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Positive voltage spikes in runaway tokamak discharges

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Introduction. Voltage spikes (VS), positive or negative, are often observed in tokamaks. Normally they are caused by a fast perturbation in the total plasma current. This fact was firstly clearly explained, with respect to the negative VS in disruptions, by Wesson, Ward and Rosenbluth [1]. The analysis of the VS provides an additional diagnostic information.

Here we analyze the positive VS in runaway dominated discharges in the small tokamak TBR-1 [2] (R = 0.3 m, a = 0.08 m). In the case of the runaway discharges, the VS are one of the characteristic features of the relaxation instability observed in many experiments in the first tokamaks [3-6]. This phenomenon is usually explained by a kinetic instability in a plasma-runaway beam system. There exist other reasons for the fast current decrease in runaway discharges as well as in normal ones, such as MHD instabilities..

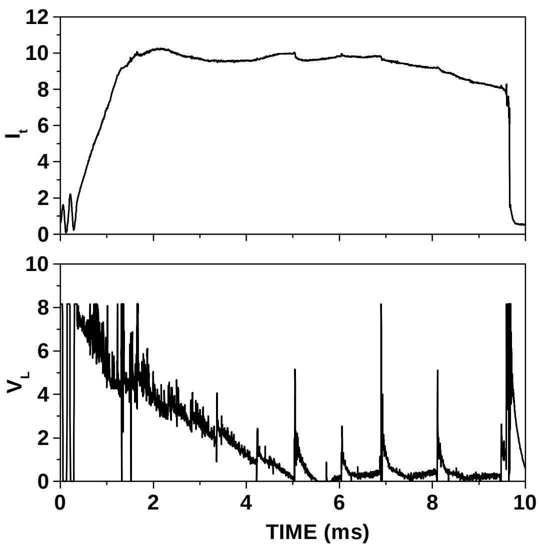

Fig. 1. Voltage spikes in a runaway discharge in TBR-1.

In TBR-1, the VS are characterized (see Fig. 1) by fast voltage increase, with a characteristic time of several microseconds, followed by exponential decay, with a time constant of a few hundred microseconds. We explain this as two-stage process. In the initial one, electric field is generated inside the plasma volume. It can be initiated by a fast decrease of the runaway current due to kinetic or MHD instabilities. In reply, positive plasma current is generated inductively. The corresponding initial toroidal electric field is determined by the values of the plasma current and resistance. The second stage is the resistive diffusion and damping of the plasma current.

In Ref. 2, we determined the plasma resistance from the VS time decay, with reasonable suppositions about the plasma inductance. In the present work, a one-dimensional diffusion equation is used for the VS analysis. This allows us to also obtain a reasonable inference of the initial electric field distribution. Furthermore, we take into account the additional runaway current generation during VS.

Theoretical model. The toroidal electric field in a cylindrical plasma column is connected with the toroidal current density by the diffusion equation

$$\frac{1}{\rho}\frac{\partial}{\partial}\rho\frac{\partial E}{\partial \rho} = \mu_0 \frac{\partial j_t}{\partial t}\,. \tag{1}$$

The toroidal current density in Eq. (2), $j_t = j_p + j_b$, is the sum of the conductivity current (plasma current) $j_p = \sigma E$ and runaway j_b current densities. Let us denote the total toroidal current before the VS as $I_{t0} = I_{b0} + I_{p0}$, where I_{b0} and I_{p0} and are the runaway and plasma currents, respectively. We suppose in our model that instabilities result in a fast decrease in the runaway current. In reply, the same but opposite plasma current is generated inductively, $I_b = I_{b0} - I_0$, $I_p = I_{p0} + I_0$ and $I_t = I_{t0}$ at $t = 0$. This gives the initial condition for the electric field in Eq. (2) as $E = j_{p0}/\sigma$ at $t = 0$.

The variation of the runaway current density during the VS is caused by the acceleration of the existing (primary) and generation of the additional (secondary) runaways. A simplified equation for the evolution of runaway current density can be written as

$$\frac{\partial j_b}{\partial t} = \frac{e^2 E}{m_e}\left(\frac{n_0}{\gamma_{eff}^3} + n_1\right) + ev_{cr}\frac{\partial n_1}{\partial t} \tag{2}$$

where n_0 and n_1 are the density of the primary and secondary runaways, respectively, v_{cr} = $(T_e/m_e\alpha)$ is the critical velocity, $\alpha = E/E_{cr}$, E_{cr} is the Dreicer (critical) electric field, T_e is the electron temperature, Λ is the Coulomb logarithm calculated for the critical velocity and γ_{eff} is the effective relativistic factor for the primary electrons. The first term in the right-hand side represents the runaway acceleration and the second one the runaway generation. Equation (2) can be obtained from the velocity moment of the one-dimensional kinetic equation assuming free acceleration for $v > v_{cr}$ and considering that, due to short duration of the VS, runaways losses can be neglected. Due to their low kinetic energy, we assume γ_{eff} =1 for the secondary electrons.

The calculations show that the change of the effective relativistic factor is small, and the secondary runaways are mainly generated at the beginning of the VS, during the first several microseconds. So, we can further assume the constant γ_{eff} and n_1. Under these simplifications and $\sigma = const$, Eq. (2) becomes linear and its analytical solution can be obtained by the standard method of separation of variables.

Let us consider initial electric field localized in a cylindrical layer of the plasma column, such that $E(\rho, 0) = E_1$ at $c < \rho < b$, $E(\rho, 0) = 0$ at $\rho < c$ and $\rho > b$, and $c < b < a$. The solution shows a strong effect of initial electric field distribution on the first phase of the VS, when the diffusion of the current is the main process, and rather weak effect on the current damping phase (see Fig. 2).

The runaway current generation during the VS results in a faster decay of the VS and a smaller decrease of the toroidal current, as compared to the results of the model which takes into account only resistive damping. The effect of runaways is small under the condition $g \ll 1$, where

$$g = \frac{\mu_0 e^2 a^2}{m_e}\left(\frac{n_0}{\gamma_{eff}^3} + n_1\right) \tag{3}$$

One can conclude that information about the plasma conductivity, localization of the instability process, and runaway parameters can be inferred by fitting the theoretical model tothe measured VS. It is necessary to take into account that this inverse problem is an ill-posed one, like most of other plasma diagnostic problems, therefore, reasonable restrictions of the VS model are required.

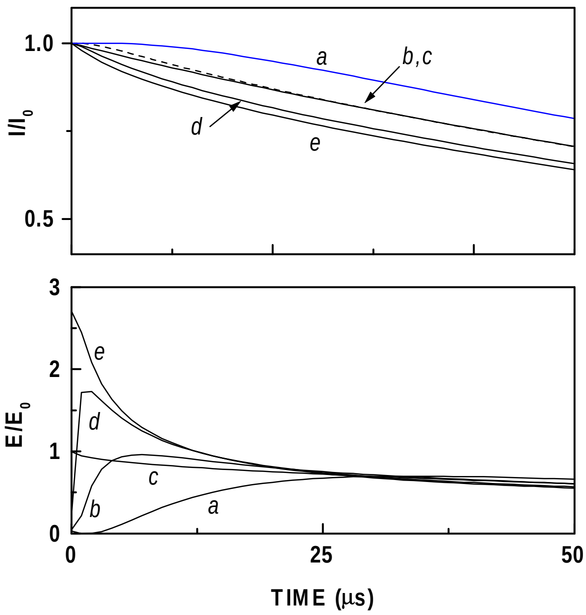

Fig. 2. Electric field on the plasma boundary and toroidal current change for different initial electric field distribution: (a) b/a=0.5; *(b) c/a*=0.6, *b/a*=0.8; *(c) c/a*=0, *b/a*=1, *(d) c/a*=0.75 *b/a*=0.95, *(e) c/a*=0.8, *b/a*=1.

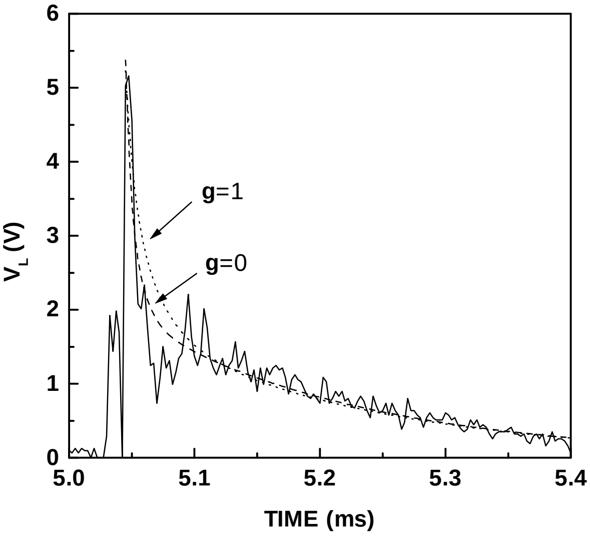

Fig. 3. Comparison of the calculated VS with the experimental one: b/a=1, c/a=0.8, T_e=15 eV at g=0; b/a=1, c/a=0.78, T_e=24 eV at g=1; Z_i =3. *The total toroidal current decrease is* ΔI_t =0.04; $\Delta I_t = I_0$ at g=0 and ΔI_t =0.57I_0 at g=1.

Analysis of experimental data. From the comparison of the measured and calculated VS (see Fig. 3), we conclude that the initial perturbation of the electric field is localized in a rather narrow region near the plasma boundary. The toroidal current change and electron temperature calculated by the Spitzer formula from the plasma conductivity have reasonable values.

The theoretical model with the parameter g=0 (no runaway effect) shows the best fit to the experimental VS (see Fig. 3). Let us discuss the possible value of the parameter g using results of our previous work [2]. In accordance with Eq. (3), we can write $g = g_0 + g_1$, where g_0 and g_1 are caused by the primary and secondary runaways, respectively.

The value of the parameter g_0 caused by the primary runaways is

$$g_0 = \frac{\mu_0 e I_{b0}}{\pi c m_e \gamma_{eff}^2 \sqrt{\gamma_{eff}^2 - 1}} \qquad (4)$$

In our case, the runaway beam carries more than 95% of the total current, The runaway effective kinetic energy is determined from the equilibrium effects as 140-360 eV; the energy increases with time. The measurements of the x-ray energy by the absorption method give the effective energy of about 400 keV at the end of the discharge. From Eq. (4), g_0 is 1.6 at 140 keV and 0.45 at W=400 keV.

To estimate the effect of the secondary runaways, we used the known formula for the steady-state runaway flux presented in Ref. 3. Due to exponential decrease of the electric field and strong dependence of the flux on the parameter $\alpha = E/E_{cr}$, runaways are mainly generated at the beginning of the VS during a time interval. $\Delta t \sim S_0 \left(dS_0 / dt \right)^{-1}$. The characteristic time of relaxation to the steady-state flux is [7] $\tau_c = \nu_e^{-1}\alpha^{-3/2}$, where ν_e is the collision frequency of the thermal electrons. For the conditions considered, $\Delta t << \tau_c$, i.e., the runaway flux is nonstationary, and the runaway density can be estimated as $n_1 \sim S_0\Delta t^2/2\tau_c$ at $t = 0$. The estimated value of n_1 depends strongly on plasma parameters. The two theoretical VS profiles in Fig. 3 are calculated assuming $Z_i = 3$, with $T_e = 15$ eV at $g = 0$ and $T_e = 24$ eV at $g = 1$. Estimations of the n_1 for these values of Z_i , T_e, and measured electron density 10^{12} cm^{-3} give, by Eg. (3), $g_1 = 0.05$ at $T_e = 15$ eV and $g_1 = 0.4$ at $T_e = 24$ eV.

We can conclude from this analysis that the effect of secondary runaway generation can be negligible small, for our conditions, due to the low plasma temperature and fast decrease of the electric field. However, the same conclusion about the effect of primary runaways would be in disagreement with runaway kinetic energies 140-400 keV deduced from equilibrium effects and x-ray energy measurements; these energies give $g_0 = 0.45 - 1.6$. This disagreement can be explained by the effects of the instability. One can see from Fig. 3 reproducible peculiarities of the measured VS: a small first step and nonmonotonic change during the diffusion phase. We can suppose that, in addition to the processes taken into account in our model, the instability, which initiates the VS, continues for some time playing a substantial role in the total current change, at least during the diffusion phase of the VS.

Conclusion. The positive voltage spikes in the time profiles of runaway discharges in TBR-1 are explained using a one-dimensional diffusion model of the toroidal electric field. According to our model, the VS is initiated by a fast small decrease in the runaway current. In reply, the same but positive plasma current is generated inductively. Together with the resistive damping of this plasma current, the diffusion model takes into account the generation of the additional runaway current. The effect of the additional runaway current generation is important under the condition $g \geq 1$ with parameter g given by Eq. (3). A comparison of the measured and calculated voltages allows us to infer an information about the plasma conductivity, initial electric field distribution and parameter g. In our case, the condition of the best fit gives $g = 0$. This result disagrees with the experimental data about the runaway kinetic energy which give $g \sim 1$. A possible explanation for this disagreement is the effect of an instability, which initiates the VS and which continues for some time, playing a substantial role in the toroidal current change.

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