

Extrapolation of Plasma Current Quench Time during Disruptions from Existing Machines to ITER

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I. Introduction

Prediction of electro-magnetic (EM) loads on in-vessel components and the vacuum vessel due to disruptions is essential for the ITER design. The most critical loads are those due to the fastest current quench and, thus, the specification for the shortest quench time in ITER must be provided on the basis of experimental data from existing machines and sophisticated numerical codes.

The ratio of the current quench time τ of ITER to that of an existing machine can be expressed conveniently by Eq. (1) [1], where τ is defined as the decay time from the initial value (I_{p0}) to zero with the average quench rate evaluated between 80% and 20% of I_{p0} ($\tau \equiv I_{p0} / \langle dI_p / dt \rangle_{80\% \rightarrow 20\%}$). Here S is the poloidal cross section area of the plasma before

disruption, η is the plasma resistivity and L_{eff} is an effective plasma inductance. The simplest way

$$\frac{\tau_{ITER}}{\tau_{EXP}} \approx \left(\frac{\eta_{EXP}}{\eta_{ITER}} \right) \left(\frac{S_{ITER}}{S_{EXP}} \right) \left(\frac{L_{eff}^{ITER}}{L_{eff}^{EXP}} \right) \quad (1)$$

to extrapolate the quench time to ITER is to use only experimentally obtained minimum values of τ/S (τ/S scaling) [1,2]. Actually, however, the difference in L_{eff} as well as the different variation of the cross section area during the disruption must be properly taken into account. In addition, the plasma resistivity could also be different due to different impurity content. Thus, the relevance of the simple τ/S scaling for the extrapolation to ITER must be carefully examined.

In this paper, we simulate one of the fast disruption shots in JT-60U with the DINA code [3] coupled with a time dependent code for impurity rate equations to evaluate the impurity radiation and plasma resistivity. Based on these results, we simulate an ITER case to predict the quench time and to investigate the relevance of τ/S scaling.

II. Models and simulation of JT-60U disruption

The disruption simulation code based on the DINA code [3] is coupled with the time

dependent code, which solves the following rate equations for a specific impurity.

$$\frac{dn_k}{dt} = \langle \sigma v \rangle_{k-1}^{\text{ion}} n_e n_{k-1} - \left(\langle \sigma v \rangle_k^{\text{rec}} + \langle \sigma v \rangle_k^{\text{ion}} \right) n_e n_k + \langle \sigma v \rangle_{k+1}^{\text{rec}} n_e n_{k+1} - \frac{n_k}{\tau_{\text{imp}}^k}, \quad (2)$$

where n_k , n_e , $\langle \sigma v \rangle_k^{\text{ion}}$ and $\langle \sigma v \rangle_k^{\text{rec}}$ are densities of k -th charge state of impurity ions and electrons, rate coefficients of ionization and recombination for the k -th charge state, respectively. τ_{imp}^k is the confinement time of impurities in the plasma. Impurity ions, which diffuse out from the plasma, are recycled back to the plasma as neutrals with recycling coefficient R_k . Rate coefficients are taken from the ADAS code [4]. Eq. (2) is simultaneously solved with the DINA code from just after the thermal quench (TQ) by the full implicit method. During the current quench phase, the impurity radiation loss power density P_{rad} is balanced with the joule input power density, P_{joule} , converted from the magnetic energy of the plasma current. Eq. (3) determines the balanced electron temperature T_e , which is used to

$$P_{\text{joule}}(T_e) = P_{\text{rad}}(T_e). \quad (3)$$

calculate the rate coefficients of Eq. (2) and the effective charge and plasma resistivity at each time step. Details of the model are described in [5].

In this model, the major unknown parameters are the initial density of hydrogen ($n_{\text{H}0}$) and the impurity ($n_{\text{Z}0}$), their recycling coefficients and confinement times. We have examined the sensitivity of the current quench time to these parameters. It is found that the quench time is generally insensitive to all parameters of hydrogen. This is because the decrease of electron temperature due to the increase of hydrogen density is effectively compensated for by the decrease of the effective charge, which results in only a small change

in the resistivity. It is also found that the essential parameters are $n_{\text{Z}0}$ and global confinement time $\tau_{\text{imp}}^* \equiv \tau_{\text{imp}} / (1 - R)$ for impurity. Figure 1 shows the current quench for one of the fast disruption shots in JT-60U (31708) [6]. In the figure, the DINA simulation result with an appropriate choice of $n_{\text{Z}0}$ and τ_{imp}^* is also shown. It is assumed that the main impurity is carbon. A fast current quench during the initial phase (< 1 ms) just after the thermal quench (TQ) implies high impurity density. A gradual

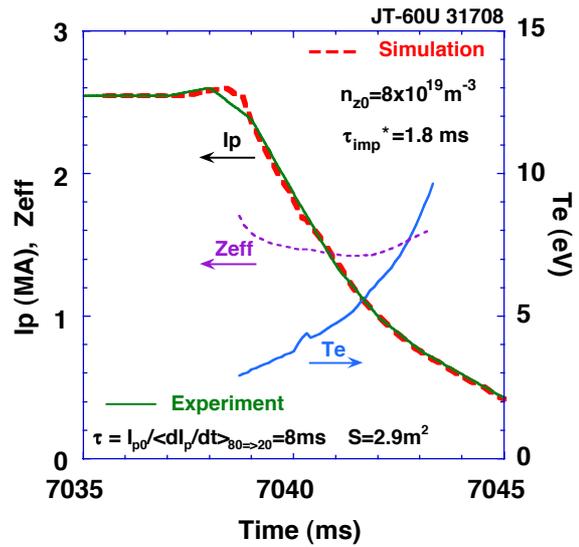


Fig. 1 Current quench waveforms of JT-60U disruption and DINA simulation.

slow down of the quench rate implies a correspondingly shorter impurity global confinement time. It is shown that a set of $n_{z0}=(7-8)\times 10^{19}\text{m}^{-3}$ and $\tau_{imp}^*=(1.8-2.0)$ ms can reproduce the experimental result fairly well. According to the lifetime calculation for carbon fiber composite divertor during the TQ that includes the vapor shielding effect [1], evaporation of $n_{z0}\approx 10^{22}\text{m}^{-3}$ carbon will be expected for the stored energy of 8.4 MJ ($\approx(2-3)$ MJ/m²) of this shot. Additional plasma shielding effect (as expected in ITER) of ≈ 0.01 could reconcile the differences in these carbon densities. For this shot, the experimental value of τ/S is evaluated as 2.7ms/m². This value is to be compared with the simulated value for the ITER case below.

III. ITER simulation

In this section, we simulate the ITER case based on an appropriate extrapolation of n_{z0} and τ_{imp}^* . This extrapolation is subject to uncertainty due to the lack of experimental data and modeling for the impurity generation, influx and density as well as the global confinement time after the TQ. Thus, we first make a primitive extrapolation of n_{z0} and τ_{imp}^* , i.e., n_{z0} is assumed to be the same as the JT-60U case (Fig. 1) and τ_{imp}^* is scaled with the square of minor radius. In the ITER case, the energy deposition density during the TQ is ≈ 20 times higher than the JT-60U case. Although total carbon generation in the ITER case will be ≈ 15 times higher according to the model calculation with vapor shielding [1], n_{z0} is similar to JT-60U since the plasma volume is larger. This case is designated as a reference case. We then simulate various cases with changing n_{z0} and τ_{imp}^* , and compare the results

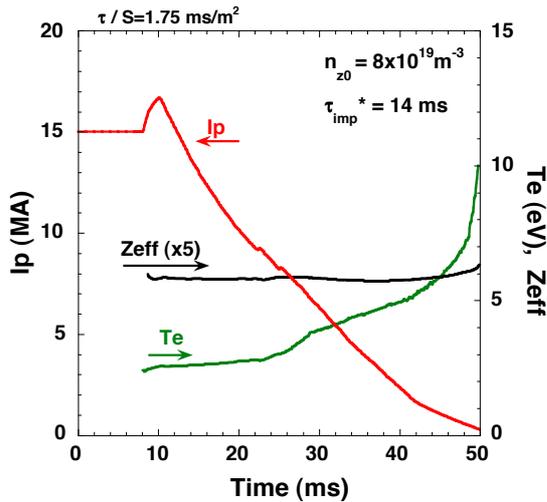


Fig. 2 Current quench waveforms of ITER based on primitive extrapolation of impurity density and global confinement time.

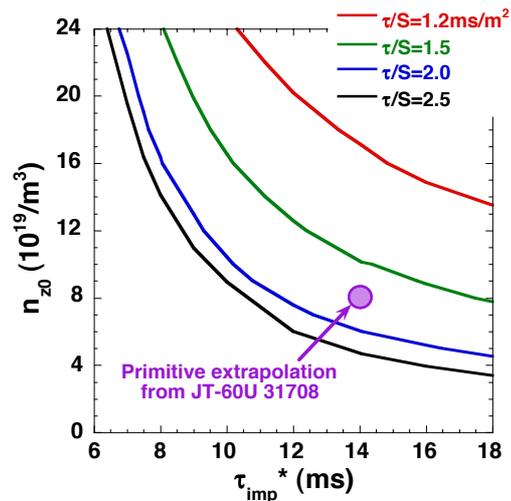


Fig. 3 Predicted τ/S in ITER for a range of impurity density and global confinement time.

with the simple τ/S scaling. Figure 2 shows a simulation result for the reference case ($n_{z0} = 8 \times 10^{19} \text{ m}^{-3}$ and $\tau_{imp}^* = 14 \text{ ms}$). From this result, τ/S is evaluated as 1.75 (37ms/21m²) ms/m². Therefore, the simulated value based on the assumed extrapolation of n_{z0} and τ_{imp}^* is somewhat smaller than that predicted by a simple τ/S scaling (2.7 ms/m²) for shot #31708 in JT-60U. Since the extrapolation includes large uncertainty, we have performed simulations for a wide range of n_{z0} and τ_{imp}^* . The results are shown in Fig. 3 as equi- τ/S lines. It is seen that the present guideline for ITER ($\tau/S = 1.8\text{-}2 \text{ ms/m}^2$) requires somewhat lower impurity density and/or shorter confinement time than the presently assumed extrapolation. Lower impurity density may be expected in ITER due to a higher plasma shielding effect because of a longer plasma to divertor target plate distance and a higher core plasma density.

IV. Conclusions and discussions

A disruption code using the DINA code coupled with impurity rate equations has been developed. It is found that impurity generation and influx to the plasma after the TQ and its global confinement time during the current quench phase are essential processes for the prediction by simulations. The code predicts somewhat shorter current quench time in ITER than by a simple τ/S scaling when primitive extrapolation is applied. Further model development on these processes is essential for a fully consistent prediction of the current quench time in ITER. Measurement of the impurity density and temperature during the current quench on existing machines would greatly contribute to the development of this modeling.

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References;

- [1] ITER Physics Basis, Nucl. Fusion **39** (1999) 2333.
- [2] M. Sugihara, et al., Proc. 20th IAEA FEC, Vilamoura (2004) IT/P3-29.
- [3] R.R.Khayrutdinov, V.E.Lukash, J.Comput.Phys., 109 (1993) 193.
- [4] H.P. Summers, JET-IR06 (1994), <http://adas.phys.strath.ac.uk/>.
- [5] H. Ohwaki, et al., this conference, P5.99.
- [6] Y. Kawano, et al., Proc. 30th EPS Conference, St. Petersburg, 2003, P-2,129.