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# *Interactive comment on* "Vlasov simulation of electrons in the context of hybrid global models: A Vlasiator approach" *by* Markus Battarbee et al.

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Response to review by Anonymous Referee #1

We wish to thank the referee for their input and evaluation of our manuscript. Below, we have included the referee comments in italics and our own response in regular text.

*This is interesting draft describing inclusion of electron physics into the global hybrid simulations. Topic is very important, and such improved models are expected to provide useful and crucial information about many magnetospheric plasma processes. Thus, paper should be published in AnGeo!*

Thank you, we agree it is an interesting topic where a lot of progress can be made!

*However, some clarifications are needed before publication. I have one general suggestion, and set of specific comments. Beside the reconnection, the electron physics in the magnetotail (the simulation do-main shown in this study) includes: (1) electron adiabatic heating during earth-ward convection and transport (e.g., doi:10.1002/2015JA021166, 10.5194/angeo-31-1109-2013 ) (2) generation of electron anisotropy at plasma flow fronts and plasma injections and further relaxation of this anisotropy via whistler wave generation (e.g., doi:10.1103/PhysRevLett.106.165001, 10.1002/2016GL069188, 10.1029/2018GL079613 ) (3) formation of strong field-aligned and transverse electron currents in the magnetotail current sheet (e.g., doi:10.1029/2007JA012760, 10.1002/2016GL072011 ) (4) electron-ion decoupling and formation of strong electric field in thin current sheets (e.g., doi:10.1029/2018JA026202, 10.1002/2016JA023325 )(5) electron precipitation altering MI coupling (e.g., doi:10.1007/s11214-016-0234_7 ) It would be very useful to discuss which of these processes can be described by the presented model.*

Thank you for the comprehensive suggestions and references to aid us in performing this evaluation. We shall expand the discussion regarding added references.

*Comments:*
*Line 43: Do you mean "reconnection in Harris current sheet"? please, separate reference to the analytical model (Harris 1962) and numerical simulations*

Yes, a good point, we shall separate them and clarify this section.

*Line 70: please, add reference to doi:10.1002/2015GL063946*

Thank you for the excellent suggestion.

*Lines 149-154: if I understand correctly, Authors exclude pressure gradient term, but include electron inertial term. This is quite unexpected solution. Ratio of electron inertial term and pressure gradient is of the order of* $\frac{V_e R}{T V_t^2}$ *where* $V_e$ *is the bulk electron speed,* $R$ *and* $T$ *are typical spatial and temporal scales, and* $V_t$ *is the electron thermal* *speed. To make this term much larger than one (neglect pressure versus inertia), one needs to consider processes with the evolution rate* $\frac{R}{T} \gg \frac{V_t^2}{V_e}$ *i.e. much faster than electron thermal speed that is the largest speed in solar wind, magnetosheath, magnetotail plasmas. Authors should explain why they can use the* $\frac{V_e R}{TVt^2} \gg 1$ *assumption in the magnetosphere.*

Thank you for bringing this up. We agree that the ratio $\frac{V_e R}{T V_t^2}$ is not expected to be much larger than one within the domain under investigation. After further evaluation, we agree that assessing the electron pressure gradient term will likely be a good choice, and are in the process of adding the necessary modules to the code. Subsequently, the manuscript will be updated with this description.

*Fig6a: Do Author suggest that this anisotropy results after 1s from the initially isotropic Maxwellian distribution? This time seems to be large in comparison with plasma timescales (inverse plasma frequency), but should be very small in comparison with global plasma/magnetic field motion responsible for betatron acceleration. Additional clarifications are needed here to explain how electrons can be heated transversely so quickly.*

As our initial distributions are indeed Maxwellian and isotropic, this does appear to be the case. We agree that betatron acceleration should not result in such changes at these time scales, but the interplay of drifts with electron oscillation appear to be behind this effect. We shall also add evaluation of how much of the seen effect is actual perpendicular or parallel acceleration, and how much is due to different temperatures of electrons convecting along field lines.

*Fig6a: I see* $T_\perp/T_\parallel$ *ratio around 1.5, what is quite large ratio for magnetosphere. Do Authors observe whistler wave generation by anisotropic electrons and following relaxation of this anisotropy?*

Thank you for the good question. Evaluation of different kind of waves (power and frequencies) generated by electrons within the target simulation domain is something that we would like to investigate in the future. However, our current implementation

approach is to maintain static magnetic fields, so the solver only captures electrostatic oscillations, which do not include whistler waves. Future expansion of the simulation code is planned to implement a more complete field solver, which could also capture whistler waves, which can then be reported in future publications.

*Line 299: electron-scale waves at PSBL are driven by electron beams from the reconnection region. Do Authors observe such an acceleration?*

Panel b of Figure 6 indicates in an orange color the regions where electron-scale oscillations visible via large values of $E_{J_e}$ are strongest, and panel a indicates regions where parallel electron pressure dominates as blue regions. Comparing these regions with the visible tail magnetic field structure indicates that electron oscillations are found throughout the PSBL region, even when pressure anisotropy is close to 1 (e.g. virtual spacecraft location 1). We do note however that at virtual spacecraft location 1 there does appear to be some parallel structure to electrons. We shall add additional figures of simulation results to visualise and exemplify the resultant dynamics.

*Lines 301-304: note, typical electron anisotropy in the magnetotail* $T_\parallel/T_\perp > 1$ *is formed by cold (subthermal) electron populations. Is this the case in simulation?*

Yes, comparison of electron temperature and temperature anisotropy plots (Figures 2c (proton temperatures but scales with electron temperatures and 6b, respectively) confirms that $T_\parallel/T_\perp > 1$ is associated with cold electron populations.

*Fig6, velocity distributions: almost all shown distributions demonstrate a certain non-gyrotropy (although weak): non-circle shape in* $v_{\perp 1}$, $v_{\perp 2}$ *plane. Such non-gyrotropy is expected in the close vicinity to the reconnection region, but should be explained outside of this region where electrons are well magnetized.*

The registered values of agyrotropy (Swisdak 2016) are indeed nonzero but still low, remaining below $5.0 \times 10^{-4}$ everywhere in the simulation domain. Please see the attached Figure 1. We see these moderate values of gyrotropy both at the magnetic reconnection topology site, and in the PSBL. The effect within the PSBL is most likely due to some hot electrons originating within the tail plasma sheet performing gyromotion which, after they have entered the lower **B** region in the PSBL, causes them to spread in the perpendicular direction. We shall investigate this further and see if finetuning our solver parameters changes this effect.

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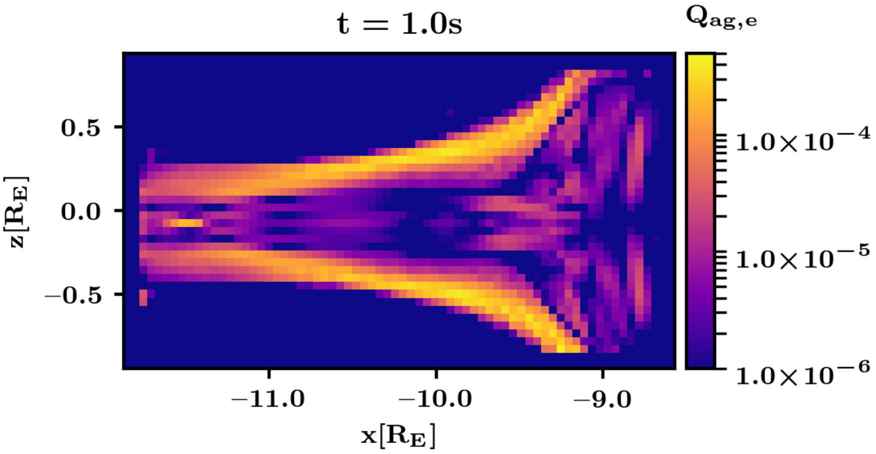

**Fig. 1.**