2nd Asia-Pacific Conference on Plasma Physics, 12-17,11.2018, Kanazawa, Japan

Magnetic Field Saturation of the Ion Weibel Instability in Interpenetrating Relativistic Plasmas

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The magnetic field is a fundamental physical quantity found everywhere in the universe. It plays essential roles in galaxy spiral arms, high-energy astrophysical phenomena, star formation, and cyclic dynamos at the interior of stars and planets. Because of its ubiquity, the origin of the magnetic field is of great interest in various research fields.

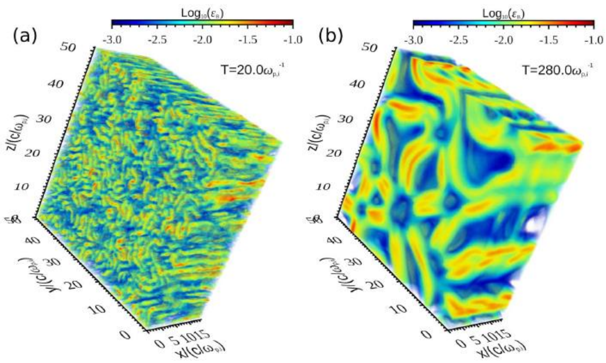
The Weibel instability arises from anisotropy in the plasma velocity distribution function. Because the instability feeds the free energy of the anisotropy and converts it into magnetic energy, it is one of the promising mechanisms responsible for the origin of the magnetic field. Following early theoretical works, numerical simulations have revealed its wide applicability. The generated magnetic field plays crucial roles in collisionless shock formation, associated particle accelerations, and afterglows of gamma-ray bursts. Recent experiments using high power laser facilities have succeeded in showing detailed images of the nonlinear structure characterized by filaments of the current.

Kato [2005] proposed a theoretical model describing magnetic field evolution in cylindrical currents of the electron Weibel instability, and found that the maximum magnetic field could be obtained when the current reached the so-called Alfven current (Alfven, 1939). This gives an upper limit of the cylindrical current in which the Larmor radius of particles in the self-generated magnetic field is comparable with the filament size, and thus determines the magnetic field saturation.

In this talk, we show the evolution and saturation of the Weibel instability in interpenetrating relativistic ion-electron plasmas by means of three-dimensional (3D) PIC simulations. Large-scale, long-term simulations enabled us to elucidate for the first time the coalescence of ion-scale current filaments and the resulting magnetic field saturation after reaching the ion Alfven current limit.

To explore the nonlinear evolution of the Weibel instability, we used a fully kinetic electromagnetic PIC code (Matsumoto et al., 2017). Simulation runs were initialized by two cold unmagnetized counter flows with a bulk Lorentz factor of gamma=5 in the laboratory frame. The beams were set in the x-direction with the periodic boundary condition in the all directions. The cold counter-streaming condition induced a very large anisotropy of the velocity distribution in the system. Consequently, the relativistic Weibel instability grew rapidly in the whole region of the simulation domain.

We found that the Weibel-generated magnetic fields sustained for long time periods after reaching the ion Alfven current limit in the 3D space; the Weibel filaments are stable during the filament merging process against secondary instabilities such as the Buneman and other electrostatic modes found in 2D in-plane simulation studies. We also found that electron heating processes continue during coalescence of ion-scale filaments in the late nonlinear stage and are crucial for the sustained magnetic field.



3D profiles of the magnetization parameter color-coded in a logarithmic scale at characteristic time stages of (a) the electron Alfven current (t=20 omega_{p,i}^{-1}), and (b) the ion Alfven current t=280 omega_{p,i}^{-1}).}

References
M. Takamoto, Y. Matsumoto, and T. N. Kato, Astrophys. J. Lett., 860, doi:10.3847/2041-8213/aac6d6, 2018