Computer Physics Communications 185 (2014) 86–95

Contents lists available at ScienceDirect

Computer Physics Communications

journal homepage: www.elsevier.com/locate/cpc

A test electron model for the study of three dimensional magnetic reconnection effects

A. Perona [a,*], D. Borgogno [b], L.-G. Eriksson [c]

[a] Centre for Fusion, Space and Astrophysics, University of Warwick, Coventry, United Kingdom
[b] Dipartimento di Energia, Politecnico di Torino, Italy
[c] European Commission - DG Research & Innovation - K6, Brussels, Belgium

ARTICLE INFO

Article history:
Received 6 December 2012
Received in revised form
22 July 2013
Accepted 23 August 2013
Available online 30 August 2013

Keywords:
Test particles
3D magnetohydrodynamics
Magnetic reconnection
Energetic electrons

ABSTRACT

Understanding the mechanisms that enable the conversion of the explosive release of magnetic energy into the electron energization that is experimentally observed in space and laboratory plasmas represents a long-standing question in the study of magnetic reconnection.

We present a test particle model able to follow the dynamics of the electron guiding centers in the presence of the electromagnetic fields characterizing a non-steady-state, three-dimensional magnetohydrodynamic (3D-MHD) description of magnetic reconnection. The resulting electron equations, based on a relativistic Hamiltonian formulation of the particle dynamics, have been implemented in a code that evolves the spatial position and the velocity of the electrons according to the fields obtained by the numerical solutions of a two-fluid reconnection model. By the calculation of the electron distribution function in the phase space, the electron kinetic moments can be obtained with a δf technique particularly suitable during the early stages of the reconnection process, which can be replaced by a full-f approach in the nonlinear reconnection phase. Thanks to its capability to reproduce the electron response in a quite realistic reconnection configuration, this numerical tool represents a new instrument for the investigation of the nonlinear electron dynamics in particularly complex reconnection regions, such as those characterized by magnetic field line stochasticity.

1. Introduction

A wide range of experimental data confirms that magnetic reconnection can be considered one of the main processes leading to electron acceleration in laboratory and in space plasmas. Satellites and spacecraft devices provide important measurements of the energetic electron fluxes and of the electric field structure in reconnection regions during solar flares [1–4] and in the Earth's magnetotail [5–9], where evidence of the link between energetic electrons and magnetic islands has also been shown [10]. *In situ* observations have also helped in reconstructing the magnetic field configuration and the simultaneous electron dynamics during reconnection events in the geomagnetotail [11]. In laboratory devices, electron energization has been observed in connection with electron phase-space holes created during magnetic reconnection [12] and other observations have confirmed the generation of accelerated electrons following sawtooth crashes and disruptions [13,14].

The main aim of the analytical and computational work on this subject consists of assessing which conditions control the particle acceleration efficiency during the reconnection process. Depending on the environment, on the magnetic field topology and on the physics that triggers the reconnection of the magnetic field lines, in fact, the evolution of the reconnection process and the energy distribution rate from magnetic field energy to plasma particle energies vary significantly. In a magnetohydrodynamical description of magnetic reconnection, in particular, the terms retained in the generalized Ohm's law determine the structure of the parallel electric field which, in turn, plays an important role in the electromagnetic energy conversion. The electric field structure strongly affects the primary production of suprathermal electrons at the X-line [15–20]. When a longitudinal (guide) magnetic field is present, the Hall and the motion-induced terms lead to a bipolar structure of the electric field which peaks in the magnetic field line pileup regions during the nonlinear phase of the reconnection process and allows for a relevant secondary acceleration of the electrons [21]. The fast production of energetic electrons by magnetic reconnection can also be explained by other acceleration mechanisms, such as repetitive reflections of the electrons from the ends of the contracting magnetic islands that form as reconnection proceeds [22] or, in the absence of a guide field, an "island surfing mechanism"

* Corresponding author.
E-mail addresses: A.Perona@warwick.ac.uk, anna.perona@polito.it (A. Perona).

0010-4655/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.cpc.2013.08.018

able to energize the electrons trapped in a small-scale magnetic island through the reconnection electric field within the diffusion region [23].

Most of these results have been obtained through particle-in-cell (PIC) simulations, mainly two-dimensional, which have also been recently used for investigating the length scales of the diffusion regions on which powerful energization of electrons by magnetic-field-aligned electric field ($E_\|$) occurs [24]. As these studies demonstrate, assessing what is the effect produced by the features of different models of magnetic reconnection on the electron energization is particularly important. A test particle technique represents a natural approach for investigating how these differences in the reconnection fields affect the electron dynamics and the efficiency of the electron acceleration. Besides giving a first, although approximate, estimate on the number of particles accelerated, this approach also provides information on the validity of the assumptions and of the closures adopted in the reconnection models. In the past, either full orbit [25–27], or guiding-center [28] test particle investigations have been carried out considering various representations of the magnetic reconnection fields. In many cases analytic reconnection solutions were adopted [29–32], with the electric and magnetic fields prescribed in such a way as to give a reasonable representation of fields in and around regions undergoing magnetic reconnection [28], and which were often considered as constant over the acceleration time scale. An alternative approach consists of studying the particle dynamics in a quasistationary configuration described by the electromagnetic fields provided by numerical simulations of the magnetohydrodynamic (MHD) equations in two-dimensional (2D) [33,34] and three-dimensional (3D) geometries [35,36,27].

The purpose of this paper is to describe a three-dimensional cartesian relativistic model of the electron guiding-center dynamics in the presence of the fields characterizing a non-steady-state MHD description of a magnetic reconnection process. The time evolution of the spatial position and of the velocity of the electrons is expressed in terms of the magnetic flux function and of the stream function calculated by the fluid magnetic reconnection equations. This electron model represents the enhanced extension to the 3D geometry of a previous analytical and numerical work aimed at investigating the electron behavior in 2D magnetic reconnection configurations [37]. The work presented in this paper is based on a mixed kinetic–fluid approach, where a kinetic description of the electron dynamics is interfaced with the fields provided by a fluid formulation of magnetic reconnection. Differently from PIC codes, which model plasmas as particles that interact self-consistently via the electromagnetic fields they themselves produce, in the test particle approach the reconnection fields that determine the particle motion are not updated through the feedback provided by the kinetic fields. This work therefore represents a first step towards a fully self-consistent reconstruction of the process, where the kinetic results will be fed back to the fluid description. Already at this first stage, however, such a test-particle method allows for an easier understanding of the role played on the electron behavior by the physical terms included in different fluid reconnection models.

The numerical code where the electron equations have been implemented is also described, as well as the optimization techniques that have been applied. This code is able to follow the dynamics of single particles and the global response of an electron population during the evolution of the reconnection fields, thus allowing the calculation of the electron kinetic moments at different stages of the process in quite realistic reconnection configurations. In particular, we have tested the performances of this electron code by coupling it to a fluid collisionless reconnection code where a strong guide field is present and where the change in the magnetic topology is driven by the electron inertial term in the generalized Ohm's law. However, other fluid models of magnetic reconnection can also be taken into account, as long as the magnetic field is sufficiently strong that the electron dynamics can be treated by the guiding-center drift theory. Furthermore, in order for the electron model to be also consistent with resistive models of magnetic reconnection, a collisional operator can be switched on in the electron code when considering events occurring at a frequency of the order of the electron–electron collision frequency.

This paper is organized as follows. Section 2 introduces the two-fluid model of the collisionless magnetic reconnection process. The equations describing the electron motion and the evolution of the electron velocity are derived in Section 3, while Section 4 presents the main features of the numerical code solving the electron equations. In order to improve the electron code performances a δf method has been adopted, which allows small fluctuations in the distribution function away from its equilibrium Maxwellian state to be resolved. This approach and the according reconstruction of the electron kinetic moments are explained in the subsections of Section 4. The numerical benchmark performed for the validation of the code is reported in Section 5 while final remarks and conclusions are drawn in Section 6. The numerical results of the electron code presented in Section 5 are particularly focused on the linear reconnection phase. This is in fact the most suitable phase for a proper comparison between the outputs of the electron code and those of the fluid reconnection code, since no deformation of the electron distribution function is expected to arise from the weak linear fields. A detailed investigation of the nonlinear results obtained by coupling the new numerical tool presented in this paper to various models of magnetic reconnection will be the subject of future publications.

2. The reconnection model

In our investigation, the dynamics of the test electrons is ruled by the fields calculated in a dissipationless model of magnetic reconnection in a plasma immersed in a strong, uniform, externally imposed magnetic field [38].

Such a magnetic configuration is typical of both laboratory and space plasma magnetic reconnection events, like sawtooth oscillations in Tokamaks and current sheets in solar coronal loops and in the Earth's magnetotail. While collisions do not represent an efficient mechanisms for the disconnection and reconnection of magnetic surfaces in these rarefied plasmas, other nonideal effects, like those associated with the electron inertia, can lead to the magnetic field-line breaking and reconnection on fast time scales [39].

In particular, the two-fluid, quasineutral ion and electron equations of this reconnection model describe the three-dimensional evolution of the magnetic flux and of the stream function in the case where only the electron inertia and the electron pressure terms are retained in the generalized Ohm's law. These terms introduce in the model two characteristic scale lengths in the form of constant parameters. The electron inertia is associated with the electrons skin depth, $d_e = \sqrt{m/(\mu_0 n e^2)}$, while the parallel electron compressibility is associated with the sonic Larmor radius, $\rho_s = \sqrt{T_e M/(eB^2)}$, related to the ion inertia, M, and to the electron temperature, T_e. Ion temperature effects are neglected. The magnetic field is expressed as $\mathbf{B} = B_0 \mathbf{e}_z + \mathbf{e}_z \times \nabla\psi$, where B_0 is the strong constant guide field component along z and $\psi = \psi(x, y, z, t)$ is the z-component of the magnetic vector potential. We adopt a Harris pinch equilibrium $\psi_{eq} = -B_{y0}\ln(\cosh(x/L))$, where L is the macroscopic scale length and B_{y0} is the characteristic magnitude of the equilibrium magnetic field. The resulting equations, normalized to L and to the Alfvén time, $\tau_A = \sqrt{nM}L/B_{y0}$, are

$$\frac{\partial F}{\partial t} + [\phi, F] - \rho_s^2[U, \psi] = \frac{\partial \phi}{\partial z} - \rho_s^2\frac{\partial U}{\partial z} \tag{1}$$

$$\frac{\partial U}{\partial t} + [\phi, U] + [\psi, J] = -\frac{\partial J}{\partial z} \tag{2}$$