Numerical simulation of thermal quench triggered by density source in HL-2A

S. L. Hu[1], D. Hu[2], J. Q. Li[1], G. Z. Hao[1] & JOREK Team[ǂ]

[1] *Southwestern Institute of Physics, PO Box 432, Chengdu 610041, China*

[2]*School of Physics, Beihang University No. 37 Xueyuan Road, Haidian District, Beijing 100083, China*

[ǂ]*See the author list of Ref [5] for a list of current team members*

Introduction

The mainstream methods of disruption mitigation system (DMS) include Shattered Pellet Injection (SPI) [1] or Massive Gas Injection (MGI) [2]. The injection penetration and density mixing are important considerations in achieving high mitigation efficiency, and they are strongly affected by MHD activities during injection. To clarify the effect of MHD-modes-induced-transport on the injection penetration, we simulate the thermal quench (TQ) during the pre-disruption phase triggered by pure deuterium (D_2) injection at different fixed deposition location employing three-dimensional (3D) non-linear reduced MHD code JOREK [5].

Physical model and simulation setting

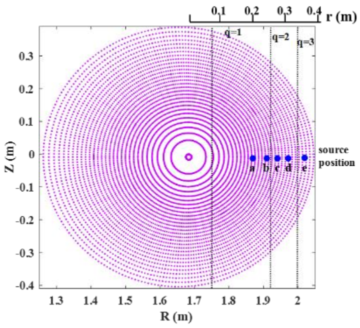

Fig 1. Flux surfaces before injecting deuterium, dotted lines represent rational surface.

Complete physics models implemented and numerical methods applied for solving the model equations in JOREK have been well documented [2-3]. We here only emphasize the essentials parameters relevant to our concerns. We refer to the equilibrium configuration of a typical Ohmic limiter discharge on HL-2A tokamak with B_t = 1.4 T, I_p = 160 KA. Central values approximately are $n_0 = 1.38 \times 10^{19}$ m^{-3}, T_0 = 0.8 kev. The resistivity and parallel thermal conductivity depend on temperature: $\eta = \eta_0 (T_0/T)^{3/2}$ and $\kappa_\parallel = \kappa_{\parallel 0}(T_0/T)^{5/2}$, where $\eta_0 = 5.3 \times 10^{-7} \Omega\mathrm{m}$ is the Spitzer resistivity and $\kappa_{\parallel 0} = 3.4 \times 10^{29}\ \mathrm{m}^{-1}\mathrm{s}^{-1}$ is the Spitzer-Härm value in our simulation, Note that η_0 and $\kappa_{\parallel 0}$ closely approach to the experimentally measured values $\eta_0 = 3.5 \times 10^{-7} \Omega\mathrm{m}$, $\kappa_{\parallel 0} = 2.0 \times 10^{29}\ \mathrm{m}^{-1}\mathrm{s}^{-1}$. Furthermore, we assume that constant 10^{24} D atoms per second are injected.

Our simulations include all toroidal harmonics from n = 0 to n = 5 or n=0 to n=10. To investigate the dependence of disruption mitigation on the location of D molecule disposition (LoD) with $R = R_D$, simulations are carried out with different penetration depth of D density source. Five typical cases are respectively $R_D = R_j$=1.87, 1.91, 1.94, 1.97 and 2.02 (m) at major radial direction, as shown in Fig.1 with j = (a, b, c, d, e) respectively. For initial equilibrium, the major radial position of the q = 1, 2, 3 surfaces are respectively 1.75, 1.92 and 2.0 (m).

Simulations on the TQ processes

After a long time steady state, active MHD fluctuation dominated by n=1 mode grows up after the D density source is imposed in simulations. As the magnetic fluctuation increases, magnetic islands are created and grow. Afterwards, magnetic flux surfaces are destroyed and become stochastic. The core electron temperature rapidly decreases, turning into a TQ phase. The slight plasma current drop and the ensuing current spike is observed as the MHD perturbations develop. These typical processes can be shown in Fig.2, in which the results for the five cases mentioned above are exhibited for comparison. Interestingly, two types of evidently different disruption behaviors are observed, which depend on whether the D density source is deposited outside or inside the q=2 magnetic surface.

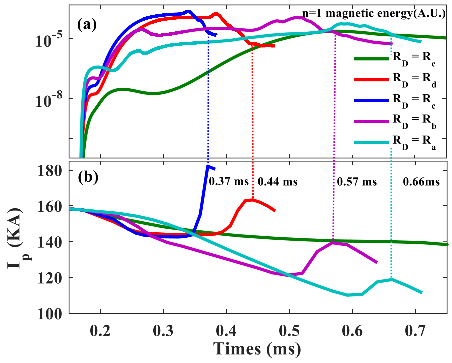

Figure 2. (a) Time evolution of the magnetic energy contained in the n=1 component for five simulations (b) Time evolution of the I_p for the corresponding case. The dotted lines indicate respective the current spike time.

The plasma current I_p and the fluctuating n=1 magnetic energy reveals a remarkable spike in case R_c, which is one of characteristic features of plasma disruptions. However, the spike is much gentle in case R_a. This observation indicates that the q=2 surface may be of crucial importance in triggering a major disruption by externally injected D density source.

We sample simulations with case R_c and case R_a as the targets for comparison and analysis. *The pre-TQ phase:* T_e at magnetic axis keep almost unchanged while the outer region are cooled down rapidly in both simulations. Significant increase of plasma density around the q=2 surface on the LFS is observed in both cases, as R_c and R_a are located just outside and inside of said surface respectively. The island O-point coincides with the D deposition region, which is similar to the observation in [2, 4]. In this phase, it can be seen that the m/n = 2/1 modes are excited around q=2 surface in both simulations, but it is much stronger in case R_c than case R_a. Furthermore, in case R_c, the 3/1 magnetic islands also appear and overlap with the 2/1 magnetic island. However, case R_a displays strong excitation of the 1/1 magnetic island.

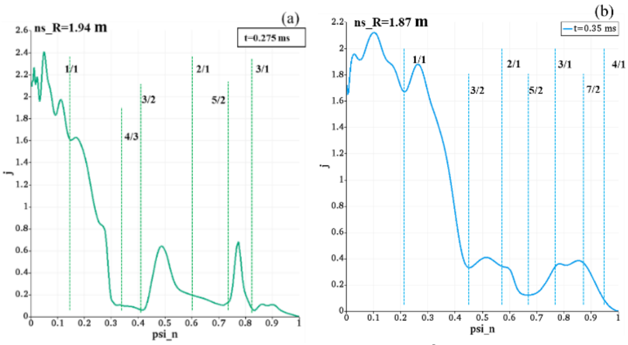

Figure 3. Toroidal current density $j_{\varphi,n=0}$ profiles at the midplane (low field side) . (a) for case R_c, (b) for case R_a.

The TQ phase: The T_e at the magnetic axis dramatically decreases, and plasma density further increases. In this stage, the MHD activity is relatively dominated by the m/n=2/1 component in case R_c while the m/n=1/1 mode dominates in case R_a. The TQ may result from successively nonlinear mode couplings, which are evidenced by local flattening of the toroidal current profile. Here, the local flattening projects the linear and/or nonlinear excitation of resonant mode. The 1/1, 2/1 and 3/1 mode are produced by MHD activity, then 2/1 mode is inward coupled with the 1/1 mode and outward coupled with the 3/1 mode. Afterwards, region near 3/2, 5/2 and 4/3 surfaces are flattened in case R_c while those around 3/2, 5/2 and 7/2 surfaces are flattened in case R_a. Therefore, the magnetic field tends to be stochastic in the region outside q=2 surface and quickly expands inwards in case R_c. while the magnetic field stochastization occurs first in the region inside the q=2 surface and expands outwards in case R_a. The TQ phase is completed at last and this stage is characterized by completely fallen-down of Te and fully stochastized magnetic field.

Particle transport during pre-disruption phase

Most importantly, we found that increases of core density significantly depends on LoD and there exists a threshold, as shown in fig. 4 (a) by the average density profiles for five cases. It can be clearly seen that the core density in case R_a is much greater than other cases. The threshold is within the *q*=2/1 surface. When the LoD crosses this threshold, the core density rises rapidly. To verify the effect of the *q*=1/1 surface, we change initial equilibrium so that the *q*=1/1 surface is shifted outward. Two cases are calculated, which corresponds to similar relative q profile position of case R_a and case R_c.

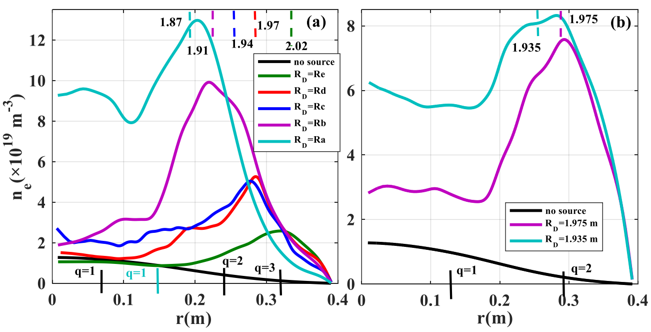

Figure 4. The average density profile, (a) five simulations in this text. The cyan short line is the q=1 suface when the 1/1 mode grows up for R_a. (b) The initial q profile shifted down, two simulations: R_D = 1.935 and 1.975 m.

Results also show that increases of core density depend on LoD (seen from fig.4 (b)). The net radial particle fluxes are calculated in figure 5. It seems that increases of core density are due to **E**×**B** convection produced by the 1/1 mode. We also compare the average particle fluxes produced by diffusion and convection inside the q=1/1 surface. The result shows that **E**×**B** convection is dominant as seen in table 1.

Table 1. The average particle flux inside minor radius

Position: (0.05-0.15) m unit: $\times 10^{22} m^2/s$

	Qn_DM	Qn_(E×B)r	Qn_VparBr
$R_D=R_c$	0.15	-65.58	1.43
$R_D=R_a$	0.24	-271.88	3.29

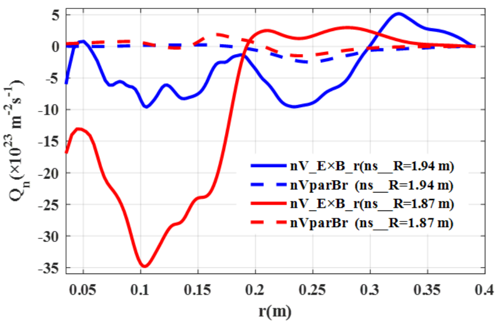

Fig5. The particle flux before magnetic energy releasing, blue color is case R_c and red color is case R_a. The velocity expression is $\boldsymbol{V}=-R^2\nabla u\times\nabla\phi+v_{/\!/}\boldsymbol{B}$, The real line is produced by the r component of first term, and the dotted lines come from second term.

Conclusion

Some common features of the TQ process in disruption triggered by externally injected D density source have been observed by adjusting the LoD, including the MHD responses dominated by the n=1 mode instabilities, a spike of plasma current and the magnetic field stochasticity first in the region of the m/n=2/1 magnetic islands. Most importantly, it is shown that the TQ may result from successively nonlinear mode couplings. Comparisons between case R_c and case R_a reveal some evident differences depending on the LoD outside or inside the q=2 surface. On one hand, the duration of the TQ phase is much shorter in case R_c than in case R_a, implying that a stronger major disruption could occur in case R_c. The magnetic fields are stochastized first in the outer region of the q=2 surface in case R_c, but in the inner region in case R_a. On the other hand, the core plasma density is visibly increased in case R_a. It seems that increases of core density are due to **E**×**B** convection produced by the 1/1 mode.

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