Role of suprathermal runaway electrons returning to the acceleration region in solar flares
Meriem Alaoui, Gordon Holman, Joel Allred, Rafael Eufrasio

How do return currents affect observations?
1. They heat the flaring corona, they can reduce the fraction of electrons reaching the chromosphere.
2. They flatten the hard X-ray spectra at lower energies if the potential drop is high enough.
3. Upward-propagating suprathermal electrons can be observed in radio emission.

Method
1. Determine the electric field strength as a function of position along loop for which the return current (RC) balances the nonthermal beam current $J_{\text{RC}} = -J_{\text{beam}}$ and $J_{\text{RC}} = J_{\text{RC,CC}} + J_{\text{runaway}}$.
2. Runaway growth rates are well-defined for weak electric field strengths compared to Dreicer field.
3. Use this to calculate the runaway current.

Main result
Three regimes of the return current explain the dynamics of the beam/return-current transport.
1. For lower injected flux densities, Ohm’s law accurately describes the system.
2. For medium range flux densities, runaway electrons become significant. They reduce the heating, reduce the XHR flattening and return suprathermal electrons to the acceleration region.
3. For higher flux densities either the RC is dominated by runaways (purely runaway regime, most likely), this further reduces the coronal heating and the XHR flattening; or current-driven instabilities produce a higher effective resistivity therefore a higher heating rate in the corona, and stronger flattening at lower energies of the observable XHR spectrum (deka-keV range).

Nonthermal Beam/Return-Current (RC) Runaway Model

Runaway electrons reduce heating in corona by reducing the electric field.

Suprathermal runaway electrons return to the looptop.

Beam flux densities where runaways become significant.

Fig 1: Cartoon of co-spatial return-current model. Electrons are accelerated above the loop top and propagate downward. Within a collision time $a$ the return current electric field is established and the beam current is balanced by the co-spatial return current. The induced magnetic field by the beam is canceled by that of the return current. For higher electric field magnitudes, more runaways are accelerated out of the RC plasma.

Fig 2: Schematic of friction force as a function of electron velocity. When the electric force exceeds the friction, electrons are freely accelerated and therefore Ohm’s law does not apply to them.

Fig 3: Schematic distributions of beam and RC. Left: As beam electrons are decelerated by the RC electric field and Coulomb collisions along the loop, the distribution flattens. In the chromosphere, Coulomb collisions dominate. Right: The higher the normalized electric field, the more runaways are accelerated. As they propagate toward the looptop they gain an energy equal to the potential drop.

Fig 4: Atmosphere in which the beam is injected. Four models are used for comparison. Heating rate in the upper corona is lowest when runaways are accounted for (RA,RC,CC). The sharp decrease in the heating rate is due to thermalization of lower energy electrons.

Fig 5: Current density using four models. In all models the beam current and RC densities are balanced along the loop. In the runaway model we further show the runaway and drilling components of RC.

Fig 6: Heating rates of two beams in two models with and without runaways.

A higher injected flux density generates a higher electric field thereby accelerating more runaways. Therefore a higher reduction of the electric field and a higher reduction of the heating rate is associated with higher injected flux densities.

Fig 9: Total potential drop (top). Runaway current fraction at the looptop (middle), and maximum normalized RC electric field (bottom). For the injection of beams with $E_b=4$ into the coronal atmospheres listed in the top panel.

Our solutions for Max $E_{\text{RC}}/E_b > 0.1$ are only qualitatively correct.

References
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