

First time-dependent SOLPS-ITER simulations of detachment burn-through on MAST-U

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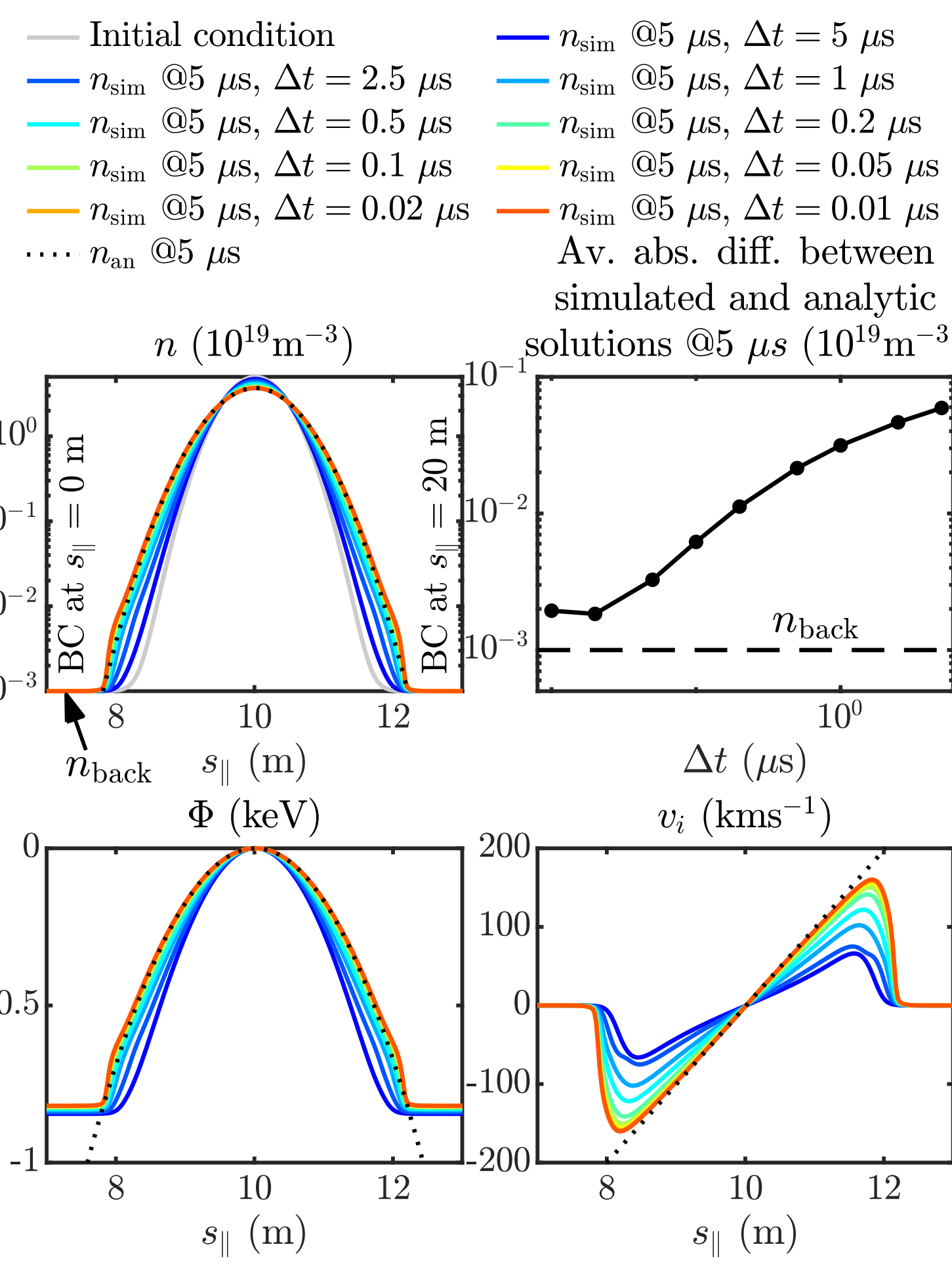
^bSee the author list of N. Vianello et al 2026 Nucl. Fusion in press (<https://doi.org/10.1088/1741-4326/ae71ec>)

SUMMARY

- We present the first interpretative simulations of transient burn-through on MAST-U in Super-X divertor (SXD) configuration, using fully time-dependent SOLPS-ITER.
- Computational cost to build a background is considerable (16 days wall clock time), but ~1 ms transient simulations run quickly thereafter
- Simulations do not align with a model whereby a single energy threshold for burn-through exists, set by the energy required to ionise the pre-existing neutral reservoir.
- Rather, loading of the target that is strongly dependent on target recycling (no recycling leads to factor ~5 higher peak target heat loads compared to instantaneous recycling). Broadly consistent with [Smith 2020].

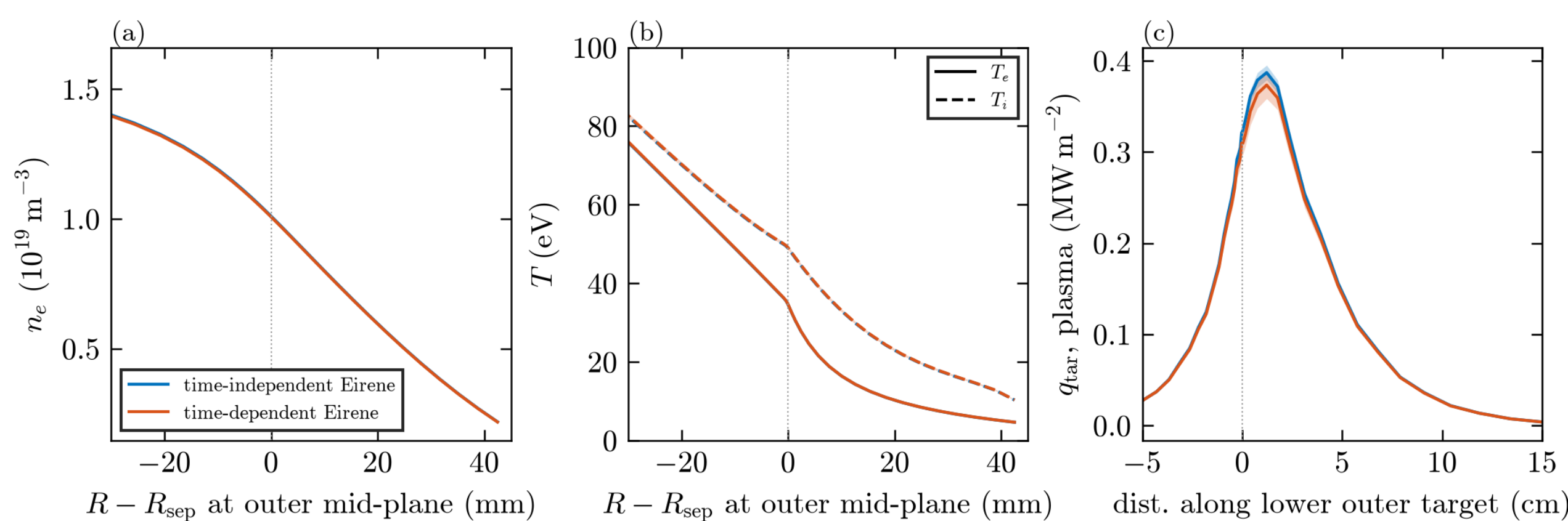
COMPARISON TO ANALYTIC SOLUTION FOR 1D ISOTHERMAL PLASMA EXPANSION INTO VACUUM

- Default:** plasma “time stepping” is just a relaxation scheme to reach steady state. Time is actually pseudo-time: the steady state is correct, but the path to it is not physical.
- Time-dependent plasma mode (this work):** implicit, time-accurate steps. Each equation rebuilds its time-derivative term from the latest values of the other variables. All damping is removed, no time step multipliers.
- This **time-dependent** model has been **verified** against the **analytic solution** for a 1D isothermal expansion of a gaussian density perturbation into vacuum [Mora 2005].
- Good agreement** when sufficient spatial and time resolution used.
- Comparison to adiabatic expansion given in [Mora 2005] not possible since his energy equation assumes constant T_e .



TRANSIENT SIMULATION SETUP; BUILDING THE BACKGROUND

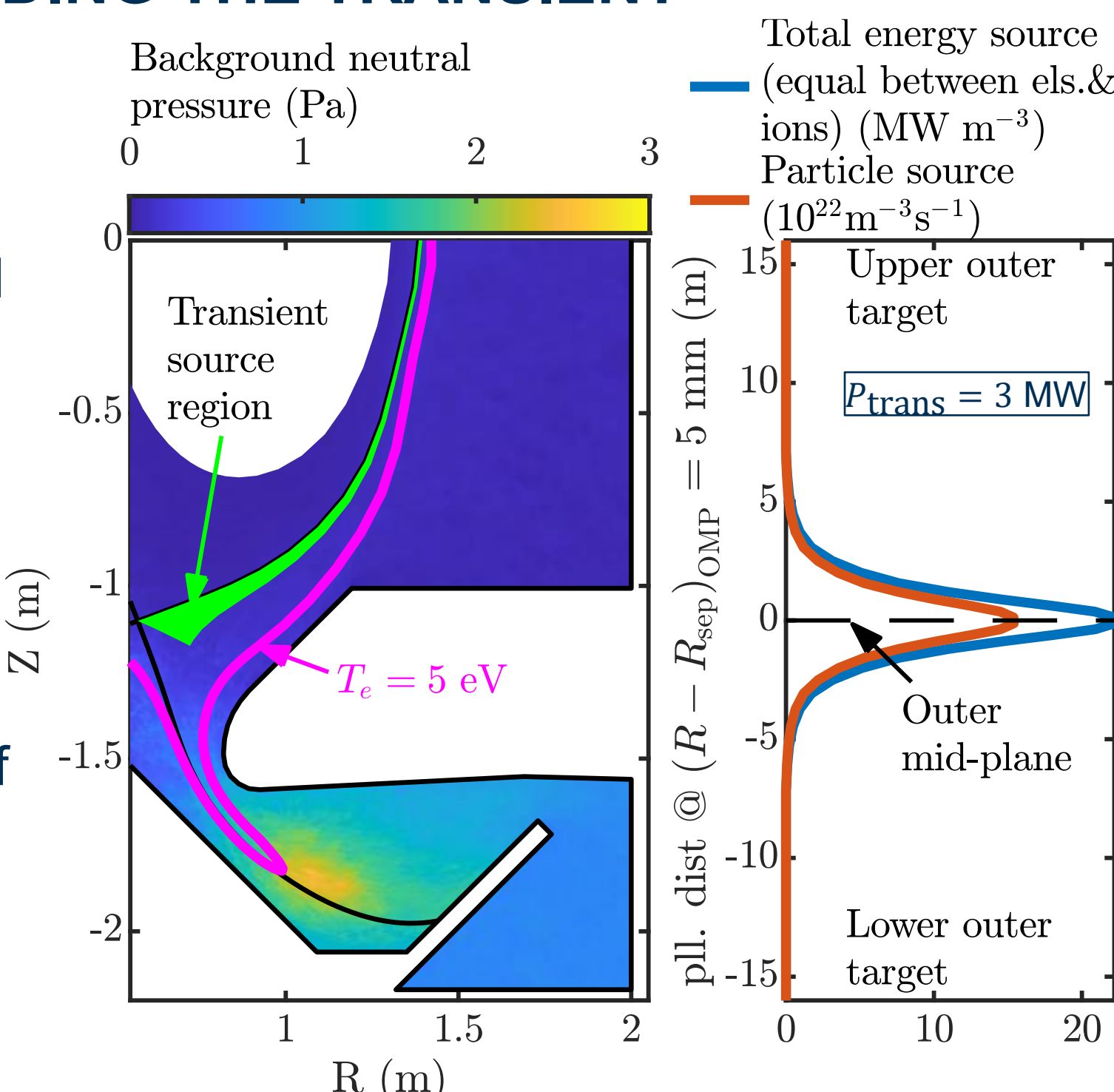
- A pure D simulation [Verhaegh 2025] was reconverged with **time-dependent Eirene** (5×10^7 trajectories resampled from the census + 2000 new trajectories launched from each strata) using the time-independent steady-state simulation as initial condition.
- Warm restart:** for the first step only, trajectories are not stopped at the time horizon. Instead, every time-horizon crossing is recorded. Census is immediately much closer to steady state and doesn't have to build slowly from nothing (thanks to JS Park).



- Caveat when adding time-dependent plasma mode on top:** our current cases are stable only because of an artificial smoothing along closed flux surfaces. Without it, the residuals grow within a step. Ongoing: time-dependent plasma with some under-relaxation and concomitant time multipliers to maintain accurate time stepping.

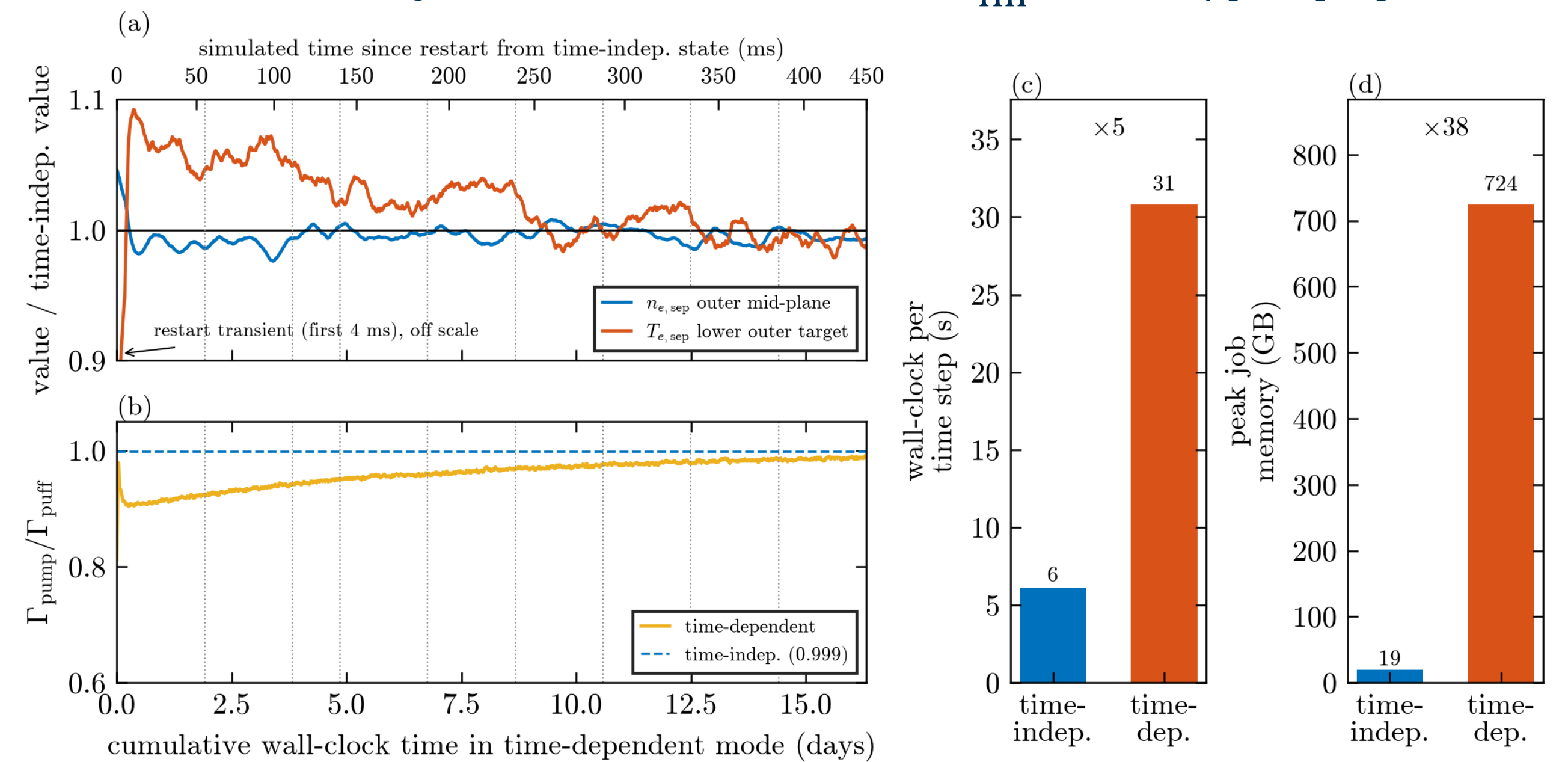
TRANSIENT SIMULATION SETUP. ADDING THE TRANSIENT

- For initial study, we use this same $P_{sep} = 1$ MW beam heated L-mode background throughout and impose an instantaneous upstream source: 1 ms duration; $\lambda_{trans} = 1$ cm width; plasma energy (S_E) and particle (S_n) source upstream s.t. $S_E = 3kT_{ped}S_n$ [Havlickova 2012] ($T_{ped} = 300$ eV chosen here, electron and ion given equal energy in reference cases).
- Simplification to have an instantaneous source removes the additional timescale of the source from our analysis.
- Total transient power P_{trans} was scanned.

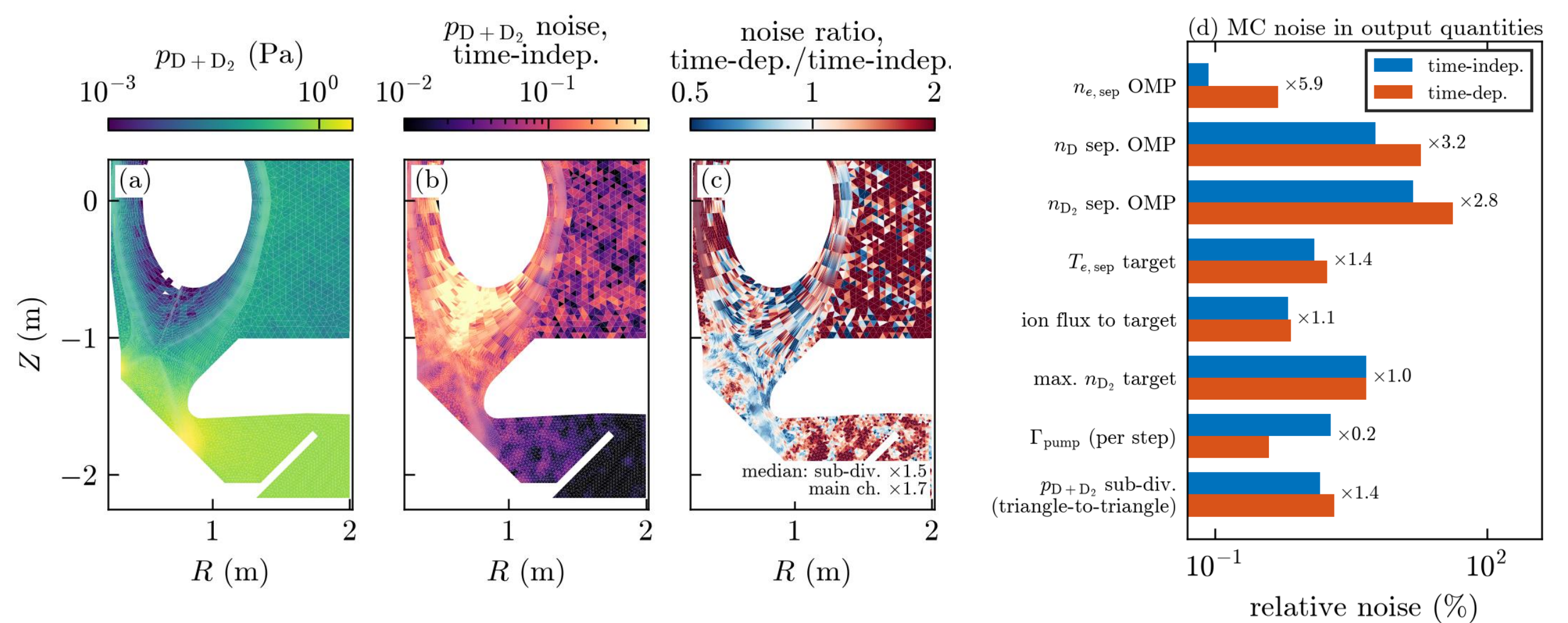


COMPUTATIONAL COST AND MONTE-CARLO NOISE

- For broadly similar noise levels (see below), **wall-clock per time step is ×5 longer and ×38 more memory intensive with time-dependent Eirene** (the census is replicated on every MPI rank; room for optimisation).
- Census size is limited by available memory per node. Impurities will push requirements beyond memory available on EUROfusion Gateway.
- Reconvergence of new backgrounds from an Eirene-time-independent steady state is expensive: **16 days wall-clock time** (14k core-hours) for 434 ms of plasma time.
- Particle balance converges slowest on a timescale $\tau_{fill} \sim \text{volume}/\text{pump_speed} \sim 0.2$ s.



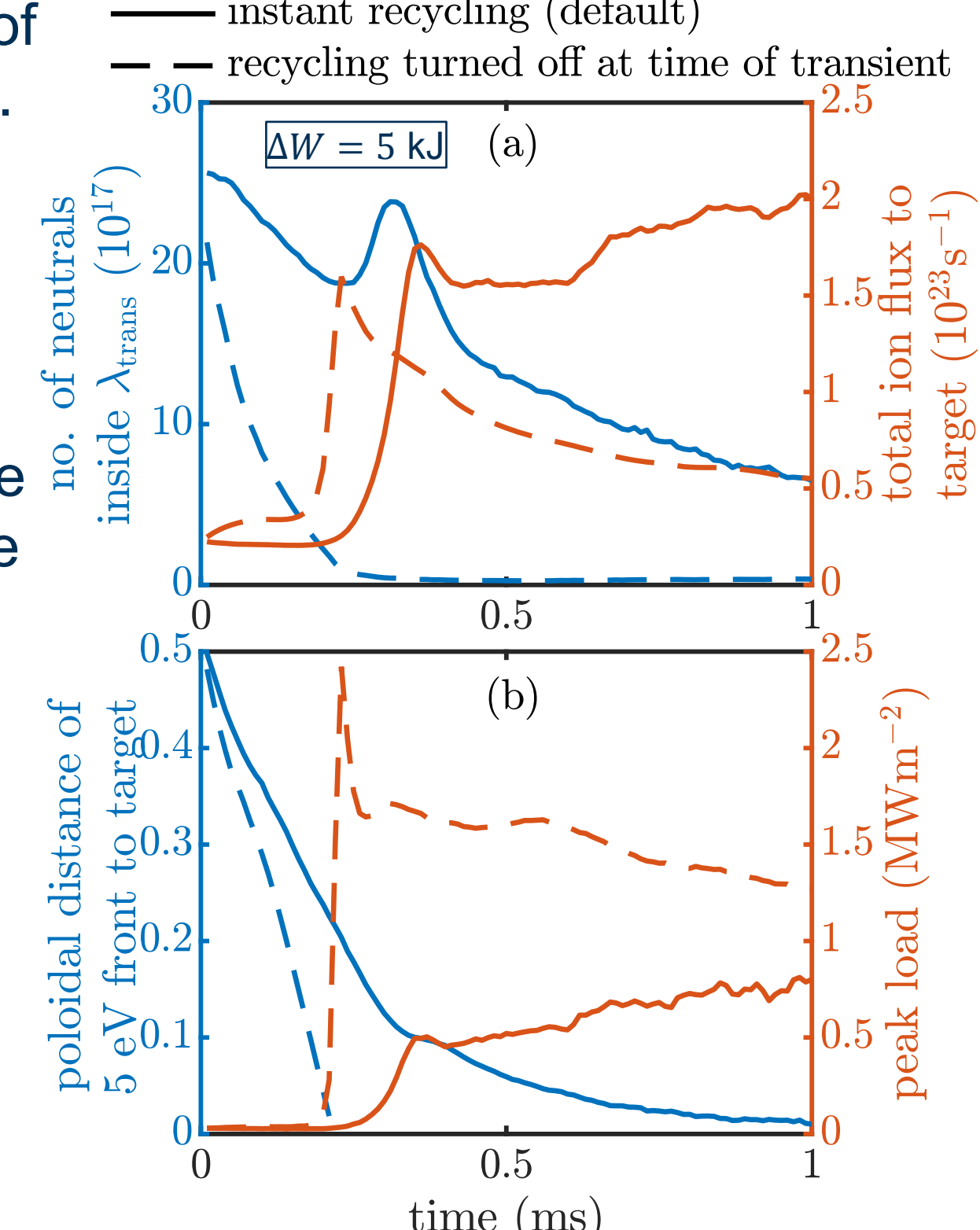
- Noise, as measured by the relative fluctuation ($\equiv \text{std}(\frac{\text{diff}(y)}{\sqrt{2}|\text{mean}(y)|})$) is **broadly similar** but slightly worse in time-dependent simulations, even with a 5×10^7 trajectory census that fills the available memory.
- The exception is the pumped flux which is x5 quieter. Reason not yet understood.
- Unclear what sets noise in time-dependent Eirene.** Estimated number of histories crossing a triangle during a step in the sub-divertor: ~30,000 in time-dependent vs ~10,000 in time-independent. From the measured noise, we get an effective number of 3,000 in time-dependent (10x less) vs 6,000 in time-independent (similar).
- Conclusion:** in the time-independent run the noise level is explained by the crossing count. In the time-dependent run it is not; copies made by resampling the census are correlated, so independent information is the number of distinct lineages, roughly: new survivors x lifetime per triangle = 8,900, at an efficiency of ~1/3.



THE NEUTRAL RESERVOIR AND THE IMPORTANCE OF RECYCLING

- The pre-existing neutral reservoir is far too small to buffer typical transients on MAST-U**
- Instead, recycling is a key driver of the degree of transient buffering
- By default, we assume **instantaneous recycling** of the incoming target ion flux (solid lines in Fig right).
- In that case, for a $\Delta W = 5$ kJ transient whose 5 eV front just reaches the target after 1 ms, the neutral reservoir inside λ_{trans} is **only depleted by ~30%** before being **boosted again by recycling**.
- By contrast, when the target is **fully pumped** at the instant the transient is initialised (dashed lines), the neutral reservoir is completely depleted and the **peak load to the target is ~5 times higher**.
- Implies that neutrals do play an important role in reducing peak heat loads, but **neutrals born from recycling** more than the **pre-existing reservoir**.
- In the default case, the 5 eV front also slows once the incoming ion flux starts to recycle from the target, which is not observed in the absence of recycling.

Typical transient energy on MAST-U	1000-10,000 J
Simulated cost to ionise the pre-existing neutral reservoir at $p_{div} = 1$ pa ($N_{neut}\epsilon_{iz}$, with ϵ_{iz} chosen as 30 eV)	12.4 J



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