DE LA RECHERCHE À L'INDUSTRIE

CEMM Meeting 2016

Non-linear dynamics of compound sawteeth in tokamak core plasmas

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Outline

- Compound sawteeth in experiments
- XTOR-2F simulations of compound sawteeth
- Internal kink mode stability during the sawtooth ramp phase

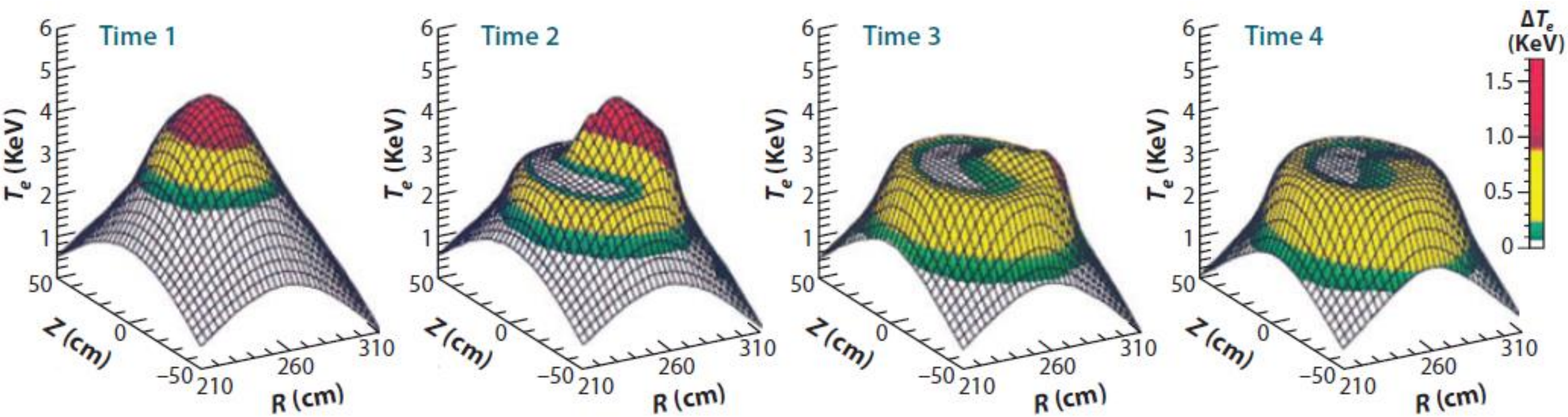
Hot core expelled out of the $q = 1$ surface during sawtooth crash

- **Radial displacement** of hot core due to the **internal kink mode**
- **Flattened temperature profile** after sawtooth crashes
- **Reconnection** of magnetic surfaces near the $\boldsymbol{q = 1}$ **surface**

  B.B. Kadomtsev, *Sov. J. Plasma Phys.* **1** 389 (1976) ; A.Y. Aydemir, *Phys. Rev. Lett.* **59** 649 (1987) ;
  F. L. Waelbroeck, *Phys. Fluids B* **1** 2372 (1989) ; D. Biskamp and J. F. Drake, *Phys. Rev. Lett.* **73** 971 (1994) ; etc…

- Ongoing efforts to model and understand sawtooth physics

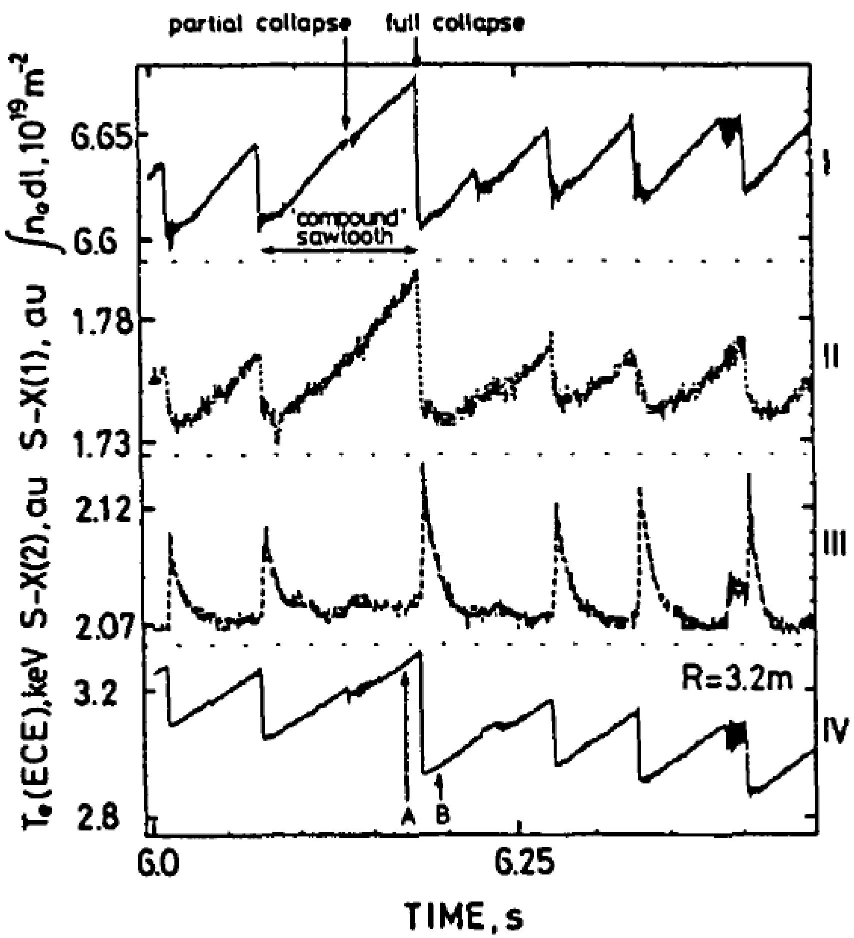
  A.Y. Aydemir, *Phys. Fluids B* **4** 3469 (1992) ; J.A. Breslau *et al.*, *Commun. Comput. Phys.* **4** 647 (2008) ;
  F. Halpern *et al.*, *Phys. Plasmas* **18** 102501 (2011) ; T. Nicolas *et al.*, *Phys. Plasmas* **21** 112305 (2012) ; etc…



E. G. Zweibel and M. Yamada, *Annu. Rev. Astron. Astrophys.* **47** 291 (2009)

Partial crashes during sawtooth ramp phase observed in experiments

- Compound sawtooth : “partial crash” **visible on measurements** (e.g. T_e,n_e,SXR)
- Otherwise, “ordinary sawtooth”



D. J. Campbell *et al.*, *Nucl. Fus.* **26** 1085 (1986)

- **Compound sawteeth** are **frequently observed** in experiments,

  W. Pfeiffer, *Nucl. Fus.* **25** 673 (1985) ;
  G. Taylor *et al.*, *Nucl. Fus.* **26** 339 (1986) ;
  S.B. Kim, *Nucl. Fus.* **26** 1251 (1986) ; etc..

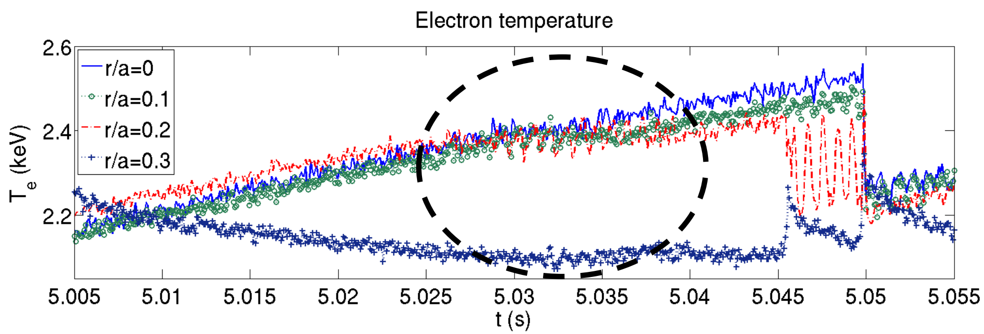
  ⟶ The dynamics of partial crashes differs from ordinary crashes

- Validation of MHD models

  Effects on plasma confinement ?
  Impurity accumulation ? etc..

Hot core is preserved and rotates poloidally during partial crashes

- **2D SXR tomographies** in TdeV and EAST show that the hot core is radially displaced & rotates poloidally, **but** not fully expelled out of the $q = 1$ surface



C. Janicki *et al.*, *Nucl. Fus.* **30** 950 (1990)
L.-Q. Xu *et al.*, *Chin. Phys. B* **23** 085201 (2014)

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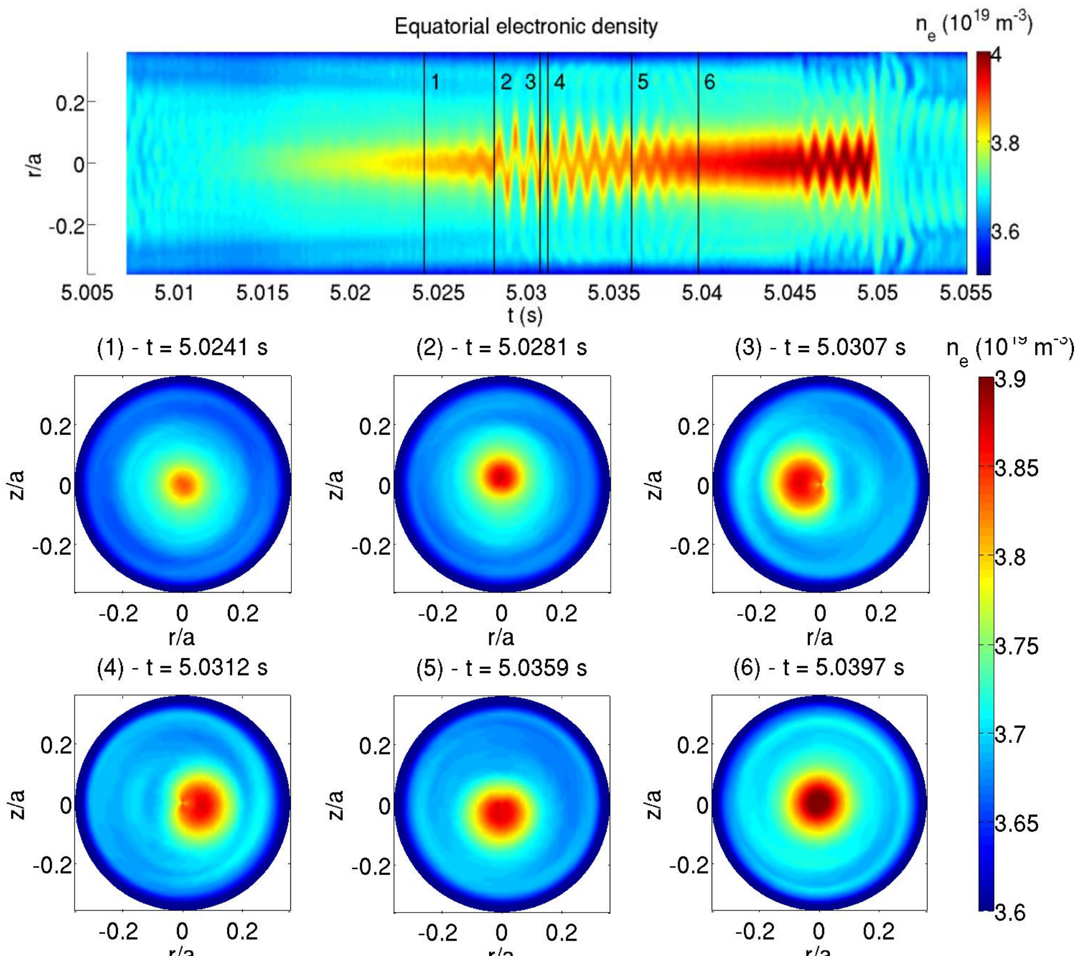
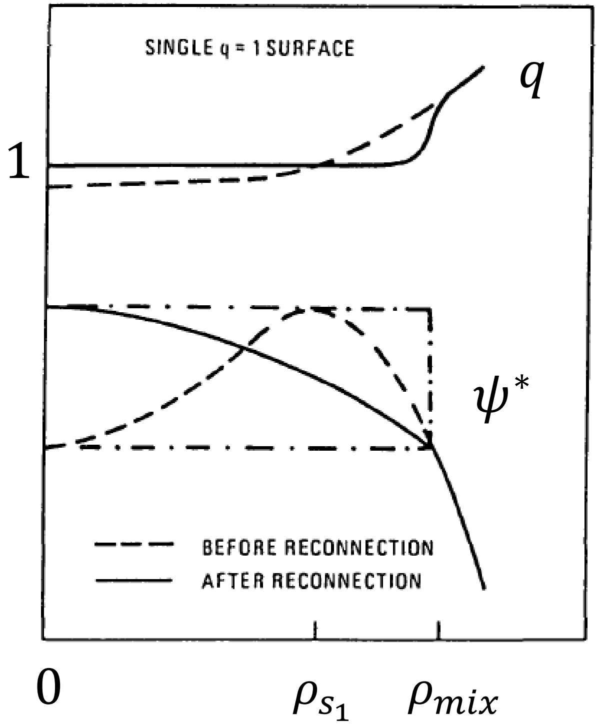


C. Janicki *et al.*, *Nucl. Fus.* **30** 950 (1990)
L.-Q. Xu *et al.*, *Chin. Phys. B* **23** 085201 (2014)

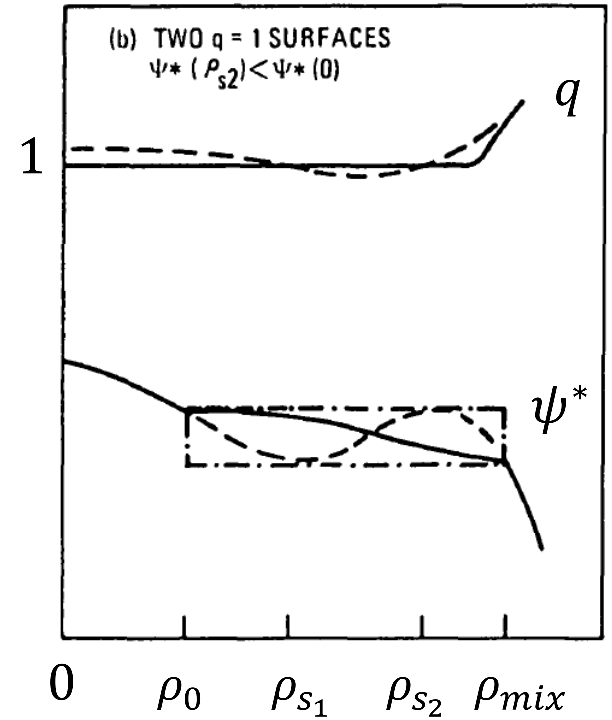
Also observed in reflectometry measurements in Tore Supra #44634

Possible explanation for partial crashes with multiple $q = 1$ surfaces

- Considering **multiple** $q = 1$ surfaces, partial reconnection located off the magnetic axis V.V. Parail and G.V. Pereverzev, *Sov. J. Plasma Phys.* **6** 14 (1980)
- Need more explanation about the onset conditions for compound sawtooth



W. Pfeiffer, *Nucl. Fus.* **25** 673 (1985)



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- Compound sawteeth in experiments

- Internal kink mode stability during the sawtooth ramp phase

- XTOR-2F simulations of compound sawteeth

MHD model in the XTOR-2F code

- The XTOR-2F code models **nonlinear** and **two-fluid full 3D MHD**

H. Lütjens and J.-F. Luciani, *J. Comput. Phys.* **229** 8130 (2010)

$$\partial_t N + \nabla.(N\mathbf{V}) + \frac{\nabla P_i}{e}.\nabla \times \frac{\mathbf{B}}{B^2} = \nabla.(D\nabla N - \mathbf{V}_p N) + S_N$$

Density equation

$$N m_i(\partial_t \mathbf{V} + (\mathbf{V}.\nabla)\mathbf{V} + (\mathbf{V}_i^*.\nabla)\mathbf{V}_\perp) = \mathbf{J} \times \mathbf{B} - \nabla P + \mu \nabla^2(\mathbf{V} + \mathbf{V}_i^*)$$

Momentum equation

$$\partial_t P + \mathbf{V}.\nabla P + \gamma P \nabla.\mathbf{V} + \frac{\gamma}{e}(T\nabla P_i + P_i \nabla T_i + P_e \nabla T_e).\mathbf{\Xi}$$
$$= (\gamma - 1)[\nabla.(N_i \chi_\perp \nabla_\perp T) + \nabla.(N_i \chi_\parallel \nabla_\parallel T\mathbf{b})] + S_H$$

Pressure equation

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \nabla \times \left(\frac{\nabla_\parallel P_e}{Ne}\mathbf{b}\right) - \nabla \times \eta \mathbf{J}$$

Ohm's law & Faraday's law

with $\mathbf{V} = \mathbf{V}_{\parallel,i} + \mathbf{V}_E$ fluid velocity, $\mathbf{V}_i^* = (\mathbf{B} \times \nabla P_i)/NeB^2$ ion diamagnetic velocity

$N = N_i = N_e$, $P = P_e + P_i$, μ plasma viscosity

- Resolution of the system with a **Newton-Krylov** solver, **fully implicit** scheme

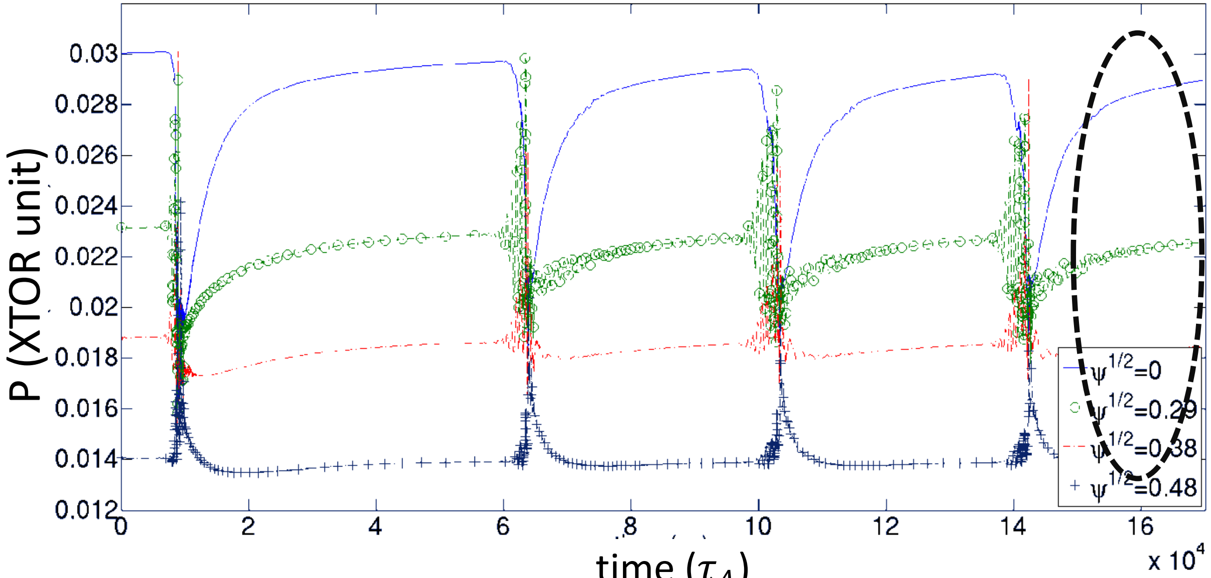
Flat q-profile during sawtooth ramp phase : the internal kink mode is unstable

- ***q*-profile** flattened after sawtooth crash and remains **flat** during ramp phase
- The internal kink mode is unstable for **low-sheared** q-profiles, even when $\boldsymbol{q} \gtrsim \mathbf{1}$

  (shear $\hat{s} = r/q \times dq/dr$)

  R. J. Hastie *et al.*, *Phys. Fluids* **30** 1756 (1987)
  H. J. de Blank and T. J. Schep, *Phys. Fluids B* **3** 1136 (1991)

- Numerical study on linear stability in accordance with analytical predictions
- However, **no partial crash** (i.e. "ordinary sawtooth")



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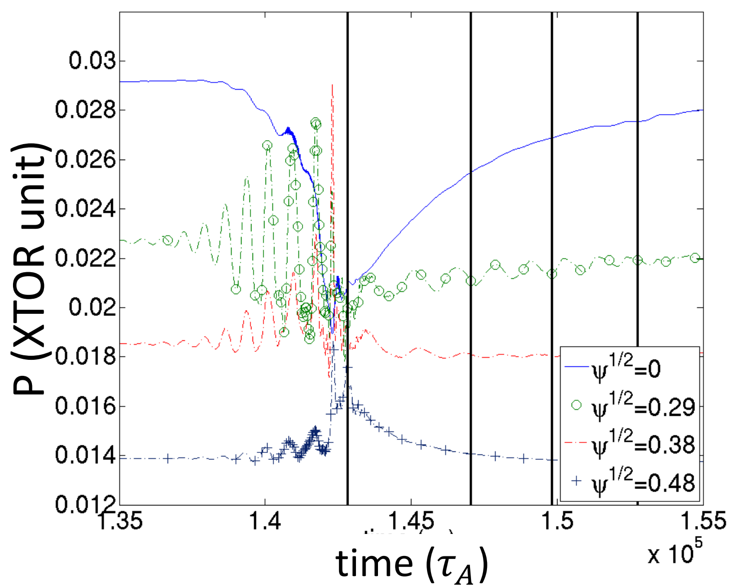
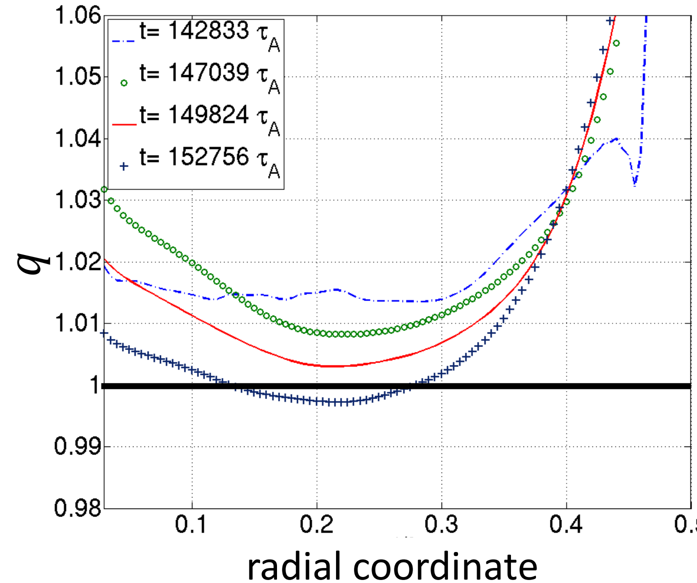
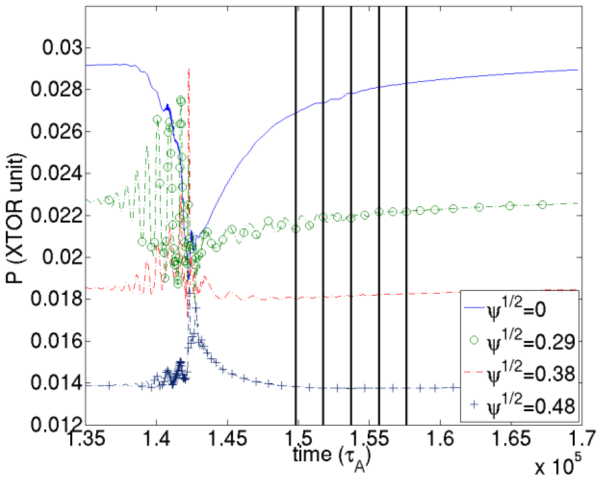
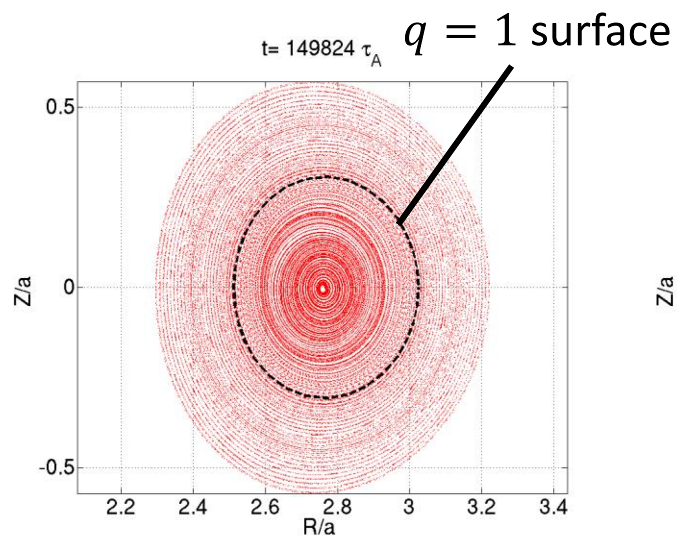
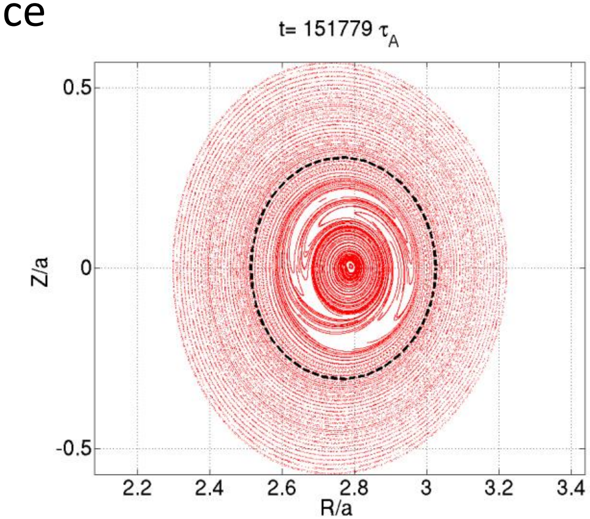




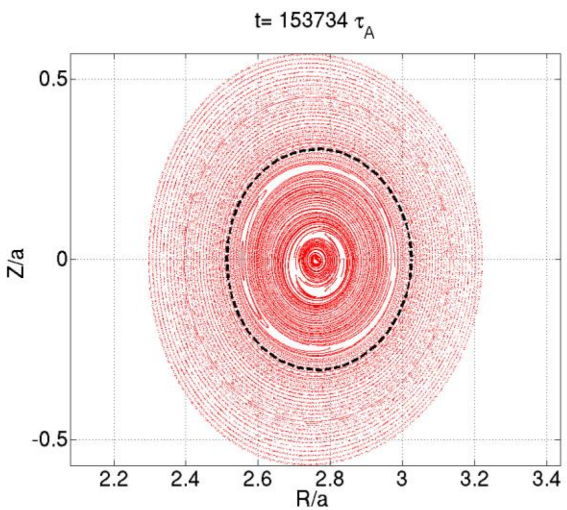
No partial crash, but instability visible in the Poincaré plots

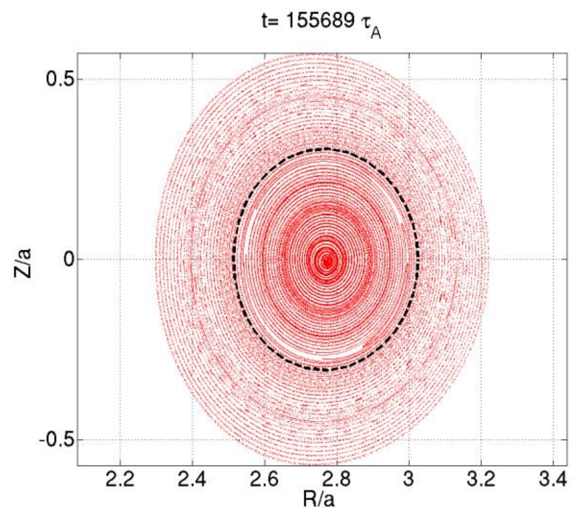


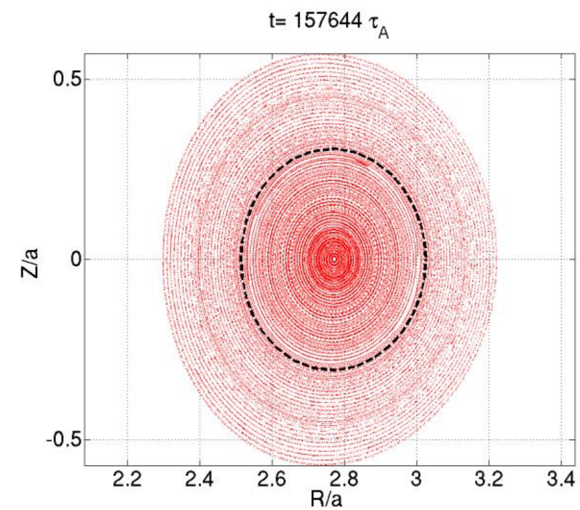




Poincaré plots : track field lines and allow to access magnetic topology







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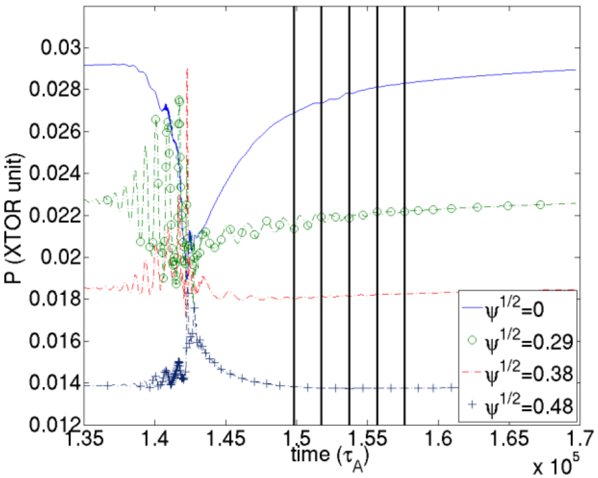
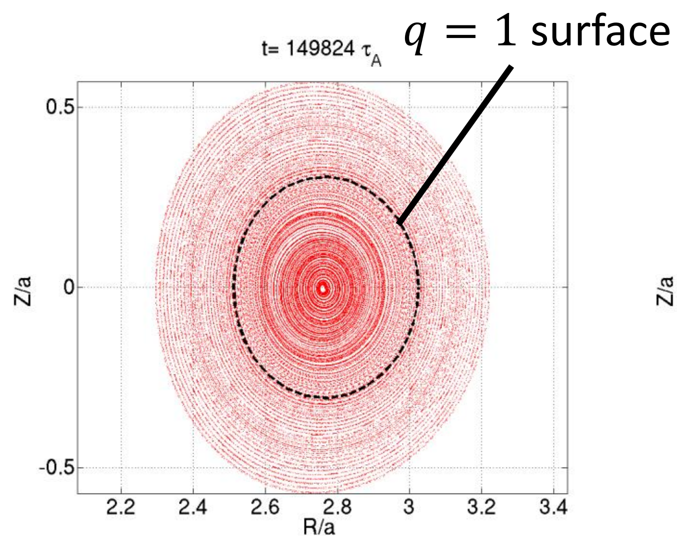
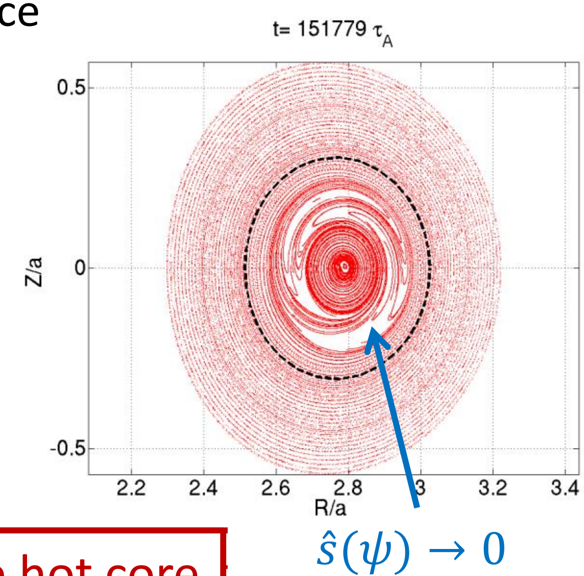
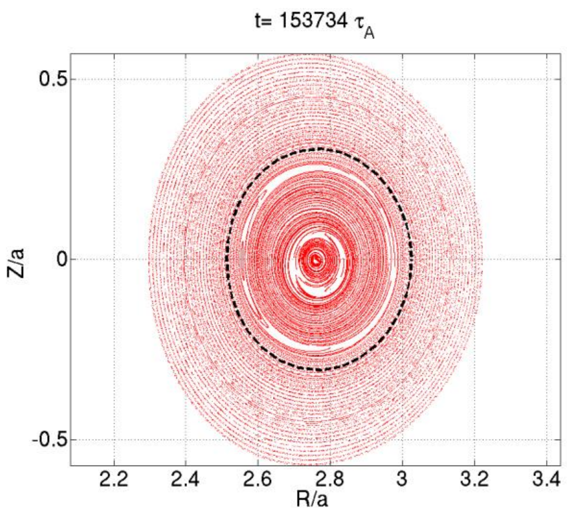
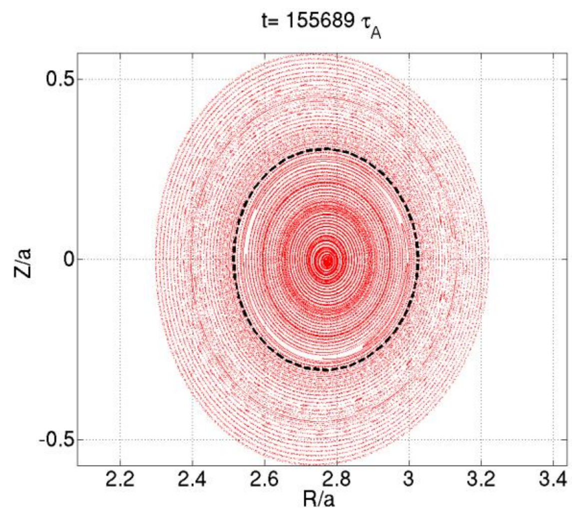


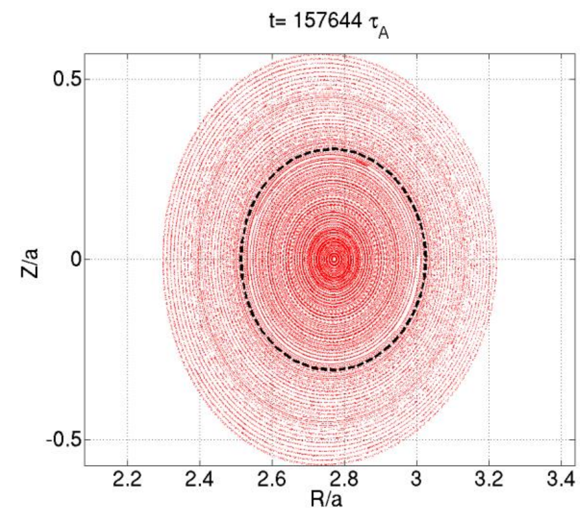




However, no radial displacement of the hot core







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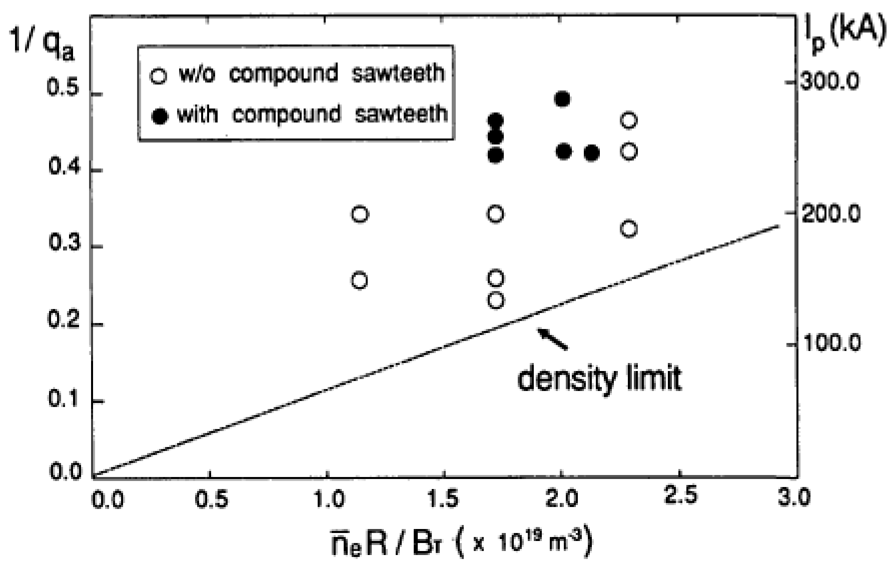
Compound ST simulations with XTOR-2F by destabilizing the internal kink mode

- Simulation of compound sawteeth in an **elliptic cross section**
- Scan on parameters $(\kappa, r_s/a)$ destabilizing the internal kink mode

H. Lütjens *et al.*, *Nucl. Fus.* **32** 1625 (1992)
A. Martynov *et al.*, *Plasma Phys. Control. Fusion* **47** 1743 (2005)
A. D. Turnbull and F. Troyon, *Nucl. Fus.* **29** 1887 (1989)



C. Janicki *et al.*, *Nucl. Fus.* **30** 950 (1990)

Compound ST simulations with XTOR-2F by destabilizing the internal kink mode

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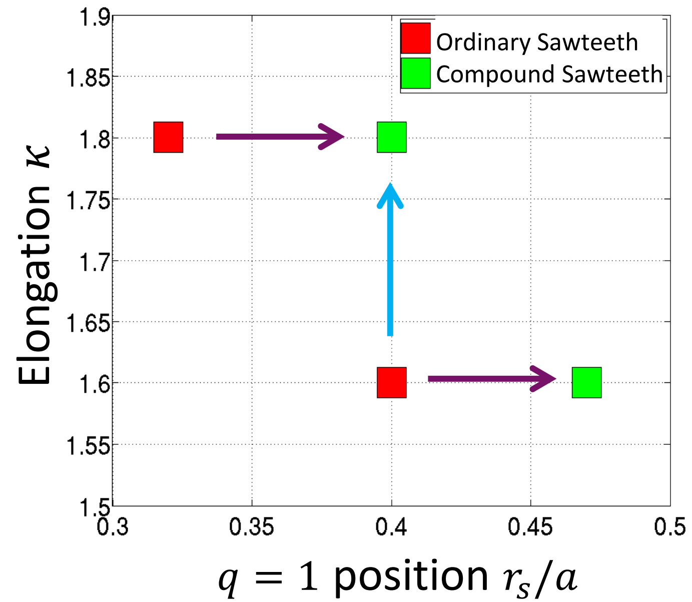
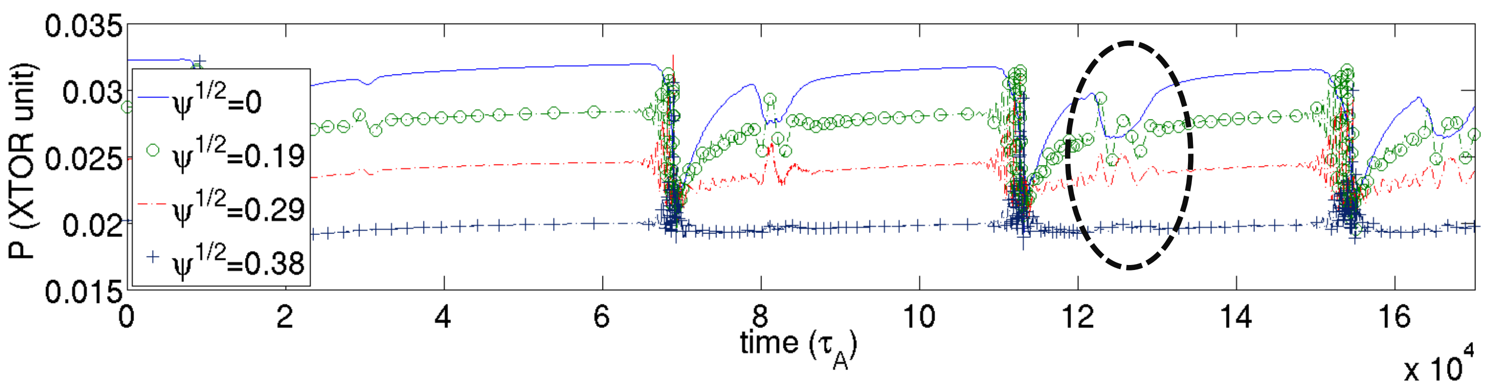
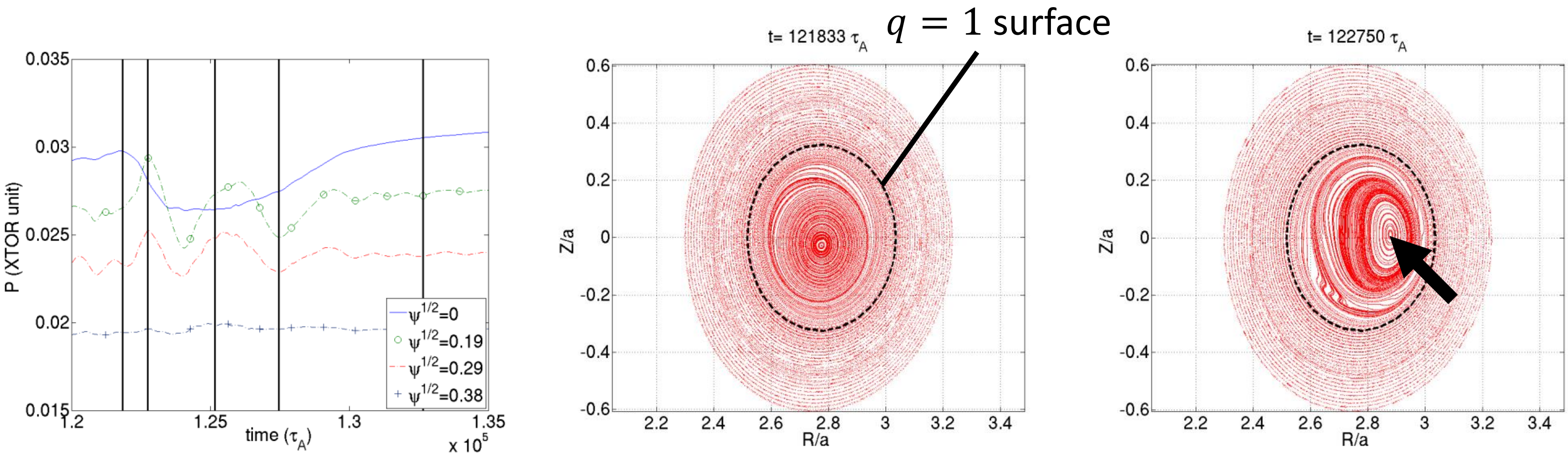
  A. Martynov *et al.*, *Plasma Phys. Control. Fusion* **47** 1743 (2005)
  A. D. Turnbull and F. Troyon, *Nucl. Fus.* **29** 1887 (1989)

- The scan of two parameters gives the effects on the internal kink mode as expected

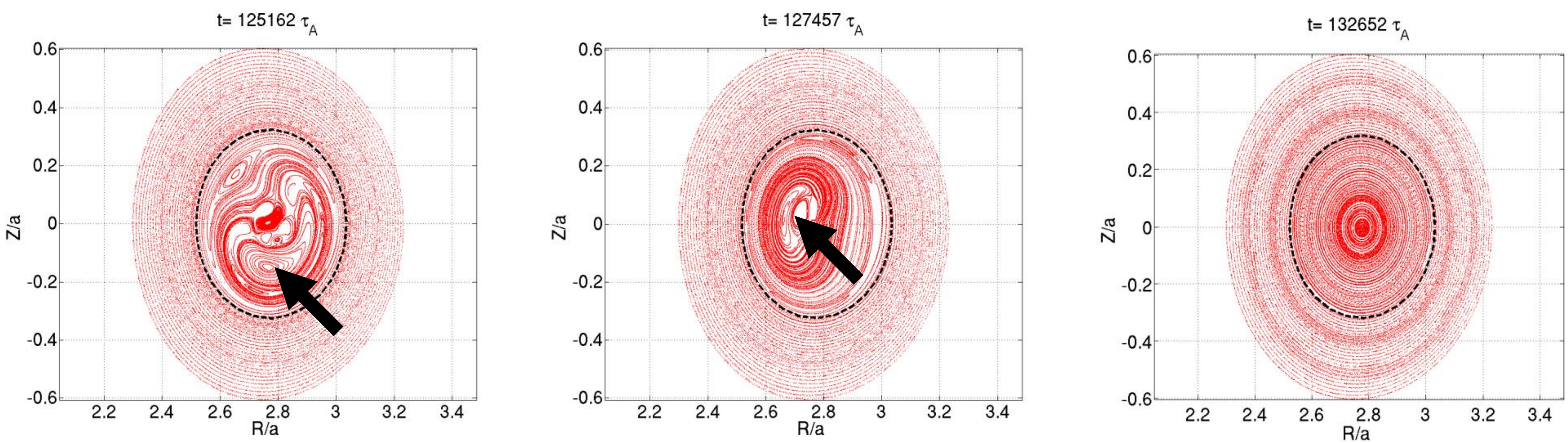




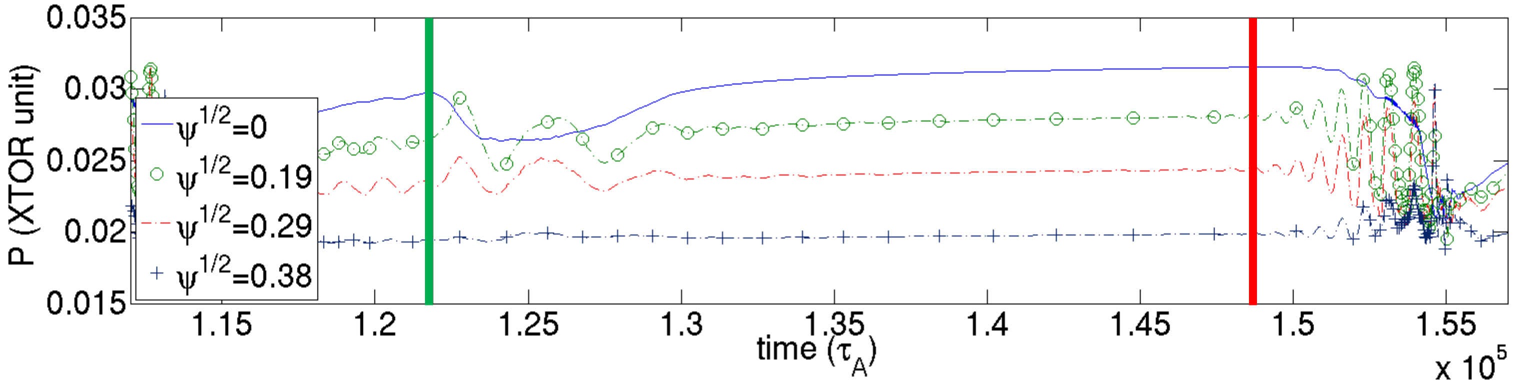
Hot core preserved during partial crash



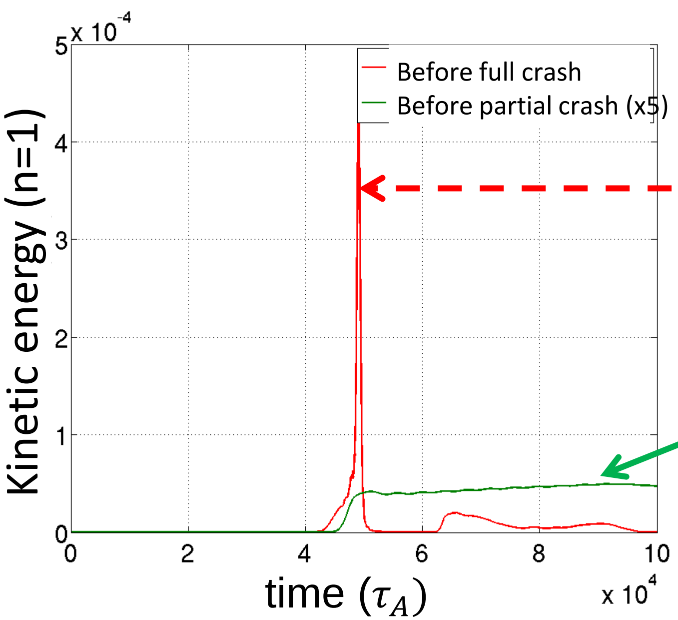
Displaced hot core remains and rotates during partial crash



The partial crash and the ordinary ST crash are of a different nature



- Restart from new equilibria reconstructed at times of interest



Typical behaviour of an ordinary sawtooth crash

Growth rate : $\gamma_{ordinary} > \gamma_{partial}$

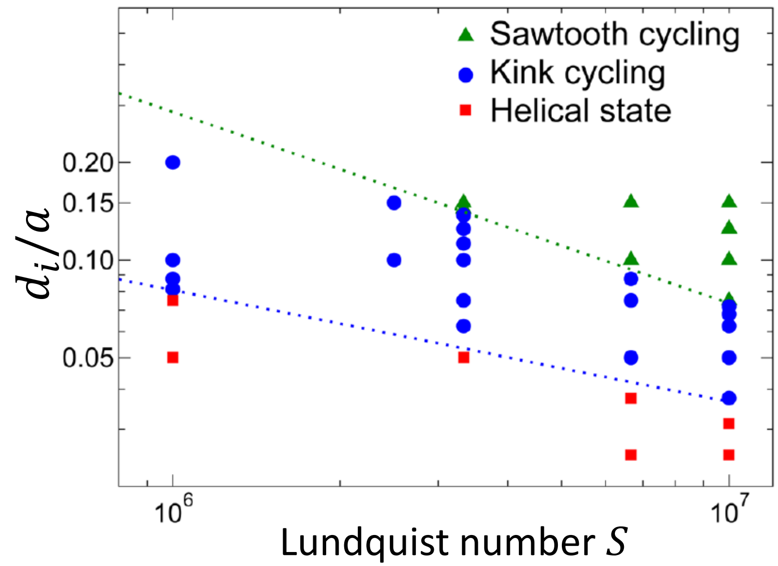
Non-linear saturation of kinetic energy :
Signature of a **saturated helical state**

F. Halpern *et al., Plasma Phys. Control. Fusion* **53** 015011 (2011)
F. Halpern *et al., Phys. Plasmas* **18** 102501 (2011)

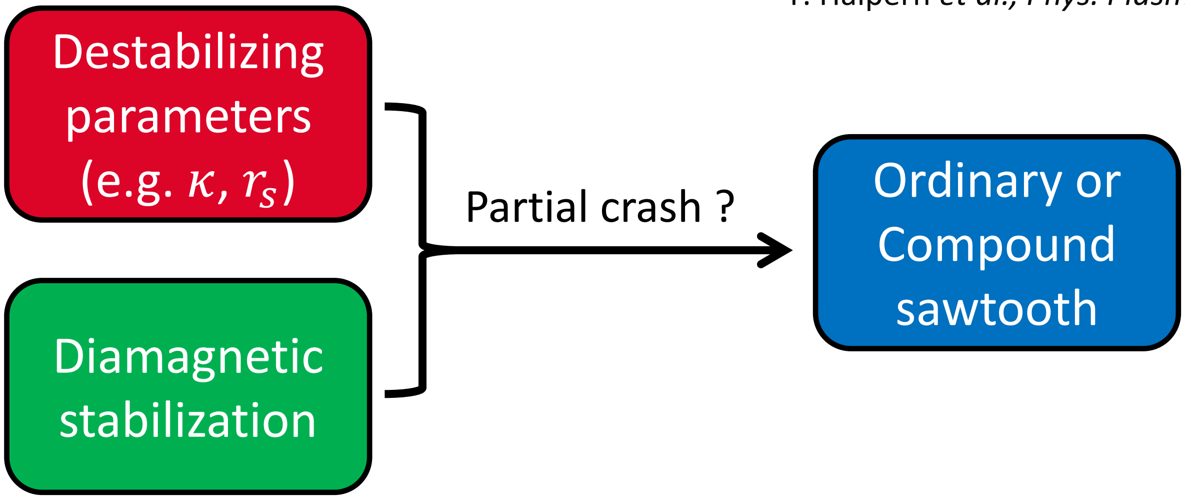
Competition between destabilizing parameters and diamagnetic stabilization

- Saturated helical state obtained for **weak diamagnetic effect**

- Internal kink mode is shown to be **unstable** due to flat q-profiles



F. Halpern *et al.*, *Phys. Plasmas* **18** 102501 (2011)



G. Ara *et al.*, *Ann. Phys.* **112** 443 (1978)

Summary and prospect

☑ The **partial crash** is characterized by the **internal kink mode** with a **displaced hot core**, which is **not fully expelled** out of the $q = 1$ surface.

☑ The internal kink mode during sawtooth **ramp phase** is **unstable**, due to **low-sheared** q-profiles

☑ Depending on the internal kink mode **growth rate** during the ramp phase, ordinary or compound sawtooth is obtained

⟶ So far, no compound sawtooth simulations in circular geometry, β_p scan

⟶ Threshold in κ, r_s/a ? Fraction of compound ST among ordinary ST ?

⟶ Competition between unstable internal kink mode and diamagnetic stabilization during sawtooth ramp phase ?

Additional Slides

Features of the XTOR-2F code

- Toroidal MHD equilibrium computed by the CHEASE code

  H. Lütjens *et al.*, *Comp. Phys. Comm.* **97** 219 (1996)

- **Finite difference** method in **radial** direction and **pseudo-spectral** method in **poloidal** and **toroidal** directions

  H. Lütjens and J.-F. Luciani, *J. Comput. Phys.* **229** 8130 (2010)

Automatically adjusted timesteps

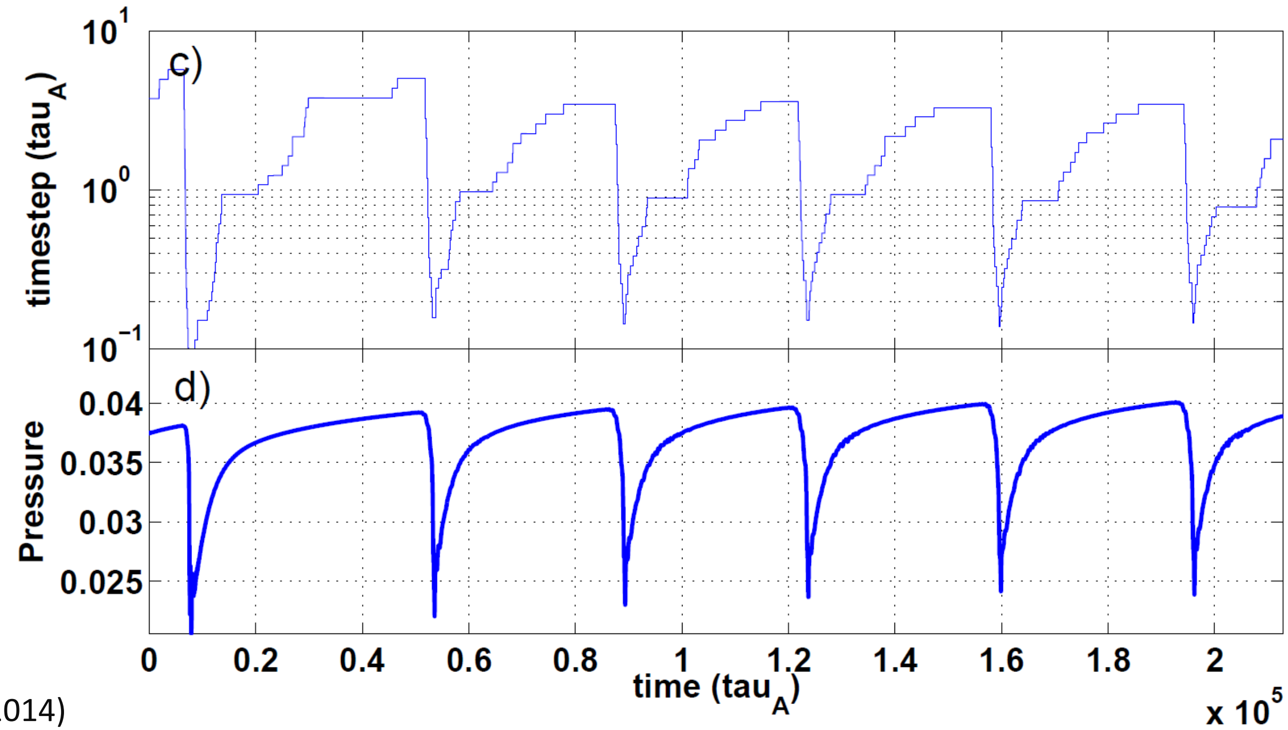
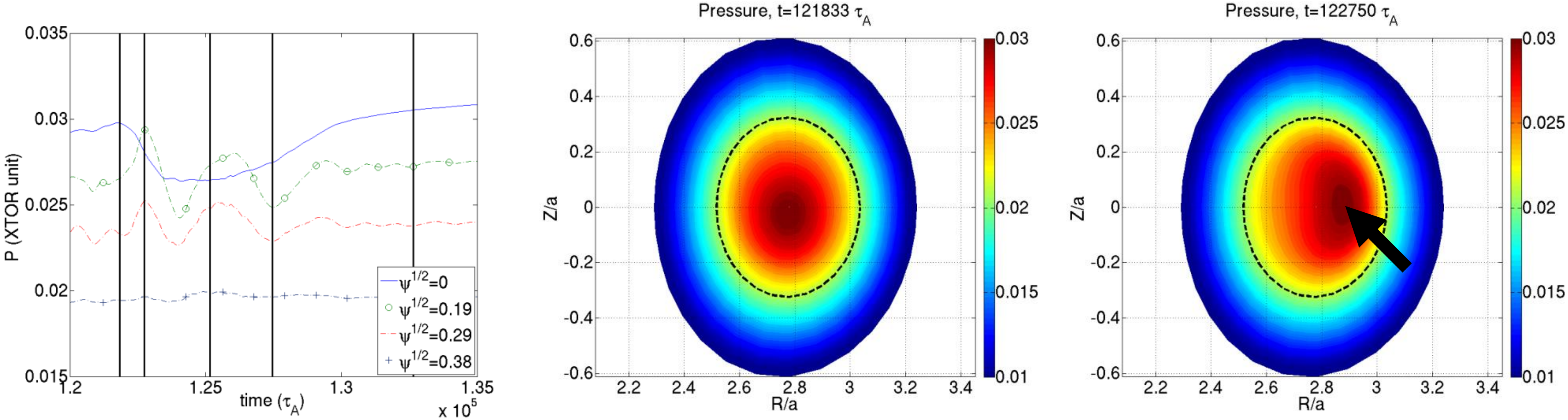
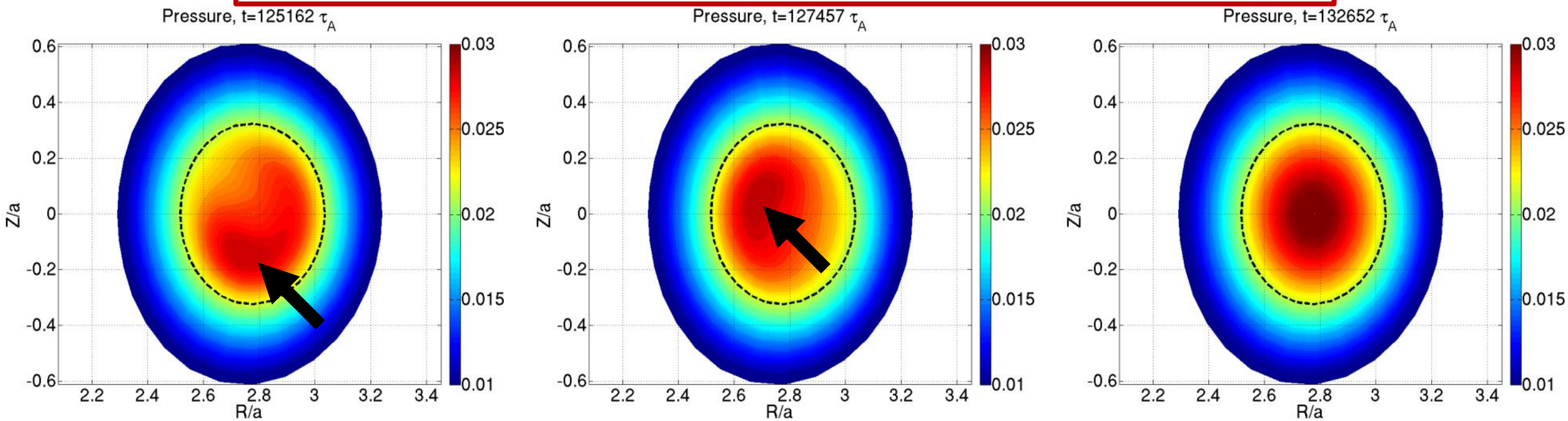


Figure from PhD thesis of T. Nicolas (2014)

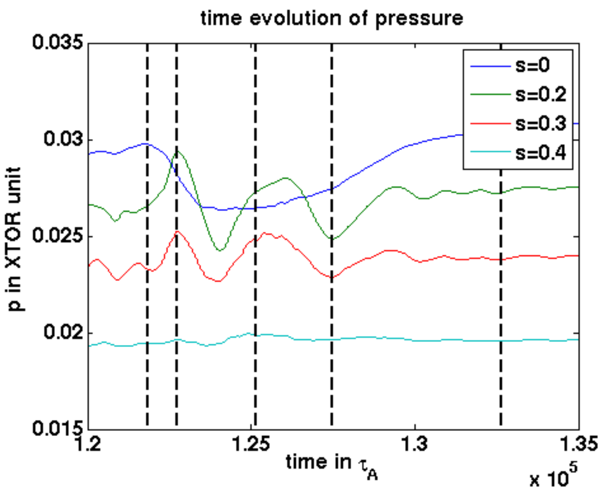
Pressure contours during partial crash

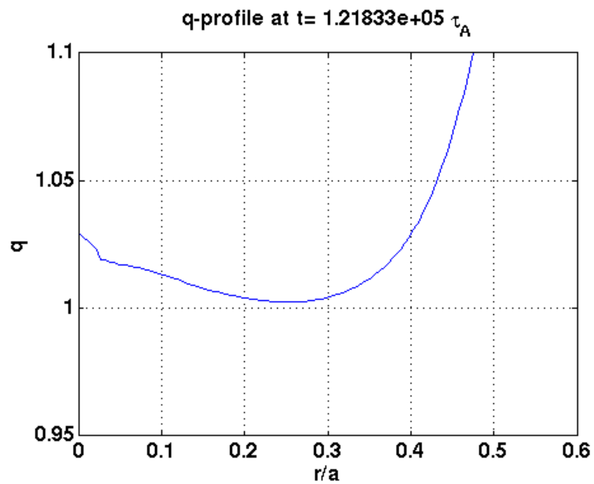


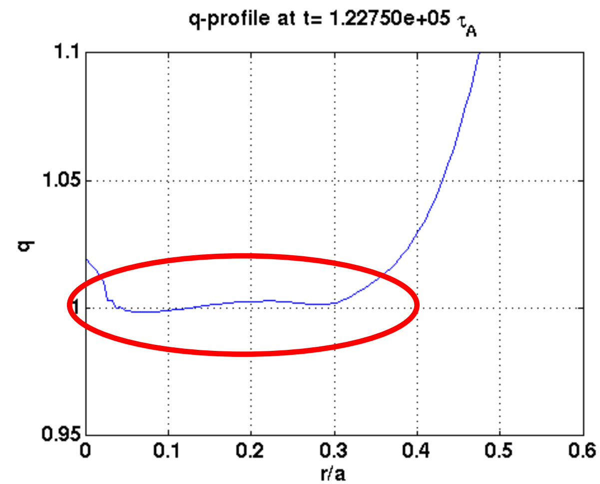
Displaced hot core remains and rotates during partial crash



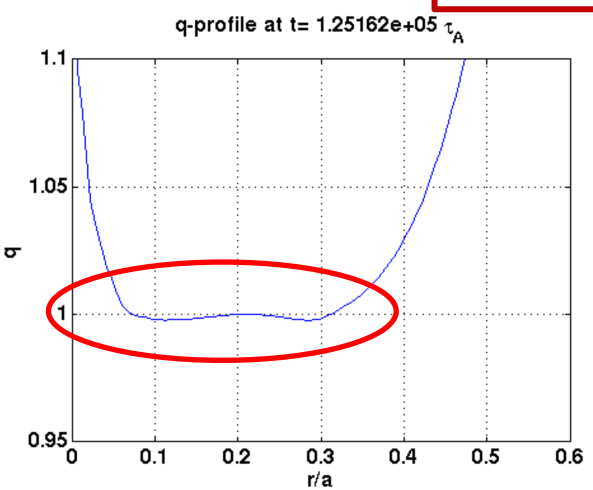
Evolution of q-profile during partial crash

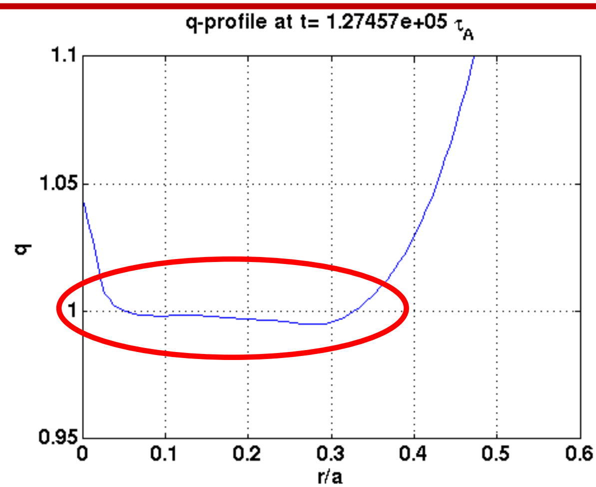


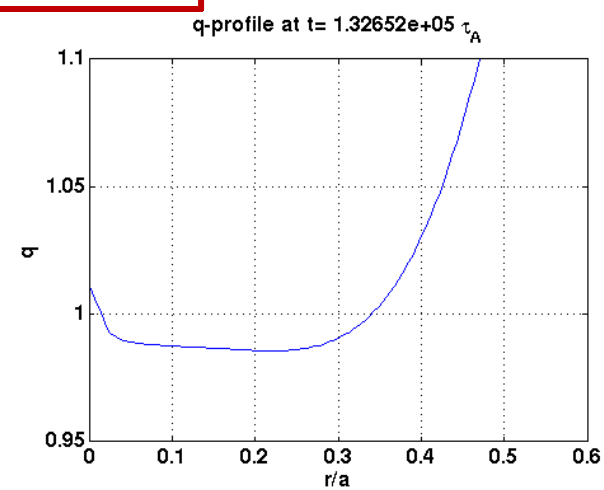




Multiple $q = 1$ surfaces during partial crash



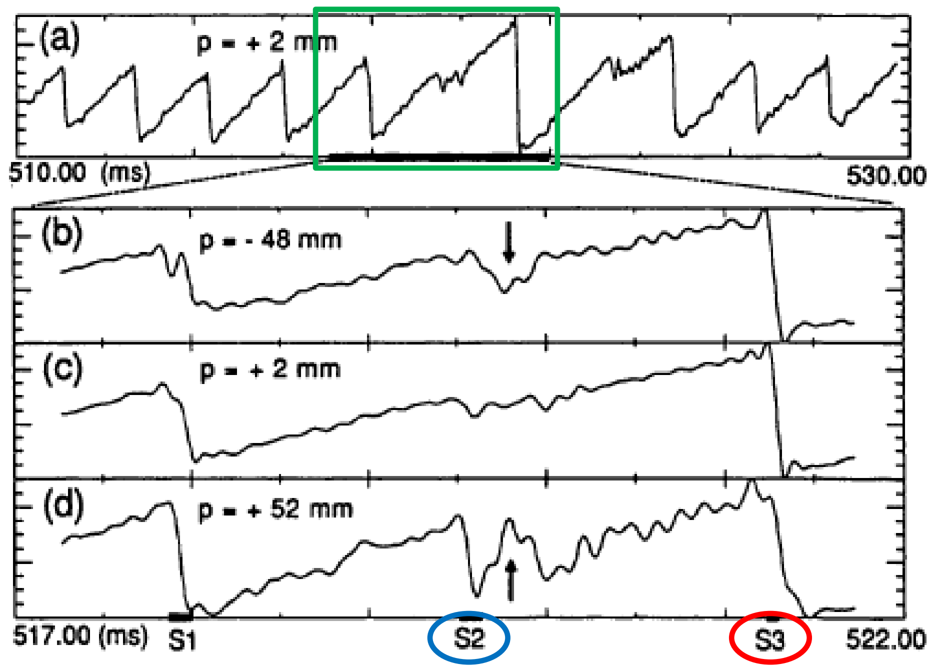




Compound sawteeth in experiments

- Fast Soft X-Ray integration often used to diagnose sawtooth crashes in tokamaks
- Compound sawteeth observed with **2D Soft X-Ray tomographies** in Tokamak de Varennes (discharge #6059, Ohmic heating)

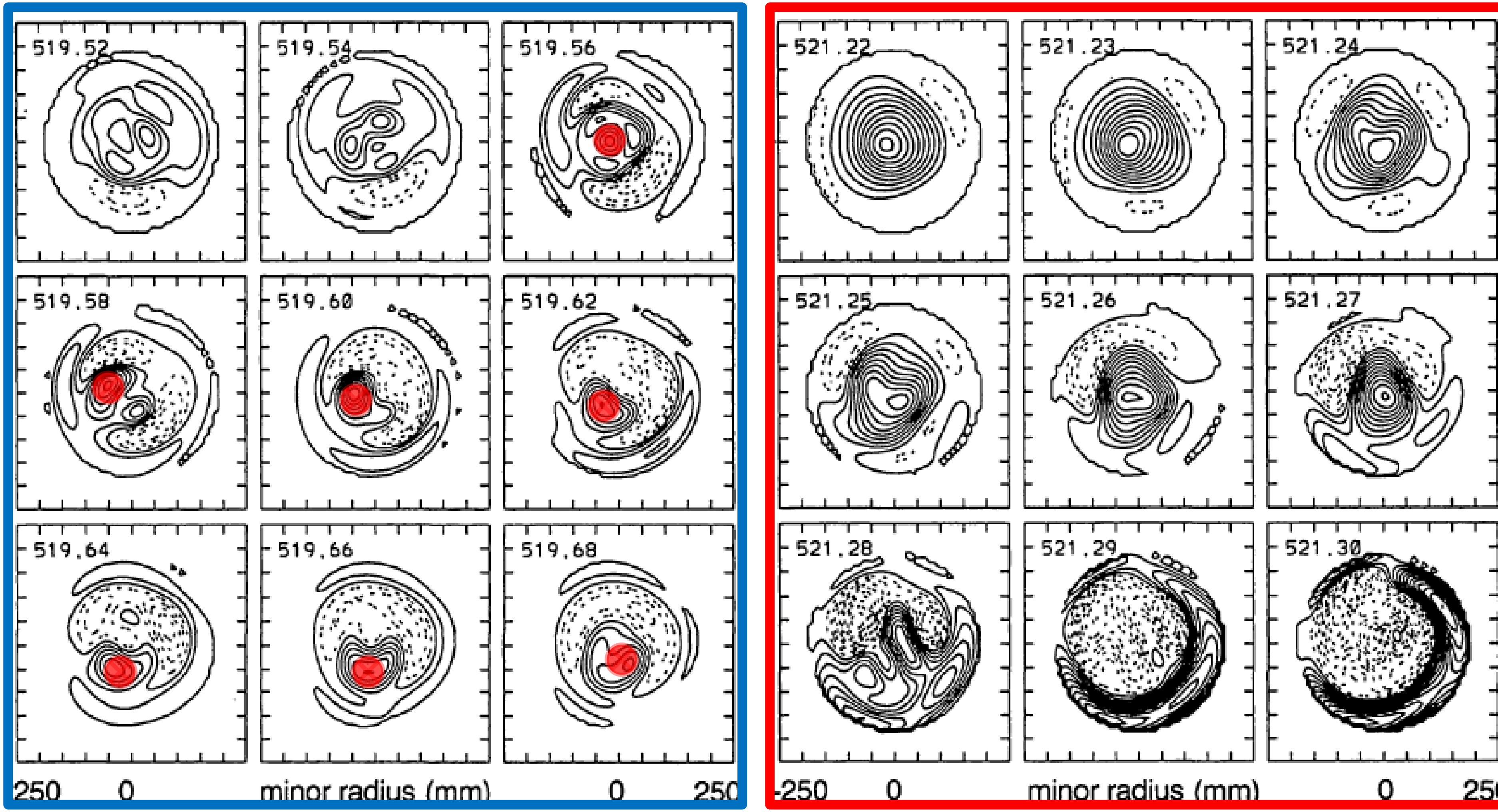
C. Janicki et al., *NF Letters* **30** 950 (1990)



- Similar observations with SXR diagnostic in other tokamaks (e.g. EAST)

L. Xu et al., *Chin. Phys. B* **23** 085201 (2014)

Hot core is preserved and rotates poloidally during partial crashes



C. Janicki et al., *NF Letters* **30** 950 (1990)

During partial crash (**blue**), **hot core** is **preserved** in central region and **rotates**

The internal kink mode is unstable during sawtooth ramp phase

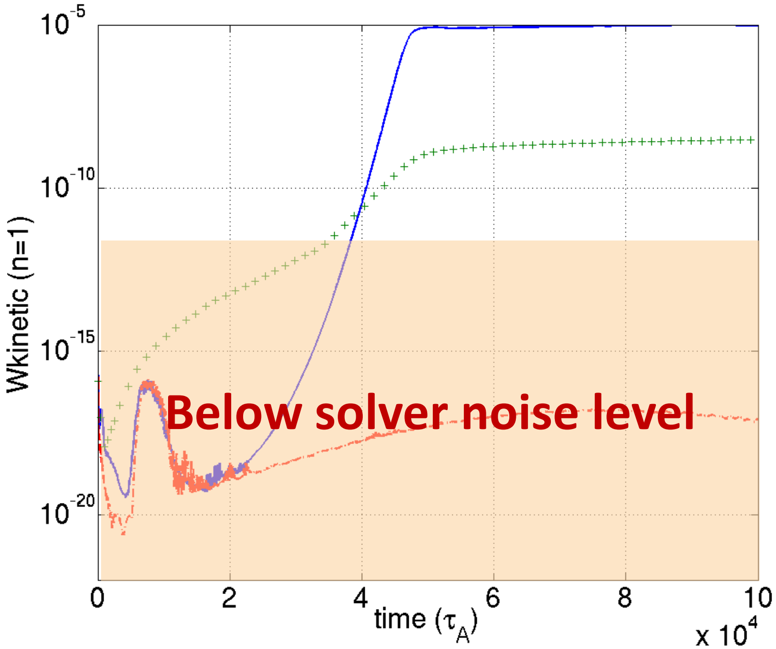
- $n = 1$ **mode** stability **before** and **after** a partial crash :

  internal kink mode is **unstable**

  ⟶ **core displacement**

- Even for the case **without** partial crash,

  unstable $(1, 1)$ **mode** during **ramp phase**



- q-profile remains **flat** during ramp phase

  ⟶ internal kink mode **unstable**

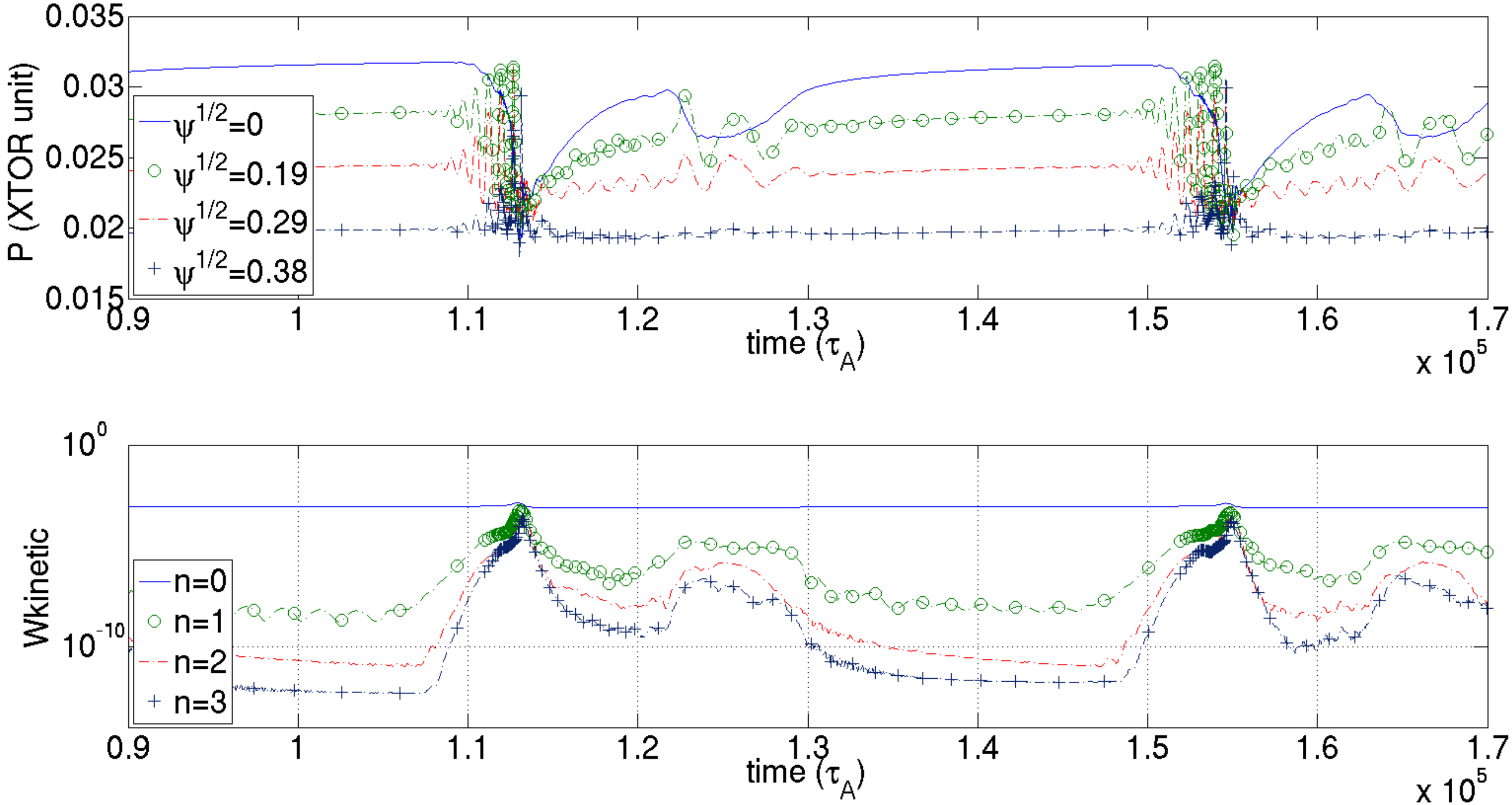
  R. J. Hastie *et al., Phys. Fluids* **30** 1756 (1987)
  H. J. de Blank and T. J. Schep, *Phys. Fluids B* **3** 1136 (1991)

- Non-linear saturation of $n = 1$ mode kinetic energy

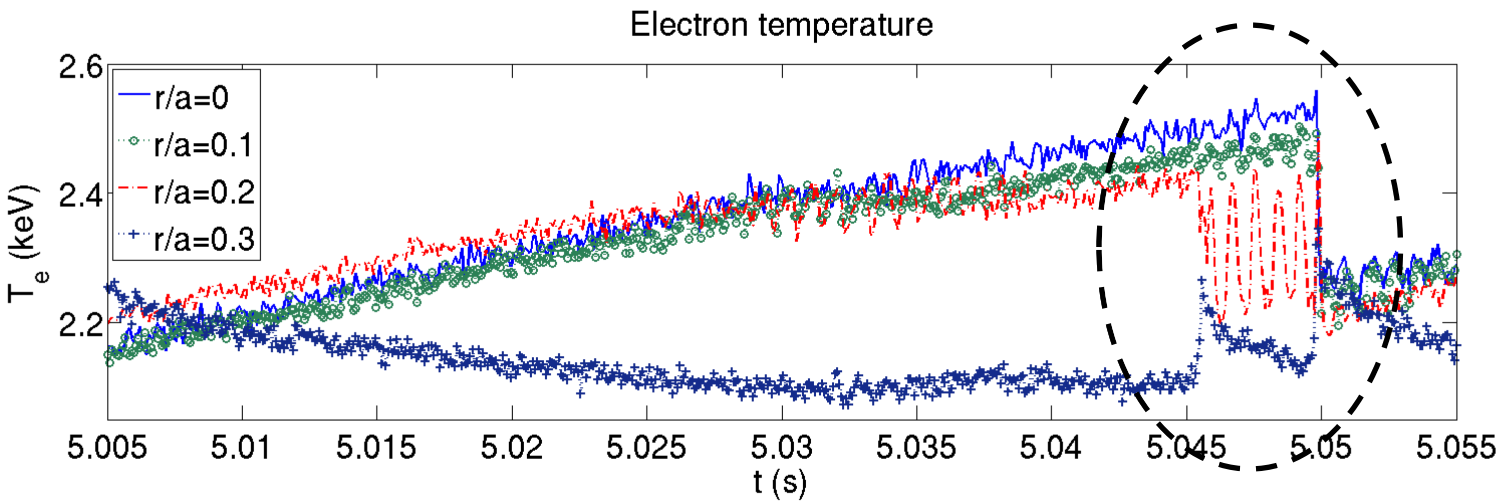
  ⟶ Signature of saturated helical state

  F. Halpern *et al., Plasma Phys. Control. Fusion* **53** 015011 (2011)
  F. Halpern *et al., Phys. Plasmas* **18** 102501 (2011)

Evolution of the kinetic energy during compound sawteeth



Sawtooth crash of ‘2nd kind’



V.S. Udintsev *et al.*, *Plasma Phys. Control. Fusion* **47** 1111 (2005)