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PIC simulations of harmonic maser emissions

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Electron cyclotron maser emission (ECME) represents an important mechanism for coherent radio emissions from various kinds of astrophysical sources. In solar active regions, ECME has been regarded as the most favored mechanism for solar radio spikes, which are characterized by high brightness temperatures, short durations, narrow bandwidths, and strong X-mode polarization.

One major problem of ECME when it is applied to spikes is how fundamental emissions can pass through the second harmonic layer without being mostly absorbed. [1] One possibility to resolve this problem is through efficient excitation of maser emissions at second or higher harmonics which are more likely to escape. Earlier studies have found that only fundamental X-mode emissions can be amplified via the loss-cone ECME in strongly magnetized plasmas. [2] To investigate such possibility, we conducted fully kinetic electromagnetic 2D3V Particle-in-cell (PIC) simulations to reveal novel mechanism of how harmonic emission can be excited via the loss-cone (and horseshoe-) ECME.

As an analogy of the auroral kilometric radiations, solar spikes could be induced by energetic electrons with horseshoe distribution which can form in flare loops. [3] We employed horseshoe distribution consisting of a shell and a double-sided loss-cone feature in PIC simulation as the driver of ECME. The density ratio of energetic electrons to total electrons varies from 1% to 50%. We found that horseshoe electrons could amplify X-mode emissions at second and third harmonics (X2 and X3) simultaneously, and the amplification gets more efficient with increasing density ratio. We estimated the brightness temperatures of the obtained X2 to be 10^{11} to 10^{15} K, consistent with the observations of spikes.

The loss-cone ECME has been widely investigated by previous studies, including linear and quasi-linear analyses. We performed a long-duration simulation to study the wave excitations induced by double sided loss-cone distribution, and non-linear interaction processes. We found that the loss-cone electron cyclotron maser instability (ECMI) could amplify X1 and Z mode waves along quasi-parallel and quasi-perpendicular directions. As a major result, we obtained significant amplifications of X2 emissions at discrete frequencies. We suggest that the X2 emissions are produced by nonlinear coalescence processes of Z+X1 and/or Z+Z. Such process represents a novel mechanism of X2 emission in strongly magnetized plasmas.

For the first time, we obtain X2 and X3 emissions simultaneously via horseshoe ECME, and X2 emissions through the indirect nonlinear wave-wave coalescence process generated by loss-cone distribution. The results shed new lights on the mechanism of harmonic maser emissions and on resolving the escaping difficulty of ECME.

References

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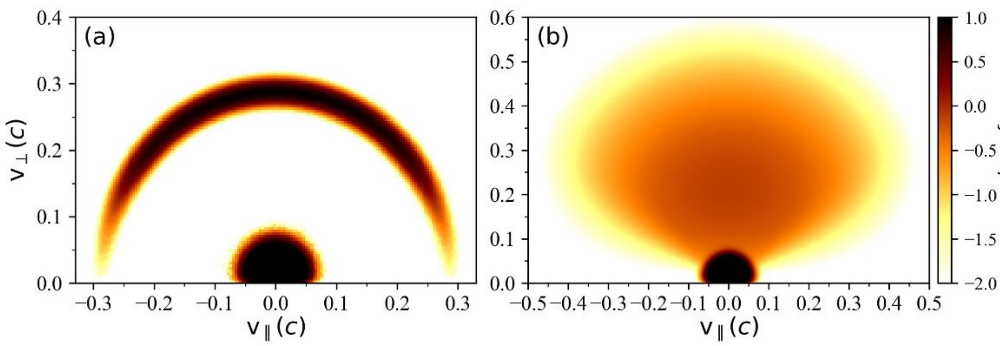

Figure 1. Snapshots of the velocity distribution at the beginning of the simulations with horseshoe (a) and loss-cone (b) distributions. The density ratio of energetic electrons to total electrons are set to be 10%.