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OPERATION LIMITS, VDEs AND HALO CURRENTS ON MAST

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Large scale mode activity and MHD limits which usually lead to plasma termination in large aspect ratio devices, often merely result in more benign Internal Reconnection Events (IREs) in Spherical Tokamaks (STs) [1]. In cases where disruptions occur they are normally associated with IRE-induced Vertical Displacement Events (VDEs).

In this first study we report on the behaviour of VDEs in MAST and their associated halo currents, and on early measurements of operation limits, where densities in excess of 1.8×Greenwald values have been observed.

Vertical Displacement Events (VDE)

The MAST central solenoid is relatively short and is intended to be used with a set of eight-turn compensating coils which are included within the P2 coil pack (see *Fig.1*). Operations to date have not used the additional compensation coils and without these the solenoid stray field is the dominant factor in determining the vertical stability of the plasma. One of the features of MAST is the use of the merging-compression scheme for plasma start-up pioneered on START [2]. During this phase the solenoid stray field is strongly stabilising, which aids plasma formation. However as the solenoid current reverses the stray field becomes more destabilising increasing the likelihood of VDEs. Because of this, the first few months of plasma operations has provided a large amount of data on VDE and halo currents. With additional development of the feedback system and commissioning of the compensation coils such VDEs should be avoidable.

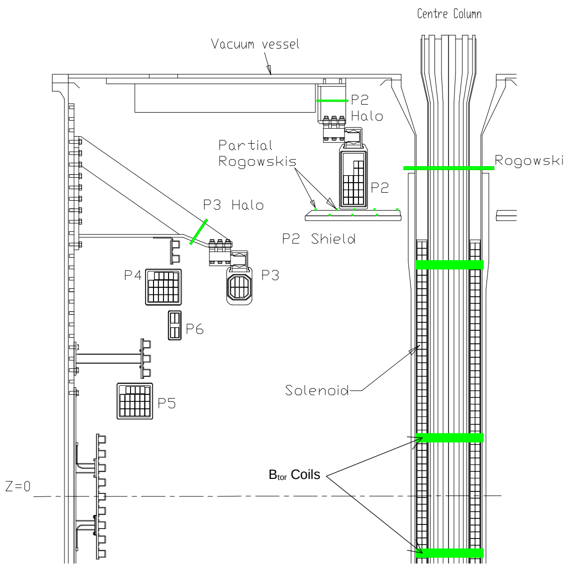

Figure 1: Schematic of MAST vessel showing position of halo current detectors

A VDE is often triggered by an IRE which introduces a rapid change in vertical position which, at present, the vertical feedback system cannot cope with. As found on START, IREs often occur following a drop in applied loop voltage, such as found at the end of the solenoid current cycle, or after long periods (15-20msec) of low or zero loop volts. In each case this will change the current profile near the plasma edge and may introduce destabilising current gradients at rational surfaces in the plasma. This type of IRE-induced VDE accounts for ~70% of VDEs observed on MAST.

MAST is equipped with a comprehensive set of halo current detectors comprising ~175 individual coils. These are divided into three groups; a set of full Rogowski coils around all the P2/P3 coil supports and around the top and bottom of the centre column (see *Fig.1*), arrays of partial Rogowski included in the P2 shield to measure radial and toroidal variations in halo currents, and bands containing 12 B_{tor} pick-up coils fixed at four heights on the centre column allowing toroidal and vertical variations in halo current to be determined.

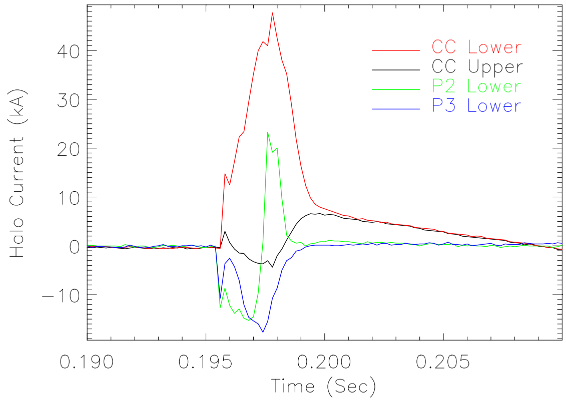

Figure 2: Total halo currents measured in P2/P3 Supports and centre column for a downwards VDE, I_p~ 390kA (shot 2223)

From the initial period of operations data on halo currents has been collected from over 300 shots, with plasma currents varying up to 1MA. Halo current data from a typical discharge at a time during a (downwards) VDE is shown in figure 2. The four traces show the total current measured in the lower P2/P3 coils supports and those flowing in the top and bottom of the centre column (here a positive value indicates currents flowing in the same direction as the TF current). At the beginning of the VDE the plasma is large and is making contact with both the P2 and P3 coils. The halo current is circulating between the centre column and P2/P3 coils. The reversal of the P2 halo current at t=0.197s coincides with the plasma hitting the limiter ribs at the bottom of the vacuum vessel (observed on high speed video film at this time). After the end of the VDE (t=0.2s onwards) the halo currents have died away, but the centre column Rogowskis show the poloidal eddy current induced by the plasma decay.

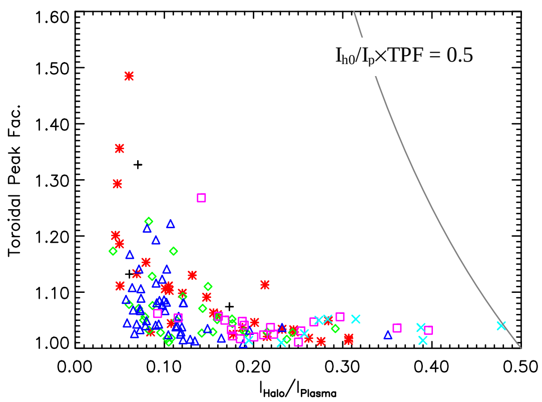

Figure 3: Toroidal Peaking Factor (TPF) for halo currents in P2 supports, calculated at time of maximum halo current. Line indicates typical design constraint for ITER-FEAT [3]

Evidence from the centre column B_{tor} coils show that the majority (70-75%) of the halo current enters the centre column within 30cm of the P2 shield (see *Fig.1*). Although, at a distance of 30cm from the P2 shield, the current sometimes shows a clear n=1 structure, at the level of the shield the current is almost completely symmetric. Figure 3, shows Toroidal Peaking Factor TPF for halo currents in P2 supports, calculated at time of maximum halo current (where we have defined TPF as 1+(Peak-Average)/Average). These results are similar to values calculate for currents in the centre column. A low level of asymmetry is important as it reduces tilting/bending forces on components (especially important for the MAST centre column).

A database has been built up containing information on all of the halo current measurements from this initial campaign. The full database is summarised in figure 3 showing the maximum total halo current fraction for each of the three main current paths, (centre column, P2 and P3 supports) as a function of plasma current. The plasma current is measured before the VDE and any associated IRE, which significantly increases I_p just before the VDE. Included are contours of constant halo current. Large halo current fractions have been observed at low plasma currents (up to 50%) usually when the plasma has decayed significantly and the aspect ratio is greater than 2. For larger plasma currents (with lower aspect ratio) the halo current fraction is much lower than this, with halo current fractions above 25% not seen when I_p is greater than 500kA.

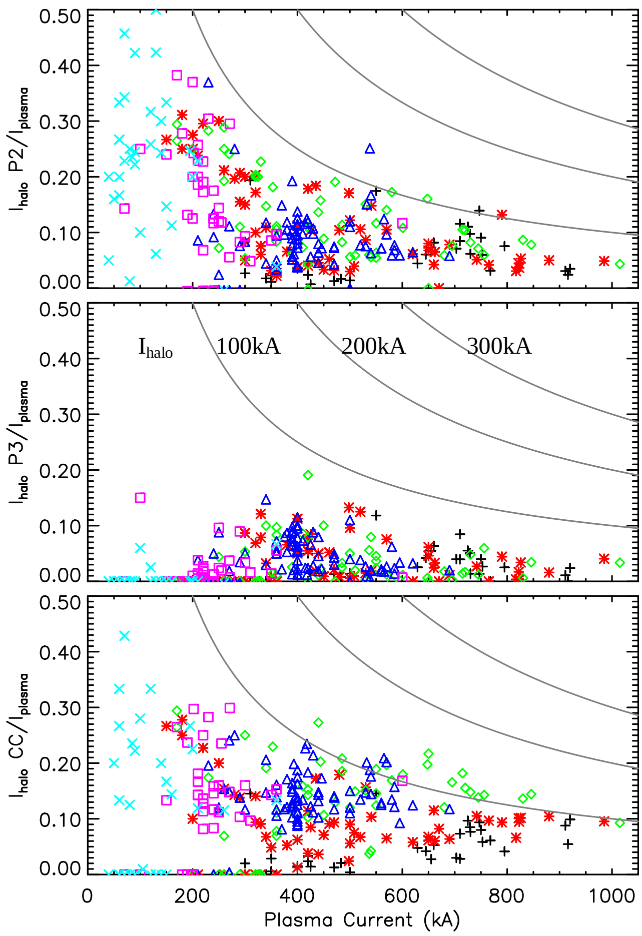

Figure 4: Summary of halo current measurements in MAST. Lines indicate curves of constant halo current. Symbols indicate where in the solenoid cycle the VDE occurred. Start-up, rampdown, flattop and decay phase (+,*,Δ,×) and also those triggered by rapid changes in loop volts (◊, ❑).

Operations at reduced TF show a general increase in halo currents, with current fractions in very low-q regimes significantly larger than under normal circumstances, though no clear trend is seen in the data.

MHD behaviour and Performance Limits

Internal Reconnection Events are observed at various points during the discharge and in particular close to density and q-limits. Preliminary experiments to investigate plasma operation at low q have been undertaken. There is presently an operational limit of q_{95} ~3.2-3.5, below which IREs and VDEs limit the plasma performance. These events could be a consequence of q-values near the edge passing through a rational value (as observed on other tokamaks, where operation can be difficult at q_{95}~3)

A number of campaigns have been carried out on MAST to study density limits. For low plasma currents (300kA), with simple gas refuelling, it was possible to produce densities well in excess of the Greenwald limit ($n_{eGr}(10^{20}m^{-3}) = I_p(MA)/\pi a^2(m)$) with Greenwald number $G = n_e/n_{eGr}$ ~1.8 obtained. Operation above these densities is typically prevented by the appearance of an IRE which drops the density significantly (as much as 50%). At higher plasma currents (I_p ~ 600kA), where n_{eGr} is higher, the highest densities achieved with gas puffing have not so far reached the Greenwald limit (typically G ~ 0.6) The is limited by length of the discharge and higher densities should be achievable with a longer plasma duration.

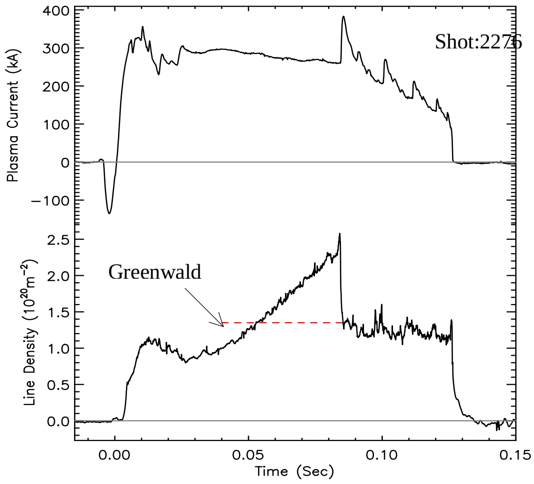

Figure 5: Operation significantly above Greenwald have been achieved. Density rise limited by IRE.

Conclusions:

A comprehensive set of halo current diagnostics have been installed on MAST and a large database created, including points with I_p in excess of 1MA. Initial halo currents measurements suggest that VDEs will not prevent MAST reaching its design limit of 2MA. Halo current fractions up to 50% have been observed at larger aspect ratio, but for larger plasmas, higher currents (>500kA) and low aspect ratio this fraction remains below 25%. Toroidal asymmetries are not so far a concern, since they are very low, except for very small halo current fractions, and well below guide lines for ITER-FEAT [3].

Operation limits have been investigated, with density limits in excess of 1.8×Greenwald observed.

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References

[1] R J Buttery *et.al.*, **Study of Internal Reconnection Events on the START Tokamak**. Proceedings 23rd EPS Conference on Controlled Fusion and Plasma Physics, (Kiev 1996). **Part** 1, pg416

[2] A Sykes *et.al.*, **The spherical tokamak programme at Culham.** (IAEA Vienna 1999) Nuclear Fusion **39**, pg 1271

[3] R Yoshino *et al.*, **Characterization of disruption phenomenology in ITER,** Proc.17th IAEA Conf.on fusion energy, Yokohama, Oct.1998. Paper ITERP1/14