Influence of Three-Dimensional Plasma Dynamics on Runaway Electron Generation at Major Disruptions in Tokamaks

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Introduction

Together with excessive electromagnetic forces and heat loads major disruptions can result in severe generation of intense beams of runaway electrons (RE) with energies up to several tens of Mega-electron-Volts (MeV) and densities high enough to create current plateaus up to 60-70% of the pre-disruptive plasma currents in present-days largest tokamaks [1-3]. Simulations of runaway process [4, 5] demonstrate the possibility to generate RE currents up to 10 Mega-Amperes (MA) in multi-MeV energy ranges at major disruptions in ITER. Interaction of such intense RE beams with surrounding surfaces inevitably will result in inacceptable thermal loads, sputtering and melting of the materials of plasma facing components (PFC) [1-2, 6]. That is why establishing trends of RE generation and studies of suppressing mechanisms for runaway process constitute a task of high importance for ITER.

This report presents the contribution into the model of RE generation during CQ at major disruptions in tokamaks. Rapid uncontrolled vertical and/or horizontal plasma motions at disruptions usually result in fast changes of disrupting plasma parameters. The influence of three-dimensional plasma dynamics and evolution of plasma cross-section configuration on RE generation process during the current quench stage have been examined. In turn, the influence of high energy RE on plasma spatial dynamics has been taken into account. The dynamics of runaway electrons, which experience the acceleration in the electric field, collisions with the plasma particles and the sum of synchrotron radiation losses due to guiding centre motion and electron gyro-motion has been considered. Primary (Dreicer) acceleration and secondary avalanching mechanism have been included into equation for modelling of runaway electron density.

Plasma dynamics and RE generation during current quench

The sequence of events in disruptions is well known and its detailed phenomenological description can be found elsewhere [1-3]. Recall only, that after phase of strong MHD activity and almost complete plasma energy collapse the disruption enters into current quench (CQ) stage. Characterization of this stage is important because of large electromagnetic forces caused by fast plasma current decrease during CQ and possible severe runaway electron generation. Usually L/R-model is used for analysis of CQ stage. In this model the resistive and inductive properties of plasma column are represented by a simple series circuit consisting of resistance ($R_p=\eta_p\cdot 2\cdot R_0/a_p^2$, η_p – plasma resistivity) and inductance ($L_p=\mu_0\cdot R_0\cdot(ln(8R_0/a_p)+l_i/2-2)$). The energy conservation equation for this circuit in large tokamaks is

$$I_p^2 \cdot R_p + \frac{d}{dt}\left(\frac{L_p \cdot I_p^2}{2}\right) = 0 \qquad (1).$$

The first term in equation (1) corresponds to resistive dissipation in the circuit and the second term corresponds to changes in magnetic energy of the plasma current-carrying loop.

In a majority of studies accomplished in the past (see, for example, [7]) it was assumed that the main changes in magnetic energy of plasma column were associated with the current quench (large dI_p/dt) at very small changes in L_p. As a result the equation (1) allowed establishing the relation between time derivatives of plasma currents and electric fields generated at CQ without taking into account possibility for significant contribution from the term containing plasma inductance time derivative: $E_{||}(t) = -\frac{L_p}{2\pi R_0} \cdot \frac{dI_p(t)}{dt}\left(1 - \frac{j_{RE}}{(j_{pl} + j_{RE})}\right)$. This expression for electric field is widely used in simulations of RE generation at disruptions. However, this approach does not take into account spatial plasma dynamics, which inevitably will affect assumptions made in frames of 'static' model. In particular, different recent experiments and their subsequent numerical analysis, e.g. [3, 6-10], as well as simulations of disruption scenarios in ITER [11], evidently demonstrate inevitable fast vertical and horizontal plasma motions and narrowing the current-carrying channel cross-section. It is obvious that plasma periphery peeling will increase total plasma inductance (about 10-15% almost in all cases in large tokamaks) and will decrease plasma current (difference will depends on current density profile):

$$\Delta I_p(t) = \int_0^{a(t)} (j_p(r,t) + j_{RE}(r,t)) \cdot 2\pi r dr - \int_{r(t)}^{a(t)} (j_p(r,t) + j_{RE}(r,t)) \cdot 2\pi r dr \cdot$$

As a result, plasma dynamics should have significant influence on RE generation. Therefore, plasma vertical and/or horizontal displacement at disruptions should be included in considerations of RE generation models. For simplicity circular plasma in the slab geometry is considered. Plasma moves with certain radial velocity resulting in total plasma inductance time derivative as following:

$$\frac{dL_p}{dt} = \left(R(t)\left(\ln\left(\frac{8R(t)}{a_p(t)}\right) + l_i - 7/4\right)\Bigg|_{t=t_1} - R(t)\left(\ln\left(\frac{8R(t)}{a_p(t)}\right) + l_i - 7/4\right)\Bigg|_{t=t_0}\right) / \Delta t$$

Velocity of plasma vertical motion during disruption in JT-60U inferred from the data of [9] corresponds to decrease of plasma minor radius with the rate of 90 m/s resulting in dL_p/dt =$4 \cdot 10^{-4}$ H/sec. Even higher rate of plasma minor radius decrease (about 100 m/s) at disruptions in Tore Supra was reported [10]. At plasma currents of order of several mega-amperes the term containing derivative of plasma inductance ($0.5 \cdot I_p \cdot dL_p/dt$) is comparable to the term containing time derivative of plasma current, even if dI_p/dt ~ 500-600 MA/sec [3]. Therefore, establishing more general relation between resistive electric field and evolution of plasma parameters and its geometry during CQ, the following equation should be used in the analysis of runaway generation process at disruptions:

$$2\pi \cdot R_0 E_{||0}(t) + L_p \tfrac{dI_p}{dt} + 0.5 \cdot I_p \tfrac{dL_p}{dt} = 0 \qquad (2).$$

Analysis of plasma spatial dynamics was carried out using equation of motion:

$\rho \frac{dv}{dt} = \sum_i F_i$, where $F_1 = 2\pi R(t) I_p(t) \cdot B_V$, $B_V = \mu_0 \cdot \frac{I_p(0)}{4\pi R_0} \cdot \left(\ln\frac{8R_0}{a_p(0)} + \beta_p + \frac{l_i}{2} - 7/4\right)$,

$\beta_p^* = \beta_p(t) + \beta_{RE}(t)$, $l_i = \ln(1.65 + 0.89c)$, $F_2 = \mu_0 \cdot \frac{I_p^2(t)}{2} \cdot \left(\ln\frac{8R(t)}{a_p(t)} + \beta_p^*(t) + \frac{l_i^*(t)}{2} - 7/4\right)$,

$\beta_{RE}(t) = 8\pi^2 a^2 n_{RE} m_e c^2(\gamma^2 - 1)/2\gamma/\mu_0 I_p^2)$, $I_p(t) = \int_0^{a(t)} (j_p(r,t) + j_{RE}(r,t)) \cdot 2\pi r dr$ and

$L_p = \mu_0 R_0(\ln(8R_0/a_p) + l_i/2 - 7/4)$. This analysis was carried out semi-implicitly in order to assess trends in plasma motions taking into account energetic RE. Following equations were used for RE generation study:

$$\frac{dn_{RE}}{dt} = \lambda_R + \frac{n_{RE}}{t_0} - \frac{n_{RE}}{\tau_{RE}}$$

$$\frac{dP_{||}}{dt} = \frac{e}{m_e c}E_{||} - \frac{e^4 n_e \ln\Lambda}{4\pi\varepsilon_0^2 m_e^2 c^3}\gamma(\gamma+\alpha)\frac{P_{||}}{P^3} - \frac{e^4 n_e \ln\Lambda}{4\pi\varepsilon_0^2 m_e^2 c^3}\frac{2B_0^2\varepsilon_0}{3m_e n_e \ln\Lambda}\left(\frac{m_e^2 c^2}{e^2 B_0^2 R_0^2} + \frac{P_\perp^2}{P^4}\right)\gamma^4\beta^3\frac{P_{||}}{P}$$

$$\frac{dP}{dt} = \frac{e}{m_e c}E_{||}\frac{P_{||}}{P} - \frac{e^4 n_e \ln\Lambda}{4\pi\varepsilon_0^2 m_e^2 c^3}\frac{\gamma^2}{P^2} - \frac{e^4 n_e \ln\Lambda}{4\pi\varepsilon_0^2 m_e^2 c^3}\frac{2B_0^2\varepsilon_0}{3m_e n_e \ln\Lambda}\left(\frac{m_e^2 c^2}{e^2 B_0^2 R_0^2} + \frac{P_\perp^2}{P^4}\right)\gamma^4\beta^3$$

$P_{||}$, $P_\perp$, P – are electron momentums: $p=mv\gamma$, $P=p/m_e c$, $P^2=P_{||}^2+P_\perp^2$, $P^2=\gamma^2-1$; γ is the relativistic factor; $E_{DR}=e^3\cdot\ln\Lambda n_e Z_{eff}/(4\pi\varepsilon_0^2 T_e)$; $E_{CR} = E_{DR}(T_e/m_e c^2)$; $\varepsilon = E_{||}/E_{DR}$.

Inclusion of RE generation into simulation of plasma horizontal dynamics shows, in principle, the probability to achieve quasi-equilibrium state in post-disrupting plasmas with REs (“quasi” – because of simplifications, semi-implicit numerical modelling, etc).

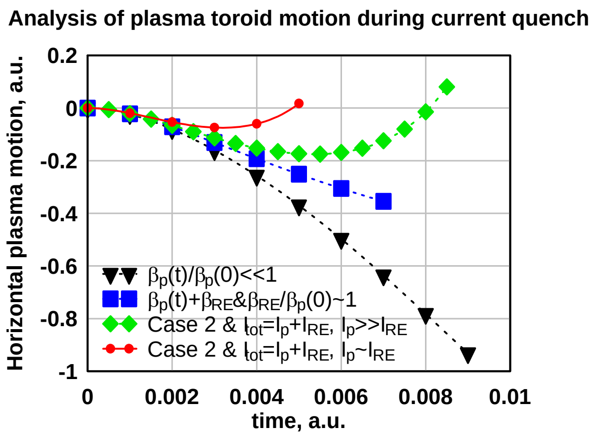

Figure 1. Analysis of plasma dynamics at different ratios between existing plasma parameters and contribution form generated RE

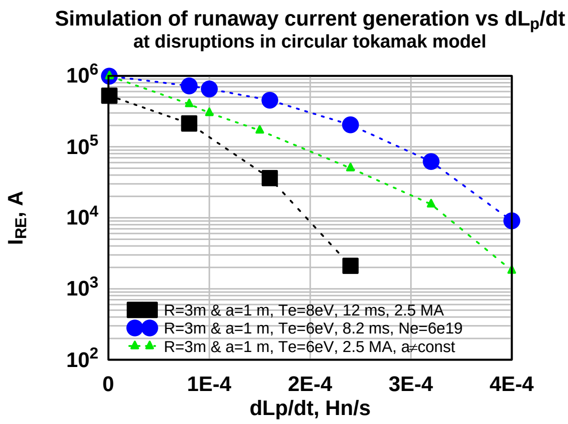

Figure 2. Dependence of generated RE currents vs. plasma inductance time derivative caused by fast plasma motions

Note that observed long-living RE currents were obtained at pre-dominantly horizontal plasma motion which has been saturated at the increase of RE currents and energies.

Influence of plasma inductance dynamics on RE generation was found (Figure 3) in the modeling of runaway process at ITER disruptions whose scenarios have been studied in [11]. The evolutions of plasma current and plasma configuration during CQ stage presented in Figure 3 of [11] have been used for assessment of inductance derivatives scales. An average derivative of the ITER external inductance in a given case has been evaluated as $dL_p/dt=3\cdot10^{-4}$ H/sec (~35 m/s). This value has been used as a top boundary in the modeling of RE density evolution for three values of post-disruption electron temperature T_e=5 eV, 8 eV and 12 eV. For these temperatures the values of CQ characteristic *e*-folding times have been inferred on the basis of given ITER plasma external inductance [1, 2]: τ_{CQ} =18.8 ms (close to τ_{CQ} =16 ms from figure 3 of [11]), τ_{CQ} =35 ms and τ_{CQ} =52 ms. As it follows from the data presented in this Figure, the fastening of plasma current-carrying channel dynamics with the following increase of inductance time derivative should cause a significant decrease of the efficiency or even vanishing of the runaway generation at large plasma current derivatives in ITER.

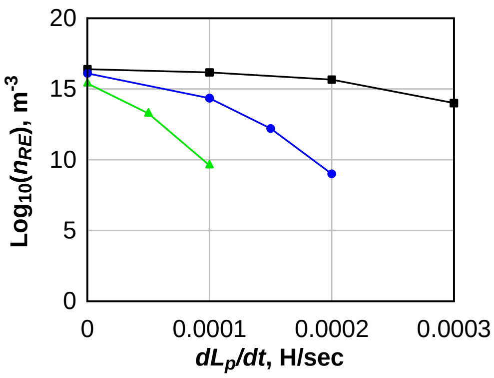

Figure 3. RE density calculated vs. dL_p/dt for disruption scenarios in ITER [11] Post-disruption electron temperatures: Te=5 eV (black squares), 8 eV (blue circles) and 12 eV (green triangles) were used with corresponding CQ e-folding times: 18.8 ms, 35 ms and 52 ms.

Summary

Fast uncontrolled vertical or horizontal plasma motions at disruptions lead to forced narrowing of plasma current-carrying channel thus increasing the plasma column inductance. The rate of inductance increase is high enough to balance the loss of plasma magnetic energy due to current quench. This re-distribution between the components containing time derivatives of plasma currents and inductances leads to decrease of resulting electric fields induced at current quench. Numerical simulations with inclusion of this mechanism have shown that with the fastening of plasma current-carrying channel dynamics the runaway electron generation at disruptions is almost vanishing. Obtained results are valid for present-days largest tokamaks and for ITER.

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