A deep insight into the Ion Foreshock with the help of Test-particles Two-dimensional simulations" by Philippe Savoini and Bertrand Lembege

Answer to the comments of referee #1;

We thank the referee for the helpful comments. Please find below our detailed answers to each comment which are indicated in bold letter. Corrections have been directly inserted in the text in blue color and sentences and/or parts of the sentences to be suppressed are also indicated.

The authors applied 2D test particle simulations based on field profiles from PIC simulations to understand how a quasi-perpendicular curved shock reflects ions. The authors tested various parameters using a self-consistent field model and a stationary field model that expands in time. The authors determine how electric field, θBN, and non-stationarity affect the reflection process. Although shocks are one of the fundamental particle accelerators throughout the universe, how shocks reflect ions is still poorly understood. This work provides many detailed results that can significantly improve our understanding. I would like to recommend the paper for publication providing that my concerns below are addressed.

About main conclusions:
I agree with the authors that El plays an important role in reflecting ions, but I doubt whether the parallel component of El can accelerate ions. El causes a potential change across the shock. I agree that El causes energy change for ions and electrons that cross the shock as stated in line 330 "this component works to decelerate incoming ions and to accelerate electrons to the downstream region". For reflected ions that do not cross the shock, however, there is no potential change before and after the reflection. I believe that the role of El is to build up a potential wall to prevent low energy ions from crossing downstream, right?

Yes, as indicated in the text, authors agree with the referee concerning the role of the electric potential wall which decelerates ions and reflects back low energy ions and some modifications have been made in the paper to be more precise.

Such reflection process is done with energy conservation when the potential amplitude is the same before and after the reflection (i.e. the total work of the electric force is null). Nevertheless, this scenario is only valid if the ions during their reflection "see" exactly the same shock profile (i.e. the shock profile has to be constant in time with a planar geometry) which is not the case here where both curvature effects and shock front non stationarity are included. In fact, the ion reflection process in this paper can be classified as follows :

1) Case 1: ions suffer a one bounce reflection in a short time. These ions are classified as "GPB" and can be associated to a Fermi type reflection. In this case, the role of the potential wall is *limited* to the reflection and not to the acceleration of the ions because ions see roughly the same shock profile both in time and in space.

2) Case 2: ions suffer a drift along the shock front and may suffer multi-bounces before being reflected back into the upstream region. These ions can stay a long/very long time (several local ion gyro-periods) within the shock front. In this case, the theory of a constant electric potential (both in time and space) is not valid anymore and its difference

between the time/space when ions hit and leave the shock front can be related to the ion acceleration parallel to the magnetic field.

The authors have clarified the role of the electric field in the text (see the beginning of the section 3.2)

The authors claim that $\boldsymbol{Et} \times \boldsymbol{B}$ drift due to convective electric field is very important. I cannot agree with this statement without mentioning the frame of reference. What about $\boldsymbol{Et} \times \boldsymbol{B}$ drift in the shock normal incidence frame, the de Hoffmann-Teller frame, or the spacecraft rest frame when observing an earthward IP shock? For example, in the HT frame without $\boldsymbol{Et}$, the drift in the solar wind rest frame corresponds to the motion of shock surface along the tangential direction. Therefore, as $\boldsymbol{Et} \times \boldsymbol{B}$ drift is frame dependent, it is important to mention the frame of reference when discussing its role.

The authors have modified the text accordingly. Nevertheless, it is important to point out that in presence of a curved propagating shock, it is not possible to define a global de Hoffman-Teller frame in our case. We remind at different locations of the text that we are in the solar wind reference frame, and the field Et herein is carried by the expanding shock front itself.

Other than $\boldsymbol{Et} \times \boldsymbol{B}$ drift, there is also grad-B drift. In the shock normal incidence frame, the direction of grad-B drift is along $\boldsymbol{Et}$ resulting in energy increase, i.e., shock drift acceleration. In the solar wind rest frame, such mechanism can cause velocity increase $\boldsymbol{dV} = 2\boldsymbol{Vn} + 2\boldsymbol{VHT}$ (where $\boldsymbol{Vn}$ is local shock normal velocity in the solar wind rest frame). As B has z component, the grad-B drift direction has XY component. Based on shock drift acceleration model, larger θBN results in larger energy increase indicating longer drift distance, which is consistent with Figure 4. Therefore, can grad-B drift at least partially affect $\theta exit - \theta hit$ as a function of θ_{BN} ?. I agree with the authors about the impact of θBN.

Thanks to the referee. Yes, the paper was not clear enough concerning this problem, and the text has been modified in order to clarify our approach. The main goal of the paper is to investigate the possible source of the ion energy gain when ions are reflected back by the shock front. In a previous paper, we have evidenced that both “FAB” and “GPB” could have the same origin, namely a ExB drift in the velocity space present at the shock front. The goal of the present paper is to go deeper and to analyze not the source of these two populations but how ions are accelerated within the shock front before backstreaming into the upstream region. Then, it is important to split this mechanism into two distinct parts:

1) the first one coming from the ExB drift which “forms” the two backstreaming populations “GPB” and “FAB” (our previous paper). Of course it is important to retrieve both with present test particles simulations.

2) the second related to the acceleration of particles themselves. We evidence two distinct processes : (i) the El_para which can accelerate ions along the magnetic field and the Et field component which can accelerate (multi-bounce) ions along the shock front (these ions suffer a gradBxB drift along the shock in the same direction of the Et field and then are accelerated by this electric field). We have clarified this point in the text.

In addition, when the Et (convective electric field coming from the plasma moving frame – aka shock front) is artificially suppressed NO ions are reflected anymore. Then, it is not possible for us to analyze the reflection process in this case. This behavior evidences that the convective electric field is mandatory to observe the ion reflection and then, is definitely more important than the grad//B force (i.e. mirror magnetic reflection) in this case.

However, in the simulation configuration, different θBN causes different MA (from 5 to 3). MA is also an important factor that can affect BI%. I think the effect of varying MA needs to be mentioned when discussing the impact of θBN.

In our geometric configuration (curved shock wave), the expanding shock decelerates in time and then, also the Mach Number from 5 to 3. Nevertheless, as evidenced in figure 1 panels 2a and 2b, the shock front can be described by an approximate circle which evidences the low dependency of MA (i.e. shock velocity) versus the θBN angle .

BI% shows burst and drops to 0 periodically in the HE model. I am wondering whether some parameters at the shock front may vary in a similar way, such as the strength of electric field and the gradient of magnetic field.

Even when the BI% drops to 0, the general shape of the shock front is unchanged. No such strong variations are observed correspondingly in the magnetic and electric fields amplitudes.

Other issues:
In Figure 1, there are upstream structures like SLAMS, foreshock cavities, and ULF waves in the FCE model (panel 2b) whereas there is nothing upstream in the HE model (panel 1b). Would upstream structures play a role and cause differences between two models? For example, they may reflect ions back downstream and decrease BI%.

The modulations observed in the quasi-perpendicular upstream region (fig. 1, panel 2b) are mainly due to (i) a propagating whistler wave and (ii) a small turbulence associated to the electron foreshock. Both fluctuations have small amplitudes and shorter time/space variations in comparison to the characteristic ion scales. Then, we did not observe any impact on the backstreaming ion dynamics (No backstreaming ions are reflected back towards the shock front).

In addition, we are interested by the reflection process itself (by defining and analyzing Θ_{hit} and Θ_{exit} quantities) which occurs exclusively within the shock front and is independent of upstream fluctuations. Then, we concluded that these upstream fluctuations have no impact on the reflection process studied in our paper.

In line 181, I am confused by the term “multi-bounces process”. Is this diffusive shock acceleration? Is this “multi-bounces” between the shock surface and upstream structures? Or is this just at the shock surface within one ion gyroradius?

This paper is the extension of a previous study [Savoini et Lembege, 2015] where ion trajectories have been extensively studied. Diagnosis evidence that multi-bounces ions stay within the shock front and are not between upstream structures and the front. Nevertheless,

we have to point out that the convective electric field present in the upstream region in the common shock reference frame is in fact present within the shock front region in the present Solar Wind reference frame. For this reason, we can argue that the ExB drift is the most important mechanism in order to account for our observations concerning the origin of the "GPB" and "FAB" populations (especially the convective Et field component in this drift).

The goal of this paper is focused on the backstreaming ions origin and not on the study of the acceleration process in term of SSA or SDA processes. We think that this specific study will need deeper investigation which is left for a further work. All associated sentences have been removed from the paper. Moreover, we have removed the term "process" which was confusing.

In lines 75-76, the induced electric field is generated by the solar wind. Does this mean that the PIC simulation is not in the solar wind rest frame?

No, the referee is right, the simulations are in the Solar Wind frame. The text was unclear and has been modified.

In line 126, the induced/convective electric field is due to the relative motion between the solar wind and the shock front. I think the convective electric field should be calculated using the local plasma bulk velocity, right? Or do the authors mean that the convective electric field is transformed from the shock rest frame ($-\boldsymbol{U} \times \boldsymbol{B}$) to the solar wind rest frame using the relative speed between the solar wind and the shock front? $\boldsymbol{Et} \times \boldsymbol{B}$ is important, but it is unclear how $\boldsymbol{Et}$ is obtained and difficult for me to check the direction of $\boldsymbol{Et}$ and $\boldsymbol{Et} \times \boldsymbol{B}$.

The induced electric field is NOT computed in these simulations from the relation –UxB but obtained self-consistently in the previous self-consistent PIC simulation directly from the Maxwell's equations. Let us remind that, since we use a spectral PIC code, we can identify separately transverse field Et and longitudinal (space effects) electric field El. In both configurations "FCE" and "HE", we can analyze these two distinct components El and Et independently. Obviously, the induced electric field corresponds to the convective electric field Et which is associated to the propagation of the curved shock front into the SW plasma. The direction of the Et field is along the curved shock front. We have modified Figure 1 in order to indicate the configuration used in this paper. The ExB drift is only responsible to the formation of the "GPB" and "FAB" populations as described in our previous paper (Savoini et Lembege, 2015). Unfortunately, by construction, it is not possible to define a global reference frame where we can cancel this field (a frame propagating with the same velocity that shock front). This difficulty is mainly due to the propagation of the curved shock wave into the Solar Wind in all directions. For this reason, we are not able to cancel artificially the Et component (as the El component) since that would mean that we had to "stop" the shock front which should be totally unrealistic.

The authors have modified the text in order to precise the definition of the Et component introduced in the present test-particle simulations (see section 2.1).

In line 192, $1\tau \approx 4\ \tau_{\mathrm{ci}}^{\mathrm{sh}ock}$. Is τ_{ci} the value in the solar wind? If it is true, the field strength at the middle of the ramp is four times the solar wind field strength. I assume that the field strength at the middle of the ramp is smaller than the downstream field strength meaning that the field strength compression ratio is larger than 4, right?

Yes, the overshoot is about 7 but the exact value depends not only on both the angle theta_Bn and the time because of the front nonstationarity, but also on the Mach number which decreases as the shock propagates. Nevertheless, the value of B = 4 measured in the middle of the ramp corresponds to the local value averaged over the time range under consideration in the present simulations (the upstream value is Bo=1.5).

The time variation of magnetic field of the shock profile can induce electric field. This component of electric field is not included in the HE model. Does this induced electric field play a role?

As mentioned above, our PIC simulations are done with a spectral code (i.e. Maxwell and Poisson equations are resolved in the Fourier space) which allows us to separate the electrostatic component (El in Poisson's equation) and the electromagnetic component induced by the time variation of the magnetic field, named Et (from Ampere equation). Then, even in the HE configuration, we can (in fact, we have to) include the Et component in order to follow the propagating shock front and we observe its impact in both FCE and HE configurations.

Figure 11 needs some more text in the conclusion section. For example, does B refer to magnetic field or magnetic mirror reflection? How the effect of EXB depends on θBN is not discussed in the conclusion section. Does black (white) mean longer (shorter) drift distance or stronger (weaker) effect on the reflection?

The authors have clarified the description of this figure in the text.

Wording problems:
Line 142, when BI% is first mentioned in the main text, I have to go back to the abstract to find its meaning.

A more precise definition has been now introduced.

I am confused by some terms. It is unclear whether "magnetic mirror reflection (Fast Fermi)", "specular reflection with the conservation of the magnetic moment", "Fermi type reflection", "Fermi type process", "mirror reflection or Fermi reflection", "Fermi type one acceleration process", "fast Fermi acceleration", and "shock drift acceleration" refer to the same process.

All these sentences refer to the same process (i.e. magnetic reflection) but we use also the term Fermi type reflection or even Fast Fermi since an energy gain of the reflected particle (i.e. a Fermi type acceleration) is associated to this reflection process while the shock front propagates. We have simplified and replaced most of these terms by magnetic reflection in the text, only in conclusion we introduce the term Fermi acceleration.

In section 2.2, the HE model is first introduced, so I expected to see the results from the HE model first instead of the FCE model in section 3. It may be better to be in the same order.

Thanks to the referee. The authors have changed the text accordingly, so that FCE case is introduced and described first, and HE case follows after

In line 77, although readers can find magnetic field configuration from the authors' previous papers, it would be better if the authors can simply add an "out-of-plane" symbol and an arrow in Figure 1 to indicate the IMF direction (and perhaps electric field direction at the shock front). Or the authors can at least refer to Figure 11.

A new plot 1a (Figure 1) has been added showing a perspective view of the simulation plane in order to clarify the shock geometry.

In lines 214-215, there are two "in particular" in this sentence. I suggest replacing the second one with "especially"
Done

In line 235, maybe it is better to revise it as "**Figure 7** shows very similar escaping angle distribution compared with Figure 4..."
Done

In line 388, "the impact of the electrostatic field" should be "the impact of the **electric** field" as both components are discussed.
Done

In line 405, impact -> Impact
Done