

## Study of low Z pellets injection for disruption mitigation in ITER like tokamaks

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**Introduction.** Major disruption mitigation is a serious problem of tokamak reactor like ITER. The probably solution of this problem is a fast massive noble gas puffing during disruption for dilution and plasma energy radiation before its contact with reactor chamber [1]. However the fast (<1 ms) gas penetration in reactor chamber like ITER is questionable. This problem can be solved by injection of gun-accelerated low Z killer-pellets [2, 3]. But ITER 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 center. The paper presents a numerical analysis of different Z (Li, C, Ar, W) high speed killer pellets injection (KPI) in ITER like plasmas with DINA code [4].

**Runaway physical model.** In the simulations the energy balance equations for electrons and ions together with hydrogen and impurity ions density transport, and magnetic field diffusion equation are solved self consistently. For runaway electron current  $j_{run}$  simulation in DINA code an avalanche model [5] was used with a source  $S_{run}$  in form of Dreicer acceleration [6].

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

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 [6]. It is assumed that the runaway electrons are kept in each closed magnetic surface and due to plasma shrinking during limiter phase a part of runaway current contained in the scrapped plasma area can be lost on the first wall.

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

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

here  $n_j$  is the concentration of  $j^{\text{th}}$  ionized ion;  $n_{H0}$  is the concentration of neutral hydrogen;  $I_j$ ,  $R_j$  and  $X_j$  are the rate coefficients for ionization, recombination and charge exchange, taken

from [8]. Radiation power for impurity can be represented as a sum of contribution from all ionisation states  $Q_z = n_e \sum_{k=0}^z n_k \cdot U_k \cdot V_p$ , where  $U_k$  are the radiation coefficients [7].

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

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

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

**Pellet ablation model.** Pellets are injected from low field side of plasma. Analytical formula is used for ablation speed of hydrogen pellet [9] with correction of ablation rate due to  $Z$  for impurity pellet [10]. 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. In simulations the main sources in energy equations are the Joule heating and impurity radiation and ionization energy losses. If the pellet is fully ablated before reaching magnetic axes, then two mechanisms of plasma cooling exist. First is the quick inward pinch of impurity ions with continuous cooling of plasma [10] and second is the fast cooling of inside region of plasma due to MHD instabilities [2].

**Modelling results.** The main subject of the paper is the study of the influence of pellet injection to the runaway electrons generation conditions during disruption. There were considered impurity pellets with radiuses  $r=0.6\sim 1.0$  cm which were injected into ITER like plasma with velocity 1000 m/s. In Fig. 1 the typical evolutions of plasma current, runaway current and plasma electron temperature during major disruption in 15MA ITER plasma without KPI are presented. The  $t=3$  ms is the time moment of plasma current quench beginning. One can see that in DT plasma the runaway current during disruption can reach 10.5 MA. In Fig. 2 the plasma and runaway currents behaviors after KPI at  $t=0$  are shown, when the pellet is fully ablated before it reaches magnetic axes. Example of the plasma parameter profiles time evolution after injection of Ar pellet is shown in Fig. 3.

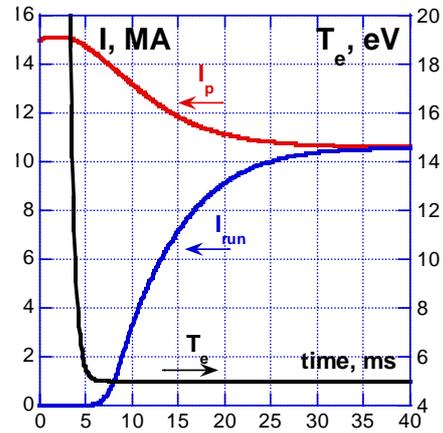


Fig. 1 Evolution of plasma current, runaway current and electron temperature during major disruption in ITER like plasma

The Li, C, Ar and W impurity pellets injection are considered. One can see that in the case of low Z impurity pellets with  $r=0.6$  cm there is no runaway current is generated. But in the case of medium Z (Argon) and high Z (Tungsten) with the same size of pellets the generation of runaway current takes place because of lower electron temperature level in comparison with low Z impurity pellets (see Fig. 4b). At the same time it was obtained that if the pellet with medium level of Z is crossing the plasma axis there is no generation of runaways. Modeling results show that the runaway electron generation is not observed if the size of injected Ar pellet is increased up to  $r=0.96$

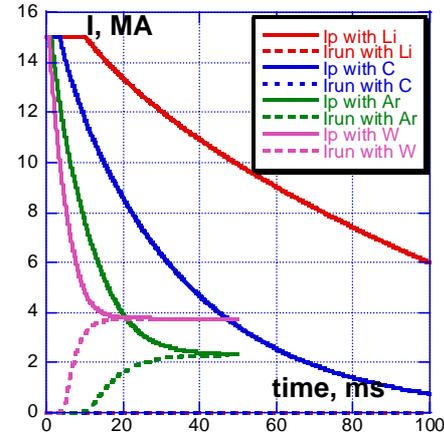


Fig. 2 Plasma and runaway current behaviors after KPI with different Z and  $r=0.6$  cm

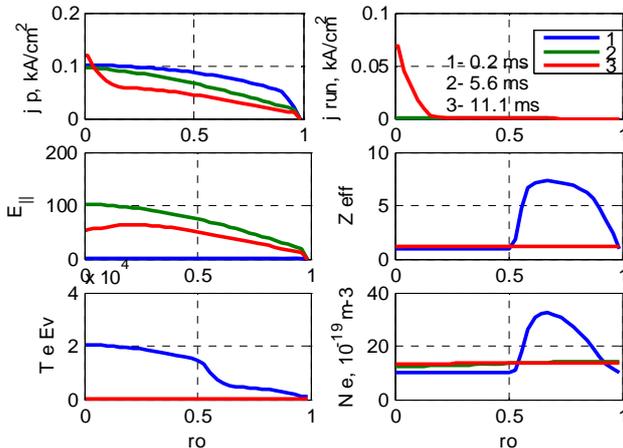


Fig. 3 Time evolution of profiles of plasma and runaway currents,  $Z_{eff}$ ,  $E_{||}$ ,  $T_e$  and  $N_e$  in the case of Ar pellet with  $r=0.6$  cm

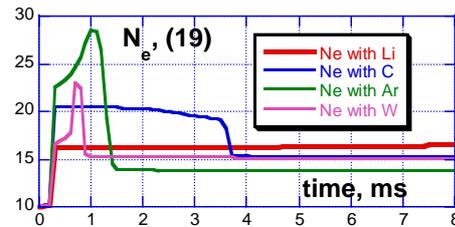


Fig. 4a Electron density waveforms as a result of KPI with different Z and  $r=0.6$  cm

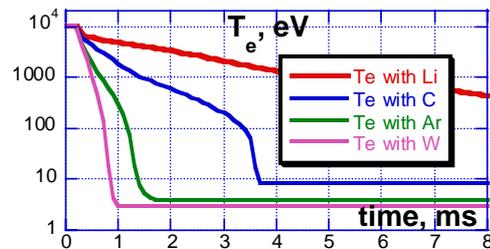


Fig. 4b Electron temperature waveforms as a result of KPI with different Z and  $r=0.6$  cm

cm as is shown in Fig.5. One can see that increasing the size of injected Argon pellet provides increasing of the plasma electron density after thermal quench (see Fig. 6a), which suppresses the runaway generation. In the cases of high Z (e.g. Tungsten), almost with all sizes of pellet the runaways are appear, except of the case of crossing by pellet of the plasma axis. Similar dependence of runaway current generation on Z of killer pellet has been studied in DIII-D experiments [10], and it was shown that Argon pellet produces runaways.

**Conclusions.** Numerical analysis of different Z (Li, C, Ar, W) high speed killer pellets injection (KPI) in ITER like plasmas has been carried out. As a result of simulations it was

shown that the increasing of  $Z$  of impurity pellets leads to generation of runaway currents.

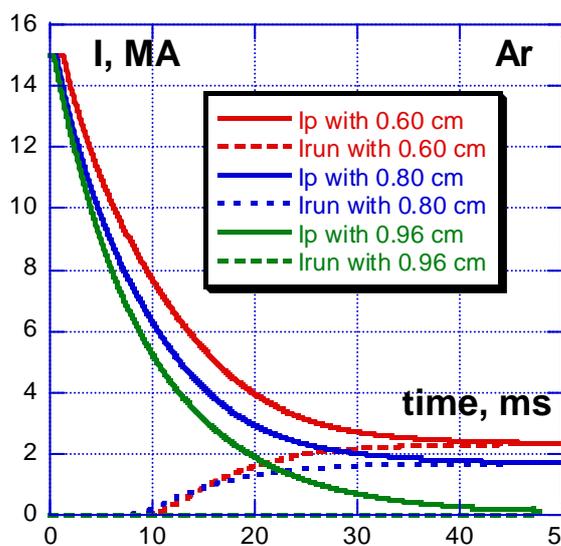


Fig. 5 Plasma and runaway currents behaviors after different size Ar pellet injection

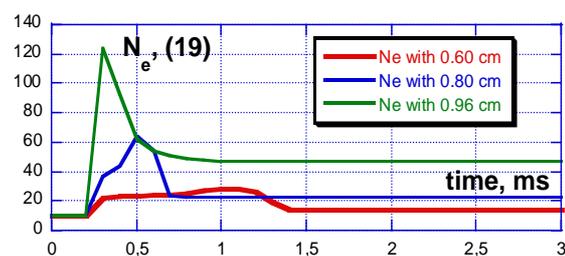


Fig. 6a Electron density waveforms as a result of different size Ar pellet injection

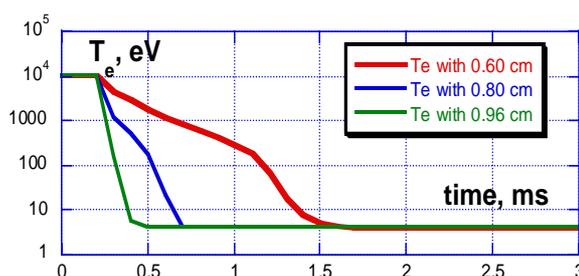


Fig. 6b Electron temperature waveforms as a result of different size Ar pellet injection

Explanation of this phenomena is that the higher  $Z$ , the higher radiation losses from plasma. Besides, the low temperature and the high  $E_{\parallel}$  increase the value of runaway current. Injection of only D pellet does not let to decrease the plasma temperature because of the low losses due to only Bremsstrahlung in comparison with the line radiation of impurity pellet.

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