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Geometric Algorithms and Longterm Dynamical Simulations of Runaway Electron

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When simulating relativistic dynamics, it is important to keep the Lorentz covariance of algorithms. Algorithms without Lorentz covariance predict different physical results in different frames, which is unacceptable. Lorentz covariance of algorithms is introduced to solve this problem. Under Lorentz transformation, both the form and performance of a Lorentz covariant algorithm are invariant. Another requirement for relativistic simulations is the long-term accuracy and conservativeness. To acquire the advantages of symplectic algorithms and Lorentz covariance, we provide a general procedure for constructing Lorentz covariant canonical symplectic algorithms (LCCSAs), based on which an explicit LCCSA for dynamics of relativistic charged particles is built.

In long-term dynamical simulations of runaway electron using LCCSA, it is discovered that the tokamak field geometry generates a toroidicity induced broadening of the pitch-angle distribution of runaway electrons. This collisionless pitch-angle scattering is much stronger than the collisional scattering and invalidates the gyro-center model for runaway electrons. As a result, the energy limit of runaway electrons is found to be larger than the prediction of the gyro-center model and to depend heavily on the background magnetic field.

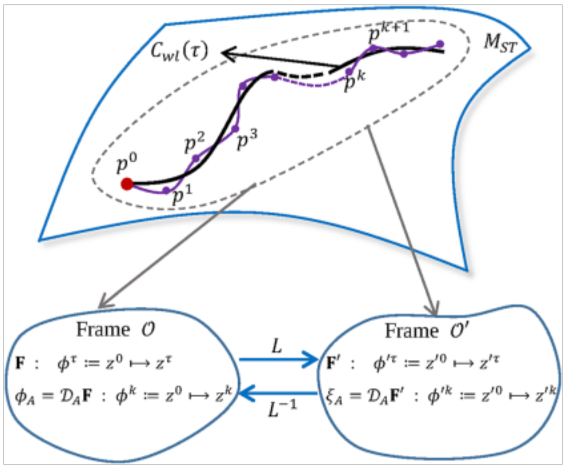

FIG. 1. Schematic diagram for the covariance of continuous systems and the Lorentz covariant symplectic algorithms. M_{ST} is the configuration space of 4-spacetime. The worldline, C_{wl}, is denoted by the black solid curve. The sequence of purple points, p^k, denotes the discrete approximation of C_{wl}. Two Lorentz frames, $\mathcal{O}$ and $\mathcal{O}'$, are chosen to express the Lorentz transformation relations. For covariant continuous system, $\mathbf{F}$ and $\mathbf{F}'$ have the same form, and their solutions in different reference frames give the same worldline on M_{ST} with the initial condition p^0. Similarly, for Lorentz covariant algorithm A, the discrete systems $\phi_A = \mathcal{D}_A\mathbf{F}$ and $\xi_A = \mathcal{D}_A\mathbf{F}'$ have the same form, and their results z^k and z'^k describe the same sequence of world-points p^k on M_{ST}.

In a more realistic setup with ripple fields, the concern of REs is not as serious as in ideal background field. Specifically, REs are confined much better than previously predicted and the maximum average energy is in the range of 150MeV, less than half of previous estimate. As a consequence, most of the energy carried by these electrons will be released through the benign process of synchrotron radiation without causing damage to the first wall.

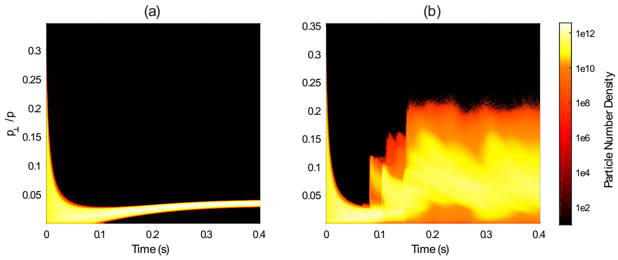

Figure 2: Evolution of the pitch-angle distribution of the REs in (a) the ideal and (b) the realistic configurations. The collisionless pitch-angle scattering due to the ripple field in the realistic configuration generates a much larger average and spread for the pitch-angle distribution.

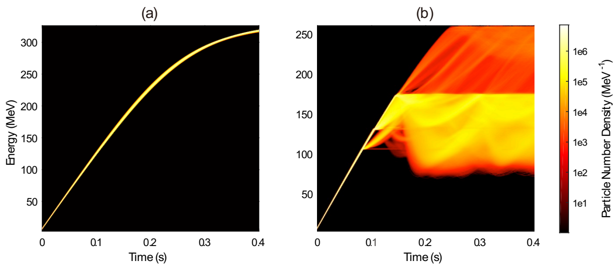

Figure 3: Evolution of the energy distribution of the REs in (a) the ideal and (b) the realistic configuration. In the ideal configuration, the energy distribution grows monotonically with time with a very small spread. Its trend is similar to the energy evolution of a single runaway electron in the ideal case. The energy distribution in the realistic configuration exhibits complex behavior, characterized by a much reduced average value and a large spread.

References

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