Harmonic Electron Cyclotron Maser Emission Excited by Energetic Electrons Traveling inside a Coronal Loop

Mehdi Yousefzadeh, Hao Ning, and Yao Chen
Institute of Space Sciences and Institute of Frontier and Interdisciplinary Science, Shandong University, Shandong, People’s Republic of China; yaochen@sdu.edu.cn

Received 2020 November 7; revised 2021 January 2; accepted 2021 January 4; published 2021 March 1

Abstract

A complete understanding of solar radio bursts requires developing numerical techniques that can connect large-scale activities with kinetic plasma processes. As a starting point, this study presents a numerical scheme combining three different techniques: (1) extrapolation of the magnetic field overlying a specific active region in order to derive the background field, (2) guiding-center simulation of the dynamics of millions of particles within a selected loop to reveal the integral velocity distribution function (VDF) around certain sections of the loop, and (3) particle-in-cell simulation of kinetic instabilities driven by energetic electrons initiated by the obtained distributions. Scattering effects at various levels (weak, moderate, and strong) due to wave turbulence-particle interaction are considered using prescribed timescales of scattering. It was found that the obtained VDFs contain strip-like and loss-cone features with positive gradient, and both features are capable of driving electron cyclotron maser emission, which is a viable radiation mechanism for some solar radio bursts, in particular, solar radio spikes. The strip-like feature is important in driving the harmonic X mode, while the loss-cone feature can be important in driving the fundamental X mode. In the weak-scattering case, the rate of energy conversion from energetic electrons to X2 can reach up to \( \sim 2.9 \times 10^{-3} \) \( E_{\text{kev}} \), where \( E_{\text{kev}} \) is the initial kinetic energy of energetic electrons. The study demonstrates a novel way of exciting the X2 mode in the corona during solar flares and provides new insight into how escaping radiation can be generated within a coronal loop.

Unified Astronomy Thesaurus concepts: Solar corona (1483); Solar activity (1475); Radio bursts (1339); Solar coronal radio emission (1993); Plasma astrophysics (1261)

Supporting material: animations

1. Introduction

Solar radio bursts represent the sudden enhancement of emission at radio wavelengths released from the solar atmosphere. Various types of bursts have been classified according to their manifestation on the dynamic spectrum, such as bursts of type I–V, millisecond solar spikes, flare decimetric continuum, and so on (Wild et al. 1963; McLean 1985; see, e.g., Feng et al. 2012; Chen et al. 2014; Li et al. 2017, and Vasantha et al. 2019 for latest studies). Among them, solar spikes are radio bursts closely associated with the impulsive stage of solar flares. Spikes are characterized by their extremely high brightness temperature of up to \( 10^{15} \) K, the highest among all types of solar radio bursts. They appear in metric-decimetric wavelengths, exhibiting very narrowband spectral width with rapidly rising intensity profile and extremely short characteristic timescales (~a few to tens of millisecond for an individual burst). Thousands of spikes can exist in an event. This leads some researchers to suggest that solar spikes represent elementary energy release events during solar flares (see, e.g., Benz 1986; Benz & Kane 1986; Fleishman & Mel’nikov 1998).

In earlier studies, electron cyclotron maser emission (ECME) is considered to be the emission mechanism of solar spikes (see, e.g., Holman et al. 1980; Melrose & Dulk 1982; Robinson 1991). The ECME mechanism was initially proposed by Twiss (1958), Gaponov (1959), and Schneider (1959). Wu & Lee (1979) realized the importance of relativistic effect in the resonance condition and applied ECME to Decametric Radiation of Jupiter. Later, the theory was used to explain solar radio bursts, such as solar spikes (Melrose & Dulk 1982; Sharma & Vlahos 1984; Aschwanden 1990) and type IIs (Wu et al. 2005). According to Wu & Lee (1979) and follow-up studies, ECME can be excited by energetic electrons with a positive gradient along the perpendicular direction in the velocity space, that is, \( \partial f / \partial v_{\perp} > 0 \) in plasmas with \( \omega_{pe} / \Omega_{ce} < 1 \). In addition, ECME favors the growth of X mode. In plasmas with \( \omega_{pe} / \Omega_{ce} > 1 \) the growth rates of the X and O modes decline rapidly, while Z (or the electrostatic upper hybrid mode at large wavenumber) and W become the dominant modes (Sharma & Vlahos 1984; Lee et al. 2009; Yi et al. 2013; Ni et al. 2020).

Most earlier studies suggest the solar spikes are excited by ECME of energetic electrons with the loss-cone distribution, that is, via the loss-cone maser. Such a distribution can form when electrons are trapped and bounced within a coronal loop. Nevertheless, unresolved issues exist that hinder us from a complete understanding of the exact emission mechanism and how one can use radio data to infer coronal properties. One major difficulty lies in the fact that any solar radio bursts are a consequence of a multiscale process. An event would start from large-scale magnetic eruptive activities in the astronomical to MHD scale, followed by particle acceleration via magnetic reconnection or shocks in the particle kinetic scale and excitation and propagation of radiations. Current computational resources are far from enough to simulate such cross-scale physics.

Another difficulty is that the loss-cone maser for solar spikes mainly excites the fundamental X mode (X1), and it is difficult for X1 to pass through the second harmonic absorption layer during its escape from the source (Melrose & Dulk 1982). This gives the escaping difficulty of ECME when it is applied to solar radio bursts. To resolve this, Melrose & Wheatland (2016) proposed that a low-density cavity exists in the source region, which can duct the X mode out. Existence of such a low-density cavity in the corona has not yet been verified.
Another option is to have direct excitation of X at higher harmonics such as X2 and X3, since the absorption rates at the third or fourth harmonic layer are considerably less compared with that at the second harmonic. Yet direct and efficient excitation of X2 and X3 is rarely reported. Most, if not all, existing studies on emission mechanism of solar radio bursts, including solar spikes, started from an analytically prescribed distribution function of energetic electrons. Such a function is not determined by the particle dynamics in a self-consistent way. In this study, we present a preliminary effort to connect macroscale dynamics of energetic electrons with microscale kinetic instabilities energized by these electrons to explain the possible emission mechanisms behind solar spikes. This is done by combining three sets of numerical techniques working at different scales. It was found that the velocity distribution functions (VDFs) deduced from the simulations contain certain interesting features that are capable of exciting emission efficiently at the second harmonic (X2) via ECME, thus providing a novel approach to resolve the escaping difficulty of ECME. The Section 2 introduces numerical techniques used here, Section 3 presents the analysis and major results, and Section 4 presents the summary and discussion.

2. Numerical Schemes

To bridge the physics of different spatial scales and simplify the effort as much as possible, we combine three sets of numerical techniques, including (1) the nonlinear force-free field (NLFFF) extrapolation method (Wheatland et al. 2000; Wiegelmann 2004; Wiegelmann et al. 2006) to describe large-scale topology of corona magnetic field within which electrons are traveling and trapped, (2) the guiding-center (GC) simplification method (e.g., Northrop 1963; Gordovskyy et al. 2010) to simulate dynamical motions of a large-number of electrons to infer evolution of their VDF, and (3) the particle-in-cell (PIC) simulation fed by the obtained VDFs to explore the excited kinetic instabilities and radiations. This represents a significantly simplified approach for the proposed study.

2.1. NLFFF Extrapolation of the Coronal Magnetic Field

To start the simulation, we selected one specific active region (NOAA AR 11283), which released a group of eruptions including three big flares (M5.3, X2.1, and X1.8) on 2011 September 6 and 7. It has been investigated in several studies (e.g., Liu et al. 2014; Ruan et al. 2014; Romano et al. 2015). Here we start from the magnetic condition before the X2.1 flare. The NLFFF extrapolation was based on the magnetogram data observed at 21:30 UT by the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012).

The HMI data and the result of extrapolation are shown in Figure 1(a), from which we observe a clear twisted flux rope structure whose eruption releases the X2.1 flare. Three representative field lines with different amount of twist are plotted. The loop shown in panel (b) contains no significant twist, and the field strengths at the two foot points are close to 1800 G and 1200 G. The location with the minimum field strength is close to the loop top. The loop in panel (c) presents the M-like topology with significant twist, and the field strengths at the two foot points are nearly 300 G and 1800 G. The location with the minimum field strength is located at the right foot point. The field line in panel (d) has more twists, and the field strength at its left foot is 1400 G, decreasing to a local minimum at 800 G, then increasing to the maximum at nearly 1300 G around the top part, and then decreasing to 400 G and further increasing to 1200 G at the right foot.

Figure 1. (a) The magnetogram of HMI for AR 11283 before the eruption of the major X2.1 flare on 2011 September 6, overplotted with field lines given by NLFFF extrapolation; (b)–(d) representative lines with different amount of twist. The color in panels (b) represents the field strength (in units of Gauss) of the lines presented in (b)–(d). The letters A–D represent the sections within which VDFs will be examined, and the letter I represents the region of injection.
As a starting point, we conduct a simulation of particle dynamics within the simple untwisted loop configuration, that is, the one shown in panel (b). Note that selection of the specific active region and the loop is just to provide a realistic magnetic condition of the corona to initiate the simulation. The loop forms a simple magnetic trap (or mirror) and represents a typical field line in the background corona overlying the preeruption flux rope structure. Using another twisted configuration would be interesting yet more complex, and the essential physics should be revealed by the study using the simple untwisted loop structure. From the extrapolation technique we can obtain three-dimensional distribution of field strength and direction along the whole loop. The information will be fed to the following GC simulation of particle dynamics as input. The timescale of the bouncing motion can be estimated with the loop length and the average energy of electrons. Here the height of the selected loop structure is about 100″, and the length is nearly 300″. Thus, it takes ~3 s for electrons with an energy of 15 keV to travel such distance.

2.2. GC Simulation of Dynamics of Energetic Electrons

The VDF of energetic electrons accounting for radio emission remains unknown. It is related to the acceleration and heating mechanism and further wave–particle interaction during solar flares. In any case, strong heating seems to be an intrinsic part of solar flares; therefore, one may obtain heated electrons with high-temperature Maxwellian-like distribution. The heated electrons will be injected into a loop that might be the postreconnection loop or one of the loops directly connected to the reconnection region. If reconnection takes place high in the corona, as indicated by the X-ray data of flares (Masuda et al. 1994; Sui & Holman 2003; Chen et al. 2017), the top of loops could be a probable place of injection. To simulate the following dynamic motion, we inject two million electrons with a Maxwellian distribution around the loop top in an impulsive way (labeled with I in Figure 1(b)). The length of the injection section is ~5″. The VDF is expressed by

\[ f_0 = \frac{1}{(2\pi)^{3/2} v_0^3} \exp \left( -\frac{u^2}{2v_0^2} \right), \]

where \( v_0 = 0.24c \) and \( c \) is the speed of light. The GC simplification is described with standard relativistic equations (Northrop 1963; Gordovskyy et al. 2010). To apply this method, the characteristic time and spatial scales of particle gyromotion should be much less than those of the magnetic field variation. For the simple untwisted large-scale loop structure, such conditions are well satisfied. The classical Bulirsch–Stoer approach is employed to solve the GC equations, which is characterized by a high level of accuracy in energy conservation.

Preexisting waves and those excited after injection can scatter electrons and modify their VDFs. To simulate such an effect, we introduce a parameter \( \tau_e \) to represent the timescale of pitch-angle scattering: within each interval of \( \tau_e \), the pitch angle of an electron will be changed to a random value in a range of \([0, \pi]\). A larger \( \tau_e \) represents weaker scattering and vice versa. We refer to Piana et al. (2007) and Chen & Petrosian (2013) for characteristic values of \( \tau_e \) during solar flares. For electrons of a few tens of Kev, \( \tau_e \) could be around 0.1–1 s. Thus, we set \( \tau_e \) to be 5 s, 1 s, and 0.5 s, to represent weak (case W), moderate (case M), and strong (case S) levels of scattering, respectively.

2.3. VPIC Simulation of ECME Driven by Energetic Electrons

We use the Vector-PIC (VPIC) open-source code released by the Los Alamos National Labs for PIC simulation. The code employs a second-order, explicit, leapfrog algorithm to update particle positions and velocities, along with a second-order finite-difference time-domain solver for evolution of electric and magnetic fields, which are described by the full Maxwell equations (Bowers et al. 2008a, 2008b, 2009).

To initiate the PIC simulation, we adopt Maxwellian distribution for background plasmas consisting of electrons and protons. The background magnetic field is set to be along \( e_z \) (\( B_z = B_0 e_z \)), and the wavevector (\( k \)) is within the \( xz \) plane. VDFs of energetic electrons are taken from the above GC simulation, and only those at the loop top are used. According to the NLFFF extrapolation, the field strength around the loop top is ~400 G, and the number density of background plasmas \( n_0 \) is assumed to be \( 10^9 \text{cm}^{-3} \); thus the ratio of plasma oscillation frequency and electron gyrofrequency, that is, \( \omega_{pe}/\Omega_{ce} \), is 0.25. This means that ECME should be important. The density ratio of energetic and background electrons \( (n_e/n_0) \) is taken to be 0.05. The grid spacing is \( \Delta = 2.7 \lambda_D \), where \( \lambda_D \) is the Debye length of background electrons and the grid number is \([512, 512, 512]\). The simulation time and domain are \( 2000 \omega_{pe}^{-1} \) for cases W and M and \( 2500 \omega_{pe}^{-1} \) for case S, and the simulation domain in space is given by \( L_x = L_z = 25 e/\omega_{pe} \). The resolved ranges of wavenumber and frequency are then \([-16, 16] \Omega_{ce}/c \) and \([0, 3.2] \Omega_{ce} \) respectively. In each cell for each species, we employ 1000 macroparticles. The charge neutrality condition is maintained.

Note that VDFs of energetic electrons within the loop change with many factors, such as time, location, form of initial distribution, location of injection, scattering effect, and so on. This results in lots of variations. Keeping this in mind, the present study is taken as a starting point along the proposed line of research, with two main aims: to determine (1) how VDFs evolve along the loop structure while considering various levels of scattering and (2) whether and how VDFs are capable of efficient excitation of harmonic X modes (X2, as well as other wave modes) so as to partially address the escaping difficulty associated with ECME. In the following, we first present evolution of VDFs within four different sections of the loop and then compare outputs of PIC simulations that are initiated by three sets of VDFs obtained at the same location (loop top) and time (1 s after injection) with different levels of scattering. Results with VDFs at other locations and times, as well as using different forms of initial distribution within a different loop structure, will be examined in the future.

3. Numerical Results and Analysis

3.1. VDFs Given by the GC Simulation

In our GC simulation, the motions of two million electrons are resolved. To evaluate evolutions of VDFs along the loop, we select four sections, referred to as A, B, C, and D (see Figure 1(b)). Their lengths are taken to be large enough (~12″) to get a sufficient number of electrons. The VDFs at a certain moment are obtained by collecting the information of all electrons within the specific section at the moment of interest.

Note that electrons with small initial pitch angles may get lost from the loop. Electrons that are bounced backward give rise to the well-known loss-cone distribution. If electrons are also mirrored from the other side of the loop, a double-sided
The Astrophysical Journal, 909:3 (8pp), 2021 March 1

Yousefzadeh, Ning, & Chen

loss-cone distribution is obtained. For the selected loop, the ratio of maximum to minimum $B$, that is, the mirror ratio, is $\sim 3$, which gives a loss-cone angle of $\sim 35^\circ$. When scattering effect is included, all electrons will get lost eventually, with stronger scattering leading to faster loss. These deductions are verified by our GC simulations.

Figures 2(a)–(d) present the temporal evolution of the obtained VDFs at different loop sections (see Figure 1(b)) for the case with weak level of scattering, i.e., case W with $\tau = 5$ s. Numbers of particles ($N$) used to get the integral VDFs are written on the top of each panel. (e)–(f) VDFs corresponding to moderate (M), and strong (S) levels of scattering for section A, also obtained at $t = 1$ s after injection. Resonance curves corresponding to the X2, X1, and Z modes are overplotted. For X2, the parameters used to plot these curves are as follows: wave frequency $\omega = 1.98 \Omega_{ce}$, the total wavenumber $k = 1.92 \Omega_{ce}/c$, propagation angle $\theta = 100^\circ$, and harmonic number $n = 2$; for X1, they are $1.08 \Omega_{ce}$, $0.65 \Omega_{ce}/c$, $35^\circ$, and 1, respectively; and for Z they are $0.96 \Omega_{ce}$, $1.15 \Omega_{ce}/c$, $100^\circ$, and 1, respectively. The animation of this figure (panels (a), (c), and (f)) for the main three cases (W, M and S) begins at $t = 0$ s and advances 0.1 s at a time up to $t = 3$ s and then continues with 2 s intervals until the end, at $t \sim 19$ s. The real-time duration of the video is 7 s.

(An animation of this figure is available.)

Figure 2. (a)–(d) The obtained VDFs at a specific time (1 s after injection) within different loop sections (see Figure 1(b)) for the case with weak level of scattering, i.e., case W with $\tau = 5$ s. Numbers of particles ($N$) used to get the integral VDFs are written on the top of each panel. (e)–(f) VDFs corresponding to moderate (M), and strong (S) levels of scattering for section A, also obtained at $t = 1$ s after injection. Resonance curves corresponding to the X2, X1, and Z modes are overplotted. For X2, the parameters used to plot these curves are as follows: wave frequency $\omega = 1.98 \Omega_{ce}$, the total wavenumber $k = 1.92 \Omega_{ce}/c$, propagation angle $\theta = 100^\circ$, and harmonic number $n = 2$; for X1, they are $1.08 \Omega_{ce}$, $0.65 \Omega_{ce}/c$, $35^\circ$, and 1, respectively; and for Z they are $0.96 \Omega_{ce}$, $1.15 \Omega_{ce}/c$, $100^\circ$, and 1, respectively. The animation of this figure (panels (a), (e), and (f)) for the main three cases (W, M and S) begins at $t = 0$ s and advances 0.1 s at a time up to $t = 3$ s and then continues with 2 s intervals until the end, at $t \sim 19$ s. The real-time duration of the video is 7 s.

(An animation of this figure is available.)

feature appears shortly after the injection, corresponding to particles with relatively large pitch angles and therefore small bouncing distance; the upper one appears with large $v_{||}$ and large-positive $v_{\perp}$, then mitigating to regions with smaller $v_{\perp}$ and negative $v_{||}$. The strips appear earlier for sections closer to the top. They are given by energetic electrons that have experienced bouncing by at least one time and arrive at the section window at the specific time. Similar multistrip features have been demonstrated earlier by White et al. (1983) in their analytical evaluation of VDFs for a one-dimensional magnetic field line. We have repeated their calculation and obtain similar results, confirming the validity of the simulation result presented here. The features are of major interest here since they emerge along the whole structure with significant positive gradients of VDFs; this makes them candidates for an efficient driver of ECME.

We also conducted GC simulations for cases with moderate (case M) and strong (case S) levels of scattering. The solutions within section A at the same time after the injection ($t = 1$ s)
are presented in Figures 2(e) and (f) (and the accompanying movie). They are basically similar to that for case W. With stronger scattering effect, electrons are lost from the loop at a faster pace, the strip feature becomes less sharp and more blurred, and the number of observable strips may decrease. For example, only a very weak signature of strips remains in case S (see Figure 2(f)).

3.2. PIC Simulations of ECME Radiation

The PIC simulations are initiated by the three sets of VDFs of energetic electrons that correspond to different levels of scattering, referred to as cases W, M, and S, respectively. The VDFs are obtained at 1 s after injection and are shown in Figures 2(a), (e), (f). The parameter setup of the PIC simulation has been presented above. In the following, we first introduce results for case W and then compare them with other cases.

3.2.1. PIC Simulation for Case W

We start from case W, which corresponds to a weak level of scattering with \( \tau = 5 \) s. The PIC-evolved distribution is presented in Figure 3(a) \((t \sim 1000 \omega_{pe}^{-1})\) and the accompanying movie. After \( t \sim 500 \omega_{pe}^{-1} \), energetic electrons start to diffuse significantly and the strip feature gets blurred, indicating strong wave– particle interaction. In Figure 4(a) we present the \( k \)-space intensity distribution of the strongest wave mode at the corresponding wavevector \( k \), and the \( \omega-k \) dispersion analysis is presented in Figure 5(a) and the online animation. We see that the strongest mode is the quasi-perpendicular \((90^\circ < \theta_B < 110^\circ)\) Z mode with frequency slightly less than \( \Omega_{ce} \), while the harmonic X mode (X2) is also at a high intensity along the quasi-perpendicular direction \((95^\circ < \theta_B < 105^\circ)\) with frequency slightly less than \( 2 \Omega_{ce} \). The X1 emission is very weak and mainly around \( 30^\circ \). Energy curves of these modes have been plotted in Figure 3(d). From the energy curves, the X2 and Z modes first grow linearly at basically the same growth rates, which are fitted to be 0.033 and 0.026 \( \omega_{pe}^{-1} \), respectively (see Figure 3(d) for fitting lines); before \( t \sim 500 \omega_{pe}^{-1} \), the two modes reach the maximum intensities of \(~2.9 \times 10^{-3}\) and \(~4.8 \times 10^{-3}\) \( E_{ke} \), respectively, where \( E_{ke} \) represents the total kinetic energy of energetic electrons.

The VDFs exhibit two types of features with positive gradients, that is, the loss-cone and the strip-like feature. To figure out the driving agency of each mode, we have plotted resonance curves onto the corresponding VDF map as shown in Figure 3(f). The curves are for the specific parameter set of \((\omega, k, \theta)\) at which the strongest intensities for the X2 and Z modes are achieved, while for X1 we select a representative propagation angle of \(35^\circ\). It is clear that the resonance curves of the X2 and Z modes almost overlap with each other, and both modes are excited by the same upper strip-like feature through the electron cyclotron maser instability (Wu & Lee 1979). The lower strip-like feature passes through the background Maxwellian distribution and is therefore unable to excite any wave mode. On the other hand, the resonance curve of X1 crosses the loss-cone feature and results in a weak excitation.

Figure 3. Upper panels: VDFs at \( t = 1000 \omega_{pe}^{-1} \) obtained by the PIC simulation for cases W, M, and S; lower panels: temporal profiles of energies of various wave modes (X2, X1, and Z), normalized to the total energy of energetic electrons (\( E_{ke} \)). Dashed lines represent exponential fitting of linear growth rates, which are 0.033, 0.0016, and 0.026 \( \omega_{pe}^{-1} \) for X2, X1, and Z in case W, respectively; 0.01, 0.0031, and 0.015 \( \omega_{pe}^{-1} \) for X2, X1, and Z in case M, respectively; and 0.0053 \( \omega_{pe}^{-1} \) for X1 in case S. Energy profiles are calculated within squares plotted in Figure 4(b). The video begins at \( t = 0 \omega_{pe}^{-1} \) and advances 100 \( \omega_{pe}^{-1} \) at a time up to \( t = 2000 \omega_{pe}^{-1} \). The real-time duration of the video is 4 s.
(An animation of this figure is available.)
In summary, for case W we get efficient excitation of Z and X2, yet without significant excitation of X1; both Z and X2 are associated with the upper strip-like feature of the VDF, while the loss-cone feature only leads to weak excitation of X1.

### 3.2.2. Comparison of PIC Simulations with Different Levels of Scattering

In this subsection, the results of PIC simulations for cases M ($\tau = 1$ s) and S ($\tau = 0.5$ s) are presented, and the differences of the three cases are highlighted. The initial and PIC-evolved VDFs are presented in Figures 2(e)–(f) and 3(b)–(c). The corresponding $k$-space intensity distribution of waves within the time range of 1500–2000 $\omega_{pe}^{-1}$ for cases S and M is presented in Figures 4(b)–(c), the results of $\omega$–$k$ dispersion analysis are presented in Figures 5(b)–(c) and the online animation, and energy curves for various wave modes are presented in Figures 3(d)–(f).

In general, it takes longer time for modes to saturate in cases with stronger scattering. As seen from the energy curves (Figure 3), in case M the durations of the linear stages of X2 and Z are both $\sim 800 \omega_{pe}^{-1}$, longer than the corresponding duration of the two modes in case W ($\sim 500 \omega_{pe}^{-1}$) and shorter.
than the duration of the linear growth of X1 in case S, which is \( \approx 1800 \, \omega_{pe}^{-1} \).

In case M, intensities of both X2 (\( \approx 3.0 \times 10^{-5} \, E_{ke} \)) and Z (\( \approx 3.3 \times 10^{-4} \, E_{ke} \)) are much smaller than those of case W, and X1 (\( \approx 2.1 \times 10^{-5} \, E_{ke} \)) becomes considerably enhanced over the noise. Ranges of frequencies and wavenumbers of the X2 (\( \approx 1.92\sim1.95 \, \Omega_{ce} \)) and Z (\( \approx 0.96\sim0.98 \, \Omega_{ce} \)) modes are quite close to those of case W. In case S, X1 becomes the strongest, reaching a maximum energy of \( \approx 3.8 \times 10^{-4} \, E_{ke} \), while both Z and X1 have energies of \( \approx 2 \times 10^{-7} \, E_{ke} \), much weaker than those in other cases. X1 has a symmetric arc-like emission pattern along the quasi-parallel to oblique direction \( (0^\circ < \theta_B < 55^\circ) \), and its intensity is close to the thermal noise level for larger \( \theta_B \). As read from the VDFs shown in Figures 2 and 3, densities of energetic electrons along the edge of the loss cone in case S are much higher than those in case W. This is due to a different level of scattering. With stronger scattering the loss-cone feature is better developed within a shorter period and the strip-like features are less significant, while for weaker scattering, a significant part of energetic electrons is still bouncing and the VDF is characterized by strip-like features at the time of interest (1 s after injection). It is apparent that the upper strip-like feature is more efficient (than the loss-cone feature) in converting electron energy into wave modes. This explains why the loss-cone feature in case W and case S plays a very different role and why the duration of the linear stage in the weaker-scattering case lasts for a shorter time.

Resonance curves shown in Figures 2(e) and (f) are plotted with parameters provided in the figure caption. Again, Z and X2 modes (if they exist) are excited by the upper strip feature in cases M and W, and the very strong emission of X1 in case S is driven by the loss-cone feature. The linear growth rate of X1 in case S is much smaller than that of X2 and Z in cases W and M.

Figure 5. Wave dispersion diagrams for (a) case W, (b) case M, and (c) case S at three propagation angles \( (\theta_B = 35^\circ, 95^\circ, \text{and} 100^\circ) \). The time interval of analysis is taken to be \( 1500 \leq \omega_{pe}^{-1} \leq 2000 \), and X2, X1, and Z stand for the harmonic X, fundamental X, and Z mode, respectively. The video begins at \( \theta_{kB} = 0^\circ \) and advances 5° at a time up to \( \theta_{kB} = 180^\circ \). The real-time duration of the video is 7 s.

(An animation of this figure is available.)

The Astrophysical Journal, 909:3 (8pp), 2021 March 1 Yousefzadeh, Ning, & Chen
Note that the similar emission pattern of X1 via the loss-cone maser has been reported by earlier studies (see, e.g., Wagner et al. 1983, 1984; Yoon & Ziebell 1995).

4. Summary and Discussion

As a starting point to bridge the large-scale dynamics and small-scale plasma kinetic maser instabilities associated with solar radio bursts, in particular, solar spikes, we developed a numerical scheme combining techniques including the magnetic field extrapolation to describe the magnetic configuration of a normal loop, the GC method to infer the temporal evolution of VDFs along various sections of the loop while taking the effect of pitch-angle scattering into account, and PIC simulations to further explore the kinetic instabilities driven by electrons with the obtained VDFs. Consistent with earlier studies, VDFs of energetic electrons that are released from the loop top manifest interesting strip-like feature with significant positive velocity gradient, together with the well-known loss-cone feature. According to further PIC simulations, the strip-like feature is essential for efficient excitation of ECME at harmonic X mode (in the weak-scattering case), while the loss-cone feature can be efficient in exciting the fundamental X mode (in the strong-scattering case). Efficient amplification of X2 favors the escape of ECME radiation from the corona, and this effectively reduces the limitation of applying ECME to solar spikes. The study provides new insight into how escaping radiation, in particular, the harmonic X mode, can be generated within a coronal loop.

In most earlier studies relevant to ECME and solar radio spikes (e.g., see Aschwanden 1990), loss-cone distributions have been applied. This distribution may lead to efficient excitation of X1 mode while being unable to drive efficient excitation of X2 or higher harmonics. During its outward escape, it is difficult for the X1 mode to pass the second-harmonic absorption layer where the absorption coefficient is notoriously large. This gives rise to the escaping difficulty of fundamental emission from the corona. To resolve this issue, efficient excitation of radio bursts at higher harmonics is required. Thus, the most significant point of this study is the efficient excitation of X2 under certain conditions. Here we demonstrate that strip-like features of VDFs can form due to the initial bouncing motion of energetic electrons that are released at the loop top. These features are formed during the early stage of the VDF relaxation toward a well-developed loss-cone distribution, and they are critical to efficient excitation of harmonic X mode.

It should be pointed out that excitation of ECME radiation depends sensitively on many conditions. The effect of pitch-angle scattering on both VDFs and further excitation of wave modes has been demonstrated. In addition, the initial distribution of electrons, injection location, the way of injection (e.g., impulsively or continuously, see White et al. 1983), and the ratio of the characteristic frequencies ($\omega_{pe}/\Omega_{ce}$) all affect the obtained form of VDFs and further excitation of various wave modes. Future study shall expand the parameter regime for a more complete understanding of the multiscale radiation processes.

The present study is supported by the National Natural Science Foundation of China (11790303, 11790300, 11973031, and 11873036). The authors acknowledge the open-source Vector Particle In Cell (VPIc) code provided by Los Alamos National Labs (LANL), Super Cloud Computing Center (BSCC, URL: http://www.bsc.cn/) for providing high-performance computing resources, and Dr. Alexander William Degeling and Xiangliang Kong (Shandong University) and Dr. Mahboub Hosseinpour (Tubriz University) for helpful discussion.

ORCID iDs
Mehdi Yousefzadeh https://orcid.org/0000-0003-2682-9784
Hao Ning https://orcid.org/0000-0001-8132-5357
Yao Chen https://orcid.org/0000-0001-6449-8838

References
Aschwanden, M. J. 1990, A&A, 237, 512
Benz, A. O. 1986, SoPh, 104, 99
Benz, A. O., & Kane, S. R. 1986, SoPh, 104, 179
Bowers, K. J., Albright, B. J., Bergen, B., et al. 2008a, in Proc. of the 2008 ACM/IEEE Conf. on Supercomputing (Piscataway, NJ: IEEE), 63
Bowers, K. J., Albright, B. J., Yin, L., et al. 2008b, PhPl, 15, 055703
Bowers, K. J., Albright, B. J., Yin, L., et al. 2009, JPhCS, 180, 012055
Chen, Q., & Petrovits, V. 2013, ApJ, 777, 33
Chen, Y., Du, G., Feng, L., et al. 2014, ApJ, 787, 59
Chen, Y., Wu, Z., Liu, W., et al. 2017, ApJ, 843, 8
Feng, S. W., Chen, Y., Kong, X. L., et al. 2012, ApJ, 753, 21
Fleishman, G. D., & Mel’nikov, V. F. 1998, PhyC, 41, 1157
Gaponov, A. V. 1959, IzRAd, 2, 450
Gordovskyy, M., Browning, P. K., & Vekstein, G. E. 2010, A&A, 519, A21
Holman, G. D., Eichler, D., & Kundu, M. R. 1980, in IAU Symp. 86, Radio Physics of the Sun, ed. M. R. Kundu & T. E. Gergely (Cambridge: Cambridge Univ. Press), 457
Lee, K. H., Omura, Y., Lee, L. C., et al. 2009, PhRvL, 103, 105101
Li, C. Y., Chen, Y., Wang, B., et al. 2017, SoPh, 292, 82
Liu, C., Deng, N., Lee, J., et al. 2014, ApJ, 795, 128
Masuda, S., Kosugi, T., Hara, H., Tsuruta, S., & Ogawara, Y. 1994, Natur, 371, 495
McLean, D. J., & Labrum, N. R. 1985, Solar Radiophysics: Studies of Emission from the Sun at Metre Wavelengths (Cambridge: Cambridge University Press)
Melrose, D. B., & Dulk, G. A. 1982, ApJ, 259, 844
Melrose, D. B., Dulk, G. A., & Cairns, I. H. 1986, A&A, 163, 229
Melrose, D. B., & Wheatland, M. S. 2016, SoPh, 291, 3637
Ni, S., Chen, Y., Li, C., et al. 2020, ApJL, 891, L25
Northrop, T. 1963, The Adiabatic Motion of Charged Particles (New York: Interscience)
Piana, M., Massone, A. M., Hurford, G. J., et al. 2007, ApJ, 665, 846
Robinson, P. A. 1991, SoPh, 134, 299
Romano, P., Zuccarello, F., Guglielmino, S. L., et al. 2015, A&A, 582, 55
Ruan, G., Chen, Y., Wang, S., et al. 2014, ApJ, 784, 165
Schneider, J. 1959, PhDVL, 2, 504
Schou, J., Scherrer, P. H., Bush, R. I., et al. 2012, SoPh, 275, 229
Sharma, R. R., & Vlahos, L. 1984, BAAS, 16, 536
Sui, L., & Holman, G. D. 2003, ApJ, 596, L251
Twiss, R. Q. 1958, AulPh, 11, 564
Vasanth, V., Chen, Y., Lv, M., et al. 2019, ApJ, 870, 30
Wagner, J. S., Lee, C. L., Wu, C. S., et al. 1983, GeoRL, 10, 483
Wagner, J. S., Lee, L. C., Wu, C. S., et al. 1984, RaSc, 19, 509
Wheatland, M. S., Sturrock, P. A., & Roumeliotis, G. 2000, ApJ, 540, 1150
White, S. M., Chen, Y., Li, C., et al. 2020, ApJL, 891, 5, 188
Wiegelmann, T. 2004, SoPh, 219, 87
Wiegelmann, T., Inhester, B., & Sakurai, T. 2006, SoPh, 233, 215
Wild, J. P., Smerd, S. F., & Weiss, A. A. 1963, ARA&A, 1, 291
Wu, C. S., & Lee, L. C. 1979, ApJ, 230, 621
Wu, C. S., Wang, C. B., Zhou, G. C., Wang, S., & Yoon, P. H. 2005, ApJ, 621, 1129
Yi, S., Lee, S.-Y., Kim, H.-E., et al. 2013, JGR, 118, 7584
Yoon, P. H., & Ziebell, L. F. 1995, PhRVe, 51, 4908