Comment on "Nonideal Fields Solve the Injection Problem in Relativistic Reconnection"

Sironi [1] (hereafter S22) reported the correlation between high-energy particles and their crossings of regions with electric field larger than magnetic field ($E > B$ regions) in kinetic simulations of relativistic magnetic reconnection [2–8]. They claim that $E > B$ regions (for vanishing guide fields) accelerate particles to the injection energy $\gamma_{\text{inj}} \sim \sigma$ (magnetization). S22 shows that if test particles are reset to low energies in $E > B$ regions, injection is suppressed. We reexamine these claims using a simulation resembling the reference case in S22 with no guide field. We show that $E > B$ regions contribute very little to injection ($\sim 10\%\gamma_{\text{inj}}$) as they only host particles for a short duration. The energization *before* any $E > B$ crossings has a comparable contribution, indicating $E > B$ regions are not unique for pre-acceleration. A new test-particle simulation that zeroes out $\mathbf{E}$ during $E > B$ does not strongly influence injection. We suggest that the procedure to exclude $E > B$ acceleration in S22 partly removes acceleration outside $E > B$, leading to a false conclusion.

We initialize a force-free layer [1,6] with the reconnecting-field-magnitude B_0 and half-layer-thickness $\lambda = 6d_e$ (skin depth). We focus on the zero-guide-field case, and refer readers to [9] on guide-field effects. We use $\sigma = 50$ and temperature $kT = 0.36 m_e c^2$, and have confirmed our conclusion holds when varying them. The dimension is $L_x \times L_z = 1600 d_e \times 1200 d_e$ and the simulation lasts $2.5 L_x/c$ (same as S22). We added a perturbation to trigger reconnection and removed the initial current-sheet contributions for all analyses. Each d_e is resolved by 4 cells with 100 positron-electron-pairs per cell. Boundaries are periodic in the x direction and conducting (reflecting) in the z direction for fields (particles). We uniformly select and trace 1.28 million particles and record the electromagnetic fields they experience every time step [10].

During injection of each particle before it reaches $\gamma = \sigma(\sigma/4)$, 79.4%(53.7%) of injected tracers have $E > B$ crossings ("$E > B$ particles"). S22 finds a stronger correlation, since they label all particles that ever crossed $E > B$ regions during the entire simulation [11]. Clearly, a significant fraction of particles are injected without needing $E > B$ [9]. Nevertheless, it is still interesting to explore if $E > B$ regions are important for $E > B$ particles.

During injection, $E > B$ particles can have multiple $E > B$ crossings. Our analysis includes all the duration when particles experience $E > B$. This time constrains the acceleration in $E > B$ regions $\Delta\gamma_{E>B} \lesssim \int qrB_0 c dt/(m_e c^2)$, where reconnection rate $r \sim 0.1$ [12–16]. For $\sigma = 50$, $\omega_{pe} t_{\text{inj}} \gtrsim 50(12.5)$ is needed for $\gamma_{\text{inj}} = \sigma(\sigma/4)$. However, the mean time that particles stay in $E > B$ regions is $\omega_{pe}\bar{t} = 4.3(1.9)$ for $\gamma_{\text{inj}} = \sigma(\sigma/4)$ and nearly *no* $E > B$ particles have time for injection. Figure 1(a) shows the distributions of particle energy gain (before reaching γ_{inj}) in $E > B$ regions, before any $E > B$ crossings, and outside $E > B$ regions after the first $E > B$ crossing. The acceleration in $E > B$ regions is insufficient for direct injections, with $\Delta\bar{\gamma}_{E>B} = 4.9(1.7)$ for $\gamma_{\text{inj}} = \sigma(\sigma/4)$. Interestingly, we find comparable acceleration before particles encounter $E > B$ [$\Delta\bar{\gamma}_{b,E>B} = 5.6(2.7)$ for $\gamma_{\text{inj}} = \sigma(\sigma/4)$]. This suggests that $E > B$ acceleration is not unique for pre-acceleration. Figure 1(a) shows that most acceleration during injection occurs outside $E > B$ regions. Having a lower upstream temperature makes the $E > B$ regions contribute slightly more but does not change our main conclusion. We evolve a test-particle component that does not "see" the electric field in $E > B$ regions, and find 88.5%(96.3%) particles are still injected compared to self-consistent particles for $\gamma_{\text{inj}} = \sigma(\sigma/4)$. No major difference exists between spectra of the test particles and self-consistent particles [Fig. 1(b)]. In contrast, when particle energies are reset to an energy of $10kT$ during $E > B$ crossings (resembling S22), injection is suppressed. This difference is because resetting particle energy removes the acceleration before and between $E > B$ crossings.

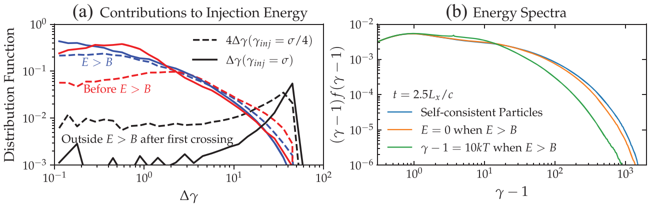

FIG. 1. (a) Distributions of energy gain for $E > B$ particles during injection: in $E > B$ regions, before $E > B$ crossing, and outside $E > B$ regions after the first crossing. (b) Spectra for self-consistent particles, test particles with $E = 0$ when $E > B$, and test particles with energy reset to $10kT$ when $E > B$ (resembling S22).

We demonstrated that the apparent correlation between particle injection and $E > B$ crossings does *not* have direct physical relation. Most injection is *not* achieved by $E > B$ regions. We have reached the same conclusion for different temperatures, σ and domain sizes, and will report elsewhere.

We are thankful for discussions with Lorenzo Sironi, as well as discussions with Joel Dahlin, Jim Drake, Colby Haggerty, Dmitri Uzdensky, and Greg Werner. We acknowledge the support from Los Alamos National Laboratory through the LDRD program, DOE office of science, and NASA programs through the Astrophysical Theory Program. The work by X. L. and Y. L. is funded by the National Science Foundation Grant No. PHY-1902867 through the NSF/DOE Partnership in Basic Plasma Science and Engineering and NASA 80NSSC21K2048. The simulations used resources provided by the Los Alamos National Laboratory Institutional Computing Program, the National Energy Research Scientific Computing Center (NERSC), and the Texas Advanced Computing Center (TACC). Q. Z. is partly supported by NASA Heliospheric Supporting Research Program through 80HQTR21T0103.

Fan Guo[1,*], Xiaocan Li[2], Omar French[3], Qile Zhang[1], William Daughton[1], Yi-Hsin Liu[2], William Matthaeus[4], Patrick Kilian[5], Grant Johnson[6], and Hui Li[1]

[1]Los Alamos National Laboratory
Los Alamos, New Mexico 87545, USA
[2]Dartmouth College
Hanover, New Hampshire 03755, USA
[3]Department of Physics, 390 UCB
University of Colorado
Boulder, Colorado 80309, USA
[4]Department of Physics and Astronomy
University of Delaware
Newark, Delaware 19716, USA
[5]Space Science Institute
4765 Walnut Street, Suite B
Boulder, Colorado 80301, USA
[6]Princeton Plasma Physics Laboratory
100 Stellarator Road, Princeton
New Jersey 08540, USA

Received 6 August 2022; accepted 21 March 2023; published 5 May 2023

DOI: 10.1103/PhysRevLett.130.189501

[*] Corresponding author.
guofan@lanl.gov

[1] L. Sironi, Phys. Rev. Lett. **128**, 145102 (2022).
[2] F. Guo, Y.-H. Liu, W. Daughton *et al.*, Astrophys. J. **806**, 167 (2015).
[3] L. Sironi and A Spitkovsky, Astrophys. J. Lett. **783**, L21 (2014).
[4] F. Guo, H. Li, W. Daughton *et al.*, Phys. Rev. Lett. **113**, 155005 (2014).
[5] G. R. Werner, D. A. Uzdensky, B. Cerutti *et al.*, Astrophys. J. Lett. **816**, L8 (2016).
[6] F. Guo, H. Li, W. Daughton *et al.* Astrophys. J. Lett. **879**, L23 (2019).
[7] P. Kilian, X. Li, F. Guo *et al.* Astrophys. J. **899**, 151 (2020).
[8] F. Guo, Y.-H. Liu, X. Li *et al.*, Phys. Plasmas **27**, 080501 (2020).
[9] O. French, F. Guo, Q. Zhang *et al.*, arXiv:2210.08358.
[10] F. Guo, H. Li, W. Daughton *et al.* Astrophys. J. **919**, 111 (2021).
[11] L. Sironi (private communication).
[12] Y.-H. Liu, F. Guo, W. Daughton *et al.*, Phys. Rev. Lett. **114**, 095002 (2015).
[13] Y.-H. Liu, M. Hesse, F. Guo *et al.*, Phys. Rev. Lett. **118**, 085101 (2017).
[14] G. R. Werner, D. A. Uzdensky, M. C. Begelman *et al.*, Mon. Not. R. Astron. Soc. **473**, 4840 (2018).
[15] Y.-H. Liu, S.-C. Lin, M. Hesse *et al.*, Astrophys. J. Lett. **892**, L13 (2020).
[16] M. Goodbred and Y.-H. Liu, Phys. Rev. Lett. **129**, 265101 (2022).