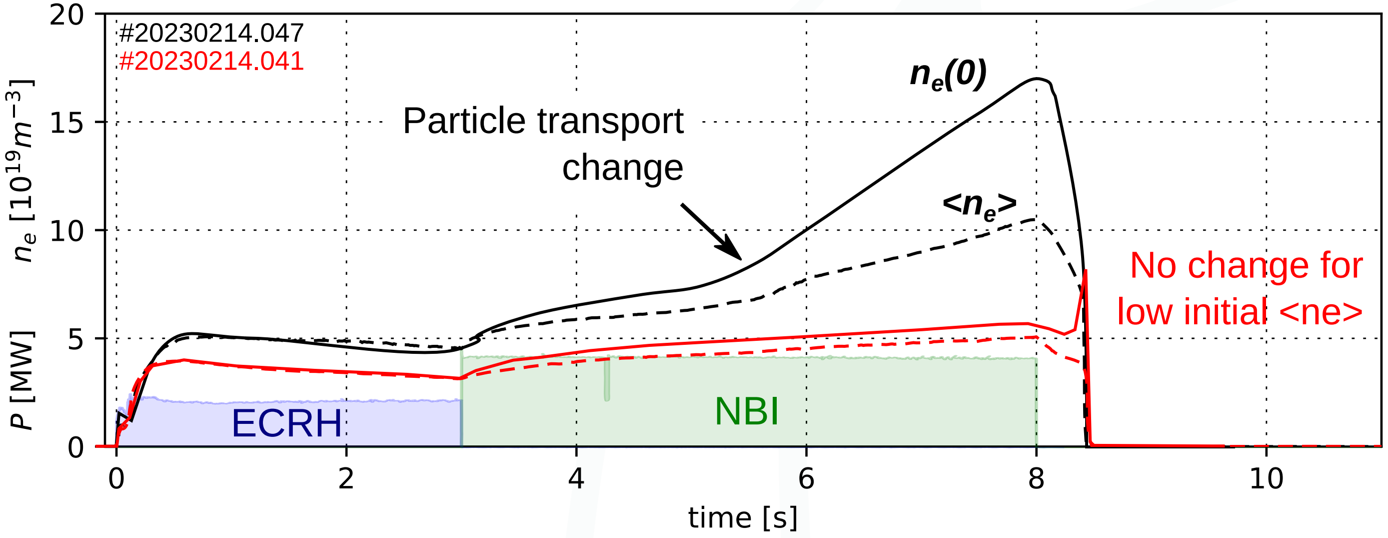
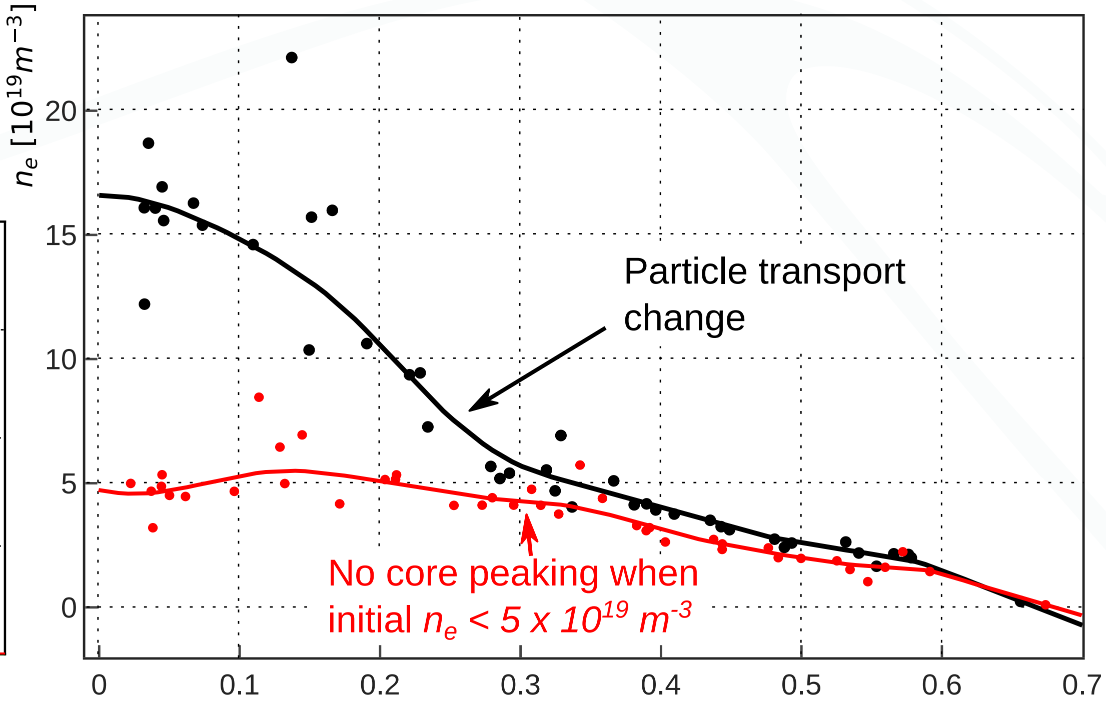
NBI core density peaking

Core density peaking with NBI (observed in OP2.1b) examined in detail.

- On-set dependence on initial density confirmed
- Abrupt change of particle transport within fixed radius when passing some threshold.
- Radial location appears to change with configuration
- Co/counter source selection has no significant effect.
- Scaling of peaking with source rate not clear (varied number of NBI sources).





NBI core density peaking

- We start with ne dl ~ 8 - 9 x 10^{19} m^{-2} in order to get into peaking immediately.
  (depends a bit on intrinsic detachment threshold of configuration)

- Rise rate of pinch+NBI seems to scale in some way with total beam current (use proxy P_{NBI}).

Maybe:
a) Scales ~linearly and then saturates.
worst for high-mirror: "NBI pump-out"??

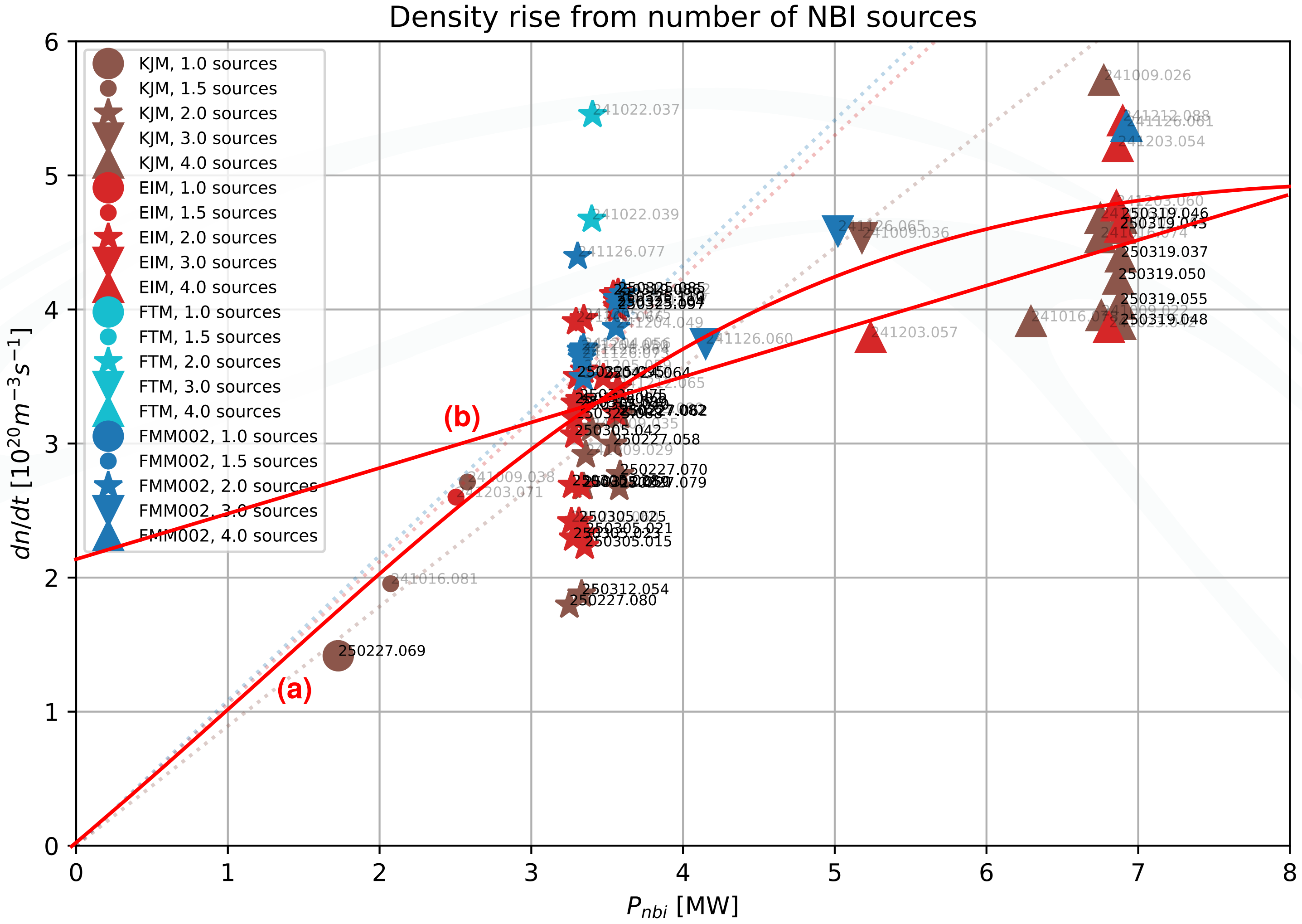
b) Scales linearly with offset due to pinch:

(If steady-state, this makes no sense but OK)

$$-\frac{\nabla n}{n} = -\frac{v}{D} + \frac{\int s dV}{V' D n},$$

Due to pinch — Due to source

Here ~50% from NBI source and pinch.
[Bozhenkov PPCF 2025 (submitted)]



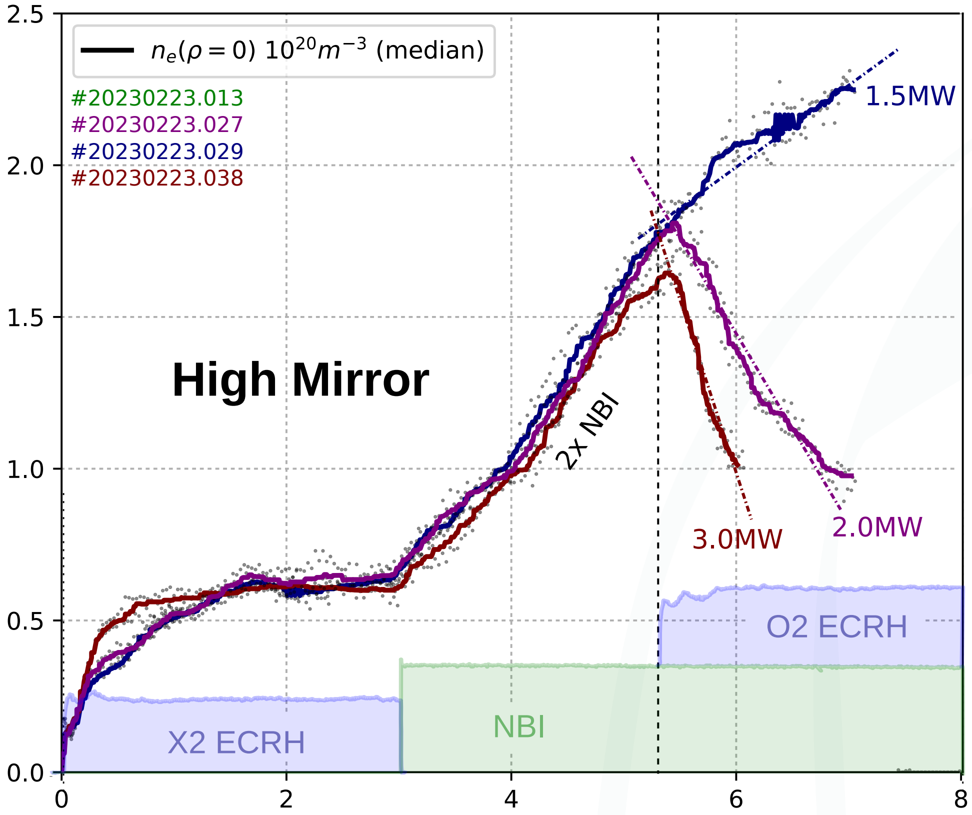
ECRH pump-out

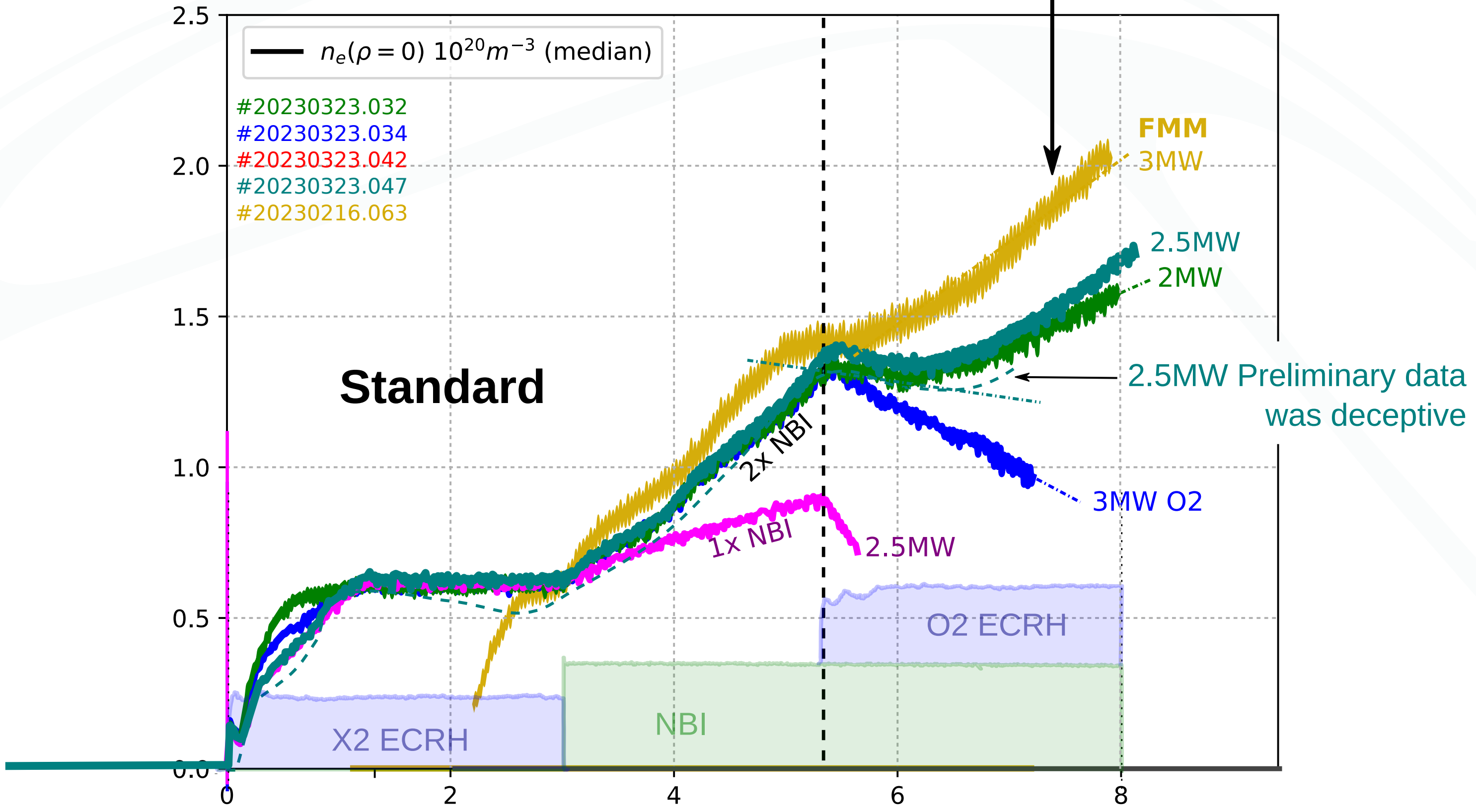
- Re-introducing ECRH pumps-out density and impurities.
- Investigated effects on pump-out rate:

Significant:
- ECRH power.
- NBI source rate
- Initial density
- Magnetic configuration

Not significant:
- O2 vs X2 absoption
- O2 off-axis (gyrotron choice)

FMM configuration: Limited pump-out even at 3MW ECRH
--> High-performance candidate.
... really config or initial n_e condition?

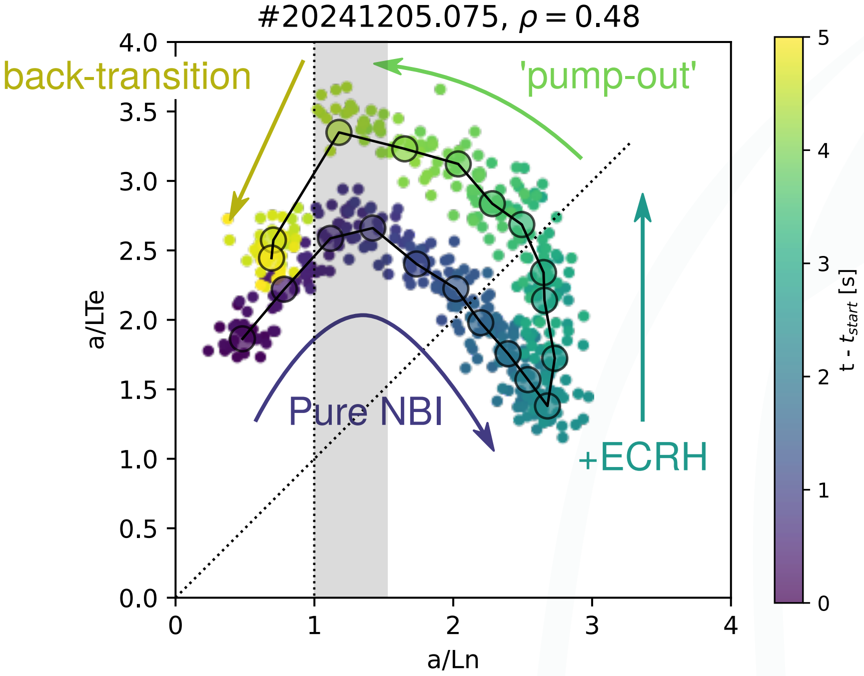


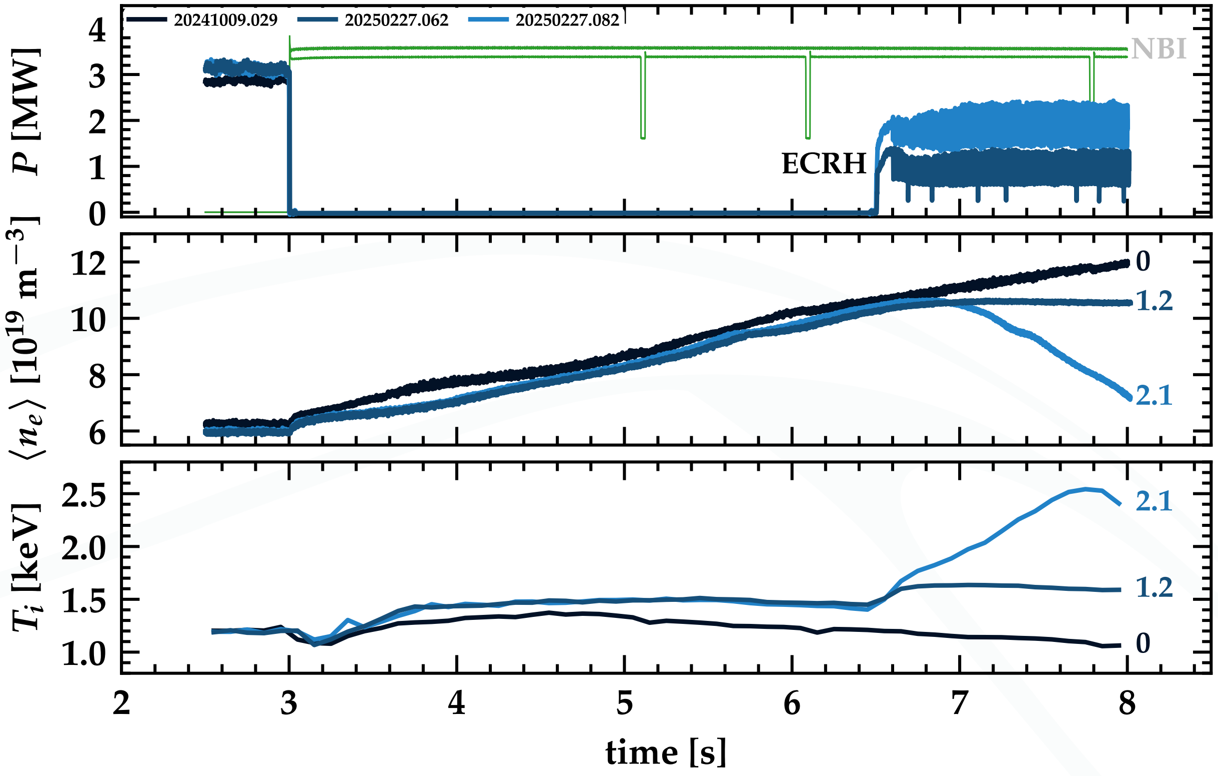


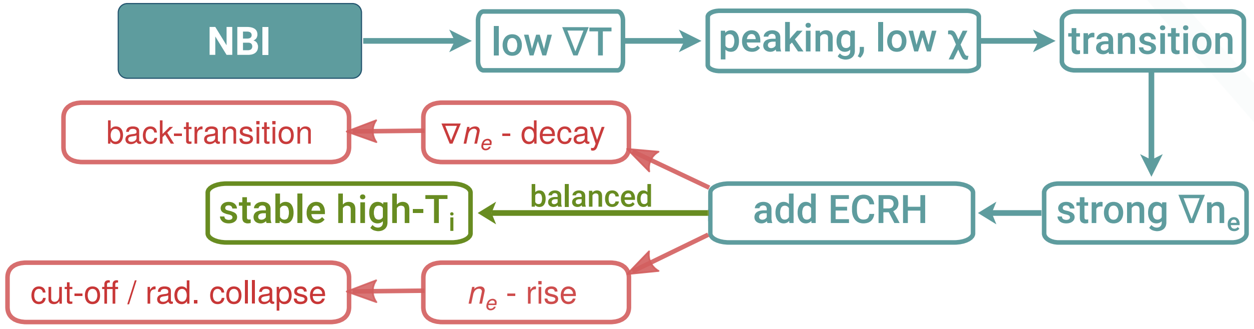
Scenario 4: NBI + ECRH reintroduction - *'pump-out'*

Heating with reduced χ_i to raise plasma temperature.

- Similar to post-pellets, but with particle source.
- Density evolution depends on ECRH power.
- Compensate particle source
  ⇒ balance for steady state





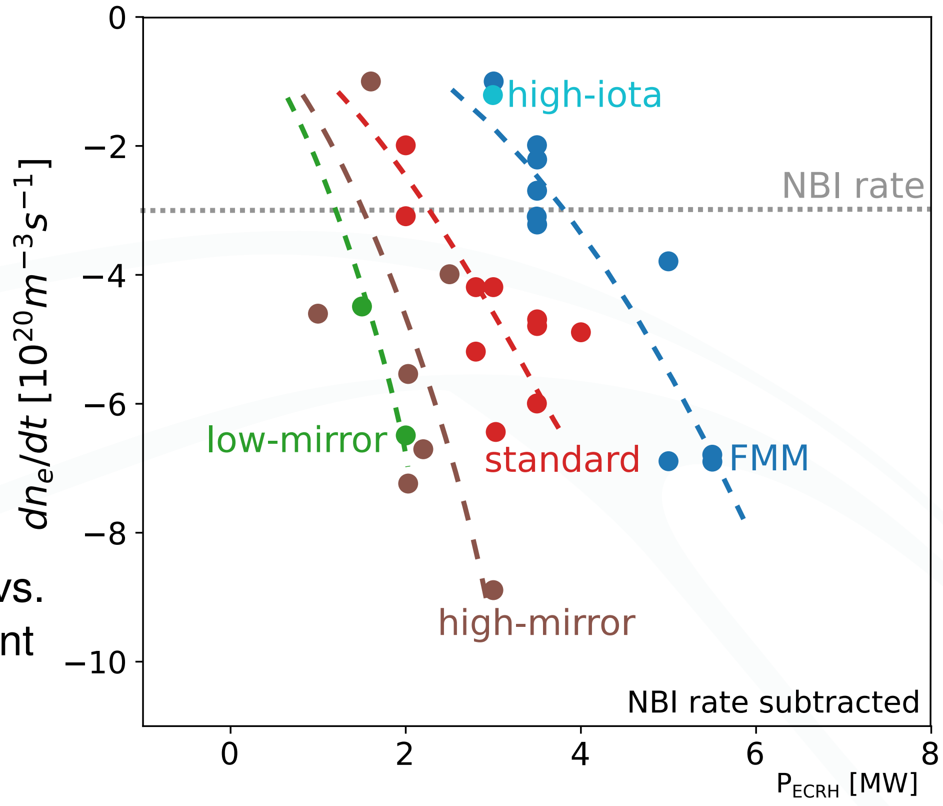


Scenario 4: NBI + ECRH reintroduction - *'pump-out'*

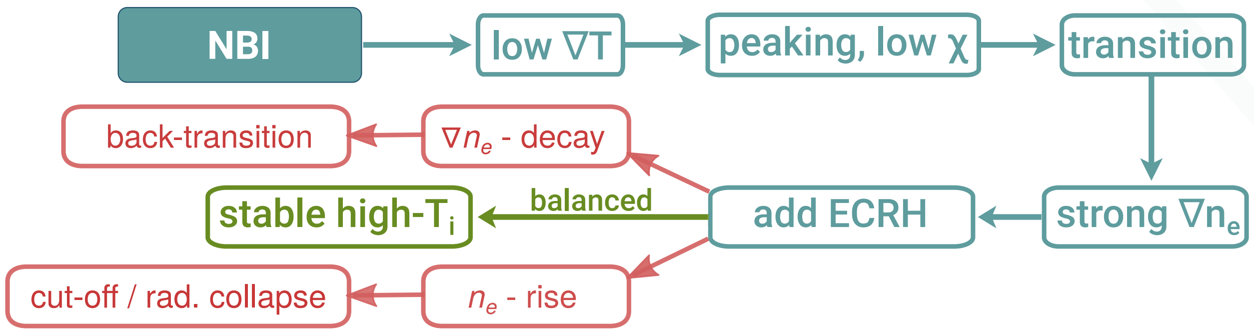
Heating with reduced χ_i to raise plasma temperature.

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



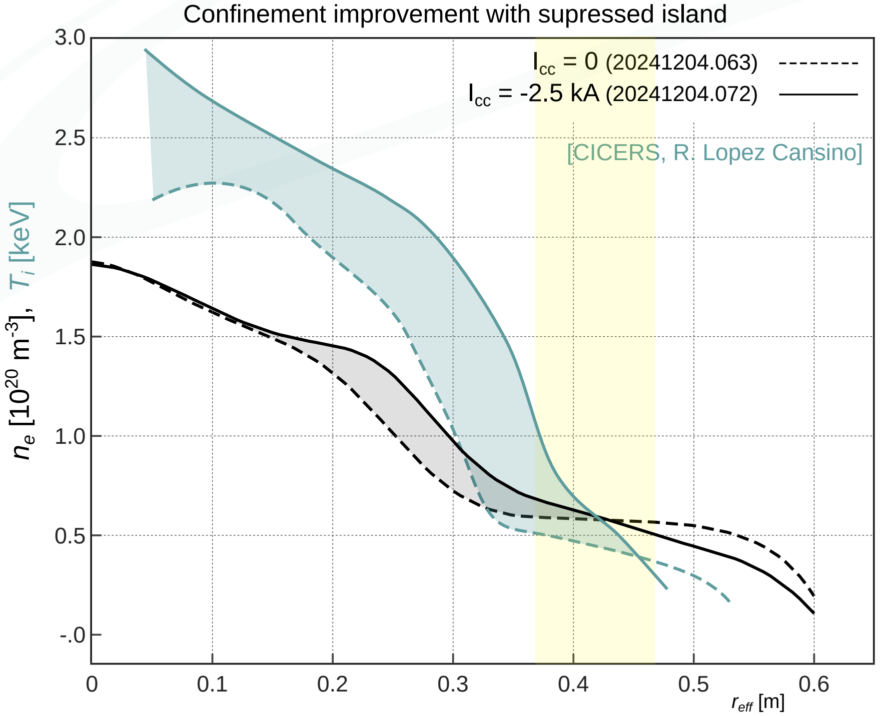
'Pump-out' rate vs. power for different configurations.

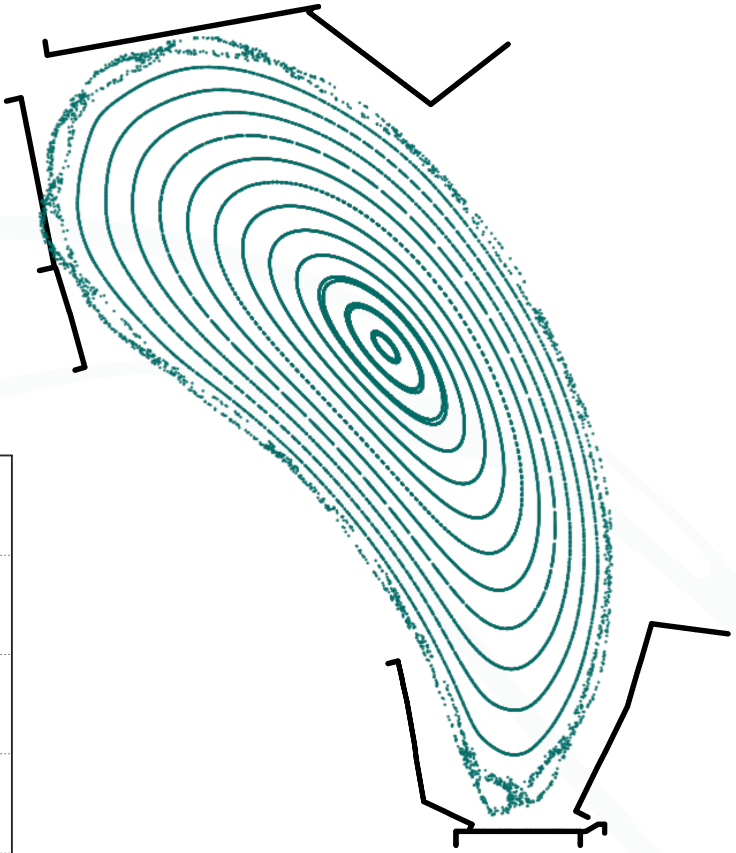


Scenario 4: NBI + ECRH reintroduction - FMM002

The balance depends on configuration

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

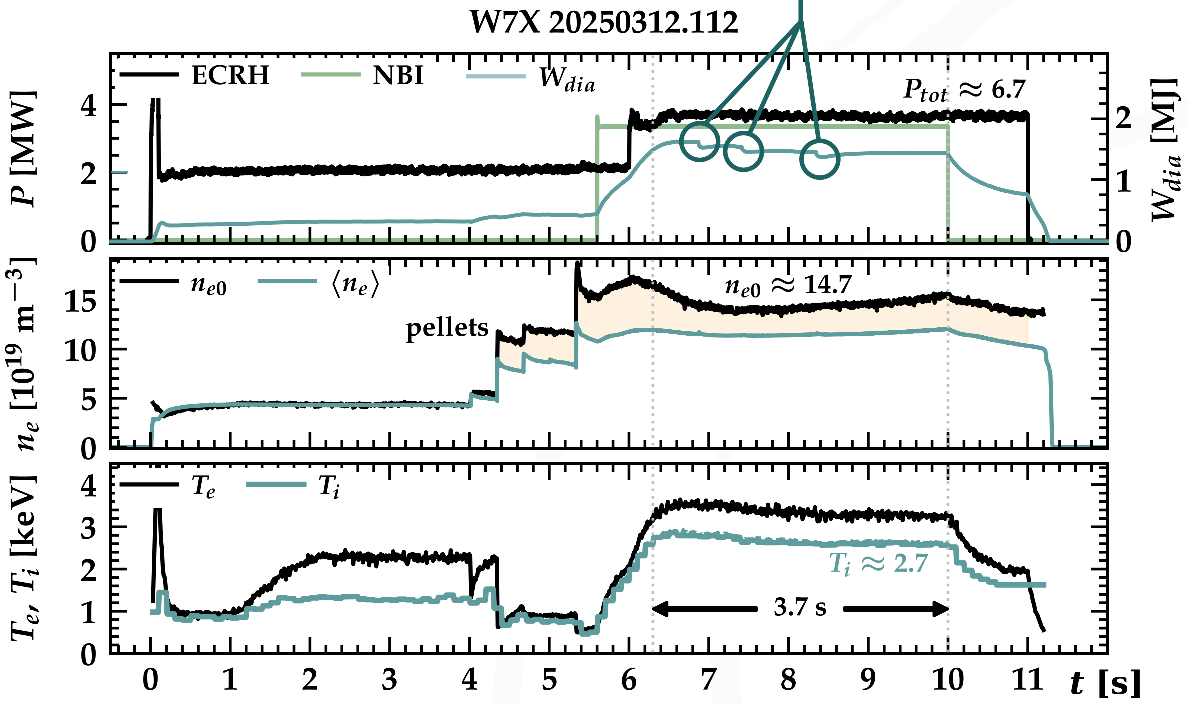


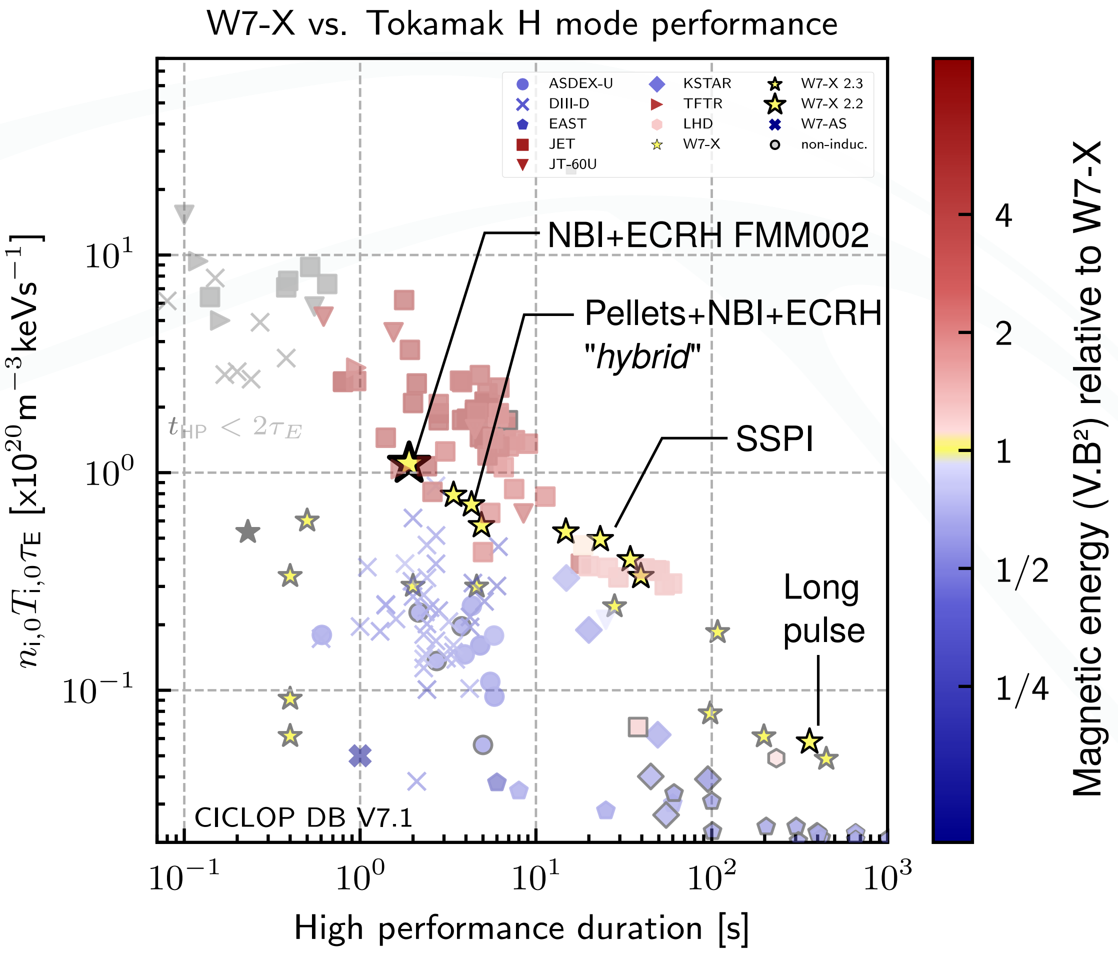


Scenario 4: NBI + ECRH reintroduction - duration

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].

- Hybrid scenario with short pellet chain to create initial density gradient
  --> Slightly longer (more time for HP)
- Fast crashes --> MHD?





Scenario 4: NBI + ECRH reintroduction - seeding

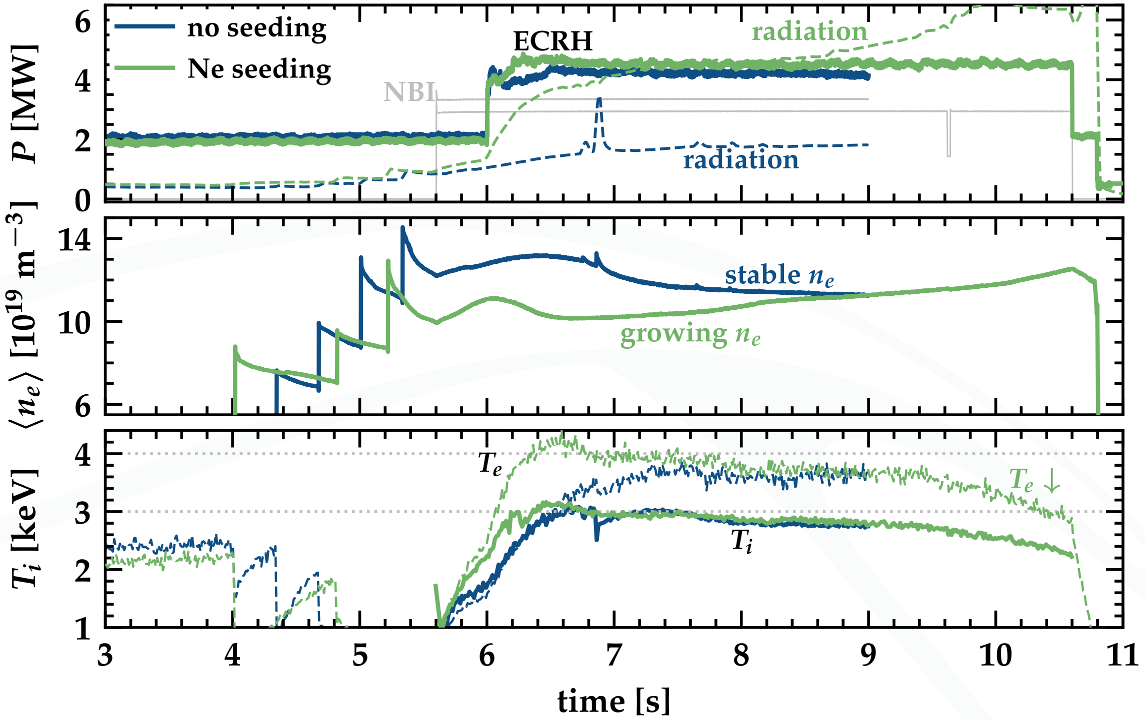
Unable to extend/repeat:

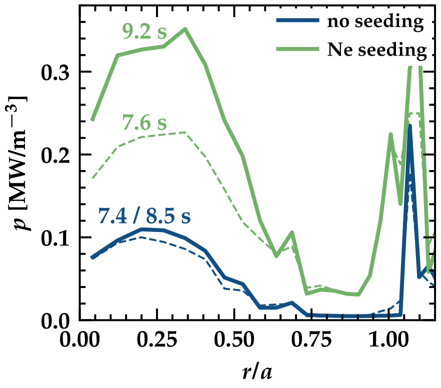
- High W_{dia} was risk for quench detect - OK for OP2.4
- Divertor heat loads (TM5h, TM7h)
  ⇒ N/Ne seeding

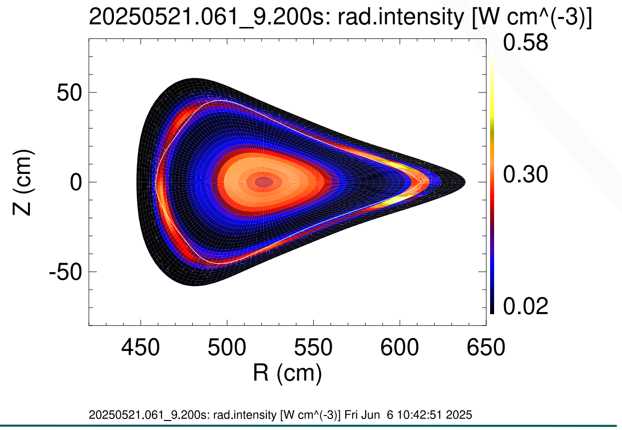
Impurity accumulation (see T. Romba's talk)

- +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.







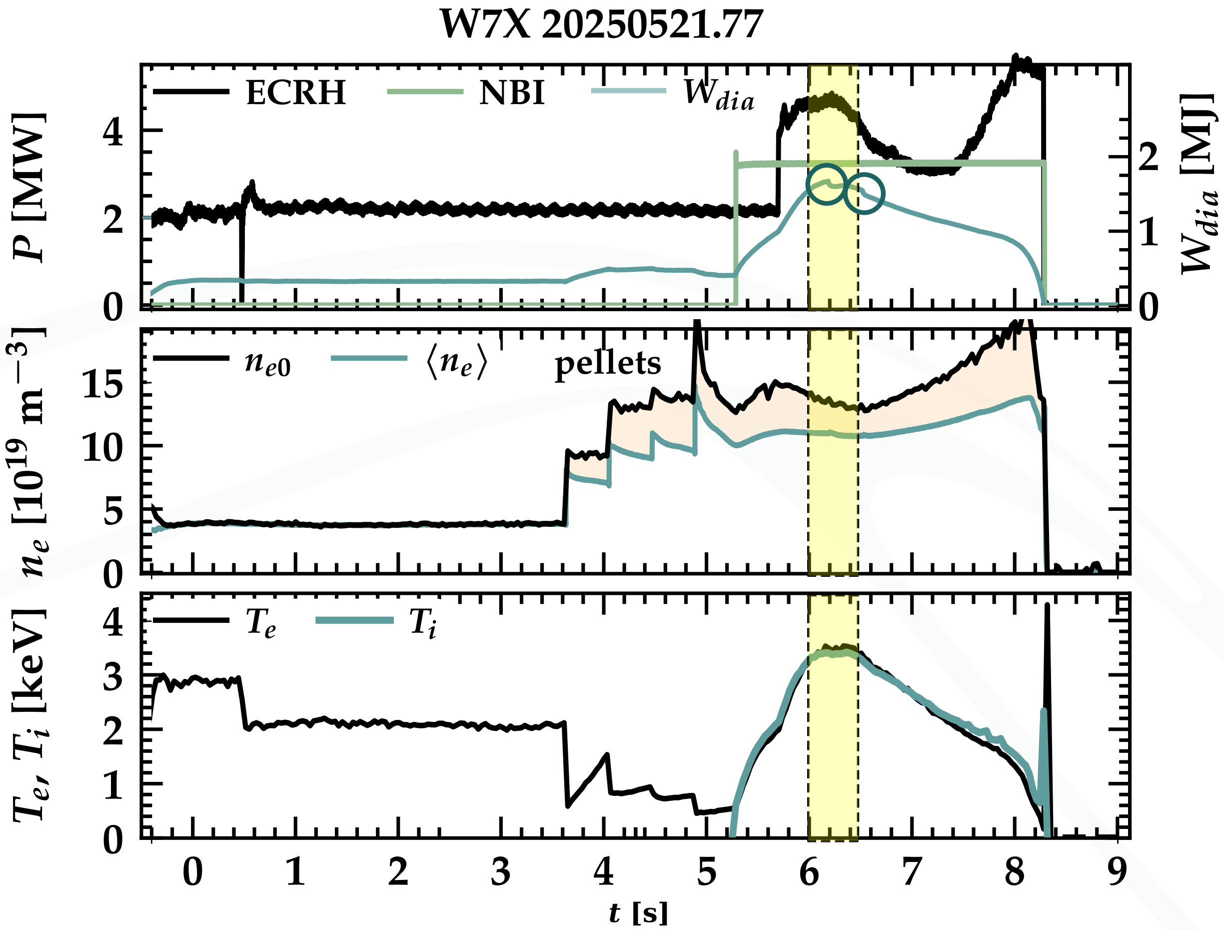
Density profile control

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.

Tested feedback of ECRH vs density [L. Krier].

- $\int n_e \, dl$ is probably not enough information --> RTTS or multichannel interferometer
- Requires live feed of P_{ECRH} to controller of radiation power fraction [V. Perseo].



- This was briefly T_i = 3.5 keV, W_{dia} = 1.5MJ with **small crashes**. Deliberate overshoot and then recovery for pulsed high beta studies?

Particle transport proposals

1) NBI peaking rate:
- EIM + FTM: finer scan of pure NBI sources including modulations - 0.5, 1.0, 1.5, 2.0, 2.5.
- Other configs: Main steps to compare: 1,2,3,4 sources. Not expecting anything.

2) ECRH pump-out:
- EIM + FTM: full scan. Finer around balance point but including min/max P_{ECRH}.
- Other configs: Big steps to find balance and document way too much and way too little P_{ECRH}.

3) Initial conditions - systematic look at pump-out of same PECRH but different start conditions:
- Reintroduction time - Full scan of t_{ECRH} for same P_{ECRH}. EIM
- Drop NBI power ~0.2s before reintro (yes, I know this is fariyl doomed to failure)

- Re-try the 'early start' (low-field-like) NBI peaking to get over the a/Ln threshold with low edge density.

Others looking at this:
- Sebastian Bannmann, Emil Overduin

- generally other people always try this in new configurations.

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 ~ 1.0
- v/D reduced by ~x3 ⇒ stronger peaking
- Final gradient would be given by balance:

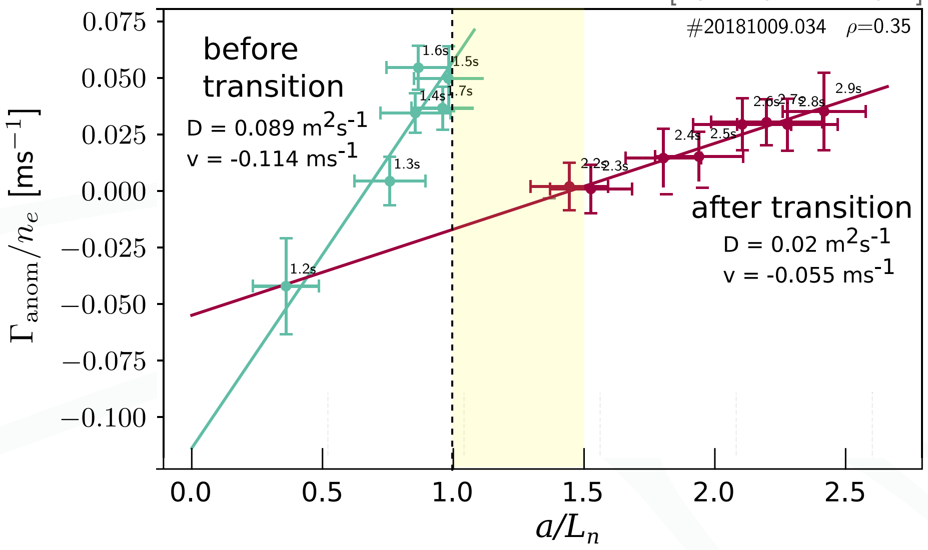
$$-\frac{\nabla n}{n} = -\frac{v}{D} + \frac{\int s dV}{V' D n},$$

Due to pinch

Due to source

Here ~50% from NBI source and pinch.
[Bozhenkov PPCF 2025 (submitted)]

[Bannmann NF 2024]



[Bannmann NF 2024]