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Relativistic Resonant and Wakefield Acceleration Driven by Large Amplitude Alfvén Waves

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Coherent large amplitude MHD waves are ubiquitous in space, and they are considered to play crucial roles in the acceleration of high energy cosmic rays. Chen et al. [1] proposed an idea of Alfvénic wakefield acceleration near a relativistic shock. Chang et al. [2] 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 by MPWA has not yet been demonstrated.

In 2009, Matsukiyo and Hada [3] 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 [4] 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 acceleration mechanism driven by large-amplitude Alfvén waves, coupled with self-generated counter-propagating waves through decay instability. Once the counter-propagating waves are generated by the decay process, particles are resonantly accelerated perpendicular to the ambient magnetic field by cyclotron resonance. Concurrently, the particles' perpendicular momentum is converted to parallel momentum via the $v \times B$ force. These particles are trapped within the propagating wave packets and continuously accelerated to extremely high energies. Additionally, the accumulation of accelerated particles generates large-amplitude wakefields trailing the Alfvén wave packets, which in turn induces wakefield acceleration. We demonstrate that this acceleration mechanism activates when the amplitude of the Alfvén waves surpasses a threshold value. The maximum achievable energy is estimated through an analysis of the particles' phase space trajectories.

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[2] F. Y. Chang, P. Chen, G-L. Lin, R. Noble and R. Sydora, Phys. Rev. Lett. 102, 111101(2009).
[3] S. Matsukiyo and T. Hada, ApJ. 692, 1004 (2009).
[4] S. Isayama, K. Takahashi, S. Matsukiyo and T. Sano, ApJ. 946 68 (2023).