Study of power re-radiation and runaway electrons generation during impurity injection for disruption mitigation in ITER.

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Massive impurity gas or pellet injection is considered as a viable candidate for disruption mitigation technique for ITER. Impurity injected pre-emptively shall be used for reduction of local energy fluxes to the divertor plates and plasma facing components in ITER by re-radiation of plasma thermal energy during thermal quench (TQ) stage of plasma disruptions. The other task for Disruption Mitigation System (DMS) is suppression of runaway electron (RE) generation in the cold resistive plasma during the next current quench (CQ) stage of disruption. Possibility of considerable power re-radiation in impurity mantle has been demonstrated in experiments on DIII-D, Tore Supra, C-Mod and AUG. The goal of the present paper is to optimize impurity species (concentrations and possible radiative mantle width) for these two tasks of DMS for ITER.

The paper presents results of the modeling of plasma response to the disruption and to the impurity injection for the reference ITER 15 MA scenario. Simulations have been carried out with the transport code ASTRA [1], integrated with the code ZIMPUR [2] calculating the dynamics of impurity ion charge states and impurity radiation. Generation of RE and the total RE current were evaluated according to the model suggested in [3]. It has been assumed that the main runaway generation mechanisms are avalanche multiplication and Driecier acceleration. Runaway electron losses were considered in tau approximation (τ_{loss} [s] ~ $1/n_e[10^{19}m^{-3}]$).

$$\frac{\partial n_{RE}}{\partial t} = \left(\frac{\partial n_{RE}}{\partial t}\right)^{Dreicier} + \left(\frac{\partial n_{RE}}{\partial t}\right)^{avalanche} - \frac{n_{RE}}{\tau_{loss}}$$

It has been also assumed that there is a seed RE current of the order of 10 kA at the beginning of CQ stage.

Dependences of radiated power fraction on the amount of injected impurities and on the width of radiated mantle have been studied. The principal goal was to determine the total number of impurity particles sufficient for re-radiation of ≥ 90% of plasma thermal energy during the short TQ stage of disruption. Heavy (Ar, Ne, C) and light (Be, Li) impurities have been chosen as the candidates for mitigation of thermal loads. Simulations usually started at the flat top stage of the ITER reference scenario with I = 15 MA. The TQ phase of disruption has been simulated by instant rise of the strong anomalous transport $\chi_e = \chi_i = D_e = D_Z = 210$ m^2/s (about 10^3 times exceeding unperturbed transport) provided the loss of the total plasma thermal energy, $W_{tot} \sim 300$ MJ, approximately in 3ms. Fig.1 demonstrates time dynamics of the discharge parameters during a disruption without impurity injection.

Fig.2 demonstrates time dynamics of discharge characteristics during TQ stage with the injection of the Ne particles ($N_{Ne\ tot} \sim 1.7 \cdot 10^{22}$) into layer with the width ~ 20cm. Width

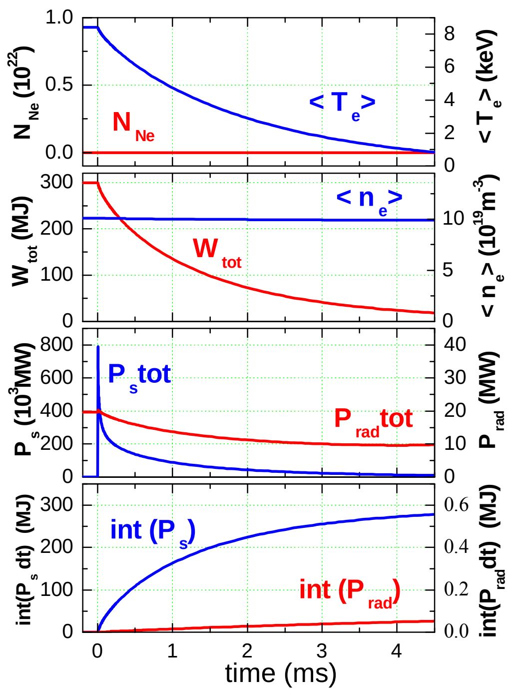

Fig.1 *Results of the modeling of TQ stage for ITER without impurity injection*

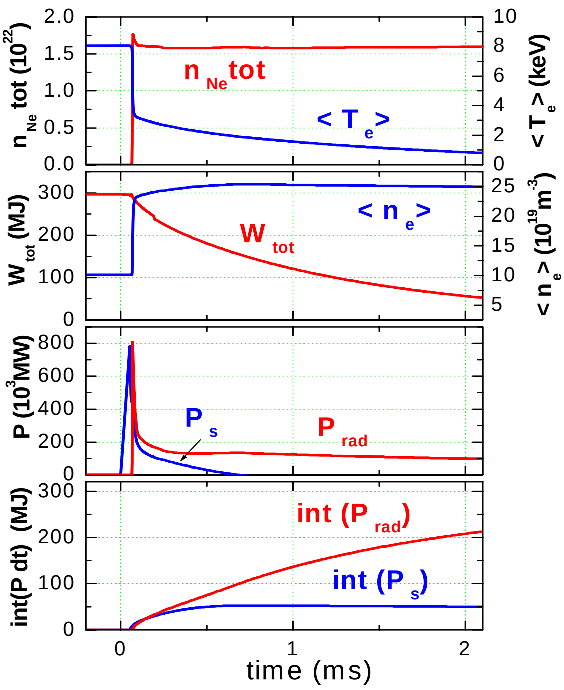

Fig.2 *Power re-radiation during TQ stage with Ne injection ($n_{Ne\ tot} \sim 1.7*10^{22}$)*

of impurity mantle at the plasma edge has been used as a parameter. After reaching necessary impurity content impurity flux to the plasma boundary was stabilized to compensate flux leaving the plasma. Flux of DT atoms was selected to keep the total number of the bulk DT particles. One can see that injection of this quantity of Ne impurity significantly (3 times) increases the average plasma density resulting in the initial drop of the plasma temperature $\langle T_e \rangle$. Later $\langle T_e \rangle$ decreases slowly. After the increase of radiation in the impurity mantle power flux through the separatrix by other channels, P_s, decreases. Time integral of powers leaving plasma with radiation int(P_{rad} dt) increases and integral of powers leaving plasma through the separatrix with transport int(P_s dt) saturates.

Dependence of the radiated power fraction versus the total number of injected Ne particles at different width of radiating mantle is presented in fig.3. Simulations show that at the radiating mantle width more than 20 cm re-radiated power fraction can exceed 90% and the total necessary number of particles increases with the radiating mantle width.

Fig.4 demonstrates the dependence of radiated power fraction on impurity species at

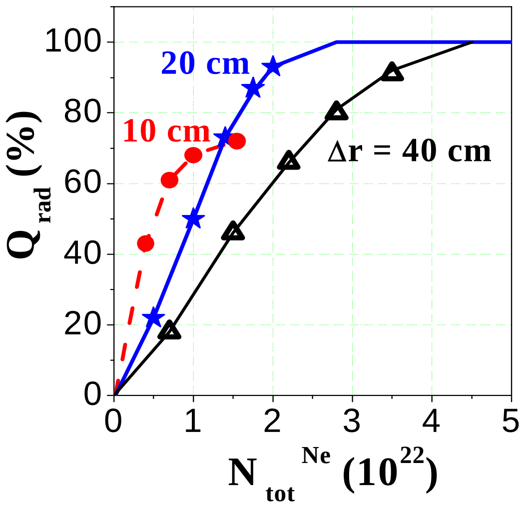

Fig. 3 *Dependence of radiated power fraction versus number of Ne particles with different width of radiating layer*

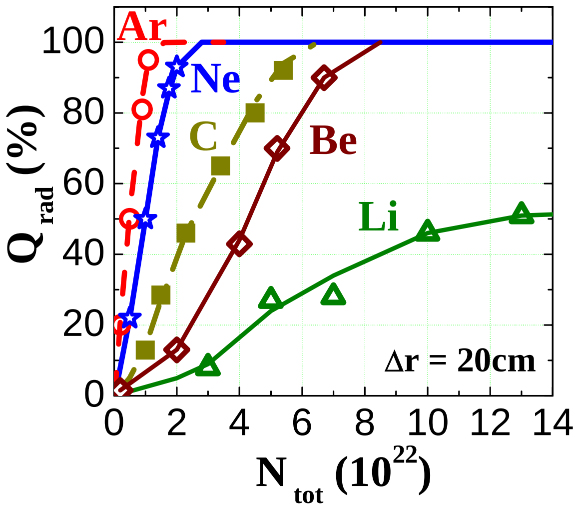

Fig. 4 *Dependence of radiated power fraction versus number of different impurities at radiating layer width 20 cm*

radiating layer width of 20cm. Impurity radiation increases and necessary number of impurity atoms drops with the rise of impurity mass. In the case of Li saturation of radiated power was found at the level of 60%. Increase of the radiated layer width did not improve the situation for Li. The possibility of using the Li for power re-radiation requires further study with analysis of concrete schemes of Li injection, proper simulation for plasma mixing and consideration of combined schemes of lithium - deuterium injection.

The following CQ stage of plasma disruption has been studied under the assumption that injected impurity is uniformly redistributed before this stage. The total amount of impurities which were able to re-radiate more than 90% of the thermal plasma energy during the preceding TQ stage was selected for simulations. The goal of the modeling of this phase was evaluation of efficiency of RE generation suppression by different impurities. Fig.5 demonstrates time dynamics of discharge characteristics for the case of Ne injection. Plasma radiation results in fast reduction of plasma temperature and, therefore, conductivity leading to the rise of longitudinal electric field and initiation of the RE generation. In considered case RE current riches ~ 6.8 MA. Necessary quantity of impurities (90% power re-radiation), values of electron temperature in the plasma core at the start of CQ, maximum RE current and time duration of this stage (80% - 20% drop of Ohmic current) are summarized in the table below.

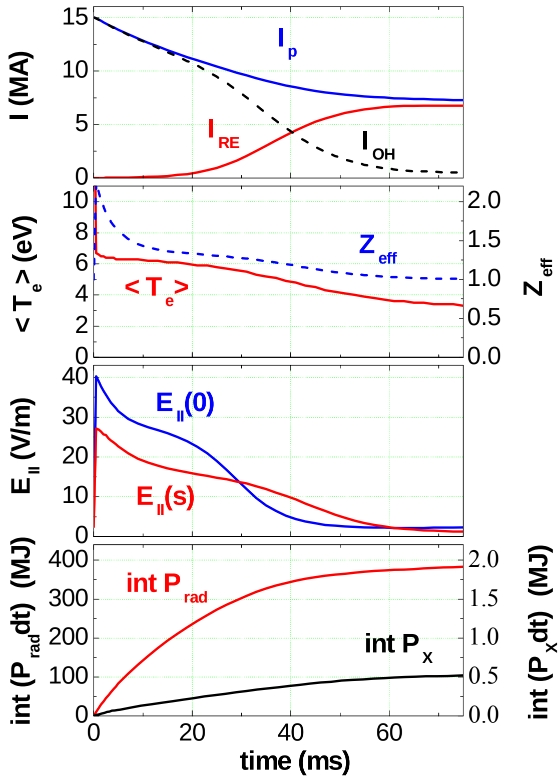

Fig.5 *CQ stage of disruption;* $n_{Ne\ tot} \sim 2*10^{22}$

	$N_{tot}, 10^{22}$	T_e, eV	I_{RE}, MA	τ_{CQ},ms
Ar	1	4.9	7.0	16
Ne	2	6.6	6.8	33
C	5.4	3	6.6	12
Be	6.6	20	0.08	320
Li	14 (60% rad)	13	1.4	145

In the case of high and middle Z impurities Te decreases to 3-7 eV resulting in high RE current ~ 6-7 MA. For the light impurities (Be, Li) the temperature has been found to be higher (till ~ 13-20 eV) and we did not see a significant RE current. For the case of Be our results are in agreement with experimental findings of JET [4] where in the case of pure Be wall no REs were observed during plasma disruptions.

Our simulations confirm that heavy impurity injection is very effective for re-radiation of plasma thermal energy but at the same time makes plasma susceptible for RE generation. This requires additional means for suppression of RE generation such as [5] or others. The most promising DMS scheme (good radiation and suppressed RE generation) seems to be the light impurity (Be, Li) injection, for example Be injection of total amount exceeding $7 \cdot 10^{22}$ particles absorbed in the plasma column. However, long time scale of CQ stage in this case required more detail estimation of forces on the Vacuum Vessel from halo and eddy currents during CQ stage. Further optimization of the impurity mix and development of the scheme for RE suppression are needed.

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