Low-beta Magnetic Reconnection under Laboratory Plasma Conditions

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Magnetic reconnection is a multi-scale phenomenon occurring in plasmas when two anti-parallel magnetic field lines come into contact. In astrophysics, it is thought to be responsible for those explosive events, such as solar flares and geomagnetic storms. However, this process is not only confined in space. In terrestrial devices, reconnection is negatively encountered during the electron disruption in fusion research. Main characteristic of reconnection is the conversion of the stored magnetic energy into plasma energy, either particles acceleration or plasma heat. In light of this important property, it is therefore worth improving our understanding on how to best exploit this natural energy conversion in laboratory applications. This work intends to tackle this gap by performing a series of fully kinetic simulations of magnetic reconnection under laboratory plasma configurations. Important applications it is believed to have in future spacecraft propulsion systems and ion acceleration systems.

Table 1: *Summary of the main parameters considered for the 9 runs with reduced mass ratio $m_r = 512$.*

Run	**B** [Gauss]	$\mathbf{T_e}$ [eV]	$\frac{\mathbf{T_i}}{\mathbf{T_e}}$
Run 1	200	0.5	0.05
Run 2	200	3	0.0083
Run 3	200	10	0.0025
Run 4	800	0.5	0.05
Run 5	800	3	0.0083
Run 6	800	10	0.0025
Run 7	5000	0.5	0.05
Run 8	5000	3	0.0083
Run 9	5000	10	0.0025

Simulations Setup We performed a series of simulations using the Fully Kinetic Massively Parallelized Implicit Moment Particle-In-Cell code iPIC3D ([2]) combining three magnetic field values and three electron temperatures, as summarized in Table 1, with a reduced mass ratio $m_r = 512$. The ultimate analysis is later addressed with a realistic mass ratios $m_r = 1836$ on the case showing the most promising outcomes, which happens to be Run 9, whose results will be shown here in this paper. The ion temperature is kept constant to the room temperature (i.e. $T_i = 0.025$ eV). The initial magnetic field profile across the current sheet reads as that commonly considered to simulate astrophysical symmetric reconnection ([1])

$$B_x(y) = B_0 \tanh\left(\frac{y}{\lambda}\right) \quad (1)$$

Density is instead kept constant across the current sheet and set as a typical laboratory value of $n = 10^{19}$ m^{-3}. The particular configuration here adopted lead to a low-β plasma ($\beta \sim 1.6 \cdot 10^{-4}$) and a balanced not-force-free reconnection condition. The simulated domain is a (20×12) $\mathrm{d_i}$ box, where d_i the ion skin depth. These values translate to a real box size of 7.2 cm, which perfectly matches the laboratory requirements. The resolution is set as $dx = dy \sim 1.33$ $\mathrm{d_e}$ (d_e the electron skin depth), given the necessity to only study the ion scale. The temporal step is $dt \cdot \omega_{c,e} = 0.662$. An initial perturbation is applied in the middle of the current sheet to trigger magnetic reconnection in a selected point. Boundary conditions are chosen open along each side for a more realistic representation.

Results Main goal of this work is to study the reconnection outflow in terms of its dynamic properties. We then analyze the x component of the ion velocity outflow over some relevant cross-sections (vertical pink dashed lines in the plots in Fig. 1, Box 1) and we plotted the velocity profiles in Box 2 of the same figure. On the top of each panel, the mean ion momentum is reported computed as

$$I_{sp} = \frac{\overline{V}_x}{g} \quad (2)$$

where $g = 9.81$ ms^{-2} is the gravitational acceleration at ground level and $\overline{V_x}$ is the average value of the x velocity component. The I_{sp} unit is then seconds.

This quantity refers to the *specific impulse* metric commonly used in the propulsion field, and gives a first insight into the potential thrust obtainable from reconnection. We notice the greatest values are achieved in cross-sections far from the reconnection site at later stages. Given its pulsed nature, we represent in Fig. 2 the I_{sp} temporal evolution across the selected cross-sections.

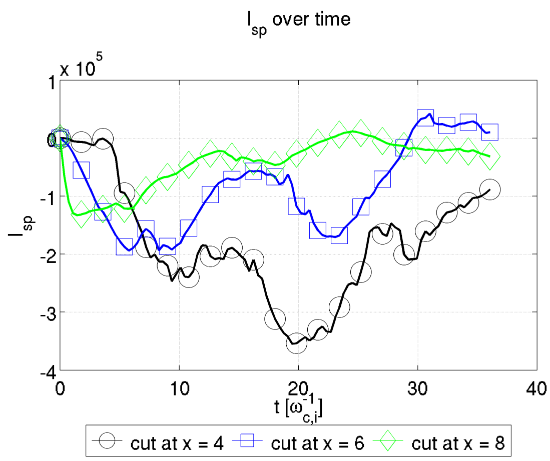

Figure 2: *Temporal evolution of I_{sp} for each cross-section considered.*

Besides the ion dynamics, we also noticed the formation of discontinuity structures in the ion flow. This is shown in Box 3 of Fig. 1 for the same outflow range, where four important macroscopic quantities are plotted at two different time steps: the

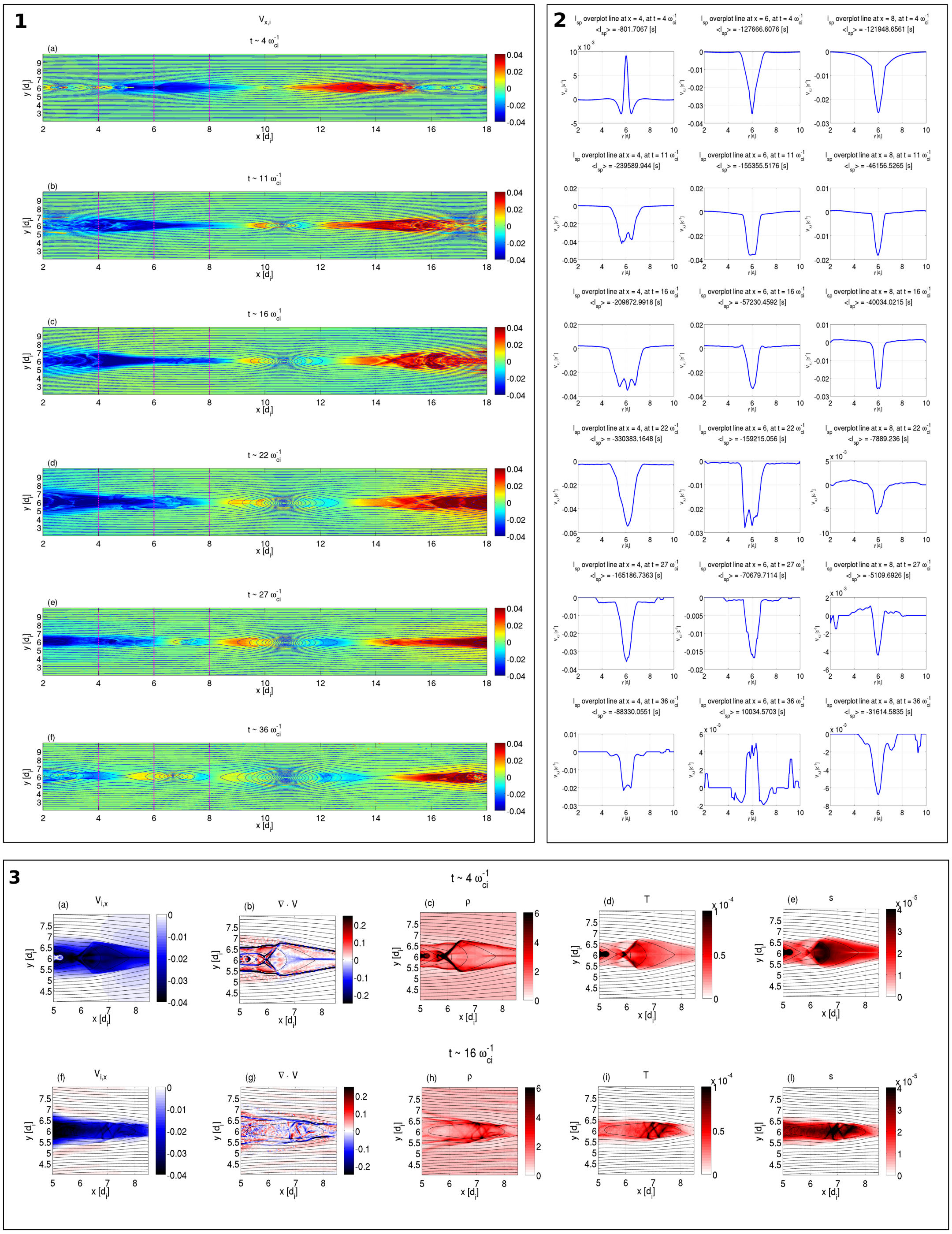

Figure 1: *Box 1: Plots of the x-component of the ion velocity at different times for the simulation a configuration as Run 9 in table 1 with realistic mass ratio. Purple lines represent the cut considered for the ion outflow analysis. Velocities are normamlized to light-speed. Box 2: Ion momentum analysis over the purple-line cross-sections in Box 1. On the top, the I_{sp} value is given for each case. Velocities are normamlized to light-speed. Box 3: Situation at the reconnection outflow highlighted by different fluidodynamic quantities: x ion velocity, total velocity divergence $\nabla \cdot V$, total mass density ρ, temperature T and entropy s (colorbar in code units).*

divergence of the total velocity, the total mass density ρ, the temperature T and the entropy s. While at earlier stages discontinuities appear regular and well-structured, later in time the situation becomes more complicated and irregular, mainly due to the formation of a magnetic island. In particular, a series of continuous discontinuities is seen forming in the early-outflow, resembling the *diamond-chain* shock-shock structure pointed out in [3,4] from MagnetoFluidodynamic (MHD) simulations.

Conclusions In conclusion, although the configuration here considered does not completely translate to a simple laboratory setup, we demonstrated that magnetic reconnection shows a great potential as laboratory particle accelerator. This particular configuration intended to give first insights into magnetic reconnection occurring under typical laboratory conditions. Future works will need to analyse the process with a more stable and easily-achievable configuration, as well as considering more commonly used plasma compositions, such as Xenon plasmas. Despite the loss channels caused by the discontinuities here analyzed, the average ions outflow velocity still shows very promising results, by attaining values as fast as high fraction of the Alfvén speed. Particular interesting application could be on future spacecraft propulsion systems and ion accelerators.

Acknowledgments The present work has been possible thanks to the Illinois-KULeuven Faculty/PhD Candidate Exchange Program. The simulations were conducted on the computational resources provided by the PRACE Tier-0 machines (Curie, Fermi and MareNostrum III supercomputers), under the PRACE Project 2010PA2844.

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