

High Performance Scenarios: Density Control and Confinement

O. P. Ford, S.Bozhenkov for the W7-X Team

01.12.2025 W7-X Program Workshop



What does 'performance' usually mean?:

Ion temperature

$$T_i$$

Stored Energy

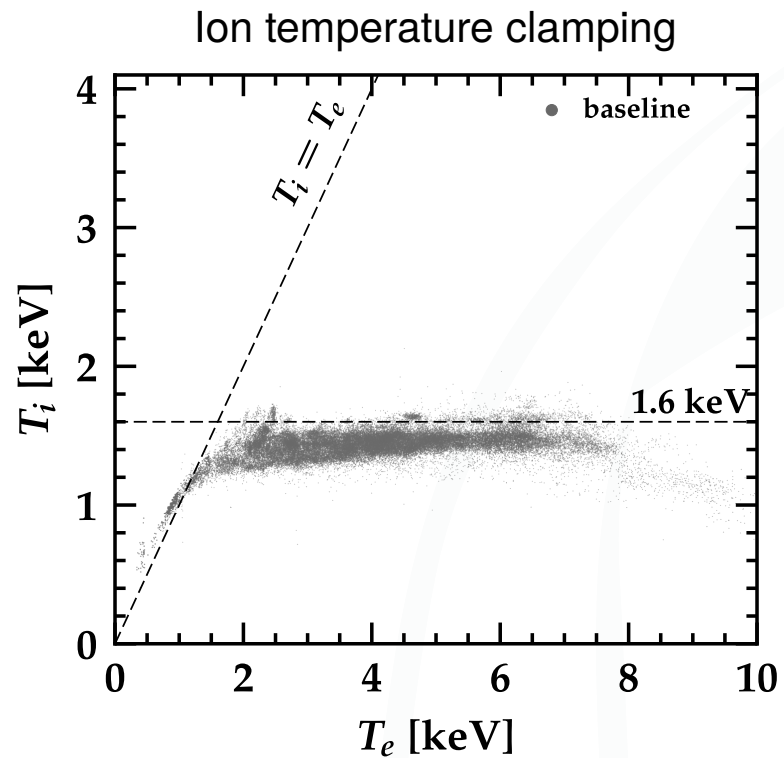
$$W_{dia} \sim n_e T_e + n_i T_i$$

Normalised pressure

$$\beta \sim W_{dia} / B$$

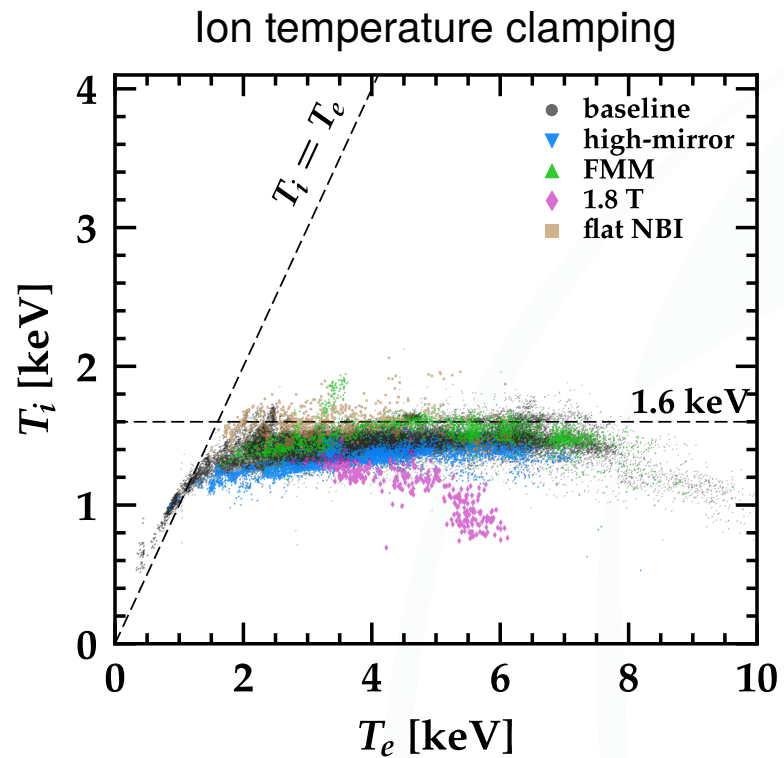
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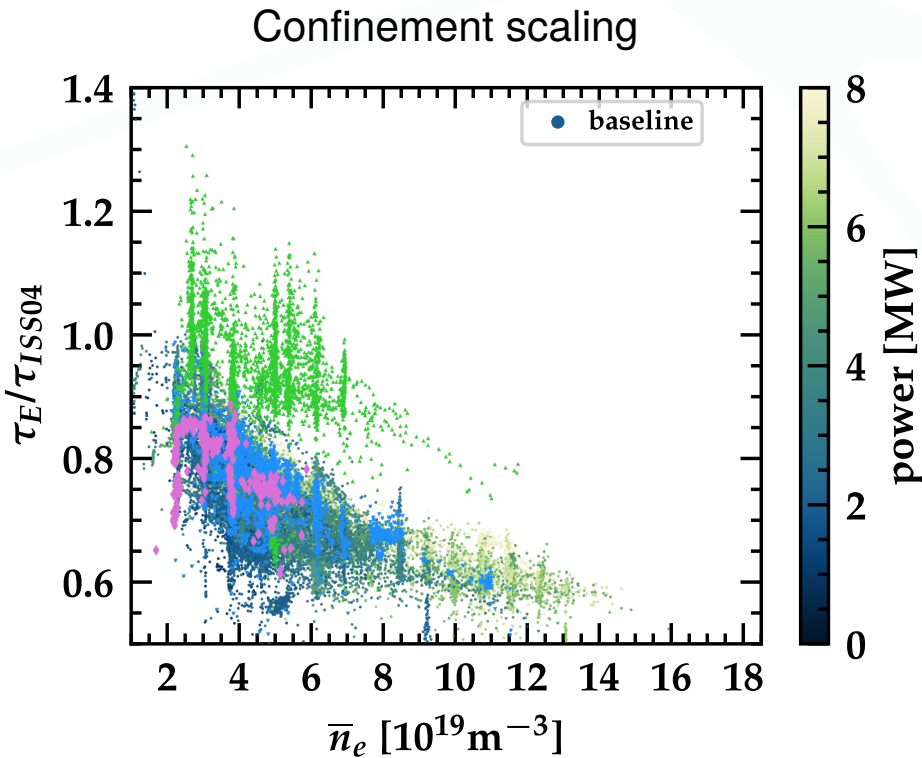
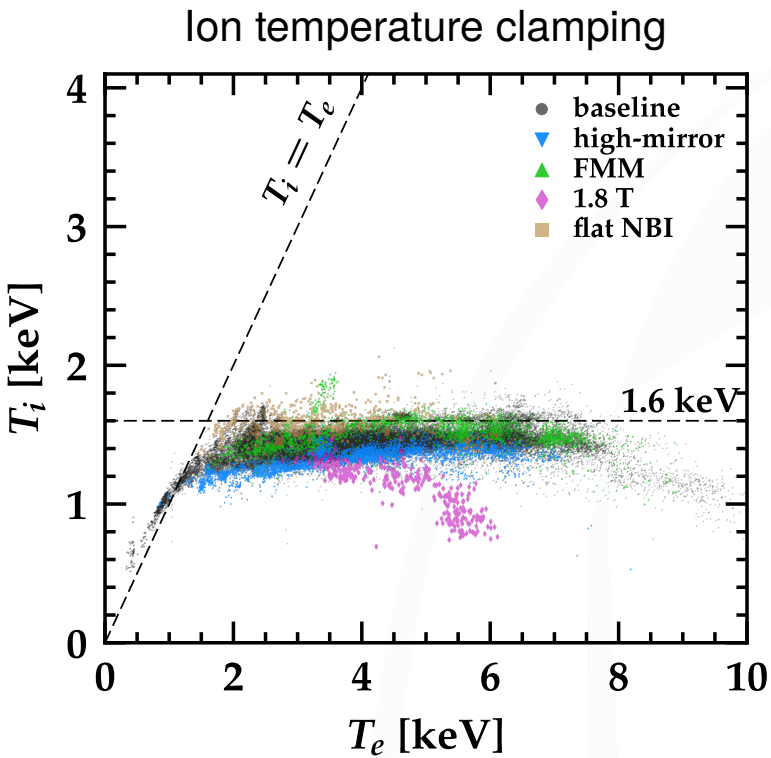
What does 'performance' usually mean?:

$$\tau_E^{ISS04} \sim a^{2.28} R^{0.64} P^{-0.61} \bar{n}_e^{-0.54} B^{0.84} I^{0.41}$$

[Yamada, NF 2005]

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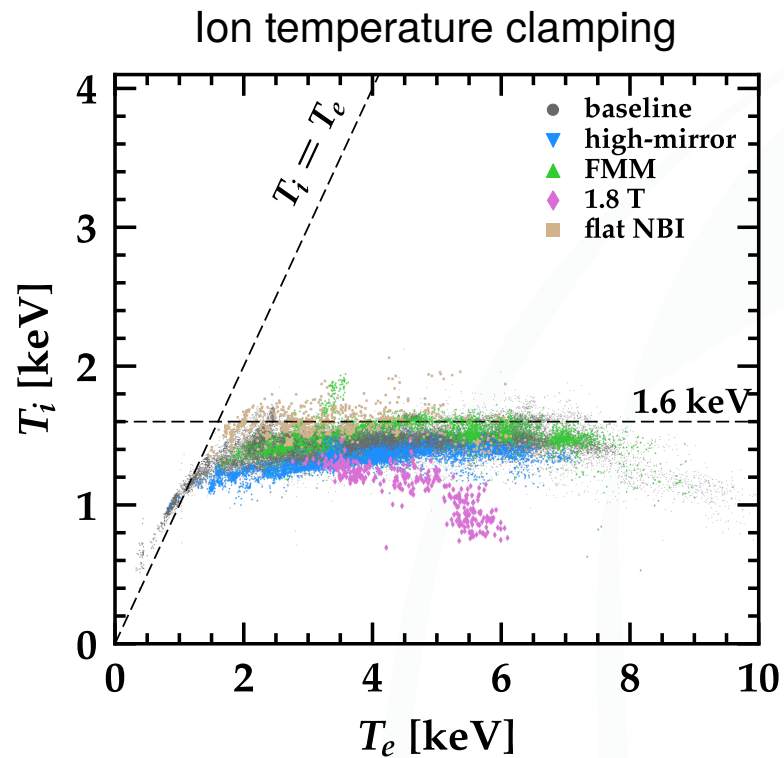
Confinement time	$\tau_E \sim W_{dia} / P$
Relative confinement time	$f_{ren} \sim \tau_E / \tau_E^{ISS04}$
Triple product	$n T \tau_E$



Reminder: T_i clamping

T_i clamping in W7-X results from 3 ingredients [Beurskens NF 2021]:

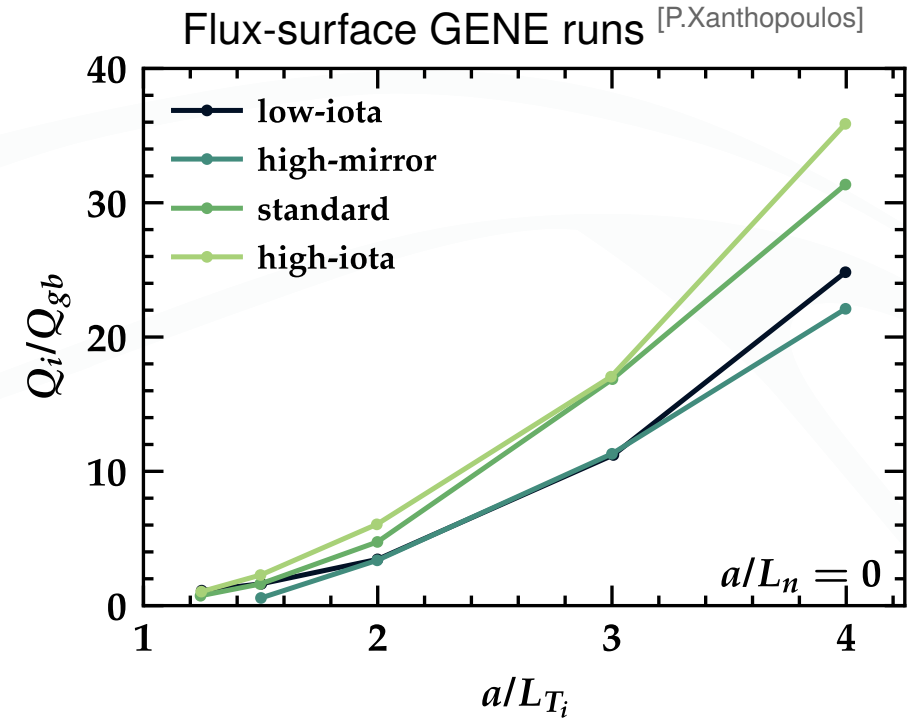
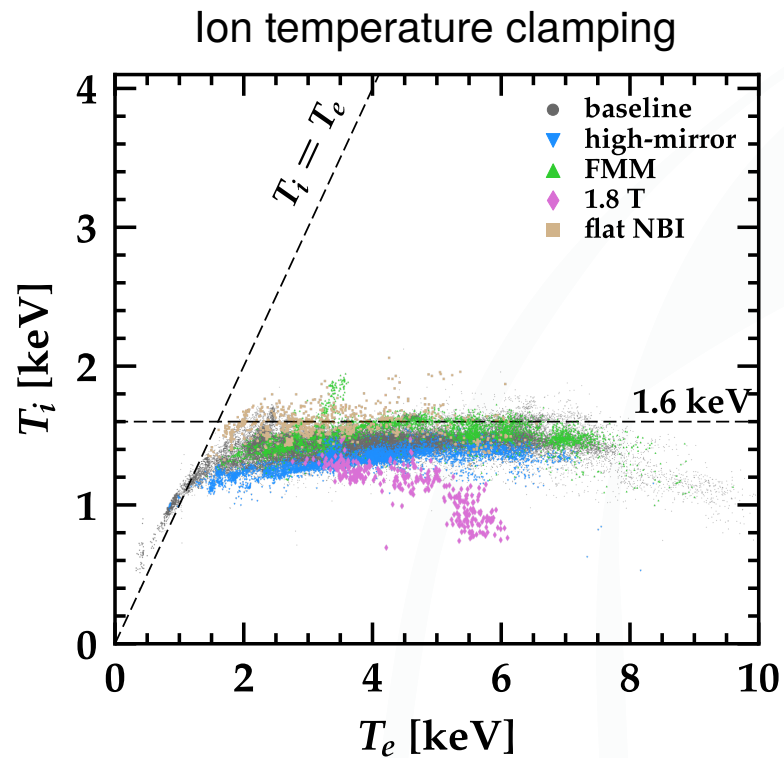
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- 2) Limited power per particle
- 3) **Strong ITG heat transport**



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Reminder: ITG supression

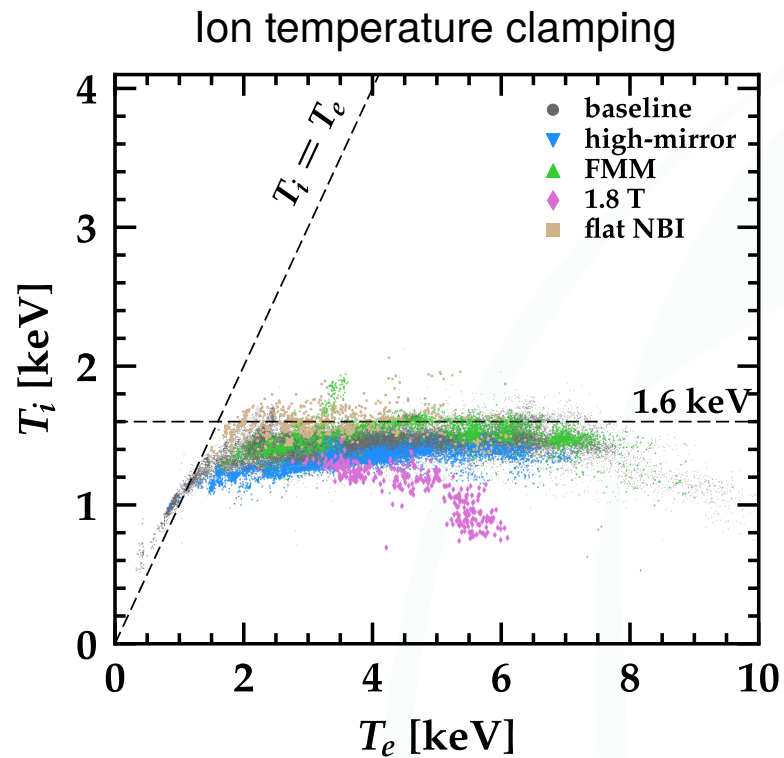
"High-performance" is achieved in W7-X with density gradients:

- Strong density gradient suppresses ITG

[Xanthopoulos PRL 2020, Carralero NF 2021 ...]

- Combined with weak TEMs in W7-X

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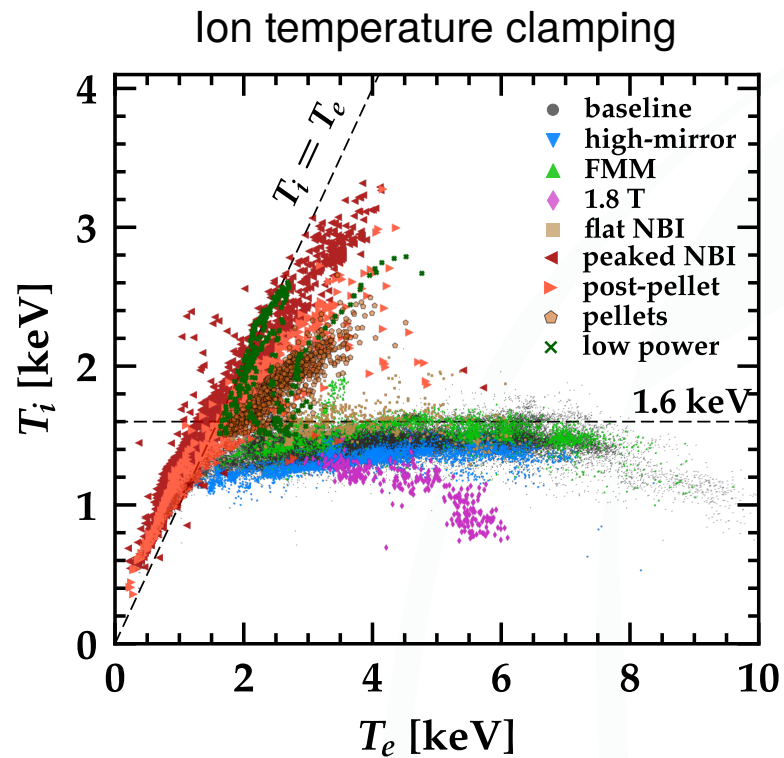
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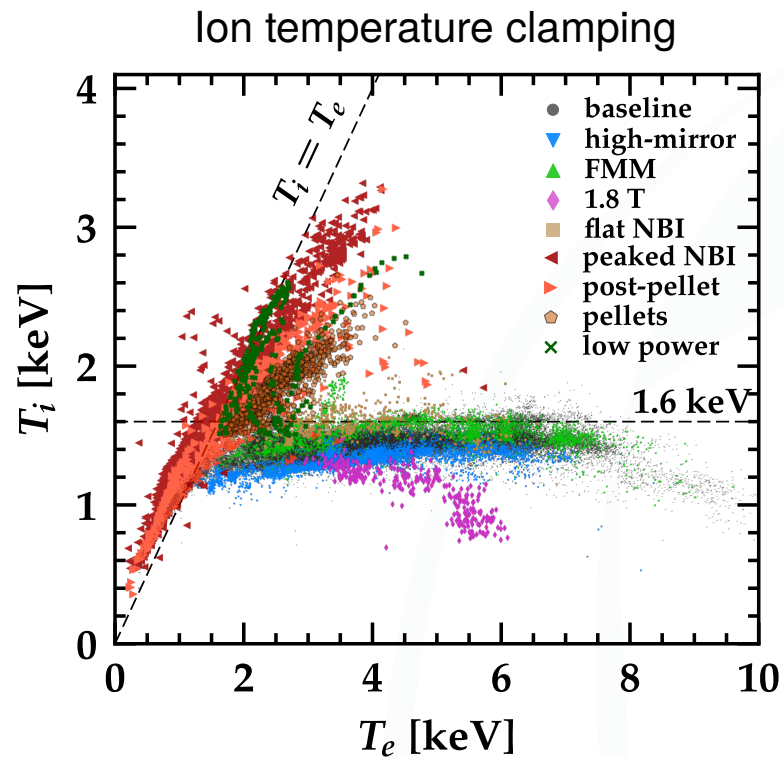
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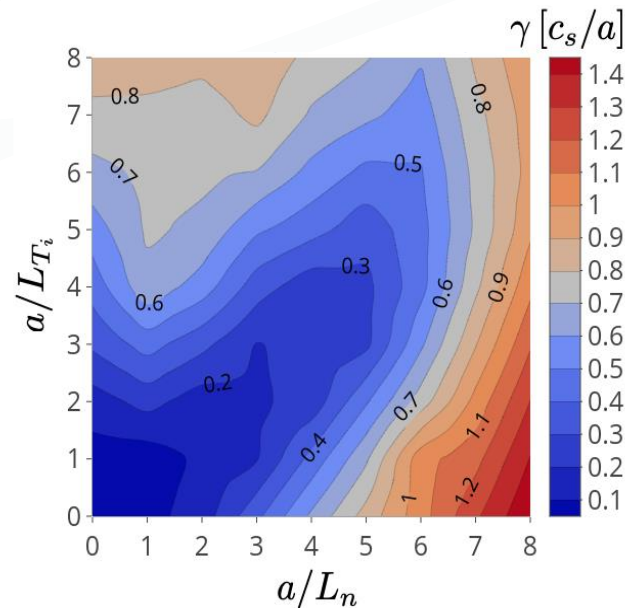
[Xanthopoulos PRL 2020, Carralero NF 2021 ...]

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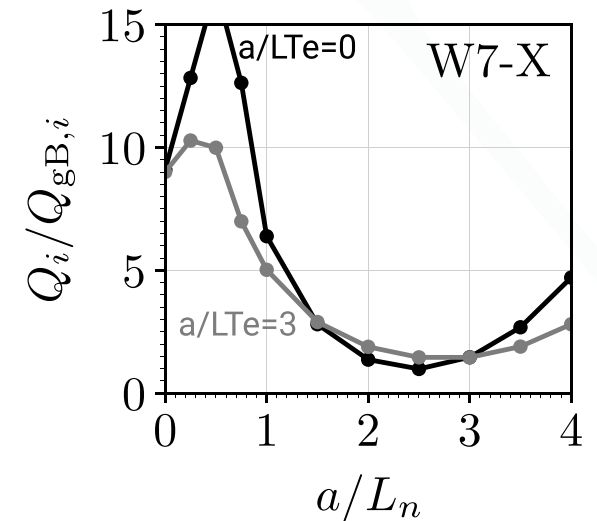
[Proll., PRL 2012, Alcuson PPCF 2020]



Linear growth rates [Alcuson PPCF 2020]



Energy flux [Thienpondt NF 2025]

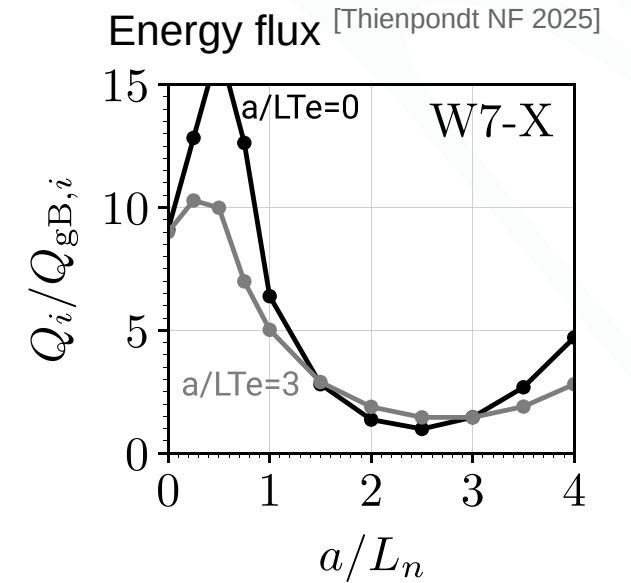
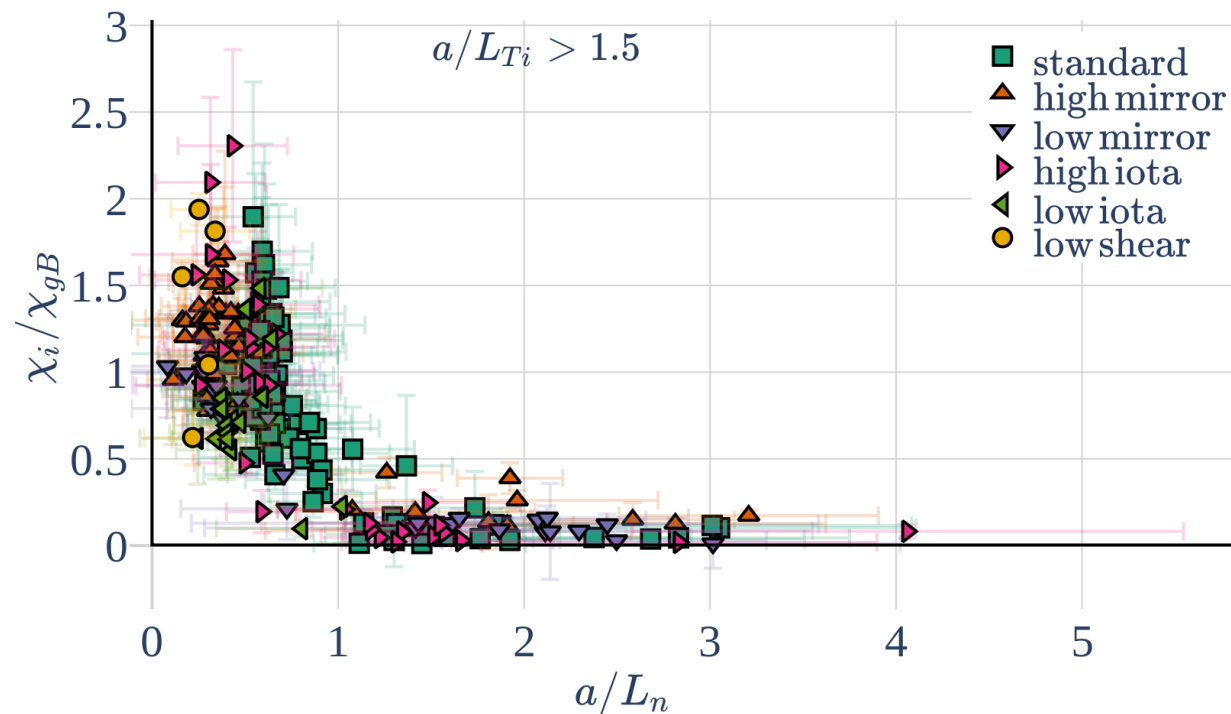


ITG supression in OP2

Measured heat fluxes from power balance [M. Wapfl RSI 2024, PPCF 2025]

- Dramatic drop of heat transport (diffusivity)

Heat transport in for OP1.2b - OP2.3 [M. Wapfl PPCF 2025]

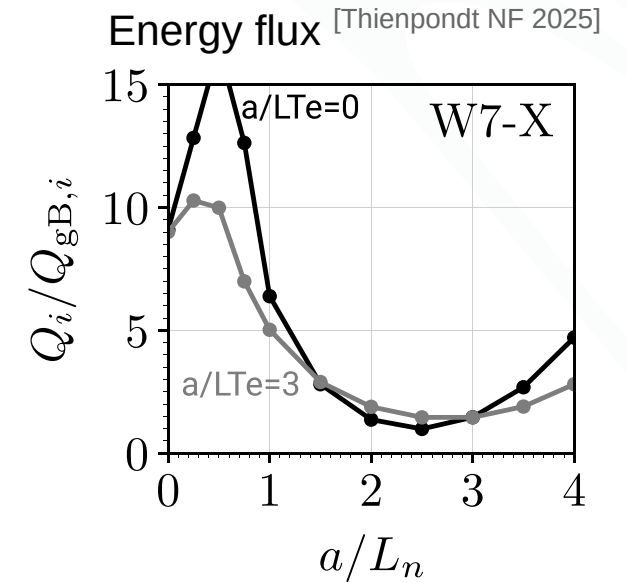
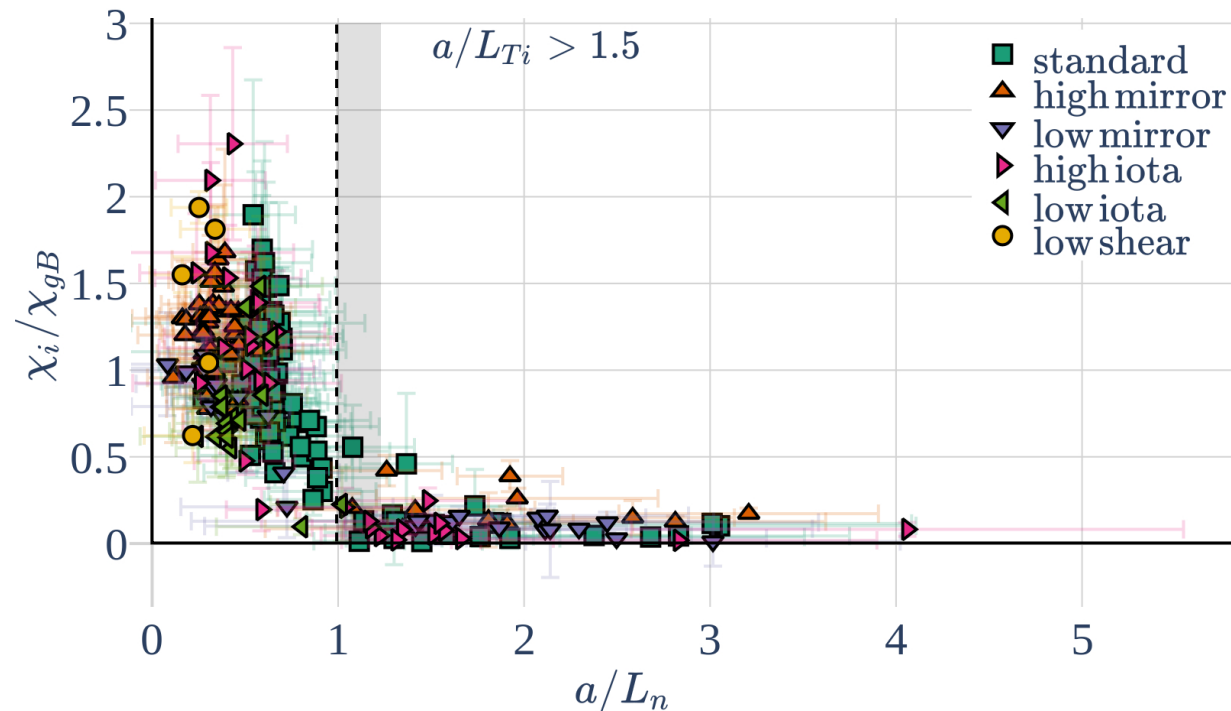


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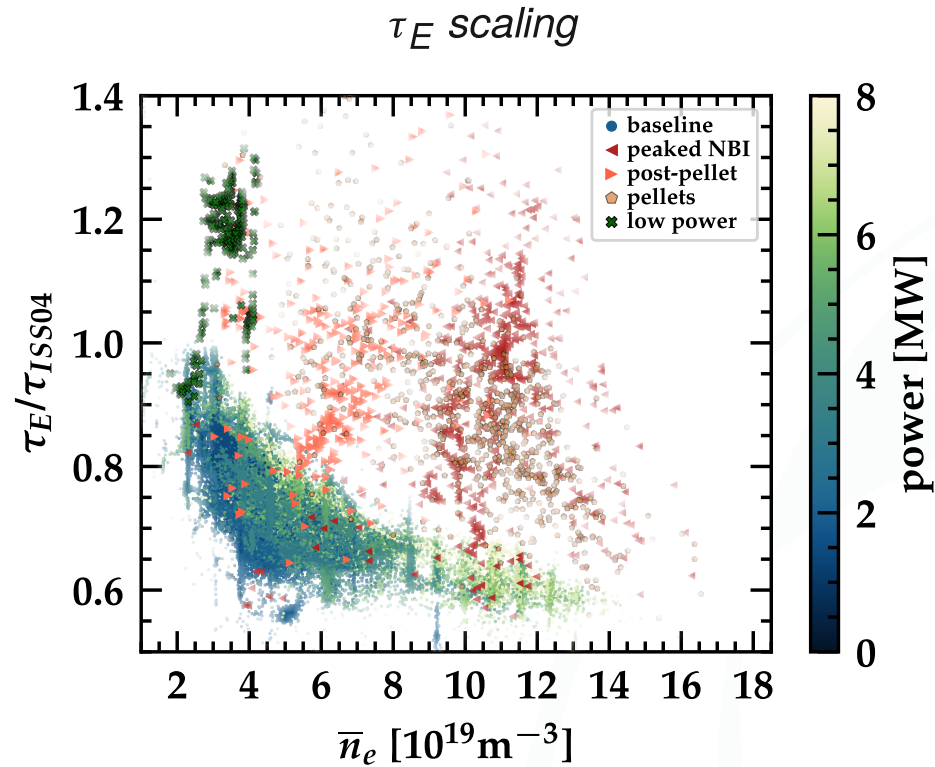
- Dramatic drop of heat transport (diffusivity) for $\sim a/L_{n_e} > 1$ (somewhere in $1.0 < a/L_n < 1.5$ depending on location/fitting)
- *Not yet certain how sharp this transition is and what it depends on.*

Heat transport in for OP1.2b - OP2.3 [M. Wapfl PPCF 2025]



Peaked density scenarios

Currently there are 4 main known operational scenarios:



Peaked density scenarios

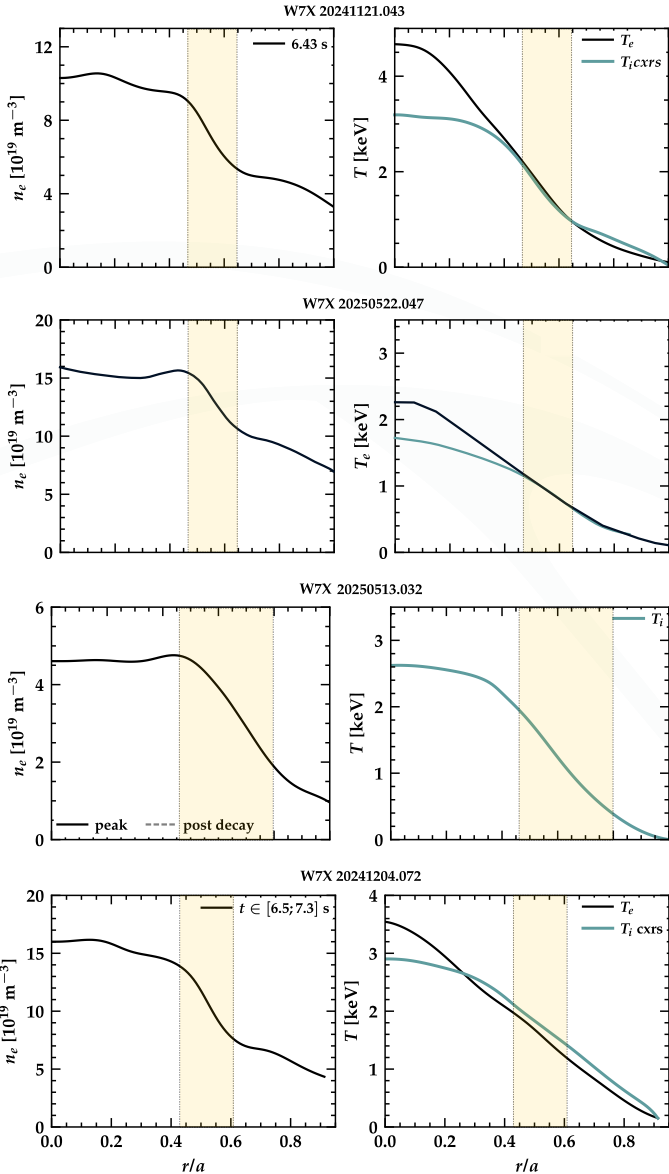
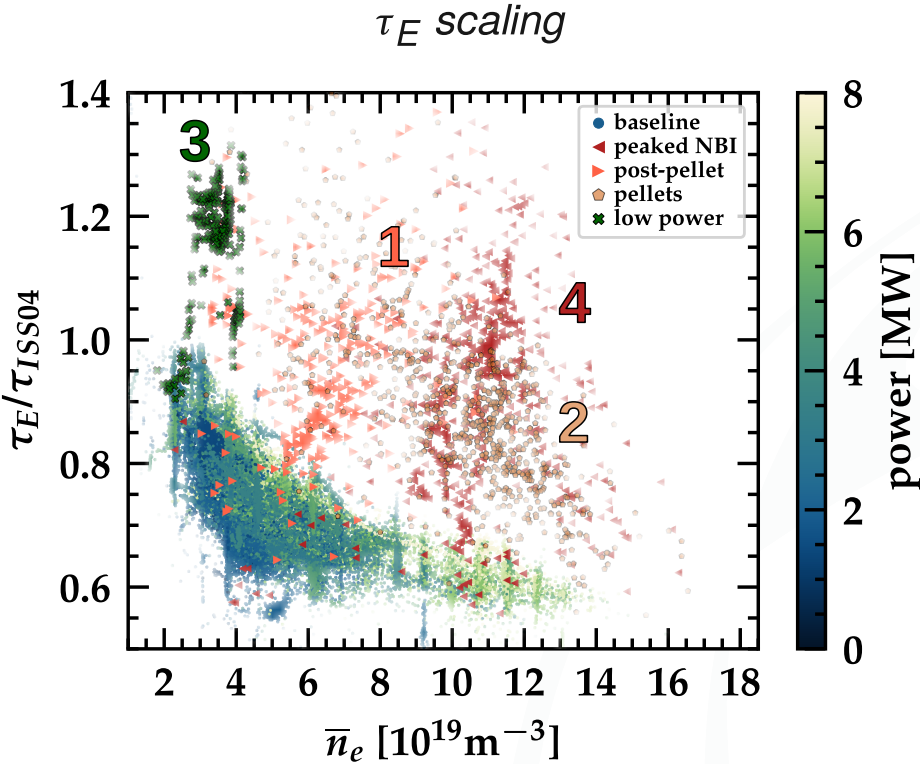
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1: Post-pellets

2: 'Steady-state' pellets

3: Low-power + ?

4: NBI + ECRH reintroduction

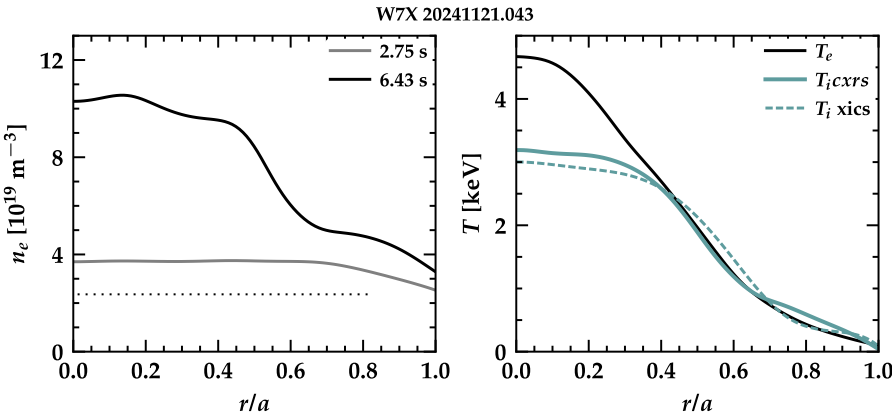
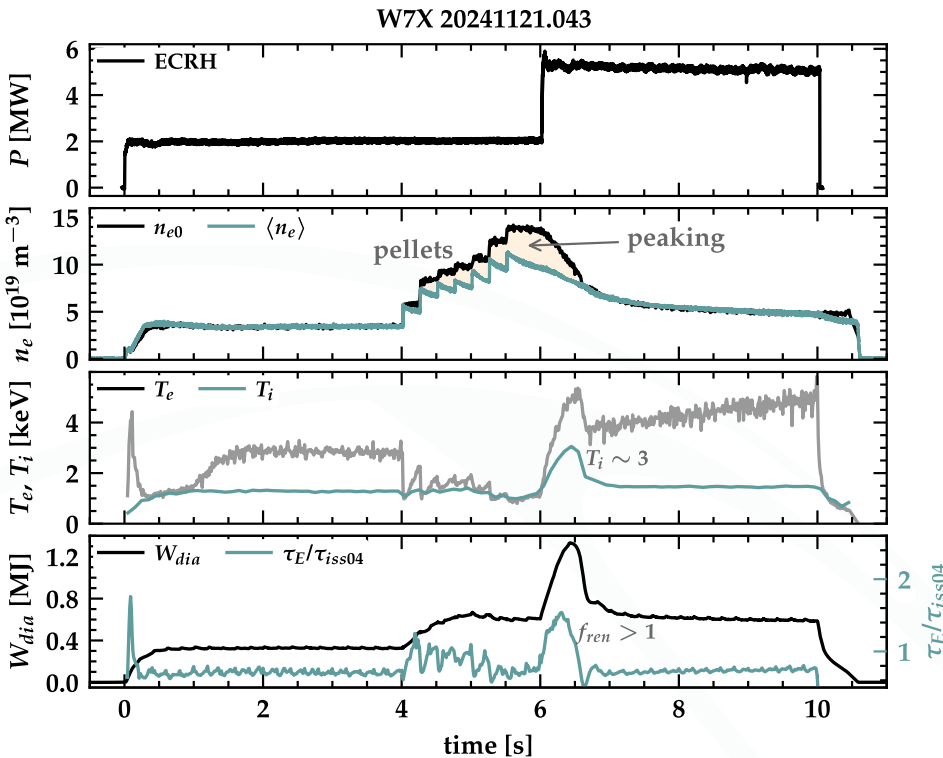


Scenario 1: Post-pellets



Fast series of pellets to raise core density then increase ECRH power to raise T_i [Baldzuhn PPCF 2020].

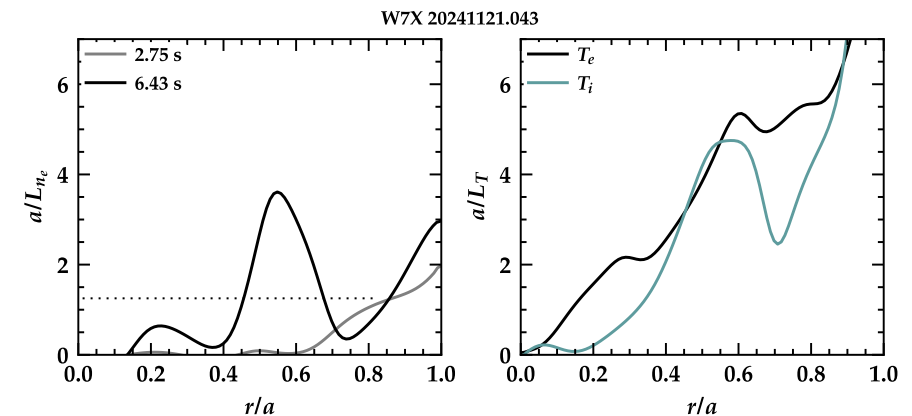
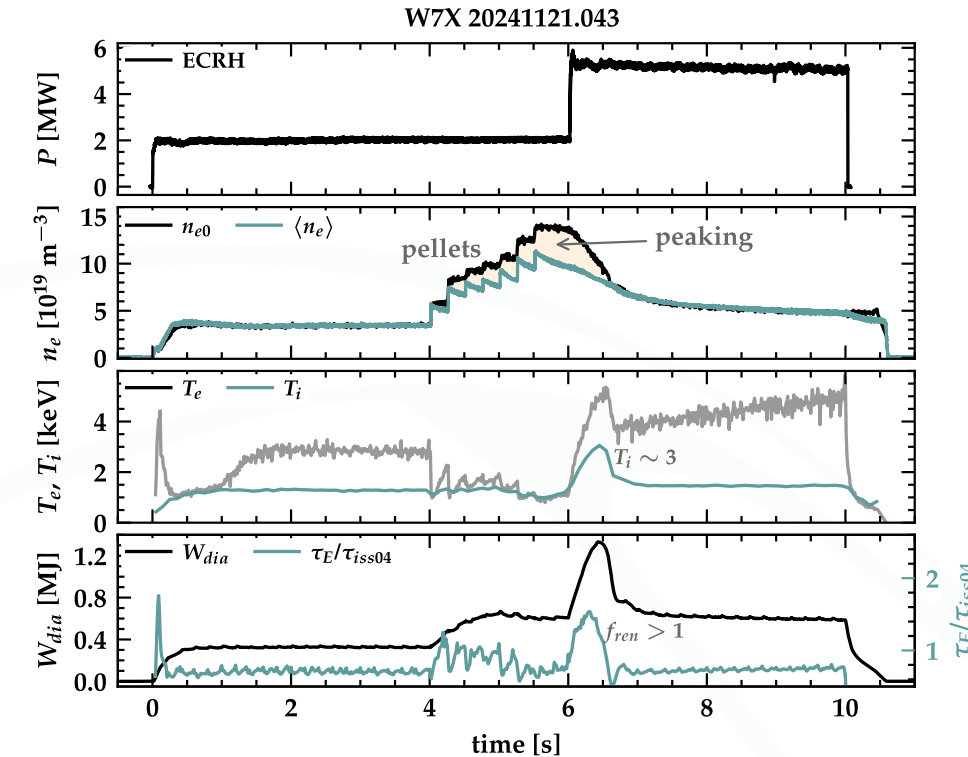
- Strong density gradient around mid-radius.
- Turbulence suppressed --> breaks T_i clamping.
- Used to show NC optimisation [Beidler Nature 2021].
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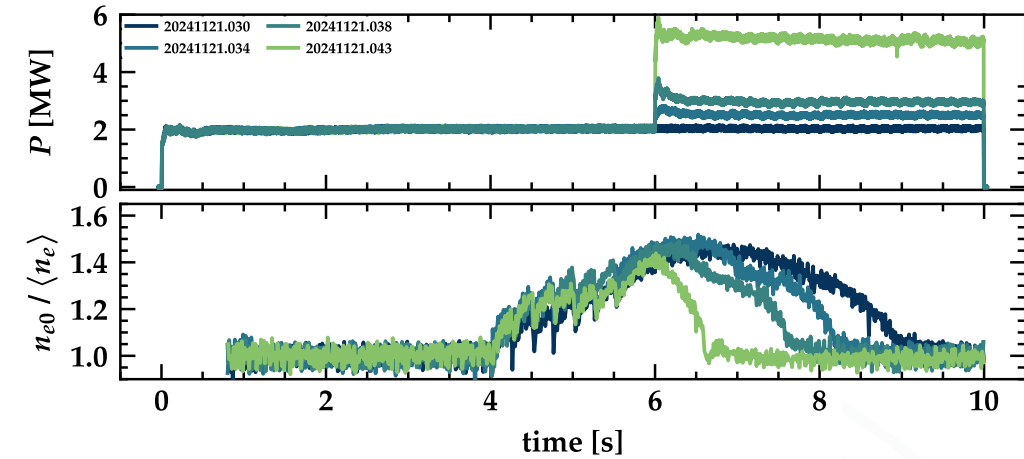
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Post-pellets: decay duration

Density gradient decays in time.

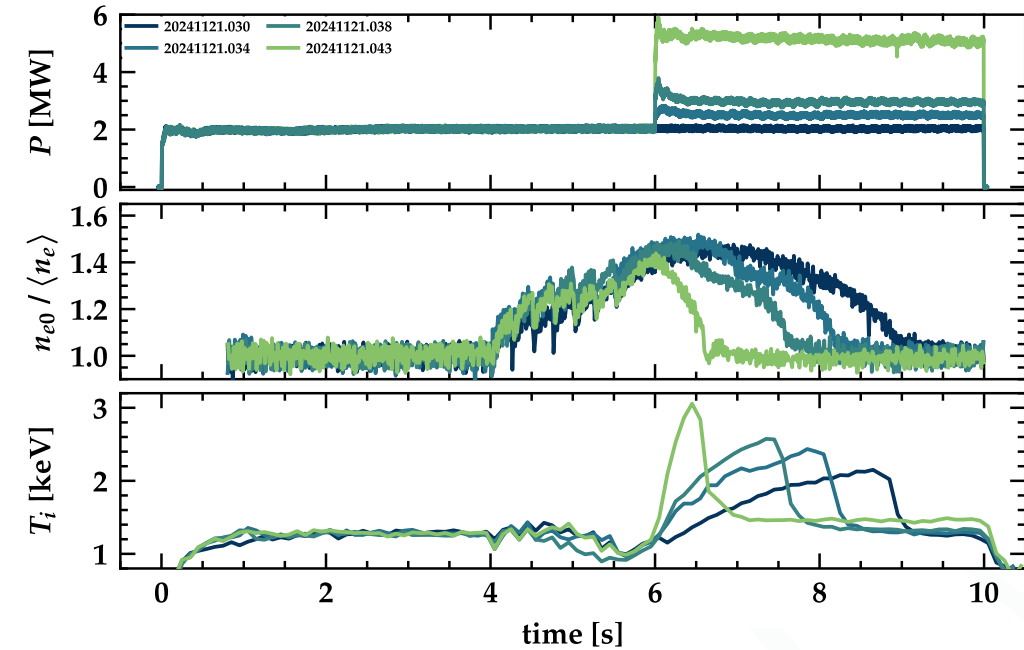
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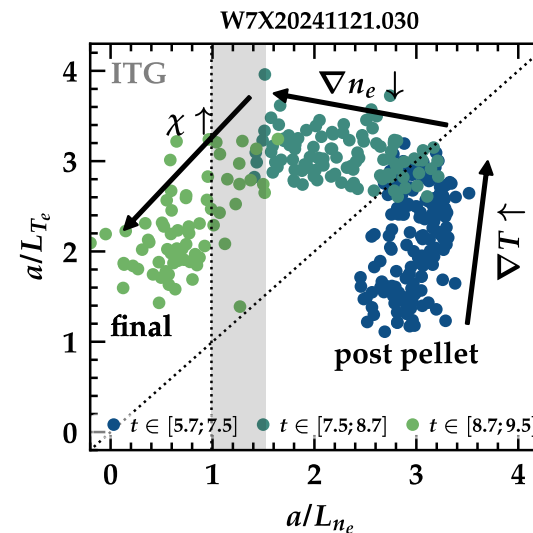
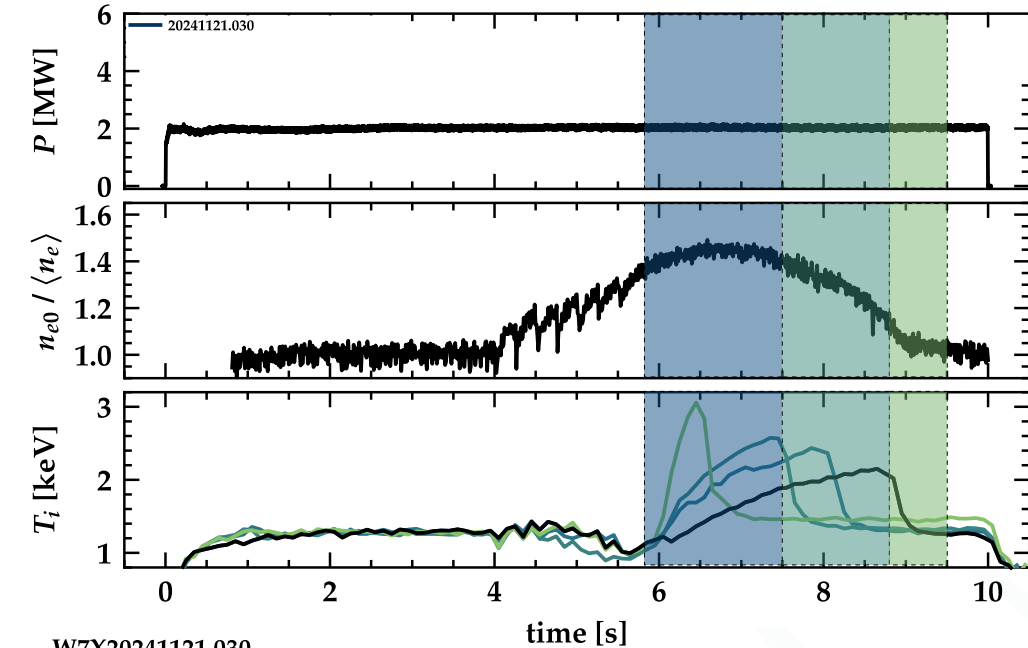
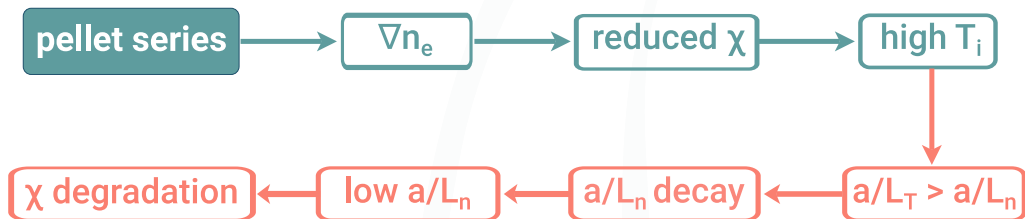
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Post-pellets: decay duration

Density gradient decays in time.

- More power $\Rightarrow$ shorter high gradient phase.
- Power controls the temperature profile.
- $a/L_T > a/L_n \Rightarrow$ density decay
- Energy transport degrades at $a/L_n < \sim 1.5$



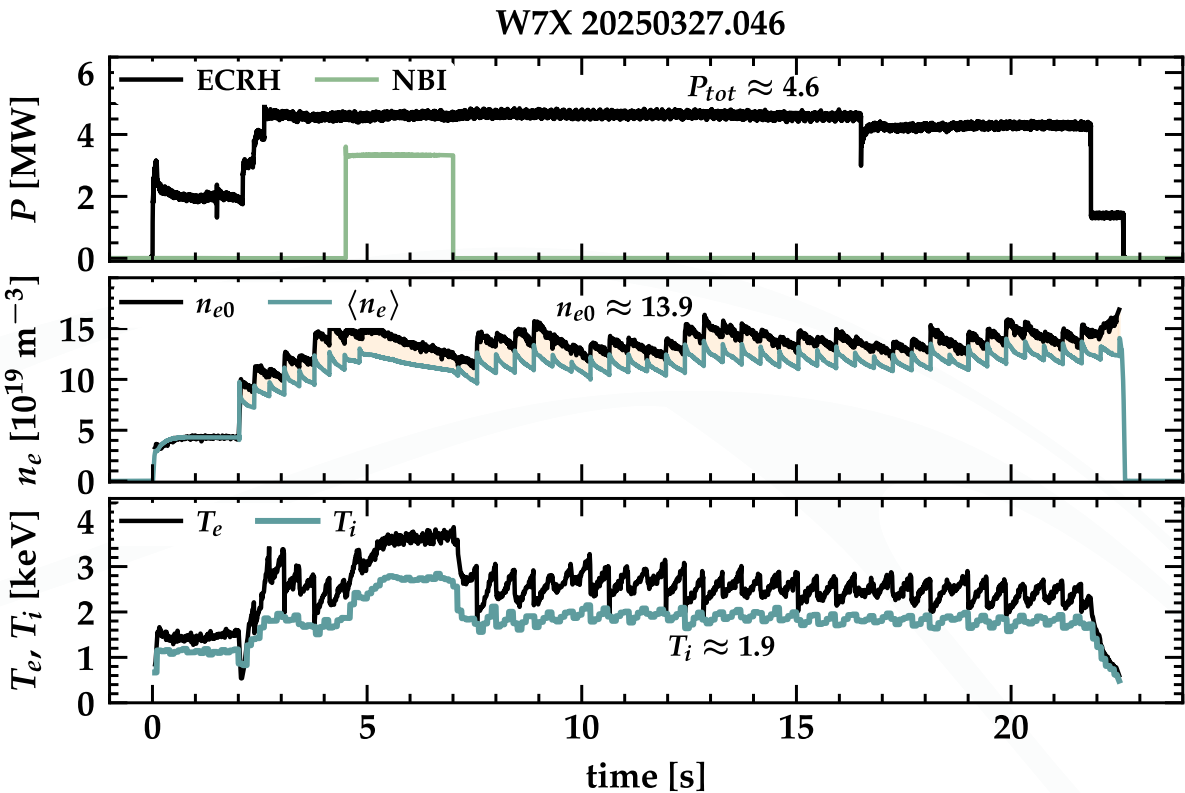
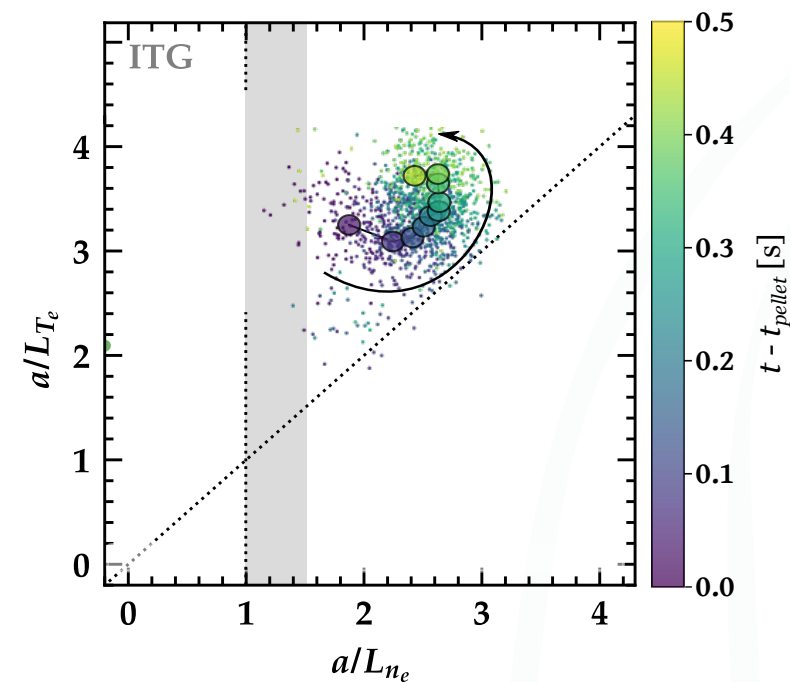
[S. Bozhenkov submitted. PPCF 2025]

Shot trajectory in the gradient plane

Scenario 2: Steady-state pellet injection

Density gradient is quasi-continuous for the right combination of pellets and power

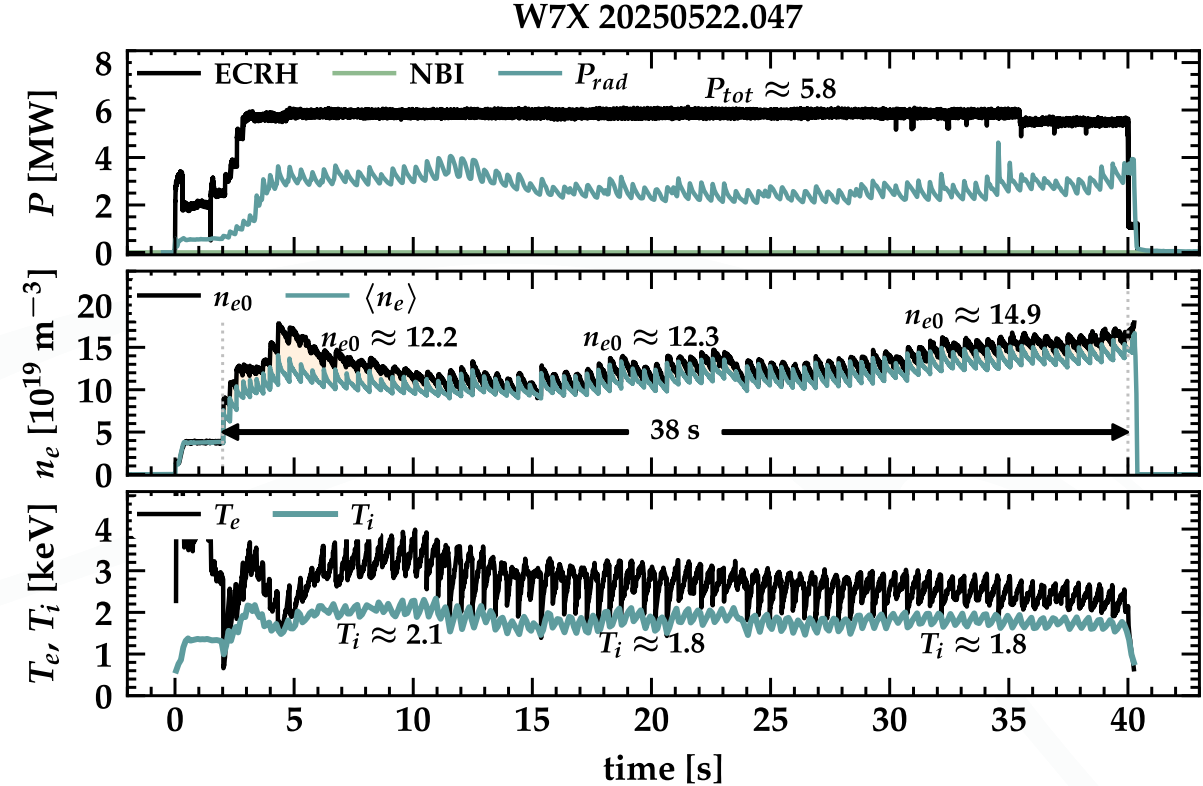
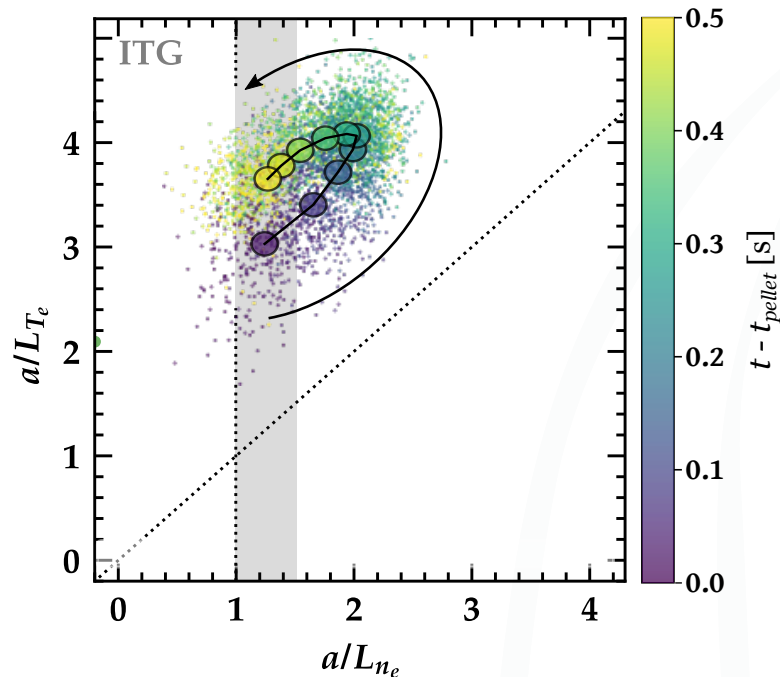
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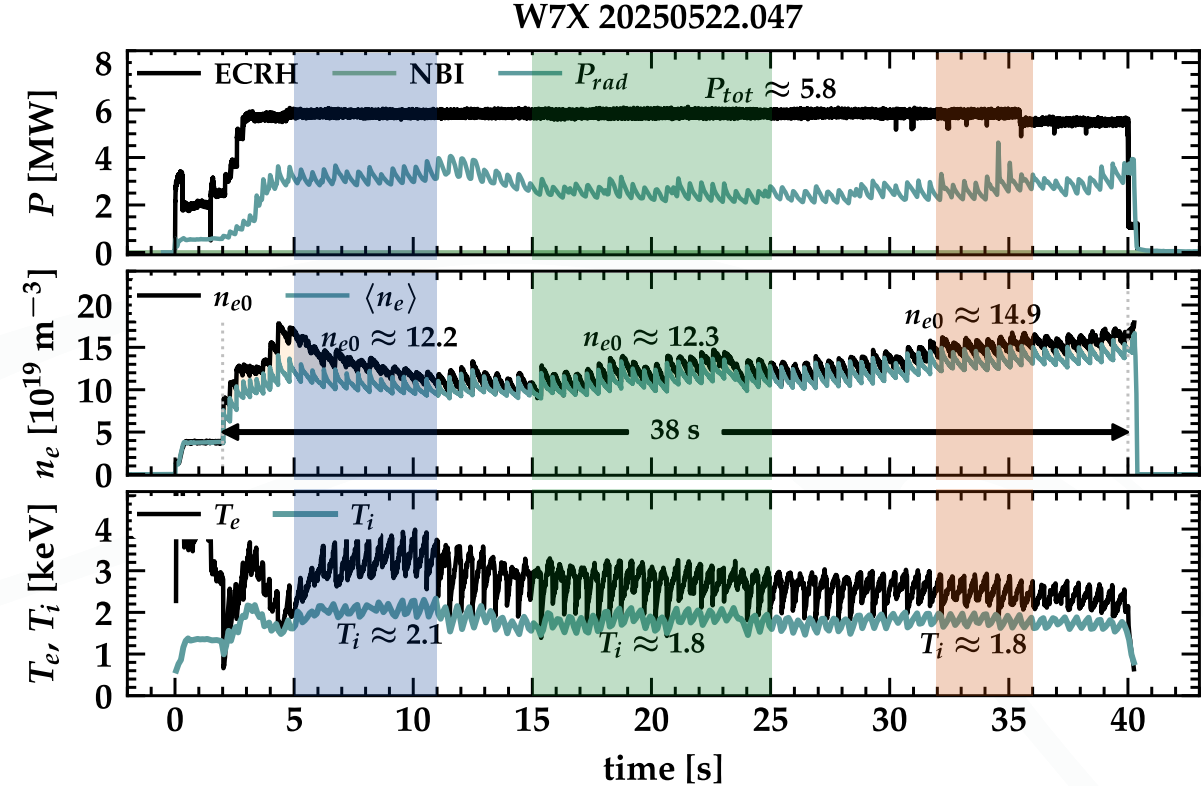
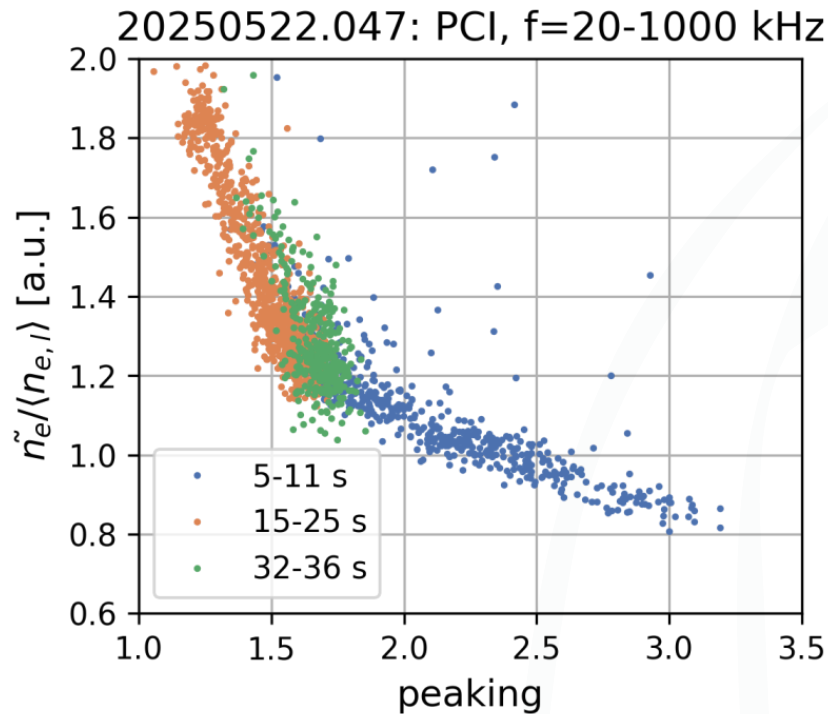
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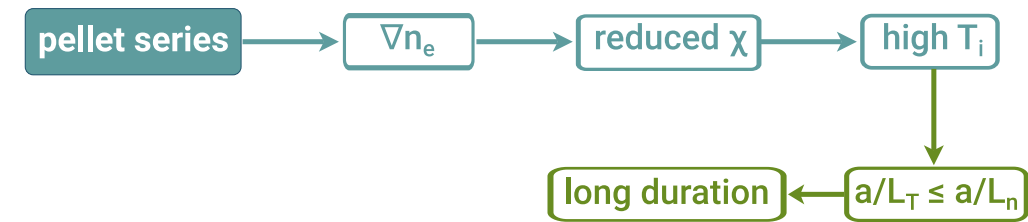
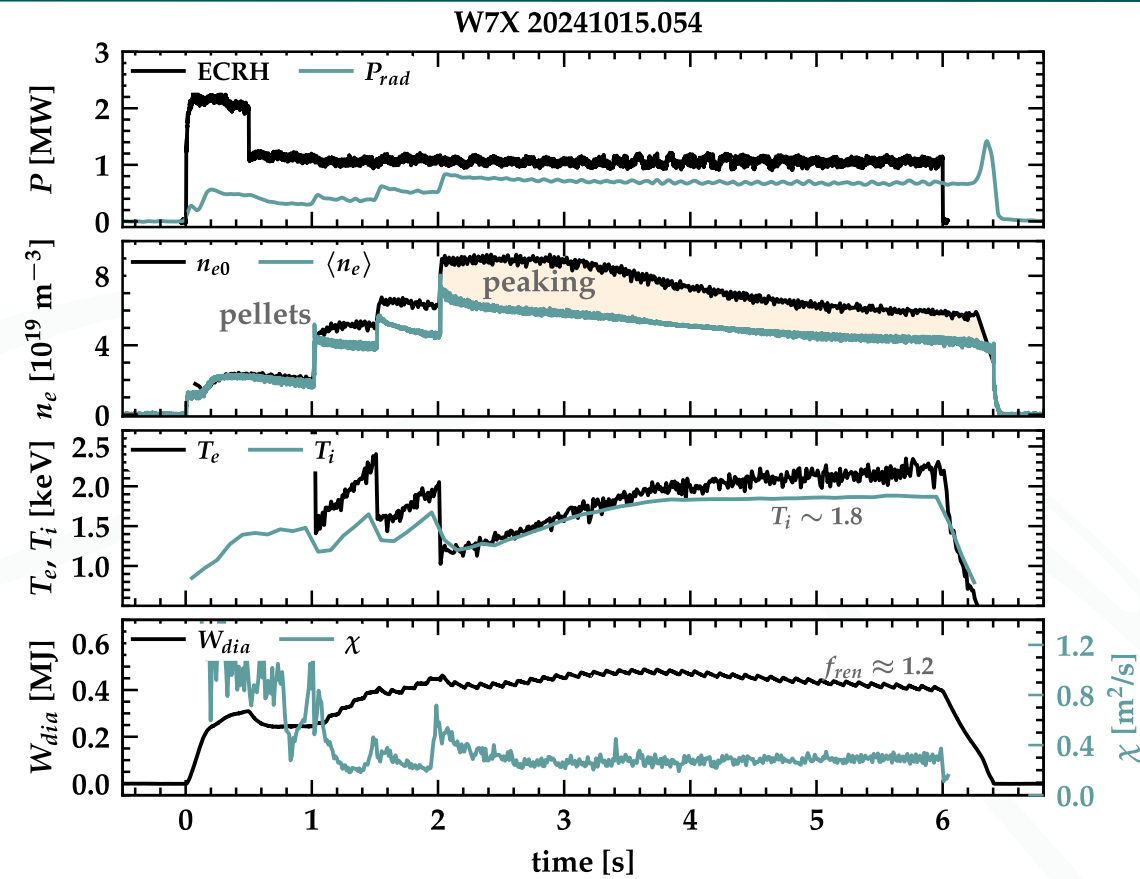
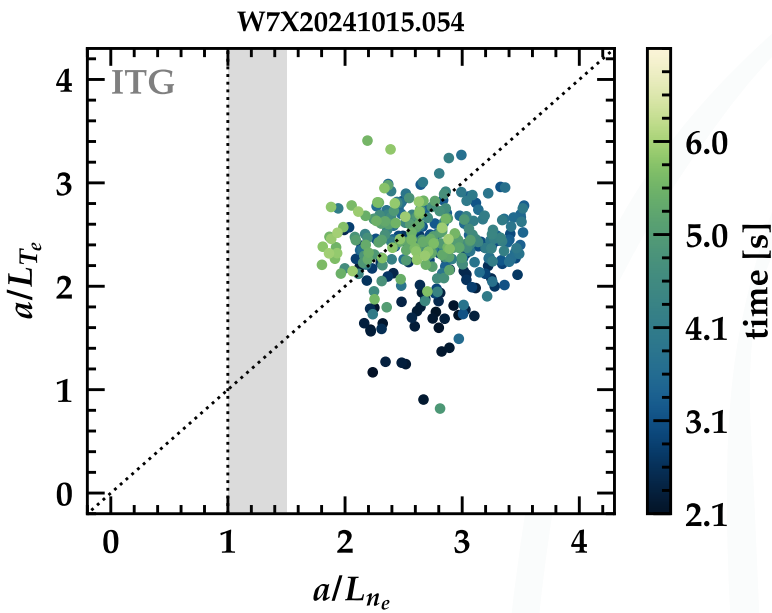
- Reduction of ion scale fluctuations with density gradient confirms turbulence suppression.

[von Stechow EPS2025 4P246]

Scenario 1: Post-pellets - low-power limit

At low power, post-pellet phase can be held for ~seconds.

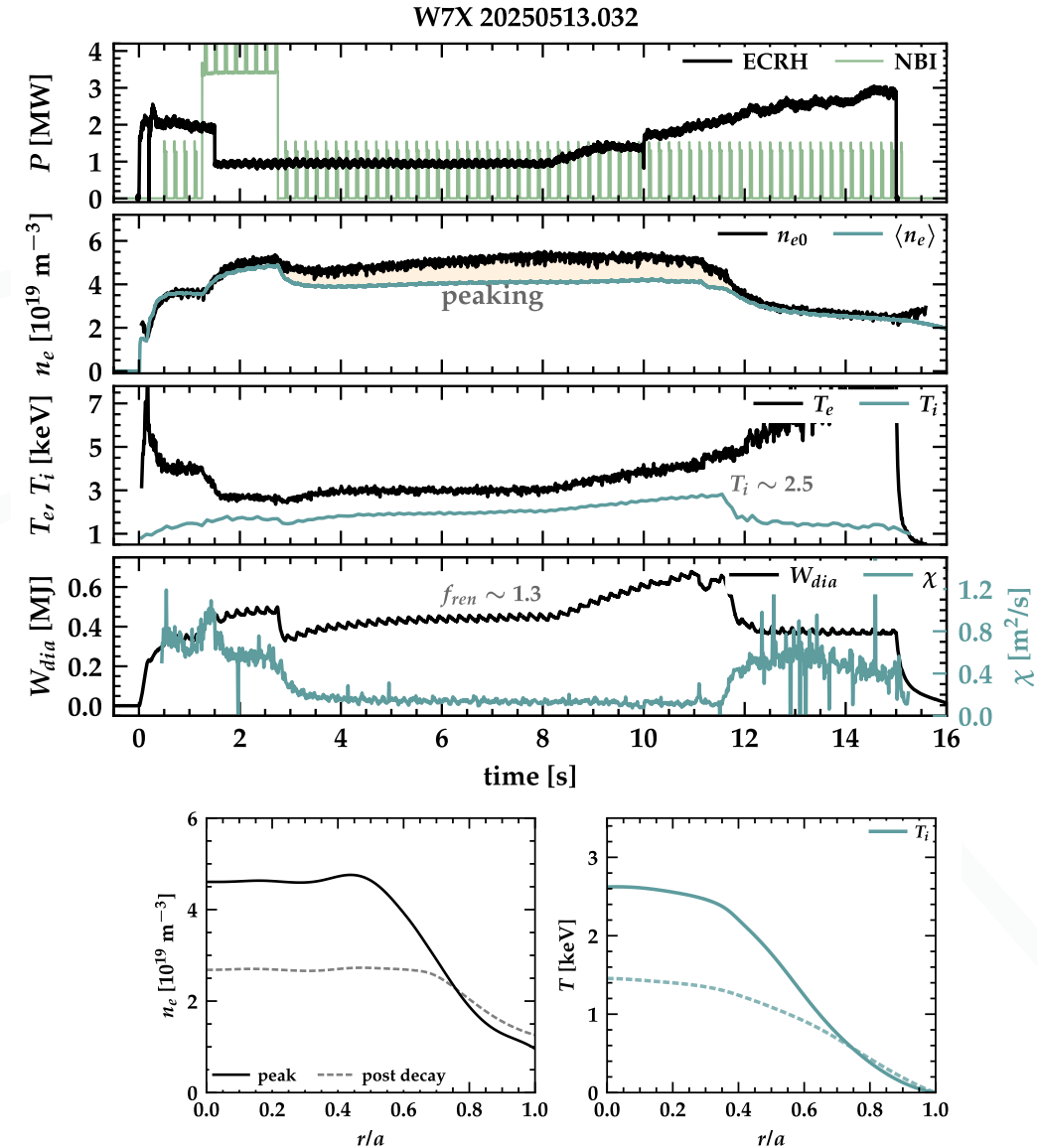
- a/L_T stays at or below a/L_n
- reduced χ_i and T_i above clamping.
- Low power limits T_i and n_e
⇒ good τ_E but poor $n T \tau_E$.



Scenario 3: No-pellets - low-power limit

This works with other ways to give the initial density rise, and *sometimes* spontaneously.

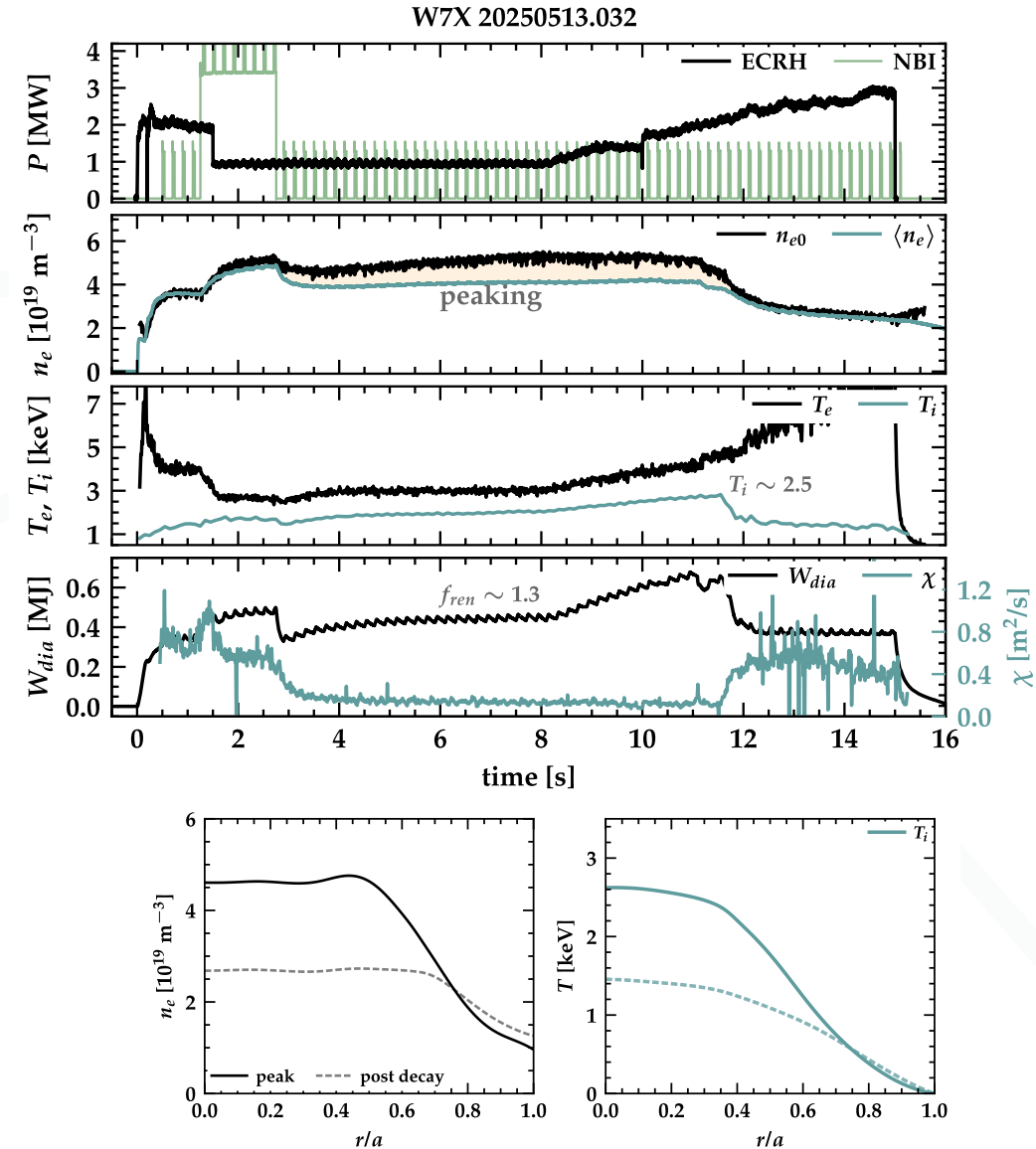
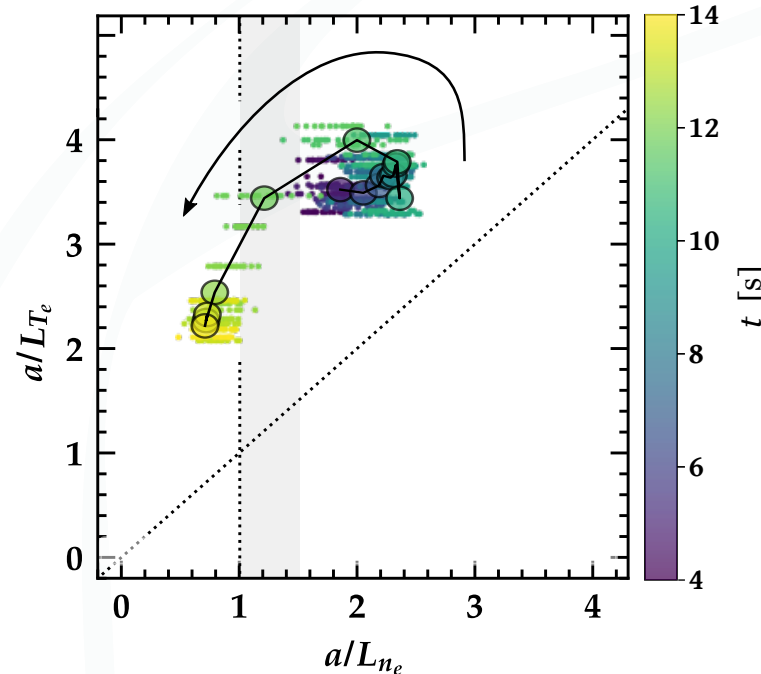
- Peaked densities with low ECRH
[Zhang PPCF 2023; Ford NF 2024; Langenberg PoP 2024]
- Requires low edge n_e and a "kick"
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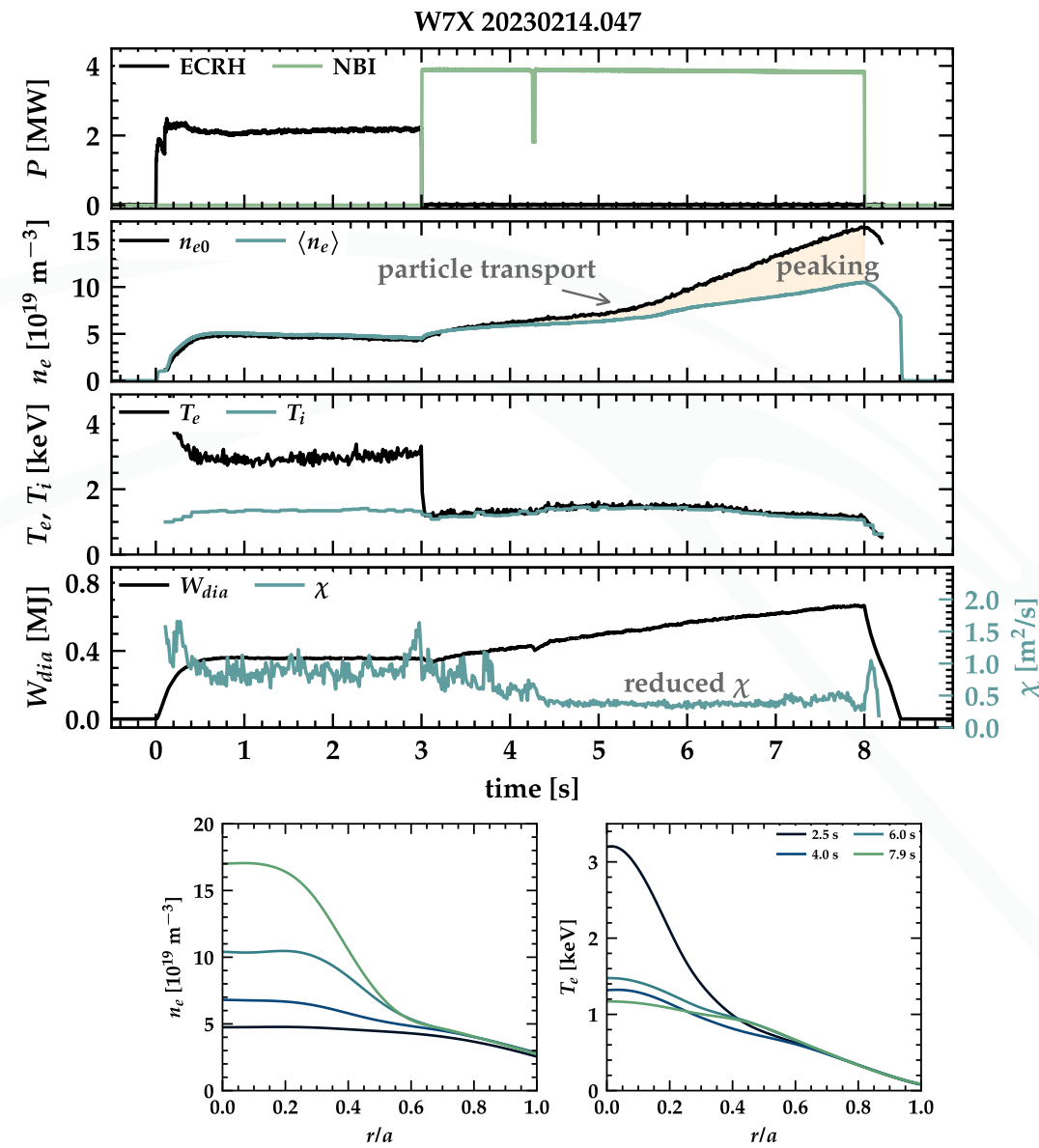
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- Raise of ECRH power collapses gradient.



Scenario 4: NBI

Generate strong density gradients with NBI [Ford NF 2024]

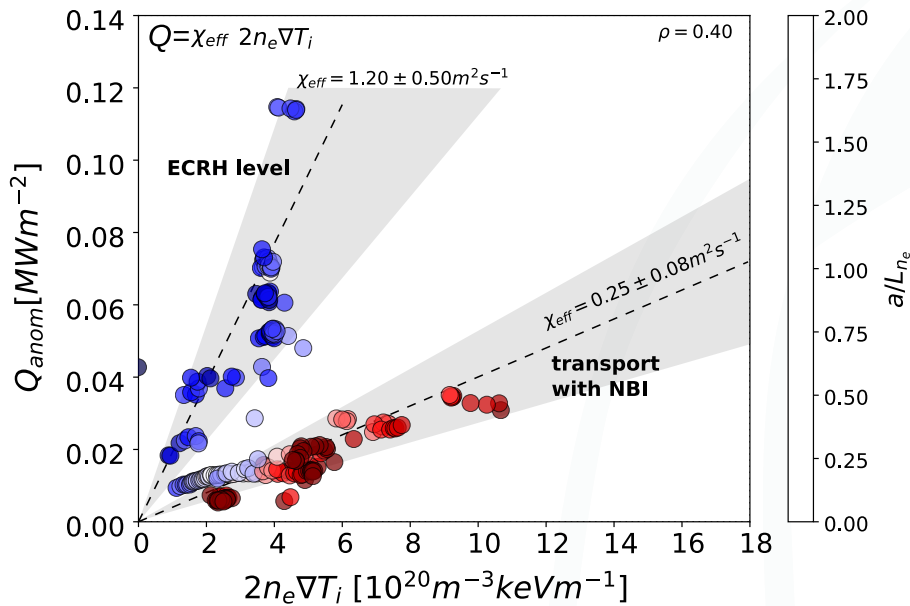
- Change in the particle transport.
- Build up of density gradient



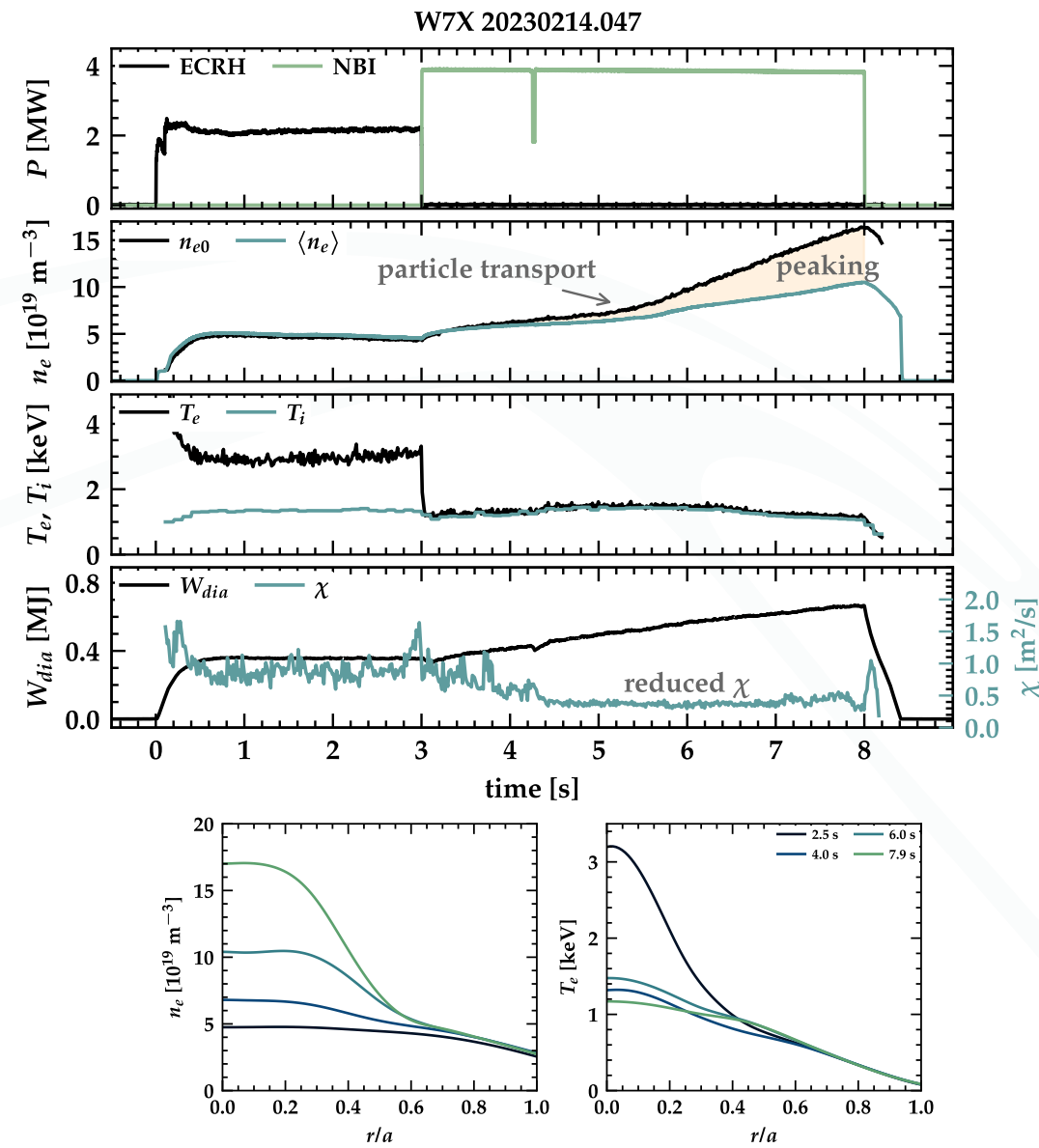
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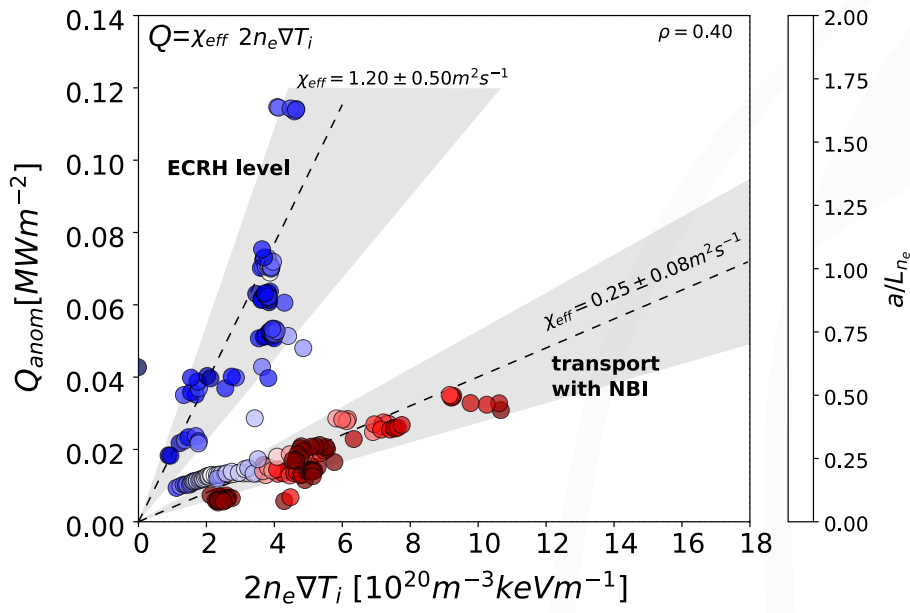
A factor of 4 reduction in heat diffusivity in NBI plasmas [Ford, NF 2024].



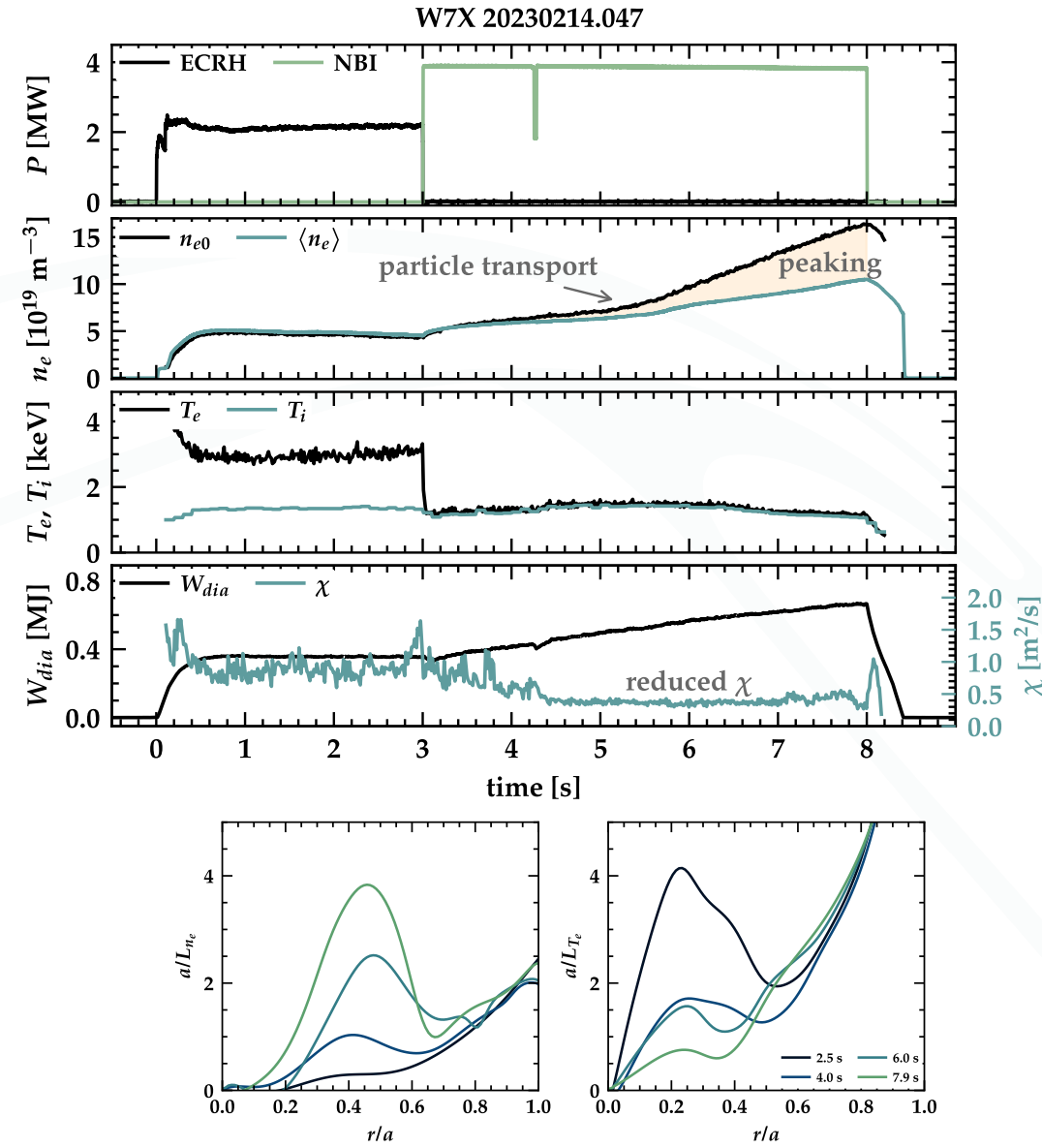
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Generate strong density gradients with NBI [Ford NF 2024].

- Change in the particle transport.
- Build up of density gradient $\Rightarrow$ reduced χ_i .
- Gradient region at smaller radius.
- reproducible, controllable with known sources



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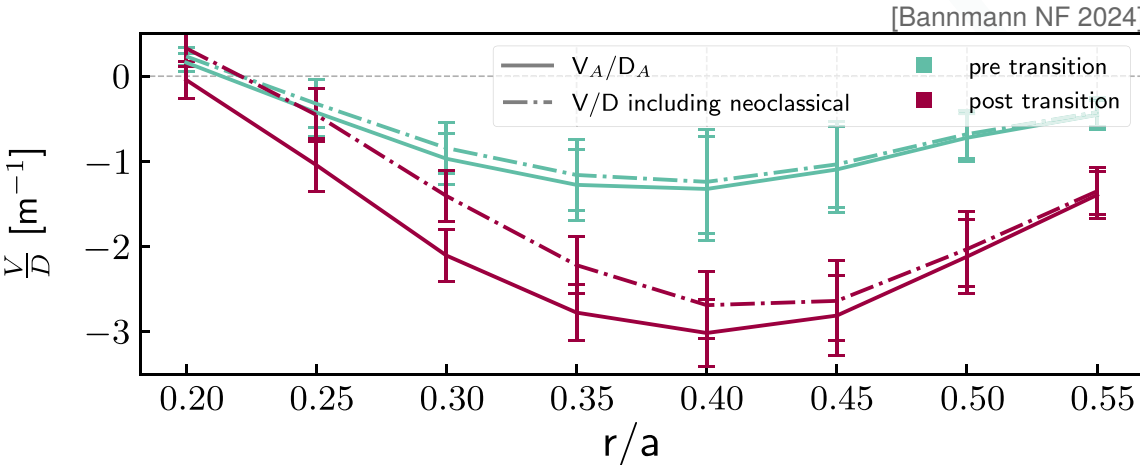
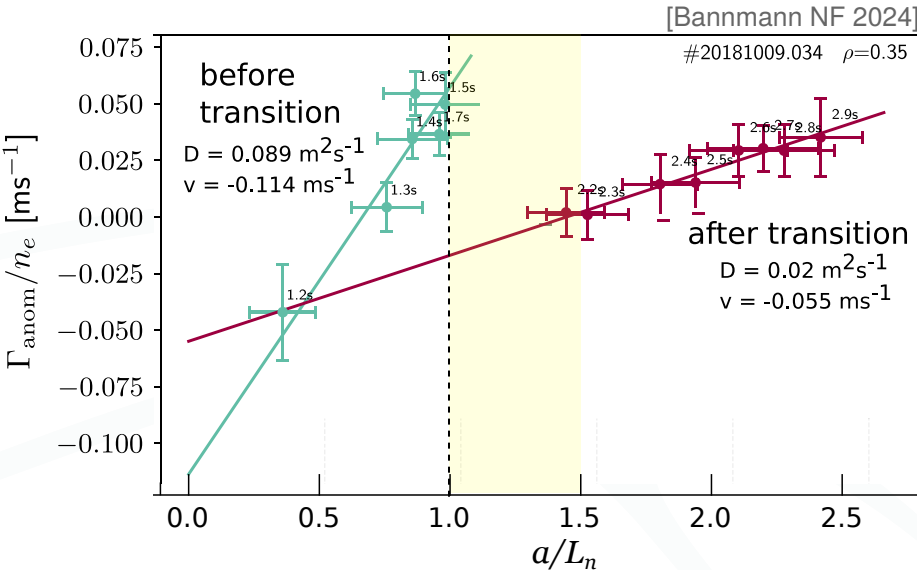
Scenario 4: NBI - particle transport



Particle transport easier to study in NBI

[Ford NF 2024; Bannmann NF 2024]

- Sudden drop of particle diffusion past $a/L_n \sim 1.0$
- v/D reduced by $\sim \times 3 \Rightarrow$ stronger peaking



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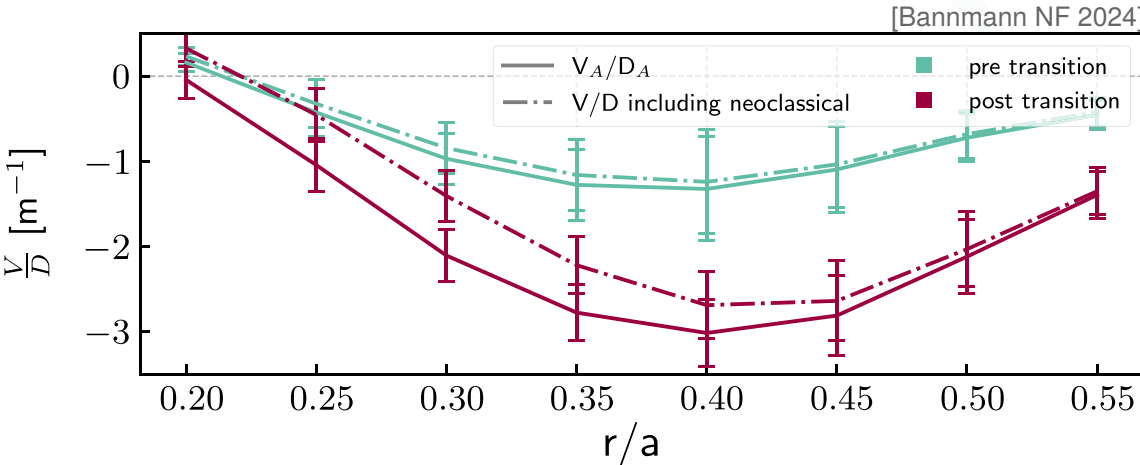
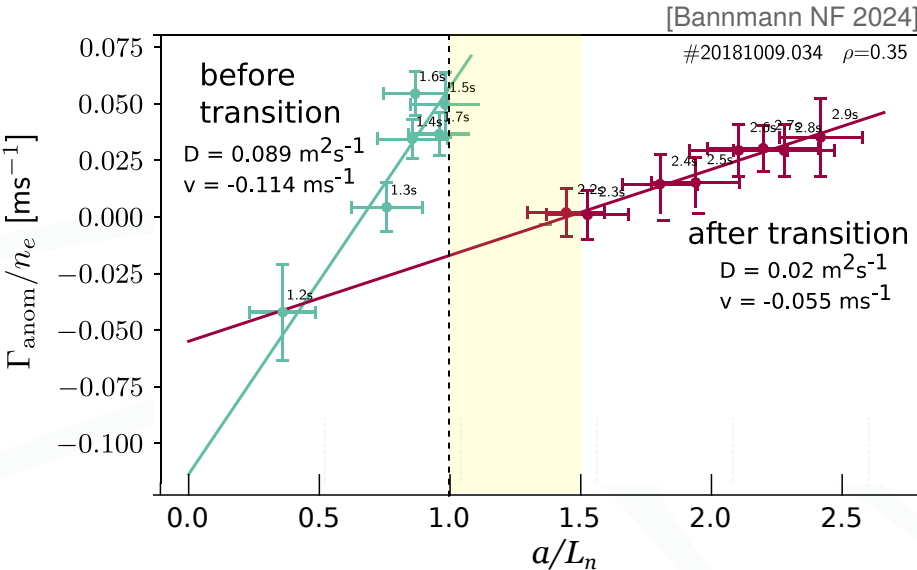


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- Final gradient would be given by balance:

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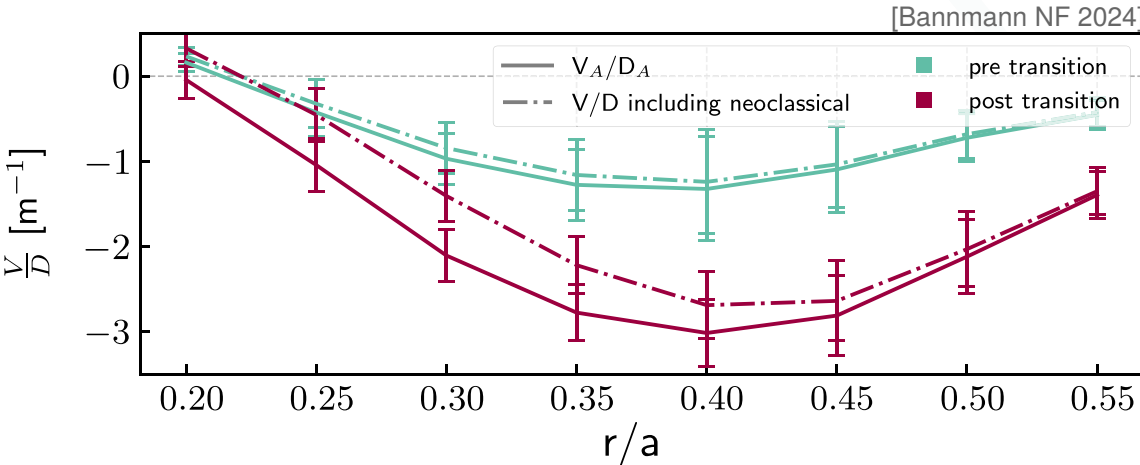
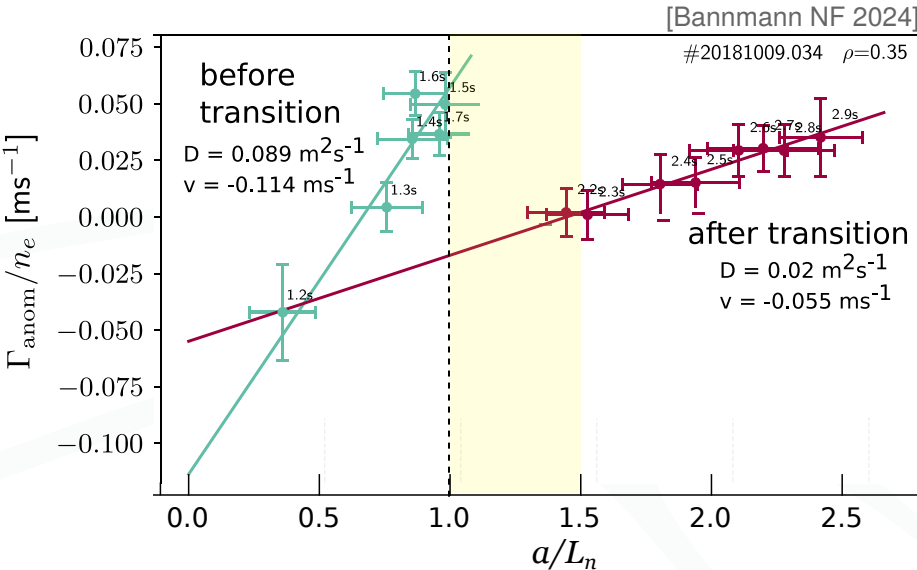
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$$-\frac{\nabla n}{n} = \underbrace{\left(-\frac{v}{D}\right)}_{\text{Due to pinch}} + \underbrace{\left(\frac{\int s dV}{V' D n}\right)}_{\text{Due to source}},$$

Here $\sim 50\%$ from NBI source and pinch.

[Bozhenkov PPCF 2025 (submitted)]

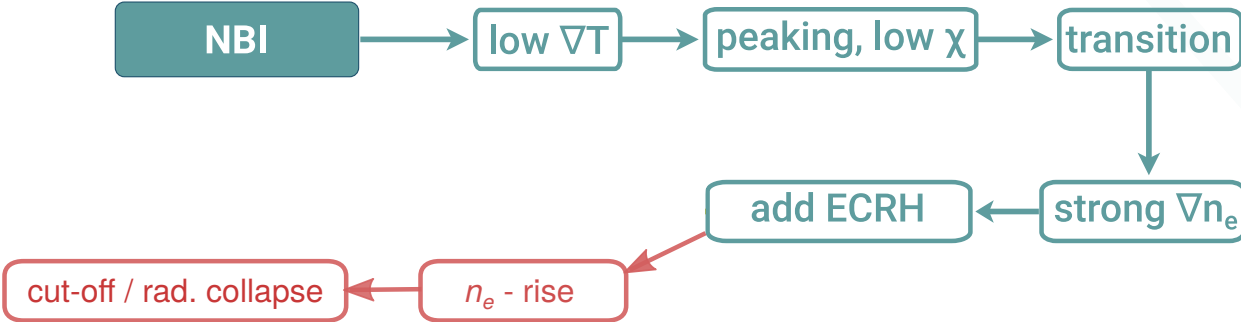
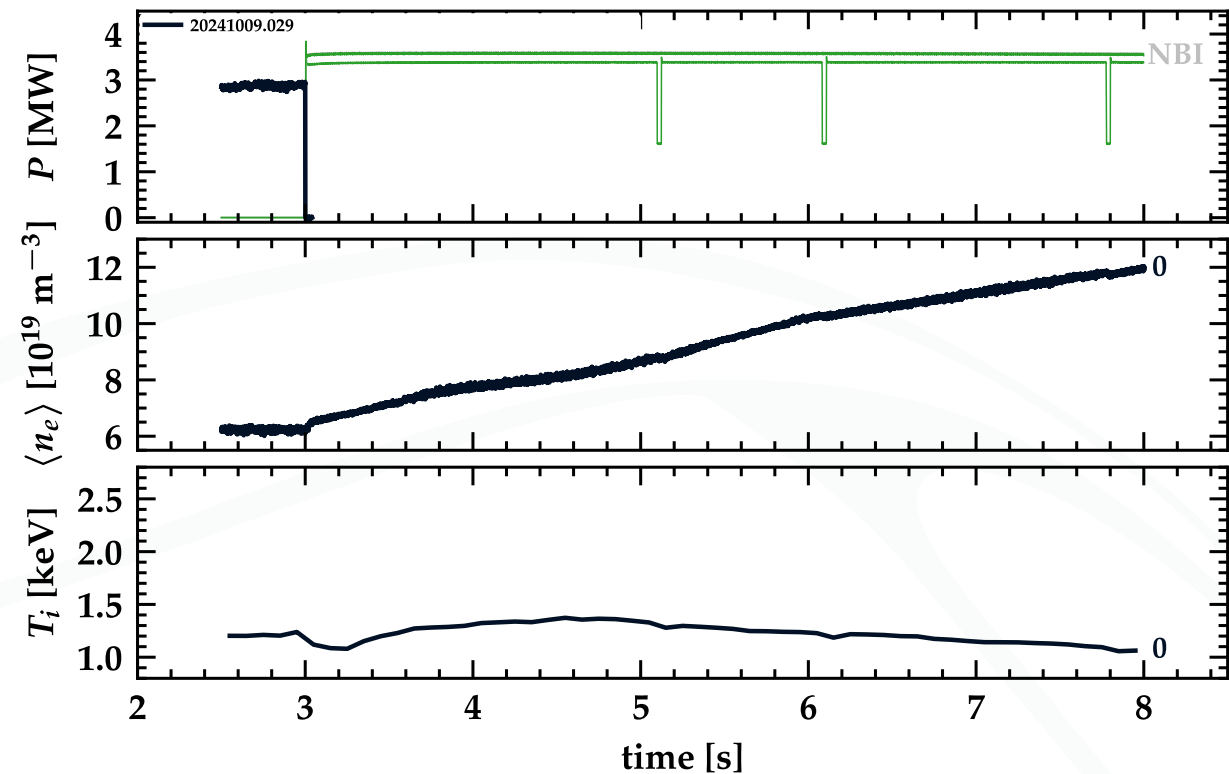


Scenario 4: NBI + ECRH reintroduction - 'pump-out'



Heating with reduced χ_i to raise plasma temperature.

- Similar to post-pellets, but with particle source.
- Density evolution depends on ECRH power.

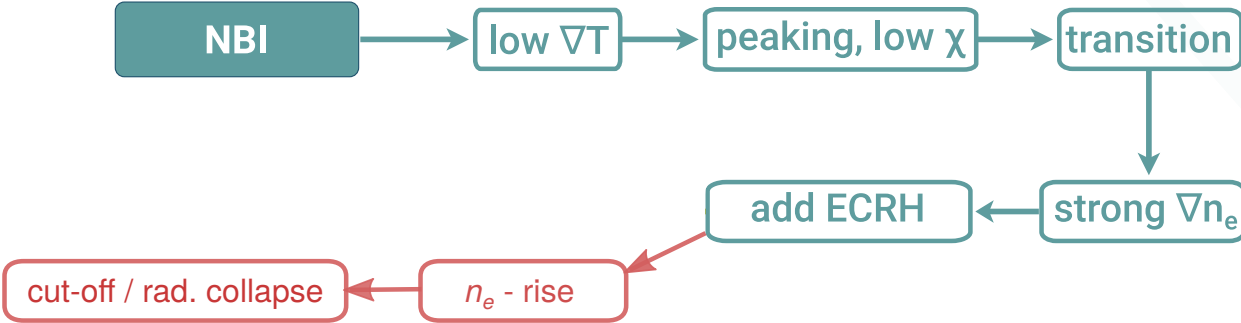
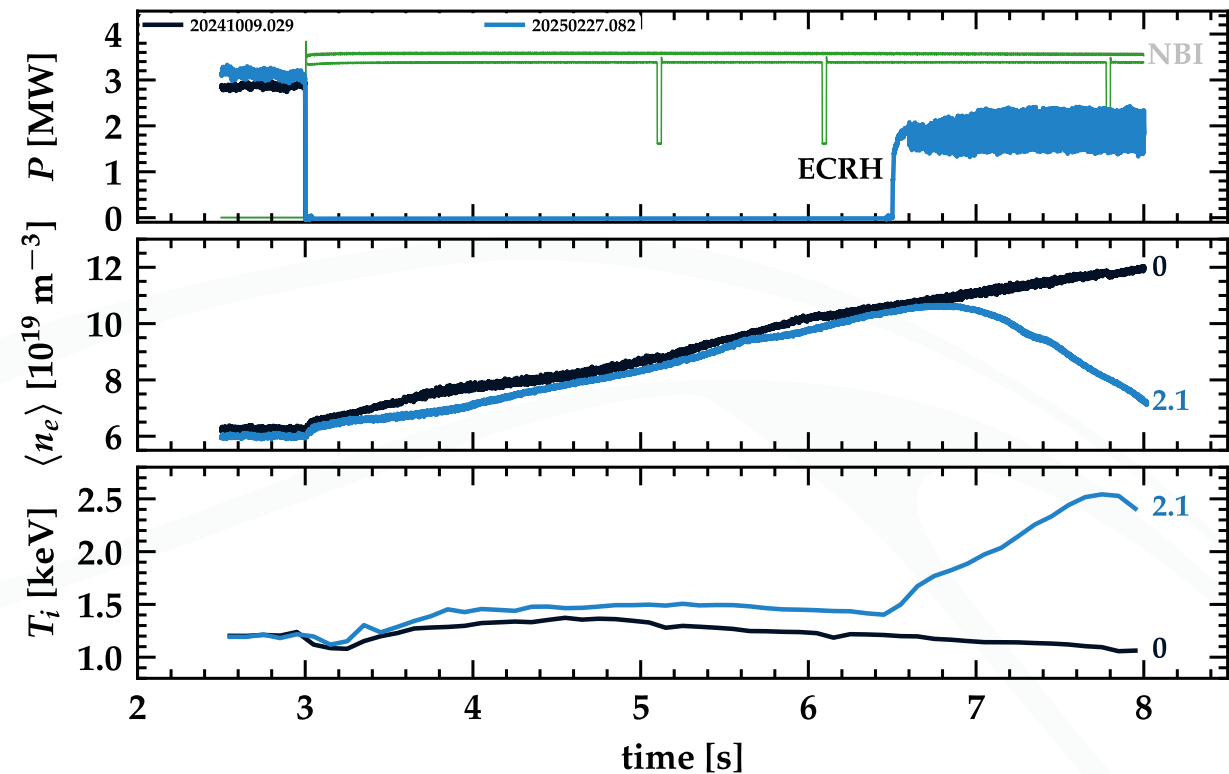


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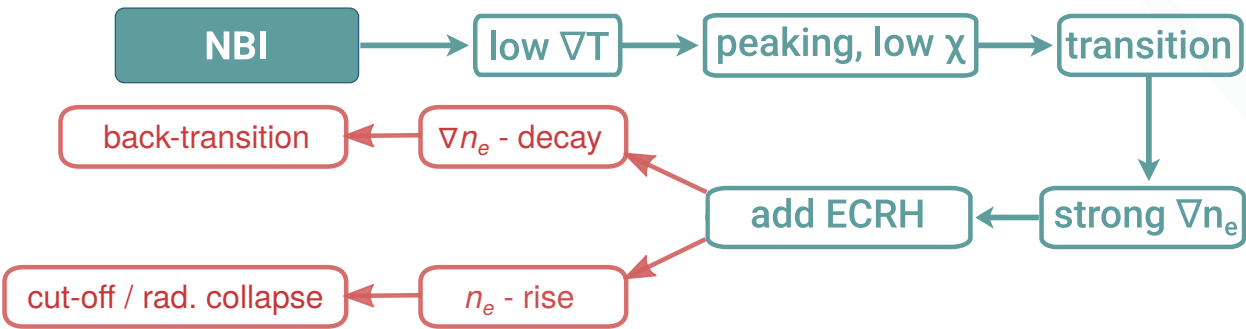
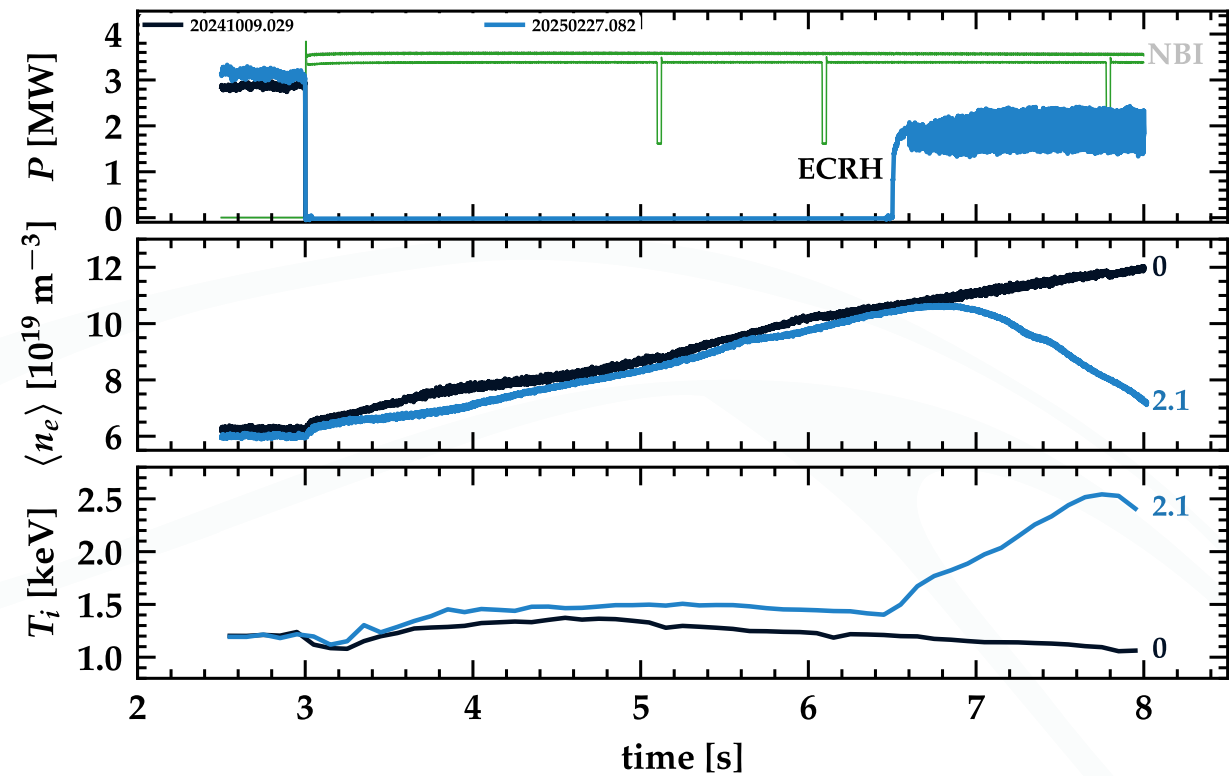
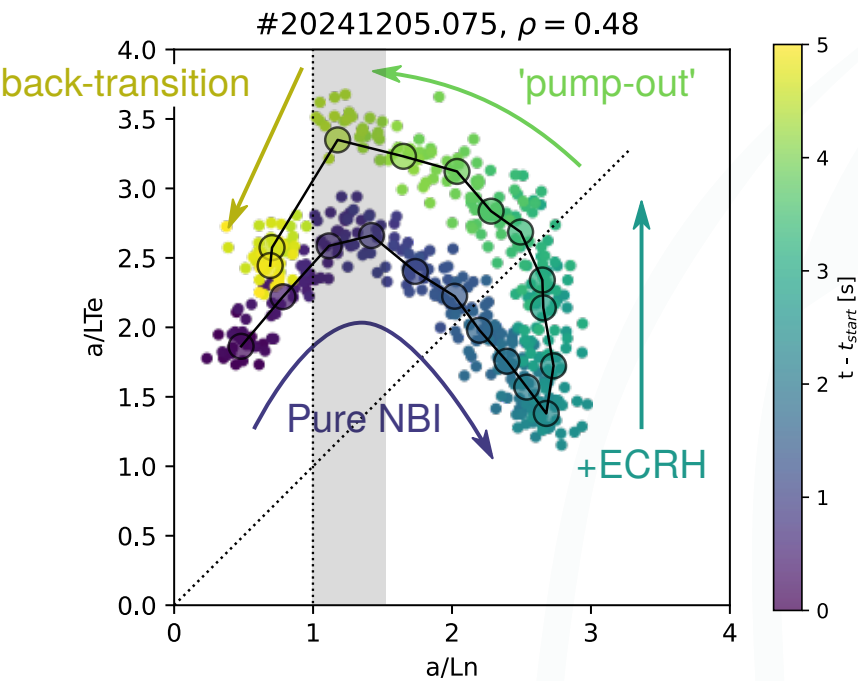


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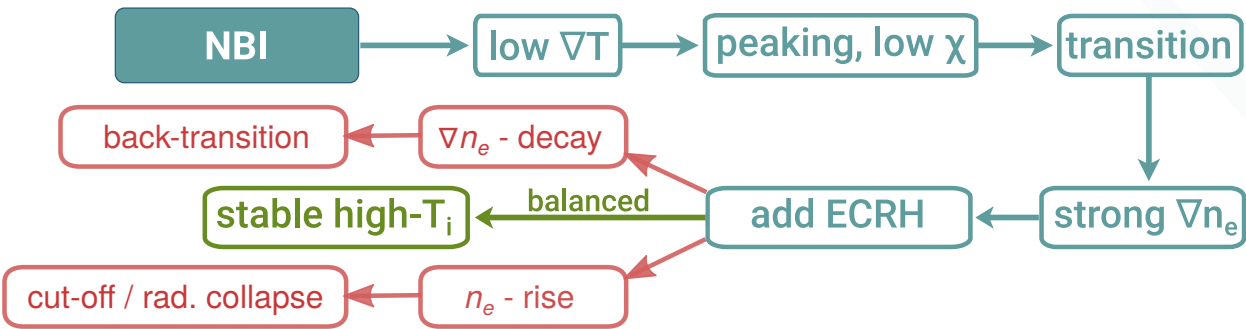
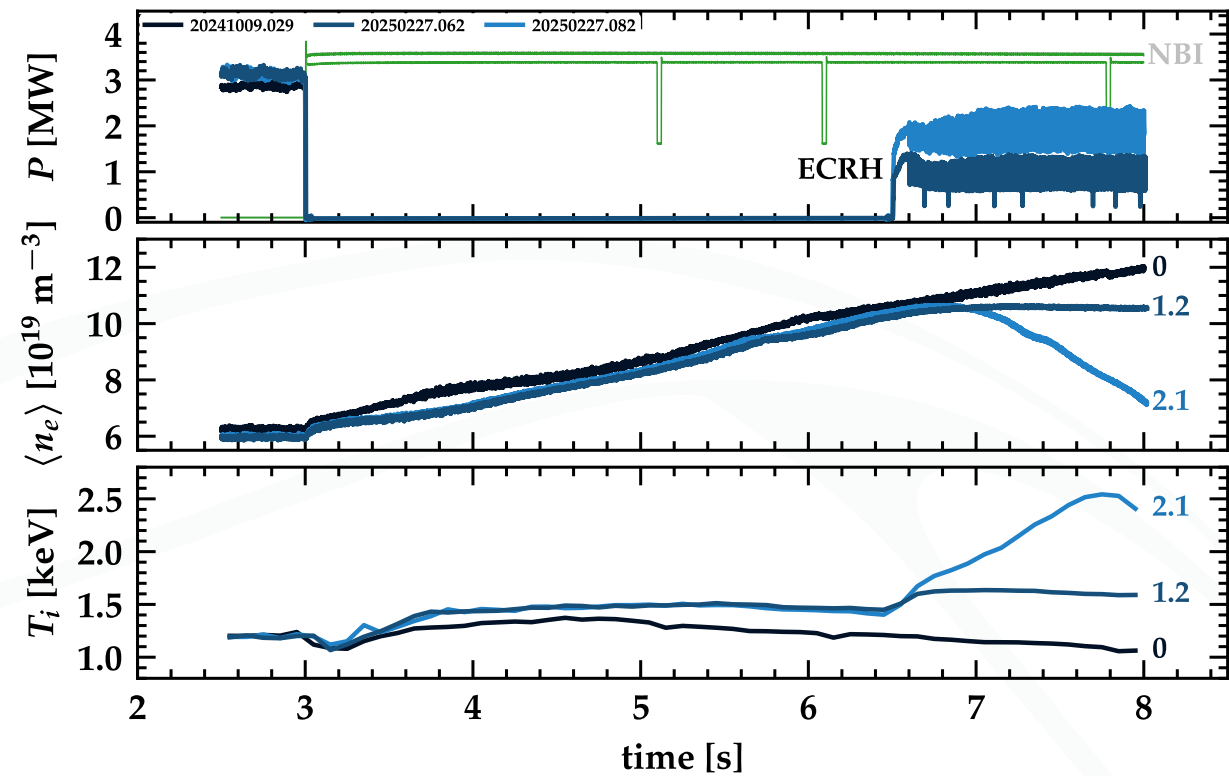
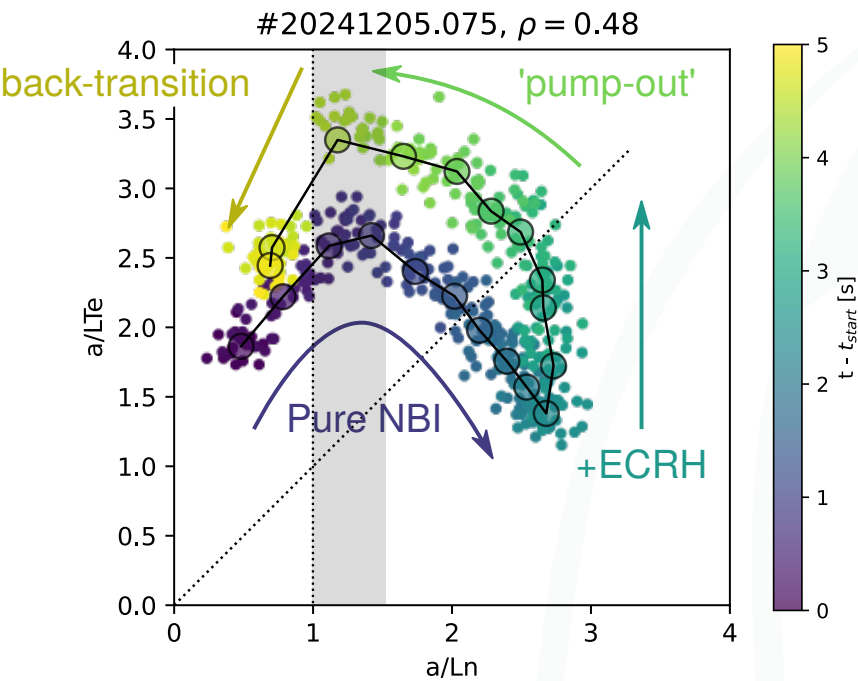


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- Compensate particle source
⇒ balance for steady state

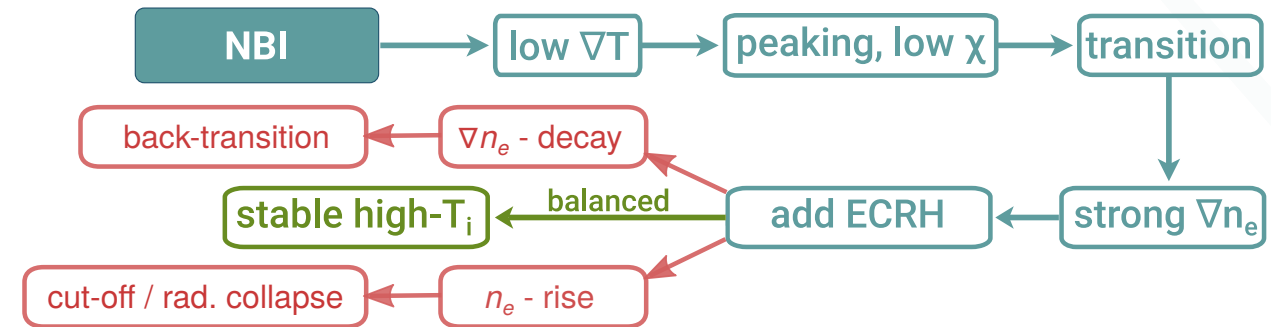


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- Balance strongly configuration dependent

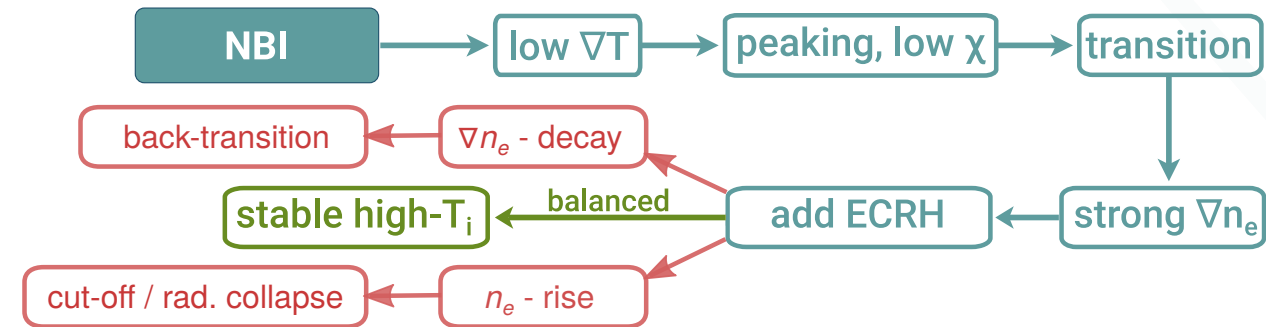
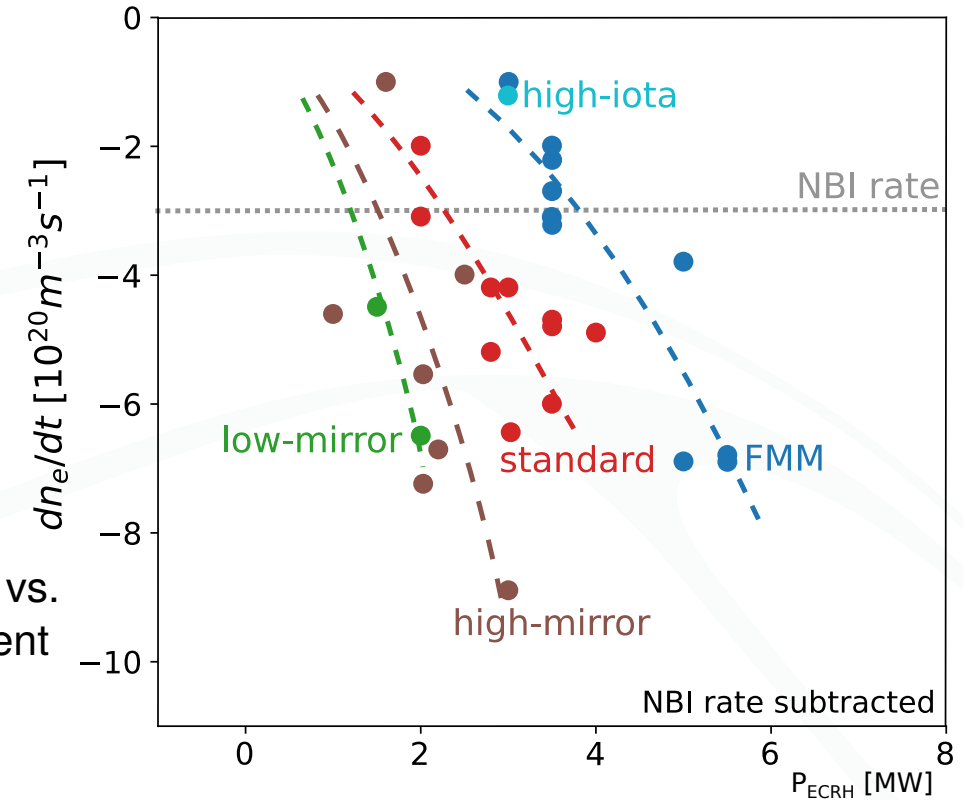


Scenario 4: NBI + ECRH reintroduction - '*pump-out*'

Heating with reduced χ_i to raise plasma temperature.

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'Pump-out' rate vs.
power for different
configurations.

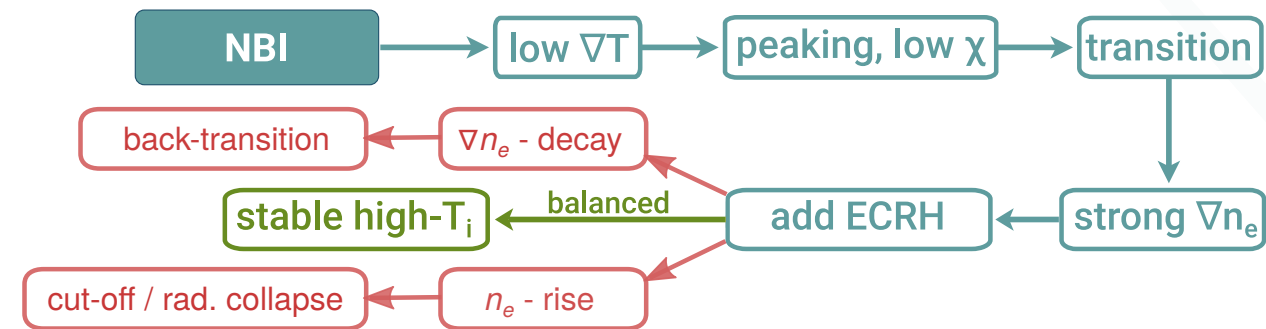
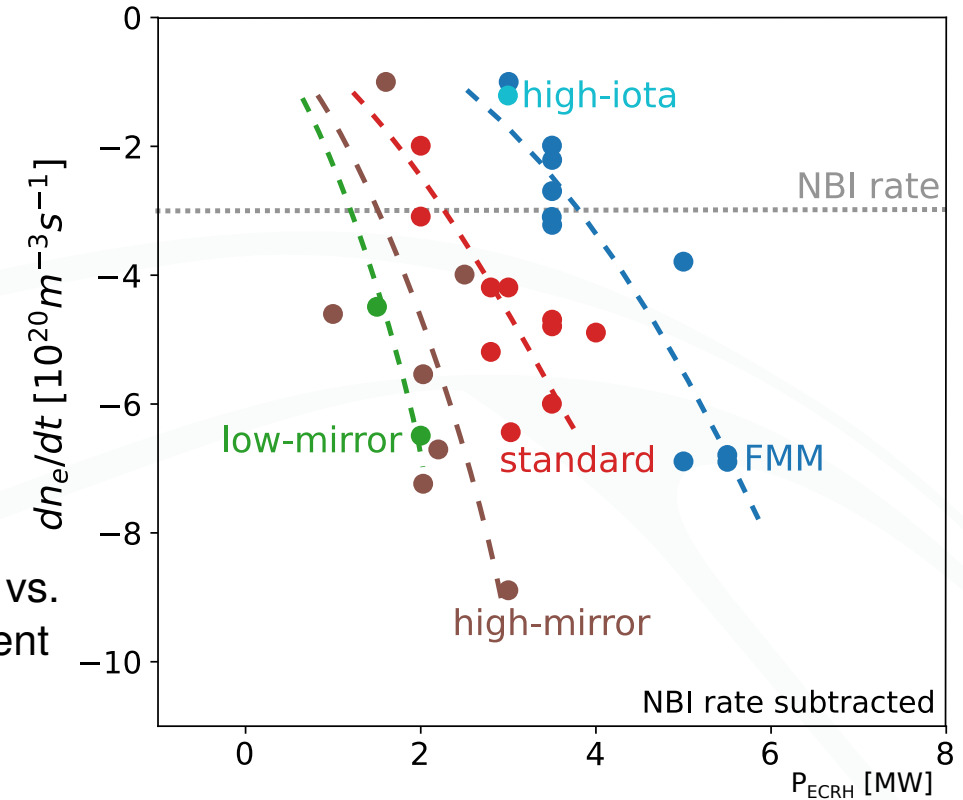


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 - Compensate particle source
⇒ balance for steady state
 - Balance strongly configuration dependent
 - Many significant contributions:
 - Beam deposition change.
 - Recycling flux change.
 - Neoclassical flux.
 - Turbulence flux.
 - *Other anomalous effects??*
- ⇒ Need systematic scans with good data.

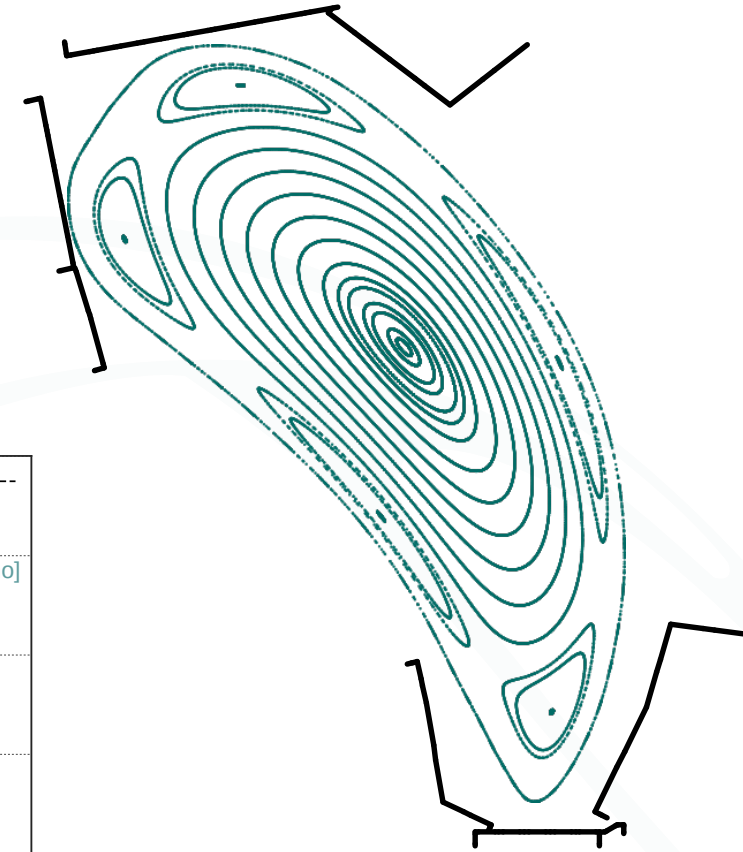
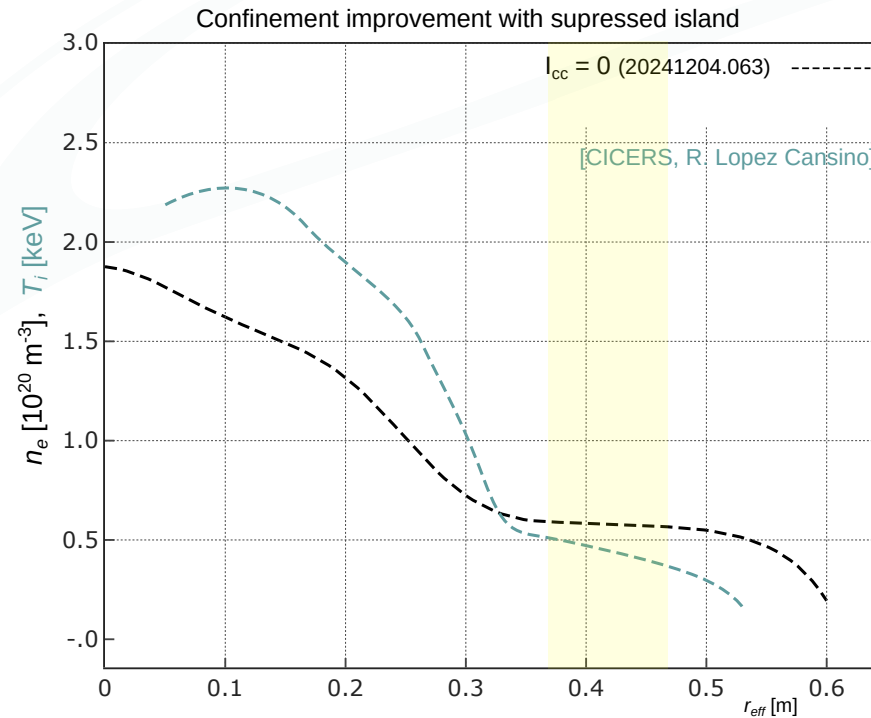
'Pump-out' rate vs. power for different configurations.



Scenario 4: NBI + ECRH reintroduction - FMM002

The balance depends on configuration

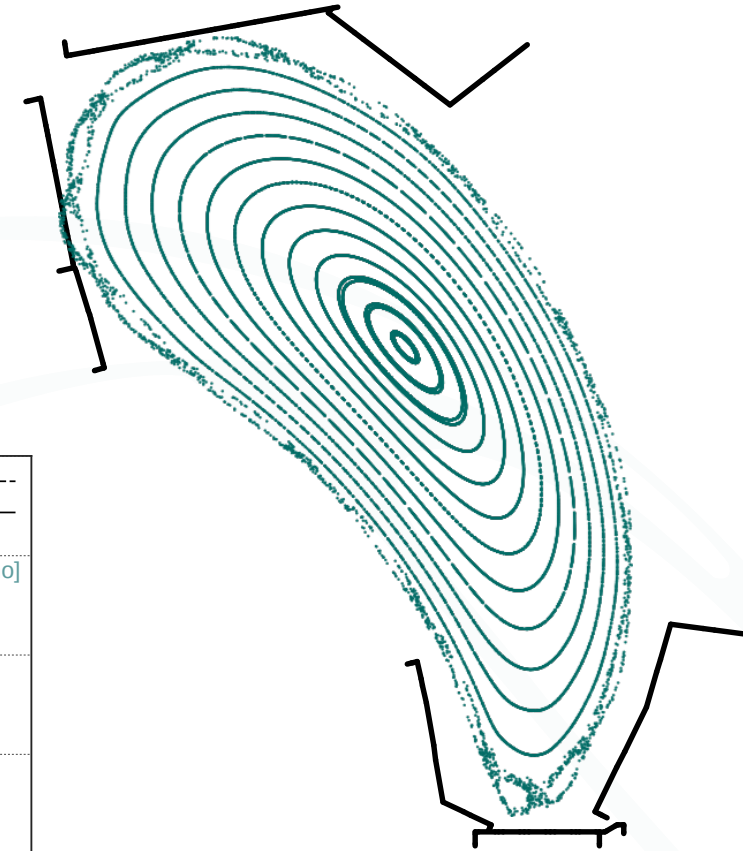
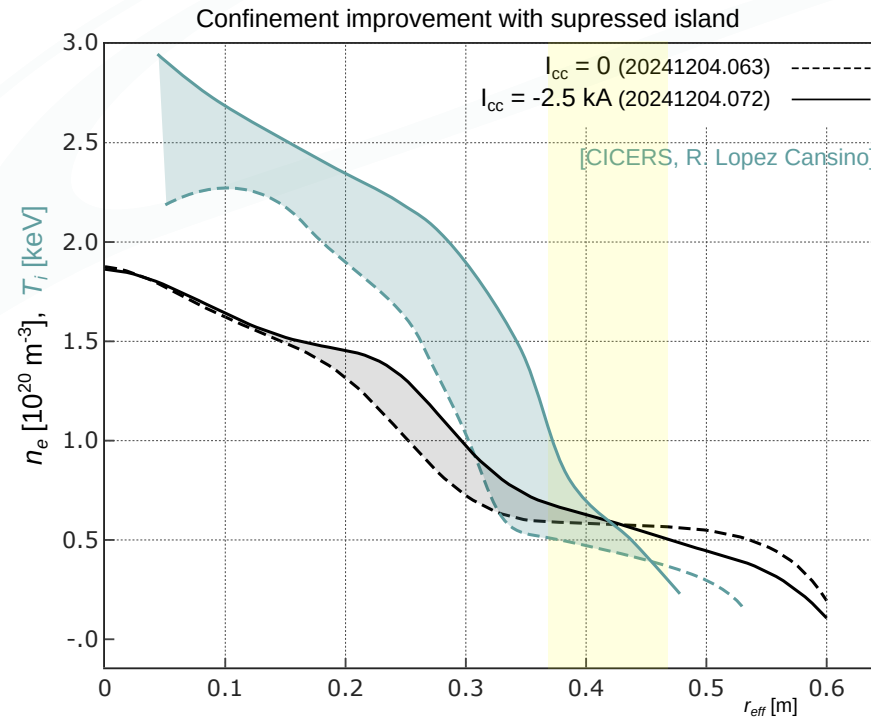
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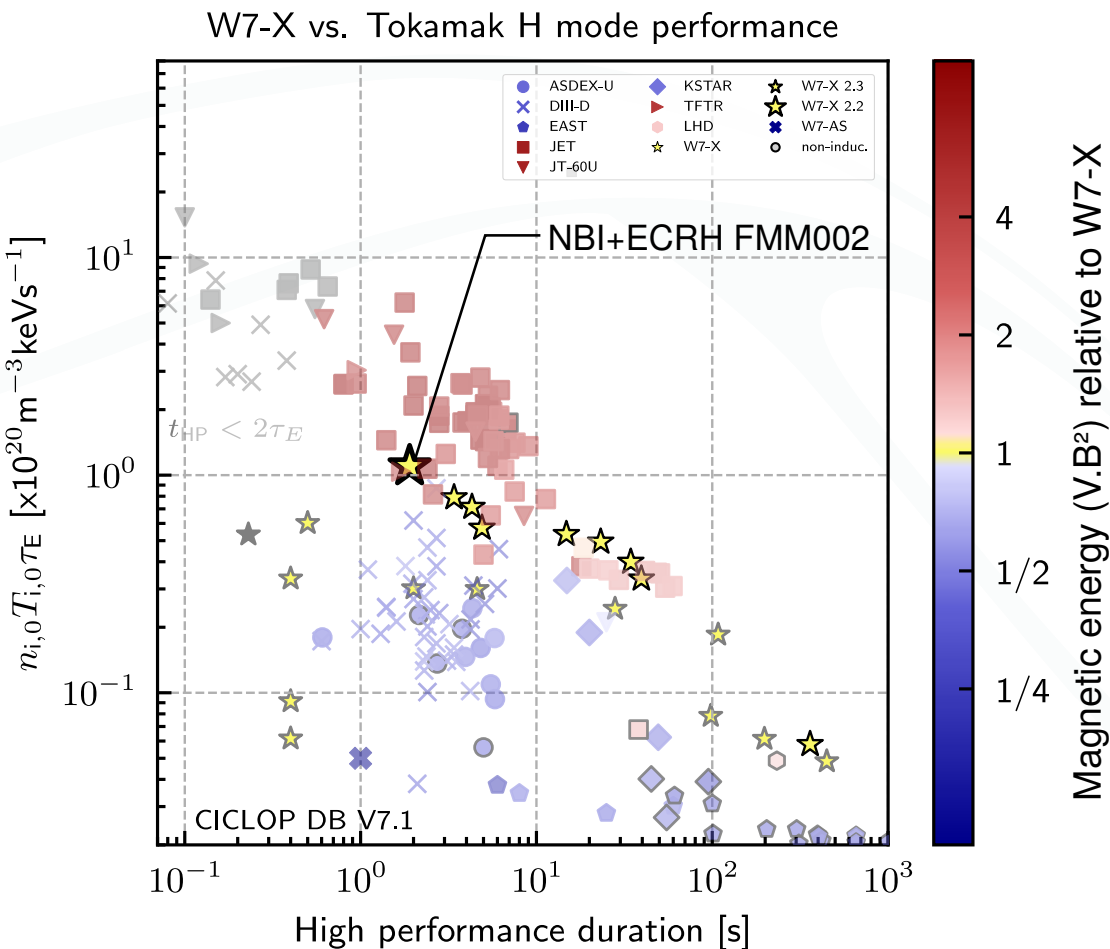
- Best in high(er)-iota: FTM/FMM002
- FMM002 has higher volume, but T_i flattened due to internal island [Lopez Cansino]
- Island suppressed with control coils
 - > Larger radius of gradients.
 - > Higher core T_i + higher stored energy



Scenario 4: NBI + ECRH reintroduction - duration



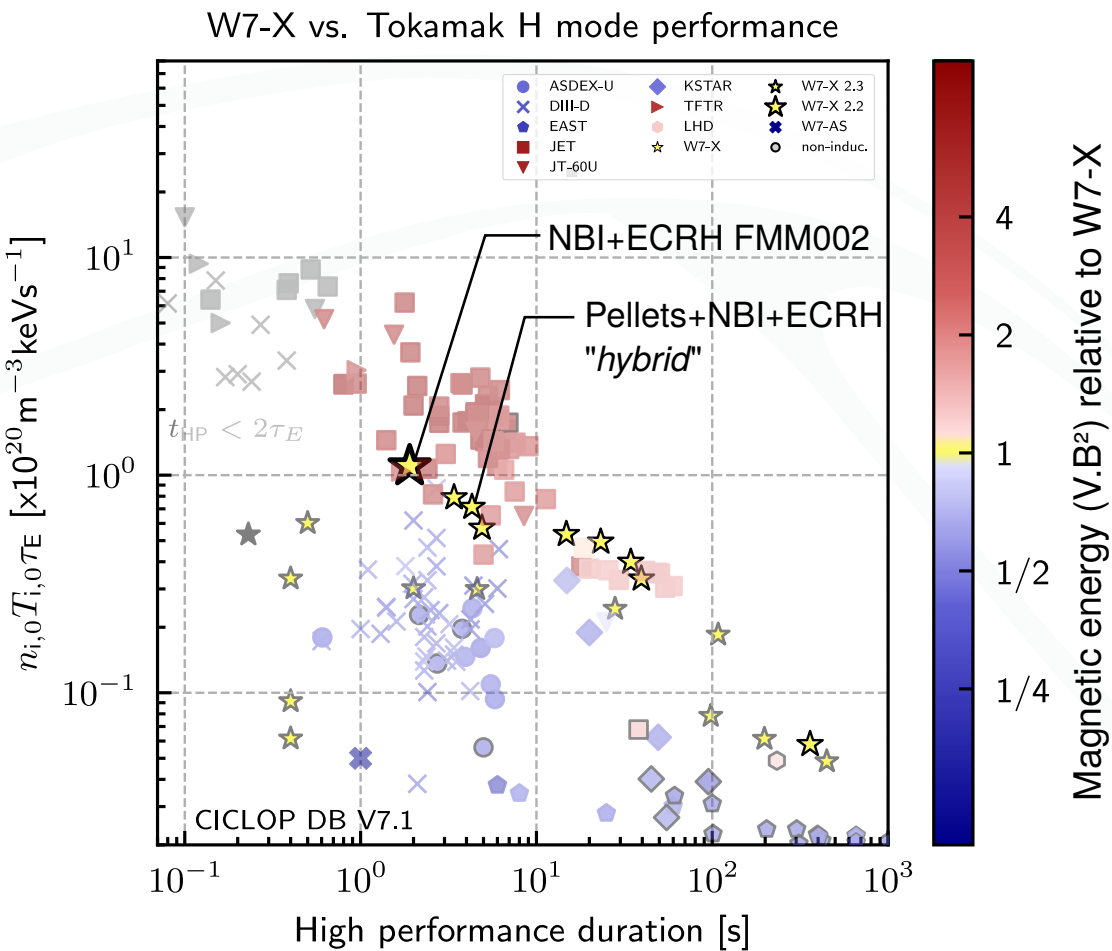
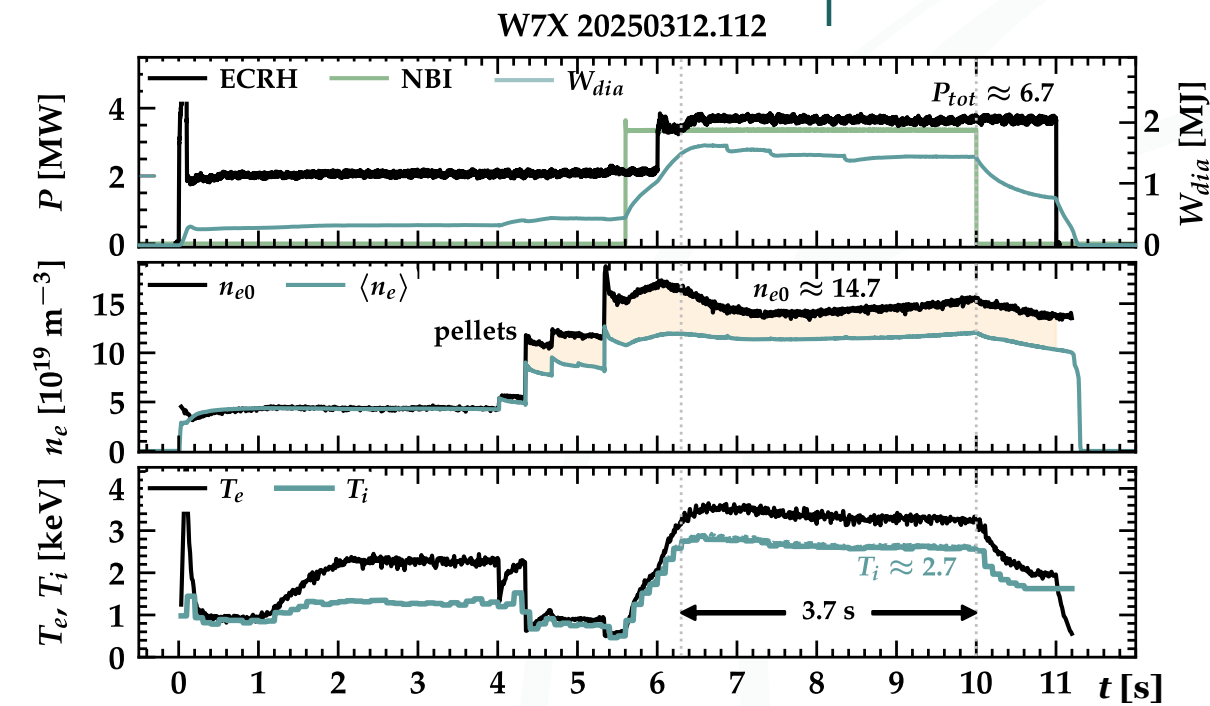
The FMM002 gives record $n T \tau_E$ equivalent to Tokamak H-modes of same size+field for 1.9 seconds.
[Bannmann submitted PRL 2025].



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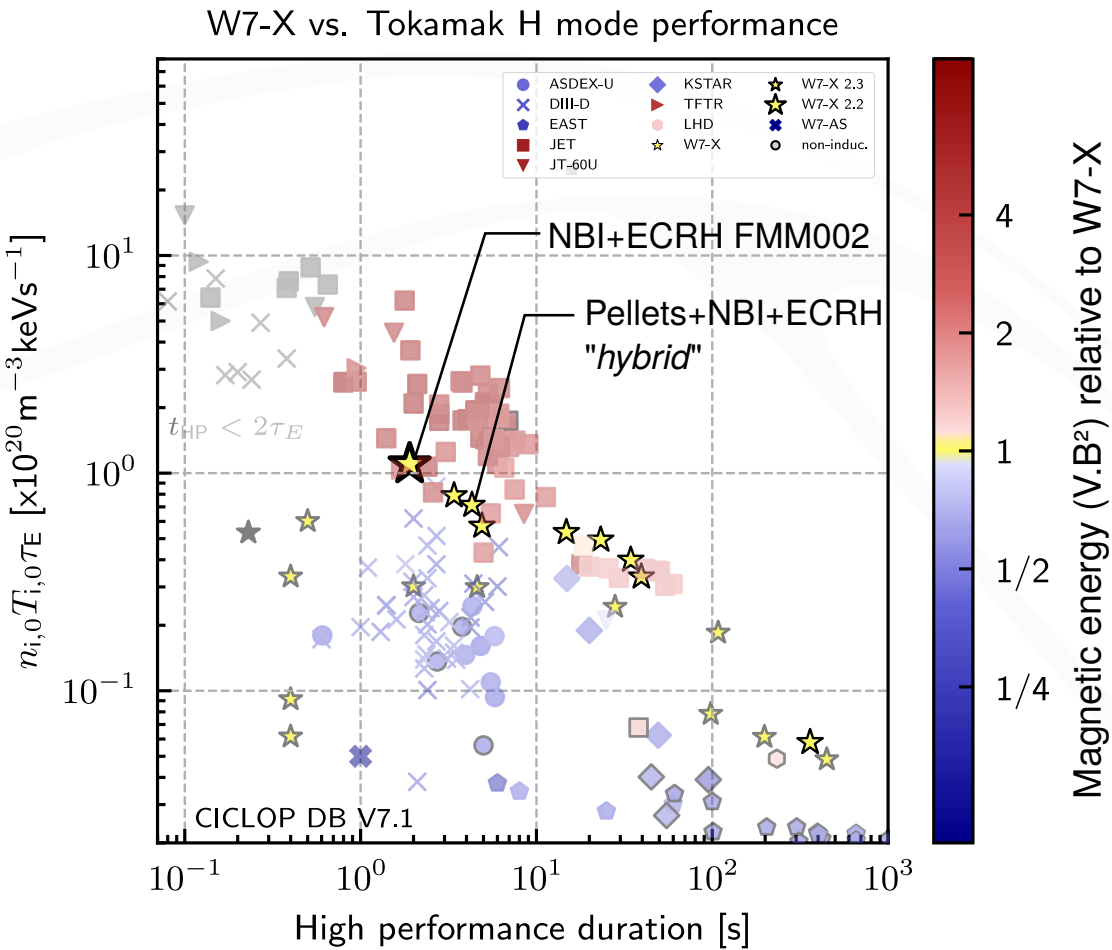
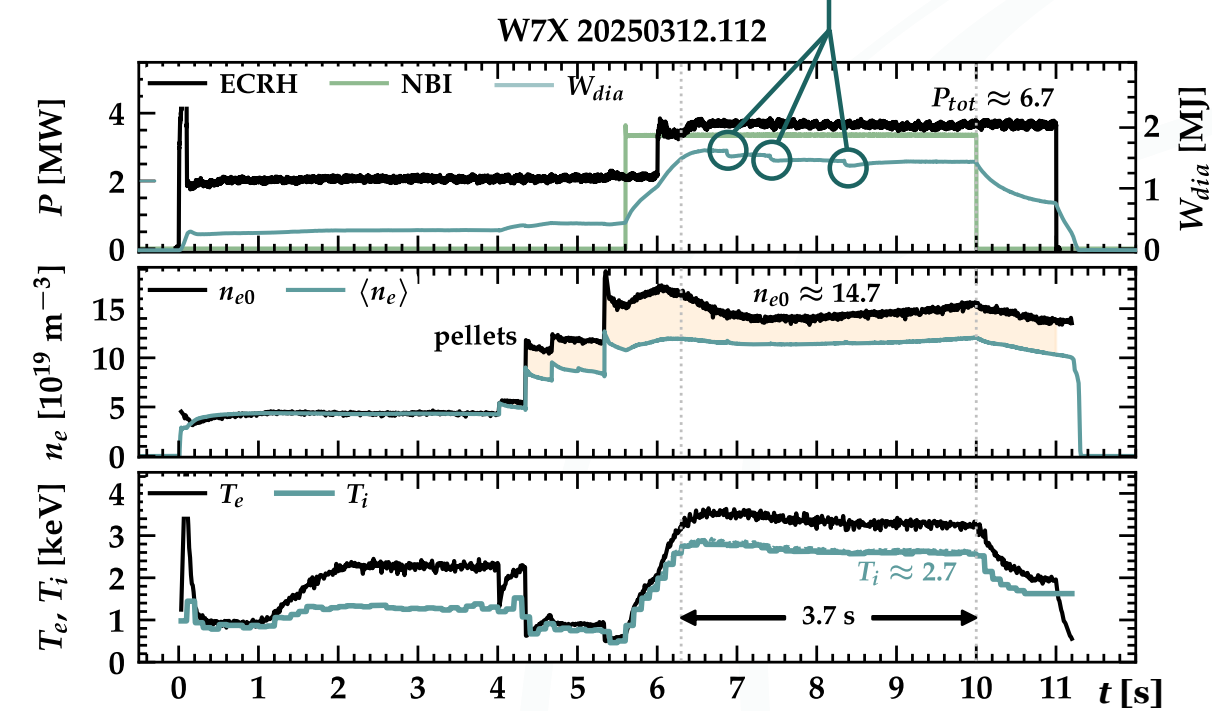
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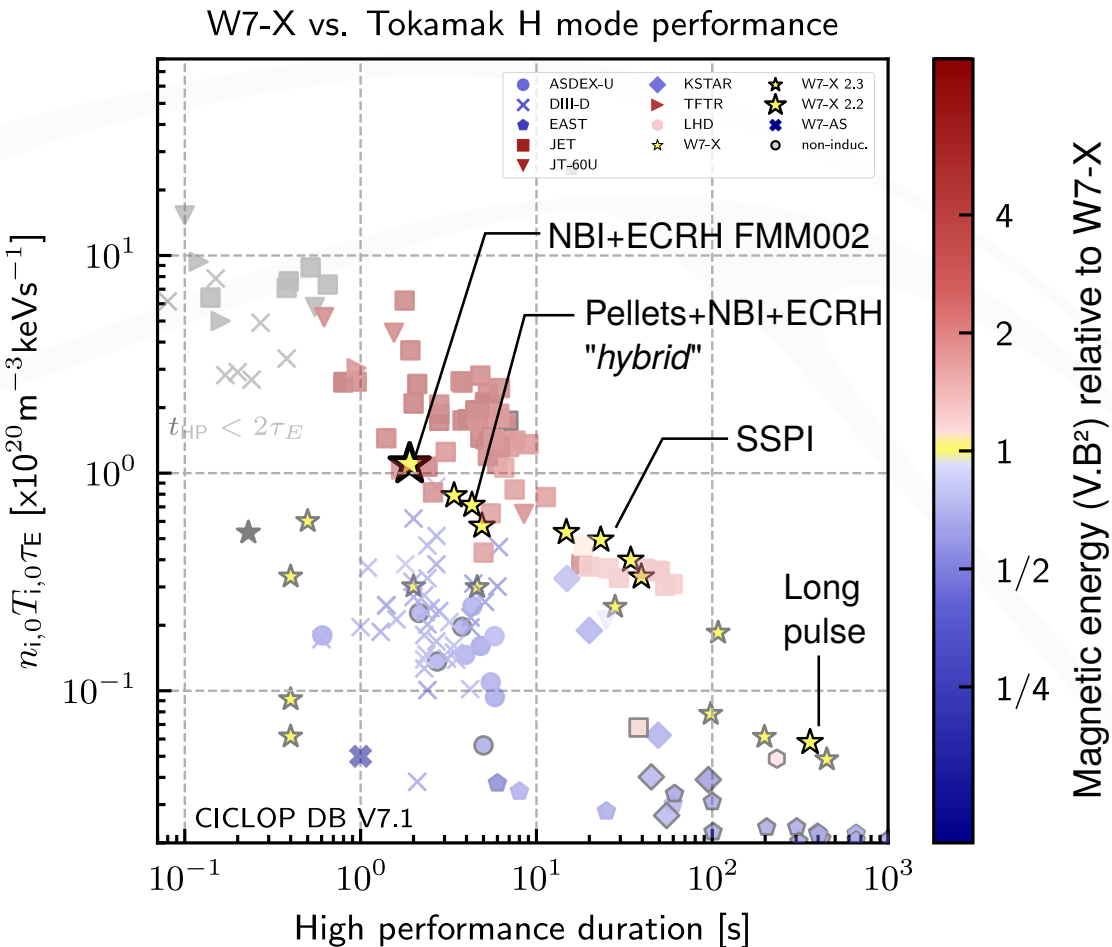
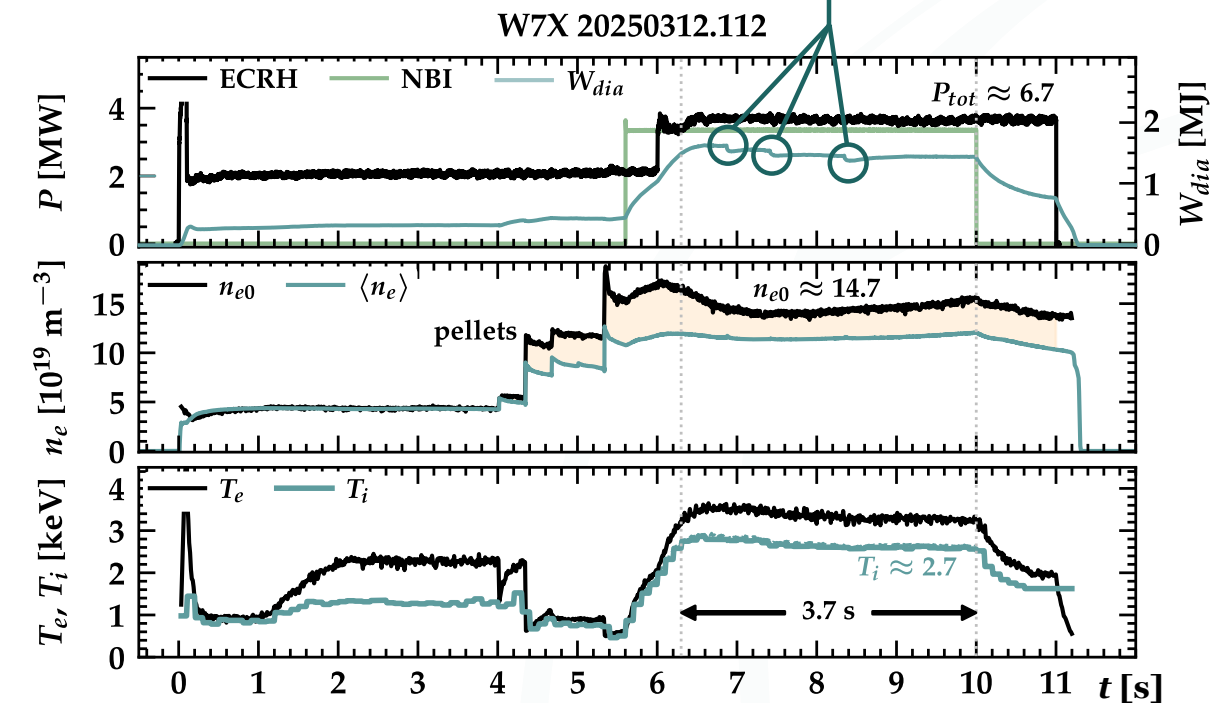
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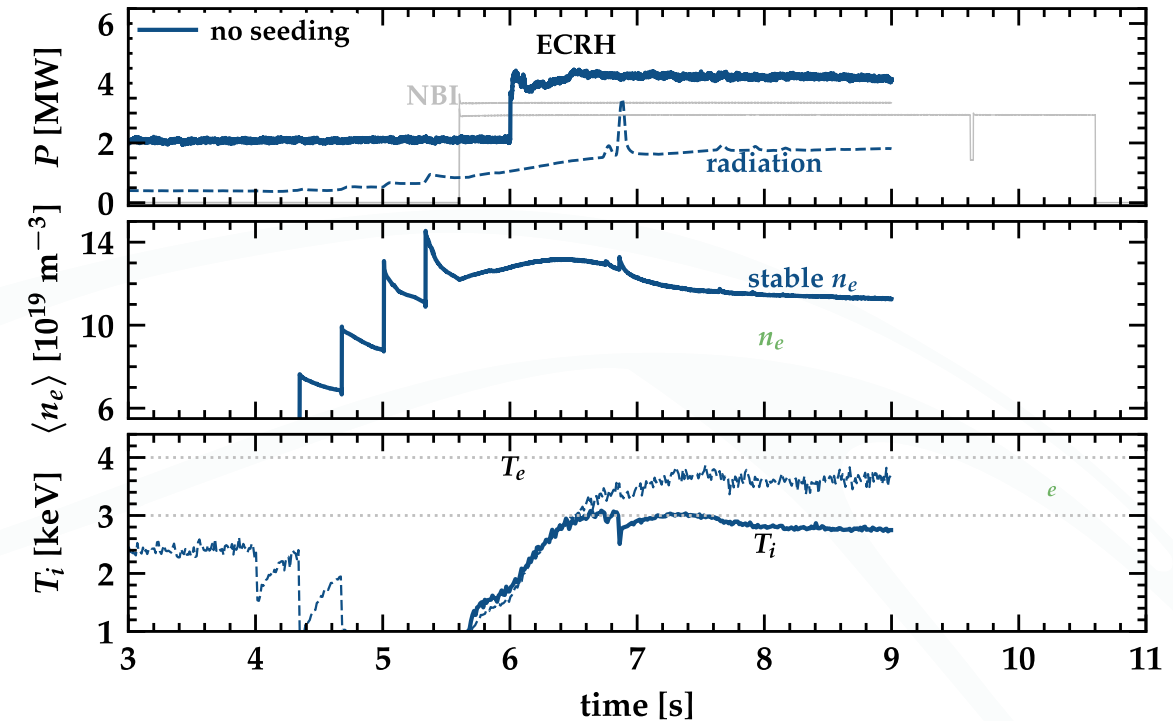
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Scenario 4: NBI + ECRH reintroduction - seeding

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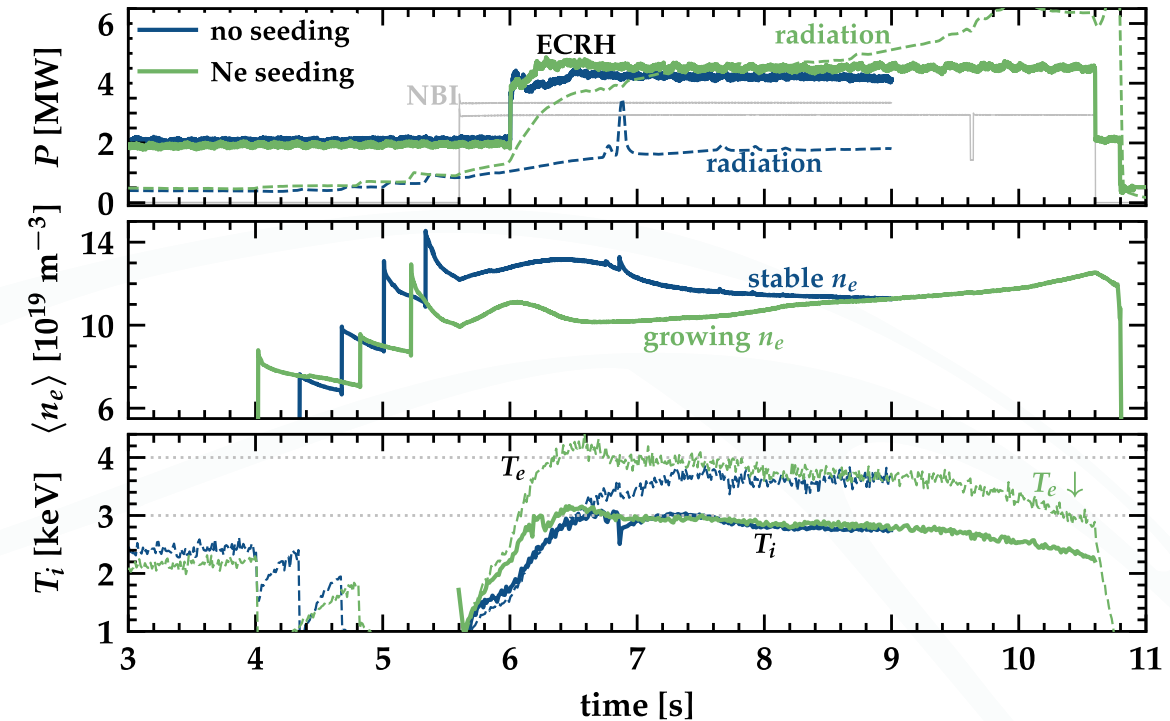
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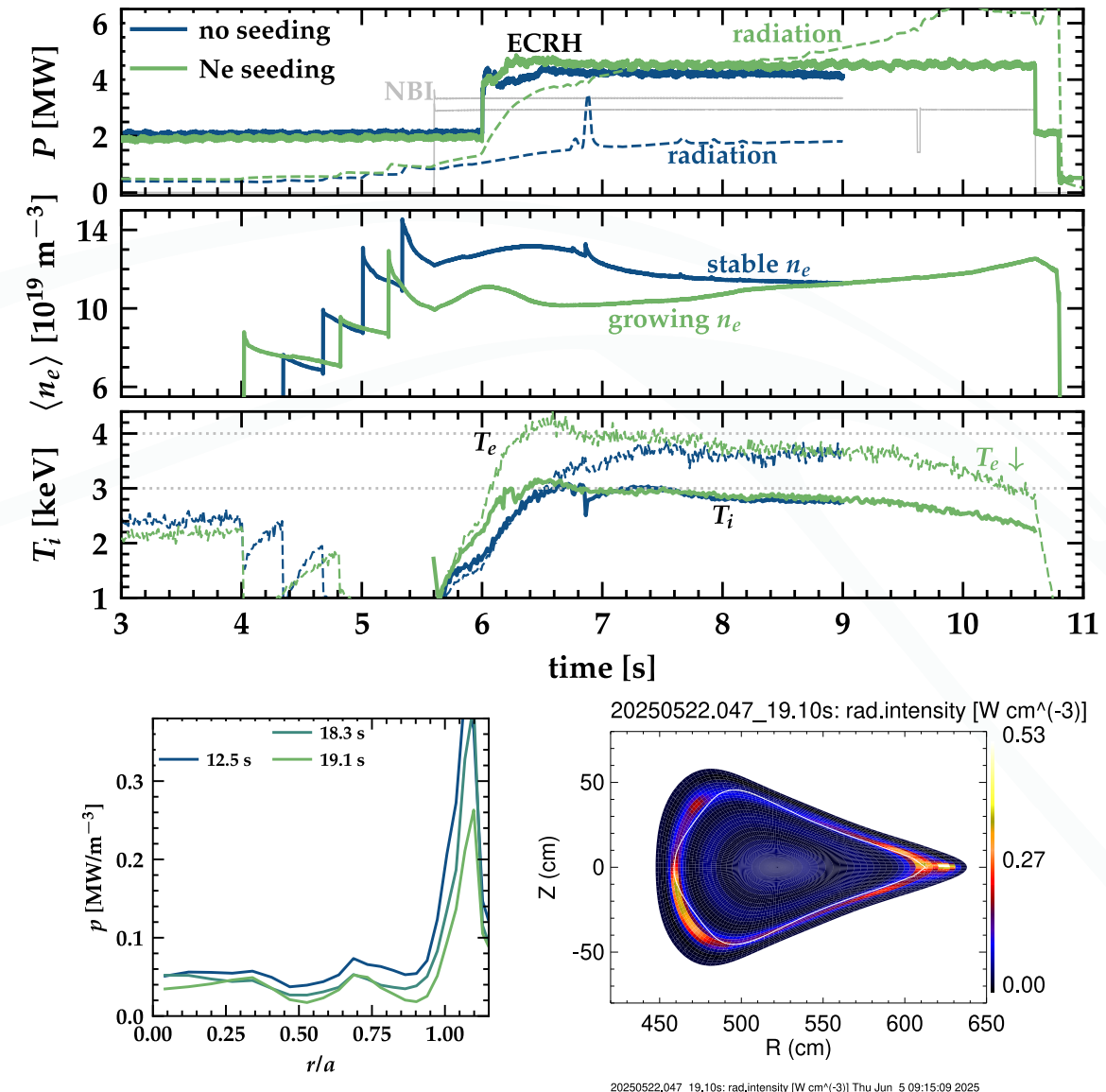
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less power flux at gradient region.
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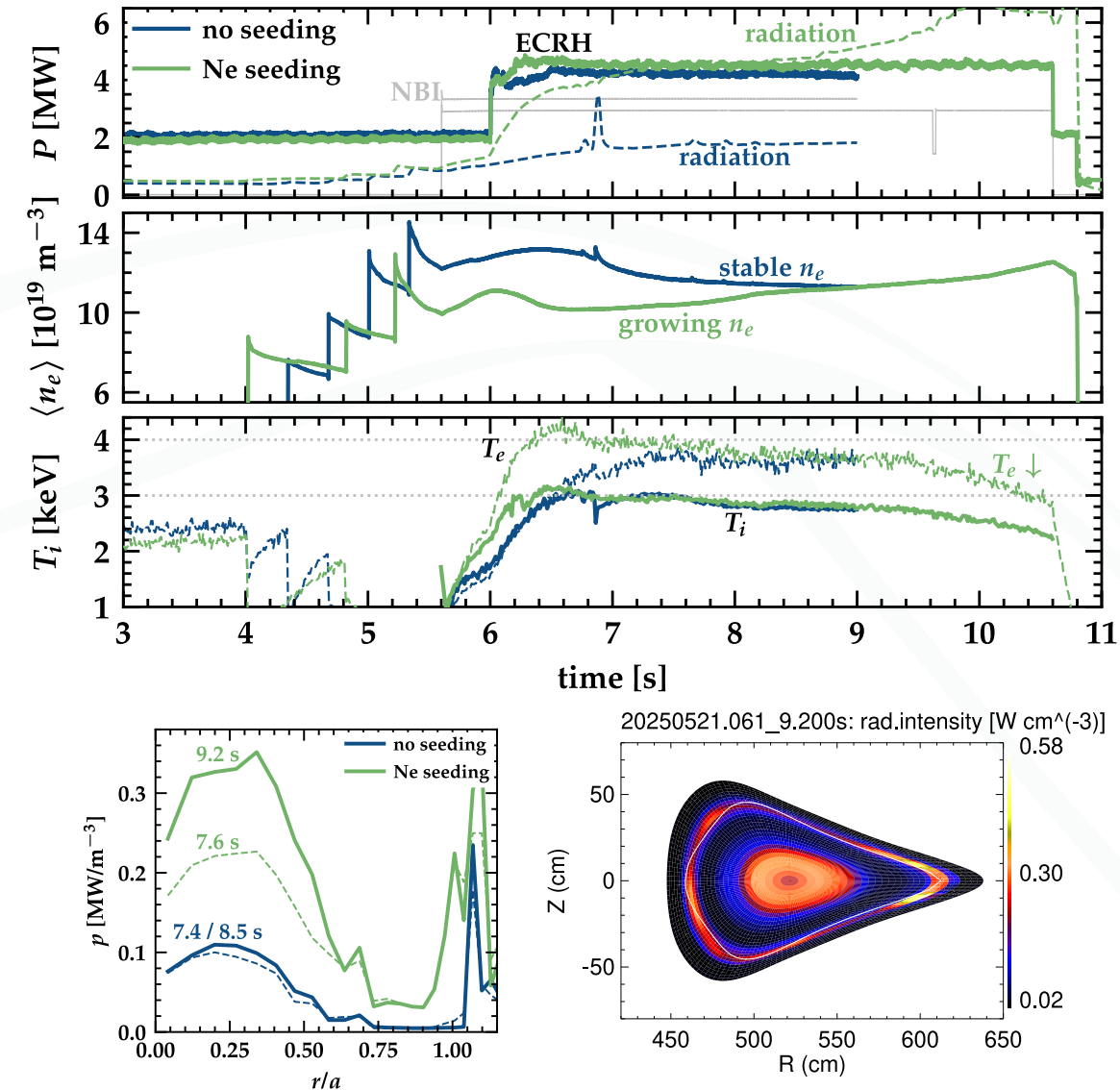
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- +0.5MW core radiation
less power flux at gradient region.
⇒ Too low pump-out ⇒ rising density
- Raising power by 0.5MW works, but now
pump-out varies also with impurity content.
⇒ feedback control required.



Maintaining density gradients is now too difficult.

ECRH pump-out effect depends on:

- Initial conditions (n_e , a/L_n , a/LT_e , a/LT_i , Z_{eff} )
- Pellet size variation + NBI breakdowns (20ms) change initial conditions.

Density profile control

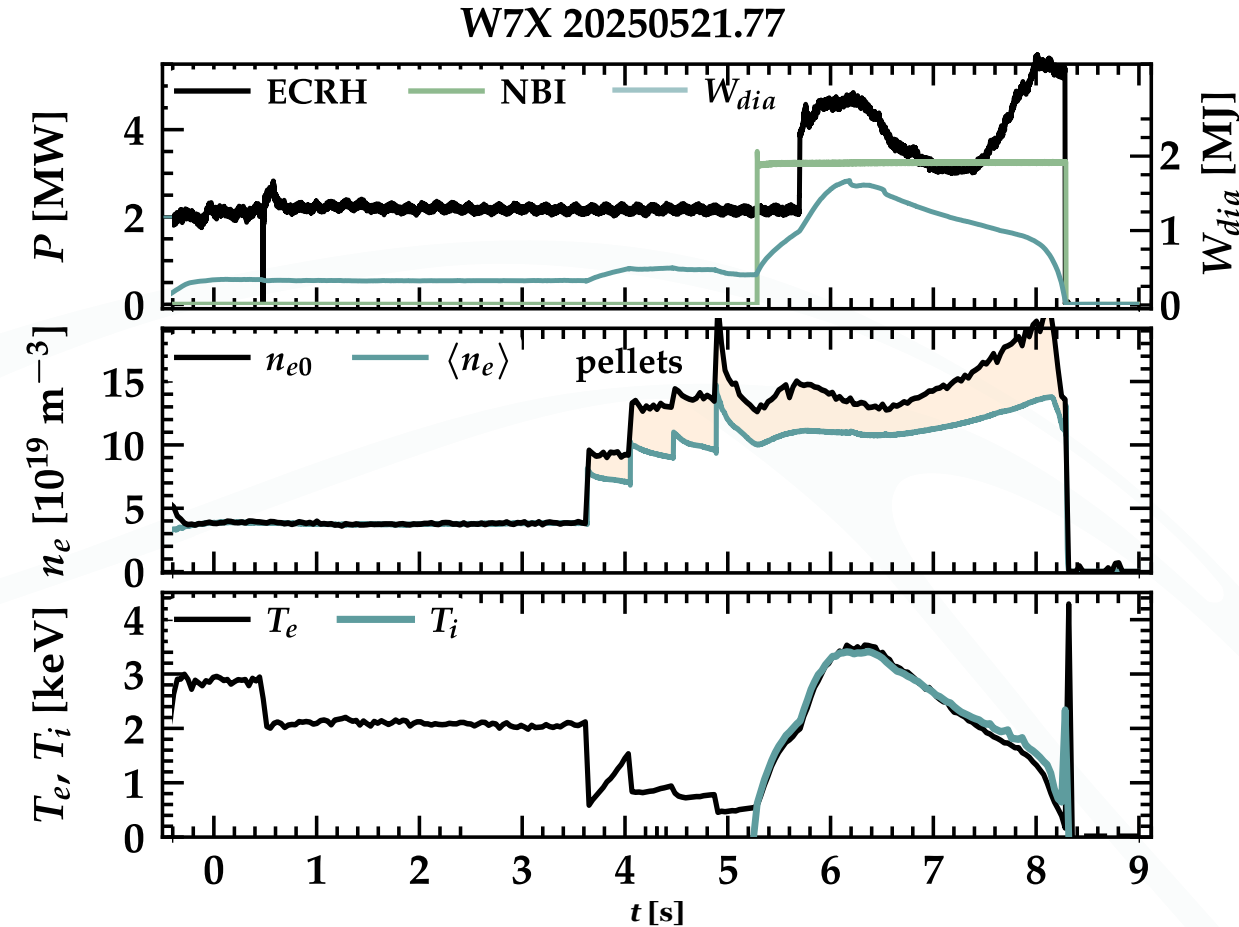
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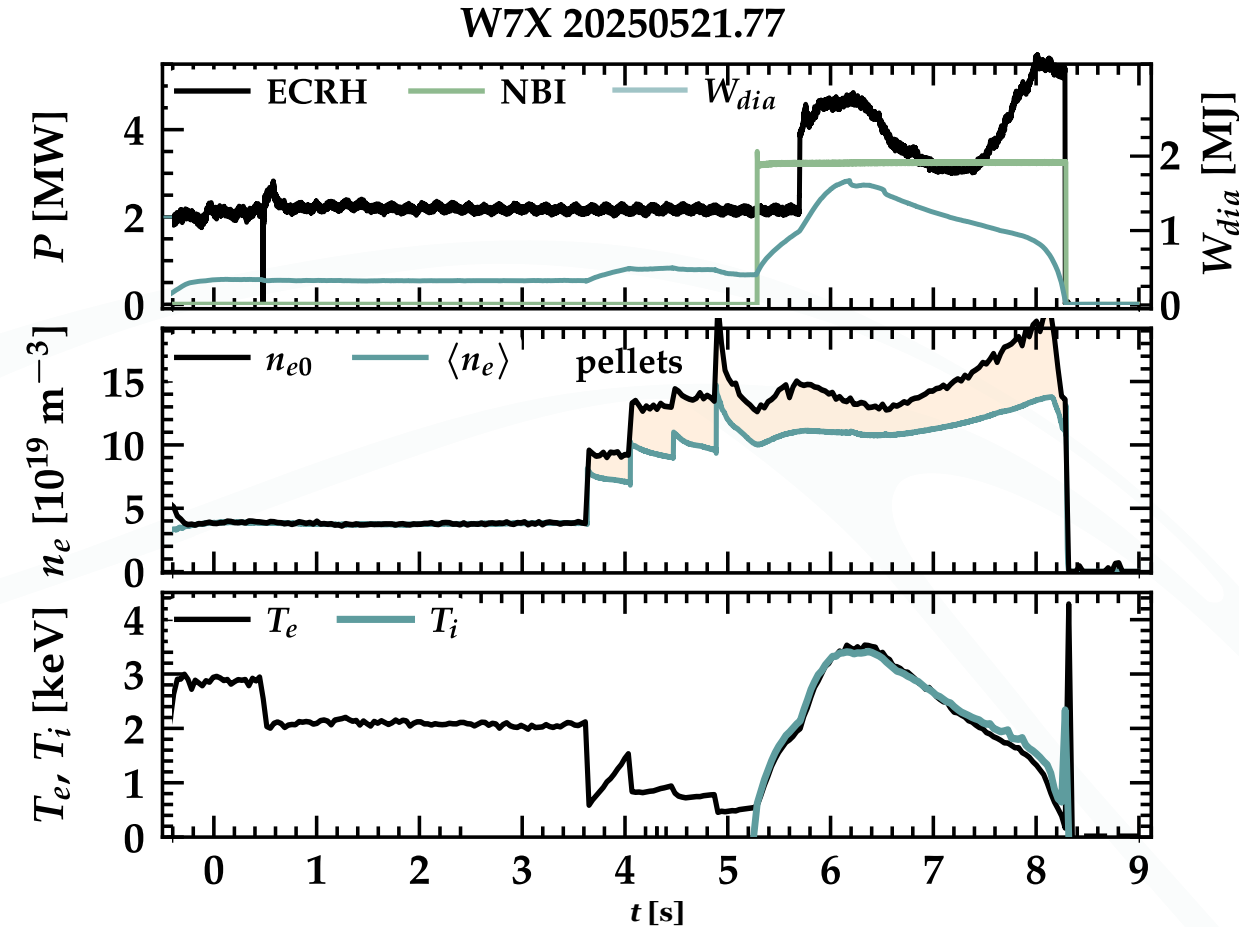
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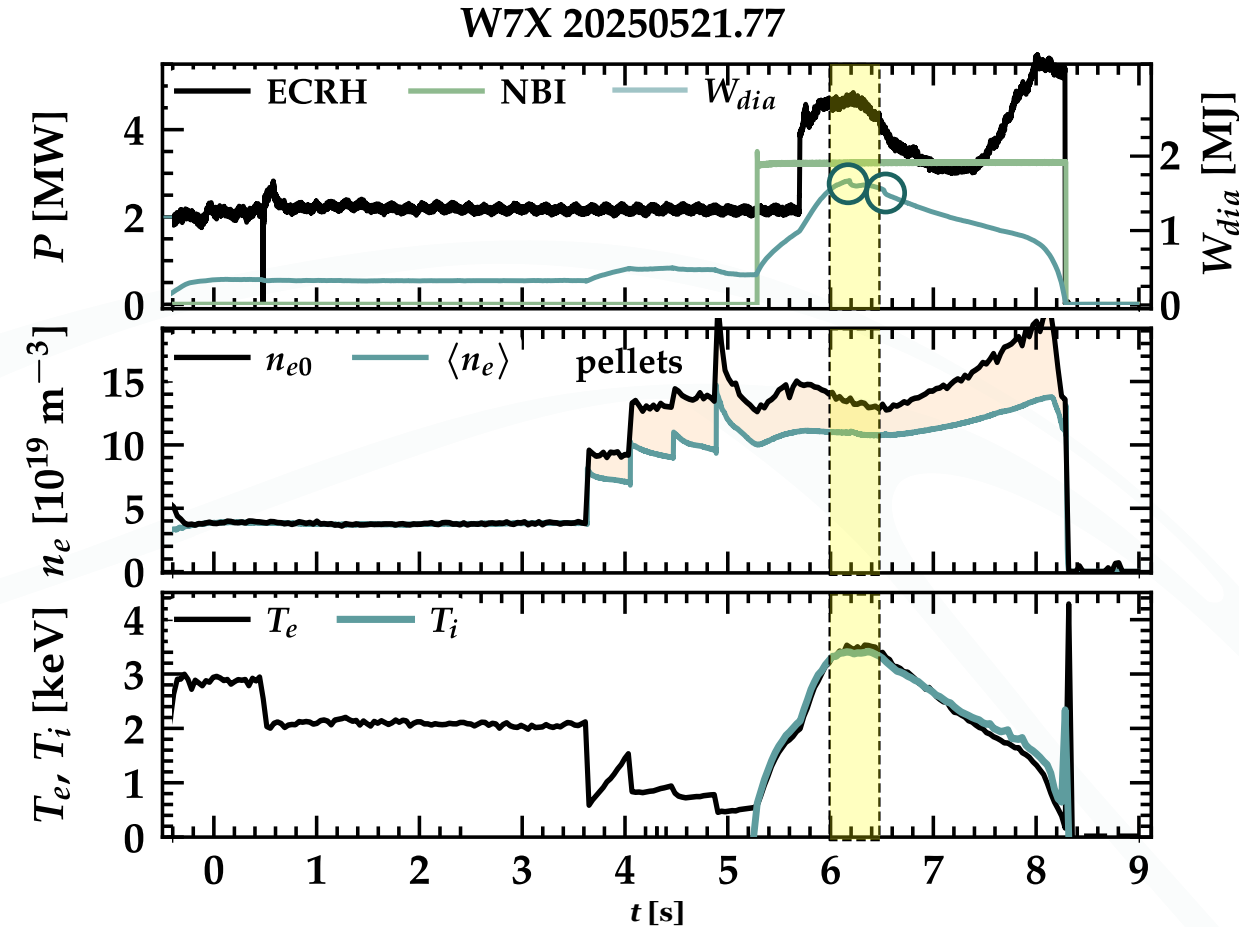
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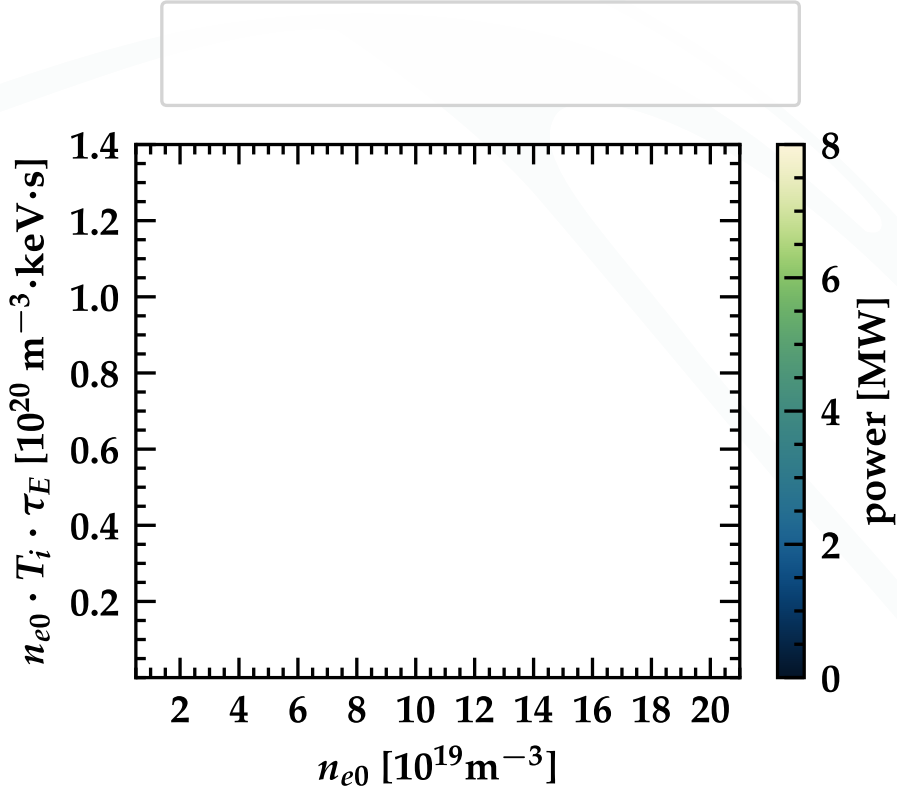
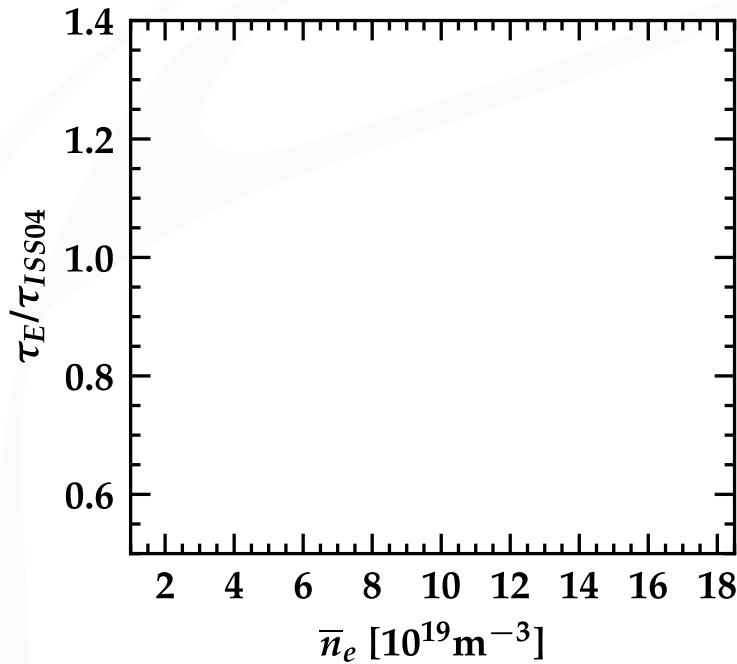
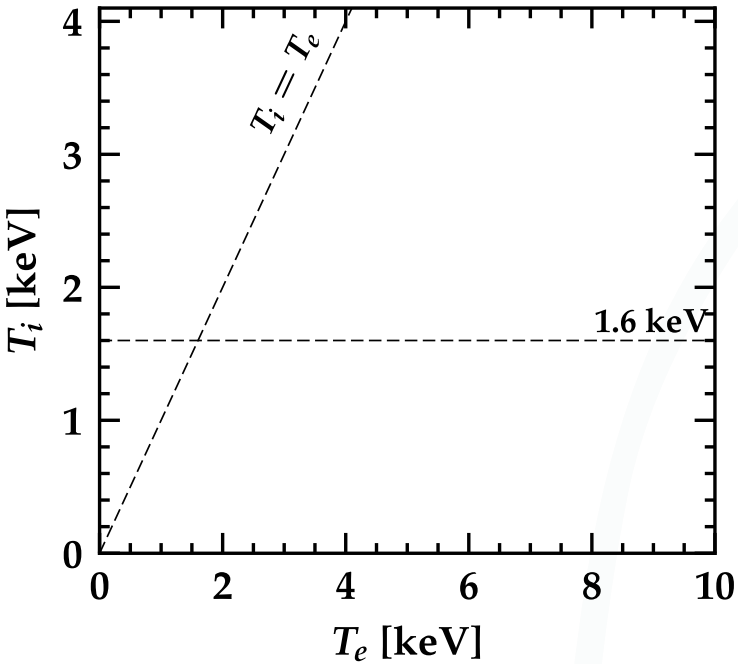
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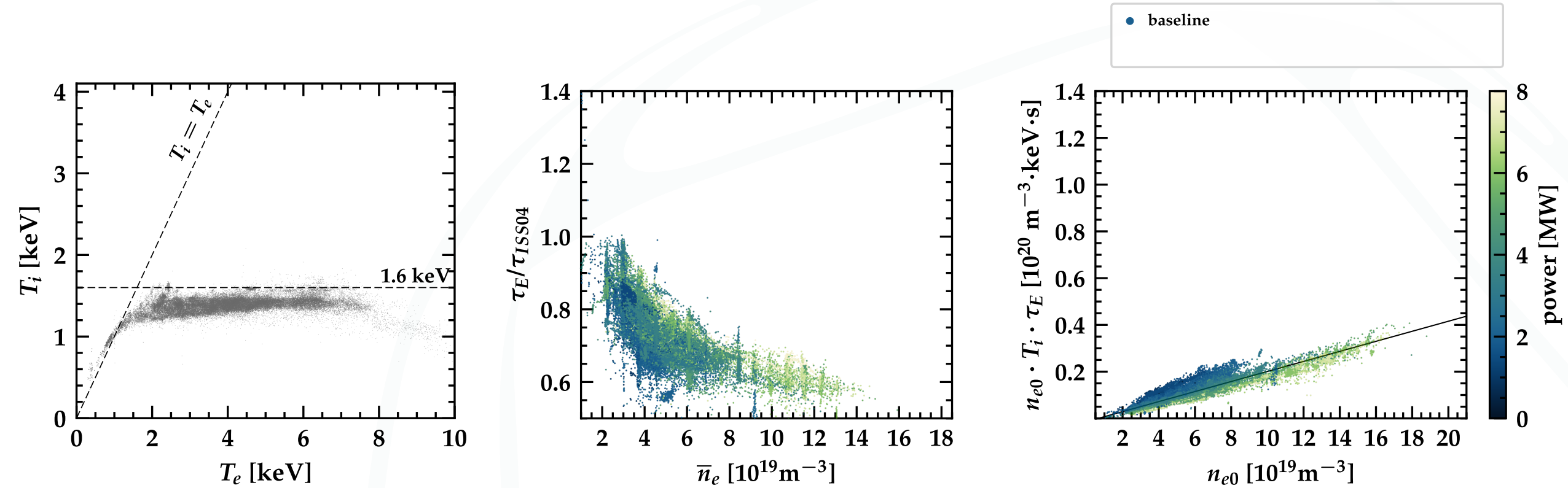
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- Requires live feed of P_{ECRH} to controller of radiation power fraction [V. Perseo].
- This was briefly $T_i = 3.5$ keV, $W_{dia} = 1.5$ MJ with **small crashes**.
Deliberate overshoot and then recovery for pulsed high beta studies?

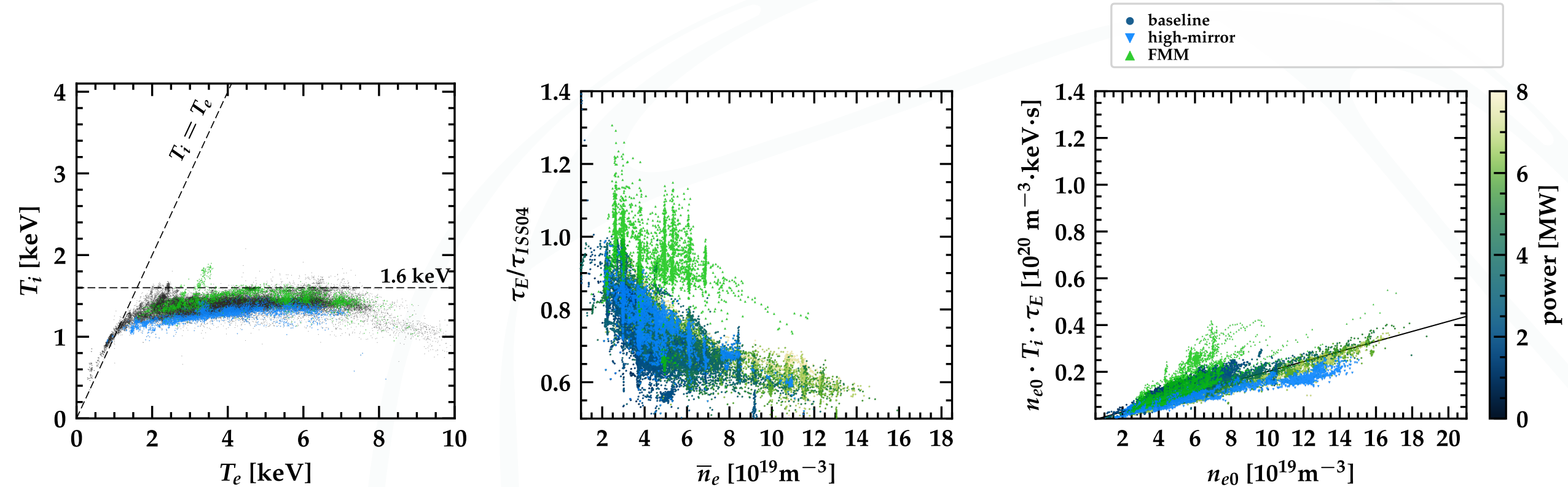




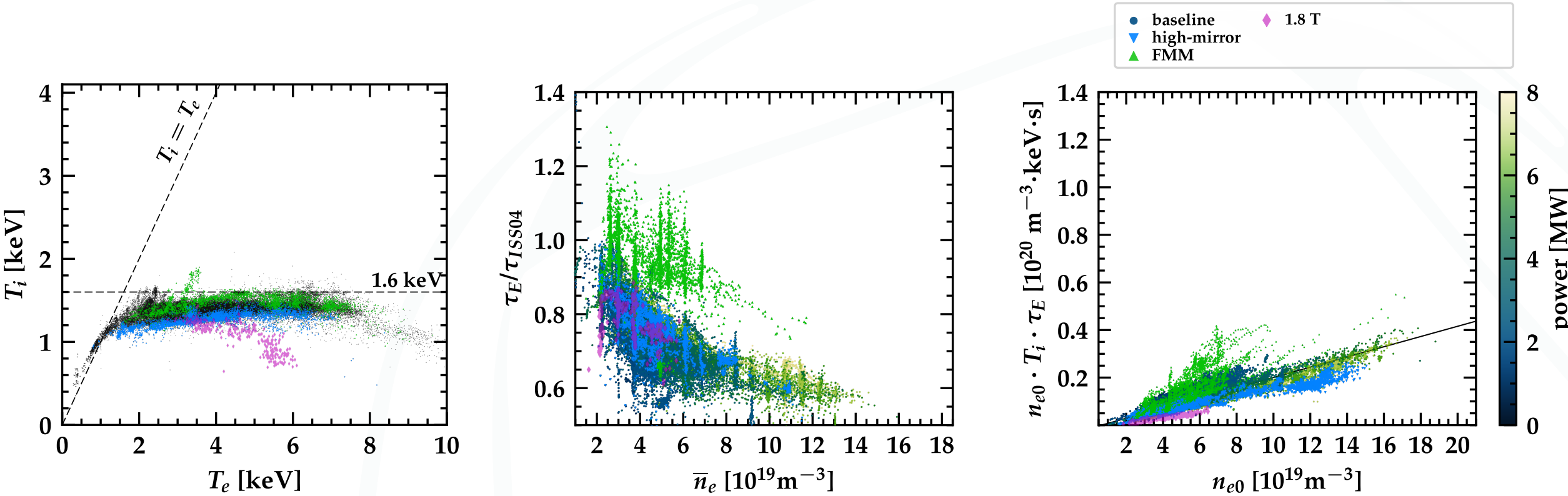
Performance summary



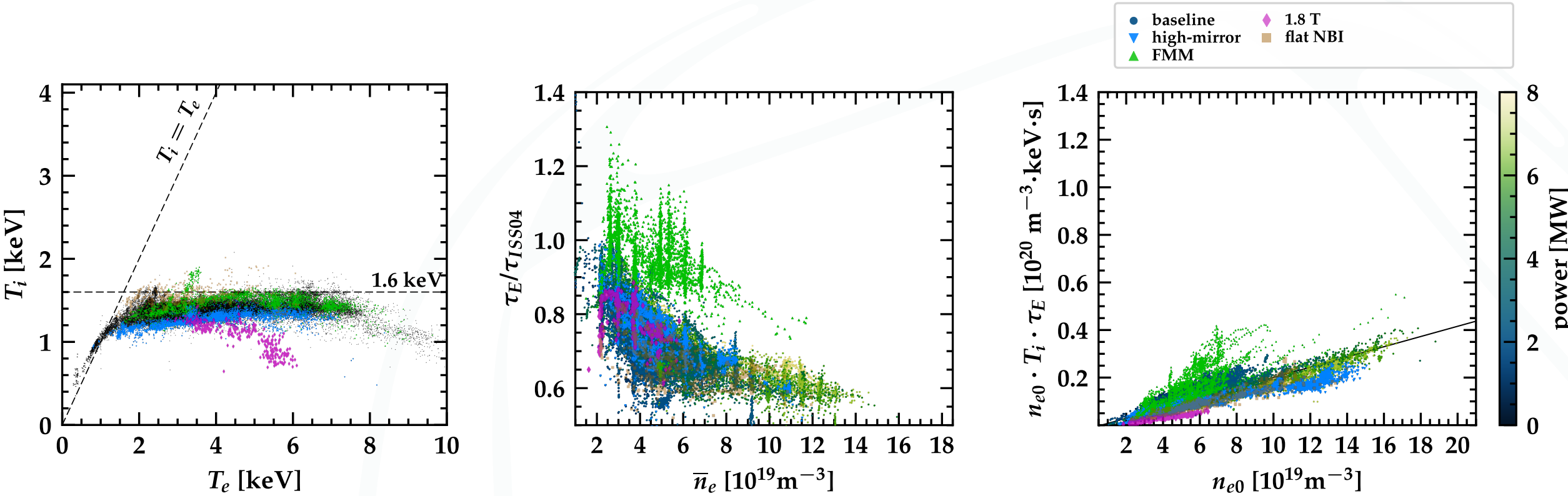
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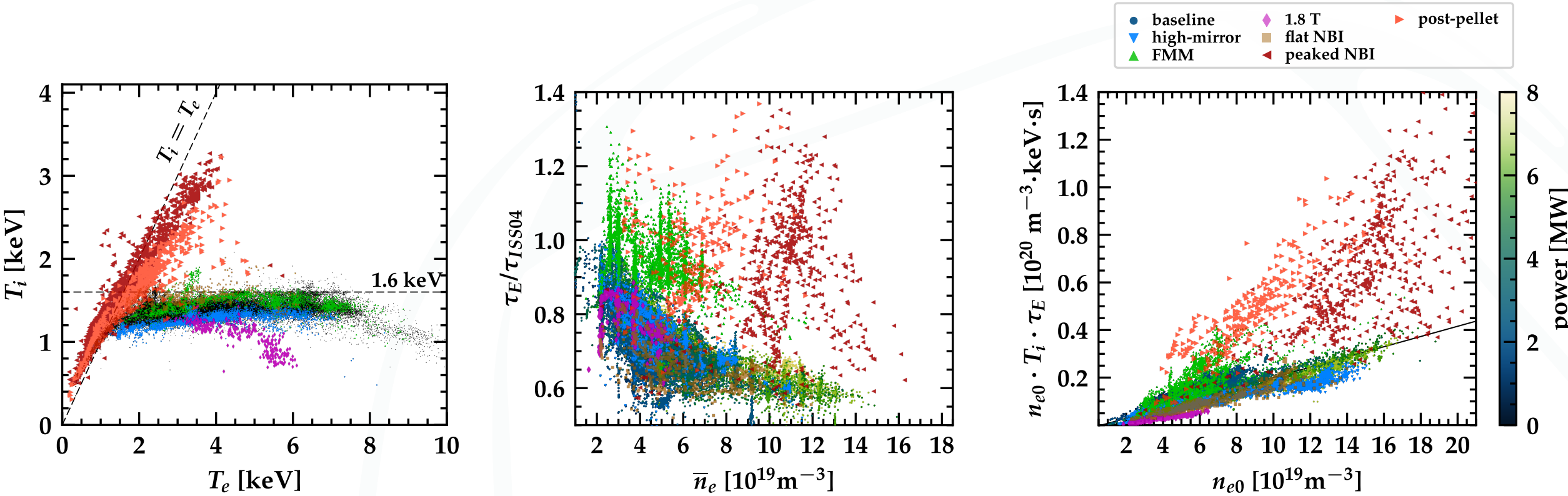
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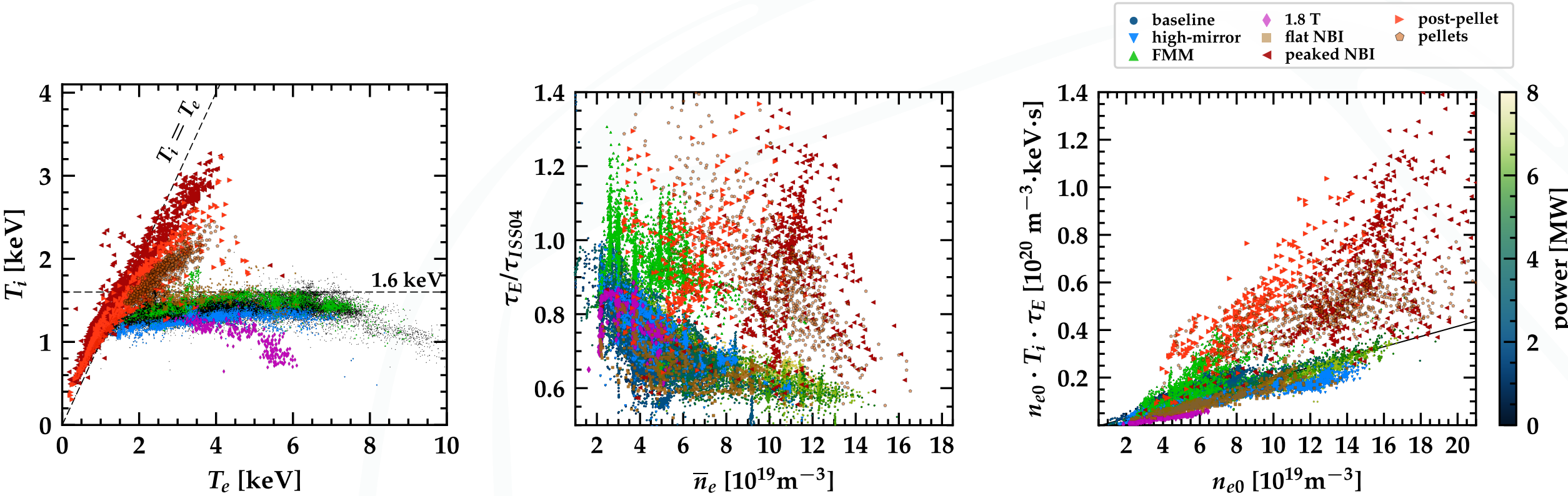
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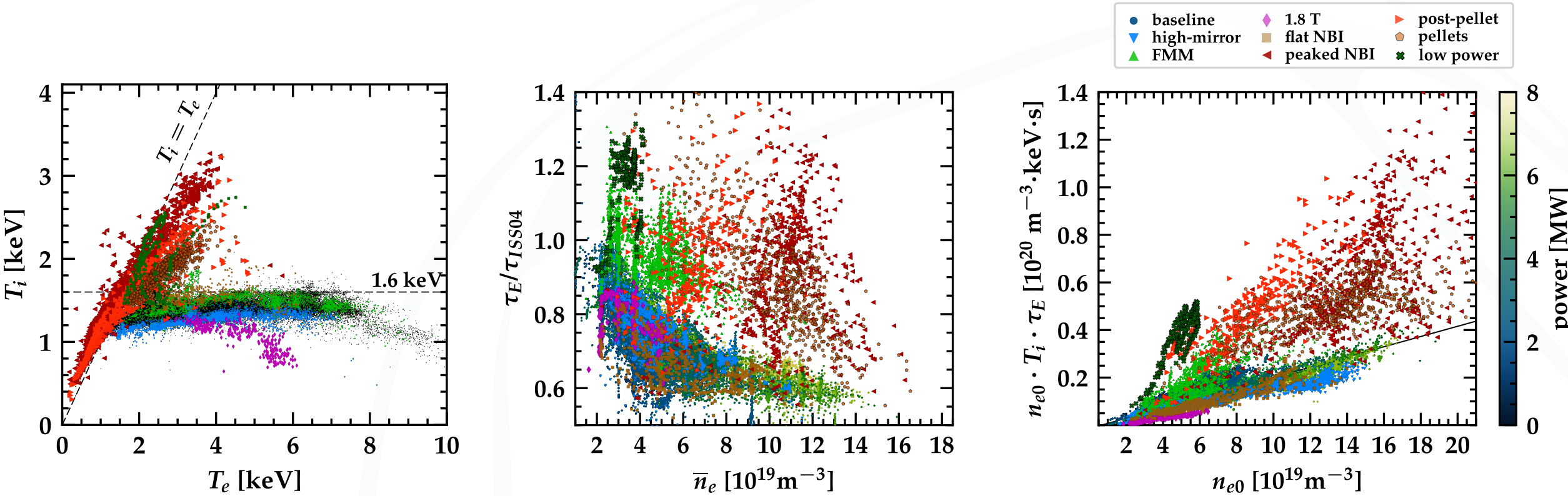
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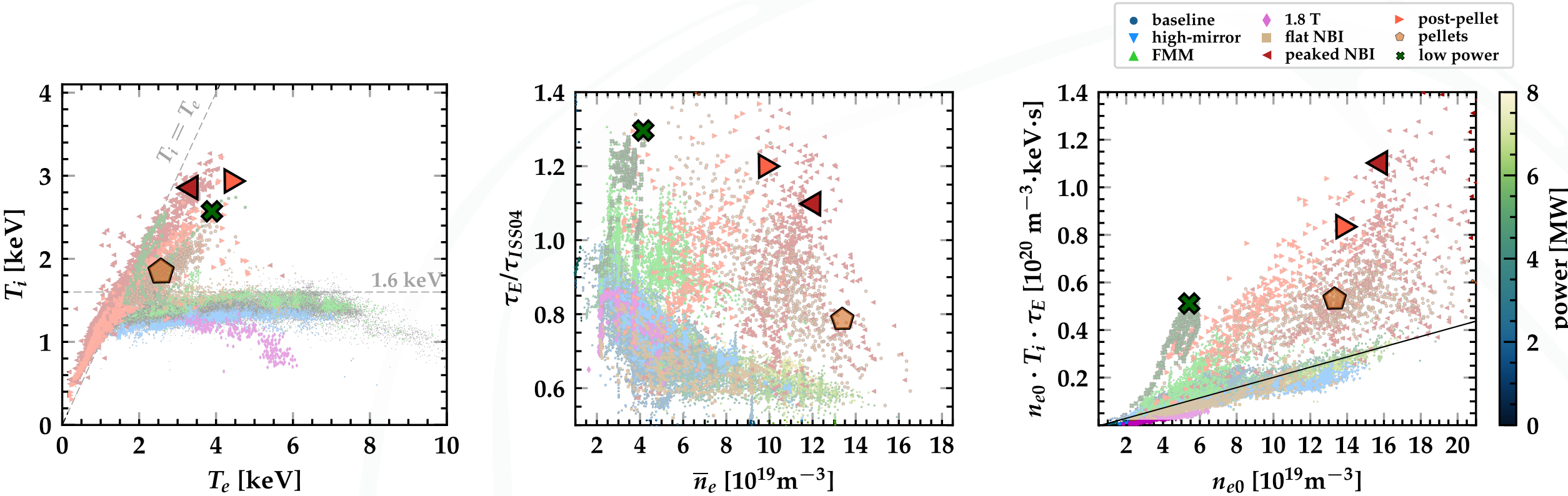
Performance summary



Performance summary



	Scenario	shot	$n_e(0), \langle n_e \rangle [10^{20} \text{ m}^{-3}]$	$T_i [\text{keV}]$	$W_{dia} [\text{MJ}]$	$\tau_E [\text{s}]$	f_{ren}	$n T \tau_E$	duration [s]
▶	1) Post-pellets	20241121.043	11, 9	2.8	1.35	0.27	1.3	0.8	0.1
◡	2) Steady-state pellet injection	20250327.046	? *very approximate values	?	?	?	?	0.5	25
		20250522.047	?	?	?	?	?	0.35	40
✱	3) Low power	20250513.032	?, 4.1	2.5	0.6	0.38	1.25	0.4	2
◀	4) NBI+ECRH	20241204.072	15, 12	2.8	1.8	0.25	1.2	1.1	1.9



Open questions and work to do...



Scenario development:

- Feedback controller to stabilise central density
- NBI+ECRH record with compatible seeding.
- SSPI at higher a/L_n , a/L_T .
- Map pellet penetration $f(T_e, n_e, \dots)$

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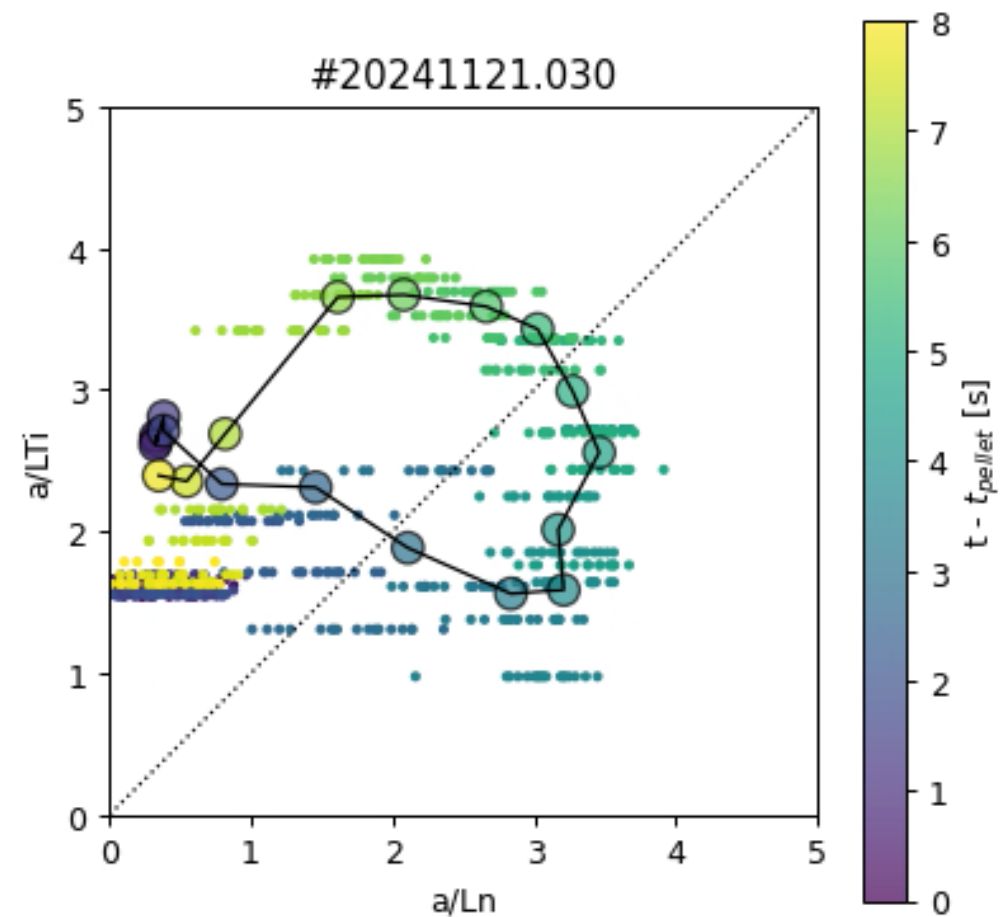
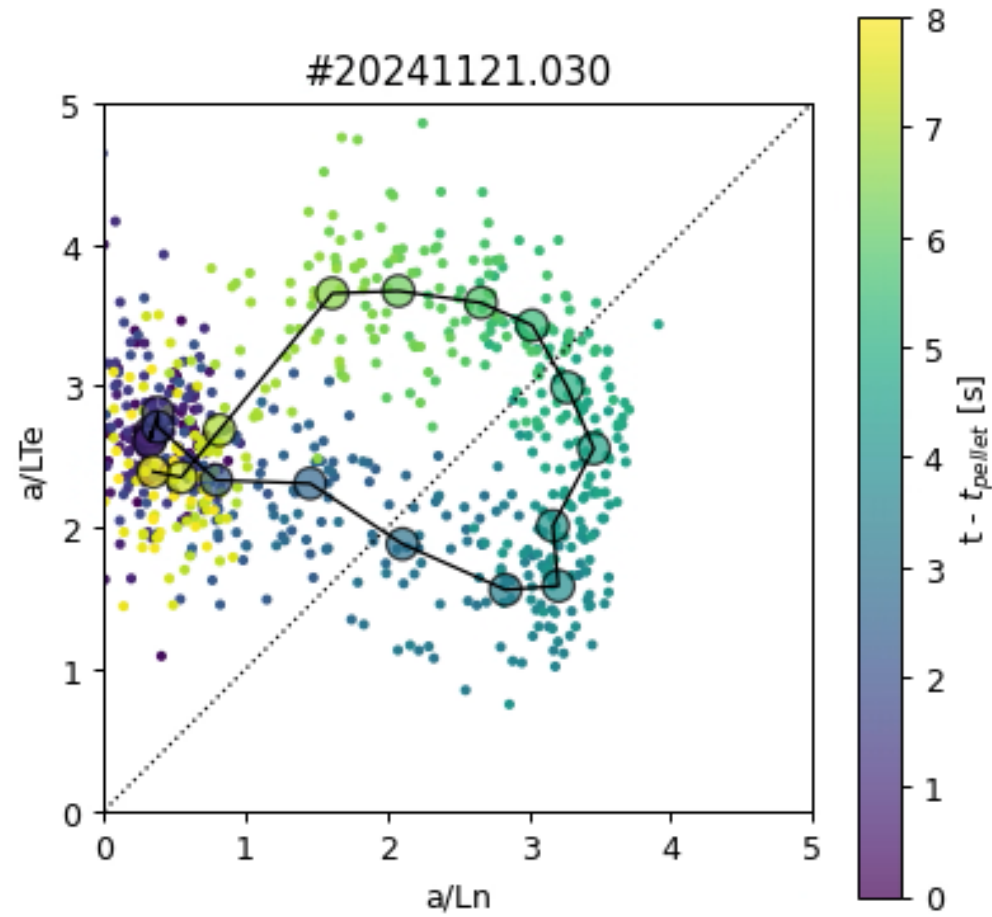
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Science / understanding:

- ECRH pump-out
 - Role of E_r in peaking and pump-out. (Initial results show no obvious change [B. Stefanoska])
 - Limit of a/L_T at a given a/L_n , limit of both together.
 - $a/L_N > \sim 1.5$ limit? other dependencies?
 - Configuration dependence of above
 - $|B|$ dependence of above
- ⇒ **Record data in every possible corner of operation space for transport code matching.**

$a/L\text{Ti}$ and $a/L\text{Te}$ in post-pellets shots

Due to the high collisionality this is basically the same.



This page has no content that is not self referential