Mechanism of runaway electron beam formation during plasma disruptions in tokamaks

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A new physical mechanism of the formation of runaway electron (RE) beams during plasma disruptions in tokamaks is proposed. The plasma disruption is caused by strong stochastic magnetic field formed due to nonlinearly excited low-mode number magnetohydrodynamic (MHD) modes. It is conjectured that the runaway electron beam is formed in the central plasma region confined inside the intact magnetic surface located between \( q = 1 \) and the closest low–order rational magnetic surfaces \( \frac{q}{m/n} = \frac{3}{2}, \frac{4}{3}, \ldots \). It results in that runaway electron beam current has a helical nature with a predominant \( \frac{m}{n} = 1/1 \) component. The thermal quench and current decay times are estimated using the collisional models for electron diffusion and ambipolar particle transport in a stochastic magnetic field, respectively. Possible mechanisms of the decay of runaway electron current due to an outward drift electron orbits and resonance interaction of high-energy electrons with the \( \frac{m}{n} = 1/1 \) MHD mode are discussed.

The runaway electrons (REs) generated during the disruptions of tokamak plasmas may reach a several tens of MeV and may contribute to the significant part of post disruption plasma current. The prevention of such RE beams is of a paramount importance in future tokamaks, especially in the ITER operation, since it may severely damage a device wall\textsuperscript{[1–3]}. The mitigation of REs by the massive gas injections (MGI) and externally applied resonant magnetic perturbations (RMPs) have been extensively discussed in literature (see, e.g., Refs. \textsuperscript{[5–7]} and references therein). However, no regular strategy to solve this problem has been developed because up to now the physical mechanisms of the formation of REs during plasma disruptions are not well understood. In spite of the numerous dedicated experiments to study the problem of runaway current generation during plasma disruptions in different tokamaks (see, e.g., \textsuperscript{[6–14]}), there is no clear dependence of RE formation of plasma parameters has been established. These numerous experiments show the complex nature of plasma disruption processes especially the formation of RE beams.

One of the important features of the formation of RE beams is its irregularity and variability of their beam parameters from one discharge to another one. This is an indication of the sensitivity of RE beam formations on initial conditions which is the characteristic feature of turbulent processes, particularly, the chaotic system. Therefore one expects that \textit{ab initio} numerical simulations of RE formation process may not be quite productive to explain it because of complexity of computer simulations of turbulent processes\textsuperscript{[15]}. The problems of numerical simulations of plasma disruptions is comprehensively discussed by\textsuperscript{[16]}.

In this Letter we propose a new physical mechanism of the formation of RE beams during plasma disruptions in tokamaks. It is based on the analyses of numerous experimental results, mainly obtained in the TEXTOR tokamak and the ideas of magnetic field stochasticity\textsuperscript{[17]}. The mechanism explains many features of plasma disruptions accompanied by RE generations.

\textbf{Main conjecture.} It is believed that the plasma disruption starts with the excitations of MHD modes with low poloidal \( m \) and toroidal \( n \) numbers, \( (m/n = 1, 2/1, 3/2, 4/3, 5/2, \ldots) \) that lead to a large–scale magnetic stochasticity (see, e.g.,\textsuperscript{[18, 19]} and references therein). The heat and particle transports in the strongly chaotic magnetic field causes the fast temperature drop and ceases the plasma current. At the certain spectrum of magnetic perturbations, for example, at the sufficiently small amplitude of the \( \frac{m}{n} = 1/1 \) mode the chaotic field lines may not extend to the central plasma region due to an intact magnetic surface located between magnetic surface \( q = 1 \) and the nearest low–order rational surfaces \( \frac{q}{m/n} = \frac{3}{2}, \frac{4}{3}, \ldots \). This intact magnetic surface confines particles in the central plasma region and serves as a transport barrier to particles during the current quench. Electrons in the confined region are accelerated by a toroidal electric field and forms the relatively stable of RE beams.

Possible structures of a stochastic magnetic field before the current quench with the RE-free discharge and with the RE discharge are shown in Figs.\textsuperscript{[1]} (a) and (b) by the Poincaré sections of magnetic field lines. It is assumed that the perturbation magnetic field contains several low–mode number \( m/n \) MHD modes with equal amplitudes \( B_{m/n} \): (a) the amplitude \( B_{11} \) of the \( m/n = 1/1 \) mode is equal to others; (b) \( B_{11} \) is four times smaller than the amplitudes of other modes. As seen from Fig.\textsuperscript{[1]} (a) for the large amplitude of the \( m/n = 1/1 \) mode the stochastic magnetic field extends up to the central plasma region destroying the separatrix of the \( m = n = 1 \) island. For the low–amplitude of the \( m/n = 1/1 \) mode shown in Fig.\textsuperscript{[1]} (b) the stochastic magnetic field does not reach
The $q = 1$ magnetic surface and covers the region outer the $q = 1$ magnetic surface. The last intact drift surface is located between the resonant surfaces $q = 1$ and $q = 4/3$.

The existence of an intact magnetic surface and its location depends on the radial profile of the safety factor and the spectrum of magnetic perturbations. The latter sensitively depend on the plasma disruption conditions and vary unpredictable from one discharge to another during plasma disruptions. This makes RE formation process unpredictable and may explain a shot–to–shot variability of the parameters of RE beams.

**Experimental evidences.** This conjecture on the mechanism of RE beam formation agrees with the important features of the experimental observations in the TEXTOR tokamak. In the experiments the plasma disruptions were triggered by gas injections (see, e.g., [8–10]). Particularly, the disruptions with REs were triggered by argon (Ar) injection, and runaway-free disruptions were triggered either by helium (He) or neon (Ne) injection. Figures 2 (I) and (II) show the time–evolutions of plasma parameters for several discharges without (#117444) and with (#119978,#117859, and #120140) REs. One should note that in the last two discharges one observed untypical RE currents with shorter decay times (see Fig. 2 (II)).

Experiments show that the penetration lengths of atoms depends on their atomic weights [20]: He (or Ne) atoms penetrate deeper into plasma than Argon atoms. The injection of these gases may finally give rise to different spectra of amplitudes of MHD modes. One can expect that the amplitude of the $m/n = 1/1$ MHD mode excited by the He/Ne injection is higher than in the case of Argon gas injection. There exits a critical perturbation level $B_{mn}$ which breaks the intact magnetic surface between the $q = 1$ and the closest low–order rational surface $[q = 3/2, 4/3, . . .]$ thus leading to the total destruction of confinement of electrons and ions. This is in agreement with the experimental observations on the existence of critical magnetic perturbation for the RE beam formation [3].

The plasma current decay in the current quench and the RE plateau regimes for all discharges is well approximated by the linear function of time $I_p(t) = a - bt$. Curve 1 corresponds to the current decay stage, and curve 2 corresponds to the RE current decay stage. Symbols $\ast$ correspond to the values of the plasma current $I_p^{(RE)}$ at the initial stage of the RE beam formation.

The plasma current decay in the current quench and the RE plateau regimes for all discharges is well approximated by the linear function of time $I_p(t) = a - bt$, with the average current decay rate $b = -\langle dI_p/dt \rangle$ as shown in Fig. 2 (III). The values of $\langle dI_p/dt \rangle$ in these regimes for several typical and untypical discharges are listed in the 2-nd and 3-rd columns of Table I and the initial values of the plasma current $I_p^{(RE)}$ at the RE plateau regime are listed in the 4-th column.

The average values of $\langle dI_p/dt \rangle$ for almost all discharges are confined in the interval (2.2, 5.6) MA/s, i.e., in one order lower than the current decay rate in the second stage. The values of $I_p^{(RE)}$ are also confined between 177 kA and 240 kA. These values of $\langle dI_p/dt \rangle$ and $I_p^{(RE)}$ are close to the ones observed in the similar experiments in the DIII-D tokamak (see, e.g., [14]).

The experimental values of the plasma current $I_p^{(RE)}$ at the initial stage of the RE beam formation correspond
to the values of plasma current flowing inside the last instant magnetic surface $\rho$. For the most typical discharges they located between the resonance magnetic surfaces $q(\rho_1) = 1$ and $q(\rho_3) = 4/3$ as shown in Fig. 3. For untypical discharges # 117859 and #120140 $I_p^{(RE)}$ have the highest and lowest values and lie at the borders of region $\rho_1 < \rho < \rho_3, \rho_2$ (see also Table I). For these discharges the current quench rates $\langle |dI_p/dt| \rangle$ take highest or lowest values: the lowest one for #117859 and the highest one for #120140. The RE current decay rate (in the 3-rd stage) for both of these discharges takes highest values. They have the shortest duration time of RE currents. One expects that the presence of several low–order $m/n = 4/3, m/n = 3/2$, and $m/n = 1/1$ resonant magnetic surfaces within the RE beam for the discharge #117859 may lead to excitations of the corresponding MHD modes. The interactions of these modes may lead to the quick loss of REs due to the formation of stochastic zone at the edge of the RE beam.

The formation of the RE beam inside the intact magnetic surface can be also confirmed by the spatial profiles of the synchrotron radiation of high–energy REs with energies exceeding 25 MeV. One observes that the radiation is localized within a finite radial extent in the central plasma region.

**Estimations of thermal quench and current quench times.** The strong radial transport along the stochastic magnetic field lines causes the losses of heat and plasma particles from the stochastic zone. The temperature drop in the fast phase can be explained by the fact that the anomalously large heat transport in a stochastic magnetic field is mainly determined by the electron diffusion. The current quench stage of disruption is determined by the particle transport in stochastic magnetic field.

Using the collisional test particle transport model in a stochastic magnetic field [21] we estimated the heat conductivity $\chi_T(\rho)$ and a characteristic heat diffusion time $\tau_H = a^2/2\chi_T$. For typical magnetic perturbations and pre-disruption plasma temperatures ($0.5 \pm 1.0$ keV) the magnitude of $\chi_T(\rho)$ has an order of several $10^2$ m$^2$/s and $\tau_H \sim 10^{-4}$ s, i.e., of the order of the experimentally observed time for the plasma temperature drop during the thermal quench after disruption. The quantitative analysis based on the numerical solution of the corresponding diffusion equation for heat transport also gives similar values for $\tau_H$.

The current quench determined by the particle transport in a stochastic magnetic field has the ambipolar nature. It is strongly collisional due to the low plasma temperature that is about from 5 eV to 50 after the thermal quench. We estimated the ambipolar diffusion coefficients $D_p$ of particles in a stochastic magnetic field shown in Fig. 1. At the above plasma temperatures the corresponding diffusion time $\tau_D = a^2/D_p$ of particles changes from 1 s to 0.3 s. Since the diffusion coefficient $D_p \propto B_{mn}^2$ and therefore $\tau_D \propto B_{mn}^{-2}$, then $\tau_D$ can be reduced to one order smaller value for three times larger perturbation than in Fig. 1. This timescale is still much longer than the experimentally observed values. However, the collisional model does not takes account the effect of the inductive toroidal electric field. One expects that the acceleration of electrons and ions by the electric field increases the radial transport of particles. To include this effect in the collisional model one can assume that the effective temperature of the plasma is higher than the measured one. The particle diffusion time $\tau_D$ for the effective temperature 2 keV is about $8 \times 10^{-3}$ s. This timescale gives the average current decay rate $dI_p/dt \approx I_p/\tau_D = 0.35/(0.8 \times 10^{-3}) \approx 44.0$ MA/s which is order of the experimental measured rates given in Table I.

In general the transport of heat and particles in the presence of RMPs is a three–dimensional problem. Par-

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### TABLE I. Decay rates $\langle |dI_p/dt| \rangle$ [in MA/s] of the plasma current $I_p(t)$ in the current quench and RE plateau regimes for several discharges.

| Discharge No. | 2–nd stage $I_p^{(RE)}$ [kA] | 3–rd stage $I_p^{(RE)}$ [kA] |
|---------------|-------------------------------|-----------------------------|
| 117444        | 47.8 ± 0.21                   | N/A                         |
| 117507        | 42.7 ± 0.71                   | 4.29 ± 0.14                 |
| 117527        | 39.4 ± 0.29                   | 5.65 ± 0.12                 |
| 117859        | 33.2 ± 1.11                   | 11.70 ± 0.50                |
| 119874        | 37.9 ± 0.60                   | 2.25 ± 0.01                 |
| 119978        | 38.8 ± 0.76                   | 3.38 ± 0.02                 |
| 120123        | 36.4 ± 0.47                   | 3.66 ± 0.01                 |
| 120140        | 47.5 ± 0.86                   | 13.91 ± 0.35                |

### FIG. 3. Radial profile of the plasma current $I_p(\rho)$ (solid curves 1 on l.h.s. axis) and the corresponding safety factor profile $q(\rho)$ (dashed curves 2 on r.h.s. axis). The rectangular (red) dots correspond to the experimentally measured values of $I_p^{(RE)}$ for several TEXTOR discharges. The plasma parameters are $I_p = 350$ kA, $B_0 = 2.4$ T, $R_0 = 1.75$ m, $a = 0.46$ m. The values of $q_0 = q(0)$ are 0.75 and 0.8, respectively. The radii $\rho_1, \rho_2$, and $\rho_3$ are the positions of the rational magnetic surfaces $q(\rho_1)=1, q(\rho_2)=3/2$, and $q(\rho_3)=4/3$, respectively.
particularly, a stochastic magnetic field with the topological structures like ones in Figs. 1 leads to poloidally and toroidally localized heat and particle deposition patterns on wall similar ones in ergodic divertor tokamaks (see, e.g., [1]).

RE beam evolution. From the described scenario of plasma disruption it follows that a typical runaway beam current is localized inside the area enclosed by the last intact magnetic surface. In general the distribution of the current density \( j \) would depend not only on the radial coordinate \( \rho \) but also vary along the poloidal \( \theta \) and the toroidal \( \varphi \) angles due to the presence of the \((m/n = 1/1)\) magnetic island. This agrees with the analysis of numerous disruptions in the JET tokamak [22]. One can assume that the radial profiles of the RE current density averaged along poloidal and toroidal angles are almost uniform. This gives the value of the safety factor at the beam axis \( q(0) \) is less than unity. This assumption is supported by a number of experimental measurements of the current profile after the sawtooth crashes in the TEXTOR, the TFTR, and JET tokamaks [23–28].

The inductive toroidal electric field accelerates electrons up to higher energies. With increasing the electrons energy their orbits drifts outwardly [29, 30] and eventually hit wall. It is illustrated in Fig. 1(a). This effect may be one of mechanisms of slow RE current decay. Calculations show that the outward drift velocity \( v_{dr} \) is of order of a few m/s for typical discharges in TEXTOR. The RE current decay rate \( \frac{dI_p}{dt} \) due to outward drift RE orbits can be roughly estimated as follow. This loss mechanism is mainly caused by the shrinkage of the beam radius \( a \). The rate of such a shrinkage \( \frac{da}{dt} \) is of order of the average outward velocity \( v_{dr} \). Since \( I_p \propto a^2 \), we have \( \frac{dI_p}{dt} \propto (2I_p/a)\frac{da}{dt} = (2I_p/a)v_{dr} \). For the typical values of \( I_p \approx 0.2 \text{MA}, a \approx 0.2 \text{m}, \) and \( v_{dr} \approx 1 \text{m/s} \) one has \( \frac{dI_p}{dt} \approx 4 \text{MA/s} \). This estimation is of order of the experimentally measured average decay rate of the runaway current listed in Table 1.

The effect of magnetic perturbation on RE beams depends on its safety factor profile \( q \). The latter varies in the interval \([q(0) < 1, q(a)]\) with its edge value \( q(a) \) less than \(3/2\) [or \(4/3, 5/3\)]. Such a RE beam is relatively stable to the effect of magnetic perturbations. The single \((m/n = 1/1)\) mode does not create the stochastic layer at the beam edge for REs with energies up to several MeVs since their drift surfaces are close to magnetic surfaces. With increasing the energy of electrons the drift surfaces strongly deviates from magnetic ones and thus creates the perturbation harmonics with higher mode numbers \( m > 1 \). The interactions of several resonance modes of perturbations may form the stochastic zone at the beam edge which leads to fast RE losses as illustrated in Fig. 1(b).

This process, probably, explains the sudden RE current drop accompanied by magnetic activity and RE bursts observed in experiments (see Figs. 2 (I) and (II), also e.g., [4, 8]).

Summary. Based on the analysis of numerous experimental data obtained in the TEXTOR tokamak we have proposed a mechanism of the RE beam formation during the plasma disruption. The plasma disruption starts due to a large-scale magnetic stochasticity caused by non-linearly excited of MHD modes with low \((m, n)\) numbers \((m/n = 1/1, 2/1, 3/2, 5/2, \ldots)\). At the sufficiently small amplitude of the \((m/n = 1/1)\) mode there exists an intact magnetic surface located between the magnetic surface \( q = 1 \) and the closest low-order rational surface \( q = m/n > 1 \) \((q = 4/3, q = 5/4 \) or \( q = 3/2) \). Such intact magnetic surface forms the transport barrier for particles in the central plasma region. Electrons in this confined region are accelerated by the inductive toroidal electric field.

This mechanism reproduces well the essential features of the measurements. Particularly, the energy and current quenches are determined by the strong electron diffusion and ambipolar transport of particles in a stochastic magnetic field, respectively. The slow decay of the RE current in the plateau phase can be explained by the slow continuous decay due to an outward shift of REs in the accelerating toroidal electric field and the spiky quick decay due to resonant interaction of high-energy REs with the \((m/n = 1/1)\) MHD mode. The effect of the external resonant magnetic perturbations on low-energy electrons (up to \(5-10\) MeV) is weak and does not cause their loss. This is in agreement with the recent experiments in the TEXTOR tokamak [31]. The detailed description of the mechanism of RE formation and the evolution of RE current based on the analyses of experimental observations will be given in a separate publication [52].

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