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THE IMPACT OF A FLYING COLLECTOR ON RUNAWAY ELECTRONS DURING CURRENT DISRUPTION IN A TOKAMAK

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Abstract

The article describes the results of numerical simulations of the temporal evolutions of plasma and runaway electron (RE) currents during the discharge disruption in an ITER scale tokamak. To solve a system of two differential equations for plasma and RE currents a zero-dimensional approach for the plasma shape is used similar to Martin-Solis et al (2015). The use of injection of tungsten collectors of runaways can significantly reduce their amount in the disrupted plasma. The requirements for the selection of collector parameters and characteristics of its injection formulated are to ensure the safer operation of the tokamak. The simulation results show that the most promising scenario for dealing with the consequences of a discharge disruption is the simultaneous injection into the plasma of several 80-gram tungsten collectors at a velocity of 250 m/s right after the thermal quench (TQ).

1. INTRODUCTION

Currently, one of the significant obstacles to the long-term and safe operation of thermonuclear fusion in tokamaks is the disruption instability of the discharge current. Research on the prevention and mitigation of discharge disruptions is relevant and very important. For large modern tokamaks (including ITER), and even more for tokamak-reactors, the disruption can lead to catastrophic consequences, up to a violation of the vacuum vessel integrity [1]. In addition to the problems associated with the removal of thermal energy from the plasma and the electromechanical loads, one of the central problems of removal of plasma magnetic energy is the generation of an avalanche current of runaway electrons commensurate with the values of the plasma current after the thermal quench. To solve these problems, disruption mitigation systems (DMS) are being developed [2]. The problems are proposed to be solved by injection impurity atoms into the plasma during the DMS ITER launch scenario. For example, amount of Ar atoms comparable or less than the plasma particle content prior to disruption may provide values of the exponential decay time τ_{CQ} for the current quench in the corresponding of 22-66 ms [3][4].

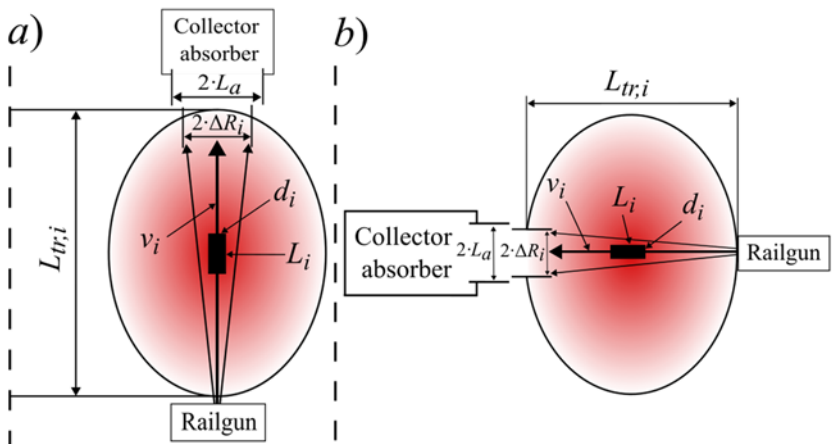
The central problem in reducing the magnetic energy of the plasma current is the generation of an avalanche current of runaway electrons commensurate with the values of the plasma current before disruption. To prevent an avalanche of RE, different ways of influencing plasma are being considered. Massive injection of the working gas is proposed which may make it possible to suppress the avalanche current by a collision mechanism [4] with an increase in the initial density of the working gas up to 100 times. However, an enhancement of plasma particle content may create a significant load on technological systems including the pumping, the isotope separating etc. In addition, it was shown in [5] that the collision mechanism can significantly reduce the avalanche current RE in ITER regimes without activating the chamber walls, which occurs during operations with DT plasmas. When the wall is activated, and the plasma has a significantly increased number of RE due to Compton scattering of gamma quanta from the wall on plasma electrons. As a result, even under conditions of suppression of the avalanche mechanism due to an increase of density, it is impossible to reduce the RE current to less than 4.5 MA in any scenario considered [5]. Another approach is to use external disturbing magnetic fields that contribute to the stochastisation of magnetic surfaces. This approach makes it possible to destroy magnetic surfaces and, because of this, RE do not multiply and reach the wall of the vacuum chamber even before they gain large amounts of energy. However, the simulation for ITER [6] showed that the perturbation imposed by the magnetic coils could create a stochastic layer only at the edge of the plasma. This is not sufficient to solve the problem of RE.

This paper suggests the development of the method proposed in [7] for suppressing the avalanche current of runaway electrons. To reduce avalanche currents, injecting a tungsten collector is proposed into the plasma immediately after the plasma thermal quench (TQ) stage. To evaluate the effectiveness of such an approach, the simulation model [7] was improved. The effect of an injected tungsten collector on the temporal evolution of the total and avalanche currents at the stage of the current quench (CQ) during discharge disruption in ITER scale tokamak was simulated.

2. DESCRIPTION OF THE INJECTION SCHEME AND REQUIREMENTS FOR INJECTION PARAMETERS

Three of the collector injection geometries proposed and discussed in [7] are shown in Fig. 1. The vertical and radial injections in the poloidal cross-section are shown in Fig. 1a,b. Fig. 1c demonstrates the tangential injection at the equatorial plane passing through a region of high field side. The length of the collector trajectory $L_{tr,i} \cong 6.8$ m, 4 m, 14 m in Fig. 1a,b,c correspondingly. Each figure shows the location of the railgun accelerator and the collector absorber. Fig. 1 schematically shows the permissible deflections from the rectilinear trajectory of the injected i-th collector ΔR_i, which should be noticeably smaller than the diameter of the receiving hole of the collector absorber $2L_a$ for each trajectory. The possibility of injecting several collectors was considered. The parameters of the i-th collector are indicated by the subscript "i". A cylindrical tungsten collector with a diameter d_i, length L_i, and mass m_i is injected at a velocity v_i at time t_i relative to the beginning of the CQ stage. Numerical estimates are performed for the plasma of the ITER scale installation with the parameters prior to the disruption given in [3],[5],[7]: $R = 6.2$ m and $a = 2$ m – major and minor plasma radii; $I_{p0} = 15$ MA – plasma current; $B_t = 5.3$ T – toroidal magnetic field; $\langle n_e \rangle = 10^{20}$ m^3 and $\langle T_e \rangle = 10$ keV – plasma volume averaged density and temperature of electrons.

The following three requirements are formulated for selecting the collector injection parameters: 1) The I_{RE} current, according to the conclusions of [5], should not exceed $I_{max} = 0.15$ MA to preserve the integrity of the ITER vacuum chamber; 2) The deflections of the collectors during flight through the plasma ΔR_i should not exceed $\Delta R_{max} = 1$ cm in order to reliably assemble the collectors in the sufficiently compact collector absorber device after their flight through the plasma and not exceed the size of the angular spreading from the railgun accelerator $\cong 10^{-3} \cdot L_{tr,i} \cong 0.7$ cm [7]; 3) For keeping the integrity of the collector during its flight through the plasma, the collector temperature T_i should not exceed $T_{max} \cong 2900$ K or 80% of the melting point of tungsten 3595 K.



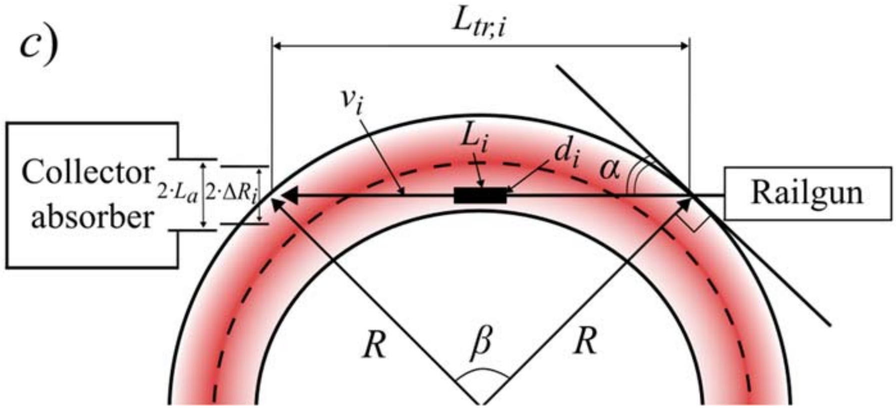


FIG. 1. a) Vertical injection scheme; b) Radial injection scheme; c) Tangential injection scheme.

3. MODEL OF PLASMA CURRENTS EVOLUTION

As in [7], [8], rapid mixing of plasma parameters is assumed at the stage of thermal quench, and the main parameters of the problem are evenly distributed inside the plasma. For the safe removal of thermal energy at the TQ stage, Ar impurity is proposed for ITER, as described in [3]. In this case, the impurity particle amount is commensurate with the plasma content before the disruption $N_p \approx 8.3 \times 10^{22}$. This injection allows to emit effectively thermal energy, as well as to control the characteristic time of current quench. The number of Ar particles is found from the joint solution of the Ohmic Heating balance equation and the equation for current decay time τ_{CQ} as in [3].

The RE current

$$I_{RE}I_{RE} = ecn_{RE} \cdot \pi \cdot k_{el} \cdot a^2, \tag{1}$$

is determined by their density n_{RE} and velocity c. Here k_{el} is the plasma elongation. The initial RE current I_{RE0} was estimated under the assumption that it is formed during the TQ stage with a characteristic decay time t_0 of the electron temperature by means of the "hot-tail" mechanism [3],[9]

Estimations of the concentration of runaways seeds n_{RE0} were done using the approach of [3],[7],[9]

$$n_{RE0} = \int_{v_c}^{\infty} f 4\pi v^2 dv \cong n_{e0}\frac{2}{\sqrt{\pi}} u_{c,min} e^{-(u_{c,min})^2}, \tag{2}$$

with

$$u_{c,min} = \left(\frac{4}{3}t_0\nu_0\left[1 + \frac{3}{2}\ln\left(\frac{E_{D0}}{2E_0}\right) - \ln\left(\frac{4}{3}t_0\nu_0\right)\right] - 3t_0\nu_0\right)^{\frac{1}{3}}, \tag{3}$$

Here, $E_{D0}=(n_{e0}e^3\ln\Lambda_{rel})/(4\pi\varepsilon_0^2 T_{e0})$ and E_0 are the values of the Dreicer field and the inductive electric field before TQ; $\nu_0=(n_{e0}e^4\ln\Lambda)/(4\pi\varepsilon_0^2 m_e^{1/2}(2T_{e0})^{3/2})$ is the frequency of electron-electron collisions before TQ; e and m_e are the charge and rest mass of the electron; ε_0 is the dielectric constant of the vacuum; $\ln\Lambda$, $\ln\Lambda_{rel}$ are Coulomb logarithms for thermal electrons before TQ and runaway electrons.

In the framework of the zero-dimensional approach, the electron density and temperature were assumed to be $n_{e0} = \langle n_e \rangle$ and $T_{e0} = \langle T_e \rangle$. To describe the plasma current decay at the CQ stage, a system of zero-dimensional equations for the total plasma current I_p and the runaway electron current I_{RE} were solved

$$\frac{dI_p}{dt} = -\frac{I_p - I_{RE}}{\tau_{CQ}}, \tag{4}$$

$$\frac{dI_{RE}}{dt} = \left(\frac{dI_{RE}}{dt}\right)_{avalanche} - I_{RE} \cdot \sum_{i=1}^{N_c}\frac{1}{\tau_i} \cdot H[t - t_i] \cdot H\left[\frac{L_{tr,i}}{v_i} + t_i - t\right]. \tag{5}$$

Here, N_c is the number of injected collectors. The inductive electric field E is related to the Ohmic current I_p - I_{RE} and the plasma resistance by the ratio

$$E = \frac{\eta_{CQ} \cdot (I_p - I_{RE})}{\pi \cdot k_{el} \cdot a^2}, \tag{6}$$

where η_{CQ} is the resistivity of the plasma, depending on the electron temperature T_{eCQ} and the effective charge Z_{effCQ} of CQ plasma [7];

Equation (4) describes the evolution of the total plasma current I_p with a current decay time τ_{CQ} in absence of RE. In equation (5), the first term on the right describes the generation of avalanche current RE I_{RE} [3]

$$\left(\frac{\partial I_{RE}}{\partial t}\right)_{avalanche} = \left(\frac{4\pi\varepsilon_0^2 m_e^2 \cdot c^3 \sqrt{\frac{3\left(5+Z_{effCQ}\right)}{\pi}}}{e^4 n_{eCQ}}\right)^{-1} \cdot I_{RA} \cdot \left(\frac{E}{E_R} - 1\right), \quad (7)$$

where E_R is the Rosenbluth field

$$E_R = \frac{n_{eCQ} e^3 ln\Lambda_{rel}}{4\pi\varepsilon_0^2 m_e c^2}. \quad (8)$$

The second term of equation (5) takes into account losses of runaways on each i-th tungsten collector with a characteristic time τ_i. This time is determined by the collector which absorbs RE moving with a velocity close to the velocity of light c on the collector cross-section area S_i perpendicular to the magnetic field line in a tokamak plasma of volume V

$$\tau_i = \frac{V}{cS_i} \cong \frac{V}{c\left[d_i L_i \sin\alpha + (\pi d_i^2/4)\cos\alpha\right]}. \quad (9)$$

Here α is the angle between the collector trajectory line and the toroidal magnetic field. Unlike the vertical injection and radial injections where $\alpha \equiv \pi/2$, the tangential injection requires considering an influence of the angle α on the collection of RE. From Fig. 1c it can be seen that the angle at the collector passage the separatrix is $\alpha_0 = \beta/2 = arcsin(L_{tr,i}/(2\cdot(R+a))) \approx 58.6°$. During the collector's passage through the plasma, the angle α decreases from α_0 to zero at the midpoint of the trajectory and then increases back to α_0.

The time delay t_i of the collector entering the plasma relative to the beginning of the CQ stage may vary. The residence time of the collector in the CQ plasma $L_{tr,i}/v_i$ is determined by its velocity v_i, the length of the trajectory $L_{tr,i}$ and this is taken into account in the equation (5) using the Heaviside functions H.

Thus, equation (4) for the total plasma current I_p and equations (5)-(7) for the avalanche current I_{RE} were jointly solved by the Runge–Kutta fourth-order method under the assumption $E >> E_R$. The initial condition for the plasma current $I_p(0)$ at the CQ stage of disruption was determined by the assumption of its possible increase in comparison with the plasma current before disruption as a result of rapid reconnection of magnetic surfaces at the TQ stage. It was assumed that, as in [3], an increase of 15% would result in $I_p(0) = I_{fr} = 1.15 \cdot I_{p0} = 17.25$ MA. The initial condition $I_{RE}(0) = I_{RE0}$ for the RE current was determined by equations (1)-(3).

4. INFLUENCE OF RUNAWAY ELECTRONS ON THE TRAJECTORY AND HEATING OF COLLECTORS

When the collector moves in the tokamak CQ plasma, runaway electrons moving along the magnetic field may cause a deflection of the collector from its initially rectilinear trajectory. To estimate the deflection of the collector due to the impulse received from RE during the $t_{fl,i} = L_{tr,i}/v_i$, it is necessary to take into account the evolution of the runaway velocity from the equation of their motion [10]

$$\frac{d}{dt}\gamma m_e v_{RE} = -\frac{e\eta_{CQ}}{\pi \cdot k_{el} \cdot a^2}\left(I_p - I_{RE}\right), \quad (10)$$

where γ is the relativistic factor. The calculations take into account that since the energy of RE is limited

$$E_{RE} = \begin{cases} \frac{m_e c^2}{\sqrt{1-\frac{v^2}{c^2}}}, E_{RE} < 20\,MeV \\ 20\,MeV, E_{RE} > 20\,MeV \end{cases}, \quad (11)$$

from above to the value of $\cong$ 20 MeV due to their energy losses, mainly due to synchrotron radiation according to [3],[6]. From the equation of the balance of forces

$$m_i a_{RE,i} = \frac{E_{RE}}{c^2} \cdot c \cdot c \cdot n_{RE} \cdot S_i = E_{RE} \cdot n_{RE} \cdot \left[d_i L_i \sin\alpha + \left(\pi d_i^2/4\right)\cos\alpha\right] \quad (12)$$

the acceleration, velocity, and deflection of the collector ΔR_i in the direction transverse to the magnetic field

$$\Delta R_{RE,i} = \int_{t_i}^{t_{fl,i}+t_i} dt \int_{t_i}^{t_{fl,i}+t_i} \left(a_{RE,i}\right) dt, \quad (13)$$

are found.

To estimate the average temperature T_i of a i-collector with a mass of m_i due to the absorption of RE energy in its volume, the zero-dimensional energy balance equation was used

$$m_i \cdot C_{Tung} \cdot \frac{dT_i}{dt} = E_{RE} \cdot c \cdot n_{RE} \cdot S_i = E_{RE} \cdot c \cdot n_{RE} \cdot \left[d_i L_i \sin\alpha + \left(\pi d_i^2/4\right)\cos\alpha\right], \quad (14)$$

From equations (11) and (14) we have

$$T_i = T_{i0} + \int_{t_i}^{t_{fl,i}+t_i} \frac{c \cdot n_{RE} \cdot E_{RE} \cdot S_i}{m_i \cdot C_{Tung}} dt, \quad (15)$$

where $T_{i0} = 293\ K$ is the initial room temperature of collector, $C_{tung} \cong 157\ J \cdot K^{-1} \cdot kg^{-1}$ is specific heat capacity and $\rho_{tung} \cong 1.9 \cdot 10^4\ kg \cdot m^{-3}$ is the density of tungsten at intermediate temperature $(T_{max} - T_{i0})/2 \cong 1300\ K$, $m_i = \rho_{Tung} \cdot L_i\ \pi \cdot (d_i/2)^2$ is the mass of the collector.

5. SIMULATION RESULTS AND THEIR DISCUSSION

The main discharge parameters $I_{p0}, n_{e0}, T_{e0}, B_t$ are listed above and selected according to [3], which presents the results of one-dimensional modelling the plasma current decay and the RE current generation expected in ITER. The characteristic decay time t_0 of the electron temperature during TQ was assumed to be equals $t_0 = 1$ ms. The density of injected Ar $n_{Ar} = 5.6\times10^{19}$ m^{-3} was chosen to provide the value of $t_{CQ} = 34$ ms of the plasma current decay so that values of the runaway avalanche current will reach $\cong$ 9 MA as in simulations of [3]. With this amount of Ar, the plasma electron density is $n_{eCQ} \cong 2.3\times10^{20}$ m^{-3}, the plasma temperature is $T_{eCQ} \cong 4.4$ eV, and the effective charge is $Z_{effCQ} \cong 1.75$. The TQ stage ends with the formation of the initial plasma current $I_{fr} = 17.25$ MA, the internal inductance $l_{int} = 0.7$ and the relativistic Coulomb logarithm $\ln\Lambda_{rel} \cong 21$ as in [3]. Taking into account the parameters defined above, the initial value of the RE seed current $I_{RE0} \cong 4$ kA was estimated according to equations (1)-(3).

To identify the most important mechanism affecting the collector temperature, the volumetric heating of the collector due to collisions with RE described above was compared with that by thermal electrons described in [7]. For this, a collector with the following parameters which are typical as will be seen later was considered: $v_i = 250$ m/s, $L_i = 110$ mm, $d_i = 11$ mm, $m_i \cong 0.2$ kg, $t_i = 0$ ms, $L_{tr,i} \cong 6.8$ m. The relative value of the volumetric heating of the collector due to absorbing RE is obtained $T_i/T_{max} \cong 0.74$ from equation (15). The relative heating of the collector surface due to thermal electrons according to the model of [7] is $T_i/T_{max} \cong 0.2$. Therefore, heating by thermal electrons was neglected in further simulations of the collector temperature for simplicity.

The collector parameters in simulations were varied to satisfy the three requirements formulated above. The simulations were performed for the vertical, radial and tangential trajectories of collectors. The time interaction collectors with the CQ plasma $t_{fl,i} \cong 27$ ms was chosen of order of the current decay time $\tau_{CQ} \cong 34$ ms. This allows us to find a range of collector velocities and masses in accordance with the three requirements and from a technical point of view of their acceleration.

The simulation results of the dependence of the avalanche current of RE on the collector parameters for each trajectory are presented in Table 1,2,3 for the vertical, radial, tangential injections correspondingly. Each table contains 4 scenarios, numbered in the first column followed by columns with an amount N_c and other parameters of collectors. The collector temperature T_i is normalized to T_{max} value, the deflection ΔR_i is normalized to R_{max} value and value of the simulated I_{RE} avalanche current value at 100 ms since the start of simulations is normalized to I_{max} value.

It can be seen from Tables 1-3 that when maintaining the residence time of the collector in the plasma and selecting their appropriate velocities, the values of the three parameters for requirement are close. This means that the evolution of currents for all injection geometries is approximately the same. The evolutions of the plasma current and avalanche current RE for scenario 1 without injection and scenarios 2 and 4 with injection of collectors 1 and 3 at $t_i = 0$ ms are shown in Fig. 2a,b respectively. It is seen from Fig.2a that without collector injection, an unacceptably large avalanche current of RE is generated in scenario 1 $I_{RE} = 56 \cdot I_{max} = 8.4$ MA.

TABLE 1. PARAMETERS OF COLLECTORS FOR THE VERTICAL INJECTION

№	N_c	v_i, m/s	d_i, mm	L_i, mm	m_i, kg	T_i/T_{max}	$\Delta R_i/\Delta R_{max}$	I_{RE}/I_{max}
1	-	-	-	-	-	-	-	56
2	1	250	10.9	109	0.2	0.78	0.2	0.86
3	2	250	10.9	109	0.2	0.2	0.04	$1.1\cdot10^{-5}$
4	3	250	8	80	0.08	0.32	0.08	$8.8\cdot10^{-4}$

TABLE 2. PARAMETERS OF COLLECTORS FOR THE RADIAL INJECTION

№	N_c	v_i, m/s	d_i, mm	L_i, mm	m_i, kg	T_i/T_{max}	$\Delta R_i/\Delta R_{max}$	I_{RE}/I_{max}

1	-	-	-	-	-	-	-	56
2	1	150	11	110	0.2	0.75	0.2	0.86
3	2	150	11	110	0.2	0.2	0.04	$1.1 \cdot 10^{-5}$
4	3	150	8	80	0.08	0.33	0.08	$1.3 \cdot 10^{-3}$

TABLE 3. PARAMETERS OF COLLECTORS FOR THE TANGENTIAL INJECTION

№	N_c	v_i, m/s	d_i, mm	L_i, mm	m_i, kg	T_i/T_{max}	$\Delta R_i/\Delta R_{max}$	I_{RE}/I_{max}
1	-	-	-	-	-	-	-	56
2	1	520	11	110	0.2	0.55	0.14	0.89
3	2	520	11	110	0.2	0.21	0.04	$1.2 \cdot 10^{-5}$
4	3	520	8	80	0.08	0.33	0.08	$1.3 \cdot 10^{-3}$

In order to reduce the RE current and meet the formulated requirements, different injection scenarios were considered. As can be seen from scenario 2, the problem can also be solved by injecting one collector with a sufficiently large mass. Acceleration difficulties increase as the mass of the collector increases. In the event of an emergency failure of the collector injection system, the current of RE can violate the integrity of the installation. Therefore, scenario 3 with the injection of two collectors with the same mass and scenario 4 with the injection of three collectors with more than twofold weight reduction was considered. It is seen that such injections satisfy all the formulated requirements. It is also seen that with the selected parameters, the problem of an emergency with the failure of one of the two injection systems in scenario 3 is solved. Due to the almost twofold weight reduction, scenario 4 seems preferable for each injection geometry.

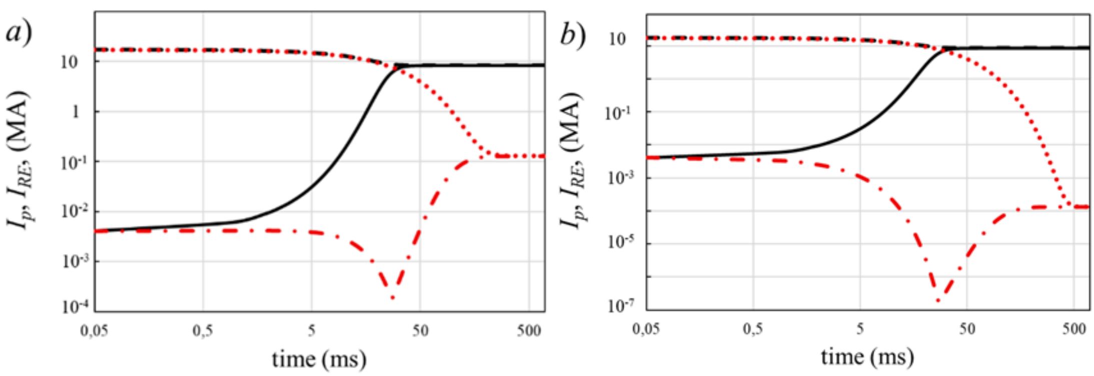


FIG. 2. Evolution of the plasma current and avalanche current without injection and with injection of 1 collector (a) and 3 collectors (b) immediately after TQ t_i = 0 ms: I_p is a dashed line, I_{RE} is a solid line without collector injection (scenario 1); I_p is a dotted line, I_{RE} is a dash-dotted line with injection (scenario 2 in Fig. a and scenario 4 in Fig. b).

In the first row of the Tables 4-6 the results of scenario 5 are shown with injection of three collectors in the event of a failure of one of the three injection systems for three injection geometries. It is seen that the formulated requirements are fulfilled, but in vicinity of its maximum values. When the diameter of the collectors decreases by 0.1 mm and the length of the collectors by 1 mm at the same velocity, their temperature in relative units takes the value $T_i/T_{max} \cong 1.04$. Also, an increase in the velocity of the injected collectors by 25 m/s while maintaining their size leads to an excess of the requirements for the avalanche current of runaway electrons $I_{RE}/I_{max} \cong 1.06$.

The maximum possible delay of the collector injection time t_i was estimated by means of simulations with t_i = 2 ms and t_i = 5 ms for scenarios 6 and 7 correspondingly as shown in Tables 4-6. The evolution of the plasma current and avalanche RE currents for scenarios 6 and 7 for the vertical injection is shown in Fig. 3.

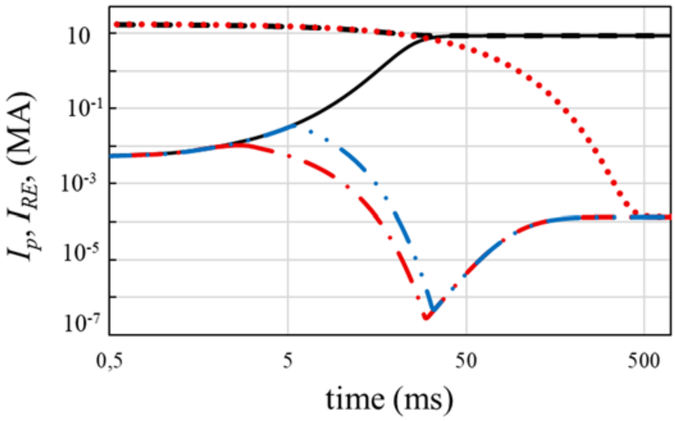


FIG. 3. Evolution of the plasma current and the avalanche current: I_p – dashed line, I_{RE} – solid line without collector injection (scenario 1); I_p – dotted line, I_{RE} – (dash-dotted line) with injection of 3 collectors with a delay of t_i = 2 ms (scenario 6); I_p – dotted line, I_{RE} – (dash-dotted line with two dashes) with injection of 3 collectors with a delay of t_i = 5 ms (scenario 7).

TABLE 4. ACCIDENT SCENARIOS FOR VERTICAL INJECTION OF COLLECTORS

№	N	t_i, ms	v_i, m/s	d_i, mm	L_i, mm	m_i, kg	T_i/T_{max}	$\Delta R_i/\Delta R_{max}$	I_{RE}/I_{max}
5	2	0	250	8	80	0.08	0.82	0.2	0.4
6	3	2	250	8	80	0.08	0.84	0.34	$8.8\cdot10^{-4}$
7	3	5	250	8	80	0.08	2.31	1.27	$8.8\cdot10^{-4}$

TABLE 5. ACCIDENT SCENARIOS FOR RADIAL INJECTION OF COLLECTORS

№	N	t_i, ms	v_i, m/s	d_i, mm	L_i, mm	m_i, kg	T_i/T_{max}	$\Delta R_i/\Delta R_{max}$	I_{RE}/I_{max}
5	2	0	150	8	80	0.08	0.83	0.21	0.5
6	3	2.5	150	8	80	0.08	0.84	0.38	$1.3\cdot10^{-3}$
7	3	5	150	8	80	0.08	2.02	1.21	$1.3\cdot10^{-3}$

TABLE 6. ACCIDENT SCENARIOS FOR THE TANGENTIAL INJECTION OF COLLECTORS

№	N	t_i, ms	v_i, m/s	d_i, mm	L_i, mm	m_i, kg	T_i/T_{max}	$\Delta R_i/\Delta R_{max}$	I_{RE}/I_{max}
5	2	0	520	8	80	0.08	0.64	0.17	0.49
6	3	4.7	520	8	80	0.08	0.95	0.62	$1.3\cdot10^{-3}$
7	3	6	520	8	80	0.08	1.32	0.99	$1.3\cdot10^{-3}$

Analysis of the results of scenarios 6,7 shows that when collector injection is delayed, the number of runaway electrons increases significantly, which can lead to both deflection of the collector trajectory and increase of its temperature. In scenario 6, they are comparable to the maximum values, but become unacceptably high in scenario 7. Thus, it follows from the results of zero-dimensional modelling that an acceptable delay in starting the collectors relative to the moment TQ is possible, but not more than ≅ 2-5 ms, depending on the injection geometry.

6. CONCLUSIONS

This paper presents the zero-dimensional model of thermal and current quenches in an ITER scale tokamak. The two equations system has been improved, for the first time, taking into account accounting the avalanche RE current suppression during the disruption event using tungsten collectors flying inside plasma immediately after TQ [7]. To ensure the safety characteristics of an ITER scale tokamak during the disruption, requirements for collector injection parameters have been formulated. They are as follows: the maximal avalanche RE current should be less than I_{max} = 0.15 MA; the deflection of the collector from a straight trajectory should be less than R_{max}=1 cm, and the collector temperature should be less than T_{max} =2900 K. Based on these requirements, scenarios were simulated for the RE collectors injection into tokamak plasma. In addition, various geometries of injection of collector trajectories described in [7] were considered. Modeling shows that most promising scenario involves simultaneous injection of 3 collectors with 80 gm mass each immediately after the TQ. From the point of view of the energy and compactness of the railgun to obtain the required velocities, the injection with the lowest collector velocity of about 150 m/s for the radial injection seems preferable. For this geometry, the simulated I_{RE}/I_{max} =$1.3\cdot10^{-3}$, $\Delta R_i/\Delta R_{max}$ =0.08 and

T_i/T_{max}=0.33 values will provide the safe discharge termination. Even in the event of accident, if one of three collectors is not injected, all the requirements for the safe discharge termination are still met. An acceptable delay in starting the collectors relative to the moment TQ is possible, but not more than 2 ms for the radial collector injection.

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