Integrated Modelling of ITER Disruption Mitigation

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Abstract. Complex variety of physical phenomena comprising disruption of a tokamak discharge requires integrated modeling approach. Recent efforts were addressed to study feasibility of the ITER disruption mitigation system (DMS) to a) mitigate heat loads on the divertor target plates and plasma facing components during the thermal quench (TQ) phase of the disruption; b) reduce electromagnetic forces on the vacuum vessel during current quench; c) avoid or control the runaway electron (RE) generation. Full disruption scenarios from “prediction” of expected disruption, till complete termination of the plasma current were simulated to determine operation domain for the ITER DMS based on massive gas injection (MGI). Consistent scenarios of mitigated disruptions are shown to be feasible with MGI parameters proposed in the ITER DMS conceptual design.

1. Introduction

The principal goal of the ITER disruption mitigation system (DMS) is to keep the heat and electro-mechanical loads on tokamak components within tolerable limits during disruption. It includes control of the thermal heat fluxes on the divertor target plates and plasma facing components during the thermal quench (TQ) phase of the disruption; limitation of the current quench (CQ) duration to reduce the electromagnetic forces on the vacuum vessel; avoidance or control of the runaway electron (RE) generation and protection of the first wall against heat loads associated with the RE losses. Massive impurity gas or pellet injection is considered as a viable candidate for disruption mitigation in ITER. Injection of noble gases such as Ne or Ar is effective for re-radiation of otherwise highly peaked TQ energy loads over the large first wall (FW) surface [1]. However, at the subsequent CQ phase of the disruption, large quantity of accumulated highly radiating impurities can reduce the CQ duration below permissible level or stimulate the development of the RE beam. As it was shown in recent DIII-D experiments [2] MGI can effectively suppress REs. The mechanism of effective dissipation of both RE current and kinetic energy due to combined effects of enhanced RE scattering on high-Z impurity nuclei and synchrotron radiation was suggested in [3].

Complex variety of physical phenomena comprising disruption of a tokamak discharge requires integrated modeling approach. The well-validated DINA code [4] is used as an integrating core module for disruption simulator development. Whenever possible the DINA results are verified by ASTRA code [5] simulations. Impurity charge state dynamics, radiation and transport are calculated by the ZIMPUR code [6]. RE kinetics is simulated with use of the improved model accounting for the high-Z impurity effects [7]. Newly developed gas flow model allows accurate accounting for the technical specifications of MGI system foreseen for ITER DMS.
Progress reached in the code development for integrated disruption simulation and first results of studying the feasibility of the ITER DMS to reach consistently its principal goals are presented in this report.

In simulations MGI gas mix (Ar or Ne plus D₂) proportion and quantity is optimized as to provide accumulation of impurity amount capable to re-radiate most of the plasma thermal energy till the end of TQ stage of disruption. The minimal quantities of impurity particles of N_Ar~1*10^{22} or N_Ne~2*10^{22} for reference inductive (15MA) scenario was predicted to be a target values to reradiate more than 90% of the plasma thermal energy [1]. Present analysis shows that MGI system of 4 gas injectors with 8kPa*m³ of total gas amount should provide effective thermal load mitigation (TM) in ITER. For timely response on disruption prediction the valves should be placed as close as possible to the plasma (in port plugs). Dominating of deuterium in the gas mix helps in acceleration of gas delivery as well as in widening the operation domain in DMS scenarios for successive mitigations of CQ.

Simple 0D analysis of [9] predicted a wide range 0.3 -10 kPa*m³ of Ne injection to mitigate thermal loads without excessive forces on the in-vessel components. However presented results of free boundary equilibrium calculations accounting for the development of VDE demonstrated significant reduction of operation domain in the case of pure noble gas injection. Then CQ duration, τ_CQ, for the assimilated Ar quantity of N_Ar=1*10^{22} particles is already close to the absolute permissible minimum value of 36ms, while the target DMS value is τ_CQ≥50ms. For Ne injection compatibility of TLM with sufficiently long τ_CQ seems to be more promising.

Simulations of CQ stage is focused in determination of MGI parameters providing safe plasma termination for both RE and no RE CQ scenarios. RE current decay time due to collisional loss of RE energy only was found to be too long for the Ne concentration range estimated as sufficient for TM. Results of RE kinetic modeling [7] were used in DINA code for the present simulations of CQ in the presence of REs. Necessary impurity quantities for safe termination of REs were estimated and shown to be feasible for ITER MGI system [10].

The causes and dynamical processes of runaway loss are not fully understood yet. RE loss can occur with significant separation in time during RE current plateau. MHD stability of the post TQ plasma with RE current is also discussed.

Three candidate systems are currently under consideration for the ITER DMS: massive gas injection (MGI), shattered pellet injection (SPI) and Be pellet injection. Present report addresses analysis of ITER MGI, which includes two subsystems for TM and RE suppression, respectively [10].

2. Thermal Loads Mitigation

ITER MGI TM subsystem consists of 4 valves up to 8kPa*m³ of total gas inventory. For the gas species Ne and Ar are considered. TM system should be triggered at disruption alarm signal. Uncertainties in disruption prediction put forward the requirement to make TM system response time as short as possible. Analysis presented in [11] shows that in-port positioning of the gas valves provides rather short reaction time from launching TM system till TQ onset which is ranged from 2.5ms to 4ms depending on gas specie and number of valves simultaneously opened. For remote location of the TM MGI valves pre-TQ time is longer 10.5 (Ne) ÷ 14.5 (Ar) ms.

Calculations were performed with use of integrated ASTRA and ZIMPUR codes updated by improved model for impurity neutral transport. Gas flow dynamics at the exit of MGI delivery
tube (entrance of the vacuum vessel) was simulated with newly developed semi-analytical model [8]. Typical evolutions of gas flow at the exit of delivery tube calculated according to model of [8] are shown in Fig.1.

Simulations of impurity assimilation and triggering the thermal quench were validated against JET experimental data. Results of [11] demonstrated dominating role of the impurity neutral dynamics in accumulation of injected noble gases in the plasma before TQ onset. Application of the model to the ITER case give quite favorable predictions on effectiveness of the ITER TM subsystem. Either Ar or Ne MGI can be used for successful TM. Even opening the single valve with 2kPa*m$^3$ of Ne provides accumulation of $3.25\times10^{22}$ Ne particles in the plasma, the quantity about 50% exceeding the limit [1] necessary for re-radiation of more than 90% of plasma thermal energy during TQ stage of disruption in inductive reference scenario. On the other hand the estimation of necessary for TM amount of radiating impurity [1] until now has no experimental confirmation. Thus ability of TM MGI subsystem to deliver maximum amount of impurity to the plasma before TQ onset is of principal importance. Then in-port location of the TM MGI valves (upper graphs in Fig.1) is preferable providing [11] 2.5÷3.2 times higher accumulation of the noble gas quantity in plasma.

3. Current Quench without Runaway Electrons

The CQ scenarios were simulated with use of the DINA code. Free boundary equilibrium calculations accounting for the realistic ITER passive and active conducting structures give accurate predictions of the plasma current decay rate altogether with evolution of VDEs. The model of major disruption (MD) implemented in the DINA code includes a sequence of definite events (Fig.2). The first one is the TQ resulting in the loss of plasma thermal energy, which makes the value of $\beta$ to be close to zero. The time duration of the TQ ($t_{mix}$-$t_0$; $t_0$ is the pre-disruption time moment, $t_{mix}$ is the time moment of plasma current profile mixing) is
assumed to be 1 ms. The next stage of the MD is the formation of plasma current bump after mixing of the plasma current profile. For the mixing model in the DINA code, an instantaneous relaxation of plasma current profile is assumed, which corresponds to the flattening of the \( q \)-profile inside the \( \rho=d_{\text{mix}} \) area (Fig. 3) at the time \( t_{\text{mix}} \). Then during the time period of \( t_{\text{mix}} < 2 \) ms, the plasma current bump appears to restore the magnetic helicity. Accordingly, the gauge-invariant helicity \( H = \int \tilde{A} \cdot \tilde{B} \, dV \) where \( \tilde{A} \) is the vector potential, \( \tilde{B} \) is the magnetic field and the integration is taken over the plasma volume) recovers to its original value before the beginning of the TQ. The value of \( d_{\text{mix}} \) is directly related to the change of the plasma internal inductance, \( \Delta l \). After the current bump, the plasma current starts to quench.

The rate of plasma current quench depends on the values of \( T_e \) and \( Z_{\text{eff}} \), i.e. is determined by radiating impurity contamination. Requirements for mitigation of electro-mechanical loads by ITER DMS are usually formulated in terms of time duration of CQ phase, \( \tau_{\text{CQ}} \). Then the safe operation domain is expected [9] to be of \( 50 \text{ms} < \tau_{\text{CQ}} < 150 \text{ms} \), where lower limit is determined by generation of excessive eddy currents in conducting structures, while higher limit is associated with potentially dangerous amplitudes of halo currents in the end of VDE.

DINA CQ simulations were done for the ITER reference inductive scenario with plasma current of 15MA. It was assumed that initially (right after TQ) the plasma temperature, density and radiating impurity were uniformly distributed. Then, temperature profile changed almost instantly according to the power balance between Joule heating and radiation of impurity. Results of the no-REs CQ simulations with different concentrations of Ne and Ar are shown in Fig.4. Fig.4 (left) shows that injection of \( \sim 2.0 \times 10^{22} \) Ne particles (the amount, estimated in [1] as sufficient for TM) results in \( \tau_{\text{CQ}} \) to be close to or a little bit higher than the lower limit of 50ms. Then injection (assimilation before start of CQ stage) of larger Ne impurity amount would be favorable for more robust mitigation of thermal loads but on the other hand, may shorten CQ time below safe operation domain. From Fig.4 (right) follows that using Ar for TM in the reference inductive scenario with \( I_p=15 \text{MA} \) leads to faster current decay. Accumulation in the plasma of the TM “target” value of \( 1 \times 10^{22} \) Ar particles [1] during pre-TQ stage results in too short CQ, \( \tau_{\text{CQ}} \sim 40 \text{ms} \).
4. Mitigation of Runaway Electrons

According to [10], maximum amount of impurities for RE mitigation/suppression (RES) in ITER will be limited to 100 kPa*m$^3$ for neon and argon ($\sim$2.25*10$^{25}$ injected particles), 50 kPa*m$^3$ for deuterium and 40 kPa*m$^3$ for helium. Technically, RES MGI subsystem consists of array of 2×12 valves similar to those for TM MGI. The valves can be launched simultaneously or according to prescribed timing. Gas from all RES MGI valves enters the VV through a single delivery tube of ~1m length. Technical solution for RES injector suggested in [10] does not allow direct application of the gas flow model of [8]. Then in our present analysis we assume that delivery time is much shorter than characteristic time scales of physical processes during CQ. In DINA simulations we model RES MGI as an instant increase of radiating impurity density in the plasma. Cold post TQ plasma allows high assimilation of the injected impurity [12]. Then assuming uniform distribution of injected noble gas particles in ITER VV we get an estimate for a maximum allowable impurity concentration of about 2*10$^{22}$ m$^{-3}$.

In simulation of RE dynamics we rely on the recent results of RE kinetic modeling [7]. This modeling comprises essential improvements of original simple model of [3]. Extension of the RE energy range down to ~1keV, principal improvement of the knock-on collision source term, corrections of collisional scattering and drag, verified model of radiative energy loss along with improvements of numerical algorithm resulted in significant decrease of calculated RE current decay rates compared to estimations of [3]. Results of RE kinetic simulations [7] employed in the present DINA CQ modeling are shown in Fig.5. One can see that RE current decay rate scales almost linearly with Ar density, $\frac{dI_{\text{re}}}{dt} \approx 8*n_{\text{Ar}}^{20}$ MA/s.

Recent DINA simulations of CQ with RE beams demonstrated very limited domain of magnetic controllability of such plasmas [13]. Then in the present analysis of VDEs with REs...
magnetic control was switched off. In this case fast upward VDE, after plasma touching the wall, is accompanied by gradual cutting of RE current carrying plasma periphery. In our simulation we assumed that electrical field appeared due to such cutting did not change much RE current in the inner plasma region but mostly led to generation of the halo and VV currents.

Typical example of DINA CQ simulations with generation of RE is shown in Figs. 6-9. RES MGI in this and the following figures was switched on at \( t = 110 \text{ms} \).

**FIG.6** Evolutions of the total plasma and RE currents (left) and currents in VV and Halo at Ar density after RES MGI of \( 10^{21} \text{ m}^{-3} \).

**FIG.7** Evolution of plasma equilibrium configuration during VDE

**FIG.8** Shrinking of the plasma surface during VDE

**FIG.9** RE current profiles at characteristic time slices of VDE development.
In this case the loss of RE current was dominated by cutting out the periphery region due to the vertical plasma motion after touching the wall. Then evolution of the RE current (Fig.6), mostly coincide with shrinking of the plasma column during VDE (Fig.8). Therefore, this is an example of unmitigated REs.

Further increase of Ar density helps to mitigate REs prior their loss to the wall. Some representative results of DINA simulations with higher Ar densities (RE current decay rates) are shown in Fig.10. Rising Ar density to ~4*10^{21}m^{-3} leads to effective suppression of REs without excessive loss to the wall (top-right figure).

Bottom picture in Fig.10 shows an example of CQ scenario with low amplitude (1kA) of the “seed current” for RE avalanche. Quantitative prediction of the seed current amplitude depends crucially on understanding the TQ physics which is now incomplete. In all other cases presented in this report seed current was chosen of 100kA. For the low amplitude of seed current RES MGI at t=110ms prevented complete substitution of ohmic current by RE one.

Additional losses of RE can appear due to development of MHD instabilities during the CQ. MHD stability of the plasma with RE beam was studied with use of the codes MISHKA [14], CASTOR [15] and KINX [16]. Preliminary analysis has shown that internal kink and tearing modes can become unstable during evolution of the RE current profile. Internal kink development associated with appearance of the sharp peak in the current density near the magnetic axis. However, this mode hardly leads to the RE loss to the wall. Resistive modes become unstable at the later phase of the RE current evolution, i.e. can play the role in the long lasted RE plateau scenarios. For the mitigated scenarios considered here fast VDE accompanied by direct loss of REs seems to be the dominant loss mechanism.
5. Summary

Simulations of mitigated disruptions scenarios in ITER demonstrated that the ITER DMS based on MGI is in principle able to reach its goals.

In-port location of TM MGI valves has significant advantages over remote one provided short (of few ms) response time in initiating TQ and 2.5÷3.2 times higher accumulation of the noble gas in plasma.

TM MGI was shown to be capable to deliver several times larger amount of impurity into plasma than previously estimated [1] as sufficient for a successful TM.

The use of neon as TM MGI gas is preferable compared to argon providing longer CQ time and, therefore, smaller electromechanical loads in the no-RE CQ scenarios.

Mitigation of REs requires injection of a large amount of impurity. The most severe demands are due to the fast VDE accompanied by the RE loss to the FW. Estimated concentration of argon for RE mitigation is of ~ 4*10^{21} m^{-3} and is feasible for RES DMS envisaged in ITER.

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References