ELECTRON CYCLOTRON MASER EMISSIONS FROM EVOLVING FAST ELECTRON BEAMS

J. F. Tang\textsuperscript{1,2}, D. J. Wu\textsuperscript{3}, L. Chen\textsuperscript{3}, G. Q. Zhao\textsuperscript{4}, and C. M. Tan\textsuperscript{2}

\textsuperscript{1} Xinjiang Astronomical Observatory, Chinese Academy of Sciences, 150 Science 1-Street, Urumqi, Xinjiang 830011, China; jftang@xao.ac.cn
\textsuperscript{2} Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
\textsuperscript{3} Purple Mountain Observatory, CAS, Nanjing 210008, China
\textsuperscript{4} Institute of Space Physics, Luoyang Normal University, Luoyang 471022, China

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ABSTRACT

Fast electron beams (FEBs) are common products of solar active phenomena. Solar radio bursts are an important diagnostic tool for understanding FEBs and the solar plasma environment in which they propagate along solar magnetic fields. In particular, the evolution of the energy spectrum and velocity distribution of FEBs due to the interaction with the ambient plasma and field during propagation can significantly influence the efficiency and properties of their emissions. In this paper, we discuss the possible evolution of the energy spectrum and velocity distribution of FEBs due to energy loss processes and the pitch-angle effect caused by magnetic field inhomogeneity, and we analyze the effects of the evolution on electron-cyclotron maser (ECM) emission, which is one of the most important mechanisms for producing solar radio bursts by FEBs. Our results show that the growth rates all decrease with the energy loss factor $Q$, but increase with the magnetic mirror ratio $\sigma$ as well as with the steepness index $\delta$. Moreover, the evolution of FEBs can also significantly influence the fastest growing mode and the fastest growing phase angle. This leads to the change of the polarization sense of the ECM emission. In particular, our results also reveal that an FEB that undergoes different evolution processes will generate different types of ECM emission. We believe the present results to be very helpful for a more comprehensive understanding of the dynamic spectra of solar radio bursts.

Key words: plasmas – radiation mechanisms: non-thermal – Sun: radio radiation

1. INTRODUCTION

Beams of energetic particles are common products in various active phenomena in space and cosmic plasmas. For the Sun, particle acceleration is most prominent in flares and coronal shock wave. It is generally recognized that the magnetic reconnection process during flares can convert magnetic energy into the thermal and kinetic energies of the accelerated particles (Masuda et al. 1994; Yokoyama et al. 2001; Harai et al. 2011; Imada et al. 2013). Lin & Hudson (1976) pointed out that as much as half of the liberated energy from flares can be converted into the acceleration of charged particles through the magnetic reconnection process. Collisionless shocks are also strong sources of fast electron beams (FEBs; Blandford & Eichler 1987). For coronal shock waves, there are two different generation mechanisms: blast waves are initiated by the plasma pressure of flares, and piston-driven shock waves are due to coronal mass ejections (CMEs; Nindos et al. 2011). The primary theory to explain particle acceleration in the vicinity of shock waves is diffusive shock acceleration (DSA; Bell 1978; Drury 1983; Blandford & Eichler 1987). Electron acceleration by quasi-perpendicular shocks has been discussed by many authors and it has been proposed that they can be accelerated through shock-drift acceleration (Wu 1984; Park et al. 2012; Guo & Giaacalone 2015). For quasi-parallel shocks, when a large-amplitude magnetic fluctuation is present, the shocks can efficiently accelerate electrons (Masters et al. 2013).

FEBs reveal themselves not only in hard X-rays and $\gamma$-ray emission, but also in radio emission (Pick & van den Oord 1990). The most direct observational evidence of FEBs in radio emission is type III bursts and decimetric blips, which have properties similar to type III events (Stihl & Benz 1987). Type III bursts are due to FEBs traveling upward along open magnetic field structures. Observations of radio bursts reveal that FEBs also propagate in the downward direction (reverse-slope drift bursts) or along closed magnetic field lines (type J and U bursts; Aschwanden et al. 1995). When electron beams propagate downward along the closed loop, electrons with large pitch angles can be reflected and captured in the loop, while electrons with small pitch angles will precipitate into the dense chromosphere. It is the precipitate and trapped electrons that produce hard X-ray and radio emission, respectively. The key issue is how a beam of fast electrons leads to the generation of solar radio bursts described above. Ginzburg & Zhelezniakov (1958) proposed so-called plasma emission. In this conventional theory, Langmuir waves play a key role. FEBs accelerated by the magnetic reconnection process or a coronal shock wave can excite Langmuir waves due to beam-plasma instability along their path when they propagate in the corona. Then, these electrostatic waves are partly converted into electromagnetic waves via nonlinear wave–wave interactions (Robinson et al. 1993; Wu et al. 1994). Reiner et al. (1998) found that plasma emission is the emission mechanism of type II bursts generated in the upstream region of the CME-driven shock. This theory, which treats the acceleration of electrons near the shock, the formation of FEBs, the generation of Langmuir waves, and the conversion of Langmuir waves into electromagnetic waves, has been studied by many authors (Knock et al. 2001; Knock & Cairns 2005; Schmidt & Gopalswamy 2008). Another important coherent theory was suggested by Twiss (1958) and Schneider (1959) which directly amplifies the electromagnetic waves at frequencies near the electron gyrofrequency and its harmonics. Electron-cyclotron maser (ECM) instability due to the wave–particle interaction is the amplification mechanism.

As a dominant mechanism for radio emission in astrophysics, ECM emission has been extensively applied to various short-duration radio bursts from magnetized planets, the Sun,
and other stars (Treumann 2006). In reference to ECM emission, the FEBs responsible for the generation of radio radiation are treated as an invariable source. However, FEBs propagating downward deeper into the solar atmosphere will lose some of their energy via interaction with the dense plasma (Pick & van den Oord 1990), and the energy spectrum of FEBs will evolve due to this energy loss process. High-resolution X-ray observations suggest that the noncollisional energy loss of FEBs which are traveling in the loop can flatten the spectrum of the footpoint source (Battaglia & Benz 2008). Furthermore, the velocity distribution of FEBs and the parameters of ambient plasma will change as they travel through complex magnetized plasma. In particular, the evolution of the energy spectrum and velocity distribution of FEBs due to energy loss processes and the pitch-angle scatter in the inhomogeneous magnetic field can significantly influence the efficiency and properties of their emission. The study of X-ray emission can provide us with information about the acceleration and evolution processes of FEBs. On the other hand, X-ray emission is closely associated with solar radio emission (Kane 1981; Aschwanden et al. 1985; Aschwanden & Guedel 1992), which indicates that X-ray and radio emission are excited by the same evolving electron beam (Kundu & Vlahos 1982; Gary 1985; Aschwanden 2002).

In this paper, we concentrate on the characteristics of ECM emission excited by evolving FEBs traveling in a coronal loop associated with a CME. We suggest that the energetic electrons which excite ECM emission are accelerated in the CME-driven shock front. Our results show that the evolution of the electron beams has a significant influence on ECM emission. With a different energy loss process, the FEBs can produce different radio emission. The paper is organized as follows. First, we introduce the basic physical model in Section 2. Second, the ECM instability excited by the energetic electrons which travel in the loop is discussed in Section 3. Finally, our discussions and conclusions are presented in Section 4.

2. THE PHYSICAL MODEL

2.1. Magnetic Field Configuration of Source Region

Beams of energetic electrons are prominently created during solar flares through the magnetic reconnection process or during CMEs by CME-driven shock waves. CMEs are defined as the outward traveling bright arc and dark cavity seen in coronagraphs (Forbes 2000). These events consist of large-scale ejections of magnetic flux and mass, and display steady expansion as they propagate from the lower corona to interplanetary space, showing two footpoints on the Sun (Chen 1997). High-resolution X-ray imaging observations show that all CMEs and prominence eruptions have giant arch structures (Svestka et al. 1997; Forbes 2000). Here, we consider the latter case and propose a magnetic field configuration for the source region as depicted in Figure 1. When the outward-propagating CMEs overtake the local fast magnetosonic wave, it can drive a forward shock ahead of the CME (Stewart et al. 1974). The CME-driven shock front is the acceleration site for solar energetic electrons. The acceleration mechanism of electrons at quasi-perpendicular shocks is shock-drift acceleration, which is simple and effective (Wu et al. 1994; Park et al. 2012; Guo & Giacalone 2015).

Zhao et al. (2014) proposed a model for the generation of radio radiation from the shock front. In their model, the Alfvén wave is first excited by the energetic ion beam accelerated in the shock front, and then a density-depleted duct can form due to the excited Alfvén wave along the foreshock boundary. Energetic electrons are also accelerated by the shock waves and a portion of the energetic electrons propagate in this density-depleted duct, which drives the maser emission and may give rise to type II bursts (Zhao et al. 2014). In our model, we also propose that the FEBs which excite radio emission are accelerated by CME-driven shock waves.

When the energetic electrons leave the acceleration site, some of them propagate along the open magnetic field line, and the remaining energetic electrons will propagate along and be trapped in the magnetic loop. When the electron beam precipitates from the looptop to the footpoint, the energetic electrons will lose most of their energy due to interaction with

Figure 1. Schematic diagram of magnetic field configuration in the source region. The energetic electrons are accelerated in the CME-driven shock front. It is suggested that energetic electrons traveling in the loop excite cyclotron maser emission and produce the radio emission.
the ambient plasma (Xu et al. 2013). The energy loss would result in a flatter spectral index and change the lower cutoff energy of the footpoint source. On the other hand, because of the complex magnetic field topology, the velocity distribution of FEBs and the parameters of the ambient magnetic plasma will also change when they propagate from the looptop to the footpoint. Therefore, the distribution functions of FEBs from the looptop to the footpoint will vary. These evolving FEBs with different evolution processes excite cyclotron maser instability and produce different radio burst events.

2.2. Evolution of FEBs

Energetic streams of electrons are created during various active phenomena. The most direct observational evidence for energetic electrons comes from X-ray, $\gamma$-ray, and radio emission. When energetic electrons escape from the acceleration site, some of them move outward into interplanetary space and often can be detected via their characteristic emission from coronal and interplanetary type III bursts. Others propagate downward along the magnetic field lines because of the convergent magnetic field, and electrons with small pitch angles will precipitate into the dense chromosphere while electrons with large pitch angles will be reflected at the mirror points. It is these precipitate and reflected electrons which produce the X-ray and radio emission. Observations frequently demonstrate that there is a looptop X-ray source in the corona and two or more footpoint X-ray sources in the chromosphere (Frost & Dennis 1971; Hudson 1978; Hoyng et al. 1981). Kosugi et al. (1988) conducted a statistical study and show that the X-ray is strongly associated with microwave emission. This indicates that they could be excited by the same energetic electron beam at different levels of the solar atmosphere.

Electron beams traveling in a closed loop will loose most of their energy. High-resolution observations of X-ray emission and the evolution of the X-ray spectrum could provide us with information to help us understand the physics of the acceleration and energy loss of the FEBs (Zharkova et al. 1995; Hannah & Kontar 2011; Xu et al. 2013). It is believed that both the looptop and footpoint X-ray emission are produced by a single FEB which travels along the loop structure from the looptop to the footpoint. The emission mechanism for the X-ray source is the thin-target bremsstrahlung at the looptop and the thick-target bremsstrahlung at the footpoints, respectively. According to this emission model, the accelerated electron beam with a power-law spectrum distribution $F(E) \propto E^{-\gamma_{fl}}$ in the corona will emit X-ray emission at the footpoint source with the photon spectrum $I(\epsilon) \propto \epsilon^{-\gamma_{fp}}$, where the spectral index $\gamma_{fl} = \delta_b + 1$, $E$ is the energy of electron, and $\epsilon$ is the photon energy (Arnoldy et al. 1968; Lin & Hudson 1976; Hannah & Kontar 2011). If the power-law electrons only encounter Coulomb collisions with the ambient plasma when they propagate into the chromosphere, then the footpoint source could produce a power-law spectrum $I(\epsilon) \propto \epsilon^{-\gamma_{fp}}$ with an index of $\gamma_{fp} = \delta_b - 1$ (Brown 1971; Hannah & Kontar 2011). This standard flare model indicates that the difference in the spectral indices between the looptop and the footpoint sources is 2 (Hannah & Kontar 2011). However, observations of solar flare demonstrate that the difference in the spectral index is inconsistent with the prediction of emission models (Masuda et al. 1994, 1995).

Petrosian et al. (2002) proposed that the average difference is about $\Delta \gamma = 1.3 \pm 1.5$ based on the survey of Yohkoh flare observations. This discrepancy between observations and predictions suggests that some other energy loss mechanism must exist in addition to Coulomb collisions. Battaglia & Benz (2008) proposed that noncollisional energy loss via the induced electric field can flatten the footpoint spectrum and lead to larger differences for the spectral indices. This induced electric field is due to the return current generated by the energetic electron beam. Hannah & Kontar (2011) investigated the spectral evolution of X-ray sources including wave–particle interactions and found that the growth of Langmuir waves can flatten the spectrum of the footpoint source. The looptop source is unchanged, and so the difference in spectral indices can be greater than 2. To study the evolution of the energetic electron spectrum traveling in the solar atmosphere we should take into account pitch-angle scattering and various energy loss mechanisms, such as Coulomb collisions, anomalous resistivity in the return current system, wave–particle interactions, etc.

For simplicity, we assume that the energy loss of energetic electrons, $\delta E$, is independent of their initial energy $E$ when electrons travel in the loop structure. Therefore, the energy distribution function of energetic electrons for the initial form,

$$F_{\text{fl}}(E) = AE^{-\delta_{fl}},$$

at the looptop will evolve into the final form because of the energy loss $\delta E$ (Xu et al. 2013):

$$F_{\text{fp}}(E') = A(E^{\delta_{fl}} + \delta E)^{-\delta_{fp}}.$$  

Here, $A$ is the normalized factor and $E' = E - \delta E$ is the energy of energetic electrons when they arrive at the footpoint (Xu et al. 2013).

Wang (2004) proposed that energetic electrons captured at the apex of the magnetic loop have a beam-like velocity distribution. In our model, electrons are accelerated in the advancing shock front. Some of the energetic electrons leave the acceleration region and precipitate along the arch structure (see Figure 1). Thus, we also propose that the precipitated electrons have a beam velocity distribution when they leave the acceleration site. On the other hand, hard X-ray observations demonstrate that energetic electrons, which can excite ECM instability, generally have an approximate power-law energy distribution with a lower energy cutoff (Lin 1974; Stupp 2000; Aschwanden 2002). The spectral index of power-law electrons is typically $\alpha = 3$ and is in the range of $\sim 2–6$ (Stupp 2000). In principle, it is difficult to describe the special form of the lower energy cutoff behavior based on observations. Wu & Tang (2008) fit the more general power-law spectrum with the lower energy cutoff behavior described by a hyperbolic tangent function. Consequently, we propose the following electron distribution function for when they leave the acceleration site:

$$F_{0}(u, \mu) = A_{0}\tanh\left(\frac{u}{u_{c}}\right)^{28}\left(\frac{u}{u_{c}}\right)^{-2\alpha} \times \exp\left[-\frac{(\mu u - u_{c})^{2}}{\beta^{2}} - \frac{u^{2}(1 - \mu^{2})}{\beta^{2}}\right],$$  

(3)
where \( u^2 = u_\perp^2 + u_\parallel^2 \), \( u = p/m \) denotes the momentum per unit mass, and \( u_\perp \) and \( u_\parallel \) are the perpendicular and parallel components of \( u \) to the ambient magnetic field, respectively. The parameter \( \mu = u_\parallel/u_0 \), \( A_0 \) is the normalization coefficient, \( \delta \) is the steepness index, \( E_c = \frac{1}{2} m u_c^2 \) describes the cutoff energy, and the hyperbolic tangent function \( \tanh(u/u_c) \) describes the lower energy cutoff behavior. \( \alpha \) is the spectrum index of the energetic electrons, and \( \beta \) is the momentum dispersions in \( u_\perp \) and \( u_\parallel \).

Based on the assumption that the energy loss of FEBs \( \delta E \) is independent of their initial energy, we can obtain the distribution function of FEBs after they leave the acceleration site as below:

\[
F_1(u, \mu) = A_0 \tanh \left( \frac{u_\perp^2}{u_c^2} + Q \right) \left( \frac{u_\parallel^2}{u_c^2} + Q \right)^{-\alpha} \times \exp \left[ \frac{\mu}{\beta^2} \left( \frac{u_\perp^2}{u_c^2} + Q - 1 \right)^2 - \frac{\left( \frac{u_\parallel^2}{u_c^2} + Q \right)(1 - \mu^2)}{\beta^2} \right].
\]

Here, \( Q = \delta E/E_c \), \( \beta = \beta/u_c \). Then, taking into account the magnetic mirror due to the magnetic field convergence at the footpoints, we obtain the distribution function of FEBs as follows:

\[
F_1(u_1, \mu) = A_0 \tanh \left( \frac{u_1^2}{u_c^2} + Q \right) \left( \frac{u_\parallel^2}{u_c^2} + Q \right)^{-\alpha} \times \exp \left[ 1 - \exp \left( 1 - \sigma \right) \left( 1 - \mu^2 \right) \right] \times \exp \left[ -\frac{\mu}{\beta^2} \left( \frac{u_\perp^2}{u_c^2} + Q - 1 \right)^2 - \frac{\left( \frac{u_\parallel^2}{u_c^2} + Q \right)(1 - \mu^2)}{\beta^2} \right] = F_1(u, \mu).
\]

Here, \( \sigma \) is the magnetic mirror ratio parameter.

3. NUMERICAL RESULTS

3.1. ECM Emission Theory

ECM emission is a well-known radiation mechanism and has been extensively applied to various solar radio bursts (Treumann 2006). Based on the cold-plasma theory, we obtain the dispersion relation of the high-frequency electromagnetic emission as (Wu et al. 2002)

\[
N_q^2 = 1 - \frac{\omega_p^2}{\omega(\omega + \tau_q \omega_ce \cos \theta)},
\]

where \( \omega_p \) is the plasma frequency of the ambient plasma, \( \omega_ce \) is the electron-cyclotron frequency, and \( N_q \) and \( \omega \) are the refractive index and frequency of the excited wave, respectively. \( \tau_q = -\sigma_q + q \sqrt{N_q^2 + \cos^2 \theta} \), \( q = \omega_ce \sin \theta / 2(\omega^2 - \omega_p^2) \), and \( \theta \) is the wave phase angle with respect to ambient magnetic field, and \( q = \pm \) denote the ordinary (O) and extraordinary (X) modes, respectively. When the frequency of the excited wave \( \omega \approx \omega_ce \), the temporal growth rate of the excited wave can be given in the following form (Wu et al. 2002):

\[
\omega_{qi} = \frac{\pi n_b}{2} \frac{\omega_p^2}{\omega} \int d^3u \gamma(1 - \mu^2) \frac{\delta}{(1 + T_q^2)R_q} \times \left( \gamma - \frac{\omega_ce}{\omega} \frac{N_q \mu \cos \theta}{c} \right) \frac{J_q(b_q)}{b_q} \times \left( \frac{\omega}{\omega_ce} \left[ \gamma K_q \sin \theta + T_q \left( \gamma \cos \theta - \frac{N_q \mu \cos \theta}{c} \right) \right] \right) \frac{J_q(b_q)}{b_q} + \frac{J_q'(b_q)}{b_q} \left( \frac{\partial}{\partial \mu} \right) \times \left( \frac{N_q \mu \cos \theta}{c} - \mu \right) \cdot F_1(u, \mu).
\]

Here,

\[
b_q = N_q \frac{\omega}{\omega_ce c} \sqrt{1 - \mu^2} \sin \theta,
\]

\[
R_q = 1 - \frac{\omega_p^2 \omega_ce \tau_q}{2\omega(\omega + \tau_q \omega_ce)^2} \left( 1 - \frac{q \tau_q}{\omega_p^2} \omega^2 + \omega_p^2 \right),
\]

\[
K_q = \frac{\omega_p^2 \omega_ce \sin \theta}{(\omega^2 - \omega_p^2)(\omega + \tau_q \omega_ce)^2}, \quad T_q = -\cos \theta / \tau_q.
\]

Above, \( n_b \) and \( n_0 \) are the number densities of the energetic electron beam and ambient plasma. \( J_q(b_q) \) is the Bessel function, and \( \gamma = \sqrt{1 + (u/c)^2} \) is the Lorentz factor.

3.2. The Growth Rate of ECM Instability

With the velocity distribution function \( F_1(\mu, u_1) \) given by Equation (5), the growth rates of the ECM emission in the O and X modes can be calculated based on Equation (7). For given parameters \( \sigma, \alpha, u_\parallel, \beta, \) and \( Q \) of FEBs and background magneto-plasma parameters \( \Omega \) and \( \sigma \) in the source region, the growth rates of the ECM instability depend on the parameters \( \omega \) and \( \theta \). Here, \( \Omega \) is the frequency ratio of \( \omega_ce \) to \( \omega_p \). Both the peak and maximum growth rates are normalized by \( \omega_ce/n_b/n_0 \). Figure 2 presents the peak growth rates with varying \( \omega \) and fixed phase angle \( \theta \). Figure 3 shows the maximum growth rates with varying \( \omega \) and \( \theta \) together versus frequency ratio \( \Omega \). Panels O1 and X2 denote the fundamental wave of the O mode and the harmonic wave of the X mode, respectively. The solid line, dotted line, and dot-dashed line denote the growth rates of the ECM instability excited at the looptop (LT), looptmid (LM), and footpoint (FP) sources, respectively. Here, the spectrum index \( \alpha = 3 \), deepness index \( \delta = 6 \), \( u_\parallel = 0.3c \), \( \beta = 0.25c \), and, for Figure 2, a frequency ratio of \( \Omega = 2 \) has been used. When the FEBs travel in the loop from the looptop to the footpoint, the parameters \( \sigma = 0, Q = 0.1; \sigma = 0, Q = 0.51 \) (O1) and \( Q = 0.7 \) (X2); and \( \sigma = 3.5, Q = 1.5 \) have been used for the LT, LM, and FP sources, respectively. In both Figures 2 and 3, the growth rates of the LM source have been enlarged by a factor of 100. This implies that the growth rates at the LT and FP sources are at least two orders of magnitude greater than that of the LM source.
We find that the energy loss process of FEBs can significantly influence the efficiency and properties of the ECM emission. The growth rates of the O1 and X2 modes all decrease rapidly with the energy loss factor $Q$. Figure 2 shows that the phase angles $\theta$ of the maximum growth rates of the LM source clearly can deviate from that of the LT and FP sources due to the energy loss of the fast electrons. The velocity distribution of FEBs will evolve due to the magnetic field inhomogeneity and may also influence the efficiency and properties of their emission. Our calculations show that the growth rates of FP sources can increase to a value comparable to those of the LT sources because of the convergent magnetic field at the footpoint. Figures 2 and 3 show that the O1 mode has larger growth rates than the X2 mode and becomes the dominant mode at the FP sources due to the loss-cone anisotropy ($\sigma = 3.5$). Figures 2 and 3 imply that if the FEBs have a moderate steepness cutoff behavior ($\delta = 6, \alpha = 3$) when they leave the acceleration region and if the loop has a magnetic mirror effect only in the footpoint region, then the growth rates at the LM sources are very small. One can anticipate that the growth rates of the LM sources will be three or four orders of magnitude smaller than those of the LT and FP sources if the FEBs lose more energy (i.e., $Q > 0.51$ or 0.7) when they travel from the looptop to the middle part of the loop. So for the cases of Figures 2 and 3, the ECM emission

Figure 2. Peak growth rates of the O1 and X2 modes excited by the FEBs which travel in the loop. The deepness index $\delta = 6$. It shows that the growth rates of LM source are two orders of magnitude smaller than that of the LT and FP sources.

Figure 3. Maximum growth rates of O1 and X2 modes as a function of the plasma parameter $\Omega$. The deepness index $\delta = 6$. The growth rates of LM source have been enlarged by a factor of 100.
from evolving FEBs which travel in the loop will form three separate radio sources.

Figures 4 and 5 present the peak and maximum growth rates as a function of phase angle $\theta$ and frequency ratio $\Omega$, respectively. The acronyms LT, LM, and FP also denote the looptop source, loopmid source, and footpoint source, respectively. The spectrum index $\alpha = 3$, deepness index $\delta = 10$, $u_c = 0.3c$, $\beta = 0.25c$, and $\Omega = 2$ in Figure 4 have been used. Here, the magnetic mirror ratio $\sigma$ and energy loss factor $Q$ have the same values as Figures 2 and 3 for the LT, LM, and FP sources. This also shows that the O1 mode will have larger growth rates than the X2 mode and it becomes the dominant mode at FP sources. By comparing Figures 2 and 4, one will find that the growth rates all increase with the steepness index $\delta$, especially for the LM sources. Figures 4 and 5 imply that if the energetic electrons have a steeper cutoff behavior (i.e., have a larger steepness index) when they leave the acceleration region, then the growth rates of the LM source are comparable to those of the LT or FP sources, and even larger than the growth rates of the FP source (see Figure 5). So for this case, the ECM emission excited by the evolving FEBs which propagate from the looptop to the footpoint will form a continuous radio source.

Also, in Figure 6, we plot the dependence of the maximum growth rates on the frequency ratio $\Omega$, where the parameters $\alpha = 3$, $\delta = 6$, $u_c = 0.3c$, and $\beta = 0.25c$ have been used. The
solid line, dotted line, and dot-dashed line also correspond to emission at the LT, LM, and FP sources, respectively. Here, we choose the parameters $\sigma = 0$, $Q = 0.1$; $\sigma = 1.5$, $Q = 0.51$ (O1), $Q = 0.7$ (X2), and $\sigma = 3.5$, $Q = 1.5$ for the LT, LM, and FP sources, respectively. This shows that the growth rates of the LM sources can be greater than those of the LT or FP sources if the magnetic field converges from the middle part of the loop and the dominant mode also shifts from the X2 mode to the O1 mode at the LM and FP sources. Figure 6 implies that if the CME loop has an effective magnetic mirror effect from its middle part, then ECM emission from the evolving FEBs which travel and are trapped in such a magnetic loop will form a continuous radio burst.

4. DISCUSSIONS AND CONCLUSIONS

Particle acceleration is one of the most significant ubiquitous processes in space and cosmic plasma. For the Sun, it is generally acknowledged that FEBs are usually produced by the magnetic reconnection process during flares or by the DSA in the vicinity of the corona shock wave. FEBs can be detected directly by X-ray, $\gamma$-ray, and radio observations and we can diagnose the FEBs as well as the solar plasma environment from solar radio bursts. When the FEBs travel in the loop, they will lose some of their energy due to various energy loss mechanisms and demonstrate a more flat spectrum. The velocity distribution of FEBs and the magnetic plasma parameters will change as they travel in the solar plasma. So it is important to study the radio emission from evolving FEBs which are traveling in the solar atmosphere.

In this paper, we discuss the possible evolution of the energy spectrum and the velocity distribution of FEBs and analyze the effects of such evolution on ECM emission. Results from our calculations show that the evolution of the energy spectrum and velocity distribution of FEBs can significantly influence the efficiency and properties of ECM emission. It is clear that the growth rates all decrease rapidly with the energy loss factor $Q$ but increase with the steepness index $\delta$ and magnetic mirror ratio $\sigma$, respectively. The growth rates of the O1 mode can be larger than those of the X2 mode and become the dominant mode at FP and LM sources due to the energy loss and evolution of the velocity distribution of FEBs. The results also show that the phase angles $\theta$ of the maximum growth rates of the LM source can clearly deviate from those of the LT and FP sources when the fast electrons lose most of their energy and the magnetic field does not converge at the LM source. If the FEBs have moderate steepness cutoff behavior ($\delta = 6, \alpha = 3$) and the loop has a magnetic mirror effect only in the footpoint region, then the growth rates at the LM sources are very small and the emission from such evolving FEBs will form three separate radio sources. If the FEBs have a steeper cutoff behavior (i.e., have a larger steepness index) or the loop has an effective magnetic mirror effect in the middle region, then the growth rates of the LM sources are comparable to those of the LT and FP sources, and the emission excited by such evolving FEBs will form a continuous radio source.

The moving type IV (IVM) burst is relatively rare and it occurs after a solar flare or a CME. Since the identification of IVM bursts, plenty of work has been conducted to explain the emission process of this rare burst. It is widely believed that IVM bursts are strongly associated with radio type II bursts (Boischot & Denisse 1957; Smerd & Dulk 1971). Kai (1969) proposed a common shock wave as the source for the generation of IVM and type II bursts. However, the radiation mechanism of the two types of bursts remains an open problem. Based on our proposed model, cyclotron maser mechanism can be the possible emission process of IVM bursts. Energetic electron beams accelerate in the CME-driven shock front and excite ECM emission along the expanding CME associated loop. If the accelerated electrons have a moderate steepness cutoff behavior and the expanding loop has a magnetic mirror effect only in the

Figure 6. Maximum growth rates of the O1 and X2 modes as a function of the plasma parameter $\Omega$. The steepness index $\delta = 6$ and the magnetic field line converges from the middle part of the loop. The results also show that the growth rates of the LM source are comparable to those of the LT or FP sources.
footpoint, then the ECM emission can form three separate radio sources, i.e., the expanded arch IVM bursts. If the energetic electron beams have a steeper cutoff behavior when they leave the acceleration site or if the CME loop has an effective magnetic mirror effect in its middle part, then these trapped electrons will excite ECM emission and form a continuous radio source, i.e., the advancing front IVM bursts.

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