RETURN CURRENTS AND ENERGY TRANSPORT IN THE SOLAR FLARING ATMOSPHERE

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ABSTRACT

According to the standard Ohmic perspective, the injection of accelerated electrons into the flaring region violates local charge equilibrium and therefore, in response, return currents are driven by an electric field to equilibrate such charge violation. In this framework, the energy loss rate associated with these local currents has an Ohmic nature and significantly shortens the accelerated electron path. In the present paper, we adopt a different viewpoint and, specifically, we study the impact of the background drift velocity on the energy loss rate of accelerated electrons in solar flares. We first utilize the Rutherford cross-section to derive the formula of the energy loss rate when the collisional target has a finite temperature and the background instantaneously and coherently moves up to equilibrate the electron injection. We then use the continuity equation for electrons and imaging spectroscopy data provided by RHESSI to validate this model. We show that this new formula for the energy loss rate provides a better fit of the experimental data with respect to the model based on the effects of standard Ohmic return currents.

Key words: methods: numerical – Sun: flares – Sun: X-rays, gamma rays – techniques: imaging spectroscopy

Online-only material: color figures

1. INTRODUCTION

In arc-shaped solar flares, huge amounts of electrons are accelerated due to magnetic reconnection. In the standard picture (Fletcher et al. 2011), accelerated electrons are injected at the top of the loop-shaped flare, move down along magnetic field lines, and, during their motion, lose energy because of various mechanisms. Coulomb collisions with ambient particles represent the most relevant mechanism to explain energy losses for accelerated electrons in loop-shaped flares. In this framework, the predominant energy loss process involves the interaction between the injected electrons and the electrons in the flaring target. Specifically, under the assumption of a cold target, the energy loss rate formula depends as $1/E$ on the electron energy $E$ (Emslie 1978), while in a warm target a more complicated formula accounts for the temperature $T$ of the ambient medium (Spitzer 1962; Longmire 1963). However, other important effects may impact this process, such as wave–particle interactions (Hoyng & Melrose 1977; Hannah & Kontar 2011) and return currents. This paper focuses on the role of return currents in the energy loss mechanism during flares and specifically utilizes measurements observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) to empirically study the mechanism of energy loss in the presence of return currents.

In their pioneering paper, Knight & Sturrock (1977) analyzed the effect of return currents on accelerated electron motion by means of electrostatic fields and using the Vlasov equation. The combination of a reverse current electrostatic field with collisions was discussed in Emslie (1980), where the impact of return currents on hard X-ray emission was also studied. Bounds for the size of the electrostatic term due to unstable electron–ion drifts are found in Emslie (1981). Brown & Bingham (1984) present another approach using electrostatic modeling. The influence of inductive fields and their interplay with the electrostatic one was thoroughly discussed and compared by Larosa & Emslie (1989) and van den Oord (1990). Starting from observations, McClymont & Canfield (1986) argued that the areas of injection are considerably small, and thus very large return currents are expected. More recently, Alexander & Daou (2007) used RHESSI observations to estimate the injection area, confirming the effects on hard X-ray emission predicted in Emslie (1980). A complete treatment of the many possible kinetic energy loss mechanisms, including Ohmic losses, was presented more recently in Zharkova & Gordovskyy (2005).

All previous papers are based on an Ohmic viewpoint, according to which the injection of a large number of accelerated electrons into the loop violates the local charge equilibrium and, in response to this violation, local currents are established by flare background electrons. In this picture, the generated return currents are driven by an electric field and the energy losses of Ohmic nature shorten the accelerated electron path before thermalization. However, a different model describing the restoration of charge equilibrium is possible, in which the production of return currents occurs instantaneously and the background particles move up coherently along the field line, while the energy loss rate due to Coulomb collisions is modified in a very peculiar manner: since a single accelerated electron appears more energetic in the rest frame of the background motion and since the energy loss rate decays with energy, we expect the resulting Coulomb collision energy loss rate to be lower than the one computed for background particles with vanishing drift velocity.

The aim of the present paper is to investigate the impact of this coherent background motion on the energy loss rate for accelerated electrons and to compare it with the competing influence of Ohmic forces induced by return currents. This comparison will be performed by following the same empirical approach adopted by Torre et al. (2012): we will (1) use hard X-ray imaging spectroscopy data obtained by RHESSI to reconstruct mean electron flux images of extended sources (Piana et al. 2007) and (2) apply the electron continuity equation to select the model for the energy loss rate that best fits the empirical electron maps.

This approach can only be used for those events showing a large X-ray emission from the loop-top, and therefore exhibiting a clear arc-shaped behavior in the electron flux maps. Only a few of these events have been observed by RHESSI, an incomplete list of which is presented in Guo et al. (2012b). Our analysis...
involves some of these observations (three M-class flares at different time intervals) and, furthermore, three X-class flares not included in the list.

The paper is organized as follows. In the next section, we derive the energy loss rate for Coulomb collisions when a coherent motion is added to the background Maxwellian distribution. In Section 3, we describe the procedure we adopted to compare various energy loss rate models. Our comparison of such models with RHESSI observations is presented in Section 4. Finally, some conclusions are drawn in the last section.

2. A GENERAL MODEL FOR THE COULOMB COLLISIONAL ENERGY LOSS RATE

The main ingredients on which our model is based are two formulae obtained by Rutherford (1911) and Butler & Buckingham (1962), respectively. In the first one, the differential cross-section, which describes the probability of a single collision of a particle of charge $Z e_-$ and mass $m$ traveling with a speed $v$ against a target particle of mass $M$ and charge $Z e_-$ moving at a velocity $w$, is

$$\frac{d\sigma}{d\Omega} = \frac{(Ze_\ast e)^2}{4 \left( \frac{Mm}{M+m} \right)^2 (v-w)^4 \sin^4 \left( \frac{\theta}{2} \right)} \cdot \quad \theta \geq \theta_0. \quad (1)$$

This expression is nonzero only for scattering angles $\theta$ bigger than a fixed small angle $\theta_0$ that is related to the Debye screening length.

The second formula describes the collisional loss rate for a particle traveling in a plasma, whose particle velocities are distributed as $f(w)$, and is given by

$$\left( \frac{dE}{dt} \right)_c = -4\pi \frac{(Ze_\ast e)^2 e^4 \Lambda}{M} \times \int \frac{(v-w) \cdot (v + \frac{M}{m} w)}{|v-w|^3} f(w) \, d^3 w. \quad (2)$$

Here, the Coulomb logarithm $\Lambda$ is related to $\theta_0$ by

$$\Lambda = -\log \left( \frac{\sin \theta_0}{2} \right) \simeq -\log \frac{\theta_0}{2}. \quad (3)$$

In order to discuss the role of coherent motion in the energy loss rate, we follow the derivation of Equation (2) given by Butler & Buckingham (1962) and modify the form of the target distribution. Here, we assume that the background particles are in a stationary solution of the Boltzmann equation, i.e., that they are distributed according to the Maxwell law but with a coherent motion induced by a drift velocity $w_0$ and a thermal velocity $w_T$ such that $Mw_T^2/2 = k_B T$, where $T$ is the temperature of the distribution and $k_B$ is the Boltzmann constant. Under these hypotheses, we have

$$f(w) = \frac{n}{\pi^{3/2} w_T^{3/2}} e^{-(\frac{v-w_0}{w_T})^2}, \quad (4)$$

where $n$ is the target electron density. Integrating over the target velocities and expressing the result in terms of $\vec{v}' = \vec{v} - \vec{w}_0$, we obtain

$$\left( \frac{dE}{dt} \right)_c = \frac{2 Kn}{M v'} \left[ \left( 1 + \frac{M}{m} \right) \frac{v' \cdot w_0}{v'^2} \right] \text{erf} \left( \frac{v'}{w_T} \right) - \frac{2}{\sqrt{\pi}} \left( 1 + \frac{M}{m} \right) \left( 1 + \frac{v' \cdot w_0}{v'^2} \right) \frac{v'}{w_T} e^{-\left( \frac{v'}{w_T} \right)^2}, \quad (5)$$

where $K = 2\pi (Ze_\ast e)^2 e^4 \Lambda$ and erf is the standard error function. It is possible to point out two terms in Equation (5) characterized by two different physical meanings. The first term corresponds to the pure thermal energy loss rate computed in a frame where the coherent velocity of the background vanishes ($w_0 = 0$). The latter term is proportional to $\vec{v}' \cdot \vec{w}_0$ and cannot be directly inferred from the pure thermal energy loss rate. Equation (5) can be simplified by assuming that $w_0$ and $v'$ are anti-parallel and that the electron–electron collisions provide the most important contribution to the energy loss. Therefore, if $v' = ve_\ast$, $w_0 = -w_0 e_\ast$, then

$$\left( \frac{dE}{dt} \right)_c = -\frac{2 Kn}{m (v + w_0)} \left[ \left( 1 - 2 \frac{w_0}{v + w_0} \right) \text{erf} \left( \frac{v + w_0}{w_T} \right) - \frac{4}{\sqrt{\pi}} \left( 1 - \frac{w_0}{v + w_0} \right) \frac{v + w_0}{w_T} e^{-\left( \frac{w_0}{w_T} \right)^2} \right]. \quad (7)$$

When $w_0$ vanishes, the previous expression reduces to the standard energy loss rate formula, which can be found in Spitzer (1962). As previously noted in the general case, including the additional assumption stated above, the energy loss rate is formed by two contributions. The one that cannot be directly inferred from the thermal energy loss rate formula is also relevant in the zero temperature limit ($w_T \to 0$), where we obtain

$$\left( \frac{dE}{dt} \right)_c = -\frac{2 Kn}{m} \frac{1}{(v + w_0) - 2 \left( \frac{w_0}{v + w_0} \right)^2} = -\frac{2 Kn}{m} \frac{v - w_0}{(v + w_0)^2}. \quad (8)$$

Figure 1 provides a qualitative analysis of the energy loss rate (Equation (5)) for different values of the kinetic energy $E_0$ associated with the drift velocity $w_0$. From this analysis, it clearly follows that when the intensity of the background motion increases, the energy loss rate of the injected electrons decreases. Furthermore, all different forms of the energy loss rate for all different values of $E_0$ assume an asymptotic behavior $1/E$ at high electron energies.
3. SELECTION OF THE ENERGY-LOSS MODEL

We now validate the model in Equation (7) with electron flux maps reconstructed from RHESSI data, following the approach introduced by Torre et al. (2012).

In the standard flare picture, electrons move from the injection region toward footpoints along magnetic field lines, losing energy along the paths. \( F(E, s) \) (electrons \( \text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1} \)) is the electron flux differential in energy along the direction \( s \) and \( N(s) \) is the column depth, and Emslie et al. (2001) proved that \( g(s; E) = N(s)F(E, s) \) (electrons \( \text{cm}^{-4} \text{s}^{-1} \text{keV}^{-1} \)) satisfies the continuity equation

\[
\pm \frac{\partial}{\partial s} g(s; E) + \frac{\partial}{\partial E} \left( \frac{dE}{ds} \right) g(s; E) = S(s, E), \tag{8}
\]

where the first sign is positive for electrons moving toward larger \( s \) and negative otherwise. In this equation, \( g(s; E) \) corresponds to the mean electron flux maps, which can be reconstructed from RHESSI visibilities (Piana et al. 2007), while \( S(s, E) \) is the source term coding the information for the injection region. The continuity equation can be interpreted to obtain

\[
R(s, E) = \left( \frac{dE}{ds} \right)_{\text{tot}} \frac{1}{g(s; E)} \int_{E}^{\infty} S(s, E')dE', \tag{9}
\]

where

\[
R(s, E) = \pm \frac{1}{g(s; E)} \int_{E}^{\infty} \frac{\partial g(s; E')}{\partial s} dE' \tag{10}
\]

is an empirical quantity determined from the electron maps. In Equations (8)–(10), the source term \( S(s, E) \) describes the injection of electrons in the flare region, and thus it is an energy gain term. Following Guo et al. (2012a), here we assume

\[
S(E, s) = \begin{cases} 
  h_s \left( \frac{E}{E_s} \right)^{-\delta} & |s| \leq \frac{L}{2} \\
  0 & |s| > \frac{L}{2}, 
\end{cases} \tag{11}
\]

where \( h_s \) (electrons \( \text{cm}^{-5} \text{keV}^{-1} \text{s}^{-1} \)) is the source amplitude averaged along the line of sight, \( \delta \) is the spectral index of the injected electrons, \( L \) represents the length of the injected region, and \( E_s \) is fixed equal to 10 keV. Since here we are interested in the energy domain, and since we shall average over different \( s \) as in Torre et al. (2012), the choice of a box-shaped injection as in Equation (11) is not really restrictive.

The total energy loss rate

\[
\left( \frac{dE}{ds} \right)_{\text{tot}} = \frac{1}{v} \left( \frac{dE}{dt} \right)_{\text{tot}}
\]

in Equation (9) represents the core of the present analysis. In the following, we will consider four possible situations.

1. **Model 1.** Hot target with charge equilibrium. This is the case displayed in Equation (7), in which the collisional target has a finite temperature and the background instantaneously reacts to the electron injection by means of a coherent motion.

2. **Model 2.** Cold target with charge equilibrium. This is what happens in Equation (7) when one fixes \( E_T = (1/2)mw_f^2 = 0 \).

3. **Model 3.** Ohmic losses. In this case, there is no drift velocity in the collisional term (Equation (7)) and the energy loss rate has the form

\[
\left( \frac{dE}{ds} \right)_{\text{tot}} = \left( \frac{dE}{ds} \right)_{\text{e}} + \left( \frac{dE}{ds} \right)_{\text{ohm}}, \tag{12}
\]

where the second term on the right-hand side describing the Ohmic losses is given by

\[
\left( \frac{dE}{ds} \right)_{\text{ohm}} = -e_\text{c}E = -ne_\text{c}^2 \eta w_0. \tag{13}
\]

Here, \( \mathcal{E} \) is the electric field that drives the return currents, \( \eta \) is the resistivity, \( n \) is the background density, and \( w_0 \) is again the background velocity. The first term on the right-hand side is the standard energy loss formula, found in Spitzer (1962), corresponding to the case when no background velocity is present and the target temperature is finite.

4. **Model 4.** Hot target without return currents. This is the model described by Spitzer (1962) and already discussed by Torre et al. (2012).

For all four models the number of free parameters to fit against the empirical \( R(E, s) \) is always 2, and in all cases these parameters are the target density \( n \) and the averaged source amplitude \( h_s \) in Equation (11). In fact, the target temperature can be fitted by using spatially integrated spectroscopy. This same spectroscopy and the charge equilibrium constraint allow us to fix the drift velocity \( w_0 \). More specifically, assuming that the injected electron flux

\[
\int_{E_s}^{\infty} \int_{-\frac{L}{2}}^{\frac{L}{2}} h_s \left( \frac{E'}{E_s} \right)^{\delta} ds dE = h_s E_s L \left( \frac{\delta}{\delta - 1} \right) \tag{14}
\]

is equal to the flux \( nN \sqrt{(2/m)}E_0 = nNw_0 \) associated with the return currents leads to

\[
h_s E_s L \left( \frac{\delta}{\delta - 1} \right) = \frac{EM}{A} \sqrt{\frac{2}{m}} E_0. \tag{15}
\]

Since the emission measure (EM) can be inferred from spectroscopy and the flare area \( A \) from the reconstructed electron maps, Equation (15) represents a constraint for \( E_0 \) and therefore for \( w_0 \).

4. MODELS VERSUS OBSERVATIONS

The analysis outlined in the previous section can be implemented in flares whose spatially resolved electron flux images are clearly arc-shaped. This happens for only a few RHESSI events, i.e., those that show a large X-ray emission from the loop top (dense target and/or injection region with low altitude). Recently, lists of these kinds of events appeared in the literature (Xu et al. 2008; Guo et al. 2012a, 2012b, 2013). From the available possibilities, we performed an analysis for various time ranges of three different M-class flares partially listed by Guo et al. (2012b), namely those that occurred on 2002 April 15, 16 and 2004 May 21, and for three X-class flares occurred on 2002 July 20, 2002 August 3 and 2011 September 24. The chosen time intervals and the relevant physical parameters are described in Table 1 for M-class flares and in Table 2 for X-class events. The time interval selection was performed based on the light curves for each event. In the case of flares that have been analyzed at different time intervals (2002 April 15 and 16 and 2004...
May 21), we always considered an interval including the activity peak and, when possible, we also included an interval in the raising and falling phases. For flares that have been analyzed in only one interval (2002 July 20, 2002 August 3, and 2011 September 24), we have considered a range around the peak. The temperature $T$, the spectral index $\gamma = 3 - 1 \text{,}^3$ and the differential EM are obtained from photon spectral fitting. The electron flux maps were obtained using detectors 3 through 9, applying the imaging spectroscopy approach in Piana et al. (2007) to obtain the electron visibility bags and applying $uv_{\text{smooth}}$ (Massone et al. 2009) as the image reconstruction algorithm in the electron domain. The reason of this choice for imaging is because, first, we needed to apply visibility-based methods and, second, as opposed to the case of footpoints, for loop-shaped events $uv_{\text{smooth}}$ provides reliable reconstructions, as shown in Massone et al. (2009). The energy range adopted is from 10 to 36 keV for all events, with an energy binning of 2 keV. In order to obtain the flare area $A$ in the fifth column of Tables 1 and 2, we proceeded as follows. For each energy, the area is computed using a method developed in Guo et al. (2012a), namely, analyzing the second-order moments of the averaged mean electron flux maps in every direction starting from the pixel with maximum emission. The event length corresponds with the largest moment while the width corresponds with the smallest one. Figure 2 (left panel) shows the computed values for $A$ at different energies in the case of the 2002 August 3 event. Since $A = A(E)$ is rather stable for all flares considered, the values of $A$ given in Tables 1 and 2 are the average values over the electron energies.

The spatial region $\Delta s = [s_{\text{min}}, s_{\text{max}}]$ over which the average of $R(E, s)$ is computed is determined as in Torre et al. (2012). Specifically, the electron flux images are considered for all energies, and for each row of each image we took the pixel with maximum intensity. We thus drew a path in each image approximating a field line. In this path, we fixed at $s = 0$ the pixel with maximum intensity and assumed that moving toward the right footpoint increases $s$ while moving toward the left footpoint decreases $s$.

The values of $h_s$ and $n$ are determined as described in the previous section, i.e., by fitting the empirical $R(E, s)$ values, deduced from the mean electron flux spectral images and averaged along $\Delta s$, against the four models of the energy loss rate. These best-fit values for $h_s$ and $n$ in the six events under analysis are given in Tables 3 and 4, where we also provide the corresponding values of the kinetic energy associated with the return currents’ velocity. Furthermore, Figures 3 and 4 contain the empirical values of $R(E)$ used for the fitting and show the best-fit curves corresponding to the four theoretical models.

### Table 1
Main Characteristics of the M-class Events Under Analysis

| Time (UT) | $\text{EM} \left(10^{39} \text{ cm}^{-3}\right)$ | $kT$ (keV) | $\gamma$ | $A$ (arcsec$^2$) | $\Delta s$ (arcsec) |
|-----------|---------------------------------|-----------|---------|-----------------|-----------------|
| 2002 Apr 15 | | | | | |
| 00:03:00–00:06:00 | $0.224 \pm 0.013$ | $2.03 \pm 0.03$ | $8.2 \pm 0.2$ | 783 | $[-7.2, -2.0]$ |
| 00:06:00–00:09:00 | $0.412 \pm 0.025$ | $1.88 \pm 0.03$ | $8.1 \pm 0.2$ | 663 | $[-7.8, -2.0]$ |
| 00:09:00–00:12:00 | $0.51 \pm 0.04$ | $1.84 \pm 0.03$ | $8.3 \pm 0.2$ | 368 | $[-9.2, -3.4]$ |
| 2002 Apr 16 | | | | | |
| 13:10:00–13:15:00 | $0.331 \pm 0.022$ | $1.83 \pm 0.03$ | $8.3 \pm 0.1$ | 216 | $[1.0, 6.2]$ |
| 13:15:00–13:20:00 | $0.55 \pm 0.04$ | $1.613 \pm 0.021$ | $9.3 \pm 0.1$ | 270 | $[1.0, 9.1]$ |
| 2004 May 21 | | | | | |
| 23:47:00–23:50:00 | $0.354 \pm 0.027$ | $1.85 \pm 0.03$ | $8.1 \pm 0.1$ | 201 | $[1.0, 3.4]$ |
| 23:50:00–23:53:00 | $0.62 \pm 0.04$ | $1.75 \pm 0.03$ | $8.5 \pm 0.1$ | 142 | $[1.0, 4.4]$ |

Notes. Column 1: time range considered; Column 2: emission measure determined from spectroscopy; Column 3: temperature determined from spectroscopy; Column 4: photon spectral index determined from spectroscopy; Column 5: flare area computed following the method proposed in Guo et al. (2012a) as described in the text; Column 6: averaging interval determined as in Torre et al. (2012).

### Table 2
Main Characteristics of the X-class Events Under Analysis

| Time (UT) | $\text{EM} \left(10^{39} \text{ cm}^{-3}\right)$ | $kT$ (keV) | $\gamma$ | $A$ (arcsec$^2$) | $\Delta s$ (arcsec) |
|-----------|---------------------------------|-----------|---------|-----------------|-----------------|
| 2002 Jul 20 | | | | | |
| 21:27:00–21:30:00 | $4.83 \pm 0.16$ | $2.17 \pm 0.02$ | $6.53 \pm 0.14$ | 535 | $[-4.8, -2.00]$ |
| 2002 Aug 3 | | | | | |
| 19:06:00–19:09:00 | $1.38 \pm 0.08$ | $2.31 \pm 0.09$ | $7.29 \pm 0.21$ | 345 | $[3.00, 10.24]$ |
| 2011 Sep 24 | | | | | |
| 09:35:00–09:39:00 | $12.77 \pm 1.99$ | $1.78 \pm 0.06$ | $8.5 \pm 0.1$ | 759 | $[2.0, 8.8]$ |

Notes. Column 1: time range considered; Column 2: emission measure determined from spectroscopy; Column 3: temperature determined from spectroscopy; Column 4: photon spectral index determined from spectroscopy; Column 5: flare area computed following the method proposed in Guo et al. (2012a) as described in the text; Column 6: averaging interval determined as in Torre et al. (2012).

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3 This relation holds exactly in the case of the Kramers bremsstrahlung cross-section, while for more general formulae it is only approximately true (Brown et al. 2008). In this context, the accuracy of the results is not affected by the use of this approximation.
From these results, we first notice that for the 2002 April 16 event (in both considered time intervals), the $\chi^2$ values for the four models are very similar. Correspondingly, the values of the kinetic energy $E_0$ associated with the drift velocity $u_0$ obtained for this event are considerably smaller than for the other two events. This is probably a consequence of the fact that this event in these time intervals is in a late phase (consequently, the panels in Figure 3 corresponding to this event show decreasing values for $R(E, s)$). For the other data sets, Model 1 systematically provides smaller $\chi^2$ values. Knowing the EM obtained from photon spectral fitting and that $EM = Vn^2$, where $V$ is the flare volume, we can validate the obtained density values. Assuming
Figure 3. 2002 April 15, 16 and 2004 May 21 events: \( R(E) \) as a function of electron energy; the blue line is the best-fit hot model with return currents, the purple line is the cold model with return currents, the red one is the model with Ohmic losses, while the orange line is for the hot model without return currents. (A color version of this figure is available in the online journal.)
that the flare has the shape of a tube, we can estimate \( V \) for every time interval starting from the electron flux maps as previously done for the area \( A \). Figure 2 (right panel) shows the volume obtained for the 2002 August 3 event as a function of energy. Since \( V = V(E) \) is also rather stable for all flares, we used its average values over the electron energies to compute the EM. We determine that the EM obtained for Model 1 has an order of magnitude agreement with the EM obtained from photon spectral fitting. On the contrary, the EM predicted by Model 3 is two orders of magnitude lower.

5. COMMENTS AND CONCLUSIONS

The presence of a return current introduces two main changes to the energy loss rate experienced by accelerated electrons. The first is the well-explored (Knight & Sturrock 1977; Larosa & Emslie 1989; van den Oord 1990; see also Holman 2012) Ohmic loss rate associated with the steady drift of the return current electrons relative to the comparatively stationary ion background. The associated additional energy loss per electron is

\[
\left( \frac{dE}{ds} \right)_{\text{ohm}} = -e\eta F - e\eta j = -e^2 \eta F, \]

where \( F \) is the local electron flux. The increased fractional energy loss relative to cold Coulomb collisional losses is

\[
\left( \frac{dE}{ds} \right)_{\text{ohm}} = \frac{e^2 \eta F}{Kn/E} = \left( \frac{\eta e^2 E}{Kn} \right) F \equiv \alpha_{\text{ohm}} F. \]

This increased fractional energy loss is proportional to the total electron flux \( F \), and thus represents a collective effect.

Another contribution to the energy loss is a reduction caused by the fact that the beam electrons are interacting with a drifting electron distribution, so that the relative velocity of the beam and target electrons increases, with a commensurate reduction in the energy loss rate. Since the collisional energy loss rate \( (dE/ds) \sim 1/E \), the ratio of energy loss rates in a drifting, compared to a stationary, electron background distribution, can be approximated by

\[
\frac{(dE/ds)_{\text{drift}}}{(dE/ds)_c} \approx \left( \frac{v}{v + w_0} \right)^2 \approx \left( 1 - \frac{w_0}{v} \right)^2 \approx 1 - \left( \frac{2w_0}{v} \right) = 1 - \frac{2}{n} \sqrt{\frac{m_e}{2E}} F. \]  

The fractional excess energy loss (compared to the reference collisional rate) is thus

\[
\frac{(dE/ds)_{\text{drift}}}{(dE/ds)_c} - 1 \approx -\frac{2}{n} \sqrt{\frac{m_e}{2E}} F = \alpha_{\text{drift}} F. \]

Since \( \alpha_{\text{drift}} \) is negative, this represents a reduced energy loss, also proportional to the beam flux \( F \).

We therefore observe that the two main effects (the drifting electron background and Ohmic losses) are both proportional to the beam flux \( F \) and work in opposite directions. This is experimentally confirmed by Figure 5, which shows the energy
For the values of the physical parameters, we have used the experimental values obtained from the fit; Column 3: return currents’ energies obtained from the fit; Column 4: target densities obtained from the fit; Column 5: averaged source amplitudes obtained from the fit; Column 6: $\chi^2$ values of the fit. The value of $h_s$ for Model 4, 2002 July 20 event, is negligible and therefore has not been reported.

(A color version of this figure is available in the online journal.)

Figure 5. Plots of the energy loss rates for the four models as a function of electron energy and normalized with respect to the target density. The event considered is the 2002 April 16 flare in the time interval 13:15:00–13:20:00.

For the values of the physical parameters, we have used the experimental values in Tables 3 and 4 show that the effects of the drifting background on the direct energy losses bring the model into significantly improved agreement with the data, which implies that the drift velocity term dominates the Ohmic one.

The main impact of this result on the theoretical picture of solar flares is concerned with the effectiveness of the emission process. Indeed, the background coherent motion due to return currents tends to lower the energy loss rate of Coulomb collisions, and therefore the path of the electrons injected in the flare tends to be longer. Accelerated electrons thus have more time to emit hard X-rays by bremsstrahlung, which increases the efficiency of the emission process.

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REFERENCES

Alexander, D., & Doschek, G. A. 2007, ApJ, 666, 1268
Brown, J. C., & Bingham, R. 1984, A&A, 131, L11
Brown, J. C., Kasparova, J., Massone, A. M., & Piana, M. 2008, A&A, 486, 1023
Butler, S. T., & Buckingham, M. J. 1962, PhRv, 126, 1
Emslie, A. G., 1978, ApJ, 224, 241
Emslie, A. G. 1980, ApJ, 235, 1055
Emslie, A. G. 1981, ApJ, 249, 817
Emslie, A. G., Barrett, R. K., & Brown, J. C. 2001, ApJ, 557, 921
Fletcher, L., Dennis, B. R., Hudson, H. S., et al. 2011, SSRv, 159, 1
Guo, J., Emslie, A. G., Kontar, E. P., et al. 2012, ApJ, 751, 129
Hoyng, P., & Melrose, D. B. 1977, ApJ, 218, 866
Knight, J. W., & Sterrock, P. A. 1977, ApJ, 217, 306
Larosa, T. N., & Emslie, A. G. 1989, SoPh, 120, 343
Longmire, C. L. 1963, Elementary Plasma Physics (New York: Interscience)
Massone, A. M., Emslie, A. G., Hurford, G. J., et al. 2009, ApJ, 703, 2004
McClymont, A. N., & Canfield, R. C. 1986, ApJ, 305, 936
Piana, M., Massone, A. M., Hurford, G. J., et al. 2007, ApJ, 665, 846
Rutherford, E. 1911, PMag, 21, 669
Spitzer, L., Jr. 1962, Physics of Fully Ionized Gases (New York: Interscience)
Torre, G., Pinamonti, N., Emslie, A. G., et al. 2012, ApJ, 751, 129
van den Oord, G. H. J. 1990, A&A, 234, 496
Xu, Y., Emslie, A. G., & Hurford, G. J. 2008, ApJ, 673, 576
Zharkova, V. V., & Gordovskyy, M. 2005, A&A, 432, 1033