Efficient and rigorous evaluation of fast particle losses in non-axisymmetric tokamak plasmas

Konsta Särkimäki
Max Planck Institute for Plasma Physics, Garching, Germany
sarkimk1@ipp.mpg.de

- Techniques presented here allow for faster evaluation of fast particle losses and connect the results to underlying transport mechanisms.
- These are applied to study alpha particle losses in ITER with various external perturbations and with a full scan on ELM control coil phases.

1. Where to improve orbit-following simulations

- Orbit-following simulations are commonly used to estimate fast particle confinement and associated wall loads.
- Benefits:
  + Can include any 3D perturbations and complicated wall geometry.
  + Based on first principles.
- Drawbacks:
  - Computationally expensive (>> 10^5 markers to assess wall loads accurately).
  - Result is guaranteed but no clear way to verify it (transport mechanisms cannot be toggled).

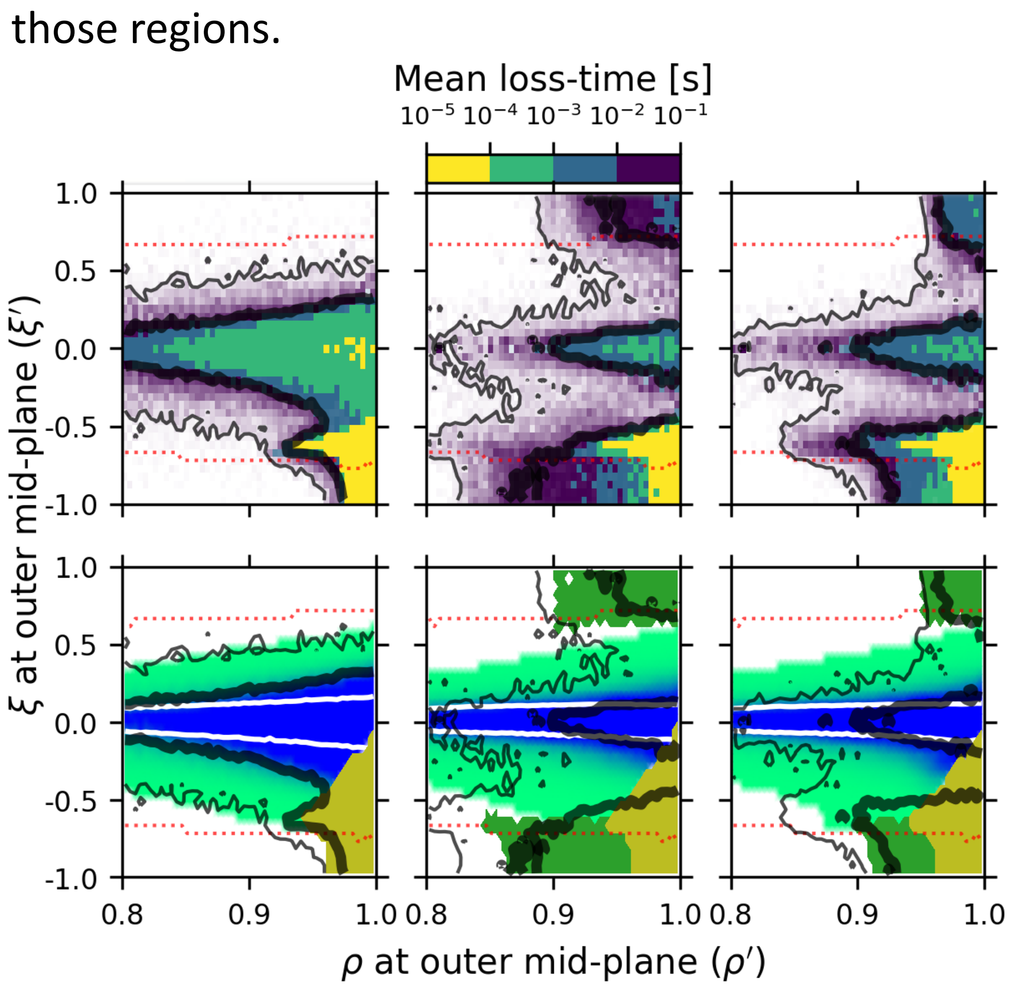
3. Marker sampling

Idea: Identify phase-space regions where losses originate and initilize markers only on those regions.

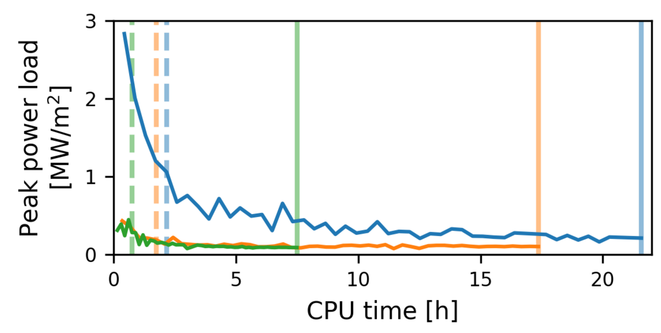
Orbit-following results (top row) and analytical estimates based on the magnetic field data (bottom row). The studied case is alpha particle confinement in ITER baseline scenario.

From left to right, the cases are: unmitigated TF ripple, mitigated ripple with test blanket modules and ELM control coils, and previous case with plasma response included.

The black thick (thin) contour shows the region with 90 % (10 %) losses. These contours are also shown at bottom row where colours indicate regions where different transport mechanisms are active.

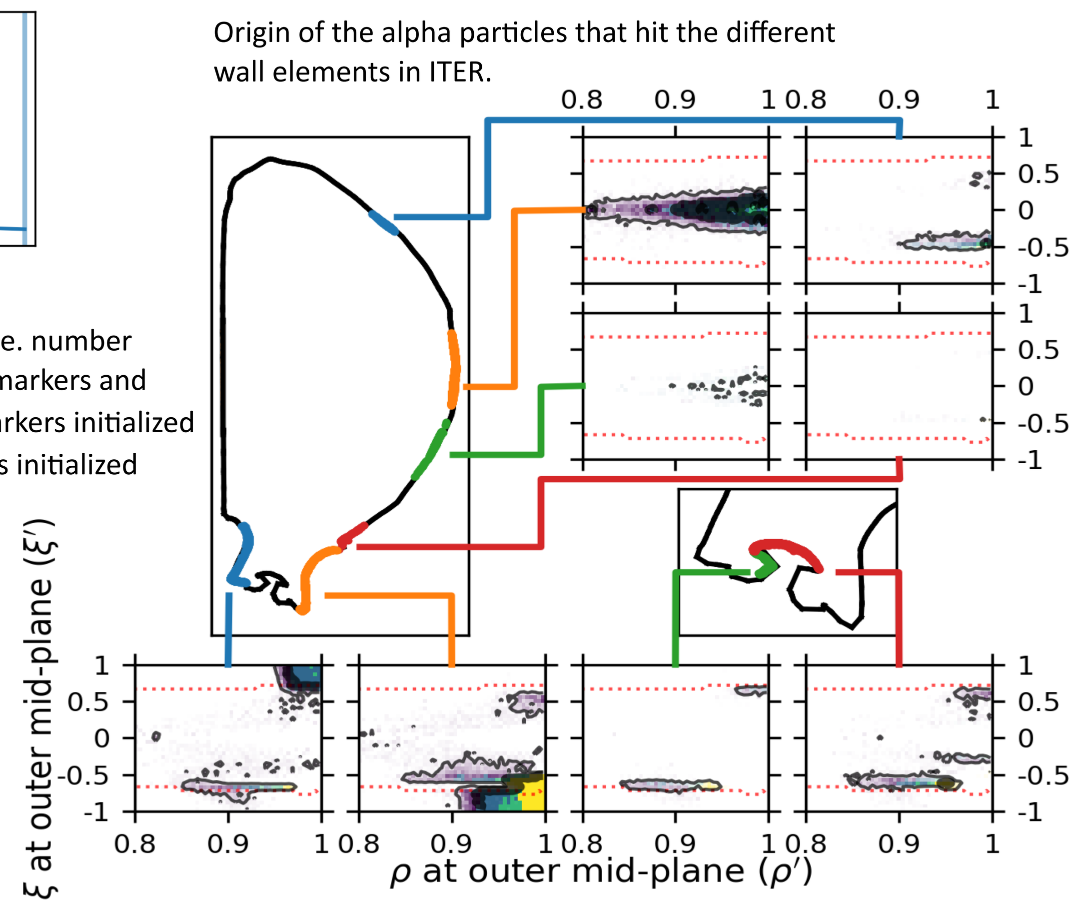


- Orbit-following simulations show that origin of the losses is localised in phase space even with various perturbations (top row).
- Loss maps can be constructed instantly from the magnetic field data (bottom row).
- Good match between analytical estimates (total losses 1.24 MW in the last column) and orbit following results (1.18 MW).



Marker sampling significantly reduces CPU time, i.e. number of markers required (solid vertical lines mark 10^5 markers and dashed lines 10^4 markers): No sampling (blue), markers initialized uniformly on (ρ', ξ') phase-space (orange), markers initialized on the loss channels (green).

Origin of the alpha particles that hit the different wall elements in ITER.



- Using analytical estimates for the loss regions and initializing markers only on those regions, or even just uniformly in (ρ', ξ') phase space can bring significant performance gain compared to uniform velocity space distribution (no sampling).
- One can further optimize by initializing markers only on those regions that contribute to the wall loads on the regions of interest.

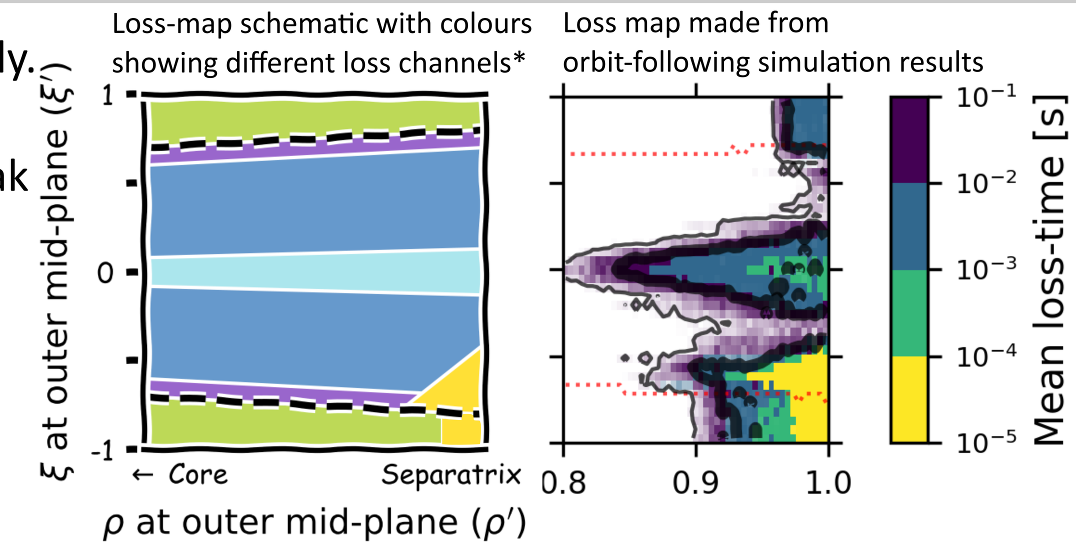
6. Further reading

Särkimäki, K. (2019). *Modelling and understanding fast particle transport in non-axisymmetric tokamak plasmas* [Doctoral dissertation, Aalto University]. http://urn.fi/URN:ISBN:978-952-60-8821-1

Särkimäki, K. (2020). *Efficient and rigorous evaluation of fast particle losses in non-axisymmetric tokamak plasmas*. Nuclear Fusion, 60(3), 036002.

2. The loss-map scheme

- A way to visualize losses intuitively.
- Orbits in an axisymmetric tokamak are characterized by (E, P_{tor}, μ).
- (P_{tor}, μ) can be mapped to ρ and pitch at outer mid-plane, (ρ', ξ'), when E is kept fixed.
- Loss channels and corresponding transport mechanisms in 3D fields can be identified from the loss map.



* First orbit losses (yellow), stochastic field line losses (green), perturbed banana transport (purple), ripple diffusion (blue), ripple trapping (light blue). Dashed lines are the passing-trapped boundary

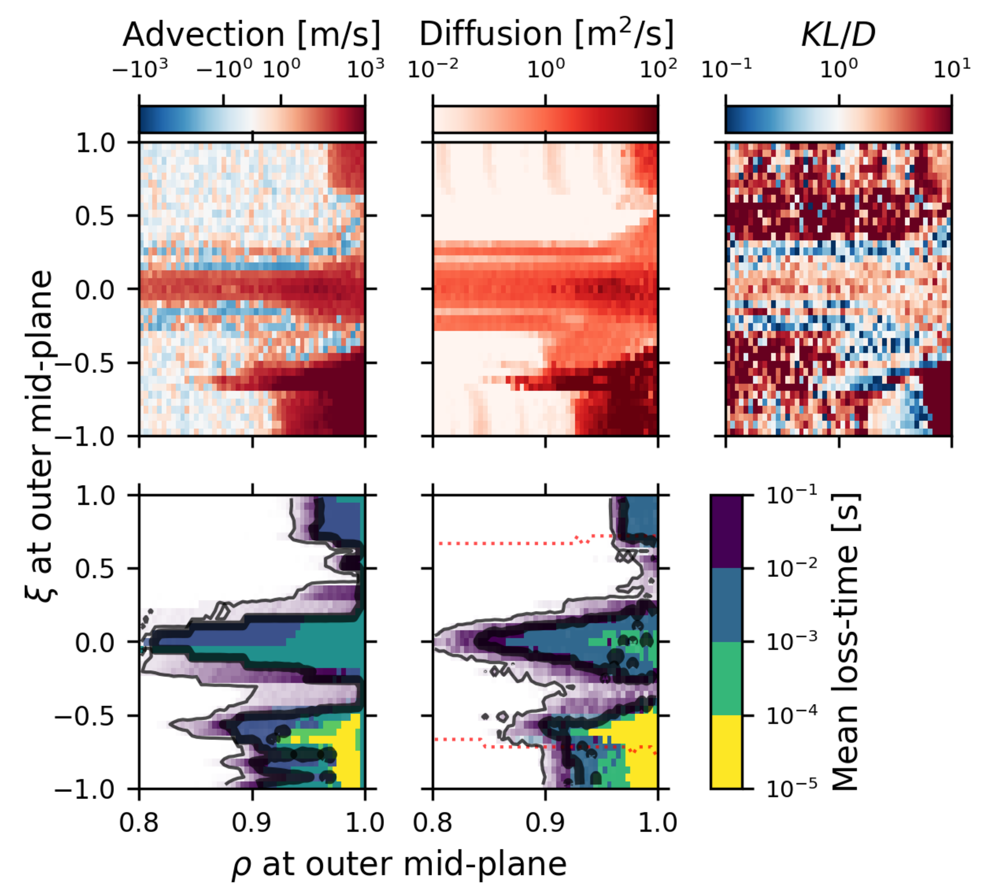
- The loss map shows the mean loss time (hue) and fraction of particles lost (intensity) from a given phase space position.

4. Advection-diffusion model

Idea: Use orbit-following code to calculate the transport coefficients and estimate losses by modelling fast ion transport as an advection-diffusion process.

Transport coefficients (top row) calculated in ITER baseline scenario with mitigated TF coil ripple, test blanket modules, ELM control coils, and plasma response. Last column is the Péclet number where the characteristic length scale is chosen as L = 0.1 m.

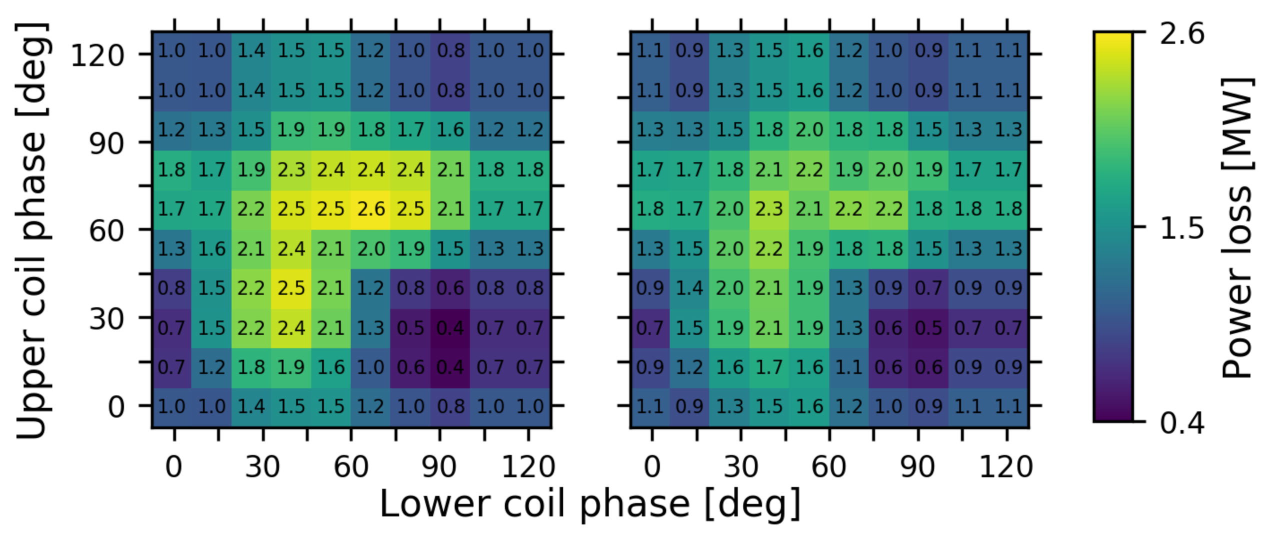
Comparison of alpha particle losses during the slowing-down process (bottom row): The advection-diffusion model result (left) and the orbit-following simulation result (right).



- Markers were traced for 1 ms to calculate the transport coefficients.
- The coefficients were then used in an advection-diffusion model to simulate the transport for the whole slowing down time (0.1 s).
- Comparison between the advection-diffusion model (total losses 1.42 MW) and equivalent slowing-down simulation (1.22 MW) show a good agreement.

5. Scan of alpha particle losses due to ELM control coils in ITER

Alpha particle losses with different ELM control coil phases. The current (45 kAt) and mode (n=3) were fixed while the phase was varied. The advection-diffusion model result is shown on left and the orbit-following simulation result on right.



- The advection-diffusion model was used to estimate alpha particle losses in ITER with different ELM control coil phases.
- This required 1/100 th of the CPU time than the corresponding scan done with orbit-following simulations.
- This scan was done in vacuum approximation and the **numbers shown here should not be taken as an prediction**.