Modeling of Major Disruption Mitigation by Fast Injection of Massive Li Pellets in ITER Like Tokamak-reactor

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Abstract. Lithium and Beryllium pellets injection in ITER like-tokamak plasmas with use of runaway current model of DINA simulation code is examined. Pellet injection is carried out during thermal quench to have possibility to shield the tokamak plasma facing components (PFC) from the local high power loads. Influence of PFC on plasma during thermal quench can be modeled by Be pellet injection. Non-coronal impurity radiation, which can be multiplied by neutral of hydrogen isotopes and ionization losses will smooth fast thermal quench power load and protect PFC in time. Current decays during disruption depending on size and effective charge of high speed (1 km/s) are studied. Thermal balance in plasma is defined by energy loss due to impurity as a result of pellet injection, which increases up to more than ~20 times the total electron contamination in the plasma volume, resulting in a relatively strong radiative dissipation of >95 % of the plasma stored energy. Due to favorable radiation properties, the Lithium pellet with mass less than 2.5 g provides the conditions for termination of the plasma current without runaway electron generation and the Lithium pellet with mass of ~ 18 g is enough to radiate the thermal energy from ITER like-plasma during the fast thermal quench. It is shown that one needs to inject more than 8 g of Beryllium to radiate the thermal energy from ITER like-plasma during the fast thermal quench and to suppress the runaway electron generation during the plasma current termination, but in that case the current decay time is too small on conditions of electromagnetic forces in vacuum vessel (< 20 ms).

1. Introduction

The safest precursor of major disruption in tokamak (almost 100% of assurance) is the fast thermal quench (FTQ) of plasma core, which finishes as a fast heat shock for all tokamak PFC. Moreover the disruption event can convert a large fraction of plasma energy to runaway electron beams, which results in to the appearance of a high electric field generation during cooling of plasma core. Thus the major disruption mitigation is a serious problem of tokamak reactor like ITER. The probable solution of this problem is a fast massive noble gas puffing during disruption for dilution and the plasma energy radiation before its contact with reactor chamber [1, 2]. Extrapolation of characteristic-time development of FTQ in ITER-like tokamak can be equal to ~1 ms [3]. However the fast (<1 ms) gas penetration in a reactor chamber like ITER is questionable. This problem can be solved by the gun-accelerated low Z killer-pellets injection (KPI) [4, 5]. In contrast to massive gas injection, the neutrals of which are stopped at the plasma edge and fill the vacuum region between the plasma and the wall, the impurity pellets can penetrate into the plasma volume. Presence of enough quantity of impurity neutrals eventually provides the destabilization of large magneto-hydrodynamic modes during the FTQ. Good solution of such problem is a use of Lithium pellets [5]. The moving lithium limiter created during the start of FTQ by the fast injected several massive Li-pellets (for example 5 with total mass 20-40 g) can shield PFC from a local high power loads [5, 6]. Lithium non-coronal radiation and ionization losses will smooth FTQ power load and protect PFC in time (mitigation of major disruption consequences). The main condition of successful shielding of PFC by this means is a moving of virtual lithium limiter from its initial position in the chamber ports to the hot plasma boundary during propagation of FTQ from plasma center to PFC (time duration of

FTQ). Mitigation of divertor thermal deposition ultimately depends on the ability to convert a significant fraction of the total plasma stored energy, $W_{tot}=W_{th}+W_{mag}$, into the strong radiation on a timescale faster than an unmitigated disruption. If the useful length between the initial position of pellets in chamber ports and plasma boundary of ITER-like tokamak will be equal to 1 m, then the final pellet velocity should be equal to ~1 km/sec. Lithium pellets can be accelerated by rail gun with current pulse (30-50 kA per pellet) cross the tokamak magnetic field. The total energy of capacitor bank used for this aim should be equal to ~ 100 kJ. In Fig. 1 the scheme of rail gun for Li pellet acceleration [7] is shown. Here the acceleration path L =1 m, the accelerated body Li (2x2x2 cm^3), the distance between rails y=2 cm, the rail width d=2 cm, the body velocity vector V.

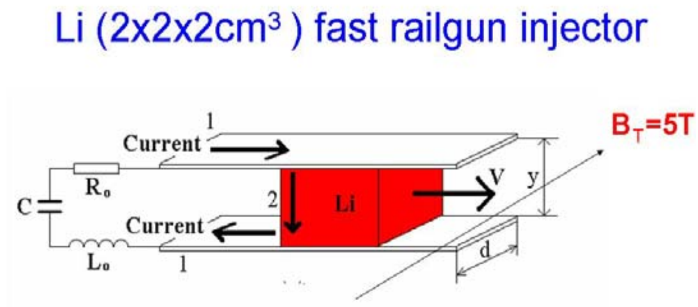

FIG. 1. Fast Li-injector [7]

Impurity radiation can be multiplied by neutrals of hydrogen isotopes, which are trapped by beryllium in PFC and can penetrate in core plasma with beryllium during FTQ. In Fig. 2 the dependence in coronal approximation of power losses due to Be impurity radiation and ionization P_{loss} on electron temperature is shown for different levels of γ_{H0}, which is the relation between densities of neutrals of hydrogen and electron density. One can see the high impact of density of hydrogen neutrals to the power losses level due to Be impurity. As for Li impurity, such impact is much lower. Influence of PFC on plasma during FTQ can be modeled by Be pellet injection.

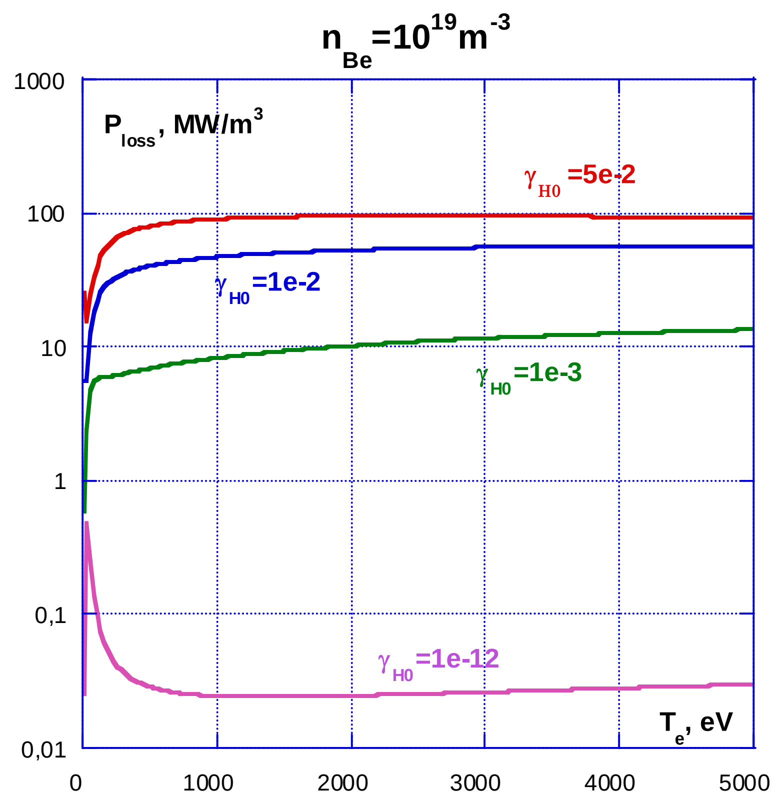

FIG. 2. Dependence of P_{loss} on T_e for different levels of relation between densities of neutrals of hydrogen and electron density

In the presented paper three main questions, connected with such method of disruption smoothing were analyzed:

1. Estimation of total amount of needed lithium;
2. Influence of neutral of hydrogen isotopes to radiation losses;

3. Electron runaway problem.

The calculations of total Li and Be (material of ITER first wall) amount needed for the cooling of ITER-like plasma were performed. The calculations were based on DINA code [8] and avalanche model of M.N.Rosenbluth and S.V.Putvinski for estimations of electron runaway generation [9].

2. The total amount of needed Lithium

For the first estimations of cooling effect by lithium ionization and radiation the so called "energy cost of atom ionization" method – a total electron energy loss during the transition of one neutral atom to coronal ionization balance can be used. Fig. 3 shows the "energy costs" of Li, Be and C ions as function of electron temperature. All calculations are carried out in coronal approximation similarly to [10]. One can see that the lithium is more effective coolant of the plasma in the range of T_e = 13-30eV in the comparison with beryllium for example, which is becoming much more effective coolant of the plasma in the range of T_e < 10 eV. In the range of T_e= 13-1000 eV the "energy costs" of one primary Li atom can be choused between 1-2 keV. The sum of all Li ionization potentials is equal to 0.2 keV.

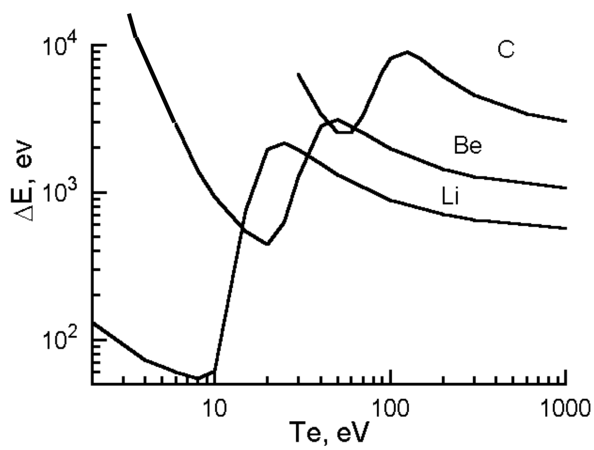

FIG. 3. The "ion energy cost" as function of electron temperature for Li, Be, C [10]

The total lithium amount (N) used for 0.5 GJ ITER-like plasma cooling by the fast Li injection can be $N\approx 3\text{x}10^{24}$ of Li atoms or 35 g of lithium if the Li "cost" is equal 1000 eV (T_e =15-1000 eV).

3. DINA simulation model

In presented DINA simulations the one-dimensional energy balance equations for electrons and ions together with hydrogen and impurity ions density transport, and magnetic field diffusion equation are solved self consistently.

3.1 Runaway physical model

For runaway electron current j_{run} simulation in DINA code an avalanche model [9] was used with a source S_{run} in the form of Dreicer acceleration [11]

$$\frac{\partial j_{run}}{\partial t} = \frac{j_{run}}{\tau \ln \Lambda}\sqrt{\frac{\pi\gamma}{3(Z_{eff}+5)}}F\left(\frac{E_{\|}}{E_c},\gamma\right) + S_{run} \, , \qquad (1)$$

where $\tau = mc/eE_c$, $ln\Lambda$ is the Coulomb logarithm, $\gamma = \gamma(r/R)$, $E_{||}$ is the current electric field and E_c is the minimum electric field below which the formation of high energy runaway electrons is not possible [11]. It is assumed that the runaway electrons are kept in each closed magnetic surface and due to the plasma shrinking during limiter phase a part of runaway current contained in the scrapped plasma area can be lost on the first wall.

3.2 Impurity radiation model

Model of dynamics of ionization state of impurities is used for simulation of impurity ionization states evolution $n_j(t)$. It has the same form for different types of impurities. Impurity ions density balance is written as

$$\frac{dn_j}{dt} = n_e \cdot n_{j-1} \cdot I_{j-1} - n_e \cdot n_j \cdot (I_j + R_j) + n_e \cdot n_{j+1} \cdot R_{j+1} + n_{H0} \cdot (n_{j+1} \cdot X_{j+1} - n_j \cdot X_j), \quad (2)$$

here n_j is the concentration of j^{th} ionization state of ion; n_{H0} is the concentration of neutral hydrogen, which is estimated to be $(10^{-3}\text{-}10^{-2})\cdot n_{e0}$ (here n_{e0} is the electron density of target plasma); I_j, R_j and X_j are the rate coefficients for ionization, recombination and charge exchange, taken from [12]. Radiation power for impurity can be represented as a sum of contribution from all ionization states $Q_Z = n_e \cdot \sum_{k=0}^{Z} n_k \cdot U_k \cdot V_P$, where U_k are the radiation coefficients [13]. Opacity effects are not taken into account.

3.3 Poloidal flux diffusion.

Ohm's law averaged on magnetic flux surfaces with inclusion of runaway current effect is written as

$$\dot{\Psi}\frac{d\Phi}{d\rho} - \dot{\Phi}\frac{d\Psi}{d\rho} = \frac{4\pi}{\sigma}\left(J\frac{dF}{d\rho} - F\frac{dJ}{d\rho}\right) + \langle jB \rangle_{run}\frac{V'c}{\sigma} \quad (3)$$

Here J and F are the plasma toroidal and poloidal currents, ψ and Φ are the plasma toroidal and poloidal fluxes, respectively, σ is the plasma parallel to magnetic field conductivity, ρ is the normalized toroidal flux and $\langle jB \rangle_{run}$ is the runaway current contribution.

3.4 Pellet ablation model.

Pellets are injected from low field side of plasma. Analytical formula is used for ablation speed of hydrogen pellet [14] with correction of ablation rate due to Z for impurity pellet [15]. During crossing of plasma magnetic surfaces and evaporation of pellet, energy conservation law on each magnetic flux tube is applied to calculate the temperature and densities. Ablation speed of pellet is calculated with use of the electron temperature value, which is taking into account the screening of pellet by means of evaporated neutral cloud [14]. In simulations the main sources in energy equations are the Joule heating, impurity radiation and ionization energy losses. If the pellet is fully ablated before reaching magnetic axes the quick inward pinch of impurity ions is taking place with continuous cooling of plasma [15], which is observed for example in disruptive plasma in T-11M with lithium limiter [16].

4. Simulation results

The main subject of the paper is the study of the radiative dissipation of the plasma stored energy as a result of pellet injection in the beginning of thermal quench and the investigation of the influence of pellet injection to the runaway electrons generation conditions during the plasma current quench (CQ) in disruption. The DINA numerical simulation self-consistently evolves the impurity ionization state distribution and radiation energy balance. There were considered the lithium pellets with radiuses r=1÷3 cm and the beryllium pellets with radiuses r=0.5÷1.25 cm, which were injected with velocity 1000 m/s into ITER-like plasma with an average target plasma temperature around 10 keV and electron density ~ $10 \cdot 10^{19}$ m^{-3}. To achieve the radiative dissipation of the 0.5 GJ plasma stored thermal energy during ~1 ms of FTQ one need to provide the averaged over thermal quench time impurity radiation power around $5 \cdot 10^5$ MW. Radiation power value during FTQ and main plasma parameters as a result of Li and Be KPI are shown in Table 1.

TABLE 1: PLASMA PARAMETERS IN RESULT OF LITHIUM AND BERILLIUM KPI

	m, g	N_{imp} (19)	P_{loss} (MW)	I_{RE} (MA)	T_e (eV)	τ_{CQ} (ms)	γ_{H0}
Lithium	2.5	21	$2 \cdot 10^5$	0	8.5	150	5e-3
	7.5	72	$3.5 \cdot 10^5$	0	7	120	5e-3
	18	170	$5 \cdot 10^5$	0	6	80	5e-3
	35	330	$10 \cdot 10^5$	0	5	60	5e-3
	61	573	$15 \cdot 10^5$	0	4.7	50	5e-3
Beryllium	1	7	$3.3 \cdot 10^3$	0	23	250	1e-3
		7	$1.5 \cdot 10^5$	1.8	4.3	60	5e-3
		7	$2.1 \cdot 10^5$	2.5	4.4	60	1e-2
		7	$2.8 \cdot 10^5$	5	2	18	5e-2
	2	13	$1.5 \cdot 10^5$	1	3.1	50	5e-3
	3.2	24	$2 \cdot 10^5$	0.2	3.3	50	5e-3
	8	57	$5 \cdot 10^5$	0	2	18	5e-3
	15	110	$10 \cdot 10^5$	0	2	18	5e-3

Here m is the mass of pellet, N_{imp} is the average impurity density, P_{loss} is the radiation power averaged over time of FTQ, T_e is the plasma electron temperature after the thermal quench, τ_{CQ} is the plasma current decay time. Data for Be pellet with m=1 g are presented for 4 levels of concentration of hydrogen neutrals, which strongly decrease the ionization level of ion of impurity due to charge exchange. One can see that in case of Be the increase of n_{H0} greatly decreases the electron temperature level and raises the runaway electron generation probability. But it was found that in the Li case the T_e

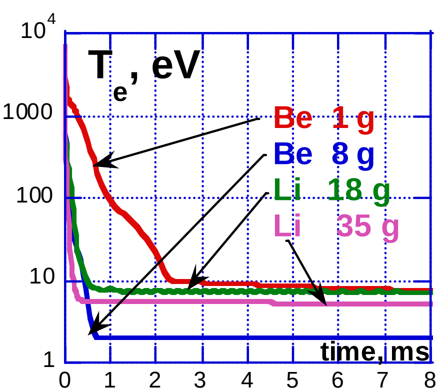

FIG. 4. T_e waveforms as a result of Be and Li KPI for γ_{H0}=5e-3

dependence on the n_{H0} level is much weaker - even if γ_{H0} is more than 5e-2 the conditions for runaway electron generation in case Li pellet injection are *not* shown up. Electron temperature waveforms as a result of KPI with different mass of Be and Li pellets are presented in Fig.4.

One can see from Table 1 data that the mass of pellets needed to be injected into ITER-like plasma are around 18 g of Li and around 8 g of Be to radiate the main part of the thermal energy stored in plasma before disruption and to shield the tokamak plasma facing components from the local high power loads during FTQ. Then even the small Lithium pellet (< 3 g) provides the ITER-like plasma current termination without runaway electron generation. The beryllium pellet with mass less than 3 g *does not* suppress the runaway electron generation during plasma current termination because of low level of electron temperature, compare to the lithium pellet case.

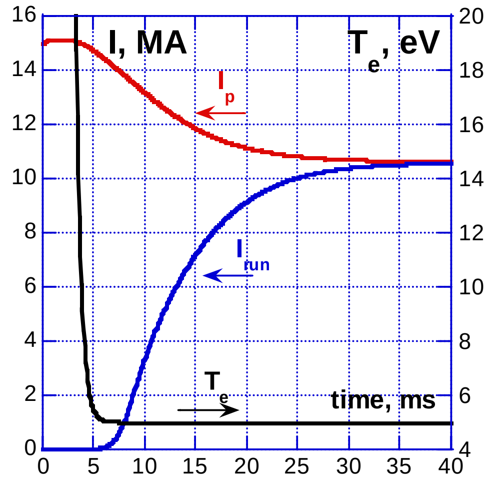

FIG. 5. Evolution of plasma current, runaway current and electron temperature during major disruption in ITER like plasma

Absence of runaway electrons in the case of Li pellet injection can be explained by higher level of electron temperature in the plasma in comparison with case of Be pellet injection. In Fig. 5 the typical evolutions of plasma current, runaway current and plasma electron temperature during major disruption in 15MA ITER-like plasma *without* KPI are presented. The t=3 ms is the time moment of plasma current quench beginning. One can see that in such plasma the runaway current during disruption can reach 10.5 MA. Relativistic runaway electrons are produced when $E_{||}$, which accelerates electrons is greater than the critical electric field, E_c and their amplification are suppressed when $E_{||}/E_c < 1$.

The main results of simulations are shown in Fig.6, which presents the plasma current decay from 15MA to 0 after injection of massive Be and Li pellets. Simulation results of disruptions in ITER-like plasma with Be pellet injection with mass within m = 1 ÷ 15 g have shown that if the

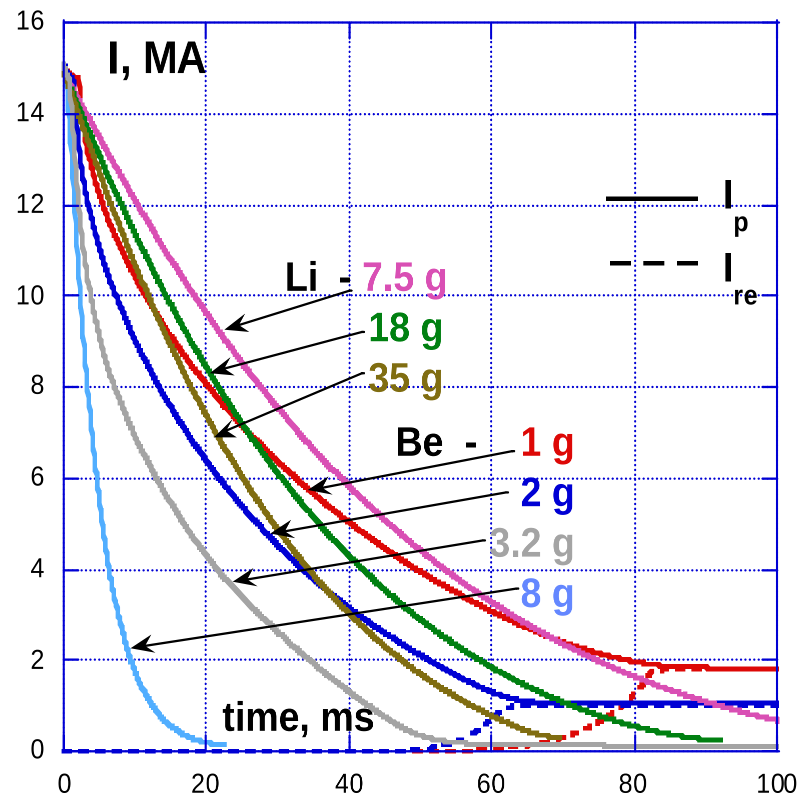

FIG.6. I_p decay during Be and Li injection for γ_{H0}=5e-3

injected mass of Be is less that 3 g (such pellet does not reach the magnetic axis of plasma) then the runaway electron current is generated during the plasma current termination.

But if the Be pellet crosses plasma magnetic axis (*m* > 3÷4 g) the plasma current termination occurs without runaway electron generation but the current decay time less than 20 ms. That is too small on conditions of electromagnetic forces in vacuum vessel In the case of Li it is enough to inject the mass less than 2.5 g to terminate the plasma current without runaway electron. Besides the runaway electrons are found to be absent for any n_{H0} level in case of Li injection, which is advantage of lithium injection.

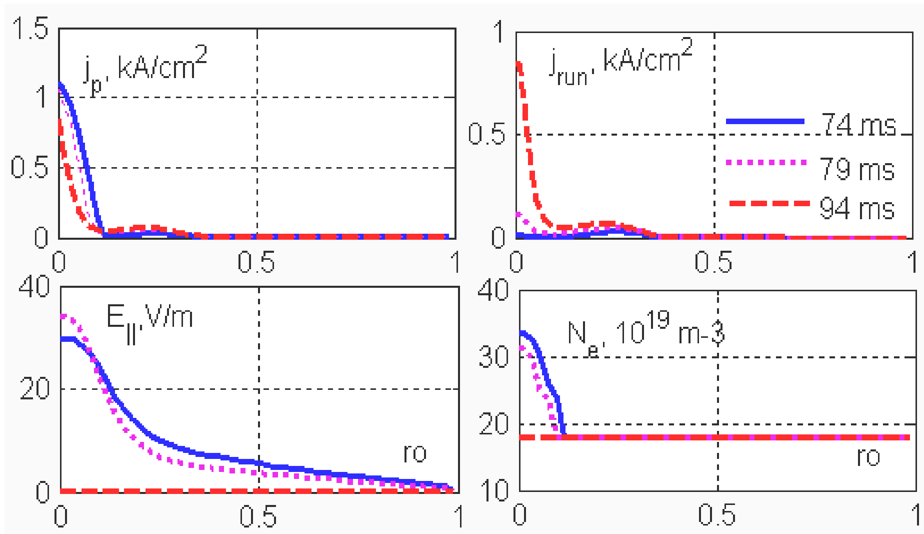

FIG. 7a. Time evolution of profiles of plasma and runaway currents, $E_{||}$, and N_e in the case of Be KPI with m=1 g

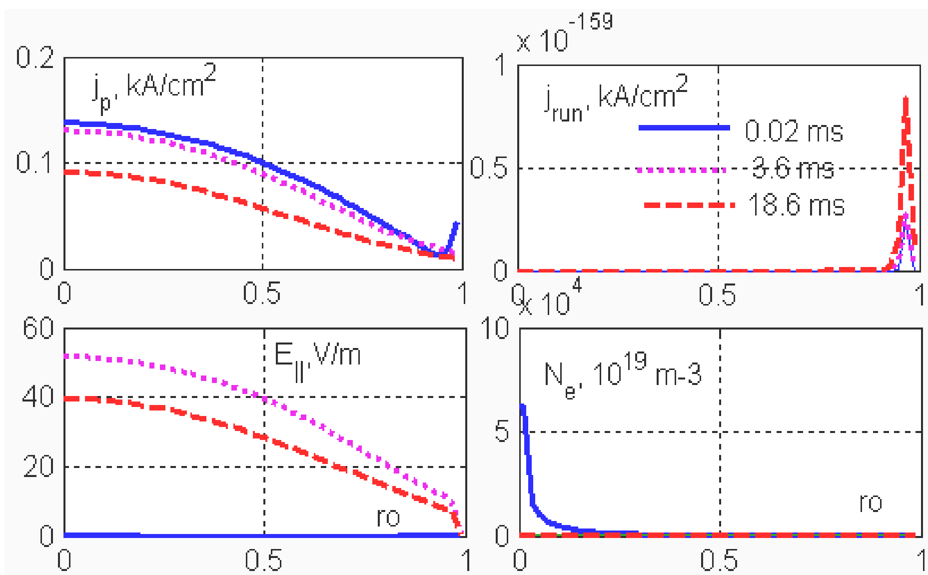

FIG. 7b. Time evolution of profiles of plasma and runaway currents, $E_{||}$, and N_e in the case of Li KPI with m=18 g

In Figs. 7 the plasma parameter profiles time evolution as a result of injection of Be and Li pellets for two KPI cases are shown. Fig. 7a corresponds to the injection of 1g beryllium pellet, which does not reach the plasma axis and does not suppress runaway generation. Fig. 7b demonstrates correspondingly the plasma parameter profiles for the case of 18g Li pellet injection without runaway electrons.

5. Conclusions

DINA numerical analysis of the high speed killer Li and Be pellets injection during thermal quench in ITER-like plasmas has been carried out. It was shown that due to favorable radiation properties, the lithium pellet with mass less than 2.5 g provides the conditions for termination of the plasma current without runaway electron generation and the lithium pellet with mass of ~ 18g is enough to radiate the thermal energy from ITER-like plasma during the fast thermal quench and to shield the tokamak plasma facing components from the local high power loads during thermal quench. On the other hand one needs to inject more than 8 g of beryllium to radiate the thermal energy from ITER-like plasma during the fast thermal quench and to suppress the runaway electron generation during the plasma current termination, but in that case the current decay time is too small on conditions of electromagnetic forces in vacuum vessel (< 20 ms). Moreover it was shown that in contrast to Li pellet injection the raise of n_{H0} level greatly decreases the electron temperature level and raises the runaway electron generation probability in case of Be KPI.

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