Modeling of pre-Thermal Quench stage of disruption in ITER triggered by Massive Gas Injection

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Massive Gas Injection (MGI) is considered now as one of the promising methods of Disruption Mitigation (DM). For ITER it is necessary to re-radiate more than 90% of thermal energy to reduce loads on divertor targets. Radiating impurity neutral dynamics was shown [1] to play the dominant role in the pre-TQ stage in MGI mitigated disruption scenarios. In particular, losses of relatively fast secondary CX and recombination neutrals were found to be responsible for low impurity assimilation under MGI. Validation of the simulation model against JET data [1] demonstrated reasonably good agreement between simulation results and experimental data. Application of the model to ITER gave favorable predictions on the capabilities of ITER TM DMS. In-port positioning of the MGI valves (delivery tube length ~1m) was shown to be preferable providing very short, of few ms, response time and effective delivery of the radiating impurity into the plasma. Here we extend analysis of [1] for steady state ITER scenario, examine potential advantages of gas mix (noble gas + deuterium) injection and explore the possibility to use remote gas valve positioning for ITER DMS.

In this work the ASTRA transport code [2] is used for the modeling of the behavior of the bulk plasma parameters and the ZIMPUR code [3] for the simulations of impurity dynamics and radiation. For the description of MGI, model [4] was employed. In the self-consistent simulations standard set of transport equations for T_i, T_e, n_d was solved with use of the Scaling Based transport Model (SBM): $\chi_e = D_d = D_z = D_0 \cdot F(\rho) \cdot F_{H\text{-}mode} \cdot F_{RS}$, $\chi_i = 2\chi_e$, where radial profile of transport coefficients was taken in the form: $F(\rho) = 1 + 3\rho_N^2$, $\rho_N = \rho / \rho_{max}$. For the radial anomalous pinch velocity we assumed $V_p = 0.5 \cdot D \cdot (\rho_N / a^2)$. Normalization coefficient D_0 was adjusted to provide coincidence of energy confinement time with ITER(98y2) scaling [5] with specified H-factor just before the beginning of pre-thermal quench phase and then fixed. In the external transport barrier region ($\rho_N > 0.93$), and in the RS region coefficients $F_{H\text{-mode}}$ and F_{RS} were used to reduce the conductivity χ_e to the level of the neoclassical ion heat conductivity, and reproduce pedestals and Internal Thermal Barrier on profiles of plasma parameters.

For impurities we consider two groups of neutrals. The primary cold neutrals coming into plasma from the wall and from the MGI system and secondary "warm" neutrals

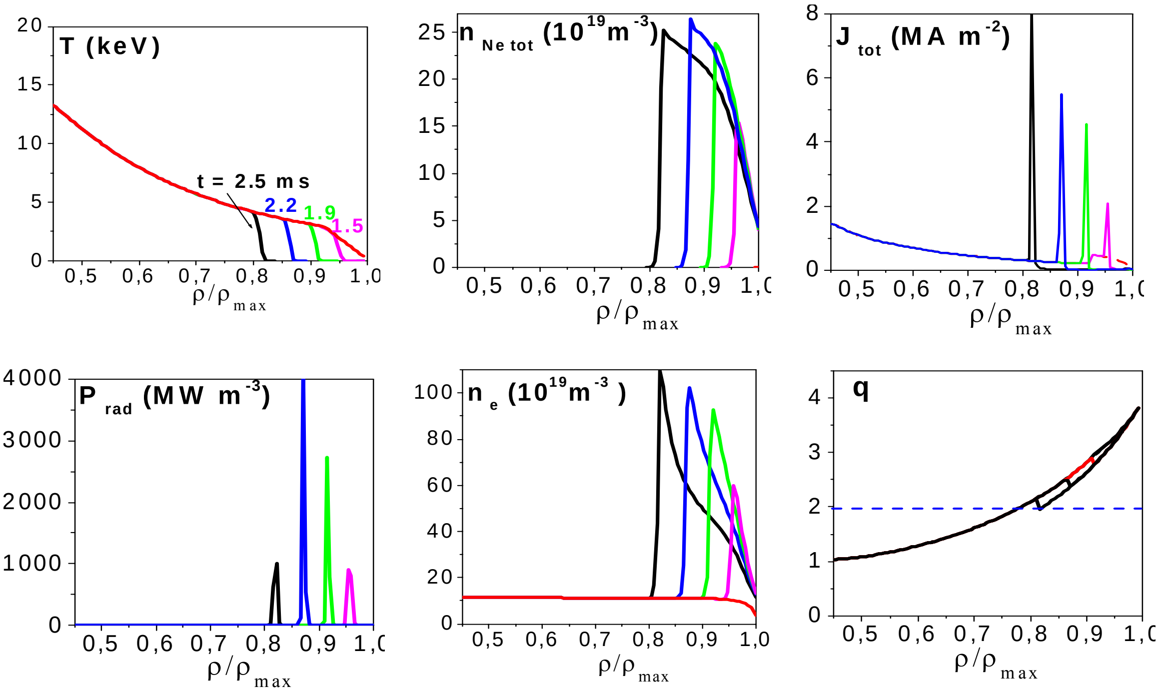

Fig.1 Typical cooling front propagation in Ne MGI forced Pre-TQ for basic inductive 15MA ITER scenario

originated due to the recombination and charge exchange of impurity ions in the plasma. These secondary neutrals can easily escape plasma through the cold periphery and provide appreciable losses of impurities during MGI.

During pre-TQ stage, cooling of the plasma periphery by MGI results in contraction of hot plasma region and current channel. Typical dynamics of radial profiles during Ne MGI for the reference inductive 15 MA ITER scenario is shown in Fig.1. When boundary of current channel approaches q =2 magnetic surface (see t=2.5ms) rise of MHD activity can provoke TQ and plasma mixing. Simulated time dynamics of plasma parameters after Ne and Ar MGI for the basic inductive ITER scenario is shown in Fig.2. In the Ne injection case impurity assimilation coefficient is f_z ~ $7.2*10^{22}/\ 7.4*10^{23}$ ~10% and $\tau_{pre\text{-}TQ}$ ~2.5 ms. In the Ar injection case f_z ~ $5.5*10^{22}/3.4*10^{23}$ ~16 % and $\tau_{pre\text{-}TQ}$ ~2.7ms but Ar gives

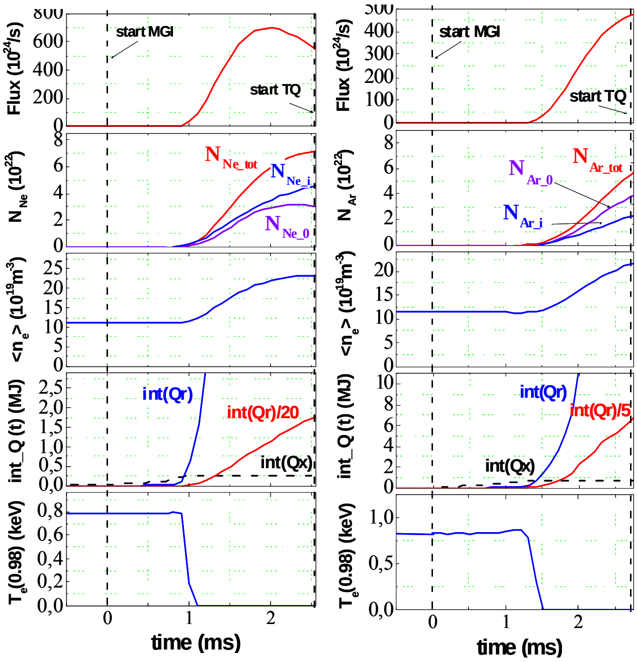

Fig.2 Time traces of various simulated parameters after Ne (left) and Ar (right) MGI for the basic inductive ITER scenario (In-port positioning of TM MGI valves).

smaller T_e in the CQ stage resulting in shortening the CQ duration and, thus, increasing the mechanical loads on conductung structures and danger of RE generation.

Using the mix of a noble gas with deuterium should rise the MGI gas flow velocity. For the first look it can help in achievement of sufficiently short plasma response time with more distant location of the MGI valves. In addition there are experimental evidences that addition of D_2 in MGI gas prevents generation of runaway electrons. Fig. 3 presents simulation results for various mixtures of Ne+D_2 injection in ITER reference inductive scenario. Fraction of Ne is shown near the curves. Some characteristic values for these cases are given in Table 1. One can see that duration of pre-TQ stage remains sufficiently short and approximately the same in all cases, and cannot serve for selection. Thus, despite the reduction in flow velocity the number of Ne particles in plasma as well as the total number of electrons are higher in the case of pure Ne.

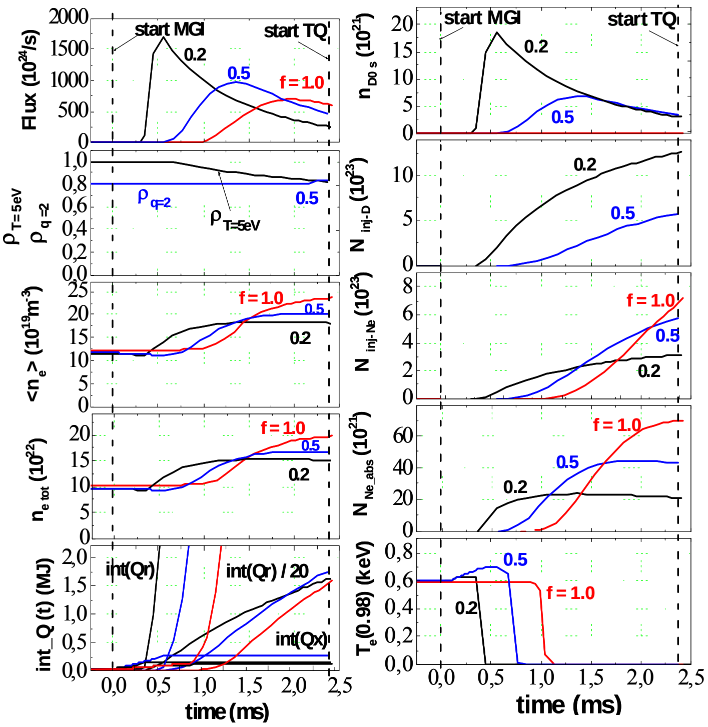

Fig.3 Time dynamics of plasma parameters during Ne+D2 MGI in ITER with different Ne fraction in the injected gas (Scen. #2)

Table 1

(L_{tube} = 1m)

Ne fraction	N_{Ne} in pl. (10^{21})	$\tau_{pre\text{-}TQ}$ (ms)	TOF (ms)	$\tau_{pre\text{-}TQ}$ – TOF (ms)	$N_{e\ tot}$ (10^{22})	$F_{asimilat}$ (%)
0.2	20.9	2.35	0.3	2.06	15.0	6.5
0.5	43.5	2.3	0.46	1.84	16.7	7.5
1.0	69.7	2.5	0.75	1.73	19.7	9.8

Simulations show that the proposed system [in-port positioning of the TM valves] is suitable also for Steady-State 9MA scenario. As it is shown in Fig. 4, calculated Pre-TQ duration time in ITER is more affected by the MGI system parameters than a discharge scenario before disruption.

Simulations of the MGI with second possible length of gas delivery tube of ~8m (Table 2) did not manifested any advantages for the gas mix injection compared to the pure Ne/Ar injection examined in [1].

Table 2
(L_{tube} = 8m)

Ne fraction	N_{Ne} in pl. (10^{21})	τ_{pre-TQ} (ms)	TOF (ms)	τ_{pre-TQ} – TOF (ms)	$N_{e\ tot}$ (10^{22})	$F_{asimilat}$ (%)
0.2	19	7.1	2.49	4.6	14	11.9
0.5	25.5	8.3	3.61	4.7	14	13.1
1.0	28	10.6	5.8	4.8	15	14

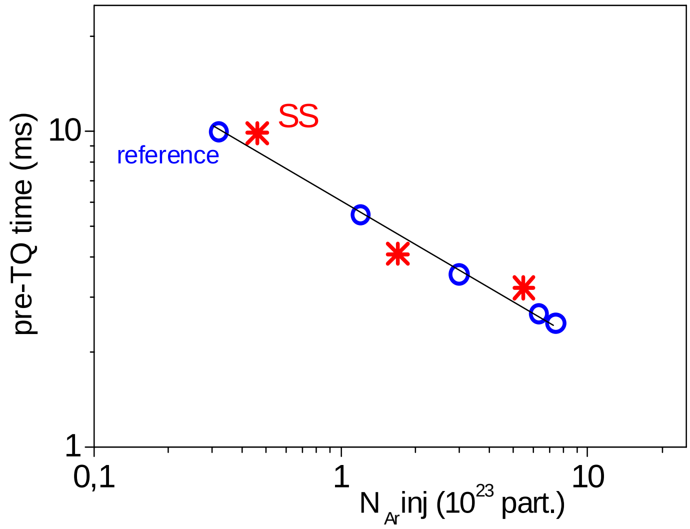

Fig.4 Dependence of pre-TQ time vs total number of assimilated Ne particles for ITER scenarios: blue circles – reference inductive 15 MA scenario, red stars – Steady-State 9 MA scenario.

Summary :

- Simulations show that in all considered cases impurity neutral dynamics plays important role in the pre-TQ stage in MGI mitigated disruption scenarios providing large impurity losses and, therefore, low impurity assimilation in plasma.
- Simulations show that pure Ne/Ar injection results in higher accumulation of radiating impurity in the plasma as well as in general rise of electron density which determine the collisional drag for REs.
- Ar MGI could result in too strong reduction of the plasma temperature and, thus, in shortening the CQ time below the tolerable (with respect to EM loads) limit and facilitating the RE generation. Thus Ne injection for TM is preferable.
- In-port positioning of the MGI valves (1m distance from the plasma) is shown to be preferable providing very short, of few ms response time and sufficient (according to estimations of [6]) impurity accumulation for TM for both inductive and steady-state ITER reference scenarios. Increase of delivering tube length to 8m results in 4 times longer pre-TQ time (~10.6 ms) and factor of 2 smaller accumulation of Ne particles in the plasma (~ 3 10^{22}). However, even with these reduced characteristics of the MGI system ITER DMS seems to be capable to provide thermal load mitigation.

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