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MAST Halo Current Simulations with DINA-CH

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Introduction: Halo currents and the associated $\mathbf{j} \times \mathbf{B}$ forces on the vacuum vessel are a primary consequence of Vertical Displacement Events (VDEs), and both have the potential to be very damaging when scaled up to ITER-size devices. Currents that flow from the peripheral plasma region into the passive structure of the tokamak are termed halo currents[1] and can produce large structural forces, worsened by asymmetries in the plasma movement. VDEs become more likely for elongated plasmas, which are inherently vertically unstable and most tokamaks, including ITER, will operate with elongated plasmas to take advantage of the higher β, and therefore higher efficiency, making disruption avoidance and halo current mitigation critical issues.

The extreme geometry of Spherical Tokamaks (STs) makes them valuable machines on which to investigate halo current behaviour and test models. The free-boundary equilibrium evolution code DINA-CH[2], a non-linear time-dependent tokamak plasma simulation code, is being used to study halo currents in the MAST tokamak. DINA-CH is an open-architecture version of the DINA code[3] that runs in the Matlab Simulink environment and is particularly useful for modelling VDEs, where linearised models break down. The DINA code has been used extensively for design of plasma position, current and shape controllers, and work has also been done on halo current simulations of ITER[4] as a means of assessing the expected range of halo current amplitudes, having been successfully bench-marked against the experimental data of JT-60U[5] and DIII-D[6].

For modelling purposes, the vertical instability can be treated as an axisymmetric problem, where the equilibrium is described by the Grad-Shafranov equation and the plasma evolved according to external fields and the currents in the surrounding conductors. Currents in the passive conductors are also evolved. In this work, the halo current model used on JT-60U and ITER has been applied on MAST, with minimal modification relating to the geometry of the machine.

MAST VDE Modelling: Previously, a complete electromagnetic model of MAST has been constructed and validated in vacuum conditions and against provoked plasma VDEs, both cases demonstrating good agreement.

For halo current modelling, the VDE was triggered by cutting the feedback control on the plasma vertical position. Figure 1 shows the experimental signals of halo current (flowing in the internal upper P3 coil and down the leg (support structure) connecting it to the vessel), plasma current and Z position for shot 15045—an upwards VDE. Here the Z signal is calculated from the central column B_v (CCBV) measurements, which give the peak of the vertical field and thereby an indication of the movement of the plasma. It differs slightly from the EFIT signal, which is the Z of the magnetic axis, but is useful for when the plasma is no longer in equilibrium and there is therefore no EFIT output. On modelling this shot it has been found that allowing the plasma to evolve naturally and forcing the disruption at the time of the current spike by lowering the plasma temperature to $T_e = 20eV$ gives only satisfactory agreement with experiment, as shown in Figure 2a. The growth rate for DINA in this case is $87.5s^{-1}$, compared with $96.3s^{-1}$ for the CCBV signal—a difference of 9.1%, indicating that a difference in the initial conditions causes the discrepancy.

The plasma position growth rate can be reproduced by using feedback control to track the Z position calculated by EFIT, as shown in Figure 2b (note an offset calculated for the halo current has been removed). However, it has been found that the halo currents calculated for simulations using EFIT feedback do not reproduce the experiment as well as those left to evolve naturally.

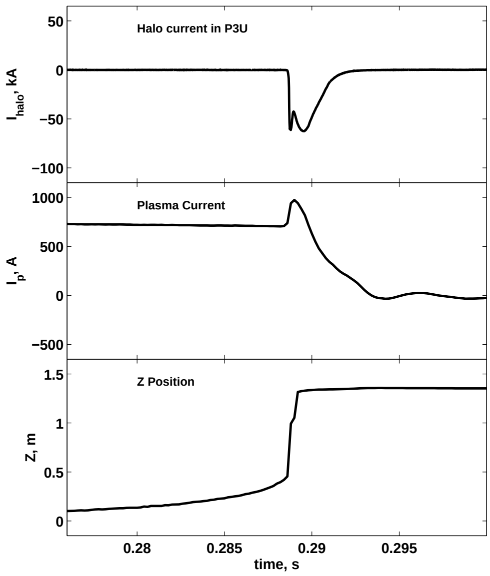
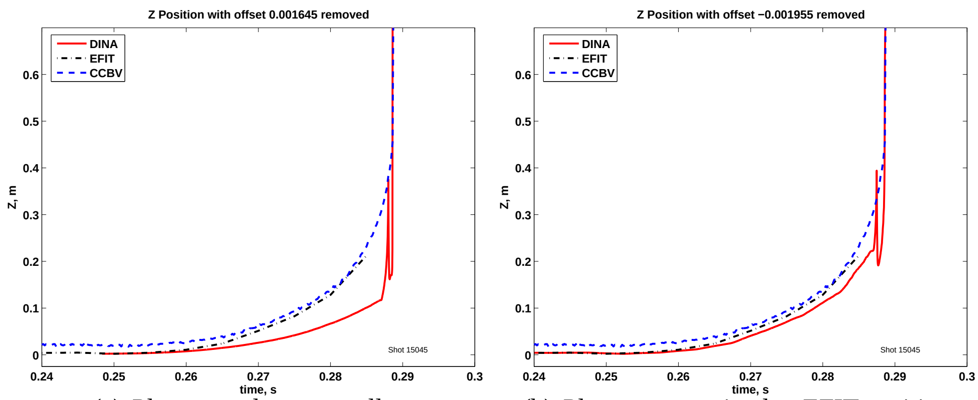


Figure 1: *Halo currents in the upper P3 leg, plasma current and plasma Z position for shot 15045.*

Calculation of Halo Currents: The first stage of the DINA calculation is the determination of flux surfaces and profiles from the solution of the Grad-Shafranov equation. Halo currents are determined for each component of interest by calculating the current flowing between adjacent flux surfaces and summing over all the surfaces that intersect the applicable region. Figure 3 shows, in poloidal cross-section, the plasma undergoing an upwards VDE. The contours represent flux surfaces, the red ones within the plasma and the blue the halo region. The black boundary line indicates the region of interest for the halo current calculation, skirting around the coils and the divertor plates. Where the blue contours intersect the black boundary line is where halo currents will flow. It should be noted that the black boundary line is used only for calculating the halo currents and does not serve any electromagnetic purpose in the simulation.



(a) Plasma evolves naturally (b) Plasma constrained to EFIT position

Figure 2: *Evolution of the plasma vertical position during the VDE.*

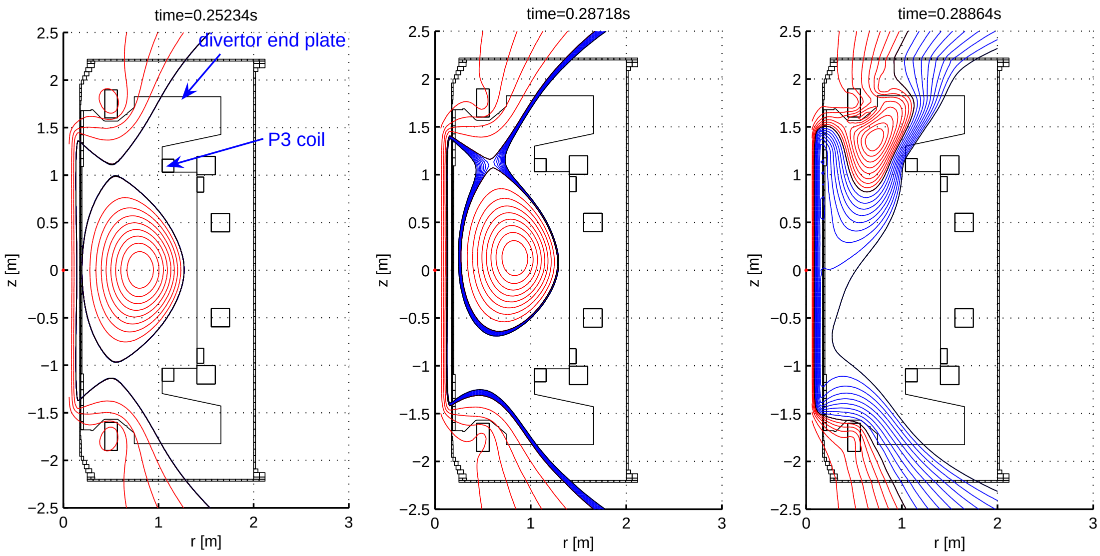
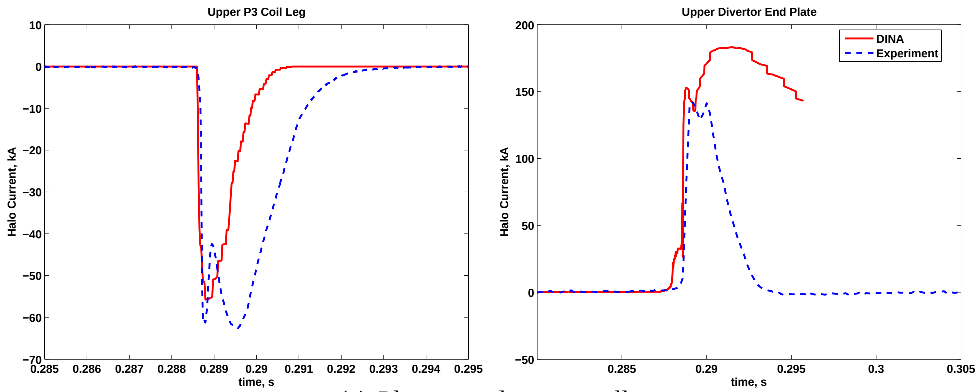


Figure 3: *Poloidal cross-section of the MAST vessel showing the halo region in blue and the black boundary line depicting the plasma-facing surfaces (simplified) with which the plasma or halo region could come into contact.*

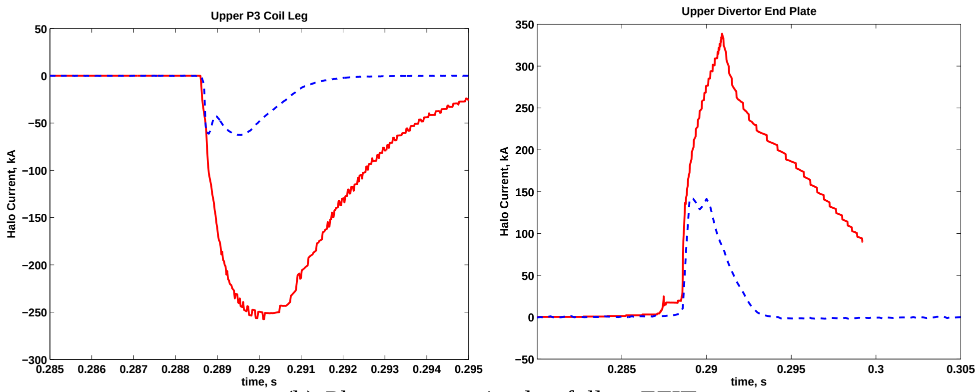
Figure 4a shows the DINA-simulated halo currents for the naturally-evolved plasma in the upper P3 coil leg and the upper divertor end plate, compared with the experimental halo current signals. These have been adjusted for a slight time offset of 1.65ms, which arises due to the unpredictable nature of the initial motion of the instability. Reasonable agreement is shown for both these regions, with the better agreement being demonstrated by the P3 coil leg. This indicates a limitation of the present halo current calculation by not considering "shadow regions" ie. areas of the boundary where the halo region intersects, but where the same flux surfaces have previously intersected another area of the boundary. One of these such regions is the far right edge of the plasma region that hits the top divertor end plate in the third image of Figure 3, having first passed through the P3 coil and leg boundary region.

The halo currents for the case where the plasma position is constrained by EFIT feedback are shown in the Figure 4b. In this case the offset is 1.97ms. It can be seen that the agreement with experiment is worse for this scenario.

Discussion: These first results show good agreement of the simulated halo currents with experimentally measured halo currents for the MAST tokamak when the plasma is allowed to evolve naturally. However, in this case the rate of change of the vertical position of the plasma is not wholly satisfactory and the model would benefit from some refinement in this area to improve its accuracy. The fact that the model itself has not been modified from that benchmarked on JT-60U and used to model ITER is encouraging as it helps to validate the intrinsic physics of the DINA-CH halo model. Future work will be concerned with further refinement of the model to better represent the features of the experiment, particularly in terms of plasma position, and giving greater consideration to the calculation of the halo currents to take into account the "shadow regions". A future enhancement of the model would be the inclusion of forces on the plasma induced by the halo currents, which it is hoped would improve the accuracy of the simulation.



(a) Plasma evolves naturally



(b) Plasma constrained to follow EFIT

Figure 4: *Total halo currents flowing into the P3 coil leg and the divertor end plates in the upper part of the vessel.*

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