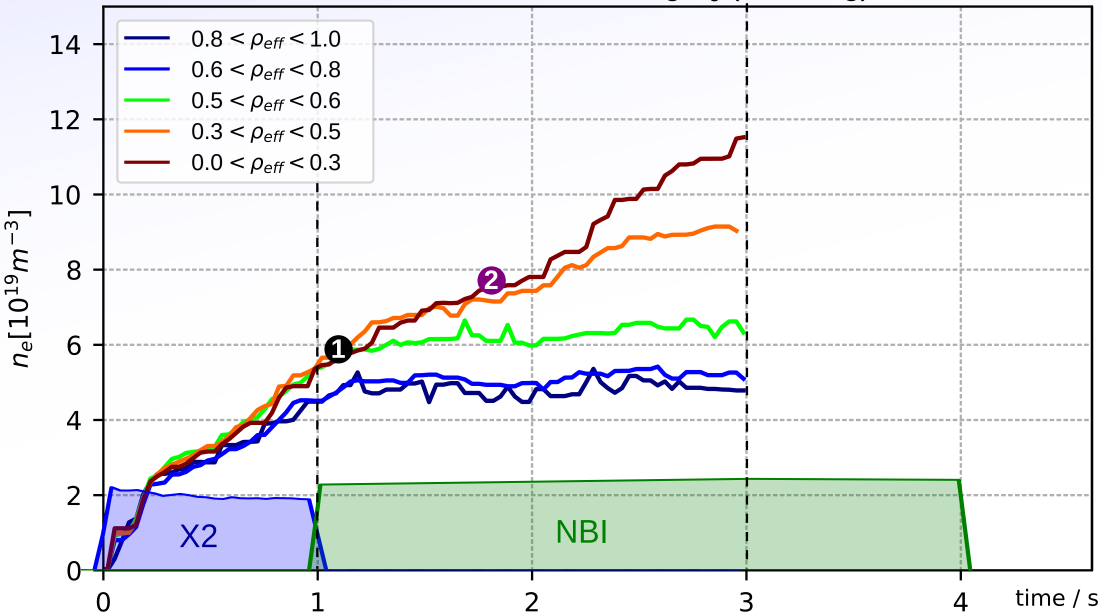

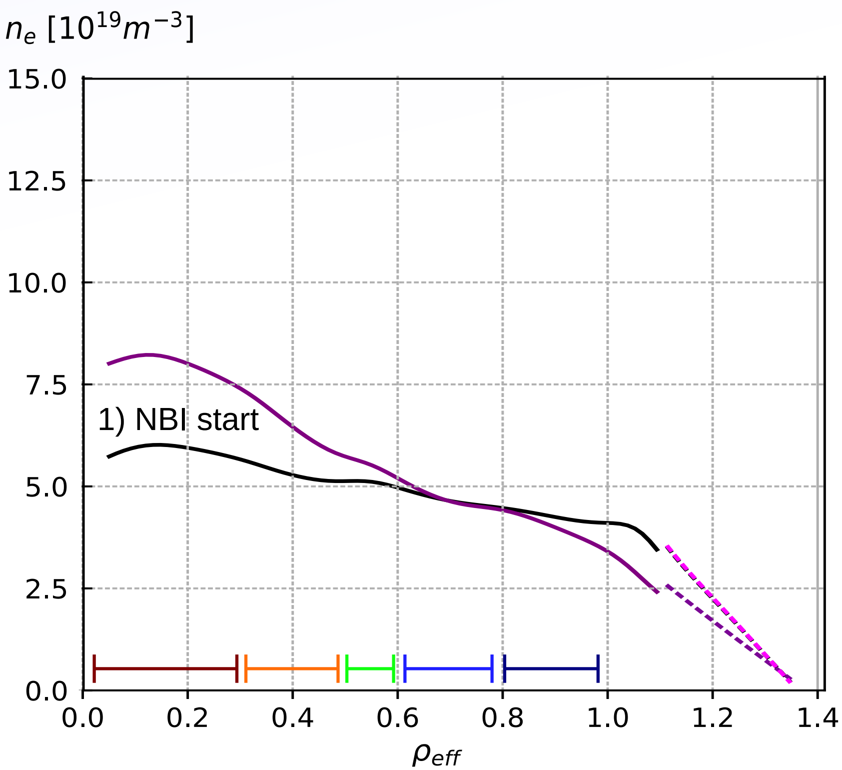

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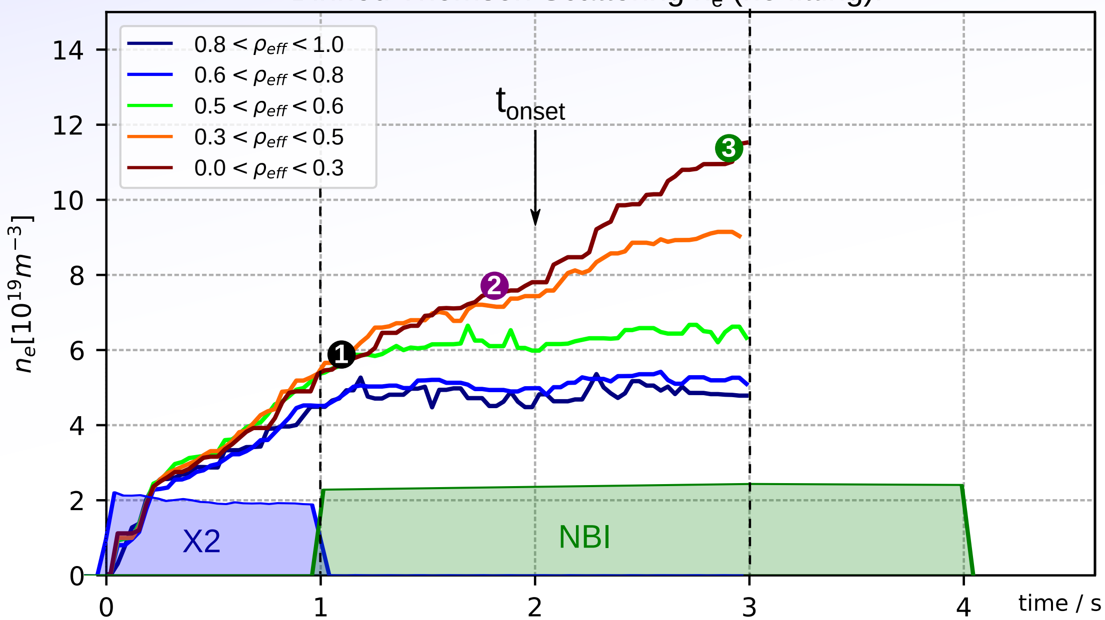

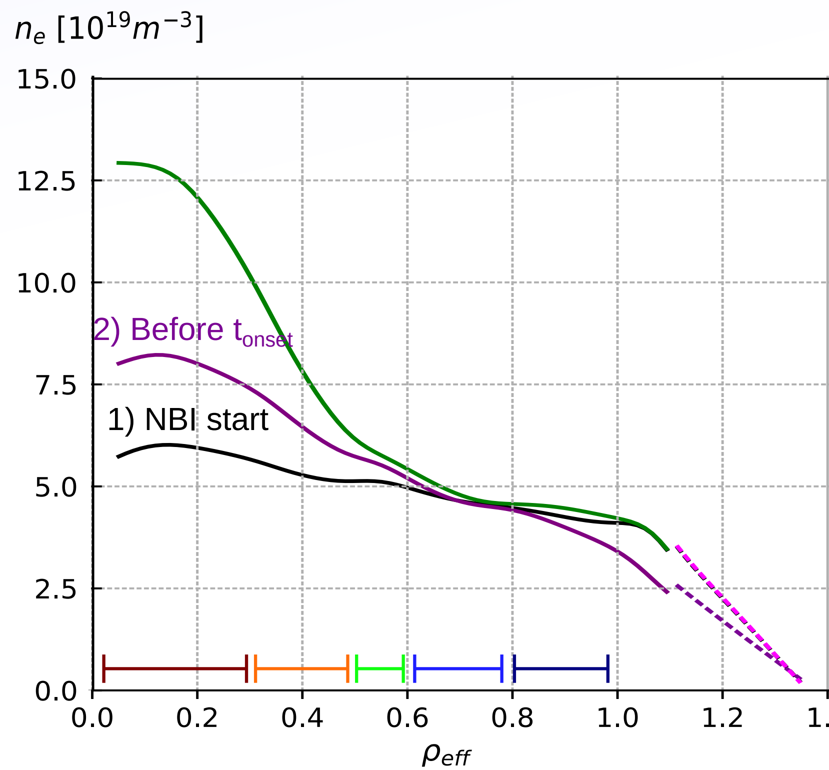

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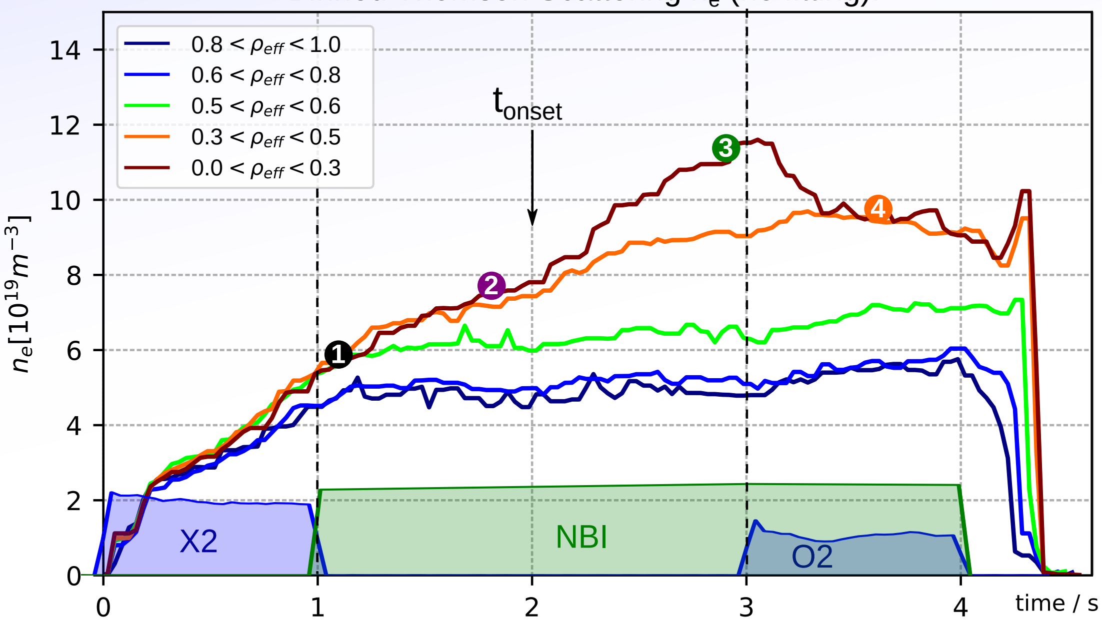
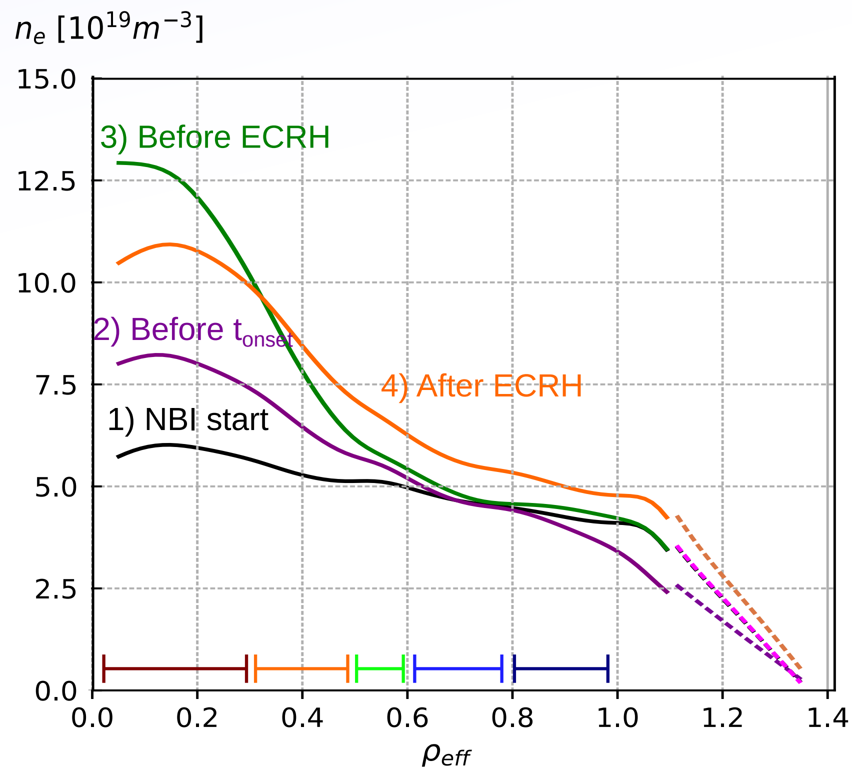


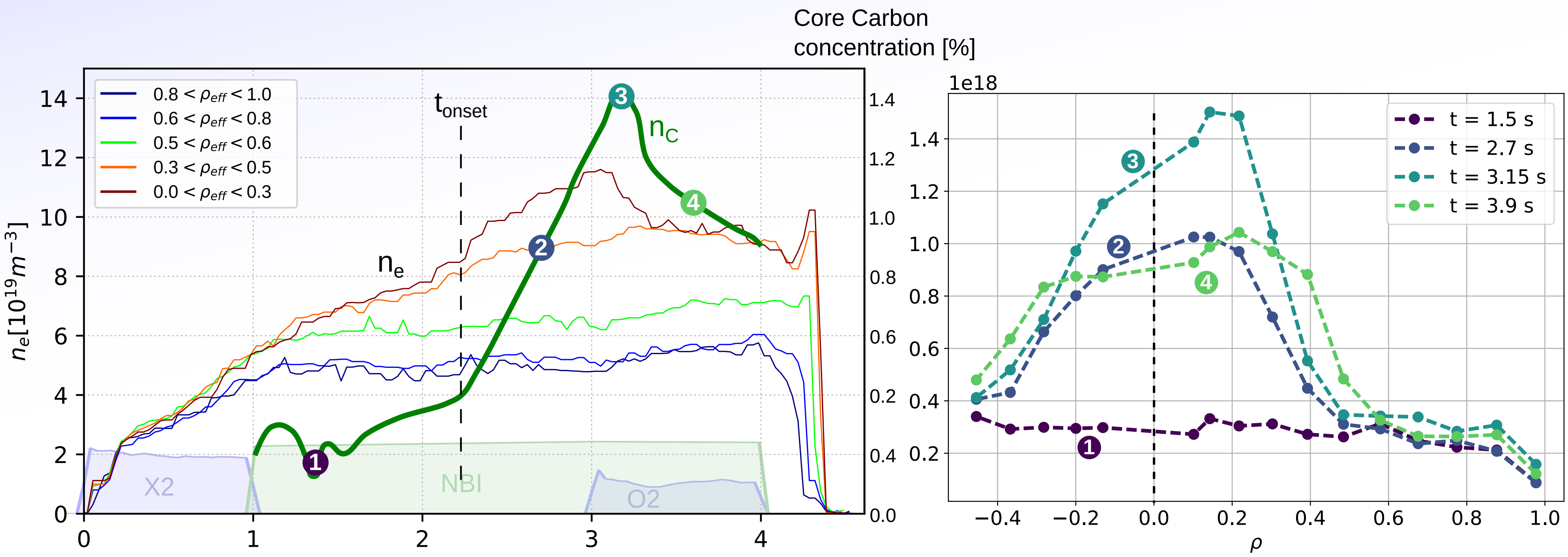


- Density peaking reduces and T_i drops.

Pure NBI density peaking - impurities

[L. Vanó]: Region of dramatically different transport seen more strongly in impurity density profiles.

- Rapid impurity influx at t_{onset}.



- Normally large impurity diffusion seen in ECRH discharges is not present during pure NBI.
- Impurities at least partially flushed out at addition of ECRH.

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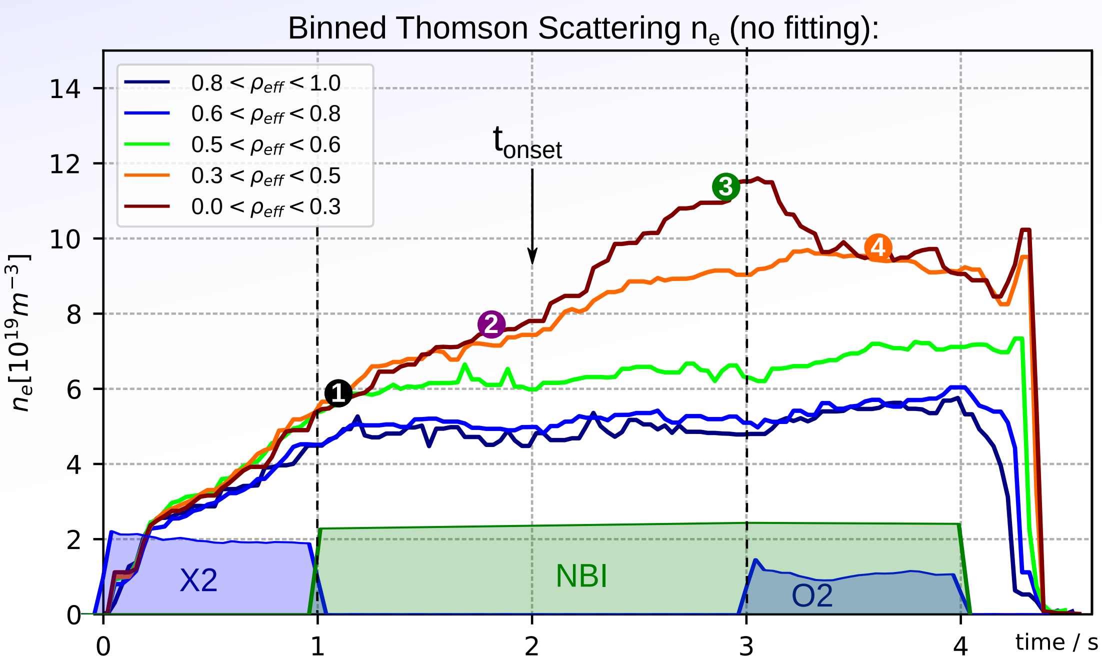

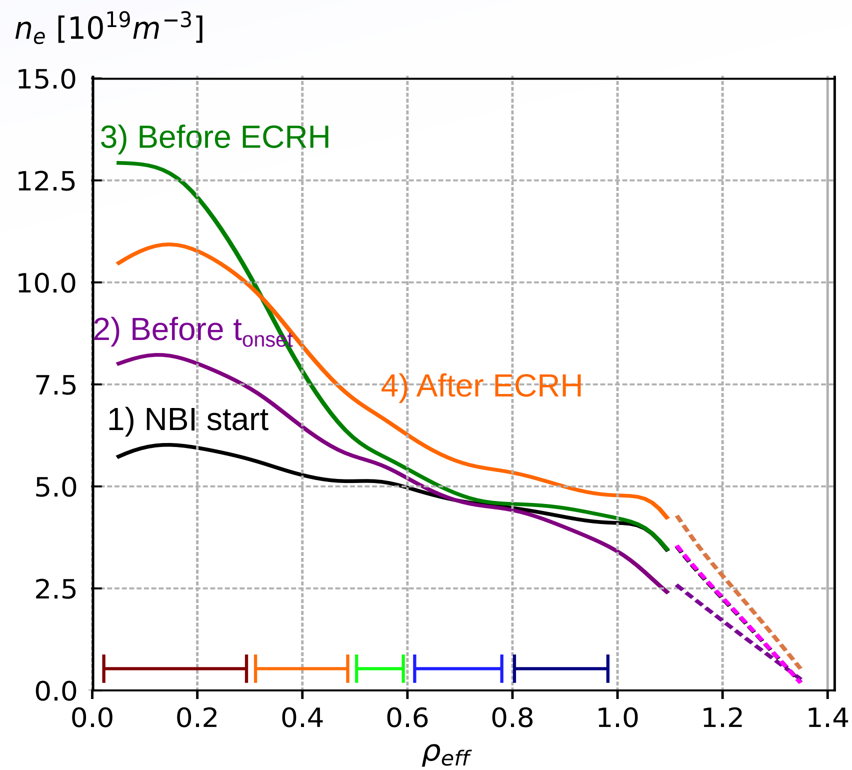

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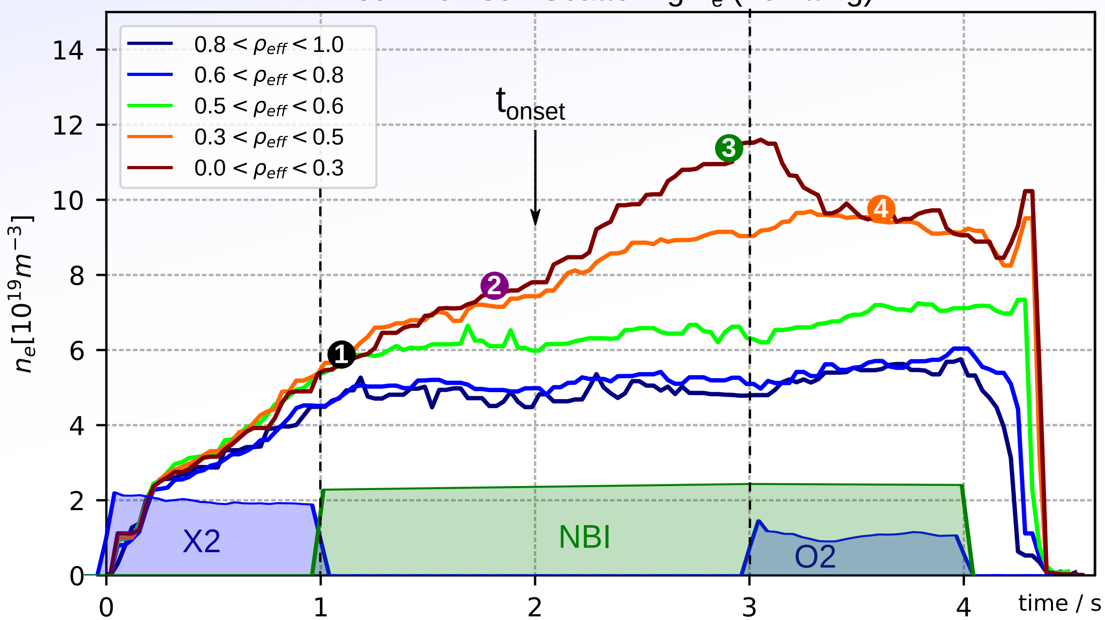
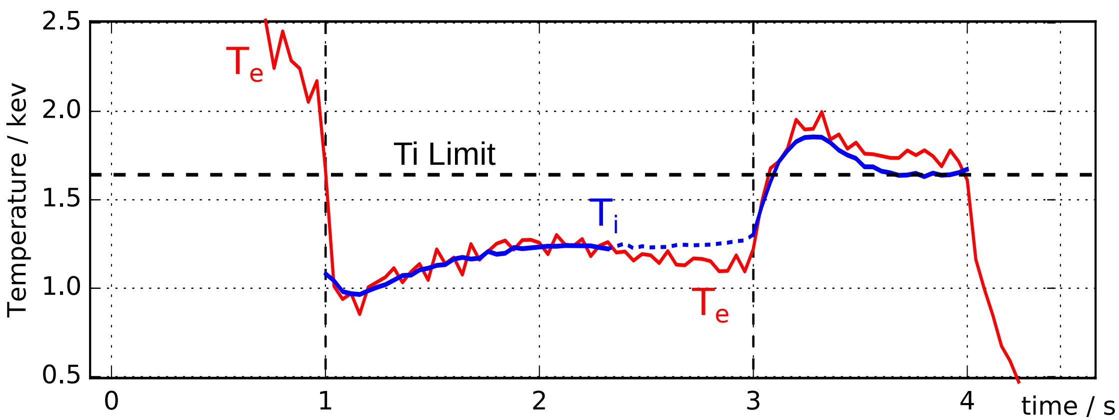
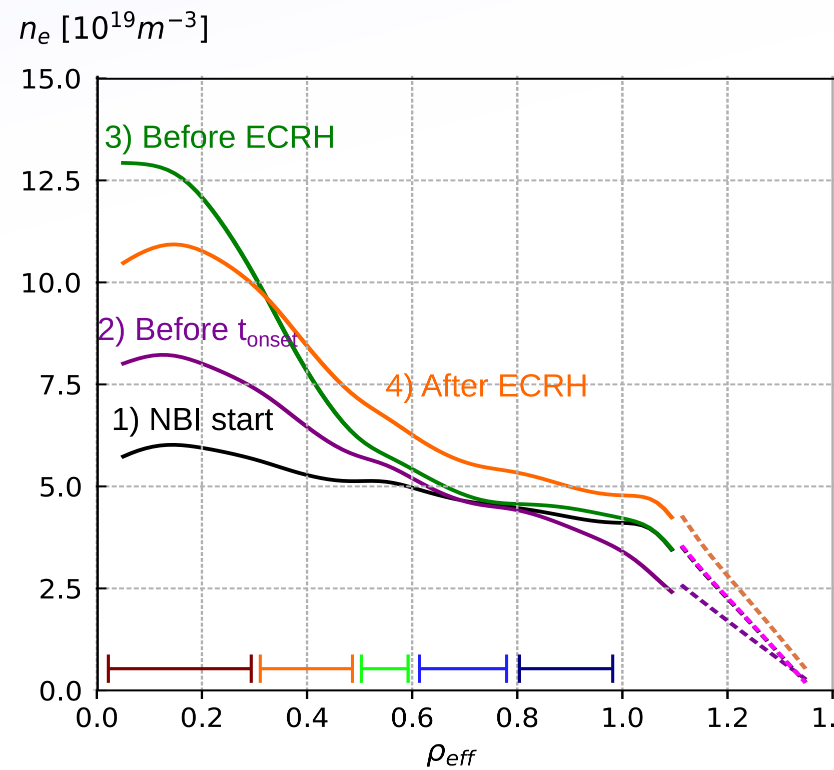






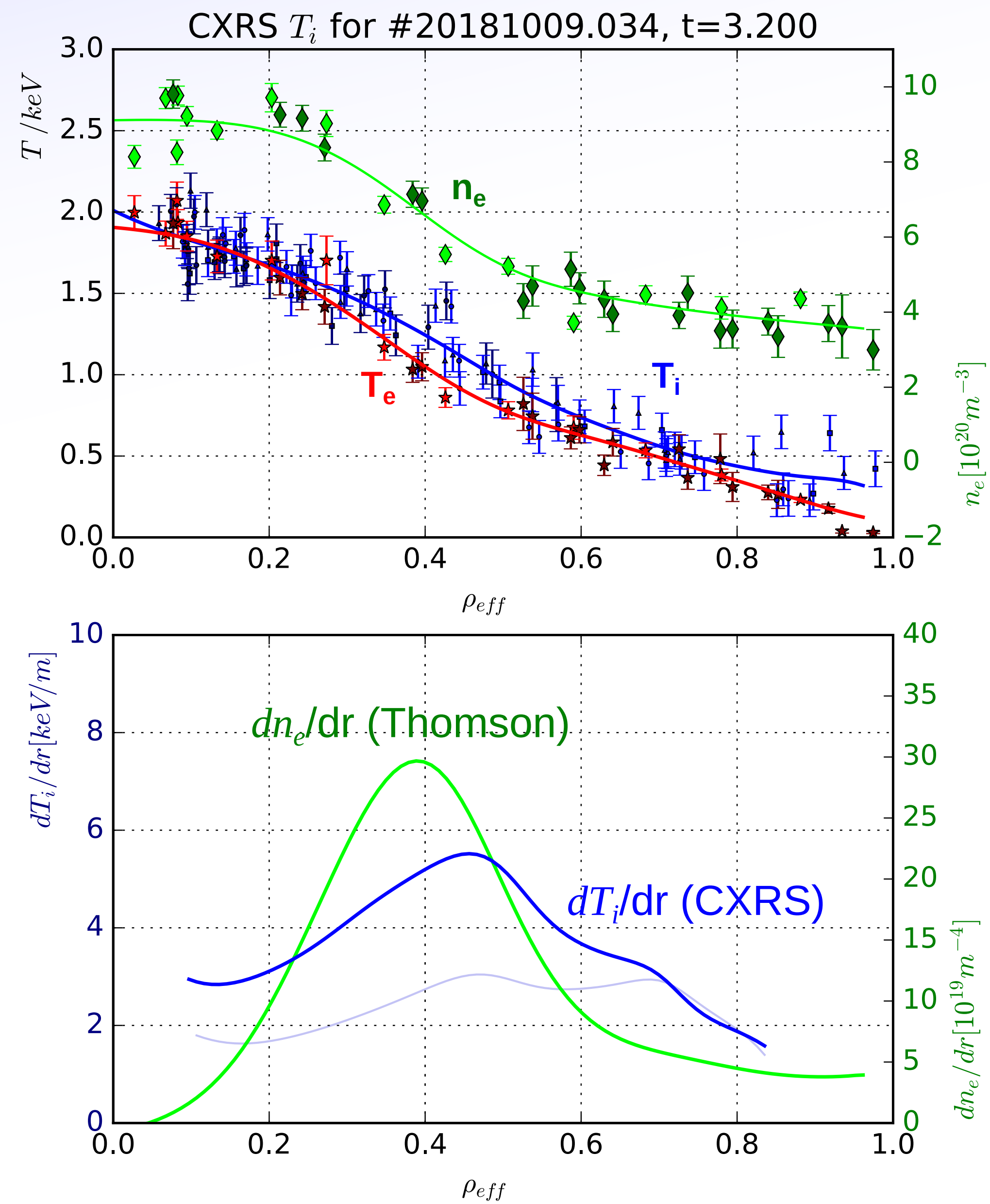
- With peaked density, 1MW of ECRH is enough to raise T_i to ~250eV above limit.

- Density peaking reduces and T_i drops.

Pure NBI density peaking - Ti gradients

During phase of ECRH addition with T_i > T_i limit, the 'unusual' T_i gradient *roughly* coincides with the spatial region of the high density gradient.

- Consistent with idea of ITG supression due to density gradient, but...



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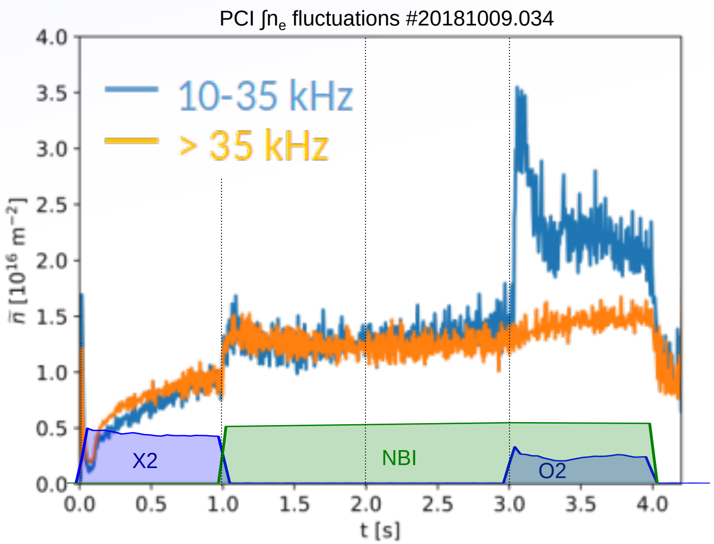
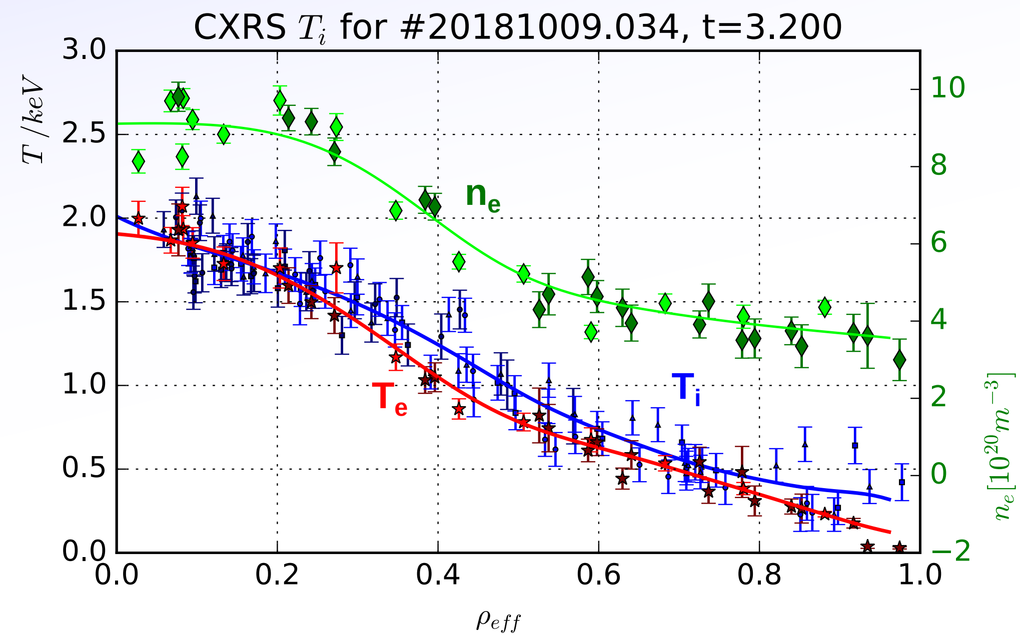
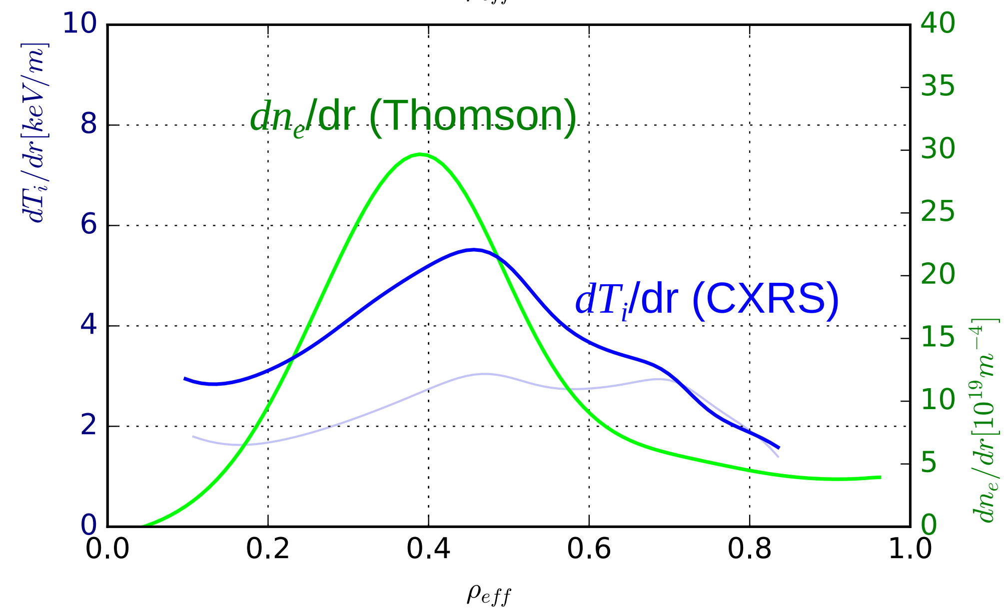
However: ~20kHz mode appears at O2 phase:







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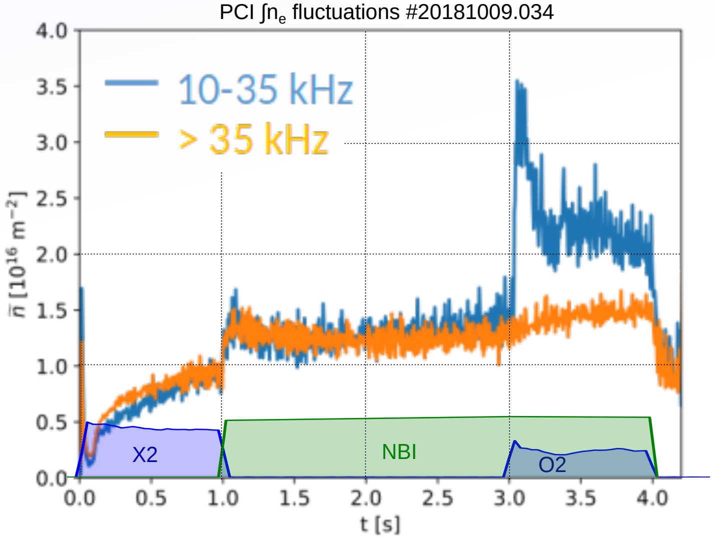
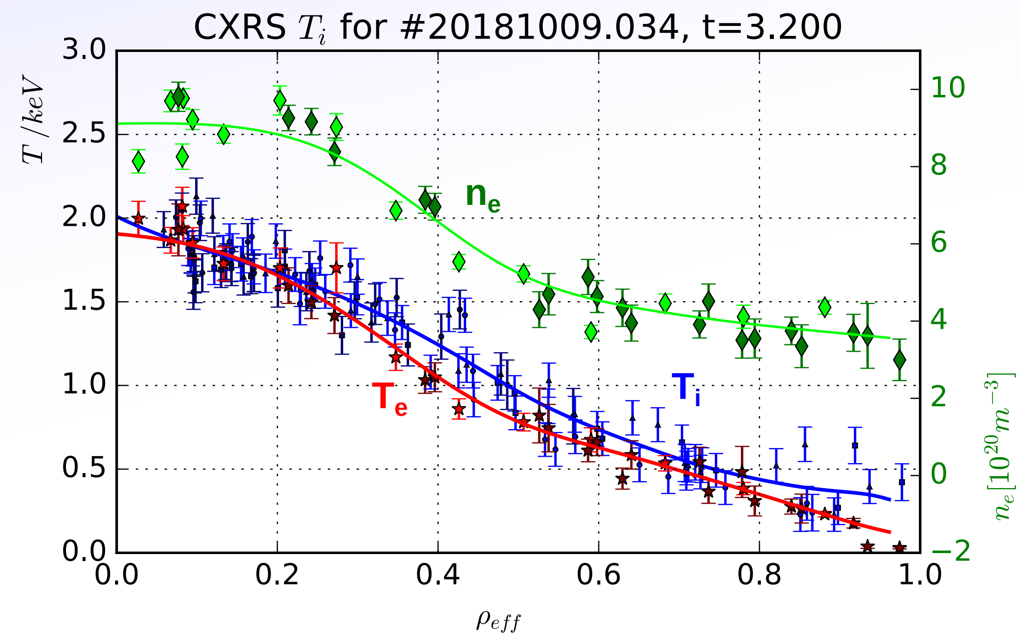
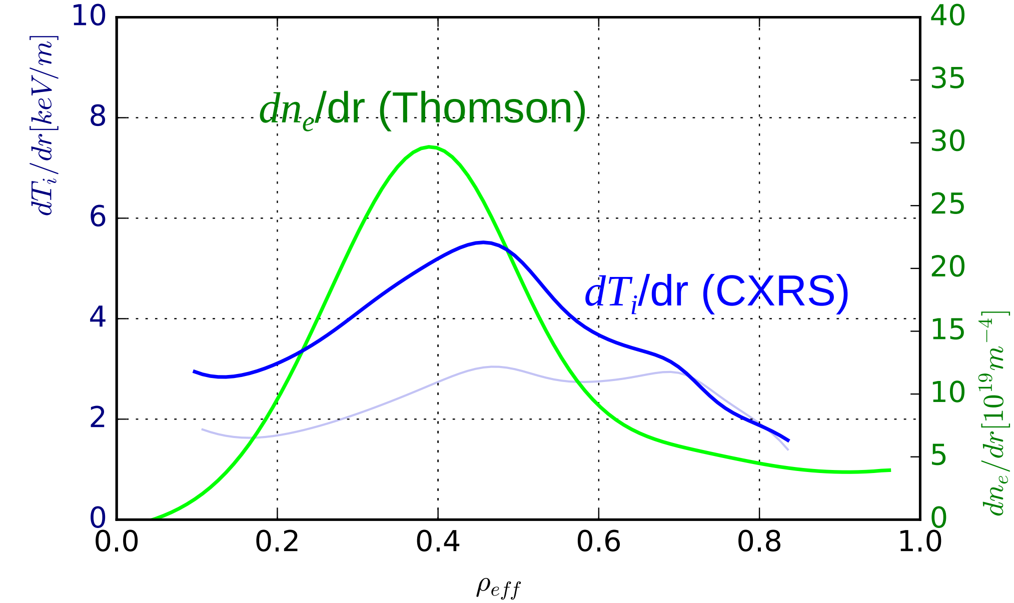
- [Z. Huang]: No evidence of reduced fluctuation level in PCI, or rise again during O2 phase.
  However: ~20kHz mode appears at O2 phase:







- Can we balance P_{ECRH}/P_{NBI} to make use of turbulence supression without losing the gradient that creates it, and simultaneously control impurities?

--> S. Lazerson - "Neutral Beam Operational and Scientific Planning for OP2"

OP1.2 NBI Results / Status report

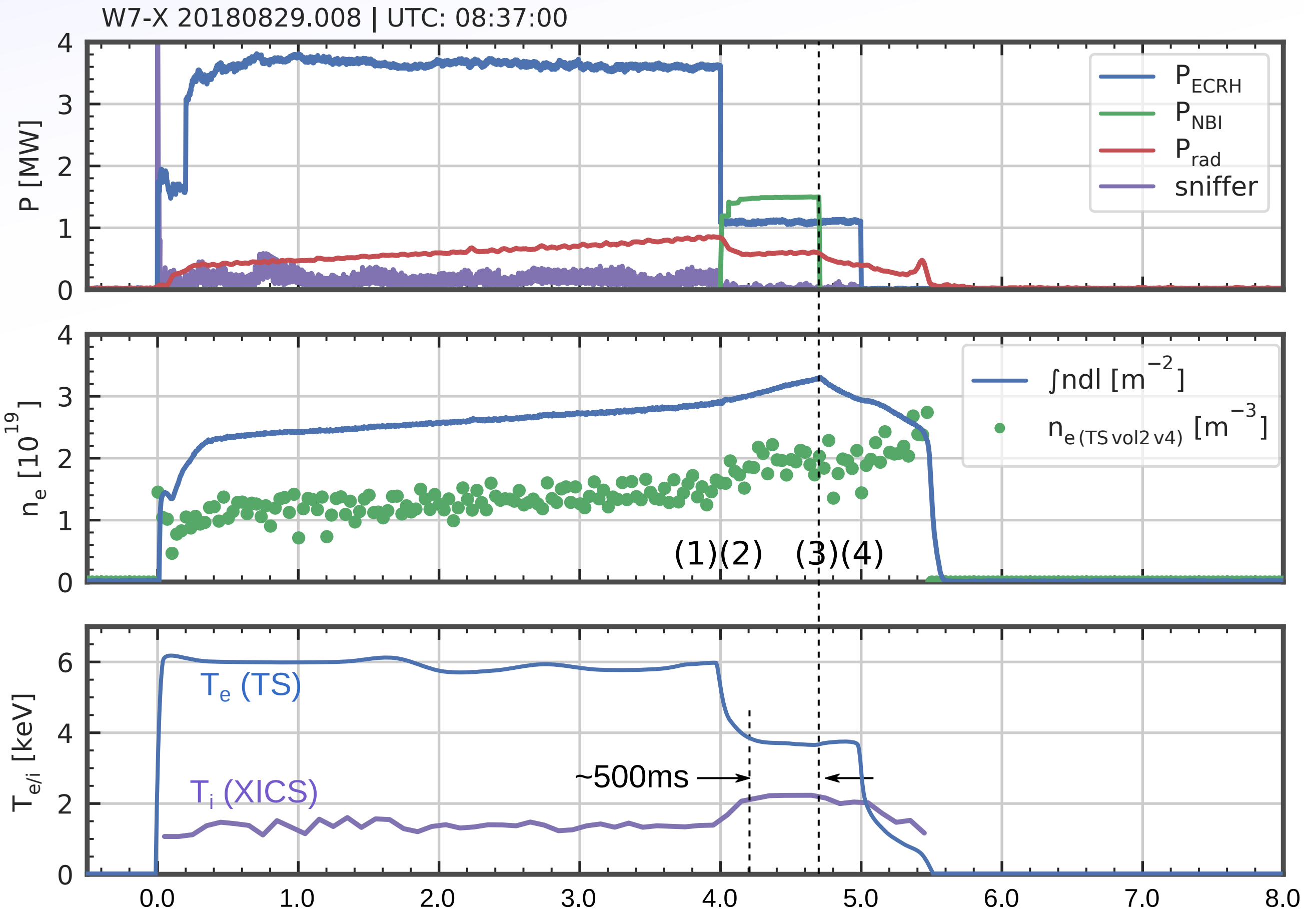
Status report:
- Injected power - Done - Will *be made routine*
- Beam divergence and model - Validated - *NBI codes must account for divergence!*
- Particle source - Done to first order - *Need to check halo transport effect.*
- Heat source - Done to first order - *S.Lazerson to make database of shots available.*
- Current drive - ...
- Fast-ion distribution - *Some information from FIDA*

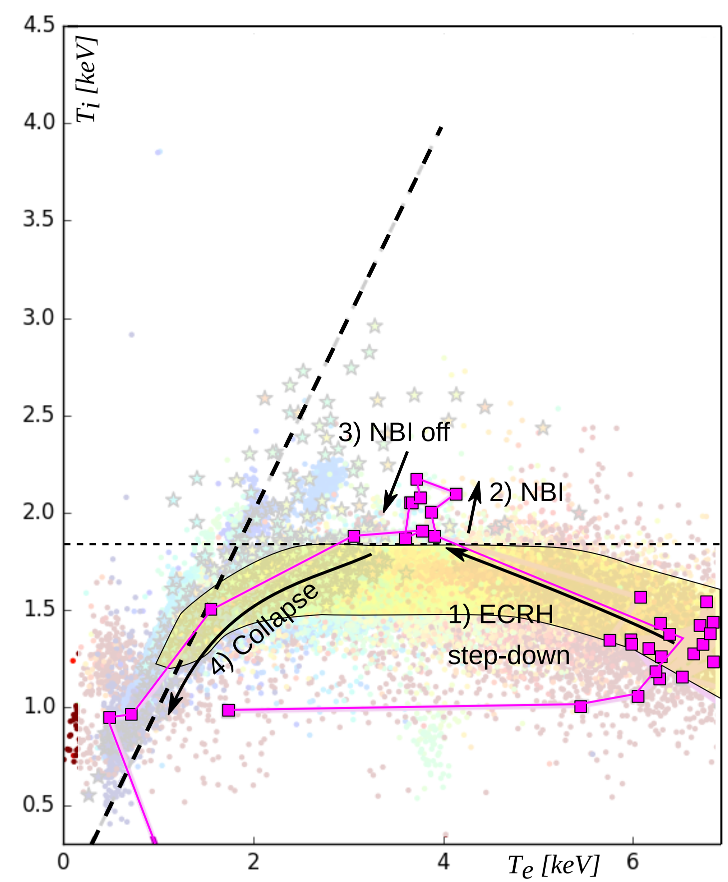
Observation results from OP1.2:
- Ion heating in standard ECRH plasmas is not seen or small, due to T_i profile clamping.
- Pure NBI plasmas:
    - Strong density peaking in core region due to unknown transport effect.
    - Strong impurity 'accumulation' and explusion in the same region.
    - T_i gradients might indicate 'turbulence supression' in NBI+O2 discharge.

BACKUP: Stationary(ish) case

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

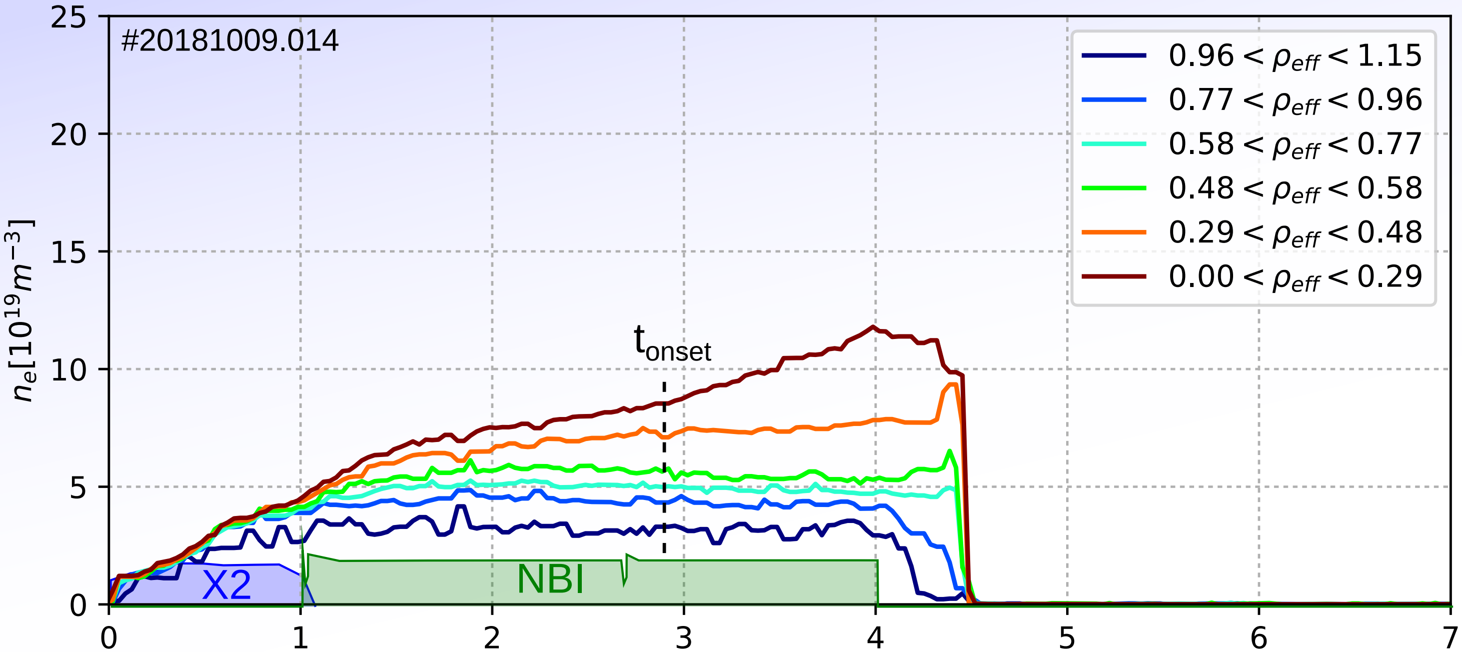
This looks like the NBI equivalent of the post-boronisation low-density high T_i shots.

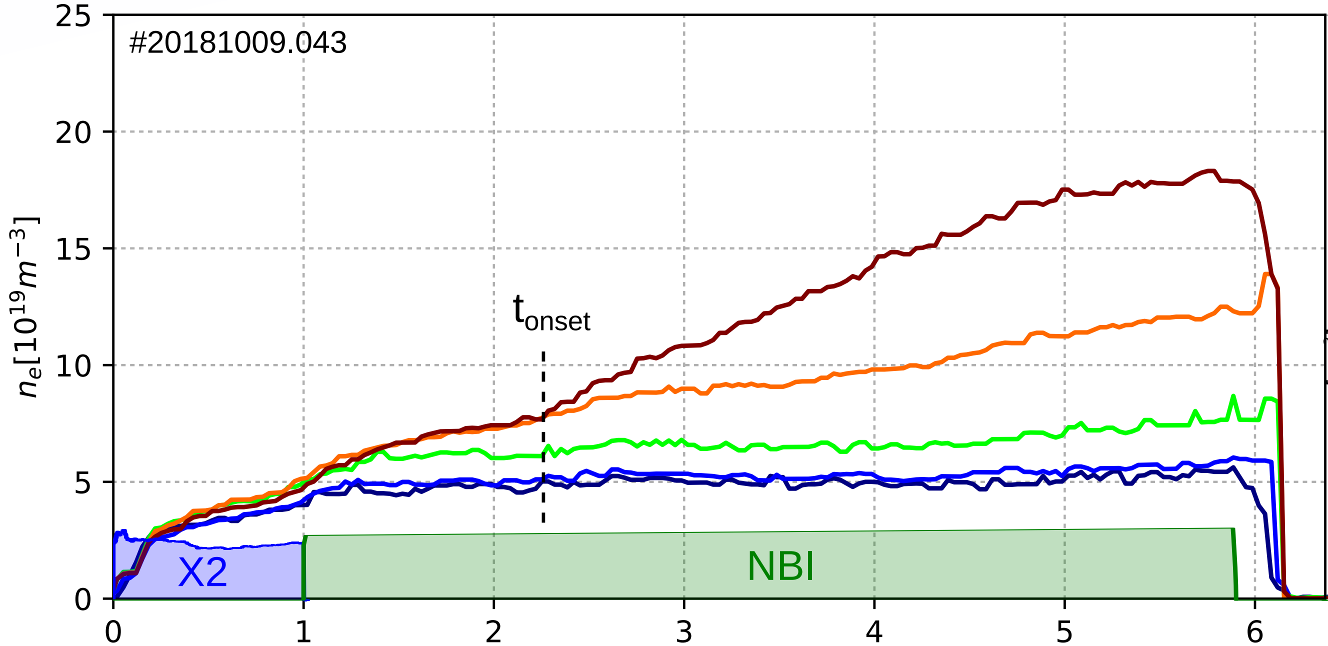


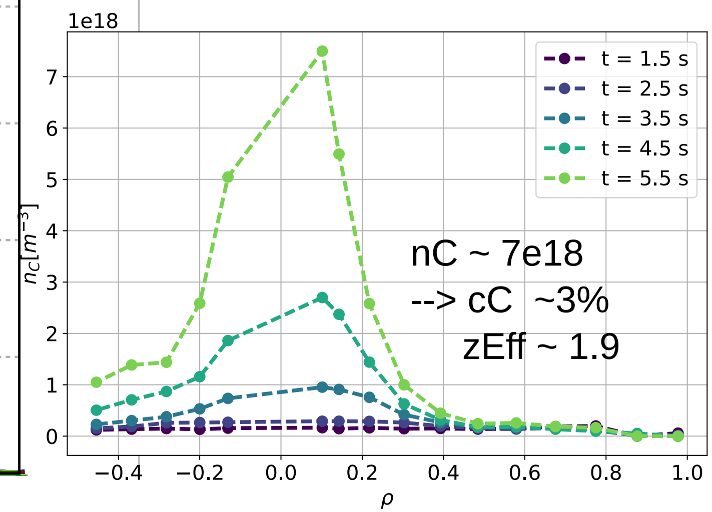


BACKUP: Pure NBI density peaking

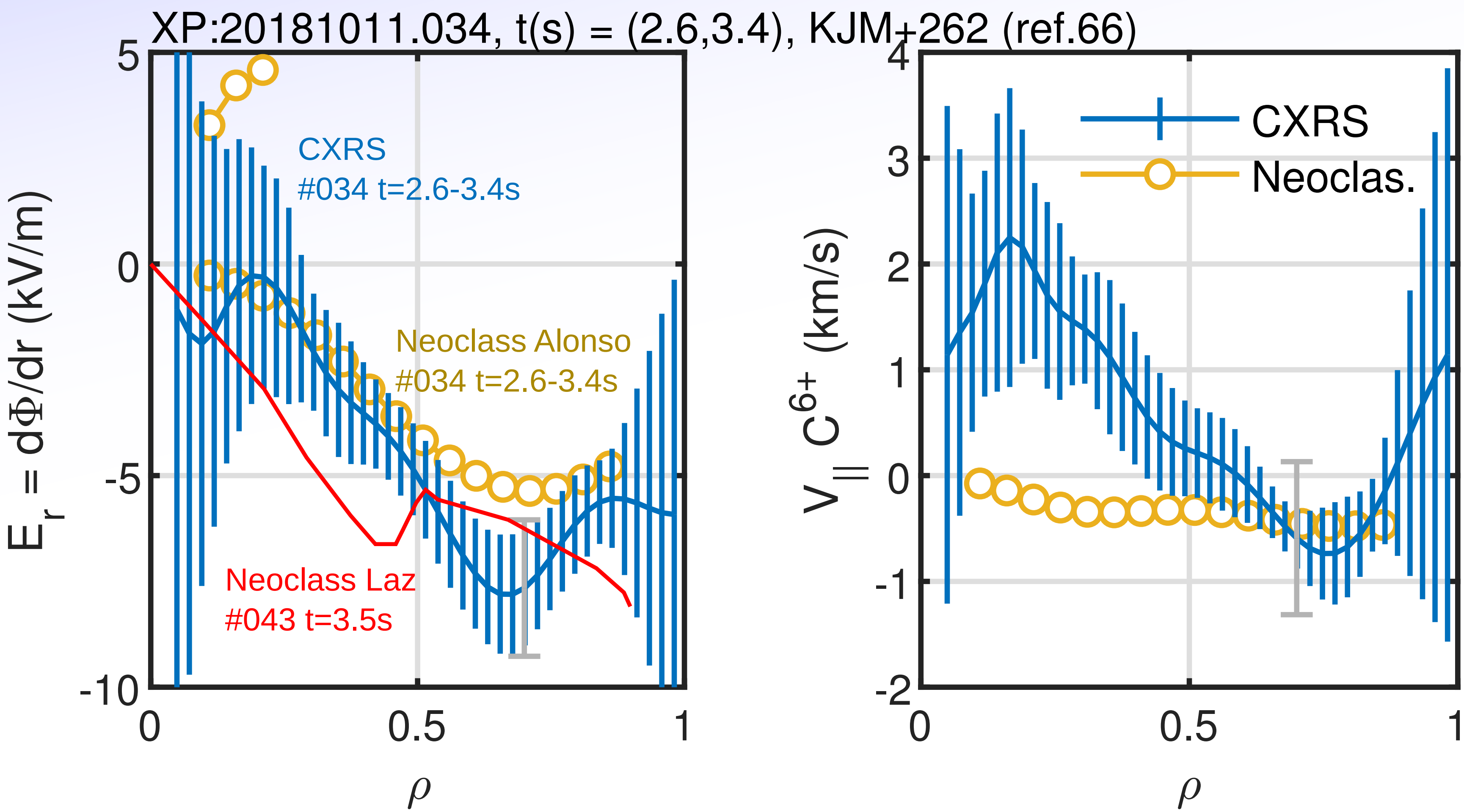
Other shots:







BACKUP: Er during NBI peaking



Case 1: NBI + O2

- NBI creates peaked density profiles with steadily increasing density.
- T_i slightly above T_i^{limit} is breifly achieved.
- ECRH kills otherwise stable peaked density - T_i drops back below limit.