# Evolution of the halo current in ASDEX Upgrade disruptions

*G. Pautasso, L. Giannone, A. Herrmann, M. Bernert and the ASDEX Upgrade Team*
*Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching*

**Introduction.** The halo current causes large electromagnetic forces and, from an engineering point of view, its magnitude and spatial distribution must be known for dimensioning the intercepted structures. This work is part of the effort made by the existing tokamaks in the framework of the ITPA MHD Topical Group to characterize the development of the halo region on the basis of experimental measurements and physical models, and provide specifications to ITER. In particular, it supports the detailed benchmark of the halo current models contained in the MHD-transport codes DINA and TSC. Simulations of ASDEX Upgrade (AUG) plasmas during vertical displacement following (VD) or preceding (vertical displacement event, VDE) a disruption are being carried out at the moment [1,2] with these codes.

**Diagnostic description.** Scrape-off-layer and halo currents are measured in AUG with shunts mounted between tiles (located on the inner wall, the upper and lower divertors) and their mechanical support. Since the lower divertor is equipped with a larger number of current sensors than the upper one, only plasmas undergoing a downward VD are analyzed here. The AUG vessel consists of 16 toroidal sectors, 4 of which (sectors 4, 10, 12 and 14) are equipped with a complete poloidal array of shunts across the lower divertor. Exceptionally, sector 4 is equipped with two poloidal arrays. One poloidal array consists of 12 shunts, i.e. as many as the number of tiles in the poloidal direction. The lower divertor in each sector is covered by 74 tiles; therefore 16 % of the divertor surface in one sector, that is 5 % of the total lower divertor surface, is equipped with shunts. The current through the heat shield is measured in 3 sectors (4, 10 and 14) at 5 of the 15 poloidal array tiles, that is on 3 % of the heat shield surface.

**Data.** The database used in this work consists of discharges disrupted during operation in 2008-09 (shot range 23210-25890). The subset analyzed is defined by the conditions $I_p \geq 0.5$ MA ($I_p$ is the toroidal plasma current before the thermal quench) and VD or VDE downwards. 10 % of the measurements are unavailable in this shot range and are substituted by neighboring (same poloidal position and closest toroidal location) measurements.

**Total halo current and TPF.** The toroidally-averaged total halo current is calculated from the AUG shunt measurements in the following way:

$$I_h(t) = \sum_{i=1,4} [\,|\sum_{j=1,6} I_{i,j}(t)\, N_j| + |\sum_{j=7,12} I_{i,j}(t)\, N_j|\,]\,/2/4 \times 16 \qquad (1)$$

where $I_{i,j}(t)$ is the current collected by the tile $i,j$, $i$=1-4 indicates the sector, $j$=1-12 stands for the poloidal position and $N_j$ is the number of tiles aligned in the toroidal direction in one sector at the poloidal location $j$. The two arrays of measurements in sector 4 are toroidally averaged before being used in the previous equation.

The toroidal peaking factor, as function of time, is defined as the ratio between the maximum halo current in one sector, inboard or outboard, and the toroidally averaged

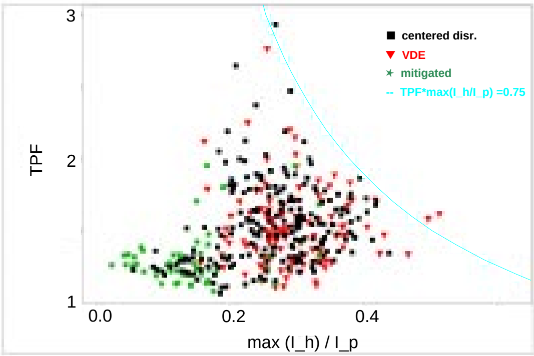



**Figure 1** . $TPF$ versus $max(I_h)/I_p$.

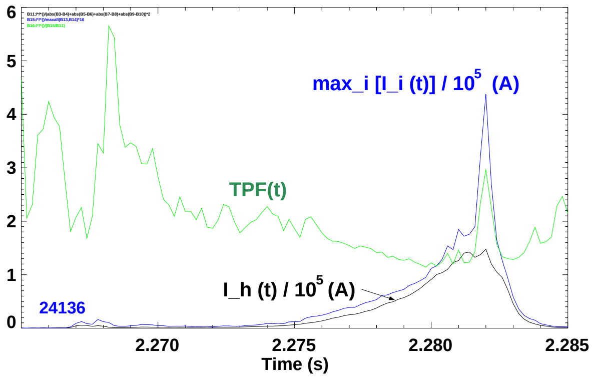



**Figure 2** . Time traces of $TPF(t)$, $I_h(t)$ and $max_i[I_i(t)]$ for the discharge of Fig. 1 with the largest $TPF$.

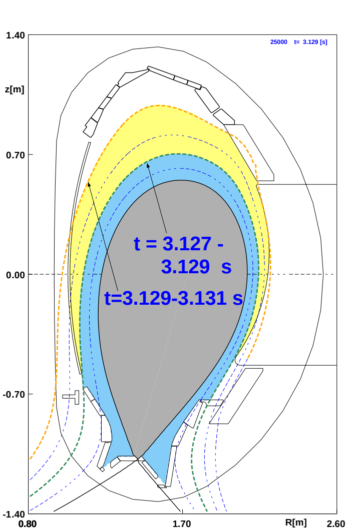
halo current per sector, $I_h(t)/16$:

$$TPF(t) = max_i[\,|\sum_{j=1,6} I_{i,j}(t)\,N_j/I_h(t)\times 16|\,,\,|\sum_{j=7,12} I_{i,j}(t)\,N_j/I_h(t)\times 16|\,] \equiv \frac{max_i[I_i(t)]}{I_h(t)} \tag{2}$$

Note that, by definition, $TPF \leq$ (number of sector halves equipped with current measurements) $= 8$.

A total of 60 shunts are used for the evaluation of $I_h$ and $TPF$. The current flowing through the heat shield amounts to less than 10 % of $I_h$. There are no equivalent measurements on the low-field-side of the inner wall (ICRH antenna limiter). Therefore it was decided to neglect this fraction of the halo current (which, by the way, does not contribute to the total vertical force) and to use both inward and outward flowing currents in the evaluation of $I_h$ and $TPF$. The shunt measurements from the heat shield are then taken into account in VD/VDE simulations, where they provide information on the extension of the halo region.

The ITER specifications for the expected magnitude of the halo current and its degree of toroidal asymmetry have been based - up to now - on data collected from several tokamaks and summarized in the plot of the $TPF$ versus the maximum halo current fraction, $max(I_h)/I_p$ (Fig. 42 of ref. [3]). This $TPF$ is, more precisely, taken at the time of the maximum halo current fraction and, if not otherwise specified, $TPF \equiv TPF(t_{max(I_h)/I_p})$ will also be used in this work. Nevertheless, there is no physics based specification for the time history of $I_h(t)$ and $TPF(t)$ at the moment. Particularly, the information on the duration of $max(I_h)$ and $TPF$, that is on the impulse exerted on the mechanical structures, is required for their design since the dynamic response of the structures can have time constants longer than the duration of these maximum loads. In addition, it is not correct to assume that the maximum localized halo current occurs at $t_{max(I_h)/I_p}$. All the data points in the forementioned plot lay under or close to $TPF \times max(I_h)/I_p = 0.75$ [3] but this boundary represents a challenging load for the mechanical design of the structures if constantly applied. $max(I_h)/I_p$ can reach 50 % in AUG, as it is shown in Fig. 1, although the mean of its statistical distribution amounts to 27 % for unmitigated disruptions; mitigated disruptions have a much lower halo current. The $TPF$ can reach the value of 3. The curve $TPF \times max(I_h)/I_p = 0.75$ is also shown in the Figure. Several discharges are close to this boundary: These have been analyzed in more detail to find



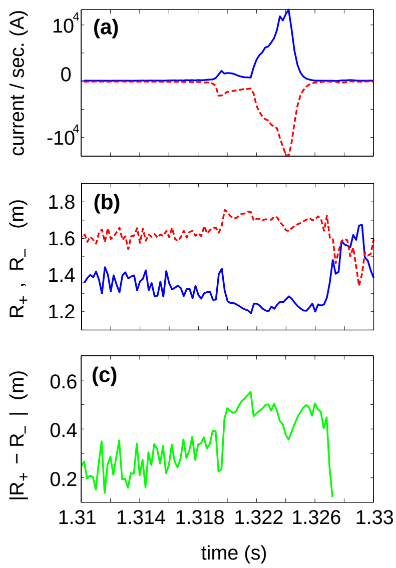




**Figure 3 (left).** Last FP equilibrium reconstruction showing the halo region extension before (t=3.127-3.129 s) and after (t=3.129-3.131 s) thermal quench.

**Figure 4 (right).** Time histories of **(a)** the halo current flowing into and out of a sector, **(b)** its barycenters and **(c)** their distance.

out under which conditions (plasma and machine parameters) the average or localized halo current can be large.

The largest values of $max(I_h)/I_p$ are reached in three VDEs, with $I_p$ = 0.6 MA, safety factor $q_{95}$=4-5 and thermal energy $E_{th} \leq 0.1$ kJ. The largest values of $TPF$ occurred with centered disruptions followed by VD - with the exception of one VDE. The three discharges close to the boundary at large $TPF$ have $I_p$ = 0.5-0.6 MA, $q_{95}$=5-6.5 and $E_{th} \leq 0.1$ kJ. Independently of where the discharge is located along the boundary, the large $max(I_h)/I_p$ or/and $TPF$ last 0.2-0.4 ms, i.e. 1-2 sampling points, and they always coincide with the appearance of a large m/n=1/1 mode; time histories of $I_h(t)$ and $TPF(t)$ for the disruption with the largest $TPF$ are shown in Fig. 2 and illustrate this fact. In all the disruptions analyzed, typically, about the time of $max(I_h)$, the plasma has displaced vertically, is limited by the divertor surface, and the toroidal current decay rate has its maximum. A 1/1 mode suddenly grows, is detected by the fast magnetic coils and its 1/1 structure is also seen on the halo current measurements. Probably the strong interaction with the tiles cools the plasma edge, steepens the current profile and destabilizes the mode. If the strong interaction with the plasma wall is missing, such as after massive gas injection, the strong MHD event is not visible and the halo current is toroidally symmetric. The 1/1 halo current structure survives for a few ms, it is generally locked or rotates slowly with a frequency $\leq 1$ kHz, at most 1.5 times around the torus. The difference between the high $max(I_h)/I_p$ and high $TPF$ data points along the boundary seems to be due to the different amplitudes of the 1/1 halo current perturbation and its occurrence in time, with respect to $t_{max(I_h)/I_p}$. How this depends on the plasma parameters is not understood.

Unfortunately it is not possible to provide meaningful error bars on the evaluation of the $TPF$ and halo fraction since the error affecting them depends also on the current which is not measured: In fact we extrapolate to the whole divertor surface the current measured on only 5 % of it, although the measurement of the current through a tile is rather accurate.

**Width.** The evolution of the halo region is being studied by simulating VDEs and centered disruptions with the DINA [1] and TSC [2] codes. In fact, the standard AUG equilibrium reconstruction code FP, does not take halo currents into account and fails to produce an output during disruptions. Nevertheless, general trends in the development of the halo region can be deduced from the spatial distribution of the measured halo current. It is clear, for example, that the halo region forms during the thermal quench and intersects the heat shield up to $z \sim 0.1$ m. An example of the halo extension in the case of a VDE is shown in Fig. 3, along with the last valid FP equilibrium before the thermal quench. During the whole current quench, currents intercept the heat shield, indicating that the halo region is filling the lower vessel half and replacing the close flux surface region. Nevertheless most of the halo current flows through the divertor tiles and the centers of gravity of its radial distribution are calculated in the following.

**Current barycenters.** The *barycenters* of the halo current flowing into and out of the divertor are defined as:

$$R_+(t) = [\sum_i \sum_{j=1,6} I_{i,j}(t)\, N_j\, R_j] / \sum_i \sum_{j=1,6} I_{i,j}(t)\, N_j \quad (3)$$

$$R_-(t) = [\sum_i \sum_{j=7,12} I_{i,j}(t)\, N_j\, R_j] / \sum_i \sum_{j=7,12} I_{i,j}(t)\, N_j \quad (4)$$

with $R_j$ being the radial location of the $j$ tile. In addition, effective barycenters, $R_+^{eff}$ and $R_-^{eff}$, can be defined by current weighting and time averaging the $R_j$s. The distance between them, $\Delta R = |R_+^{eff} - R_-^{eff}|$, is a measure of the effective length of the poloidal path of the halo current in the vessel. The resulting vertical force is $F_z \simeq \Delta R B_t I_h$. A typical time behavior of the halo current and its barycenters is shown in Fig. 4 for a beta-limit centered disruption. The halo region is spatially developed in space right at the thermal quench and the current barycenters move from the inner and outer divertor plates towards the dome during the VD. $R_+^{eff}$ and $R_-^{eff}$ vary within 10 cm and $\Delta R =$ 0.41 +/- 0.05 m throughout the database considered. In addition, $\Delta R$ tends to be larger for mitigated disruptions, in which the plasma - and with it $R_+$ and $R_-$ - does not move significantly towards the divertor dome. These results are qualitatively and quantitatively similar to those from DIII-D [4].

**Summary.** Disruptions with $TPF \times max(I_h)/I_p \simeq 0.75$ have been analyzed; large values of halo current and its asymmetry last 0.2-0.4 ms and coincide with the fast growth of a short lived m/n=1/1 mode. The question whether 2D MHD thansport codes can reproduce $max(I_h)/I_p$ is under investigation. The issues, how long such a large current and its asymmetry can survive in ITER, and how the AUG measurements relate to the long lasting asymmetries of halo and toroidal current in JET, are subjects of study within the ITPA MHD Topical Group. The halo region forms during the thermal quench and remains large during the whole current quench. Only a small fraction of the halo current flows through the heat shield; the current barycenters, located in the divertor, vary within 10 cm throughout the database. Simulations are needed to map the current density to the flux surfaces and are in progress.

## References

[1] V.E. Lukash et al., contribution P4.140 to this conference

[2] Y. Nakamura et al., contribution P2.184 to this conference

[3] ITER Physics Expert Group on Disruptions , Plasma Control , MHD and ITER Physics Basis Editors, 1999 Nucl. Fusion **39** (1999) 225

[4] D.A. Humphrey et al., *Predictive Modeling of Plasma Halo Evolution in Post-Thermal Quench Disrupting Plasmas,* 33rd EPS Conference on Plasma Phys. Rome 19-23 June 2006 ECA Vol. 301, P-5.137 (2006)