ID: 1047 TH/P7-12

MODELING OF BASIC PHYSICS ISSUES IN TOROIDAL PINCHES AND TOOLS FOR PERFORMANCE CONTROL

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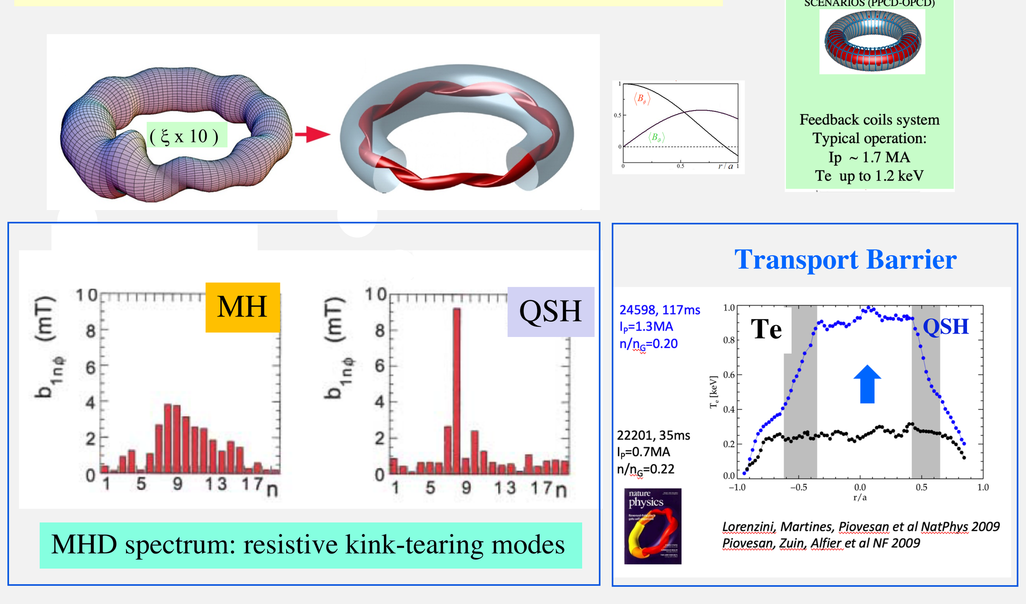
BACKGROUND RFP-helical self-organization

The RFP tends to saturated KINKED plasma for Ip above ~ 1 MA (RFX device)

Advanced operation required in RFX-mod
CLEAN MODE CONTROL and/or NON-CONVENTIONAL SCENARIOS (PPCD OPCD)
Feedback coils system
Typical operation:
Ip ~ 1.7 MA
Te up to 1.2 keV



MHD spectrum: resistive kink-tearing modes

Lorenzini, Martines, Piovesan et al NatPhys 2009
Piovesan, Zuin, Alfier et al NF 2009

METHODS / IMPLEMENTATION

Model equations …

SpeCyl code - simple visco-resistive approx.
Cappello & Biskamp Nucl. Fus. 1996

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\wedge(\mathbf{v}\wedge\mathbf{B}) - \nabla\wedge(\eta\,\mathbf{J})$$

$$\frac{d\mathbf{v}}{dt} = \mathbf{J}\wedge\mathbf{B} + \nu\nabla^2\mathbf{v}$$

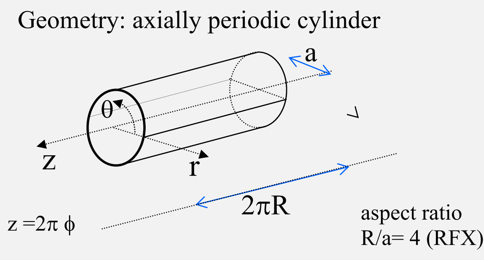
$$\rho \equiv 1, \quad \nabla p \equiv 0$$

$\eta = \tau_A/\tau_R$ two dimensionless parameters with assigned radial profiles

Lundquist: $S = 1/\eta$
Viscous Lundquist $M = 1/\nu$

r — Finite difference
θ, φ — Spectral formulation
t — Predictor-corrector + semi-implicit

Geometry: axially periodic cylinder



aspect ratio R/a= 4 (RFX)

"typical" boundary conditions:

- $B'_z = 0$ (constant magnetic flux Φ)
- Constant E_z
- m,n: Ideal boundary / With MP on B r m,n (~ 1%, 2%, 4 %...) / Thin shell + vacuum layer +ideal wall
- velocity field: no slip.

initial conditions define Φ, Iz

EXTENDED BACKGROUND

Model equations … transformed $t \to \bar{t} = \sqrt{\frac{\eta}{\nu}}\,t$ $\mathbf{v} \to \bar{\mathbf{v}} = \sqrt{\frac{\nu}{\eta}}\,\mathbf{v}$

(η , ν) ⇒ (*H* , *P*)

Magnetic Prandtl $\mathbf{P} = \nu/\eta = S/M$
Hartmann number $\mathbf{H} = (\nu\eta)^{-1/2}$

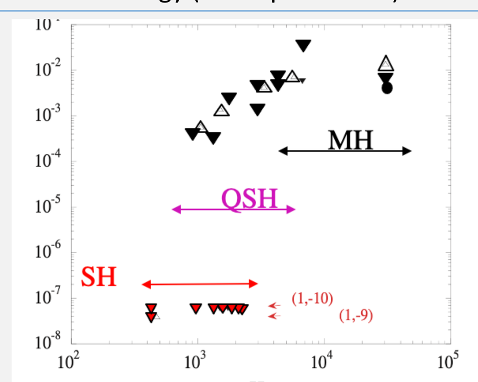
Continuous transition to helical regimes ruled by: H

$$\frac{\partial \bar{B}}{\partial \bar{t}} = \nabla\wedge(\bar{v}\wedge\bar{B}) - \nabla\wedge(H^{-1}\,\bar{J})$$

$$\frac{1}{P}\frac{d\bar{v}}{d\bar{t}} = \bar{J}\wedge\bar{B} + \nabla^2(H^{-1}\,\bar{v})$$

$$\rho \equiv 1, p \equiv 0$$

m=0 mode energy (order parameter) versus **H**

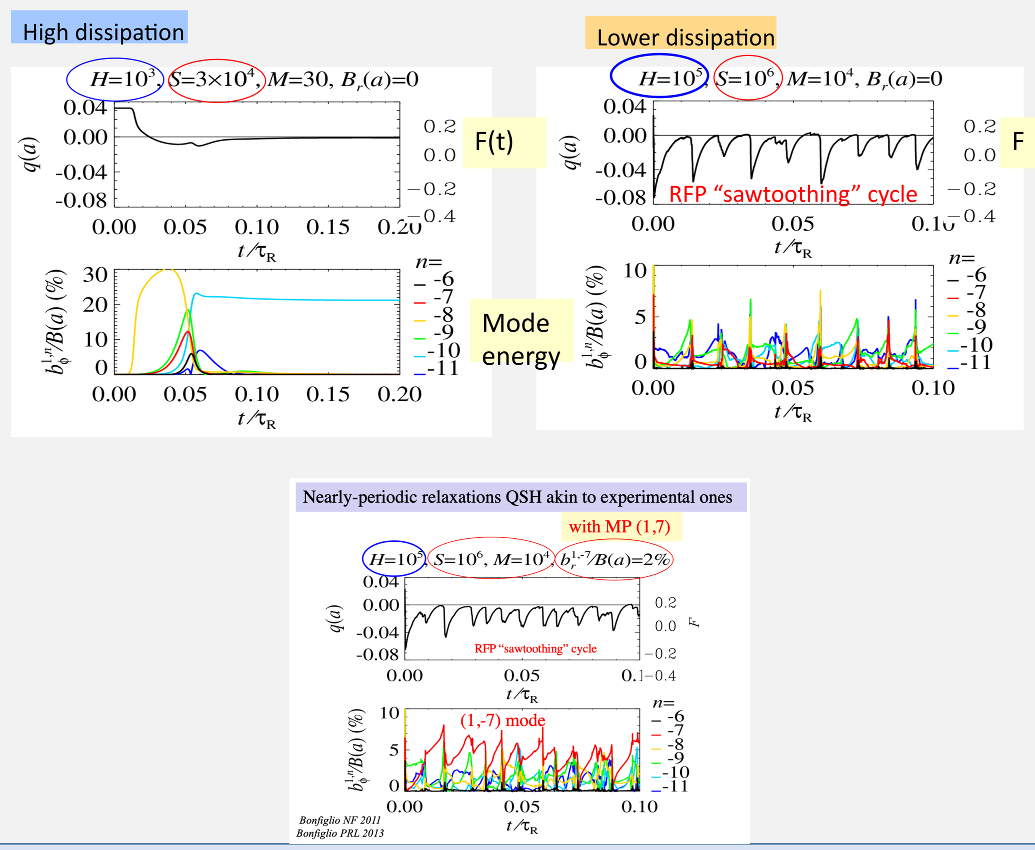


Cappello & Escande PRL2000
Cappello PPCF 2004

SpeCyl 3D simulations: first relaxation to reversed state, then … (ideal BC)

Saturated kink
Single Helicity - SH

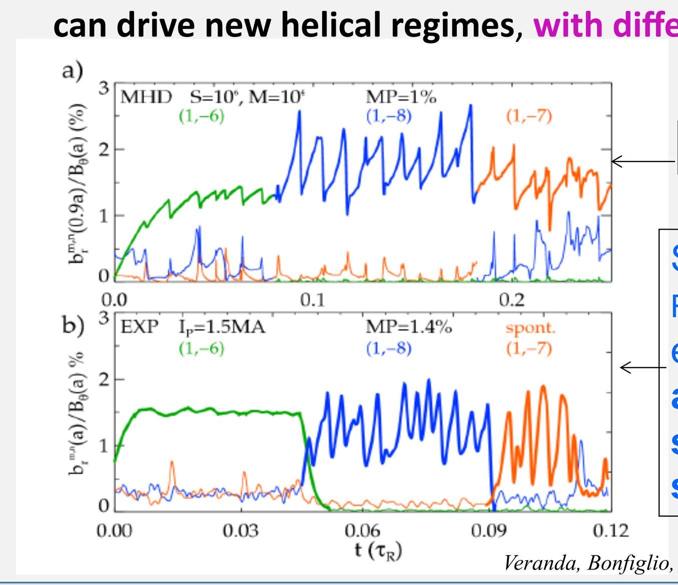
nearly-periodic relaxations
Multiple Helicity - MH



Bonfiglio NF 2015
Bonfiglio PRL 2013

Successful confirmation in RFX-mod

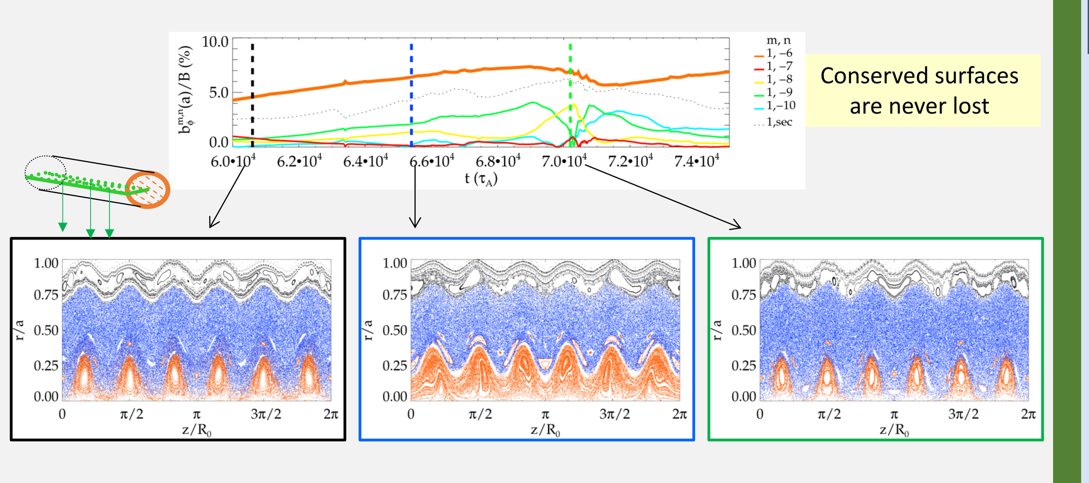
Small edge Magnetic Perturbations (MP)
can drive new helical regimes, with different pitch:



Successful RFX-mod experiments: **alternative *n*s stimulated by seed MP**

Veranda, Bonfiglio, Cappello et al NF 2017

More efficient **CHAOS HEALING** by stimulating n=6 (Non-Resonant)



Escande Paccagnella Cappello PRL 2000
Veranda, Bonfiglio, Cappello et al NF 2020

ABSTRACT

Recent progress about **helical self-organization** studies is reported.
Extensive exploitation of **3D nonlinear visco-resistive modeling**, **SpeCyl code**, which describes **current-driven dynamics typical of pinch** configurations in cylindrical geometry.
Magnetic topology studies are based on the Field Line Tracing code NEMATO and a **new refined tool to detect Lagrangian Coherent Structures** is compared with results from a **temperature equation solver.**

The following Physics Issues in **helical self-organization** are addressed:

- Boundary Conditions and dimensionless parameters impact, (RFP, and circular Tokamak)
- Formation of internal transport barriers, (RFP)
- Temporary loss of operational point, reconnection events, (RFP and circular Tokamak),
- Alfvén waves excitation (RFP and circular Tokamak),

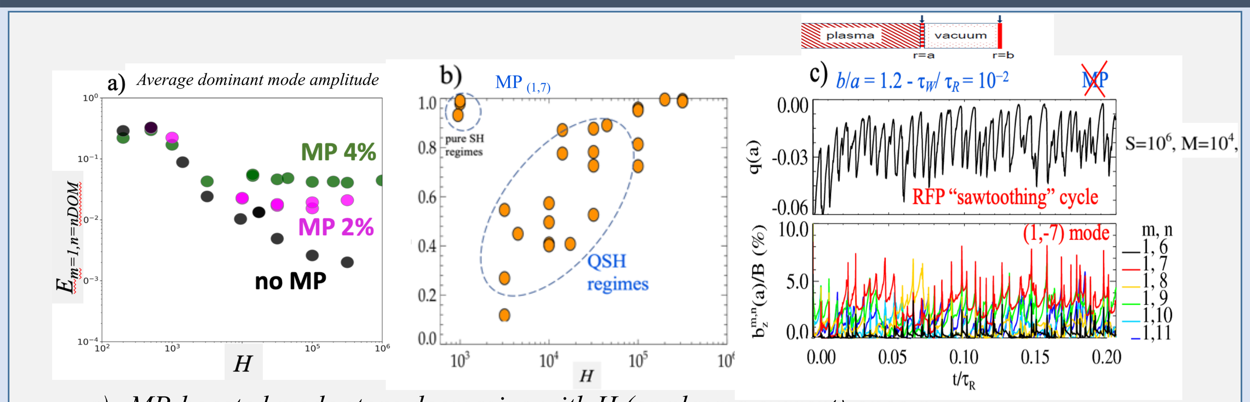
RESULTS show:

- **Reasonable comparison (validation) with RFP experimental observations,**
- **Similarities between RFP and Tokamak-like configuration.**

In addition:

- data analysis tools, machine learning "autoencoding" techniques, are here trained for the first time on an RFP data analysis case,
- a possible fundamental mechanism for ion heating in plasmas is presented.

1. 3D MHD KEY ROLE OF BOUNDARY CONDITIONS (MP)
Seed finite radial magnetic field favours Helical regime

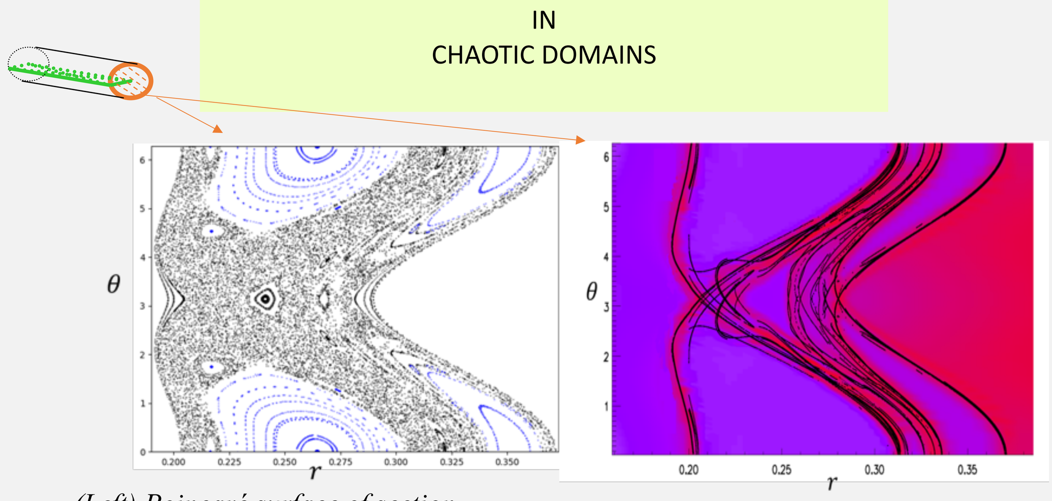


a) MP-boosted mode stops decreasing with H (or plasma current) once a saturation amplitude is reached (proportional to MP%).
b) QSH persistence increase with H, similarly to what observed in RFX-mod experiments in the interval of 0.8-1.2 MA
(compare highlighted dots with Figs. 4 and 5 of ref. [11])
a) Self-organized intermittent 1/7 helical regime in RFP simulations with **resistive thin shell and vacuum layer** (no applied MP)

Veranda et al NF 2020
Pizzan et al Fusion Eng. Des. 2018

2. LAGRANGIAN COHERENT STRUCTURES
TRANSPORT BARRIERS

LAGRANGIAN COHERENT STRUCTURES (LCS) AND
TEMPERATURE GRADIENTS
IN
CHAOTIC DOMAINS

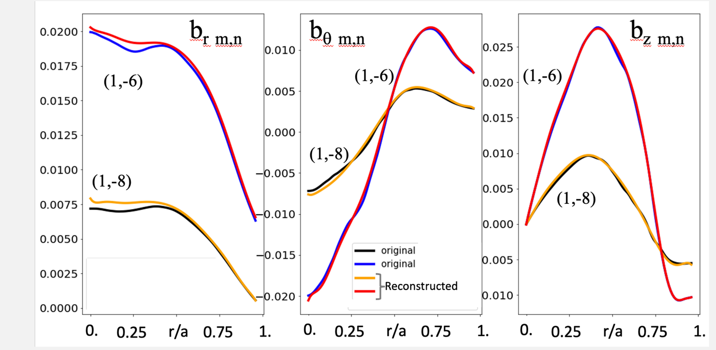


(Left) Poincaré surface of section,
(right) **Lagrangian Coherent Structures** (black curves) locate in regions with larger gradT
Temperature gradient map (colour map), from a temperature equation solver [16]
(The anisotropy ratio employed to obtain the picture on the right is $\chi_{\parallel}/\chi_{\perp} = 10^7$)

3. MACHINE LEARNING DATA ANALYSIS FOR MODE RECONSTRUCTION

In view of experimental validation (RFX-mod2) of the advanced diagnostic LCS tool :
Data analysis machine learning (ML) technique has been trained on the numerical RFP simulation data

The modes eigenfunctions have been reconstructed back from the ML algorithm using the sole values of the magnetic field at the boundary after Neural Network training.



Magnetic field components by 3D nonlinear MHD during the formation of a realistic QSH regime [10]:
ORIGINAL blue and black,
RECONSTRUCTION from ML algorithm in red and orange

CONCLUSION

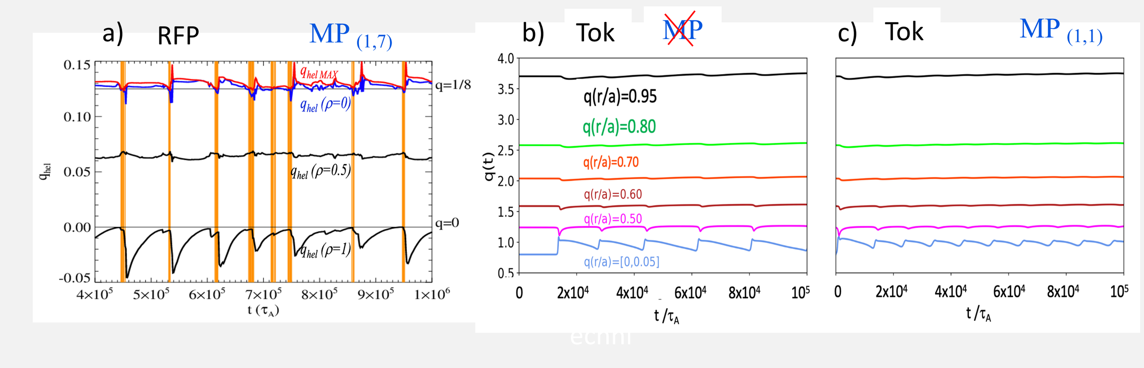
Basic physics issues encountered in toroidal pinches have been addressed and most recent results are here reported. In particular, **the current driven physics of helical self-organization is addressed by relying on simple visco-resistive 3D nonlinear MHD modeling and related benchmarked numerical tools**. Barriers formation for magnetic field lines and temperature, temporary loss of operational point, reconnection-relaxation events are shown. A data analysis tool, machine learning "autoencoding" technique, is here trained for the first time on an RFP data analysis case.

A possible mechanism for ion heating as produced by non-resonant low-frequency Alfvén waves is also presented, which was initially considered as possible mechanisms for RFP anomalous particle heating.

Together with previous results on the discovery of new RFP helical states, experimentally reproduced in RFX-mod by suitable use of edge Magnetic Perturbations, MP, the recent progress give confidence in the realistic description obtained within our basic modeling, which might therefore provide a useful set of means to train and validate advanced data analysis tools, like machine learning techniques, with the aim of understanding and optimizing magnetic configurations.

See companion contributions: Marrelli EX/P7-4 Gobbin EX/P7-2 Zuin EX/P7-3

4. 3D MHD: SAWTOOTHING (RFP AND TOKAMAK)
AMPLITUDE AND FREQUENCY CAN BE "TUNED" BY MP



a) RFP case: helical safety factor (q_{hel}) at different effective radii ρ, MP(1,-7) $\eta = 10^{-7}, \nu = 10^{-4}$.

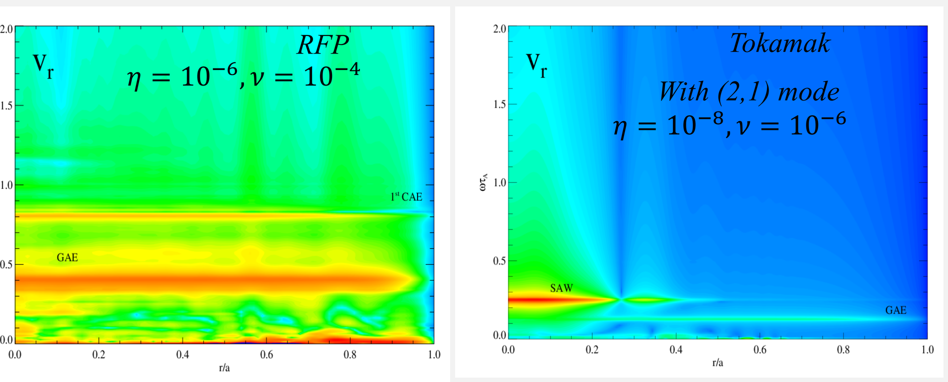
b), c) TOKAMAK: safety factor $q(r)$ at different radii r without/with MP(1,1) $\eta = 10^{-6}, \nu = 10^{-4}$.

MPs amplitude: RFP = 2% in the TOKAMAK = 0.8% (with respect to the poloidal field at the edge).

NOTE: In RFPs, during sawtoothing activity, at the crash/reconnection time, ion heating has been highlighted in Madison Symmetric Torus experiment [see S. Gangadhara et al, Phys. Plasmas 15, 056121 (2008) and therein references]

5. 3D MHD: SAWTOOTHING (RFP AND TOKAMAK)
ALFVèN WAVE EXCITATION

Spectrograms of velocity perturbations (m=1, n=0) at reconnection event



The colour scale is the same in both panels.
Excitation of Alfvén eigenmodes, quite strong in the RFP configuration, is significant in the tokamak configuration too, when a (2,1) mode is present.
In particular, the global Alfvén eigenmode (GAE) is observed in both configurations.

The spectrum of the Alfvén eigenmodes excited in RFP configurations is in reasonable quantitative agreement with experimental findings in the RFX-mod device [21].

6. STUDIES OF THE ADIABATIC INVARIANTS
NON-RESONANT WAVE PARTICLE ENERGY TRANSFER

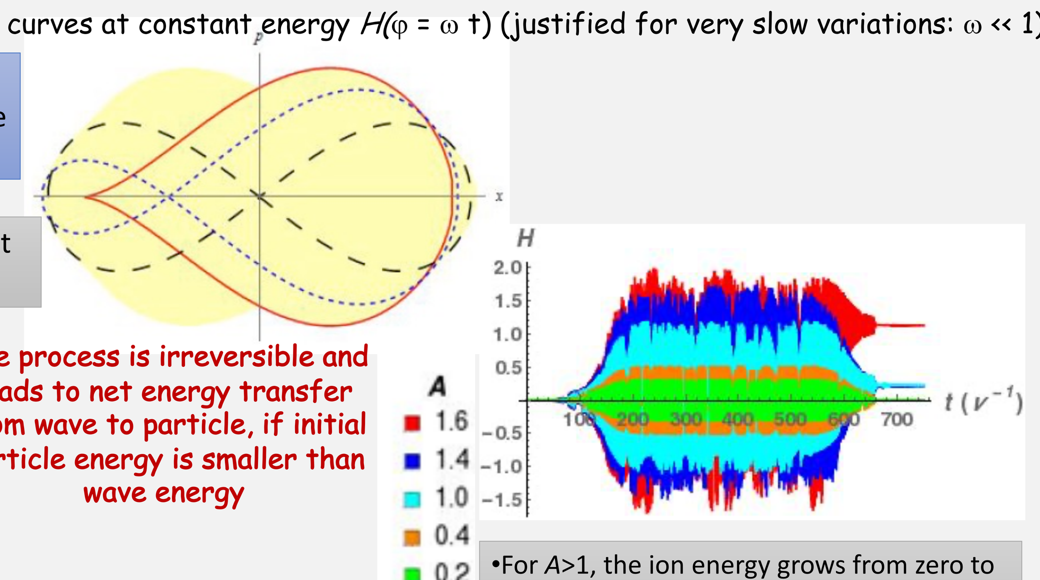
Paradigmatic case of non-resonant ion heating:
Hamiltonian dynamics of a particle in a uniform magnetic field plus plane wave

$$H = \frac{p^2}{2} + \frac{x^2}{2} - A\sin(x - \omega t)$$

The ion follows phase-space (x,p) curves at constant energy $H(\varphi = \omega\, t)$ (justified for very slow variations: ω ≪ 1).

For *A* >1 there is a pulsating separatrix over a fraction of the wave period

Separatrices at different φ's



The areas of the lobes change → orbits must cross the separatrix at the X-point and thus move to different phase-space basins (=different energy)

The process is irreversible and leads to net energy transfer from wave to particle, if initial particle energy is smaller than wave energy

•For *A*>1, the ion energy grows from zero to order *A*
•*E* ~1 → ion energy ~ coronal temperature

*The figure shows time traces of particle' energy when the wave is slowly turned on and switched off. As long as the amplitude **A** is lower than unity, the dynamics is adiabatic and the particle return to its initial rest state. For **A** greater than unity, dynamics is non-adiabatic and the particle gains a net amount of energy.*

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