TSC Modelling Approach to Mimicking the Halo Current in ASDEX Upgrade Disruptive Discharges

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1. Introduction

Robustness of the machine against electromagnetic (EM) and heat loads under various disruption conditions is essential in ITER. EM and heat loads vary according to plasma behavior during disruptions and VDEs. Hence, sophisticated disruption codes that are well validated using an ITER-relevant experimental database are required for reliably predicting representative disruption and VDE scenarios. Of particular importance for the assessment of EM loads on vacuum vessel (VV) and in-vessel components is the halo current which achieves a maximum during VDEs as indicated by various physics parameters, significantly among which are the width and temperature of the halo region. However, halo current models have a limited development so far with a few exceptions such as a validation study of the JT-60U halo current modelling using the DINA code [1]. Recently, several experimental groups have prepared systematic halo current data in the framework of the ITPA MHD Topical Group, and further model development and validation with these data need to be performed using another axisymmetric, two-dimensional, free boundary code, TSC [2].

To enhance an understanding of the maximum halo current and large vertical shifts, a reference discharge was selected from those included in the ASDEX Upgrade disruption database. This paper presents the dynamic evolution of the VDE and halo current for an ASDEX Upgrade disruptive discharge. Secondly, systematic TSC simulations were performed to mimic the observation of a slow VDE of hot plasma and an ensuing fast downward-going VDE during a subsequent plasma current quench (CQ). Careful parameter adjustment of the temperature and width of the halo region was examined to mimic measurements of the halo current.

2. Disruptive Discharge Selected from the ASDEX Upgrade Database

Disruptive discharge #25000 was selected because it is considered a dangerous scenario with a slow VDE of hot plasma that touches the divertor tiles, a subsequent thermal quench (TQ), an immediate fast CQ and a large halo current.

Switching off vertical control at t ~ 3.0 sec, a hot plasma of the H-mode discharge with a low internal inductance of l_i ~ 0.67 undergoes a slow, downward-going VDE from an initial position of R_p = 1.62 m, Z_p = 2 cm above mid-plane. At t ~ 3.127 sec, the plasma comes into contact with the divertor tiles, degrading confinement. Right after contact between the plasma and the divertor tiles, TQ occurs at t ~ 3.130 sec. A fairly small, positive spike of the plasma current of δI_p ~ 20 kA was observed at TQ. Reduction in l_i was small. Therefore, it is likely that the flattening of the plasma current profile, often observed in normal disruptions, was not significant in discharge #25000. A fast plasma CQ followed the TQ. Consequently, a large halo current emerged, especially in the later phase of the CQ.

Figure 1.1 illustrates the temporal evolution of the profile of halo current flowing into and out of individual divertor tiles and heat shields. The halo current was broadly distributed

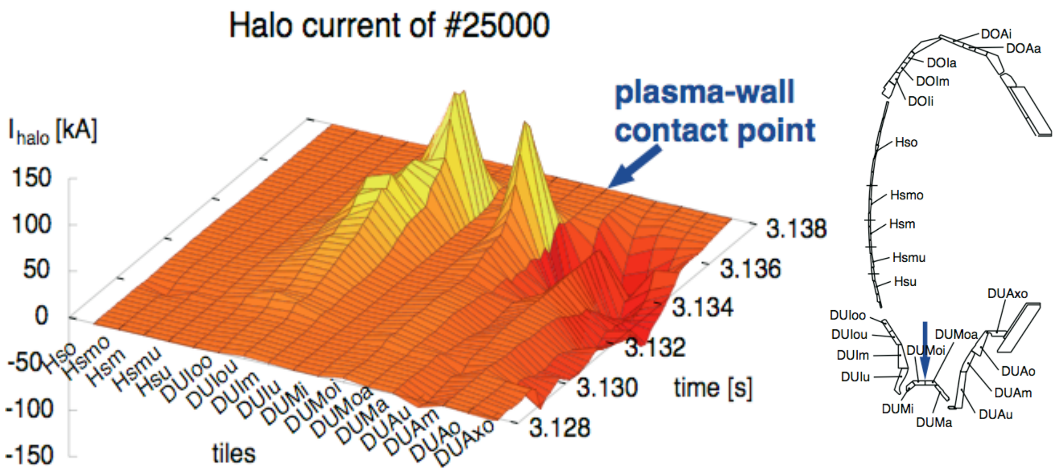

Fig. 1.1 Temporal evolution of the halo current profile flowing into and out of the individual divertor tiles (DUxx) and heat shields (HSxx).

across discrete areas of the heat shields. Throughout the disruption, the plasma contact point with the divertor tile remained between the center dome tiles of DUMoi and DUMoa.

3. TSC simulation of the ASDEX Upgrade Discharge (#25000)

Using TSC, the dynamic evolution of a slow VDE discharge (#25000) was reproduced over its entire time period, starting with an initial equilibrium at t ~ 3.100 sec prior to the TQ and proceeding until the end of the discharge (t ~ 3.137 sec).

3.1. TSC structure model of the ASDEX Upgrade

The VV of the ASDEX Upgrade is composed of bellows and thick sectors [3]. Total toroidal resistance is 0.28 mΩ, mainly concentrated in the bellows sector. In order to create the TSC structure model, the periphery of the poloidal cross section of the VV was divided into 340 segments, each of which is represented by an axisymmetric filament. In addition to the toroidally circulating eddy current, a saddle-like eddy current may flow on the thick sector with a very low poloidal resistance of 0.025 mΩ, and with a detour around the bellows sector. This saddle current can be modeled using two, dipole toroidal currents with a zero net current.

Unlike the VV, the divertor tiles, heat shields and structures in contact with the divertor and VV are toroidally discontinuous structures, though they are poloidally continuous and, hence, form the flow path of the halo current. These structures may affect plasma behavior because the magnetic field penetrates them. In the present TSC modeling, these toroidally discontinuous structures are represented by a twin loop in which opposing passive coils are connected.

A passive stabilizing loop (PSL) installed inside the VV plays an important role in stabilizing VDE. The upper (PSLo) and lower (PSLu) loops are electrically connected with each other by a bridge; in addition each loop is closed by a resistor of low conductivity. Therefore, the total loop current is modelled to allow almost zero net current. In the TSC simulation, the external circuit of VV, PSL and divertor tiles was simultaneously solved as surrounding passive conducting structures. The values of the PF coil currents are identified at each point in time from the experiments.

In the TSC, the plasma boundary defined by a set of limiter points allows the uninterrupted passage of the halo current into the divertor tiles and heat shields.

3.2. Dynamic evolution of VDE, plasma current quench and halo current

The initial plasma equilibrium of the disruptive discharge (#25000) was carefully reproduced, using the ASDEX Upgrade experimental data at t ~ 3.100 sec. The plasma with I_p ~ 791 kA, l_i

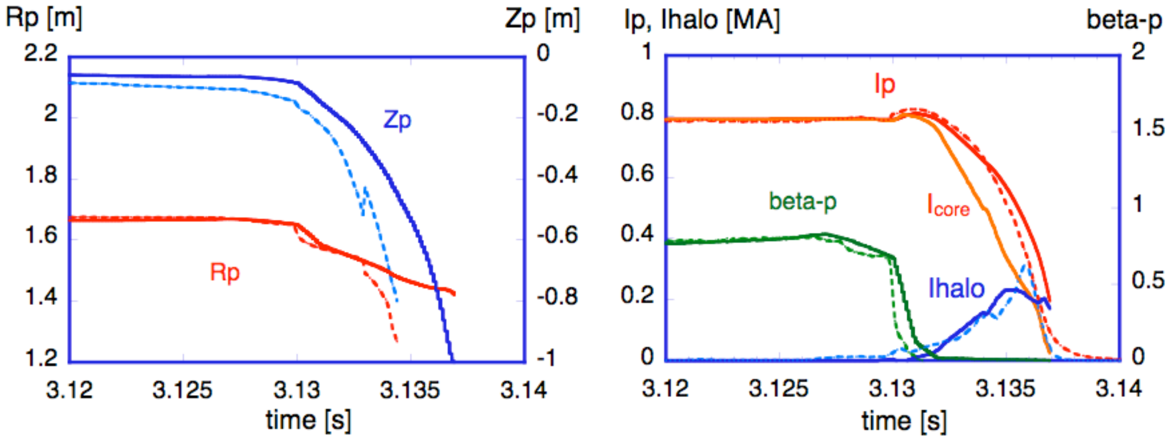

Fig. 2.1 TSC simulation (solid line) and experimental observation (broken line) of ASDEX Upgrade disruptive discharge #25000. Switching off vertical control at t ~ 3.1001 sec, hot plasma undergoes a slow, downward-going VDE. At t ~ 3.127 sec, the hot plasma has contact with divertor tiles in the experiment (broken line). A TQ was modelled to occur by forcing a sudden drop in beta-p at t ~ 3.130 sec. A forced flattening of the plasma current profile at TQ reproduced a fairly small, positive current spike of δI_p ~ 20 kA, as observed in the experiment. A fast CQ followed after the TQ, and a spontaneous VDE was also reproduced. Consequently, a large halo current emerged, especially in the later phase of the CQ by adjusting halo parameters. Here, I_p denotes total toroidal current, including toroidal halo current, while I_{halo} directly measured on divertor tiles and heat shields denotes the poloidal component in experiment.

~ 0.71, β_p ~ 0.74, a volume of 12 m^3, and κ ~ 1.8, was positioned at $R_p = 1.67$ m, $Z_p = -3.5$ cm from mid-plane. Switching off vertical control at t ~ 3.1001 sec, the hot plasma undergoes a slow, downward-going VDE. In Fig. 2.1, the dynamic evolution of the spontaneous VDE, plasma current and halo current is presented over the entire time period until the end of the discharge (t ~ 3.137 sec). Here, the current I_p denotes the total toroidal current including the toroidal halo current, while the halo current I_{halo} directly measured on the divertor tiles and heat shields denotes the poloidal component in experiment. At t ~ 3.127 sec, the plasma comes into contact with the divertor tiles, degrading confinement. Right after contact between the plasma and the divertor tiles, a TQ was modelled to occur by forcing a sudden drop in plasma pressure (beta-p) at t ~ 3.130 sec. As observed in the experiment, a fairly small, positive spike of the plasma current of δI_p ~ 20 kA was reproduced by introducing a forced flattening of the plasma current profile at TQ. A fast plasma CQ follows after the TQ. A spontaneous VDE was also reproduced in a manner similar to experimental observations. Consequently, a large halo current emerged, especially in the later phase of the CQ as measured in the experiment. Here, in order to reproduce the generation of the halo current, we adjusted the halo parameters such that T_e^{halo} ~ 12 eV and width (w^{halo}) of the halo region comprised up to ~ 40% of the plasma core flux.

Figure 2.2 shows the temporal evolution of the TSC plasma equilibria during the disruption. These temporal snapshots clearly show that the halo current flows over the halo region and circulates beyond the divertor tiles and the heat shields. Figure 2.2 indicates that the halo region is broadly distributed on part of the heat shields as confirmed in Fig. 1.1 from the experiment. By adjusting parameters related to temperature and width of the halo region, we have learned to mimic the evolution of the halo current as measured in the ASDEX Upgrade. The results of our modelling efforts are as follows: 1) An increase in the halo current by raising the temperature or extending the width slows down the VDE; 2) Further extension of the halo width beyond a certain point does not increase the halo current; 3) No adjustment of halo region parameters succeeds in reproducing a halo current equal to levels observed right after the TQ. One possible cause of the large halo current may be the non-inductive bootstrap current observed in the H-mode discharge #25000, which disappears at

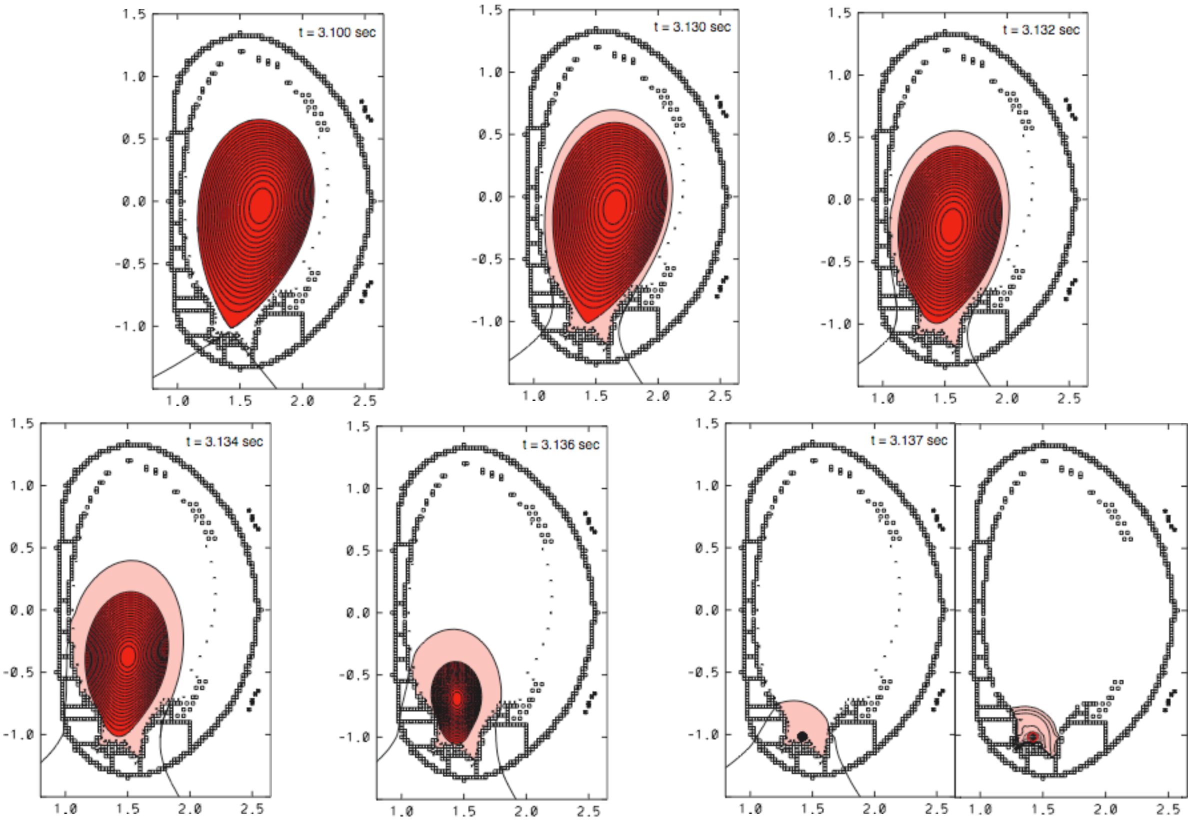

Fig. 2.2 Temporal evolution of the TSC plasma equilibrium during the disruption. Initial equilibrium at t = 3.100 sec; plasma contacting with tile at t = 3.130 sec; plasma after TQ at t = 3.132 sec; and plasmas during the CQ at t = 3.134 sec, 3.136 sec and 3.137 sec, respectively. Plot of the poloidal current density is attached at t =3.137 sec. Halo current flow in the halo region is distributed broadly on part of the heat shields as shown in Fig. 1.1 from the experiment.

the TQ. Hence, a positive inductive current could appear in the halo region.

4. Summary

Characteristics of the VDE and halo current were analyzed for a reference discharge (#25000) selected from the ASDEX Upgrade disruption database. Using the width of the halo currents measured on ASDEX Upgrade divertor tiles and heat shields, systematic simulations with TSC were performed to mimic the dynamic evolution of the VDE and halo current of the ASDEX Upgrade. Evolution of the plasma current was reproduced for the duration of a CQ. A spontaneous, downward-going VDE was reproduced accurately in a manner that closely resembled experimental observations. Adjusting the temperature and width of the halo region succeeded in mimicking evolutions of the halo current as measured in the ASDEX Upgrade. In order to develop a reliable halo current model for predicting ITER disruption scenarios, further TSC modelling studies are needed to simulate other disruptive discharges contained in the ASDEX Upgrade disruption database and are now underway.

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[3] H. Preis, “Numerical Analysis of Eddy Currents and Magnetic Forces in the Vacuum Vessel of ASDEX Upgrade”, 12th Symposium on Fusion Technology (SOFT-12), Jülich, Germany (1986) 447-451.