Pitch-angle distribution of accelerated electrons in 3D current sheets with magnetic islands

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ABSTRACT

Aims. This research aims to explore variations of electron pitch-angle distribution (PAD) during spacecraft cross reconnecting current sheets (RCSs) with magnetic islands. The results can benchmark the sampled characteristic features with realistic PADs derived from in-situ observations.

Methods. Particle motion is simulated in 2.5D Harris-type RCSs using particle-in-cell (PIC) method considering the plasma feedback to electromagnetic fields. We evaluate particle energy gains and PADs in different locations and under the different directions of passing the current sheet by a virtual spacecraft. The RCS parameters are comparable to heliosphere and solar wind conditions.

Results. The energy gains and the PADs of particles would change depending on the specific topology of magnetic fields. Besides, the observed PADs also depend on the crossing paths of the spacecraft. When the guiding field is weak, the bi-directional electron beams (strahls) are mainly present inside the islands and located closely above/below the X-nullpoints in the inflow regions. The magnetic field relaxation near X-nullpoint converts the PADs towards 90°. As the guiding field becomes larger, the regions with bi-directional strahls are compressed towards small areas in the exhausts of RCSs. Mono-directional strahls are quasi-parallel to the magnetic field lines near the X-nullpoint due to the dominant Fermi-type magnetic curvature drift acceleration. Meanwhile, the high-energy electrons confined inside magnetic islands create PADs about 90°.

Conclusions. Our results link the electron PADs to local magnetic structures and directions of spacecraft crossings. This can help explain a variety of the PAD features reported in the recent observations in the solar wind and the Earth’s magnetosphere.

Key words. Plasmas – Acceleration of particles – Sun: heliosphere – Sun: solar wind – Magnetic reconnection

1. Introduction

Suprathermal electrons in the solar wind with energies above the Maxwellian thermal core (usually > 50 eV at 1 AU) reveal complex structures, such as nearly isotropic halos with lower-energy electrons, and well-directed energetic electron beams, or strahls. The strahls are found as mono-directional stripes of the red/yellow colour aligned with 0° or 180° in the electron pitch-angle distributions (PADs). The PAD spectrograms of suprathermal electrons represent a tool that helps to reveal the dominant strahl direction, which is aligned with the magnetic field and often directed away from the Sun (e.g., Vocks et al. 2005; Štverák et al. 2009; Anderson et al. 2012; Graham et al. 2017; Horaites et al. 2018). PAD patterns can also help to identify the heliospheric current sheet (HCS) crossings, or other changes in the global interplanetary magnetic field (IMF) configuration like crossings of borders of highspeed streams/flows in the solar wind (Crooker et al. 2004; Simunac et al. 2012).

For example, during the IMF sector boundary crossing, the electron PAD profiles reveal the reversal of magnetic fields with a quick disappearance of one stripe and the appearance of the opposite one when the IMF polarity changes (Gosling et al. 2006). However, the observations of solar wind energetic electrons (above 2 keV) show that the locations of their motion reversals do not always coincide with the locations (and times) of these magnetic field reversals (McComas et al. 1989; Kahler & Lin 1995; Crooker et al. 2004). Instead, the PADs near the HCS often show specific and widely discussed features, namely, defocused beams called heat-flux dropouts, dispersionless vertical patterns, signals of unstable strahl directions, and so-called bidirectional (or counter-streaming) strahls (Crooker et al. 2004; Pagel et al. 2005; Crooker & Pagel 2008; Foullon et al. 2009; Kajdic et al. 2013).

Although, the Cluster observations have recorded interplanetary coronal mass ejections (ICMEs) crossing with the strahls moving perpendicular to IMF and associated with two reconnecting current sheets occurred at the edges of the ICME (see, for example, Chian & Muñoz 2011). Most recently, the Parker Solar Probe (PSP) found that the strahls the strahls frequently maintain 180° in the PAD when the radial anti-Sunward magnetic field components (B_R) reverse the direction, indicating the local magnetic field lines are bent like S-shape (Kasper et al. 2019).

Despite registered at the 1 AU, the counter-streaming strahls (bi-directional beams observed at both 0° and 180°)
were first attributed to an extended magnetic loop with both ends rooted in the corona (e.g., Gosling et al. 1987; McComas et al. 1989; Feuerstein et al. 2004). There were explanations of the dropouts and (sometimes) bidirectional strahls coming from the large-scale loops detached from a single reconnection null point in the solar wind. The Sunward strahls move back to the Sun because the whole HCS is entangling and bending backwards to the Sun. (Crooker & Pagel 2008; Foullon et al. 2009). However, the recent solar wind observations and theoretical simulations (Zharkova & Khabarova 2012, 2015) have demonstrated that the bidirectional strahls observed in PADs when spacecraft cross the HCS can be the signatures of particles passing through magnetic reconnection sites (or current sheets) occurring at closed IMF structures (e.g., the HCS or magnetic islands), not necessarily connected to the Sun.

These current sheets in the solar-wind environment are due to certain processes in the interplanetary space, e.g., by the interaction of the magnetic field at HCSs or by the interaction of IMF with the ICMEs. The thin elongated RCSs between the reversed magnetic field lines are often broken down by tearing instability into multiple islands. The RCSs thus become turbulent and contain multiple X-nullpoints rather than a single X-nullpoint (Loueiro et al. 2005; Drake et al. 2006; Huang & Bhattacharjee 2010; Karimabadi et al. 2011; Markidis et al. 2012). These magnetic islands undergo merging and contracting motions, during which the particles get accelerated (Drake et al. 2006; Oka et al. 2010; Xia & Zharkova 2018).

The theoretical and numerical studies of magnetic reconnection are typically performed with a 2D anti-parallel reconnecting magnetic fields with an additional guiding magnetic field in the third dimension. Depending on the parameter regimes, the Fermi processes could dominate the other energization mechanisms (de Gouveia Dal Pino & Lazarian 2005; Nishizuka et al. 2013; Guo et al. 2014; Lapenta et al. 2015; Dahlin et al. 2017; Xia & Zharkova 2020). A reconnecting HCSs filled with magnetic islands would provide an ideal environment to generate locally accelerated energetic particles (Matthaeus et al. 1984; Drake et al. 2009; Lazarian et al. 2012; Zhang et al. 2014; Eyink 2015; le Roux et al. 2015; Zank et al. 2015; le Roux et al. 2016; le Roux et al. 2018; Roux et al. 2019; Li et al. 2019).

The out-of-plane guiding field also plays an important role in particle acceleration as it would eject the accelerated electrons and ions to opposite semiplanes when particles escape from the RCS (Zharkova & Gordovskyy 2004, 2005; Pritchett & Coroniti 2004; Siversky & Zharkova 2009). This charge separation was detected in some flares (Hundhausen 1958; Siversky & Zharkova 2009; Muñoz & Büchner 2016). The particle acceleration was also observed in the thin elongated RCSs obtained by bidirectional strahls in the higher-energy channel and heat-flux dropouts in the lower-energy channel at the same time (Khabarova et al. 2020).

In this paper, we further explore the PAD structures in the magnetic islands generated by magnetic reconnection using a self-consistent PIC approach. The numerical method is described in Section 2. Interesting PAD features have been found by stimulating different satellite crossing paths, and compared to multi-spacecraft observations in Section 3. We discuss the implications of our results in Section 5.

2. Simulation model

Previously, particle acceleration in coalescent and squashed magnetic islands have been studied using a PIC method (Verboncoeur et al. 1995) by introducing a static background magnetic field introduced by a magnetic reconnection process described by an MHD approach, which defines the original magnetic field configuration of the reconnection before the electric and magnetic fields induced by the plasma feedback to accelerated particles are formed (Siversky & Zharkova 2009; Xia & Zharkova 2020). Here we adopt the self-consistent 2.5D PIC code (Bowers et al. 2008) to follow the particles dragged into an RCS by magnetic diffusion process during the appearance of magnetic islands generated by magnetic reconnection.

2.1. Initial magnetic field topology

The simulations start with a Harris-type current sheet (CS) in the $x - z$ plane:

$$\begin{align*}
B_x &= -\frac{2L_z}{L_x} \delta B_0 \sin \left( 2\pi \frac{z - 0.5L_z}{L_z} \right) \cos \left( \frac{\pi x}{L_x} \right), \\
B_y &= b_y B_0, \\
B_z &= B_0 \tanh \left( \frac{x}{d_{cs}} \right) + \delta B_0 \cos \left( 2\pi \frac{z - 0.5L_z}{L_z} \right) \sin \left( \frac{\pi x}{L_x} \right)
\end{align*}$$

Xia & Zharkova (2020) studied particle acceleration in magnetic reconnection with both single X-nullpoint and magnetic islands topologies using Particle-in-Cell (PIC) codes, which includes the plasma feedback due to the accelerated particles. The polarization electric fields introduced by the charge separation are presented in the exhausts of both types of RCSs (Zharkova & Gordovskyy 2004; Zenitani & Hoshino 2008; Cerutti et al. 2013). Due to the different energy gains between transit and bounced particles, the accelerated particles form a “bump-on-tail” in the energy distribution and generates turbulence via the two-stream instability (Buneman 1958; Siversky & Zharkova 2009; Muñoz & Büchner 2016).

This gap between the energy gains of the two groups of particles is also presented in the PADs. As the observed PADs are split to different energy bands, e.g., by the STEREO SWEA instrument (Sauvaud et al. 2008), more accelerated transit electrons dominate the higher-energy channel and behave differently from the lower-energy bounced particles and thermal particles. Xia & Zharkova (2020) has demonstrated that PADs of electrons is sensitive to the guide field near a single X-nullpoint. Furthermore, a hypothetical crossing path through the simulated magnetic islands obtained both bi-directional strahls in the higher-energy channel and heat-flux dropouts in the lower-energy channel at the same time (Khabarova et al. 2020).

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where $d_{cs}$ is the half thickness of RCS. The $B_{0y}$ is the initial guide field, which is perpendicular to the reconnection plane. We compared the results with $b_y = B_{0y}/B_{0z} = 0$ and 1 in this paper.

The initial reconnection electric field $\mathbf{E}_{\text{static}}$ induced by the ambient particles dragged into diffusion region with the velocity $V_{\text{inflow}}$ by a reconnection process, is assumed to be constant as inside the reconnecting region so outside it. This electric field is thus, perpendicular to the current sheet (XZ) plane:

$$\mathbf{E}_{\text{static}} = \{0, E_0, 0\}, \quad (3)$$

where the max amplitude of $E_0$ is calculated from the plasma inflow into the RCS: $E_0 = V_{\text{inflow}} B_0$.

2.2. Plasma feedback

The electromagnetic fields inside current sheet $\mathbf{E}$ and $\mathbf{B}$ has two components: a background one $\mathbf{E}_{\text{static}}$ and $\mathbf{B}_{\text{static}}$, described in section 2.1 and the local components $\mathbf{E}$ and $\mathbf{B}$ induced on a kinetic scale by accelerated particles. Hence, the total electromagnetic fields inside a current sheet are defined as $\mathbf{B} = \mathbf{B}_{\text{static}} + \mathbf{B}$, and $\mathbf{E} = \mathbf{E}_{\text{static}} + \mathbf{E}$.

The electric and magnetic fields induced by accelerated particles are calculated with Maxwell’s equations as follows:

$$\frac{\partial \mathbf{E}}{\partial t} = \varepsilon_0 \nabla \times \mathbf{B} - \frac{1}{\varepsilon_0} (j_e + j_p), \quad (4)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad (5)$$

where $j_e$ and $j_p$ are the current densities of electrons and protons updated by the particle solver. Maxwell’s equations are solved numerically by standard finite-difference time-domain method (FDTD).

2.3. Accepted parameters

The initial ambient density profile in a current sheet is described as follows:

$$n = n_0 + n_0 \sech^2 \left( \frac{x}{d_{cs}} \right). \quad (6)$$

The simulations are performed with a mass ratio $m_i/m_e = 100$, a background plasma density $n_0 = 0.2$, a frequency ratio $\omega_{pe}/\Omega_{ci} = 1.5$, and $d_{cs} = 0.5d_i$, where $d_i$ is the ion inertial length. The temperature ratio $T_i/T_e$ are tested with 5 (the geomagnetic tail) and 1 (the solar wind environment) for comparison. The simulation domain is $L_x \times L_z = 51.2d_i \times 12.8d_i$ using $2048 \times 512$ cells and 100 particles per cell. The periodic boundary conditions are applied to both the electromagnetic field and particles along $z$- and $y$-directions. Along the $x$ direction, the conducting boundary condition for the electromagnetic field and open boundary condition for particles are used. The simulations generally run over a long time $t \approx 60\Omega_{ci}^{-1}$, where $\Omega_{ci}$ is the ion cyclotron frequency.

2.4. Simulation of current sheets with magnetic islands

Magnetic reconnection is triggered by a small distortion $\delta B_0$ in $B_z$ at the beginning of the simulation:

$$\delta B_0 = \nabla \times \delta A_y, \quad (7)$$

where

$$\delta A_y \propto \cos \left( 2\pi \frac{z - 0.5L_z}{L_z} \right) \cos \left( \pi \frac{x}{L_x} \right) \quad (8)$$

satisfying the conditions:

$$\nabla \cdot \mathbf{A} = 0, \quad (9)$$

$$|\delta B_0| = 0.03B_0.$$

The distortion initiates fast reconnection to occur near the centre of the simulation box shown in Fig. 1. Due to the periodic boundary condition at both ends of the $z$-axis, the simulation domain at later times represents the RCSs with a chain of magnetic islands that is different from the previous studies in a single X-nullpoint geometry with the open exhausts (Xia & Zharkova 2020).

3. Simulation results

3.1. General comments on particle acceleration in a 3D RCS

3.1.1. Charge separation effect

In a 3D current sheet with single X-nullpoint, the neutral ambient plasma is dragged into the diffusion region, where magnetic field reconnection occurs. Proton and electrons become drifting in the same direction along the current sheet midplane from the X-nullpoint towards the CS exhaust, while being accelerated by a reconnection electric field (Zharkova & Gordovskyy 2004; Zharkova et al 2011; Xia & Zharkova 2018). Particles are then ejected from the RCS when they gain the critical energy required for them to break from a given magnetic field topology (Zharkova & Agapitov 2009). Because in a magnetic field accelerated protons and electrons also gyrate in the opposite directions, they become ejected into the opposite semiplanes from the current sheet midplane in 3D magnetic topologies with a guiding field (Zharkova & Gordovskyy 2004; Pritchett & Coroniti 2004). Although, the particle separation would become partial or even negligible if the guiding field is weak (Zharkova & Gordovskyy 2005).

Note that Zharkova & Gordovskyy (2004) provided the analytical solution of the motion equations in 3D magnetic topologies explaining that this charge separation between electrons and protons (ions). The tangential velocity $V_T$ and the ejection positions of the particle $s \propto (q_i/m_e)^{1/2}$ (see the Eq. (8) in section 3.1 in Zharkova & Gordovskyy 2004). Therefore, for a given 3D magnetic field topology with a guiding field, the electrons (with a negative charge) can be ejected to the positive side ($X > 0$) from the midplane ($X = 0$) while protons (with a positive charge) should be ejected to the negative side ($X < 0$) from the midplane. This charge separation is confirmed by numerous other simulations (see, for example, review Zharkova & et al 2011, and references therein).

The first important consequence of different motions of electrons and protons in an RCS comes from the fact electrons need much shorter drift length than the protons to gain the critical energy (a few hundred meters v.s. a few kilometres in the corona) (Zharkova & Agapitov 2009). In the flare current sheet, the electrons become first ejected from the RCS and try to run away from an RCS into a magnetic loop. But they become returned by the electric field of the accelerating protons, which are still residing in...
the midplane, thus forming an electron cloud about the current sheet located on a loop top (Siversky & Zharkova 2009) often seen in flares as hard X-ray coronal sources (Zharkova & et al. 2011). These first escaping electrons can be the triggers of solar flare onsets or flare pre-cursors, while the flare itself happens after the protons reach the critical energy and break from the magnetic topology of the RCS precipitating together with electrons into (either the same or opposite) magnetic loop legs (Zharkova & Gordovskyy 2004; Zharkova & Agapitov 2009).

The PIC simulations of particle acceleration in a low-density current sheet reproduce the similar results obtained from the test-particle simulations showing the charge separation in the velocity phase space in the RCSs (Siversky & Zharkova 2009; Zharkova & Khabarova 2012). Although, for higher ambient plasma density, the accelerated particle density and energy distributions reveal noticeable differences from the test-particle approach where the asymmetry of ejected protons and electrons is more distinguishable in the energy distributions rather than in the density distributions. Recently, the similar charge separation has been confirmed for current sheets with magnetic islands, using both the test-particle and PIC approaches (Xia & Zharkova 2018, 2020).

The **second important consequence** of different motions of electrons and protons in a 3D RCS is the induction of a polarization electric field $E_p$ between these particles of opposite charges across the current sheet midplane. The $E_p$ (could only be derived from PIC simulations) is larger than the reconnection electric field by up to two orders of the magnitude (see also Siversky & Zharkova 2009; Zharkova & Khabarova 2012; Xia & Zharkova 2020). The induced $E_p$ is mainly perpendicular to the RCS midplane (Siversky & Zharkova 2009; Zharkova & Khabarova 2012) and is found increasing with higher ambient plasma density (Xia & Zharkova 2020). This $E_p$ is shown to define the velocity profiles of ions in the heliosphere during their crossing the heliospheric current sheet HCS, as shown in a comparison of the PIC simulations with the in-situ observations of the ion velocity profiles (Zharkova & Khabarova 2012).

### 3.1.2. Transit versus bounced particles of the same charge

For the particles with the same charge, a distinction also exists if they enter the RCS from opposite boundaries (Siversky & Zharkova 2009; Zharkova & et al. 2011): The particles that enter the RCS from the side opposite to the side from which they are ejected are classified as **transit** particles. While the particles that enter the RCS from the same side where they are ejected become decelerated while reaching the midplane, are classified as **bounced** particles. The transit particles gain energy from the moment they enter the RCS and move towards the midplane, while bounced particles lose their energy during their migration from the CS edge towards the midplane (Zharkova & Gordovskyy 2005). As a result, the ‘transit’ particles gain much higher energies and form power-law energy spectra (Litvinenko 1996), while the ‘bounced’ electrons gain much smaller energies and often have quasi-thermal energy spectra (Zharkova & Gordovskyy 2005; Siversky & Zharkova 2009; Xia & Zharkova 2018, 2020).

Therefore, the electrons accelerated in the RCS are split into the two distinct groups in energy: the low-energy ‘bounced’ electrons and high-energy ‘transit’ electrons. The threshold of the separation by energy is dependent on the magnetic field topology. The uneven spatial and energy distributions of transit and bounced particles across the midplane are well distinguishable in the test-particle approach and are a bit smoother in the PIC approach (Siversky & Zharkova 2009; Xia & Zharkova 2018). As a result, the accelerated electrons/protons have ‘bump-on-tail’ energy distributions, which naturally triggers plasma turbulence due to Buneman instability (Buneman 1958).

Moreover, the asymmetry between the transit and bounced particles is also identified in the PADs. The corresponding PADs in higher-energy (transit particles)
and lower-energy (bounced particles) channels were explored near a single X-nullpoint of the heliospheric current sheet, which showed bounced electrons turning from the current sheet at some distance away from the midplane (Zharkova & Khabarova 2012). The preliminary results for PADs in RCSs with a few magnetic islands exhibited a bi-directionality of the transit electron PADs in the higher-energy channel when the satellites (or virtual observer) moves across the magnetic island (Khabarova et al. 2020).

This opens a new perspective to analyse in more details the PADs of electrons (proton PADs are less accessible) accelerated in RCSs without and with magnetic islands using different physics parameters in space, which can be observed when a virtual spacecraft crosses these areas in different directions. The results can benchmark some in-situ observations recorded by the real spacecraft crossing similar structures in the heliosphere.

3.2. Electron PADs in the vicinity of a single X-nullpoint

In the current research, we will start by exploring the electron PADs in a 3D RCS with a single X-nullpoint as an illustration. When the reconnection starts or when magnetic islands are formed, we assume a spacecraft (we call it hypothetical spacecraft or virtual spacecraft) moves straightly across the RCS at different locations and different angles, like the green vertical line perpendicular to the RCS midplane in Figure 2 (P). The virtual spacecraft records the data of electron PADs on its way. Since accelerated electrons would have both transit and bounced particles with high- and low-energies as explained in section 3.1.2, we will split the PADs to higher-energy and lower-energy channels. This split is motivated by the channels usually present in the satellite payload for electron observations in the solar wind (e.g. the electron analyser SPAN-E of the SWEAP instrument on the Parker Solar Probe covers 32 energy bands from 2 eV to 1.8+ keV) (Kasper et al. 2019).

Without any guide field \((b_g = 0)\) in the single X-nullpoint scenario, the electron PADs in all energy channels are symmetric with respect to the reconnection midplane \(x = 0\) in Figure 2(a1, a2), because the magnetic field does not impose any separation by charge, and no transit and bounced particles formed. Some electrons dragged into the RCS are accelerated to higher energies. They form high-energy beams and ejected away from the X-nullpoint. So their pitch angles ranging in \([10 \pm 10]^\circ\) at \(x < 0\) and \([170 \pm 10]^\circ\) at \(x > 0\) (the sign changes because \(B_x\) sign is reversed across the midplane in (a1). The other electrons gain less energy and form a wide range of pitch angles in (a2), thus, having nearly homogeneous distribution and joining the ambient plasma electrons already present inside the RCS.

If the guiding field is strong, the PADs become strongly asymmetric across the midplane. E.g. only the electrons with pitch angles of 180° are featured in the simulation performed for a thicker current sheet \((d_x = 10)\) and \(b_g = 1\) as shown in Figure 2(b1, b2). It is evident that when the guiding field becomes stronger, the transit electrons with higher energy and narrower pitch angle dispersion \((175 \pm 5)^\circ\) become dominant in the opposite semiplane (the right part in Fig. 2(b1)). This emphasises a preferential direction of motion for higher-energy electrons as they represent the transit particles, which gain more energy (Litvinenko 1996; Zharkova & Gordovskyy 2005; Siversky & Zharkova 2009) (see section 3.1.2).

While the counter-streaming (bounced) electrons appear in the lower energy channel showing the electrons entering RCS at the pitch angle of \((0 \pm 15)^\circ\) at \(x > 0\) approaching the distance of 50 \(r_i\) and ejected at the pitch angles of \((160 \pm 20)^\circ\). This results in energy dropouts for the bounced lower-energy electrons around the midplane as shown in Fig 2(b2), which is often recorded in the in-situ observations (Khabarova et al. 2020). The lower-energy electrons at \(x < 0\) include bounced particles and those entering the CS that will move to the well-directed high energy beam ejected in \(X > 0\) shown in Fig. 2(b1).

3.3. Electron PADs in magnetic islands

The magnetic field topology is more complicated in magnetic islands. The simulation described in section 2 formed small magnetic islands and later merged to a large island located across the periodic boundary, which is similar to other simulations done by Drake et al. (2006); Daughton et al. (2011). Owing to the periodic boundary condition at both ends of the \(z\)-axis, the simulation domain represents the RCSs with a chain of magnetic islands. This is different from the previous studies carried out for a single X-nullpoint topology with open exhausts, or with a chain of coalescent and squashed magnetic islands (Xia & Zharkova 2020). Let us investigate the two cases of magnetic field topologies: with weak and strong guiding fields.

We assume that the virtual spacecraft crosses the simulation domain under different angles along the directions shown in Figs. 3 (for weak guiding field) and 4) (for strong guiding field). The most compelling regions, including a) the vicinity of X-nullpoints, b) the midplane, and c) the magnetic island edges, are inspected by several paths shown in the thick green lines.

The energy threshold \(\epsilon_{\text{threshold}}\) between the higher- and lower-energy bands enables us to distinguish the different PADs induced by transit and bounced particles. Based on the selected parameters described in section 2, we found \(\epsilon_{\text{threshold}} = 9.67\epsilon_{th}\), where \(\epsilon_{th}\) is the initial thermal energy. We start with \(T_i/T_e = 5\) as there are numerous observations with such the thresholds reported from the MMS mission (Oieroset et al. 2002; Huang et al. 2016; Oka et al. 2016).

3.3.1. Weak guiding field:

If the virtual spacecraft vertically crosses the X-nullpoint regarding the reconnecting midplane (left column of Figure 3), it records the high-energy electrons with wide PADs peaking near 90° within the narrow region \(< 0.5d_i\) near the midplane (a2). There are some weak signs of bi-directional beams with narrow PADs centred about 0° (bottom) and 180° (top). Meanwhile, the lower-energy electrons shown in (a3) reflect the bi-directional beams exiting clearly in range \([-2, -0.25d_i]\) below and \([0.25, 2d_i]\) above the X-nullpoint.

When the crossing path is quasi-parallel to the midplane (right column of Figure 3), the bi-directional beams in the higher-energy channel are more distinct in the islands \((z = 0 - 12d_i, 40 - 51.2d_i)\), which are \(\sim 14d_i\) away from the X-nullpoint in panel (b2).

While the edges of the magnetic island near the X-nullpoint still reveals the feature with the distinct PAD...
Fig. 2. PADs of electrons observed when a hypothetical spacecraft crosses the RCS with a single X-nullpoint. The top panel (P) shows that the sampled crossing path of the spacecraft is perpendicular to the RCS midplane (green solid line). The in-plane magnetic field topology is drawn in black lines with the amplitudes of $B_y$ ($b_g = 1$ case) coloured as the background. The PADs of high-energy electrons (second row) and lower-energy electrons (third row) obtained from (a0) are presented in (a1) and (a2). The PADs shown in (b1) and (b2) are recorded along the same path as in (a1) and (a2) when the virtual spacecraft crosses an RCS with no guiding field ($b_g = 1$).

About $90^\circ$ in the higher-energy channel. Different from the vertical path shown in (a1-3), the counterpart of the bi-directional markings in the islands (panel b2) in the lower-energy channel shows nearly dispersionless vertical patterns in panel (b3). While weak bi-directional strahls are also seen in the lower-energy channel at the exhausts of magnetic islands (towards the X-nullpoint).

To understand the obtained results, let us use the findings of the paper by Xia & Zharkova (2020), who evaluated different energisation terms for particle acceleration in RCSs with the guiding-centre drift approach (Drake et al. 2006; le Roux et al. 2015). The energy change of particle $s$ mainly come from:

$$\frac{d\epsilon}{dt} = E_i J_i + \frac{P_\parallel}{B} \left( \frac{\partial B}{\partial t} + \nabla E \cdot \nabla B \right) + \frac{P_\perp}{B} (\nabla E \cdot \kappa B),$$

where $\epsilon$ is the total kinetic energy of the particles of the same species. The first term count on the right-hand side (RHS) counts for the contribution from the parallel electric field $E_i$, and $J_i$ stands for the parallel current. The second term corresponds to Betatron acceleration, which is linked to magnetic field compression or expansion. The third term describes curvature-drift acceleration (Fermi-type), where the curvature $\kappa = b \cdot \nabla b$ with $b$ as the unit vector along $B$, and $P_\perp, P_\parallel$ are the parallel and perpendicular pressures. The previous results have shown that the contribution from $E_i J_i$ is much smaller than the other two terms (Dahlin et al. 2017; Xia & Zharkova 2020).

From the current results in Fig. 3(b3), we can deduce that lower-energy (bounced) electrons are scattered in the magnetic island with wide PADs. While the transit electrons follow magnetic field line curvature and gain their energy from X-nullpoints on both sides of the island (Xia & Zharkova 2018), which are due to the first-order Fermi type acceleration. Thus, their pitch angles would have PADs directed along $0^\circ/180^\circ$ in (a2, b2) extending from the exhausts into the magnetic islands. Meanwhile, the beams directed about $90^\circ$ are located near the X-nullpoint in (a3, b3), which is consistent with strong magnetic field relaxation in this region.

3.3.2. Strong guiding field:

When the guide field is strong, e.g., $b_g = 1$ in Figure. (4), it reduces the compressibility of the magnetic field, while keeps particles longer within a given magnetic topology. Thus the $90^\circ$ beams would disappear from the location close to the X-nullpoint. Instead, Fermi-type curvature-drift acceleration becomes dominant.

We also notice that it is harder to observe bi-directional strahls during particle acceleration in this magnetic topology. The only region the spacecraft observed counter-streaming beams is in the exhaust, between $\delta z = 4 \sim 9$ away from the X-nullpoint at the end of the magnetic island, in the lower-energy channel in Figure. 4(a3). On the other hand, the strahl is near $180^\circ$ at X-nullpoint. It shifts toward $90^\circ$ as the spacecraft moves close to the separatrices in the higher-energy channel of Figure. 4(a2).

Furthermore, we re-ran the simulation with ambient particle temperature ratio $T_i/T_e = 1$, which is more com-
Fig. 3. PADs observed when a hypothetical spacecraft crosses the RCS in different angles at $t = 33\Omega_i$: left column: the path perpendicular to the midplane $x = 0$, right column: the path quasi-parallel to the midplane. The colorbars in the top row indicate the amplitudes of generated $B_y$ with the in-plane magnetic field topology (black lines), and the paths of the spacecraft (green line). Middle and bottom rows present the PADs of higher- and lower-energy electrons seen on the paths. The simulation starts with no guide field ($b_g = 0$).

Fig. 4. PADs observed by a virtual spacecraft in the simulation starting with a strong guide field ($b_g = 1$) at $t = 33\Omega_i$: left column: the path perpendicular to the midplane $x = 0$, right column: the path across the separatrices. The magnetic field and the paths of the spacecraft (green lines) are demonstrated in the top row. Middle and bottom rows present the PADs of higher- and lower-energy electrons observed on the paths.

It produced similar features as the $T_i/T_e = 5$ case, such as the bi-directional strahls in a narrow region of the exhaust for $b_g = 1$, and its existence around the X-nullpoint for the $b_g = 0$ case. The main change of the electron PADs in magnetic islands is shown in Figure (5). As for the same threshold, the bi-directional signals are obscure in the higher-energy channel. The damping of the signals in the islands could be due to the larger gyroradius of electrons as $T_e$ increases from $1/5T_i$ to $T_i$.

Therefore, one can see that the observability of either the counter-streaming strahls or heat-flux dropouts is highly dependent on the magnetic field topology and the crossing paths of real spacecraft. If the spacecraft can only access the regions far away from the X-nullpoint, it is likely to pick up the unidirectional strahl of high-energy electron.
beams. Energetic particles fly away diagonally from the main X-nullpoint when the guiding field is strong, while lower-energy electrons would be recorded well before the current sheet crossing (Xia & Zharkova 2020). However, if the spacecraft passes across the current sheet with magnetic islands under different directions as explored in this paper, different patterns of PADs are formed. They uniquely reflect the magnetic field topological specifics and the angle under which this reconnection site is observed. This can be a very useful tool for diagnostics of physical conditions of the environment producing energetic particles.

4. Comparison with in-situ observations

4.1. Observations with the previous space missions

In this paper, we explore the relationship between electron PADs and the magnetic topologies in 3D RCSs. Obviously, real spacecraft trajectories would not cross the RCSs in straight lines as considered in Figs. 2, 3 and 4. However, the presented simulations can pour some lights on different PAD features formed by energetic particles while spacecraft pass certain regimes of RCSs. In this part, we demonstrate some evidence from previously recorded by different missions near the Earth.

Our previous PIC simulations of particle acceleration near a single X-nullpoint for 3D magnetic topologies with strong guiding field (Xia & Zharkova 2020) have shown the appearance of counter-streaming high-energy electrons diagonally from the X-nullpoint, formed by transit particles, from the one hand, and the lower-energy electrons, formed by bounced particles, located inside and away from the X-nullpoints, from the other hand. In the observations, WIND spacecraft at 1 AU recorded the U-shape (horseshoe-like) PADs of low energy (bounced) electrons near the RCS (Zharkova & Khabarova 2012) similar to those shown in Fig. 2(b2). The electron strahls observed with WIND and STEREO in multiple magnetic islands in the heliosphere are also consistent with our current PIC simulations of energetic electron acceleration in RCS with a chain of magnetic islands and their ejection from exhausts at both ends of the chain (Xia & Zharkova 2020).

See, for example, the electron PADS obtained in recent simulations of coalescent and squashed magnetic islands in 3D RCSs for a weak guide field $b_g = 0.1$ showed that the bi-directional strahls can be complemented with the heat-flux dropout (low energy electrons) seen inside magnetic islands (see Fig. 2). WIND data between 00 : 00 : 00 – 08 : 00 : 00, 2007-May-29 in Khabarova et al. 2020, for rapid changes of electron PADs in the current sheet with magnetic islands.

Such field-aligned bi-directional jets of high-energy electrons have been also reported in the magnetotail (Fujimoto et al. 1997; Oieroset et al. 2002; Egedal et al. 2005; Pritchett 2006; Manapat et al. 2006; Oka et al. 2016), in the CSS of heliosphere (McComas et al. 1989; Foullon et al. 2009; Rouillard et al. 2010) where a strong guiding magnetic field is not a surprise, and at the font of an interplanetary coronal mass ejection (ICME) (Zank et al. 2015) where strahls are moving perpendicular to the interplanetary magnetic field but parallel to the magnetic field of the ICME current sheet. Besides, there are also bi-directional electron beams in the lower-energy channels have been found at the edge of a magnetic island (Huang et al. 2016).

On the other hand, the PADs of energetic electrons centered about 90° have been related to trapped and mildly accelerated electrons in magnetic islands (Fu et al. 2013; Yao et al. 2018; Wang et al. 2019). These in-situ measurements are consistent with our findings in Fig. 4(b2, b3). The THEMIS mission also reported similar PADs when it crossed the reconnection diffusion region of the magnetotail (Oka et al. 2016), such as the quasi-perpendicular (90°) and bi-directional distributions.

The detailed study in this paper shows that $\sim 90°$ strahls are accumulated near the X-nullpoint at the end of magnetic islands when $b_g = 0$, and shift into the magnetic islands when $b_g$ is large. Hence the simulation in Fig. 3(b2, b3) suggests that WIND was travelling across a magnetic island pool with a strong guiding field.

Therefore, the observers can distinguish whether the spacecraft was passing single or multiple O- and X-nullpoints in these current sheets by evaluating electron PADs and distinguishing those between quasi-parallel and quasi-perpendicular directions.

4.2. New observations with the Parker Solar Probe

Most recently, during Perihelion 1 of Parker Solar Probe (PSP), 21 RCSs have been identified by the paired rotational discontinuities bounding the exhausts (Phan et al. 2020). Although, due to the low resolution ($\geq 275$s) of the spacecraft PAD measurement at this moment, PSP could only sample 0 – 4 times in the RCS, or even record < 2 samples during the surveyed time. Still, we are able to identify two events (ID 7 and 15 in the table of Phan et al. (2020)) showing the electron PAD patterns near a single X-nullpoint.

The PADs in different energy bands and the change of magnetic field components are shown in Figure. 6(a1, a2). The period of the first RCS crossing is 65.7s, and the guiding field was weak (0.82 nT). The electron beam streaming from the Sun (Kasper et al. 2019) is locally discontinued. The reversing of the mono-directional strahls from 180° to 0° across the RCS is presented in the higher-energy channels $> 253$ eV, which is consistent with Figure. 2(a).

The second case is presented in Figure. 6(b1, b2). It shows a heat-flux dropout in the higher-energy channel ($> 55$ eV). The uni-directional strahl at 180° could be a combination of local accelerated electrons and the electron beams from the Sun. Meanwhile, the transition of mono- to bi-directional beams in the lower-energy ($< 45$ eV) matches rather closely to the features of PADs presented in Figure. 2(b). Since the observed guiding field was rather weak (0.89 nT), while the simulation in Fig. 2(b) was made for a stronger guiding field, this good fit is likely to be caused by an increase the current sheet width to 100$\rho_i$, for which the previous single X-nullpoint simulation was carried out.

Also, we wish to emphasise that the energy threshold for lower- and higher-energy electrons, when their PADs become qualitatively different, is $\sim 50$ eV. This is smaller than the value of $\geq 100$ eV obtained from the measurements near 1 AU in the solar wind (Khabarova et al. 2020), which suggests the reconnection event in the RCS measured by PSP was weaker.
5. Conclusion

In the current paper, we studied the electron pitch-angle distributions in different parts of the magnetic islands during the magnetic reconnection. Our self-consistent PIC simulations considered the 2.5D reconnection models with a strong or weak magnetic guiding field and different electron-to-proton temperature ratio. Furthermore, we collected the electron PADs along the paths of the virtual spacecraft in different directions through the simulation regions, which can emulate real in-situ observations. This is a supplement to the previous studies considering the RCSs either with a single X-nullpoint geometry or with a few coalescent and squashed magnetic islands (Xia & Zharkova 2020).

To understand the simulation results, we first reiterate the two key properties of particle acceleration in 3D RCSs with a single X-nullpoint: 1) separation of protons/ions from electrons with respect to the current sheet midplane if $B_g > 0$; 2) different motions of transit and bounced particles (depending on which edge of the RCS they enter) within the same species. These properties introduce the asymmetry to the particle energy distributions and PADs across the RCS midplane.

As shown in the previous study (Xia & Zharkova 2020), in an RCS with a single X-nullpoint the transit particles are ejected as high-energy strahls with rather narrow pitch angles centred about 0° or 180°, depending on the side from X-nullpoint. While the bounced electrons gain much less energy because they cannot reach the current sheet midplane where strong particle acceleration happens. They have wide PADs centred in the direction dependent on the ratio of magnetic field components. These two populations of energetic electrons are well distinguished in the models and can be easily observed from in-situ observations. In the most recent PSP database, we have identified two RCSs showing the PAD features in the vicinity of a single X-nullpoint. We expect the high cadence data from Solar Orbiter will provide more insight into the RCS structures. That helps us to carry out a further comparison of the electron PADs closer to the Sun with our predictions.

Although the parameters of the energy spectra and PADs would change accordingly in magnetic islands, the asymmetry ejection is still present when the particles are ejected from the exhausts (Xia & Zharkova 2018). For example, when the magnetic guiding field is weak, it is easy for spacecraft to observe bi-directional strahls: the signals cover a wide range in the magnetic islands in the higher-energy channel due to the counter-streaming energetic electrons coming from the two X-nullpoints at both ends of the magnetic islands. A comparison of electron PADs in the simulations with different $T_i/T_e$ suggests that it is harder to capture the bi-directional beams inside the islands in the solar wind than in the geomagnetic tail environment due to the higher electron temperature. We also notice the bi-directional strahls are complemented with heat flux dropout (low energy electrons) seen inside magnetic islands (Khabarova et al. 2020). Such field-aligned bi-directional strahls of high energy electrons have observed by many instruments in the current sheets of magnetotail (MMS) (Oieroset et al. 2002; Egedal et al. 2005; Pritchett 2006; Manapat et al. 2006; Oka et al. 2016), of the heliosphere (WIND, THEMIS) (McComas et al. 1989; Foullon et al. 2009; Rouillard et al. 2010), and at the font of ICMEs (STEREO) (Zank et al. 2015).

The implementation of a strong guiding magnetic field in this model provides significant changes in the view of PADs. The bi-directional strahls only exist in the exhaust region in the lower-energy channel, similar to the previous findings near a single X-nullpoint (Xia & Zharkova 2020). The counter-streaming energetic beam from another X-nullpoint is strongly suppressed by the guiding field. Nevertheless, bi-directional signals are accessible in the lower-
energy channels in the exhausts for both $T_i/T_e = 1$ and 5, with or without a strong guiding field. This signal has been detected in many observations (McComas et al. 1989; Crooker et al. 2003; Pagel et al. 2005; Rouillard et al. 2010; Simunac et al. 2012; Huang et al. 2016).

The PADs in higher-energy channels rotate from quasi-parallel (near the X-nullpoint) to quasi-perpendicular (in the magnetic island away from the X-nullpoint), highly depending on the crossing path in the simulation domain. In fact, the PADs of energetic electrons are centred $\sim 90^\circ$ as observed in some cases (Fu et al. 2013; Yao et al. 2018; Wang et al. 2019). The detailed study in this paper shows that $\sim 90^\circ$ strahls are located near the X-nullpoint at the end of magnetic islands when guiding field is weak, and shift inside the magnetic islands when the guiding field becomes large.

These findings in electron PADs, in addition to their energy distributions, can be a helpful diagnostics tool helping to explain a whole range of the disperse electron PAD observations from near the Earth to the inner heliosphere.

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