# Helical flow in the RFX-mod Reversed Field Pinch experiment

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The RFX-mod experiment explored in the last two years the maximum plasma current range, up to 2 MA, for a Reversed Field Pinch configuration. It has been found that for high enough plasma current a spontaneous transition occurs towards a single helicity equilibrium and in particular a further improvement of the magnetic configuration has been observed in RFX-mod with the spontaneous transition to the Single Helical Axis state (SHAx) [1], so that the configuration is dominated by a helical magnetic structure, whose magnetic axis is the former island O-point. Transitions to such states were also successfully sustained [2] during the whole discharge flattop by inducing an external magnetic perturbation according to the dominant mode. Aim of the present paper is the study of the flow features, associated to this helical magnetic island, from the experimental point of view and comparing these results with theoretical hints presently under investigation in RFX-mod (R/a=2m/0.459m).

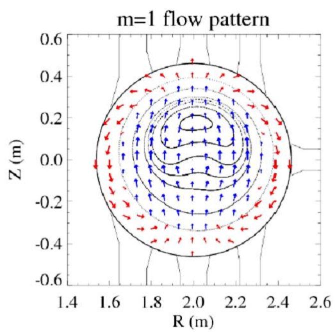


**Fig.1** Flow map reconstruction on a poloidal section from passive Doppler spectroscopy.

*Core flow properties*. Through radially inner (Boron) and outer (Carbon) radiation measurements based on passive Doppler spettroscopy and performed at a given toroidal position, a reconstruction of the flow map have been obtained [3], exploiting the toroidal rotation of helical island associated to the dominant mode m=1 n=-7, where m and n are the poloidal and toroidal numbers respectively. The resulting flow map in a poloidal section is shown in Fig. 1 and compared with the local magnetic equilibrium reconstruction. The m=1 flow structure in the core is recognizable and tightly related to the magnetic island shape, furthermore an inversion of the flow in the outer region is observed. At edge an inversion is also observed along the poloidal direction where the helical magnetic axis approaches the first wall. A statistical analysis has been obtained by inducing increasing amplitude $b_r^{(1,-7)}$ (a) magnetic perturbation at edge and observing an increasing trend of measured flow and of its shear [2].

*Edge flow properties*. The edge magnetic topology feature characterizing a typical high current discharge during a SHAx state is shown in Fig.2. It represent a Poincaré plot obtained by a Field Line Tracing Code (FLiT) [4], in the edge radial-toroidal plane, at a given time instant. The oscillating black line represents the LCFS featuring the typical modulation (m=1, n=-7) due to the helical magnetic island. The presence of a chain of m=0 magnetic islands, resonating at the reversal surface of the main toroidal magnetic field, as well a modulation of their radial position driven by the (1,-7) mode are evident.

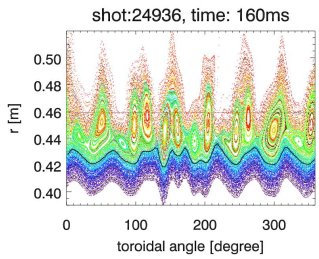


**Fig. 2** Poincarè plot obtained at edge (FLiT code) during a QSH state on a radial-toroidal section, θ=340°.

Also edge parameters can be monitored, exploiting the toroidal rotation of helical island, in particular as a function of local radial magnetic shift, $\Delta_{r(1,-7)}$, by diagnostics at a given toroidal position. In Fig.3 the time modulation of parallel and perpendicular Mach numbers, $M_{\|}$ and $M_{perp}$, with respect to edge magnetic field, as deduced by a Gundestrup probe in a floating potential configuration [5], results well correlated with the local shift. Positive $\Delta_{r(1,-7)}$ values mean towards the first wall and where the shift is maximum the measurement point is in the closest position to the magnetic island axis [6]. In particular in this condition an increase in both $|M_{\|}|$ and $|M_{perp}|$, confirmed also by toroidal flow, $v_{\phi}$, as deduced by Gas Puffing Imaging (GPI) [7], and a change of sign in the $M_{\|}$ is observed, similar to what found with spectroscopy measures [6]. In addition a statistical analysis confirmed the average pitch of edge flow is consistent with the helical magnetic pitch. A trend to increase of $|M_{\|}|$, $|M_{perp}|$ and of the total module, M, for increasing values of local radial shift is shown in Fig. 3. Data are obtained as average of the specific quantity, i.e $M_{\|}$, in the time interval where the $\Delta_{r(1,-7)}$ >0 and associated to the maximum $\Delta_{r(1,-7)}$ value in the same time interval. The behavior is more clear for $M_{\|}$ and taking into account that, for a

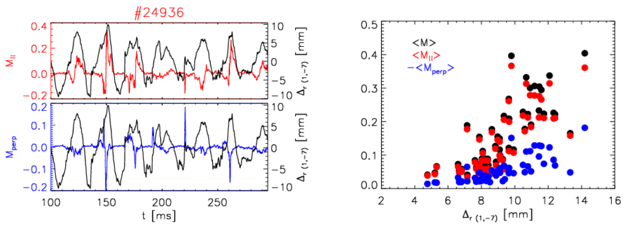


**Fig. 3** Time evolution of $M_{par}$ and $M_{perp}$ compared with the local $\Delta_{r(1,-7)}$ (left panel); Average Mach components vs local maximum shift amplitude (right panel)

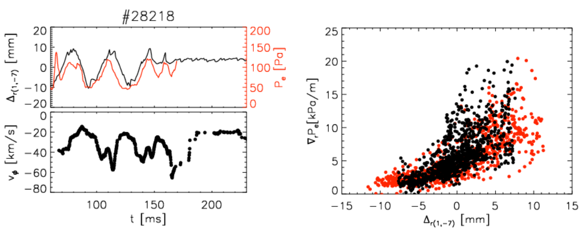


**Fig.4** (left) Time evolution of $v_{\phi}$ and $P_e$, at r/a=0.97, compared with the respective local shift; (right) statistical comparison of $\nabla_r P_e$ during spontaneous (red) and induced (black) magnetic perturbation.

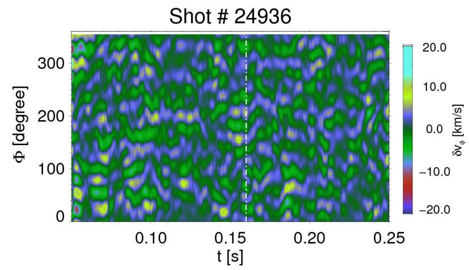


**Fig. 5** Time evolution of the $\delta v_\phi$ toroidal map

given plasma current and equilibrium [8], $\Delta_r^{(m,n)}(a) \propto b_r^{(m,n)}(a)$, this behavior is reminiscent of the increase observed in the core flow and of its shear $b_r^{(1,-7)}(a)$ [2].

The behavior of flow and Mach time traces is similar also for the case of externally sustained magnetic island (i.e. shot #28218, where the local applied perturbation is rotating up to 170 ms). As an example the $v_\phi$ measured by the GPI is shown (Fig. 4). It can be observed that the $v_\phi(t)$ coherently cease oscillating for t> 170ms. In the same location the Thermal Helium Beam (THB) [7] provides a measurement of pressure radial profile, $P_e(r)$, in the r/a range 0.95 ÷1. The modulation of $P_e(r)$, associated to the local $\Delta_{r(1,-7)}(t)$ is confirmed as previously observed [6]. A statistical comparison of $\nabla_r P_e$, measured during spontaneous and externally sustained helical islands (Fig. 4), does not evidence noticeable differences of edge profiles between the two ways of operation. The complete toroidal array of electrostatic probes embedded in the first wall, part of the ISIS system [9], allows an estimate of the toroidal flow fluctuations time evolution, $\delta v_\phi$, as a function of the toroidal angle. The method is based on the wavelet analysis and is described in [10]. In Fig. 5 the $\delta v_\phi,(t,\phi)$ for the same shot of Fig. 2 and 3 is shown. The $\delta v_\phi,(t,\phi)$ pattern evidences the features of the n=-7 modulation. The understanding of its relationship with the local magnetic shift deserves further studies, and in general the effect of wall proximity for edge measurements has to be accounted for.

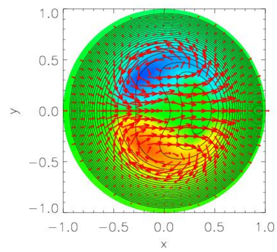


**Fig. 6** Example (#28202) of dynamo flow map (red arrows) on a poloidal section. Color scale indicates values of electrostatic potential, on the magnetic equilibrium reconstruction (black lines).

*Theory investigations on helical flow.* Among theory studies on this subject in RFX-mod, the application of an innovative approach [11] for the calculation of the dynamo flow map is in progress. The procedure provides a 3D map of dynamo flow, calculated on the basis of the magnetic equilibrium reconstruction as deduced from experimental measurements, and presently requires a self consistent calculation of the plasma resistivity profile. Preliminary results of dynamo flow map are shown in Fig. 6 for shot #28202. It can be observed the flow pattern results similar to the experimental one shown in Fig. 1.

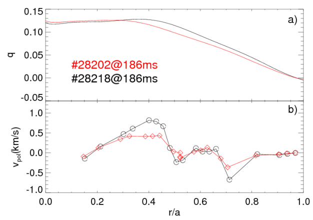

Fig. 7 Average poloidal flow (b) calculated with DKES/PENTA codes and their respective q profile (a) for #28202 and #28218 shots.

A further field of investigation is represented by the calculation of flow radial profile, originated by ambipolar electric field and averaged on each flux surface, through the DKES/PENTA[12] codes applied to RFP for local neoclassical transport computations [13]. In particular the flows and equilibria obtained in the shots #28202 and #28218 with increasing $b_r^{(1,-7)}$ (a), respectively are compared (Fig. 7). The simulations are obtained by keeping the same density and temperature profiles in both cases, so that only the effect of magnetic equilibria are accounted for: a higher value of poloidal flow in the region of q´≅0 for larger $b^{(1,-7)}_r(a)$ is found, with a trend similar to experimental findings. A further theme for interpretation of edge flow experimental findings is devoted to the study of helical plasma wall interaction, related to the magnetic radial shift perturbation. The observations of localized source and sink of particles, characterizing the plasma wall interaction typical of strong magnetic locking at lower plasma current, are being applied [14]. The balance between ion and electron fluxes provides an ambipolar electric field with an electrostatic potential map (see Fig.8) in the edge, consistent with the presence of a flow convective cell [14]. A flow modulation at edge could be related to the edge magnetic topology and both m=0 chain and m=1, n=-7 radial modulation can play a role on this respect.

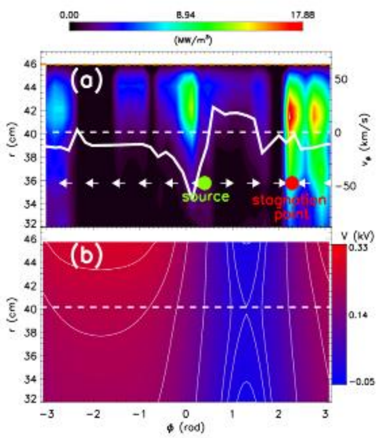

Fig. 8 (a) Toroidal distribution of bolometer emissivity and associated flow; (b) simulation of the relative electrostatic potential map.

Thanks to a noticeable set of diagnostics the existence of a helical flow associated to the helical magnetic configuration is uncovered. Among the mechanisms driving this flow configuration, effects related to the dynamo electric field, a possible contribution due to the presence ambipolar electric fields related either to neoclassical effects or driven by a helical plasma wall interaction, are presently under investigation.

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