SIMULATION OF STOCHASTIC TRANSPORT AND DEPOSITION OF SEED RUNAWAY ELECTRONS DURING ITER SPI

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1. INTRODUCTION

Runaway electrons (REs) pose a significant threat to the safe operation of future high-performance tokamaks such as ITER. During plasma disruptions, REs can be generated and multiply via the avalanche mechanism, potentially causing severe damage to plasma-facing components once they deposit on the first wall. This study investigates RE transport behaviour in stochastic magnetic fields as a part of disruption mitigation scheme, focusing on ITER plasma scenarios after Shattered Pellet Injection (SPI).

The research employs a guiding-center simulation using the Particle Tracing Code (PTC) [1] with high-order conservative magnetic moment formulation [2]. The simulations are based on fluid fields produced by JOREK MHD simulations [3], which models the stochastic magnetic configurations during disruption mitigation. The PTC code tracks the trajectories of REs in the magnetic fields, allowing for detailed analysis of their transport and deposition characteristics. The study examines multiple time slices from JOREK simulations with different stages of magnetic field stochasticity, and we discovered some notable findings which are introduced below.

2. SELF-SIMILAR RE DENSITY PROFILES

The normalized density profiles of REs in stochastic fields exhibit self-similarity regardless of initial distribution, energy, or pitch angle (for passing particles) (Fig. 1), while the trapped particles have a much different profile (blue lines in Fig. 1 (b)). This self-similarity emerges within tens of microseconds, much faster than the field evolution timescale, enabling the use of static field snapshots for transport studies, although a much peak initial distribution will take longer time to reach the self-similarity. This phenomenon is observed across different field configurations with varying levels of stochasticity, and the shapes of the profile are different according to field.

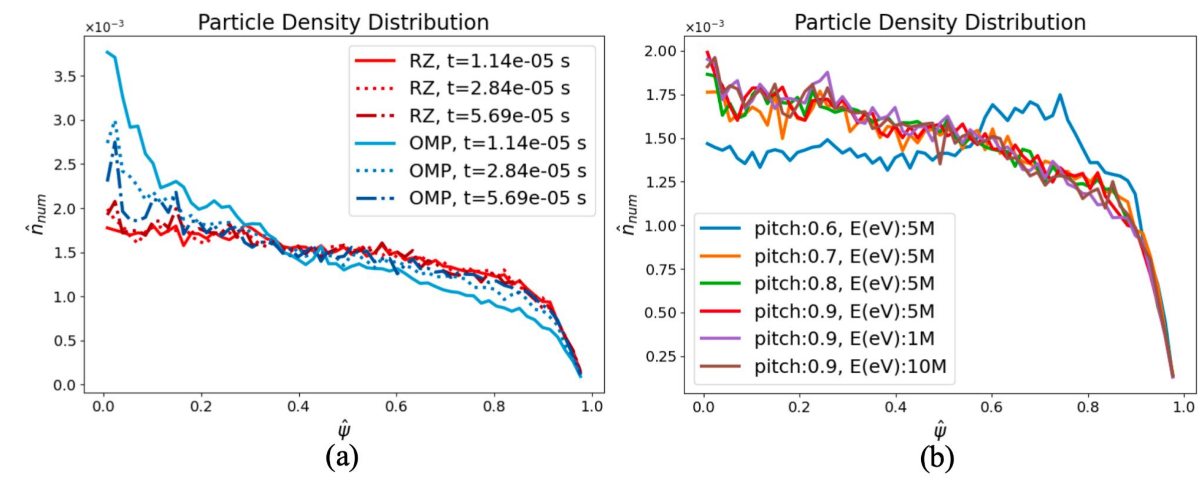

Fig. 1 The normalized density profile vs. normalized flux of REs in stochastic field. (a) Initial schemes are randomly distributed on a poloidal surface (RZ) and evenly in the out-mid-plane at phi = 0 (OMP); (b) Initial energy or pitch angle is represented as the legend.

3. LOST DISTRIBUTION

REs' loss in fully stochastic fields without electric acceleration and Radiation Reaction force follows an exponential decay pattern (Fig. 2, a). Together with the self-similar RE density profile, this suggests the presence of an eigen-solution of the RE stochastic transport. The characteristic loss time is determined to be approximately 50 μs for the most stochastic field. This loss rate varies with particle energy, decreasing rapidly for energies below 5 MeV and then exhibiting a slower decline with fluctuations at higher energies, indicating challenges in effectively suppressing high-energy REs through stochastic transport. This energy dependence suggests stochastic transport effectively removes lower-energy REs, but high-energy RE suppression may require additional mechanisms. This exponential decay directly drives the observed self-similar density profiles mentioned above. However, exponential decay does not persist in fields with less stochasticity, as the movement of REs is not dominated by the diffusion process, resulting in a "long-tail" on the lost counts curve.

We also investigated the distribution of lost REs when they hit the first wall of the device. Firstly, they mostly hit the inner divertor (Fig. 2, b). Then the average lost length of particles gradually decreases from the magnetic axis outward, aligning with the expected diffusion from the core to the periphery (Fig. 2, c).

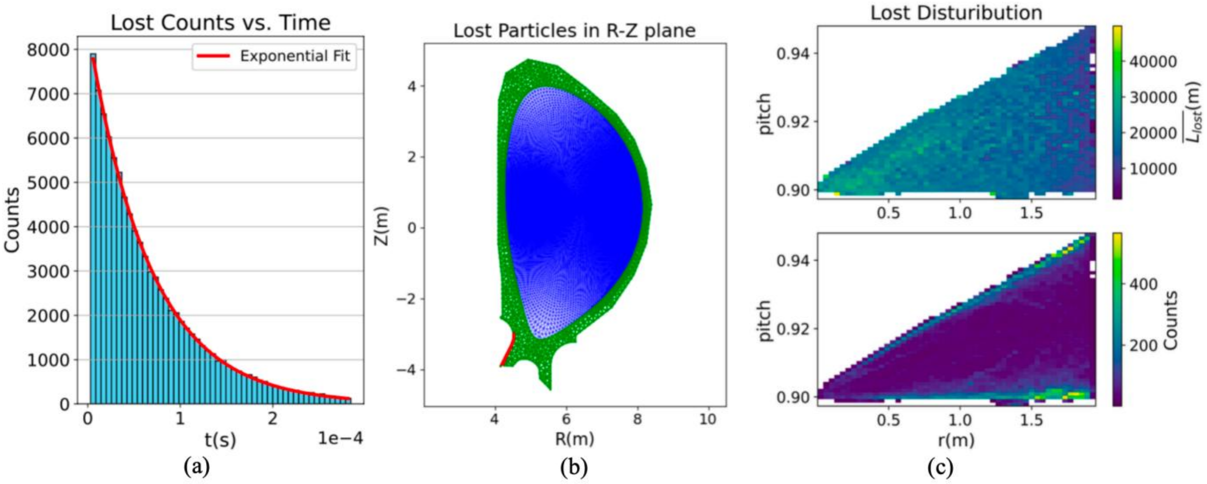

Fig. 2 Lost Distribution. (a) Lost particles over time, bins show the number of lost REs in each time grid. (b)Red dots indicate the hit points of lost REs, while blue and green triangles represent the simulation mesh. (c)The average length and the count number vs. the initial minior radius and pitch angle of REs' passage before they get lost .

4. CONCLUSION

The findings have significant implications for the development of disruption mitigation strategies in future high-performance tokamaks. The self-similar density profile suggests the presence of eigenmodes of transport within the stochastic fields. The characteristic loss times observed can be compared with avalanche timescales to evaluate the effectiveness of stochastic fields in depleting seed runaway electrons (REs) before significant multiplication occurs. Understanding the transport and deposition patterns offers valuable insights for optimizing mitigation techniques and protecting plasma-facing components from localized RE impacts. Future work will focus on calculating the transport coefficients from the numerical results and further analyzing them to enhance the robustness of these findings, as well as including the radiative drag and collision effect.

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