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Runaway Current Plateau Formation during Disruptions in the FTU Tokamak

J.R. Martín-Solís [1], B. Esposito [2], R. Sánchez [3], F.M. Poli [4], L. Panaccione [2]

[1] *Universidad Carlos III de Madrid, Avda. de la Universidad 30, 28911-Madrid, Spain.*
[2] *Associazione Euratom-ENEA sulla Fusione, CR.Frascati, 00044-Frascati, Roma, Italy.*
[3] *Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge,TN 37831, U.S.A.*
[4] *Centre de Recherches en Physique des Plasmas, EPFL, Lausanne, Switzerland.*

Abstract Observations of a large production of runaway electrons during disruptive events in the FTU tokamak will be reported. The formation of a runaway current plateau is observed during the start-up and flat-top phase of low density OH (ohmic) disruptions as well as during LH (lower hybrid) heated disruptions, carrying up to $\sim 80\%$ of the pre-disruptive plasma current. The largest runaway currents are correlated to the slowest plasma current decay rates, trend which is opposite to that observed in most tokamaks. We attribute these features to the acceleration of pre-existent suprathermal electrons during the decay phase of the disruption. These results could be relevant for the operation of next step devices such as ITER, in case that a disruption occurs during LHCD.

1. Introduction There is a great concern about the potential damage that energetic runaway electrons created during the current quench phase of a disruption may cause if they impact on the first wall structures of the tokamak. Experimentally, runaway electron current plateaus of several mega-amps (up to 50% of the pre-disruption plasma current) have been reported during disruptions in large tokamaks like JET [1] or JT-60U and it has been predicted that in the case of a disruption in ITER as much as two thirds of the pre-disruption current might turn into runaway current, mainly due to the avalanche mechanism. Both theoretical modelling of runaway production during disruptions [based on the primary (or Dreicer) and secondary (or avalanche) generation mechanisms], as well as the experiment, suggest that the runaway production rate is correlated with the current quench rate. For instance, recent disruption data from JET show a fairly linear dependence of the runaway current on the plasma current derivative as well as on the pre-disruptive plasma current [2].

In this paper, we report on experimental observations during disruptions in the FTU tokamak which appear to show quite unexpected features. Runaway current plateaus are observed during the current ramp-up and flat-top phase of low density OH disruptions and, more frequently, in disruptions happening during LH. The fraction of the pre-disruption plasma current that is converted to runaway current is found to be very large, up to $\sim 80\%$ of the pre-disruption current. Moreover, the runaway current plateau does not increase with the current derivative as expected, but becomes instead smaller the faster the current decay rate is.

2. Observations The analyzed set of disruptions belong to the 2001 experimental campaign. About half of them were OH disruptions and the other half occurred during LH injection. In contrast to the behavior observed in OH disruptions, when runaway current plateaus were observed in only $\sim 2\%$ of the cases (low density discharges), they were found in $\sim 15\%$ of the LH disruptions, with typical parameters: deuterium discharges, plasma current $I_p \sim 0.3$ or $0.5\,\mathrm{MA}$, toroidal magnetic field $B_0 = 5-7\,\mathrm{T}$ and central line averaged density $\overline{n}_e = (4-12)\times 10^{19}\,\mathrm{m}^{-3}$. The wave frequency was $f = 8\,\mathrm{GHz}$, the wave parallel refractive index $N_{||} = 1.5$ or 1.8 (resonant electron energy $\sim 100-175\,\mathrm{keV}$) and the input power varied in a range from 0.3 to 2 MW. A typical disruption showing current plateau formation is shown in Fig. 1 [LH Discharge No. 19989; pre-disruption plasma current $I_p \simeq 0.52\,\mathrm{MA}$; $B_0 \simeq 7.1\,\mathrm{T}$; $\overline{n}_e \simeq 5\times 10^{19}\,\mathrm{m}^{-3}$; $P_{LH} \simeq 1.7\,\mathrm{MW}$; parallel refractive index $N_{||} = 1.8$]. A runaway current plateau is observed at the end of the disruption current quench ($I_r \simeq 0.3\,\mathrm{MA}$)[Fig. 1 (a)]. The loop voltage signal during the disruption is indicated by the dashed line in Fig. 1 (a). The usual initial negative loop voltage spike [1] is followed by a positive voltage spike associated to the large electric field induced by the plasma cooling during the thermal quench which appears to be correlated to the plasma current derivative. The final positive voltage spike is associated to the conversion of the runaway current plateau into resistive current when the plasma column interacts with the vessel structures. The runaway measurements are indicated in figure (b): the first (and direct) indication of runaway presence is obtained by comparing the data collected by a set of BF_3 counters (full line) that detect only neutrons with the data collected by a NE213 scintillator sensitive to both neutrons and gamma-rays (dashed line). During discharges with negligible runaway population, a perfect overlapping of the two traces is observed. But when runaways are present, the NE213 signal shows an excess of gamma-ray events and no longer equals the BF_3 measurements. The measurements shown in figure (b) reveal the formation of a large runaway population. The increase in the photoneutron emission is noticeable and lasts for the whole runaway current plateau. The increase in the scintillator signal is even more pronounced and usually saturates. In contrast, in disruptions without runaway current plateau, the neutron signals typically fall at the time of the disruption or, at most, show a peak at the beginning of the current decay which corresponds to a small runaway production.

An estimate of the runaway energy may be obtained assuming that runaways are produced at the start of the current quench, $\delta W = ec\int E_{||}\,dt \approx -(ec/2\pi R_0)\int L(dI_p/dt)\,dt \approx ecL\delta I_p/2\pi R_0$ ($\delta I_p = I_p - I_r; L \approx \mu_0 R_0$), which gives a range of energies of $\sim 3-17\,\mathrm{MeV}$ for the discharges studied. The total energy of the runaway beam $W \approx N_r\delta W$ ($N_r \equiv$ number of runaways) is found to scale as $W \propto I_r\,(I_p - I_r)$ and reaches its maximum when the runaway current amounts to $\sim 50\%$ of the pre-disruptive plasma current.

The most interesting observation in these experiments is that the runaway current may reach as much as $\sim 80\%$ of the predisruptive current, which is much larger than what is observed even in the largest tokamaks. For instance, the largest fraction reported in JET is $\sim 50\%$ [2]. Also remarkable is the fact that, in these discharges, the largest runaway production rates are not correlated to the fastest current quench rates. In Fig. 2 (left), the fraction of runaway current formed during the disruption is plotted against the maximum plasma current quench rate. This fraction clearly decreases with the current derivative, which is in contrast to the increase observed in other devices [2].

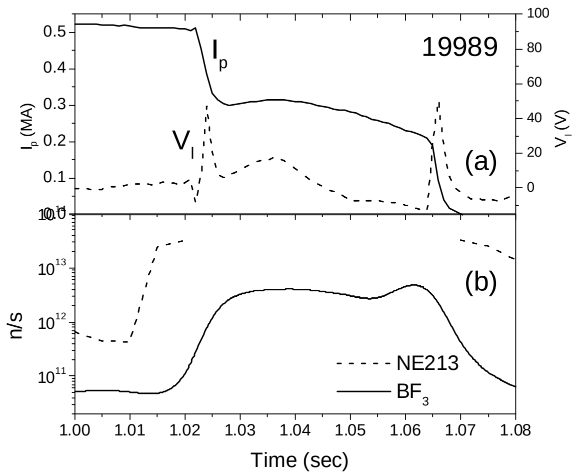

Figure 1: A plasma disruption showing the formation of a 0.3 MA runaway current: (a) Plasma current (full line) and loop voltage (dashed line) traces; (b) Neutron measurements: BF_3 (full line) and NE213 (dashed line) signals.

3. Interpretation The I_r/I_p fraction expected from the Dreicer and avalanche mechanisms can be estimated by modeling the evolution of the runaway current profile j_r self-consistently with the toroidal electric field $E_{||}$ obtained from the induction equation in cylindrical geometry,

$$\mu_0 \frac{\partial j_p}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial E_{||}}{\partial r}\right] = \frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial \eta(j_p - j_r)}{\partial r}\right], \tag{1}$$

where η is the resistivity and we assume that the plasma current j_p is replaced by the runaway current during the current decay. The runaway current is estimated by assuming that all runaways travel at the speed of light ($j_r = en_r c$) and that the runaway density increases as the sum of primary (Dreicer) and secondary generation,

$$\frac{dn_r}{dt} = n_e \nu_{coll} \lambda + \frac{n_r}{\tau_s} \tag{2}$$

where ν_{coll} is the collision frequency, λ is the (relativistic) Dreicer birth rate factor and τ_s represents the typical avalanching time. Again, the result [shown in Left Fig. 2 with dashed-dotted lines for two values of the density during the current decay: $n_e = 5 \times 10^{19}\,\mathrm{m}^{-3}$ (lower) and $n_e = 2 \times 10^{19}\,\mathrm{m}^{-3}$ (upper)] is that I_r/I_p should increase with the quenching rate, which is opposite to the observed trend. Moreover, the resulting runaway current is too low. One would need to assume a disruption electron density of $\sim 2 \times 10^{19}\,\mathrm{m}^{-3}$ to reproduce the observed runaway current fractions $\sim 50\%$. This value is however quite lower than the pre-disruption electron density, and one expects the density to increase during the disruption due to impurity influx (indeed observed in FTU).

The proposed explanation for the large runaway production observed in these discharges is that the pre-disruptive suprathermal electrons (created during LH injection or present in low density OH discharges) are accelerated during the disruption. The idea is that part of the suprathermal current survives during the disruptive event and becomes,

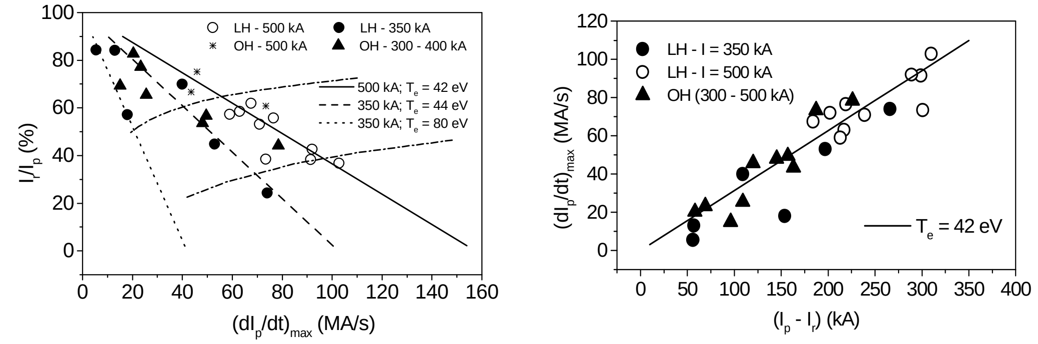

Figure 2: **Left:** For the analyzed FTU runaway current plateau disruptions: Fraction of runaway current vs maximum current derivative during the disruption current quench; **Right:** Maximum current derivative during the disruption current quench vs $I_p - I_r$ (data for OH disruptions from previous campaigns have also been included for comparison).

at the end of the current quench, the observed runaway current plateau I_r. In this case, one would expect to find that $I_r \sim I_{sth}$ at the end of the current decay, being I_{sth} the suprathermal current at the start of the disruption. Therefore, large runaway current plateaus would be related to small resistive pre-disruption currents $I_{res} = I_p - I_{sth}$ and, therefore, to small values of the electric field ($E_{||} = \eta j_{res}$; $j_{res} = j_p - j_r$) and current derivative (dI_p/dt). This is indeed what is observed in the experiment as Left Fig. 2 shows. In fact, numerical simulations of the current profile evolution (using again Eqs. 1 and 2) assuming an initial resistive current $I_{res} = (I_p - I_r)$ reproduce quite well the current evolution observed in all the cases using electron post-thermal-quench temperatures $T_e \sim 40-50\,\mathrm{eV}$ and a sufficiently large density (typically $\sim 10^{20}\,\mathrm{m}^{-3}$) to avoid significant primary or secondary generation. A linear dependence is also obtained between I_r/I_p and $(dI_p/dt)_{max}$ which has been plotted in Left Fig. 2 for two values of the pre-disruptive plasma current (full line for $I_p = 500\,\mathrm{kA}$ and dashed line for $I_p = 350\,\mathrm{kA}$), which fits the experimental data for $T_e = 40 - 45\,\mathrm{eV}$. Only in a few cases the current evolution is so slow that a larger $T_e \sim 80 - 100\,\mathrm{eV}$ (dotted line) must be assumed.

There is a second way to confirm that these runaways are formed via the acceleration of suprathermal electrons. If $(dI_p/dt)_{max}$ is plotted vs. the resistive current $I_p - I_r$ for all discharges with similar electron temperatures, it should be found that all the data collapse onto the same straight line *independently* of the pre-disruptive current I_p. This is indeed the case as shown in Right. Fig. 2 (the straight line has been obtained assuming $T_e = 42\,\mathrm{eV}$ which is the value that best fits the experimental data).

References

[**1**] J.A. Wesson et al., Nucl. Fusion **36** (1989) 367.
[**2**] V. Plyusnin et al., Nucl. Fusion **46** (2006) 277.