Simulation of Type III Solar Radio Bursts

Laboratory for Plasma Astrophysics, Faculty of Engineering
Takuya Kitamoto and Jun-ichi Sakai
m042094@ems.toyama-u.ac.jp

We investigate the wave emission process of solar Type III radio bursts from magnetic reconnection region in a solar flare by using two dimensional, electromagnetic, relativistic Particle-In-Cell (PIC) code. We initially impose two plasma populations, background dense plasma and hot electrons that can be generated by magnetic reconnection process in a solar flare. We investigated two cases: model (1) where the hot electron beams propagate obliquely to the magnetic field, while in model (2) the hot electron beams propagate along the magnetic field. We found that hot electron plasmas lead to the generation of Langmuir waves and the generated Langmuir waves can be converted to the electromagnetic waves (solar Type III radio bursts) through the linear direct mode conversion process. The second harmonic emission is generated with time delay and the amplitude larger than that of fundamental emission.

Keywords: Sun-flares, Sun-Type III bursts

1 Introduction

It is well known that most of the solar radio emission occurs during flares and associated flare plasma dynamics. A flare-associated Type III burst occurs at the impulsive phase which is more intense at meter wavelengths and may have a continuum attached to it (see for reviews, Goldman et al. 1986, Aschwanden 2004). It is believed that Type III bursts are caused by mildly relativistic electrons ($\approx 10 - 100\text{keV}$) that are produced in impulsive solar flares, because bursts commonly occur in groups of ten or more, with a separation of seconds (Wild et al. 1963; McLean 1971).

A fundamental question concerning the origin of Type III bursts is to understand how they correlate with the mildly relativistic electrons and Langmuir waves produced from the electrons. Spacecraft measurements have verified the existence of both the electron streams and Langmuir waves produced from the electrons (Lin 1970). The next question concerning the origin of Type III bursts is to understand how the generated Langmuir waves can convert to electromagnetic waves associated with the observed bursts. There are two classes of generation mechanisms of Type III bursts, nonlinear wave-wave coupling processes (Lin et al. 1986)-the coalescence of two Langmuir waves, first proposed by Ginzburg and Zheleznyakov (1958) and direct emission-mode conversion due to density inhomogeneity (Field 1956; Zheleznyakov 1970; Melrose 1980). Thejappa et al. (1993) evaluated emission mechanisms at $\omega_{pe}$ using ULYSSES observations and concluded that the direct mode coupling mechanism is a most plausible process for Type III bursts.

In this paper we investigate the wave emission process of solar Type III radio bursts from magnetic reconnection region in a solar flare by using two dimensional, electromagnetic, relativistic Particle-In-Cell (PIC) code. This work is motivated from recent simulation results by Saito and Sakai (2004a, 2004b) who showed that during two current loops coalescence mildly relativistic electrons can be generated near the current sheet where magnetic reconnection occurs. We initially impose two plasma populations, background dense plasma and hot electrons that can be generated by magnetic reconnection process in a solar flare. We investigate two cases: model (1) where the hot electron beams propagate obliquely to the magnetic field, while in model (2) the hot electron beams propagate along the magnetic field. We found that hot electron plasmas lead to the generation of Langmuir waves and the generated Langmuir waves can be converted to the electromagnetic waves (solar Type III radio bursts) through the linear direct mode conversion process. It is shown that the second harmonic emission is generated with time delay and the amplitude larger than that of fundamental emission.

In §2 we present our simulation model and simulation results. In §3 we summarize our results.

2 Simulation Model and Simulation Results

The left figure in Fig.1(a) shows a schematic picture of a scenario for generation of Type III bursts from magnetic reconnection region associated with a solar flare. The dashed circle shows the region where hot electron beams are generated by the elec-
where $\beta$ is plasma beta in low density region and is taken as $\beta = 0.125$. The number density $n_0$ in low density region is 100/cell, while the density in the dense region is 900/cell. The electron beam density is 5% of dense plasma density. Other parameters are as follows: the electron thermal velocity of dense plasma $v_{th,e} = 0.1c$, the electron beam velocity $v_b = 0.3c$, the beam thermal velocity $v_{b,th} = 0.2c$, the time step $\omega_{pe} \Delta t = 0.05$, mass ratio $m_e/m_i = 1836$, Debye length $v_{th,e}/\omega_{pe} = 1.0\Delta$, the collisionless skin depth $c/\omega_{pe} = 10\Delta$. The ratio of $\omega_{ce}$ to $\omega_{pe}$ is 0.4 in low density region.

Figure 2 shows the simulation results for model (1). Fig.2(a-1) shows the electron phase space plot $(V_x - X)$ at $\omega_{pe} t = 50$. As seen in Fig.2(a-2) at $\omega_{pe} t = 50$, we observe the electrostatic field $E_x$ associated with hot electron beam instability that can be excited in the region where the hot electron beam exists in the region of $0 \leq x \leq 400$. To understand the wave property of the excited $E_x$ fields, we performed two-dimensional time-space Fourier transformation of the $E_x$ obtained from the data ($0 \leq \omega_{pe} t \leq 50$ and $0 \leq x \leq 256$). As shown in Fig.2(a-3) where $\omega$ is normalized by $\omega_{pe}$ in the low density region, we obtain the dispersion relation for $E_x$ that clearly shows the dispersion relation of the Langmuir waves (dashed elliptic region) due to the hot electron beam in the frequency range of the electron plasma frequency between high density ($3 \omega_{pe}$) and low density ($\omega_{pe}$). We also observe the Langmuir waves back-scattered from the region of the density inhomogeneity in the_dispersion relation. Fig.2(b-1) shows the electron phase space plot $(V_x - X)$ at $\omega_{pe} t = 75$. Fig.2(b-2) shows the electromagnetic field component $E_z$ at $\omega_{pe} t = 75$. The electromagnetic waves generated from the region where the hot electron beam instability occurs propagate to the positive x-direction.

To understand the wave property of the emitted electromagnetic waves, we performed two-dimensional time-space Fourier transformation of the $E_z$ obtained from the data ($0 \leq \omega_{pe} t \leq 100$ and $600 \leq x \leq 1624$). As shown in Fig.2(b-3) where $\omega$ is normalized by $\omega_{pe}$ in the low density region, we obtain the dispersion relation for the $E_z$. From the obtained dispersion relation we find two excitation regions of waves: high-frequency electromagnetic waves, and waves of upper-hybrid frequency range. The wave emission mechanism of the high-frequency electromagnetic waves corresponding to the solar Type III bursts is due to the direct linear-mode conversion from the Langmuir waves that is caused from the density inhomogeneity. From the movies of the $E_z$ field, we find that in the early phase only high-frequency electromagnetic waves are excited, then the whistler waves with large amplitude are excited and they modulate the high-frequency
waves like a group of high-frequency bursts. While the low-frequency whistler waves can be excited from the decay process of the excited Langmuir waves.

Next we present the simulation results for model (2) in Fig.3 where magnetic field is parallel to the electron beams. Fig.3(a-1) shows the electron phase space plot \((V_x - X)\) at \(\omega_{pe}t = 50\). As seen in Fig.3(a-2) at \(\omega_{pe}t = 50\), we observe the electrostatic field \(E_x\) associated with hot electron beam instability that can be excited in the region where the hot electron beam exists in the region of \(0 \leq x \leq 400\). To understand the wave property of the excited \(E_x\) fields, we performed two-dimensional time-space Fourier transformation of the \(E_x\) obtained from the data \((0 \leq \omega_{pe}t \leq 50\) and \(0 \leq X \leq 256\)). As shown in Fig.3(a-3) where \(\omega\) is normalized by \(\omega_{pe}\) in the low density region, we obtain the dispersion relation for \(E_x\) that clearly shows the dispersion relation of the Langmuir waves (dashed elliptic region) due to the hot electron beam in the frequency range of the electron plasma frequency between high density (\(3 \omega_{pe}\)) and low density (\(\omega_{pe}\)). We also observe the Langmuir waves back-scattered from the region of the density inhomogeneity in the dispersion relation. Fig.3(b-1) shows the electron phase space plot \((V_x - X)\) at \(\omega_{pe}t = 75\). Fig.3(b-2) shows the electromagnetic field component \(E_z\) at \(\omega_{pe}t = 75\). The electromagnetic waves generated from the region where the hot electron beam instability occurs propagate to the positive x-direction.

To understand the wave property of the emitted electromagnetic waves, we performed two-dimensional time-space Fourier transformation of the \(E_z\) obtained from the data \((0 \leq \omega_{pe}t \leq 50\) and \(0 \leq X \leq 256\)). As shown in Fig.3(b-3) where \(\omega\) is normalized by \(\omega_{pe}\) in the low density region, we obtain the dispersion relation for the \(E_z\). From the obtained dispersion relation we find only high-frequency electromagnetic waves contrast to the previous model(1) where three excitation regions of waves are observed. The wave emission mechanism of the high-frequency electromagnetic waves corresponding to the solar Type III bursts is due to the direct linear-mode conversion from the Langmuir waves that is caused from the density inhomogeneity.

Next we examine the timing of fundamental and second harmonic emissions by using previous dispersion relations. Fig.4 (a-1) for model (1) shows the time history of fundamental emission obtained from the inverse Fourier transformation by using data of \((-4 \leq kc/\omega_{pe} < 4\) and \(1.2 \leq \omega/\omega_{pe} \leq 1.7\) (shown by dashed rectangle (F)) and the time history of second harmonic emission obtained from the inverse Fourier
transformation by using data of \(-4 \leq kc/\omega_{pe} \leq 4 \) and \(2.3 \leq \omega/\omega_{pe} \leq 3.0\) (shown by dashed rectangle (S)). As seen in Fig.4(a-1) the second harmonic emission is delayed with the amplitude stronger than the fundamental emission.

Fig.4(a-2) for model (1) shows the time history for \(E_x\) (Langmuir wave) that is obtained from the inverse Fourier transformation by using data of \((0 \leq kc/\omega_{pe} \leq 16 \) and \(1.5 \leq \omega/\omega_{pe} \leq 3.5\), and the time history for \(E_z\) (including both Fundamental and Second harmonics) is obtained from the inverse Fourier transformation by using data of \((-4 \leq kc/\omega_{pe} \leq 4 \) and \(1.2 \leq \omega/\omega_{pe} \leq 4.0)\). As seen in this figure, the energy conversion rate to the Type III bursts from the Langmuir waves is about from \(1\%\) to \(10 \%\).

Fig.4(b-1) for model (2) shows the time history of fundamental emission obtained from the inverse Fourier transformation by using data of \((-4 \leq kc/\omega_{pe} \leq 4\) and \(0.7 \leq \omega/\omega_{pe} \leq 1.15\) (shown by dashed rectangle (F)) and the time history of second harmonic emission obtained from the inverse Fourier transformation by using data of \((-4 \leq kc/\omega_{pe} \leq 4\) and \(1.7 \leq \omega/\omega_{pe} \leq 3.3\) (shown by dashed rectangle (S)). As seen in this figure, the second harmonic emission is also delayed with the amplitude of two order of magnitude stronger than the fundamental emission.

Fig.4(b-2) shows the time history for \(E_x\) (Langmuir wave) that is obtained from the inverse Fourier transformation by using data of \((0 \leq kc/\omega_{pe} \leq 16 \) and \(1.5 \leq \omega/\omega_{pe} \leq 3.5\), and the time history for \(E_z\) (including both Fundamental and Second harmonics) is obtained from the inverse Fourier transformation by using data of \((-4 \leq kc/\omega_{pe} \leq 4 \) and \(1.2 \leq \omega/\omega_{pe} \leq 4.0)\). As seen in this figure, the energy conversion to the Type III bursts from the Langmuir waves is quite efficient and in the late stage (about \(\omega_{pet} = 100\)) the amplitude of the Type III bursts becomes comparable to that of the Langmuir waves.

**3 Summary and Discussions**

We investigated the wave emission process of solar Type III radio bursts from magnetic reconnection region in a solar flare by using two dimensional, electromagnetic, relativistic Particle-In-Cell (PIC) code. We initially impose two plasma populations, background dense plasma and hot electrons that can be generated by magnetic reconnection process in a solar flare. We investigated two cases: model (1) where the hot electron beams propagate obliquely to the magnetic field, while in model (2) the hot electron beams propagate along the magnetic field. We found that hot electron plasmas lead to the generation of Langmuir waves and the generated Langmuir waves can be converted to the electromagnetic waves (solar Type III radio bursts) through the linear direct mode conversion process. The second harmonic emission is generated with time delay and the amplitude larger than that of fundamental emission. It is found that when the hot electron beams propagate along the magnetic field, namely the hot electron beams escape to the interplanetary space, the Type III bursts can be generated more efficiently from the Langmuir waves. It is under investigations to include both the dynamics of magnetic reconnection region and the wave emission process presented in this paper.
References


