KINETIC MODELING OF PARTICLE ACCELERATION IN A SOLAR NULL-POINT RECONNECTION REGION

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ABSTRACT

The primary focus of this paper is on the particle acceleration mechanism in solar coronal three-dimensional reconnection null-point regions. Starting from a potential field extrapolation of a Solar and Heliospheric Observatory (SOHO) magnetogram taken on 2002 November 16, we first performed magnetohydrodynamics (MHD) simulations with horizontal motions observed by SOHO applied to the photospheric boundary of the computational box. After a build-up of electric current in the fan plane of the null point, a sub-section of the evolved MHD data was used as initial and boundary conditions for a kinetic particle-in-cell model of the plasma. We find that sub-relativistic electron acceleration is mainly driven by a systematic electric field in the current sheet. A non-thermal population of electrons with a power-law distribution in energy forms in the simulated pre-flare phase, featuring a power-law index of about −1.78. This work provides a first step toward bridging the gap between macroscopic scales on the order of hundreds of Mm and kinetic scales on the order of centimeter in the solar corona, and explains how to achieve such a cross-scale coupling by utilizing either physical modifications or (equivalent) modifications of the constants of nature. With their exceptionally high resolution—up to 135 billion particles and 3.5 billion grid cells of size 17.5 km—these simulations offer a new opportunity to study particle acceleration in solar-like settings.

Key words: acceleration of particles – magnetic reconnection – Sun: flares – Sun: corona

Online-only material: color figures

1. INTRODUCTION

During solar flares, an enormous amount of energy is released, in particular in the form of highly energetic non-thermal electrons. It is generally accepted that the underlying release mechanism is magnetic reconnection. In connection with a reconnecting current sheet, strong large-scale electric fields can build up (Liu et al. 2009 and references therein), leading to direct acceleration of particles beyond thermal velocities, while fluctuating electric fields created by reconnection and other dynamic events can lead to stochastic acceleration (e.g., Miller et al. 1996, 1997; Petsosian et al. 2006).

During the last decade, high-resolution observations of solar magnetic fields from several solar space missions and ground-based observations, such as YOHKOH, Solar and Heliospheric Observatory (SOHO), Transition Region and Coronal Explorer (TRACE), RHESSI, Hinode, STEREO, Solar Dynamics Observatory, and Spitzer Space Telescope (e.g., Longcope et al. 2005; Ko et al. 2003; Milligan et al. 2006; Priest & Schrijver 1999; Sui et al. 2004; Aulanier et al. 2007; Kumar et al. 2012; Jess et al. 2008) have brought new insights into interconnecting and X-ray loops, the current sheet in the reconnection region, upflow velocities of chromospheric evaporation as a result of the impact of non-thermal particles, and white-light emission during flares and instabilities as possible drivers, providing substantial support for existing solar flare and coronal mass ejection models.

Additionally, new three-dimensional (3D) coronal magnetic reconnection and acceleration models (e.g., Priest & Titov 1996; Vlahos et al. 2004) as well as the rapid expansion of computing resources for large-scale simulations (Isobe et al. 2007; Galsgaard & Pontin 2011; Toriumi & Yokoyama 2012) have opened up a new chapter in the understanding of the formation of current sheets and particle acceleration sites in 3D reconnection regions. But what is lacking is an interconnected understanding of how microscopic plasma physics scales interact and exchange information with macroscopic large-scale magnetohydrodynamics (MHD) scales in the solar atmosphere. MHD scales provide the environment for particle acceleration to happen, but it is unclear how the complex nonlinear feedback from much smaller scales onto the overall behavior of the plasma above the solar surface is handled by nature.

Most studies have made use of the fact that the temporal evolution of the large-scale magnetic field in the solar atmosphere can to a first approximation be described by compressible MHD. But fluid approaches are limited to thermal particle distributions, which is not sufficient to describe the kinetic aspects of magnetic reconnection that convert magnetic field energy into particle kinetic energy. A proper description of such processes requires taking into account the back-reaction of kinetic processes on the large-scale dynamics. Nevertheless, test particle MHD simulations (e.g., Turkmami et al. 2005, 2006; Browning et al. 2010; Dalla & Browning 2005, 2008; Rosdahl & Galsgaard 2010) give a good idea of the overall acceleration region framework. In such simulations, MHD fields evolve independently of the motion of the test particles. There is no immediate back-reaction from the accelerated particles onto the fields, which is potentially a serious limitation, especially since the changes of the electric field that would be induced by the accelerated particles can be large compared to the background field induced by magnetic reconnection (Siversky & Zharkova 2009). The lack of feedback can lead to exaggerated particle acceleration, as has been noted by, for example, Rosdahl & Galsgaard (2010), since there is no limitation for the energy gain of particles. Furthermore, kinetic instabilities can be of importance for the fast reconnection onset in solar flares, and more generally for the evolution of the current sheets in reconnection regions (Bárta et al. 2010). There is therefore a need for realistic self-consistent kinetic simulations.
to examine micro-scale processes in plasmas and to be able to properly take into account back-reactions from the particles to the fields.

The main challenge for kinetic simulations on scales of solar events is the enormous dynamic range involved. Explicit particle-in-cell (PIC) simulations have to resolve characteristic kinetic scales and are restricted to very small physical sizes, due to limitations that arise from conditions for code stability as well as from resolution criteria. These computational restrictions have so far prevented investigations of the coupling of kinetic to MHD scales using kinetic simulations, and have thus prevented self-consistent modeling of particle acceleration in solar flares. There has mainly been one interlocked model attempt by Sugiyama & Kusano (2007), who ran PIC simulations embedded in a large-scale MHD simulation with PIC boundary conditions defined by the surrounding MHD domain. The particle information was similarly passed from the MHD to the kinetic simulation areas as done in the present study. But the complexity of the problem especially in the transition zone between MHD and PIC zones combined with the simultaneity of the two simulations limits the applicability of such attempts significantly. In the present study, we introduce a new method to meet the challenge of multi-hierarchy simulations and use the method to investigate particle acceleration mechanisms in a solar reconnection pre-flare event using ultra-large-scale kinetic modeling. We further discuss the limitations of this new way to combine microscopic and macroscopic scales.

In Section 2, we describe the numerical methods and their implementation, while in Section 3 we introduce the experimental setup and the necessary modifications and list the most important simulations we performed, indicating their relative roles and importance. In Section 4, we present and discuss the results including a comparison to observational studies. Finally, in Section 5, we summarize the results, present our conclusions, and give an outlook onto future work.

2. METHODS

We perform PIC simulations using the Photon-Plasma code (Haugbølle 2005; Hededal 2005), which solves the Maxwell equations

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}$$  \hspace{1cm} (1)

$$\epsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mu_0 \mathbf{J},$$  \hspace{1cm} (2)

together with the relativistic equation of motion for charged particles

$$m \frac{d(\gamma \mathbf{v})}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$  \hspace{1cm} (3)

on a staggered Yee lattice (Yee 1966). We use SI units, scaled so the unit of length is 1 km, the unit of time is 0.1 s, and the unit of density is $10^{-12}$ kg m$^{-3}$.

The Lorentz force is computed by interpolation of the electromagnetic fields $\mathbf{E}$ and $\mathbf{B}$ from the mesh to the particle positions, employing a cubic scheme using the 64 nearest mesh points. The code integrates the trajectories of protons and electrons moving in the electromagnetic field with a Vay particle mover (Vay 2008). The charge density $\rho$ is determined by weighted averaging of the particles to the mesh points using the same cubic scheme as for the field to particle interpolation, to avoid self-forces. The currents are found using a new sixth-order version of the Esirkepov charge conservation method (Esirkepov 2001) that is consistent with the field solver. The field equations are solved on the mesh using an implicit second order in time and sixth order in space method. Because the solver is charge conserving and the fields are properly staggered, Gauss’ law is obeyed and the $\mathbf{B}$ field is kept divergence free to numerical precision.

The boundaries of the domain are fixed for the magnetic fields and open for particles. Particles can escape and new particles are added to the box from “ghost cells” outside the physical boundaries, where the conditions are specified from values in the MHD snapshot. In the current short-duration kinetic simulations, the field values in the boundaries are held fixed. In longer duration simulations, they could be made time dependent by performing interpolations in time between MHD snapshots. See also Haugbølle et al. (2012).

Below we introduce for the first time a modification of the elementary charge $q$, in addition to and analogous to the well-known speed of light ($c$) modification that has previously been used in many cases (e.g., Drake et al. 2006). Since all the micro scales (in general gyro radii, skin depths, and Debye lengths) are inversely proportional to the charge per particle, one can increase the micro scales until they are resolvable on macroscopic scales by decreasing the charge per particle sufficiently.

While changing the ratio of micro to macro scales by a large amount may appear to be a very drastic approach, the method can be defended on both qualitative and quantitative grounds: from a qualitative point of view, it may be argued that as long as one retains a proper ordering of non-dimensional parameters, as discussed in more detail below, one should expect to see essentially the same qualitative behavior, albeit with (possibly large) differences in quantitative aspects. From a quantitative point of view, one can indeed attempt to predict how these quantitative aspects depend on the modifications of $q$ and $c$, to be able to extrapolate—at least to an order of magnitude—to values that would be typical in the unmodified system.

Adopting this approach enables us to perform explicit PIC simulations of large-scale plasmas. With the parameter values used here we resolve the electron skin depth $\delta_{\text{skin},e}$ with at least 3.8 grid cells and the Debye length with at least 0.3 grid cells. For the time stepping, we use a Courant condition of 0.4, considering the light crossing time in a grid cell as well as the local plasma frequency.

3. SIMULATIONS

In order to investigate the particle acceleration mechanism around a 3D reconnection region, we started out with a Fourier transform potential extrapolation of a SOHO/Michelson Doppler Imager magnetogram from 2002 November 16 at 06:27:00 UT, 8 hr prior to a C-flare occurrence in the AR10191 active region. This is similar to the setup by Masson et al. (2009).

As there is no vector magnetogram available for this event, a nonlinear force-free extrapolation has not been feasible. The potential field magnetic configuration arising from the extrapolation mainly showed two connectivity regions, separated by a dome-shaped “fan surface” (Craig et al. 1997), each including a spine structure, which is the symmetry line intersecting the fan at the magnetic null point. Although we initially strove for
the given setup it did not lead to a flare-like plasma eruption. The MHD simulation hence describes a pre-flare phase with a characteristic 3D magnetic reconnection region.

We define the inner spine as the spine intersecting the solar surface inside the dome-like surface delimited by the fan plane, while the outer spine reaches up into the corona before returning to the photosphere several tens of Mm away from the null point (Figure 1). The magnetic field lines in the fan plane meet at the magnetic null point, which is located at about 4 Mm above the photospheric boundary. The dome-like fan plane is a typical feature of a parasitic polarity magnetic null-point topology originating when a vertical dipole field emerges into a weak horizontal field, and thus left the overlying plasma and magnetic field enough time to adapt to the displacement.

The line-tied photospheric boundary motions indirectly reshuffled the fan-spine geometry at its footpoints by a pressure increase onto the fan plane, which caused a relative displacement of the magnetic field lines inside and outside the fan plane of the magnetic null point, respectively, resulting in the formation of a current sheet in the fan plane. The displacement of field lines also causes a relative displacement of the two spines, which then leads to magnetic reconnection at the null point and a growing resistive electric field in the fan plane. A detailed description of the MHD simulations and their results are published in a companion paper (Baumann et al. 2013).

For the present study, we used an MHD simulation with an initial particle density of $6.8 \times 10^{12}$ cm$^{-3}$, a temperature of $5 \times 10^{5}$ K, and an applied driving speed of 20 km s$^{-1}$. After 240 s of simulated solar time, the null-point area showed clearly enhanced current densities parallel to the magnetic field, indicating that a dissipative process was taking place. We choose this as the starting point for the 3D relativistic PIC simulation. To minimize computational constraints due to the plasma frequency, we rescale the density from the essentially chromospheric value of $6.8 \times 10^{12}$ cm$^{-3}$ used by Masson et al. (2009) partway toward values more characteristic of an active region corona, so that it becomes instead $1.28 \times 10^{11}$ cm$^{-3}$.

Figures 1(a) and (b) illustrate the initial PIC simulation setup, by showing the chosen cutout of a snapshot from the MHD simulation, as seen along the x- and y-axes, respectively. The outer spine extends to the right of Figure 1(b), while the fan surface spreads out over the rest of the area. Due to the initial difference in the fan-plane eigenvalues (Masson et al. 2009), a slight asymmetry in the fan surface is noticeable. The inner spine can be recognized inside the volume spanned by the fan-plane field lines in Figure 1(a).

For the kinetic simulations, we use the Photon-Plasma code on a uniform grid. A cutout of the MHD simulation box with dimensions $44 \times 25 \times 16$ Mm is chosen for a set of simulations, covering cell sizes from 70 km down to 17.5 km corresponding to uniform grids with up to $2518 \times 1438 \times 923$ cells. The simulations are generally performed with 20 particles per species per cell, covering up to 30 solar seconds. We neglect gravitation, since the aim of this study is mainly to assess the electron acceleration mechanism, for which the influence of the gravitational force is negligible. The initial ion velocities consist of two components, a random thermal velocity drawn from a Maxwellian distribution plus the bulk velocity from the MHD simulation. For the electron velocities, we use the sum of a random thermal velocity drawn from a Maxwellian distribution, the bulk velocity, and the velocity due to the initial electric current. The initial electric field is simply taken as the advective electric field $(-\mathbf{u} \times \mathbf{B}$, where $\mathbf{u}$ is the

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2 For computational reasons, we tapered off the vertical magnetic field toward the boundaries of our horizontally periodic MHD model, and the height of the null point is therefore different from the case in Masson et al. (2009).
MHD bulk velocity) from the MHD simulation, which will be self-corrected by the system after the first few time steps of the kinetic simulation, by adapting the electric field as well as the electric current to balance the system.

3.1. Modifications to Resolve Kinetic Scales

It is common in MHD and PIC simulations to convert physical units into numerically more convenient code units. Such a rescaling leaves the simulated physical situation completely unaffected and all parameters can easily be rescaled back to physical units at any time. Because they leave the ratio of scales unaffected, these kinds of conversions between units of measurement are not sufficient to allow explicit PIC codes to address the multi-scale issues discussed below.

Magnetic reconnection is a typical example of multi-scale physics, where microscopic scales interact with and couple to macroscopic scales. While kinetic scales in the solar corona are on the order of millimeters, coronal structures such as the ones investigated here have scales on the order of tens of Mm. This range of spatial scales is impossible to cover by explicit kinetic simulations—now as well as in the foreseeable future.

Explicit PIC codes are subject to a number of numerical stability constraints. For the code that we use here, one of them is that the Debye length, defined as

$$\lambda_D = \frac{\sqrt{\epsilon_0 k_B T / n_e q_e^2}}{\omega_p},$$

where $k_B$ is the Boltzmann constant, $T$ is the temperature, $\epsilon_0$ is the vacuum permittivity, $n_e$ is the electron density, and $q_e$ is the electron charge, should be at least on the order of a fraction of a grid cell $\Delta s$:

$$0.3 \Delta s \lesssim \lambda_D.$$  \hspace{1cm} (4)

In addition, there are also stability constraints on the time step set by the speed of light and the plasma frequency

$$\Delta t < \Delta s/c,$$ \hspace{1cm} (5)

$$\Delta t \lesssim 2/\omega_p.$$ \hspace{1cm} (6)

In summary, code stability requires that the time step needs to approximate resolve the light-wave and plasma-wave propagation and that the grid spacing should not severely underresolve the electron Debye length. When these conditions are marginally fulfilled in the global simulation domain, they are typically (except for the speed of light condition) fulfilled with a good margin in most computational cells, which helps to improve the accuracy of the numerical solution.

Additionally, we need to fulfill the following approximate equality:

$$\delta_{\text{skin}} \approx \text{a few } \Delta s.$$ \hspace{1cm} (7)

This requirement arises to ensure a reasonably faithful representation of the plasma, as employing too few grid cells per skin depth suppresses sub-skin depth plasma behavior, while, for a fixed number of grid cells, having too many grid cells per skin depth results in a model where the kinetic scales and the MHD scale are not sufficiently separated, and consequently, the MHD behavior is lost. Given these constraints, we would require approximately one septillion ($1 \times 10^{24}$) grid cells for an unmodified simulation to simultaneously resolve the microscopic and macroscopic scales in the problem. This fundamental constraint notwithstanding, bridging the large-scale difference is in fact approachable. One can either change some of the physical properties (e.g., the magnetic field strength or the plasma density) or, equivalently, modify some of the constants of nature. As long as such modifications of the physical properties of the system do not change the large-scale behavior, they may be helpful by decreasing the gap between microscopic and macroscopic scales.

We first introduce two possible sets of modifications of the physical properties which conduce to decrease the large gap between the micro scales and the macro scales, using three modification parameters, which are closely related to each other, so that only two of them are so to speak free parameters, while the third one is a result thereof. One of the reasons for this is an MHD variable constraint; we wish to maintain the relative importance of magnetic and fluid pressure, i.e., we wish to keep the plasma beta parameter unchanged in each type of modification. The goal is to change micro scales, which cause the previously mentioned numerical constraints, Equations (4)–(7), i.e., increasing the Debye length $\lambda_D$, decreasing the span of velocities (equivalent to decreasing the speed of light), and decreasing the plasma frequency. In type A modifications, we change the magnetic field strength by a factor $b < 1$, implying a change in the density to keep the pressure balance. This increases the length scales ($\lambda_D$, the gyroradius $r_g$, and the skin depth $\delta_{\text{skin}}$) and at the same time decreases the frequencies ($\omega_g$ and the gyrofrequency $\omega_g$) by the same factor, while leaving the temperature and hence the sound speed $v_s$ and Alfvén speed $v_A$ of the system unchanged.

Type B modifications address the macroscopic speed ratios. We start by changing the temperature by a factor $t^2$, which then leads to an increase in the acceleration of gravity $g$ by the same factor, as the scale height is proportional to $T/g$. The consequences of this modification are that speeds increase by a factor $t$, while the length and frequency ratios are forced to change to achieve these required modifications, which means that for this type of change one cannot maintain the micro-scale ratios.

These modifications of physical properties are equivalent to changing the constants of nature $q$ and $c$, the unit of charge and the speed of light. Then $q^{-1}$ determines the ratio between micro and macro scales through the charge density and $c^{-1}$ influences the ratio of the speeds. $\mu_0$ needs to be kept constant, in order to keep the magnetic pressure and hence the plasma beta unchanged, hence $\epsilon_0$ is the parameter that needs to be modified.

Here is a summary of these two types of modifications:

**A: Physical changes:** $B \sim b, \rho \sim b^2, T = \text{constant}$

**Consequences:** $\lambda_D \sim \delta_{\text{skin}} \sim r_g \sim b^{-1}, \omega_p \sim \omega_g \sim b, v_A \sim v_s \sim v_{\text{th}} = \text{constant}$

**B: Physical changes:** $T \sim t^2, g \sim t^2, B \sim t, \rho = \text{constant}$

**Consequences:** $\lambda_D \sim t$, but $\delta_{\text{skin}} \sim \omega_p = \text{constant}, v_A \sim v_s \sim v_{\text{th}} \sim t$.

The idea of modifying the constants of nature has previously been employed. Drake et al. (2006) reduced in their approach the speed of light $c$, while Silvoversky & Zharkova (2009) reduced the particle density, which has the same effect on the micro scales as lowering the charge per particle. In fact, one can show that changes of, on the one hand, temperature and particle density, and on the other hand, of the speed of light and the charge per particle, have similar effects: decreasing the speed of light or increasing the temperature (squared) both reduce the ratio of the speed of light to the thermal speed, and decreasing the particle density or the charge per particle both increase the ratio of micro to macro scales (adjusting at the same time the magnetic field so as to keep the plasma beta the same). So, in that sense, our changes of the speed of light and the electric charge per particle effectively corresponds to simulating a coronal region with a very high temperature and a very low particle density.
Apart from the modifications discussed above, a reduction of the ratio of the electron to proton mass from 1836 to 18 is used. This is done to decrease the gap between the ion and electron plasma frequency and skin depths to acceptable values. It is a standard trick in PIC simulations, and mass ratios above 16 are normally considered enough to separate the two scales.

Decreasing the ratio between the different speeds (e.g., by lowering the speed of light) are generally motivated by an assumption that if the speeds are nevertheless much smaller than the speed of light, one expects only very marginal changes in the dynamics, while the savings in computing time (which scales as the speed of light) are considerable.

Changing the charge per particle with a large amount (on the order of $10^2$ here) is very drastic, but is necessary to bring micro scales into a realm that is resolvable with current computing resources. To lowest order, such a change of scales is not expected to change the magnetically dominated dynamics dramatically; charged particles are still forced to move essentially along magnetic field lines, with gyration orbits oriented in essentially the same manner with respect to the large-scale structures. What changes is exactly what is required to change, namely, the ratios between micro and macro scales. Any effect that depends on this ratio then changes in an in principle predictable fashion, and one can, a posteriori, attempt to compensate for this, when analyzing and discussing the results, as is done below in Section 4.2.

A crucial point when modifying the constants of nature is to ensure that the hierarchy of characteristic speeds, times, and length scales are, to the largest extent possible, kept as in the real average coronal environment. For the characteristic speeds, this hierarchy is

$$v_d < v_{th,p} \sim v_s < v_{th,e} < v_A < c,$$

where $v_d$ is the average electron drift speed that arises due to the electric current, $v_{th,p(e)}$ is the thermal speed of protons(electrons), $v_s$ is the speed of sound, $v_A$ is the Alfvén speed, and $c$ is the speed of light. For the corona, the values of these inequalities can be approximated by the following numbers ($\text{km s}^{-1}$):

$$0.002 < 90 < 3900 < 12,000 < 300,000.$$  

In contrast to MHD simulations of a solar event, the magnitude of the parameters of a scaled PIC simulation cannot be directly compared to observationally obtained values, since the modifications of the constants of nature have an influence on the magnitudes of the parameters. But estimating what the corresponding solar values would be is possible, by careful rescaling.

We measure all quantities in scaled SI units (unit of length = 1 km, unit of time = 0.1 s, and unit of mass density = $10^{-12}$ kg m$^{-3}$).

### 3.2. Modification Validation

To analyze the influence of the presented modifications onto the physical processes at work, we performed several simulation runs with different physical resolutions and modifications of $q$ and $c$. A subset of the relevant simulations may be found in Table 1, which summarizes the typical initial run parameters for each simulation.

Run 1S is the smallest run, which therefore corresponds to the size category $S$, while category $M$ runs have double the physical resolution and $L$ simulations correspondingly a four times higher physical resolution. Runs 1S, 3M, and 5L have a constant ratio of the cell size per kinetic scale and hence test the numerical convergence of the simulation results. Run 5L is of special interest, due to its drift speed that is lower than the thermal electron speed, as is the case in the real Sun. Furthermore, a comparison of runs 3M and 2M shows the effects of a change of the micro scales while keeping the resolution constant. These two case comparisons are especially interesting when considering the kinetic energy distribution for high-energetic particles as, e.g., power-law indices can be validated against observations. In both cases, as presented in Section 4.5, the distributions are, despite their differences in the modification of the constants of nature, very similar and, as mentioned in Section 5, their power-law indices are comparable to observational results. This indicates that the influence of the chosen numerical resolutions onto the physical acceleration process of particles in the reconnection region is small. Run 4M is specifically interesting when looking at the upper energy limit of the kinetic energy distribution of particles, as it shows the influence of an increase in the speed of light onto the energy gain of particles. Very little difference in the energy distribution could be found, which attests to the reduction of the speed of light as a reasonable modification as long as one conforms to the speed hierarchy. We also increased the systems temperature by a factor of two for runs 2M and 3M resulting in runs 2M$_T$ and 3M$_T$. This increase in temperature causes the high-energy tail to (partially) drown in the thermal particle energy distribution, so that a study of the nature of non-thermal particle acceleration in the chosen magnetic field geometry is no longer possible as no clear distinction between the two energy ranges can be made.

The results of these modification studies are reported in Section 4.5 in more detail. Section 4.2 additionally discusses the
resulting electric fields of most simulation runs, listed in Table 1. In summary, we note that except for the under-resolved run 1S, the electric fields of simulations with different modifications cover a rather small range of values.

4. RESULTS AND DISCUSSION

There are several objectives with these experiments, but the most important one is to establish whether any particle acceleration (i.e., production of non-thermal particles) takes place in the experiments and if so, what the main particle acceleration mechanism at work is. As we demonstrate and discuss below, non-thermal particles are indeed being produced. Their energy distributions are approximate power laws, with slopes similar to the slopes inferred from observations of the bulk of sub-relativistic accelerated electrons in magnetic reconnection events in the solar corona.

Most importantly, the presented simulations manifest the main electron accelerator as being a systematic electric field, which evolves relatively slowly, and which we therefore characterize as being essentially a “direct current” (DC) electric field. This does not mean that the field is completely stationary, nor that time evolution is unimportant. What it does mean is that we can demonstrate that power-law distributions of electrons can be created even by nearly stationary electric fields, as a result of basically geometric factors, and without reliance on a recursive process in time. Such systematic electric fields occur in our experiments in connection with the strong current sheets that build up as a consequence of the imposed stress on the magnetic field.

In the beginning of the PIC simulations we generally observe a strong increase in the electric current density and the electric field in the fan plane, close to the location where the relative inclinations between the magnetic field lines of the two conductivity domains—the inner and outer fan-plane area—are largest, but also close to the inner spine. Due to the boundary conditions chosen, we see a motion of the inner spine as well as a relative motion between the inner and outer spines, where their relative distance increases with increasing stress and decreases as the system relaxes, as also discussed in the corresponding MHD simulation article (Baumann et al. 2013). The photospheric boundary motion triggers magnetic reconnection at the null point by adding shear between the inner and outer spine. Due to the increasing magnetic field strength with increasing distance from the null, these particles will essentially follow the magnetic field lines, and will, unless reflected by a magnetic mirroring effect, likely impact the solar surface where the strongly bent outer spine intersects with the photosphere. The other (larger) fraction of non-thermal particles passes the null point and impacts the photosphere on the northwest side of the fan plane (to the left in Figure 2). A comparison of this impact region with the observations of this event reveals several similarities, as discussed in Section 4.4. The electrons in the fan plane experiences a strong acceleration parallel to the magnetic field inside the current sheet while approaching the null point.

4.1. The Occurrence of Electric Fields in MHD and PIC Experiments

A systematic electric current develops in the fan plane as a result of the photospheric driver, which introduces a near discontinuity in direction of the magnetic field in the two regions with different connectivity, outside and inside the fan plane. This occurs already in the MHD experiment, where the electric current \( \mathbf{J} \) is identically equal to \( \nabla \times \mathbf{B} \) (disregarding constant factors), and where the corresponding electric field in the local reference frame, here called the **diffusive electric field**, is given by an Ohm’s law of the type \( \mathbf{E} = \eta \mathbf{J} \), where \( \eta \) is a numerical resistivity.

Apart from rapid fluctuations (on plasma frequency timescales), a similar equality between \( \nabla \times \mathbf{B} \) and the electric current \( \mathbf{J} \) must also hold in the PIC experiment. Because the PIC simulations are collisionless one would perhaps expect that the diffusive part of the electric field, initially not inherited from the MHD simulation (only the advective, \(- \mathbf{u} \times \mathbf{B}\), part is kept in the PIC initial condition), would remain negligibly small. The results of our experiment shows, however, that this is not the case. Instead of remaining small, the diffusive electric field actually grows in magnitude, although it generally remains much lower (after taken into account the modifications as per Section 4.2) than in the MHD simulation from which the PIC simulations were started.

On closer inspection, the reason for the growth of the electric field becomes obvious: the charged particles that carry the electric current—this is primarily the electrons—cannot go wherever they want by following the slightest whim of a tiny electric field (in the frame of reference moving with the current). Instead, they are in general forced to follow magnetic field lines. But even along field lines, the charged particle motions are not unhindered; already modest (local or global) increases of the magnetic field can force a charged particle to become reflected. In addition, systematic or fluctuating cross-field components of the electric field may cause charged particles to drift away from its initial field line, especially in low magnetic field strength regions, and in regions with significant shear of magnetic field lines; i.e., precisely in regions with significant net electric currents.

In particular, it is clear from the very definition of the concept that magnetic reconnection causes a continuously on-going change of magnetic connectivity, and that this change occurs exactly in the place where the largest electric current needs to be maintained.

The component of the electric field along \( \mathbf{B} \), \( \mathbf{E} \parallel \mathbf{B} \), corresponds closely to the diffusive electric field in MHD when considering the corona. \( \mathbf{E} \parallel \mathbf{B} \) is plotted together with the magnitude of \( \mathbf{E} \) in \( \text{V m}^{-1} \) for runs 1S, 2M, 3L, 2M', and 3M' in Figure 3. In the snapshot from the MHD run used for the PIC simulations, we find diffusive electric field values of about 29 \( \text{V m}^{-1} \). A comparison of the locations of high diffusive electric fields in the MHD with regions of high \( \mathbf{E} \parallel \mathbf{B} \) in the PIC simulations show that the peak values can be found in both cases in the current sheet, while when comparing the advective electric fields, it reveals that, unlike in the MHD case, the PIC advective electric fields peak again in the current sheet. In the MHD case, this quantity is high in most of the domain around the null point, while in the PIC case it is only
While most medium-resolution runs (Table 1) show comparable values to the values obtained in the MHD simulations. But, as previously mentioned, our modifications of the constants of nature prevent us from directly comparing these electric field values to the values obtained in the MHD simulations. As shown in the next section, we are able to make a qualified guess as to what the PIC electric fields would be in the real solar case, which we further compare to the MHD electric fields. While most medium-resolution runs (Table 1) show comparable electric fields (Figure 3), with differences of a factor of 2–3, run 1S is under-resolved, and clearly disagrees with all other simulation runs.

Charged particles moving in a realistic (non-smooth) electromagnetic field effectively experience a “resistance,” and a non-negligible, systematic electric field is needed to maintain the electric current \( \mathbf{J} \) consistent with \( \nabla \times \mathbf{B} \), as required by the Maxwell equations. Below we demonstrate that, at least in our numerical experiment, it is this systematic electric field that is mainly responsible for the particle acceleration. We then argue that, since the same phenomena must occur in the real solar case, a similar particle acceleration mechanism must be at work there.

### 4.2. The DC Electric Field as the Particle Accelerator

The systematic electric field which develops across the fan-plane peaks where the electric current density is largest. This is where particles are mainly being accelerated and where the major contribution to the power-law energy distribution population presented in Section 4.5 comes from. Its origin is the tendency for an imbalance between the current density and the curl of the magnetic field, which occurs as a consequence of the dissipative reconnection processes. As magnetic field lines are reconnected, the charged particles that flow along them become “misdirected” and need to be replaced by the acceleration of new particles that are now, instead of the previous ones, situated correctly with respect to the magnetic field and its curl.

Tracing particles with kinetic energies in the high-energy tail and interpolating the fields to the particle position in time steps of 0.003 s for 5 solar seconds in run 3M, the direct correlation between a continuous energy gain for electrons and a negative electric field component in the direction of motion is apparent. These non-thermal particles are primarily found in regions close to, or inside, the current sheet of the fan plane, where the electric current density is highest. In Figure 4, seven representative non-thermal particles that gain energy during approximately 4 solar seconds are shown using different colors. Plotted to the left are their energy, the electric field component pointing in the direction of the particle velocity \( E \| \mathbf{v} \), the cosine of the pitch angle \( \cos(B, v) \), and the gyroradius \( r_g \). An indication of the particle speeds may be obtained by observing the paling of the line color in their trajectories to the right which are superposed on the images of the sum over electric current density slices. The upper panel shows the sum of \( xy \)-slices from a height of 2.5–2.9 Mm illustrated in Figure 4(a) (see top of figure), while the lower panel displays \( xz \)-slices averaged over 12.6–13.4 Mm in the \( y \)-direction as shown in Figure 4(b). Both background images are taken at time \( t = 6 \) s and raised to the power 0.5.
to enhance the visibility of the fine structures. It is essential to mention that these images only change slightly during the presented time interval. The null point is located at [26.5, 13.9, 2.8] Mm, illustrated by a cross-hair. Note that the particle trajectories are marginally displaced, due to their projection onto the current density planes.

Similar plots, but for particles that lose energy, are shown in Figure 5. Electrons starting from the right-hand side of the current sheet first feel a very diffuse and rapidly changing electric field, due to a fragmentation of the current sheet, which first develops there. This behavior is most evident when looking at the green energy bump around time 5 s in the first panel of Figure 4. In such fluctuating regions, there is a constant competition between the dominance of the perpendicular electron movement in between the strong $E \parallel B$ patches and the parallel motion inside an $E \parallel B$ region. But once a particle is inside a current filament the velocity is mostly directed oppositely to the electric field, and electrons then experience a rapid acceleration, due to which the perpendicular energy relative to the magnetic field becomes negligible and the electrons move almost parallel to the magnetic field (the cos(pitch angles) in Figures 4 and 5). The gyroradius is permanently very small (on the order of 3–8 km), meaning that electrons tightly follow the magnetic field lines. When particles approach the null point (marked by the cross-hair in the graphics), their gyroradius naturally grows, as $r_g \propto v_\perp \cdot B^{-1}$. At the same time, the magnetic field is weak enough that the electrons are no longer strongly confined to the magnetic field lines, and they are instead directly accelerated by the electric field, rather independent of their orientation relative to the magnetic field. Particles entering the region close to the

Figure 4. Seven randomly chosen accelerated electrons (colored lines) from the power-law energy tail of run 3M. The background gray-scale images to the right are the sum over electric current density slices. See the text for detailed information.

(A color version of this figure is available in the online journal.)
The strongest current sheet may also experience a modest growth in gyroradius, as the magnetic field there is rather weak.

Small-scale regular oscillations which can especially be seen in the $E\parallel v$ and in the $\cos$ (pitch angle) in the panels of Figures 4 and 5 occur at a frequency of about $7.65 \text{ s}^{-1}$, which is of the order of the plasma frequency.

Figure 3 as well as in Figures 4 and 5 electric field values which are affected by our modifications of the constants of nature. We therefore need to address how to transform these values back, in order to make them comparable to the MHD simulation results as well as to observations.

For this purpose we start out with the force that an electron with charge $q$ and mass $m_e$ experiences when moving in an electric field $E$, assuming that the DC electric field is the main particle accelerator $F = qE = m_e a$. We further neglect the displacement current since the accelerating electric field—ignoring small-scale turbulence—is persistent. At time $t$ and after having covered a distance $L = (1/2)at^2$ the electron has a velocity $v$ of

$$v = at = (2La)^{1/2} = \left(\frac{2LqE}{m_e}\right)^{1/2}. \tag{10}$$

The electric current has to balance the magnetic field through Ampère's law

$$J = \mu_0^{-1}\nabla \times B \approx \mu_0^{-1}\frac{\Delta B}{\Delta L}, \tag{11}$$

where $\Delta B$ is the typical change in the magnetic field across the current sheet and $\Delta L$ is the thickness of the current sheet. The current is generated by moving the electrons

$$J = nvq = n \left(\frac{2Lq^3E}{m_e}\right)^{1/2}, \tag{12}$$

where $n$ is the particle density. Using the above two expressions for $J$, we obtain an equation for the total energy gain of a single particle due to the electric field

$$qE L = \mu_0^{-2}\left(\frac{\Delta B}{\Delta L}\right)^2 \frac{m_e}{2n^2q^2}. \tag{13}$$

Given that this acceleration only happens inside the current sheet the expression can be interpreted as the maximum acceleration a single electron can obtain, if it moves continuously inside the current sheet over the distance $L$.

To relate Equation (13) to our simulations and real observations, we need the scaling of $\Delta B$ and the current sheet thickness $\Delta L$. $\Delta L$ is determined by stability constraints, as instabilities diffuse the current away, in case it shrinks below a certain thickness $\Delta L$. There have been several studies in 2D and 2.5D on the current sheet thickness concluding that $\Delta L$ is comparable to the size of the diffusion region, as noted in laboratory experiments by Ji et al. (2008), as well as in PIC simulations by Hesse et al. (2001). But these magnetic geometries are not directly comparable to our case, in which most of the diffusion takes place in the current sheet rather than around an idealized magnetic X-point geometry. In fact, very little is known about the thickness of 3D fan-plane current sheets. We therefore cover here the
most probable cases. We assume the smallest length scale over which a coherent large-scale plane of current can be maintained is either the electron gyroradius \( r_g \) in the magnetic field or the electron skin depth:

\[
\Delta L \approx \frac{m_e v_{th,e}}{q B} \quad \text{(gyroradius)}
\]

\[
\Delta L \approx \left( \frac{m_e}{\mu_0 n q^2} \right)^{1/2} \quad \text{(skin depth)}
\]

(if \( \Delta L \) is instead of the order of the ion gyroradius it would be larger than the estimate in Equation (14) by a factor \((m_{i,p}/m_e)^{1/2}\), which is about a factor of four in our case). If we rewrite \( \Delta B \) as a fractional change in the magnetic field \( \Delta B = \varepsilon_B B \), and express \( B \) and \( \Delta B \) in terms of the Alfvén speed \( v_A \) in the plasma

\[
v_A^2 = \frac{B^2}{\mu_0 n m_p} = \frac{\Delta B^2}{\varepsilon_B^2 B \mu_0 n m_p}
\]

two elegant expressions emerge for Equation (13), defining the maximal electron energy generated by the DC acceleration

\[
q E L = \varepsilon_B^2 E_A^2, (\Delta L \sim \text{gyroradius})
\]

\[
q E L = \varepsilon_B^2 E_{th,e}, (\Delta L \sim \text{skin depth})
\]

where \( E_A = (1/2)m_p v_A^2 \) is the “kinetic Alfvén energy,” which is needed to move information in the system, and \( E_{th,e} = (1/2)m_e v_{th,e}^2 \) is the thermal energy of the electrons. If the current sheet thickness is related to the gyroradius, then the higher the temperature, the smaller the acceleration of an individual particle. A higher temperature is also reflected in a larger gyroradius, but the total energy available for acceleration induced by Ampère’s law is the same, and hence there must be more, but lower energy, particles in a thicker current sheet. On the other hand, if the current sheet thickness is related to the electron skin depth the maximum energy should be independent of the temperature. Note that the right-hand side of Equations (17) and (18) only contains macroscopic fluid parameters. Equations (17) and (18) provide an estimate of the electric field and its dependency on the charge per particle; the charge times the electric field magnitude is to lowest order a constant and hence our modifications in charge \( q \) are reflected in \( q_{mod} \) are in a \( q_{mod} \) times too large electric field, where typically \( q_{mod} \approx 2 \times 10^6 \). Equations similar to Equation (17) or (18) are what we expect to be able to test in the future. As for now the numerical resolution is not sufficient for an experiment to resolve typical gyroradii with enough grid cells, while simultaneously resolving the large-scale plasma.

In the current experiments, the current sheet thickness is essentially determined by the grid spacing, and is generally a few times \( \Delta s \); about an order of magnitude larger than the typical electron gyroradii, and about half an order of magnitude larger than the typical proton gyroradii. If, at the same elementary charge per particle \( q \), we were able to increase the numerical resolution in order to resolve the gyroradii and the current sheet became correspondingly thinner, then according to Equation (13) the maximum energy gain would increase with the square of the \( \Delta L \) factor, so with 1–2 orders of magnitude.

We conclude that a conservative estimate of the current sheet electric field in the Sun would be smaller by at most the factor

\[
2 \times 10^6
\]

by which the elementary charge per particle has been reduced, and it could possibly be 1–2 orders of magnitude larger. Taking 4000 V m\(^{-1}\) as a typical magnitude of the electric field in our experiments, it thus come up with a conservative estimate on the order of 2 mV m\(^{-1}\) for the solar electric field in a situation analogous to the one we model (which is not a flaring situation). Using a less conservative estimate based on the argument of numerical resolution, the electric field is on the order of 20–200 mV m\(^{-1}\). In comparison, electric fields during solar flares are inferred to be on the order of thousands of V m\(^{-1}\) (Qiu et al. 2002).

4.3. Magnetic Field Geometry versus Power-law Distribution

As the current sheet channels make up a very small fraction of the domain, most particles will not exhibit the correct angle to exactly pass through an acceleration channel, but will instead be deflected by the magnetic field, ending up outside the current sheet without undergoing a continued acceleration. Hence, most particles are not continuously accelerated. The electric current itself is mainly carried by the lowermost part of the power-law distribution, as illustrated in Figure 6, which shows the contributions from the particles to the electric current density from three equally large regions of log(energy) of the power-law tail from run 5L. The particles of the lowest bin are most probably in constant exchange with the thermal particle distribution. Figure 7 sets the power-law tail in relation to the bulk flow (average velocity of a given species inside a cell) and the thermal particles. The power-law tail dominates over the thermal contribution with respect to contributions to the electric current density. About 0.2% of all electrons in the computational box make up the non-thermal electrons high-energy tail of the distribution. Five percent of the total electron energy is carried by the power-law tail particles, while most of this energy is in the most energetic particles of the power-law tail, as illustrated in Figure 8. But, if we only consider particles with a negative vertical velocity, thus moving toward the bottom of the box, and additionally reside in a zone on the lower quarter of the box of 1.9 x 10\(^{13}\) km\(^3\) (from approximately 0.175–1.750 Mm above the bottom boundary), the energy share coming from the power-law tail amounts to over 50% and we find more than 5% of all particles in the high-energy tail population in run 5L, while the total number of electrons in this cutout is about 1.52 x 10\(^7\). These are the particles that on the real Sun would be accelerated in
the chromosphere, leaving an imprint in the form of observable bremsstrahlung emission.

4.4. Comparison with Observations

Considering the observations of this particular reconnection event, in addition to the bright ribbons observed in Hα and UV at the intersection of the fan and the chromosphere (Masson et al. 2009), the chromospheric footpoints of the interchange reconnection region show also soft and hard X-ray signatures during the impulsive phase with a peak intensity slightly northward of the null point, as shown at the top of Figure 5 in Reid et al. (2012). This coincides well with the impact region of the power-law electrons in our simulation which travel along the fan plane and finally hit the lower boundary. Figure 9 shows the non-thermal electron energies in the simulation at their impact regions on the lower boundary of the box accumulated over \( t = 4–9 \) s. The small difference in the location of the peak intensity compared to observations (Masson et al. 2009; Reid et al. 2012) can at least partly be explained by the driving pattern, which is of course only an approximation to the real photospheric boundary motion. The second reason may be the overall magnetic field at the start of the simulation, which is an outcome of an MHD simulation, which was again initialized from a potential field extrapolation.

However, our electron energies are clearly lower than what is needed for the observed emission spectra to be produced. Hence, it is important to emphasize that we do not model the observed flare event, but rather the pre-flare phase. One reason is that we use an MHD state taken at a time well before the flare event. Another reason is, as shown in Baumann et al. (2013), that the boundary driver in the MHD simulations, representing the observed horizontal magnetic field motion in the active region, does not provide enough shear and stress to the system to result in an abrupt energy release. Despite that, we expect the qualitative nature of the acceleration mechanism to be the same in the flare phase as in its pre-phase, since the overall magnetic morphology during a flaring process does not significantly change, but displays a larger current and hence a larger parallel electric field is required.

4.5. The Energy Distribution and the Influence of the Modifications

Looking at the energy histogram of the same particles considered in Section 4.3, downward moving in a cutout of the lower part of the simulation box (see top illustration in Figure 10), we find a Maxwell–Boltzmann distribution combined with a \( dN/d\ln E = E dN/dE \) power-law index of about \(-0.78\), corresponding to a \( dN/dE \) distribution power-law index of \(-1.78\) (see Figure 10). A power-law index of \(-1.78\) implies that the electric current resulting from the power-law population is mainly carried by the low-energy electrons, while the kinetic energy is mainly carried by the highest energy constituents, visualized in Figure 8. The color code in Figure 10 shows the temporal evolution of the energy distribution function for downward-moving particles in the cutout. The power-law index for the full simulation box is similar. Figure 10 further shows that the tail slope rapidly converges toward the power-law index of about \(-1.78\), indicating an impulsive acceleration of electrons. The weak, apparently non-thermal tail present in
the distribution function from the very beginning (black solid line), does not share origin with the power-law tail that is created dynamically at later times. It arises due to the electric current in the MHD current sheet (the initial electron velocities are drawn randomly from a Maxwellian distribution, shifted with a systematic velocity to maintain the local electric current density). It is entirely due to the high values of the drift velocity necessitated by our rescaled units, but does not influence the later creation of accelerated particles; they appear also in tests where the electrons are not given a systematic initial velocity. A comparison of the different electron energy distributions from the simulation runs listed in Table 1, as previously mentioned in Section 3.2, may be found in Figures 11 and 12. For these plots, all electrons in the full simulation domain are used. The histograms are not normalized by the number of particles in order to allow for a better power-law index comparison between the different runs. The thermal distribution is the same for all simulations having initially the same temperature profile and it is stable over at least 12 solar seconds, as shown as an example in run 5L (Figure 10). The non-thermal energy tail part quickly approaches a power-law index of about $-0.78$ for all runs, independently of their resolution. The power law itself is mainly a consequence of the DC systematic electric field particle acceleration and together with the cutoff of the energy histogram presumably a result of the available electric potential difference in the system, which is determined by the current sheet thickness. The thickness, on the other hand, is controlled by the magnetic field geometry and its evolution.

For simulations initially with a higher temperature, see Figure 12—the non-thermal part of the energy distribution drowns in the thermal part. With a plasma beta in the corona $\ll 1$, a change in the temperature is not expected to significantly change the overall electric field (also see Figure 3) and thereby the maximum energy that can be gained by a particle.

Observational support for the power-law index received from our simulations can be found in, e.g., Krucker et al. (2007). There have also been a number of test particle investigations of current sheets, such as Turkmani et al. (2006), Wood & Neukirch (2005), and Zharkova & Gordovskyy (2005) finding similar electron power-law indices—and even slightly harder. But such comparisons are dangerous, as these studies were conducted using the test particle approach and the latter additionally assumed a simplified 3D magnetic and electric field configuration, presumably having a significant influence on the power-law index as partially studied by Zharkova & Gordovskyy (2005).

5. CONCLUSIONS

We presented the first of a kind PIC study of a realistic AR topology. In this study of a pre-flare 3D reconnection region near a 3D magnetic null point in the solar corona, the main electron acceleration mechanism has been shown to be the parallel systematic, almost stationary electric field ("DC" electric field),
building up as a consequence of the magnetic reconnection and dissipation close to the null point and in the fan-plane current sheet of this well-defined magnetic topology. We estimate from dissipation close to the null point and in the fan-plane current building up as a consequence of the magnetic reconnection and flares (e.g., Krucker et al. 2007). We also present a discussion of the expected dependency of the electric field on the modified elementary charge per particle; showing that the product $E \cdot q$ is expected to be conserved to lowest order. The verification of this relation must be left for future studies due to the current restrictions on computational resources.

The different modification options given in this article serve to reduce the ratio between micro and macro scales, which is required in order to overcome numerical constraints when simulating realistic physical scales of active regions. The main parameter change used to increase micro scales is a reduction of the elementary charge per particle, essentially equivalent to a reduction of the particle density. As part of the model validation, we found the electric field values and the non-thermal energy distribution to be only weakly dependent on the applied modifications of the constants of nature. In spite of the modifications of the constants of nature necessary to make this experiment possible we expect that the physical processes in the experiment are qualitatively similar to those in the real Sun, and we therefore see these kinds of studies as a very valuable tool for studying the coupling between kinetic and MHD scales in semirealistic models.

From studies of the locations of the non-thermal electrons and of their acceleration paths we conclude that the magnetic field geometry and its temporal evolution are likely to be the main factors controlling the power-law index measured in this experiment. We further show that in the lower part of the computational box the electron energy is predominantly in the non-thermal component, with a particle impact area that correlates well with the observations by TRACE, SOHO, and RHESSI (Masson et al. 2009; Reid et al. 2012).

In the future, we hope to strengthen our findings with even higher resolution simulations, and we additionally plan to study the temporal dependence of the power-law index by employing longer simulation runs, which would at the same time provide an opportunity to study ion acceleration.

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