Simulation of stochastic seed RE transport and deposition after ITER dual-SPIs by PTC & JOREK

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Introduction

- Shattered Pellet Injection (SPI) is one of the primary Disruption Mitigation System (DMS) of ITER.
- It’s first objective is the thermal quench mitigation, concerning the uniform deposition of the thermal energy onto the first wall.
- It also has to take into account of the Current Quench mitigation, such as the requirement of the electro-magnetic force load and most importantly, **the runaway electron suppression**.
- It is desirable to deplete the seed runaway electron within the plasma as much as possible already during the thermal quench, so that they do not participate in the avalanche.
- PTC test particle simulation is carried out using JOREK fluid field to analyze the RE transport and loss during the TQ mitigation .

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Background: JOREK simulation

We consider two kinds of equilibria: the baseline and the “degraded” H-mode. The latter represents the H-L back transition in the precursor phase. The thermal energy is 370MJ and 190MJ respectively

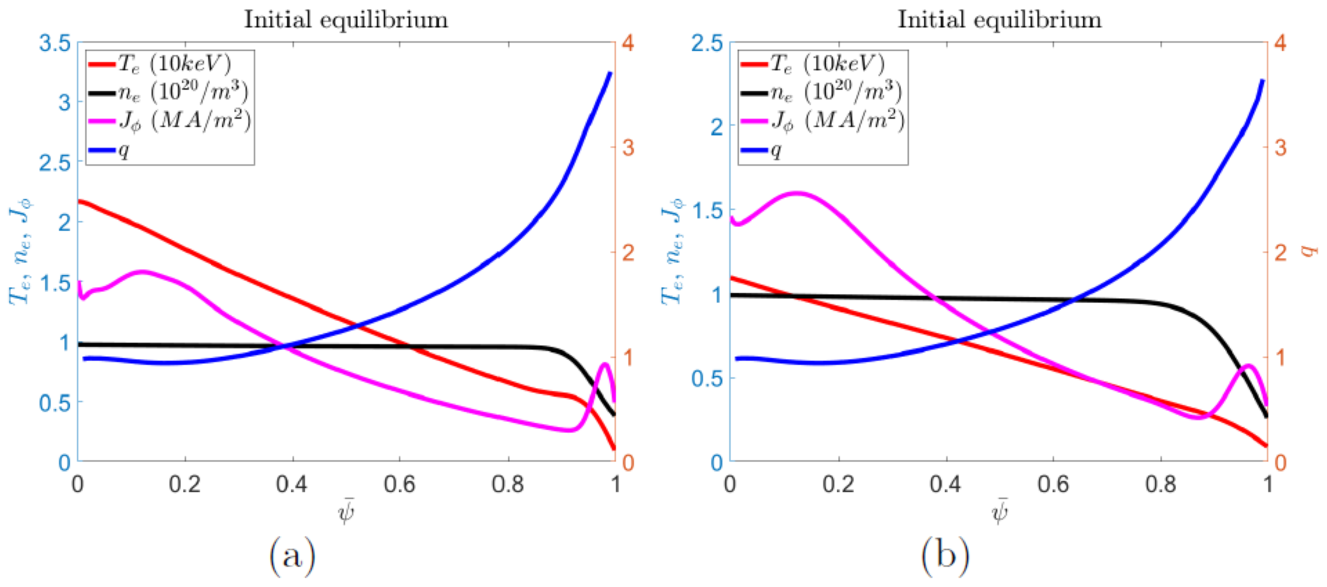
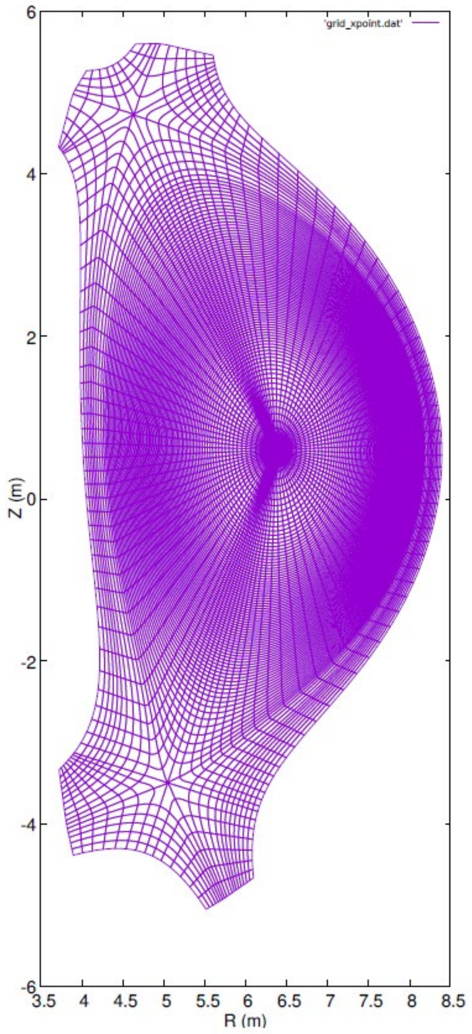


Figure 1. The initial equilibria of (a) the baseline H-mode and (b) the degraded H-mode, $\bar{\psi}$ is the normalized poloidal flux.



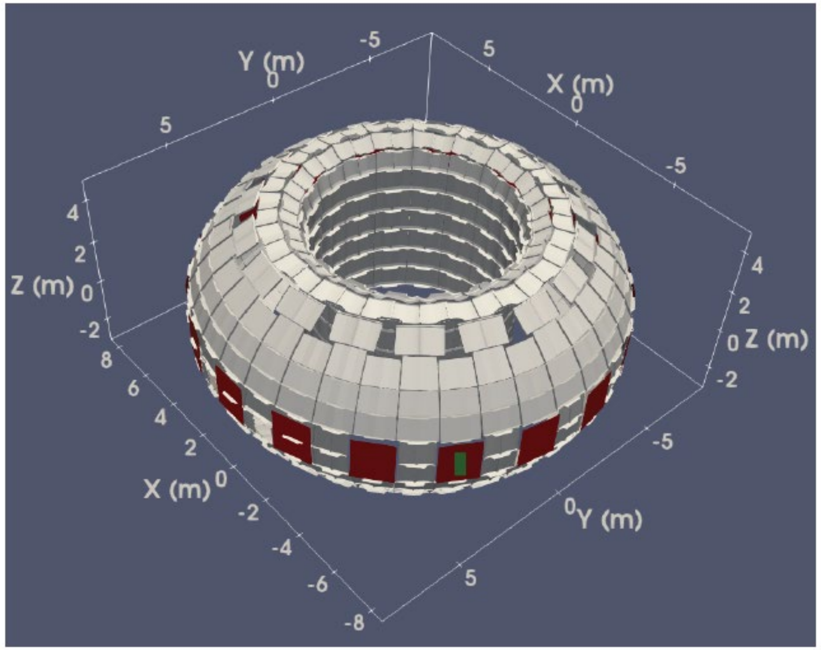
D. Hu *et al* Nucl. Fusion **64** (2024) 086005

SPI parameters

- Dual-SPI ports at EQ-08 and EQ-17; Two kinds of pellets: full-pellet and quarter-pellet; Statistical Fragmentation model for fragment size.
- Injection velocity $500m/s$, velocity spread $\pm 40\%$, vertex angle 20°.

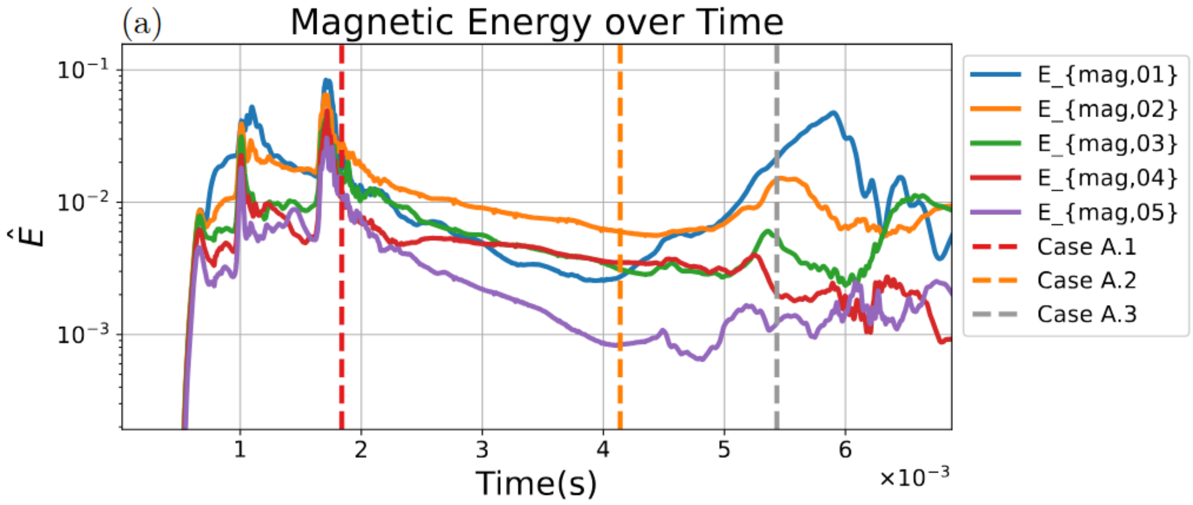
Notation	Equilibria	Neon	Hydrogen	Frag.	Delay	Tor. Angle
BH-FP-dt0 (case 1)	baseline	$2 \times 2.5 \times 10^{22}$	$2 \times 1.8 \times 10^{24}$	300	$0ms$ (Asymm.)	180°
DH-FP-dt0 (case 2)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 1.8 \times 10^{24}$	300	$0ms$	180°
DH-QP-dt0 (case 3)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 4.5 \times 10^{23}$	100	$0ms$	180°
DH-QP-dt1 (case 4)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 4.5 \times 10^{23}$	100	$1ms$	180°
DH-QP-dt0-ff (case 5)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 4.5 \times 10^{23}$	1000	$0ms$	180°
DH-QP-dt0-120 (case 6)	degraded	$2 \times 2.5 \times 10^{22}$	$2 \times 4.5 \times 10^{23}$	100	$0ms$	120°
DH-QP-stg (case 7)	degraded	2×0 $+2 \times 2.5 \times 10^{22}$	$2 \times 5 \times 10^{23}$ $+2 \times 4.5 \times 10^{23}$	100 100	$0ms$ (Staggered)	180°

TABLE I. The injection parameters for the SPI considered in this study. Note that for BH-FP-dt0 there exists an asymmetry between the plumes although they are injected at the same time.



Example: the DH-QP-dt1 case

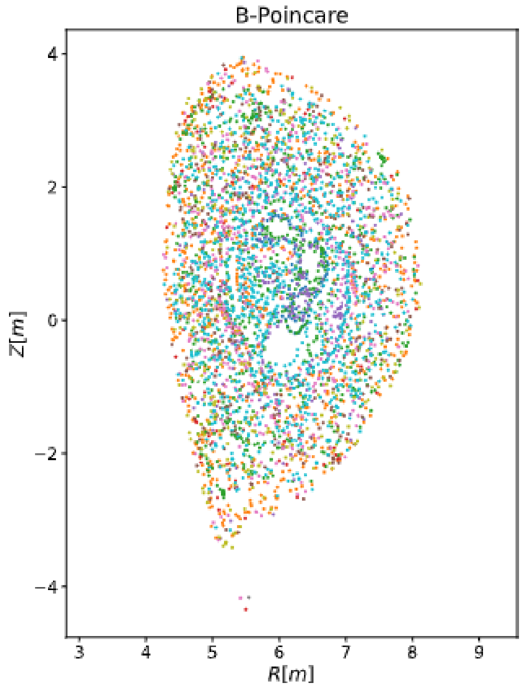
- Several MHD peaks throughout the TQ mitigation, the flux surfaces go through breaking-healing-breaking cycles.
- A few time slices is chosen around the peaks and the valleys of the MHD amplitude. A few cases for other JOREK runs are also chosen.



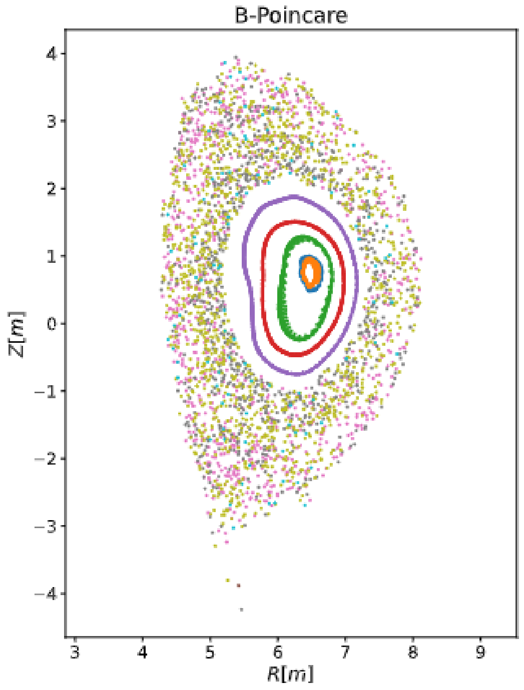
Fluid Case	Notation	Characteristic	Time(ms)
DH-QP-dt1	A.1	Strongly stochastic magnetic field	1.839
	A.2	Inner Flux surfaces restored	4.139
	A.3	Core crash, prevalent stochasticity again	5.433
DH-QP-dt0	B	Strongly stochastic in this injection	6.499
DH-QP-dt0-120	C	Strongly stochastic in this injection	1.863

PTC simulation based on JOREK results

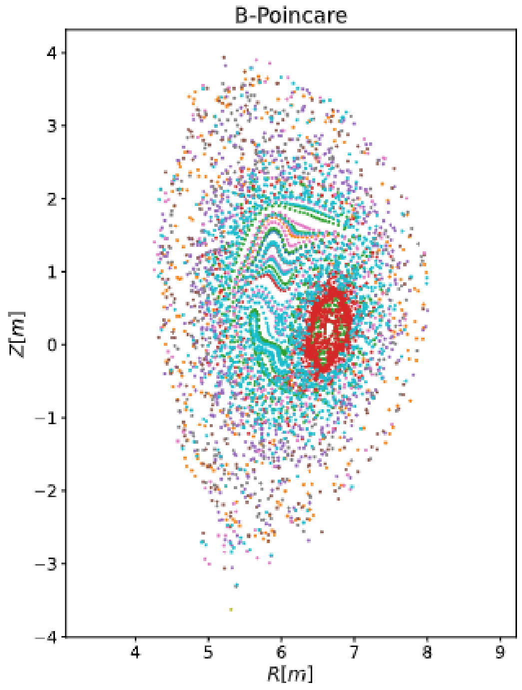
- In general, we found the RE characteristic loss time to be one order of magnitude **shorter** than the evolution time of the stochastic field.
- The transport is directly linked to the stochasticity, as expected.



(b) A.1



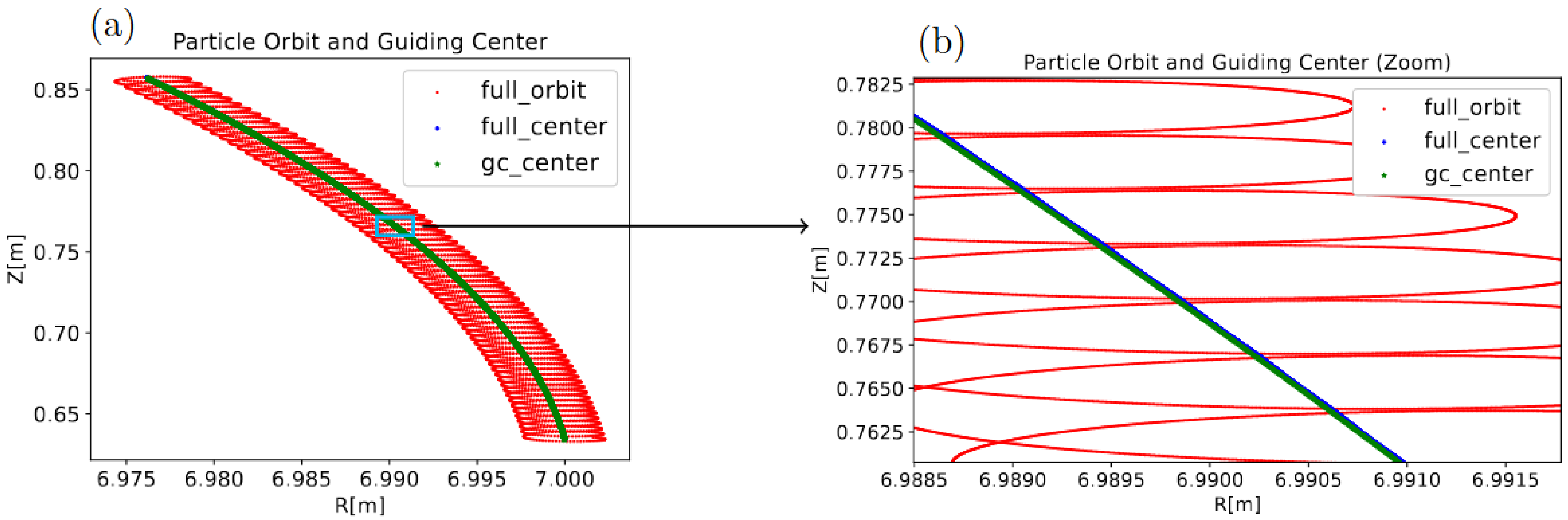
(c) A.2



(d) A.3

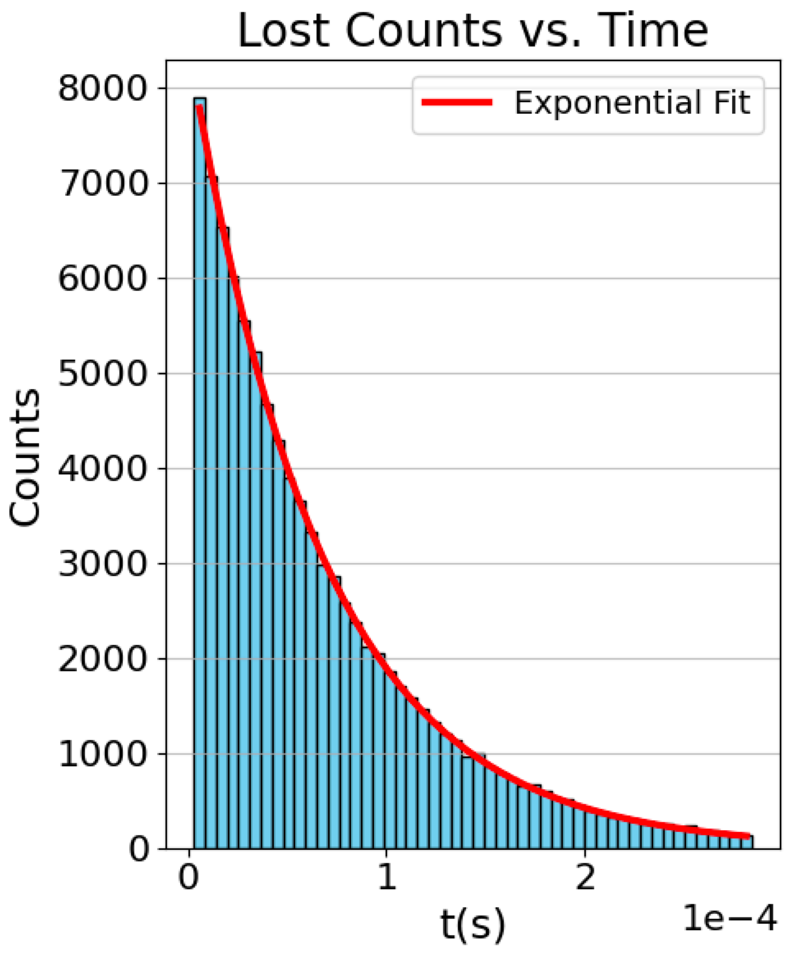
Higher order magnetic moment

- PTC RE guiding center pusher (by RK4) has been developed (S. Liu, J. Plasma Phys 2022) using the higher order magnetic moment (C. Liu, Nucl. Fusion 2018), and **benchmarked against equilibrium full orbit results**.
- A few improvement regarding the field curvature is added now and **tested against the full orbit result in ITER stochastic field**.



Characteristic loss time

With sufficiently stochastic magnetic field (DH-QP-dt1, **1.839ms**):



The RE loss exhibit good **exponential feature**, as previously reported by G. Papp et al 2015.

RE loss rate：

$$N_{loss}(t) = -\frac{\mathrm{d}N(t)}{\mathrm{d}t} = \frac{1}{\tau} \cdot N_0 \cdot \exp\left(-\frac{t}{\tau}\right)$$

The characteristic loss time $\tau = 6.6547 \times 10^{-5} s$.

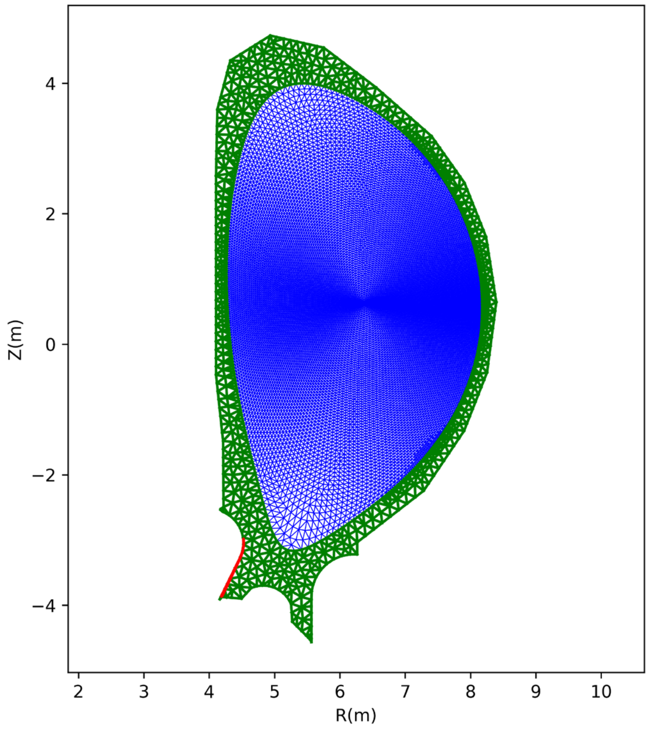
This timescale is much shorter than the MHD evolution time.

The fitting coefficient： $R^2 = 0.9996$

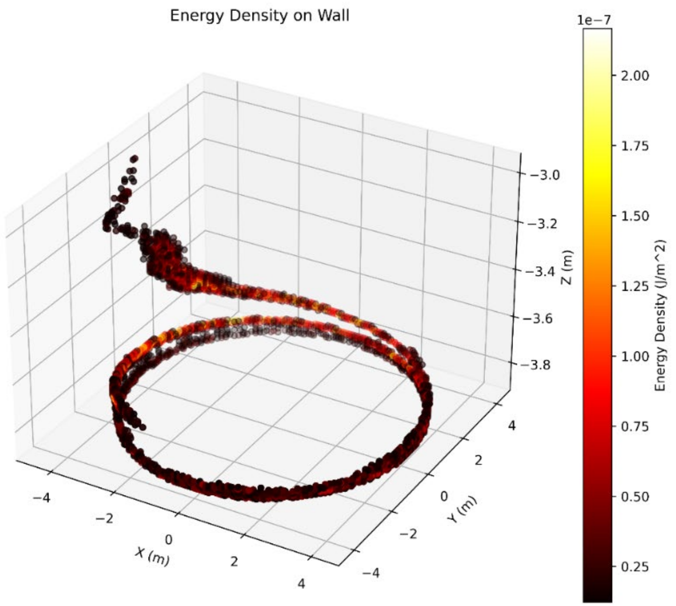
G Papp et al 2015 J. Plasma Phys 81 475810503

Characteristic loss distribution

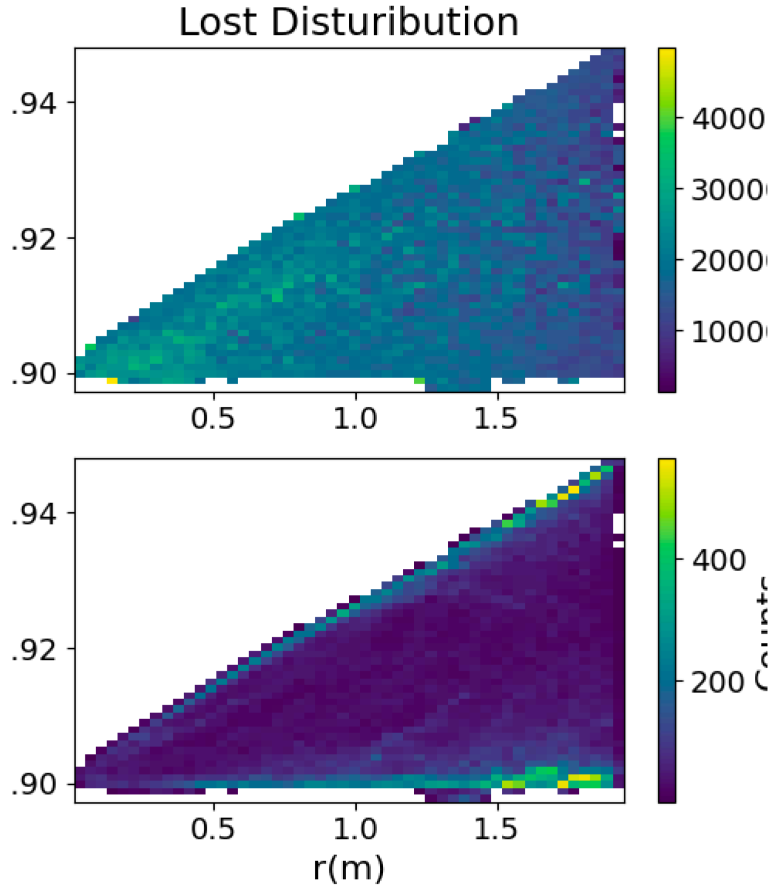
The RE loss on the wall for DH-QP-dt1, **4.839ms**:



RZ plane projection



Relative heat distribution



The loss length

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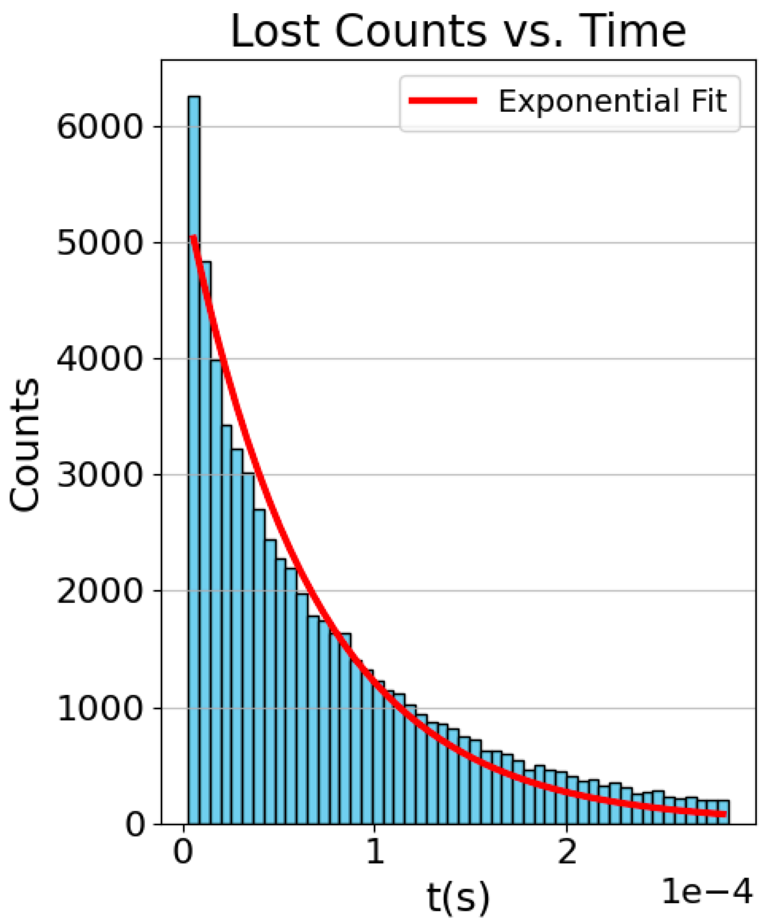
The partially healed surfaces...

For cases with partially healed flux surfaces（DH-QP-dt1, **4.139ms**）：



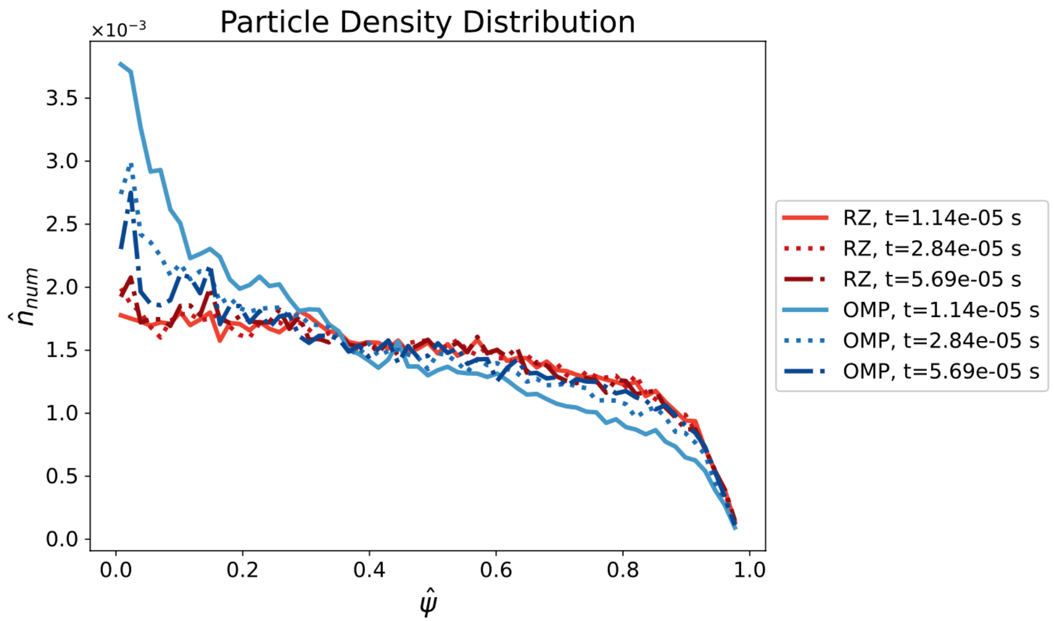
The closed flux surface incurs long tail deviation of the RE loss from the exponential behavior.

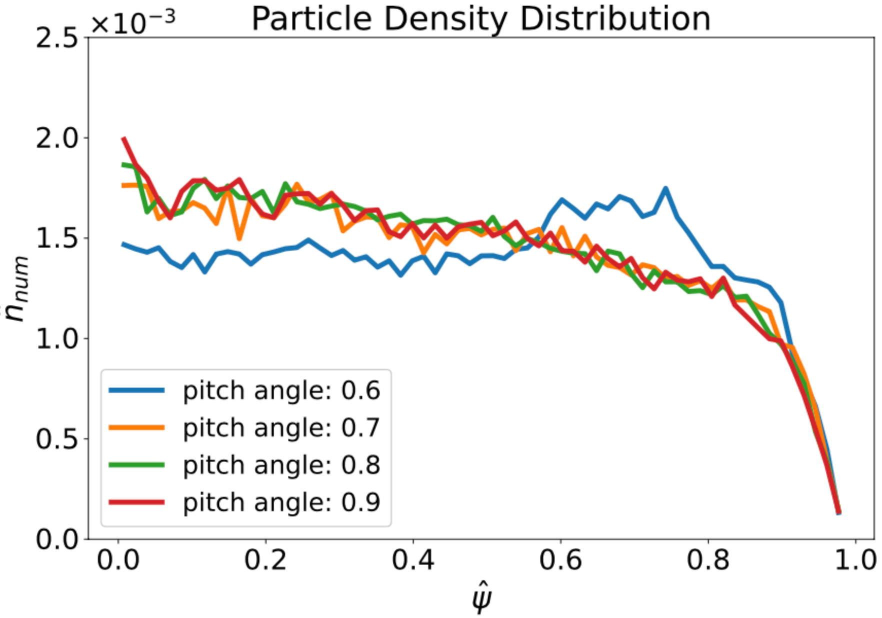
Ignoring the long tail fitted loss time is $\tau = 6.6216 \times 10^{-5} s$, comparable with the previous case. Fitting parameter $R^2 = 0.9643$

The comparing loss time might be an illusion created by loss of the outer REs.

Self-similar RE profile

With sufficiently stochastic field (DH-QP-dt1, 1.839ms) , **the RE density profile evolves towards a self-similar one**, consistent with the exponential RE loss. The characteristic timescale to reach such a profile is about $50\mu s$. **Faster than the MHD evolve time**. Independent of pitch angle and energy.





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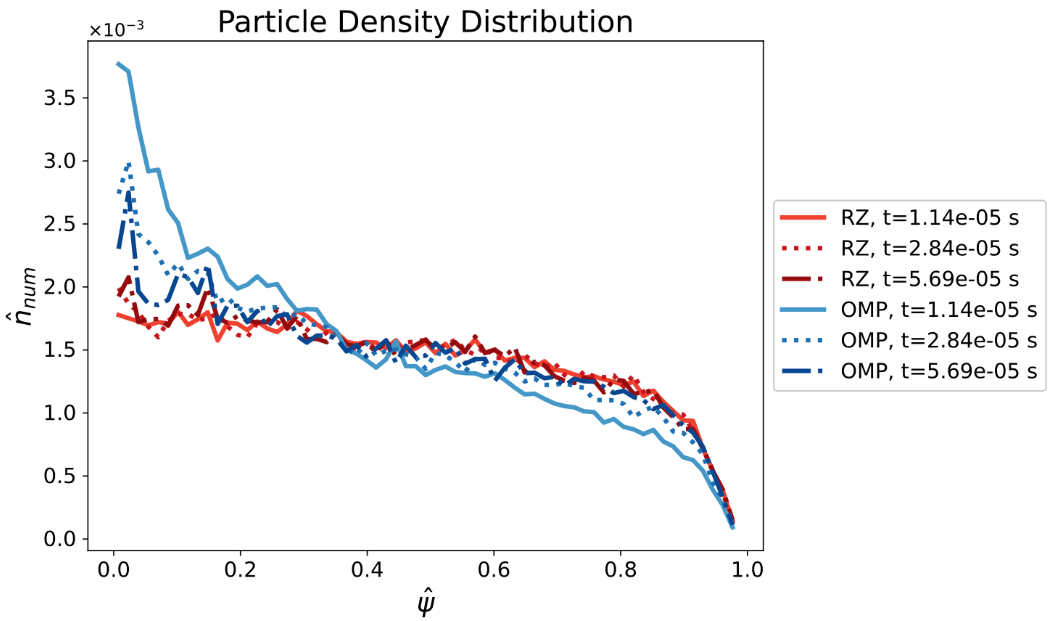
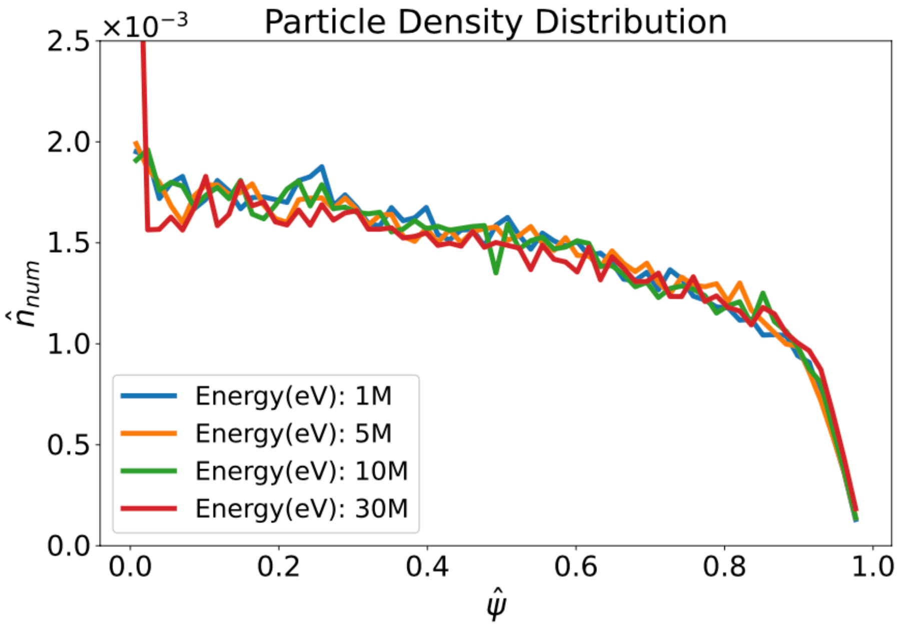
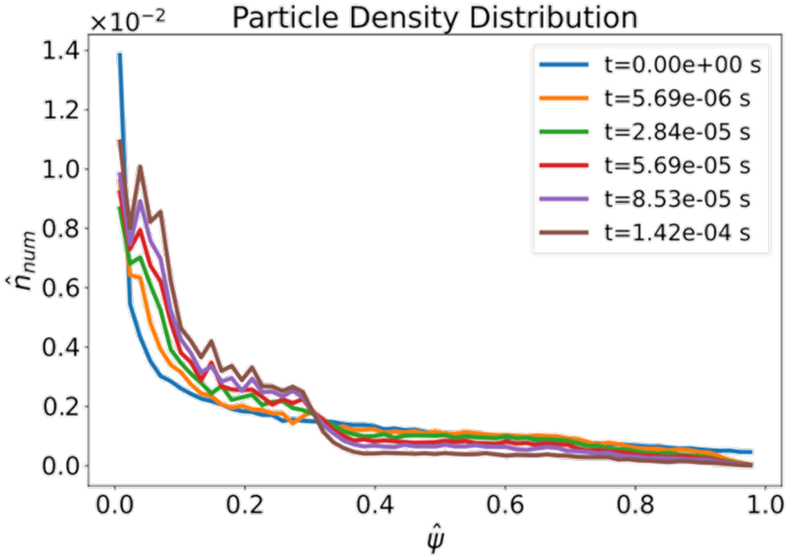


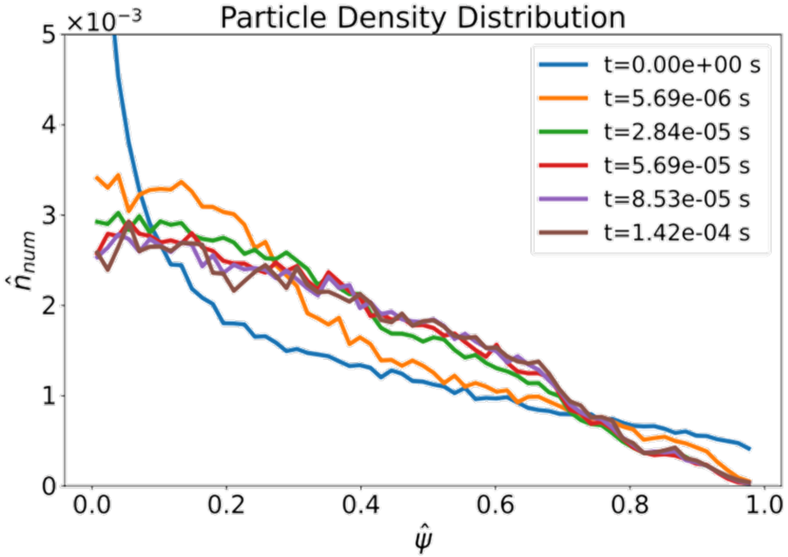


Self-similar RE profile

- Partially healed flux surfaces break such self-similar profile…….
- Pitch angle = 0.9, $E = 5MeV$, a): DH-QP-dt1, 4.139ms; b): DH-QP-dt1, 5.433ms
- The normalized RE core profile becomes more peaked as the RE confinement there is relatively better.



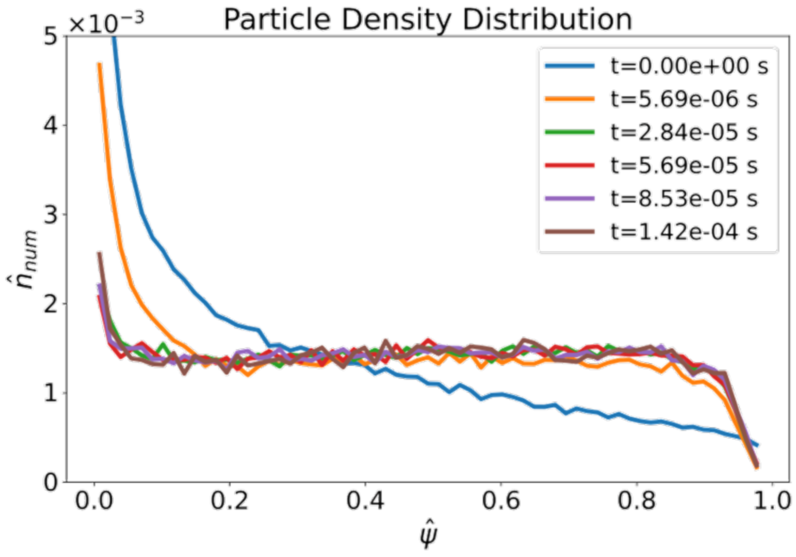
(a)



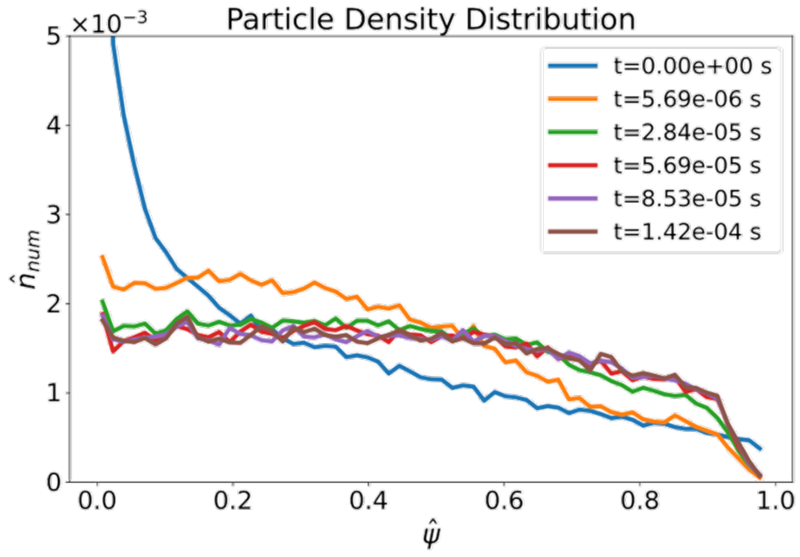
(b)

Self-similar RE profile

- The exact shape of the self-similar profile depends on the magnetic field.
- Pitch angle = 0.9， E = 5 MeV。(a): DH-QP-dt0, 6.499ms; (b): DH-QP-dt0-120, 1.863ms， both cases with sufficiently stochastic magnetic field。
- Despite the difference in the ultimate profile, both cases reach their respective self-similar profile.



(a)



(b)

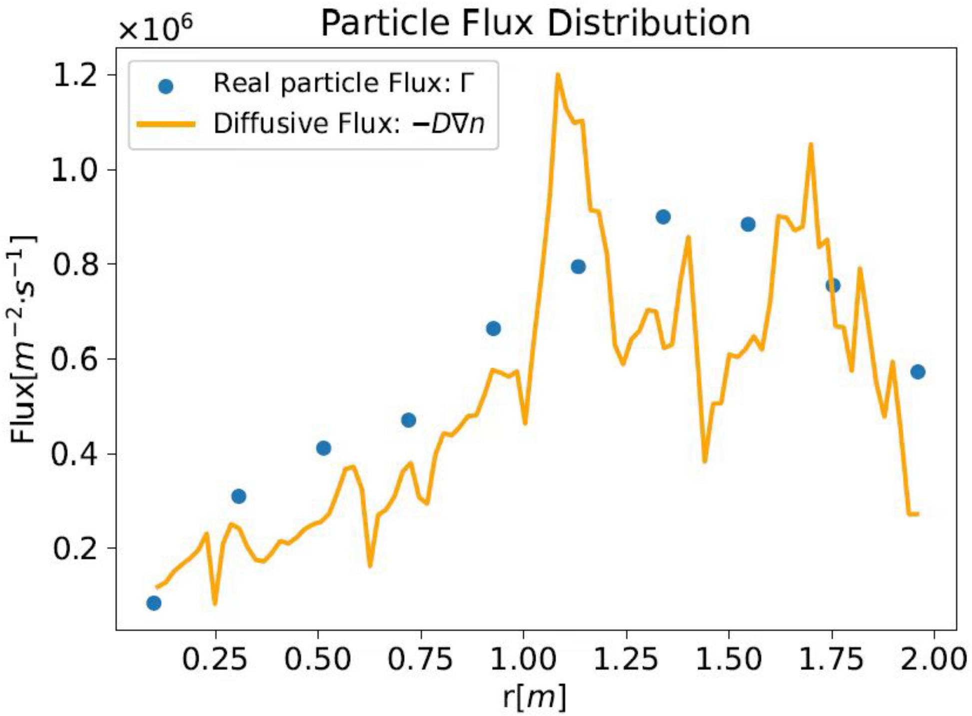
The diffusive RE flux

Tracing the variance of the Poincare points, one could extract the RE transport coefficients [1]:

$$K_{r_0} = \frac{\mu_r - r_0}{\tau}, \qquad D_{r_0} = \frac{\sigma_r^2}{2\tau},$$

It is found that the diffusive flux $\Gamma = -D\nabla n$ reproduce the general trend and order of magnitude of the total particle flux.

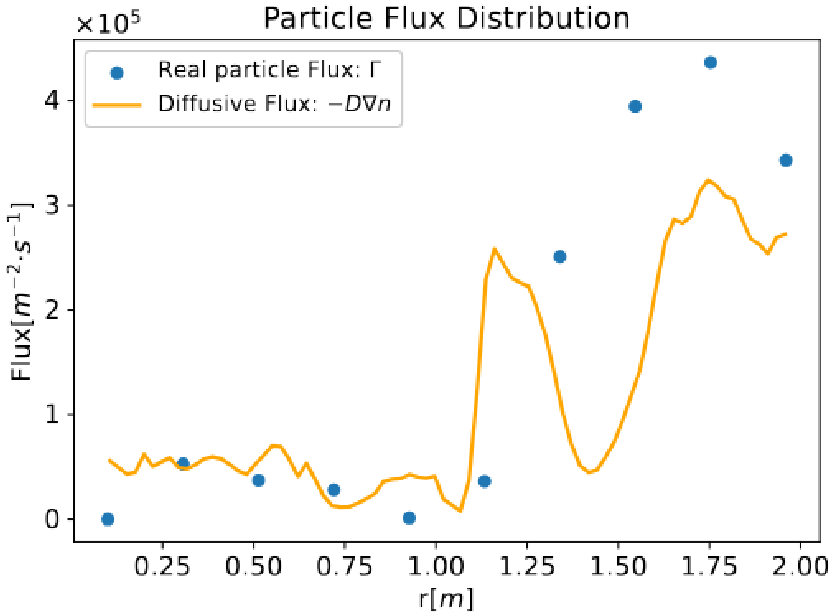
Some deviation might be due to the noise in ∇n.



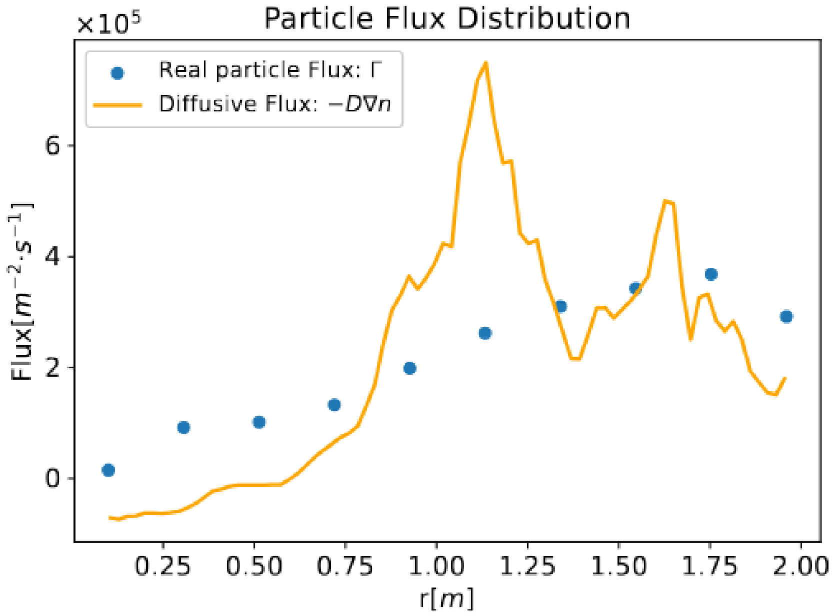
[1]K. Särkimäki, et al, Confinement of passing and trapped runaway electrons in the simulation of an ITER current quench, Nucl. Fusion 62 8 (2022) 086033

The diffusive RE flux

Not so good agreement in the case of not-so-stochastic field line:
(a): DH-QP-dt1, 4.139ms; (b): DH-QP-dt1, 5.433ms;



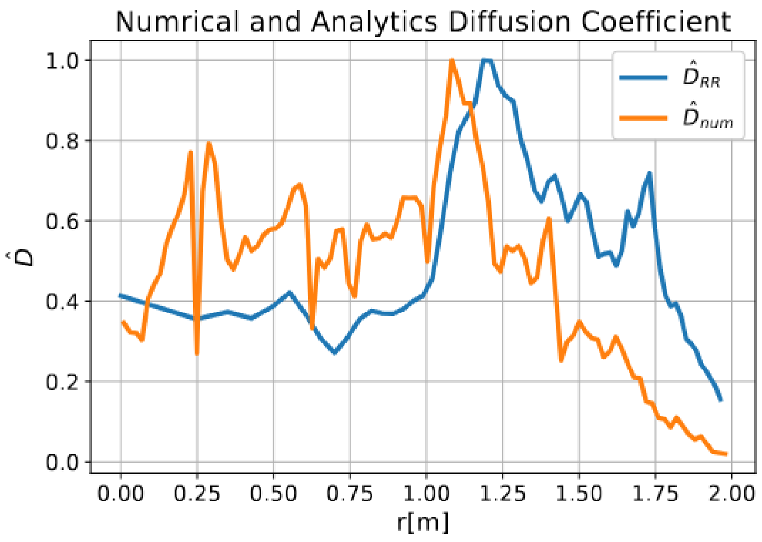
(a)



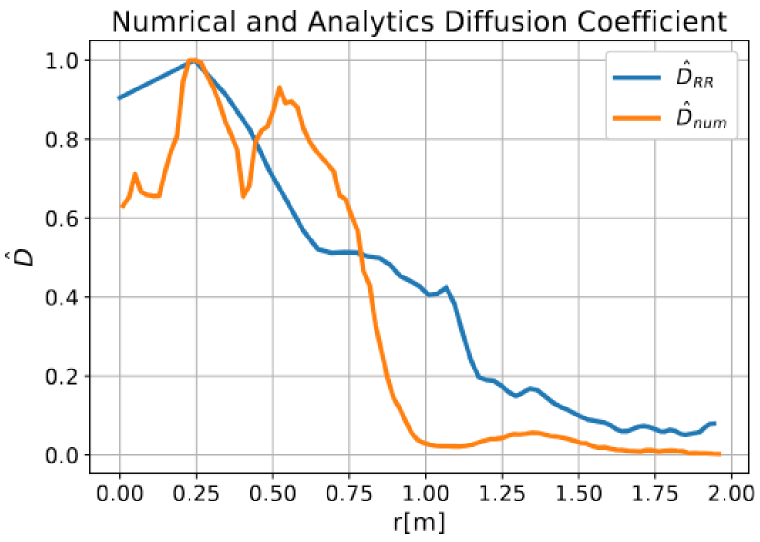
(b)

Comparison with QL theory

The statistical diffusion coefficient could be further compared with the Rechester-Rosenbluth (RR) coefficient [1] assuming constant auto-correlation length L_0: $D_{RR} \backsim v_{\parallel} L_0 \langle b^2 \rangle$.



(a)



(b)

A. B. Rechester, M. N. Rosenbluth, Electron Heat Transport in a Tokamak with Destroyed Magnetic Surfaces, Phys. Rev. Lett. 40 1 (1978) 38-41.

RE transport simulation discussion

- The RE density profile exhibit self-similar feature during their transport within sufficiently stochastic magnetic field. This coupled with the exponential density decay suggest a **transport eigen-mode**. The RE loss time is found to be **one order faster** than the MHD evolve time. Confirming previous DREAM results.

- The self-similar profile is mostly independent of the RE energy, initial distribution and pitch angle (so long as they are passing), but depends on the stochastic field. **The convergence time to this self-similar profile is faster than the MHD evolution time & the RE loss time**.

- The total RE flux could be explained by a **pure diffusive flux** relatively well, given that the field is sufficiently stochastic. The statistical diffusion coefficient reproduce the trend predicted by the RR model.