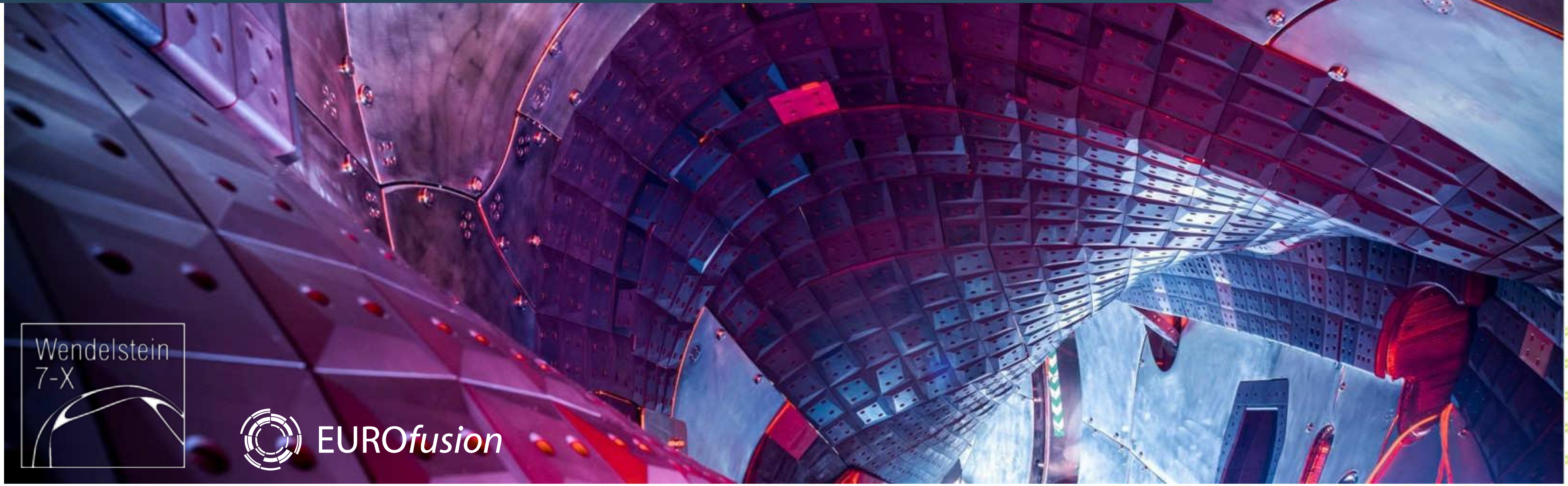
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

S42: NBI+ECRH in high-mirror

Presented by Oliver Ford on behalf of the W7-X Team



TF-I Meeting. 3rd February 2023

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Proposals

Prio-I:

oliford_002	Threshold of P_ECRH into pure NBI for heat transport change	Scenario-development
stato_022	ECRH into pure NBI with no X2 absoption	
dacar_006	Turbulence in suppressed turb. scenarios (DR, PCI, CECE, SXR)	Measurement specifics
thir_002	Threshold P_ECRH for impurity transport change	
alkn_004	Beta effects on edge topology	Measurements at high-beta
cbra_011	XMCTS Shafranov shift at different betas	
kbr_10	Alfvén Eigenmodes in high beta	
mspolaor_002	Edge EM turbulence in high beta (MPM probe)	
tya_023	MHD stability in high performance	

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Prio-2:

astechow_011	Turbulence "matching" between pure ECRH and NBI	Modification request

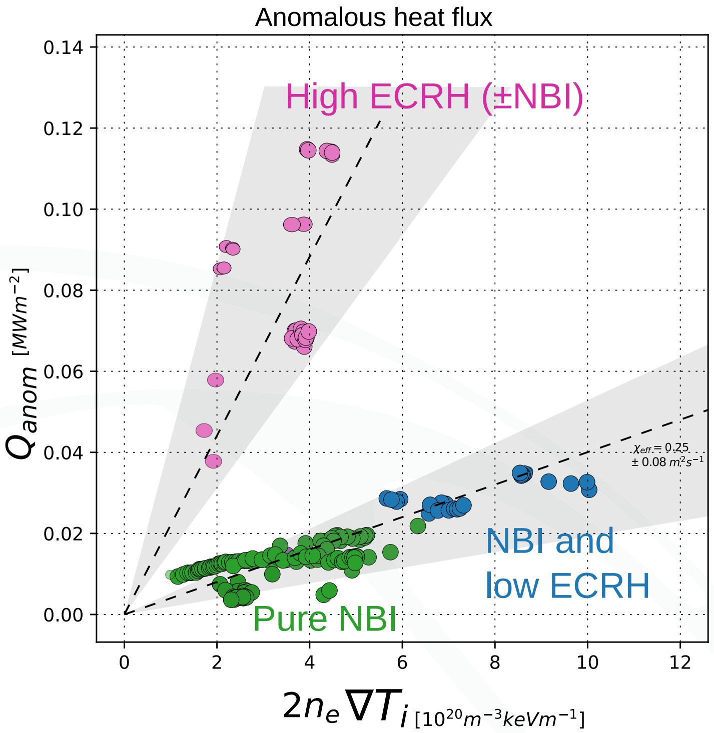
Additional:

cswee_001, twegner_007	Impurity transport in NBI+ECRH	Cover in passing

NBI+ECRH scenario development

oliford_002 - Threshold of P_{ECRH} into pure NBI for heat transport change

Hypothesis: Some threshold ECRH power exists where density pump-out is strong enough to switch to reduced turbulence.



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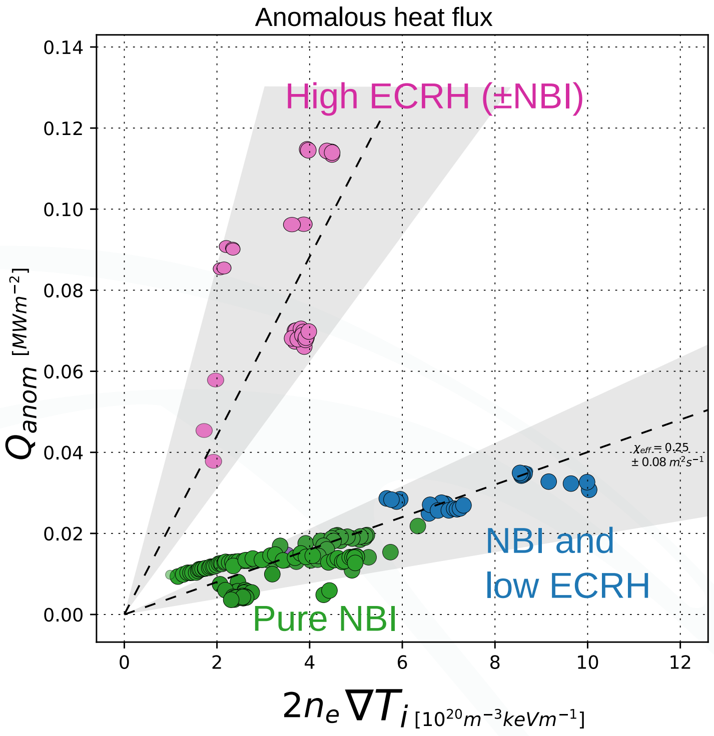

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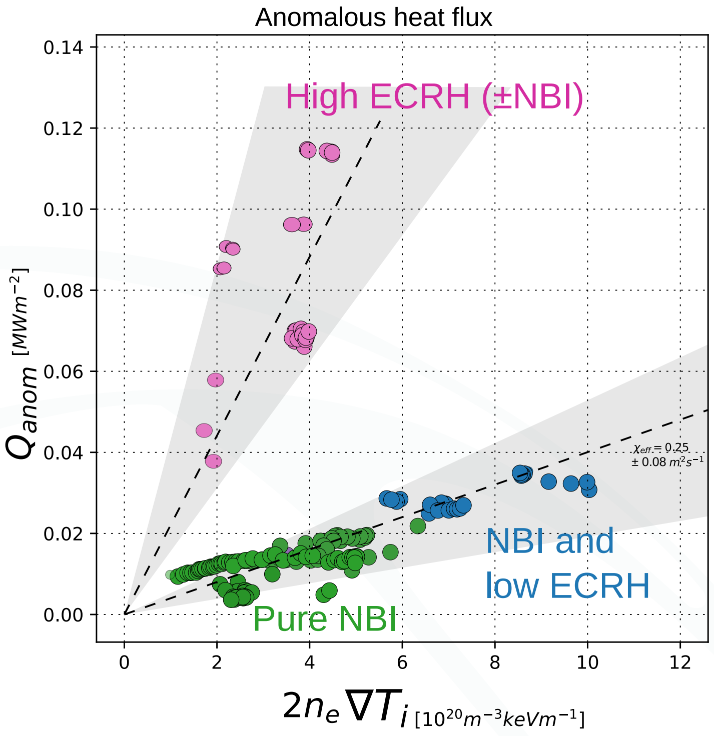

Base waveform for most shots:
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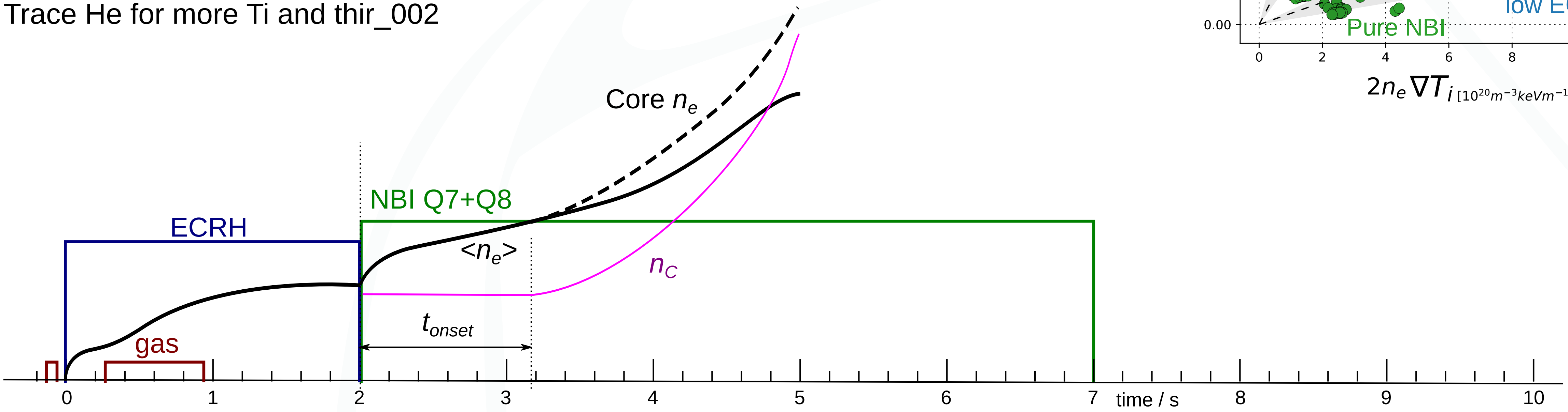
- Match ECRH power for astechow_011
- Trace He for more Ti and thir_002



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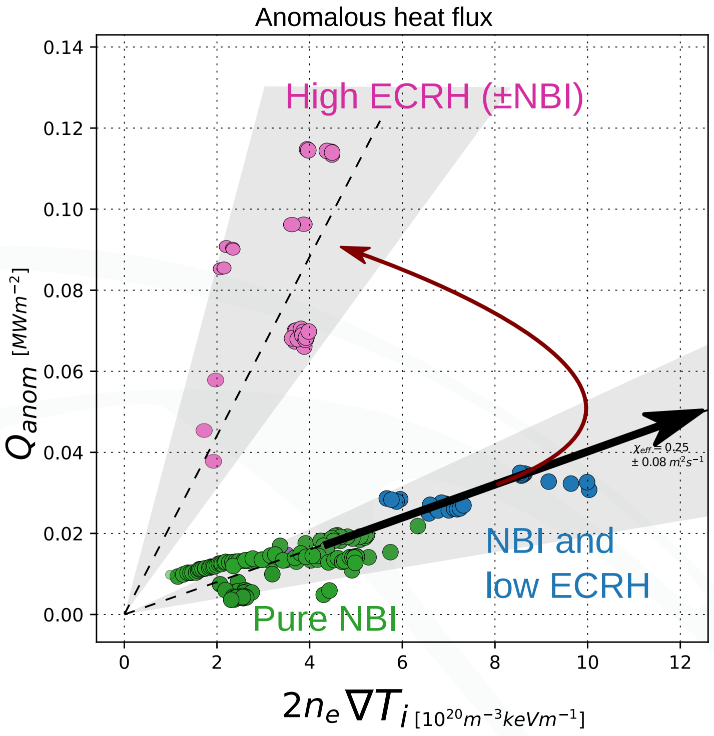

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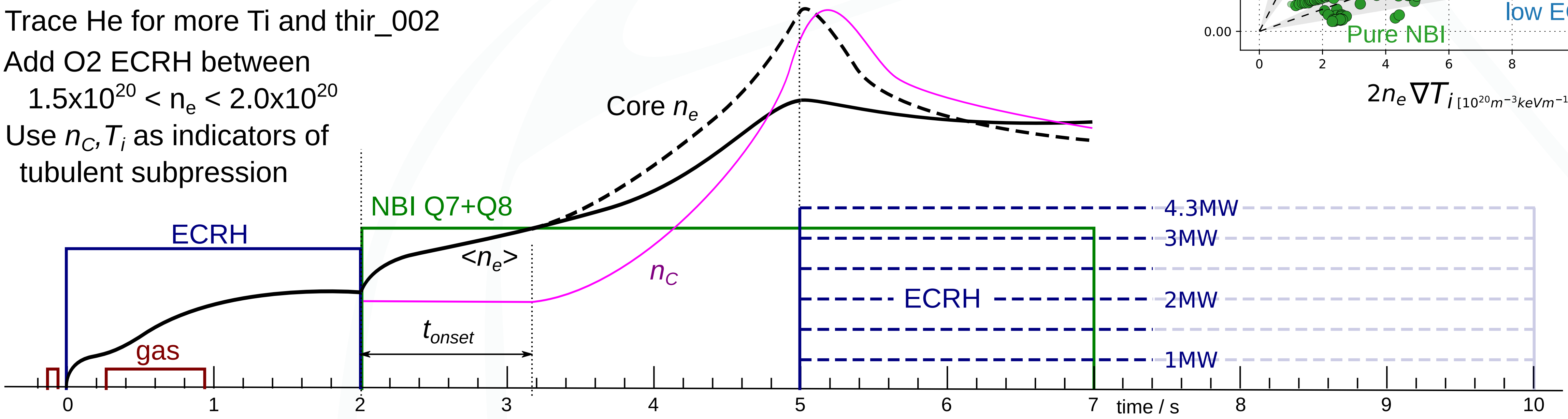

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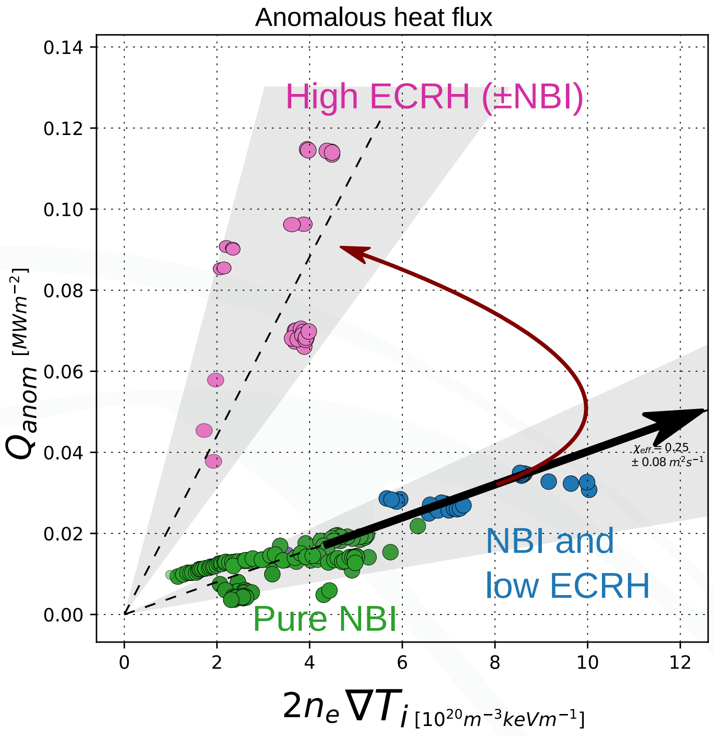

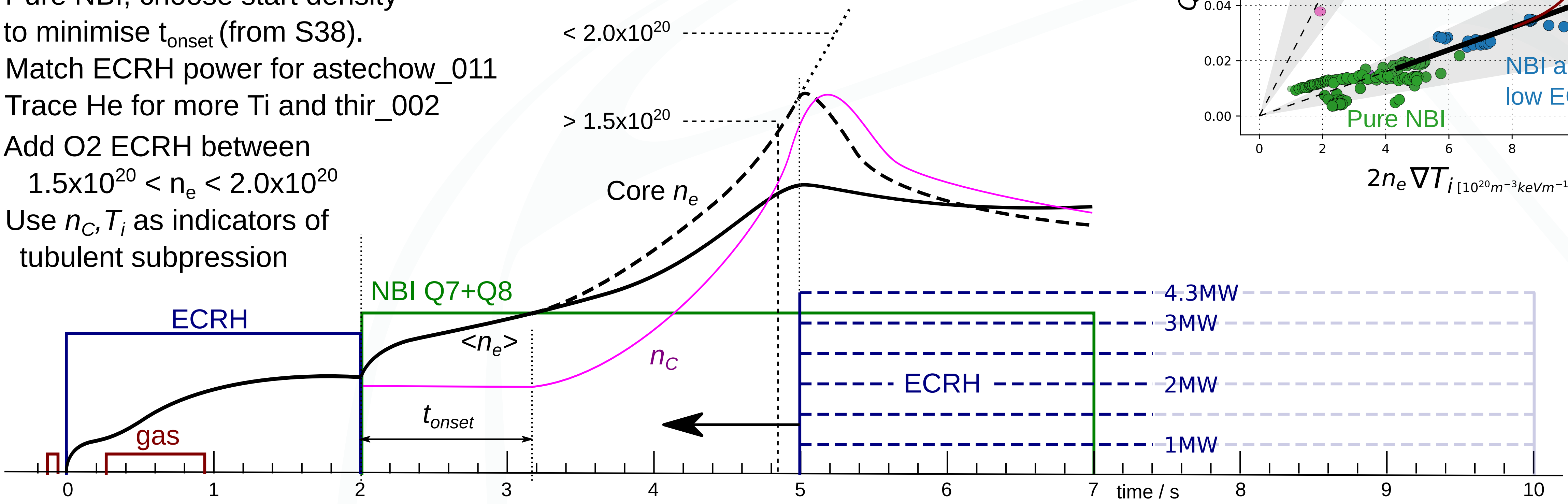

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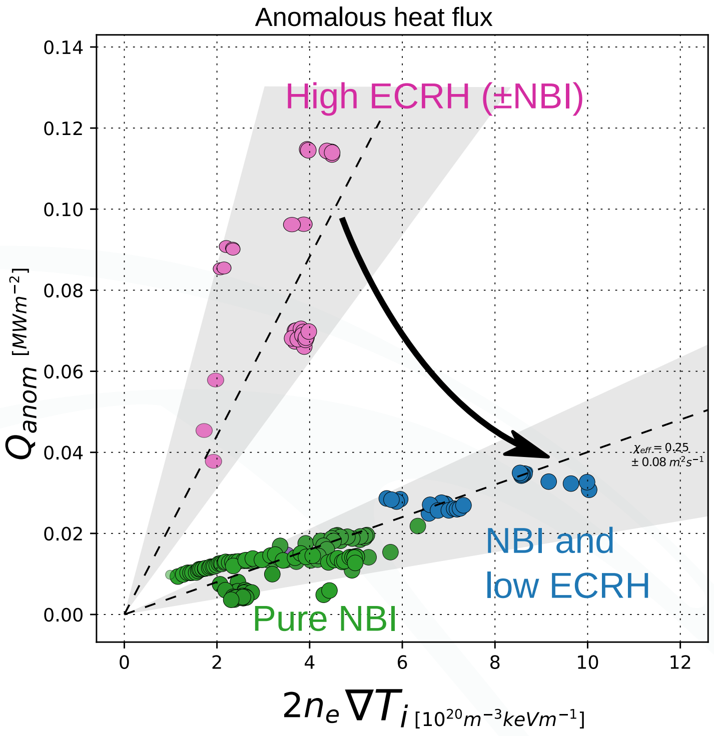

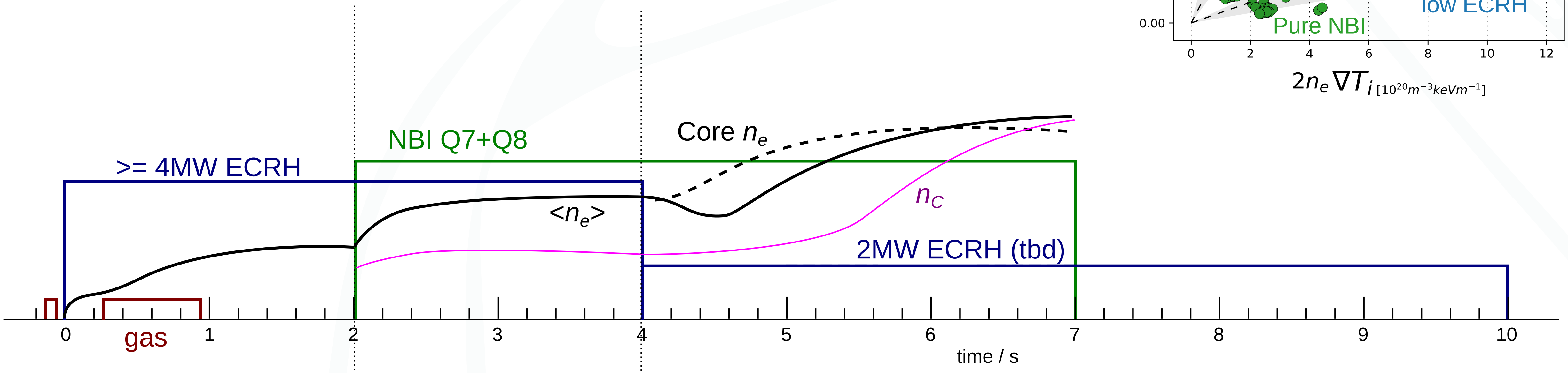

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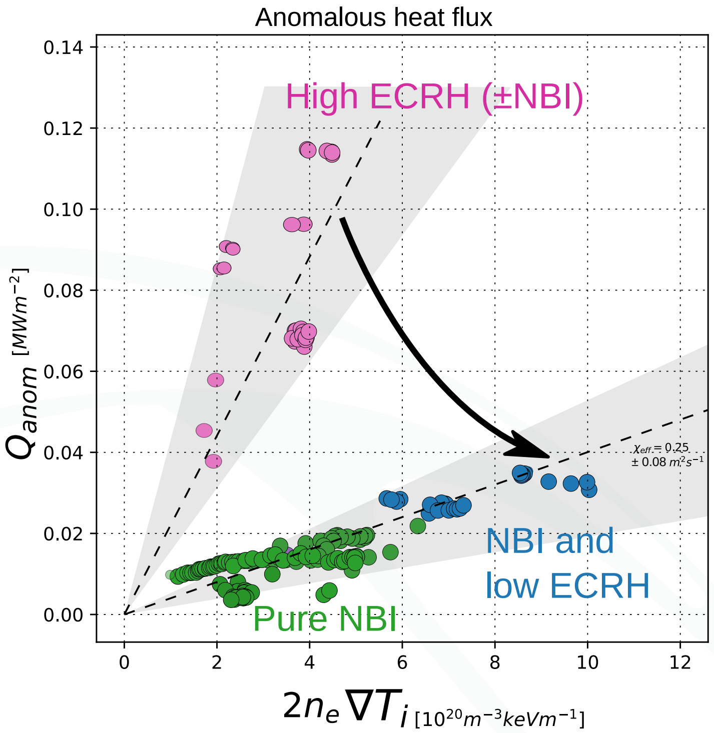

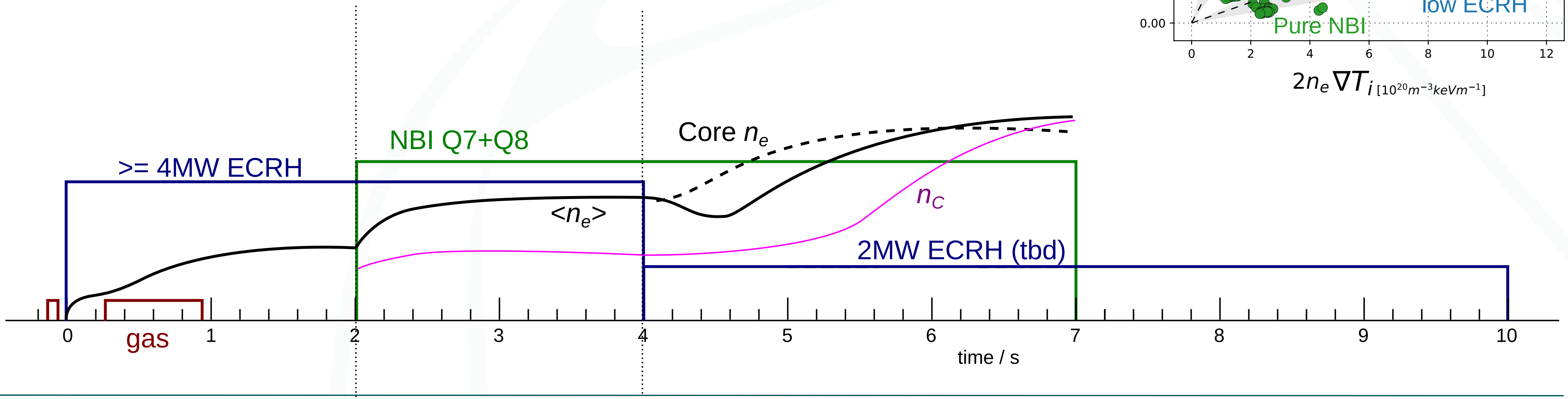

Diagnostic repeats

For dacar_006, thir_002, mspolaor_002:
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- dacar_006: Doppler reflectometer: multiple 250ms sweeps = ~1s of integration
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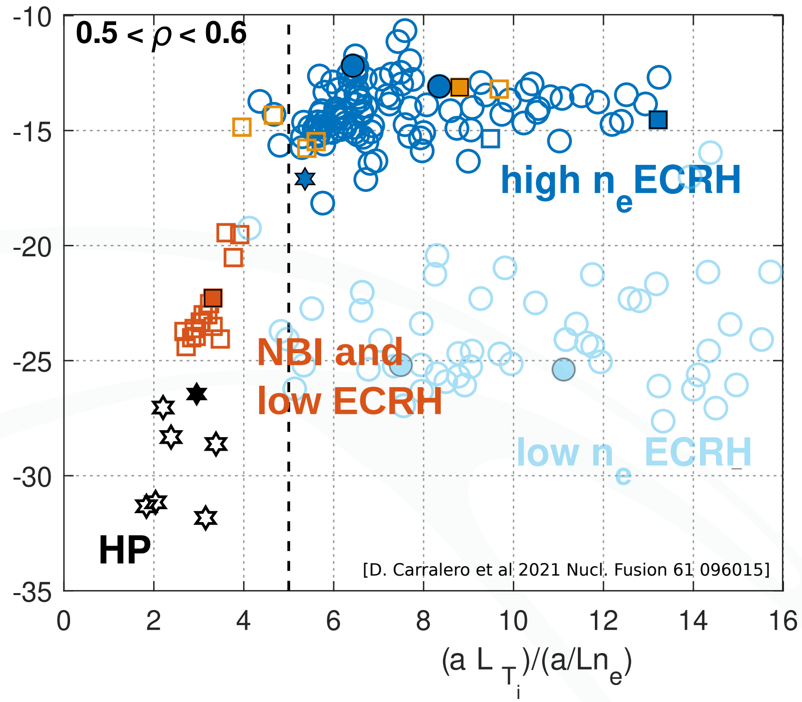

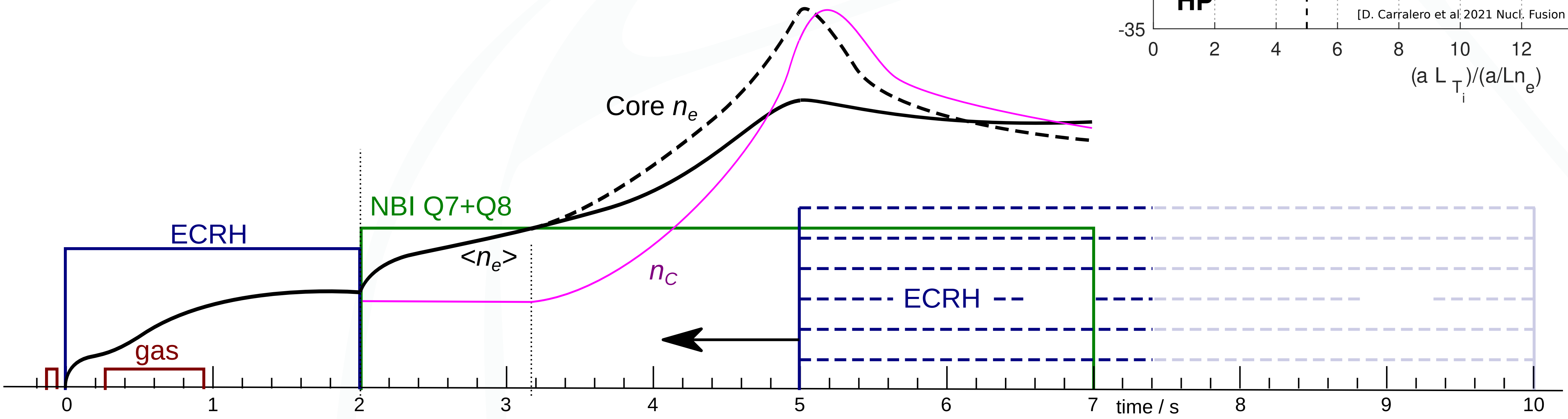

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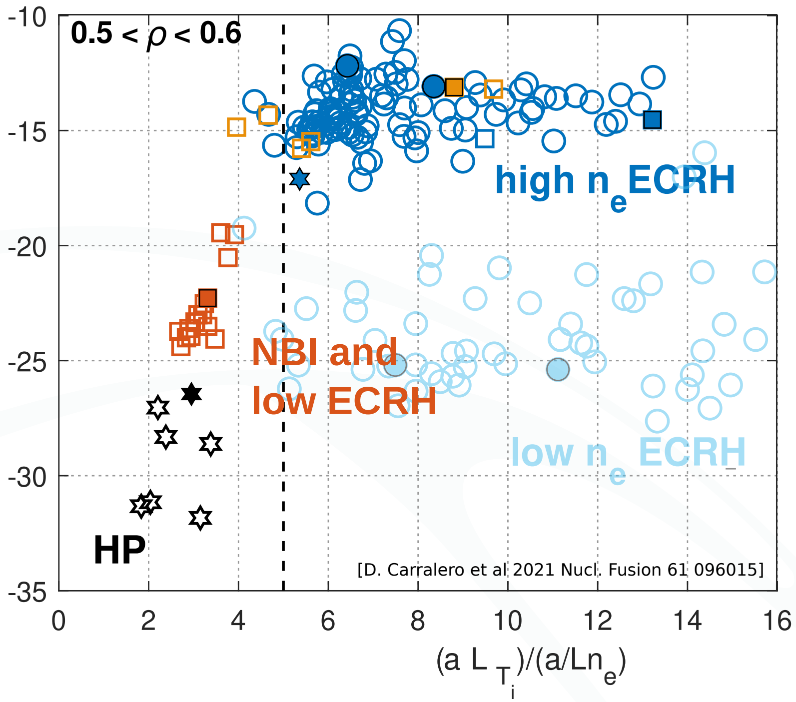

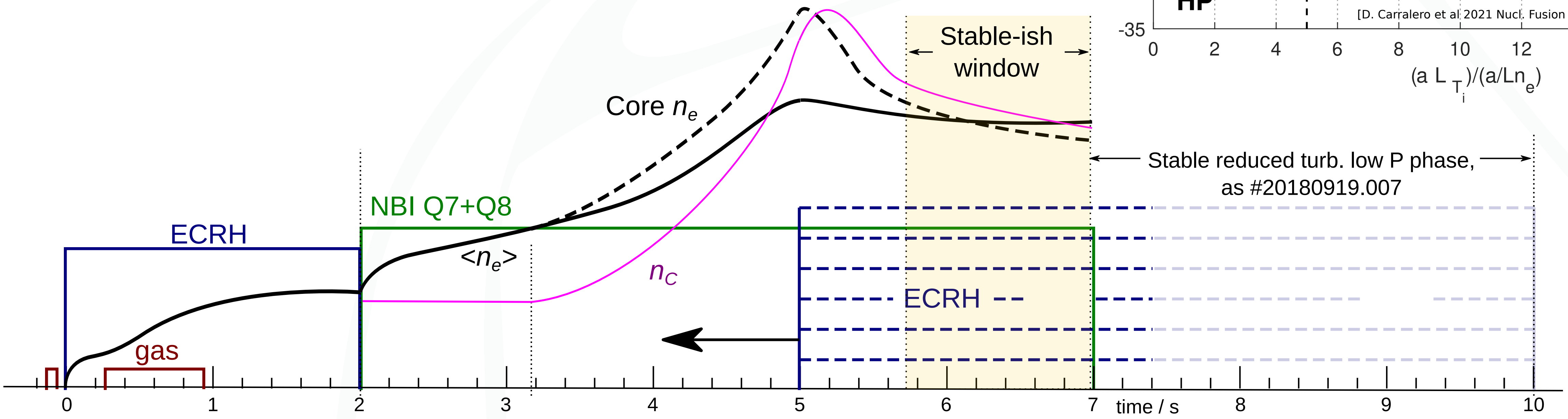

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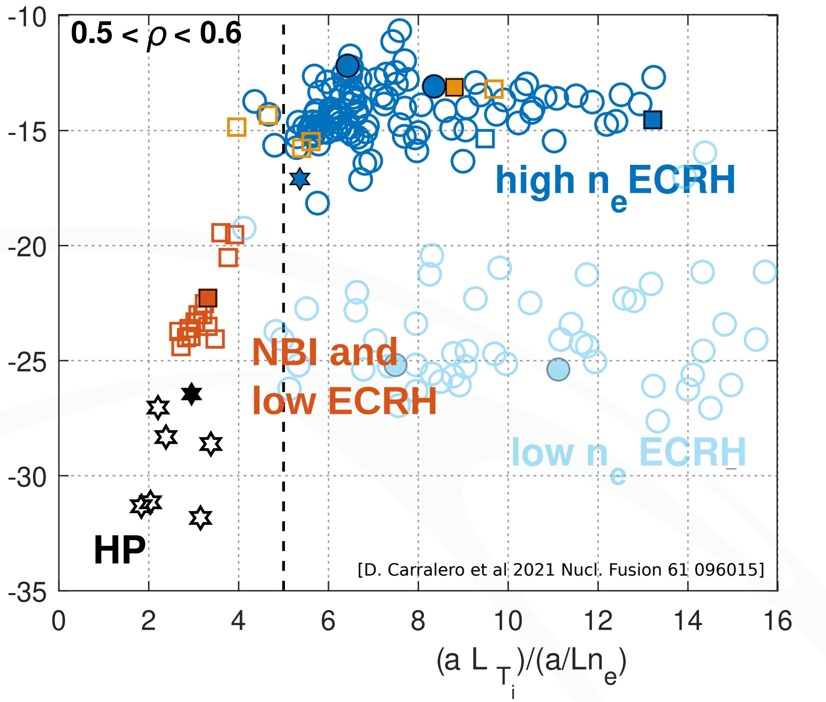
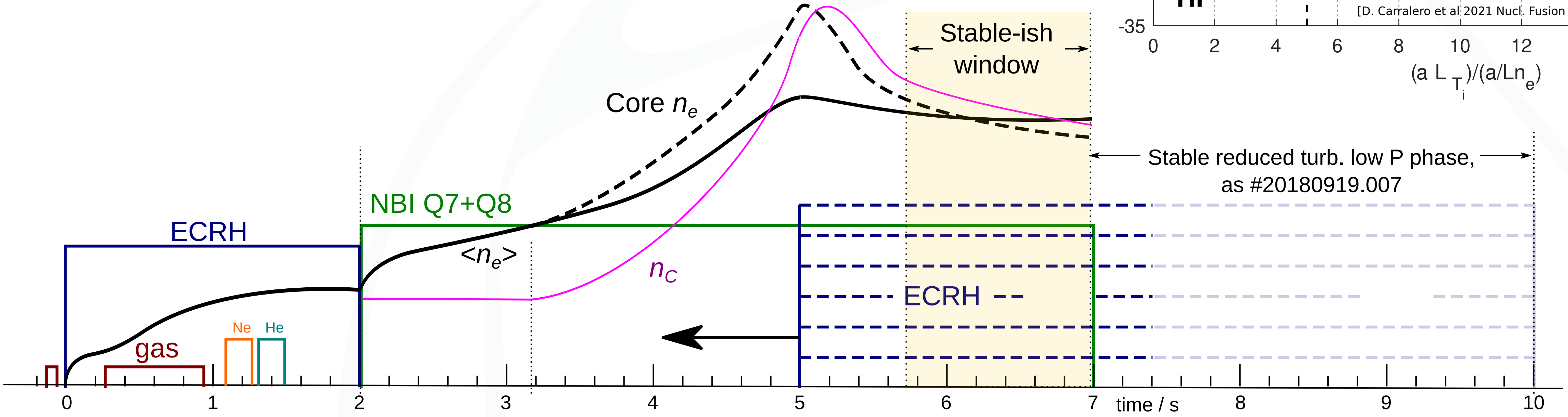
- oliford_002, dacar_006: One 'super-carbon' CXRS --> 130 points T_i profiles.





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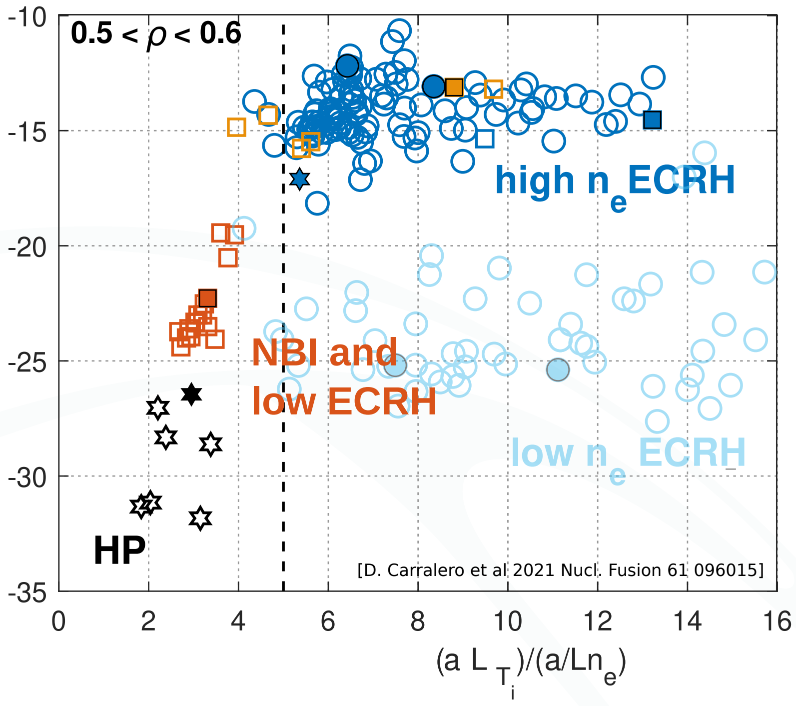
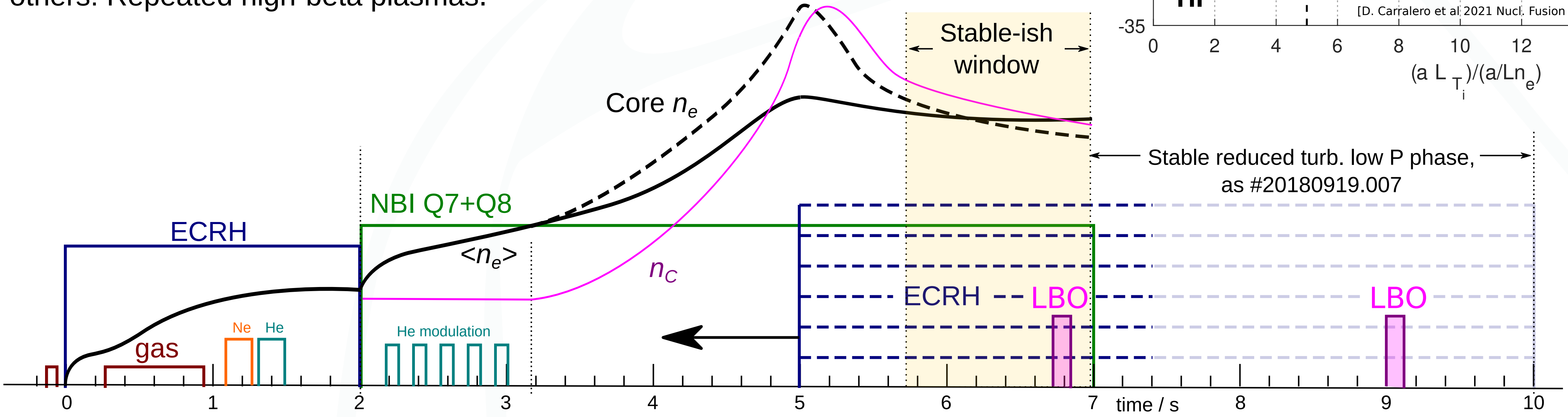
- thir_002: He modulation before onset to confirm high particle transport.
- cswee_001, twegner_007: Fe LBO injection for impurity measurements.
- others: Repeated high-beta plasmas.





Additional sources

If NI20 (source 3 and/or 4) available:
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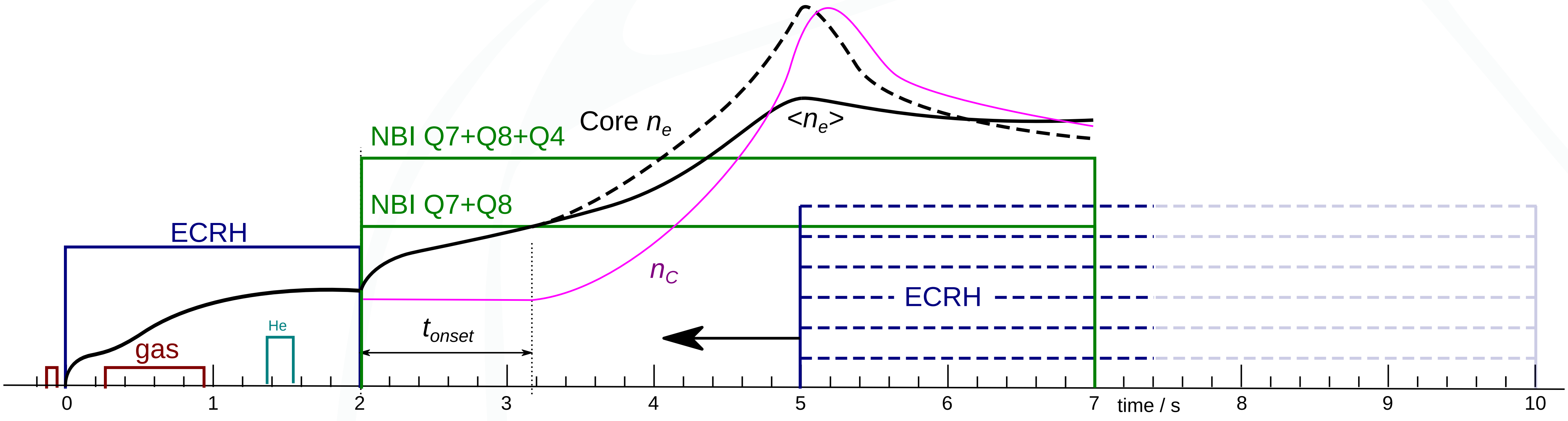
- requires one pure-NBI shot with 3/4 sources for density profile check for O2. (also, energy extension?)



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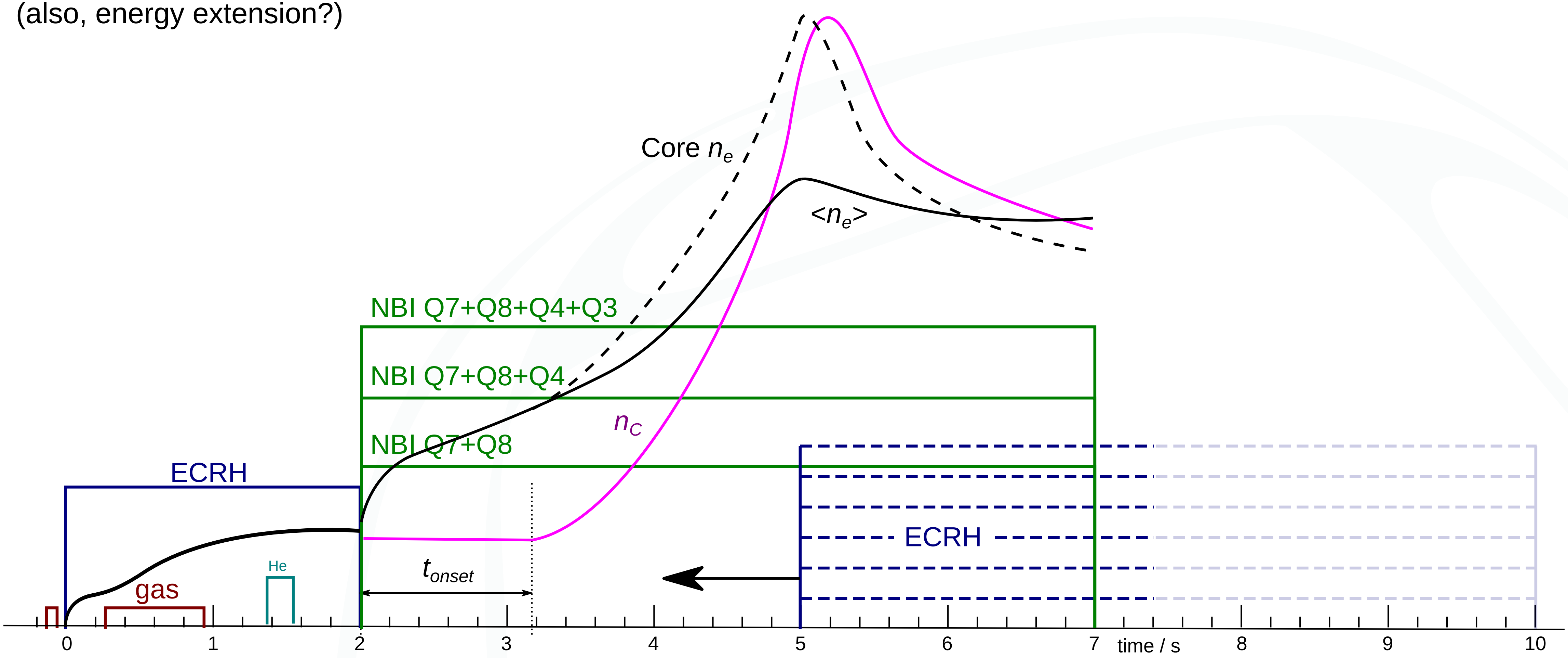

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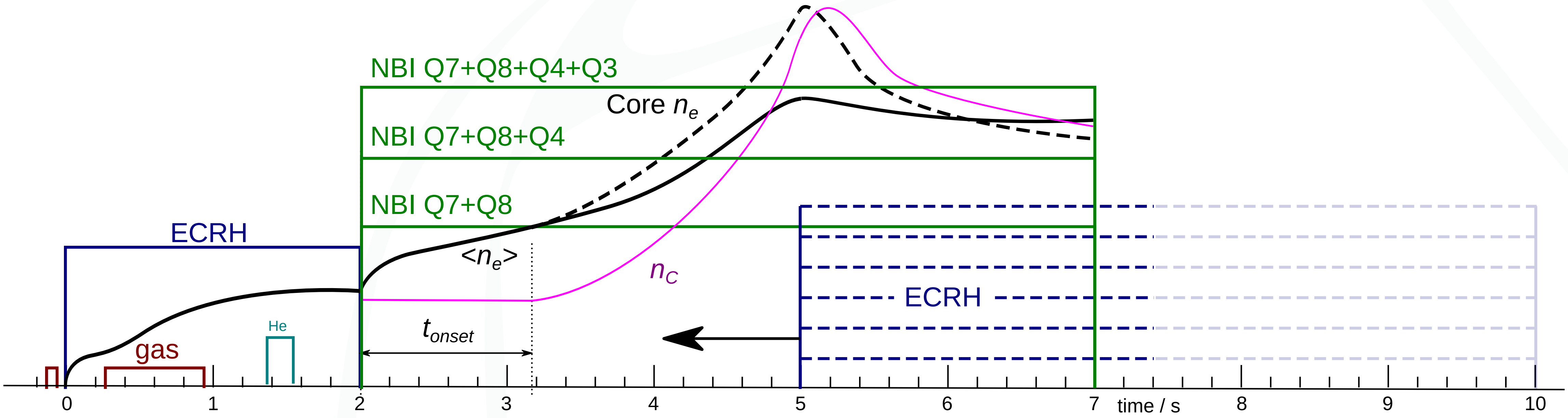

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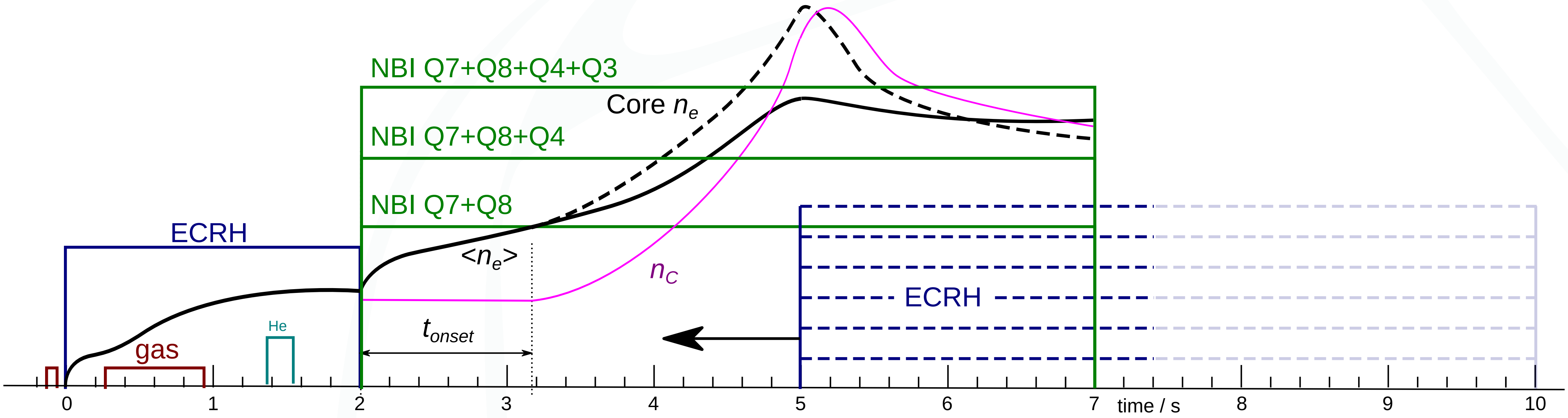

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Almost certainly not possible, but *critically* important! --> contingency?
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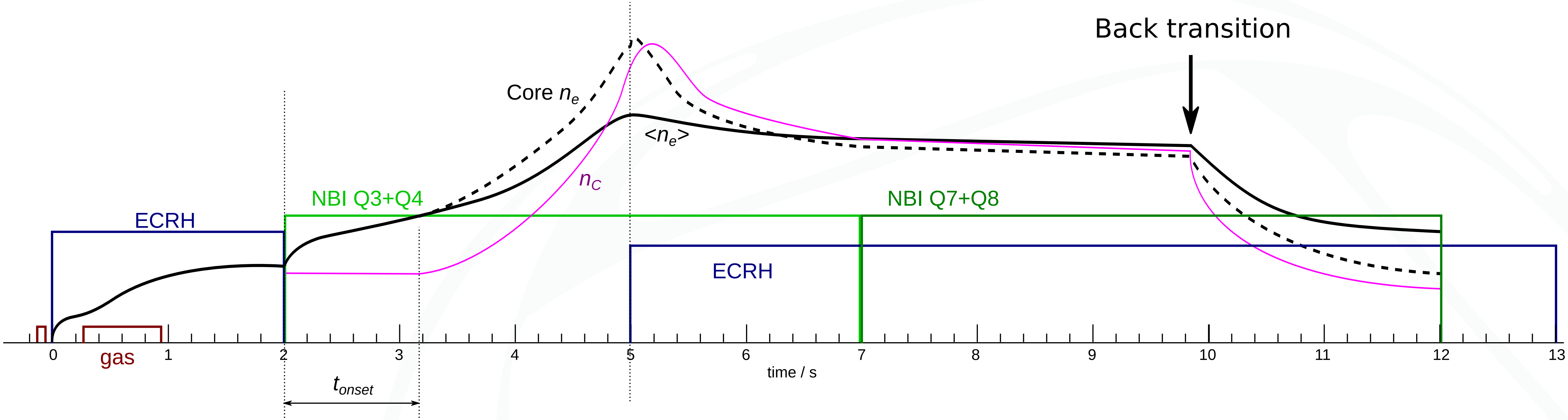

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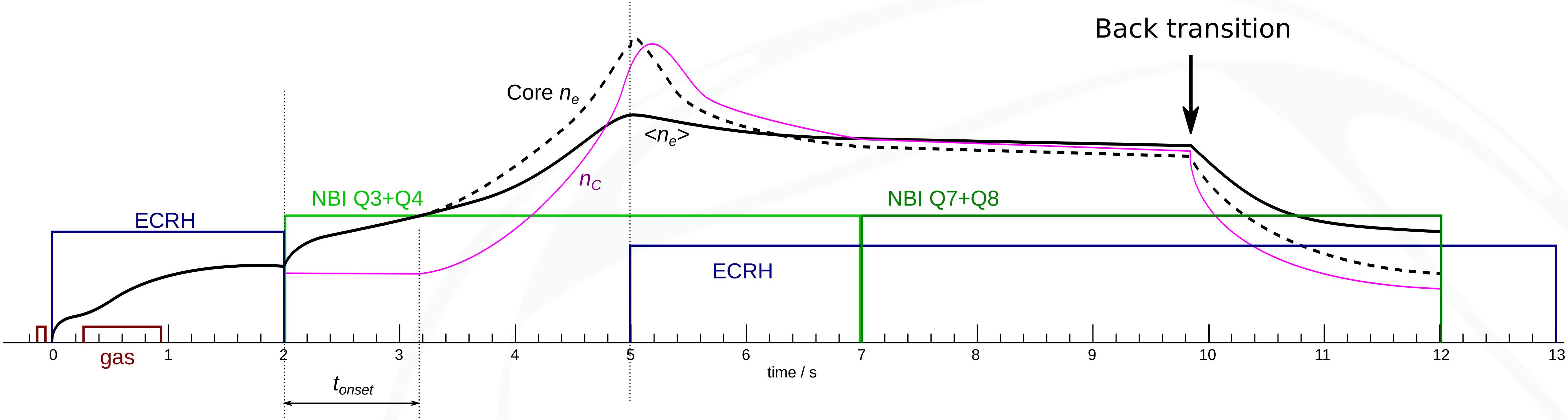

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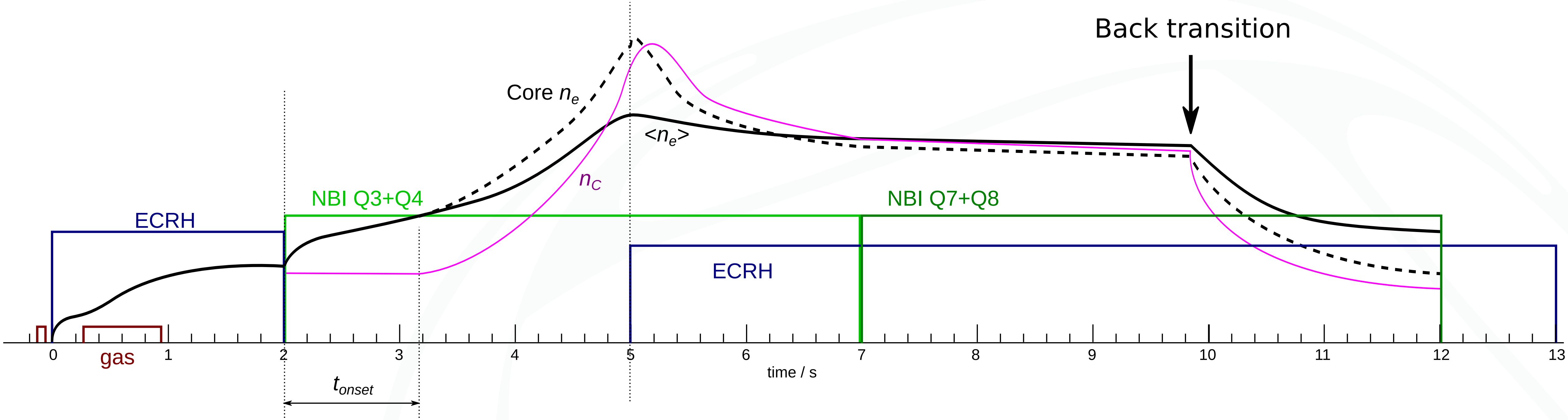

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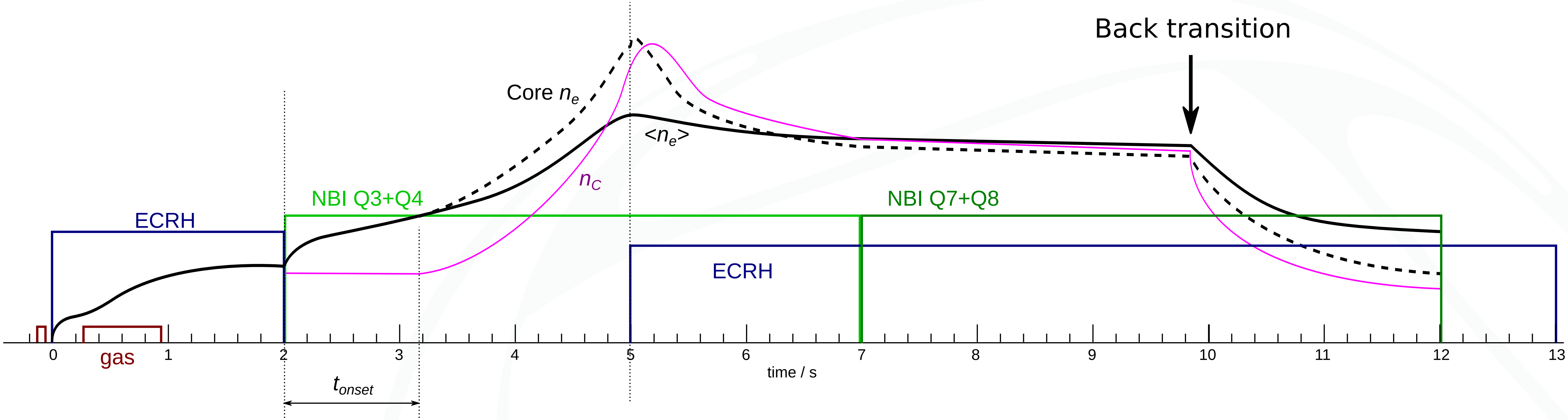

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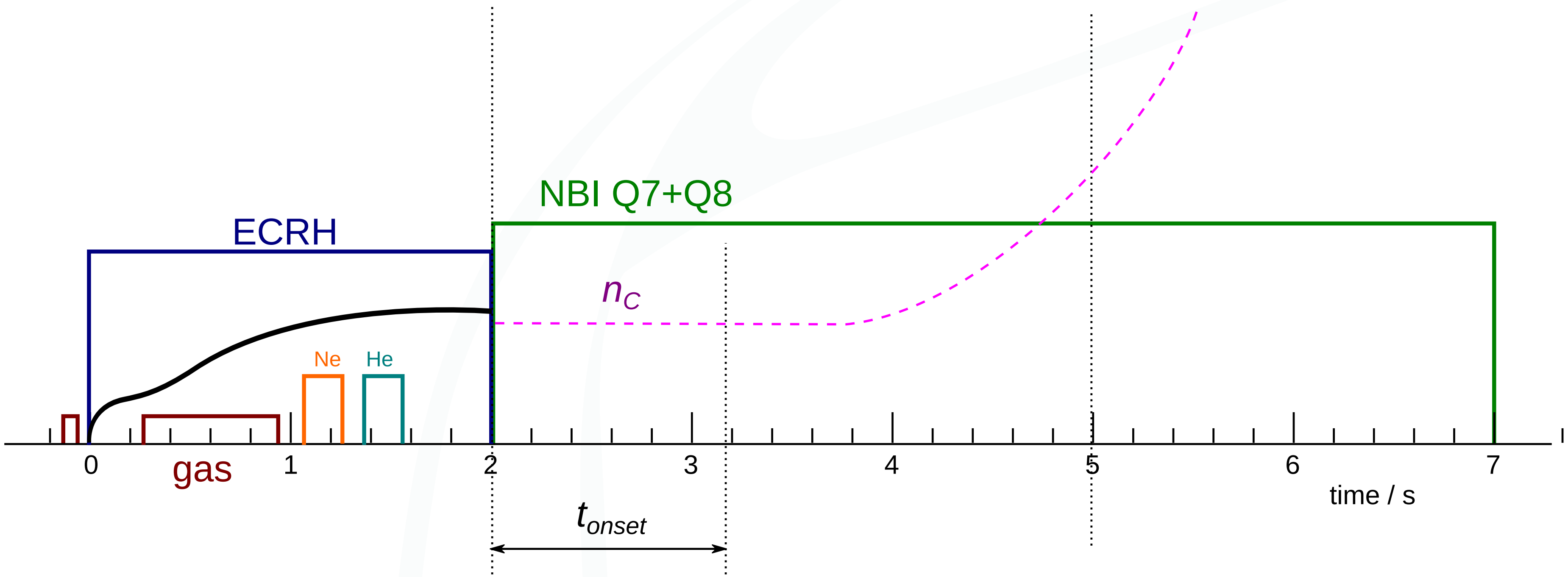

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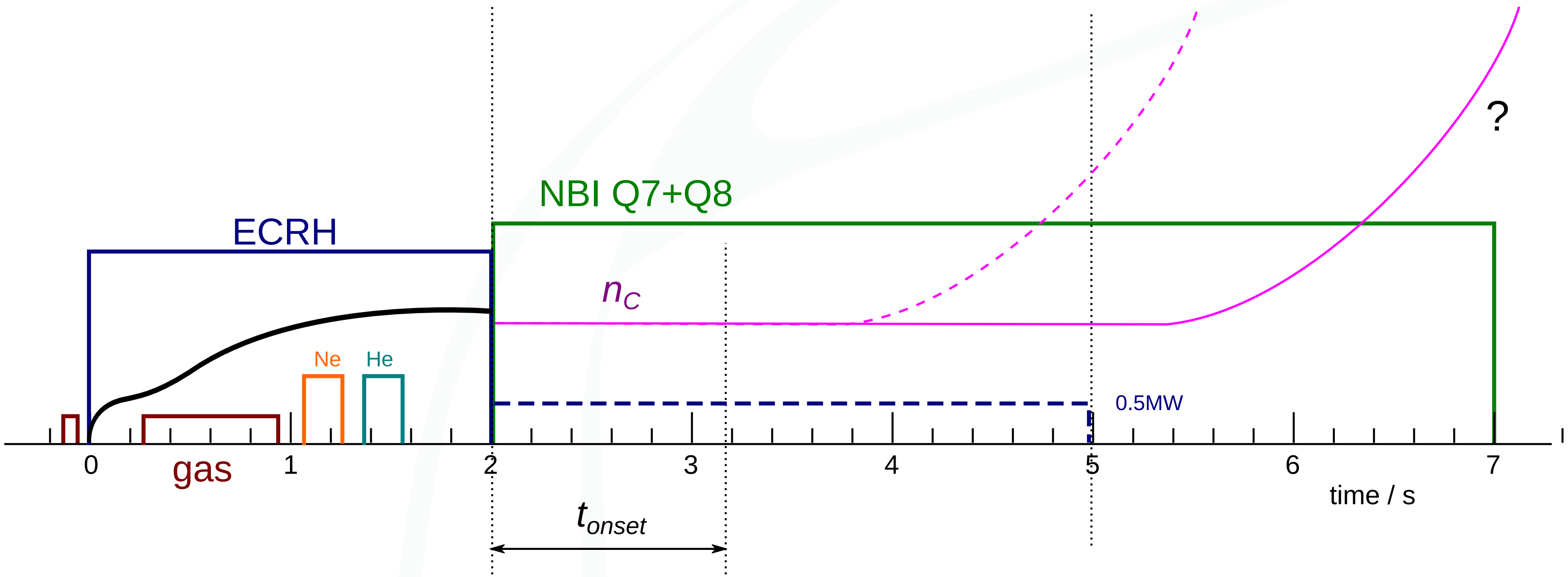

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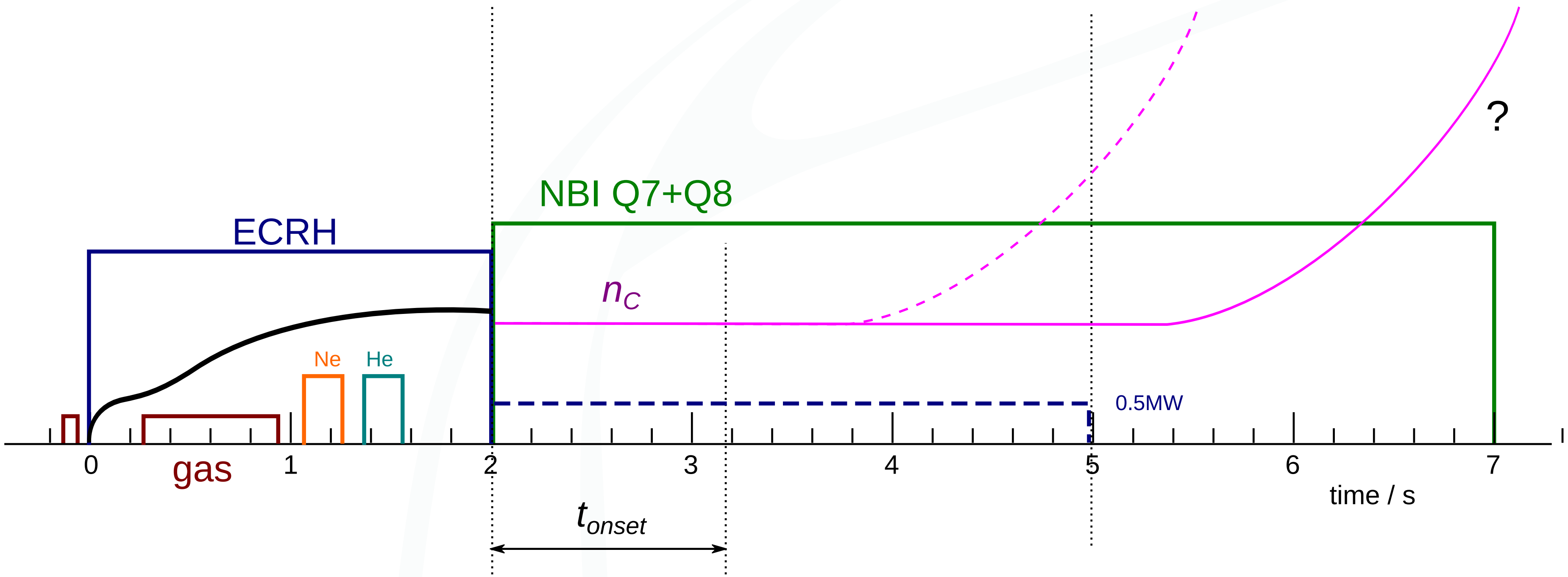

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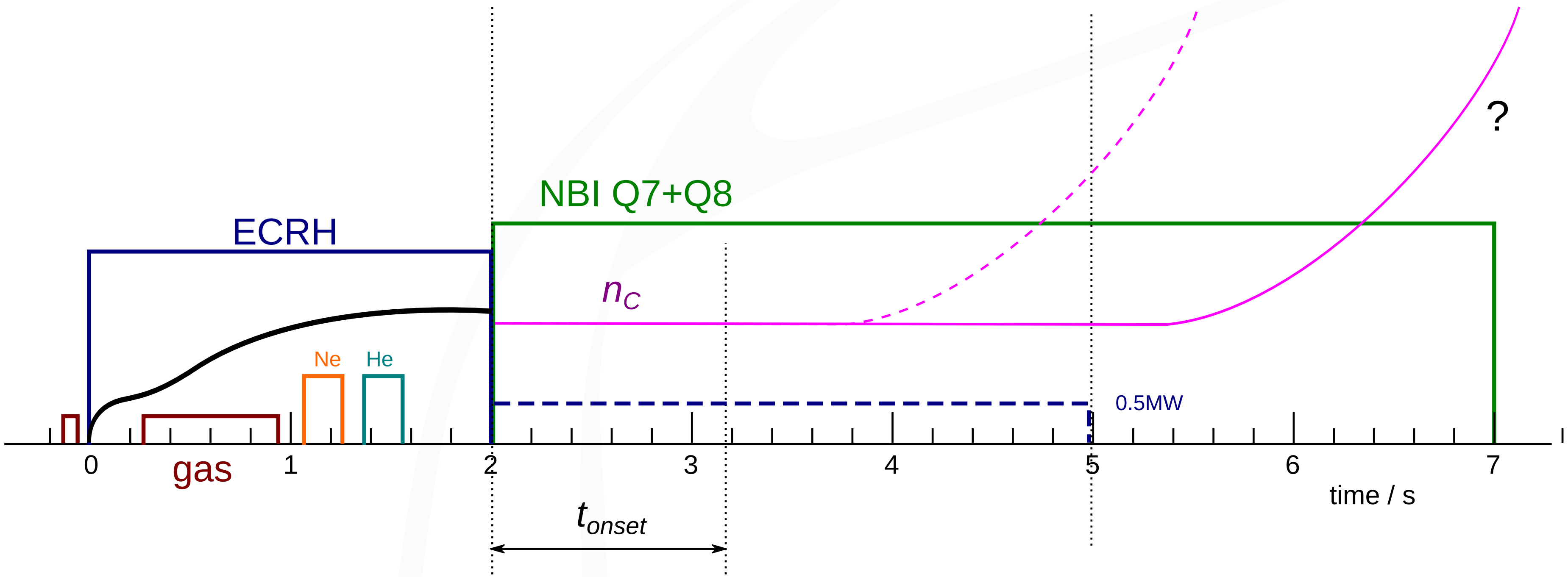

Shot list

Note: Currently no ECRH-only program during NBI regeneration. Any ideas from prio-I proposals??

Safety | Scenario dev. | Diagnostic

#	Description	O2 ECRH	NBI	Diagnostic purturbation	Proposals
1	Pure NBI test to check density evolution	0 MW	Q7, Q8	If OP allows: He modulation, LBO, GPI	-
2	- ECRH only -				
3	NBI+O2, as #20221201.058 but lower ne	3MW	Q7, Q8	Trace He only, maybe GPI	stato_022, oliford_002, thir_002, +beta*
4	- ECRH only -				
5	NBI+O2, higher power (skip if Ti(#3) already drops to 1.5keV)	4MW	Q7, Q8	Trace He only, maybe GPI	stato_022, oliford_002, thir_002, +beta*
6	- ECRH only -				
7	NBI+O2, mid-power, #20221201.054 from other side	2MW	Q7, Q8	Trace He only, maybe GPI	oliford_002, stato_022, thir_002, +beta*
8	- ECRH only -				
9	NBI+O2, identity #181009.034 above O2 cut-off	1MW	Q7, Q8	Trace He only, maybe GPI	stato_022, oliford_002, thir_002, +beta*
10	- ECRH only -				
11	NBI+O2, threshold scan, between boundary in 3,5,7,9	1.5MW (tbd)	Q7, Q8	Trace He only, maybe GPI	oliford_002, stato_022, thir_002, +beta*
	-- switch power supplies to Q4 (+Q3) here if repeats require < 3.5MW (< 3MW if Q3 also) ---				
12	Repeat 3/5/7/9 for diagnostics. CXRS super-carbon	1.5MW (tbd)	Q7, Q8	Trace He only, maybe GPI	dacar_006, thir_002, mspolaor_002, +beta*
13	- ECRH only -				
14	Repeat 3/5/7/9 for diagnostics. Fe injection. Trace Ne.	1.5MW (tbd)	Q7, Q8	Fe injection. Trace Ne. GPI, MPM	dacar_006, thir_002, mspolaor_002, +beta*
15	- ECRH only -				
16	Repeat 3/5/7/9 for diagnostics (Drop for #25 if 4 sources available)	1.5MW (tbd)	Q7, Q8	Trace Ne. GPI, MPM	dacar_006, thir_002, mspolaor_002, +beta*
17	- ECRH only -				
18	Approach from NBI+high ECRH	1.5MW (tbd)	Q7, Q8	Only in lead-out	oliford_002, stato_022, thir_002, +beta*
	-- switch power supplies to Q4 (+Q3) ---				
19	3+ sources pure NBI	0 MW	Q7, Q8, Q4	If OP allows: He modulation, LBO, GPI	-
20	- ECRH only -				
21	3+ sources NBI + O2 ECRH	2MW (tbd)	Q7, Q8, Q4	Trace He only	oliford_002, stato_022, thir_002, +beta*
22	- ECRH only -				
23	7s NBI+ECRH for back-transition (unlikely to be possible)	2MW (tbd)	Q7,Q8,Q3,Q4	All in in 5 < t < 7s	oliford_002, stato_022, thir_002, +beta*
24	- ECRH only -				
25	Onset suppression	0.5MW	Q7, Q8	Yes, after 6s	thir_002
26	- ECRH only -				
27	NBI+O2, threshold scan, between boundary in 3,5,7,9,11	1.5MW (tbd)	Q7, Q8	Yes, all	oliford_002, stato_022, thir_002, +beta*
28	- ECRH only -				
29	Repeat 3/5/7/9/11 for diagnostics (Drop for #25 if 4 sources available)	1.5MW (tbd)	Q7, Q8	Trace Ne. GPI, MPM	dacar_006, thir_002, mspolaor_002, +beta*

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20	- ECRH only -				
21	3+ sources NBI + O2 ECRH	2MW (tbd)	Q7, Q8, Q4	Trace He only	oliford_002, stato_022, thir_002, +beta*
22	- ECRH only -				
23	7s NBI+ECRH for back-transition (unlikely to be possible)	2MW (tbd)	Q7,Q8,Q3,Q4	All in in 5 < t < 7s	oliford_002, stato_022, thir_002, +beta*
24	- ECRH only -				
25	Onset suppression	0.5MW	Q7, Q8	Yes, after 6s	thir_002
26	- ECRH only -				
27	NBI+O2, threshold scan, between boundary in 3,5,7,9,11	1.5MW (tbd)	Q7, Q8	Yes, all	oliford_002, stato_022, thir_002, +beta*
28	- ECRH only -				
29	Repeat 3/5/7/9/11 for diagnostics (Drop for #25 if 4 sources available)	1.5MW (tbd)	Q7, Q8	Trace Ne. GPI, MPM	dacar_006, thir_002, mspolaor_002, +beta*

Shot list

Note: Currently no ECRH-only program during NBI regeneration. Any ideas from prio-I proposals??

Safety | Scenario dev. | Diagnostic

#	Description	O2 ECRH	NBI	Diagnostic purturbation	Proposals
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3	NBI+O2, as #20221201.058 but lower ne	3MW	Q7, Q8	Trace He only, maybe GPI	stato_022, oliford_002, thir_002, +beta*
4	- ECRH only -				
5	NBI+O2, higher power (skip if Ti(#3) already drops to 1.5keV)	4MW	Q7, Q8	Trace He only, maybe GPI	stato_022, oliford_002, thir_002, +beta*
6	- ECRH only -				
7	NBI+O2, mid-power, #20221201.054 from other side	2MW	Q7, Q8	Trace He only, maybe GPI	oliford_002, stato_022, thir_002, +beta*
8	- ECRH only -				
9	NBI+O2, identity #181009.034 above O2 cut-off	1MW	Q7, Q8	Trace He only, maybe GPI	stato_022, oliford_002, thir_002, +beta*
10	- ECRH only -				
11	NBI+O2, threshold scan, between boundary in 3,5,7,9	1.5MW (tbd)	Q7, Q8	Trace He only, maybe GPI	oliford_002, stato_022, thir_002, +beta*
	-- switch power supplies to Q4 (+Q3) here if repeats require < 3.5MW (< 3MW if Q3 also) ---				
12	Repeat 3/5/7/9 for diagnostics. CXRS super-carbon	1.5MW (tbd)	Q7, Q8	Trace He only, maybe GPI	dacar_006, thir_002, mspolaor_002, +beta*
13	- ECRH only -				
14	Repeat 3/5/7/9 for diagnostics. Fe injection. Trace Ne.	1.5MW (tbd)	Q7, Q8	Fe injection. Trace Ne. GPI, MPM	dacar_006, thir_002, mspolaor_002, +beta*
15	- ECRH only -				
16	Repeat 3/5/7/9 for diagnostics (Drop for #25 if 4 sources available)	1.5MW (tbd)	Q7, Q8	Trace Ne. GPI, MPM	dacar_006, thir_002, mspolaor_002, +beta*
17	- ECRH only -				
18	Approach from NBI+high ECRH	1.5MW (tbd)	Q7, Q8	Only in lead-out	oliford_002, stato_022, thir_002, +beta*
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High-beta

Most prio-I proposals ask simply for 'high beta'.
What we have achieved so far:

Shot	**#181016.037**	**#181009.034**	**#221201.053**	**#221207.054**	**#221207.058**
Short desc	Pellets HP	NBI+ECRH	NBI/2+ECRH	SS NBI+ECRH	Torsten's hammer
NBI	0	3.5	1.7	3.5	3.5
ECRH	5	1	1	2	3.5
ne dl [10^19]	8	11	9	5	16
Ne(0) [10^19]	8.5	12	7.5 (boz prelim)	5.5 (boz prelim)	25 (boz prelim)
Wdia	1.1	0.7	0.5	0.5	1
Ti(0)	3	1.8	1.8	2	1.5
Te(0)	3.5	2	1.8	2	1.5
Axis beta	1.80%	1.50%	0.90%	0.70%	2.40%

With more sources / more gyrotrons, could be more...

Power supplies and Wdia

Safety | Scenario dev. | Diagnostic

In #20221201.058 we achieved:
3.5MW NBI, 3.5MW ECRH, $n_e(0) \sim 2.2 \times 10^{20}$, $T_{i/e}(0) \sim 1.5$keV, Wdia = 1.0MJ, beta(0) ~ 2.0%

We need to reduce the density to ~1.8×10^{20}. Linear extrapolation --> Wdia = 900kJ
2 NBI sources + all existing gyrotrons available now (4.3MW) = 1.1MJ

If B1, F5 gyrotrons become available: Wdia = 1.4MJ
3 NBI sources and all gyrotrons: 6MW NBI + 3.9MW ECRH --> Wdia > 2MJ

Current ECRH status [component logbook page]:
A1 - 820 - 250 kW -- shared power supply with NBI Q4 (1750 kW)
A5 - 770 - 300 kW -- shared power supply with NBI Q8 (1750 kW)
B1 - 550 kW (not yet fully available)
B5 - 810 - 300 kW
C1 - 600 - 250 kW -- shared power supply with NBI Q3 (1750 kW)
C5 - 850 - 250 kW -- shared power supply with NBI Q7 (1750 kW)
D1 - 710 - 250 kW
D5 - not available
E1 - 790 - 400 kW
E5 - 650 - 200 kW
F5 - 550 kW (not yet fully available)

NBI + ECRH: Heat transport

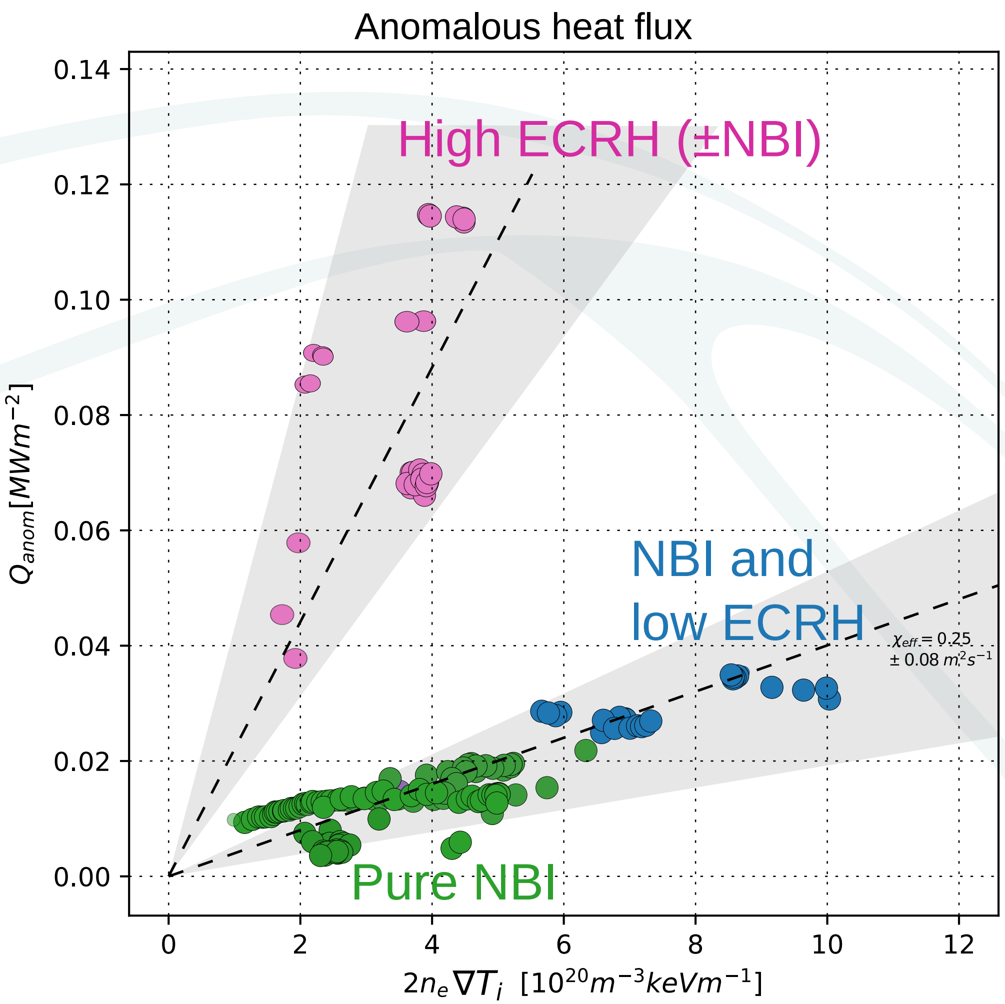
Plan:

I: Explore boundary between low and high heat diffusivity, optimise NBI/ECRH balance.

- Approach from higher and lower ECRH plasmas.

- Compare with similar 'optimum confinement' at W7-AS, drawing on experience. Is this similar physics?

- Compare global confinement of NBI/ECRH balance with similar series already performed at LHD.



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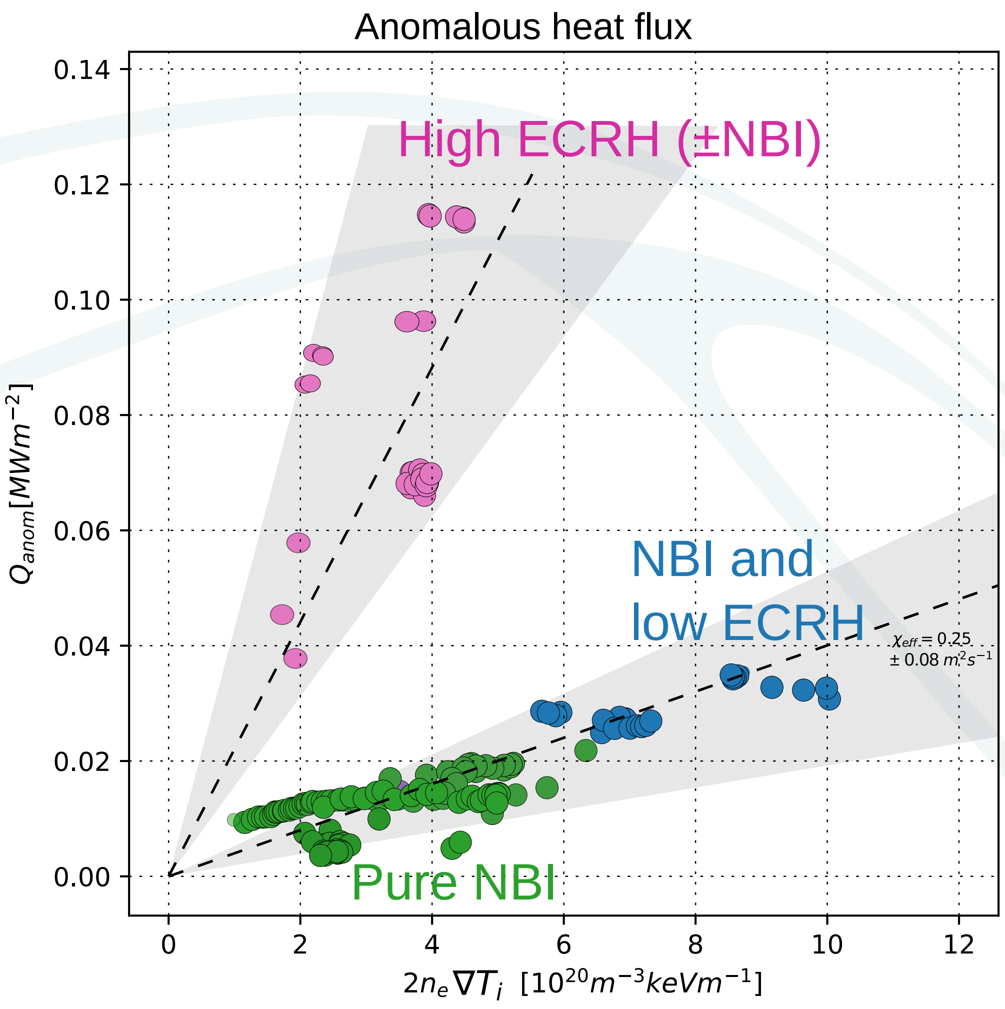

Analysis/results:

- Precise dependence of heat diffusivity on density gradient.
- Assesment of the generality and scaling of the scenario.
- An optimised NBI/ECRH scenario for use in later studies, e.g. impurity transport, turbulence, detachment compatibility etc...

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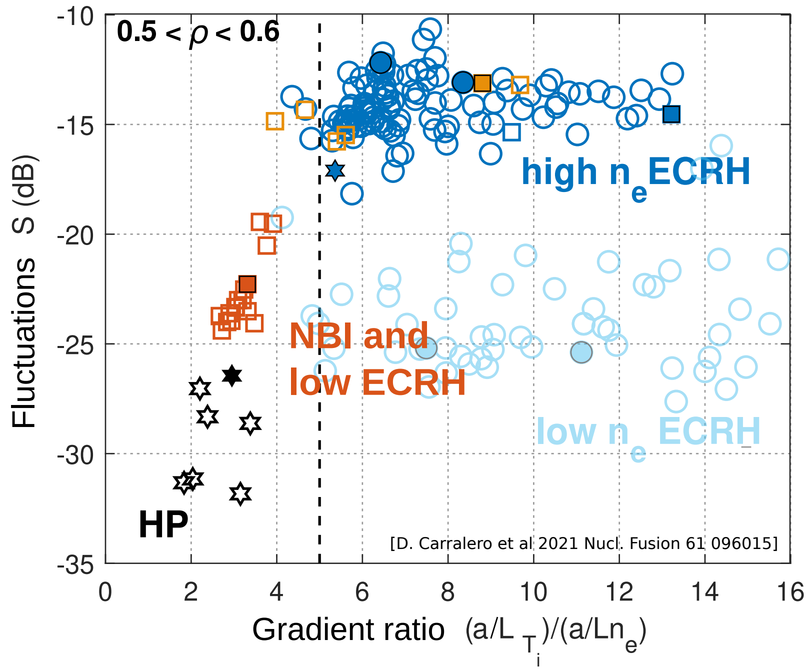
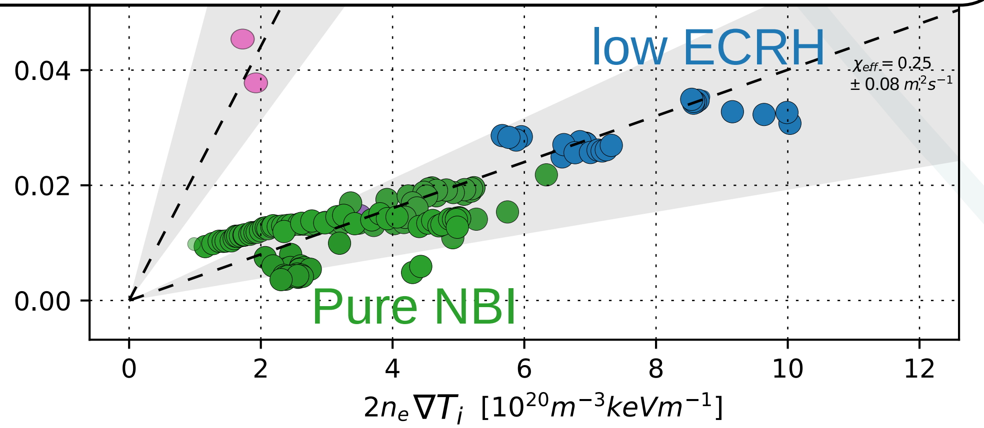
- Turbulent fluctuation measurements for in all scenarios for turbulence studies --> see talk by A. von Stechow



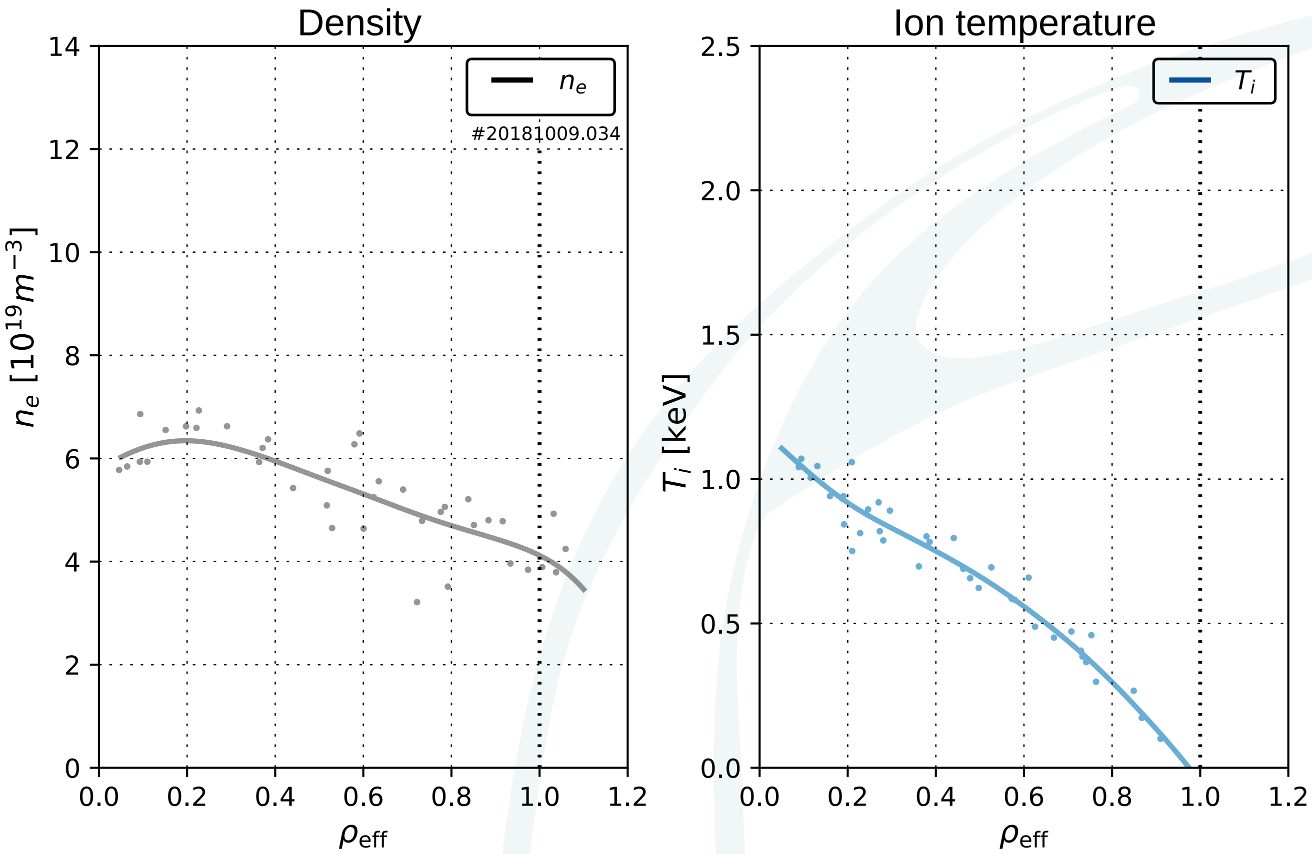
Turbulent fluctuations from Doppler reflectometer reduced in NBI+low ECRH compared to equivalent ECRH



NBI + ECRH: Heat transport

Background:

- Steep density gradients lead to ~4x lower heat diffusivity than in high ECRH.
- Low ECRH power (< 1MW) does not significantly increase anomalous diffusivity, so allows increase in T_i.



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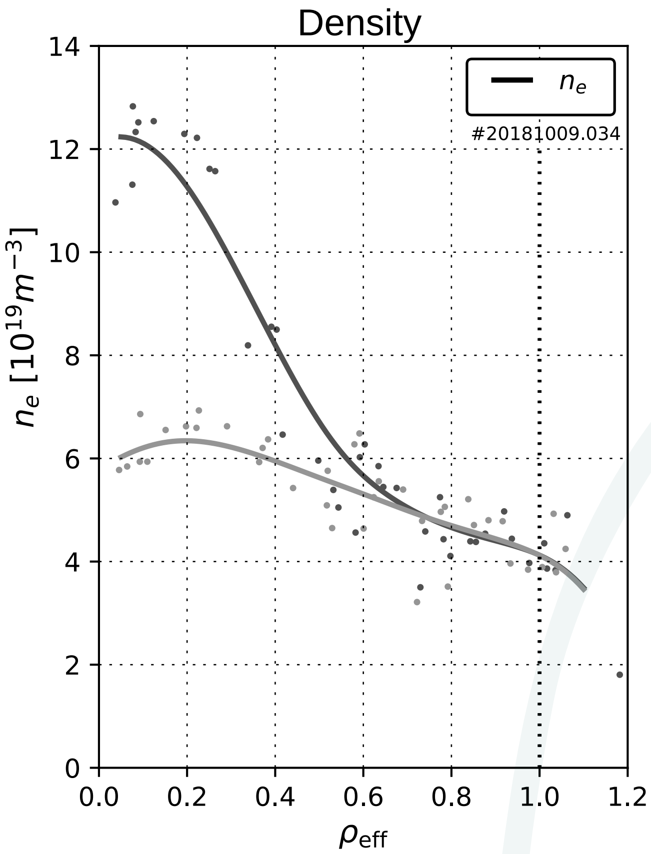

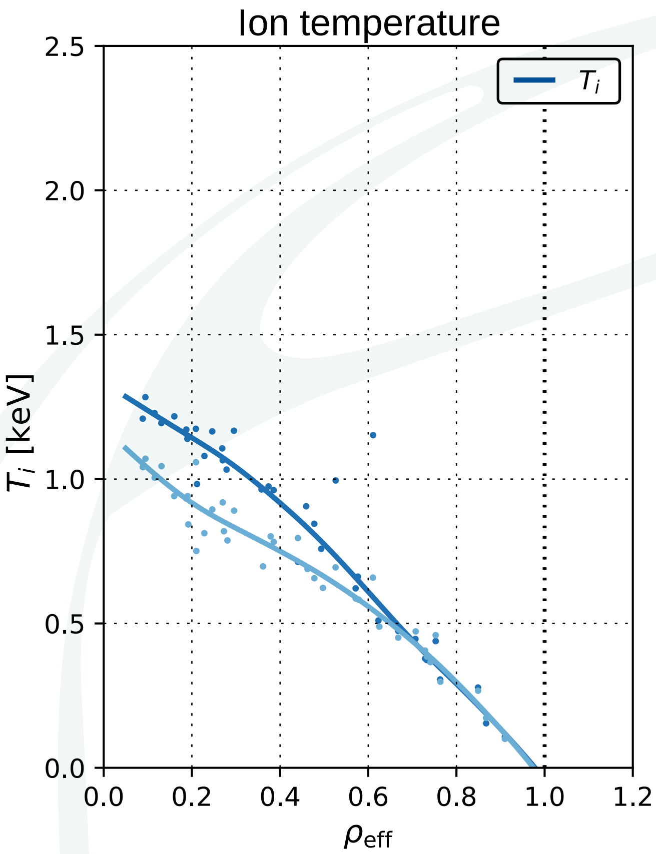

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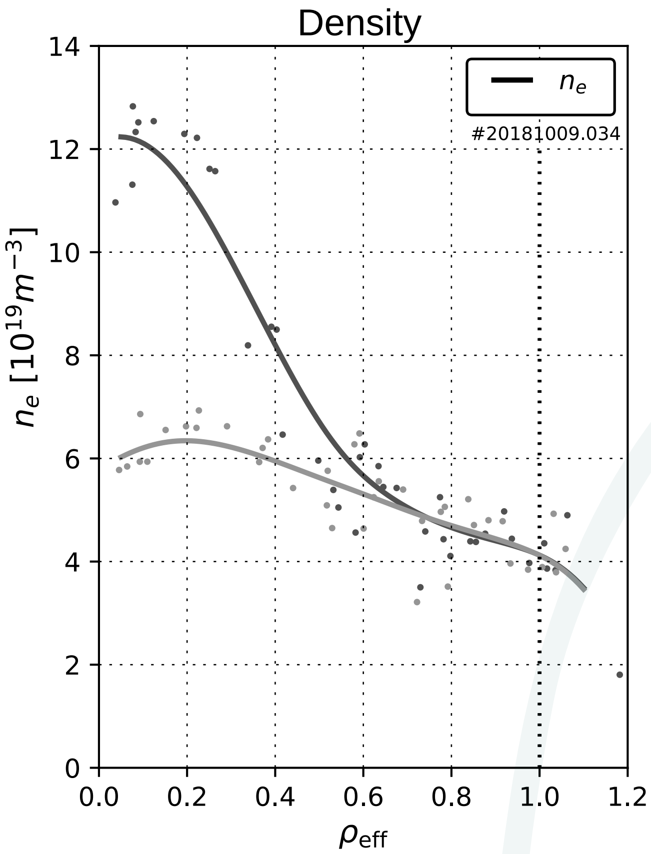

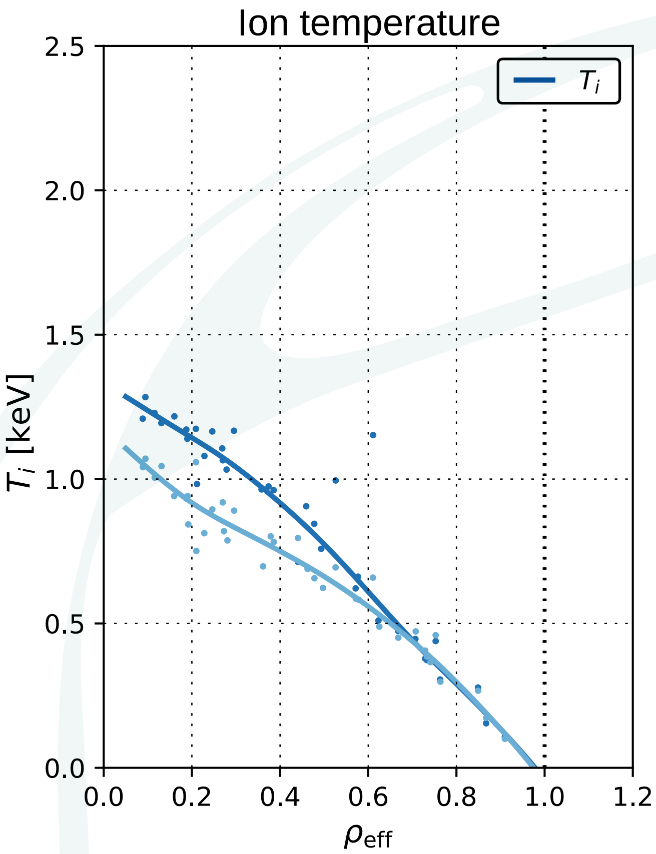

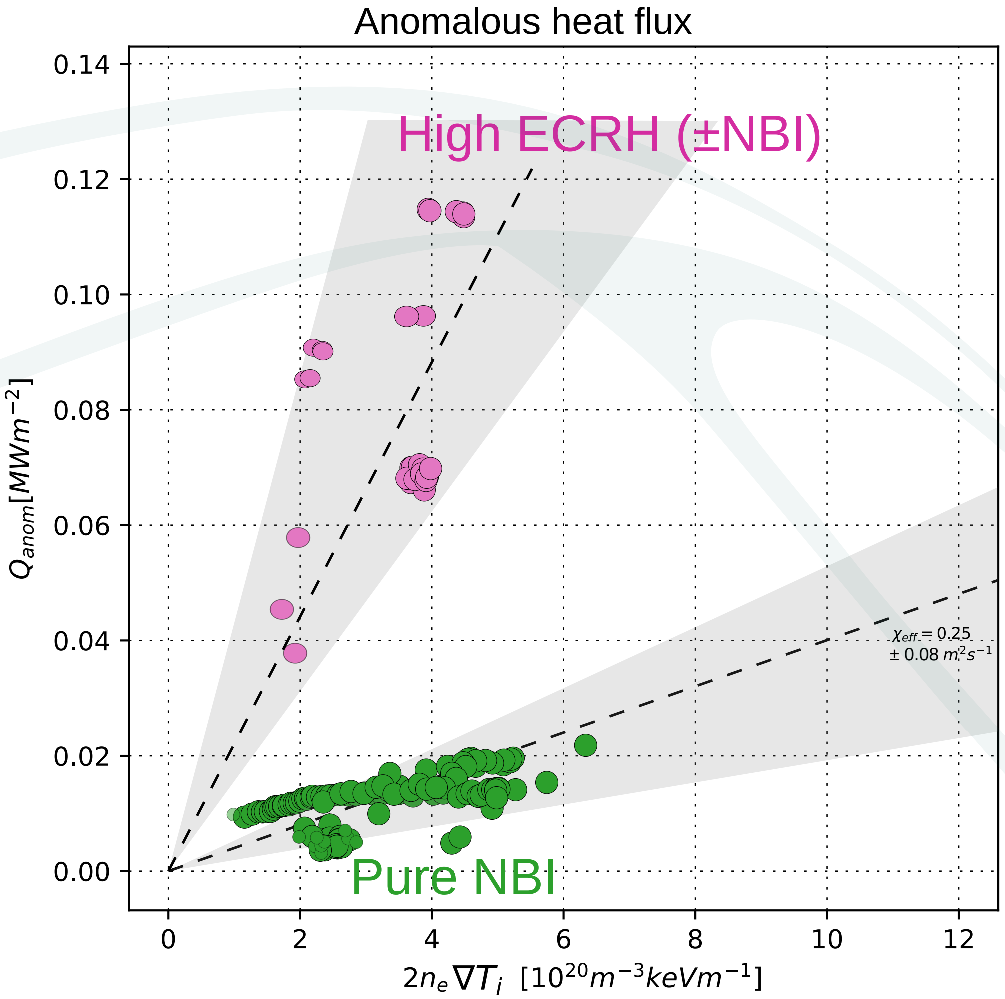

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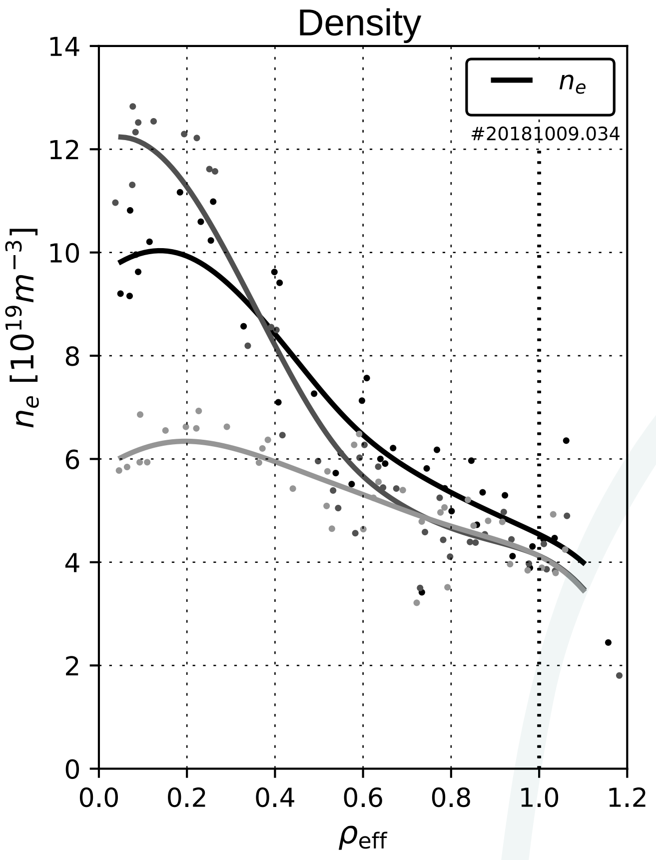
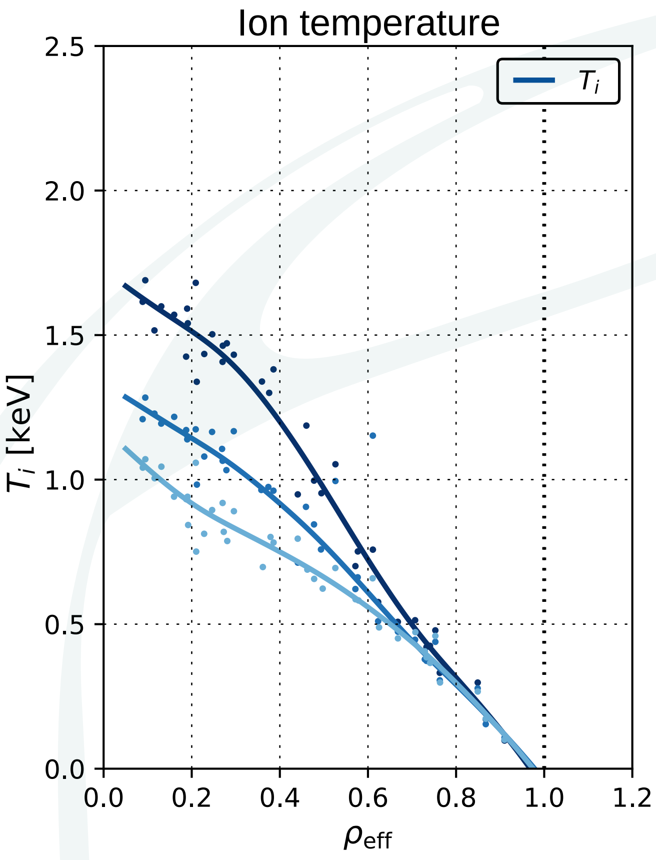
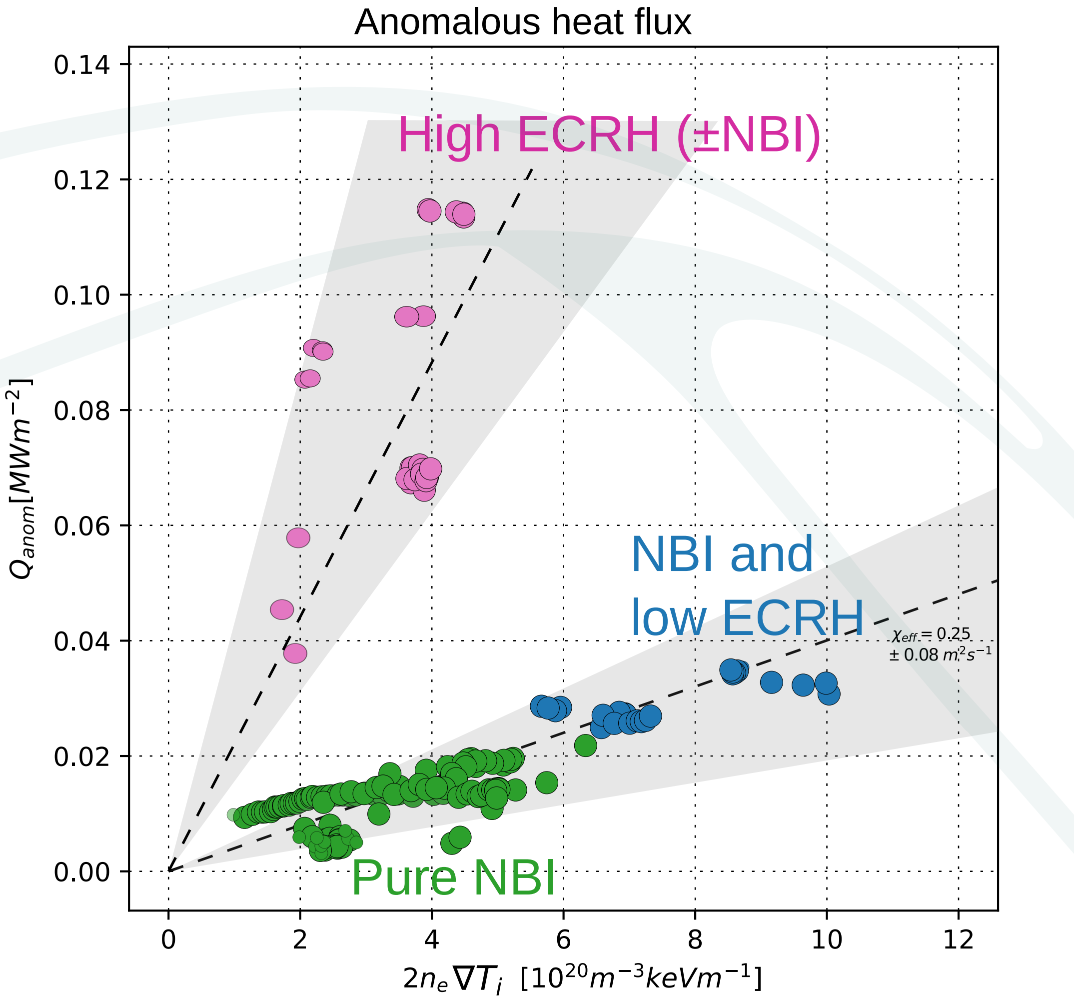
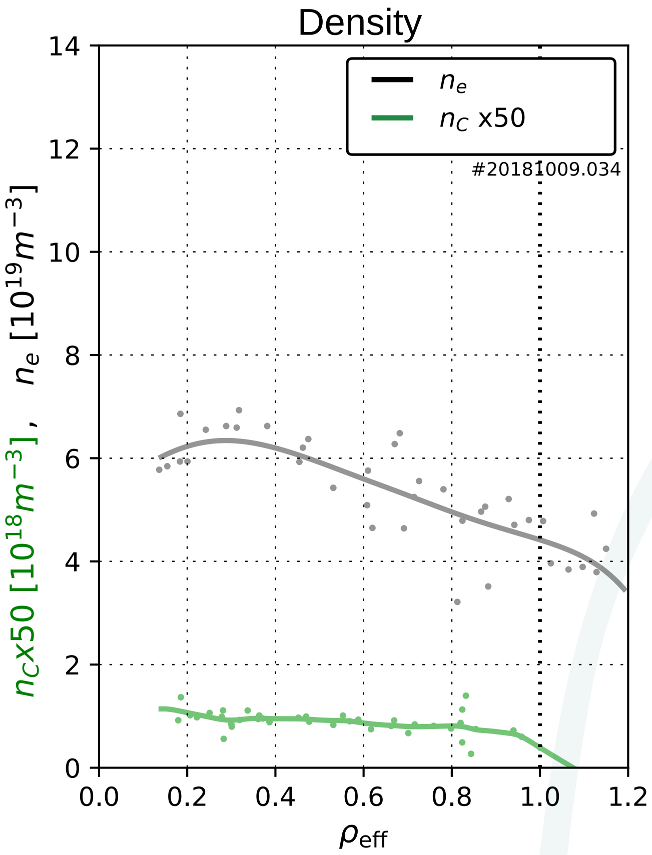






Pure NBI: Impurity transport

Background:



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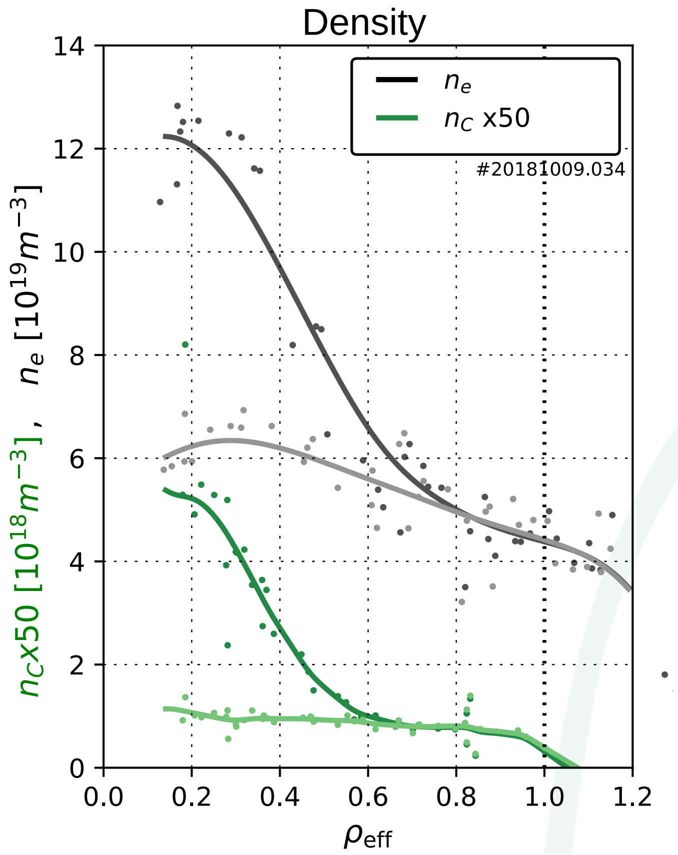
Background:

- Impurity transport in pure NBI discharges also drops neoclassical levels, and remains there [L. Vano].
- Leads to very strong impurity accumulation.



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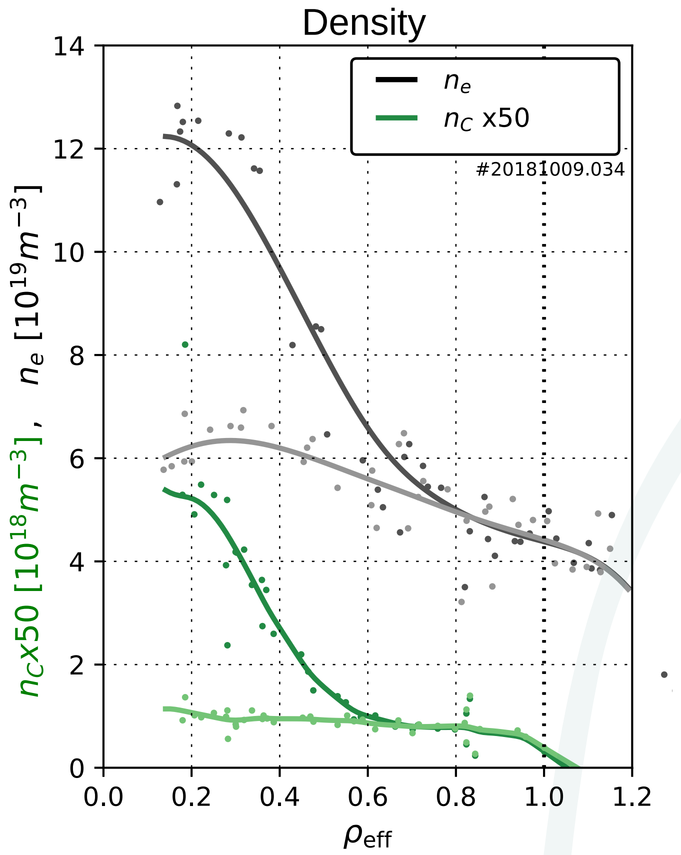

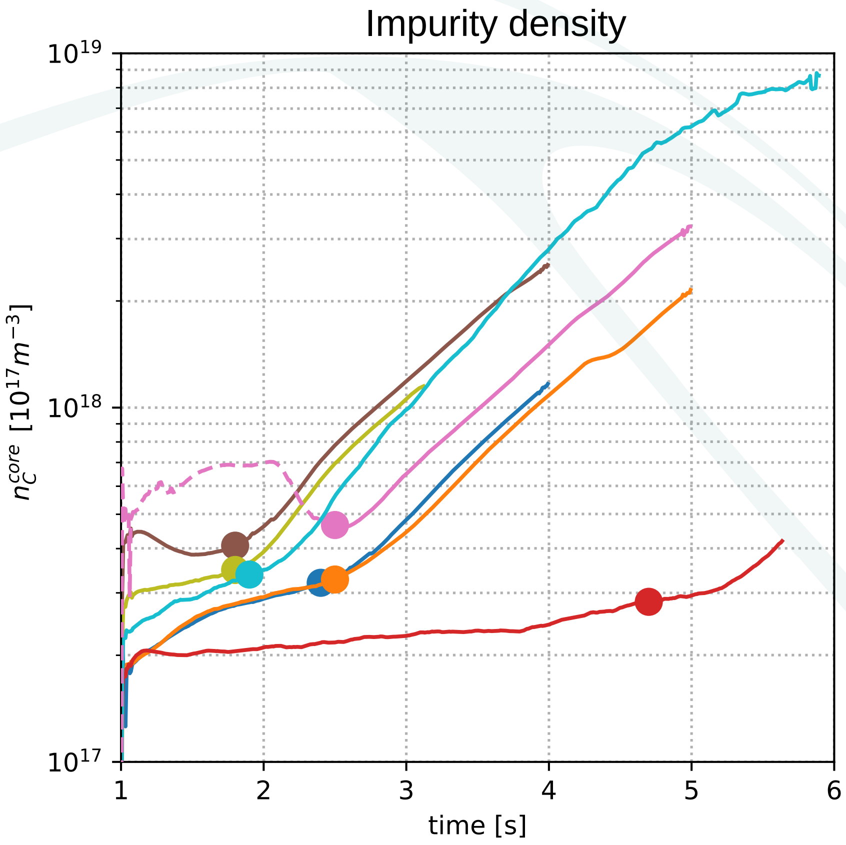

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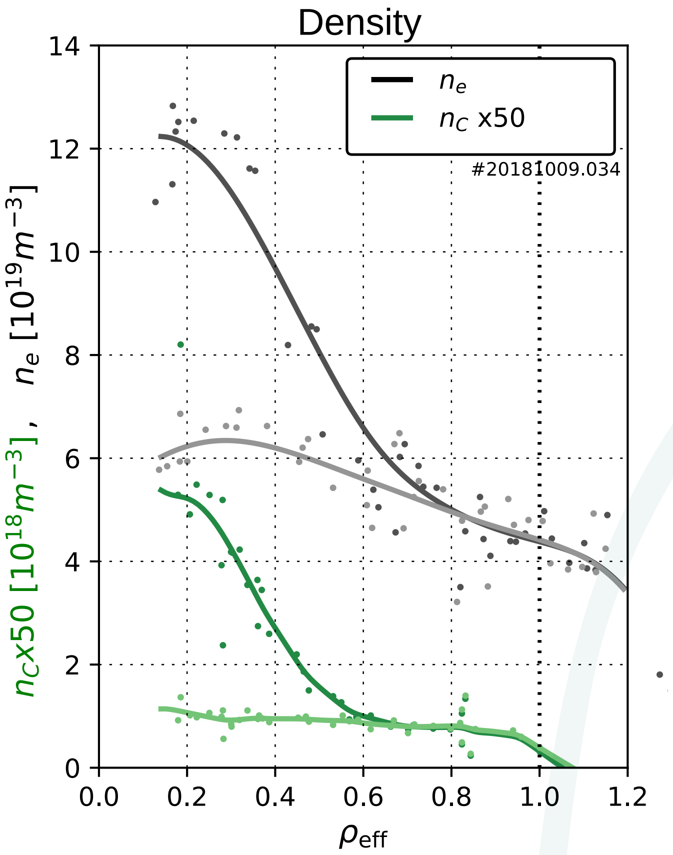

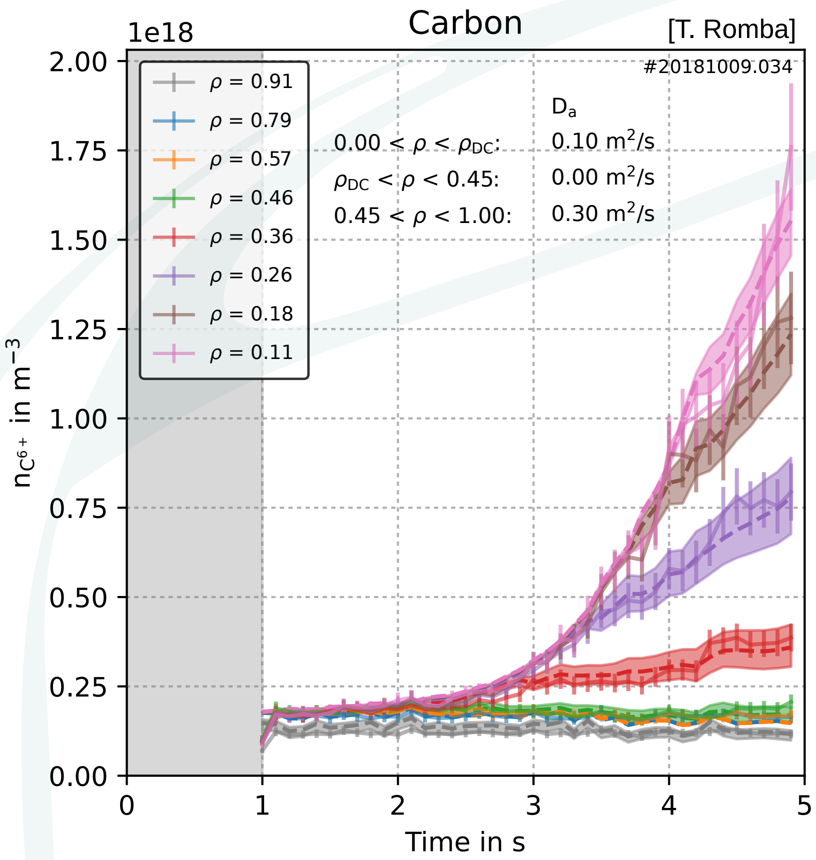

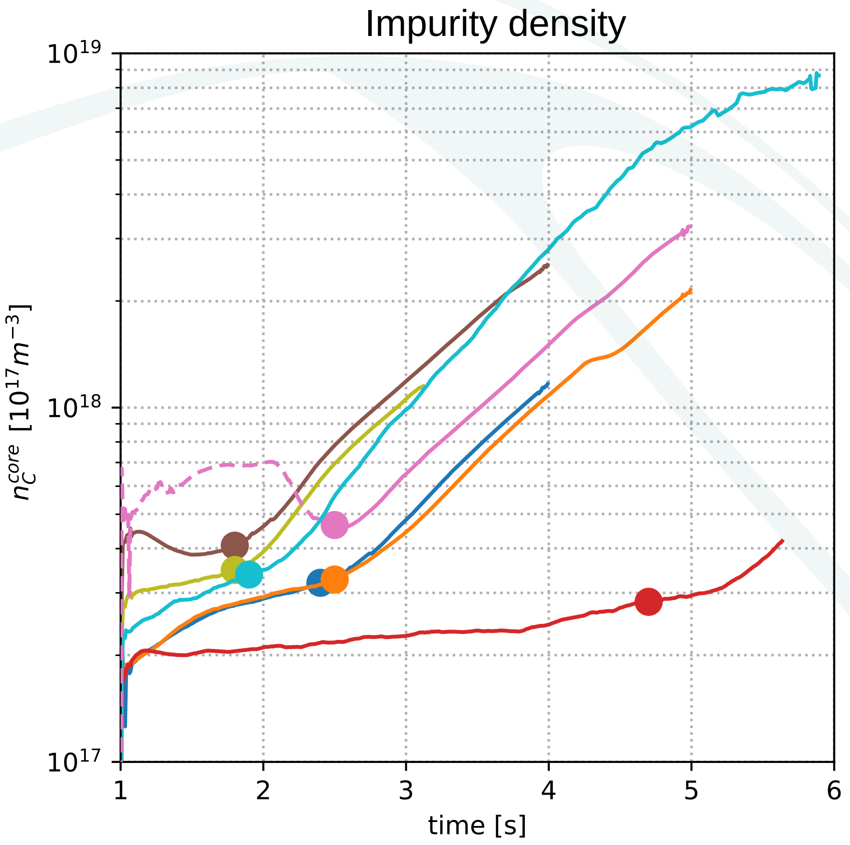

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