Active Quasi Single Helicity transitions at high plasma densities

A. Altichieri, T. Bolzonella, A. Fassina, P. Franz, K.J. McCollam[1], M.E. Puiatti, P. Scarin, G. Spizzo, D. Terranova

Consorzio RFX, Associazione EURATOM-ENEA, Corso Stati Uniti 4, 35127 Padova, Italy

[1] Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA

Introduction The spontaneous transition from Multiple Helicity (MH) to Quasi Single Helicity (QSH) plasmas gives access to an improved confinement regime in the Reversed Field Pinch configuration with the presence of strong internal electron temperature barriers. Operational boundaries for this transition have been extensively studied in recent years and showed that high plasma currents and low electron densities are important control parameters together with optimal control of magnetic boundaries [1,2]. To improve the global performance properties of QSH plasmas, the increase of the maximum density compatible with the MH-QSH transition seems to be a key issue. An innovative technique that combines active modification of current profiles and temporary increased ohmic input power has been recently tested in the RFX-mod device and proved to be able to actively stimulate transitions to QSH at a normalized electron density much higher than the previously observed limit.

Experimental Setup RFX-mod is a large Reversed Field Pinch device currently (R=2.0m a=0.46m) with high plasma current capabilities ($I_{max} \leq 2.0$MA) and advanced real time MHD control systems. Reliable operations at high current (≈1.5MA) allow access to a region where spontaneous transitions between MH to QSH states become frequent. The diagnostic systems used in this study include an extensive set of approximately 600 local magnetic probes, which gives information on modal composition of the magnetic field and on magnetic boundary conditions; fast evolving electron temperature profiles are obtained by a multichord double filter soft X-ray spectrometer [3] which estimates the temperature profile on ten lines over the outermost half of the plasma column, with a bandwidth in the range of the kHz and a spatial resolution of 4.0cm. A higher spatial resolution, up to 7mm, is allowed by the Thomson scattering diagnostic (TS) [4], which extends its observation range to the whole plasma column at the price of a lower acquisition frequency (50Hz). Density profiles are measured by a CO_2 interferometer [5].

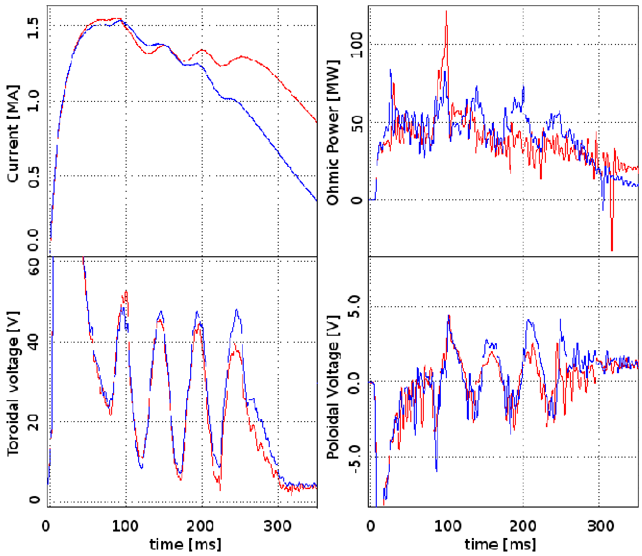

Figure 1: Time traces of the main plasma quantities involved in these experiments for two different discharges: 29101 (red) and 29102 (blue). Top row: plasma current (left) and ohmic power (right). Bottom row: toroidal (left) ad poloidal (right) loop voltage signals.

In past experiments, the technique known as OPCD (Oscillating Poloidal Current Drive) involving sinusoidal oscillations of the poloidal loop voltage system proved to be able to periodically reduce the need for dynamo action (co-dynamo, negative V_p oscillations in figure 1) and to improve plasma performances in terms of electron temperature and energy confinement time [6]. It has to be noted that, given the intrinsically cyclic nature of the OPCD technique, co-dynamo phases are always followed by counter-dynamo ones (positive V_p oscillations in figure 1) where discrete reconnection events are stimulated causing back transitions from QSH to MH state. Unfortunately in RFX-mod the effectiveness of this technique seems to be limited at high plasma currents ($I_p \geq 1.5$ MA) mainly by the increased power input and the consequent problematic plasma-wall interaction control.

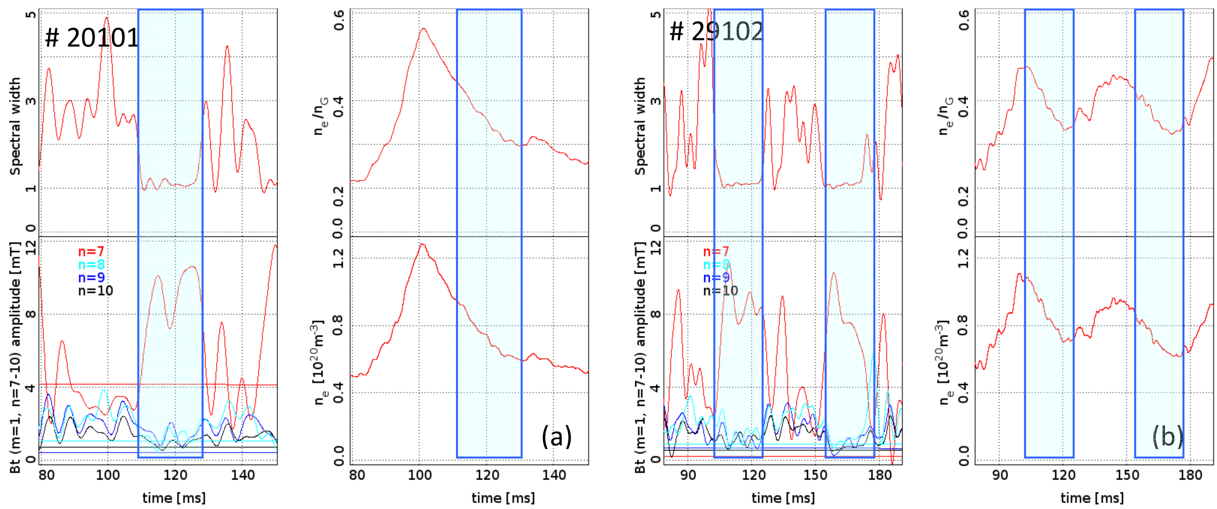

Figure 2: Pulse 29101(a) and 29102 (b) QSH transitions and density behaviour. QSH phases are highlighted by light blue panels and can be identified by values of the spectral width parameter (top left) close to one.

As a result, a new method has been proposed which combines poloidal and toroidal oscillations, the latter being supposed to modulate ohmic power input to the plasma, increasing it during OPCD's counter-dynamo phase in order to provide an extra heating source which will produce better conditions for the plasma to transit to QSH conditions which are favourite during the co-dynamo phase. An example of these oscillations is shown in Figure 1 which also allows understanding that oscillations are active only during the flat-top phase of a discharge which is otherwise produced in the standard way.

Experimental evidence of high-density QSH transition Figures 2(a) and (b) show two pulses (respectively 29101 and 29102) in which the density control is accidentally lost while performing such experiments, reaching high values for RFX-mod: in 29101 a single high density event which can be traced back to a localized plasma-wall interaction (PWI) that boosts up the density value to more than $1.2x10^{20}$ m^{-3} which is more than twice the optimum electron density for the given sustaining voltage and, which is more significant, reaches a n/n_G value of about 0.55. Note that the pulse is fairly well sustained before and after the event, where the density is almost constant and equal.

Pulse 29102 is similar, besides the fact that it shows more than one PWI event and correspondent density spikes; maximum n_e values reached by every event are in the range of $1.0x10^{20}$ m^{-3} and n_e/n_G is frequently above 0.4. The "spectral width" panel reported in each plot allows to recognize QSH states characterized by a parameter defined following [7] as $N_s=[\Sigma_n(W_n/\Sigma_{n'}W_{n'})^2]^{-1}$, where W_n is the energy of the (m=1, n) mode. In particular, for pulse 29101 a long QSH phase is identified by spectral width value close to one between 110 and 125 ms. Traces of magnetic modes with (m=1, n=[7-10]) consolidates this consideration as the (m=1, n=7) mode amplitude is largely dominant in amplitude over the remaining secondary modes. It is also worth noting that at t=110ms the MH to QSH transition starts around a n/n_G value of 0.45. For pulse 29102, two QSH phases can be identified between 105-125 and 155-170 ms: in both cases n/n_G is larger than 0.4. These events are interesting since QSH transitions were believed to have a critical n/n_G value below 0.4 for low current discharges (0.8MA) and an even more severe constraint on high current (1.2MA) operations obtainable with a strict control on the reversal parameter (q(a)≈-0.005) where n/n_G appeared to be kept under 0.1-0.2 [2]. The persistence of these QSH periods is also significant since they last more than 10 energy

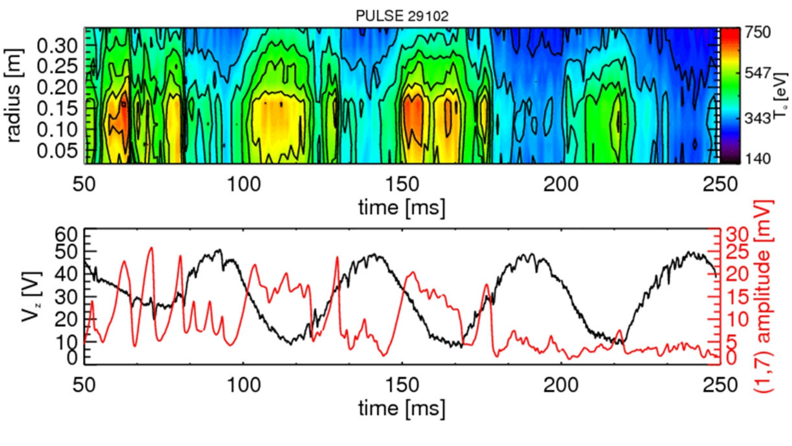

Figure 3: Pulse 29102: a clear relation between temperature oscillations (top) and QSH transitions (bottom, red trace) is visible.

confinement times ($T_i = T_e$ is assumed in the τ_E evaluation for an average value during the QSH periods of $\tau_E \approx 2ms$).

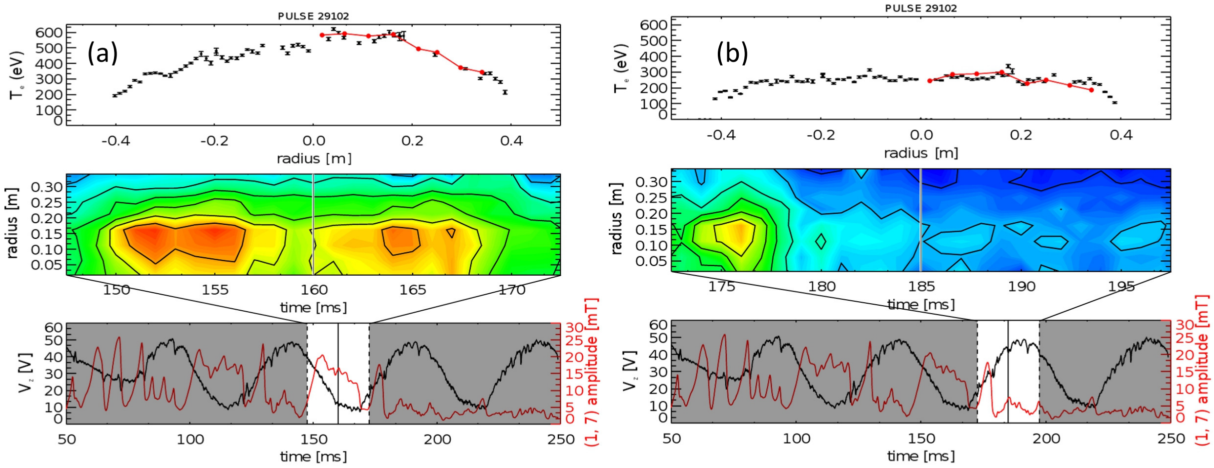

Figure 4: Pulse 29102: temperature profile and magnetic structure detailed time evolution during QSH (a, left) and MH (b, right) periods. On top panels Thomson scattering (black) and SXR (red) profiles are overlapped to highlight their very good agreement. Middle panels show the time evolution of temperature profiles by the fast SXR diagnostics, colour bars are the same of figure 3, top panel.

QSH are expected to heat the internal region of the plasma, the one more affected by the helical deformation, via the formation of strong internal electron temperature barriers: by means of the SXR, it is possible to observe these hot structures inside the plasma column following Te profile evolution through time. This analysis is shown in Figure 3, which highlights the coincidence of hot internal structures identified by the SXR with QSH phases (the red line in the bottom panel shows the dominant mode amplitude). This is particularly evident for pulse 29102, in which two QSH transitions are stimulated by external oscillations and are separated by strong MH phases which cool down the plasma (see Figure 4). These results can be validated by comparing them with TS profiles in selected instants (one hot, figure 4(a), and one cold, 4(b)), ensuring that the whole plasma column is kept under control and confirming that electron temperature almost reaches 1keV, which is considered amongst the highest values for RFX-mod. Future plans include the application of the same technique during controlled variations of plasma density such as gas puffs or injection of large pellets.

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