*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.107 (2004)*

Influence of the q=0 surface on transport in the reversed-field pinch

A. Cravotta[1,2], S. Cappello[1], D.F. Escande[3], L. Marrelli[1], P. Martin[1,2], I. Predebon[1], G. Spizzo[1], R.B. White[4]

[1] *Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, Padova, Italy*
[2] *Dipartimento di Fisica, Università di Padova, Via marzolo 8, Padova, Italy*
[3] *UMR 6633, CNRS-Université de Provence, Marseille, France*
[4] *Princeton Plasma Physics Laboratory, Princeton, NJ, USA*

Both $m = 0$ and $m = 1$ instabilities are playing a crucial role in the RFP dynamics, and they might significantly affect transport in the RFP. The effects of core resonant $m = 1$ modes on transport are rather well known. In the standard Multiple Helicity state, where a large number of them are simultaneously present in the plasma with similar amplitudes, they produce a significant level of magnetic chaos. Comparatively less is known about the role of $m = 0$ modes, localized at the reversal surface, i.e. where the safety factor q vanishes.

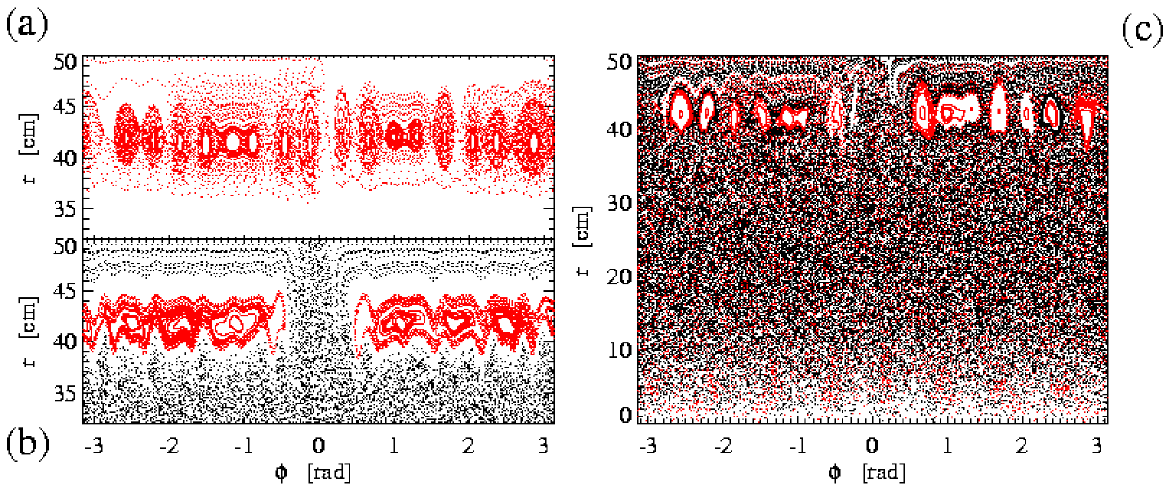

Figure 1: *(a) Poincaré plot showing the structure due to $m = 0$ modes only; (b) Poincaré plot showing the beating structure due to the $m = 1$ modes; (c) the final structure, due to the interaction of $m = 0$ and $m = 1$ modes. Chaos develops in the locked mode region ($\phi = 0$), and in the region of the x-points of the $m = 0$ islands.*

This paper focuses on the first systematic study of the effects of $m = 0$ modes on transport in the RFP, using the Hamiltonian guiding center code ORBIT [1] coupled to the three dimensional MHD code SpeCyl [2]. This study shows that there is a $m = 0$ structure localized at the reversal surface, generated by both $m = 1$ and $m = 0$ modes.

In the ideal absence of $m = 1$ modes, the $m = 0$ modes form a chain of islands at the reversal radius: since there is a symmetry conserved ($q = 0$), these islands do not develop chaos, as it is evident in Figure 1(a). On the other hand, $m = 1$ modes alone form a structure at the reversal, due to the beating of the different (1,n) cosine harmonics (Figure 1(b)). In the case of $m = 1$ modes, there is no symmetry conserved, so chaos can develop in the plasma.

Despite this, the beating structure extends in a continuous way throughout the toroidal angle ϕ, and is broken only at $\phi = 0$, in correspondence to the toroidal location of the localized bulging of the plasma column, well known in the RFP community as 'slinky structure' or 'locked mode' [3, 4]. The 'slinky' is due to the phase alignment of the $m = 1$ modes, and provides a direct topological connection between the core and the edge of the plasma (see black points in the Poincaré plot of Figure 1(b)).
The combination of $m = 0$ islands and $m = 1$ beating gives birth to a chain of islands, which arises in simulations at the reversal (see Figure 1(c)). The topological properties of this structure are rather complicated, and include: (a) a preferential channel of magnetic field stochastisation (a "funnel") in correspondence to the locked mode; (b) more localized sources of magnetic chaos, in correspondence to the x-points of the $m = 0$ islands. Despite this complicated features, it is interesting to notice that still closed flux surfaces are present. We verified that this feature is independent of the boundary conditions ($\tilde{b}_r(a) = 0$ or $\tilde{b}_r(a) = 0$, being a the position of the vessel, and $\tilde{b}_r$ the radial component of magnetic field fluctuation), and of the finiteness of the spectrum in n wavenumber.

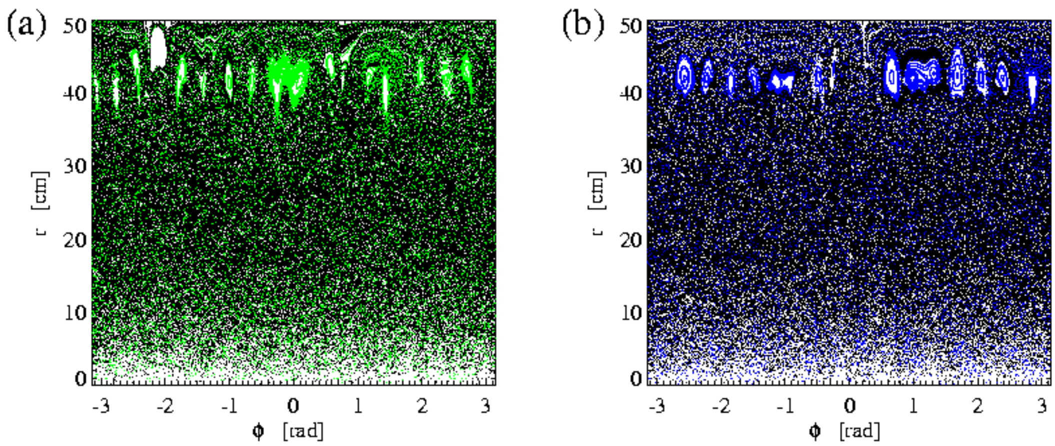

Figure 2: *(a) Poincaré plot showing the m=0 structure at the reversal, when the m=0 and m=1 phases are random; (b) the same, with phase locking. It is evident the "funnel" due to the locked mode, and which is a preferential way of transport between core and edge plasma.*

The phase alignment of $m = 0$ and $m = 1$ modes is playing an important role, as shown in Figure 2: if the phases are random (Figure 2(a)), chaos creeps through the x-points of the $m = 0$ islands, but no preferential way of particle loss is evident; if the phases are aligned, the preferential way exists, and is obviously coincident with the slinky structure (Figure 2(b)).
Topological properties of the structure at the reversal translate into transport properties, as shown by calculating the loss time, in absence of collisions, of test particles deposited in the core. This work extends previous analyses done in RFX [5]. The loss time is defined as the time spent by 50% of the particles, plus one, to travel from the deposition radius (r =10 cm) to a prescribed radius, $r = \bar{r}$. Particles that reach $r = \bar{r}$ are lost. By varying $\bar{r}$, one can obtain a profile of loss time, $\tau_{loss}(\bar{r})$. Even if the loss time of test particles is not fully

representative of the transport properties of the plasma as a fluid in the reversal region, it is a strong indication of what happens to particles when reaching the conserved flux surfaces at the reversal.

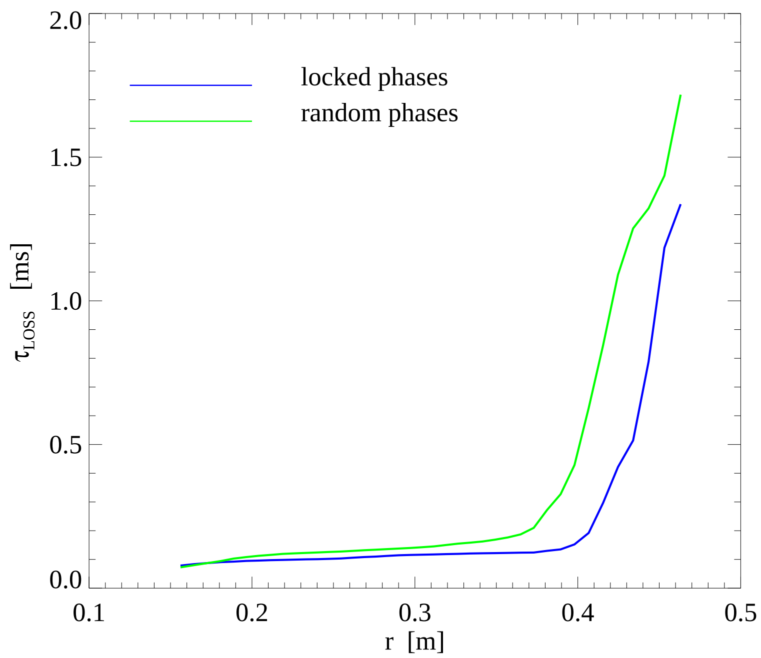

Figure 3: *Radial profile of loss time in the two limiting cases of phase locking (blue) and random m = 0 and m = 1 mode phases (green).*

The profile of τ_{loss} for the two cases of Figure 2 is shown in Figure 3: $\tau_{loss}(\bar{r})$ is rather flat in the core, and displays a steep gradient near the reversal surface, which is consistent with the topological picture given above, and which is consistent also with the typical density and temperature profiles in standard discharges in the RFP configuration [6, 7]. With the caveat that our analysis neglects the role of electrostatic turbulence and toroidal effects this suggests that there exists a transport barrier located at the reversal. Note that the loss time $\tau_{loss}(\bar{r})$ is to be intended as an average over the toroidal angle ϕ. When the phases of the various modes are aligned, the loss time at the edge decreases of a factor $\simeq 30\%$ (blue line in Figure 3). This additional contribution to transport is to be completely ascribed to the presence of the locked mode, as anticipated in [8]. It is interesting to observe that this figure is similar to the calculated fraction of particle flux due to the locked mode, as deduced from Langmuir probe measurements [9].In the core, the difference is negligible [5]. Choosing a collisionless case permitted us to concentrate on magnetic aspects of transport. But more complete analyses (including Coulomb's and neoclassical collisions) are ongoing. Preliminary results give us a qualitatively unchanged scenario, with again a transport barrier active at the edge.

Whether these $m = 0$ modes have always a negative effect on confinement or a positive effect is still an open issue. Recently published results in the Japanese TPE-RX experiment [10] show that particle diffusivity scales with $m = 0$ mode amplitude. The simulations made with ORBIT confirm this picture: the result of a parametric study of the evolution of loss times with the amplitude of $m = 0$ modes shows that the loss time of particles decreases by 50% when doubling the amplitude of $m = 0$ modes, as shown in Figure 4.

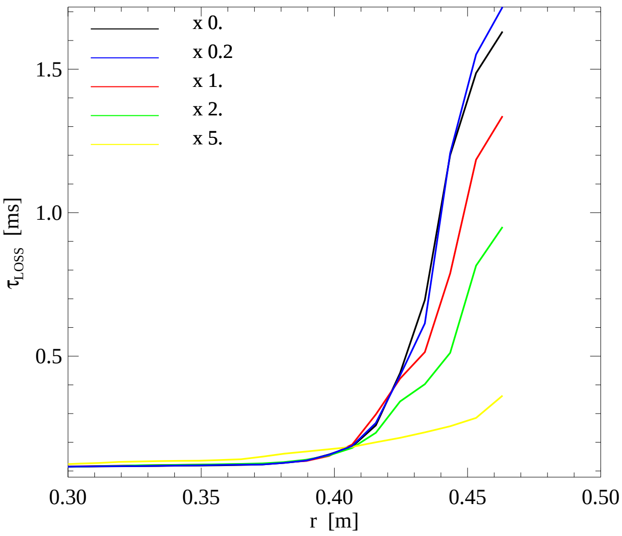

Figure 4: *Radial profiles of loss time, comparing different levels of $m = 0$ mode amplitude: the reference case (x1) is the RMS value of fluctuations given by Specyl; x2 means a RMS value doubled with respect to the reference.*

In fact, by increasing the $m = 0$ amplitude in presence of a certain amount of $m = 1$ modes, the chaos at the x-points of the $m = 0$ islands is favored. Moreover, the spontaneous phase relation between $m = 0$ and $m = 1$ modes is such that the o-point of the $m = 0$ island is partially overlap-ping the x-point of the $m = 1$ beating (i.e., the locked mode). In this way, chaos develops also through the x-point of the beating. Anyway there exists a correct combination of phases that aligns the o-points of $m = 0$ islands, and o-point of the beating, so that the growth of the $m = 0$ modes could be beneficial. A study of this subject is ongoing work. In any case, this optimal phase combination has to be imposed to the plasma by external means, and this can suggests interesting scenarios for future RFX experiments.

References

[1] R.B. White and M.C. Chance, Phys. Fluids **27**, 2455 (1984)

[2] S. Cappello and D. Biskamp, Nucl. Fusion **36**, 271 (1996)

[3] R. Fitzpatrick, Phys. Plasmas **6**, 1168 (1999)

[4] M. Valisa *et al.*, Journal of Nucl. Mater. **241-243**, 988 (1997)

[5] F. D'Angelo and R. Paccagnella, Phys. Plasmas 3, 2353 (1996)

[6] A. Intravaia, L. Marrelli, P. Martin, *et al.*, Phys. Rev. Lett. **83**, 5499 (1999)

[7] D. Gregoratto, L. Garzotti *et al.*, Nucl. Fusion **38**, 1199 (1998)

[8] T. Tamano *et al.*, Phys. Rev. Lett. **59**, 1444 (1987)

[9] G. Serianni, A. Murari, G. Fiksel *et al.*, Plasma Phys. Control. Fusion **43**, 919 (2001)

[10] A. Canton, Y. Hirano, P. Innocente, H. Koguchi, and R. Lorenzini, Plasma Phys. Control. Fusion 46, **23** (2004)