Plasma Disruption and VDE Modeling in Support of ITER

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Abstract: Accurate modeling of major disruption and vertical displacement events in ITER is necessary to determine the halo current amplitude during these events and hence the electromagnetic loads on the machine components. Predictive simulations for MD and VDE events in ITER have been carried out using DINA and TSC codes. However, in these simulations, the halo current amplitude depends critically on the choice of the halo parameters, namely the temperature and width of the halo region. Due to lack of credible experimental data of these two parameters and also no sound physics based model so far, these parameters are chosen rather ad-hoc in the simulations. For validating simulations with existing experiments, these parameters are chosen carefully for each experimental discharge so as to give a good match between the experiments and simulations. But for predictive simulations for ITER, this creates a problem as to what values to be chosen for these parameters. To resolve this issue, a concerted effort to validate the TSC model against a wider set of experiments in different machines is presently underway. We have selected a set of four shots in DIII-D and 5 shots CMOD, which are being simulated in TSC. The halo parameters are set carefully only for one experiment in each machine and for the rest of the shots, they are kept unchanged. Thus the difference between the experimental and simulated halo current amplitude in these discharges would give an indication of the possible error in predictive modeling. We have already modeled three DIII-D discharges and 1 CMOD discharges in which, we can reproduce the peak halo current amplitude within about 10-15% of their experimental value.

1. Introduction

Major Disruptions (MDs) of the plasma current and Vertical Displacement Events (VDEs) are a major concern in any tokamak, as they are not only a hindrance to steady state operations of the machine, but also subject the machine components to large electromagnetic forces. There will be no exception in ITER, but especially due to the large plasma current of 15MA in ITER, the halo current can also be high and that crossed with the ITER's large toroidal magnetic field, can subject the machine to unprecedented JxB forces. Thus, the ITER first wall, vacuum vessel and all in-vessel components must be designed to withstand these large forces.

The projected halo current amplitude during ITER MDs and VDEs are presently based on DINA simulations [1] and extrapolations from the database of these events in present day experiments. However, the problem with this approach is two-fold: first, it would be extremely difficult to design and build ITER or any reactor grade tokamak if extrapolations from the outliers of present experimental database are considered, e.g., the non-axisymmetric VDEs in JET. Secondly, in the modeling predictions from DINA, which were also benchmarked with TSC simulations, there are uncertainties in the predictions due to the model assumptions. While the TSC and DINA code predictions match very well with each other [2], especially when similar model assumptions are used, the most significant uncertainty in the model assumptions lie in the key halo parameters, namely the temperature of the halo region (T_{halo}) and width of the halo region (W_{halo}). These are two key parameters, which determine finally the amplitude of the halo current. Generally in both DINA and TSC simulations, due to a lack of experimental data on T_{halo} and W_{halo}, as also the absence of a sound physics model means that their values are usually adjusted ad-hoc to best match experimental data.

To analyse in detail the effect of these two key halo parameters on the halo current amplitude and the projected MD/VDE forces in ITER, a concerted effort is presently underway under a working group WG-10 of the ITPA MHD topical group, to benchmark the codes with a wide variety of experimental data. In the past, the TSC code simulations were benchmarked with experiments in ASDEX-UG and NSTX, which was reported earlier [3]. These were followed by further benchmarking of the TSC code against four different VDE discharges in ASDEX-UG [4]. Figure 1 gives an example of comparison of

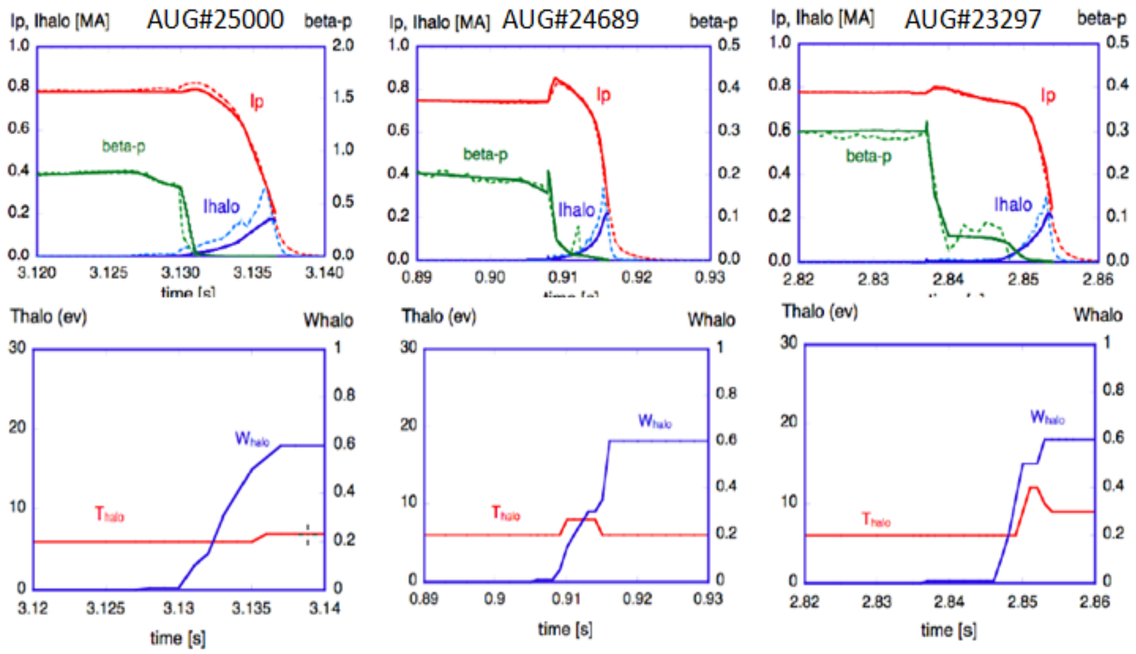

Figure 1: TSC simulations of disruption shots 25000, 24689 and 23297 in ASDEX-UG. The top row gives the evolution of simulated (solid lines) and experimental (dashed lines) I_p, I_{halo} and poloidal beta. The lower row gives the width and temperature of the halo region set in the simulations

the TSC simulation results with the experimental data in ASDEX-UG – the top row shows the evolution of plasma current (I_p), poloidal halo current (I_{halo}) and plasma poloidal beta in simulation and in experiments. Obviously there is very good match between the TSC simulations and the experiments values. But the problem lies in the choice of the W_{halo} and T_{halo} used in the simulations shown in the bottom row. It is to be noted that in each of these simulations, W_{halo} and T_{halo} are adjusted to get the best match between the simulated and experimental data. This poses a problem in predictive simulations for ITER in deciding what are the ideal values of T_{halo} and W_{halo} to be chosen. To resolve this, the WG-10 is presently carrying out benchmarking simulations with TSC with a wider set of experimental data, mainly with representative discharges in the DIII-D and CMOD tokamaks. In DIII-D we have selected a set of 4 VDE discharges, while in CMOD we have selected 3 MD and 2 VDE discharges for these simulations, which best represent the variety of such scenarios in these two machines. In all these discharges there are very good measurements of the halo currents at poloidally different tile locations, which should help in benchmarking the halo width model used in TSC. The simulations are carried out in TSC for the disruptive/VDE phase of these discharges.

2. TSC Simulations of the disruption/VDE shots

The simulations are started with the initial plasma equilibrium about 4-5 milliseconds before the onset of the thermal quench (TQ) in case of MD shots and after the onset of VDE for the VDE shots. The plasma equilibrium at that experimental time point is carefully reproduced in TSC to have a very good match between the experimental reconstructed and simulated equilibria including the shape, location of the magnetic axis, density and temperature profiles, poloidal beta and internal inductance. The machine geometry, including the vacuum vessel and first wall components are carefully represented in very good detail in TSC, with possible poloidal halo current paths clearly defined. The plasma evolution is then followed in TSC with experimental coil currents set as inputs to the simulations. The current peaking post the TQ is simulated through a hyper-resistivity parameter [5] introduced in the Ohm's law. Beyond the current peaking the current quench (CQ) occurs naturally in the simulations with a rate determined mainly by the post TQ plasma temperature, the plasma vertical growth rate, the evolving poloidal field configuration and the machine geometry. The halo current is switched on in the simulations at the time when the plasma becomes limited. The transport equations are not solved in these simulations and the TQ is simulated by artificially dropping the plasma pressure to emulate the experimental data of the central electron temperature.

In these simulations, the halo current parameters T_{halo} and W_{halo} are set carefully only for one of the representative discharges in the machines. For the simulations of the other experimental discharges for that machine, these parameters are kept unchanged and only the initial plasma and coil current parameters are used to mimic a predictive modeling scenario. Thus we believe the difference between the experimental and simulated halo current amplitudes for these discharges would give an idea of the possible percentage error in the predictive simulations.

3. Modeling of DIII-D discharges

For DIII-D we have selected four discharges for these simulations, namely shot numbers 154143, 154144, 158207 and 144838, all Type-I VDEs in DIII-D. We have completed the simulations for the first three shots, while simulations for shot #144838 are presently ongoing. Figure 2 below gives the experimental data of plasma and total poloidal halo currents, plasma vertical position and the central electron temperature measured in the soft X-ray channel.

We have adjusted the T_{halo} and W_{halo} parameters only for the shot #154143, which is an unmitigated forced downward VDE discharge triggered right from an H-mode at 2000msec. The plasma column goes into a downward VDE, touches the bottom wall and a fast thermal quench occurs between 2030.73-2030.81msec, thus in about 80μs. The shot #154144 is almost identical to #154143 until the current quench, but thereafter has a slower current quench and larger/longer halo pulse than #154143, probably due to decreased gassing from the wall. The shot #158207 in comparison has a much faster VDE motion with shorter duration but almost equally high halo current. In the

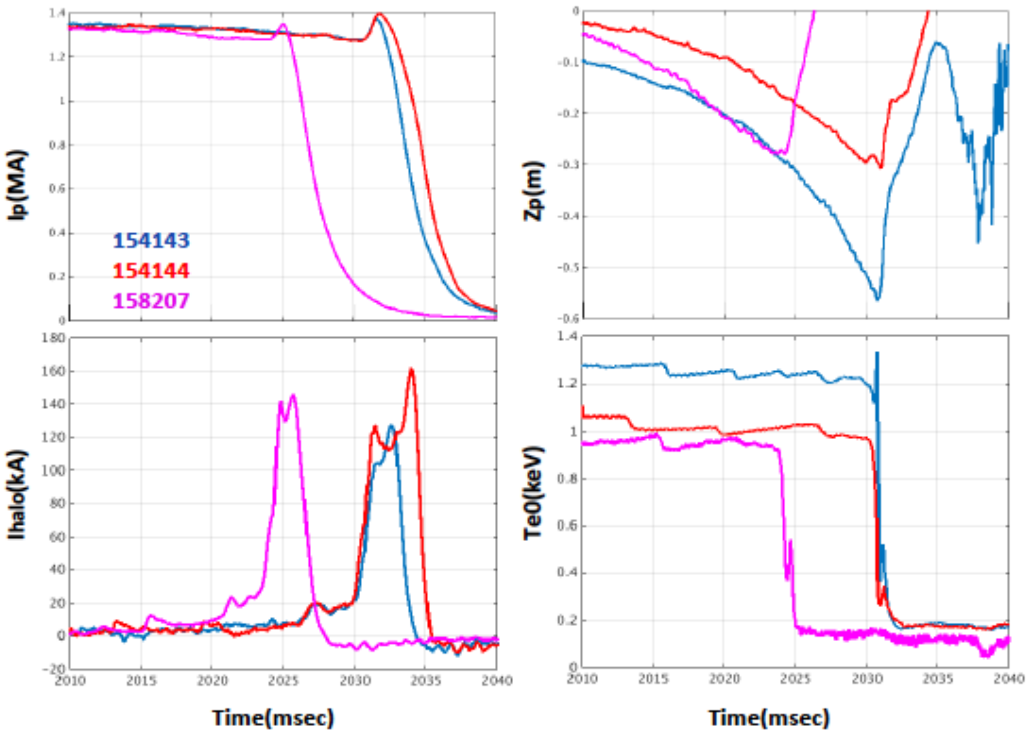

Figure 3: (Clockwise from top left) Evolution of the plasma current, vertical position, central electron temperature (Soft X-ray measurements) and the halo current in DIII-D forced VDE shots 154143, 154144 and 158207, which are modeled in TSC.

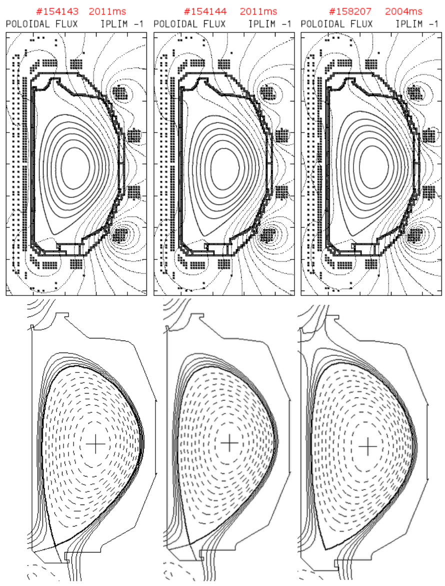

Figure 2: TSC simulated equilibria (top row) and EFIT reconstructed equilibria (bottom row) for DIII-D shots 154143, 154144 and 158207 at the time of start of the simulations.

Table 1: Comparison of equilibrium parameters of the DIII-D shots 154143, 154144 and 158207 in EFIT reconstructions against TSC calculated values at the time of start (shown in parenthesis at the top) of the simulations.

	154143 (2011ms)		154144 (2011ms)		158207 (2004ms)	
	EFIT	TSC	EFIT	TSC	EFIT	TSC
Ip(MA)	1.365	1.365	1.339	1.339	1.334	1.334
Xmag(m)	1.709	1.708	1.705	1.708	1.731	1.729
Zmag(m)	-0.050	-0.050	-0.0704	-0.0701	-0.047	-0.048
betap	0.604	0.602	0.513	0.509	0.620	0.618
li(GA)	0.601	0.583	0.596	0.583	0.596	0.591
qmin	1.17	1.13	1.346	1.1942	1.717	1.702
q95	3.263	3.265	3.131	3.170	3.162	3.169

simulations of these discharges it is of utmost importance to have the DIII-D vessel, in-vessel components and poloidal field coil system to be modeled in TSC as accurately as possible and also to have the initial TSC calculated plasma equilibria at the start of the simulations to have almost identical to the reconstructed DIII-D equilibria. We have created for DIII-D a detailed model of the vacuum vessel and the in-vessel components and PF coil system on a 2cm x 2cm computational grid with the poloidal halo current path in the first wall and vacuum vessel defined in reasonable detail. We have first tested the L/R time of the vessel and passive structure against the engineering parameter for the m=1 mode and it the TSC calculated value of 4.6msec and 6.2msec respectively with only vessel and vessel plus other in-vessel components are identical to the engineering value. The initial plasma equilibria at the start of the simulation, for the three discharges simulated is shown in Figure 3 and the equilibrium parameters as calculated in TSC as against EFIT reconstructed values are shown in Table 1. In these simulations, the equilibrium control systems are switched off after calculations of the initial equilibrium and the plasma column is allowed to drift freely, with the poloidal field due to the PF coil currents set identical to the experimental values. The halo current model is switched on as soon as the plasma becomes limited.

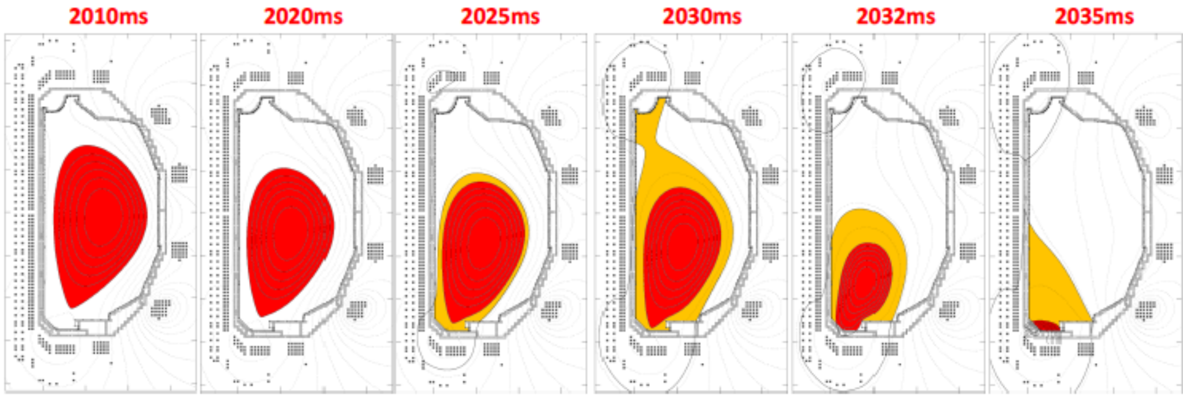

Figure 4:TSC simulated flux surface evolution of the disrupting phase of the VDE shot #154143. The orange region of the open flux surfaces represents the halo region.

Figure 4 shows the equilibrium flux surfaces of the disrupting plasma in VDE and the halo region as modeled by TSC. It is interesting to note that during the evolution of the halo region in this model, the halo region can be in contact simultaneously with both upper as well as bottom-inner part of the first wall, as is seen in the flux surface plot at time 2030msec. Such a halo region would allow halo currents to flow from the plasma both to the lower-inner as also the upper part of the first wall and their support structures to the vacuum vessel, which should show in the poloidal distribution of the

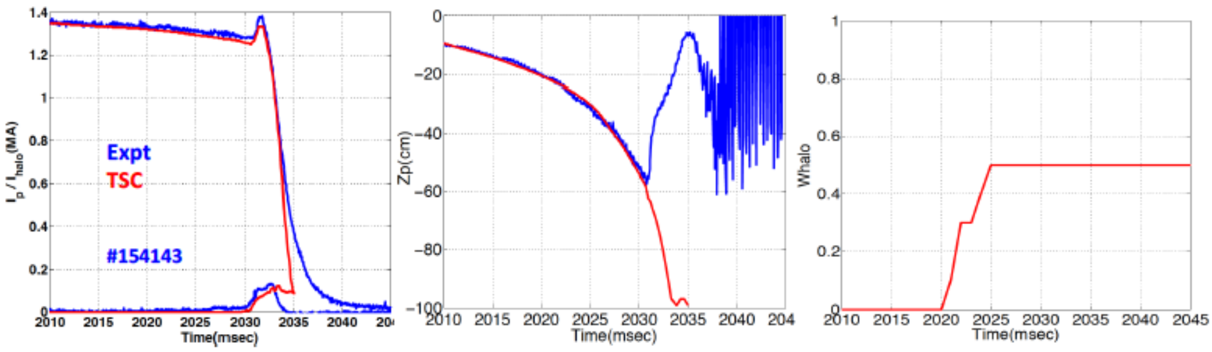

Figure 5: Simulated and experimental plasma current, halo current, plasma vertical position and the halo width temporal profile used in the simulation for DII-D shot #154143.

halo current measurements. We have not done the detailed investigation of the poloidal halo current distribution, which we intend to do in future. The evolution of the plasma and halo currents and the plasma vertical position as modeled by TSC and in the experiments, as also the assumed halo width evolution in the model for shot #154143 are shown in Figure 5. The halo current model is switched on after 2020msec when the plasma becomes limited and its width is raised linearly from 0 to 0.5 (fraction of plasma flux in the halo region) in 5msec and thereafter kept constant, while the halo temperature is kept constant at 6.5eV. It is evident that TSC can follow the plasma current evolution to very good accuracy, except for some difference in the final dying Ip evolution, during which the experimental data shows a smoother current termination, which TSC cannot follow. The vertical position is also followed in TSC to very good accuracy. The difference between the experimental Zp after about 2031msec is due to the fact that the experimental data considers the current center of the plasma including the expanding halo region, while TSC plots only the center of the closed flux region. The halo width evolution temporal profile used for #154143 is kept identical to the other 2 DIII-D shots modeled – #154144 and #158207. Figure 6 shows the experimental and simulated plasma and halo current evolution in these two shots. In these simulations also, TSC can follow both the Ip quench and the peak halo current amplitude to very good agreement with the experiments and the peak halo current amplitude matching to within 10-15% of the experimental value in the simulations. Although there is some difference in the durations of the halo current, the reasons for which we are presently analyzing.

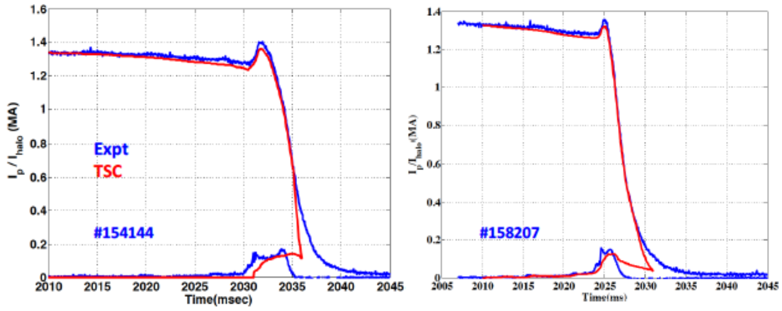

Figure 6: Experimental (blue) and TSC simulated (red) Plasma and poloidal halo current evolution in DIII-D VDE shots 154144 and 158207.

4. Modeling of CMOD discharges

For CMOD, we have selected the shots 1020801010, 1020801025, 1021010022, 1020903026 and 1020904014. Of these, the first three are MD shots, while the last two are VDEs. The shots were selected from the database carefully with having maximum Ihalo/Ip fraction, initial plasma current before onset of MD/VDE above 1MA. Of particular interest are the shots 1021010022, which clearly shows signature of rotating halo current and the VDE shot 1020904014, which shows a polarity reversal in the halo current. Figure 7 shows the evolution of the measured plasma and halo currents, vertical plasma centroid position and the central electron temperature in the MD shot 1020801010 on the left column and the VDE shot 1020903026, where

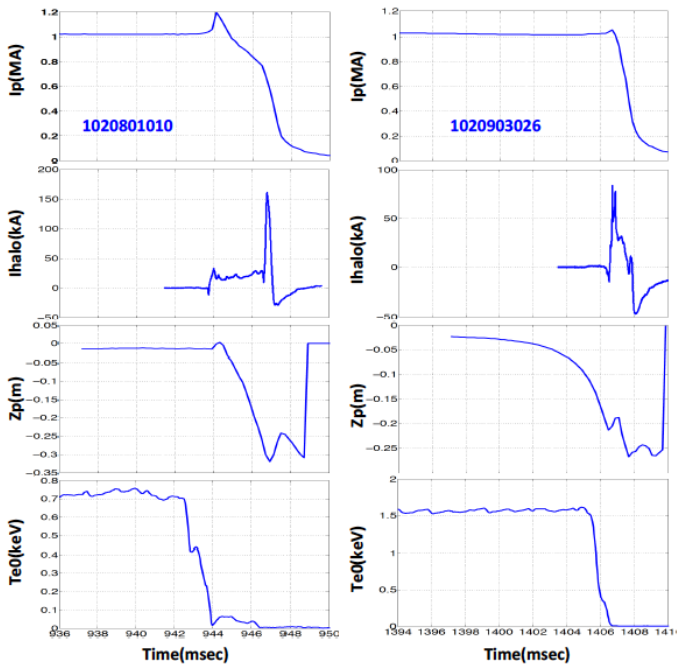

Figure 7: Evolution of plasma and halo currents, vertical position and central electron temperature in CMOD disruption shot 1020801010 (left column) and VDE shot 1020903026 which are modeled in TSC.

we have plotted only the part of the discharges modeled in TSC. The other MD and VDE discharges also have similar behaviour for these parameters. It is to be noted that the MD discharges start with the TQ, followed by the CQ and vertical drift of the plasma column, while in the VDE discharges start with the vertical drift, while the plasma temperature and current remains constant till the edge safety factor becomes low, finally leading to TQ due to MHD events and subsequently the CQ. This general behavior is flowed in all the MD/VDE discharges. Thus the MD shot simulations are also carried out by first calculating the plasma equilibrium about 5msec prior to the TQ and then emulating the TQ by artificially dropping plasma pressure to follow the experimental central electron temperature. In the VDE shot simulations, the plasma equilibrium at the start of the VDE is reproduced and the plasma is allowed to move freely by switching off the control systems and the thermal quench emulated similarly by dropping the pressure.

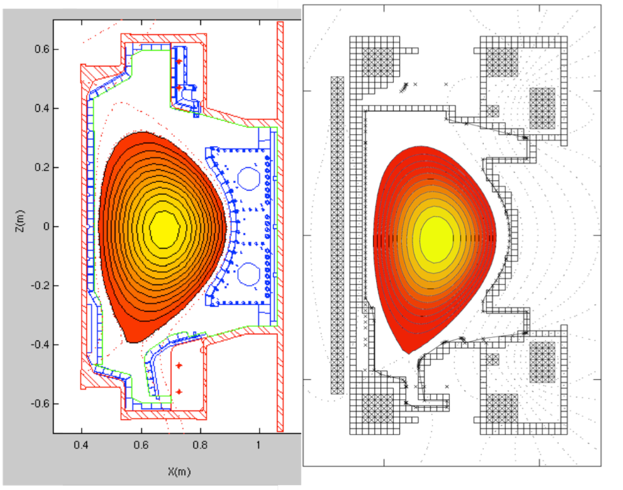

Figure 8: EFIT reconstructed (left) and TSC calculated plasma equilibrium for CMOD shot #1020801010 at 940.0msec, which shows very good match.

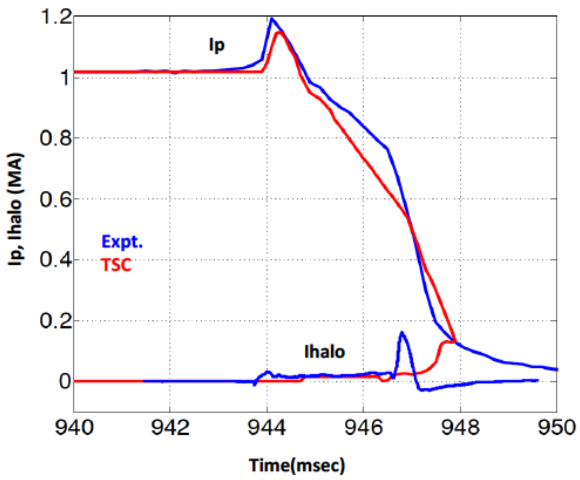

Figure 9: Plasma and halo current evolution in TSC simulations and experiment for CMOD shot #1020801010

We have carried out simulations for the shot #1020801010 and we present here the preliminary results, while simulations for the other discharges are in progress. For the CMOD simulations also, we have carefully calculated the initial plasma equilibria for the shots at the start of the simulation and validated it with EFIT reconstructed equilibria. Figure 8 shows the comparison of the EFIT reconstructed equilibrium with the TSC calculated equilibrium at 940.0msec when we start the simulation for this shot, which shows a very good match. In fact we have calculated the initial equilibria for all the CMOD shots to be modeled and like in the DIII-D cases, for all of these shots, the TSC calculated plasma equilibrium parameters match closely with the EFIT reconstructed values. The evolution of the experimental and TSC simulated plasma and halo currents between 940-950 msec are shown in Figure 9. While TSC is able to follow the Ip quench to good accuracy, there is some difference. The experimental Ip quench shows clearly two different decay rates – one a bit slower quench after the current peaking till 946.5msec, then a faster quench between 946.5-947.5msec. This could be due to a small change in the residual plasma temperature post TQ, which is difficult to determine from the experimental data due to high noise and very small temperature value post TQ. We have assumed a constant plasma temperature of 10eV in the simulations, which is kept constant post thermal quench. We are still investigating if assuming different plasma temperature during these times can reproduce the dual slope in the Ip quench. We are able to reproduce the nature of the halo current evolution in CMOD for this discharge, which shows an initial period of low halo current, finally terminating with a rapid peaking to 126.15kA. In the simulations also there is an initial period of about 2.5msec of low halo current and then a rapid peaking to about 114.6kA, although the time of the peaking of the halo currents differ in the simulations – it appears about a millisecond later than in the experiment. This could be due to the difference in slopes in the Ip quench, which we are investigating now. Figure 10 shows the evolution of the flux surfaces in this simulation with the halo current model switched on from 945msec. During the fast current quench phase, as the core plasma column shrinks and the halo region expands, the wetted area of the first wall changes, which is also determined to a large extent by the machine geometry. The effect of this on the poloidally distributed halo current measurements should be carefully analysed.

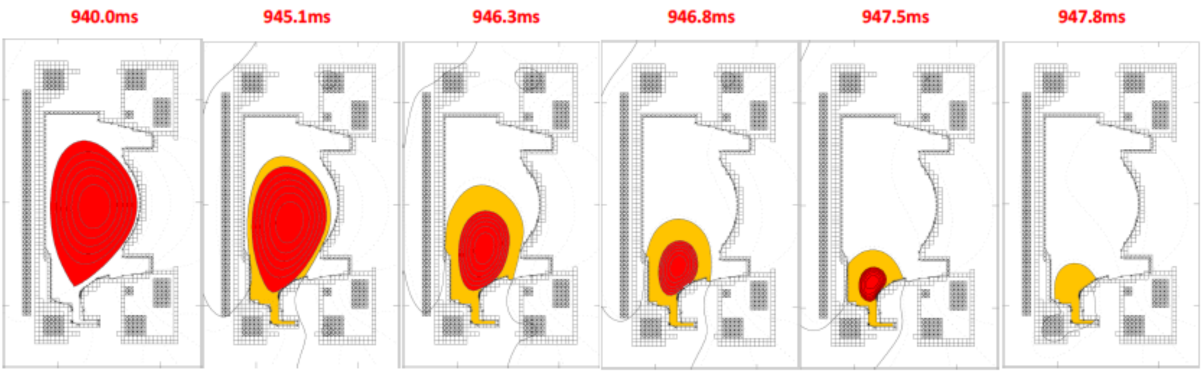

Figure 10: Flux surface evolution in TSC simulations of CMOD shot #1020801010

5. Summary

Benchmarking simulations of major disruptions and VDEs for a number of DIII-D and CMOD discharges are being carried out in TSC to have more insight into the adhoc halo current models used in these and other similar simulations. We believe that the results of these benchmarking simulations should provide a good estimate of the possible errors in the prediction of the halo current amplitudes arising from uncertainties of the halo parameters. We have so far carried out the benchmarking simulations in 3 discharges in DIII-D and one in CMOD and in all these cases we can reproduce the peak halo current amplitude to about 10-15% of the experimental value even with the ad-hoc model. We have also implemented new diagnostics in the TSC code to get the space resolved halo current distribution around the separatrix point. The simulated spatial distribution of the halo current will be compared with the experimental data in DIII-D and CMOD with the measurements in the Rogowski/partial Rogowski coils in the tiles and support structures. This will give a very good idea of how well the experimental halo current widths are reproduced in the simulations.

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