

Ultrahigh-Energy Particle Acceleration due to Nonlinear Alfvén Waves in Relativistically Flowing Plasmas

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The observation of ultrahigh-energy cosmic ray events exceeding the Griesen-Zatsepin-Kuzmin(GZK) cutoff (about 5×10^{19} eV for protons originated from a distance larger than about 50 Mpc) presents a theoretical challenge regarding their composition and origin. Recently it has been proposed that wakefields excited by nonlinear Alfvén waves in a relativistically flowing plasma can lead to ultrahigh-energy particle acceleration[1]. In the absence of flow, the ratio of electric to magnetic field for Alfvén waves is low (on the order of V_A/c , where V_A is the ambient Alfvén speed), however, in the presence of relativistic plasma flow the ratio is enhanced to V_{flow}/c , where V_{flow} approaches the speed of light. Therefore, the relativistic flow and plasma wakefields excited by the nonlinear Alfvén waves contribute to unidirectional acceleration.

The acceleration efficiency relies on the nonlinearity of the plasma wakefield. In order to characterize the strength and structure of the pondermotive potential in the relativistic Alfvén wakefield and determine the energy spectrum of the accelerated particles, we utilize a relativistic electromagnetic particle-in-cell simulation model[2,3]. The simulation model has one spatial dimension in the x-direction and all three velocity components (1D-3V). Fast Fourier transforms are used to compute the fields quantities from Maxwell's equations and the particle time advancement is made in accordance with the relativistic equations of motion. Standard space-time centering and the leapfrog method are applied to the difference equations. Periodic and outgoing electromagnetic wave boundary conditions have been implemented in the model but only results for the periodic case will be shown.

As a first step we consider a localized, Gaussian Alfvén wave pulse, with linear polarization, propagating parallel to an ambient magnetic field, B_o , in an initially uniform electron-positron plasma with zero temperature. The system size was chosen to be $L_x = 4096\Delta = 273c/\omega_{pe}$ with $\Delta = 0.06c/\omega_{pe}$ and time step $\Delta t = 0.2\omega_{pe}^{-1}$. The Gaussian pulse was centered at $x_o = 900\Delta = 60c/\omega_{pe}$ with a width of $50\Delta = 3.3c/\omega_{pe}$. The electromagnetic fields (\vec{E}, \vec{B}) and velocities (\vec{v}) were initialized consistent with a low frequency Alfvén wave propagating in the x-direction and the electromagnetic fields,

$\bar{E} = E_y + iE_z$, $\bar{B} = B_y + iB_z$, satisfy $\bar{E} = (i\omega/c k)\bar{B}$. The velocities are given by $\bar{v}_{e+} = e\omega\bar{B}/k(\omega - \Omega_e)mc$ and $\bar{v}_{e-} = -e\omega\bar{B}/k(\omega + \Omega_e)mc$, which in the limit $\omega < \Omega_e$ is approximately $\bar{v}_{e+} = \bar{v}_{e-} = -(\omega/k)(1/\Omega_e)(e\bar{B}/mc)$. The wave phase speed is about the Alfvén speed, which is $v_A = c/\sqrt{1 + 2\omega_{pe}^2/\Omega_e^2}$, and we use $\omega_{pe} = \Omega_e$.

The preliminary results of the Alfvén pulse propagation and wakefield generation are shown in Figures 1-3 corresponding to three different time slices (Figure 1 is the initial time). We use linearly polarized fields with $B_z = E_y = 0$ for this first case and an initial pulse strength of $B_y/B_o = 0.2$. In the upper left panel the p_y and p_z momentum components for the positrons and electrons are shown and the upper right panel are the B_y and E_z electromagnetic fields. The bottom left panel is the momentum component, p_x , and the longitudinal or electrostatic field, E_x , is displayed in the bottom right panel. Note that the p_x component is initialized as a Gaussian, with very small amplitude, since there is a transient set-up of this momentum in the first cycle of the wave. The initial level is adjusted to the strength of the wave and produces a clearer wakefield structure.

The results of Figure 2 and 3 show that the pulse moves across the domain in the x-direction at the proper group velocity with minimal dispersion for these parameters. A wakefield is clearly observed behind the pulse and is the main result we have obtained so far. The particle acceleration is not significant, however, because of the relatively small amplitude of the pulse and the stationary plasma. We are currently investigating more extreme parameter regimes where nonlinearity is expected to dominate. One sample test case, with pulse strength $B_y/B_o = 1.33$ and initial width of 160 cells= $10c/\omega_{pe}$, is shown in Figure 4 where a larger amplitude pulse exhibited steepening and breakup into subpulses or solitary structures (of scale size c/ω_{pe}). Significant particle acceleration along the direction of propagation is observed in the vicinity of the localized subpulses.

With this model we are currently investigating wakefields within the cold plasma limit and making comparisons with the theoretical description for both electron-positron and electron-ion plasmas[4,5]. We are systematically investigating the influences of warm plasma effects, strong pulse nonlinearity, plasma flow and multi-dimensions.

References

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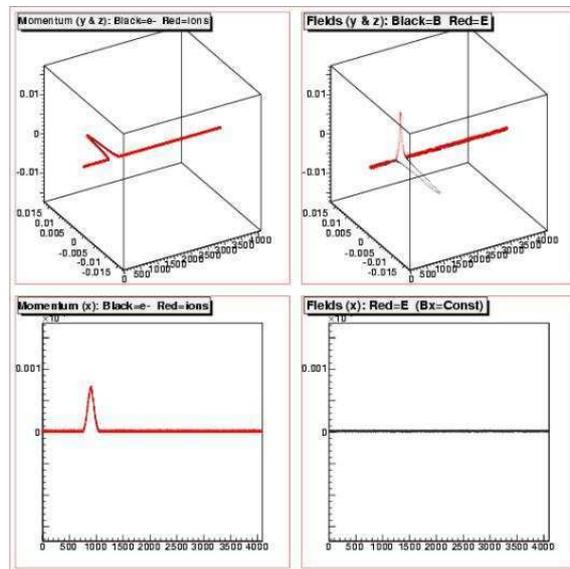


Figure 1: Initial momentum and fields for Alfvén pulse. In the momentum phase space, black refers to electrons and red to positrons (not ions as mentioned in the caption).

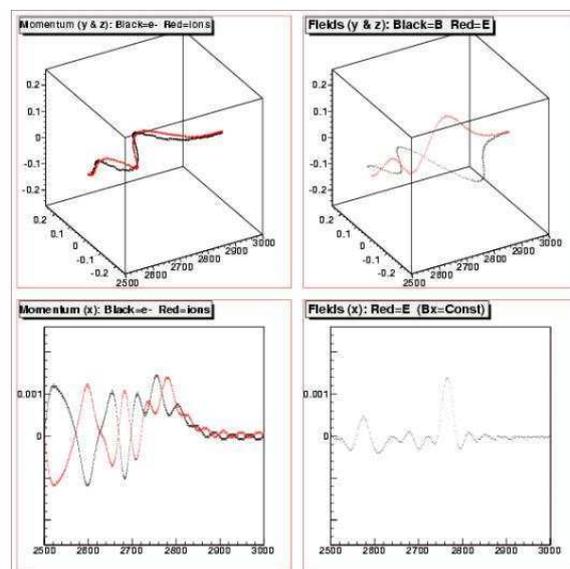


Figure 2: Momentum and fields at a later time showing development of a wakefield behind the Alfvén pulse.

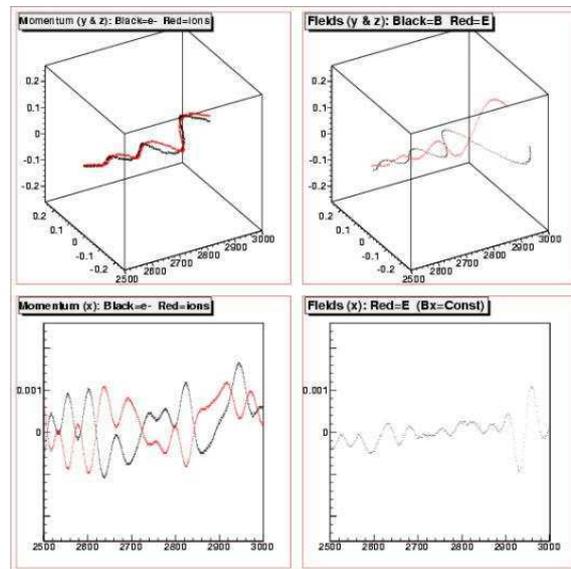


Figure 3: Momentum and fields at a later time as pulse nears the right boundary.

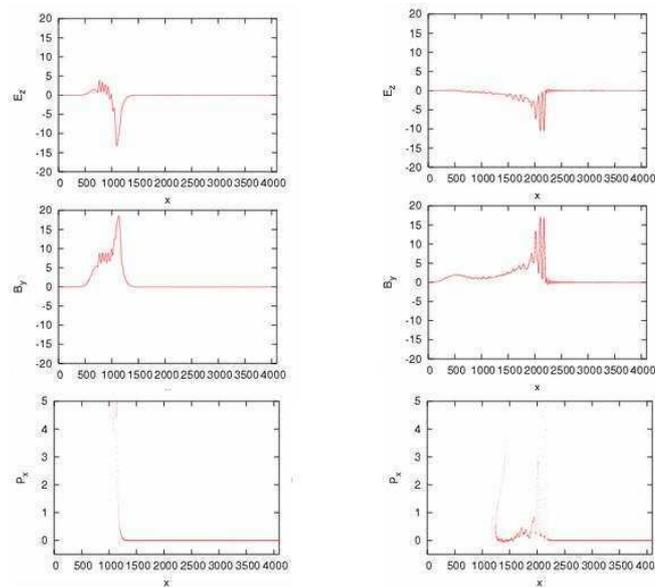


Figure 4: Momentum (p_x) and fields (B_y, E_z) for large amplitude Alfvén pulse ($B_y/B_0 = 1.33$) at two different time slices (three left panels and three right panels).