# H&CD APPLICATION FOR CONTROL OF MHD INSTABILITIES

ITER INTERNATIONAL SCHOOL, CHINA, LESHAN, 20-24 JULY, 2026

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# OUTLINE OF THE LECTURE

Introduction into MHD

- Plasma stability
- Energy principle
- Main characteristics of MHD instabilities

Physics and control of

- Classical and Neoclassical Tearing Modes (TMs and NTMs)
- Sawteeth and continuous (1,1) mode

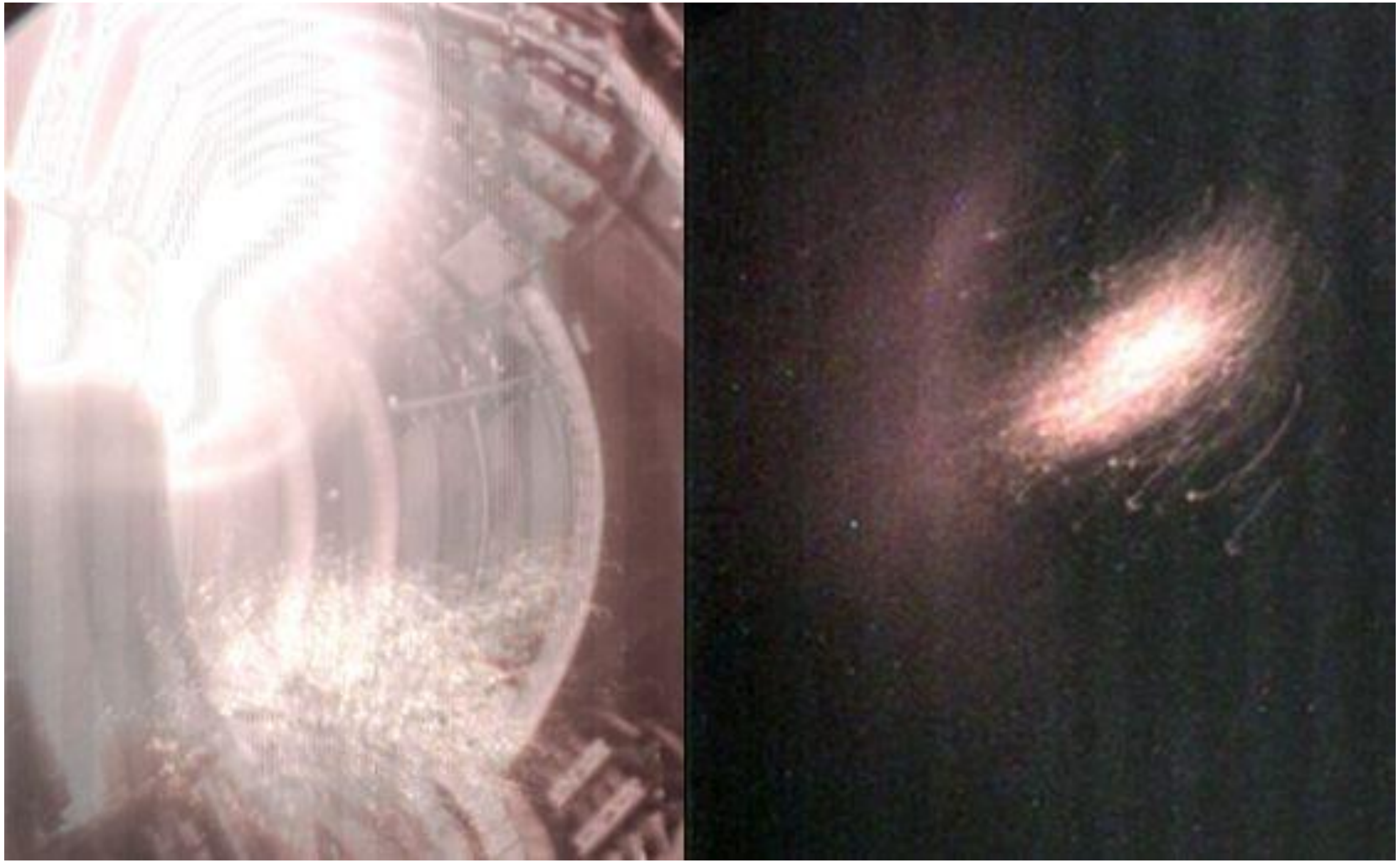
Conclusions

# WHY DO WE NEED TO STUDY MHD INSTABILITIES?

One example is here.

MHD instabilities:

- Can significantly reduce performance.
- They can also lead to disruptions.



## WHAT MEANS MHD?    MHD = MAGNETO-HYDRO DYNAMIC

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (n\vec{v})$$ equation of continuity

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v}\right) = -\nabla p + \vec{j}\times\vec{B}$$ force equation

**MHD = fluid equations for conducting media + Maxwell equations**

$$\vec{E} + \vec{v}\times\vec{B} = \eta\,\vec{j}$$ =0 if η=0 Ohm's law

=> frozen-in B lines

$$\frac{d}{dt}\left(\frac{p}{\rho^{\gamma}}\right) = 0$$ equation of state

plus Maxwell's equations for *E* und *B*

Single fluid MHD:

- Conservation laws
- Force balance (like in mechanics)
- Adiabatic equation
- Electromagnetic equations (Maxwell's eq.)

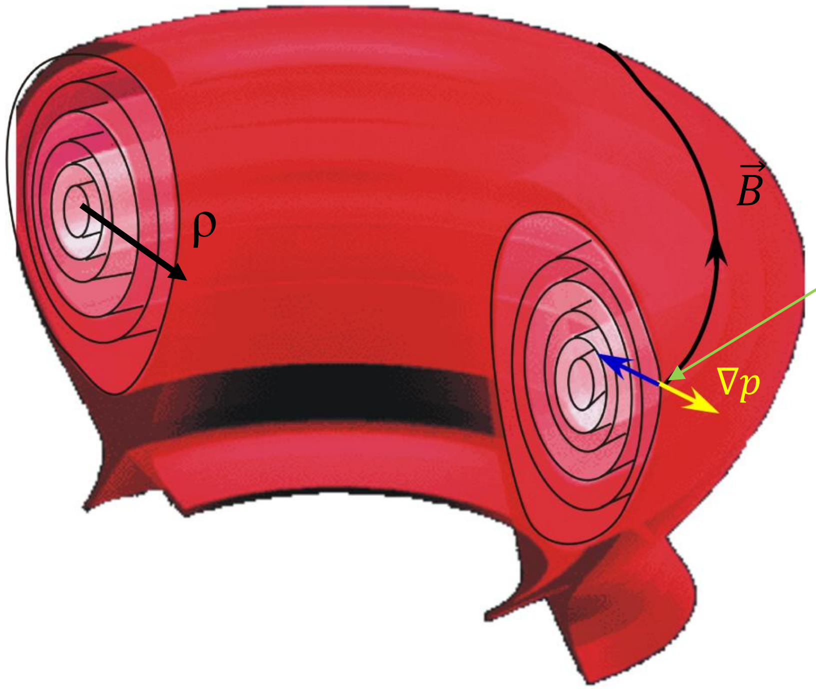
# EQUILIBRIUM IN TOKAMAK

$$\rho \frac{d\vec{v}}{dt} = \vec{J} \times \vec{B} - \nabla p$$

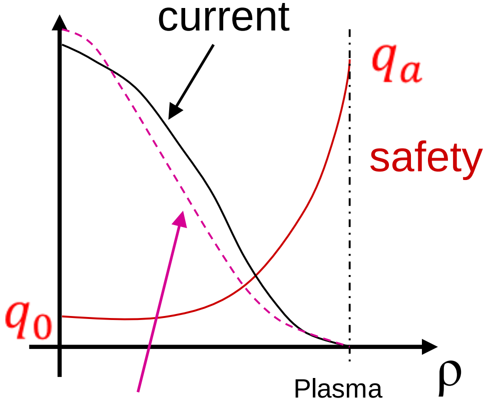
0

In a tokamak, equilibrium means:

The **balance of forces** between the *pressure gradient* and the *magnetic force* at each point inside the plasma.




$$\vec{j} \times \vec{B} = \nabla p$$




$$q = \frac{poloidal\_rotation\_angle}{toroidal\_rotation\_angle}$$

magnetic shear
$$s = \frac{r}{q(\mathrm{r})}\frac{dq}{dr}$$

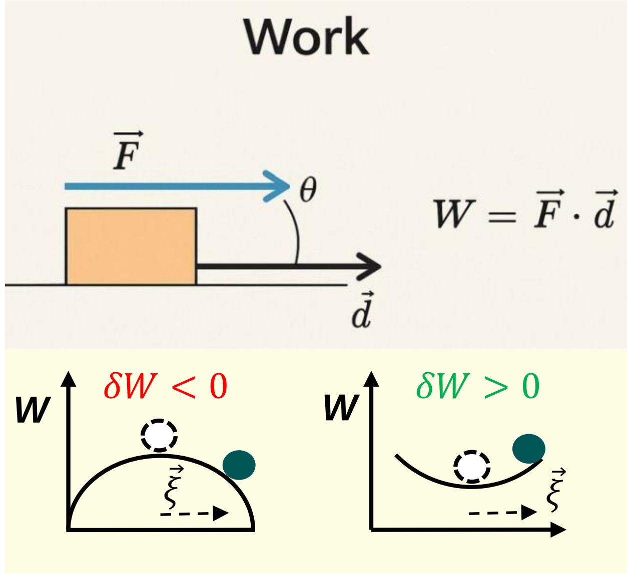
$$\beta_t \equiv \frac{\langle p \rangle_{volume}}{\frac{B_t{}^2}{2\mu_0}} = \frac{kinetic\_plasma\_pressure}{magnetic\_field\_pressure} = \beta_N \frac{I_p}{aB_t}$$

$$\beta_N = \frac{\beta_t a B_t}{I_p}$$

normalized beta
(allows to compare different tokamaks! Not the same as normal beta!)

# STABILITY CONDITION IN PLASMA

If the force is unbalanced: $\vec{F} = \underbrace{\vec{j} \times \vec{B}}_{\text{magnetic force}} - \underbrace{\nabla p}_{\text{plasma pressure force}} \neq 0$




One can calculate energy changes for a given displacement $\vec{\xi}$

$$\delta W = \frac{1}{2} \int \vec{\xi} \cdot \vec{F} d\tau$$

Linearization:
$A = A_0 + A_1$
0 – equilibrium
1 - perturbation

Pressure driven instabilities

Current driven instabilities

$$\delta W = \frac{1}{2} \int_{plasma} \left( \underbrace{\gamma p_0 \left( \nabla \cdot \vec{\xi} \right)^2}_{>0} + \left( \vec{\xi} \cdot \nabla p_0 \right) \nabla \cdot \vec{\xi} + \underbrace{\frac{B_1^2}{\mu_0}}_{>0} - \vec{j}_0 \cdot \left( \vec{B}_1 \times \vec{\xi} \right) \right) d\tau + \underbrace{\int_{vacuum} \frac{B_{vac}^2}{2\mu_0} d\tau}_{>0}$$

Always positive (stable)!

Unstable only if $\delta W < 0$

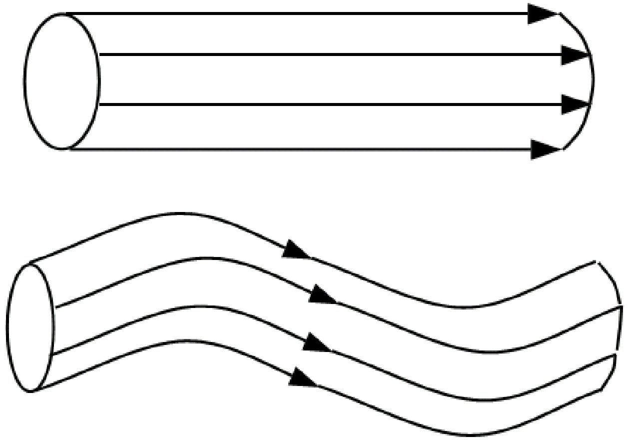
Wesson, Tokamaks, 3rd Edition
Freidberg, Ideal MHD

# FREE ENERGIES TO DRIVE MHD MODES

MHD

current driven instabilities

(kink mode)



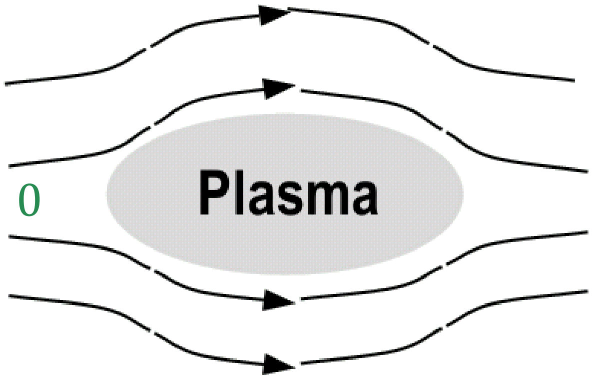
$\delta W < 0$

MHD

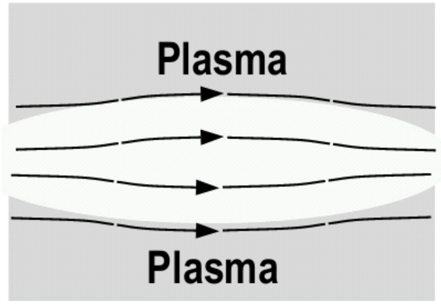
pressure driven instabilities

(interchange mode)

$\delta W > 0$



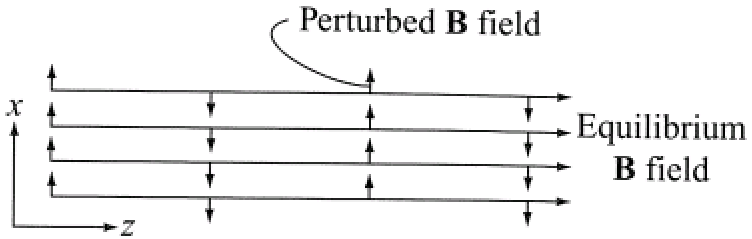

$\delta W < 0$

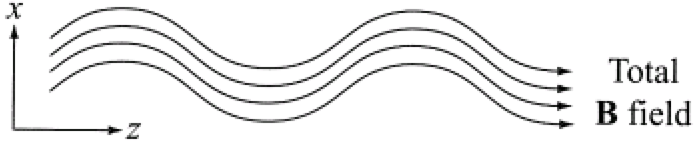



Kinetic effects

fast particles driven instabilities

(Alfvén modes)




Fusion products (αs) interact with Alfvén waves *much* better than thermal plasma.

First question: What is the driving force?

EUROfusion iter china eu india japan korea russia usa ASDEX Upgrade

# RESISTIVITY COULD BE IMPORTANT AS WELL!

Amper‘s law

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

Consider equilibrium Ohm's law...

$$\vec{E} = -\vec{v} \times \vec{B} + \frac{1}{\sigma}\vec{J}$$

...and analyse how magnetic field can change:

Advection (flux is frosen into magnetic field, no topological changes)

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} = \nabla \times \left(\vec{v} \times \vec{B}\right) - \frac{1}{\mu_0 \sigma} \nabla \times \left(\nabla \times \vec{B}\right)$$

magnetic diffusion (changes topology)

Important note: In fusion plasma two-fluid effects dominate and effective resistivity is much larger than Spitzer resistivity.

Typical time scale of resistive MHD:

$$\tau_R = \mu_0 \sigma L^2$$

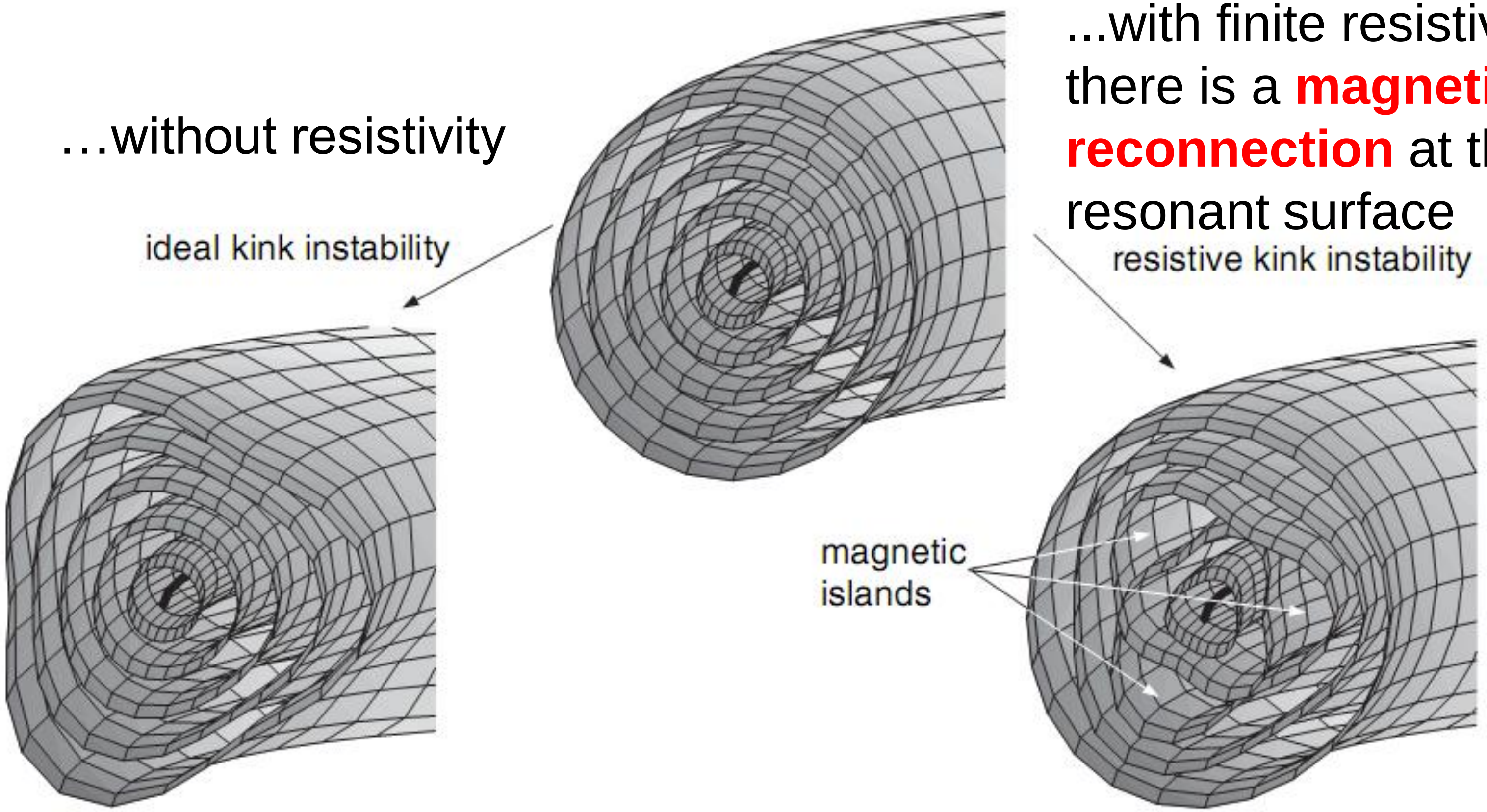
Since $\sigma$ is large for a hot plasma, $\tau_R$ is slow (~ sec for 0.5 m) – irrelevant?

# RESISTIVITY COULD BE IMPORTANT AS WELL!

MHD instabilities can develop at the rational surfaces

…without resistivity

...with finite resistivity, there is a **magnetic reconnection** at the resonant surface




Zohm,
Scripts

IDEAL

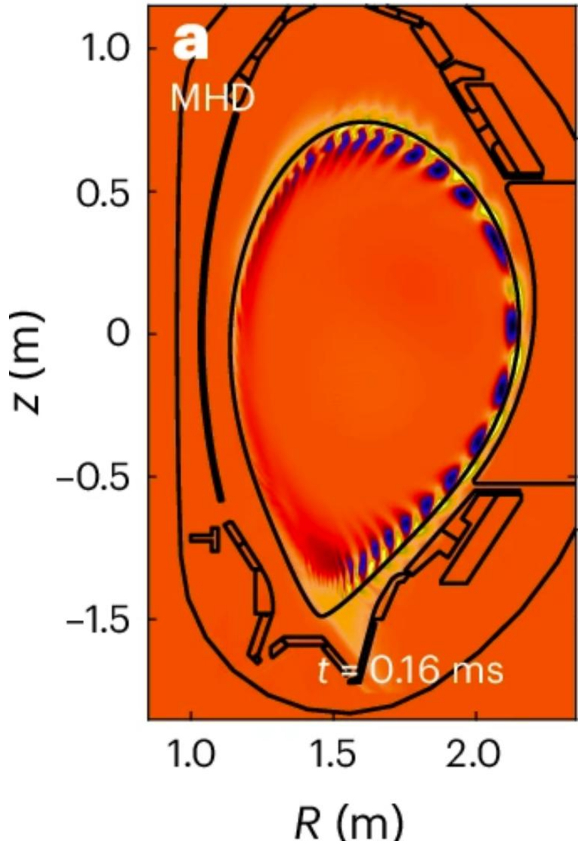
RESISTIVE

Resistivity changes topology locally, but the effect is global: new variants of global configurations.

Second question: Are topological changes (resistivity) important?

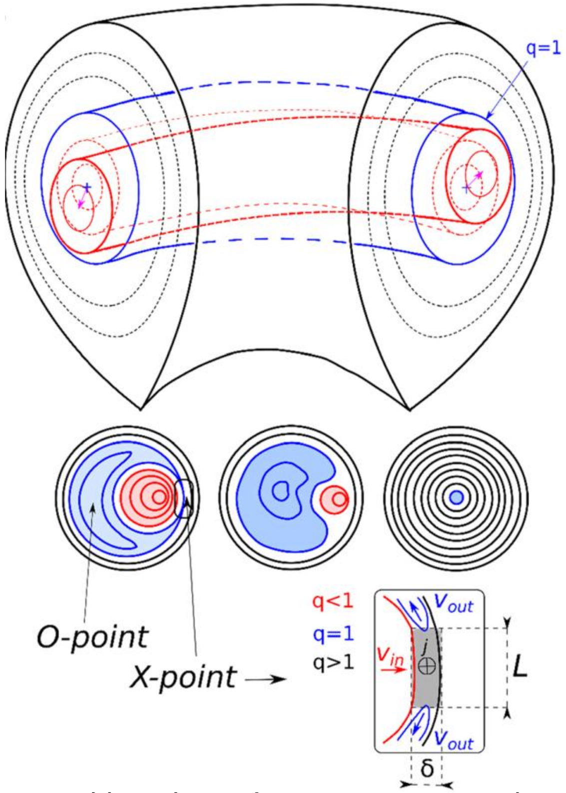
# LOCATION OF THE INSTABILITIES

**Edge**
Edge Localized Modes (ELMs)



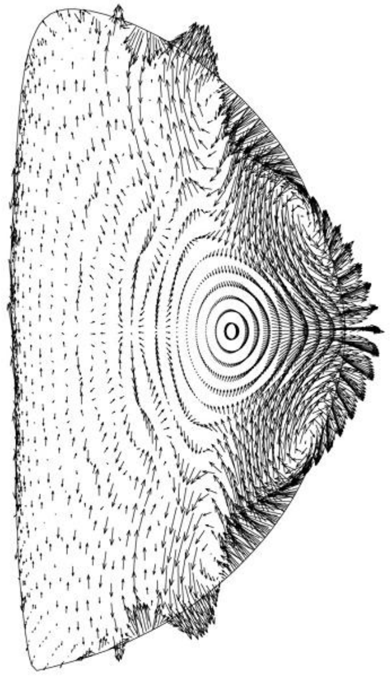

J. Dominguez-Palacios et.al. *Nature Physics*, p43 (2025)

**Core**
Sawteeth




V. Igochine Phys. Plasmas 30, 120502 (2023)

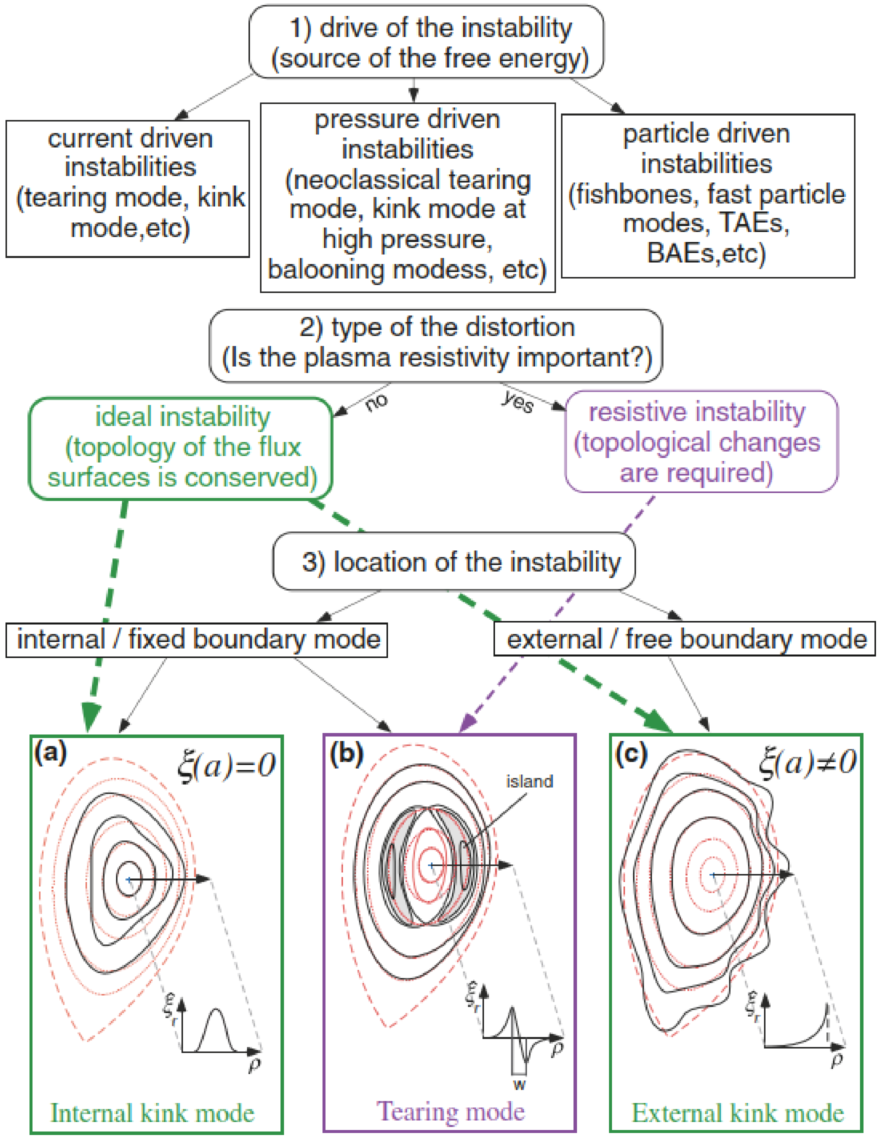
**Global**
Resisitve Wall Modes (RWMs)



[T. Luce, PoP, 2011]

Third question: Where the instability is located?

# BASIC CLASSIFICATION OF MHD INSTABILITIES




These 3 questions

1. Source of the energy
2. Resistive / ideal
3. Location

give you basic information about MHD instability.

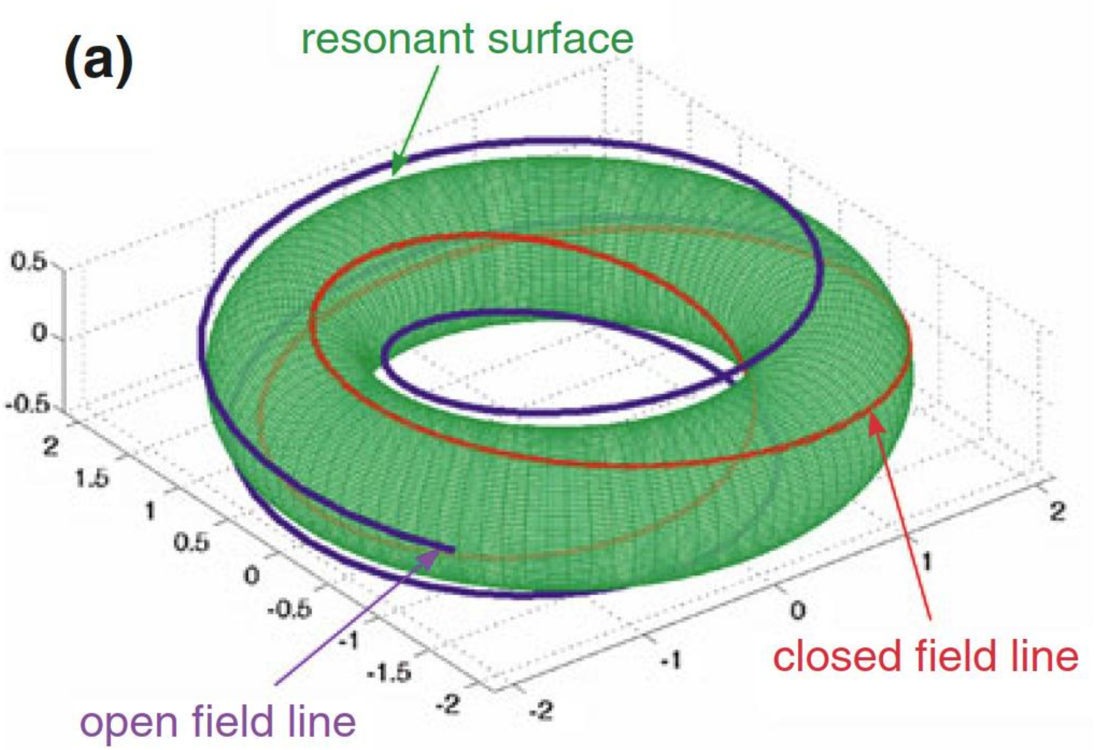
**Important**: Mixed case or transition from one type to another are possible!

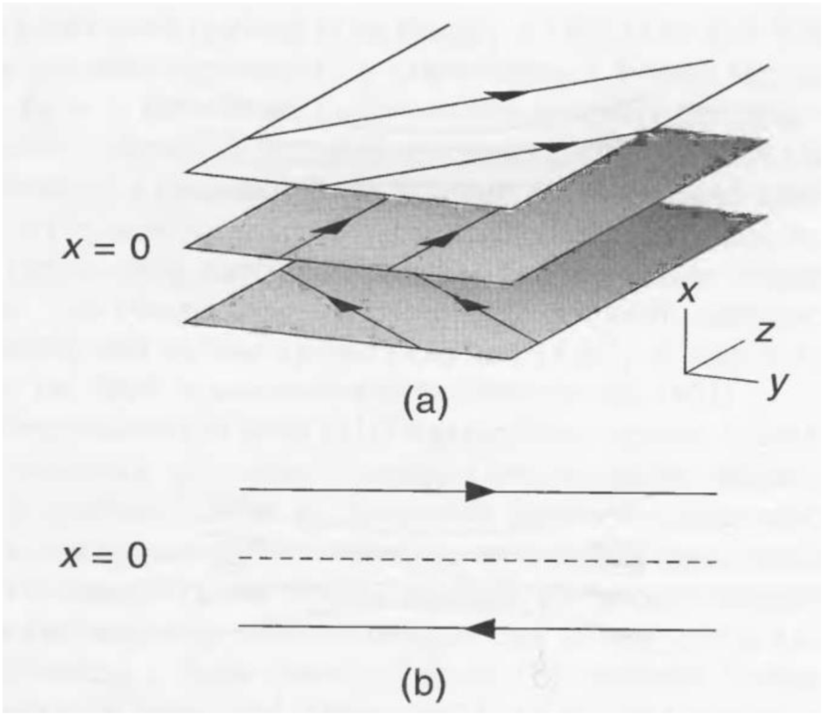
From Book: V. Igochine (ed) “Active Control of Magneto-hydrodynamic Instabilities in Hot Plasmas”, Springer, 2015

# TEARING MODES AND THEIR CONTROL

## CLASSICAL TEARING MODE (TM)
## NEOCLASSICAL TEARING MODE (NTM)

# RECONNECTION ON 'RATIONAL' MAGNETIC SURFACES




Magnetic field lines can be:

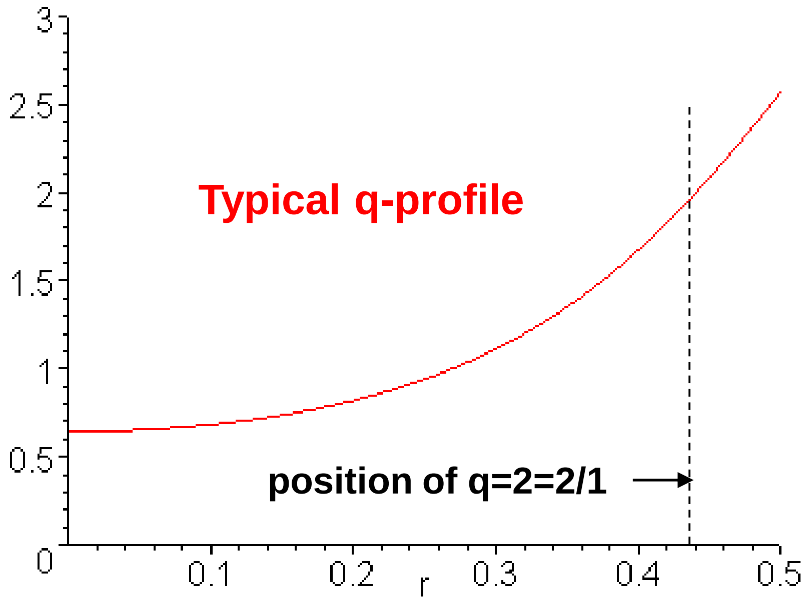
- Open
- Closed (q=m/n = poloidal/toroidal)

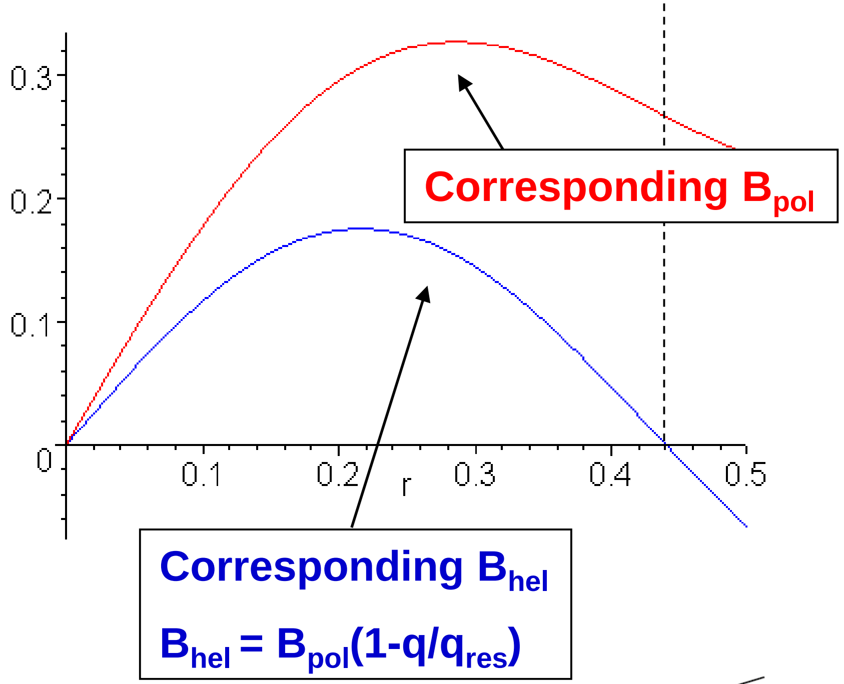
These are places where instability is developing.

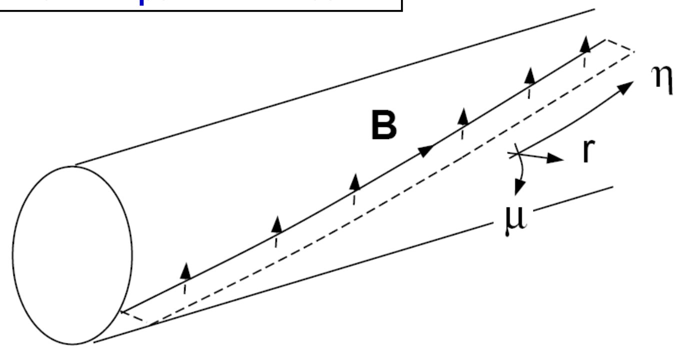
Helical field (i.e. ‚poloidal' field relative to resonant surface) changes sign:

- reconnection of helical flux can form new topological objects - islands

# RECONNECTION ON ‘RATIONAL’ MAGNETIC SURFACES



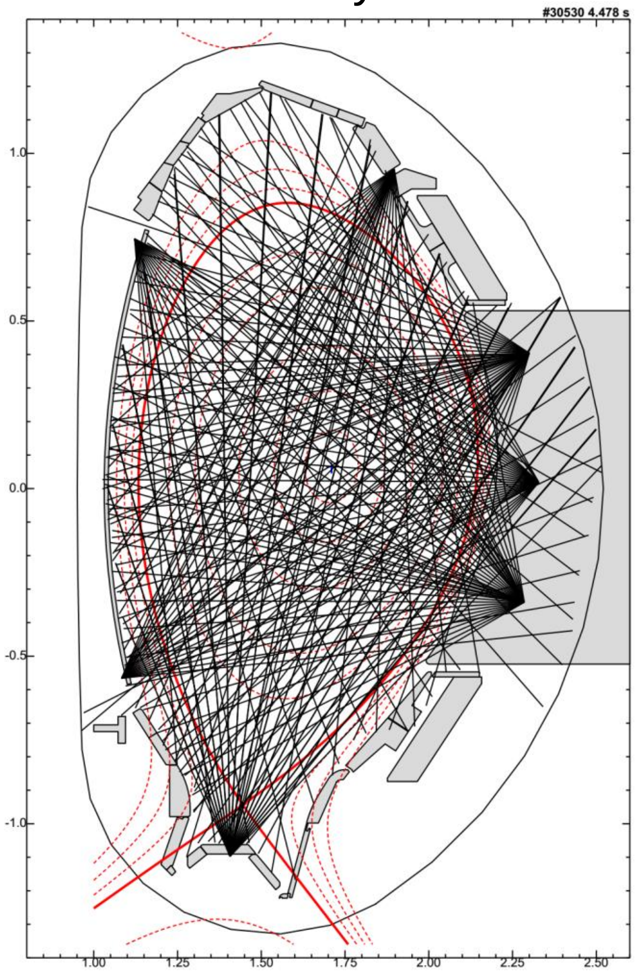



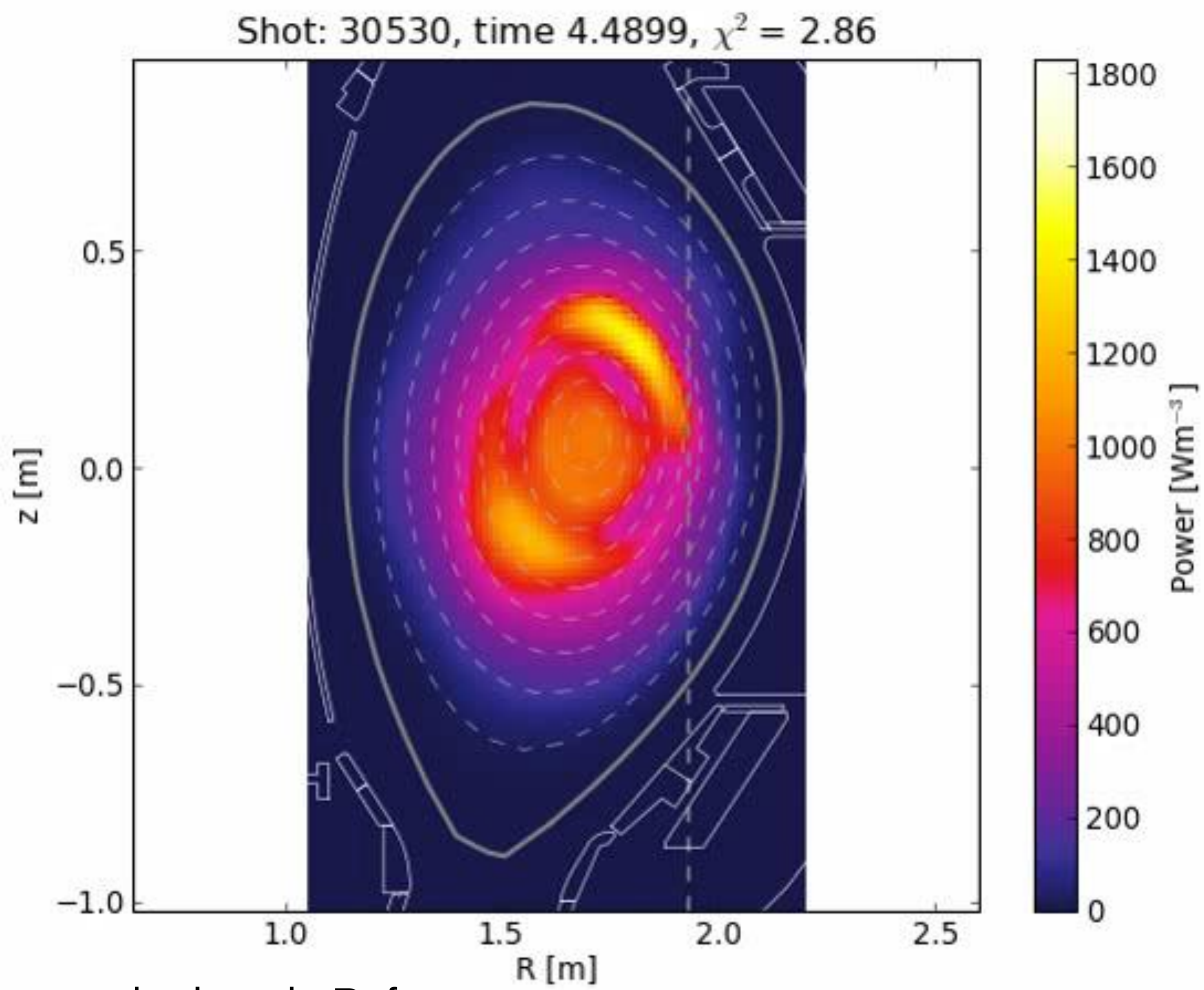

Important: Only helical part of the flux is reconnected!

# EXAMPLE OF A TEARING MODE IN ASDEX UPGRADE

Soft X-ray lines




Tomographic reconstruction




1 Drive:
- curret driven (TM)
- Pressure driven (NTM)

2 Resistivity:
Important. Resistive.

3 Location:
Aprox. around mid radius

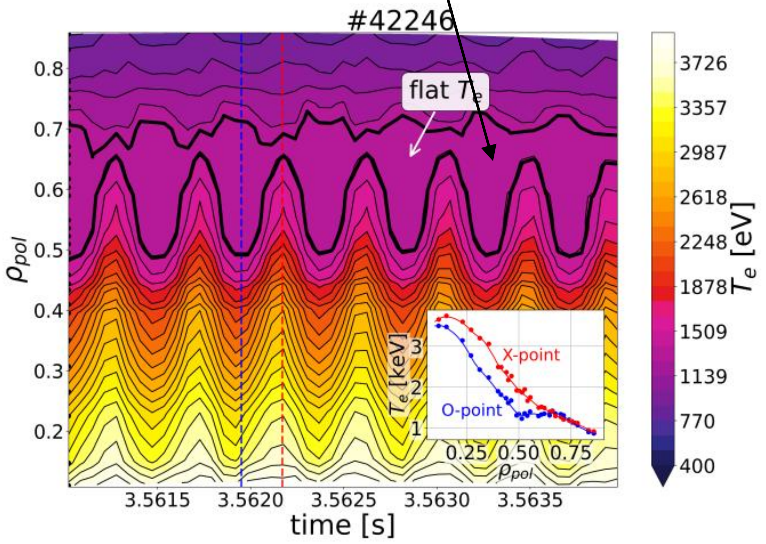
Details of tomographic reconstruction method are in Ref. **[T. Odstrčil, .et.al. RSI, 2016]**

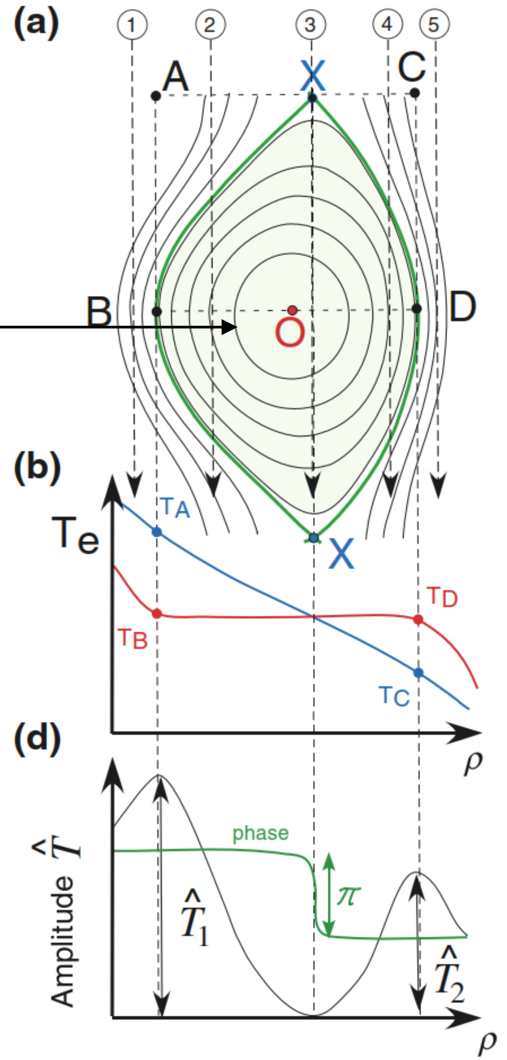
# WHAT IS THE PROBLEM?

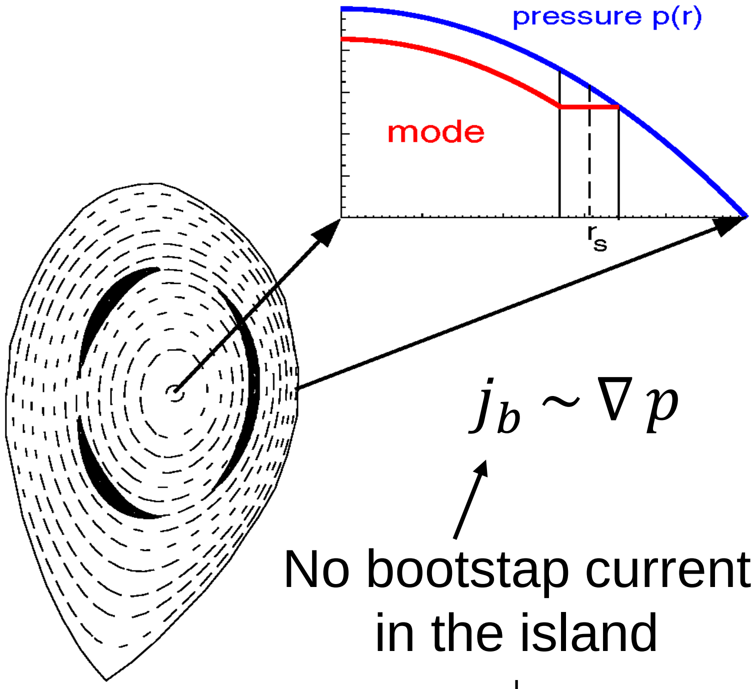
After reconnection confined region is created

↓

Temperature is constant in this region




$$j_b \sim \nabla p$$

No bootstap current in the island

↓

Current hole in the island

↓

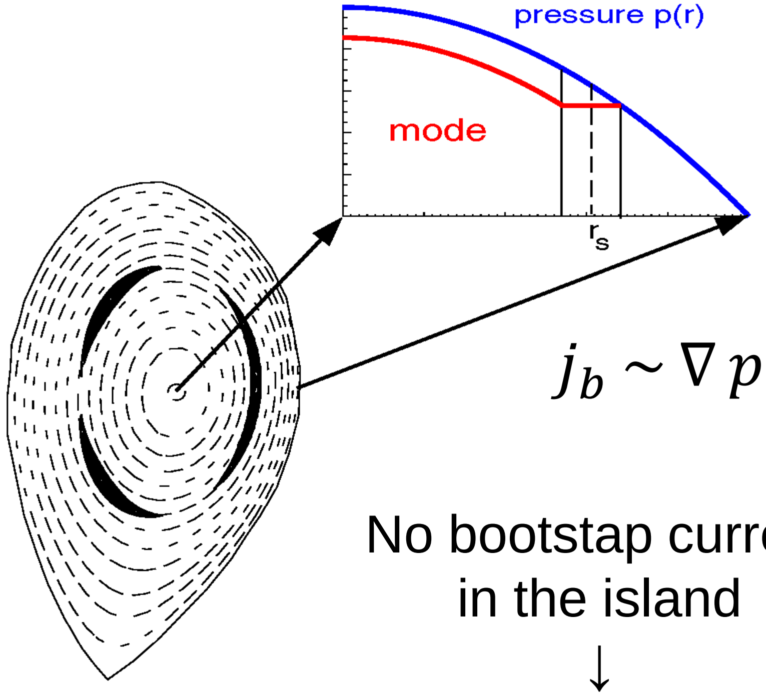
Mode grows

# WHAT IS THE PROBLEM, AND WHAT CAN BE DONE ABOUT IT?

Main problem: Neoclassical Tearing Mode (NTM) flattens pressure and temperature profile → smaller $\beta_N$ (Fusion power ~ $\beta_N^2$ )

Possible approaches:

- keep the mode at small level (small influence on the plasma confinement)
- replace the missing bootstrap current in the island
- modify density and(or) temperature profile, reduce the probability of the NTM excitation
- counteract trigger events which could lead to NTMs
- completely avoid dangerous resonant surfaces (3,2) and (2,1)

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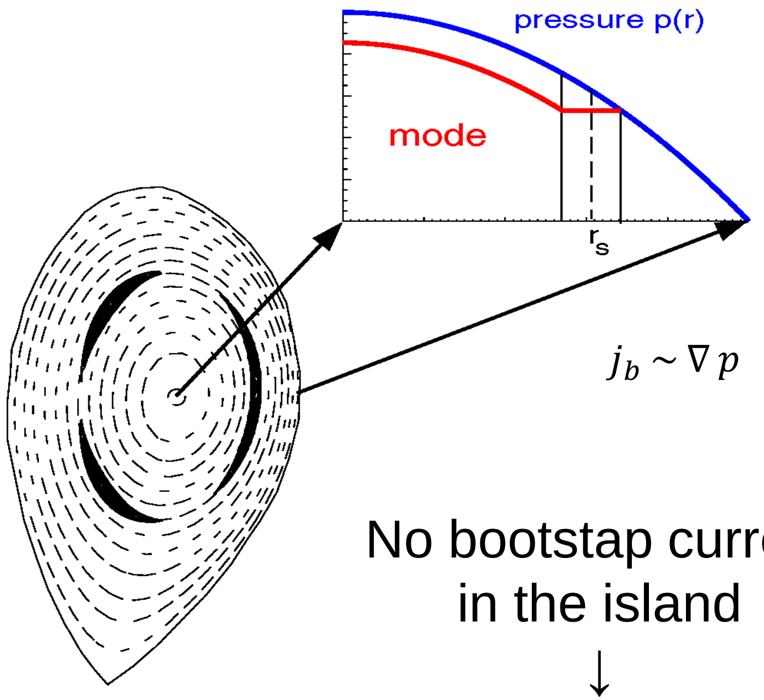



Possible approaches:

- keep the mode at small level (small influence on the plasma confinement)

These two are the most important and **require ECCD**

- replace the missing bootstrap current in the island
- modify density and(or) temperature profile, reduce the probability of the NTM excitation

- counteract trigger events which could lead to NTMs
- completely avoid dangerous resonant surfaces (3,2) and (2,1)

No bootstap current in the island

↓

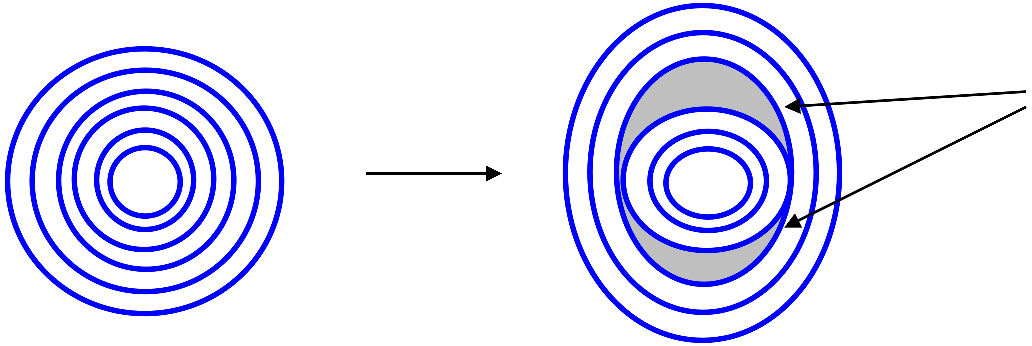
Current hole in the island

↓

Mode grows

# MHD DESCRIPTION OF TEARING MODE FORMATION

from force balance $\vec{j} \times \vec{B} = -\nabla p$ using high aspect ratio approximation one gets:



Scalar Magnetic Potential $\psi \sim W^2$

Tearing mode equation
(for outer region, ideal MHD!)

$$\underbrace{\frac{1}{r}\frac{d}{dr}\left[r\frac{d\psi}{dr}\right] - \frac{m^2}{r^2}\psi}_{\substack{vacuum,\\ Laplacian\ operator}} = \underbrace{\frac{\frac{dj(r)}{dr}}{\frac{B_\theta}{\mu_0}\left(1 - \frac{nq}{m}\right)}}_{plasma}\psi$$

$$\vec{B}_1 = \vec{\nabla}\psi \times \vec{e}_\phi,$$
$$B_{1,r} = -\frac{1}{r}\frac{\partial\psi}{\partial\theta},$$
$$B_{1,\theta} = \frac{\partial\psi}{\partial r}.$$

Deformation of flux surfaces opens up island of width W

- Tearing Mode equation ($\nabla p = j \times B$) singular at resonant surface:
  implies kink in magnetic flux $\psi$, jump in $B$
  $\Rightarrow$ current sheet on the resonant surface

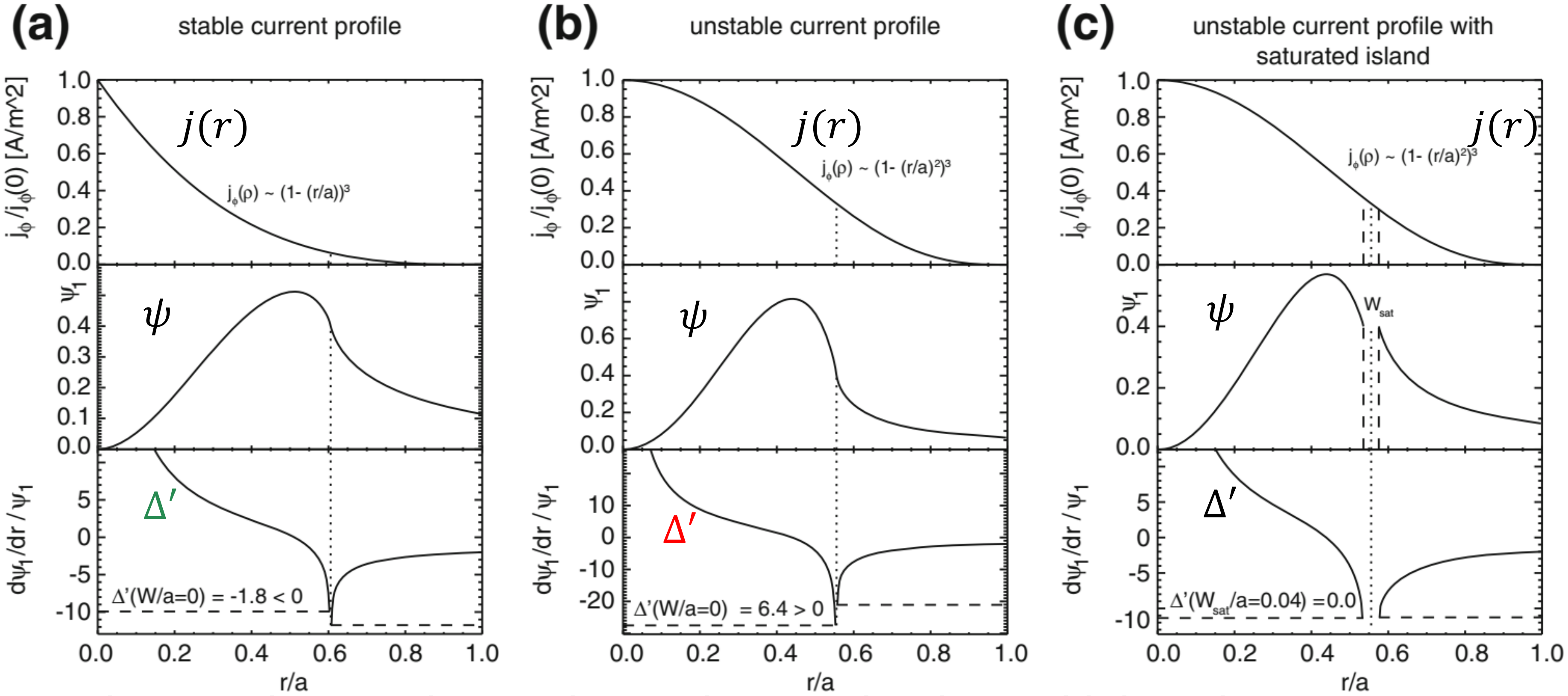
**$\psi(r)$: helical magnetic flux**
**$j(r)$: current profile**
**$q(r)$: safety factor profile**
**$m,n$: mode numbers**

# TM - "CLASSICAL" TEARING MODE

Solution of tearing mode equation for different profiles and island size

$$\underbrace{\frac{1}{r}\frac{d}{dr}\left[r\frac{d\psi}{dr}\right]-\frac{m^2}{r^2}\psi}_{\substack{vacuum,\\ Laplacian\ operator}} = \underbrace{\frac{\frac{dj(r)}{dr}}{\frac{B_\theta}{\mu_0}\left(1-\frac{nq}{m}\right)}\psi}_{plasma}$$

From Book: V. Igochine (ed) "Active Control of Magneto-hydrodynamic Instabilities in Hot Plasmas", Springer, 2015

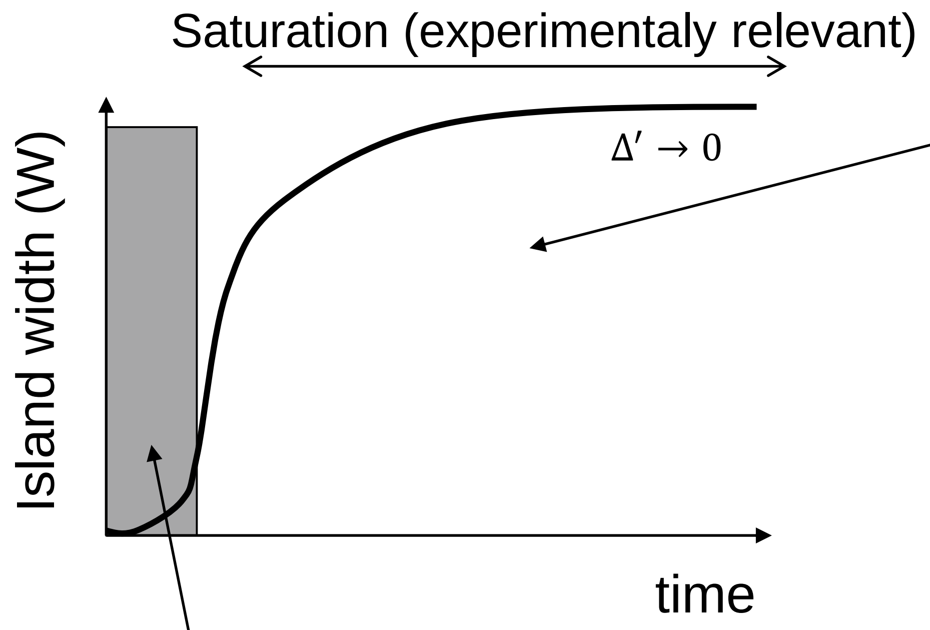



Solution of tearing mode equation can be made continuous, but has a kink at the resonant surface (surface current!) The parameter defining stability is delta prime:

$$\Delta_0' = \lim_{\delta\to 0}\left(\left(\frac{\partial}{\partial r}\ln(\psi_1)\right)\Bigg|_{r_{res}-\delta}^{r_{res}+\delta}\right) = \lim_{\delta\to 0}\left(\left(\frac{\psi_1'}{\psi_1}\right)\Bigg|_{r_{res}-\delta}^{r_{res}+\delta}\right) \quad > 0\ unstable! < 0\ stable!$$

**Classical tearing mode is a current driven instability (depends on current profile shape).**

# EVOLUTION OF TEARING MODE




Nonlinear phase,
Rutherford, 1973, Phys. Fluid

Linear phase (island width ≤1 cm.)
Furth, 1963, 1973, Phys. Fluid
Aprox. 70ms for typical parameters

Rutherford equation describes experimentally relevant evolution of the island width:

$$\frac{dW}{dt} = 1.66\frac{\eta}{\mu_0}(\Delta'(W) - \alpha W)$$

The island width (W)
has saturated value at

$$\Delta'(W_s) = \alpha W_s$$

Unfortunately, other effects play important roles and this equation should be extended

# EVOLUTION OF TEARING MODE

**Modified Rutherford Equation** (MRE) for
island width (W) is intensively used in control of TMs and NTMs

Island width ($W$) evolution →

$$\frac{dW}{dt} = a_1 \Delta' + a_2 \frac{\nabla p}{W} - a_3 \frac{I_{ECCD}}{W^2}$$

current gradient, for small $\nabla$p, $\Delta'$ dominates
⇒ 'classical Tearing Mode',**TM** current driven
⇒ typicaly can appear at start-up and during disruption

for larger $\nabla$p, pressure gradient dominates:
⇒ ,Neoclassical Tearing Mode', **NTM**, pressure driven
⇒ aprox. for $\beta_N$>1, at the flat-top phase

adding an externally driven helical current can stabilise

# EVOLUTION OF TEARING MODE

**Modified Rutherford Equation** (MRE) for
island width (W) is intensively used in control of TMs and NTMs

Island width ($W$) evolution

$$\frac{dW}{dt} = a_1 \Delta' + a_2 \frac{\nabla p}{W} - a_3 \frac{I_{ECCD}}{W^2}$$

Here, even a relatively small amount of ECCD can remove the problem!

current gradient, for small $\nabla$p, $\Delta'$ dominates

- ⇒ 'classical Tearing Mode‘,**TM** current driven
- ⇒ typicaly can appear at start-up and during disruption

for larger $\nabla$p, pressure gradient dominates:

- ⇒ ‚Neoclassical Tearing Mode‘, **NTM**, pressure driven
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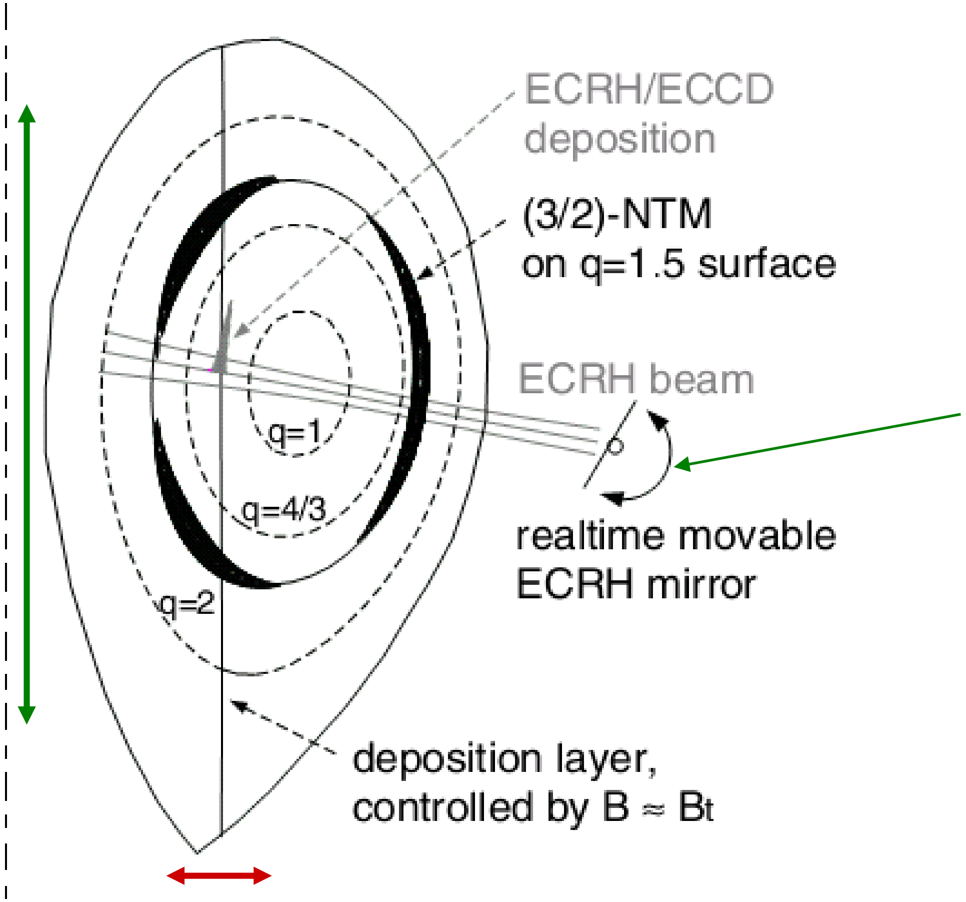
adding an externally driven helical current can stabilise

# NTM STABILIZATION WITH ECCD

ASDEX Upgrade




The aim is to fill the current hole in the island by replacing the missing bootstrap current.

Changes up and down along the resonance is possible with mirror

(ITER design)

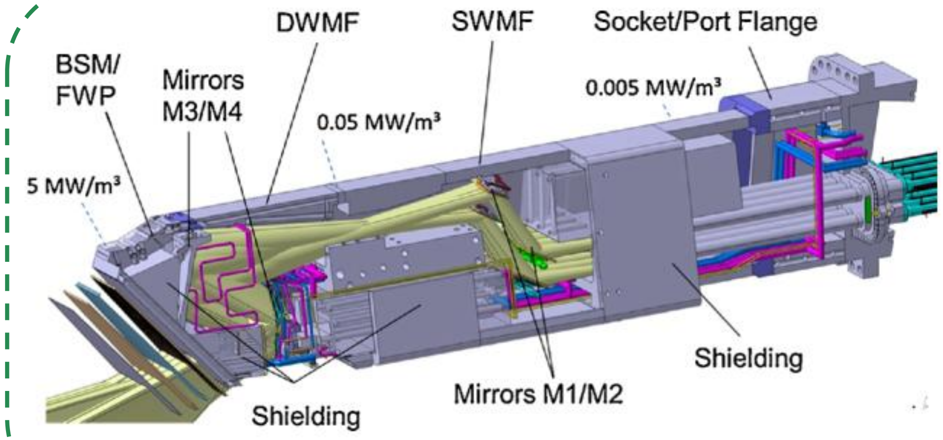



Fig. 1. The ITER ERCH Upper Launcher.

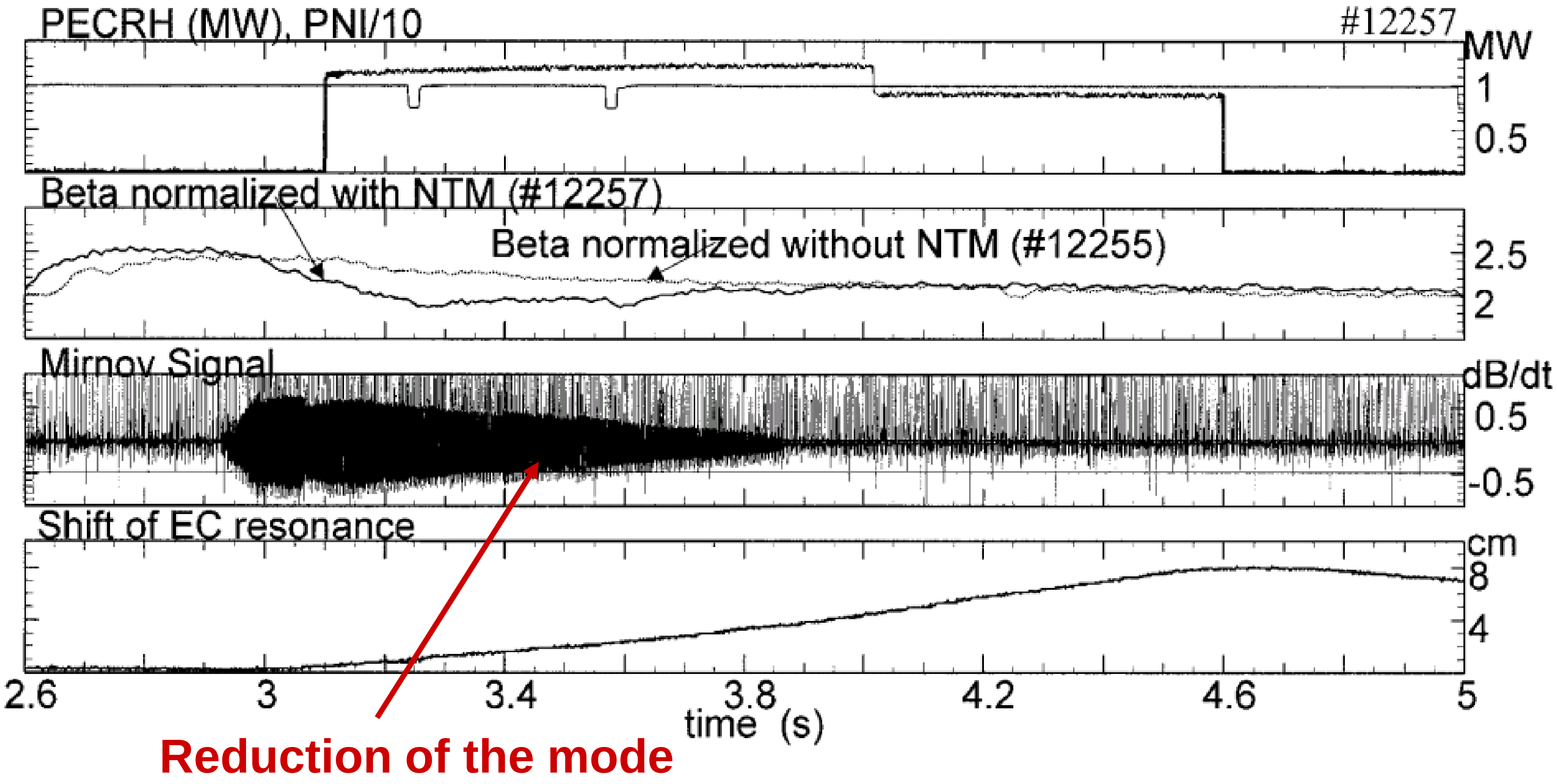
ITER has four steerable upper ECH&CD launchers for NTM control

[D. Strauss et.al., Fusion Engineering and Design 146 (2019) 23–26]

Changes of the resonant layer position with $B_{tor}$ (not an option in big tokamaks)

# FIRST STABILIZATION OF NTM

NTM was stabilized for the first time in ASDEX Upgrade more than 20 years ago




Scan of the resonance position was done by changing $B_{tor}$ at that time.

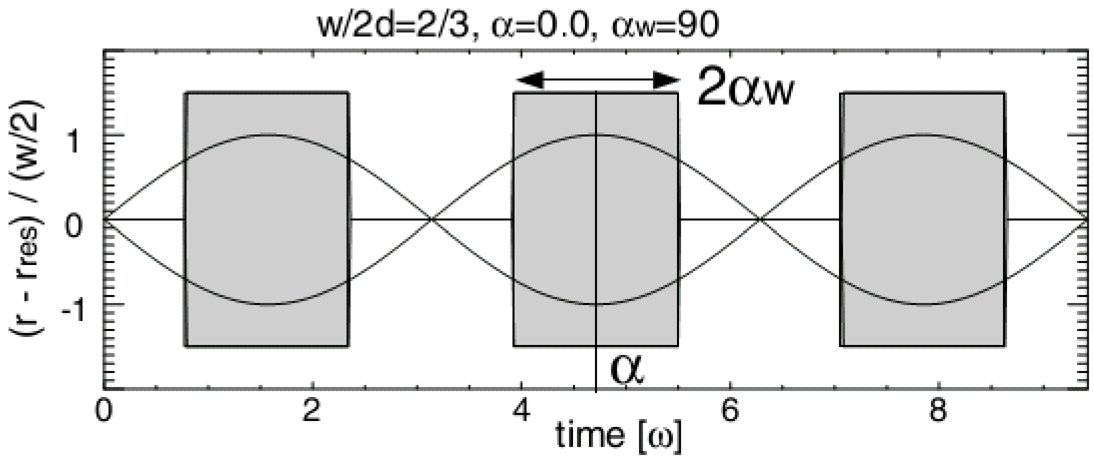
Gantenbein, PRL, 2000 & Zohm NF, 1999

# MODULATED STABILIZATION OF NTM

Modulated ECCD is more effective compare to constant ECCD in case of broad deposition.

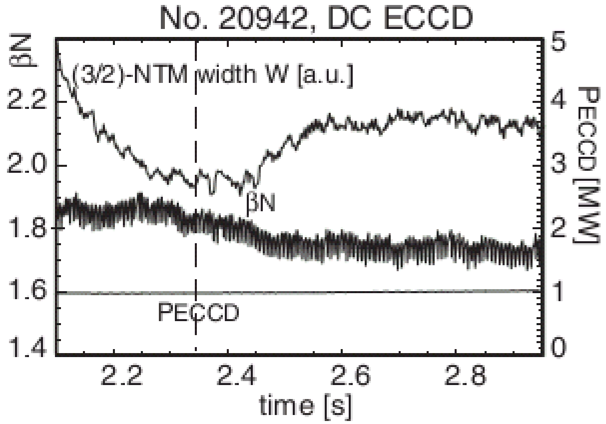
We better fill the current hole in this case.

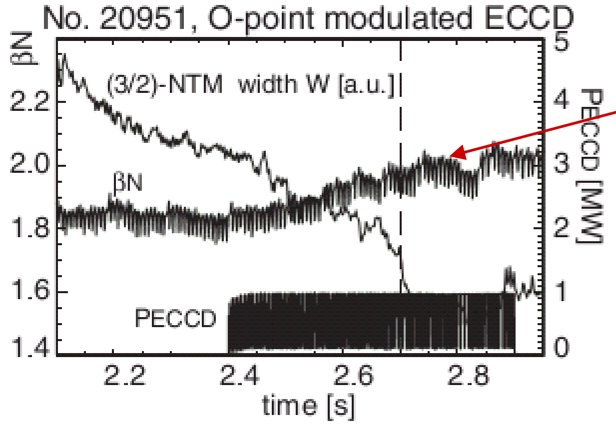
…but we loose the half of the power from gyrotrons…




**Toroidal position:** magnetic measurements

**Radial position:** ECE

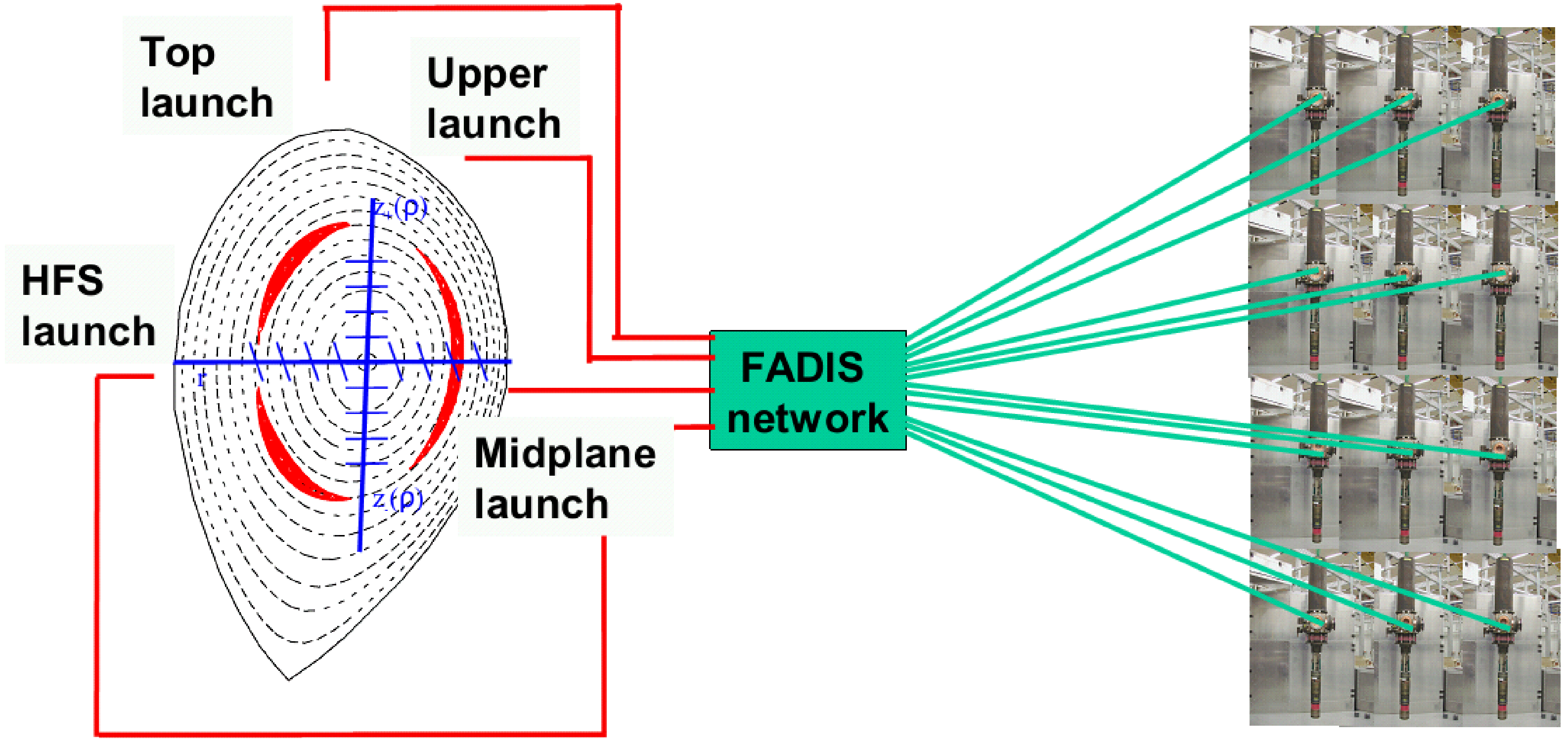


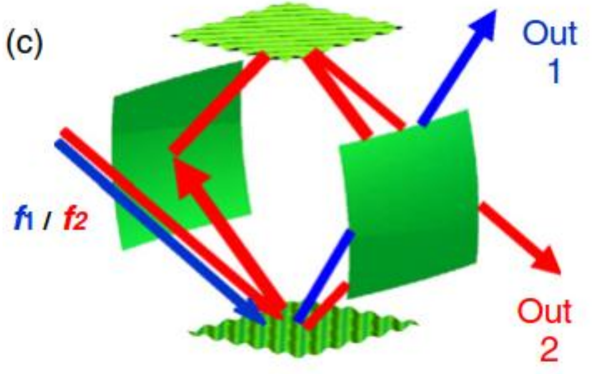

higher beta in case of O-point modulation

**Maraschek et.al., PRL, 2007**

# ECRH / ECCD FOLLOWING SPATIALLY THE O-POINT




First successful experiments on NTM stabilization
W. Kasparek et.al.
*Nucl. Fusion* **56** (2016) 126001

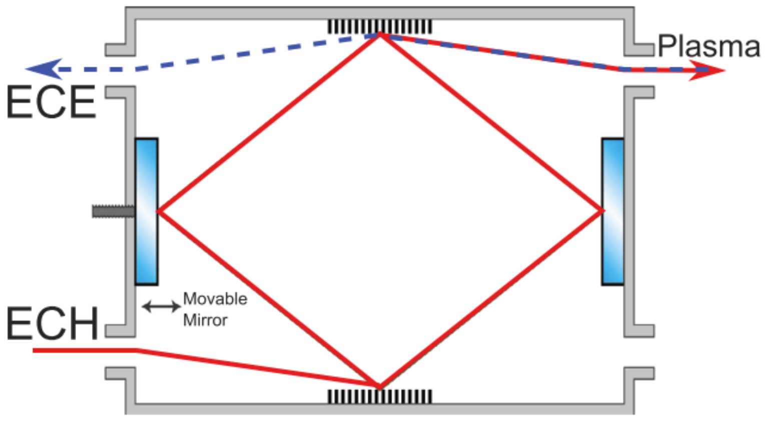


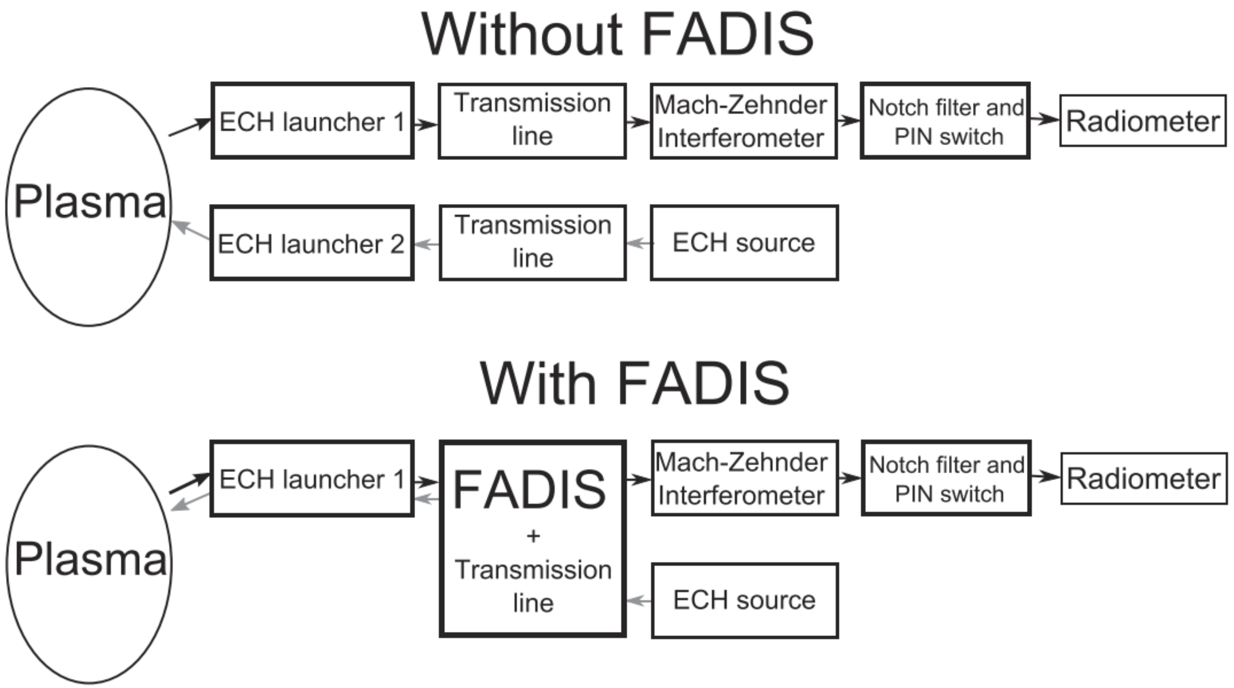

- ECCD in O-point only is more efficient than DC operation ⇒ 50% duty cycle
- gyrotrons with small frequency variations can be combined and switched to different transmission lines via a FADIS (FAst DIrection Switch) ⇒ follow O-point in 3d with ideally 100% duty cycle

Details about the fast switch are here
W. Kasparek *et al* 2008 *Nucl. Fusion* **48** 054010

# INLINE ECE

Inline ECE setup measures ECE via the same path where ECH is applied.



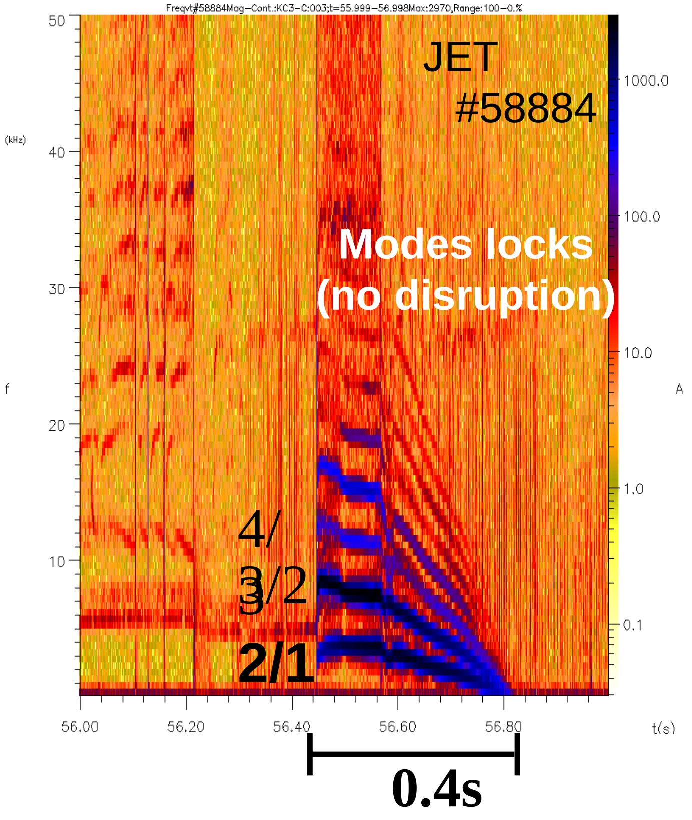

[H. van den Brand et al *Nucl. Fusion* **59** (2019) 016013]

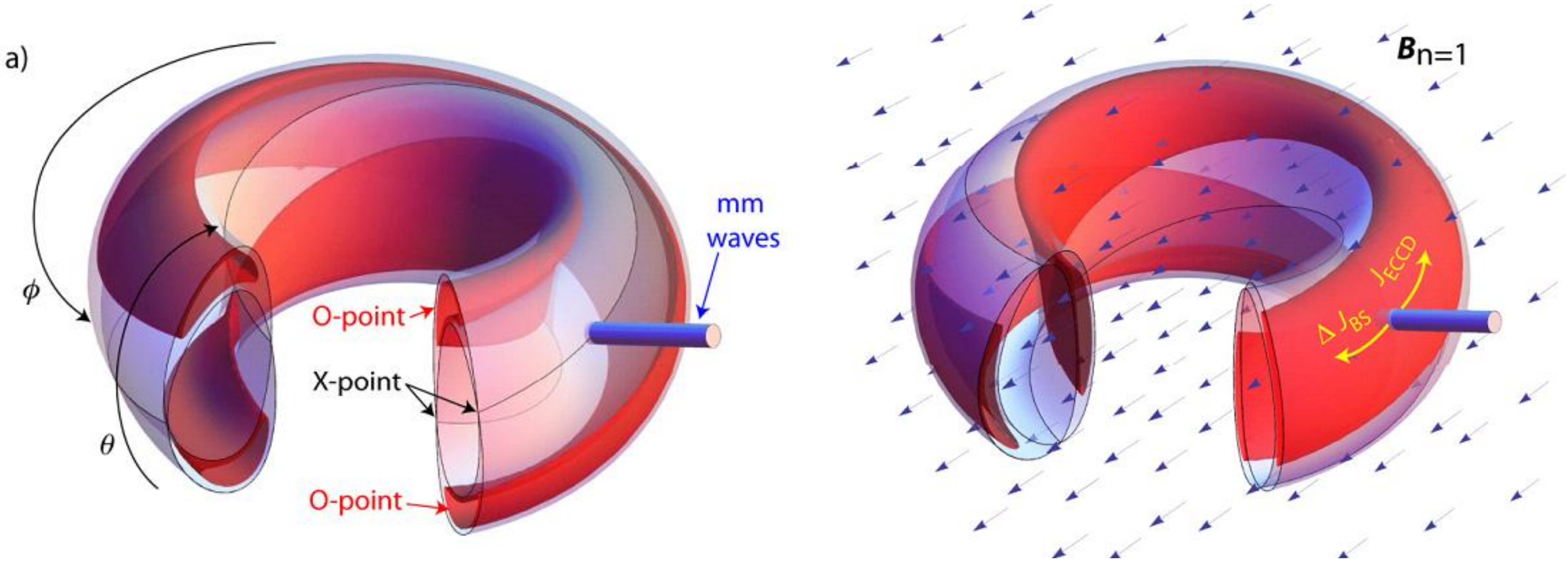
Main advantages:

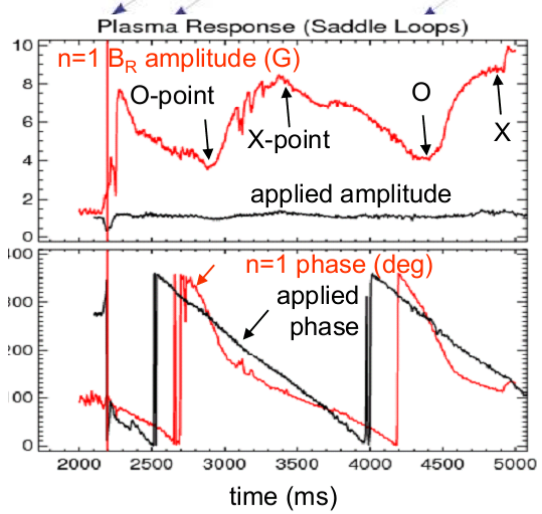
- Can be used with and without FADIS
- Provides additional information about **radial localization** of NTM. This is missing from magnetic measurements!

## WHAT IF THE MODE IS LOCKED?

Modes can lock rapidly (within 0.4s in this JET case)



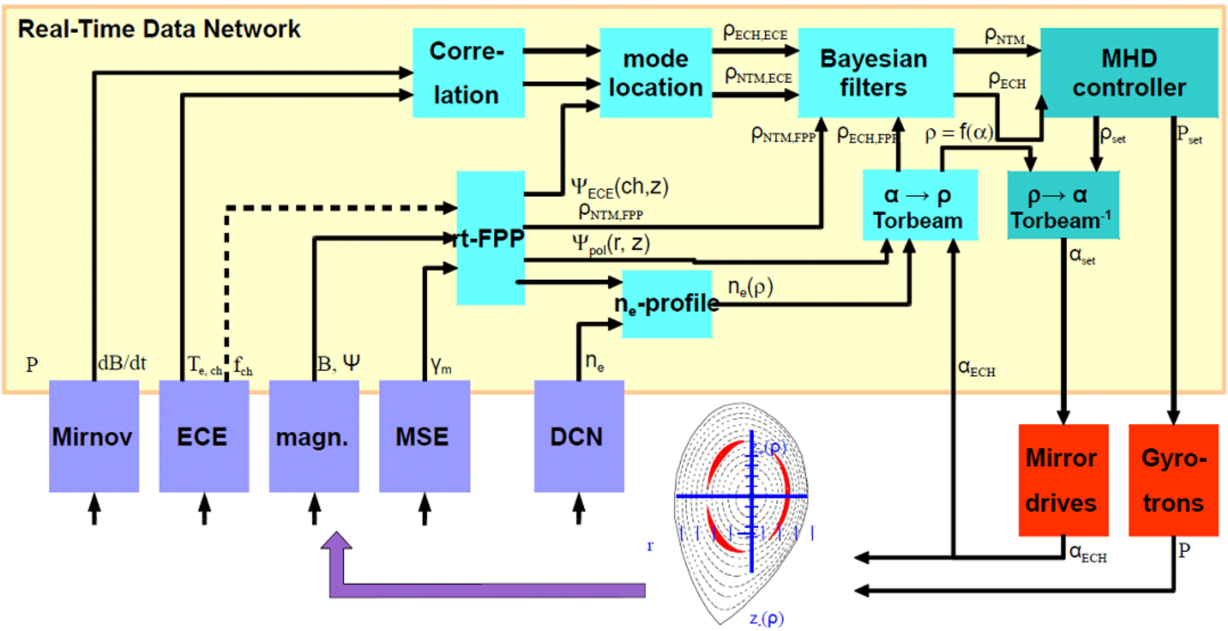

In this case O/point of the island could be inaccessible for ECCD!

External fields can be used to rotate the mode!

[F. A. Volpe et al *Phys. Rev. Let.* **115**, 175002 (2015)]

# INTEGRATED AND PREEMPTIVE NTM CONTROL

**The control of NTM** is part of the control of MHD, which **is part of the integrated control** in ASDEX Upgrade.




- magnetics provide rt equilibrium and expected $\rho_{(N)TM}$'s $\Rightarrow \rho_{(N)TM,Eq}$
- ECE/SXR/… detects mode location, if still possible $\Rightarrow \rho_{(N)TM,ECE}$, W
- Mirnov diagnostic provides mode numbers, W and LM $\Rightarrow$ m,n, W, LM
- rt - raytracing code (TORBEAM) provides $\rho_{ECCD}$ $\Rightarrow \rho_{ECCD}$

**Pre-emptive action is better** than suppression

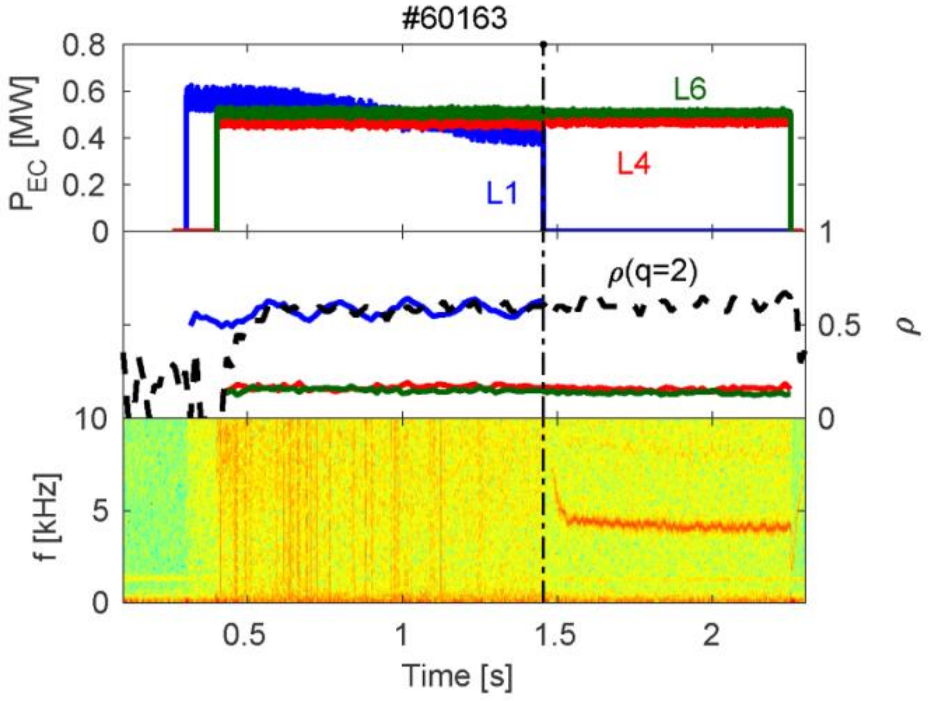
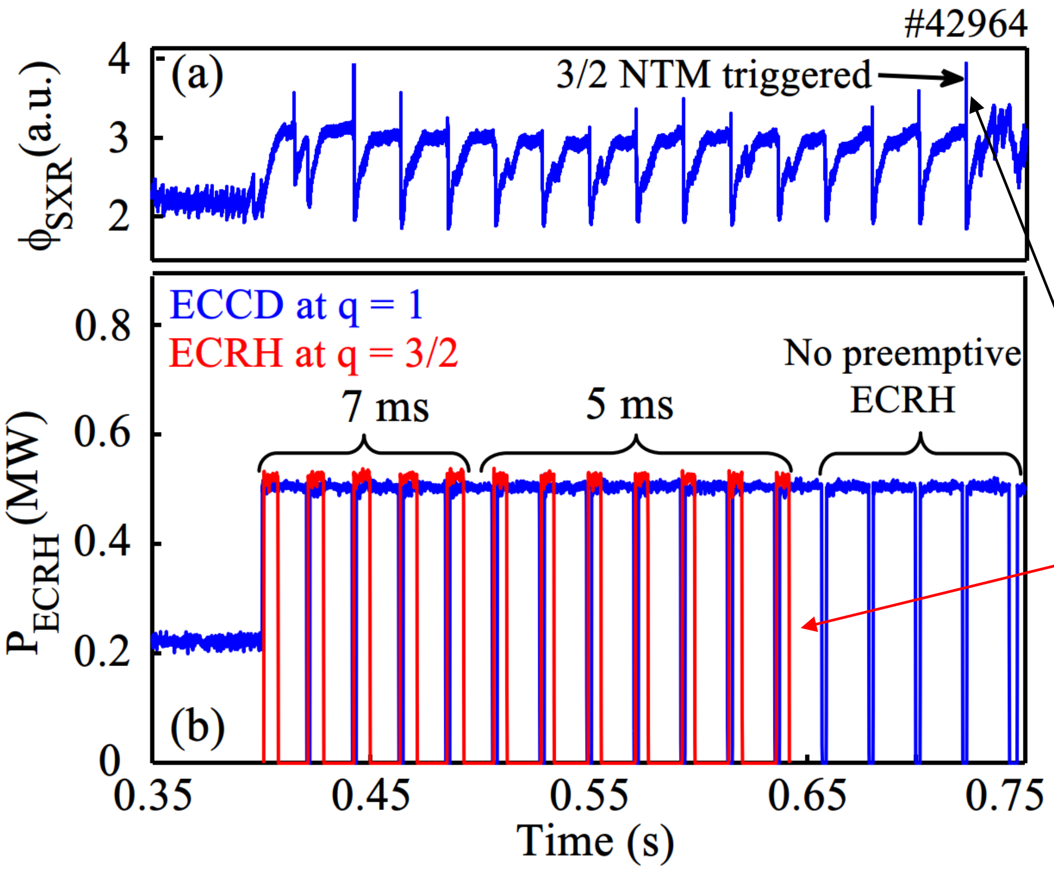



**Figure 3.** An example of NTM prevention experiments with continuously sweeping preemptive EC beam on TCV: (a) EC power traces; (b) deposition locations of different EC launchers; (c) 2/1 NTM spectrogram.

[M Kong et al 2022 *Plasma Phys. Control. Fusion* **64** 044008]

# EXAMPLE OF INTEGRATED CONTROL

**The control of NTM seeding as a part of sawteeth control**.




[G.P. Canal et al *Nucl. Fusion* **53** (2013) 113026]

Internal sawteeth crashes are controlled in this case (*we discuss what this is in the next chapter*).

These crashes can trigger NTM.

We knew when these crashes comes and add preemptively ECCD at the right place.

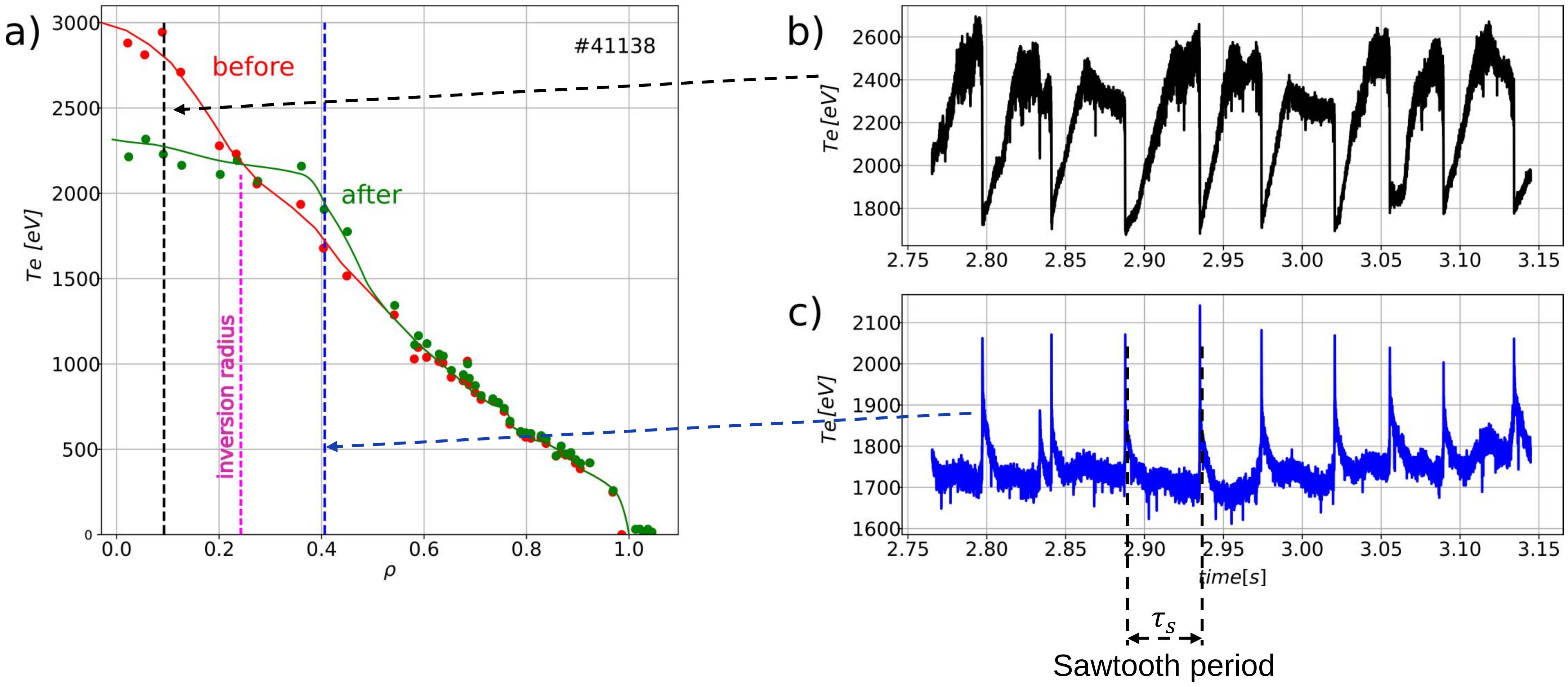
If this is not done, NTM is triggered! Otherwise, everything is fine!

# SAWTEETH, (1,1) MODE AND THEIR CONTROL

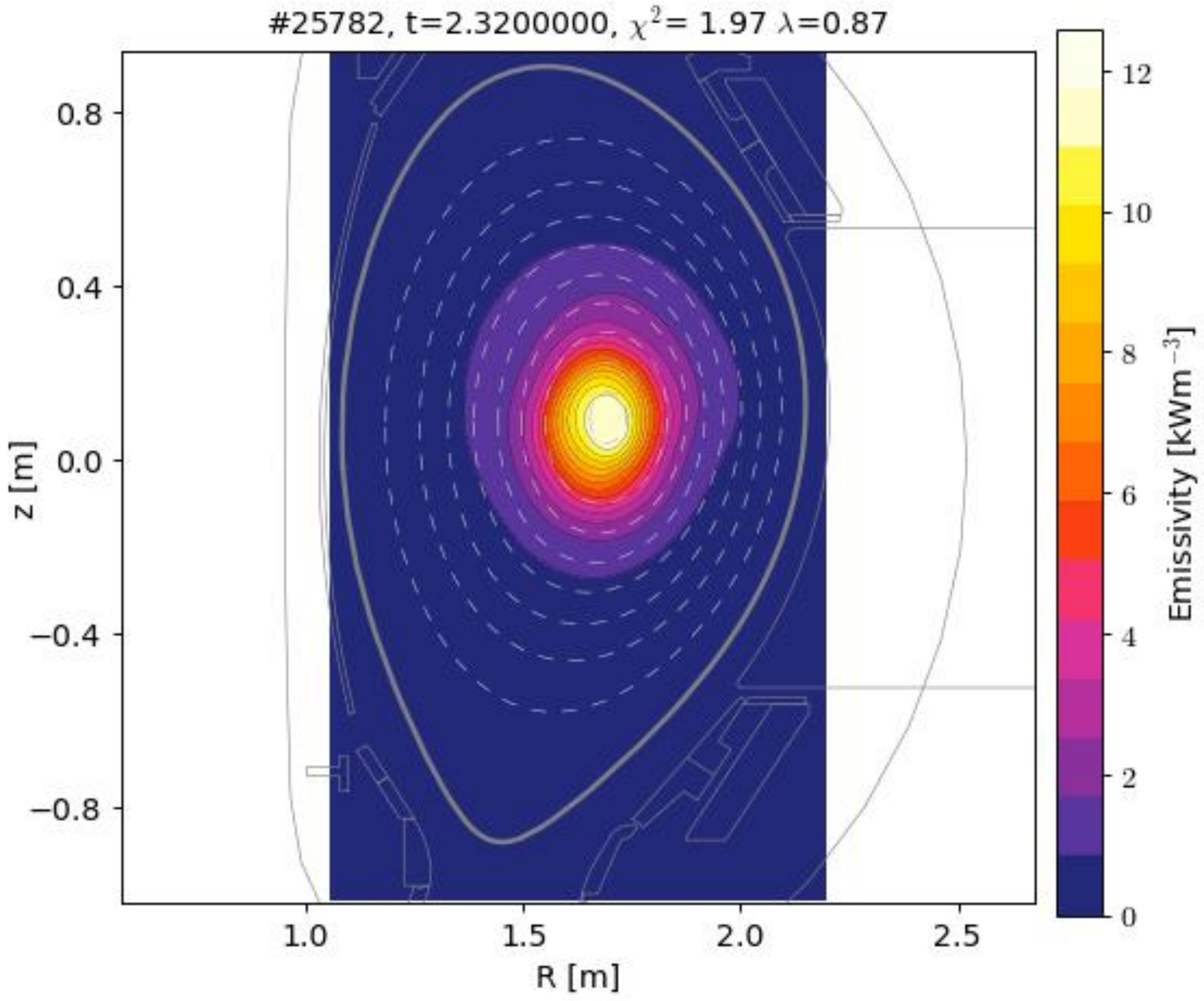
# WHAT WE SEE DURING SAWTEETH

$T_e$ is redistributed in the centre

SXR signals looks like sawteeth



# VISUALIZATION OF THE CRASH AND SHORT SUMMARY




<u>1 Drive:</u>

- pressure
- current
- fast particles

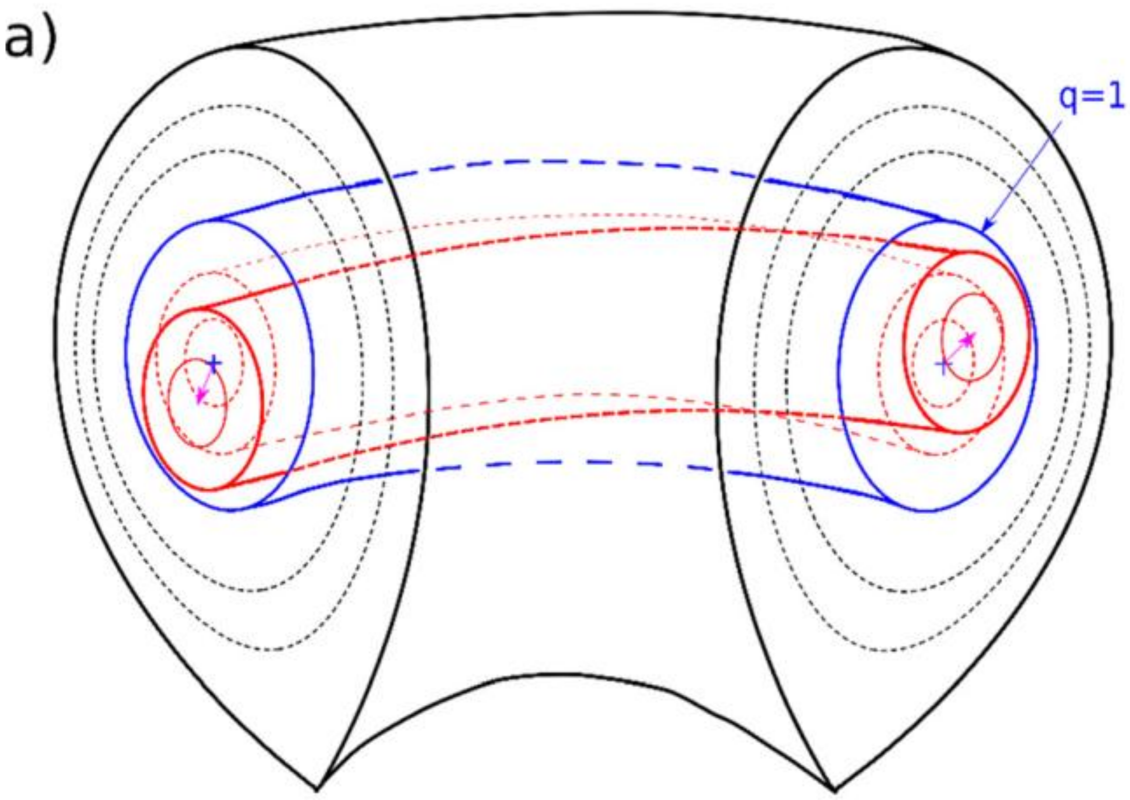
<u>2 Resistivity:</u>
Important.
Resistive.

<u>3 Location:</u>
Core localized

Sawteeth can trigger NTM.
This is one reason for the control,
…but not the only one.

# INTERNAL KINK MODE IN THE CORE

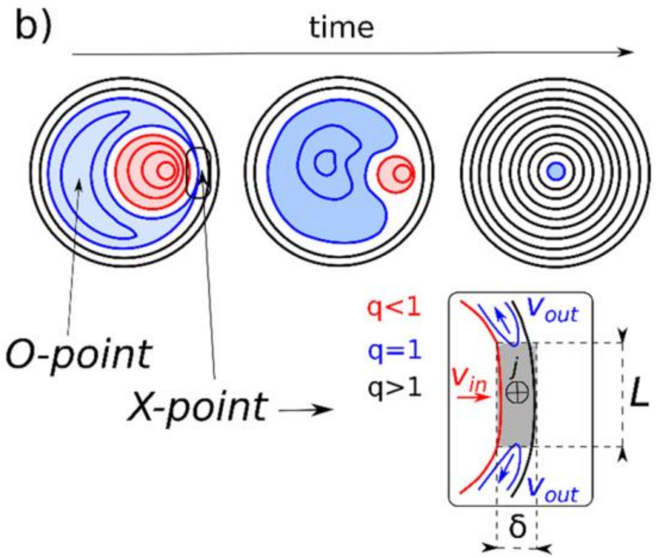
A Tilt and Shift of the Core Plasma.




Sawteeth: internal (1,1) kink mode at q=1

During the crash event, **magnetic reconnection** mixed the core plasma with that from the outer region, see review

[V. Igochine, *Phys. Plasmas* **30**, 120502 (2023)]

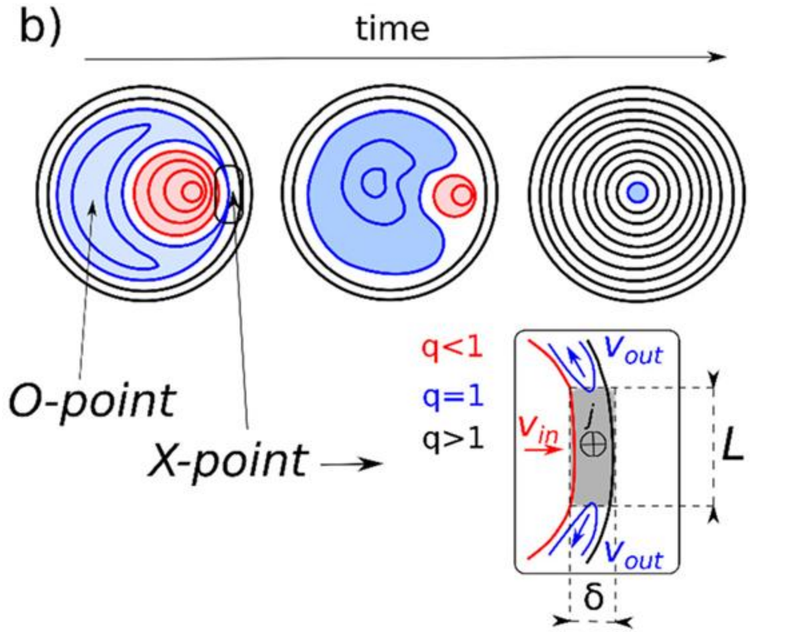



**There is still no final model for the crash phase, but this is one of the best controlled instabilities**

# CRASH PHASE

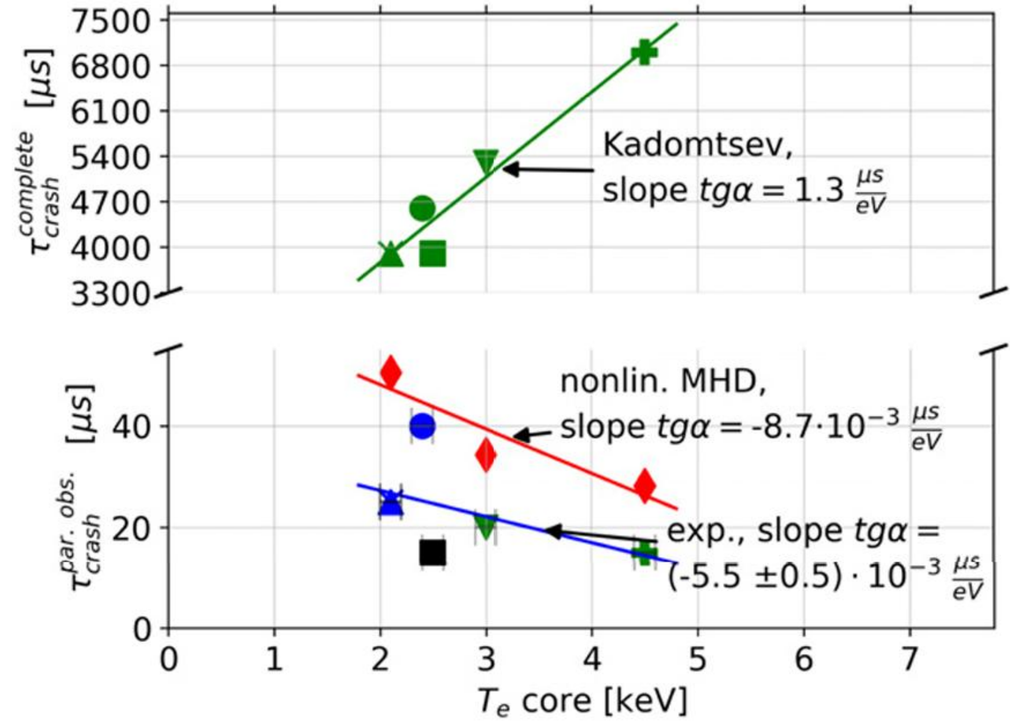
This is Kadomtsev model for sawtooth crash.

*Description and comparison with other models in review [V.Igochine Phys. Plasmas 30, 120502 (2023)]*




$$\tau_K = \frac{r_{q=1}}{v_{in}} = \sqrt{\frac{r_{q=1}^2 \mu_0}{\eta} \frac{r_{q=1}}{v_A^*}} = \sqrt{\tau_R \tau_{A*}} \gg \tau_{exp}$$

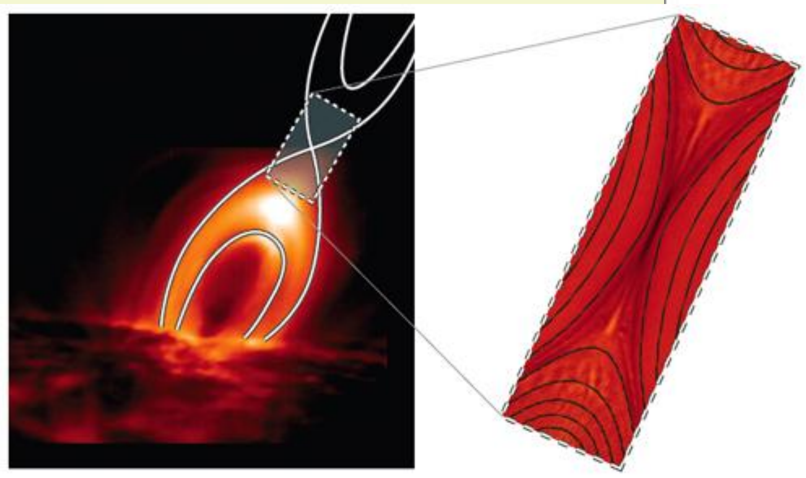
Kadomtsev model **is two order of magnitude off!** 2-fluid MHD gives correct predictions and not only for crash time. There are still many open questions regarding the exact crash dynamic.



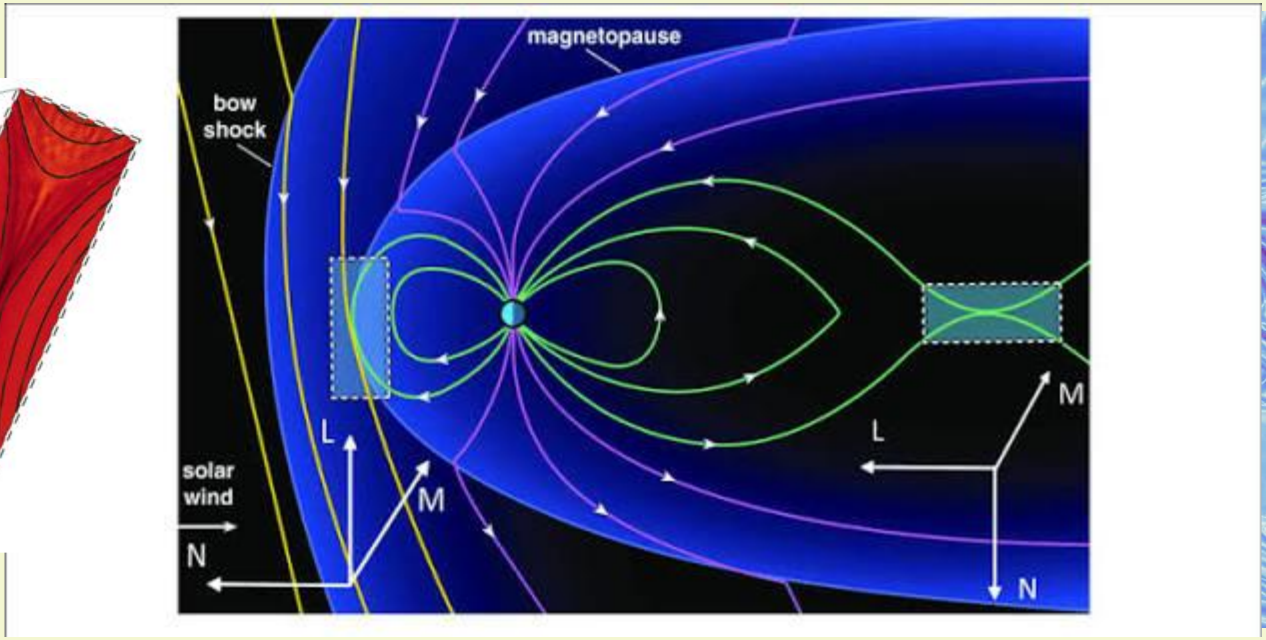

*[O. Samoylov,,V.Igochine, et.al. Nucl. Fusion 62 (2022) 074002]*

# SIDE REMARK: MAGNETIC RECONNECTION

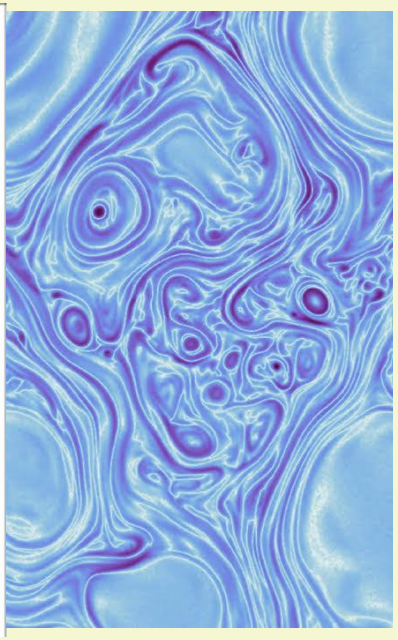
**Magnetic reconnection in collisionless plasmas is a common problem for fusion, solar physics, magnetosphere, magnetic reconnection in electron–positron plasmas, etc.**



**Solar flares**




**Magnetosphere**



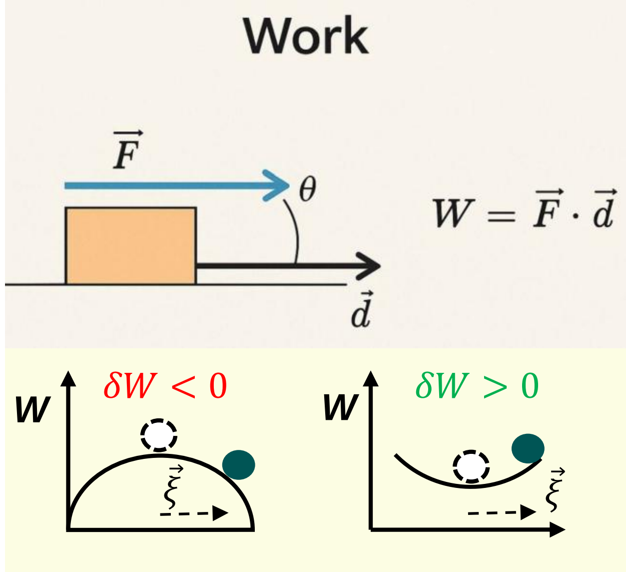
**Turbulence**

Only a few problems in plasma physics have such a wide range of systems to consider. Reconnection is a fundamental problem in plasma physics and an active area of research. Despite the progress, there is still no final theory. Different mechanisms are important in different regimes.

Some cases are here [Masaaki Yamada, Russell Kulsrud, and Hantao Ji “Magnetic reconnection” REVIEWS OF MODERN PHYSICS, 2010]

# STABILITY CONDITION IN PLASMA

If the force is unbalanced: $\vec{F} = \underbrace{\vec{j}\times\vec{B}}_{magnetic\ force} - \underbrace{\nabla p}_{plasma\ pressure\ force} \neq 0$




One can calculate energy changes for a given displacement $\vec{\xi}$

$$\delta W = \frac{1}{2}\int \vec{\xi}\cdot\vec{F}d\tau$$

Linearization:
$A = A_0 + A_1$
0 – equilibrium
1 - perturbation

Pressure driven instabilities

Current driven instabilities

$$\delta W = \frac{1}{2}\int_{plasma}\left(\underbrace{\gamma p_0\left(\nabla\cdot\vec{\xi}\right)^2}_{>0} + \left(\vec{\xi}\cdot\nabla p_0\right)\nabla\cdot\vec{\xi} + \frac{B_1^2}{\underbrace{\mu_0}_{>0}} - \vec{j}_0\cdot\left(\vec{B}_1\times\vec{\xi}\right)\right)d\tau + \underbrace{\int_{vacuum}\frac{B_{vac}^2}{2\mu_0}d\tau}_{>0}$$

Always positive (stable)!

**Unstable only if $\delta W < 0$**

Wesson, Tokamaks, 3rd Edition
Freidberg, Ideal MHD

# NEXT ORDER APPROXIMATIONS ARE NECESSARY

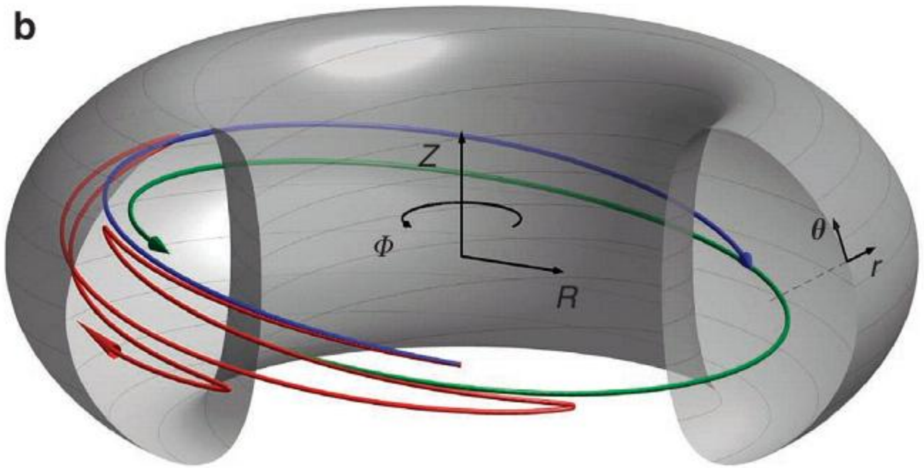
To understand stability of the (1,1) mode we have to compute next terms in the energy functional expansion $\delta W = \mathcal{O}(\varepsilon^4)$

M.N. Bussac, R. Pellat, D. Edery, and J.L. Soule, "Internal kink modes in toroidal plasma with circular cross-section," *Phys. Rev. Lett.* **35**, 1638 (1975).

If one takes into account now new terms depends on:

- pressure gradient (Bussac term),
- perpendicular current,
- toroidal curvature,
- Compressibility.

$$\delta W \approx 6\pi^2 \frac{B_0^2 r_1^4}{R_0^3} |\xi_r(0)|^2 \left[1 - q(0)\right] \left[\beta_{\rm crit}^2 - \beta_p^2(r_1)\right]$$




Unstable only if $\beta_p > \beta_{crit} \sim 0.3$
(1,1) internal kink mode is **pressure driven**!

Kinetic effects are also influence on the (1,1) mode stability: **fast particle driven**

# PORCELLI MODEL FOR TRANSPORT STUDIES AND CONTROL

MHD — kinetic effects

$$\delta W = \delta W_{\mathrm{mhd}} + \delta W_{\mathrm{KO}} + \delta W_{\mathrm{fast}}$$

This is the MHD part discussed up to now

Kruskal–Oberman term, which represents the effect of collisionless thermal trapped ions (typically is stabilizing)

Conditions for the crash (Porcelli model):

1) All possible stabilizing/destabilizing terms goes to δW
2) Existence of the q=1 surface (q0<1)
3) when δW is close to zero, the mode dynamics is determined by microscopic effects in a narrow layer around the q = 1 surface. Here the **magnetic reconnection** is the main player (connected to the shear at q=1).

[F Porcelli et.al. Plasma Phys. Control. Fusion 38 (1996) 2163]

Alphas, ICRH, NBI, profiles

$$\frac{\delta W}{s_1} < const$$

Local ECCD

$$s_1 = \frac{r}{q(\mathrm{r})}\frac{dq}{dr}\bigg|_{r=r_{q=1}}$$

# CONTROL WITH ICRH HEATED MINORITIES IN JET

[Graves et al., Nucl. Fusion 50, 052002 (2010)]

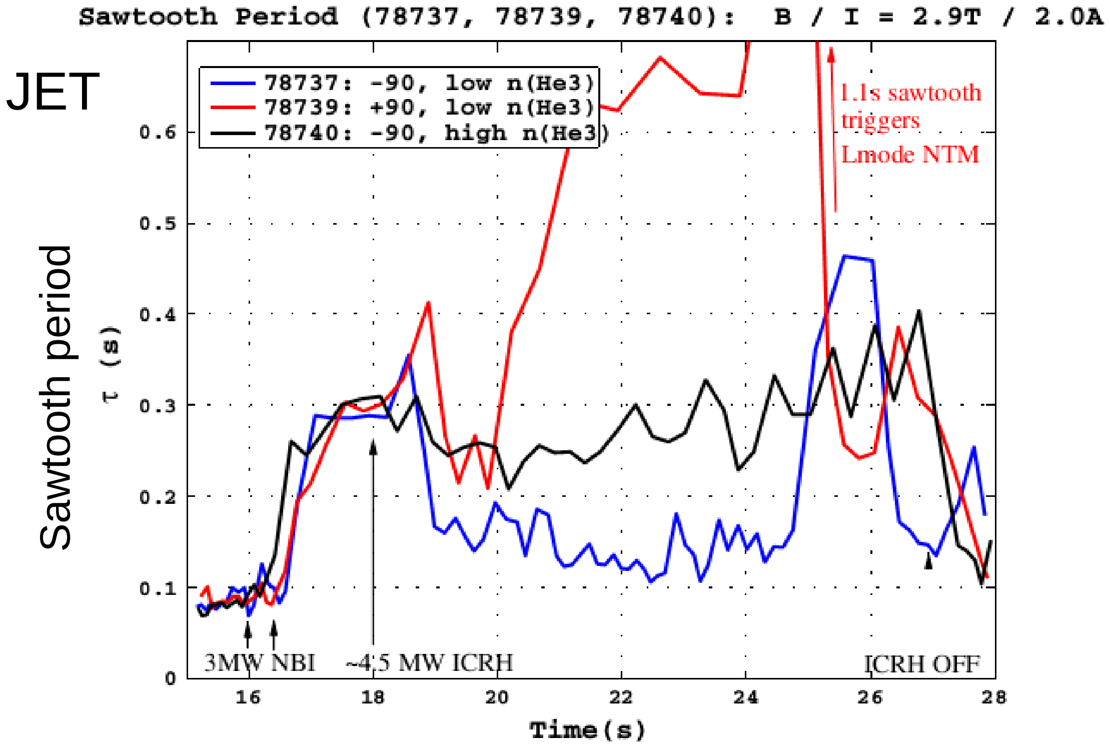



**Figure 5.** The sawtooth period for 78737 (−90° phasing, low concentration $^3$He), 78740 (−90° phasing, high concentration $^3$He) and 78739 (+90° phasing, shown also in figure 1).

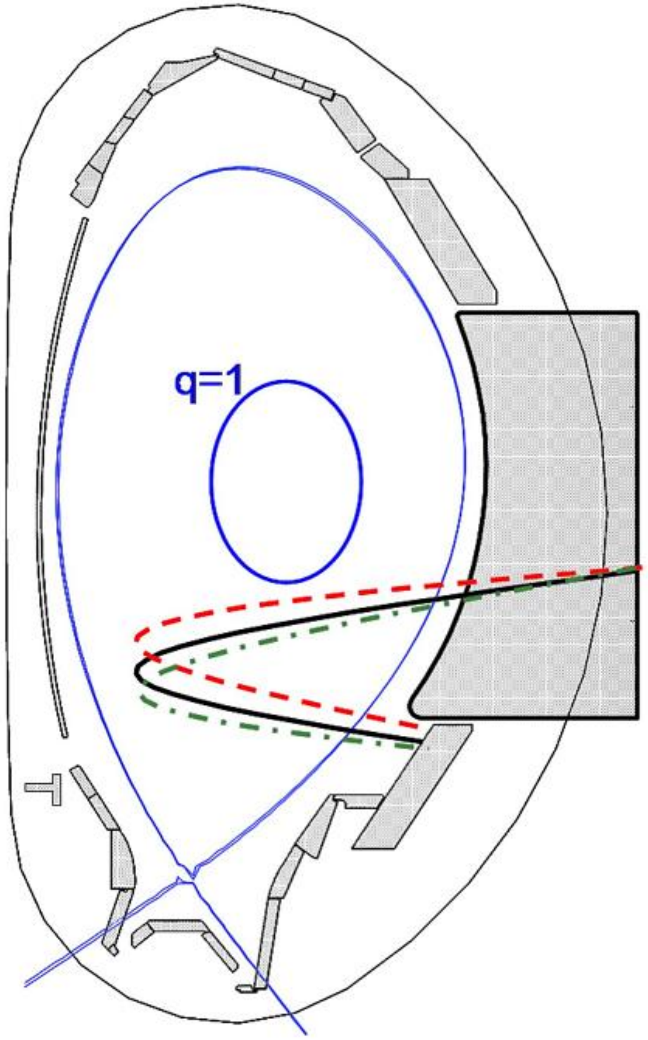
Current drive is negligible because we are influence on minority (no influence on $s_1$). The effect strongly depends from the $^3$He concentration (challenge for control).

Main effect has kinetic nature (change δW)

$$\frac{\delta W}{s_1} < const$$

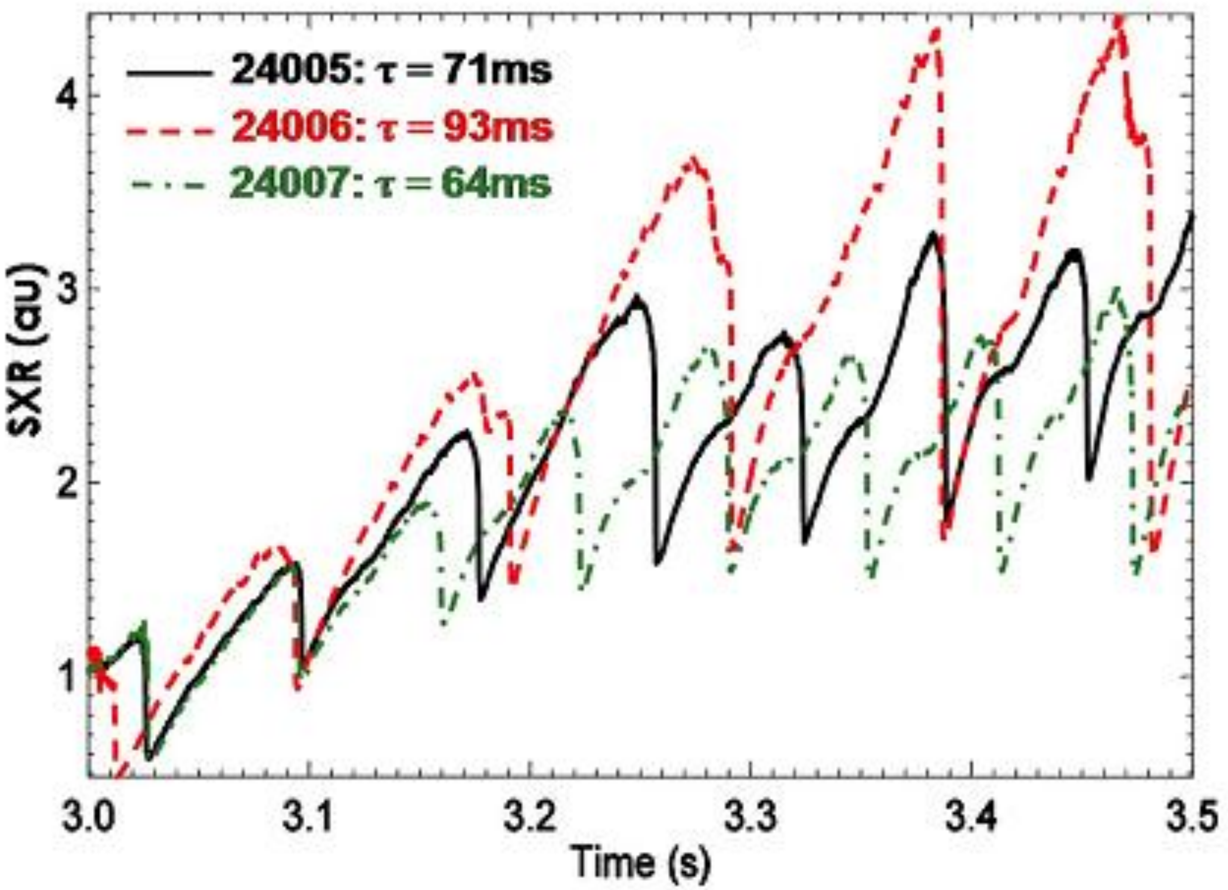
More details: The strongest effect on mode stability is for a $^3$He concentration of only 1%. When there is too much $^3$He, the energy of the particles in the tail of the distribution becomes too low to have a strong effect on the kink mode whereas too little $^3$He means that the absorbed power is low and the broader distribution function leads to increased fast ion losses.

# CHANGES OF THE FAST IONS POPULATION




NBI direction is tilted

FIG. 1. (Color online) The beam trajectories of the off-axis PINI in ASDEX Upgrade as the PINI is tilted on its support. Also shown for comparison is the approximate position of the $q=1$ surface.




[I.T. Chapmen, V.Igochine, et.al.Nucl. Fusion 49 (2009)]
[I.T. Chapmen et.al. Physics of Plasmas 16 (2009)]

**Position of the NBI with respect to q=1 surface is important**

# CHANGES OF THE BEAM DIRECTION

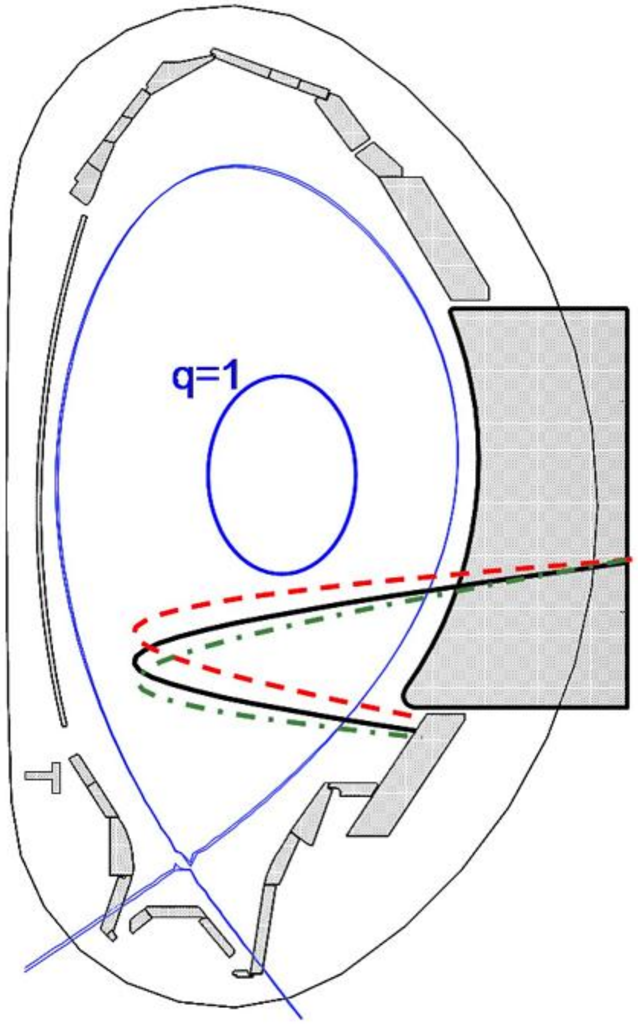
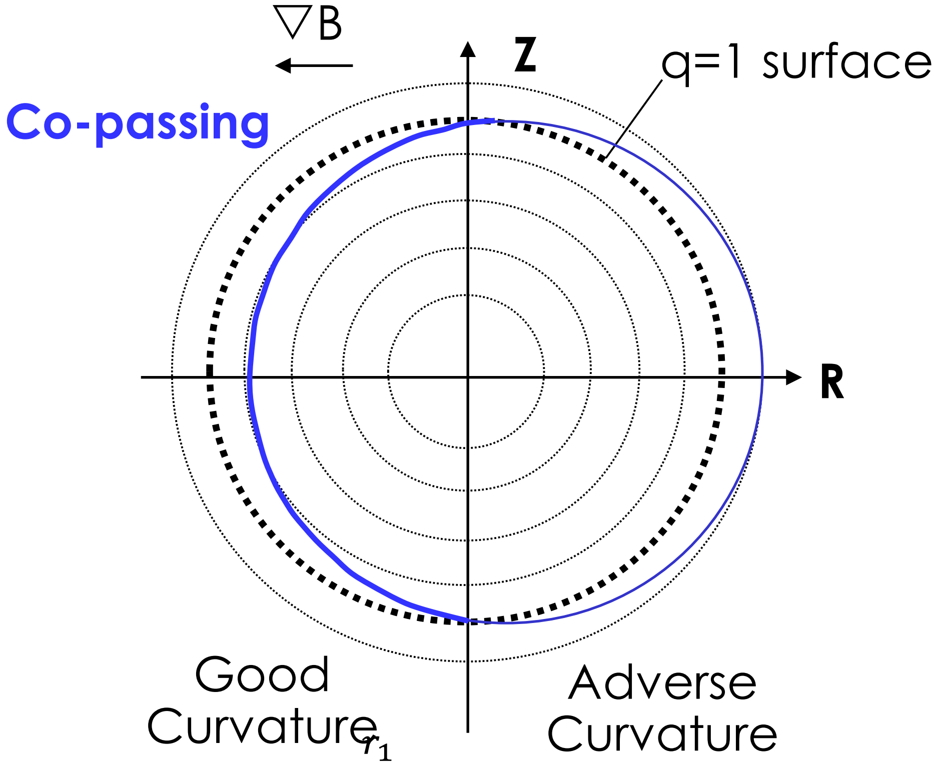



FIG. 1. (Color online) The beam trajectories of the off-axis PINI in ASDEX Upgrade as the PINI is tilted on its support. Also shown for comparison is the approximate position of the $q = 1$ surface.



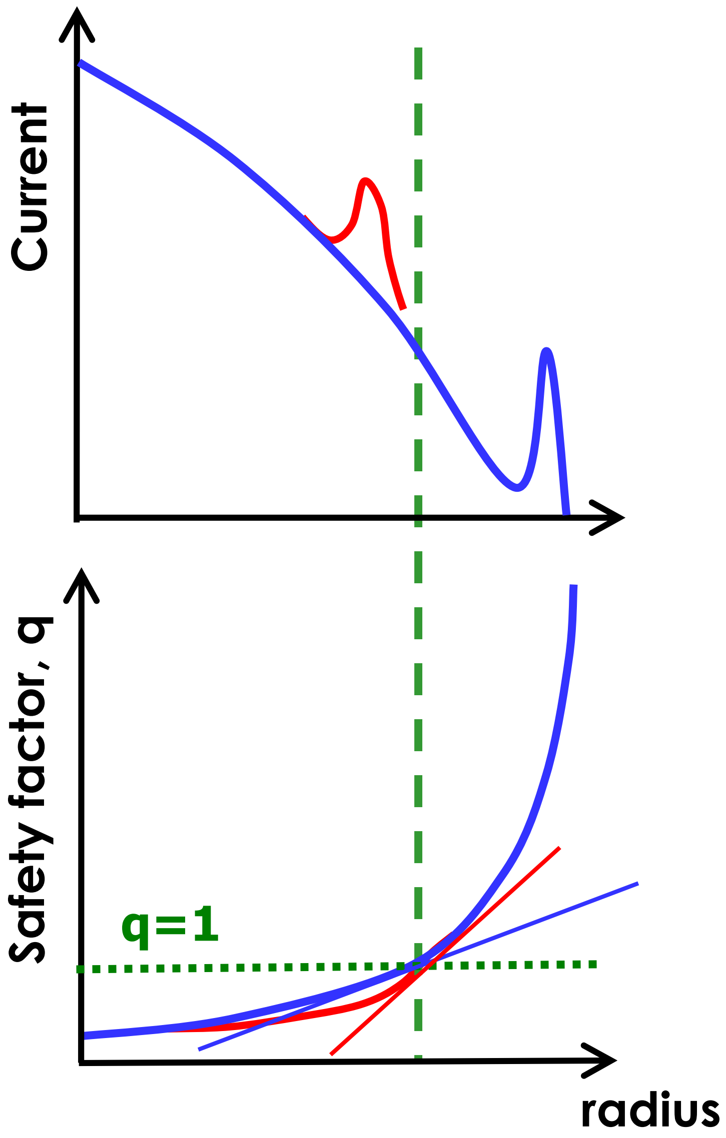

$$\delta W \sim -\int_0^{r_1} (\xi \cdot \nabla \langle P_h \rangle)(\xi \cdot \kappa) dr \neq 0$$

**Co-pass, $\langle P_h \rangle' |_{r_1} < 0 \rightarrow$ stabilising**

**Co-pass, $\langle P_h \rangle' |_{r1} > 0 \rightarrow$ destabilising**

**[Graves, PRL, 2004; Graves, PoP, 2010; Chapman et al, PPCF, 2008]**

# SWTEETH CONTROL WITH ECCD




**Trigger condition:** $$\frac{\delta W}{s_1} < const$$

A perturbation is applied to the initial current profile (inside q=1)

↓

More current means more poloidal field, so q drops

↓

q=1 is moved outwards

↓

Magnetic shear at q=1, $s_1$ (~gradient of q) increases

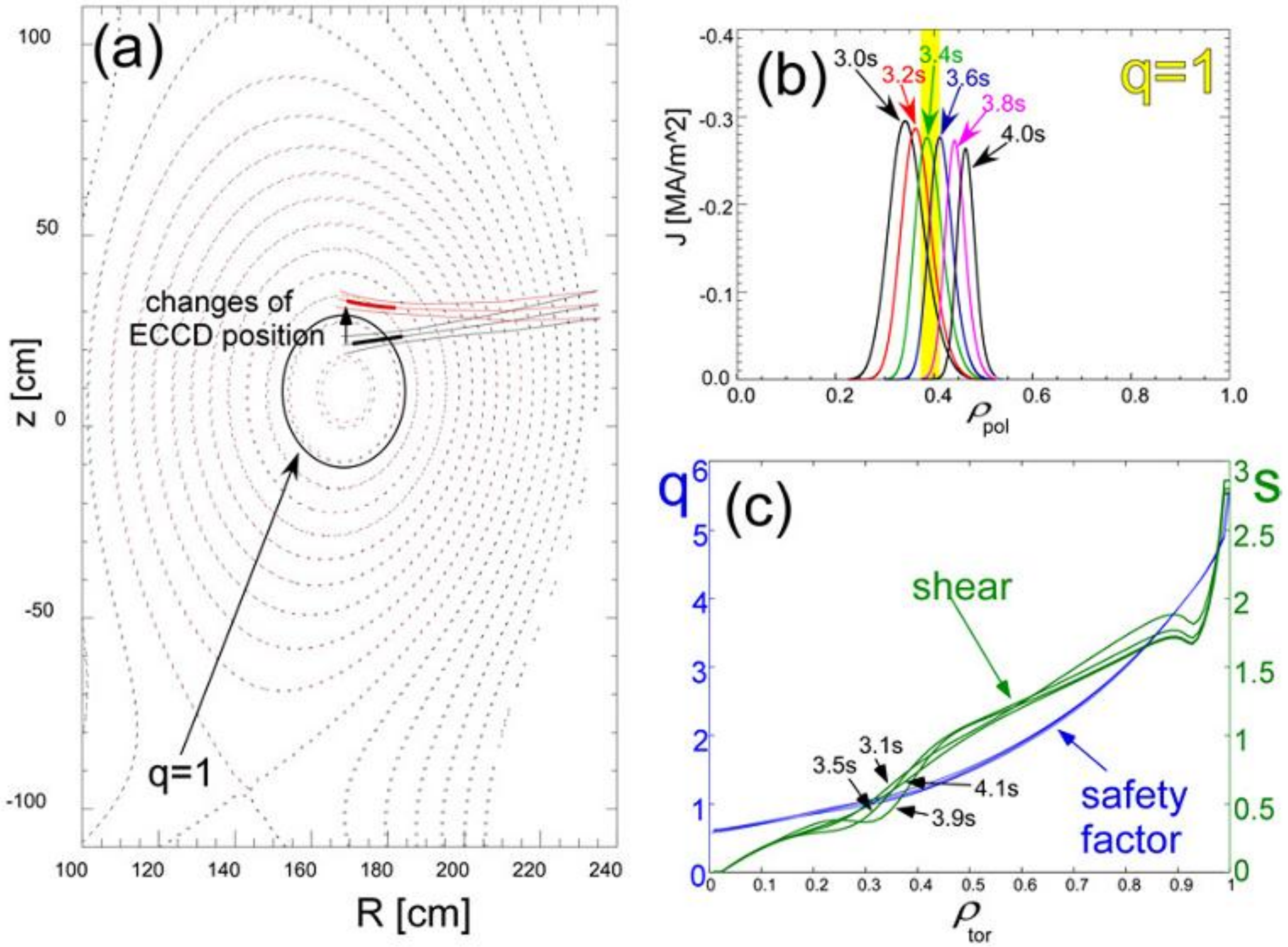
# DESTABILIZATION OF FAST PARTICLE STABILIZED SAWTEETH

<u>ITER relevant situation:</u>

ICRH heating creates fast particles (mock up alpha particles in ITER).

Central ECRH heating keeps the temperature profile constant (this avoids effects Te profile on the (1,1) mode stability).

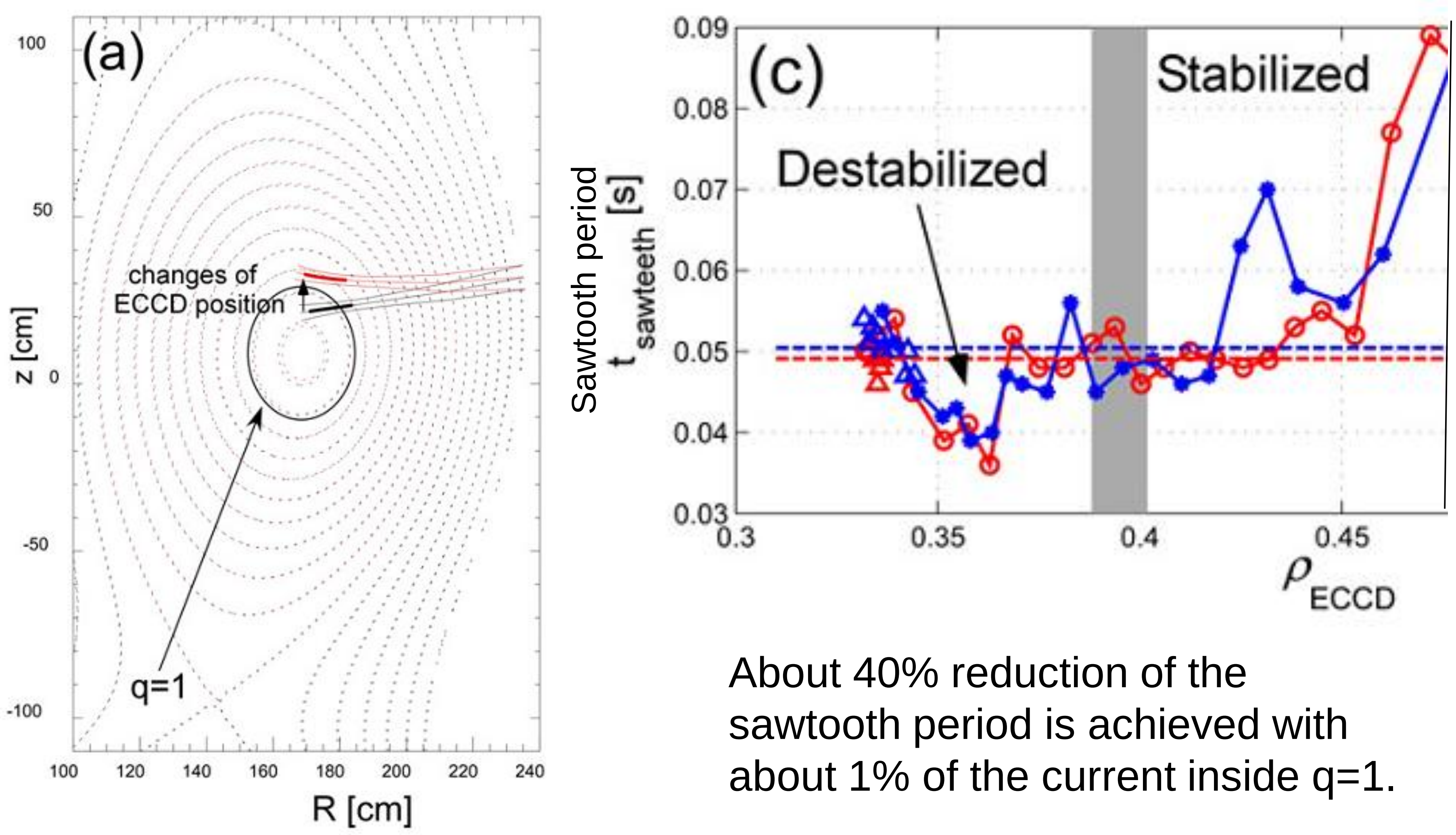
ECCD is applied around q=1 surface to change shear.




The current in the order of 1% changes only derivative of current profile.

[Igochine et.al. Plasma Phys. Control. Fusion 53 (2011)]

# DESTABILIZATION OF FAST PARTICLE STABILIZED SAWTEETH

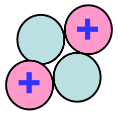



About 40% reduction of the sawtooth period is achieved with about 1% of the current inside q=1.

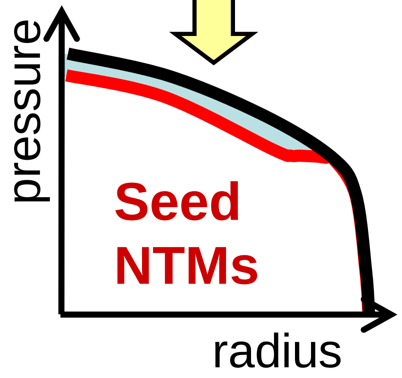
**[Igochine et.al. Plasma Phys. Control. Fusion 53 (2011) ]**

# CONTROL OF SAWTEETH IN ITER

$$\frac{\delta W}{s_1} < const$$



Alpha particles will stabilise the internal kink, increasing $\tau_{saw}$




Planned control via ECCD to increase local shear

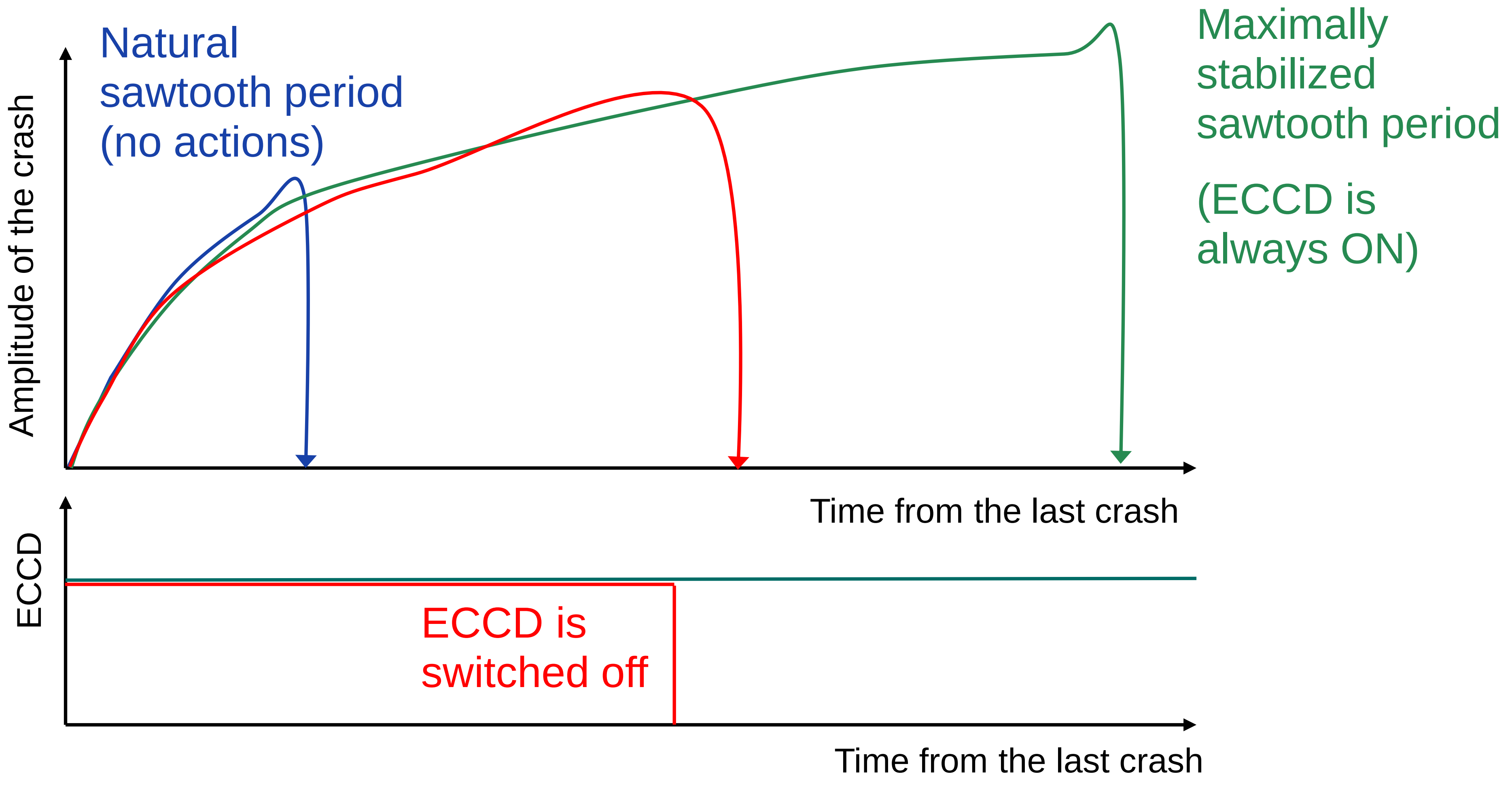
Results <u>in presence of fast particles</u> from ASDEXUpgrade [Igochine PPCF 2011] & TORE SUPRA [Lennholm et al, PRL 2009] show that ECCD control is very effective

Passing ions from ICRH can destabilise sawteeth [Graves et al, PRL, 2009]

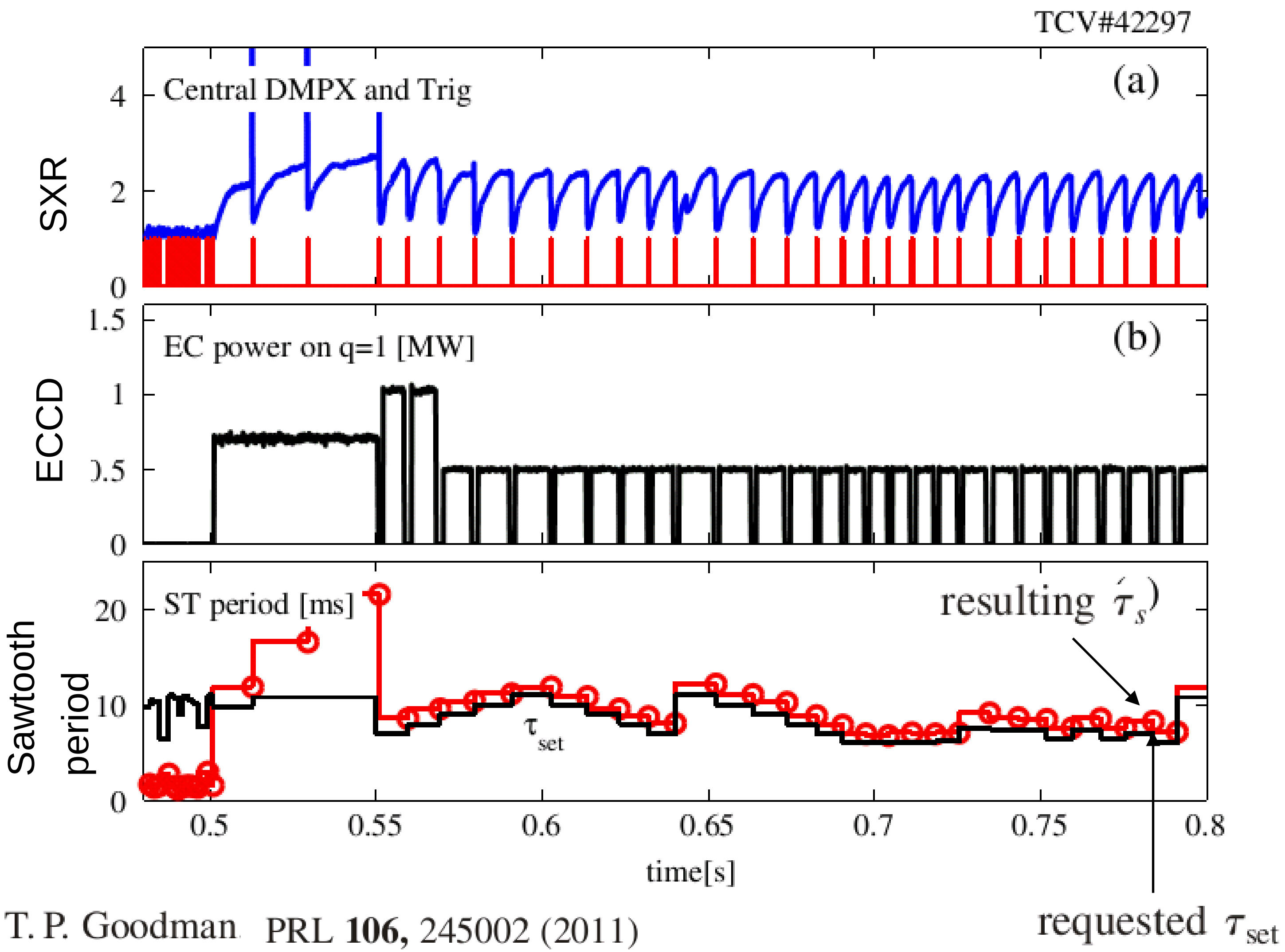
NB: $He^3$ minority ICRH in ITER will not drive sufficient current, but kinetic effects will help

# PACING CONTROL OF SAWTEETH

Sawtooth period can be controlled by removing the stabilizing effect



# PACING CONTROL OF SAWTEETH

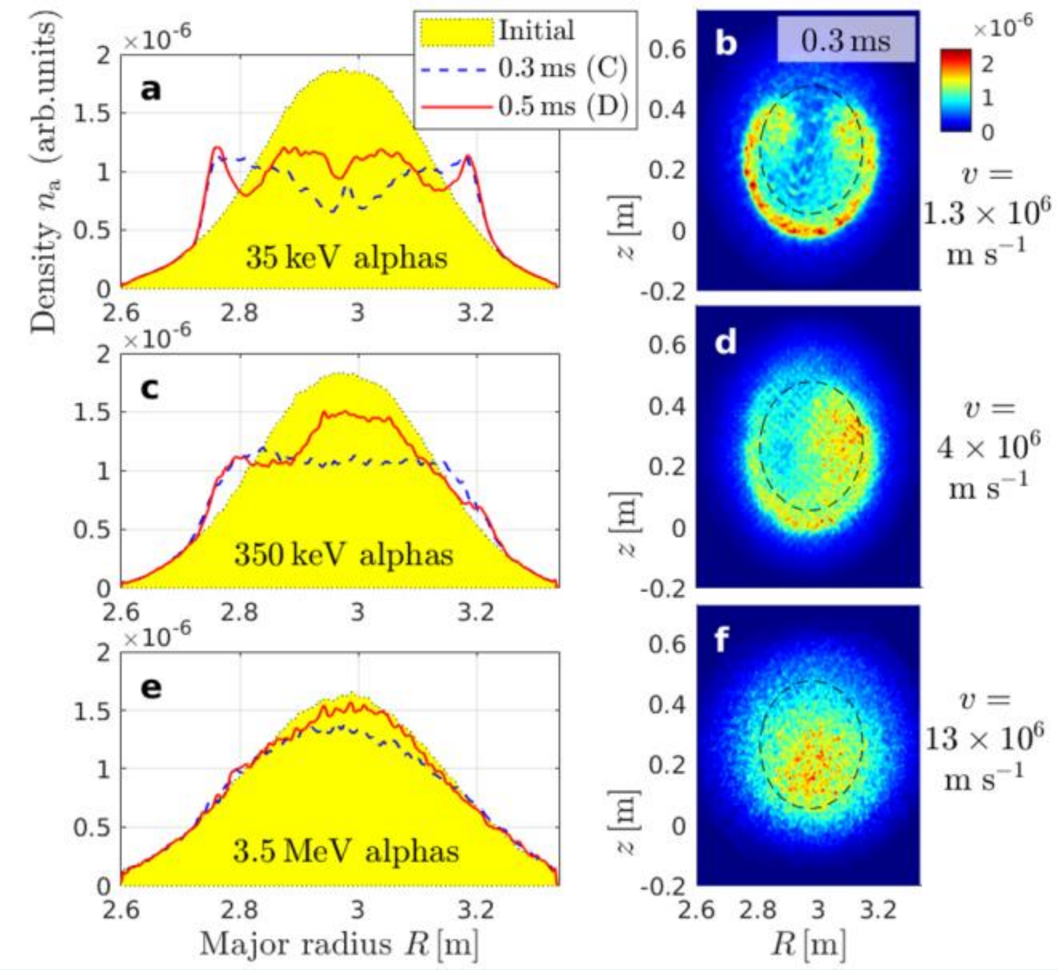



T. P. Goodman PRL **106,** 245002 (2011)

The pacing technique shows very good results within a certain range of parameters.

This example from TCV shows that **requested sawtooth period** is the same as **experimental sawtooth period.**

# USE OF SAWTEETH TO REMOVE HELIUM ASH




Numerical simulations shows that correctly chosen sawteeth can remove

Helium ash (slowed down alpha particles)

and do not disturb the fast particle population.

Sawteeth have potential to be a tool to remove helium ash from the core.

**Here, instability is a potential solution, not the problem!**

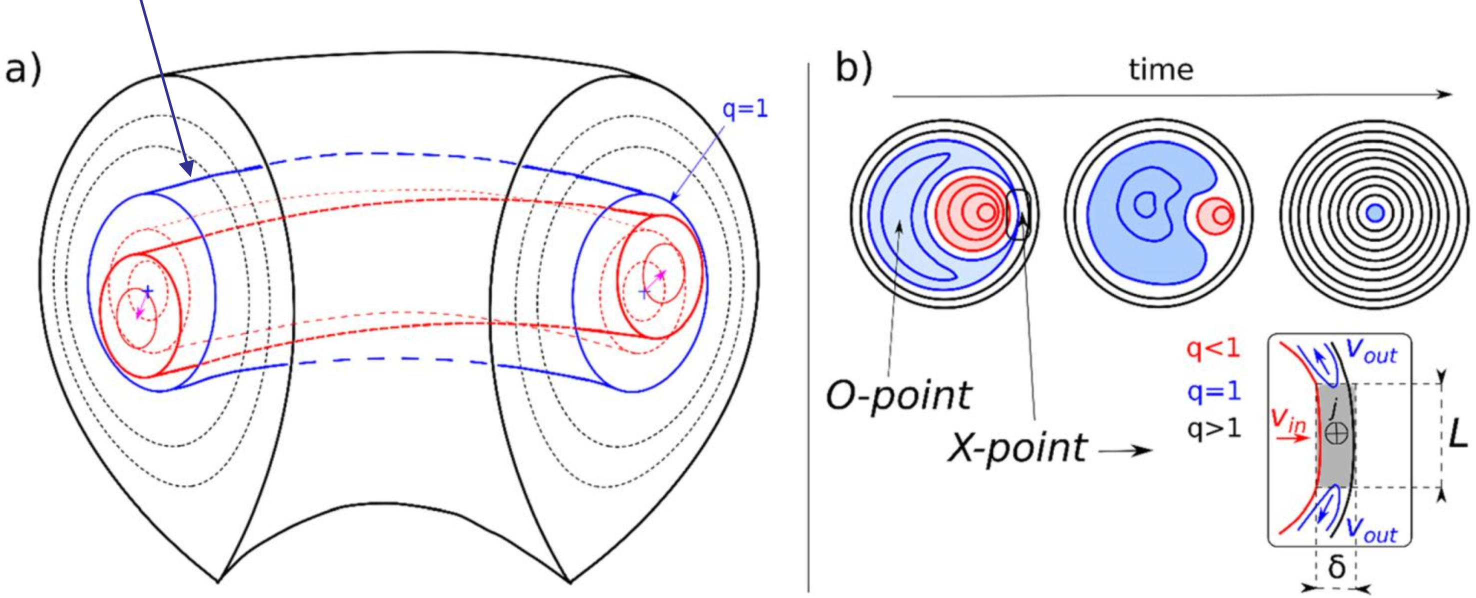
[Bierwage et.al., Nature Communications, 2022]
open acess https://doi.org/10.1038/s41467-022-31589-6

# INTERNAL (1,1) KINK INSTABILITY

1) Sawteeth

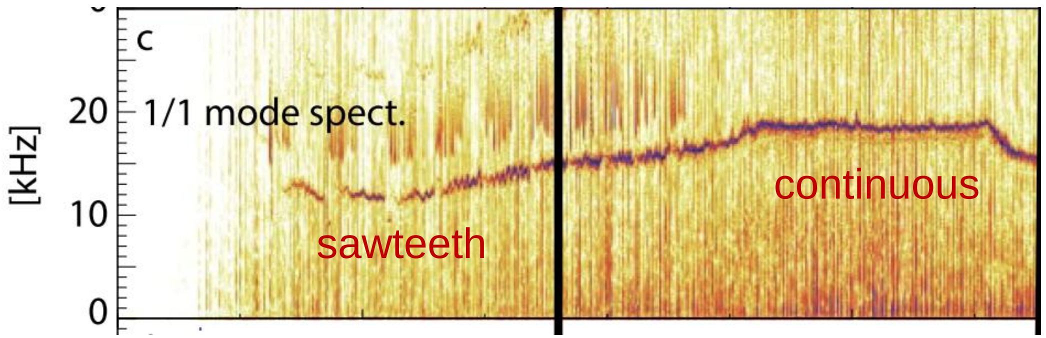
Internal (1,1) kink mode.

q=1 surface




A Tilt and Shift of the Core Plasma.

2) Continuous (1,1) mode




3) Other types of (1,1) behaviour (fishbones) and transition phases between (1) and (2)

# TRANSITION BETWEEN SAWTEETH AND CONTINUOUS (1,1)

**Simulations** (non-linear, 2-fluid, XTOR-code)

[Halpern et.al., Phys. Plasmas 18, 102501 (2011)]

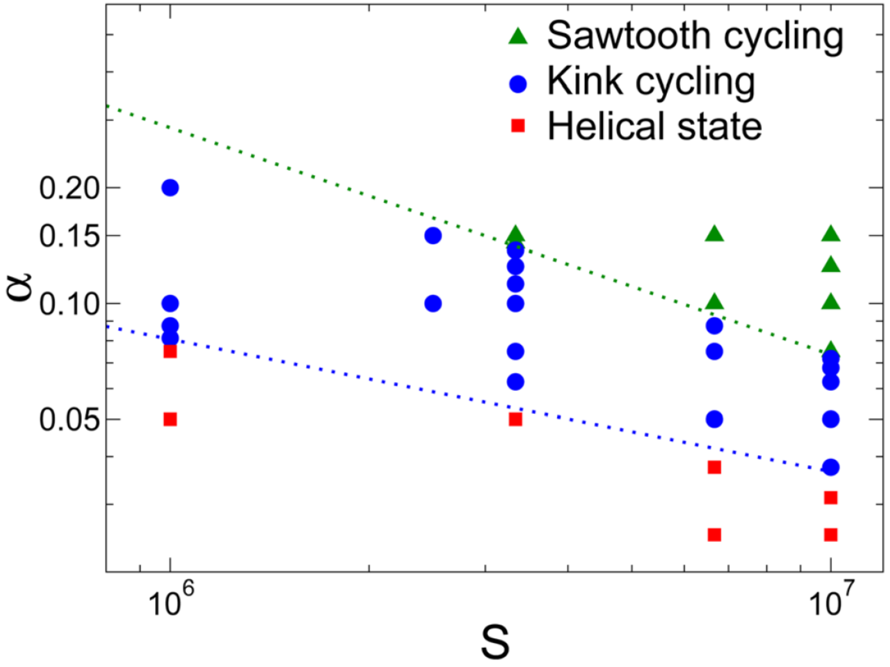



FIG. 6. (Color online) Cyclic regimes found as a function of $\alpha = (\omega_{ci}\tau_a)^{-1}$ and $S = 1/\eta$.

**Experiment** (TCV, elongation scan)

[H Reimerdes et.al., 2006 Plasma Phys. Control. Fusion 48 1621]

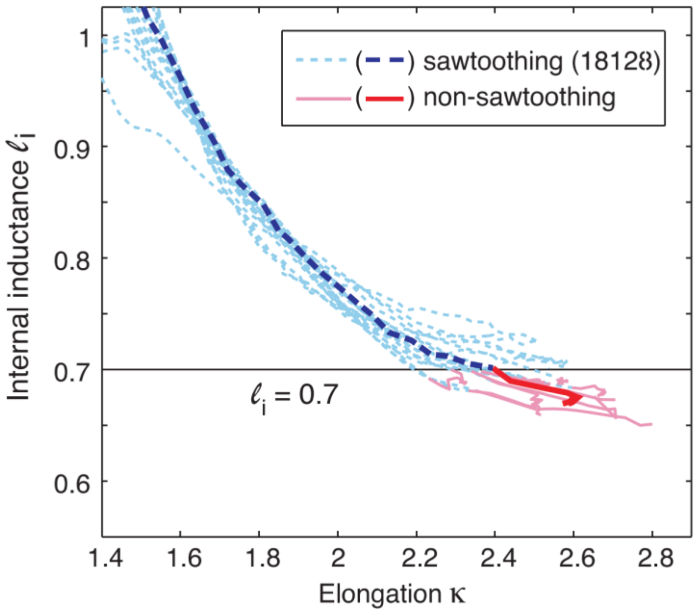
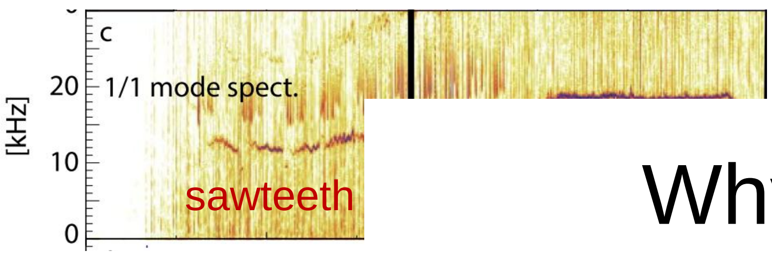



**Figure 3.** The transition from a sawtoothing to a non-sawtoothing phase in discharges with different densities and $I_p$-ramp-up scenarios occurs at varying values of elongation, but at the same value of the internal inductance $\ell_i$. Discharge #18128, for which a detailed analysis of its MHD activity is presented in section 2.3, is highlighted.

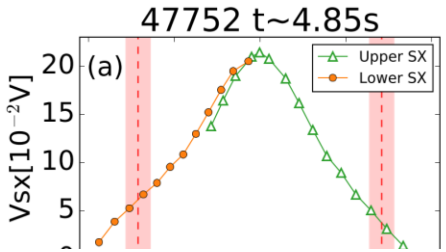
Variation of the plasma parameters leads to transitions between different (1,1) mode behaviour in theory and in experiments. **Both variants are result of the same (1,1) instability** at different conditions.

# CONTINUOUS (1,1) MODE IS NOT AN EXOTIC CASE

**ASDEX Upgrade**



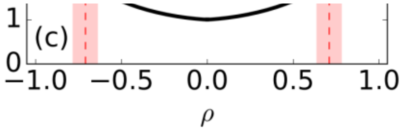

[A. Burckhart et a
(2023) 126056 ]




**JT-60U**

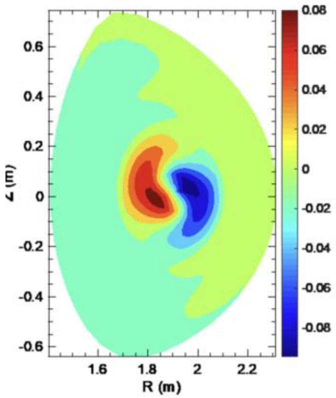
[T Bando et al 2011 Plasma Phys. Control. Fusion 61 (2019) 115014 ]


Why are we interested in this?
Because, in some cases, confinement is good with the (1,1) mode!




Continuous (1,1) mode is not an exotic regime. It is observed on all main tokamaks. The same as sawteeth.

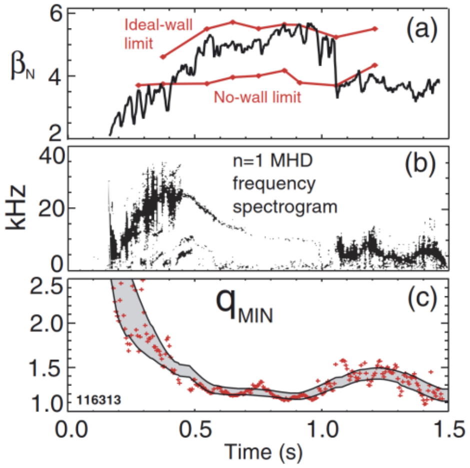
**EAST**




[L. Xu et al
Nucl. Fusion 63 (2023) 076007]

**NSTX**

[J. E. Menard PRL 97, 095002 (2006) ]




Here are just a few cases with continuous (1,1) mode.

# EXAMPLE OF 3D EQUILIBRIUM FOR ITER

Plasma crossection at different toroidal positions

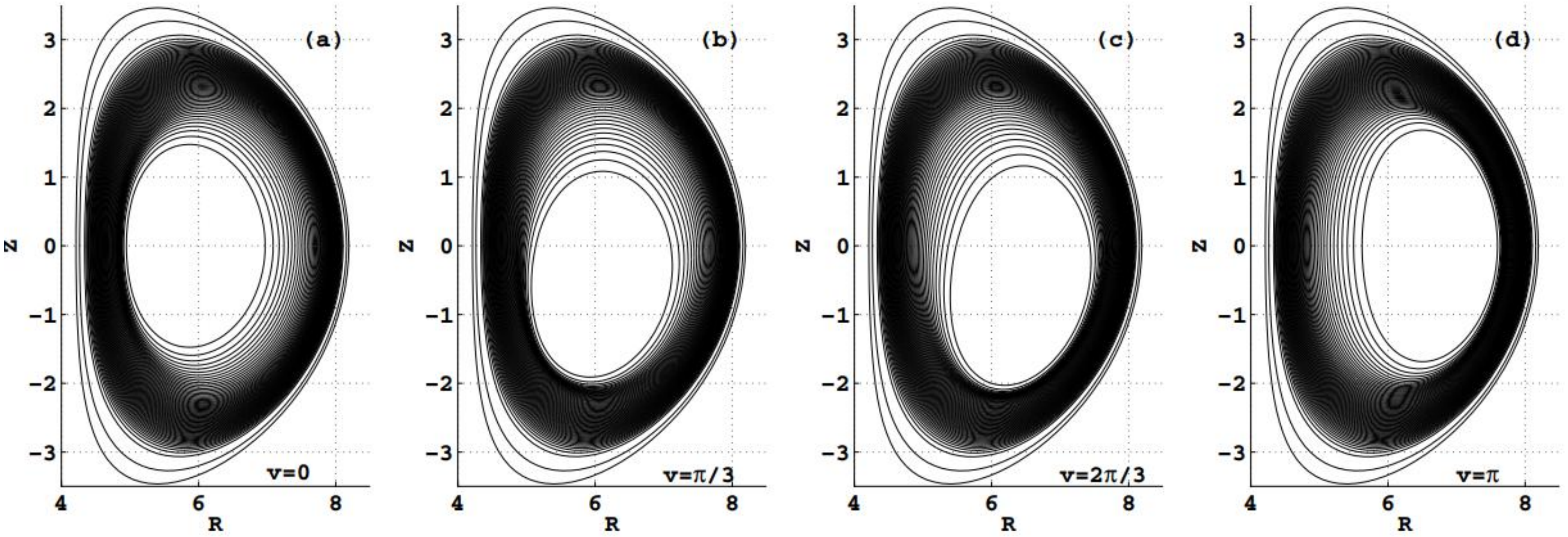



**Figure 4.** Contours of constant pressure at cross sections with toroidal angle (*a*) $v = 0$, (*b*) $v = \pi/3$, (*c*) $v = 2\pi/3$ and (*d*) $v = \pi$ for an ITER hybrid scenario equilibrium with 13.3 MA toroidal plasma current. *R* and *Z* are in metres.

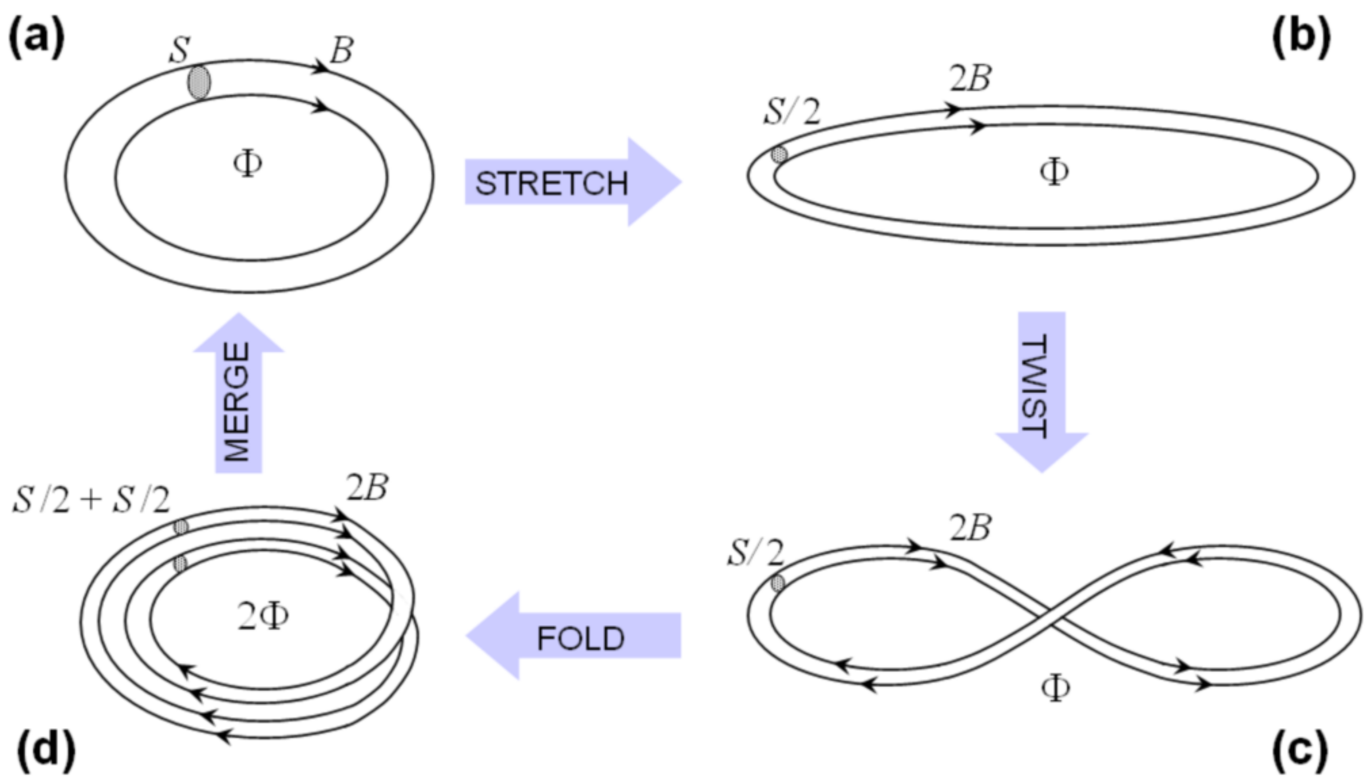
[W A Cooper *et al* Plasma Phys. Control. Fusion 53 (2011) 024002]

# PLASMA DYNAMO

Zeldovich anti-dynamo theorem (1957):

A purely two-dimensional flow cannot act as a dynamo.

3D is important to convert instability velocity into current redistribution!




**Plasma flow / movement → Magnetic field / current redistribution**

# NECESSARY CONDITIONS FOR THE DYNAMO

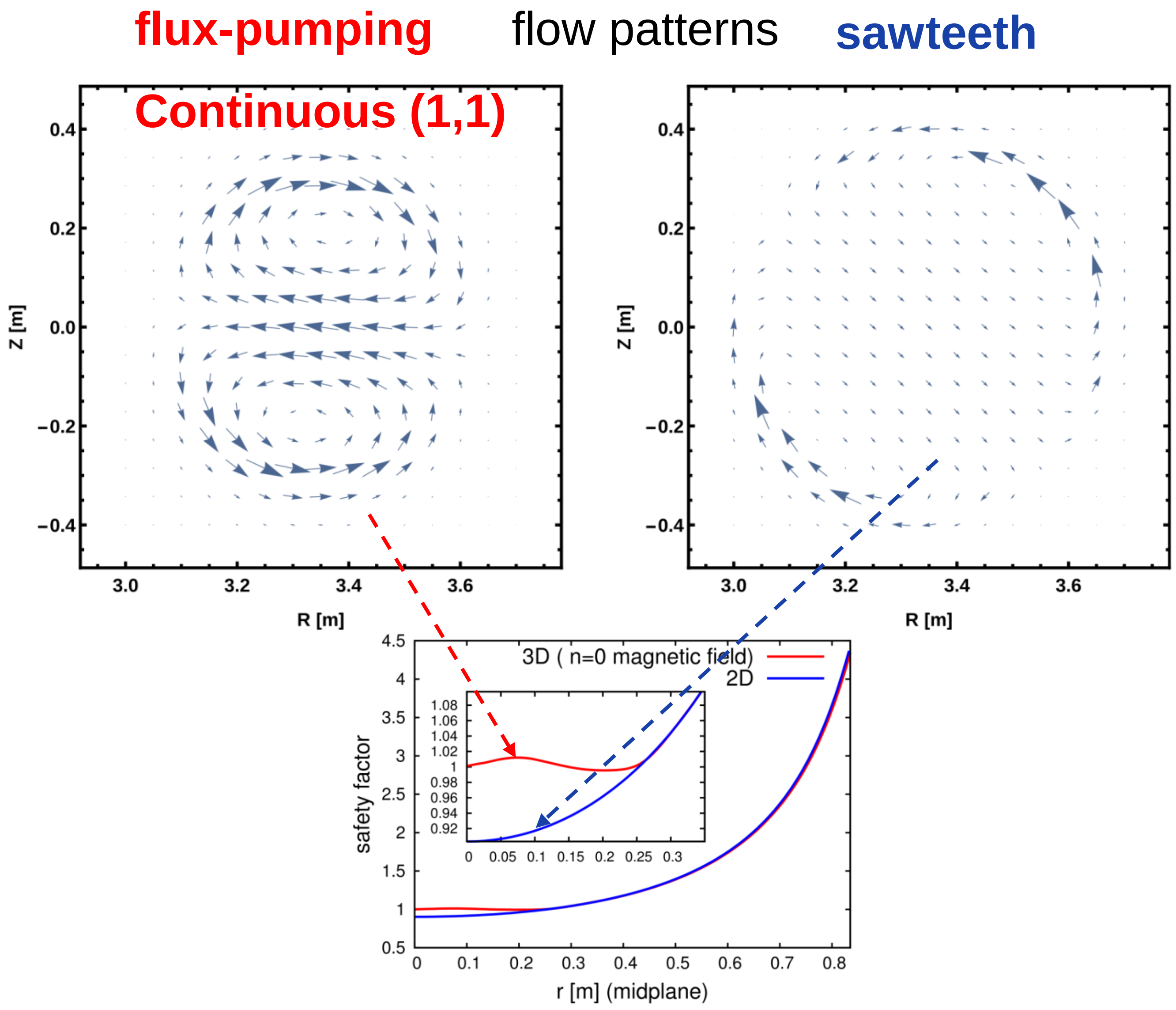
**Necessary conditions** for the dynamo in a tokamak:

- **Pressure gradient** in the core:

  drive for (1,1) instability, creates plasmas flow.

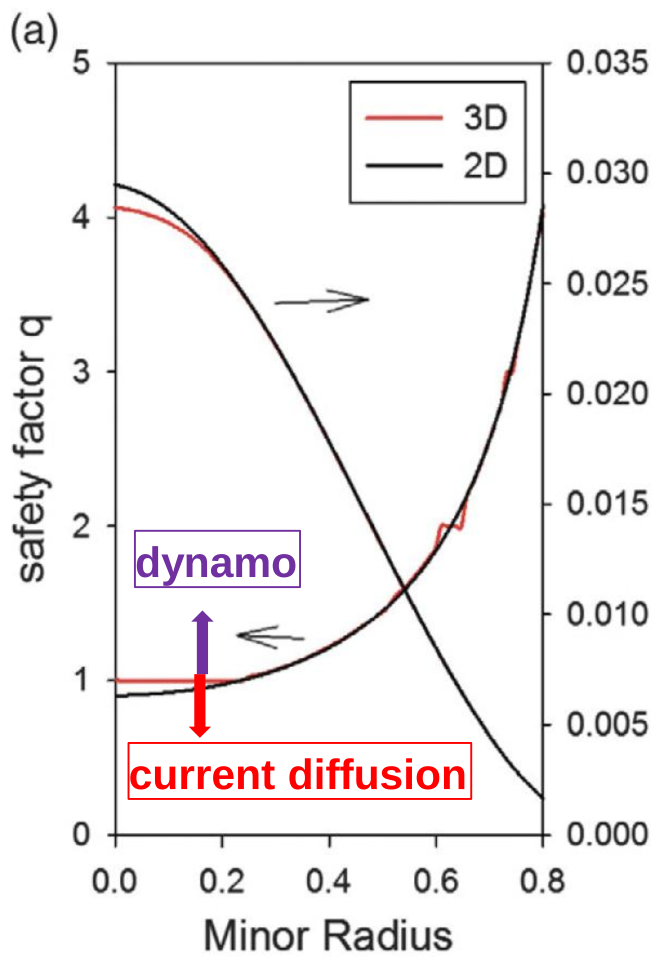
- **Flat q-profile** region around q=1:

  allows a global flow in the core, otherwise the flow is damped.




Krebs *et al.* Phys. Plasmas **24**, 102511 (2017)

# HOW DYNAMO WORKS?




**[Jardin et.al., PRL 115, 215001 (2015)]**

Current diffusion makes current profile more peaked

↓

**safety factor (*q*) goes down in the core**

↓

(1,1) mode destabilized close to q=1

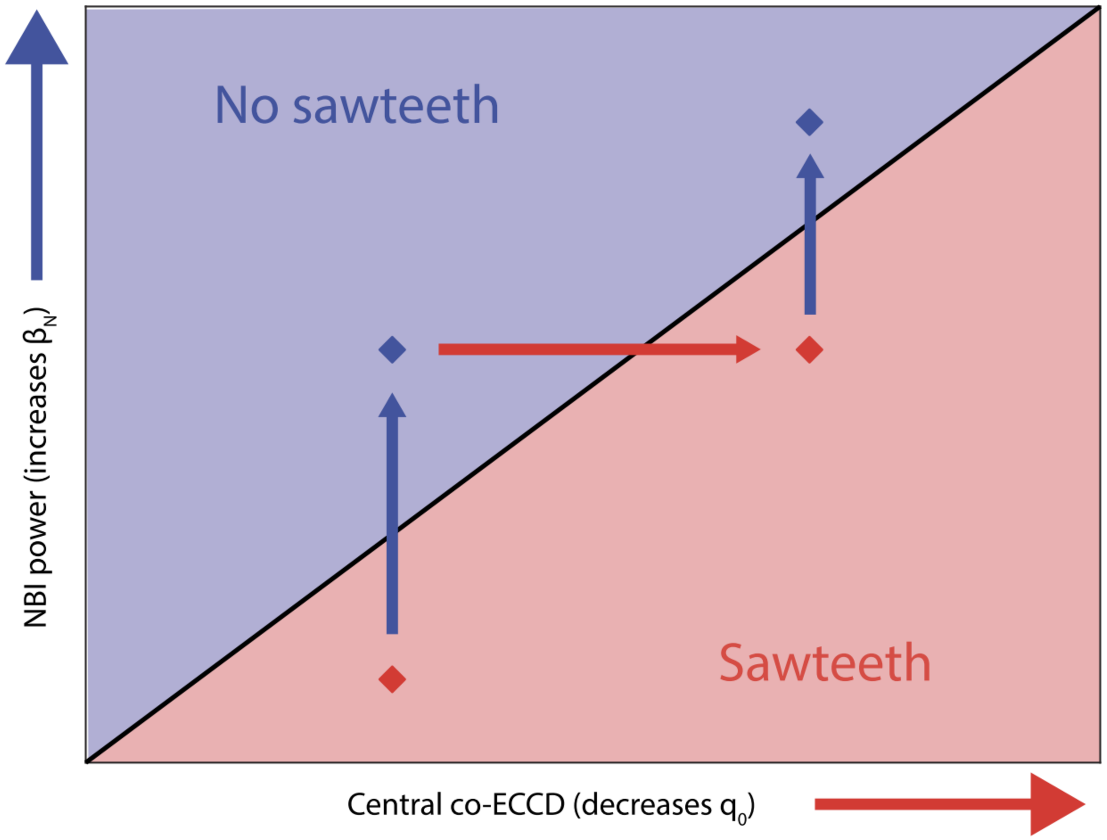
↓

**The 3D flow induces and redistributes the current off-axis (q-profile is pushed up!)**

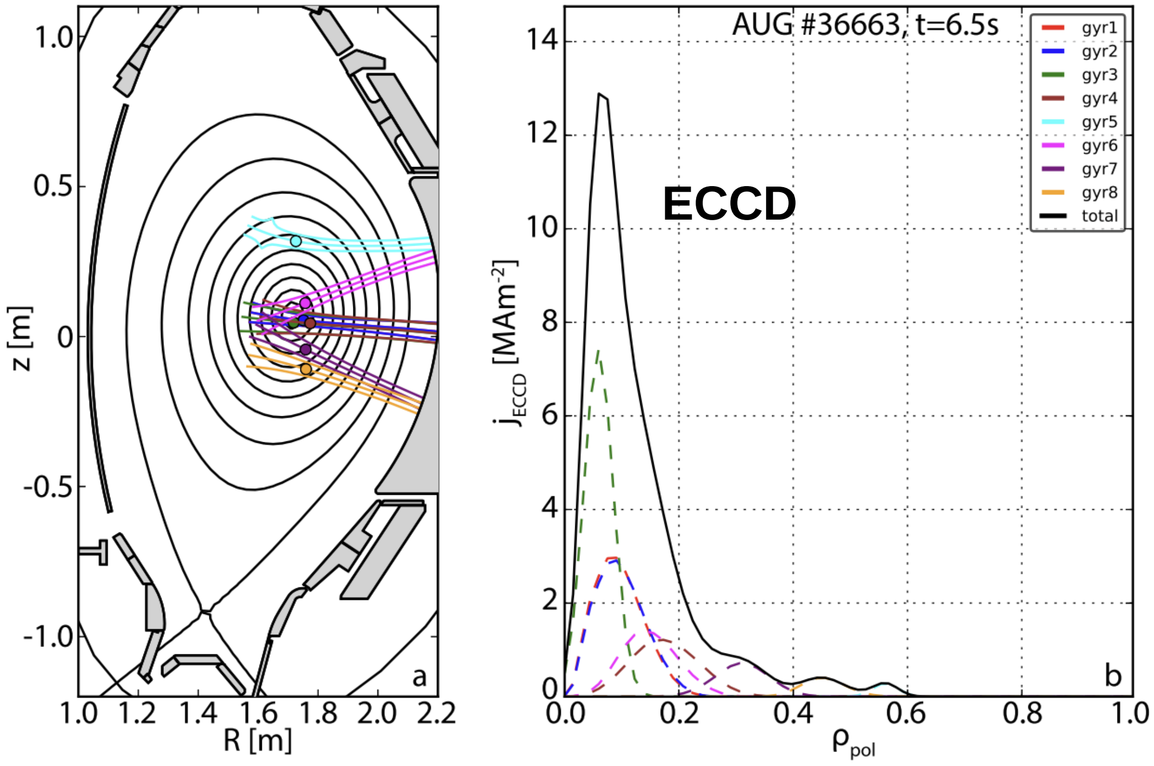
↓

Plasma finds an equilibrium, when both forces are balanced

# TRANSITION BETWEEN SAWTEETH AND FLUX-PUMPING



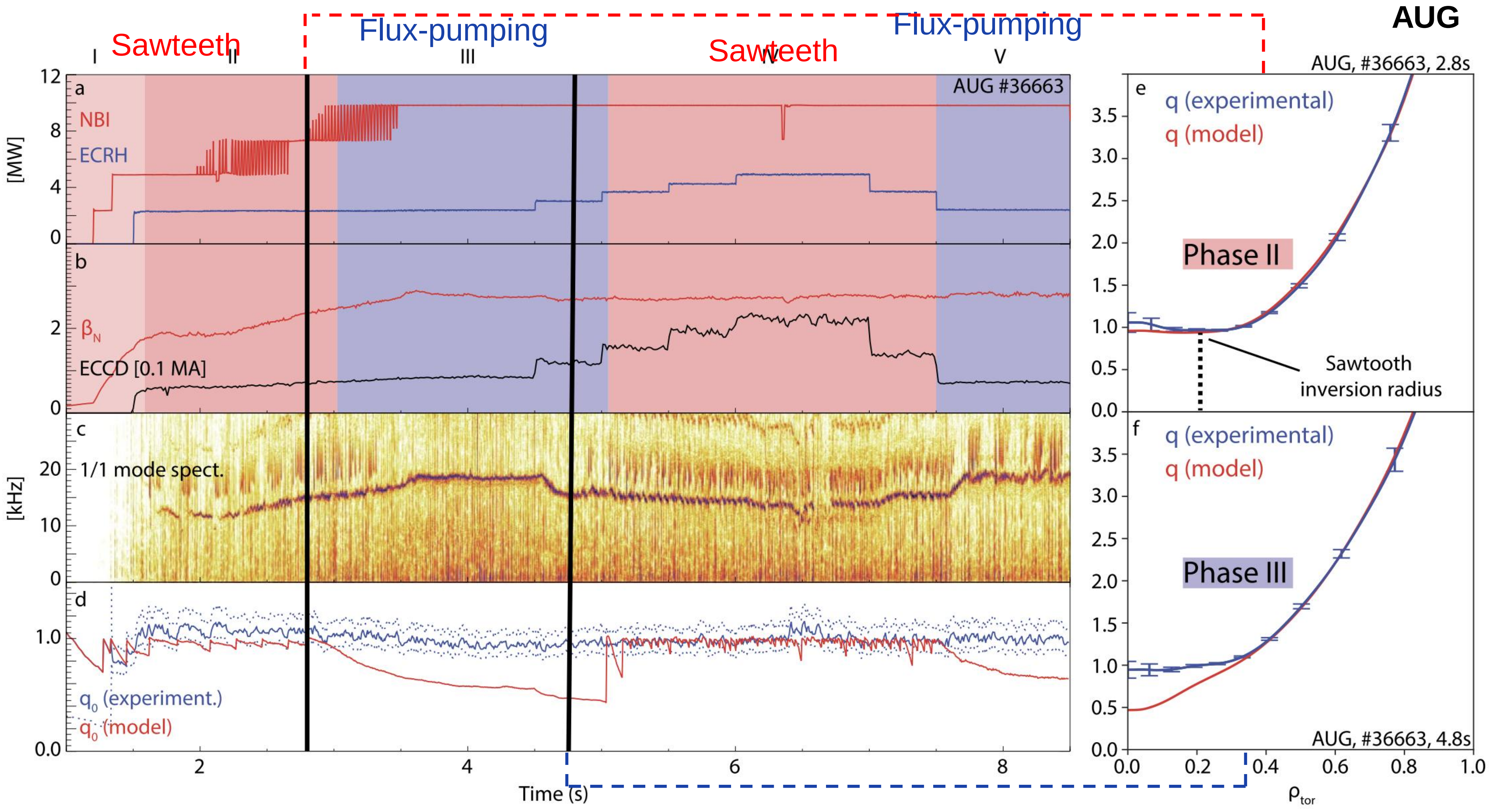

ASDEX Upgrade




Actuators: **NBI** (pressure profile) and **ECCD** (safety factor / current profiles)

A. Burckhart *et al* Nucl. Fusion **63** (2023) 126056

# TRANSITION BETWEEN SAWTEETH AND FLUX-PUMPING

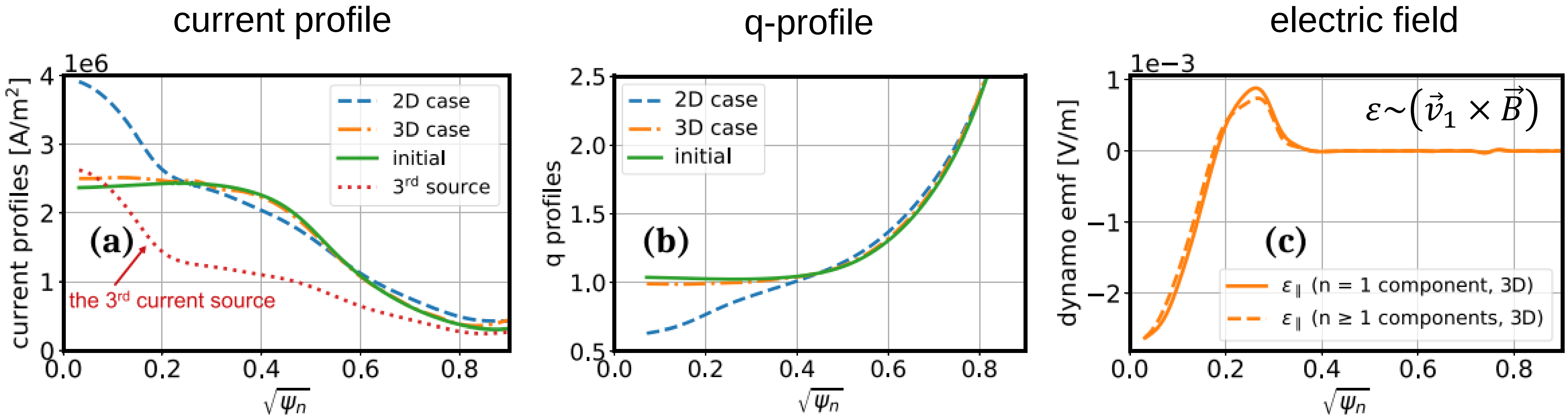



Porcelli model works for sawteeth.

Disagreement between modelling and simulations for flux-pumping shows existence of the effect and need for the model!

A. Burckhart *et al* Nucl. Fusion **63** (2023) 126056

# NON-LINEAR MHD SIMULATIONS (JOREK CODE)




[H. Zhang *et al, Nucl. Fusion 65 (2025)* 066001]

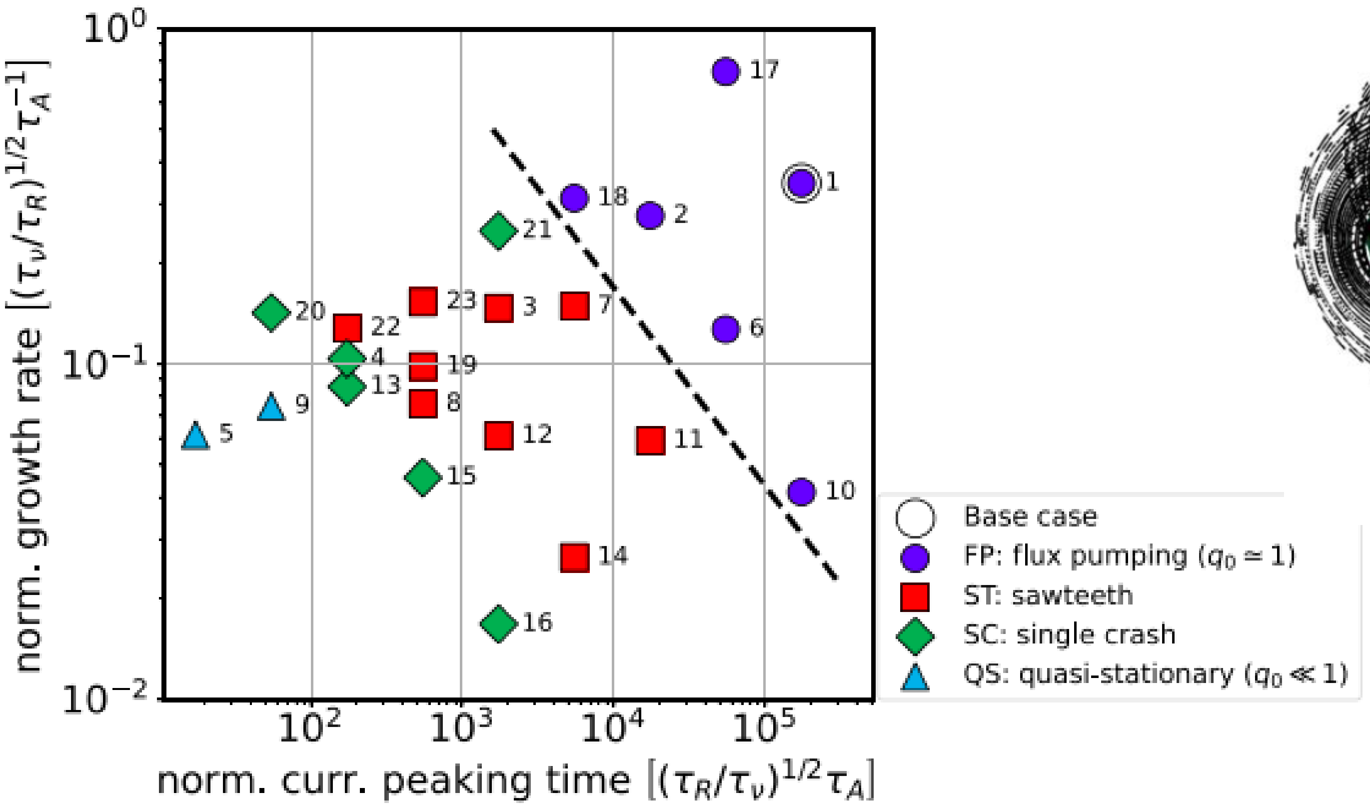
Two important results:

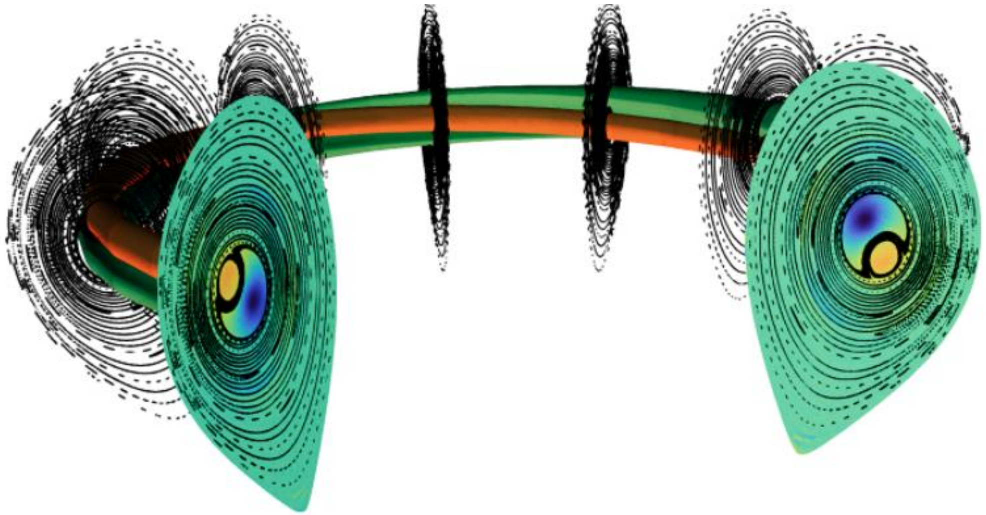
- **flux-pumping** does not generate current. It **redistributes the current** from the core to more off-axis region
- *n=1* is important, but higher *n* components give contribution to flux-pumping as well.

# SEARCH FOR THE SIMPLIFIED MODEL FOR FLUX-PUMPING

non-linear MHD simulations (long & expensive)

linear MHD (fast & cheap)



[H. Zhang *et al* Nucl. Fusion **66** (2026) 076027]

Relation between initial growth rate of the instability (linear MHD aprox., can be calculated relatively fast) and behavior in non-linear regime (long time simulations, expensive) was found.

# STUDIES OF FLUX-PUMPING

Current research:

Identification of the transition boundary and projection to ITER

- Experiments on ASDEX Upgrade, MAST-U, EAST + JET analysis
- Non-linear MHD simulation (JOREK) and development of simplified model
- Implementation of the model to a transport code (ASTRA)

Next steps:

Testing the compatibility of flux-pumping with different divertor plasma solutions

- Experiment on ASDEX Upgrade, MAST-U, EAST
- Modeling with set of non-linear MHD and SOL codes

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iter
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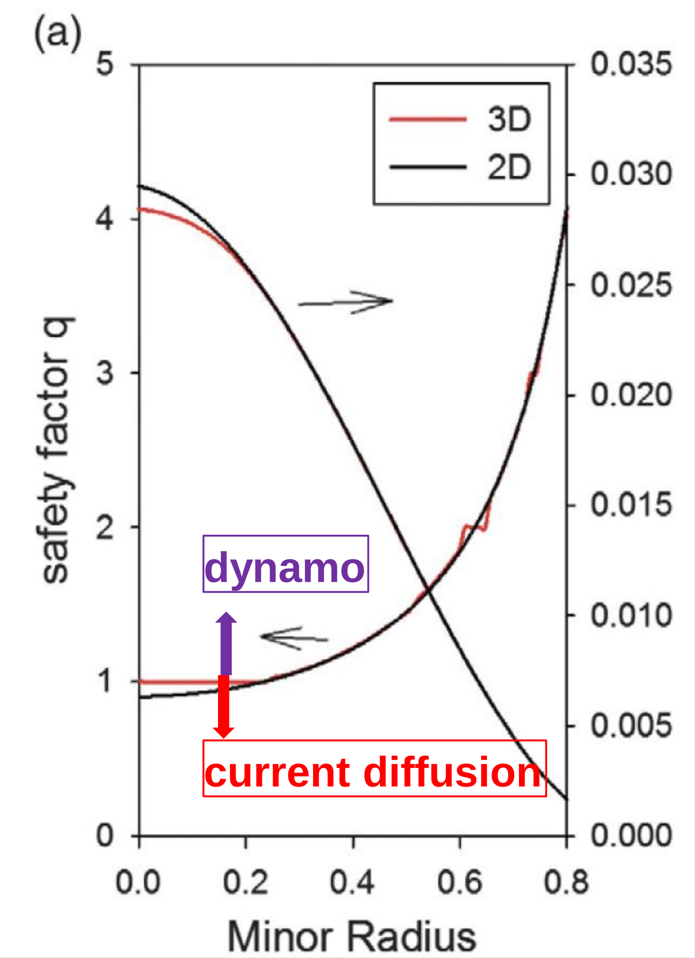
ASDEX Upgrade

# WHY THIS STATIONARY (1,1) MODE IS SO IMPORTANT?

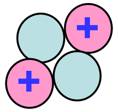
Flux-pumping (dynamo):

- exists when $\beta$ above a threshold (**high $\beta$**);
- leads to dynamo effect, which redistributes current to off-axis region (**off-axis current drive**);
- is naturally **sawteeth-free** and **self-regulating** (no sophisticated control);
- is a potential **regime for ITER/DEMO**;
- can be **combined with sawteeth** phases.




**Here, instability is a potential solution, not the problem!**

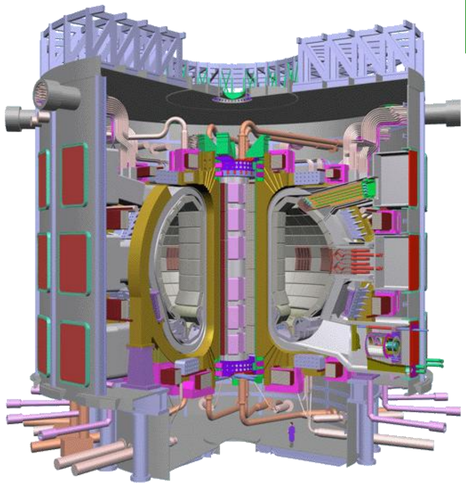
# HOW CONTROL OF (1,1) COULD LOOK LIKE IN ITER/DEMO?



Alpha particles increase pressure in the core

Transition to sawteeth (possibly with additional H&CD actuators) and remove Helium ash

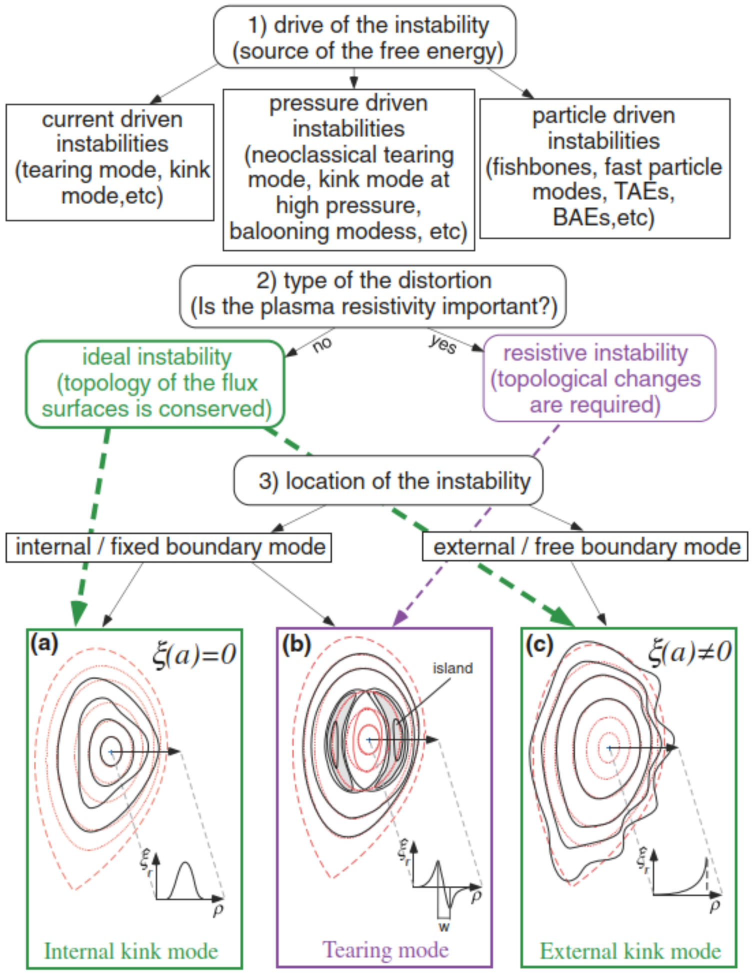
Transition to flux pumping (possibly with additional H&CD actuators)



Slow down of alpha particles (Helium ash is in the core)

# CONCLUSIONS

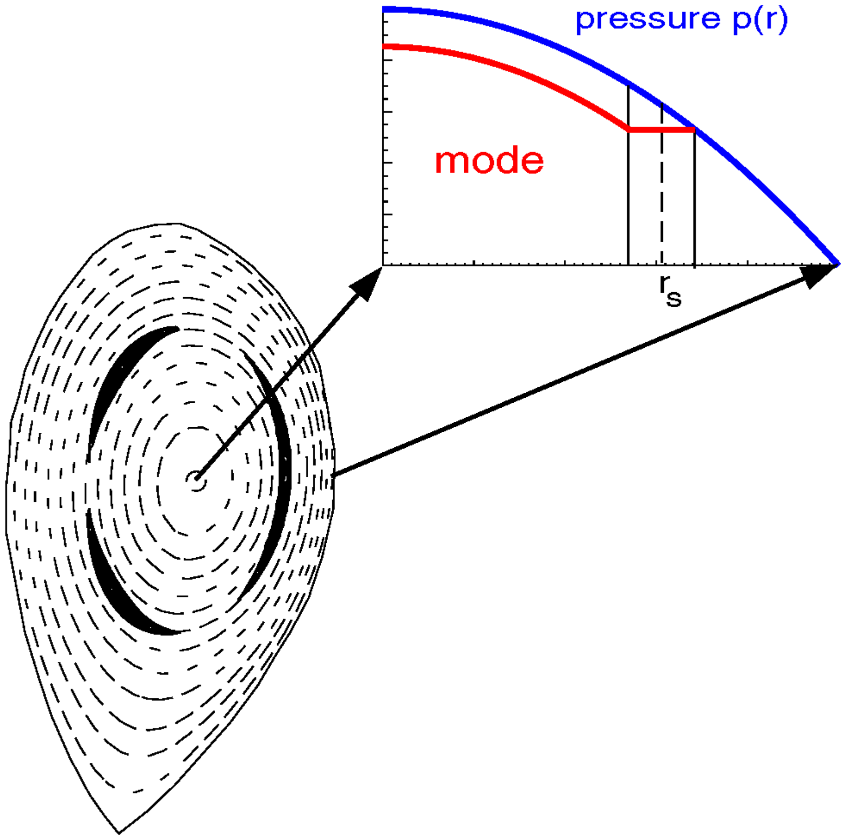
# MAIN TAKE AWAY: MHD INSTABILITIES




One has to answer on three question to start to work with an instability

1. Source of the energy
   - Pressure
   - Current
   - Fast particles
2. Resistive (typically slow) / ideal (typically fast)
3. Location
   - Core
   - Edge
   - Global

# MAIN TAKE AWAY: NTM CONTROL



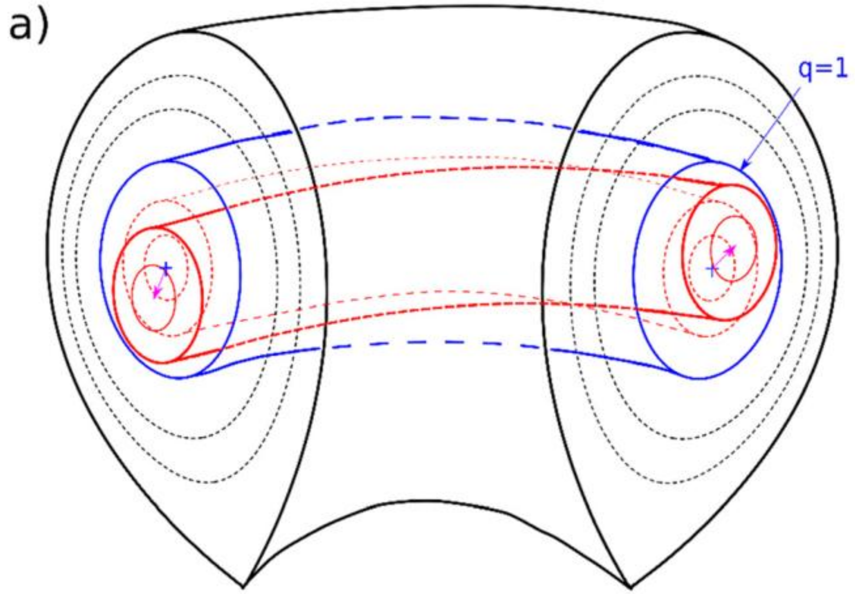

Negative side:

- Large NTM strongly limits confinement
- NTMs can lead to disruption

Control is possible (main tool is ECCD). One needs:

- good pression
- correct timing for ECCD deposition
- integrated control is foreseen for ITER
- preemptive control shows to be the most efficient

# MAIN TAKE AWAY: (1,1) CONTROL




Sawtooth and continuous (1,1) modes should be controlled together with NTMs.

Negative side of (1,1):

- can trigger NTM

Possible positive sides of (1,1):

- Can be potentially used to remove Helium ash from the core
- Can be used to redistribute current off-axis and get better performance

# CONCLUSIONS

The active control and prevention of MHD instabilities is one of the key requirements for controlling the plasma in current tokamaks and ITER.

H&CD is the mandatory actuator for MHD control. The H&CD is primarily required for controlling sawteeth and NTMs but also help a lot with other instabilities.

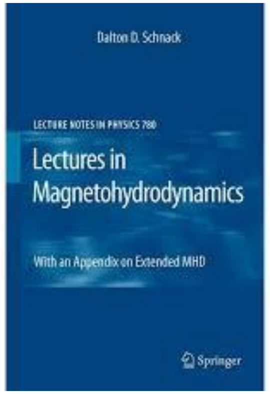
Instabilities do not always mean reduction of the confinement. Recent results show that it can be used for current redistribution and removing Helium ash from the core.

It is expected that active research in this area will result in improved plasma scenarios for ITER.

# REFERENCES AND PUBLICATIONS

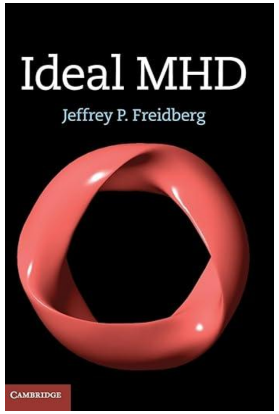
Nice and clear written course on MHD

**Dalton Schnack, “Lectures in Magnetohydrodynamics**: With an Appendix on Extended MHD“, Springer 2009



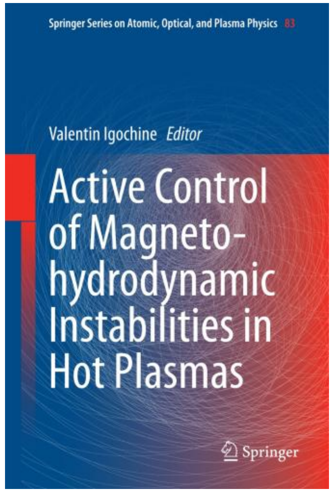

Classics on Ideal MHD

**Jeffrey Freidberg, “Ideal MHD”**, Cambridge University Press, 2007




Control of particular instabilities (sawteeth, ELM, disruptions, etc.)

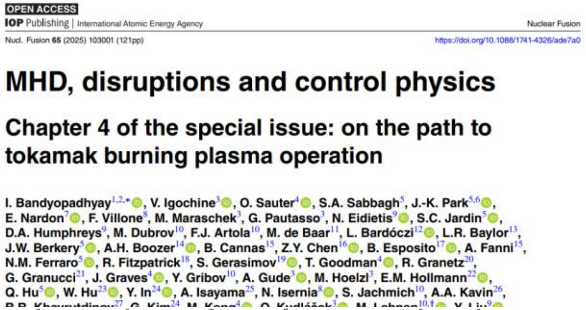
**V. Igochine (Ed.), “Active control of MHD instabilities in hot plasmas”**, Springer2015




Nuclear Fusion Special Issue: On the Path to Tokamak Burning Plasma Operation (**Chapter 4, MHD**)

**I.Bandyopadhyay, V.Igochine, O. Sauter, et.al.**

**Nucl. Fusion 65 (2025**) 103001 (121 pages)



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Nucl. Fusion 65 (2025) 103001 (121pp) https://doi.org/10.1088/1741-4326/ade7a0

**MHD, disruptions and control physics**

**Chapter 4 of the special issue: on the path to tokamak burning plasma operation**

I. Bandyopadhyay[1,2,*], V. Igochine[3], O. Sauter[4], S.A. Sabbagh[5], J.-K. Park[5,6], E. Nardon[7], F. Villone[8], M. Maraschek[3], G. Pautasso[3], N. Eidietis[9], S.C. Jardin[5], D.A. Humphreys[9], M. Dubrov[10], F.J. Artola[10], M. de Baar[11], L. Bardóczi[12], L.R. Baylor[13], J.W. Berkery[5], A.H. Boozer[14], B. Cannas[15], Z.Y. Chen[16], B. Esposito[17], A. Fanni[15], N.M. Ferraro[5], R. Fitzpatrick[18], S. Gerasimov[19], T. Goodman[4], R. Granetz[20], G. Granucci[21], J. Graves[4], Y. Gribov[10], A. Gude[3], M. Hoelzl[3], E.M. Hollmann[22], Q. Hu[5], W. Hu[23], Y. In[24], A. Isayama[25], N. Isernia[8], S. Jachmich[10], A.A. Kavin[26],

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