

Asymmetric halo currents in ASDEX Upgrade disruptions

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Introduction. The origins of the asymmetries of the halo currents and of the forces on the vessel during disruptions remain a subject of interest ^[1]; in fact their understanding could lead to the reduction or suppression of the asymmetries with beneficial effects on the mechanical components of the tokamak. The possible origins of such asymmetries are: MHD modes in plasma ^[2], halo-wall instabilities ^[3] and asymmetries in the machine itself. Several disruptions in flat-top in the shot range 13000-14050 of ASDEX Upgrade were considered with the aim of analyzing the asymmetries of the halo currents and the correlation among the asymmetries, the MHD activity during the disruption and the plasma parameters. The chosen plasma discharges had different values of plasma parameters and were terminated by a midplane disruption with VDE-downwards or by a disruption following VDE.

Shunt measurements. The halo currents in ASDEX Upgrade are measured by resistive roads (*shunts*) mounted between divertor tiles and divertor support. The divertor is equipped with 90 shunts distributed in poloidal and toroidal arrays. In this work we make mostly use of a toroidal array of shunts mounted below 8 tiles located at the same poloidal location (indicated with *DUAm*, see Fig.1) and at 8 different toroidal positions, in 8 of the 16 toroidal sectors.

Asymmetries in the halo currents and modes. The SXR, the Mirnov coils and the halo current measurements show a quite interesting picture of the MHD activity affecting the plasma after the disruption. Typical post-disruption scenarios are described in the following.

- Shot **13027** disrupted in the midplane at $t = 4.242$ s because of density limit at 600 kA (see Fig. 2a). The plasma has a $|q_{95}| = 5.7$ and a lower-single-null before disruption, and it undergoes a VDE-downwards. The current quench lasts 14 ms, which is relatively long and the disrupted plasma has the time to reheat enough for the SXR emission to become detectable again. The SXR camera, which views the plasma from the outer midplane horizontally, shows (see Fig. 3) that the plasma has nested flux surfaces and its core kinks while shifting to the bottom of the vessel. At $t = 4.255$ s the SXR emission terminates abruptly because of a reconnection event. The appearance of a toroidal perturbation of the halo current at $t = 4.256$ s, just after the reconnection event seen in the SXR, is easily identified on top of the $n=0$ basic structure of the halo current (Fig. 2b). This structure rotates in the negative toroidal direction ($I_p > 0$, $B_t < 0$) at 500 Hz.

- Shot **13191** disrupted at $t = 2.003$ s (Fig. 4a) after a VDE due to control error. The current quench lasts up to $t = 2.008$ s, at which time the initial plasma current of 800 kA has vanished. The plasma had original a $|q_{95}| = 4.5$ at the start of the VDE and $|q_{95}| \simeq 2$ at the time of disruption. The halo currents in the DUAm tiles (Fig. 4b.) also show the $n=1$ perturbation, similarly to shot 13027, appearing just after the disruption.

- The halo currents do not always exhibit large toroidal asymmetries or/and the $n=1$ structure. In shots with relatively symmetric halo currents the SXR emission is not visible anymore after disruption and the magnetic measurements show the succession of several voltage spikes. This suggests that these plasmas suffer of strong MHD activity which prevents them from reheating and developing the configuration leading to the

n=1 structure.

Comments. The n=1 perturbation of the halo current is always clearly seen in plasmas similar to shot 13027 (density limit at $|q_{95}| \simeq 5-6$) and in disruptions following a VDE (with $|q_{95}| \simeq 2$ at the disruption time like shot 13191). The n=1 structure does not necessarily rotate. After the disruption the equilibrium reconstruction program FP (Function Parametrization) fails to deliver reliable values of q_{95} ; an approximate estimation of q_{95} is obtained afterwards with the formula

$$q_{cyl} = c(R_{curr} - R_{in})(z_{curr} - z_{low})/(I_p R_{curr}) \quad (1)$$

(I_p is the total toroidal current in plasma, including the halo region; z and R are the vertical and radial position of *curr*, the plasma current center, of *in* and *low*, the innermost and lowermost points of the plasma surface; c is determined by fitting q_{cyl} to q_{95} before disruption; the toroidal magnetic field is assumed constant).

The n=1 structure is always clearly correlated with a reconnection phenomenon seen by several diagnostics and appears when $|q_{cyl}|$ approaches or becomes smaller than 2. The SXR emission drops abruptly after a strong kink-like movement of the plasma center, the H_α signal and the heat load measured by the thermography show a large flux of particles and heat to the structures and the Mirnov coils a strong positive voltage spike. The Mirnov coils in the lower part of the vessel are saturated but the poloidal arrays of halo current measurements show a poloidal structure consistent with a m=1 poloidal mode number of the n=1 structure (the relative Figure is omitted because of space limitation).

The role of q_{cyl} in the appearance of the n=1 structure is clearly seen in Fig. 2a and Fig. 4a and confirmed by the scatter plot in Fig. 5 showing the contour plot of the local toroidal peaking factor, *tpf* (ratio of maximum to toroidally averaged halo current measured at the DUMa tiles), as function of q_{cyl} at the time of the max halo current and of q_{95} before disruption. The *tpf* reaches its maximum for $q_{cyl} \sim 2$ and $4 < |q_{95}| < 5.5$. For shots which disrupt with a small $|q_{95}| \simeq 2-3$ in the midplane the current quench is rather fast and turbulent; the n=1 mode is not seen and the *tpf* at the time of max halo current remains relatively small.

The n=1 halo structure is also suppressed or its amplitude reduced with the injection of killer pellet in shots similar to 13027 as already reported for DIII-D [5]. The same cannot be said for disruption-softening experiments carried out with impurity puffing where the n=1 is still clearly observed (in spite of the significant reduction of the average toroidal halo current). This suggests that a reduction of the plasma current peaking at the center (which can be assumed after pellet injection) reduces the *ftp*.

The several observations reported above are consistent with the following picture. The m=1 n=1 structure of the halo current has to grow on the q=1 surface; at the time of the asymmetry growth the $q_{cyl} \sim 2$. It is not clear if the q=2 surface plays a role in triggering the [1,1] mode or if this mode is triggered by the interaction of the q=1 surface with the wall. In any case, the dominant role of the q=1 surface is consistent with parametric studies of the current profiles and with the following facts: when the toroidal plasma current profile is flat then the q=1 surface is small or absent and therefore (1) after killer-pellet, (2) in turbulent post-disruption phases and (3) in plasmas with a fast current quench (no reheating, no reappearing of the flat post-thermal-quench current profile, absence of SXR emission) the [1,1] structure is not seen.

Review of related works. The halo currents integrated in time and the forces on the

vessel in JET [6] were first reported to be toroidally asymmetric (with mode number $n=1$). Reference [7] already pointed out the determinant role of the safety factor and of the current quench rate in determining the appearance of large $n=1$ toroidal modes and sideways vessel displacements in JET ($q_{cyl} < 1.5$ and $dI_p/(I_p dt) < 30$ 1/s).

A clear helical structure in halo currents was reported for the first time to have been seen in Alcator C-Mod [4]. The structure is described as a combination of a $n=0$ component and a $n=1$ component of comparable magnitude; the $n=1$ structure rotates with a few kHz in the direction opposite to I_p and B_t . No correlation between the toroidal asymmetry and /or rotation of halo currents with global parameters of the disruption was found.

The halo current is seen to rapidly increase and to reach its maximum after an MHD event in JT-60U [8]. The MHD event is observed in disruption following a VDE when $q \sim 1$ (the q of the last close flux surface) and it is *sometimes* accompanied by a toroidal $n=1$ structure rotating at a frequency of 500-700 Hz.

The first attempts to explain the origin of the halo currents pointed at MHD instabilities [2] and at a plasma-wall instability with a stable plasma core [3]. In Ref. [1] the halo current asymmetries are attributed to saturated 2/1 or 1/1 external kink modes. The qualitative dependence of the TPF (peak to average toroidal peaking factor of the halo current integrated over the divertor plate) on I_h/I_p follows from geometric considerations. The magnitude of the TPF depends on the level of saturation of the kink modes and should be calculated by appropriate MHD models for plasma and wall.

Conclusions. A clear $m=1$ $n=1$ perturbation of the halo current is seen in many ASDEX Upgrade disruptions; it is clearly correlated with q_{cyl} dropping below 2 and with a MHD event. The local degree of asymmetry of the halo current can be relatively large ($f_{tp} \simeq 3.5$). There is clear indication that avoiding the reappearing of the current profile after thermal quench and reducing or eliminating the region inside of the $q=1$ surface in the plasma suppresses the [1,1] asymmetry. The experimental observations from several tokamaks suggest that the $n=1$ halo current asymmetry originates on the $q=1$ surface and is probably the manifestation of a common MHD phenomenon.

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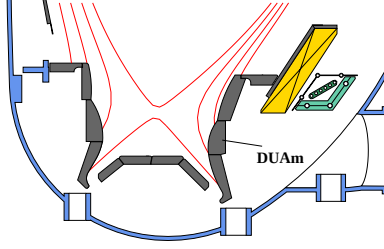


Figure 1. Divertor structure.

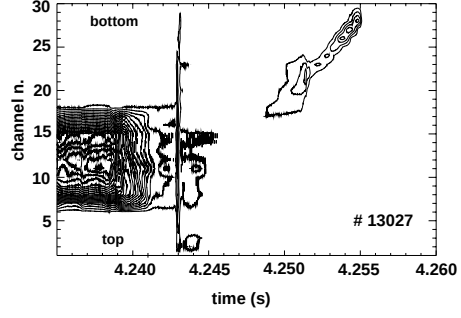


Figure 3. Contour plot of the SXR emission (channel 30 is the lowermost).

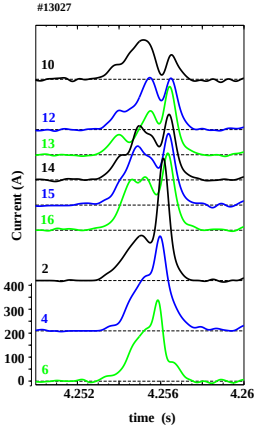
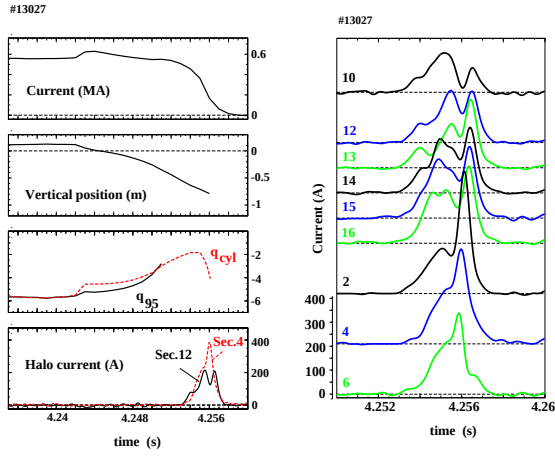


Figure 2. (a) Time traces of several plasma parameters and of the halo current measured at the DUAm tiles positioned in sector 4 and 12, 180 degree apart. (b) Time traces of the halo current measured at the 8 tiles of the DUAm toroidal array in sectors 10, 12, etc..

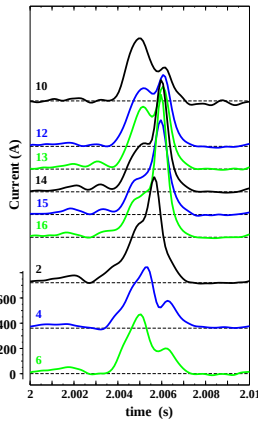
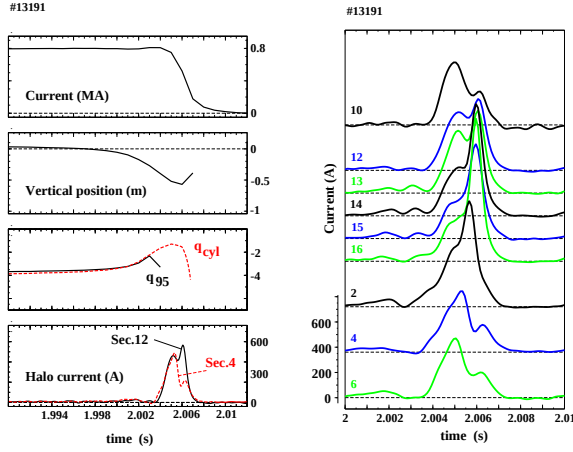


Figure 4. (a) Time traces of several plasma parameters during a VDE followed by disruption. (b) Time traces of the halo current measured at the 8 tiles of the DUAm toroidal array.

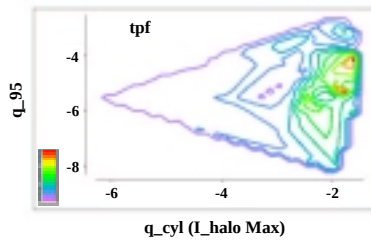


Figure 5. Contour plot of the local "toroidal peaking factor" as function of q_{cyl} at the time of maximum halo current and of q_{95} before disruption.