Comment on “Nonideal Fields Solve the Injection Problem in Relativistic Reconnection”

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In a recent Letter, Sironi [1] (S22) reported the correlation between particles accelerated into high energy and their crossings of regions with electric field larger than magnetic field (\(E > B\) regions) in kinetic simulations of relativistic magnetic reconnection [2,7]. They claim that electric fields in \(E > B\) regions (for a vanishing guide field) dominate in accelerating particles to the injection energy \(\gamma_{\text{inj}} \sim \sigma\) (magnetization). They suggest that the diffusion regions host particles for a sufficient time for efficient injection. S22 presented test-particle simulations showing that if particle energies are reset to low energies in \(E > B\) regions, efficient injection is suppressed. This issue has strong implications for modeling large-scale reconnection system, and thus important to resolve.

This Comment re-examines these claims by analyzing a simulation resembling the reference case in S22 using VPIC [8]. We find nearly no particle stayed in \(E > B\) regions long enough to achieve injection by the reconnecting electric field. The acceleration in \(E > B\) regions only contributes a small fraction to the injection energy (~10% \(\gamma_{\text{inj}}\) on average) [6]. The energization before any \(E > B\) crossings has a comparable contribution, indicating \(E > B\) regions are not unique in pre-accelerating particles. A new test-particle simulation shows that zero-outing electric fields in \(E > B\) regions does not strongly influence the injection. We suggest that the procedure used in S22 to exclude \(E > B\) acceleration partly removes acceleration outside \(E > B\) regions, leading to a false conclusion that injection by \(E > B\) regions is a necessary prerequisite.

The initial magnetic field \(\mathbf{B} = B_0 \tanh(z/\lambda)e_x + B_0 \sech(z/\lambda)e_y\). \(B_0\) is the reconnecting-field magnitude and \(\lambda(= 6\ \text{skin depth} d_e)\) is the half-layer-thickness. \(\sigma = 50\) and temperature \(kT = 0.36m_e c^2\). The box size is \(L_x \times L_y = 1600d_e \times 1200d_e\) and the simulation lasts \(2.5L_x/c\), with a small perturbation added to trigger reconnection. Each \(d_e\) is resolved by 4 cells with 100 positron-electron-pairs per cell. Boundary conditions are periodic in the \(x\)-direction and conducting (reflecting) in the \(z\)-direction for fields (particles). We trace 1.28 million particles uniformly and record the electromagnetic fields they experience at every time-step [9]. The reconnection dynamics and nonthermal energy spectra in the magnetically-dominated regime have been well documented [2,7,10].

During injection \(\gamma \rightarrow \sigma(\sigma/4), 77.5\%(51.0\%)\) of the injected tracers have \(E > B\) crossings ("\(E > B\) particles"). S22 found a stronger correlation, since they label all particles that ever crossed \(E > B\) regions during the entire simulation, rather than just during injection [11]. Clearly, there is a significant fraction of particles injected without the need to cross the \(E > B\) regions [12]. Nevertheless, it is still interesting to explore if \(E > B\) regions are important for particles that crossed those regions before achieving injection.

During injection, \(E > B\) particles can have multiple \(E > B\) crossings. Our analysis includes all the duration that particles are in \(E > B\) regions. The time tells the limit of acceleration in the regions \(\Delta \gamma_{E > B} \lesssim \int q \tau d\gamma dt/(m_e c^2)\), where reconnection rate \(\tau \sim 0.1\). For \(\sigma = 50\), \(\omega_{pe} \tau_{\text{inj}} \gtrsim 50\) is needed for \(\gamma_{\text{inj}} = \sigma(\omega_{pe} \tau_{\text{inj}} \gtrsim 12.5\) for \(\gamma_{\text{inj}} = \sigma/4\). Fig. [1] shows the time distribution of \(E > B\) particles stayed in \(E > B\) regions during injection. The mean time that particles stay in those regions is \(\omega_{pe} \bar{t} = 4.2(1.8)\) for \(\gamma_{\text{inj}} = \sigma(\sigma/4)\) and nearly no \(E > B\) particles have time to reach \(\gamma_{\text{inj}}\). Fig. [1] shows the distribution of particle energy gain (during injection) in \(E > B\) regions (blue), before \(E > B\) crossings (red), and
outside \(E > B\) regions after the first \(E > B\) crossing (black). Consistently, the acceleration in \(E > B\) regions is too little for direct injections, with \(\Delta \gamma_{E>B} = 4.8(3.6)\) for \(\gamma_{inj} = \sigma(\sigma/4)\). Interestingly, we find comparable acceleration before particles encounter any \(E > B\), giving \(\Delta \gamma_{b,E>B} = 5.6(2.5)\) for \(\gamma_{inj} = \sigma(\sigma/4)\). This suggests that \(E > B\) acceleration is not unique in pre-accelerating particles. Note that this result is consistent with Fig. 3 in S22, but unfortunately overlooked in their interpretation. Fig. 1b also shows that most acceleration during injection occurs outside \(E > B\) regions. We evolve a test-particle component in the simulation that does not “see” the electric field in \(E > B\) regions (so no acceleration during each crossing), and find 84\% (94\%) for \(\gamma_{inj} = \sigma(\sigma/4)\) compare to self-consistent particles are still injected. There is no significant difference between energy spectra of the test-particles and self-consistent particles (Fig. 1c). In contrast, when particle energies are reset to an energy of \(10kT\) during \(E > B\) crossings (resembling S22), particle injection is suppressed. Obviously, this difference is because resetting particle energy removes the acceleration before and between \(E > B\) crossings.

Our analysis demonstrated that the apparent correlation between particle injection and \(E > B\) crossings do not have direct physical relation. Most acceleration for \(E > B\) particles is not achieved by \(E > B\) regions. We have reached the same conclusion for different \(\sigma\) and domain sizes, which will be presented elsewhere.

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