TSC modelling of major disruption and VDE events in NSTX and ASDEX-Upgrade and predictions for ITER

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Abstract. A concerted effort has been launched to accurately predict electromagnetic loads in ITER due to plasma major disruptions (MDs) and vertical displacement events (VDEs) using the Tokamak Simulation Code (TSC) and compare the predictions made earlier using the DINA code. In this effort the TSC model is first benchmarked with experimental observations in ASDEX Upgrade and NSTX. The upgraded TSC model is then used in predictive simulations for ITER for different MD and VDE scenarios with upward or downward plasma motion and fast or slow current quench depending on the post thermal quench plasma core temperature. The simulation results are compared with earlier DINA predictions.

1. Introduction

Vertical Displacement Events and Major Disruptions of the plasma current will induce large electromagnetic forces on the ITER machine. Estimation of these forces based on accurate modelling of these events is necessary for a robust ITER design. Originally the estimates for electromagnetic forces on ITER were carried out with the help of DINA simulations [1]. However, since simulations of these events may be significantly influenced by model assumptions of a given code it is important to validate the results against other codes like TSC, as also benchmark and update the codes with experimental data. In the 2008 IAEA FEC, we had presented [2] results of TSC simulations of fast MDs and slow VDEs and compared these simulation results with that obtained from DINA modelling, which, even though largely showed similar plasma behaviour, had certain differences in the predictions for the plasma current quench times and halo current magnitudes. It has further been decided to update both the models after benchmarking them with experimental observations in NSTX and ASDEX Upgrade (AUG) devices and use the updated codes to make more accurate predictions for ITER. Moreover, in 2009, the design of the ITER vacuum vessel, CS and some of the PF coils as also other in-vessel components like blanket modules (BMs) incorporated certain necessary changes, resulting in small but finite change of the electromagnetic parameters in the ITER machine. This has also necessitated in updating the TSC model of ITER with the new parameters and recalculation of the disruption and the VDE forces. In this paper, we present TSC modelling of the VDE and MD events in NSTX and AUG devices, which help in improving and validating the models used in the code. The predictive modelling results for ITER with the updated code, including the force predictions, are also presented. Section 2 describes the ASDEX Upgrade modelling and its comparison with experimental data and the NSTX modelling is presented in Section 3. The predictive modelling for ITER and comparison with the earlier DINA predictions are presented in Section 4. The results are summarised in Section 5.

2. TSC Modelling of Halo Current in ASDEX Upgrade Disruptive Discharge

AUG is equipped with an elaborate set of magnetic diagnostics to specifically measure halo currents and forces during major disruptions and VDEs and has developed an extensive database of these events. A reference discharge #25000 of the AUG was selected from the disruption database, in which a VDE was intentionally initiated by switching off vertical control at t ~ 3.0 sec. Consequently, the hot plasma of the H-mode discharge undergoes a slow, downward-going VDE. 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 occurs at t ~ 3.130 sec. A fast plasma CQ followed the TQ. Consequently, a large halo current emerged, especially in the later phase of the CQ. Using TSC, the dynamic evolution of the disruptive discharge was reproduced over its entire time period, starting with an initial equilibrium prior to thermal quench (TQ), undergoing a process of ensuing fast downward-going VDE during a subsequent plasma current quench (CQ) and proceeding until the end of the discharge.

A detailed model of the AUG vessel, passive stabilizer loops, other in-vessel components and the PF coils have been created in TSC. Using this model we have carried out the simulations of the above AUG discharges. The simulated plasma and halo current evolutions in TSC exhibit behaviour similar to the experimental observations. Parameter adjustment of the temperature and width of halo region appears to mimic the evolution of the halo current measured in AUG.

Figure 1 illustrates the temporal evolution of halo current flowing into and out of individual divertor tiles and heat shields. The halo current was broadly distributed 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.

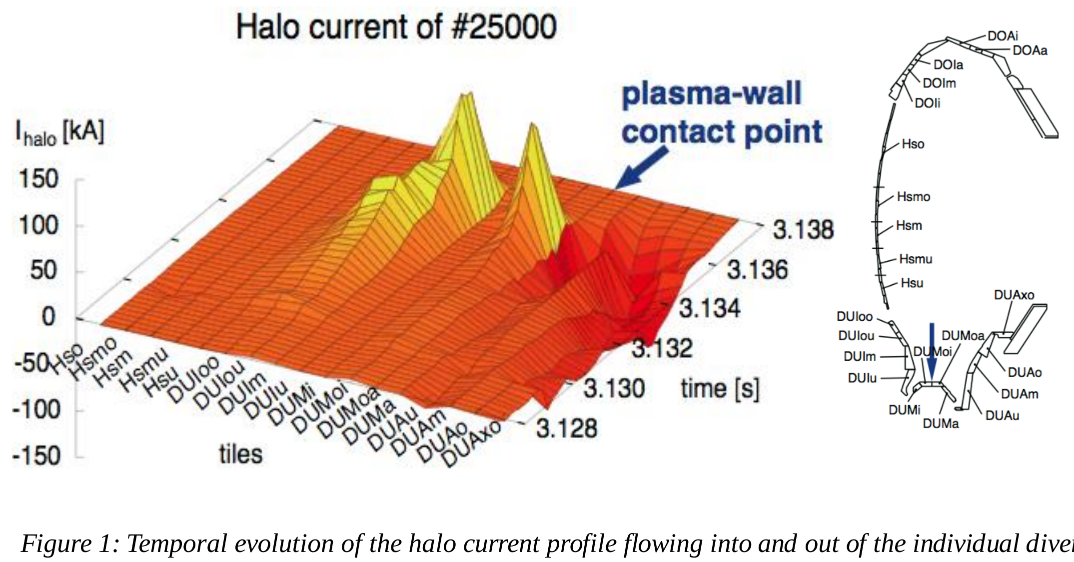

Figure 1: Temporal evolution of the halo current profile flowing into and out of the individual divertor tiles (DUxx) and heat shields (HSxx).

2.1 TSC simulations for ASDEX Upgrade

In order to create the TSC structure model, the periphery of the poloidal cross section of the VV with total toroidal resistance of 0.28 mΩ 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 of the VV with a very low poloidal resistance of 0.025 mΩ. This saddle current with a detour around the bellows sector 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. In the present TSC modelling, these toroidally discontinuous structures are represented by a twin loop in which opposing passive coils are connected.

The passive stabilizing loop (PSL) in AUG 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.

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 ~ 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 Figure 2, the dynamic evolution of the spontaneous VDE, plasma current and halo current (poloidal for experiments and toroidal for simulation) 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 (β_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. 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 initial plasma core flux.

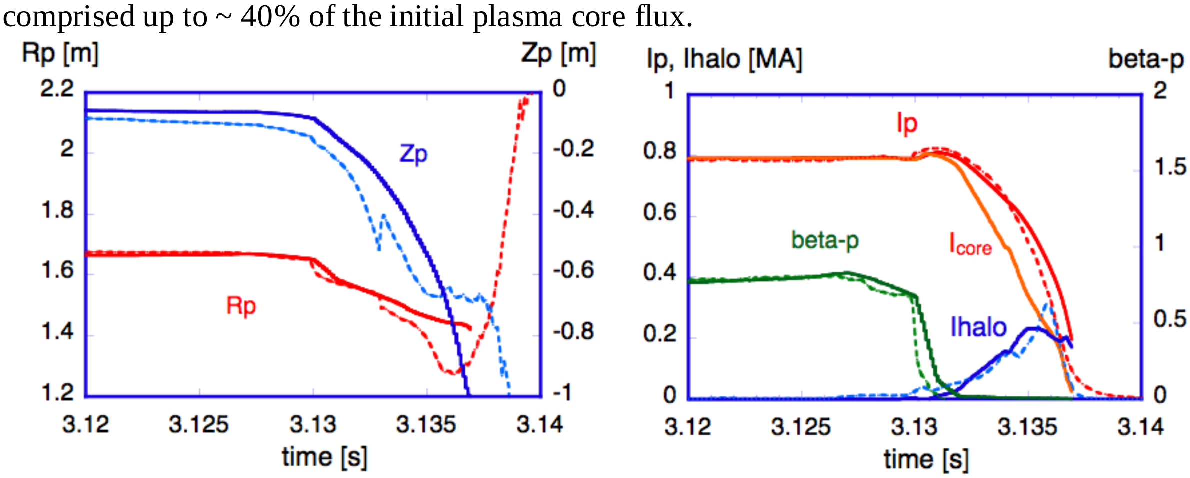

Figure 2: TSC simulation (solid line) and experimental observation (broken line) of AUG disruptive discharge #25000. On left are the evolutions of the plasma radial and vertical positions, while on right are the plasma and halo toroidal currents.

Consequently, a large halo current emerged, especially in the later phase of the CQ as measured, apart from two different points from the experiment as below. First, 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 the TQ. Hence, a positive inductive current could appear in the halo region. Secondly, TSC did not reproduce maximum halo current at t ~ 3.136 sec. 3D effect might be necessary to reproduce this large poloidal halo current. Actually, 1/1 kink mode is observed at this time moment. This ASDEX Upgrade data might be a challenge to the 2D modelling, and still remains to be elucidated.

2 NSTX Modelling

NSTX also has an extensive set of magnetic diagnostics that give information about the plasma motion and distribution of induced and transmitted currents during the disruption. These include: (1) Rogowski loops on the center column, (2) arrays of toroidal field sensors to measure poloidal current flowing in the vessel wall (both inner ring and outer ring) and (3) arrays of instrumented tiles on the outer divertor that provide highly localized measurements of the current going into the tiles. A series of "forced VDE" experiments have been done, for which shot 132186 (downward) and 132422 (upward) are typical. The downward shot measured halo currents of almost 100kA in the vacuum vessel inner ring, and the upward shots measured 40 kA. The dominant experimental trend is that the maximum halo current observed scales with the I_P (plasma current) quench rate. This is consistent with the currents being driven by rapid flux swings [3].

We have modeled a series of these experiments using TSC in order to show under what assumptions we can best reproduce the experimental trends. The TSC halo current model [4] specifies the width of the halo region to be a constant percentage of poloidal flux contained within the plasma, and the halo temperature to be an input constant. Figure 3 shows the initial results of these simulations with TSC in which a halo width corresponding to 40% of initial closed flux in the halo region and a halo temperature of 5eV was assumed. More details and converged results of these smulations will be presented in FEC2010.

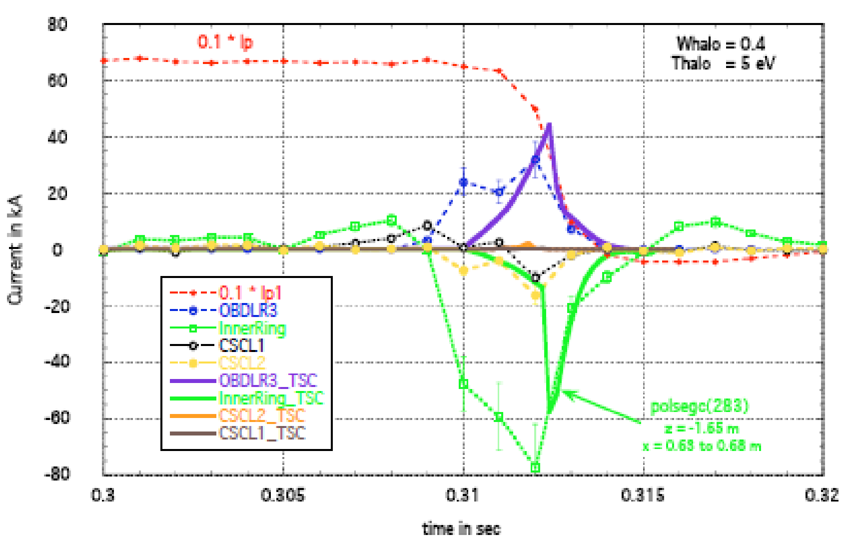

Figure 3: Comparison of Experimental data of NSTX discharge 132859 and (preliminary) results of TSC simulations of the same discharge. In this simulation a halo width corresponding to 40% of initial closed flux in the halo region and a halo temperature of 5eV was assumed.

3 ITER Simulations

A new electromagnetic model of ITER in the TSC code, that is much more detailed than the one used during the earlier results presented in FEC 2008, involving the two shells of the vacuum vessel, the PF coils, in vessel components like the blanket modules (BMs), the Cu cladding, triangular support and the divertor inboard rail has been created. In this new ITER model, both the inner and the outer vessel shells are now poloidally continuous to allow poloidal currents to flow through them. Furthermore the BMs are modelled as a lumped set of '*wires*' with toroidal breaks (zero net toroidal current), but having poloidally continuous current path from the blanket to the inner vessel shell. Thus, using this model, it is possible to model poloidal halo currents to flow from the plasma to the blanket modules, then to the vessel and further back to another BM and finally back to the plasma. The new electromagnetic parameters of the new model, e.g., the L/R times have been checked through plasma less current decay simulations with the engineering values as also values used in the DINA code. In the MHD model, the fluid velocities are put to zero at the boundary of the plasma region, i.e., at the first wall.

We have now completed one set of disruption and VDE simulations for all the representative ITER scenarios, namely the slow and fast major disruption (MD) cases, the upward (UP) and downward (DW) fast VDE cases as also the DW slow VDE cases. These cases are treated in the TSC (as also DINA) modelling in the following way: In all the cases the initial plasma equilibrium is taken as the ITER reference scenario II, SOB case with I_p= 15MA, l_i=0.85, β_p =0.72. In the MD simulations, the disruption is initiated through an artificial beta collapse with the plasma at the nominal position, which triggers a thermal and hence a current quench. The electron temperature post thermal quench is set either 6eV or 55eV in the fast and slow quench cases respectively. The plasma current peaking and profile flattening immediately following the thermal quench is modelled in TSC through a hyper-resistivity model, while that in DINA is modelled through a helicity injection model. The position control systems are switched off after the thermal collapse and the plasma evolution is followed as it moves vertically with a speed decided by the vertical position growth rate, shrinking as it moves till the magnetic axis hits the first wall. The halo current is switched on in TSC at around 30ms in the simulations when the plasma becomes limited. In both the MD as also the VDE cases, the halo width in TSC is taken such that 10% of the initial poloidal flux in the close flux region is kept in the open flux region of the halo. The halo temperature is kept same as the core temperature. The current quench time is decided by the electron temperature post thermal quench.

It is to be noted here that assumption of constant temperature is used for comparison of plasma characteristic behaviours between DINA and TSC. For the preparation of the ITER reference MD and VDE scenarios, given Ip quench pattern (linear or exponential with a pre-determined time constant) is to be followed in both codes through a feedback applied on the plasma thermal conductivity values to set T_e giving the desired Ip quench time. For the case of slow current quench, simulation results with constant T_e are to be directly used for the ITER reference scenarios.

In the VDE simulations, the VDE is initiated by simply switching off the plasma position controllers. The plasma starts moving vertically much slowly compared to the MD cases in the absence of any thermal quench initially. The halo current is switched on when the plasma comes in contact with the first wall and thermal quench is initiated when the edge safety factor (q95) touches 1.5. Post thermal quench temperature in the core as also the halo temperature is same as in the MD cases corresponding to the slow and fast quench cases. The UP and DW cases are initiated with a different initial vertical position.

4.1 Simulation Results

In the MD simulations, for fast current quench (T_e=6eV after beta collapse) case, as shown in Figure 4, the initial I_p decay rate is comparable in DINA and TSC in the first ~25ms when the plasma is yet to touch the first wall and there is no halo current flowing and the plasma is not yet limited. However, with the onset of the halo current after about 28ms, TSC shows considerably slower I_p quench, the thin red curve showing the overall toroidal plasma current including the core and the halo region in TSC has to be compared with the blue curve of DINA. The difference is possibly due to the difference in the halo model in the two codes. While the halo width is comparable (~10%) in both codes, in TSC the halo region is in addition to the closed flux region, the size of which is determined by the instantaneous plasma position and the distance of the limiter/first wall from the plasma. In comparison in DINA, the overall plasma cross-sectional area including the halo and the closed flux region is decreasing with plasma current decay. Also compared to DINA, the initial current peaking post beta collapse is somewhat less in TSC; which can be however be improved by varying the hyper-resistivity parameters used in TSC to simulate plasma current profile flattening. But this probably does not affect the I_p quench time or peak halo current magnitude, which is about 2 times in TSC than in DINA and also lasts for a longer duration. The overall behaviour is very similar to that seen with the old ITER model reported in FEC2008.

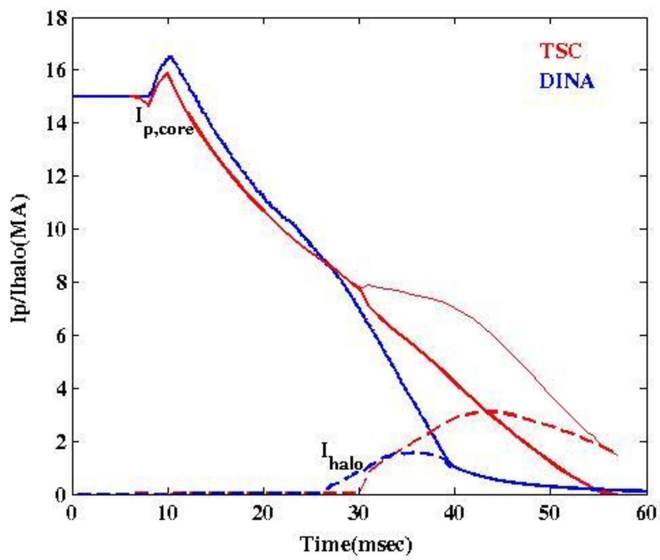

Figure 1: Evolution of the plasma current in TSC (red) and DINA(blue) simulations. The solid thick red curve shows the toroidal plasma curent in the core (closed flux surfaces), while the thin red curve that including both the core as also the halo region.

Figure 5 shows the evolution of the plasma flux surfaces in the MD (6eV) case, as it moves vertically upwards. The last plot on the bottom right shows the final poloidal current contours, including both the halo in the plasma halo region and in the upper part of the BMs, as also the poloidal eddy currents due to diamagnetic effects in other BMs and in divertor and the vacuum vessel. A post-processor called TWIR has been developed at PPPL for using the magnetic field and poloidal and toroidal current data from the TSC simulations for calculating the electromagnetic loads on various parts of the FW and the vacuum vessel. Details of the force calculations will be presented in FEC2010.

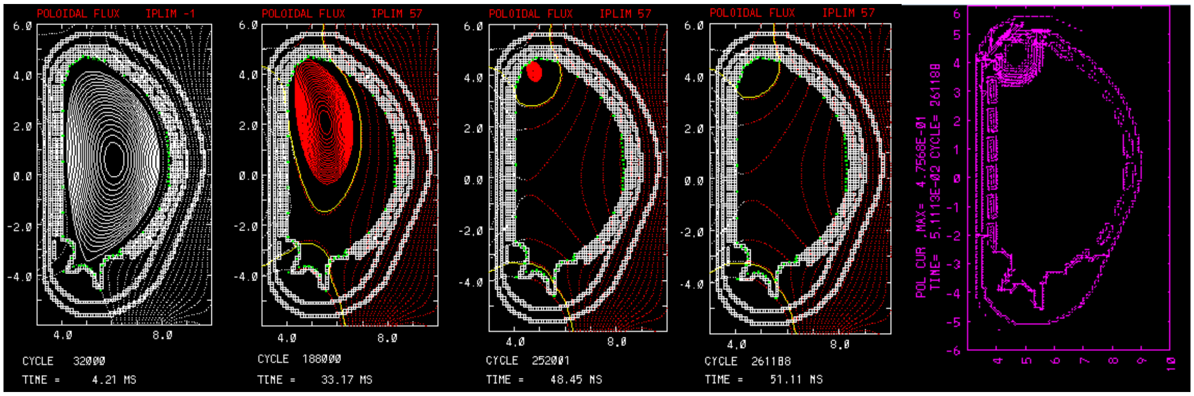

Figure 2: Plasma flux surface evolution and (extreme right) the poloidal current vector plots in the final current termination phase in TSC for central MD case of ITER with fast current quench. The solid yellow curve shows the boundary of the halo region.

We have also carried out the UP and DW-VDE cases with final fast current quench as well as the case of DW-VDE with final slow current quench. In the UP case, the initial plasma vertical position is 0.598m compared to the nominal 0.568m in the DW cases. As shown in Figure 6, in TSC the beta collapse is initiated about 30ms later than in DINA when the plasma edge safety factor (q_{95}) reaches 1.5. In both the DW and the UP cases, as seen in Figure 6, the Ip quench after beta collapse in DINA is somewhat faster than that seen in TSC resulting in higher maximum halo currents of about 4.2 and 2.4MA in TSC respectively, which is about 40-50% more than the corresponding cases in DINA. Probably the most important case for ITER is that of the slow DW VDE, as this case predicted the maximum halo current magnitude in DINA and as a result the maximum VDE induced vertical load on the ITER machine. However, for this case, the maximum predicted halo current in TSC is almost a factor of 2 lower than in DINA.

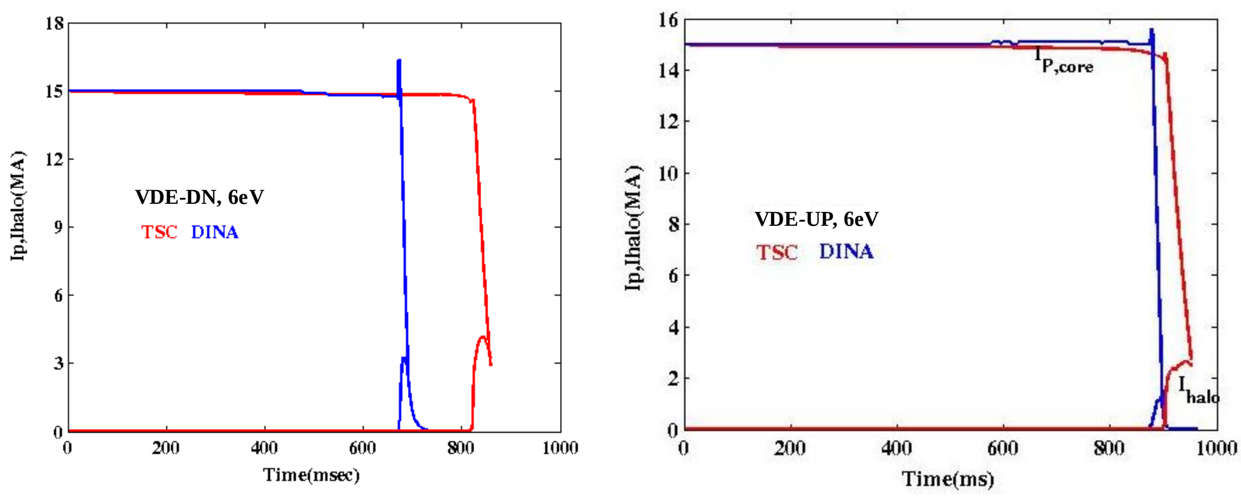

Figure 6: Plasma and halo current evolution in DW and UP VDE case in TSC with fast current quench.

5. Summary and Conclusions

To investigate in detail the ITER VDE and Disruption scenarios using the TSC code and in particular validate earlier DINA results used for predicting electromagnetic forces in ITER, a concerted effort has been undertaken to first validate the TSC model with experimental data in AUG and NSTX devices. The initial results of these experimental validations are encouraging and the TSC model is being updated through this benchmarking process. With the updated TSC code, a new detailed electromagnetic model of ITER has been created and simulations have been carried out for both central MD as well as slow and fast VDE cases in ITER and the results are compared with DINA. Following table summarises main differences in the model predictions:

Scenario	**Peak Halo Current magnitude (MA)**	
	TSC	DINA
MD with fast I_p quench (6eV)	3.7	1.8
VDE-UP with fast I_p quench (6eV)	2.4	1.6
VDE-DW with fast I_p quench (6eV)	4.2	3
VDE-DW with slow I_p quench (55eV)	3	6

The reasons for the different predictions by the two codes could be due to several differences in the two models, for example in the plasma resistivity or halo width models used. Also there might be some differences in model validation procedures of both codes. In both the experimental validations in NSTX and AUG as also in the predictive simulations for ITER, TSC is run in a purely predictive mode. Only the initial experimental coil currrents and broad plasma parameters like core Ne, T_e etc are used to create the initial equilibrium and the other critical parameters like post disruption plasma core and halo temperatures, as also halo width are selected rather intuitively and optimized through parameter scoping till a best experimental match is obtained. This is a reasonable approach for testing the robustness of the predictive model as firstly for ITER, we have to depend on assumptions for these parameters and secondly, even for present experiments, often the experimental data for these parameters are difficult to get in the disrupting phase of the plasma. On the other handthe experimental validation of DINA in experiments (not shown in this paper) are generally carried out in a fiting mode before TQ using magnetic data (magnetic probes and flux loops). During CQ phase, in DINA the plasma core and halo temperatures are adjusted to fit the simulated plasma current decay to the experimental values for the examinations of the employed halo width model. A better approach would be to validate both the codes in a truly predictive mode with experimental data and then use predicted core and halo temperatures and width for predictive simulations for ITER. The detailed model differences are presently under investigation to narrow down the differences in predicted maximum halo current amplitude and will be reported in FEC2010.

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