Kinetic open boundary simulation of driven reconnection for TS-3 laboratory plasma merging experiment

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Abstract — Using the Particle Simulation of driven Magnetic reconnection for an Open boundary (PASMO) with parameters similar to the University of Tokyo Spherical Torus (TS-3) experiments a fully kinetic electromagnetic simulation is performed. Upstream boundary conditions in the simulation are modeled after electric fields calculated from measured TS-3 magnetic probe data. Preliminary simulation results are compared with TS-3 data and future direction is discussed.

Keywords — magnetic reconnection, plasma simulation, particle in cell (PIC), field reversed configuration (FRC).

I. INTRODUCTION

Magnetic confinement fusion promises to be a viable solution to the current energy crisis, with the conventional tokamak being the most popular design to date. However, the conventional tokamak is not commercially effective due to its large size and cost; a more compact and cost effective design is necessary. Compact tori such as the FRC [1] and ST [2] have shown promising results as a replacement. In plasma merging magnetic reconnection was found to the dominant dynamic process [3]. For the application of magnetic confinement fusion, magnetic reconnection is essential to magnetic self-organization processes [4]. In addition to fusion plasmas, magnetic reconnection is also a vital process in astrophysical applications such as the heating and self-organizing mechanism behind solar flares [5] and in the magnetosphere [6].

Magnetic reconnection is a physical process by which the magnetic topology changes, or magnetic field lines break and reconnect, releasing magnetic energy in the form of kinetic and thermal energy [7] [8] [3]. Magnetic reconnection can be loosely broken down into two categories, a collisional regime and a collisionless regime. The Sweet-Parker solution predicts a relatively thick current sheet with reconnection outflows mediated by the Alfvén velocity, \(v_A = B/\sqrt{\mu_0 n e m_e} [7]\). In the collisionless case a narrow current layer forms and the reconnection rate is considerably faster. The electron outflow in the collisionless case is mediated by Whistler waves for the anti-parallel reconnection and it is mediated by kinetic Alfvén waves for the guide field case [9]. Magnetic reconnection is a complicated process and many mysteries are left unsolved such as what mechanism provides the breaking and reconnection of field lines.

In particular particle acceleration during magnetic reconnection has remained a long-standing problem. Observations of nonthermal particle acceleration during magnetic reconnection exist in nature, such as in solar flares [10] and the magnetotail [11]. While observations of nonthermal particles coming from sites of magnetic reconnection have been found, a clear theory in which how they are formed remains elusive. For example, in the Earth's magnetotail the highest possible energies (as magnetic reconnection was currently understood) are calculated to be 2keV, which come from the upstream electron Alfvén outflow velocity, where B is the magnetic field strength [12]. However, electron energies as high as 100keV have been reported coming from the magnetotail. Clearly, new theories regarding particle acceleration are in order.

The TS-4 device allows for in depth reconnection study through the merging of two tori. Measurements of particle acceleration phenomena such as energy analysis in the TS-4 are difficult compared to measurements of the 2-D magnetic probe array on the R-Z plane. Hence, particle trajectories are simulated using magnetic probe data to provide a preliminary examination of particle acceleration during reconnection.

II. SIMULATION MODEL

The particle-in-cell simulation is fully electromagnetic detailing plasma phenomena at a kinetic scale. A PIC simulation divides a calculation area into grids upon which charge and current are deposited from moving electrons and ions. Electromagnetic fields are then calculated from the charge and current which move the particles in turn. The equations of motion in question are as follows:
\[ \frac{d(y \mathbf{v}_k)}{dt} = \frac{q_k}{m_k} \left( \mathbf{E} + \frac{\mathbf{v}_k}{c} \times \mathbf{B} \right), \]
\[ \frac{d\mathbf{x}_k}{dt} = \mathbf{V}_{k'}, \]
\[ \gamma_k = \frac{1}{\sqrt{1 - \frac{v_k^2}{c^2}}}. \]

Combined with Maxwell’s equations one can calculate the field quantities to the grid from the current and charge given by:

\[ \mathbf{j}(x, t) = \sum_{k=1}^{N} \frac{q_k v_k(t)}{c} S(x - x_k(t)), \]
\[ \rho(x, t) = \sum_{k=1}^{N} q_k S(x - x_k(t)), \]

where \( S(x) \) represents the shaping function of the particles and is a triangle with base equal to twice the grid spacing \([13]\). Units are normalized as follows:

\[ m = m_{\text{sim}} m_e, \quad q = q_{\text{sim}} e, \quad t = t_{\text{sim}}/\alpha_e, \quad v = v_{\text{sim}} c, \quad x = x_{\text{sim}} c/\alpha_e, \quad E = E_{\text{sim}} m_e c \alpha_e / e, \quad B = B_{\text{sim}} m_e c \alpha_e / e. \]

A Harris equilibrium is used for the initial conditions \([14]\); the governing equations are as follows:

\[ B_2(y) = B_0 \tanh(y/L), \]
\[ P(y) = (B_0^2/8\pi) \text{sech}^2(y/L), \]
\[ j_y(y) = -(c B_0/4\pi L) \text{sech}^2(y/L), \]
\[ n_p(y) = n_{p0}/\cosh^2(y/L). \]

Boundary conditions include both an upstream and downstream portions for driven reconnection. See Fig. 1 for a graphical interpretation \([13]\). Most simulations are performed on an un-driven system whereby boundary conditions are periodic. This can create unphysical problems \([13]\) and also does not represent the TS-3 well.

The upstream boundary is governed by an \( \mathbf{E} \times \mathbf{B} \) drift mediated by an upstream electric field. See Fig. 2 \([13]\) for a graphical interpretation of the upstream process. Initially the particle distribution can be seen in (a). Then after the particles have been moved (b) some cross the \( y \) boundary and are kept in the simulation. Some are not; this can be seen in (c). After which new particles are loaded into the system (d) and a shifted Maxwellian is maintained predominately; some particles must be replaced to account for charge neutrality in the system. Normally this \( E \) field is constant, however, for our purposes this was changed, as will be described in the next section, to accommodate a time dependent TS-3 calculated electric field.

Particles can freely flow into and out of the downstream boundary. See Fig. 3 \([13]\) for a graphical interpretation. Portion (a) depicts the initial particle distribution. Portion

\[ \text{Fig. 1. Schematic of PASMO upstream and downstream boundaries.} \]

\[ \text{Fig. 2. Graphical interpretation of PASMO upstream boundary process.} \]
II. UPSTREAM TS-3 ELECTRIC FIELD

PASMO’s driven electric field normally evolves from zero, developing a Gaussian profile gradually, to a constant value. In Fig. 4 one can see the development of the Gaussian profile up until the normalized time of 100. At the final time of 400 Fig. 4 depicts the TS-3 electric field calculated from measured data. In between the sample times of 100 and 400 electric field values are linearly interpolated. Fig. 2 shows electric field values at later simulation times, all calculated from TS-3 data. This enables a more realistic PIC simulation of TS-3 phenomena. Phenomena such as the anomalous resistivity and ion heating measured in the TS-3 [15] would require a more specific simulation to verify pertinent physics responsible. Simulations with the revised electric field are planned to be performed once numerical stability and accuracy is confirmed. Subsequent simulations were conducted with parameters similar to the TS-3 but the electric field remains constant.

III. PRELIMINARY SIMULATION

For a preliminary comparison of TS-3 experimental data a simulation was run on a time frame similar to the TS-3’s. See Fig. 6 and Fig. 7 for the out-of-plane current, the current sheet, and Bx, the reconnection magnetic field shown at the onset of reconnection, \(t_{\omega_c} = 1000\). The mass ratio \(m_i/m_e = 100\) for the PIC simulation. The temperature ratio \(T_i/T_e = 1.0\). TS-3’s experimentally measured data is similar to PASMO’s. While collisionality is somewhat different in both cases, collisionality is less of a problem in PIC simulations compared to other types of simulations. PASMO represents a collisionless case. For our purposes of researching mechanisms responsible for ion heating and anomalous resistivity collisionless physics are indeed responsible. The size and shape of the reconnection region well approximate that of the TS-3’s. Simulations with revised electric field input will be conducted in the near future.
V. CONCLUSION

PASMO, a particle in cell simulation for kinetic open system magnetic reconnection investigation was implemented to study reconnection phenomena in the TS-3. The input electric field was changed to accommodate actual TS-3 data. Preliminary simulations were run showing similar features as compared to the TS-3.

Small scale kinetic phenomena are challenging to measure in the TS-3. Many widely used experimental methods fail or are inadequate in measuring particle acceleration and wave particle interactions. With the high density of the TS-3 and low Debye length the space charge limitations cannot be met on Retarded Field Energy Analyzers. Ion Doppler in the TS-3 is line averaged and cannot show particle profiles. Performing PIC simulations with parameters as close to experimentally measured values makes for effective and necessary research. Additionally, direct particle calculation such as particle orbit simulations from experimentally measured data are limited by the experimental data, i.e., two fluid physical effects can only be calculated. And hence to extend direct calculation methods additional simulations such as a PIC simulation must be run.

PASMO has been revised to use direct TS-3 experimental electric fields; however the numerical stability of implementation still needs to be examined. After which fully three-dimensional simulations can be run. Also, with calculated fluid data from PASMO orbit trajectories can be calculated which will be invaluable in identifying particle acceleration mechanisms.

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REFERENCES