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Magnetic field threshold for runaway generation in tokamak disruptions

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Experimental observations on large tokamaks show that the number of runaway electrons produced in disruptions depends sensitively on the magnetic field strength. The presence of a whistler wave instability (WWI) excited by runaway electrons may be the reason for this observation since the linear growth rates of these waves are such that they are stable for high magnetic field (so the runaway beam can form) but unstable for low magnetic field. The quasi-linear diffusion process due to the WWI represents a very efficient pitch-angle scattering mechanism for runaways and consequently may stop runaway beam formation. In this work, the criterion for runaway suppression by WWI is compared with a criterion for substantial runaway production obtained by calculating how many runaway electrons can be produced before the induced toroidal electric field diffuses out of the plasma.

Introduction

In tokamak disruptions a beam of relativistic runaway electrons is sometimes generated, which can cause damage on plasma facing components due to highly localized energy deposition. This problem becomes more serious in larger tokamaks with higher plasma currents and understanding of the processes that may limit or eliminate runaway electron generation is very important for future tokamaks, such as ITER. In present tokamak experiments it is observed that the number of runaway electrons generated depends on the magnetic field strength. Several tokamaks have reported that no runaway generation occurs unless the magnetic field B exceeds 2 T [1]. Above this threshold, the runaway generation shows a non-linear dependence on B, and a doubling of B results in an increase of the photo-neutron production by two orders of magnitude [2]. A possible explanation for this observation is that the runaway beam excites whistler waves that scatter the electrons in velocity space and prevents the beam from growing further [3, 4]. Here we will analyze the magnetic field threshold for runaway generation based on the WWI and compare with the H-criterion for substantial runaway production derived in [5, 6] based on the coupled dynamics of plasma current and runaway generation.

WWI

The runaway electron beam has a strongly anisotropic velocity distribution and the anisotropy is the free-energy source that may drive whistler waves unstable. When the degree of anisotropy exceeds a critical level, unstable whistler waves, with frequencies well below the non-relativistic electron cyclotron frequency ω_{ce} but above the ion cyclotron frequency ω_{ci} are excited. Numerical simulations in [3] showed that most important interaction occurs the anomalous Doppler resonance $\omega - k_{\|} v_{\|} = -\omega_{ce}/\gamma$, where ω is the wave frequency, $k_{\|}$ and $v_{\|}$ are the wave number and particle velocity parallel to the magnetic field and γ is the relativistic factor. The interaction with these waves leads to scattering of the electrons, so the degree of anisotropy is decreased. The linear growth rates of these waves are such that they are stable for high magnetic field (so the runaway beam can form) but unstable for low magnetic field. The linear stability analysis shows that the frequency and wave number of the most unstable wave is $k_0 v_A/\omega_{pi} = 1/2$, $k_{\|0} c = 2\omega_{ce}/c_Z$ and $\omega_0 = \omega_{ce}/c_Z$. From the linear instability threshold for the most unstable wave we can derive a threshold for the magnetic field

$$B_T > \frac{20 j_r T_{eV}^{3/2}}{n_e e c Z^2}, \tag{1}$$

$j_r = n_r e c$ is the runaway current density, B_T is the toroidal magnetic field in teslas, T_{eV} is the post-disruption electron temperature in eVs and n_e is the electron density. Equation (1) represents a limit on the runaway current. The lower the magnetic field and higher the post-disruption temperature the less runaways are needed to overcome collisional damping of WWI.

The evolution of the runaway distribution affected by the quasi-linear diffusion process associated with WWI has been studied in [4]. It was shown that the wave-particle interaction leads to a broadening of the runaway distribution in the perpendicular direction accompanied by a reduction of the runaway velocity distribution gradients, so that the instability growth rate is reduced. The numerical analysis shows that the whistler wave induced isotropization depends on n_e in a more complicated way than the linear threshold suggests, due to the fact that for lower n_e the convective damping is strong enough to be comparable with the collisional damping.

For typical post-disruption plasmas of JET [7], with plasma density $n_e = 4 \cdot 10^{19}$ m^{-3}, magnetic field $B = 2$ T, plasma temperature $T_e = 20$ eV, the threshold runaway current density is $j_r \simeq 2$ MA/m^2 for $Z = 1$, which is of the same order of magnitude as the observed one. If the magnetic field is higher, for the same runaway current density, plasma density and temperature, the whistler wave is stable, and it cannot stop the runaway beam formation. Note that the threshold is very sensitive to the post-disruption temperature and therefore it is difficult to make reliable quantitative predictions without knowing the final temperature. However, if the plasma parameters are such that the whistler wave is destabilized, the time-scale of the isotropization is of the order of 10^{-5} s and should lead to a rapid quench of the resonant part of the runaway beam as soon as the secondary runaway production sets in.

H-criterion

Based on the approximative solution of two coupled differential equations for the runaway electron density and plasma current, a criterion for substantial runaway generation was derived in [5, 6]. The zero-dimensional model describes the time-dependence of the electric field induced by the falling plasma current and takes into account the combined effect of primary and secondary runaway generation due to the rising electric field. From knowing only basic plasma parameters, it is then possible to construct an analytical criterion that gives an estimate whether or not a major fraction of the current will be converted to runaway electrons, and this is given by

$$H = \sqrt{\frac{2\pi}{3}\frac{L}{\mu_0 R}\frac{I_0}{I_A \ln\Lambda}} - \frac{E_D}{4E_\parallel} - \sqrt{\frac{2E_D}{E_\parallel}} + \ln\frac{m_e c^2}{T_e} + \frac{11}{8}\ln\frac{E_D}{E_\parallel} > 0 \qquad (2)$$

where the plasma inductance can be assumed to be $L \simeq \mu_0 R$, I_0 is the plasma current and $I_A = 0.017$ MA is the Alfvén current. The ratio of the Dreicer field and parallel electric field can be obtained from $j_\parallel = \sigma E_\parallel$ and $j_\parallel = 2B/\mu_0 q R$ to be $E_D/E_\parallel = (3\mu_0 e n_e q R/B)\sqrt{\pi T_e/2m_e}$ where n_e and T_e denote the post-disruption electron density and temperature. Numerical simulations confirm the validity of the criterion given by (2).

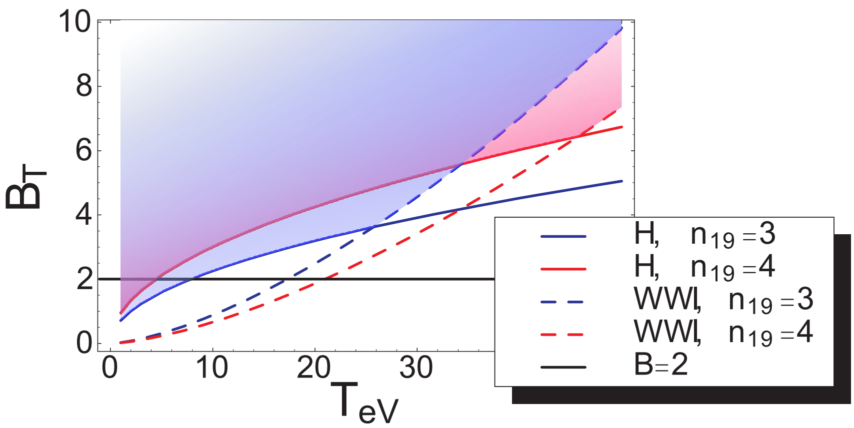

Figure 1 *Critical magnetic field for significant runaway generation as a function of* T_{eV} *for different electron densities. The solid lines are from the H-criterion, and the dashed lines are from the WWI-threshold. Above the dashed lines whistler waves are stable and runaway beam can form. Above the solid lines* $H > 0$ *and substantial runaway generation is expected. The other parameters are* $q = 1.5$, $R = 3$, $I_0 = 2$ MA *(for the H-criterion),* $j_r = 2\ \mathrm{MA/m^2}$ *(for the WWI-threshold).*

Similarly to the WWI-threshold, the H-criterion shows that runaway generation is expected only for magnetic fields above a certain threshold, which depends on the initial plasma current and post-disruption electron density and temperature. The dependence on the temperature is weaker than the one obtained in the WWI-case. Approximately, for JET-like values, the H-criterion can be written as

$$B_T > n_{19}\sqrt{T_{eV}}/2I_{MA} \tag{3}$$

where $n_{19} = n_e 10^{-19}$ and I_{MA} is the plasma current in megaamperes.

For low temperatures, the magnetic field threshold for stability is very low, and therefore the WWI cannot stop the runaway beam formation. Thus, the runaway-free region is determined by the H-criterion for low electron temperatures and the WWI-threshold for higher temperatures. The intersection between the two curves depends strongly on the electron density. If the electron density is high, then the H-criterion is expected to determine the magnetic field threshold.

Conclusions

For a given temperature and runaway fraction, if the magnetic field is below a critical value, the whistler wave can be destabilized by relativistic secondary runaway electrons. This mechanism offers a possible explanation for why the number of runaway electrons generated in tokamak disruptions depends on the strength of the magnetic field. The threshold for the instability is significantly affected also by the plasma temperature. Lower runaway fractions are needed for destabilization in plasmas with high temperature, since the collisional damping is lower then. If the post-disruption temperature is low then whistler waves are stable and WWI cannot stop the runaway beam formation. Runaway generation is then determined by the H-criterion and does not occur below a certain magnetic field.

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