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Corresponding Author: Dr Clare Emily Jane Watt, Ph. D.

Corresponding Author's Institution: University of Alberta

First Author: Clare Emily Jane Watt, Ph. D.

Order of Authors: Clare Emily Jane Watt, Ph. D.; Robert Rankin

Abstract: We investigate electron acceleration due to shear Alfvén waves in a collisionless plasma for plasma parameters typical of 4-5 R_E radial distance from the Earth along auroral field lines. Recent observational work has motivated this study, which explores the plasma regime where the thermal velocity of the electrons is similar to the Alfvén speed of the plasma, encouraging Landau resonance for electrons in the wave fields. We use a self-consistent kinetic simulation model to follow the evolution of the electrons as they interact with the wave, which allows us to determine the parallel electric field of the shear Alfvén wave due to both electron inertia and electron pressure effects. The simulation demonstrates that electrons can be accelerated to keV energies in a modest amplitude wave. We compare the parallel electric field obtained from the simulation with those provided by fluid approximations.

Electron acceleration and parallel electric fields due to kinetic Alfvén waves in plasma with similar thermal and Alfvén speeds

Clare E. J. Watt and Robert Rankin

Department of Physics, University of Alberta, Edmonton, AB, Canada, T6G 0T1

Abstract

We investigate electron acceleration due to shear Alfvén waves in a collisionless plasma for plasma parameters typical of $4 - 5R_E$ radial distance from the Earth along auroral field lines. Recent observational work has motivated this study, which explores the plasma regime where the thermal velocity of the electrons is similar to the Alfvén speed of the plasma, encouraging Landau resonance for electrons in the wave fields. We use a self-consistent kinetic simulation model to follow the evolution of the electrons as they interact with the wave, which allows us to determine the parallel electric field of the shear Alfvén wave due to both electron inertia and electron pressure effects. The simulation demonstrates that electrons can be accelerated to keV energies in a modest amplitude wave. We compare the parallel electric field obtained from the simulation with those provided by fluid approximations.

Key words: kinetic simulation, self-consistent, Landau damping

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Email address: cwatt@space.ualberta.ca (Clare E. J. Watt).

20 1 Introduction

21 Evidence from high-latitude in-situ observations of Earth's magnetosphere
22 indicates that shear Alfvén waves measured near the plasma sheet possess
23 sufficient parallel Poynting flux which could, if converted to parallel electron
24 energy flux, be responsible for some instances of auroral brightening (Wygant
25 et al., 2000, 2002; Keiling et al., 2002, 2003; Chaston et al., 2005; Dombek
26 et al., 2005). However, the details of this conversion process are still not well
27 understood.

28 For example, there is still much discussion regarding the location of the auroral
29 acceleration region which is governed by waves. For those electrons which are
30 accelerated through a quasi-static potential drop to form discrete auroral arcs,
31 the evidence indicates that this acceleration occurs in a region at $2-3R_E$ radial
32 distance. However, it has not yet been determined whether wave-mediated
33 auroral acceleration only occurs at the same location as the potential drop, or
34 whether it occurs higher up, nearer $4-5R_E$ radial distance (Janhunen et al.,
35 2004, 2006), or indeed whether both cases are possible.

36 In order for shear Alfvén waves to accelerate electrons in the field-aligned
37 direction, there must exist a component of the wave electric field in the parallel
38 direction. Shear Alfvén waves can support a parallel electric field when the
39 perpendicular scale length is comparable to the electron inertial length $\lambda_e =$
40 c/ω_{pe} (Goertz and Boswell, 1979), or the ion acoustic gyroradius $\rho_{ia} = C_s/\Omega_i$
41 (Hasegawa, 1976). Here, c is the speed of light, $\omega_{pe} = (n_e q_e^2 / (m_e \epsilon_0))^{1/2}$ is
42 the electron plasma frequency, $C_s = (2k_b T_e / m_i)^{1/2}$ is the ion acoustic speed,
43 $\Omega_i = q_i B_0 / m_i$ is the ion gyrofrequency, n_α is the number density, T_α is the

44 temperature, m_α is the mass, and q_α is the charge of plasma species α . The
 45 inertial regime ($k_\perp \lambda_e \sim 1$, where k_\perp is the perpendicular wavenumber) is
 46 more suitable for $2-3R_E$ radial distance, where it is expected that $v_{th,e} \ll v_A$
 47 ($v_{th,e} = (2k_B T_e / m_e)^{1/2}$ is the electron thermal speed and $v_A = B_0(\mu_0 n_i m_i)^{-1/2}$
 48 is the Alfvén speed). However, at $4-5R_E$ radial distance, the ambient electron
 49 population is more energetic (see e.g. Wygant et al., 2000), and it is more
 50 likely that $v_{th,e} \sim v_A$. Although this plasma regime is between the inertial
 51 and the kinetic ($k_\perp \rho_{ia} \sim 1$) limits, it may be important for shear Alfvén
 52 wave acceleration, since a significant number of electrons will be in Landau
 53 resonance with a shear Alfvén wave. If the wave can also support a parallel
 54 electric field at this location, then conditions are optimal for parallel electron
 55 acceleration.

56 Chaston et al. (2003) studied the behaviour of test-particle electrons along ge-
 57 omagnetic field lines between 100km and $5R_E$ altitude, using both kinetic and
 58 inertial corrections to the two-fluid wave solution. The results from this study
 59 predicted that the parallel electric field carried by the shear Alfvén wave would
 60 be reduced from that predicted by only using the inertial approximation, since
 61 the kinetic approximation for the parallel electric field has the opposite sign to
 62 that determined by the inertial approximation. However, a test-particle simu-
 63 lation is not able to clarify how the electron acceleration is affected by both a
 64 reduction in parallel electric field due to the kinetic correction, and an increase
 65 in the number of resonant particles due to the higher temperature electrons
 66 at $4-5R_E$ radial distance. To study these effects completely, it is necessary
 67 to take the whole distribution function into account. In this paper, we use a
 68 self-consistent kinetic simulation code to investigate the acceleration of elec-
 69 trons by shear Alfvén waves in plasma with $v_{th,e} \sim v_A$. Section 2 describes

the simulation code and physical model used to study this phenomenon, and Section 3 details the results from a case study which demonstrates the similarities and differences between the $v_{th,e} \sim v_A$ intermediate regime and the $v_{th,e} \gg v_A$ inertial regime, which has been reported previously. We present our conclusions in Section 4.

2 Simulation Model

The simulation code used to obtain the results in this paper is the self-consistent drift-kinetic simulation code developed by Watt et al. (2004), which has previously been shown to compare favourably with in-situ FAST satellite observations (Watt et al., 2005, 2006). The model follows the evolution of three variables: the scalar potential ϕ , the parallel component of the vector potential A_{\parallel} and the electron distribution function f_e . By using the potential description of the electromagnetic shear Alfvén waves, we can describe the physical system in one dimension. It is assumed that electrons carry the parallel current and that ions carry the perpendicular current. Parallel ion motion is neglected. The electron distribution function is allowed to evolve in time on a fixed grid in phase space according to the gyro-averaged Vlasov equation:

$$\frac{\partial f}{\partial t} + \left(p_{\parallel} - \frac{q_e}{m_e} A_{\parallel} \right) \frac{\partial f}{\partial z} + \left[\frac{q_e}{m_e} \left\{ \left(p_{\parallel} - \frac{q_e}{m_e} A_{\parallel} \right) \frac{\partial A_{\parallel}}{\partial z} - \frac{\partial \phi}{\partial z} \right\} \right] \frac{\partial f}{\partial p_{\parallel}} = 0, \quad (1)$$

where $p_{\parallel} = v_{\parallel} + (q_e/m_e)A_{\parallel}$ is the parallel canonical momentum per unit mass, v_{\parallel} is the parallel velocity coordinate, z is the parallel spatial coordinate and t is time. Note that in this paper, we consider a spatially uniform ambient magnetic field, and so the magnetic mirror term in the Vlasov equation is not required.

93 The potential variables are defined on fixed grid-points in the spatial (z) do-
 94 main. Using the first moment of the distribution function as the source term
 95 for the parallel current, we consider the parallel component of Ampère's Law
 96 $(\nabla \times \mathbf{B})_{\parallel} = \mu_0 J_{\parallel}$, to obtain an expression for the parallel component of the
 97 vector potential:

$$98 \quad A_{\parallel} = \frac{\mu_0 q_e \int_{-\infty}^{\infty} p_{\parallel} f dp_{\parallel}}{k_{\perp}^2 + \mu_0 \frac{q_e^2}{m_e} \int_{-\infty}^{\infty} f dp_{\parallel}}, \quad (2)$$

99 Here, we neglect the displacement current and assume that all perpendicular
 100 variations can be expressed in the form $\exp(-ik_{\perp}x)$, where x is a perpendicular
 101 coordinate. Under the latter assumption, all the perpendicular gradients can
 102 be reduced to factors of ik_{\perp} , and in this fashion, we can reduce the simulation
 103 model to only one spatial dimension.

104 The system of equations is closed through the polarization current equation,
 105 which is combined with the perpendicular component of Ampere's Law under
 106 the same assumptions as above to obtain:

$$107 \quad \frac{\partial \phi}{\partial t} = -v_A^2 \frac{\partial A_{\parallel}}{\partial z}. \quad (3)$$

108 The simulation domain length is $L_z = 4.7R_E$ and we assume uniform ambi-
 109 ent magnetic field strength, and uniform initial plasma number density and
 110 temperature. In the magnetosphere, these three quantities vary along the field
 111 line with scale lengths that are much smaller than $1R_E$. However, we ignore
 112 these variations in the present study.

113 We are interested in studying the behaviour of shear Alfvén waves along au-
 114 roral field lines at geocentric distances of $4 - 5R_E$. Hence, we choose magnetic
 115 field and plasma values which are representative (Wygant et al., 2000; Chaston

116 et al., 2003): $n_e = 10^5 \text{ m}^{-3}$, $B_0 = 8.7 \times 10^{-7} \text{ nT}$, $T_e = 500 \text{ eV}$. Note that the
 117 observations indicate a slightly higher electron temperature ($T_e \sim 1 - 2 \text{ keV}$)
 118 than is used here, but we limit our study to $T_e = 500 \text{ eV}$ in order to ensure
 119 that the velocity grid does not have to cover large velocities which would re-
 120 quire a relativistic treatment. A temperature of $T_e = 500 \text{ eV}$ is sufficient to
 121 demonstrate the behaviour we want to study. In this plasma regime we have
 122 $v_{th}/v_A = 0.22$, $\beta_e = 2.7 \times 10^{-5} \ll m_e/m_i$ and the important scale lengths are
 123 $\lambda_e = 16.8 \text{ km}$ and $\rho_{ia} = 3.71 \text{ km}$.

124 The electron distribution function in the simulation is initialized with a Maxwellian
 125 distribution function. The potentials are initially set to zero at all points in
 126 the simulation domain, and a pulse potential of the form $\phi(t) = (1/2)\phi_0(1 -$
 127 $\cos[2\pi(t/t_1)])$ is added to the scalar potential at the top of the simulation
 128 domain ($z = 4.7R_E$) for $0 < t < t_1$, where $t_1 = 0.25 \text{ s}$ and $\phi_0 = 600V$. The
 129 initial perpendicular electric field strength corresponds to $E_\perp = 60 \text{ mV/m}$, and
 130 changes self-consistently as the wave interacts with the plasma. The pulse trav-
 131 els in the $-z$ direction until it reaches the lower boundary, where the boundary
 132 conditions for the potentials are such that the wave is partially reflected (see
 133 *Watt et al.*, [2004]): $A_\parallel = -\mu_0 \Sigma_P \phi$, where Σ_P is the height-integrated Peder-
 134 sen conductivity. We are interested only in the behaviour of the plasma before
 135 the pulse reaches the lower boundary, and therefore the boundary condition
 136 is not particularly important for the calculations presented here.

137 The perpendicular scale length of the wave for this case study is chosen to
 138 be $\lambda_\perp = 6.3 \times 10^4 \text{ m}$ ($k_\perp = 10^{-4} \text{ m}^{-1}$), which, when mapped to ionospheric
 139 altitudes, corresponds to a scale length of 8.2km. Observational studies of au-
 140 roral arc widths (Knudsen et al., 2001) indicate that this is a reasonable choice
 141 of perpendicular scale. The key wave parameters are therefore $k_\perp \lambda_e = 1.68$

142 and $k_{\perp}\rho_{ia}(=k_{\perp}\lambda_e v_{th,e}/v_A)=0.37$. Note that ρ_{ia} is often used as a convenient
 143 shorthand in place of $\lambda_e v_{th,e}/v_A$, which can lead to the impression that it is
 144 ion effects which generate the parallel electric field in the kinetic limit. How-
 145 ever, the parallel electric field in the kinetic limit arises from finite electron
 146 pressure, and so when $k_{\perp}\lambda_e v_{th,e}/v_A \sim 1$, there will be a finite parallel electric
 147 field even if $T_i = 0$ (Nakamura, 2000). In this intermediate plasma regime of
 148 $v_{th} \sim v_A$, both electron inertia and electron pressure are important for the
 149 formulation of parallel electric fields. Neither the kinetic nor inertial limits are
 150 appropriate for $v_{th,e} \sim v_A$, and so a fully kinetic code is necessary to study
 151 the nonlinear shear Alfvén wave-particle interactions.

152 **3 Simulation Results and Discussion**

153 Figure 1 shows some selected plasma and field diagnostics from a simulation
 154 with the initial plasma parameters given in the previous section. Each quan-
 155 tity is displayed as a function of time at $z = 1R_E$, i.e. the pulse has travelled
 156 through $\sim 3.7R_E$ of plasma before reaching this point. Figure 1(a) shows
 157 the differential electron energy flux of the downward moving electrons, (b)
 158 shows the absolute value of the parallel electron energy flux ($Q_{\parallel} = \int v^2 v_{\parallel} dv$),
 159 (c) shows the parallel current ($J_{\parallel} = q_e \int v_{\parallel} f dv$), (d) shows the perpendicu-
 160 lar electric field ($E_{\perp} = -\nabla_{\perp}\phi$), (e) shows the parallel electric field ($E_{\parallel} =$
 161 $-\partial A_{\parallel}/\partial t - \partial\phi/\partial z$), and (f) shows the perpendicular magnetic field perturba-
 162 tion ($B_{\perp} = (\nabla \times A_{\parallel})_{\perp}$). The pulse shape exhibits a slight change from it's
 163 original sinusoidal form, with modest steepening of the leading edge, but this
 164 steepening is not as pronounced as in the inertial cases reported in Watt et al.
 165 (2004, 2005). In those cases $q\phi \gg k_B T_e$, but here we have $q\phi \sim k_B T_e$ because

166 the electron temperature is much higher. Note that the electromagnetic field
 167 perturbation observed for $1.02 < t < 1.25$ s is a signature of the reflected
 168 pulse. This upward travelling pulse has a smaller amplitude because there is
 169 only partial reflection at the lower boundary.

170 Previous studies (Watt et al., 2005; Watt and Rankin, 2006) of electron accel-
 171 eration due to shear Alfvén waves have shown that the parallel electron energy
 172 flux Q_{\parallel} will be enhanced due to this acceleration. However, it is important to
 173 distinguish an increase in Q_{\parallel} which is due to the resonantly accelerated beam
 174 electrons, and an enhancement which corresponds to the parallel current of
 175 the wave that is carried by the electrons. The vertical dashed line in Figure 1
 176 shows the approximate time when the beam electrons have almost all passed
 177 $z = 1R_E$ and the signature of the parallel current begins. For the inertial cases
 178 reported in previous publications, the steepened wave profile made it easy to
 179 identify which Q_{\parallel} signature was due to the beam, and which signature was due
 180 to the wave parallel current. This was because the wave profile followed the
 181 same steepened characteristics. In this case, the individual signatures of the
 182 accelerated beam electrons and the parallel current are not as easy to distin-
 183 guish, but it is clear that the parallel electron energy flux is enhanced before
 184 the parallel current starts to increase, and so at least some of the parallel
 185 electron energy flux shown in Figure 1(b) is due to the resonantly accelerated
 186 beam electrons which arrive before the shear Alfvén wave pulse.

187 Figure 1(a) shows evidence of resonantly accelerated electrons in the form of
 188 an energy-dispersed beam for $0.53 < t < 0.65$ s. These electrons have energies
 189 between 3.3keV and 9.0keV. Non-MHD effects reduce the phase speed of the
 190 wave below the Alfvén speed $v_A = 6.0 \times 10^7$ m/s. In this simulation, the pulse
 191 moves down the simulation domain with a measured speed of $v_{ph} \sim 3.4 \times$

192 10^7m/s . Hence the resonant electron energy is 3.19keV . From the differential
 193 electron energy flux in Figure 1(a), it can be seen that electrons are accelerated
 194 above this resonant energy, and form a high-energy beam.

195 Even though the maximum parallel electric field amplitude in the interme-
 196 diate regime ($v_{th,e} \sim v_A$) has the same magnitude as that reported previ-
 197 ously in inertial regime studies (Watt et al., 2004; Watt and Rankin, 2006),
 198 $E_{\parallel} \sim 0.2 \text{ mV/m}$, it can be seen that electrons are accelerated to much higher
 199 energies, keV instead of hundreds of eV. This is only possible because the
 200 resonant phase velocity is high, and the hot electron distribution function
 201 provides sufficient electrons with matching velocities.

202 There has been much discussion regarding the calculation of the magnitude
 203 of the parallel electric field in the intermediate plasma regime ($v_{th,e} \sim v_A$)
 204 (Chaston et al., 2003; Shukla and Stenflo, 2004; Chaston, 2004). For interest,
 205 we have calculated the parallel electric field in the inertial and kinetic limits,
 206 even though neither accurately apply to this situation. In the inertial limit we
 207 have (e.g. Lysak, 1990):

$$208 \quad E_{\parallel,i} = -\frac{\lambda_e^2}{1 + \lambda_e^2 k_{\perp}^2} \frac{\partial}{\partial z} \nabla \cdot \mathbf{E}_{\perp}, \quad (4)$$

209 and in the kinetic limit:

$$210 \quad E_{\parallel,k} = \frac{\lambda_e^2 v_{th}^2}{v_A^2} \frac{\partial}{\partial z} \nabla \cdot \mathbf{E}_{\perp}. \quad (5)$$

211 Figure 2 shows the parallel electric field as determined from the self-consistent
 212 simulation potentials $E_{\parallel,s} = -\nabla_{\parallel} \phi - (\partial A_{\parallel} / \partial t)$ (solid line), $E_{\parallel,i}$ (dashed line),
 213 $E_{\parallel,k}$ (dotted line), and finally from the sum of the electric field approximations
 214 $E_{\parallel,i} + E_{\parallel,k}$ (dot-dashed line). The simulation parallel electric field is indeed

215 reduced from the inertial approximation. However, what is most surprising is
 216 that it is reduced by exactly the amount predicted from the kinetic approxima-
 217 tion (note that the dot-dashed line is difficult to make out in Figure 2 because
 218 it lies almost exactly on top of the E_{\parallel} from the simulation). Hence, the ap-
 219 proximations used by Chaston et al. (2003) appear to yield the correct parallel
 220 electric field. Note that the parallel electric field in the studies presented here
 221 is a diagnostic of the simulation code and not an intrinsic simulation variable
 222 [i.e., it does not appear in equations (1)-(3)]. It is also important to note that
 223 equations (4) and (5) relate the size of the parallel electric field to the gra-
 224 dient of the perpendicular electric field, E_{\perp} . In this simulation, E_{\perp} varies in
 225 response to the plasma evolution. This evolution of E_{\perp} can be a change in
 226 profile (e.g. nonlinear steepening) or a change in amplitude due to the wave
 227 particle interactions. Analysis of wave and plasma energy changes in the sim-
 228 ulation presented here shows that by the time the wave reaches $z = 1R_E$,
 229 it has converted 37% of its Poynting flux to accelerated electron energy flux
 230 (energy flux contained in the beam electrons which arrive before the pulse).
 231 Although a combination of equations (4) and (5) yields a very good approxi-
 232 mation for E_{\parallel} , it is also necessary to have the correct form of E_{\perp} . Therefore,
 233 in order to obtain the correct amplitude and profile for the parallel electric
 234 field, and therefore the correct numbers and energies of accelerated electrons,
 235 a self-consistent simulation code is essential.

236 Watt et al. (2006) showed using a self-consistent simulation code with a non-
 237 uniform magnetic field that as a pulse travels through regions of increasing
 238 Alfvén speed (e.g. travels along a magnetic field line from the plasma sheet
 239 towards the ionosphere) it can catch up to previously accelerated electrons and
 240 accelerate them further, to even higher energies, through the same resonant

241 process. The results of Watt et al. (2006) and the results presented here suggest
 242 that electrons resonantly accelerated to keV by shear Alfvén waves at $4 - 5R_E$
 243 radial distance may experience further acceleration by the same wave as the
 244 wave progresses to regions of higher Alfvén speed closer to the Earth. In order
 245 to test this prediction, we plan to extend our simulation code to follow the
 246 evolution of a pulse and its interaction with the ambient electron population
 247 from radial distances of $5R_E$ to 200km altitude in order to investigate the
 248 conditions for excitation of high-energy electron beams when one takes into
 249 consideration the changing temperature, number density and magnetic field
 250 profiles in this region.

251 **4 Conclusions**

252 We have investigated, using self-consistent kinetic simulations, the similarities
 253 and differences between shear Alfvén waves in an intermediate ($v_{th,e} \sim v_A$)
 254 regime of parallel electron acceleration for plasma parameters that are appro-
 255 priate to radial distances of $4 - 5R_E$. Previous studies of electron acceleration
 256 in this plasma regime have been performed using a test-particle approach,
 257 which required the use of assumptions regarding the form of the parallel elec-
 258 tric field. Using our self-consistent code, we can be confident that the parallel
 259 electric field we obtain is correct, and that the parallel electron acceleration
 260 seen is quantitatively more realistic.

261 We have shown that the expression for the parallel electric field as a function of
 262 the gradient of the perpendicular electric field as used by Chaston et al. (2003)
 263 provides a reasonable approximation to the parallel electric field obtained from
 264 a fully nonlinear self-consistent simulation that includes the necessary electron

265 inertia and electron pressure effects.

266 A definitive answer as to whether electrons are accelerated by shear Alfvén
267 waves at $2 - 3R_E$ or $4 - 5R_E$ radial distance will require the marriage of a
268 large number of in-situ observations and sophisticated nonlinear kinetic mod-
269 els which include the effects of plasma and magnetic field inhomogeneities.
270 However, the self-consistent simulation results shown in this paper indicate
271 that for plasma conditions typical of $4 - 5R_E$ radial distance, shear Alfvén
272 waves can accelerate electrons in the parallel direction to keV energies for
273 modest amplitude waves and hence our results motivate further study of elec-
274 tron acceleration in this plasma regime.

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Fig. 1. The time evolution of plasma and wave diagnostics from the simulation run at $z = 1R_E$: (a) the differential electron energy flux of the downward moving electrons, (b) the absolute value of the parallel electron energy flux, (c) the parallel current, (d) the perpendicular electric field, (e) the parallel electric field, and (f) the perpendicular magnetic field perturbation.

Fig. 2. The parallel electric field determined from simulation parameters: due to simulation potentials $E_{\parallel,s} = -\nabla_{\parallel}\phi - (\partial A_{\parallel}/\partial t)$ (solid line); approximation due to inertial effect $E_{\parallel,i}$ (dashed line); approximation due to kinetic effect $E_{\parallel,k}$ (dotted line), and the sum of the electric field approximations $E_{\parallel,i} + E_{\parallel,k}$ (dot-dashed line)

Figure 1

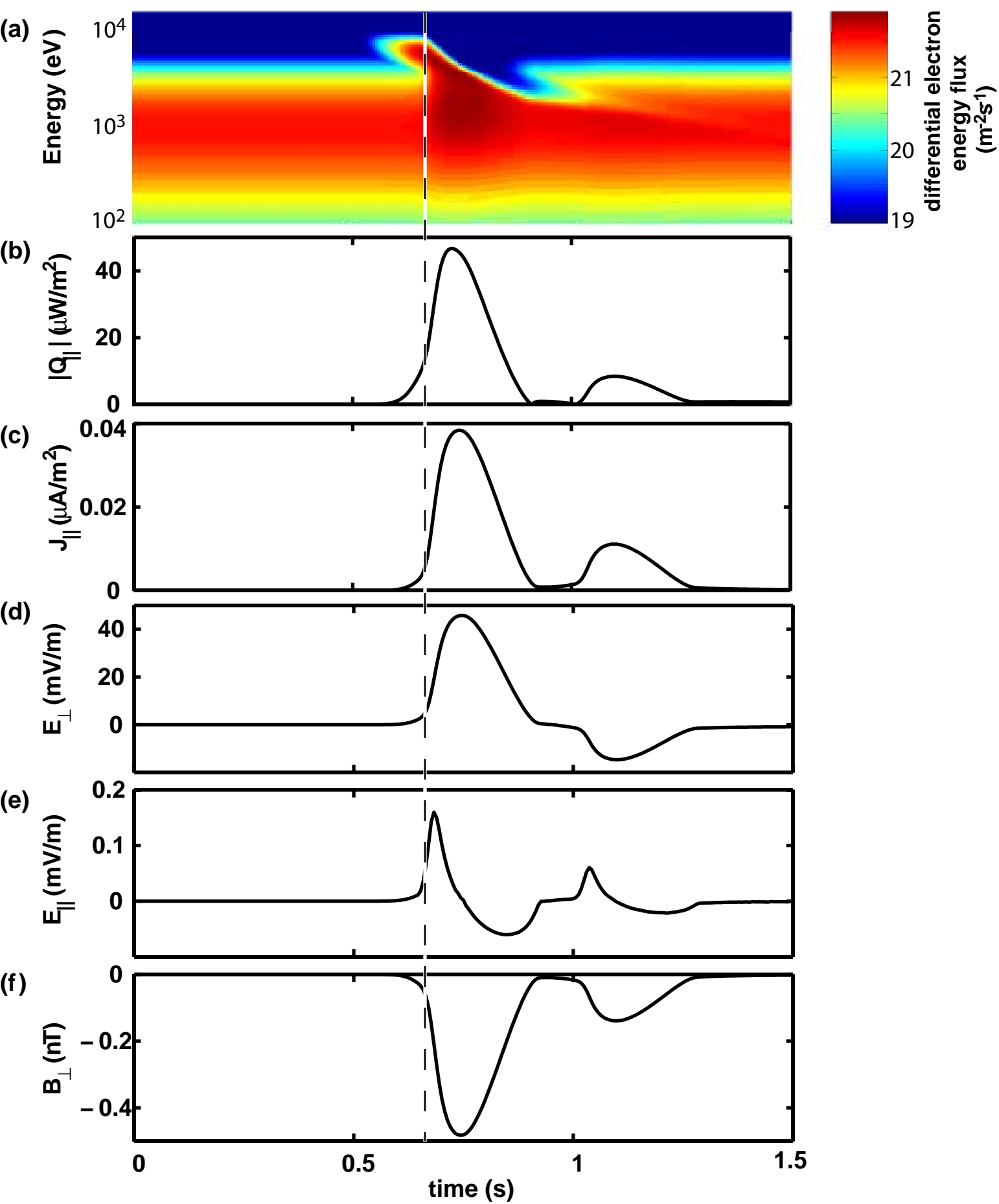


Figure 2

