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EFFECT OF THE PLASMA GEOMETRY EVOLUTION ON RUNAWAY ELECTRON GENERATION IN TOKAMAK DISRUPTIONS.

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Introduction. Runaway electrons (REs) generated during disruptions constitute a serious problem for large-scale tokamaks [1-3] resulting in high heat loads, melting and sputtering of the materials of the plasma facing components (PFC) and vacuum chamber [4]. The main mechanism responsible for runaway production in disruptions is considered to be an avalanching of the high-energy electrons due to close electron-electron collisions between existing runaway and thermal electrons [5,6]. The secondary avalanching is not possible without the primary generated runaways that can exist in the pre-disruptive plasma, or they can be produced during the thermal quench [7,8]. A comprehensive understanding of the trends of disruption-generated runaway electrons is needed to avoid their detrimental consequences. Despite a continuous character of the electron acceleration in high electric fields during disruptions there are large uncertainties in the measurements of runaway electron parameters and their modelling due to fast changes of plasma and magnetic configuration properties. This paper presents the contribution into development of the model of runaway electron generation at disruptions, in which mutual dependencies between the evolution of runaway electron parameters and plasma configuration have been investigated.

Modelling of the runaway electron generation during disruptions in large tokamaks

The sequence of events in disruptions is well known and its detailed phenomenological description can be found elsewhere [2-4]. Large resistive electric fields occurring due to abrupt loss of the plasma energy within a very short time cause the primary RE generation. Gaining very high energies the primary REs [7,8] inevitably will serve as a seed population for the secondary avalanching process. The interaction between these two mechanisms has been studied with the aid of numerical modelling carried out using a test particle model [9] taking into account the evolution of the runaway beam geometry. A set of equations (1)-(3) has been solved at the initial conditions inferred from the experimental data (plasma current, density, etc.) or reasonably assumed plasma parameters (temperature, Z_{eff}, etc) [10], which were close to the experimental data obtained in JET experiments on disruptions and disruption generated REs [2-4]. The evolution of electric field in the plasma has been modelled taking into account that RE current substitutes the plasma resistive current and the plasma current decays exponentially during disruption with the characteristic *e*-folding time $\tau_p=I_p*(dI_p/dt)^{-1}\equiv L_p/R_p$. For simplicity, it was assumed that REs are perfectly confined ($\tau_{RE} \to \infty$).

$$\frac{dP_{\|}}{dt}=\frac{e}{m_e c}E_{\|}-\frac{e^4 n_e \ln\Lambda}{4\pi\varepsilon_0^2 m_e^2 c^3}\gamma(\gamma+\alpha)\frac{P_{\|}}{P^3}-\frac{e^4 n_e \ln\Lambda}{4\pi\varepsilon_0^2 m_e^2 c^3}\frac{2B_0^2\varepsilon_0}{3m_e n_e \ln\Lambda}\left(\frac{m_e^2c^2}{e^2B_0^2R_0^2}+\frac{P_\perp^2}{P^4}\right)\gamma^4\beta^3\frac{P_{\|}}{P} \qquad (1)$$

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

$$\frac{dn_{RE}}{dt}=\lambda_R-\frac{n_{RE}}{\tau_{RE}}+\frac{n_{RE}}{t_0} \qquad (3)$$

Where $\alpha = Z_{eff} + 1$, λ_R – is the conventional primary runaway generation rate, $P_{||}$, $P_{\perp}$, P – are the parallel, perpendicular and total electron momenta normalized to $m_e c$, $P^2 = \gamma^2 - 1$, γ – is the relativistic factor, B_0 – is the toroidal magnetic field, R_0 – is the plasma major radius, n_{RE} – is the density of runaway electrons, $E_{DR} = e^3 ln\Lambda n_e Z_{eff}/4\pi\varepsilon_0^2 T_e$ – is the Dreicer field, $E_{CR} = E_{DR}\,(T_e/m_e c^2)$, $\varepsilon = E_{||}/E_{DR}$.

$E_{||}(t) = -\frac{L_p}{2\pi R_0}\frac{dI_p(t)}{dt} = \eta_p j_p(t)(1 - \frac{I_{RE}(t)}{I_p(t)})$ – is the evolution of the parallel electric field,

$t_0 = \frac{4\pi\varepsilon_0^2 m_e^2 c^3}{e^4 n_e}\sqrt{\frac{3}{\pi}(Z_{eff}+5)}(\frac{E_{||}}{E_{CR}} - 1)^{-1}$ – is the secondary avalanching growth characteristic time. Post-disruption electron temperature values ($T_e \cong$ 5-15 eV) have been calculated from the known characteristic plasma current *e*-folding time (10 ms<τ_p<20 ms) and the given plasma inductance $L_p \cong 4.5\cdot10^{-6}$ H [3]. Simulations have been carried out at $T_e \cong$ 10 eV. RE current densities can achieve values j_{RE}≥1 MA/m^2 inferred from the calculated n_{RE} with the dominating population of REs caused by the avalanching process (Figure 1a). As it was expected, the only primary (Dreicer) mechanism of RE generation resulted in significantly higher energy of REs in comparison to the avalanching process (Figure 1b).

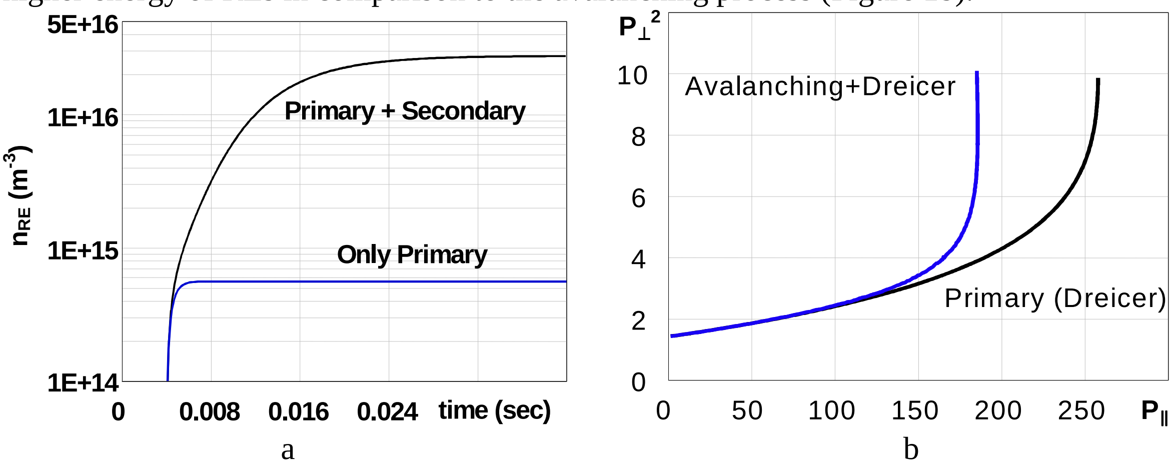
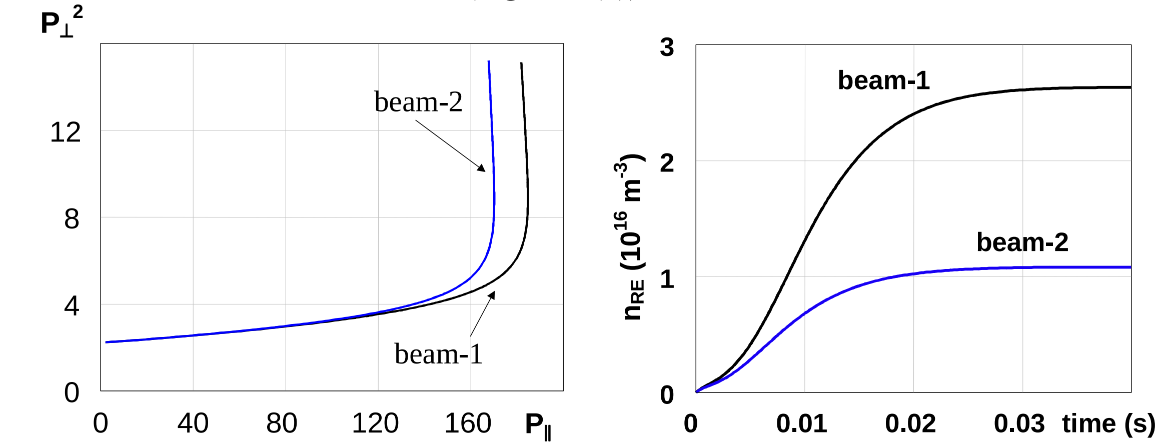


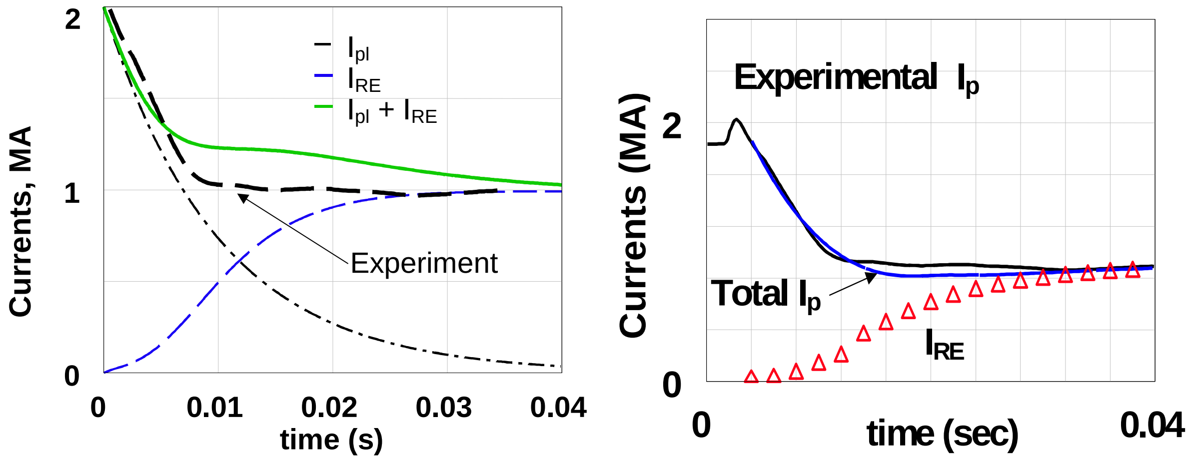
Figure 1. Calculated runaway electron density (a) and runaway electron trajectories in a momentum space (b) for primary only and for primary+avalanching mechanisms of runaway electron generation

These RE current density values at the RE beam radius a_{beam}≅0.5 m have provided close agreement between the modelled and experimental values of runaway current plateaus (in the case studied: $I_{REcalc} \cong I_{REexp} \sim 1$ MA) [4]. Cross-section size of current-carrying channel has been inferred from the measurements of soft X-ray emission caused by the interaction of RE beam with background plasma [3]. Modelling results adequately correspond to the experimentally established trend for conversion rate of the plasma resistive currents into runaways during disruptions [4]. However, to achieve the fit between the temporal evolutions of the calculated RE parameters and experimental data it was necessary to carry out detailed numerical studies taking into account that runaway beam cross-section may vary in time and space due to strong magnetic perturbations during disruptions [4,11]. The evolution of the beam geometry inevitably will influence on the RE parameters, since the variation of ratio between the RE current and resistive fraction of plasma current will change the evolution of toroidal electric field $E_{||}$ due to current substitution effect. The simplest way to verify this issue is to model the evolution of the test runaway electron in a momentum space and temporal evolution of the RE density for two cross-sections of runaway beam (Figures 2 (a,b)). Increase of the RE current (as a result of larger beam cross-section) at other equal initial plasma and runaway generation parameters (I_{pl} = 2MA, τ=0.01, *Ln*Λ = 15, n_e = $5\text{x}10^{19}$ m^{-3}) decreases the maximal RE densities and energies. Figure 3 (a) presents the comparison between evolutions of the measured plasma current and total calculated current, which consists of two fractions: calculated RE current (I_{RE}) and exponentially decayed resistive part (I_{pl}=2MA*exp(-t/0.01). The best fit of the evolution of calculated currents to the experimental data was obtained taking into account the evolution of the beam cross-section from a=0.2 m till to a=0.5m (Figure 3 (b)).



a *b*

Figure 2. Test electron trajectories in momentum space (a) and evolution of RE densities (b) calculated for two cross-section sizes of RE beams generated during disruptions ($a_{beam2}=2a_{beam1}$). Modelling initial conditions: I_p = 2 MA, T_e = 10 eV $n_e=5\cdot10^{19}$ m^{-3}, Z_{eff} =4, LnΛ = 15, plasma current decay time is 10^{-2} sec.

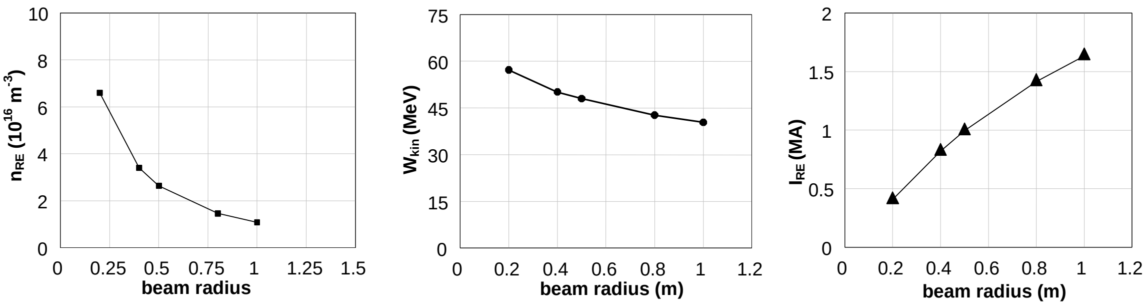


a *b*

Figure 3. Comparison of the measured plasma current to the calculated total current (RE current+plasma resistive current) for constant (a) and time-varied RE beam cross-section (b).

Detailed scan on RE beam size shows that calculated current conversion rate can exceed the experimental upper bound if the RE beam will occupy the whole plasma cross-section (Figure 4) despite significant decrease of the RE density. At some combinations of the disruption parameters the current conversion rate can achieve 100%, which never has been observed in experiments. Similar results have been obtained in [12], where under certain conditions practically all the initial plasma current was converted in runaways. Several mechanisms are considered as possible reasons for the observed in experiments 60 % upper bound for the current conversion rate. REs are sensitive to magnetic fluctuations, which decrease the characteristic life-time of the runaways: $\tau_{RE}=a^2/5.8D_r$, where $D_r \approx \pi q R_0 c (b_r/B_0)^2$

is the coefficient of the radial diffusion caused by the presence of magnetic field perturbations with the magnitude b_r. Very large magnetic perturbations lead to the enhanced losses of fast particles and limit the energy and total amount of REs at the early stage of disruptions. However, with the increase of W_{kin} REs become less sensitive to the magnetic turbulence. Another mechanism can be understood from the analysis of the runaway orbit outward drift as the RE energy increases: $d_r = c/\omega_{ce}\ (q/P_{\|})(\ P_{\|}^2 + P_{\perp}^2/2)$. From this expression one can obtain condition for the energy of RE at which it will drift outside the confining region created after disruption [4]: $P_{\perp}^2 = 2(d_r/q*\omega_{ce}/c*P_{\|} - P_{\|}^2)$. So, that even under conditions of the perfect confinement the runaway electrons can produce intense photo-neutron emission interacting with PFC due to outward shift of the runaway orbit.



a *b* *c*

Figure 4. Dependence of the calculated RE density (a), maximal kinetic energy (b), and RE currents vs. runaway beam radius.

Summary. Numerical simulations of the RE generation process during disruptions performed in frames of a test particle model have shown strong dependence of the runaway process on the runaway beam geometry evolution. Despite substantial decrease of the RE density the increase of the beam cross-section resulted in unrealistically large RE currents. These results indicate the necessity for detailed investigation of the mechanisms responsible for RE losses and implementation of these processes into numerical models.

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