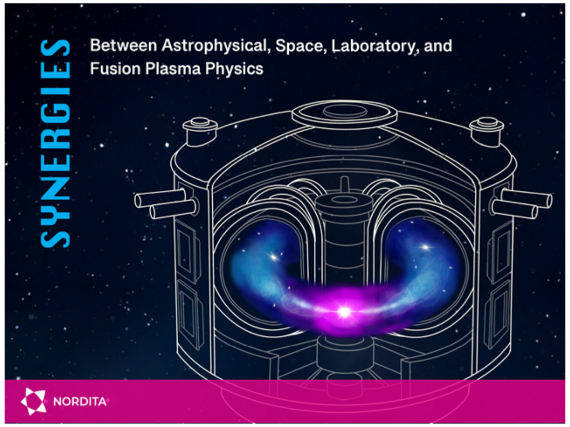
Magnetic reconnection in fusion plasmas

Barbara Momo

Thanks to many colleagues: Roberto Cavazzana, Luigi Cordaro, Marco Gobbin, Italo Predebon, Silvia Spagnolo, Gianluca Spizzo, Marco Veranda, Matteo Zuin and many others

Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete)



Introduction

- What is magnetic reconnection?
- What are fusion plasmas?
- What are principal reconnection events in fusion plasmas?

- What is magnetic reconnection?

Reconnection: a way to reach a minimum energy state

We can intend reconnection as a way for magnetized fluids to reach a state of minimum energy. This gives rise to the tendency for a magnetized fluid to undergo a magnetic reconnection if the new equilibrium, to which it evolves after reconnection, has a lower energy.

Yamada, Kulsrud and Ji, RMPP 2010

Magnetic reconnection is usually defined as a change in the B-line topology
The **topology of a set of B-lines is closely linked to the definition of magnetostatic equilibrium**: **there is a unique magnetostatic equilibrium for each magnetic topology**, which is the state that minimizes the energy of the magnetic field while preserving its topology.

Kruskal and Kulsrud, 1958

Reconnection: a way to reach a minimum energy state

So: any change in the magnetic topology implies a different equilibrium with a different energy.

- When B-field lines are reconnected, the plasma undergoes an **abrupt change in the magnetic topology** of the configuration
- This puts the plasma in a **non-equilibrium state**: JxB forces are generated that must be relaxed along the new B-lines (and J-lines), by viscous or inertial terms, until the new magnetostatic equilibrium is reached, with lower magnetic energy
- resulting in the **conversion of magnetic to kinetic energy**
- which is **then converted into heat, radiation or particle acceleration**

$$\bar{J} \times \bar{B} \neq 0$$

Magnetic reconnection is so important because it can lead to a **rapid conversion of magnetic energy to other forms**

Yamada, Kulsrud and Ji, RMPP 2010

Magnetic topology and *flux freezing*

Magnetic topology – the geometry of the magnetic field: one can represent any magnetic field by a set of lines that densely fills the system. The lines are tangent to the magnetic field everywhere, and their density equals the field intensity. But **magnetic field lines have no physical identity in absence of matter.**

Yamada, Kulsrud and Ji, RMPP 2010

***Flux freezing*:** only in the presence of an infinitely conducting plasma moving with the field lines, **a physical identity can be assigned to the lines**: any plasma on a given flux tube stays on there as it moves and cannot move to another line: the magnetized fluid is configured according to the topology of B

$$\frac{\partial B}{\partial t} = \nabla \times (\bar{v} \times \bar{B}) + \cancel{\eta\nabla^2\bar{B}}$$

In an ideal plasma, **B** cannot diffuse

Magnetic reconnection: non-ideal evolution of B

Magnetic reconnection: implies **the breaking of some B-lines at some place**, with the consequent change in the magnetic topology. This is the result of a non-ideal evolution of B

$$\frac{\partial B}{\partial t} = \nabla \times (\bar{v} \times \bar{B}) + \eta \nabla^2 \bar{B}$$

Diffusion of **B** necessary for magnetic reconnection

So, magnetic reconnection occurs in magnetized plasmas and is essentially the opposite of flux freezing.

But magnetic reconnection occurs through a **reorganization of the currents flowing in the magnetized fluid (change in the topology of the J-lines) and therefore a reconfiguration of B-lines too**. Reconnection is linked and due to the dynamics of **charged particles**!

Global causes of reconnection

Magnetic reconnection is always a **geometrical problem**, related to the distribution of the currents in the plasma

- By applying an **external force** (fusion energy in stars, heating in fusion devices, …) to a magnetized fluid, the magnetic configuration slowly evolves toward equilibrium, **storing magnetic energy on a global scale**.
- **At some point**, if resistive dissipation is not enough to maintain the equilibrium, the equilibrium becomes unstable due to **excess magnetic energy and accumulation of currents**, so **global instabilities develop driving self-reorganization of the plasma** towards a new equilibrium with **lower magnetic energy** through a process of fast magnetic reconnection.
- The magnetic energy released during fast reconnections is the **free energy** stored in the system during a slow initial phase in which the magnetized fluid evolves according to external forces

So: it seems that if the energy supplied to the system reaches a certain threshold, the distribution of currents will find a way to reach a new configuration, with less magnetic energy, and therefore less 'confined', and with an increase in entropy… It recalls a **catastrophic transition(*) between two configurations of different J distribution with different topology and lower magnetic energy. Equivalently, in terms of B**.

(*) In mathematical terms: by continuously varying a parameter, the system jumps to a distinct solution, of a different nature, when a threshold is exceeded. In our case, the parameter is the energy supplied to the system.

The drop in magnetic energy

The drop in the magnetic energy is absorbed by the matter, i.e. charged particles of the plasma

B does not do work on the particles (motion perpendicular to the Lorentz force), but defines the geometry of their trajectory. It is E that does work on the particles, being able to transfer energy to them (kinetic energy).

How can a binding force - the B-field - transfer its energy? In a reconnection this happens with a change of topology, in particular of the plasma currents

$$\frac{\partial B}{\partial t} = -\nabla \times \bar{E}$$

When the system reaches a certain threshold, there is a change in the system that involves **induced electric fields**

The **free energy** available and released upon reconnection **is the magnetic energy generated by the internal currents in the plasma**

$$W^* = \int \frac{B^{*2}}{2\mu_0} dV$$

Open problems

- Which is the trigger of the reconnection?
- Why reconnections are so fast?
- How does the transfer of energy from magnetic to kinetic occur, i.e. what are the mechanisms that produce the induced electric field?
- …

In **2D models** (as Sweet-Parker), magnetic reconnection is **determined by local physics in a current sheet** (or nearby), leading to a change in the macroscopic properties of the plasma (flow, thermal energy). **Local dynamics are crucial in determining the rate of reconnection and the magnetic energy released, whereas the causes are related to global instabilities, due to the storage of magnetic energy on global scales**

Yamada, Kulsrud and Ji, RMPP 2010

3D models are interesting too, which change the paradigm of 2D 'Sweet-Parker-type' models: do not involve any dependence on local physics aspects or strong local current sheets. **They are based on the ideal evolution of the B field and the magnetic chaos or turbulence of 3D magnetic systems**, without the need for (strong) dissipative terms to trigger reconnection.

Boozer 2019
Lazarian 2020

Signatures of magnetic reconnection

- Existence of current sheets and re-organization of the currents in the plasma
- Change in the magnetic topology
- Abrupt decreasing of magnetic energy, in favor of kinetic energy
- Heating and acceleration of particles
- Excitation of Alfvèn waves

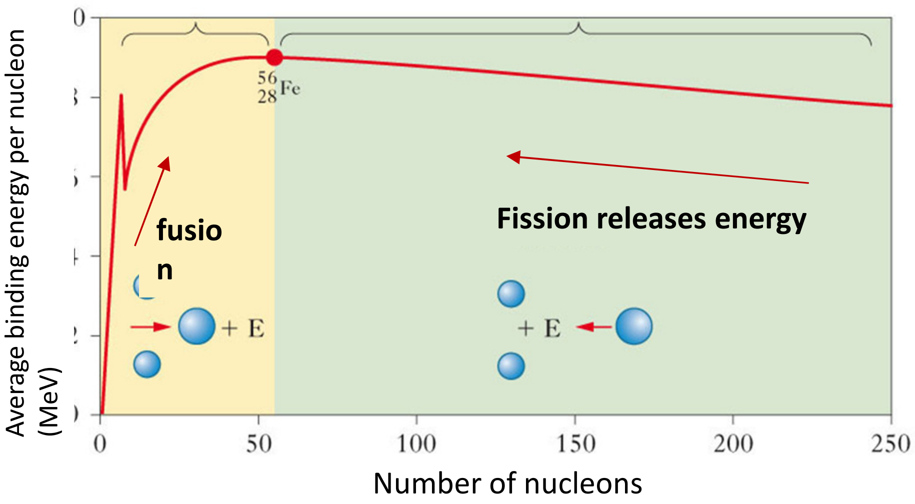
In this presentation I will mainly present experimental evidences of magnetic reconnection in toroidal fusion devices. But I will present also some numerical result from 3D non-linear MHD simulations where all these signatures of magnetic reconnection are found

But, first, what does **fusion plasmas** mean?

- What are fusion plasmas?

Fusion reactions

The curve of binding energy



Iron-56 (and Nickel-62) is the most stable nucleus in the universe (it has the highest binding energy per nucleon)

The fusion of elements up to atomic numbers 26-28 (iron and nickel) is an exothermic reaction, meaning it releases thermal energy (or heat), because the nucleus produced by the reaction has less mass than the sum of the masses of the reacting nuclei. That 'missing' mass Δm has been transformed into a huge amount of energy (radiation and kinetic energy of the products, distributed among them inversely proportional to their masses, due to conservation of momentum)

$\Delta E = \Delta mc^2$ = energy that is released by forming new nuclei in a fusion or fission process

Fusion: the star energy

Sun core parameters:

Density:

150 g/cm³ **10^{32} m^{-3}**

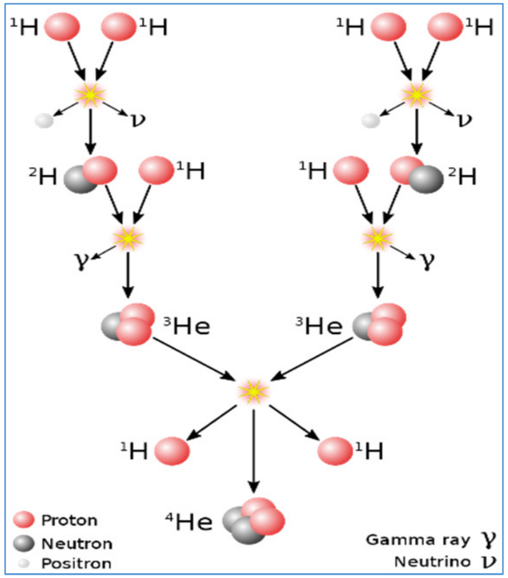
1 g/cm³ H_2O *10^{28} m^{-3}*

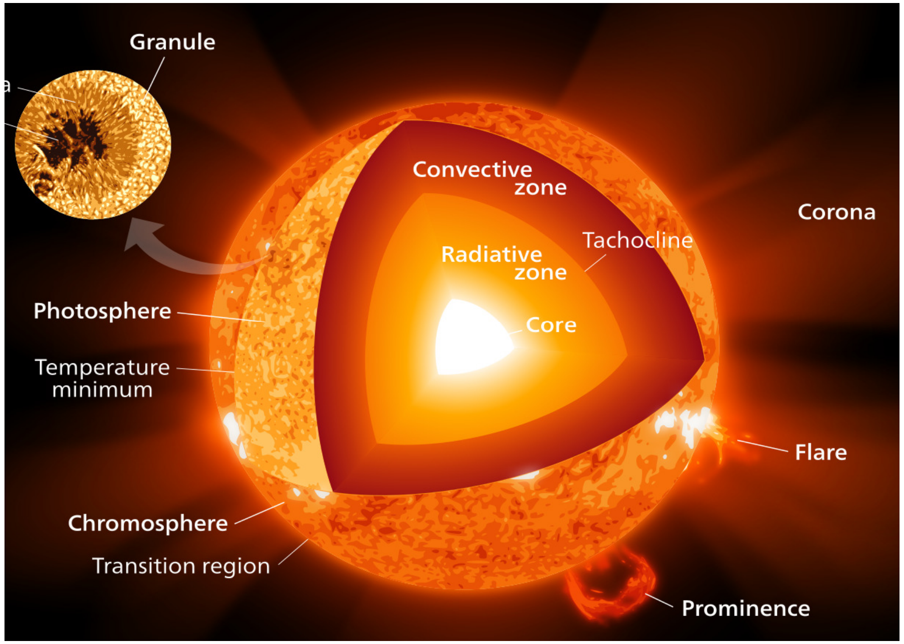
Temperature:

15 million °C **1.5 keV**

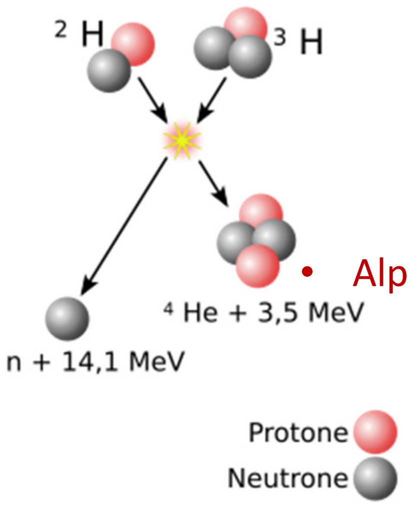
Power density: **276 W/m^{-3}**

R. Cavazzana - Toward fusion reactor





2 grams of Hydrogen
~ 36 ml water -
=
22 metric ton of carbon

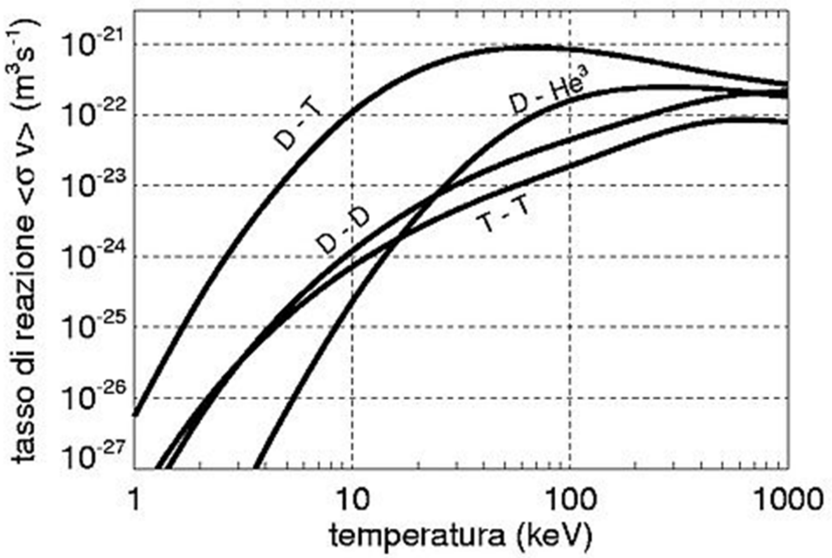
- 

  - Alpha particle

- $$\begin{aligned} D + D &\to T\ (1.01\ \mathrm{MeV}) + p\ (3.01\ \mathrm{MeV}) \\ &\to He^3\ (0.82\ \mathrm{MeV}) + \boxed{n\ (2.45\ \mathrm{MeV})} \end{aligned}$$

Under special conditions, these energetic neutrons are revealed during reconnection events in deuterium plasmas

Fusion cross section



One has to bring the plasma to **very high temperatures** and let the desired fusion reactions happen, keeping the plasma in equilibrium

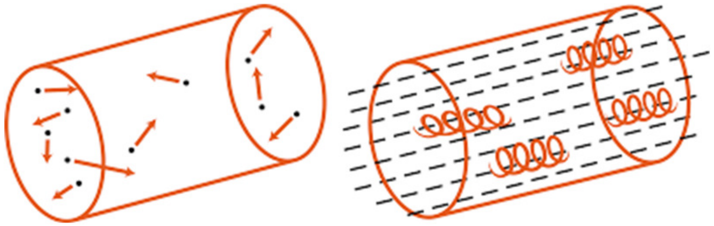
Fusion plasmas: magnetic confinement

The properties of **charged particles in a magnetic field** are exploited to confine the plasma: the **Lorentz force** constrains the particles to a **gyromotion** (or spiral orbits) around the **magnetic field lines**

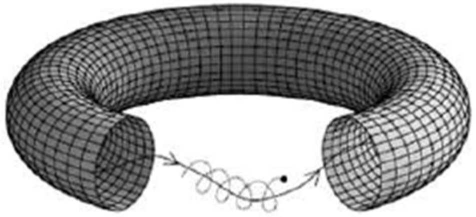
The general behavior of fusion plasmas allows a **MHD treatment**: magnetic confinement relies on the balance between the **plasma kinetic pressure** (which drives expansion) and the **magnetic tension (or pressure)** in the equation of motion of a magnetized plasmas seen as a fluid of charged particles

$$\bar{J} \times \bar{B} = \nabla p$$

This is at the basis of the **MHD equilibrium** of the magnetic configuration



$$\bar{F} = q\bar{v} \times \bar{B}$$



By bending the field lines into a closed loop (a **torus**), end losses are eliminated.

Of course, **MHD** equations governs each plasma on a big enough spatial scale, but particular solutions are found in toroidal systems due to particular **boundary conditions**!

The equilibrium magnetic field

Eq. motion

$$\bar{J} \times \bar{B} = \nabla p$$

Ampère's law

$$\nabla \times \bar{B} = \mu_0 \bar{J}$$

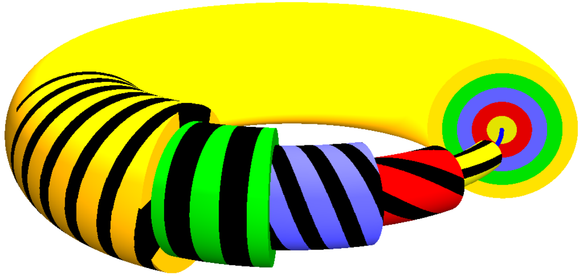
Divergence free of B

$$\nabla \cdot \bar{B} = 0$$

MHD equilibrium defines the so-called **magnetic flux surfaces: nested surfaces of constant pressure, on which magnetic field and current-density lines lie:**

$$\bar{J} \times \nabla p = 0$$
$$\bar{B} \times \nabla p = 0$$

Magnetic flux surfaces

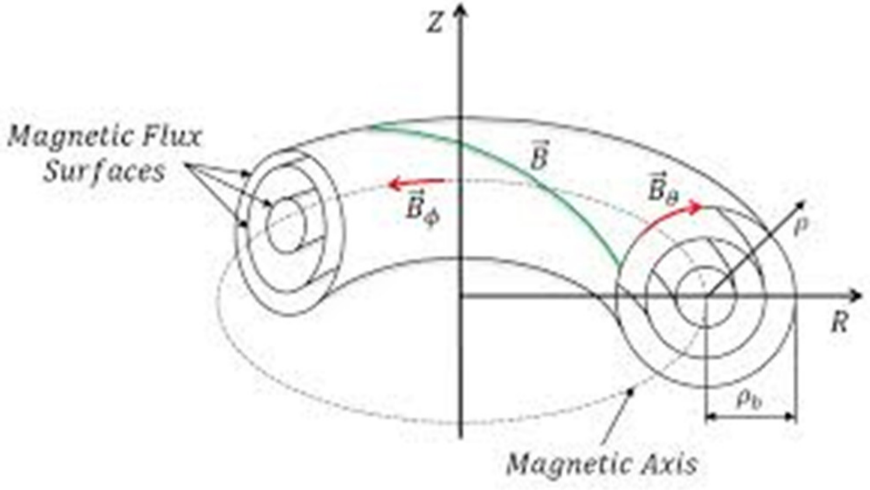


Nested flux surfaces

Different equilibrium magnetic configurations define **different shapes of nested magnetic flux surfaces, with different confinement properties**

Typical coordinates on a torus

Toroidal coordinates



Toroidal coordinate systems are defined by:

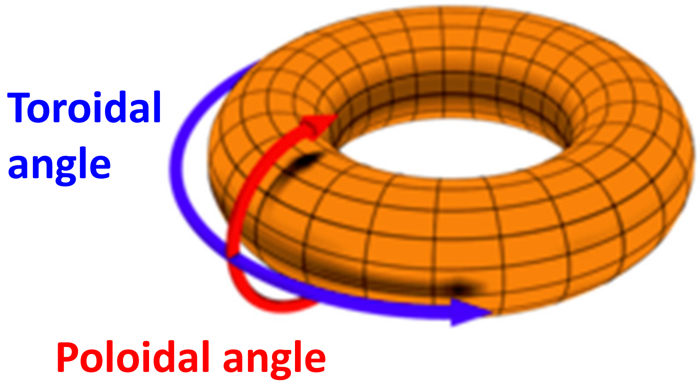
- a **radial variable** to label the magnetic flux surface (**a MHD equilibrium must exist**!)
- two angles: a **poloidal** angle and a **toroidal** angle

$$(\rho, \vartheta, \varphi)$$

Radial coordinate

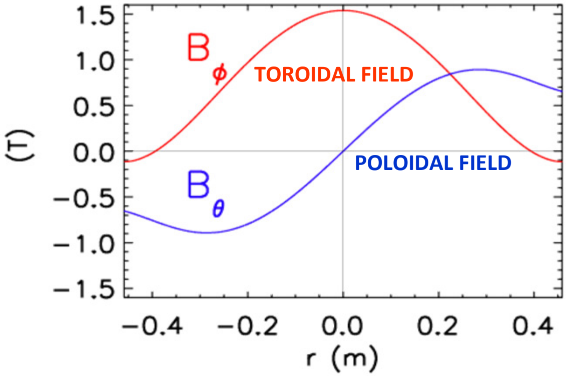
Poloidal angle

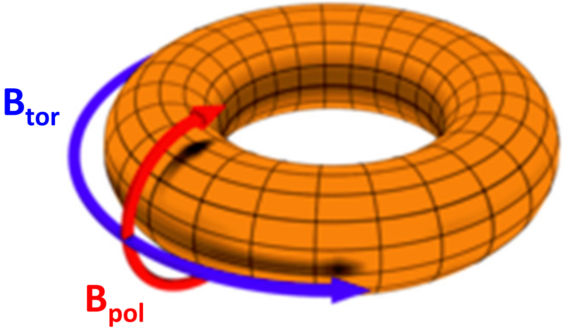
Toroidal angle



The MHD equilibrium

In the equilibrium situation, on each flux surface, the magnetic field is a combination of a toroidal $\mathbf{B}_{\mathbf{tor}}$ and a poloidal $\mathbf{B}_{\mathbf{pol}}$ magnetic field components.





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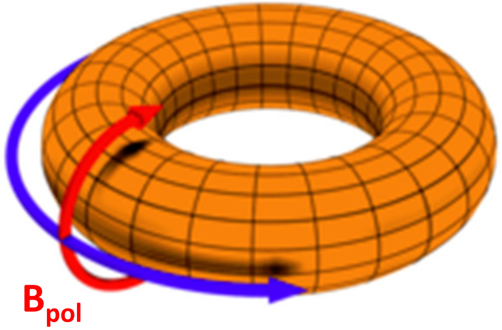
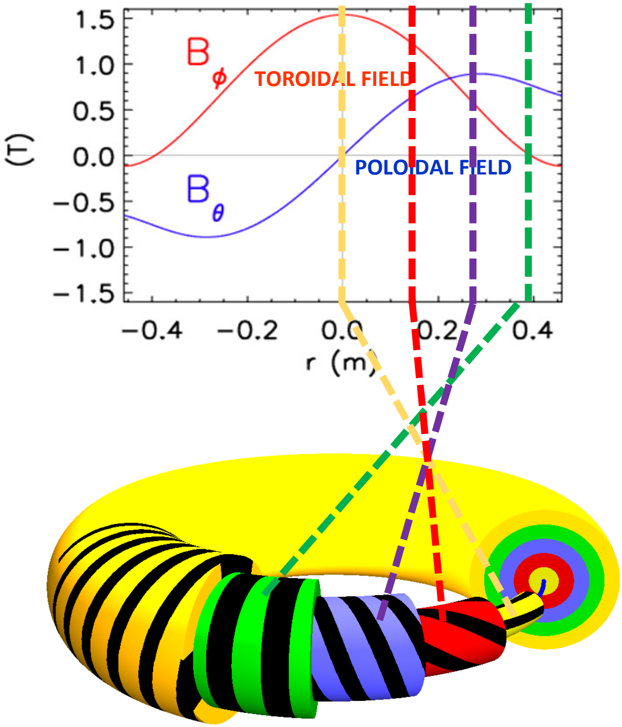




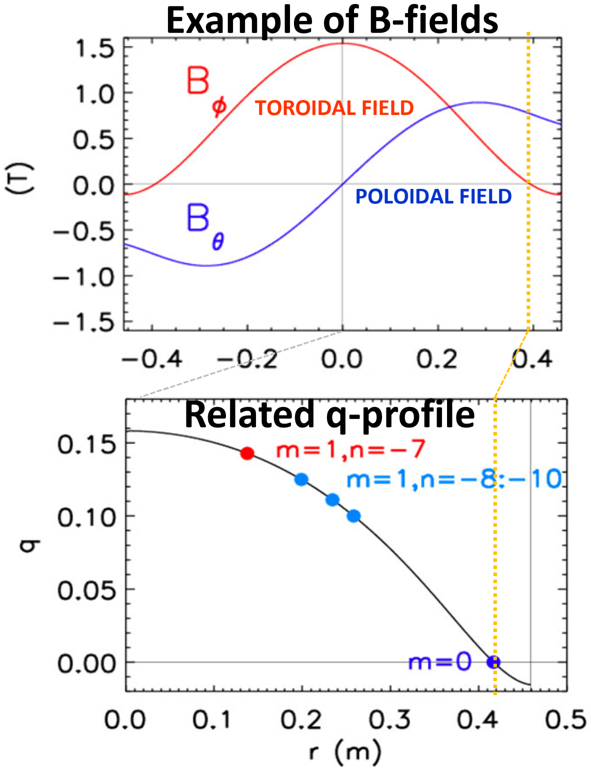
So **magnetic field lines wrap helically around every magnetic flux surface.** On each flux surface, B-lines have different helical twist.

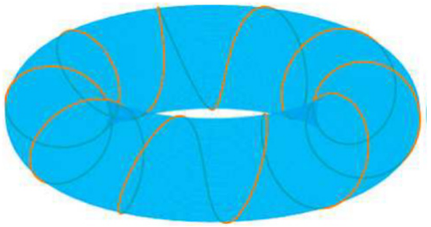
The shape of B depends on the magnetic configuration. This is an example of typical RFP plasmas

A topological property: the q-profile

The safety factor (q-profile) is a topological quantity that gives **a measure of the helical twist of the magnetic field lines on each flux surface** - so can be a label of magnetic flux surfaces (ρ=q)

- When a single B-line densely fills – and geometrically maps – a magnetic flux surface, q is an irrational number defining the so-called irrational surfaces
- When B-lines close on them self after a finite number of toroidal and poloidal turns around the torus, q can be defined by the ratio between these two numbers. These special surfaces are called rational surfaces.





q=m/n=1/10

$$q = \frac{m}{n}$$

m= number of **toroidal** turns

n = number of **poloidal** turns

Stability: why the q-profile

The q-profilet **models the distribution of the currents** in the plasma and it is closely related to the **stability** of the MHD equilibrium

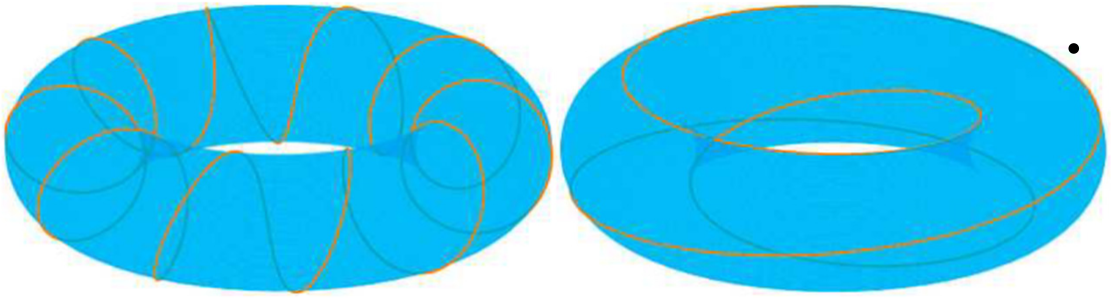
An analogy…

When B-lines close on them self after a few windings around the torus, instabilities are easy to occur

To develop an intuition about why the q-profile is related to the stability of the MHD equilibrium it defines, and the meaning of the *special rational surfaces*, we use an **analogy**.

Remembering that flux surfaces are the result of the balance between a kinetic pressure force that tends to expand and a magnetic tension that compresses it, let's imagine a flux surface like a balloon, where now the gas pressure must be balanced by the tension of the walls. But let's imagine **simulating this tension with a steel wire that wraps around the surface**:

- if the surface is entirely covered by the turns of one single wire, (irrational-q or rational-q of very high order), the surface is **stable**
- If the wire closes on itself after a few turns (rational-q), and a lot of wires are needed to cover the surface, the surface is more unstable, and the pressure will more easily tend to escape in some points, changing the shape of the balloon – i.e. changing the topology of the magnetic flux surface **forming magnetic islands**

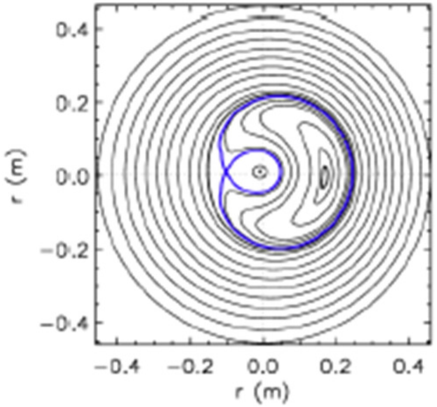


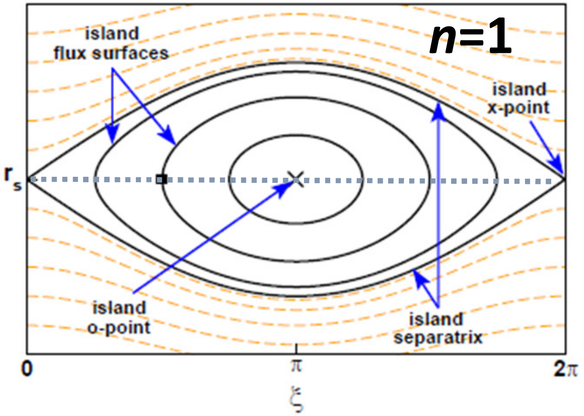
(a) $q = 1/10$ (b) $q = 2$

Figure 1.10: Two examples of magnetic field lines characterised by different safety factors [16].

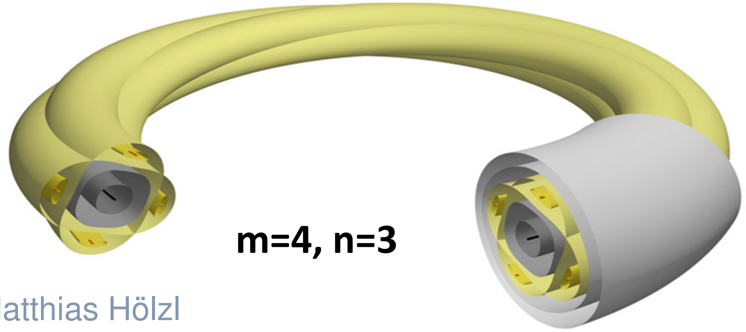
Resistive plasma instabilities: tearing modes and magnetic islands

Tearing instabilities: $q = \frac{m}{n}$ **= rational value**





Resistive instability that grows on magnetic flux surfaces defined by a **rational** value of the q-profile and brings to the formation of **magnetic islands, that break the magnetic flux surface through a magnetic reconnection process**

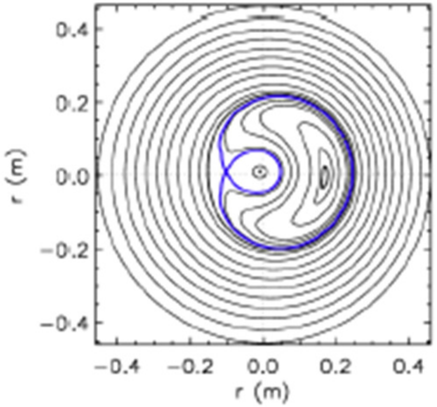


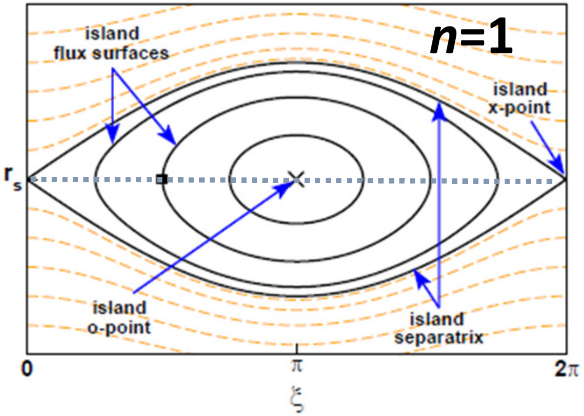
Matthias Hölzl

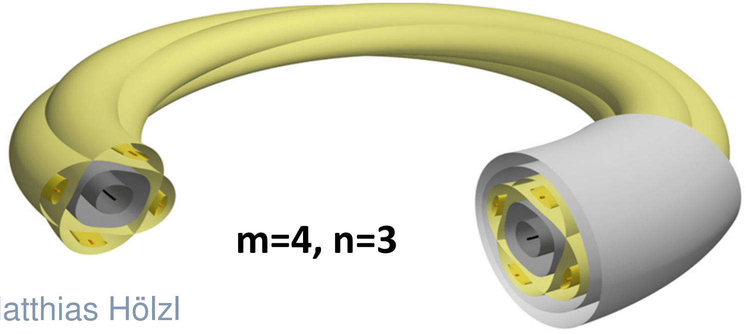
So q defines the idealized plasma equilibrium, given by conserved nested flux surfaces, which in the reality are frequently deformed or broken by magnetic instabilities

Resistive plasma instabilities: tearing modes and magnetic islands

Tearing instabilities: $q = \frac{m}{n}$ **= rational value**







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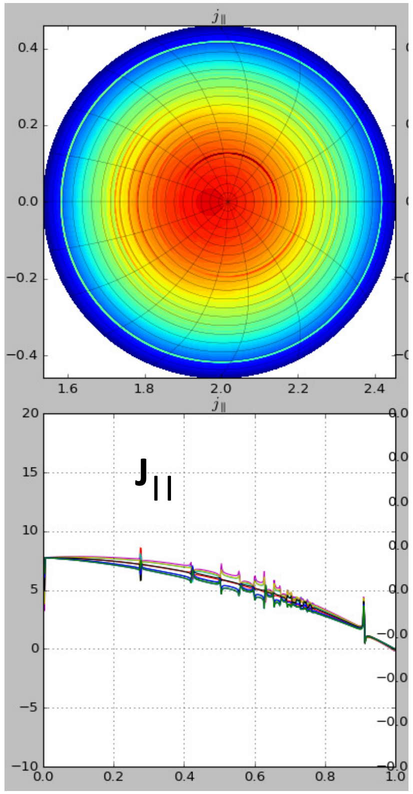


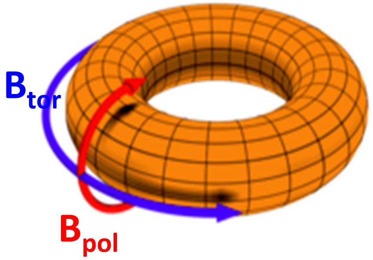
Example from a circular RFP plasma

Current driven instabilities: they are driven by excess of current density and ∇J

Formation of **islands** through a **reconnection process** that involves the existence of **current layers on resonant surfaces**

Current curring configurations

How to create the magnetic configuration in tokamaks and RFPs?



- B_{tor} is first produced by external coils
- B_{pol} is produced by the toroidal current

- A plasma current I_{tor} is induced in the toroidal direction to produce B_{pol}
- B_{pol} confines the high pressure plasma by a compressing **pinch** force.

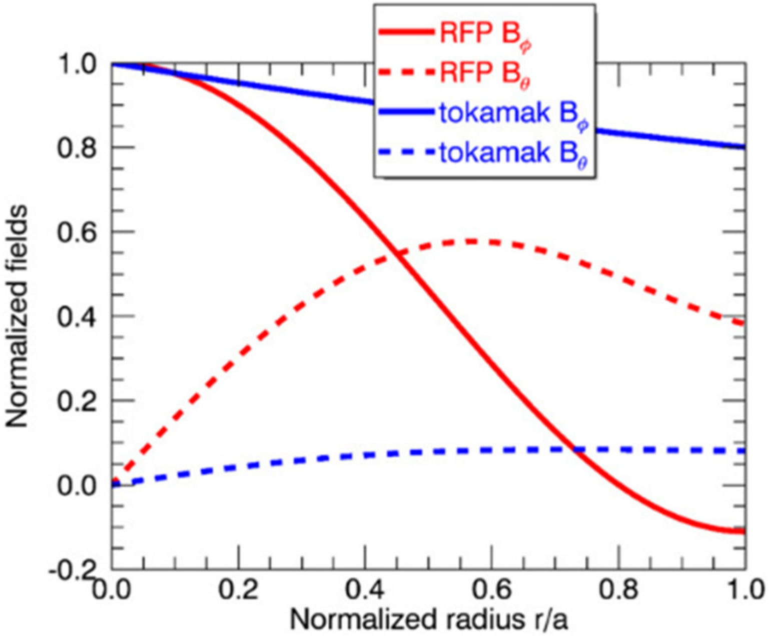
- **The total B_{tor}** is supplied differently between Tokamak and RFP …

Tokamak: a strong toroidal field is supplied externally. $B_{tor} >> B_{pol}$

RFP: the toroidal magnetic field is created mostly by internal currents. $B_{tor} \sim B_{pol}$

Significant component of the internal poloidal currents in the RFP come from a **dynamo** mechanism, and by **magnetic reconnection** that plays a key role

Current curring configurations

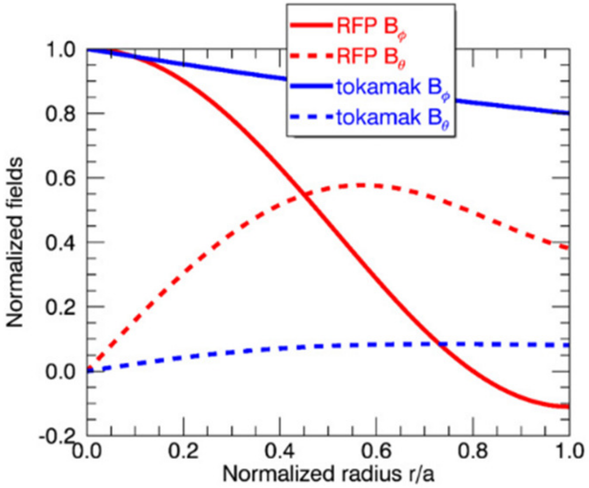


At the same plasma current, the **tokamak** has much higher applied toroidal magnetic field with respect to the **RFP**

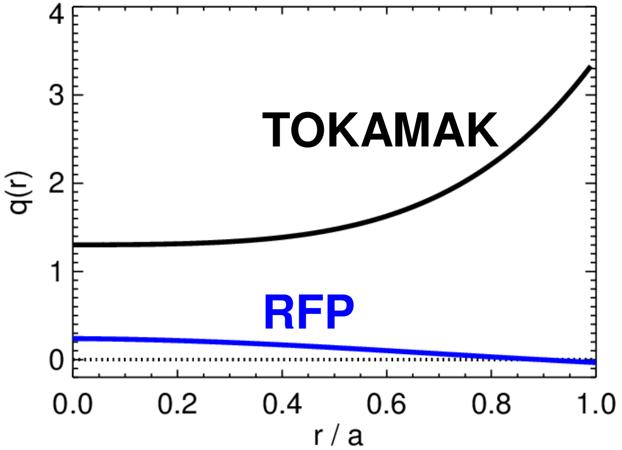
or

At the same toroidal magnetic field, the **tokamak** has much lower currents flowing in the plasma, whereas **RFP** features large current density

Current curring configurations



Examples of q-profiles of different MHD equilibria



The q-profile gives a measure of the degree of external action with respect to self-organization of the plasma

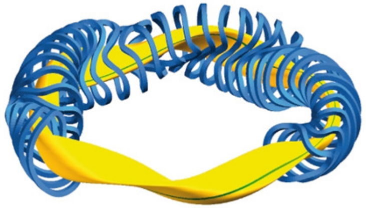
$$q \sim \frac{r B_{tor}}{R B_{pol}}$$

External/internal action

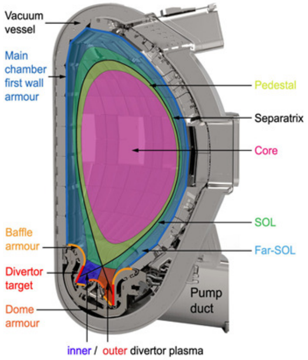
Due to internal currents

And this has important consequences on the phenomenology of reconnection events because the free energy released is related to the magnetic energy of **internal** origin

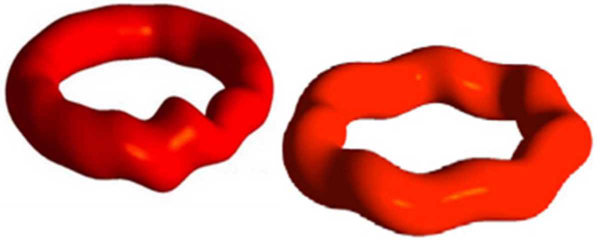
Fusion plasmas: Stellarators, Tokamaks, RFPs



Stellarator



Tokamak

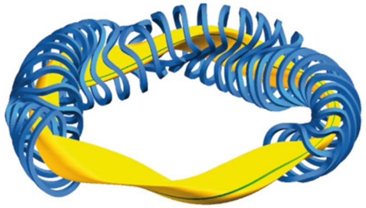


Reversed Field Pinch (RFP)

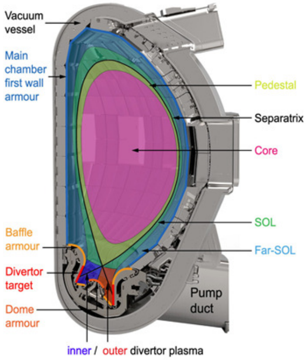
Plasma current

Plasma auto-organization

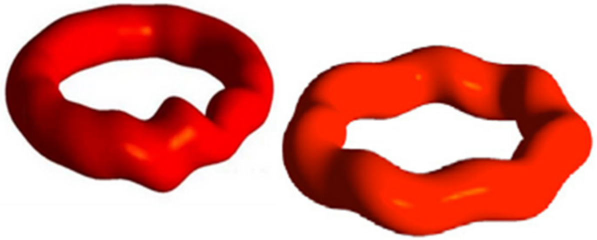
Fusion plasmas: Stellarators, Tokamaks, RFPs



Stellarator



Tokamak



Reversed Field Pinch (RFP)

Magnetic reconnection 'intensity'

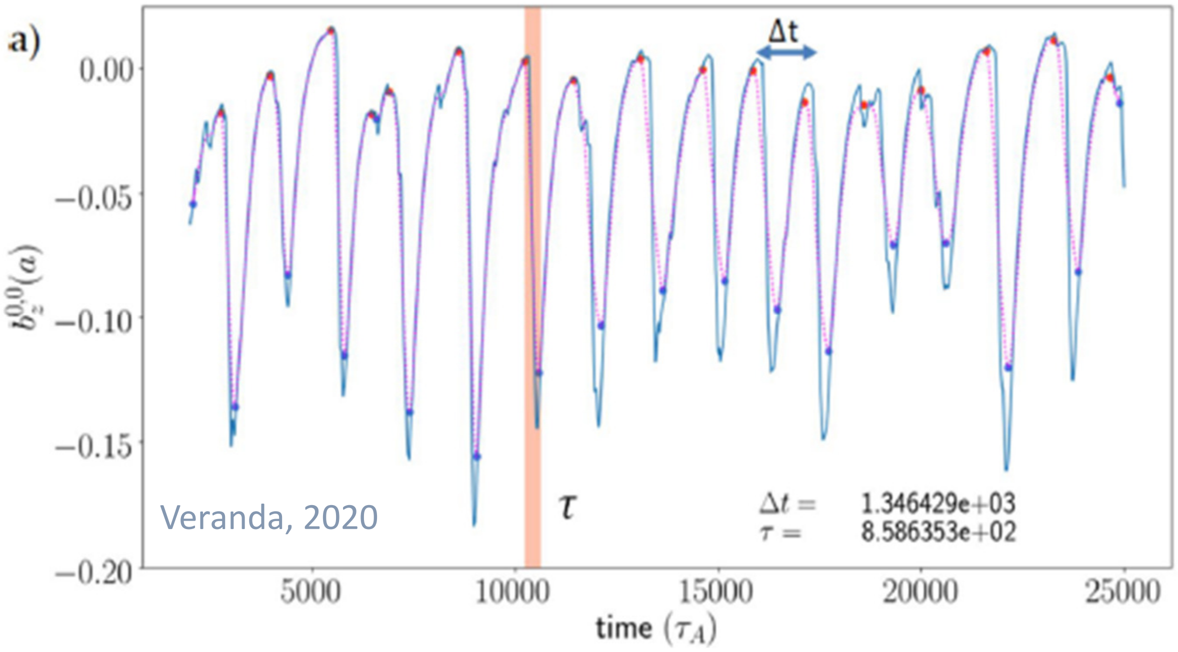
Plasma current / Plasma auto-organization

The magnetic energy of internal origin is **free energy** and released in a reconnection process

- What are principal reconnection events in fusion plasmas?

Reconnection events in fusion plasmas

Reconnection events in **tokamak** and **RFP** share **a common cycle**



Veranda, 2020

It is a non-linear cycle involving **two different timescales**

- The characteristic time between reconnection events, **Δt**
- The characteristic temporal duration τ of the reconnection event, usually called the time of the **fast *crash***

The reconnection cycle

By applying an external force to a plasma

- the magnetic configuration **slowly** evolves toward equilibrium
- storing energy on a global scale.

At some point

- the new equilibrium becomes unstable due to excess magnetic energy and accumulation of currents
- so global instabilities develop
- driving self-reorganization of the plasma towards a new equilibrium with lower magnetic energy through a process of **fast** magnetic reconnection.

During the slow phase

- the plasma evolves restoring the magnetic energy that is released during the fast crash phase

It is always a **geometrical problem**, related to the distribution of the currents in the plasma, and so to the shape and value of the **q-profile**: **instabilities are determined by the magnetic field and boundary conditions, and this is what basically differentiates reconnection events in tokamaks and RFPs, in addition to the amount of free energy.**

Reconnection events in tokamak and RFP

Tokamak: $B_{tor} >> B_{pol}$

the internal magnetic field B_{pol} is much smaller than the external one B_{tor}, so **magnetic reconnections leads to small changes in the magnetic field profile** (and therefore of the q-profile) due to **localized** reorganization of the current density

The most famous experimental evidence of **global** magnetic reconnection in tokamak is the **sawtooth cycle**, **driven** by an internal MHD instability

RFP: $B_{tor} \sim B_{pol}$

Plasma currents play a fundamental role in determining the magnetic fields, so **magnetic reconnections leads to the reorganization of the whole configuration (through a reorganization of the currents in the whole configuration)**

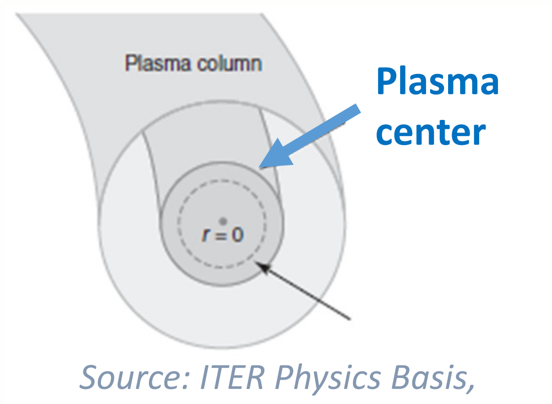
The most famous experimental evidence of **global** magnetic reconnection in RFP is the **magnetic self-organization**, **driven** by **tearing mode** instabilities occurring a multiple radii

In both cases the instabilities that drive magnetic reconnection are destabilized by strong **current density gradients**, arising from a dangerous accumulation of the currents in the center of the plasma

Short summary break

Signatures of reconnection

- Existence of **current sheets** and **re-organization of the currents** in the plasma
- Change in the **magnetic topology**
- Abrupt **decreasing of magnetic energy, in favor of kinetic energy**
- **Heating and acceleration of particles**
- Excitation of **Alfvèn waves**



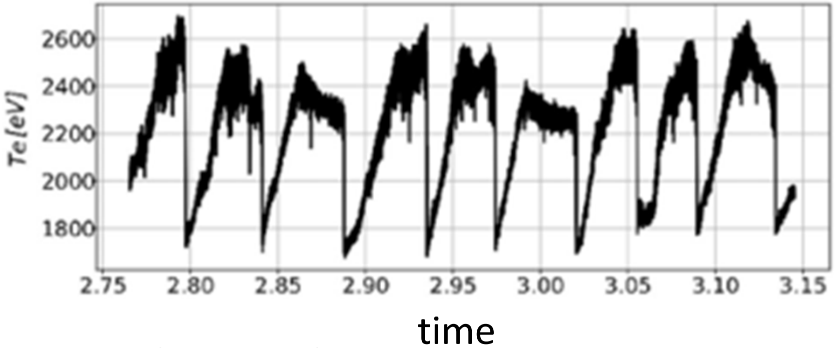
Source: ITER Physics Basis, Chapter 3 [58] – H. Zohm 2015

Tokamak: $\mathbf{B_{tor} >> B_{pol}}$
the internal magnetic field B_{pol} is much smaller than the external one B_{tor}, so **magnetic reconnections leads to small changes in the magnetic field profile**

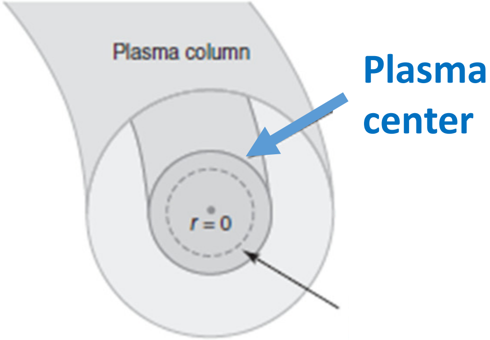
RFP: $\mathbf{B_{tor} \sim B_{pol}}$
the internal and external magnetic field are comparable, so **magnetic reconnections leads to the reorganization of the whole configuration**

Tokamak: sawtooth crash

Electron temperature evolution in the central region of the plasma during sawtooth oscillations



Asdex-Upgrade measurements
V. Igochine, 2023



Source: ITER Physics Basis, Chapter 3 [58] – H. Zohm 2015

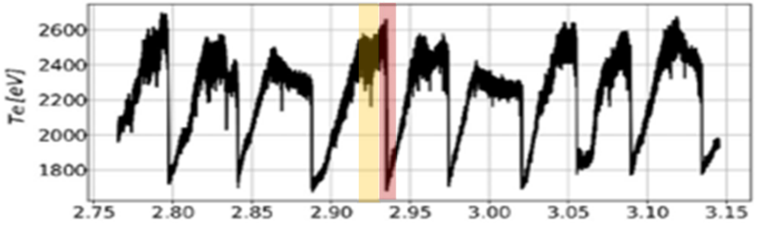
Discovered in 1974 in ST tokamak from analysis of electron temperature dynamics in the plasma center: they showed the **characteristic cyclic instability** whose time traces resemble the shape of sawteeth.

Sawtooth crashes are observed in all tokamaks

Soon after **this instability was linked to a reconnection phenomenon** which affects a large part of the plasma center.

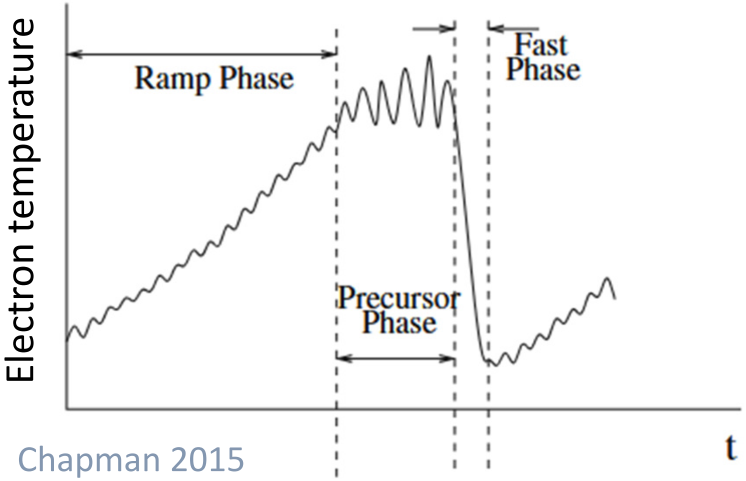
The sawtooth cycle

Electron temperature evolution in the central region of the plasma during sawtooth oscillations



V. Igochine, 2023

time

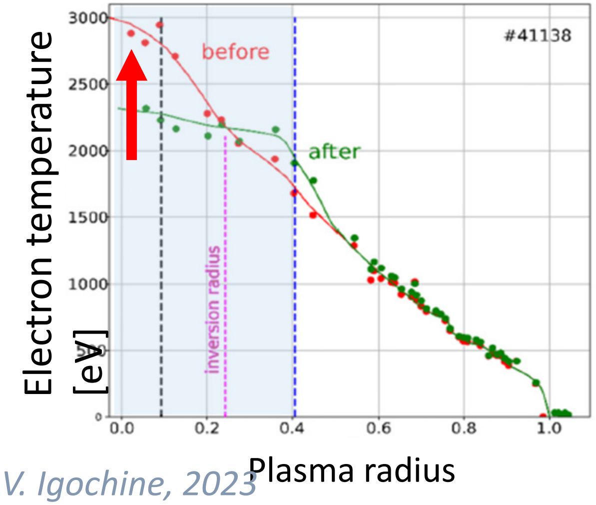


Chapman 2015

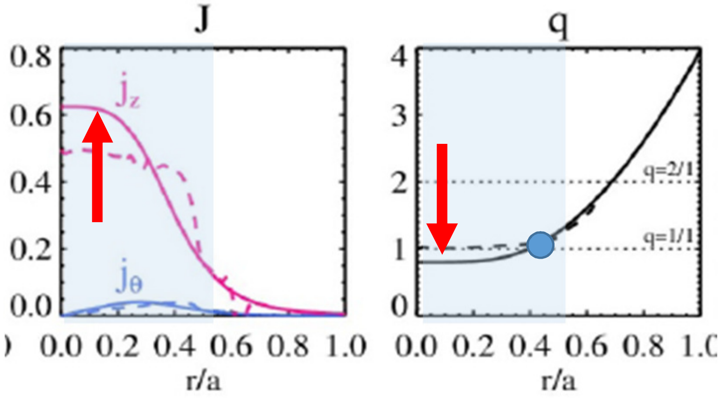
The reconnection cycle:

1. An initial slow phase characterized by
   - The rise of the core temperature due to plasma heating
   - Accompanied by the peaking of the current density **J** and therefore the formation of ∇J
2. **A precursor slow phase** characterized by the growth of a helical MHD core instability destabilized by ∇J
3. A consequent **fast crash** of the core temperature, that redistributes the plasma (temperature and **J)** outwards from the plasma center, with a change in the magnetic topology
4. A new equilibrium is then slowly recovered

The slow precursor phase



V. Igochine, 2023

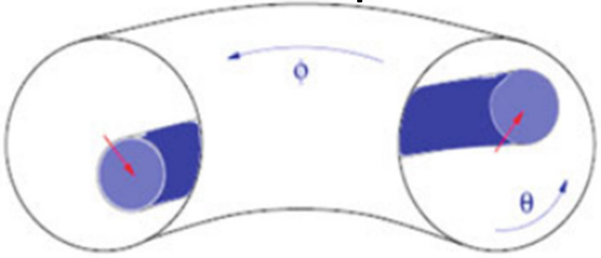


A.Kryzhanovskyy (2024)

- While Te and J peak, ∇J forms, the q-profile lowers its central value, a magnetic oscillation is destabilized in the plasma core: an **ideal** $^{(*)}$ **internal kink displacement**, which is manifest as the precursor oscillation, takes the form of a tilt and a shift of the core plasma

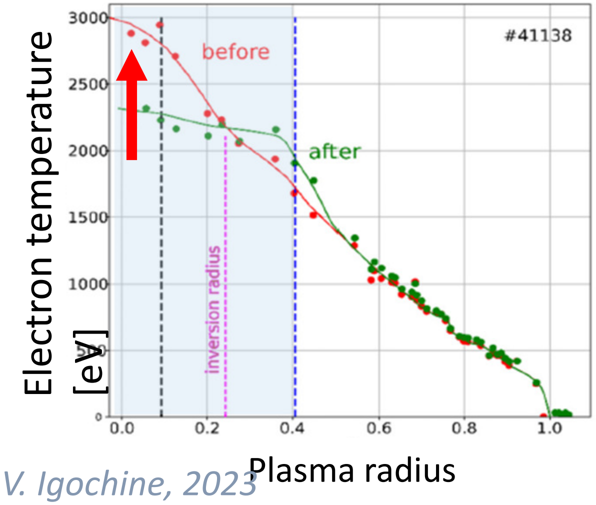
(*) ideal: does not reconnect!

Internal kink displacement

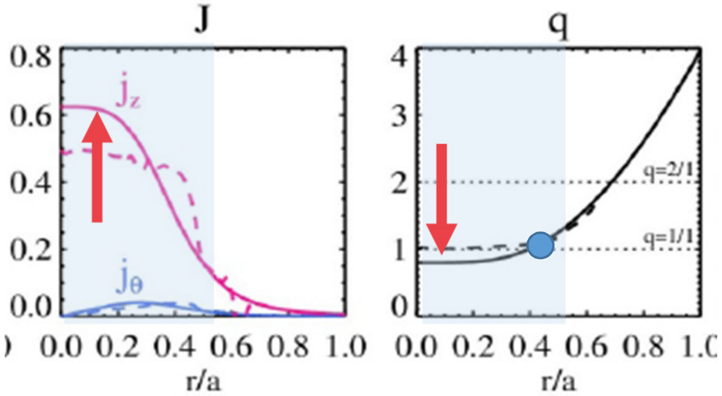


Chapman 2015

The slow precursor phase

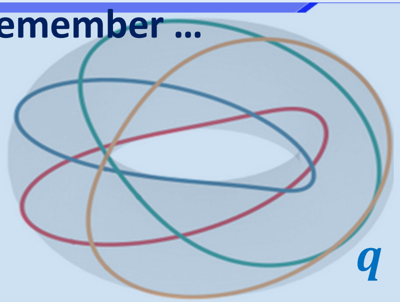


V. Igochine, 2023



A.Kryzhanovskyy (2024)

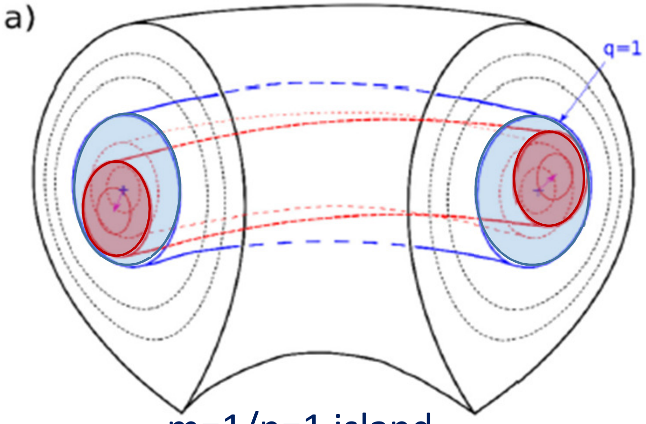
Remember …



$$q = \frac{m}{n} = \frac{1}{1}$$

When B-lines close on them self after a few windings around the torus, instabilities are easy to occur. In particular magnetic islands appears around resonant surfaces q=m/n

V. Igochine, 2023



m=1/n=1 island

- **A helical resistive$^{(*)}$ instability** with the kink periodicity is excited around the resonant q=1 surface when **q=1** enters the plasma
- It grows non-linearly with the formation of a **(m=1,n=1) magnetic island** in the plasma core through a reconnection process

(*) resistive: it can reconnect!

from slow to fast crash…

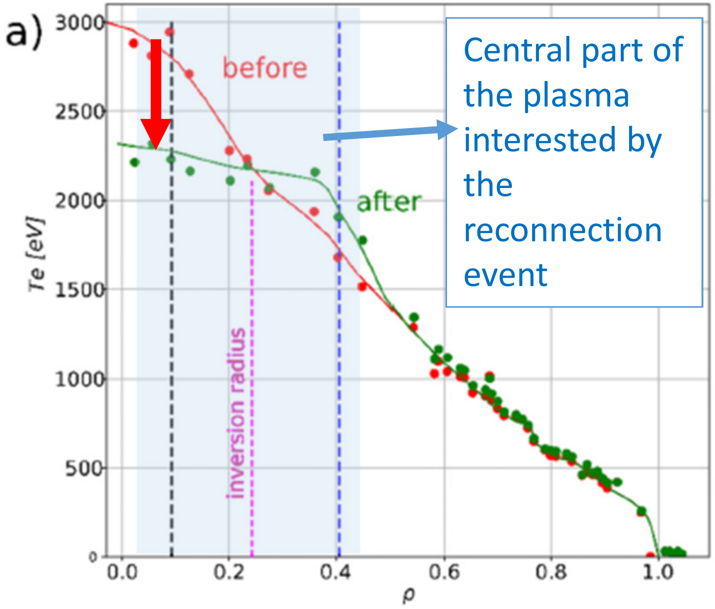
Magnetic reconnection is driven by an internal MHD mode excited after a gradual change of the magnetic equilibrium, and it is determined by the **growth rate** of the MHD instability

It grows non-linearly, but its amplitude is not the only important parameter to define the trigger of the crash phase. Differential plasma rotation may be important…

… but the **trigger** of the reconnection phase is still an open question

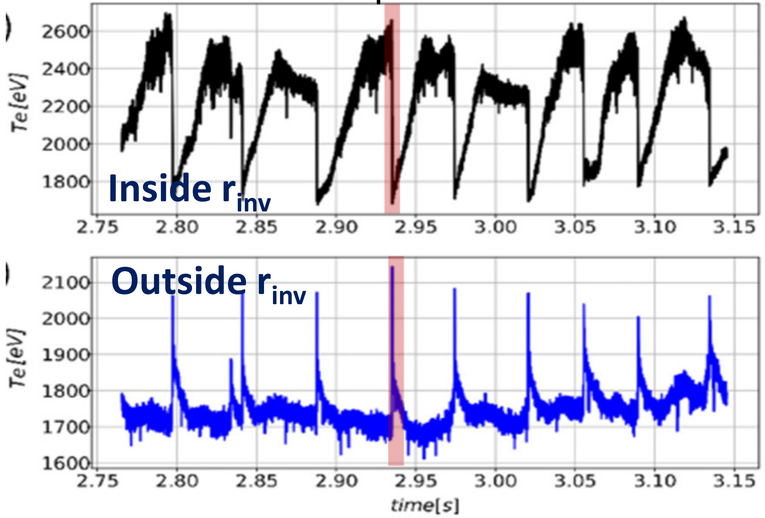
The fast crash phase

V. Igochine, 2023



Central part of the plasma interested by the reconnection event

Electron temperature evolution



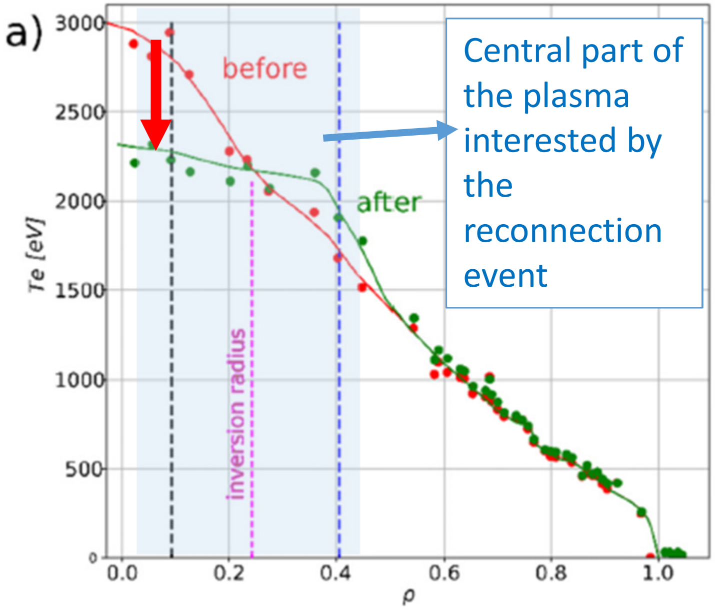
V. Igochine, 2023

The crash event redistributes the core temperature from the inside to the outside of an inversion radius (where Te remains constant): fast heat conduction through the reconnection region is observed

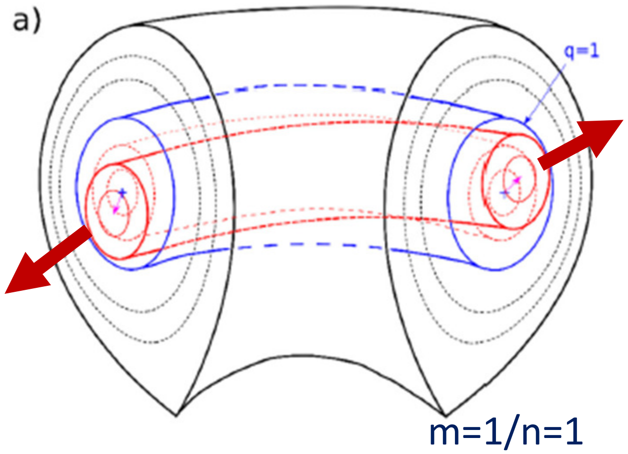
This rapid drop in the core temperature is accompanied by heating of the plasma outside the inversion radius, indicating the **crash of the central Te** and the consequent **heat pulse** travelling outwards

The fast crash phase: a localized event

V. Igochine, 2023



Central part of the plasma interested by the reconnection event



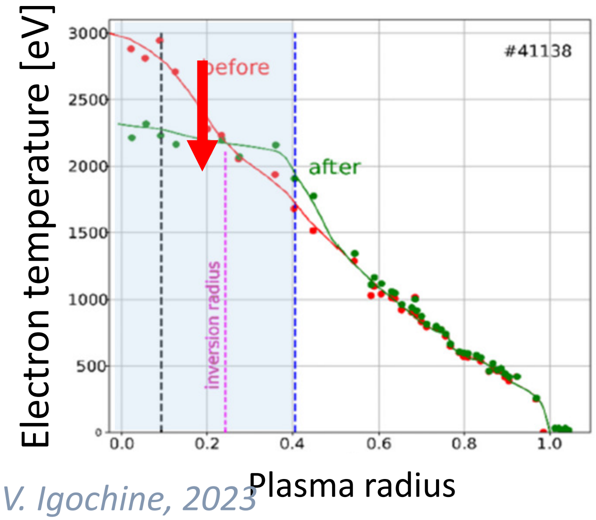
Heat flows from the X-point

V. Igochine, 2023

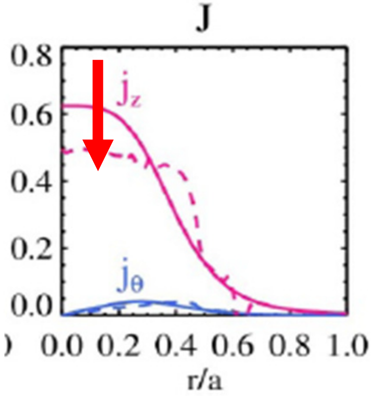
The crash event redistributes the core temperature from the inside to the outside of an inversion radius: fast heat conduction through the reconnection region is observed

In particular, **heat flows from the core, locally in the poloidal plane, through the X-point** of the magnetic islands, as seen universally across the main tokamaks

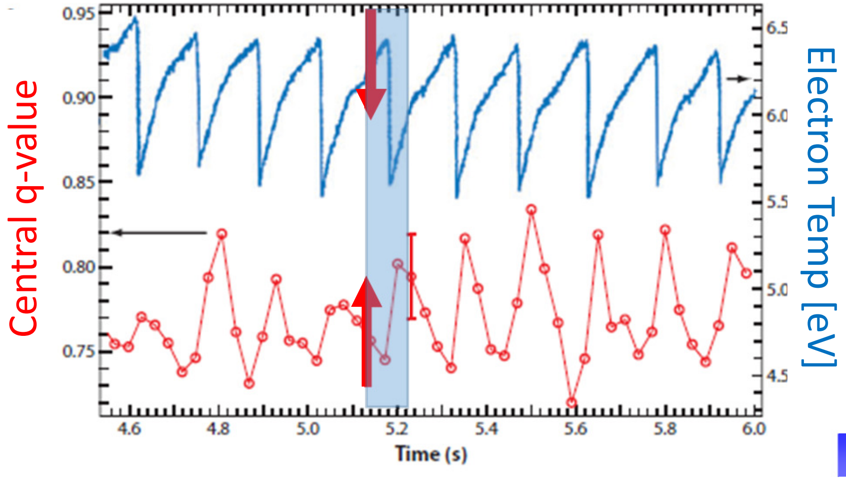
The fast crash phase



V. Igochine, 2023



A.Kryzhanovskyy (2024)



- The crash event **redistributes the core temperature and plasma** from the inside to the outside of an inversion radius r_{inv}
- **J is flattened** inside r_{inv} too, with a redistribution of the current density that higher the central value of q and smooths the gradient, removing the drive of the instability
- At the same time, mixing the plasma inside r_{inv}, **redistributes the poloidal flux**, again such that the conditions for the instability to grow are lost. So the process stops and the cycle begins again

The fast crash phase: numerical modelling

The self-consistent modeling of the crash is still an open problem.

- **Reconnection time = crash time** = time for temperature flattening during the crash (tens of μs): **Too fast** to be explained by 2D models like Sweet-Parker, even adding two-fluid terms to Ohm’s law.
- 2D models, with appropriate Ohm’s law, may capture the basic mechanism of the sawtooth crash, but there is a physics element still missing that determines the amount of reconnected flux: **stochasticity of B-lines?**

The fast crash phase: numerical modelling

The self-consistent modeling of the crash is still an open problem.

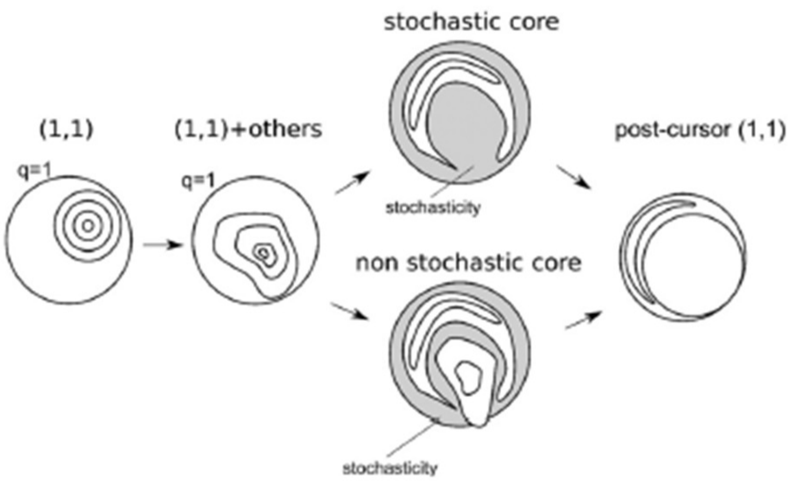


FIG. 8. Possible evolution during the sawtooth crash starts from single (1,1) components. Further components appear at the next stage, which leads to partial stochasticity (non-stochastic core) or full core stochasticity. In both cases, the heat extraction is local through the X-point. The gray region represents the stochastic region.

V. Igochine, 2023

Stochasticity

- **It is the result of magnetic reconnection**, which destroys the original magnetic topology (*)
- **It is a good candidate for the explanation of the crash phase**: the separatrix around the island should be stochastic, the core of the island could be either stochastic or not: this allows to efficiently extract the heat from the core, **locally** from the X-point as seen in experiments

(*) stochasticity requires a mix of perturbations with sufficiently large amplitudes due to the interaction of several harmonics of the (m=1,n=1) instability during the crash.

The fast crash phase: other signatures of magnetic reconnection

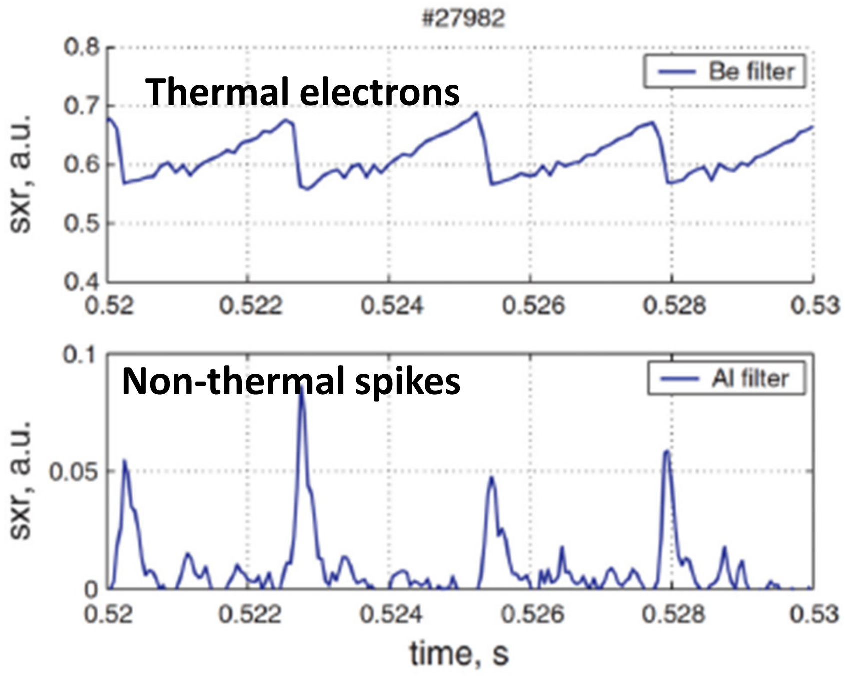


FIG. 14. Soft x-ray signals are obtained with different energy filters. At the top 47 μm beryllium foil, and at the bottom 308 μm aluminum foil. Non-thermal spikes are visible after each crash on the bottom plot. Reproduced with permission from Klimanov *et al.*, Plasma Phys. Control. Fusion **49**, L1 (2007). Copyright 2007 IOP Publishing.

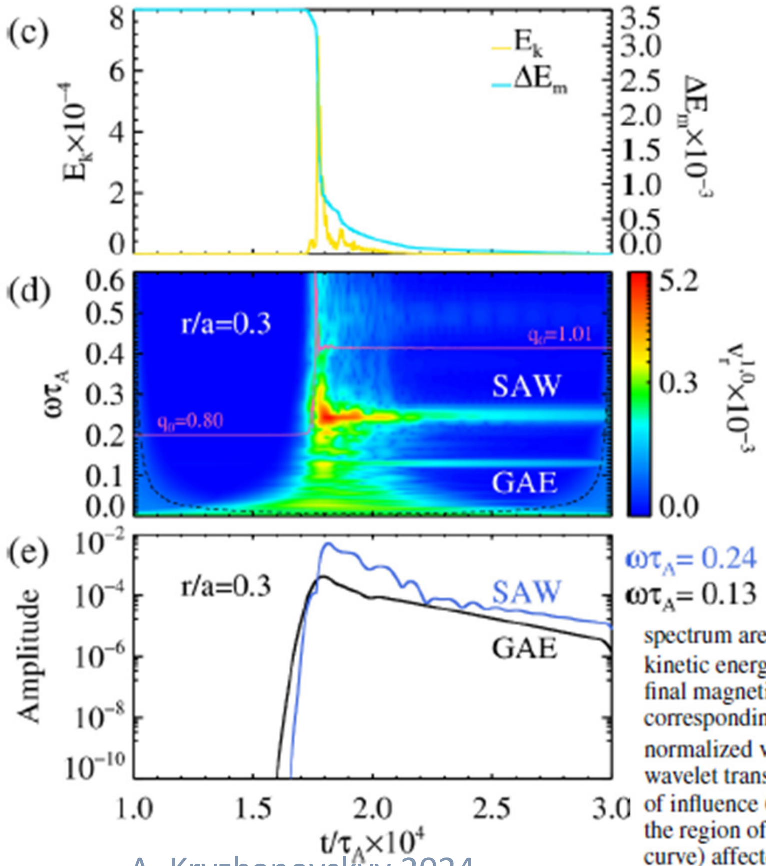
TCV measurements, Plasma Phys. Control Fus. **49** (2007) reported by V. Igochine 2023

- **Fast crashes are accompanied by the generation of suprathermal electrons at the q=1 surface**

Radiation produced by these electrons during the crash can be observed by electron cyclotron emission (ECE) and hard X-ray diagnostics

The fast crash phase: other signatures of magnetic reconnection

Numerical evidence of Alfvén waves triggered at the sawtooth reconnection



A. Kryzhanovskyy 2024

spectrum are plotted in gray. (*c*) Evolution of the total magnetic and kinetic energies, where $\Delta E_m = E_m - E_m^f$ with $E_m^f = 386627$ the final magnetic energy at the end of the simulation. (*d*) The corresponding evolution of the frequency spectrum of the normalized velocity field component $v_r^{1,0}$, obtained with continuous wavelet transform (CWT), at a fixed radius of $r/a = 0.3$. The cone of influence (COI) is plotted in dashed black curve and is defined as the region of the wavelet spectrum (underneath the dashed black curve) affected by edge effects which may distort the resulting spectrum. The evolution of the central safety factor is shown in pink. (*e*) Amplitude of $v_r^{1,0}$ at fixed frequencies $\omega\tau_A$ corresponding to observed Alfvén modes.

- **Fast crashes are accompanied by the generation of Alfvèn waves**

Which are also shown by 3D non-linear MHD visco-resistive numerical simulation by Specyl code

Short summary

Signatures of reconnection

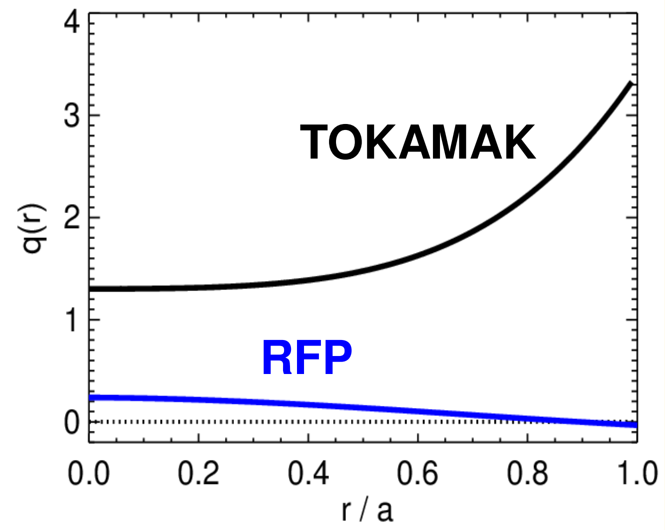
- ✓ Existence of **current sheets** and **re-organization of the currents** in the plasma
- ✓ Change in the **magnetic topology**
- ✓ Abrupt **decreasing of magnetic energy, in favor of kinetic energy**
- ✓ **Heating and acceleration of particles**
- ✓ Excitation of **Alfvèn waves**

Owing to the redistribution of heat, particle and poloidal flux, sawtooth crashes limits the peaking of temperature, density and current density profiles

The decreasing of the averaged stored magnetic energy has a negative impact on the energy confinement time

But enhanced particle transport can be beneficial to avoid impurity accumulation in fusion plasmas

Short summary break: tokamak vs RFP



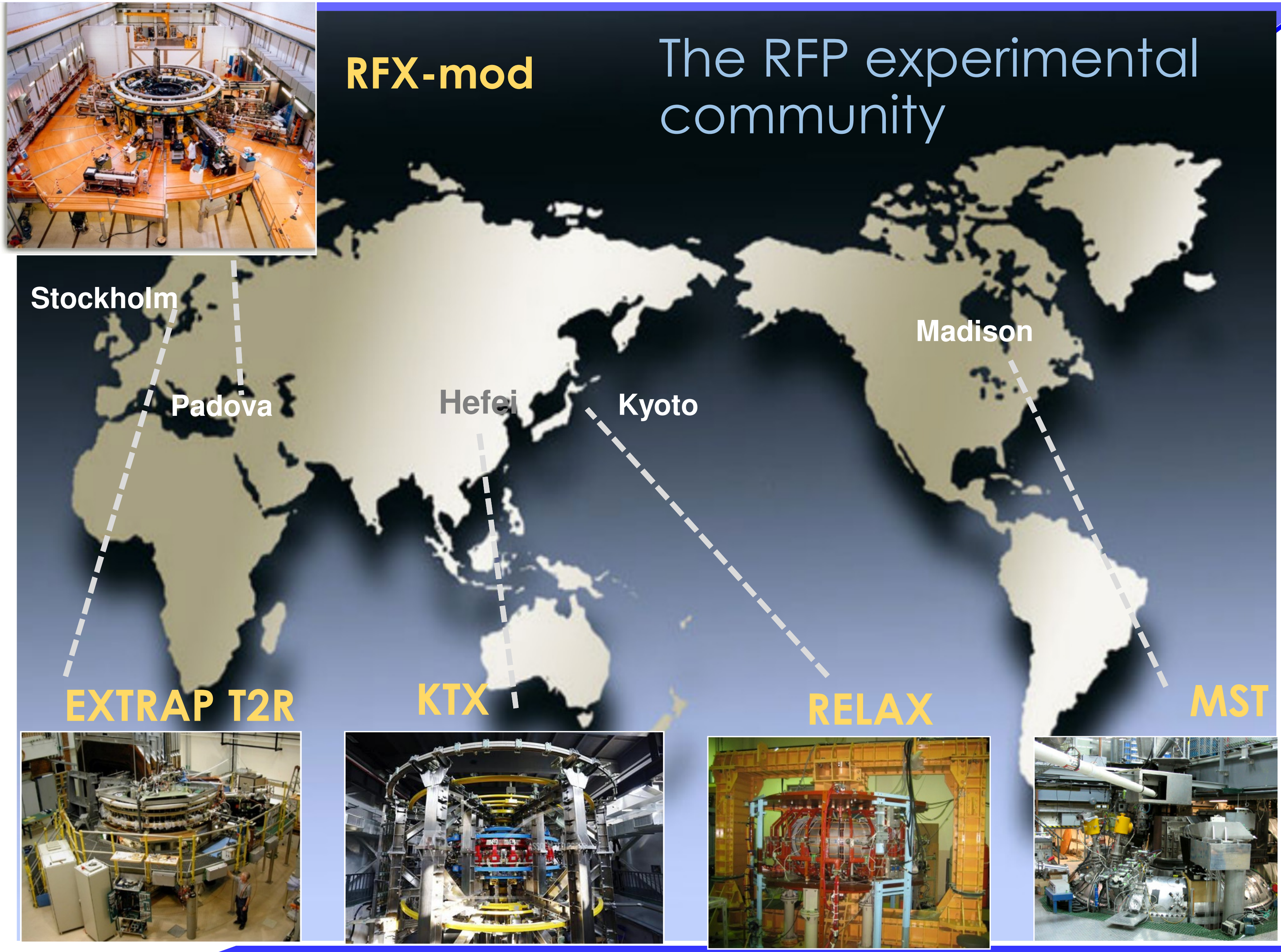
RFP looks like the tokamak but with much lower applied magnetic field at the same plasma current

Tokamak: **B_{tor} >> B_{pol}**
the internal magnetic field B_{pol} is much smaller than the external one B_{tor}, so **magnetic reconnections are triggered by relatively small MHD instabilities and leads to relatively small and localized changes in the magnetic field profile**

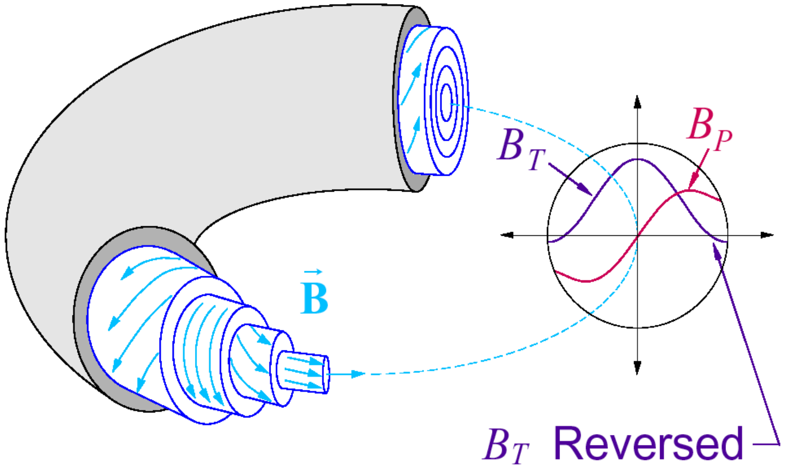
RFP: **B_{tor} ~ B_{pol}**
the internal and external magnetic field are comparable, so magnetic reconnections leads to the reorganization of the whole configuration.

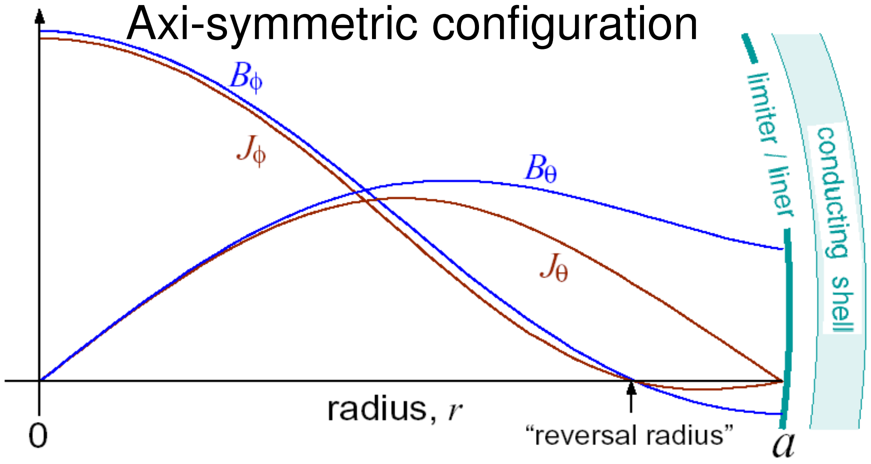
Strong MHD instabilities and the auto-organization of the plasma plays a fundamental role in maintaining the configuration

The RFP experimental community



The Reversed Field Pinch configuration





On the magnetic axis the toroidal magnetic field dominates:

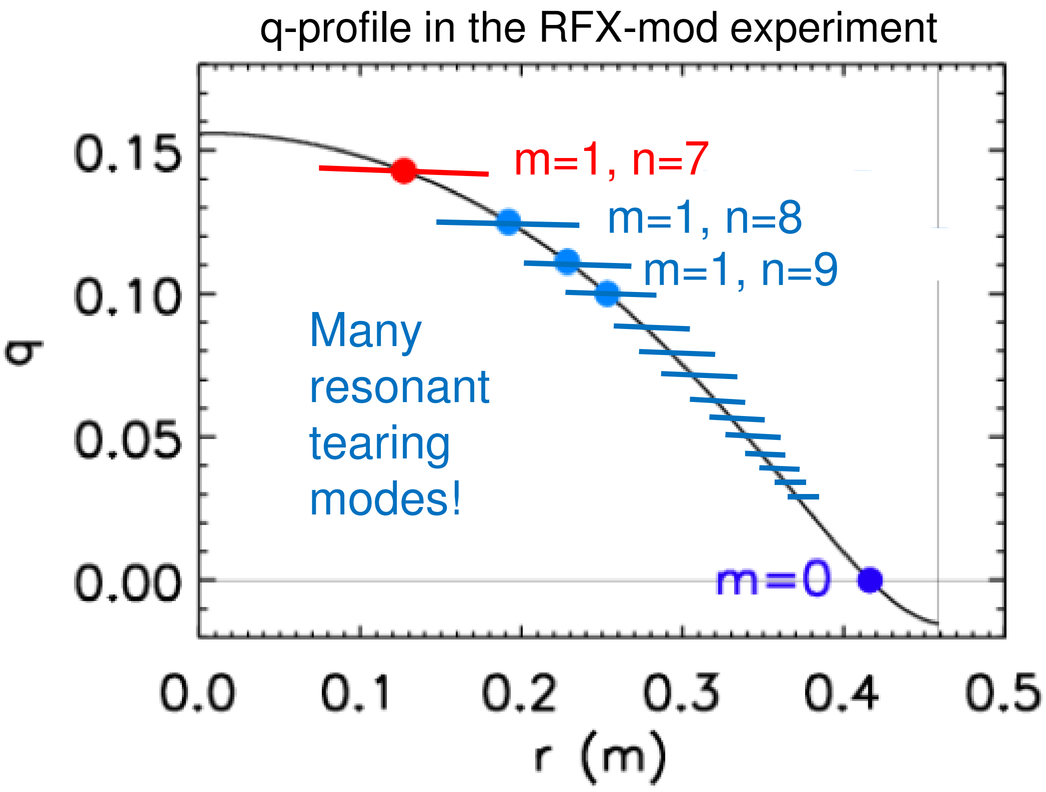
$$B \cong B_\varphi \qquad J_{//} \cong J_\varphi$$

At the edge the magnetic field is almost poloidal:

$$B \cong B_\vartheta \qquad J_{//} \cong J_\vartheta$$

- Self-organization plays an important role: most of B in the plasma is produced by currents flowing in the plasma itself

q profile and MHD spectrum in the RFP



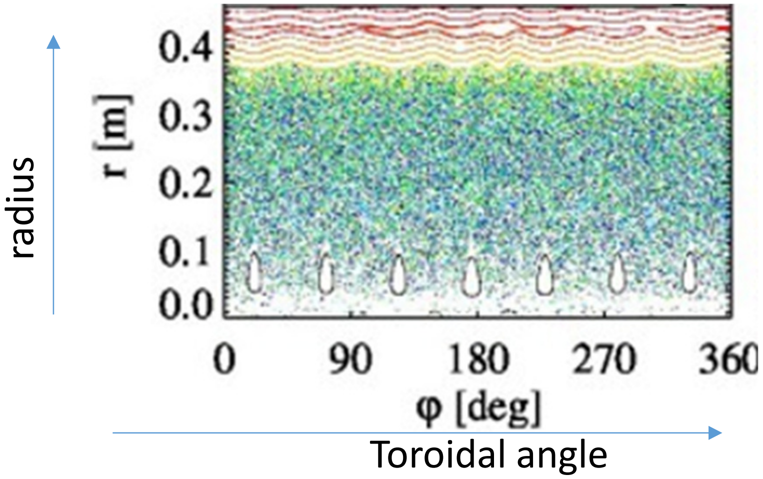
- The safety factor has a spatial profile decreasing from the core outwards, with q(0)<1
- This brings to the **growth and saturation of several tearing modes** in the plasma volume, driven by ∇J
  - The **internal** region is characterized by several (m=1**)** resonances with **helical symmetry**
  - The **edge** region is characterized by several (m=0) resonances with **poloidal symmetry**

q profile and MHD spectrum in the RFP

The dynamics of tearing instabilities is responsible for:

1. **Formation of several magnetic islands** across several resonant flux surfaces

2. **Generation of magnetic chaos/stochasticity** due to overlapping of magnetic islands



3. The generation of the poloidal current that sustains the magnetic configuration producing large part of the B_{tor}

I. Continuous dynamo effect

$$\frac{\partial B}{\partial t} = \nabla \times (\bar{v} \times \bar{B}) + \eta \nabla^2 \bar{B}$$

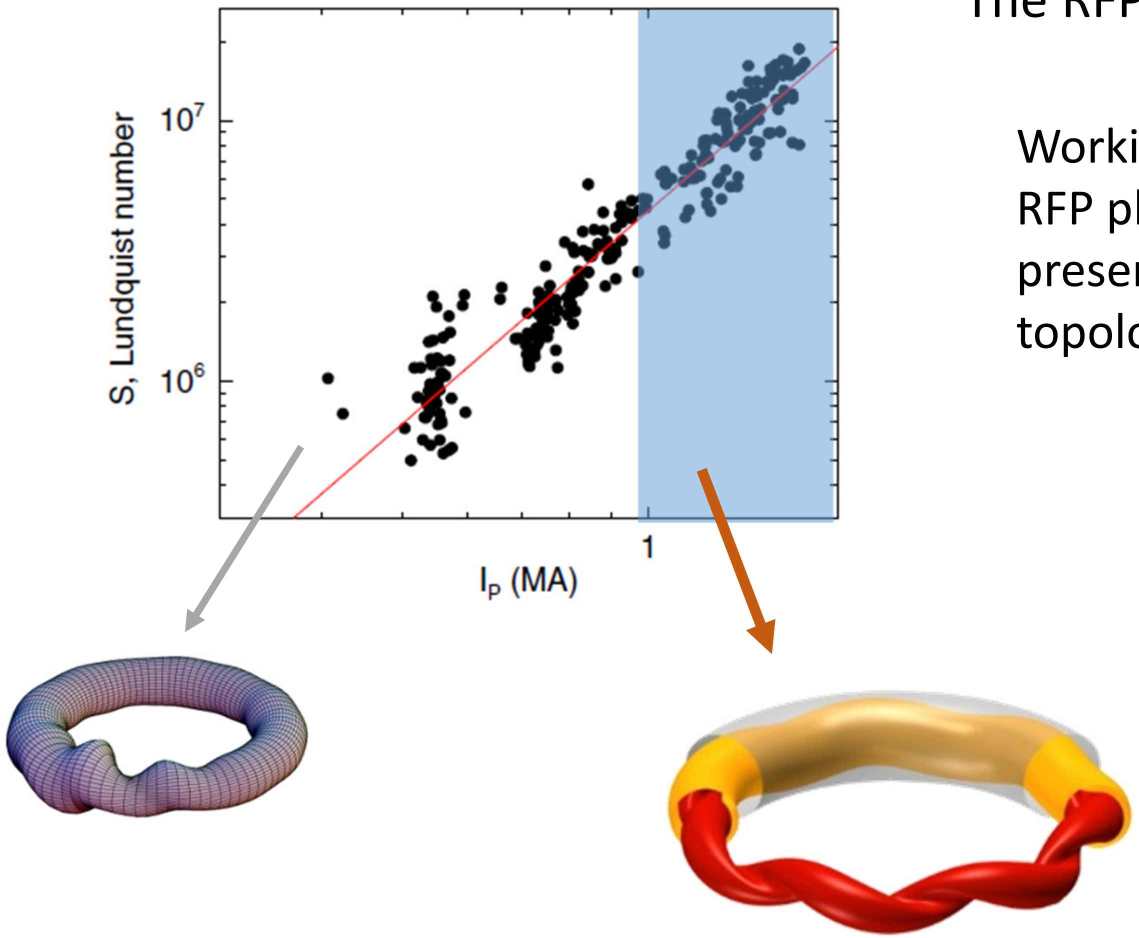
Resistive diffusion of **B**

$$E_\theta = (\tilde{v} \times \tilde{B})_{pol} = \tilde{v}_\varphi \tilde{B}_r$$

II. Cyclic and impulsive reconnection events that sustain the configuration generating toroidal flux through the **redistribution of the current density**

Plasma current

Scaling from RFX-mod data



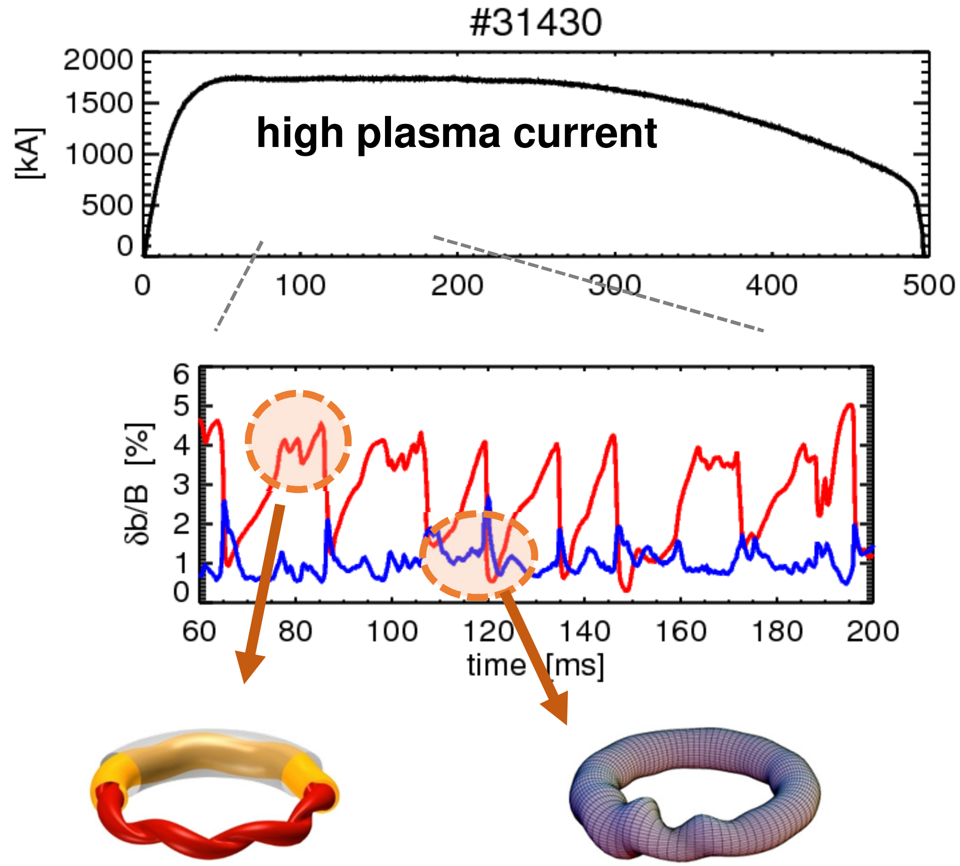
The RFP can work at various plasma currents.

Working at lower or higher plasma currents, RFP plasmas are characterized by the presence of two possible magnetic topologies

At higher plasma currents, the magnetic configuration is dominated by a **helical magnetic structure** that **spontaneously** develops in the **plasma core**

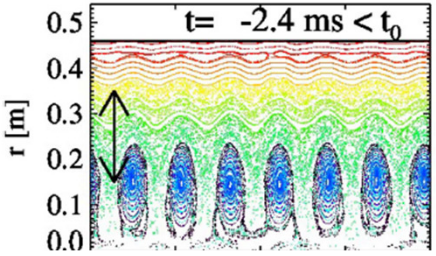
Plasma current and magnetic topology

Time trace of the internal **tearing modes**.
(From RFX-mod data)

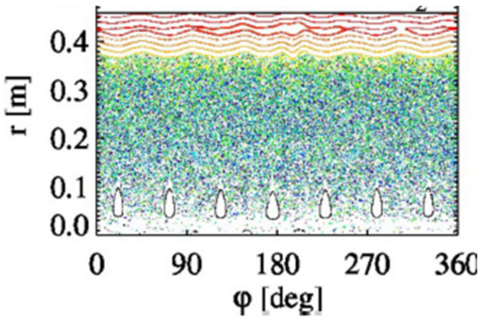


The helical magnetic equilibria are only **intermittent**

- Phases in which the dominance of a single tearing mode brings to the helical states

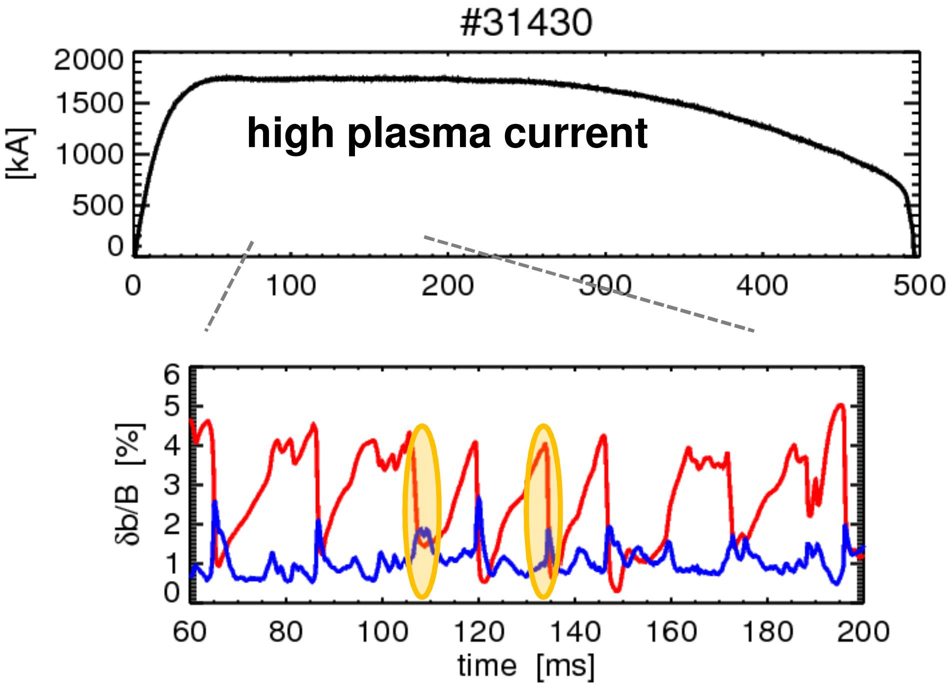


- And phases in which the magnetic configuration is dominated by magnetic chaos due to many island overlap



Plasma current and magnetic topology

Time trace of the internal **tearing modes**.
(From RFX-mod data)

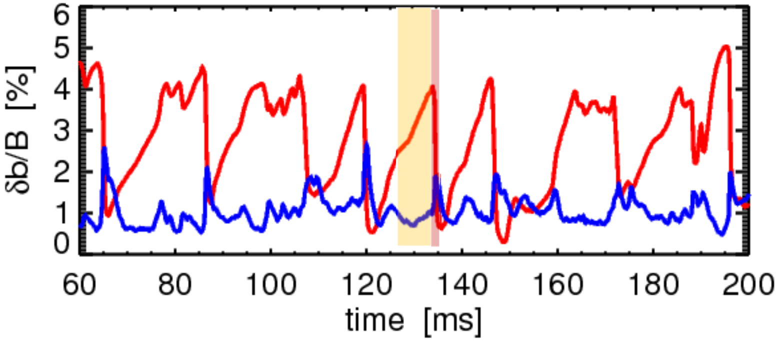


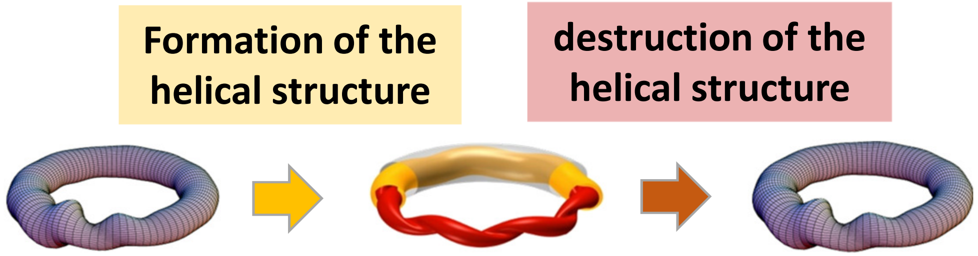
The helical magnetic equilibria are only **intermittent**

- All these spikes, that bring the configuration from the helical to the more chaotic one, are the signature of **impulsive magnetic reconnection events**
- **Tearing modes are the magnetic instabilities that govern the reconnection event**
- **Both at low and high plasma current**, but acting on different magnetic topologies

The reconnection event

Time traces of **tearing modes**





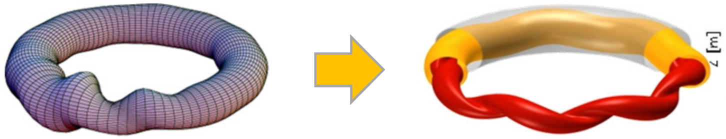
At high plasma current, the impulsive reconnection destroys the helical topology

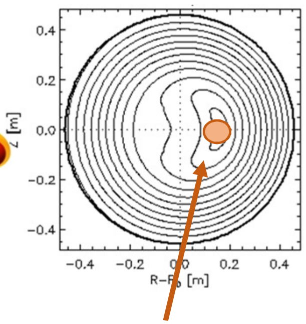
Let's see the **reconnection cycle**

- slow initial phase related to the formation of the helical structure
- **precursor slow** phase (a silent phase in which magnetic instabilities start to grow)
- A **sequence of fast events** during the crash phase that
  - Redistributes the current density
  - Destroys the helical magnetic topology
  - Transfers magnetic energy to heating and acceleration of particles

The slow precursor phase

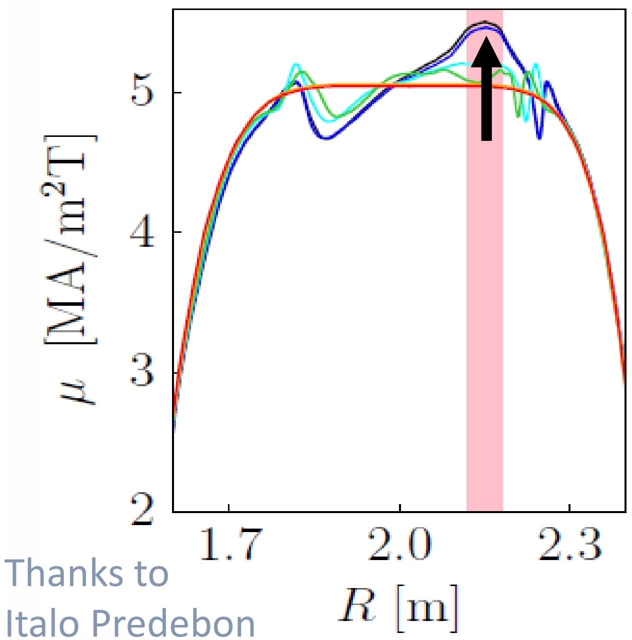
Formation of the helical structure





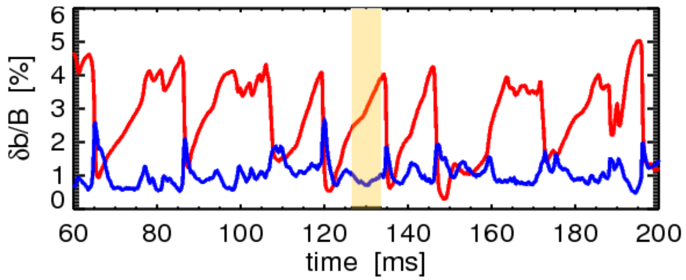
Helical axis

(Jpar/B) profiles at various time instants



Thanks to Italo Predebon

Time traces of **tearing modes**

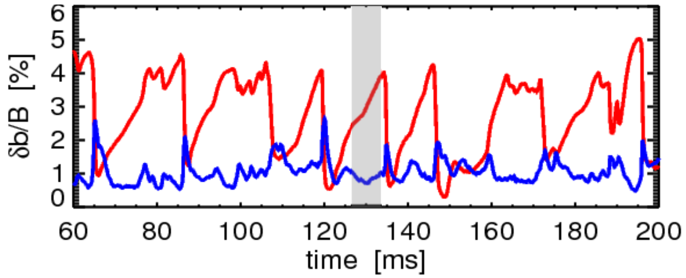


1. The formation of the helical structure in the plasma center comes with a **slow current peaking** on the helical axis
2. Then, **current structures** of the other tearing modes **align and approach each other at a random but precise spatial position**

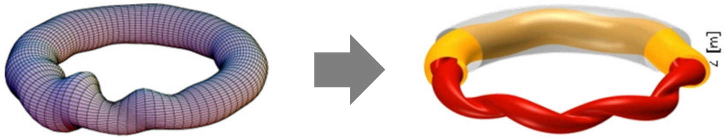
Reconnection is a **localized event** that begins at a **specific point in space**

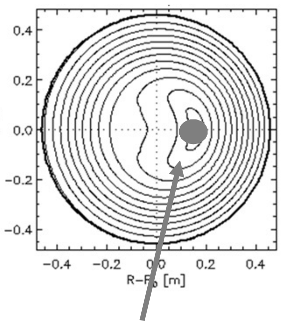
Trigger of the fast crash?

Time traces of **tearing modes**



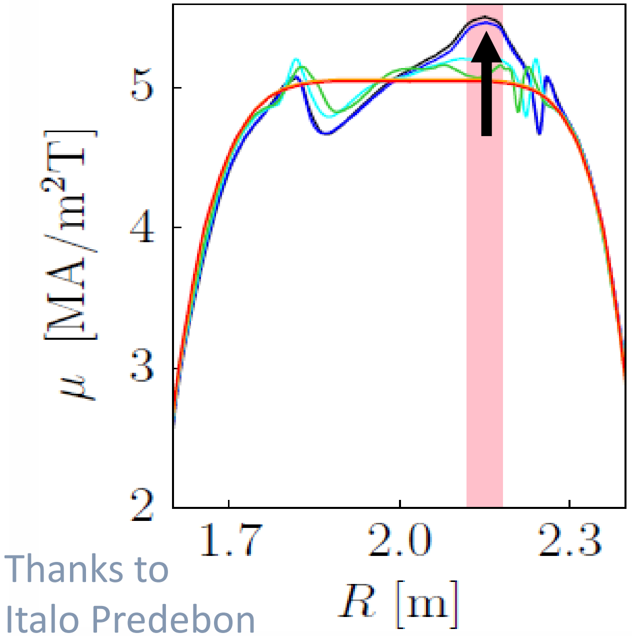
Formation of the helical structure





Helical axis

(Jpar/B) profiles at various time instants



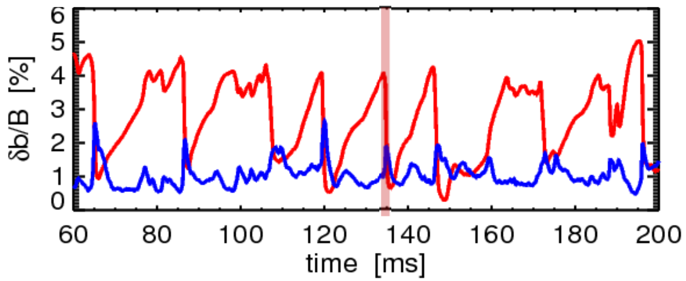
Thanks to
Italo Predebon

1. The formation of the helical structure in the plasma center comes with a **slow current peaking** on the helical axis
2. Then, **current structures** of the other tearing modes **align and approach each other at a random but precise spatial position**

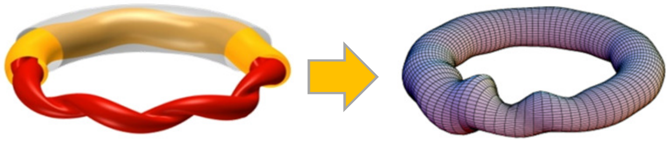
Whereas the **trigger** of the fast phase of the reconnection is still an **open point**, current peaking and approaching of current structures may be at the origin of the growth of tearing modes and of the crash

The fast crash phase

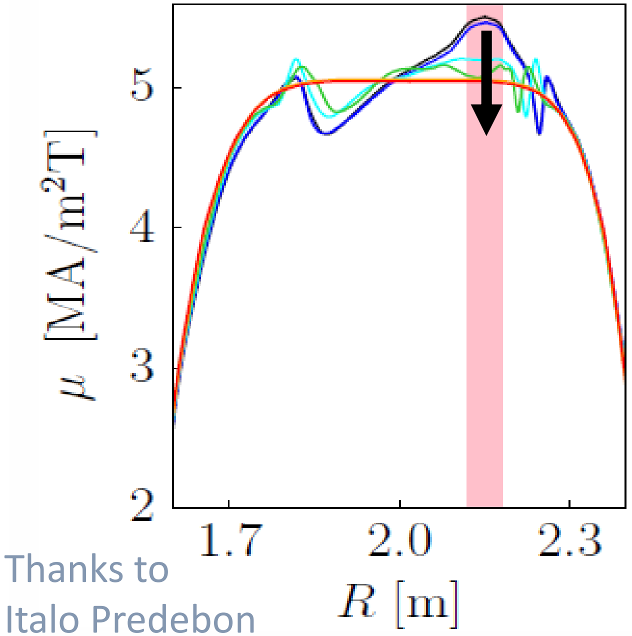
Time traces of **tearing modes**



destruction of the helical structure



(Jpar/B) profiles at various time instants



Thanks to
Italo Predebon

Once the fast crash is triggered:

- The peaked helical current density **flattens**, but very rapidly compared to the slow current peaking time
- The helical structure is destroyed

The parallel current density evolution

Parallel current density reconstruction from RFX-mod data

Example for a high plasma current averaged discharge

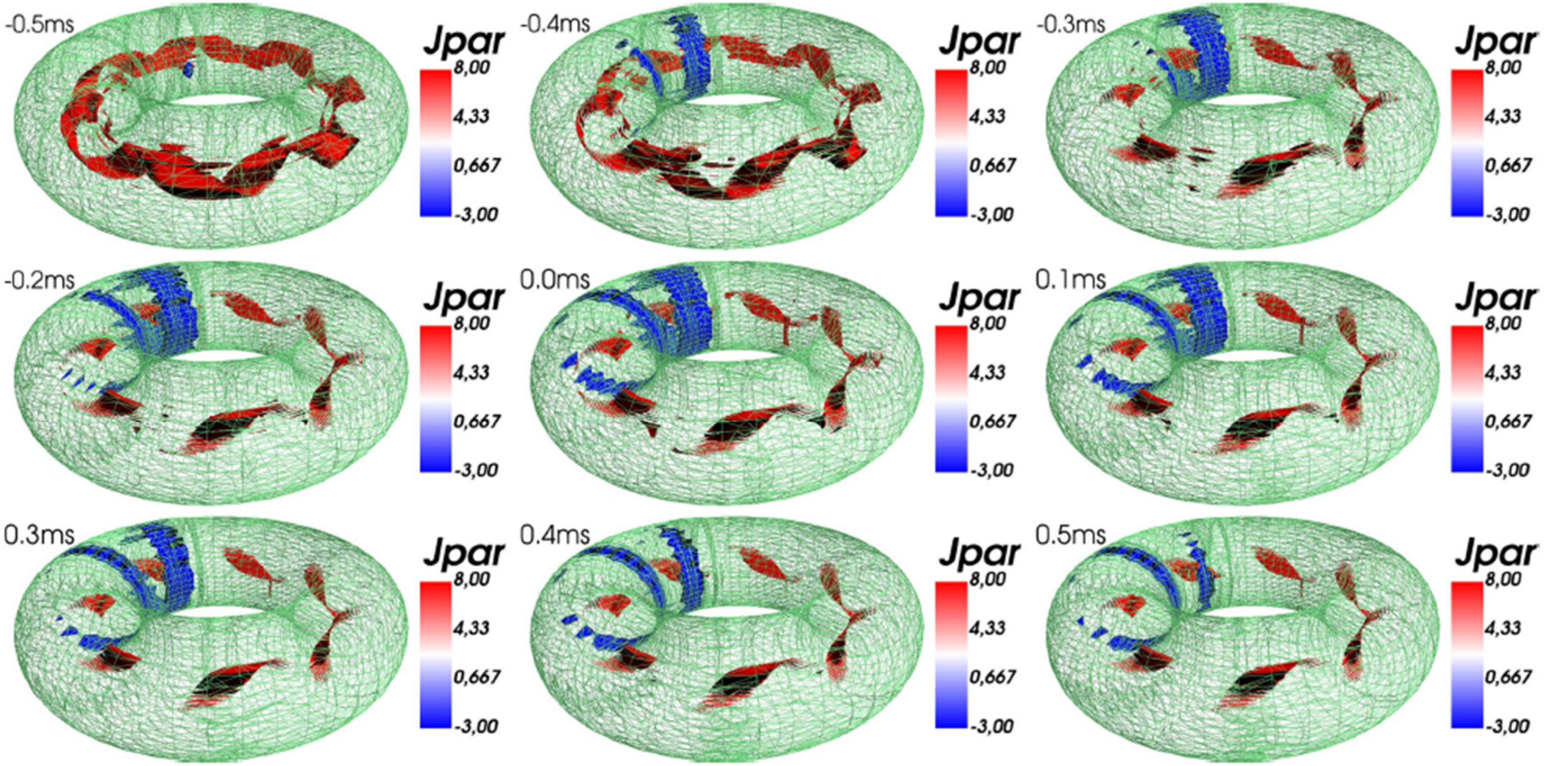


Figure 11. Averaged discharge. 3D plots of $J_{\|}$, together with the reversal surface (in green), at some instants in the interval $[t_2, t_6] = [-0.5, +0.5]$ ms.

B. Momo 2020, thanks to Heinz Isliker

Radial redistribution of the parallel current density:

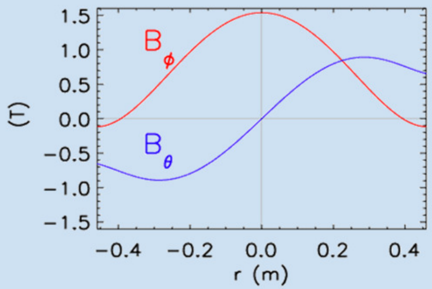
- involves the entire profile
- Brings to the **conversion of helical magnetic flux into toroidal magnetic flux**

The edge (poloidal) current sheet

Remembering…

These impulsive reconnections are responsible for sustaining the configuration **generating the toroidal flux through the radial redistribution of the parallel current density**.

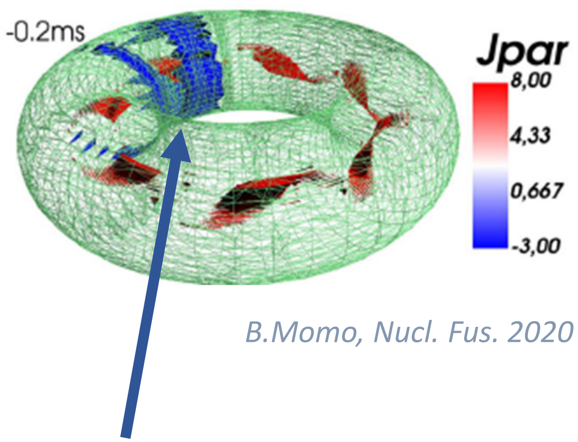
remembering…



At the RFP edge, B-lines are almost poloidal

$$B \cong B_\vartheta \qquad J_{//} \cong J_\vartheta$$

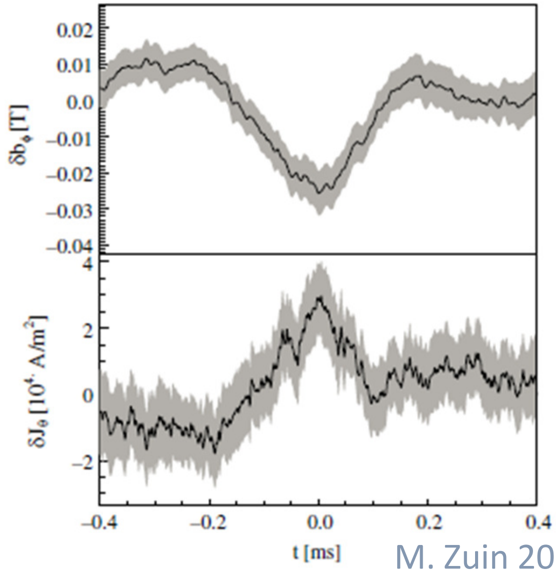
Parallel current density **reconstruction** from RFX-mod data



B.Momo, Nucl. Fus. 2020

The edge poloidal current sheet that generates the toroidal flux, therefore sustaining the configuration against resistive diffusion

Edge **measurements** from RFX-mod data

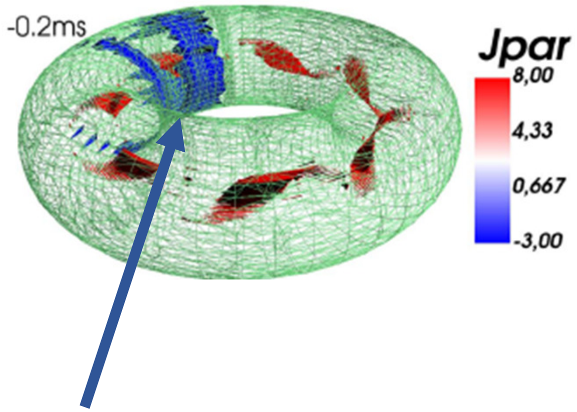


M. Zuin 2009

The edge poloidal current sheet associated to magnetic reconnection has been **measured** during a crash in low-plasma current discharges

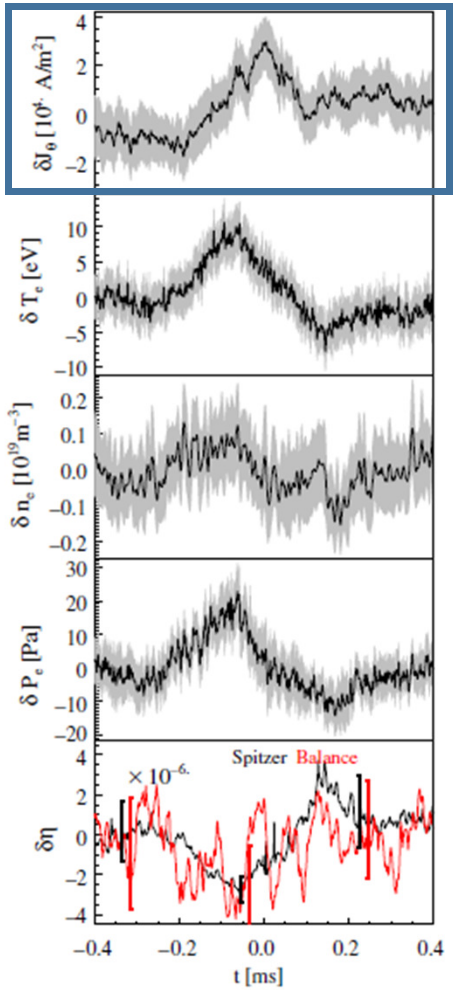
The edge (poloidal) current sheet

Parallel current density **reconstruction** from RFX-mod data



The edge poloidal current sheet that generates the toroidal flux to sustain the configuration against resistive diffusion

Edge **measurements** from RFX-mod data M. Zuin 2009



The **edge poloidal current sheet** has been measured during a crash in low-plasma current discharges

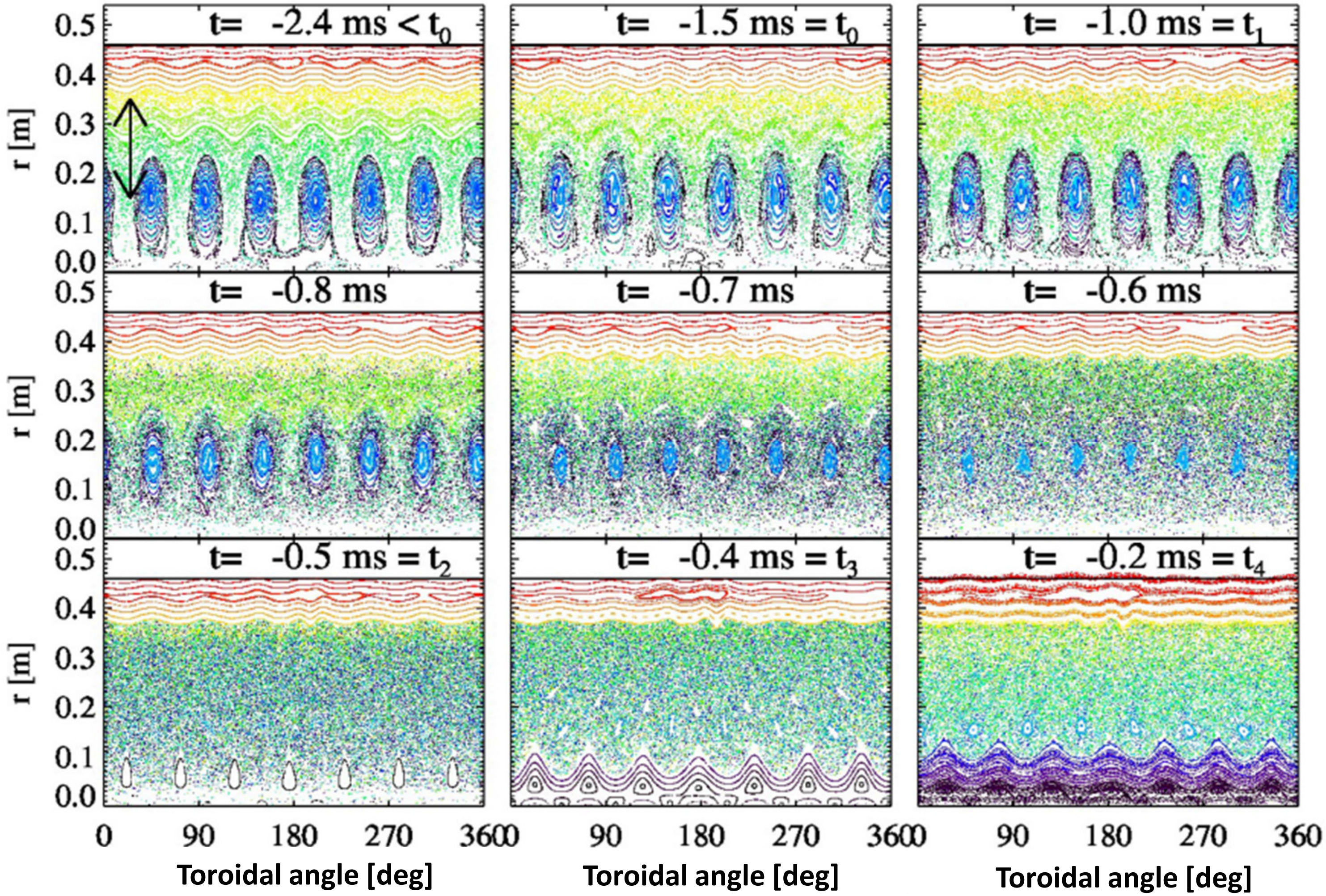
Zuin et al, **PPCF** (2009)

The poloidal current sheet **strongly perturbs the plasma parameters** at the edge.

The current sheet is hotter and denser with respect to surrounding plasma

The magnetic topology evolution

Magnetic topology reconstruction from RFX-mod data
Example for a high plasma current averaged discharge



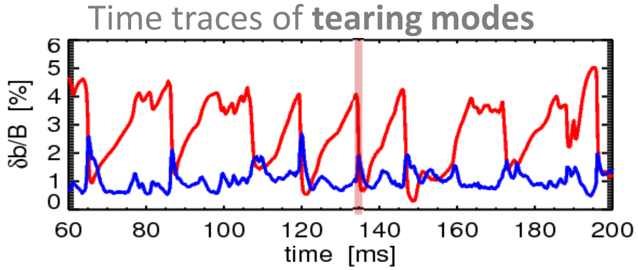
The redistribution of the currents is reflected in:

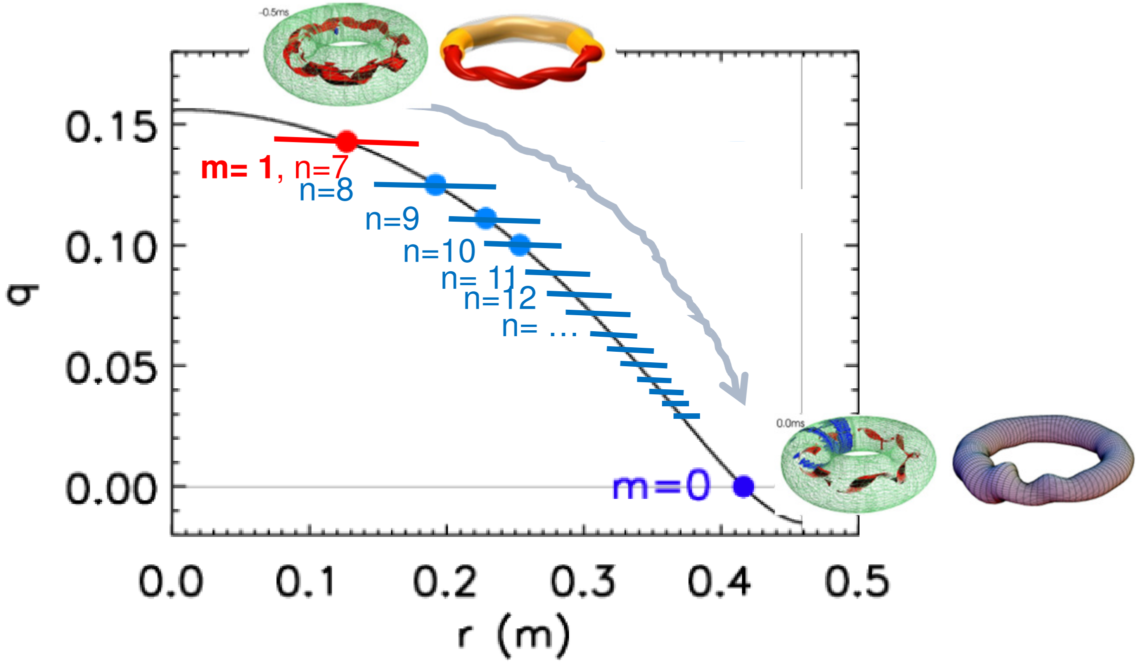
- the **time evolution of any plasma quantity**
- the **macroscopic change of the plasma shape**
- a **global modification of the magnetic topology**

Note that the crash happens in a **chaotic background**

B. Momo 2020
Other on magnetic topology:
P. Porcu 2024, G. Spizzo 2026

The fast crash phase





- The crash phase can be defined as a sequence of stages, that start in the core and propagate towards the edge following the q-profile.

- Compatible with a scenario in which reconnection occurs at various surfaces, **occurring *almost* simultaneously in an impulsive manner**, therefore leading to a global relaxation of the plasma

- Note that the crash happens in a **chaotic background**

Short summary break

- During the reconnection process there is a **radial re-distribution of the plasma current density.** These are the crashes that sustain the configuration with the **generation of toroidal flux** against the resistive diffusion
- Accelerated and heated particles are detected during reconnection events

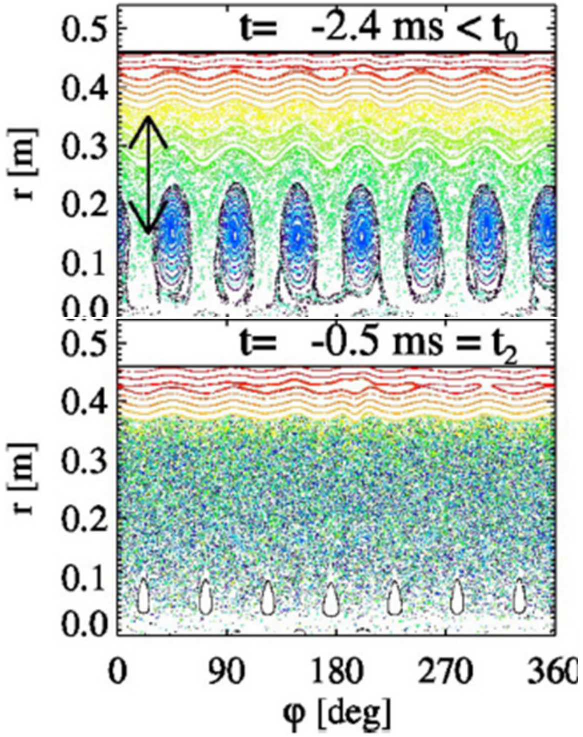
- The redistribution of the currents is reflected in the macroscopic change of the plasma shape and in the time evolution of any plasma quantity.

Other signatures of reconnection: energy transfer to charged particles

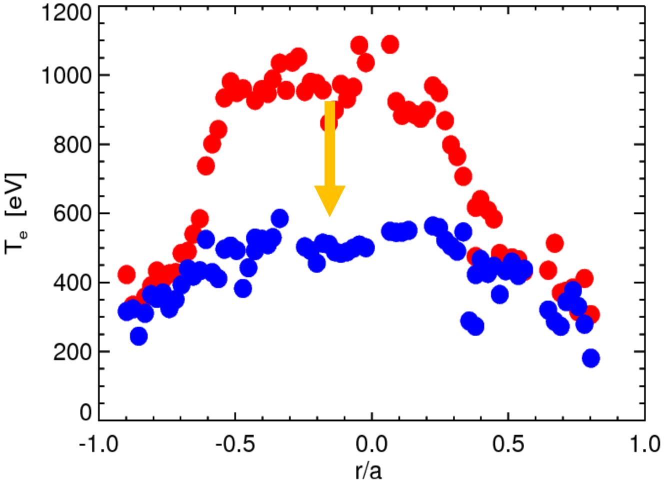
- The magnetic energy released during a crash is converted to kinetic energy
- then dissipated in **particle heating or particle acceleration**.
- **Alfvén waves** are also excited at the crash.

Accelerated and heated particles are detected during reconnection events with a **very good temporal and spatial coincidence with the reconnection event**

Electron temperature during reconnection events



Electron temperature crash during a high-plasma reconnection event



Data from RFX-mod

M. Gobbin 2022

Because of the stochastization of the magnetic field, **the electron thermal energy is rapidly lost from the plasma during a crash due to rapid parallel transport.**

The decay in the magnetic energy thus is not feeding the electron thermal component

Generation of fast electrons during reconnections

X-ray flux from bremsstrahlung emission from MST data

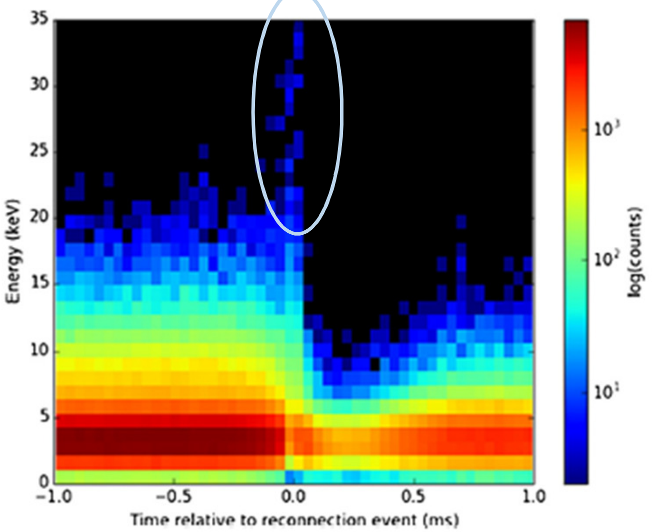


FIG. 3. The evolution of x-ray energy relative to MR (0 ms), with colors indicating x-ray flux. Black indicates no flux and dark red indicates high flux.

DuBois, 2017

X-ray energy spectrum reveals the **formation of energetic electrons** during magnetic reconnection **-** whereas the electron thermal content is reduced due to enhanced stochastization

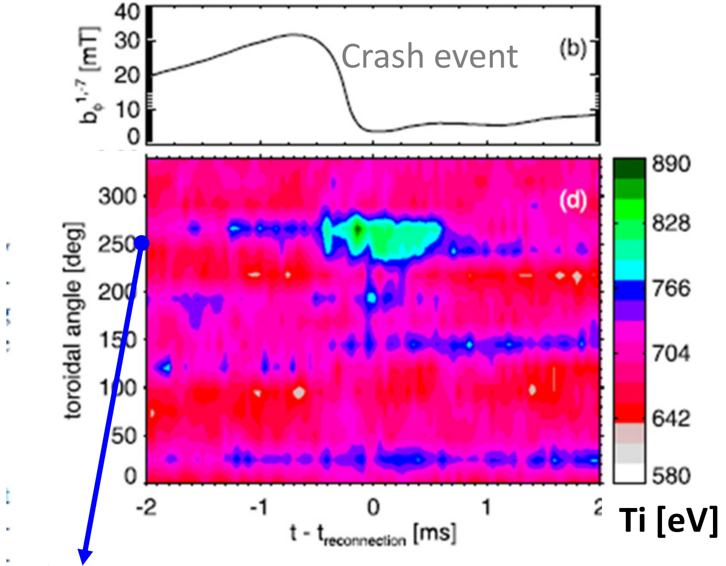
After the reconnection event, the high energy x-ray flux decays rapidly, implying **that energetic electrons are quickly lost**, consistent with expectations from **stochastic transport**

Measurements suggest an energization process that **favors the perpendicular direction ($T_\perp > T_\parallel$),** with pitch angle scattering into the parallel direction, followed by rapid parallel transport.

The dynamics of the x-ray tail correlate with the dynamics of tearing modes and magnetic energy released by magnetic reconnection, implying a **turbulent process** is the most likely cause for the anisotropic energetic electron tail formation.

Ion heating during reconnection events

M. Gobbin 2022

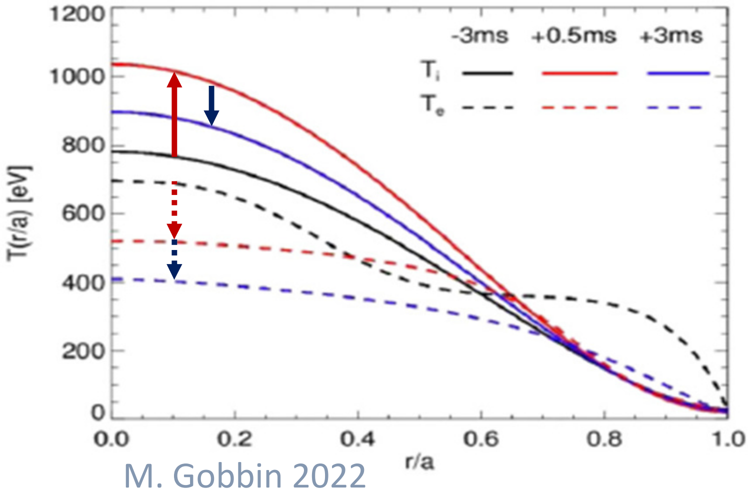


Position of the NPA diagnostic in RFX-mod

Average distribution of neutrals during several RFX-mod discharges

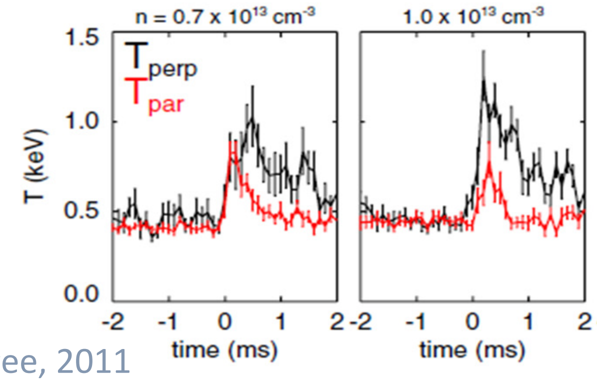
- **Clear increase in the ion temperature** when the reconnection and the associated localized poloidal current sheet occurs in the region observed by the diagnostic

- The ion heating mechanism is **mainly concentrated in the core** region, near resonant surfaces



M. Gobbin 2022

Ion heating during reconnection events

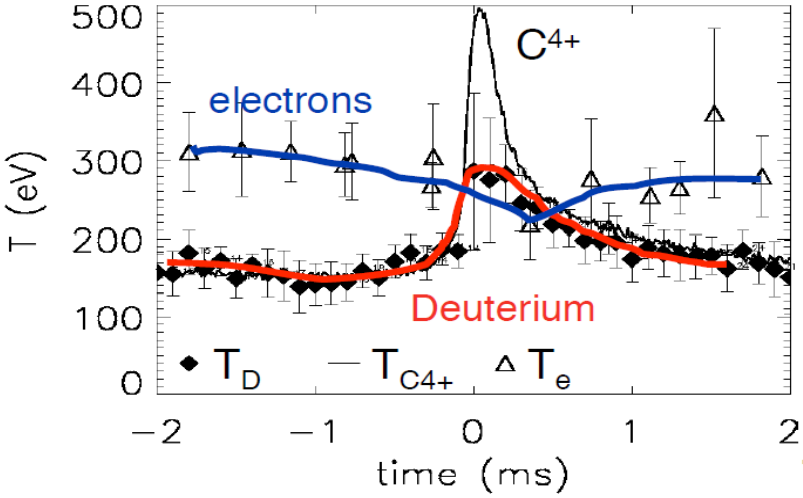


Magee, 2011

- A **local anisotropy** has been observed in the heating process that favors the perpendicular degree of freedom **$T_\perp > T_\parallel$**

- Perpendicular energization is also observed for electrons, which suggests similar mechanisms may operate simultaneously on electrons and ions.

Magee, 2011



Data from MST

- Both impurities and majority components are rapidly heated

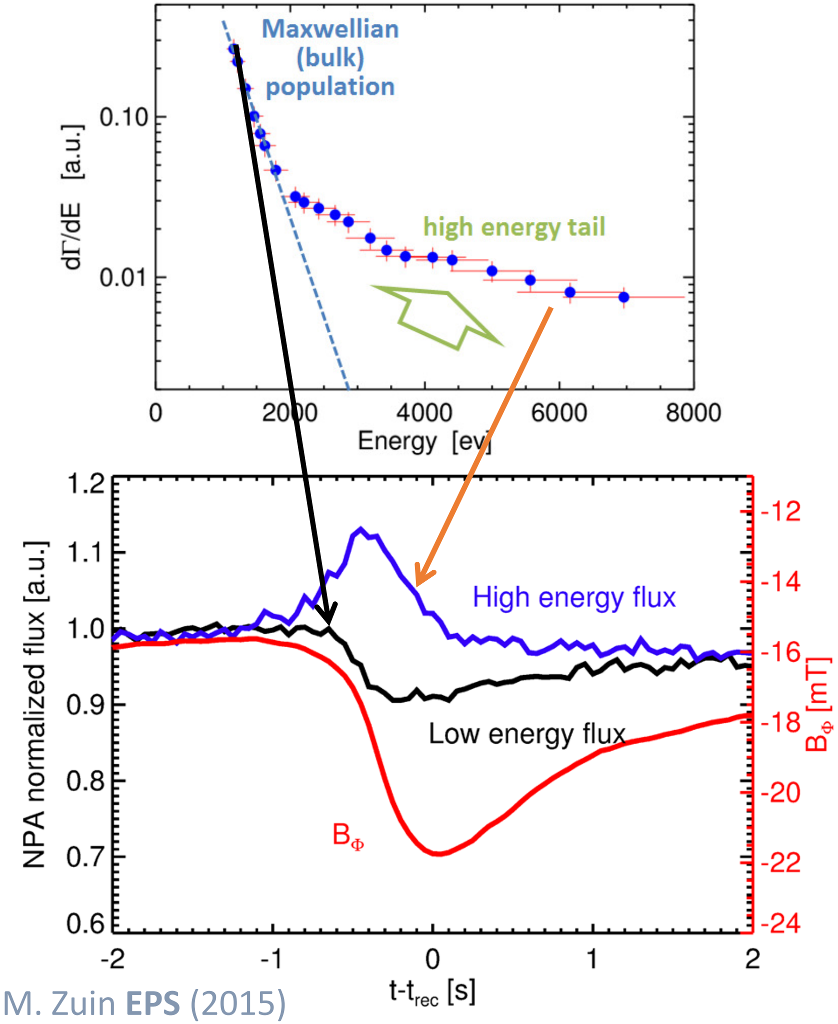
- Electron thermal content reduced

Gangadhara, 2007

- the time scale for heating is of order of the reconnection time (100 μs), while the time scale for cooling is generally longer, and likely determined by energy transport.

Generation of fast ions during reconnections

Average distribution of neutrals during several RFX-mod discharges



M. Zuin **EPS** (2015)

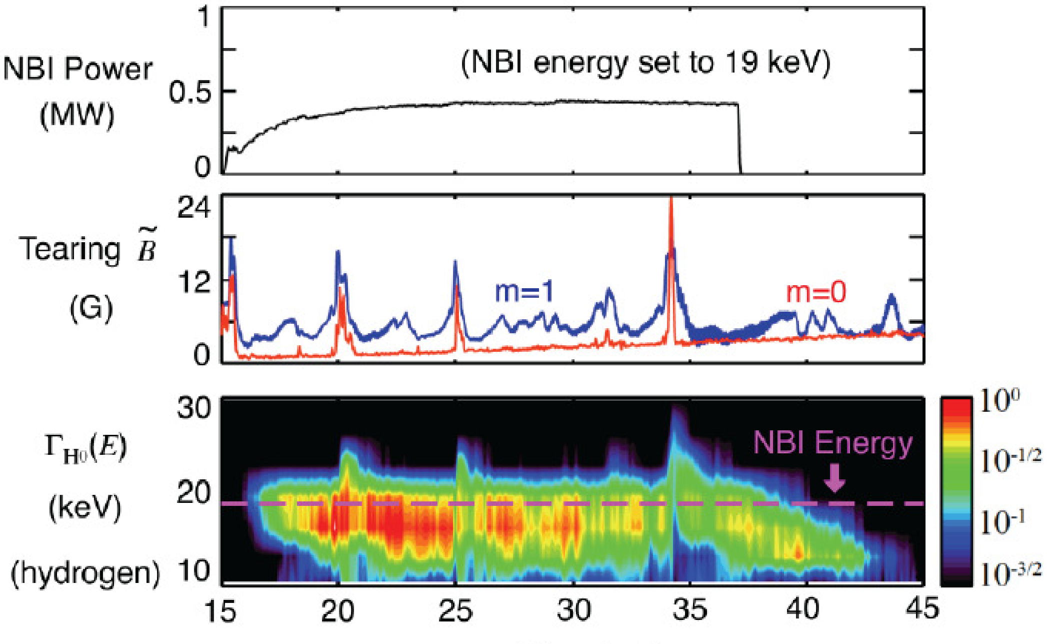
- A **population of** **suprathermal ions** **is generated: the non-maxwellian tail is enhanced during magnetic reconnection**

- The high energy flux starts before the ion heating process

- The majority ion distribution function is very nearly Maxwellian, but there exist a **tail** of fast ions which is generated at the reconnection event, that represents a few percent of the total ion population (but very important for fusion reactions!)

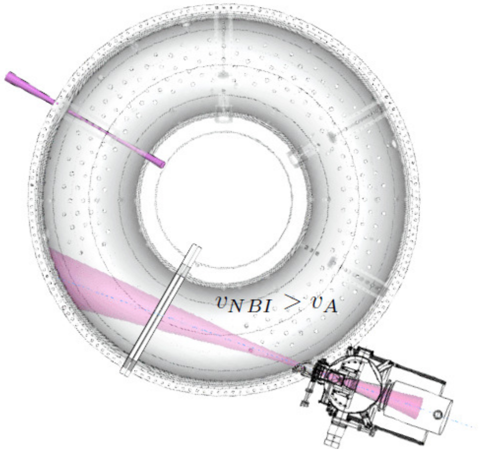
Magee, 2011

Generation of fast ions during reconnections



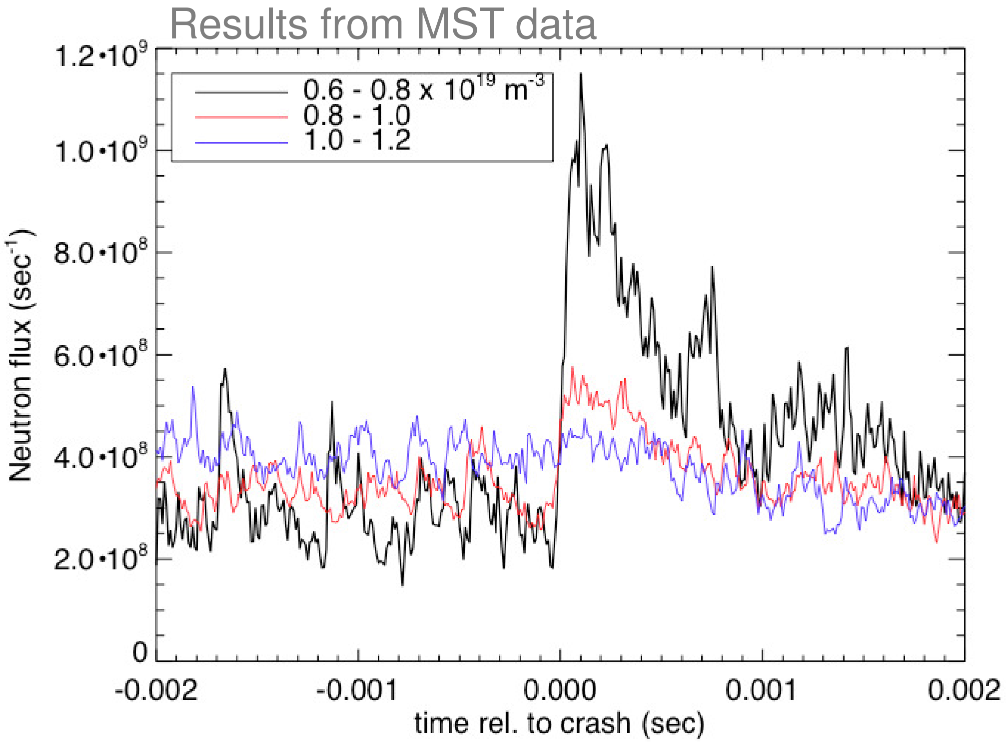
Anderson 2013

Fast ions from Neutral Beam Injection are energized above the injection energy during reconnection events.



Neutral Beam
Injection at 19 keV

Neutron production


Results from MST data

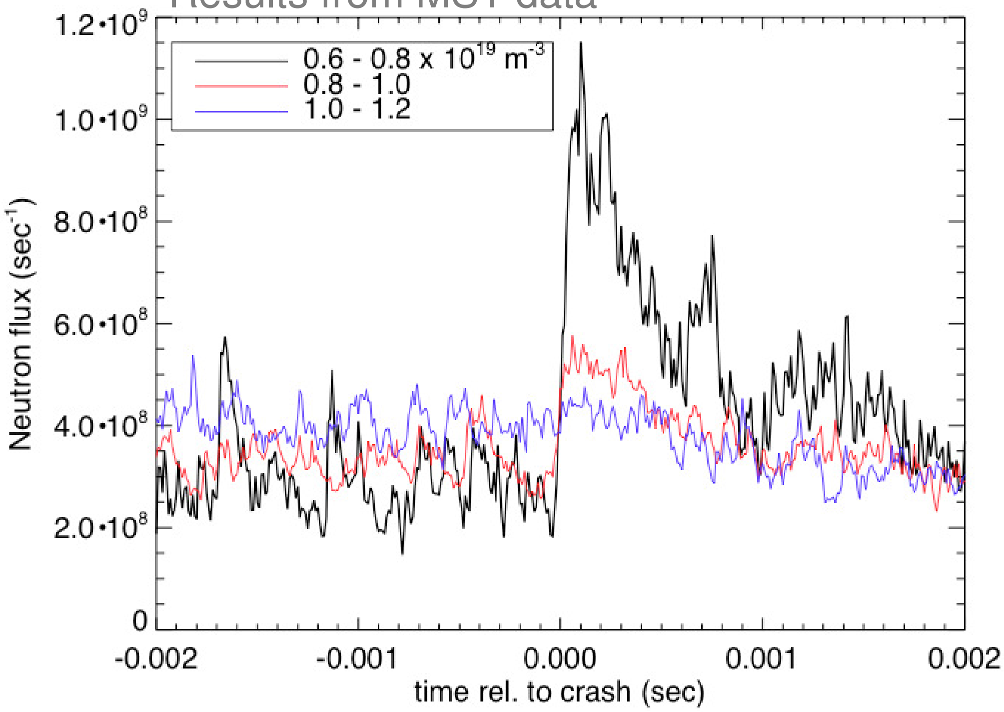
In **deuterium** plasmas, an **increase of neutron fluxes** is found at the reconnection, with a clear **density dependence**

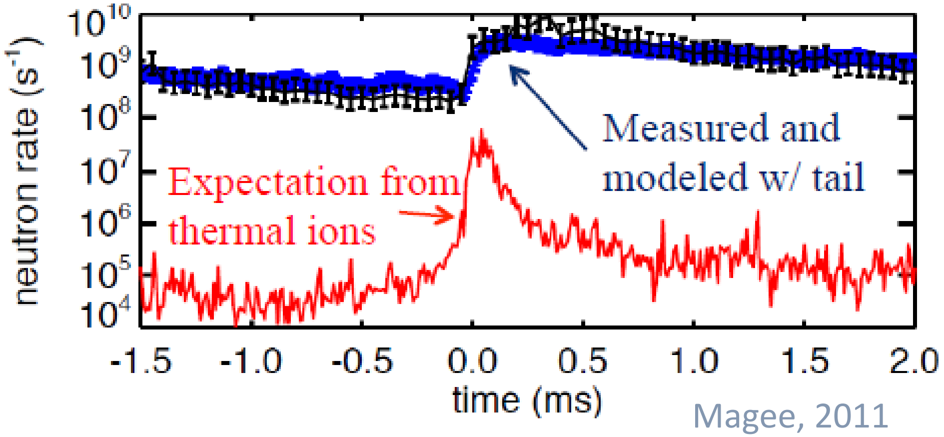
The measured neutron flux enhancement higher in lower density plasmas. This is contrary to the expectation for thermal fusion (~n^2) and **consistent with the expectation for fast ion fusion** (less friction).

$$\begin{aligned} \mathrm{D}+\mathrm{D} &\rightarrow \mathrm{T}\ (1.01\ \mathrm{MeV}) + \mathrm{p}\ (3.01\ \mathrm{MeV}) \\ &\rightarrow \mathrm{He}^3\ (0.82\ \mathrm{MeV}) + \boxed{\mathrm{n}\ (2.45\ \mathrm{MeV})} \end{aligned}$$

Neutron production

Results from MST data





Magee, 2011

$$\begin{aligned} D + D &\rightarrow T\ (1.01\ \mathrm{MeV}) + p\ (3.01\ \mathrm{MeV}) \\ &\rightarrow He^3\ (0.82\ \mathrm{MeV}) + \boxed{n\ (2.45\ \mathrm{MeV})} \end{aligned}$$

The **DD fusion** cross section is extremely sensitive to ion energy, **so a small number of fast ions has strong impact on DD neutron fluxes**

The neutron production from MST plasmas is completely dominated by fast ions

Alfvén waves excited at the reconnection

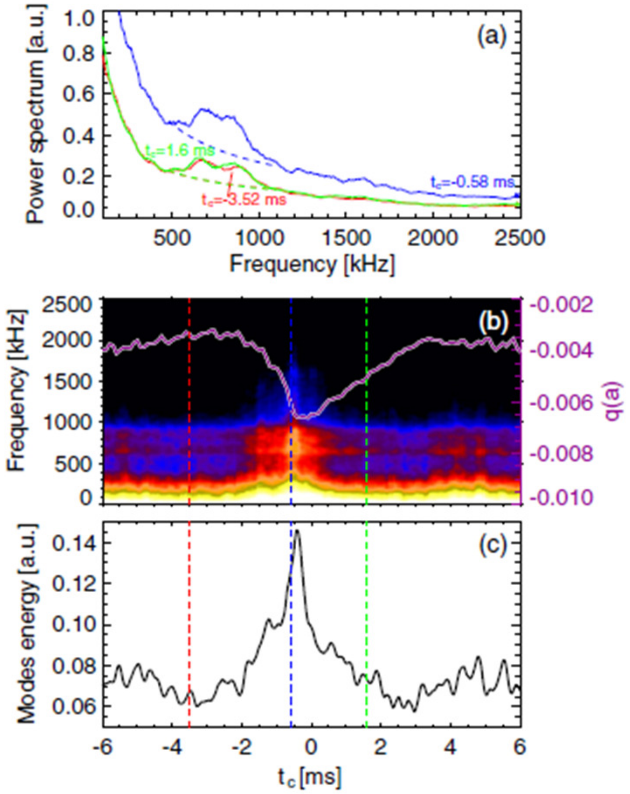


Figure 8. (*a*) Power spectra of a $\dot{B}_\theta$ signal referring to three instants of the crash evolution. (*b*) Spectrogram obtained averaging different time intervals centred on a crash event (the solid line represents the averaged $q(a)$). (*c*) Time evolution of the energy of the modes.

S. Spagnolo 2011

A variety of **Alfvén eigenmodes** are observed in RFX-mod ohmic plasmas, with no additional heating indicating the presence of self-generated fast particle population

The global increasing of the spectrum at the reconnection event does not occur with the same importance at all frequency, but **the amplitude of the AEs spectrum is particularly enhanced**

Energy associated with AEs: **its amplitude has practically doubled** during the reconnection event

Numerical tools

- **The nonlinear 3D MHD visco-resistive** approximation in the SpeCyl code

Can describe and predict experimental behavior during magnetic reconnection in the RFP

$$\rho(\partial_t \boldsymbol{v} + \boldsymbol{v}\cdot\nabla\boldsymbol{v}) = \boldsymbol{J}\times\boldsymbol{B} + \frac{1}{M}\nabla^2\boldsymbol{v}$$

$$\partial_t \boldsymbol{B} = \boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B} - \frac{1}{S}\boldsymbol{J})$$

$$\nabla\times\boldsymbol{B} = \boldsymbol{J}$$

$$\nabla\cdot\boldsymbol{B} = 0$$

- Cappello, Biskamp NF (1996)
- Chacòn CPC (2004), Chacòn PoP (2008)
- Bonfiglio, Chacòn, Cappello PoP (2010)
- Finn, Chacòn PoP (2005)
- Ciaccio, Veranda, et al PoP (2013)
- Veranda et al NF (2017), NF (2019)

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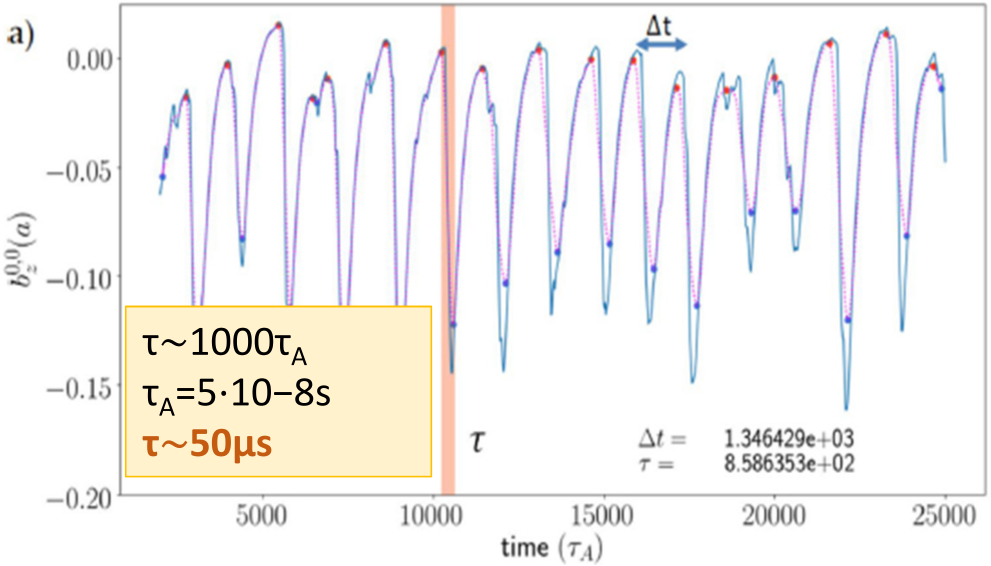
$$\partial_t \boldsymbol{B} = \boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B} - \frac{1}{S}\boldsymbol{J})$$

$$\nabla\times\boldsymbol{B} = \boldsymbol{J}$$

$$\nabla\cdot\boldsymbol{B} = 0$$

- **Fast** reconnection has been found, in a **very good agreement with experimental reconnection time**

Veranda, 2020



$\tau \sim 1000\tau_A$
$\tau_A = 5\cdot 10{-}8$s
$\tau \sim 50\mu$s

- Cappello, Biskamp NF (1996)
- Chacòn CPC (2004), Chacòn PoP (2008)
- Bonfiglio, Chacòn, Cappello PoP (2010)
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Numerical tools

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$$\nabla\times\boldsymbol{B} = \boldsymbol{J}$$

$$\nabla\cdot\boldsymbol{B} = 0$$

- Evolution of the **parallel current density** and localized edge poloidal current sheet

Veranda, 2020

Edge poloidal
current sheet

- And related **magnetic topology** evolution

[1] Cappello, Biskamp NF (1996)
[2] Chacòn CPC (2004), Chacòn PoP (2008)
[3] Bonfiglio, Chacòn, Cappello PoP (2010)
[4] Finn, Chacòn PoP (2005)
[5] Ciaccio, Veranda, et al PoP (2013)
[6] Veranda et al NF (2017), NF (2019)

Numerical tools

- **The nonlinear 3D MHD visco-resistive** approximation in the SpeCyl code

$$\rho(\partial_t \boldsymbol{v} + \boldsymbol{v} \cdot \nabla \boldsymbol{v}) = \boldsymbol{J} \times \boldsymbol{B} + \frac{1}{M} \nabla^2 \boldsymbol{v}$$

$$\partial_t \boldsymbol{B} = \boldsymbol{\nabla} \times \left(\boldsymbol{v} \times \boldsymbol{B} \; - \frac{1}{S} \boldsymbol{J}\right)$$

$$\nabla \times \boldsymbol{B} = \boldsymbol{J}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

[1] Cappello, Biskamp NF (1996)
[2] Chacòn CPC (2004), Chacòn PoP (2008)
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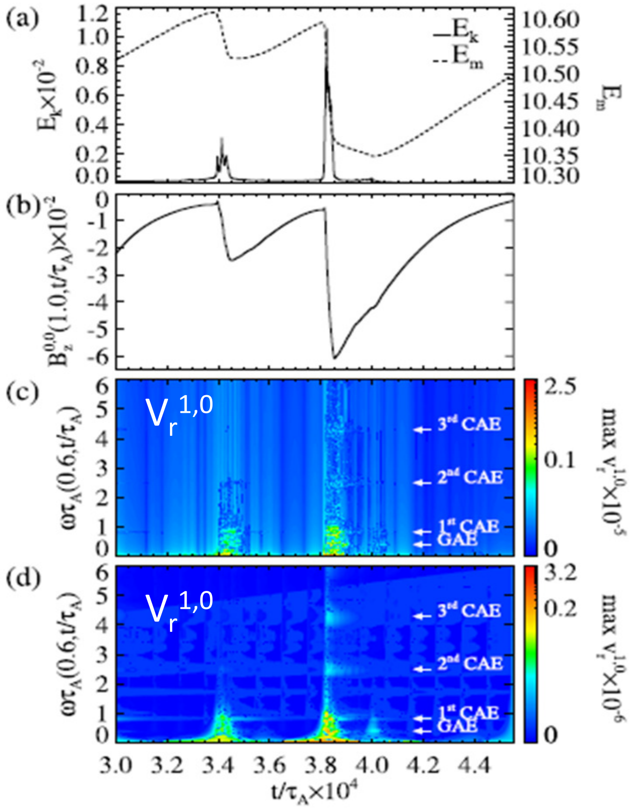
[4] Finn, Chacòn PoP (2005)
[5] Ciaccio, Veranda, et al PoP (2013)
[6] Veranda et al NF (2017), NF (2019)

- Fast ion effect in Ohmic plasmas: the **excitation of Alfvén waves by magnetic reconnection**



Kryzhanovskyy, 2022

Short summary break: tokamak vs RFP

Reconnection events in the RFP w.r.t. Tokamak

Similarities

They share a similar reconnection cycle:

- The growth of tearing instabilities due to an accumulation of currents and the formation of ∇J in the plasma centre that brings to the formation of magnetic islands through a reconnection process
- The trigger of a fast crash phase in which probably magnetic stochasticity plays a fundamental role
- Fast reconnection
  - It is a localized event both in Tokamak and RFP
  - It brings to a plasma mixing across original magnetic flux surfaces, and to enhanced magnetic stochasticity
  - Heating and acceleration of charged particles, together with Alfvén waves have been detected

Differences

- Tokamak: reconnections involve the central part of the plasma
- RFP: involve the whole magnetic configuration

Open for discussions…

Reconnection as a localized event

- **Tokamak**: poloidally localized at the X-point of the island. Is it toroidally localized too?
- **RFP**: toroidally localized where currents structures - related to the presence of many islands – get closer. Is it poloidally localized too?

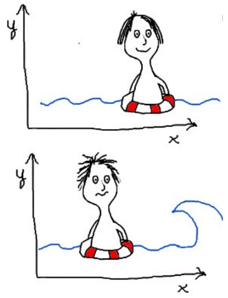
Reconnection in a chaotic background…

- Which is the role of magnetic islands and magnetic chaos in triggering fast magnetic reconnection
- Note that even the formation of magnetic islands happens through a magnetic reconnection process. In RFPs energetic particles are always detected…
- RFPs could be good devices to understand this difference

Reconnection generates electromagnetic turbulence? In RFX-mod there are evidence of edge turbulence generation in coincidence of the crash

In the next future a new RFP will start working: RFX-mod2 in Padova, Italy!

- Advanced systems for the control of plasma instabilities
- many diagnostics for the characterization of reconnection events will be available, with high temporal and spatial resolution



Dedicated to my dad

And to my mum

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