Helical plasma-wall interaction in the RFX reversed-field pinch: toroidal effects, localization and role of sidebands

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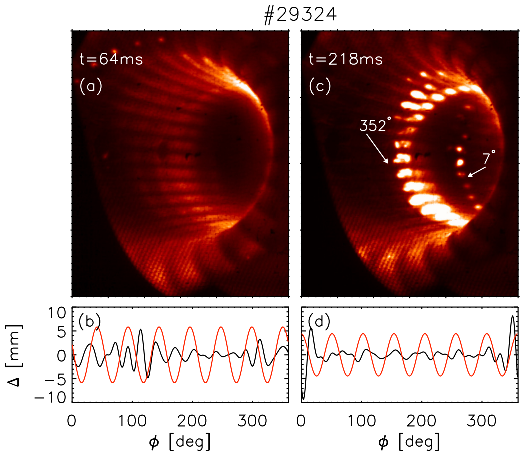
Outline

- Motivation: study of plasma-wall interaction (PWI) in the RFX edge, with helical symmetry [1]
- With a large $m/n = 1/7$ mode resonating in the core, electron pressure, floating potential and edge topology (field connection length, Poincaré recurrence time) follow the dominant helical symmetry, with a $\sim 25\%$ of $0/7$ correction [2, 3, 4]
- What about the $m = 1, n > 7$ "secondary" modes?
- Purpose of this contributed paper is to explore the role of these modes.

Outline/2

Helical state (QSH) $\equiv$ good core confinement +

good helical SOL in the plasma edge



CCD time frames with a QSH state: (a) far from the "phase locking", (c) in the locking region

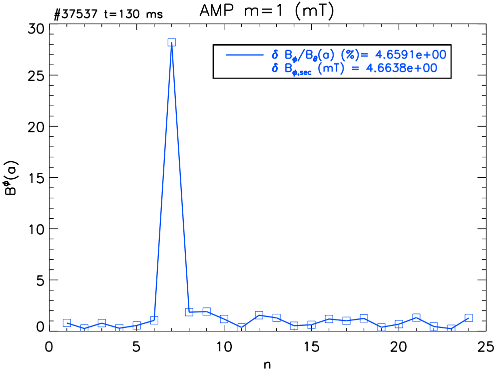
- Secondary modes phase-lock together – but **not** to the wall! See frames (c),(d) → phenomenon well-known in the RFP [5]
- The locking structure involves modes with $m = 1$ and $n \geq 8$
- The locking seems to dominate PWI at the "locking angle", despite the QSH
- Is this result consistent with the knowledge we have of the RFX-mod edge helical topology?

The code

- Reference scenario [2, 3, 4] : RFX-mod discharge # 37537, $t = 130$ ms, high current, low-density case ($I_p = 1.4$ MA, $n/n_G = 0.07$), good helical core with peak $T_e = 1.2$ keV.
- We use the guiding center code ORBIT [6].

- Secondary modes: $\delta B_\phi = 4.66$ mT ($\delta B^r_{res} = 5.24$ mT @ resonance)
- Scan in secondary mode amplitude: scale the modes $m = 1, n = 8 - 24$ and all $m = 0$ by a factor $0.2 \leq A \leq 6$

$A = 1$ is the reference run.

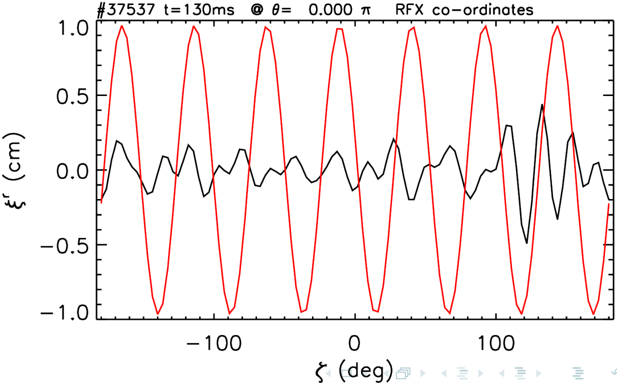


- Important parameter to describe RFX edge [7]: ideal displacement

$$\xi^r = \vec{\xi} \cdot \nabla r = \frac{\psi_1}{\psi_0'} = \frac{\psi_1}{r\left(\frac{1}{q} - \frac{n}{m}\right)} \quad (1)$$

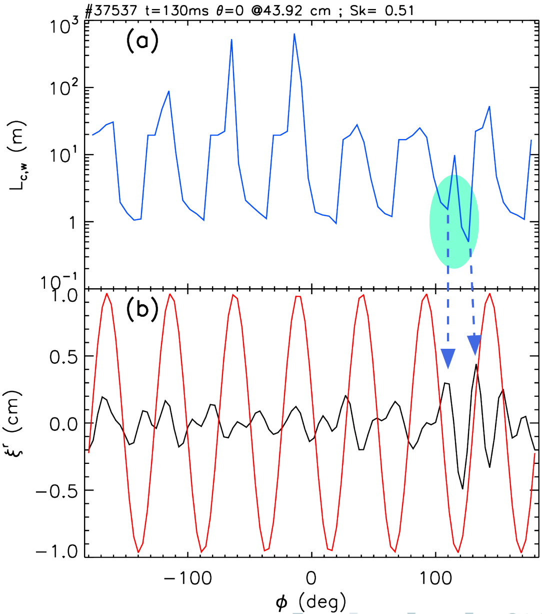
- Good phenomenological parameter "*Scarin number*" $S_k = \frac{\xi_{sec}}{\xi_{dom}}$
- In the reference $A = 1$ run we get $S_k = 0.51$

red is the dominant mode, **black** the secondary modes



Reference case $S_k = 0.5$

- Large-scale symmetry of connection length $L_{c,w}$ is $m/n = 1/7$, consistent with literature [2, 3, 4]
- ... BUT at $\phi \sim 120°$ two additional minima appear (cyan shade)
- Phenomenology is similar to the homoclinic lobes (a.k.a. "fingers") in the divertor region of tokamaks with RMPs [8]



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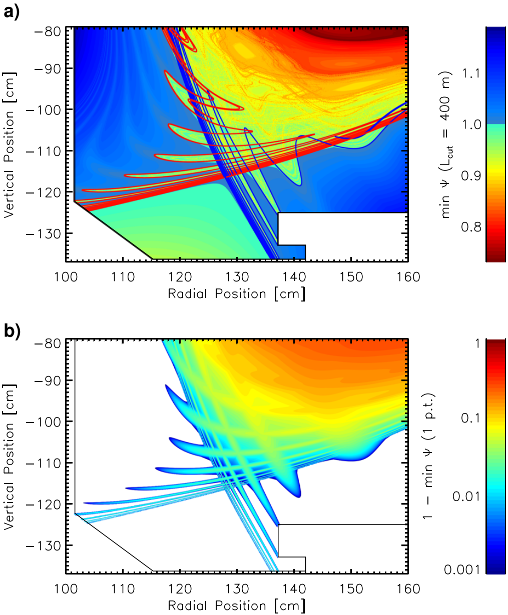
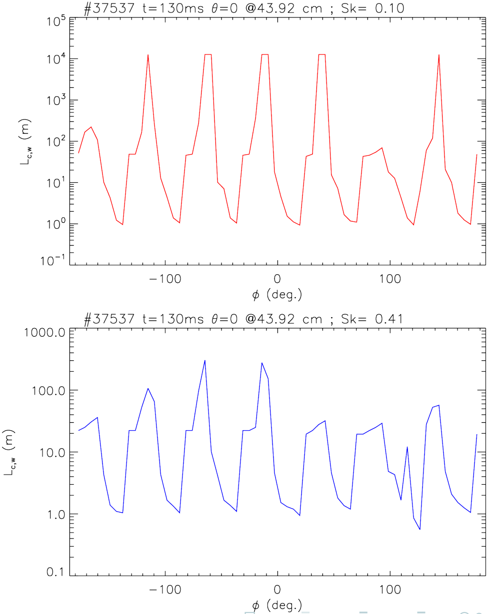


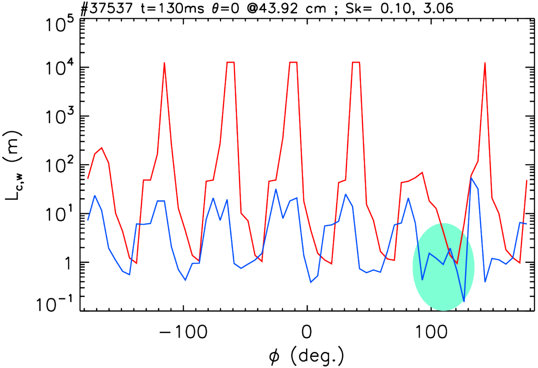
Scan: $A = 0.2,\ S_k = 0.1$

- Ideal case: $A = 0.2$ ($S_k = 0.1$), there is no distortion of the helical $L_{c,w}$ pattern due to locking
- A threshold value is $A = 0.8$ ($S_k = 0.4$): the two additional minima start to be visible



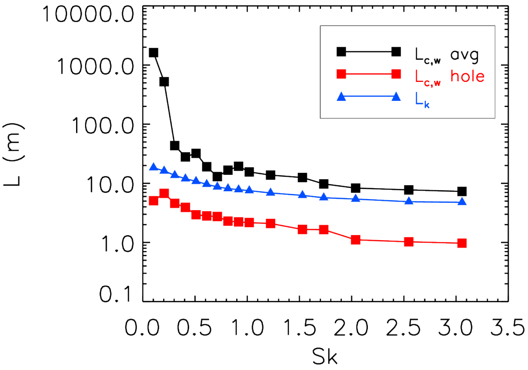
Full scan: $0.2 \le A \le 6$, $0.1 \le S_k \le 3$

- When increasing A, $L_{c,w}$ decreases everywhere
- The region of low $L_{c,w}$ at the locking angle broadens



Statistical analysis

- The average $L_{c,w}$ decreases everywhere as a function of A, not only in the locking region ("hole")
- On average, the RFX edge is ergodic, $\langle L_{c,w} \rangle > L_k$, with L_k the Kolmogorov length evaluated at $\psi_p = 0.72$ ($r = 35$ cm)
- The "hole" is always laminar, $L_{c,w}^{hole} < L_k$

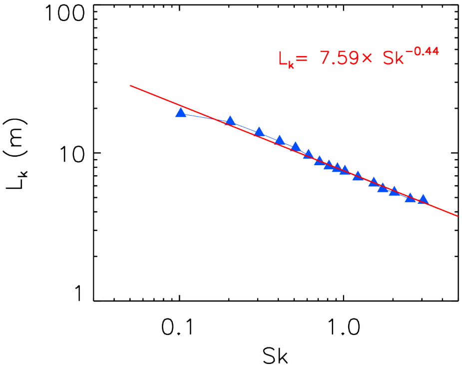


Parenthesis . . .

- The scaling of L_k with S_k is of the type $L_k \approx 8 \times S_k^{-0.44}$
- It is consistent with a scaling of the Lyapunov exponent

$$\sigma_r \sim (D_m)^{1/3} = \left(\frac{\delta B}{B}\right)^{\alpha/3} \quad (2)$$

- In the RFX case, $\alpha = 1.6$ [9], hence $\sigma_r \sim \delta B^{0.53}$
- By definition, $L_k = 1/\sigma$



Newcomb eigenfunctions on RFX-mod [a]

[a] P.Zanca and D.Terranova, PPCF **46** (2004) 1115.

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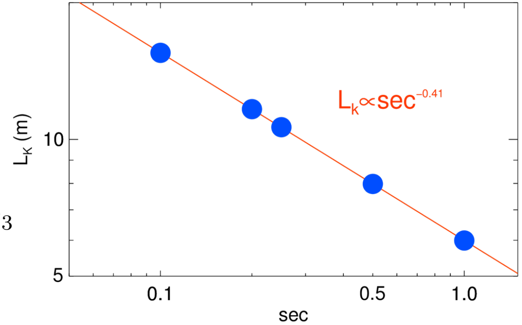
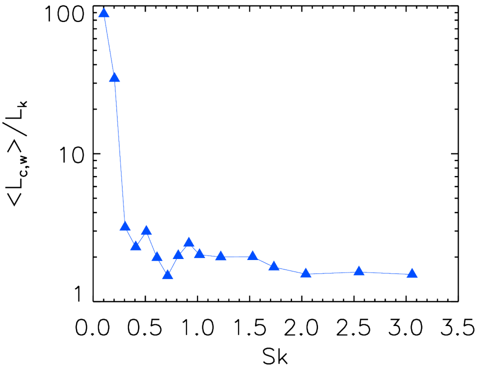


3D MHD visco-resistive code SpeCyl [a]

[a] S.Cappello and D.Biskamp, NF **36** (1996) 571.

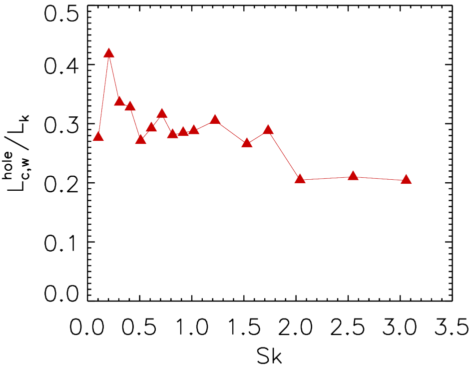
Threshold for a good SOL

- $S_k > 0.3$ $(A > 0.6)$ there is little change, $\langle L_{c,w} \rangle / L_k \approx 2$
- Instead, for $S_k \leq 0.3$ connection lengths increase by 2 orders of magnitude $\rightarrow$ good SOL
- In the upgraded RFX-mod2 machine, a lower S_k value could be reached, with an improvement of plasma performance



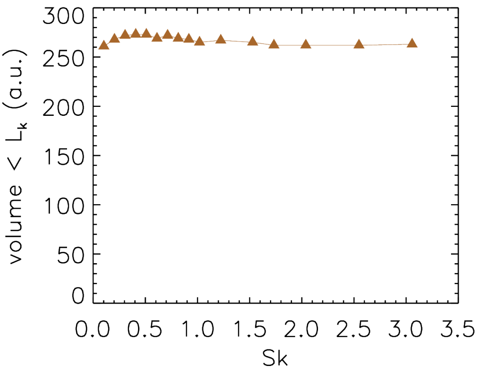
Homoclinic lobes at ϕ_{lock}

- The ratio $L^{hole}_{c,w}/L_k \approx 0.3$ for all values of A
- The locking region (homoclinic lobes) is always "laminar" (in RMP terminology)
- It provides a shortcut for electron transport, from the hot core directly to the wall (already shown in the case of 3D RFP MHD simulations [10])



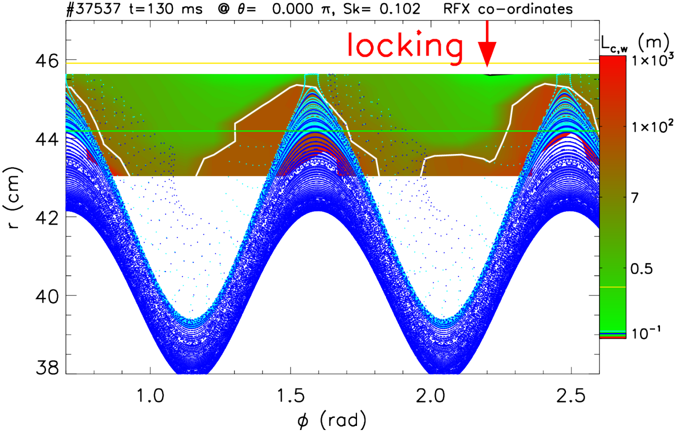
Volume of laminar edge

- Despite the fact that the edge topological texture is better at low A, the volume of laminar plasma $L_{c,w} < L_k$, is constant $\forall A$
- It is not correct to state that the "hole widens" by increasing the secondary mode amplitude A



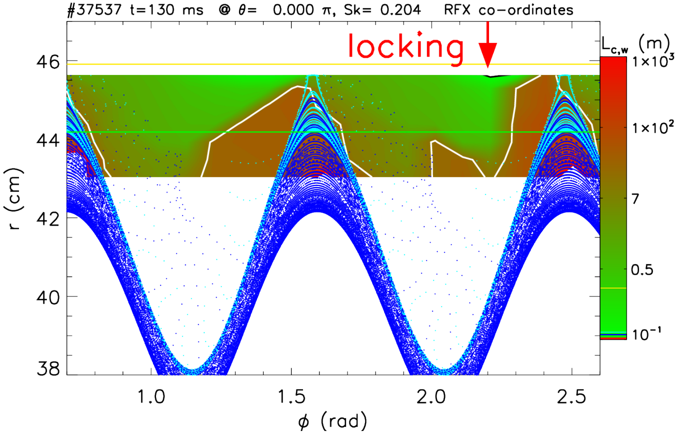
Sequence: $A = 0.2$ ($S_k = 0.1$)

- Contour of $L_{c,w}$ and Poincaré with $n = 7$ modes, only
- Two toroidal periods of the $n = 7$ mode



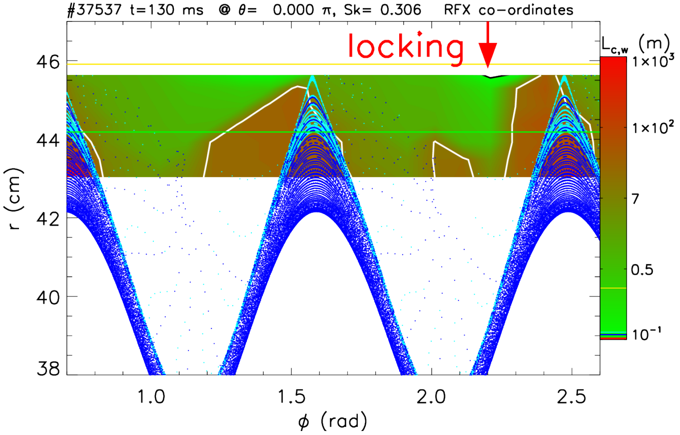
Sequence: $A = 0.4$ ($S_k = 0.2$)

- Contour of $L_{c,w}$ and Poincaré with $n = 7$ modes, only
- Two toroidal periods of the $n = 7$ mode



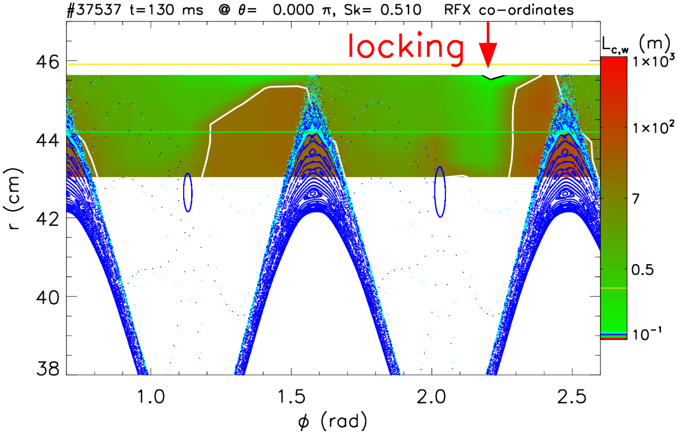
Sequence: $A = 0.6$ ($S_k = 0.3$)

- Contour of $L_{c,w}$ and Poincaré with $n = 7$ modes, only
- Two toroidal periods of the $n = 7$ mode



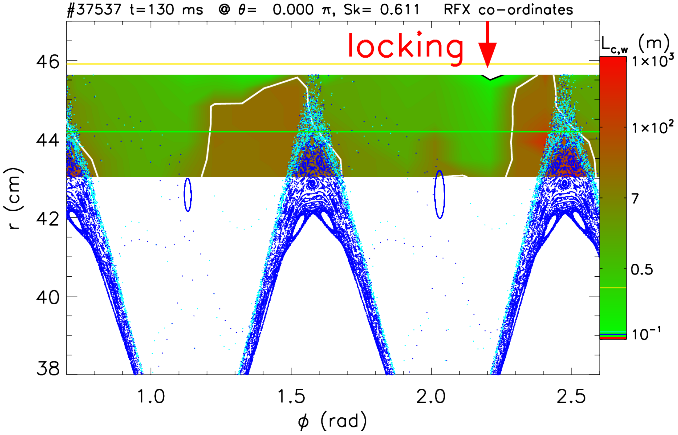
Sequence: $A = 1$ $(S_k = 0.5)$ reference run

- Contour of $L_{c,w}$ and Poincaré with $n = 7$ modes, only
- Two toroidal periods of the $n = 7$ mode



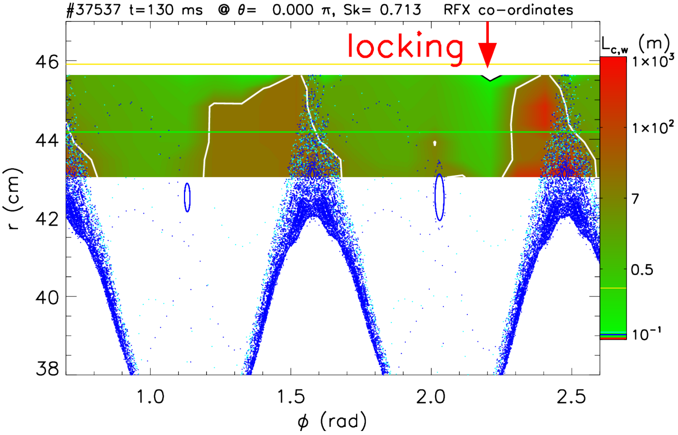
Sequence: $A = 1.2$ $(S_k = 0.6)$

- Contour of $L_{c,w}$ and Poincaré with $n = 7$ modes, only
- Two toroidal periods of the $n = 7$ mode



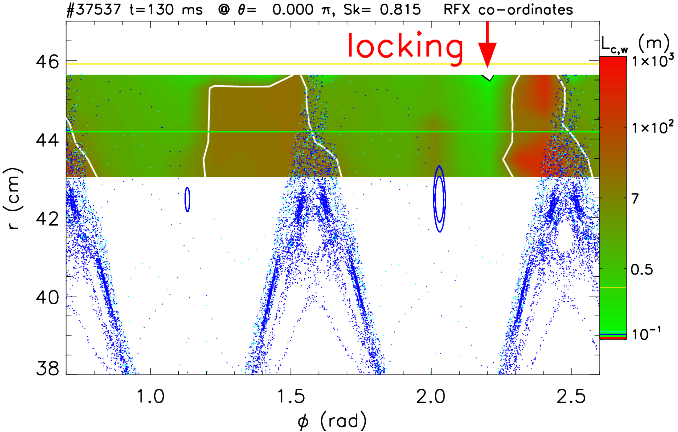
Sequence: $A = 1.4$ $(S_k = 0.7)$

- Contour of $L_{c,w}$ and Poincaré with $n = 7$ modes, only
- Two toroidal periods of the $n = 7$ mode



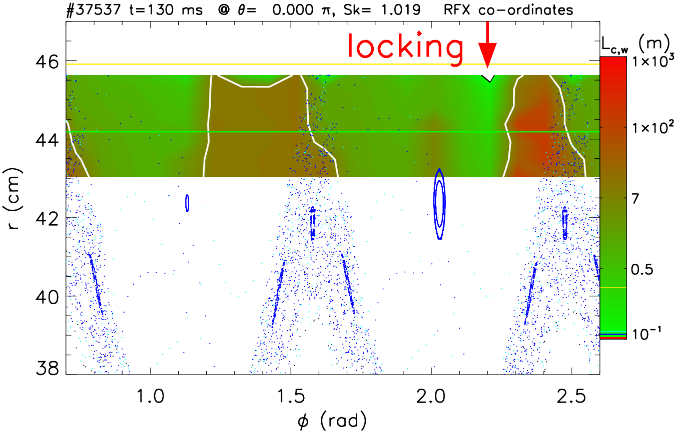
Sequence: $A = 1.6$ $(S_k = 0.8)$

- Contour of $L_{c,w}$ and Poincaré with $n = 7$ modes, only
- Two toroidal periods of the $n = 7$ mode



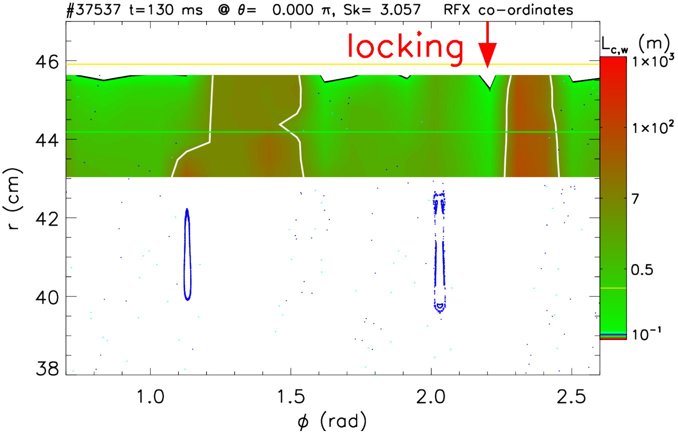
Sequence: $A = 2$ $(S_k = 1)$ threshold for crash [1]

- Contour of $L_{c,w}$ and Poincaré with $n = 7$ modes, only
- Two toroidal periods of the $n = 7$ mode



Sequence: $A = 6$ $(S_k = 3)$ MH state

- Contour of $L_{c,w}$ and Poincaré with $n = 7$ modes, only
- Two toroidal periods of the $n = 7$ mode



- The $0/7$ and $1/7$ islands are separated by a resonance layer: in previous work we have shown that this layer determines PWI in the RFX-mod [2, 3, 4]
- $S_k = 0.7$ seems to be the critical value for stochastization of this layer
- Apply the Chirikhov overlap criterion: "hard" version

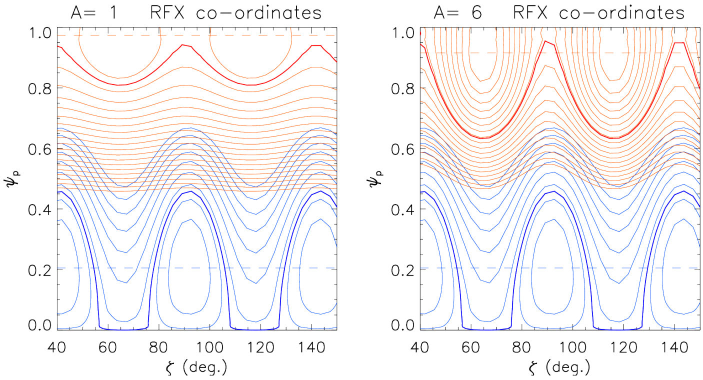
$$K = \frac{w_{1,7} + w_{0,7}}{2|r_{rev} - r_{1,7}|} \tag{3}$$

where $q(r_{rev}) = 0$ is the *reversal surface*

- "Soft" version [1]: $K \approx 2/3$
- 'But $1/7$ "islands" are very large, so a quasilinear estimate of the widths w is not possible $\rightarrow$ we have to employ the helical flux $\chi = m\psi_p - n\psi$

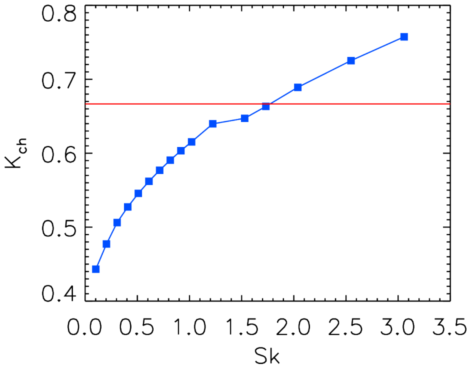
[1] According to numerical estimates on the disappearance of the last KAM surface in the Standard Map, see Lieberman & Lichtenberg, chap.4, p.292

- Example of calculation: $S_k = 0.5$ (reference) and $S_k = 3$ (MH state)
- The separatrices are the lines in **bold**



Estimate of Chirikov K

- $K = 2/3$ corresponds to $S_k = 1.7\ (A = 3.4)$, a value well beyond the layer stochastization in the Poincaré (see Sec. 4)
- Well-known limitation of the Chirikov overlap criterion (Lieberman & Lichtenberg, chap.4)



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- Well-known limitation of the Chirikov overlap criterion (Lieberman & Lichtenberg, chap.4)
- More refined methods are e.g. Escande & Doveil, J. Stat. Phys. **26** (1981) 257.

Conclusions

- Scan in "secondary" mode ($m = 1, n > 7$) amplitude $0.2 < A < 6$, with $A = 1$ the reference scenario, shows the presence of homoclinic lobes at the locking angle.
- Phenomenology in all respects similar to the divertor "fingers", see e.g. [8]
- In vicinity of the locking angle ϕ_{lock}, electron transport is shortcut from the hot core, directly to the wall.
- The concept is not new (already shown in the case of 3D RFP MHD simulations [10] . . .), but here it is revisited within the RMP terminology ("ergodic" and "laminar" zones)
- The channel @ ϕ_{lock} deepens with increasing A, but all of the topology deteriorates
- Two thresholds can be recognized: $A \sim 0.6$ ($S_k = 0.3$) for the removal of the channel, and $A = 1.4$ ($S_k = 0.7$) for the stochastization of the resonance layer in between the $0/7$ and $1/7$ islands.

[1] P. Scarin, M.Agostini, G.Spizzo and P.Zanca
in *Fusion Energy Conf. (Proc. 27th Int. Conf. Gandhinagar, India, 22–27 October 2018)*, p.EX/P8-14.

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Nucl. Mater. Energy **12** (2017) 913.

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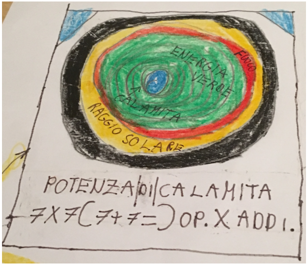
Phys. Rev. Lett. **96** (2006) 025001.



My 8-year-old son's tokamak project

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