Velocity-space Signature of Backward Runaways

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Introduction: Runaway electrons are those electrons that are accelerated to very high energies by an electric field exceeding the Dreicer field [1]. These electrons start out with velocities so large that collisions cannot restrain their monotonic acceleration to high energy. The Dreicer or runaway velocity demarks which electrons have high enough energy to run away.

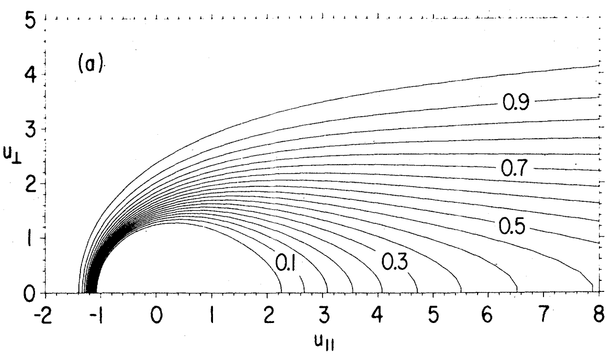

Figure 1: Contours of Runaway Probability [3].

However, since collisions are a random event, it is not quite precise to term an electron as being a runaway or not. Rather each electron has a certain *probability* of running away [2]. The runaway probability can be rigorously defined as the probability that an electron reaches an arbitrarily high energy before it plummets to zero energy. Electrons that are initially slow will sample the phase space available to them, with high probability of passing through zero energy prior to sampling higher energy. Contours of runaway probability in velocity space (normalized to the runaway velocity v_R) for ion charge state $Z = 1$ are shown in Fig. 1 [3]. Note that finite runaway probability is not limited to electrons going in the same direction as the electric field force. Electrons that run counter to the electric field force are slowed down by the field, but, if they have enough energy perpendicular to the electric field direction, collisions may be infrequent enough that these electrons may never pass through zero energy before eventually being accelerated to higher energy by the electric field. Thus, they may run away in the direction opposite to their initial velocity direction. Note that this is not an effect possible in one-dimension, since then the electron originally traveling in one direction must first pass through zero-velocity in order to change directions. Electrons that originally run counter to the force exerted by a dc electric field, but then are accelerated in the direction of the force of the dc electric field are called *backward runaways* [3].

The concept of runaway probability is particularly important in the case of rf-heated discharges. This is because runaways may be produced during rf heating of the tail of the electron velocity distribution function. The tail heating occurs either to simply heat the plasma or to drive noninductive currents [4]. What is then important is the production of runaways due to the rf waves, which in turn depends on the differential probability of an electron running away, given that it was heated, compared to before it was heated. In *current ramp-up* experiments [5], backward runaways play a particularly important role. As the lower hybrid waves increase the tokamak current, an electric field is induced that opposes the lower-hybrid driven current. Because the lower hybrid waves increase the energy of the superthermal electrons that move in the direction that that supports the electron current, the wave heating generates specifically backward runaways. This regime has recently attracted renewed experimental attention [6]. This current ramp-up regime is particularly promising because the rapid recharge of the transformer, done cyclically, makes the average current drive much more efficient [4]. Moreover, it was recently recognized that this method of operating a tokamak lends itself to a synergy with the advantageous hot-ion mode operation of tokamaks [7].

Asymptotic Perpendicular Velocity of Runaway Electrons: The runaway perpendicular temperature was in fact considered previously by Fernandez-Gomez et al [8]. However, while an extensive description of the runaway tail was provided, no distinction was made between the runaways based on their origin, namely whether backwards or forwards. Recently, the associated synchrotron emission, which depends on the perpendicular temperature, has also been considered [9]. We suggest here that backward runaways can be distinguished in perpendicular energy from the normal, or forward, runaways. Suppose that the electric field is turned on at time $t = 0$, when the distribution function is approximately Maxwellian. In that case, the forward runaways will be those with approximately thermal perpendicular distributions in energy. However, the backward runaways will be comprised only of those that pitch angle scatter in energy in the perpendicular direction to an extent that they can become collisionless, in other words, on the order of the runaway velocity. Electrons that pitch angle scatter less than this amount have very low probability of running away, as can be seen from Fig. 1. Of course, very few electrons will pitch angle scatter greater than this amount since collisions are very rare at such high velocities.

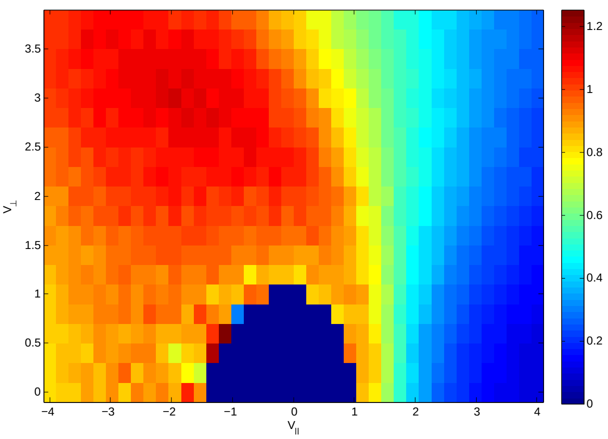

Figure 2: Standard deviation of $V_\perp$ at $T = 6\tau$.

Hence, we expect to see backwards runaways bunched in perpendicular velocity space with a velocity around v_R. That this so can be seen from Fig. 2, which shows the densities of standard deviation of the perpendicular energy at $t = 6\tau$, which is the time when the averaged $v_\parallel$ of runaway electrons is about 9 times of the critical runaway velocity. The small standard deviation of the very slow electrons indicates stopped electrons (dark region around $v_\parallel = 0$). Notice that the forward runaways are indeed peaked around $W_\perp = 0$. However, the runaways that are originate at $v < -v_R$, are exhibit perpendicular energy $W_\perp$ spreads on the order of the runaway energy, $mv_R^2/2$. The simulations here are preliminary, but the main effects can be seen. Since the backwards runaways require high $W_\perp$ to avoid getting stopped when going through the point $v_\parallel = 0$, we can thus expect a peaking of the backward runaway perpendicular energy at non-zero $W_\perp$.

Implications of the Distinctions of Runaway Electrons: This signature of the backward runaways is important for two reasons: The first reason is academic; by distinguishing signatures of the runaway origin, the physics of the discharge might be better measured and understood in detail. The second reason is practical; by understanding the distinguishing features of the backward runaways, we might be better able advantageously to limit their production, to limit their duration in the machine, or to control how they become unconfined.

Runaway electrons, if unconfined in the tokamak, are energetic enough to cause significant damage to the tokamak vacuum vessel. In normal tokamak operation, namely in steady state or near steady state operation, the electric field is generally too small to cause many runaways. However, the Ohmic start-up regime, when the density is not so large, is more susceptible to large numbers of (forward) runaways. More worrisome is that, should the tokamak disrupt, the quenching of the current also causes large voltage spikes, which is accompanied by destructive (forward) runaway production. Because the forward runaways have little perpendicular energy, it would be harder to manipulate these electrons with magnetic field perturbations. There may, of course, be other collisionless instabilities caused by the large currents of these electrons.

Consider now the issue of backward runaways. In the current ramp-up regime, or equivalently the transformer recharging regime, significant numbers of runaways may be produced, and in all probability they would be predominantly backward runaways. However, the large difference in perpendicular energy distribution makes the backwards runaways both easily distinguished and more susceptible to manipulation through magnetic fields.

Whereas the forward runaways occur as a result of voltage drops that are large and unintended, it is a feature of the current ramp-up regime that the voltage should be as large as possible. This is because the efficiency of the average current drive is optimized when lower hybrid current significantly exceeds the plasma current, inducing the large counteracting electric field. Thus, as opposed to the forward runaways, the backward runaways occur in an intentional regime where their production is naturally occurring. Whether the runaways produced are backwards runaways or the normal forward runaways, the worry is that they could be deleterious to tokamak operation. However, in the case of backward runaways, perhaps some use can be made of the very glaring distinguishing feature, namely that they have very high $W_\perp$, the energy perpendicular to the electric field, much higher than do the forward runaways, and that this energy occurs in a narrow band peaked around the runaway energy $mv_R^2/2$, as opposed to the forward runaways, which are peaked at with a thermal spread of energies around $W_\perp = 0$. It might be hoped that this large difference in perpendicular energy distribution makes the backwards runaways both easily distinguished and more susceptible to manipulation through magnetic fields. One might then contemplate the use of this distinguishing feature in removing these electrons before they can accelerate to higher energies yet and thereby become more dangerous.

Other signatures of Runaway Electrons: Apart from the fact that backwards runaways might be distinguished from the forward runaways on the basis of perpendicular temperature, they might also be distinguished on the basis of location in the plasma, striking the wall in different spots or persisting for different times. For large times, or large parallel energies, synchrotron emission should, however, blur these distinctions. For shorter times, some signatures should remain. One interesting speculation is the signature of backwards runaways in the minor radial direction in tokamaks that might result from the brief trapping of these electrons as they cross $v_\parallel = 0$ at high $W_\perp$, making their treatment similar to that required in non-uniform magnetic field geometry for knock-on accelerated electrons at high perpendicular momentum [10].

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