RETURN CURRENT INSTABILITY IN FLARES

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Abstract.

We consider the problem of ion-acoustic wave generation, and resultant anomalous Joule heating, by a return current driven unstable by a small-area thick-target electron beam in solar flares. We find that, contrary to the usual assumption, the hard X-ray bremsstrahlung emission may actually be enhanced in comparison to conventional thick-target models. This present paper is a summary of the work of Cromwell, McQuillan and Brown (1988).

Introduction.

It is now commonly believed that electron beams propagating downwards in the solar atmosphere play a major role in the production, by collisional bremsstrahlung, of hard X-ray bursts during the impulsive phase of solar flares. Electron beam injection sets up a **cospatial, beam-neutralising return current** (e.g. Hoyng, Brown and van Beek, 1976). Therefore, the beam loses additional energy in driving the return current against the finite resistivity of the plasma. We might well ask: Does this aggravate the low efficiency problem of thick target models? What effect does return current instability have on hard X-ray production?

Electrostatic wave generation by an unstable return current will lead to anomalously large values of resistivity. (Here we consider the ion-acoustic instability as this has the lowest threshold drift speed in an unmagnetized plasma). The effect on hard X-ray emission will be twofold:

(a) The electric field driving the return current will rise, reducing the lifetime of beam electrons. Therefore, the **nonthermal yield will decrease.**

(b) Plasma heating, ηj^2, will rise. Therefore, the **thermal yield will increase.**

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Model.

We assume a homogeneous, unmagnetized fully ionized hydrogen plasma consisting of two Maxwellian components (ambient electrons and ions) of density n_p which are initially isothermal ($T_e = T_i = T_0$). We intend to evaluate the thermal and nonthermal X-ray yields from our beam-plasma system. This requires tracking the evolution of $T_e(t)$, $T_i(t)$ and $\eta(t)$ using the following dynamic temperature equations (which neglect losses, for simplicity):

$$\frac{3}{2} n_p \frac{dT_e}{dt} = \frac{3}{2} n_p \frac{(T_i - T_e)}{\tau_{eq}} + \frac{K j_p}{e E_0} + \chi_{ia} \eta_{ia} j_p^2 \tag{1}$$

$$\frac{3}{2} n_p \frac{dT_i}{dt} = \frac{3}{2} n_p \frac{(T_e - T_i)}{\tau_{eq}} + (1 - \chi_{ia}) \eta_{ia} j_p^2 \tag{2}$$

where $K = 2\pi e^4 \ln\Lambda n_p$ in the usual notation.

χ_{ia} and $(1 - \chi_{ia})$ are, respectively, the fractions of the ohmic dissipation, $\eta_{ia} j_p^2$, absorbed by the electrons and ions, as a result of scattering off ion-acoustic waves; η_{ia} is the extra contribution to the plasma resistivity due to the presence of these waves.

The heating equations (1) and (2) apply to the cylindrical volume bounded by the minimum beam stopping length, s_{min}, because it is only this region which is heated continuously throughout the simulation. Due to Coulomb collisions and Ohmic dissipation of the return current, the electron beam stopping length is:

$$s = \frac{E_0}{e \eta j_p + (K / E_0)} \tag{3}$$

where E_0 is the mean beam electron energy.

To investigate return current instability we assume a small-area beam and the typical flare parameters: $A = 10^{16}\mathrm{cm}^2$, $n_p = 10^{11}\mathrm{cm}^{-3}$, $E_0 = 25 keV$, $T_0 = 5.10^6 K$.

Marginal Stability Approach.

In the classical heating regime $v_d < v_{crit}(T_e, T_i)$, the critical drift speed for the onset of ion-acoustic instability, and $\eta_{ia} = 0$. Equations (1) and (2) can then be solved easily. In a turbulent plasma, however, to circumvent the complexities of the relevant nonlinear plasma physics, we assume the **marginal stability** hypothesis: the plasma remains on the boundary between unstable growth and damping for that particular microinstability ($\gamma = d\gamma/dk = 0$). We therefore set $v_d = v_{crit}(T_e, T_i)$ at instability onset.

We have a prescribed beam current evolution, $j_b(t) = -j_p(t)$, in our model: a linearly increasing function of time, from zero to a typical large electron flux of $10^{36} s^{-1}$ over the beam rise time, t_r. Therefore, since $v_d(t) = \dfrac{j_p(t)}{n_p\, e}$ is known, we can solve equations (1) and (2).

We wish to calculate the thermal bremsstrahlung from the rapidly heated plasma. For comparison, we evaluate the conventional thick-target nonthermal bremsstrahlung from the same beam **but with Coulomb collisional losses only** (as would be relevant to a beam with larger area $A \sim 10^{18}$-$10^{19}\mathrm{cm}^2$).

Adopting reasonable beam and atmospheric parameters we find that rapid anomalous Ohmic heating occurs in a substantial plasma volume. This large hot plasma emits thermal bremsstrahlung hard X-rays ($\gtrsim$20 keV) comparable to, or exceeding, the nonthermal bremsstrahlung which would have been emitted in a conventional collisional thick target.

However, it turns out that there is a contradiction which can arise in the marginal stability treatment in some parameter regimes. Its origin is most easily demonstrated by retaining only the anomalous (ion-acoustic) terms in equations (1) and (2). Applying the condition of marginal stability leads to:

$$\eta_{ia}^{MS} \sim \frac{T_e^{1/2}}{1-\chi_{ia}^{MS}(1+\frac{T_i}{2T_e})} \tag{4}$$

where:

$$\chi_{ia}^{MS} \simeq 1 - \frac{c_s}{v_{crit}} \tag{5}$$

From equations (4) and (5) it follows that marginal stability fails for $(T_e/T_i)_{onset} \lesssim 4.8$, since negative, i.e. unphysical, values of resistivity are obtained. Or, equivalently, for our prescribed beam current evolution, failure occurs for sufficiently rapid beam rise times, $t_r \lesssim 1s$. **For $T_e/T_i \lesssim 4.8$ a marginally stable plasma evolution is not possible: the dual constraints of a driving electron beam and the heating properties of ion-acoustic waves are incompatible in marginal stability.**

The failure of marginal stability in this regime is, we believe, directly related to the neglect of plasma wave energy density, W, in the energy equations (1) and (2). Underlying the marginal stability hypothesis is the assumption that $dW/dt = 0$ only over negligibly short times compared to the heating timescale. If this is not true then W will become much larger and then the plasma would be even more rapidly heated, on timescales far shorter than the beam rise time t_r, until eventually $dW/dt = 0$. To confirm this interpretation we have conducted numerical simulations (Cromwell, 1987) on beam-driven ion-acoustic wave growth. These simulations show that, for $T_e/T_i > 4.8$, the waves are rapidly switched on and off, as the plasma oscillates about the marginal stability curve, and that the values of W and dW/dt remain very low; marginal stability is, therefore, applicable here. However, for $T_e/T_i < 4.8$, non-negligible values of W and dW/dt are indeed attained and very rapid heating occurs. In these cases, the marginal stability concept is no longer applicable because the form of the driver is incompatible with zero wave growth rate at these T_e/T_i and must be replaced by an alternative method (i.e., a proper wave growth analysis).

Conclusions

Our work may be summarized as follows. For $(T_e / T_i)_{onset} \gtrsim 4.8$ (i.e. beam rise time $t_r \lesssim 1s$), Ohmic dissipation of a beam-driven return current can result in a higher hard X-ray bremsstrahlung efficiency than in a conventional collisional thick target. For $t_r \gtrsim 1s$, marginal stability is not applicable and we envisage that catastrophic heating will occur in small volumes. Once the value of T_e / T_i has increased sufficiently in such a catastrophically heated volume marginally stable heating will then take over. This may lead to the propagation of a front of catastrophically heated plasma through a flaring loop. Such a process might give rise to rapid oscillations in the hard X-ray profile (cf. Kiplinger *et al.*, 1983).

Further work requires the inclusion of spatial dependence of the plasma quantities, together with possible loss mechanisms (e.g. thermal conduction and plasma expansion). Accurate modelling of plasma turbulence in the regime where catastrophic heating occurs is also certainly desirable.

In conclusion, we believe that the essential result presented here of enhanced Ohmic return current dissipation leading to rapid plasma heating to hard X-ray temperatures will remain unaltered. The simple model we have described has yielded useful information and clearly demonstrated the importance of return current instability on the hard X-ray signature of flares.

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