

# PLASMA WAVE GENERATION BY THICK TARGET ELECTRON BEAMS IN SOLAR FLARES

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## Abstract

We investigate numerically the effect of a finite density gradient on the Langmuir wavelevel produced by an electron beam in the flaring solar corona. The energy losses and associated plasma heating resulting from the presence of a beam-neutralizing reverse current are taken into account. The density and temperature structure of the background plasma are determined self-consistently, assuming steady state energy balance and hydrostatic equilibrium. The implications of our results for flare acceleration mechanisms are discussed.

## 1. Introduction

Solar hard X-rays, observed during the impulsive phase of flares, are believed to be produced by electron-ion bremsstrahlung, the electrons having been heated or accelerated to energies of a few tens of keV. The "thick target" model requires a large flux of collimated electrons to be injected continuously from a site in the corona into the chromosphere, where most of the X-rays are produced. The transport of such a beam through the corona is governed by both Coulomb collisions and collective plasma processes. Emslie and Smith (1984) showed that thick target beams may become 2-stream unstable, because of the collisional depletion of low velocity electrons. The resulting Langmuir wave turbulence may constitute an important source of coherent microwave radiation at the 2nd harmonic of the plasma frequency. In this paper we present numerical calculations of the thick target plasma wave level, allowing self-consistently for the response of the background coronal plasma to an electron beam energy input.

## 2. The Atmospheric Model

We consider a one dimensional flaring coronal loop, the steady state temperature of which is determined by a balance between electron beam heating and thermal conduction. The total energy deposition rate is given by

$$I_T = I_B + I_R + I_W$$

where  $B$ ,  $R$  and  $W$  refer to beam collisional heating, reverse current Ohmic heating and Langmuir wave heating. We adopt an empirical functional form for  $I_T$

$$I_T(z) = I_0 e^{-z/l} \quad (1)$$

where  $z$  is the distance from the point of beam injection, and  $I_0$ ,  $l$  are constants. Solving the equations of steady state energy balance and hydrostatic equilibrium (neglecting radiative losses and gravity), we then obtain for the temperature  $T$  and density  $n$ :

$$T = T_0 \left( 1 - \frac{7I_0 l}{2\kappa_0 T_0^{7/2}} [z - l(1 - e^{-z/l})] \right)^{2/7}$$
$$n = n_0 \left( 1 - \frac{7I_0 l}{2\kappa_0 T_0^{7/2}} [z - l(1 - e^{-z/l})] \right)^{-2/7}$$

where  $T_0$ ,  $n_0$  are constants and  $\kappa_0$  is the (Spitzer) thermal conduction coefficient. We have assumed  $dT/dz = dn/dz = 0$  at  $z = 0$  (the loop apex).  $T_0$  is obtained by setting  $T = 0$  at  $z = L$  (the transition region). To achieve self-consistency for a given set of parameters, it is necessary to make initial estimates of  $I_0$  and  $l$ , and to proceed thereafter by iteration: having solved the wave-particle kinetic equations, we can obtain new values of  $I_0$ ,  $l$  by fitting the corresponding heating rate to Eq.(1). This may be continued until the values of  $I_0$ ,  $l$  in successive iterations differ from each other by less than one standard error in the cases which were studied, convergence was found to occur rapidly.

### 3. Wave-Particle Kinetic Equations

Neglecting pitch angle scattering, the transport equations for beam electrons (injected along the ambient magnetic field) and Langmuir waves may be written in the form

$$v \frac{\partial f}{\partial z} - \frac{c\eta}{m} j_b \frac{\partial f}{\partial v} = \frac{e^2 \omega_p^2}{m} \frac{\partial}{\partial v} \left( \frac{\ln v / v_e}{v^2} f \right) + \frac{\pi \omega_p}{mn} \frac{\partial}{\partial v} \left( vW \frac{\partial f}{\partial v} \right) + \frac{2Kn}{m^2} \frac{\partial}{\partial v} \left( \frac{f}{v^2} + \frac{v_e^2}{v^3} \frac{\partial f}{\partial v} \right) \quad (2)$$

$$\frac{3v_e^2}{v} \frac{\partial W}{\partial z} + \frac{1}{2} \frac{d \ln n}{dz} \frac{\partial}{\partial v} (v^2 W) = e^2 \omega_p^2 \frac{\ln v / v_e}{v} f + \frac{\pi \omega_p}{n} v^2 W \frac{\partial f}{\partial v} - \gamma_c W \quad (3)$$

where  $f$  is the electron distribution,  $W$  is the Langmuir wave spectrum,  $j_b$  is the electron beam current,  $\eta$  is the Spitzer resistivity,  $K = 2\pi e^4 \Lambda$  ( $\Lambda$  the Coulomb logarithm), and  $\gamma_c$  is the collision frequency. The rest of the notation is standard (In Eq.(3),  $v$  may be interpreted physically as the Langmuir wave phase velocity). Numerical solutions of Eqs.(2) and (3) were obtained for two types of boundary condition at  $z = 0$ :

#### Boundary Condition A

$$f[v(E)] = n_0 \left( \frac{m}{2\pi k_B T_0} \right)^{1/2} e^{-E/k_B T_0} + m F_0^{\delta-1} (\delta - 1) (E_0 + E)^{-\delta}$$

i.e. a Maxwellian plus a displaced power law.  $F_0$ ,  $E_0$  and  $\delta$  are constants,  $F_0$  being the total flux of beam electrons.  $k_B$  is Boltzmann's constant. This injection profile is used to compare our results with those of Emslie and Smith (1984).

#### Boundary Condition B

$$f[v(E)] = n_0 \left( \frac{m}{2\pi k_B T_0} \right)^{1/2} e^{-E/k_B T_0}, \quad E \leq E_1$$

$$f[v(E)] = f_0, \quad E_1 < E < E_0$$

$$f[v(E)] = m F_0 E_0^{\delta-1} (\delta - 1) E^{-\delta}, \quad E \geq E_0$$

where  $F_0$  is the injected flux of electrons with energies above  $E_0$ , and  $E_1$ ,  $f_0$  are uniquely constrained by  $T_0$ ,  $n_0$ ,  $F_0$ ,  $E_0$  and  $\delta$  (if  $f(v)$  is assumed to be continuous). If the acceleration process can be described using quasi-linear theory, energy can only be transferred from waves to particles if  $\partial f / \partial v < 0$  - turbulent acceleration cannot produce an electron spectrum with a positive slope. So the injected beam distribution which is most efficient at producing the observed hard X-rays (photon energies  $\gtrsim 25$ keV) will be given by boundary condition B.

### 4. Numerical Results

#### Boundary Condition A

Results were obtained with the following parameters:  $F_0 = 10^{18}$  electrons  $\text{cm}^{-2} \text{s}^{-1}$ ;  $E_0 = 20$ keV;  $\delta = 4$ ;  $L = 10^9$ cm;  $10^9 \text{cm}^{-3} \leq n_0 \leq 10^{11} \text{cm}^{-3}$ . For each chosen value of  $n_0$ , Eq.(1) gives an acceptable representation of the heating rate. The best-fit peak temperatures lie in the range  $9 \times 10^6 \text{K} - 15 \times 10^6 \text{K}$ .

Contrary to Emslie and Smith, a positive slope never appears in the electron distribution -  $W_p$  never rises significantly above the thermal noise level. This is due to the following stabilizing effects:-

- (i) The background plasma density rises along the direction of beam propagation.
- (ii) Landau damping of plasma waves is enhanced by reverse current Ohmic heating.
- (iii) The formation of a positive  $\partial f/\partial v$  is suppressed by reverse current energy losses and by collisional diffusion close to the thermal speed.

#### Boundary Condition B

The beam parameters were chosen to give the same thick target hard X-ray yield as condition A:  $F_0 = 1.25 \times 10^{17}$  electrons  $\text{cm}^{-2} \text{s}^{-1}$ ;  $E_0 = 20 \text{keV}$ ;  $\delta = 4$ . As before,  $L = 10^9 \text{cm}$  and  $10^9 \text{cm}^{-3} \leq n_0 \leq 10^{11} \text{cm}^{-3}$ . In the low density case ( $n_0 \lesssim 10^{10} \text{cm}^{-3}$ ), Langmuir instability occurs downstream of the injection point due to the collisional depletion of beam electrons in the plateau region of velocity space. The contributions of collisional, Ohmic and wave heating are shown in Figure 1 ( $n_0 = 10^9 \text{cm}^{-3}$ ) and Figure 2 ( $n_0 = 10^{10} \text{cm}^{-3}$ ); the corresponding Langmuir wavelevels are shown as solid lines in Figures 3 and 4. As  $n_0$  is increased, we find that the wave energy density falls off rapidly, and becomes increasingly localized in space towards the point of injection. When  $n_0 = 10^{11} \text{cm}^{-3}$ , a high level of turbulence occurs *only* at the boundary ( $W_p/nk_B T$  decays on a length scale of  $\lesssim 10^4 \text{cm}$ ). This is because the plasma density (and hence the rate of Landau damping) increases along the length of the loop: the plasma/beam density ratio is so high that even a very small relative change in  $n$  can drastically reduce the wavelevel. The important conclusion to draw is that the Langmuir wavelevel associated with a thick target beam depends much more sensitively on the boundary conditions (i.e. the shape of the injection profile) than on any propagation effects.

Figures 3 and 4 also illustrate the effects of refraction: the dotted lines show the wavelevel which is obtained when the  $dlnn/dx$  term in Eq. (3) is neglected. Clearly the density scale height is sufficiently large that wave refraction is of relatively minor importance.

## 5. Conclusions and Discussion

We have attempted to model the collisional and quasi-linear evolution of a thick target electron beam in a fully self-consistent manner, taking into account the response of the background plasma to a prescribed beam input. We have shown that the collisional depletion of low velocity electrons does *not* necessarily give rise to a 2-stream instability, and that a high level of Langmuir turbulence will only result if the electrons have a plateau-type distribution at the point of injection. Fundamental or 2nd harmonic microwave emission from flares, if it exists, is therefore a product of the acceleration process. The “reverse drift” microwave bursts reported by Stähli and Benz (1987) do appear to represent the plasma radiation signature of downward-propagating beams, but these events are highly transient. For the majority of hard X-ray events, there is no compelling evidence for the existence of simultaneous plasma emission. This suggests that the injected electron spectrum is either a monotonic decreasing function of velocity along the streaming direction, or is close to being isotropic. Any candidate acceleration mechanism would then be constrained accordingly. This conclusion may be premature, however, since Langmuir waves may be strongly damped due to, for example, stochastic density fluctuations (Muschietti *et al.*, 1985). If that were the case, one would also be forced to rule out Langmuir turbulence as an agent for particle acceleration.

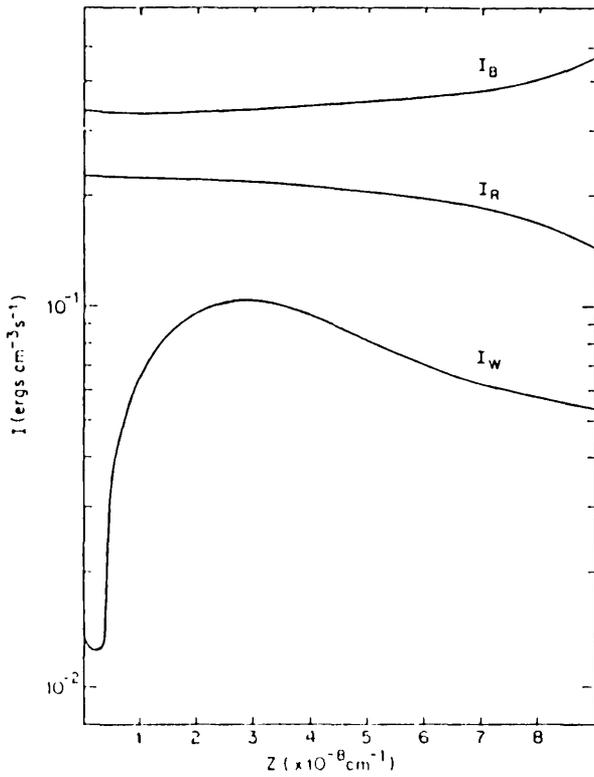
A more detailed account of this work, and its application to a specific solar flare, can be found elsewhere (McClements 1988).

## Acknowledgement

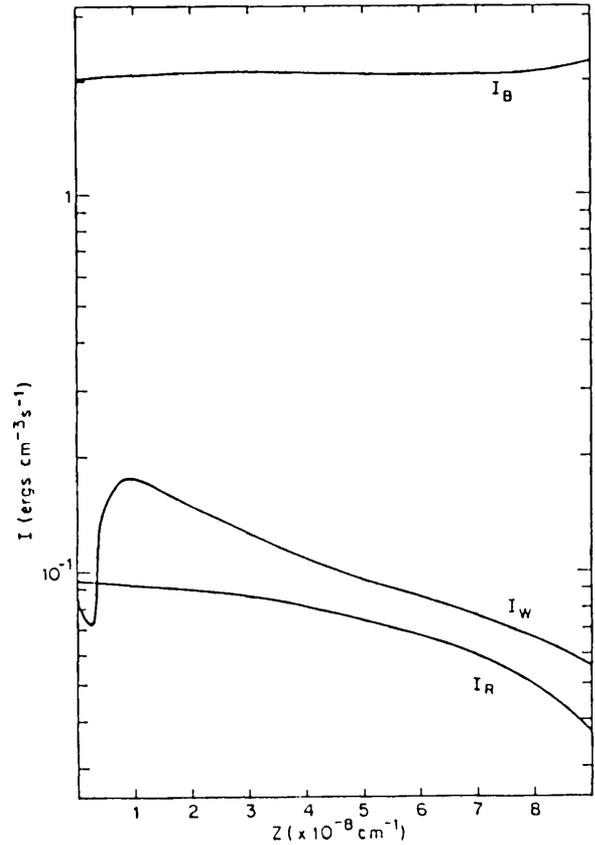
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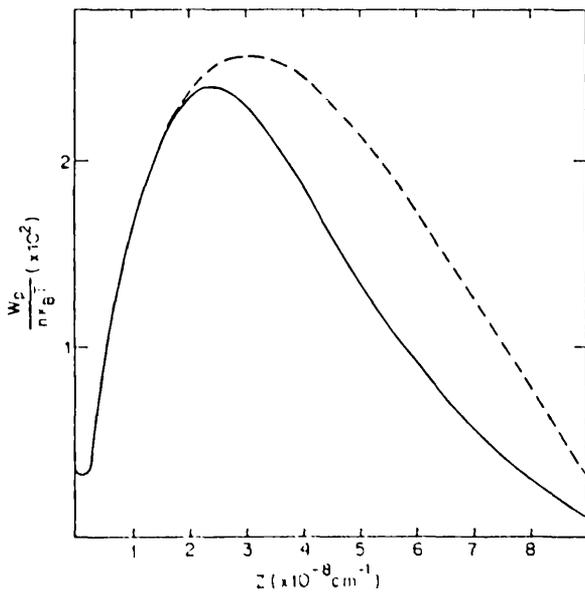
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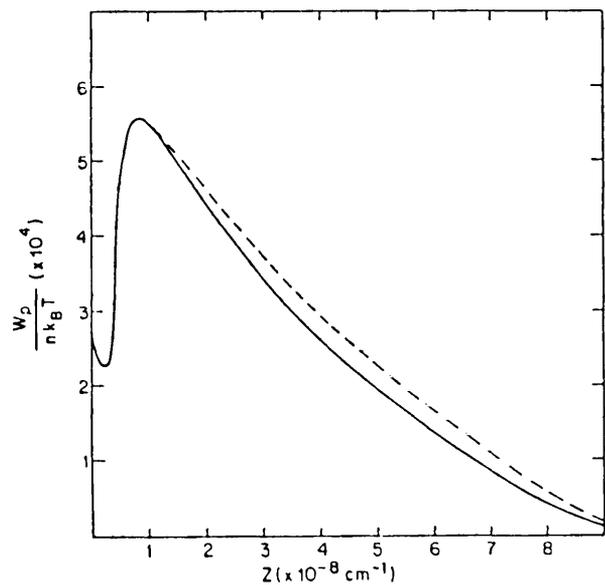
**Fig 1**  $I_B$ ,  $I_R$  and  $I_W$  as functions of  $z$ , for the case of boundary condition B and with  $n_0 = 10^9 \text{cm}^{-3}$ .



**Fig 2** As Figure 1 except with  $n_0 = 10^{10} \text{cm}^{-3}$ .



**Fig 3** Langmuir wave energy density (normalized to the thermal energy density) as a function of  $z$ , for the case of boundary condition B and with  $n_0 = 10^9 \text{cm}^{-3}$  (solid line). The wavelevel which is obtained when the density gradient term in Eq.(3) is omitted is also shown (broken line).



**Fig 4** As Figure 3 except with  $n_0 = 10^{10} \text{cm}^{-3}$ .