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Generation and mitigation of runaway electrons: spatio-temporal effects in dynamic scenarios

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The understanding and control of runaway electrons (RE) is a top priority of the nuclear fusion program because, if not avoided or mitigated, RE can severely damage the plasma facing components of a tokamak. Two key open problems are the generation and the impurity-based mitigation of RE. The first problem requires the computation of the production rate of RE. That is, given a plasma state, determine how many RE are produced during the thermal and current quench phases of a disruption. The second problem requires the simulation of the interaction of RE with partially ionized impurities in the presence of spatio-temporal evolving electric and magnetic fields. The study of these problems is motivated by the practical challenges of finding the optimal impurity injection protocol for the controlled shutdown of a plasma (avoiding or minimizing the generation of RE) and the design of impurity injection strategies for the effective dissipation of the RE beam once it is formed.

The main goal of this paper is to advance the current understanding of RE generation and mitigation by presenting a numerical study focusing on the role played by usually neglected, or highly approximated, spatio-temporal effects. Of particular interest is the dependence of the RE production rate on general dynamic scenarios exhibiting time dependent plasma temperature and electric fields as well as RE beam losses due to radial transport. The study of spatio-temporal effects in the mitigation of RE by impurity injection is also an important goal of this paper. Most of the results will focus on prescribed electric and magnetic fields on a given plasma state. However, preliminary results on self-consistent effects involving coupling of the kinetics of RE to temperature and electric field evolution models will also be presented.

The study of these problems has been a topic of significant interest in the fusion community and many important results have been obtained over the last decade, see for example the recent review paper [1] and references therein. What distinguishes the study presented here from previous work is the focus on spatial effects and the unique approach followed. This approach is based on the combination of a probabilistic Backward-Monte-Carlo method (BMC) [2] and kinetic simulations using the Kinetic Orbit Runaway electron Code (KORC) [3]. The BMC method is based on a direct numerical evaluation of the Feynman-Kac formula that establishes a link between the solution of the adjoint Fokker-Planck problem for the probability of runaway, PRE, and the stochastic differential equations describing the dynamics of RE in the presence of collisions. Computationally, the BMC is a deterministic algorithm that reduces the problem to the evaluation of Gaussian integrals that can be efficiently computed with high accuracy using Gauss-Hermite quadrature rules. Reference [4] discussed how the BMC can be used to efficiently compute the coupling between a fluid and a kinetic description of RE dynamics.

Figure 1 shows an example of a BMC computation of the PRE, incorporating spatial dependence. Going beyond our previous study [2], that limited attention to the computation of the PRE for a given momentum and pitch angle, we extended the BMC to account for radial transport, which in this example is modeled as a diffusive process. The numerical implementation of this 3D extension uses hierarchical sparse-grid interpolation methods with piece-wise polynomials to approximate the map from the phase space to the runaway probability. Also, to handle the sharp transition layer between the runaway and non-runaway regions we use adaptive refinement techniques [5]. Another important extension of the BMC that will be discussed in this paper is the computation of the PRE in time dependent scenarios incorporating models for the temperature and electric fields evolution during the thermal quench.

Figure 2 shows an example of a KORC simulation of a RE beam in time-dependent magnetic and electric fields in the presence of impurities. For these simulations, KORC has been extended by incorporating state-of-the-art collisional models with partially ionized impurities and spatio-temporal models of impurity transport [6]. As indicated by the vertical dashed line, in this simulation, the evolution of the RE beam can be divided in two stages. For $t<0.015$, as shown in panel (b), there are no RE lost to the wall. However, as shown in panel (a), the energy of the beam actually increases. Interestingly, this increase of the energy is accompanied by a decrease of the parallel (zero pitch angle direction) current due to strong pitch angle scattering or the RE with the impurity. For $t>0.015$, the fraction of RE lost to the wall significantly increases. This happens because, in this simulation, the time evolution of the magnetic field exhibits a strong horizontal displacement and the RE "peel off"at the high-field side. This loss of confinement leads to a decrease of the RE energy (shown in panel (a)) but this is mostly due to the deconfinement of high energy RE and not because impurity-driven dissipation which, as seen in the green curve in panel (b), is small. The main message of this simulation is that the assessment of the effectiveness of impurity-based RE mitigation is a complex problem involving the competition of different physics mechanisms (magnetic confinement, electric field evolution, coulomb drag, pitch angle scattering, and impurity transport and ionization) with different times scales. In particular, if as in the simulation shown in Fig.2, the time scale of the magnetic field evolution is faster than the time scale of the stopping power of the impurity, then the RE might hit the plasma facing components of the tokamak before they can be significantly slowed down. Simulations exploring this general scenario in the context of DIII-D experiments will be discussed in Ref.[6].

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