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Relativistic resonant and trailing-field acceleration induced by large amplitude Alfvén waves in a strong magnetic field

S. Isayama[1], S. Matsukiyo[1], T. Sano[2] and S. H. Chen[3]
[1] Department of Advanced Environmental Science and Engineering, Kyushu University
[2] Institute of Laser Engineering, Osaka University
[3] Department of Physics, National Central University
e-mail(speaker): isayama@esst.kyushu-u.ac.jp

Acceleration of cosmic particles by large amplitude Alfvén waves has been studied with various acceleration mechanisms including the wakefield acceleration driven by Alfvén waves [1-3]. Chang et al. [4] presented the theory of relativistic magnetowave-induced plasma wakefield acceleration (MPWA) and demonstrated wakefield excitation driven by right-hand polarized Alfvén (whistler mode) waves. However, the generation of relativistic particles through MPWA has not yet been demonstrated, complicating the wakefield acceleration scenario by requiring the inclusion of an unverified mechanism involving the mode conversion from Alfvén waves to EM waves.

In 2009, Matsukiyo and Hada [5] showed that a relativistic Alfven wave in a pair plasma is unstable to form the coherent standing wave form which consists of counter propagating Alfvén waves. Recent studies [6] have also shown that when the amplitude of the two counter propagating Alfven waves exceeds critical amplitude any particles irreversibly gain relativistic energy within a short time regardless of their initial energy.

In this study, we propose a novel particle acceleration mechanism driven by large-amplitude Alfvén waves in a strong magnetic field. The acceleration process proceeds through multiple stages triggered by counter propagating wave-particle resonant acceleration (CWRA) via decay instability. Initially, parent and daughter Alfvén waves resonantly accelerate particles perpendicular to the ambient magnetic field. The resultant modulation of wave envelope leads to the formation of charge separation fields within the wave packet. These electrostatic fields subsequently enhance further acceleration within a few relativistic gyroperiods through gyroresonant surfing acceleration (GRSA) [7]. During this, the $\mathbf{v}\times\mathbf{B}$ force facilitates momentum transfer from the perpendicular to the parallel direction. In the later stage, particles become trapped by the parent wave and gain additional energy through single wave resonant acceleration (SWRA). Furthermore, the accumulation of accelerated particles induces electrostatic trailing fields behind and at the tail of the wave packet, which drive trailing-field acceleration (TFA) of other electrons. The combined effects of these mechanisms, CWRA followed by GRSA and SWRA, result in highly relativistic electron energy. This multi-stage acceleration process provides new insights into the generation of high energy cosmic rays in astrophysical environments.

References

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