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Halo Currents in a Circular Tokamak : Measurements on TORE-SUPRA

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Halo currents, induced in the first wall components during major disruptions, are a real concern for large Tokamaks. Previously reported by most of the elongated Tokamaks, where they can cause severe damage during vertical displacement events (VDE), they have now been observed on Tore-Supra with a circular shaped plasma. A new set of voltage pick-up points has been installed behind one of the inner wall panels : measurements are in reasonable agreement with a simple model, predicting halo current intensities around 5 to 10% of the pre-disruptive plasma current value. The mechanical strength of the first wall is sufficient to support the induced constraints.

I) Halo current simplified model

In a Tokamak, the radial position R_P of the plasma is controlled by a fine tuning of the vertical magnetic field B_v, created by external coils, in interaction with the plasma current I_p. This radial force $F_{eq} = 2\pi R_P.I_p.B_v$ balances the internal pressure (magnetic and kinetic) of the plasma. During a disruption, the sudden loss of the temperature destroys this balance, and the plasma is pushed inward on a time scale too short for any power supply reaction. With its circular cross-section, Tore-Supra plasma is vertically stable : this fast movement is thus purely horizontal, toward in high field side inner wall (figure 1). When the plasma collapses against a limiter, or divertor plates, strong currents are induced in the first wall elements and in the scrape-off layers : the halo currents.

A simplified model [1], allows an estimation of their intensity with some assumptions :

{i} The current flows successively in the first wall elements in contact with the plasma, and in the scrape-off layer, where it follows the magnetic field lines.

{ii} The electrical resistance ρ_p is dominated by the scrape-off plasma : $\rho_p = R_P.q_\psi / a_P.\delta.\sigma$, where a_P is the small radius of the plasma, q_ψ is the safety factor at the edge, δ is the thickness of the scrape-off layer and σ its resistivity.

{iii}The driving electric field E_H is given by the shrinking of the flux of the toroidal field B_T encircled by the plasma edge : $E_H = B_T.\partial(\pi a_P^2)/\partial t = 2\pi.B_T.a_P.v_R$, where v_R is the horizontal velocity of the plasma : $v_R = \partial R_P/\partial t$.

The values of δ and σ are not known experimentally. Their product can be estimated within a factor 2 with the results from JET and DIII-D [1] : $\delta.\sigma \approx 1800\ \Omega^{-1}.m^{-2}$. Replacing the safety factor q_ψ by its circular approximation, the halo current intensity $I_H = E_H/\rho_P$ can be written as $I_H = Ip.v_R/v_H$, where $v_H = 1/\mu_0.\delta.\sigma \approx 450$ m/s.

The forces induced in the first wall by interaction of these halo currents and the toroidal field are $F_H = L_H.I_p.B_T.v_R/v_H$, where L_H is the length of the vertical current path in the wall. For typical parameters values, $L_H = 50$ cm, $I_p = 1.5$ MA, $B_T = 5$ T and $v_R = 50$ m/s, this force reaches 400 kN (i.e. 40 tons). It is of the same magnitude as the change in the equilibrium force F_{eq} due to the disruption : $\Delta F_{eq} = ½\mu_0.I_p^2.\Delta\beta \approx 560$ kN for $\Delta\beta = 0.4$.

II) Diagnostic set-up

The Tore-Supra inner wall is a toroidal belt limiter located on the high field side. It is made of 108 poloidal panels. One of these has been equipped with 17 voltage pick-up points (figure 1). A set of wires, twisted together to avoid the formation of loops, connects these points to differential amplifiers. 16 signals are obtained, as voltage differences between eight upper and eight lower points, relatively to the central point (equatorial plane).

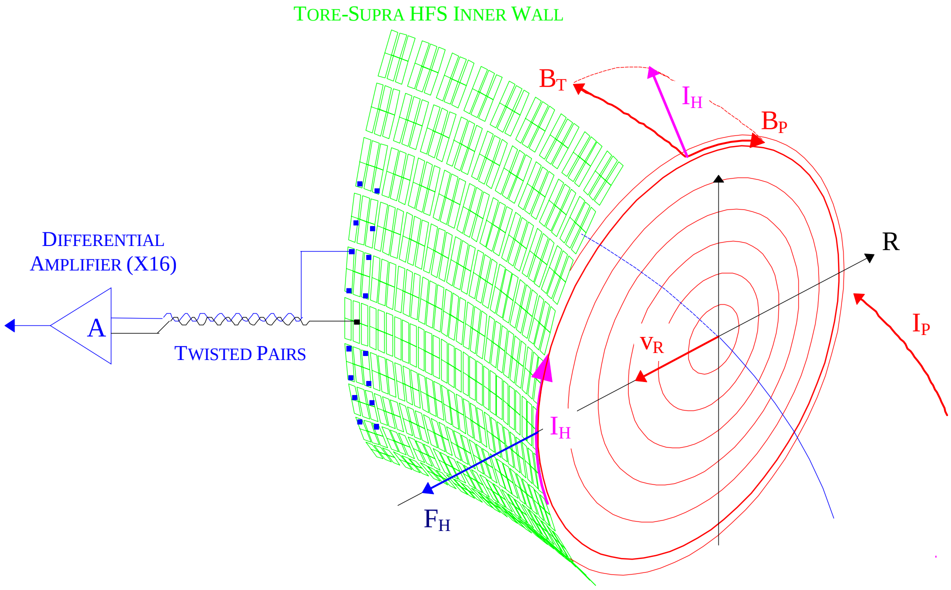

Fig. 1 : Halo current geometry and experimental set-up (1/18 of the inner wall is plotted).

III) Experimental results

During a typical disruption, a strong signal is observed on the voltage pickup, correlated with the plasma current fall (figure 2-A).

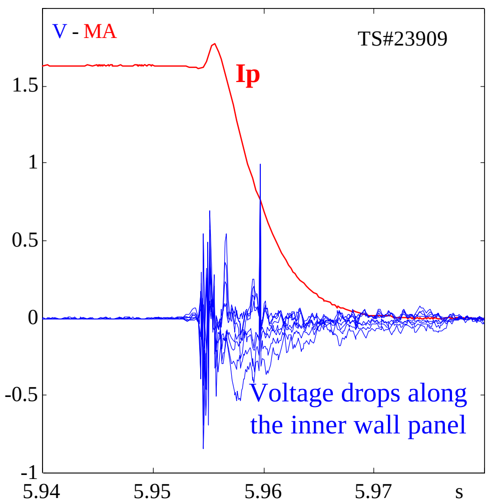

Fig. 2-A : Typical signal versus time

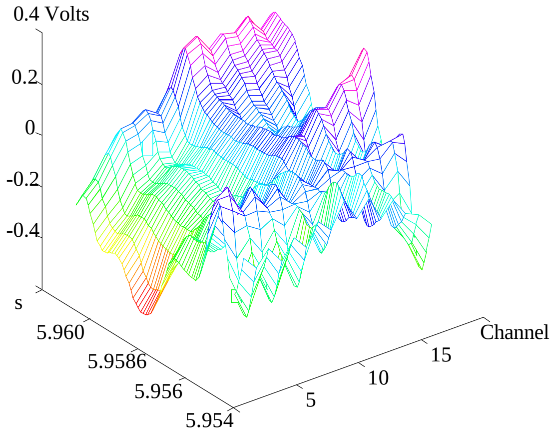

Fig 2-B : Signal versus time and channel number

After a temporal smoothing (low pass < 2 kHz), a structure is observed versus the channel number (figure 2-B), which clearly indicates that the signal is not random noise picked up along the transmission lines. The odd and even channels show the same evolution, with a systematic deviation (figure 3-A) : it corresponds to the voltage induced along the toroidal direction. The time evolution of this voltage is more or less the same for all pick-up points pairs, and follows the plasma current fall (figure 3-B). It must be stressed that the current measurement is performed behind the first wall, which provides a low pass filtering (≈ 500 Hz). The absolute values are much lower than the 1/108 of the total loop voltage (typically 300 V/turn), as most of the voltage drop occurs between successive panels rather that across the panel where the measurement is performed.

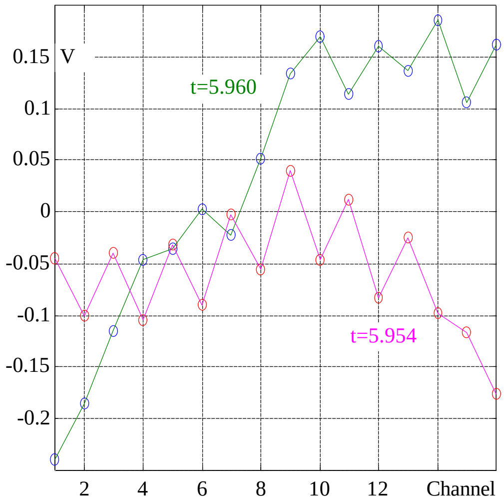

Fig. 3-A : Signal structure versus Channel number

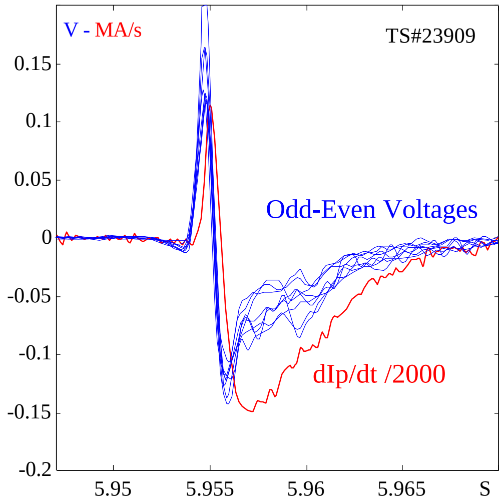

Fig 3-B : Evolution with time of the toroidal voltage

The mean value obtained for each pair represents the poloidal voltage along the panel. The structure versus the poloidal angle θ is regular (figure 4-A), and evolves rapidly with time. At each time, a parabolic fit versus θ is performed (figure 4-B). This fit is composed of an odd and an even component, relatively to the equatorial plane (θ = 180 deg.).

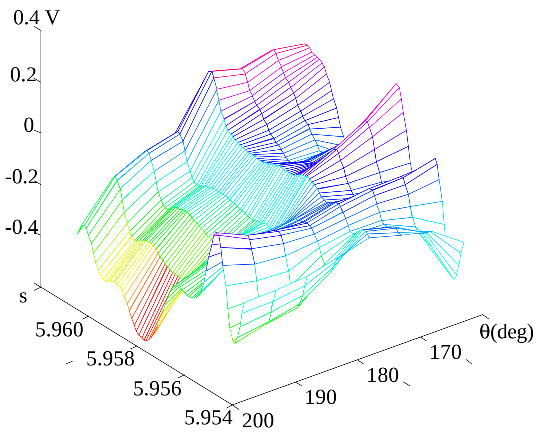

Fig. 4-A : Poloidal Voltage versus time

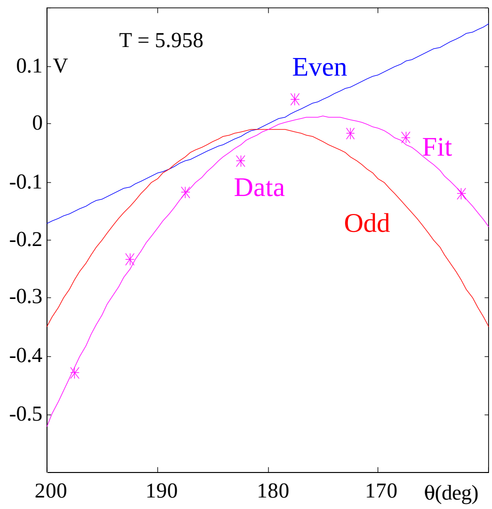

Fig 4-B : Odd and Even components in the signal

It is assumed that the halo currents correspond to the odd component. The even component is related to eddy currents, flowing in closed loops in the first wall, and induced by local variations of the poloidal field during the plasma ramp down. To get the total halo current intensity, this voltage W_H has to be divided by the resistance of the panel ρ_W and multiplied by the number of panels $N_W = 108$, with the assumption of toroidal axisymmetry. ρ_W has been measured at 1.6 mΩ/40 degrees, but this value can be altered by the mechanical connection of the panel to the vacuum vessel and other elements.

The plasma position is determined with poloidal and radial magnetic coils, using the vertical flux method [2]. The reliability of the calculation decreases when the plasma radius becomes too small or the current too low. None the less, the radial velocity is measured during most of the ramp down : it increases almost linearly with time, and reach around 100 m/s toward the end of the disruption (figure 5-A). The expected values of $I_H = I_P.\partial R_P/\partial t/v_H$, with v_H = 450 m/s, are in a good agreement with the measurements.

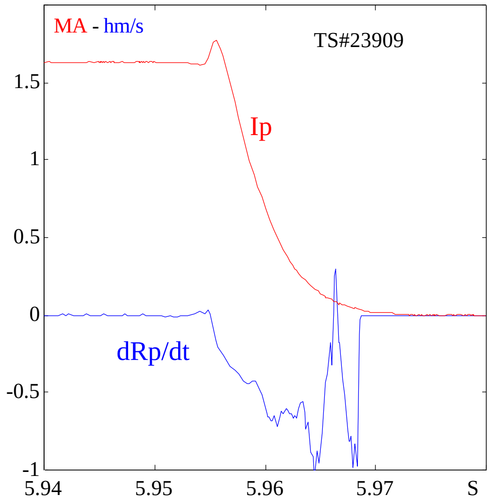

Fig. 5-A : Plasma current and velocity

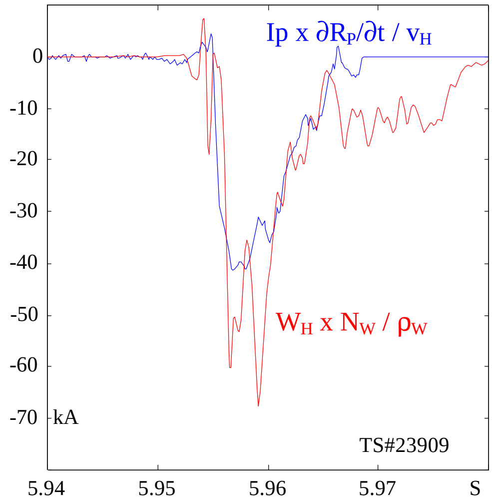

Fig 5-B : Experimental and calculated Halo current

The fast spikes observed on W_H, which are not correlated to plasma movements, might be due to local inhomogeneities in the halo current distribution, not seen on the global plasma equilibrium. In addition, at the end of the disruption, the values for R_P are no longer valid, and the comparison becomes meaningless.

The induced forces F_H, deduced from these measurements, are well within the mechanical specifications of the first wall elements. The geometry of these forces is also more favourable in this case of a vertically stable plasma than for VDE's, since the main component of the force is only radial, and does not cause any global displacement of the vessel.

IV) Summary and references

The measurements of halo currents has been achieved with success on Tore-Supra. Observed intensities are in the range of 5% to 10% of the plasma current value, which is around one third of that observed on Asdex-U for comparable plasma size and current [3]. This difference is mainly explained by a slower velocity of the plasma during the disruptive ramp down, in which the vertical equilibrium is maintained. The resulting forces are tolerable for in-vessel elements, and no damage has been observed in Tore-Supra related to these currents. To get more precision about this phenomena, more diagnosed points would be needed, in particular to assess the toroidal asymmetries which have been observed on other Tokamaks.

[1] G.W. PACHER et al., 17th EPS Conf. on Controlled Fusion, AMSTERDAM, p423-426, 1990
[2] T. WIJNANDS et al., Fusion Technology vol. 32, p471-486, 1997
[3] G. PAUTASSO et al., 22nd EPS Conf. On Controlled Fusion, BOURNEMOUTH, pIV37-40, 1995