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Generation of oblique whistler waves by an energetic electron beam

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Diffusive shock acceleration (DSA) stands as the leading candidate for producing high-energy particles, such as cosmic rays believed to be accelerated at supernova remnant shocks. However, it still faces a challenge known as the electron injection problem, as it cannot efficiently accelerate electrons with low energies. Overcoming this challenge necessitates higher-frequency waves capable of scattering these low-energy electrons to confine them around the shock.

Matsukiyo et al. (2011) proposed a self-generation mechanism wherein energetic electrons reflected in the upstream region of the shock locally excite oblique whistler waves. These waves scatter the electrons back toward the shock, potentially contribute to effective confinement of electrons close to the shock. Similar oblique wave generation ahead of the shock has been observed in simulations of non-relativistic shocks with various parameter regimes (e.g., Guo et al. 2014, Kobzar et al. 2021, Bohdan in 2022). It is also interesting to note that oblique wave generation mechanisms by an electron heat flux have been discussed for different astrophysical contexts, including the solar wind (Verscharen et al. 2019), solar flares (Roberg-Clark et al. 2019), and intracluster medium (Roberg-Clark et al. 2018). Understanding the wave generation mechanism by an energetic electron beam may help to solve the injection problem.

Our study aims at improving the understanding the conditions required for wave generation and the resulting scattering efficiency. We conduct two-dimensional (2D) Particle-In-Cell (PIC) simulations with a simplified periodic model to reduce the computational costs and, at the same time, ease the theoretical analysis. Our model assumes that the plasma consists of three particle population: background ions and electrons, and a hot electron beam propagating along an ambient magnetic field.

We have confirmed that, as predicted by Verscharen et al. (2019), the system becomes unstable when the beam velocity is larger than the electron Alfven velocity. We observe that the generated waves propagate at an angle of approximately 80 degrees with respect to the background magnetic field and the wave amplitude at saturation is around 0.1 times the background magnetic field. Our ongoing investigation focuses on exploring the dependence of wave generation on the beam velocity and the plasma to cyclotron frequency ratio. This investigation aims to understand the factors determining the saturation level and scattering efficiency in a realistic system.