Experimental Characterization of Microtearing Modes in the RFX-mod Reversed Field Pinch Plasma

M. Zuin

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Microtearing modes

- The microtearing (MT) mode is a high wave number drift-tearing mode driven unstable by the electron temperature gradient, (the long-wavelength counterpart is essentially current driven).
- MT modes can lead to chains of magnetic islands, whose overlapping brings to local stochastization of magnetic field lines => effective contribution to the thermal diffusivity through electron parallel motion along the wandering field lines.
- MT are expected to become stable at relatively low collisionality, $\nu << \omega^*$
- MT modes are nowadays studied either in connection with edge transport, or in the core of medium-temperature devices, in connection with strong ITBs and their possible coupling with other microinstabilities, like the electron temperature gradient (ETG) modes.
- Simulations for MAST show that MT appear to influence of the pedestal width, thus somehow affecting the ELM cycle (Wilson EPS2015)

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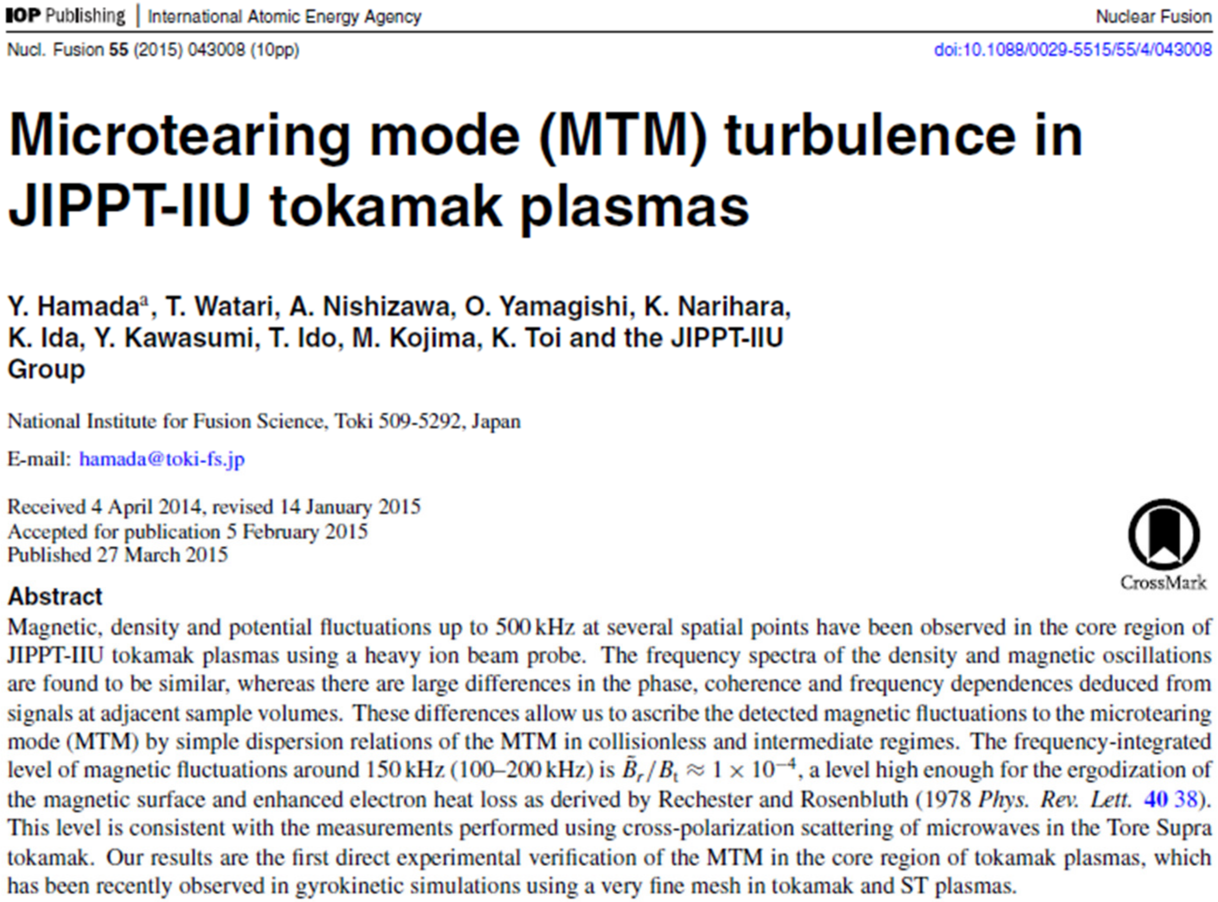
MT in the tokamak

Hamada et al. NF 2014



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Microtearing mode (MTM) turbulence in JIPPT-IIU tokamak plasmas

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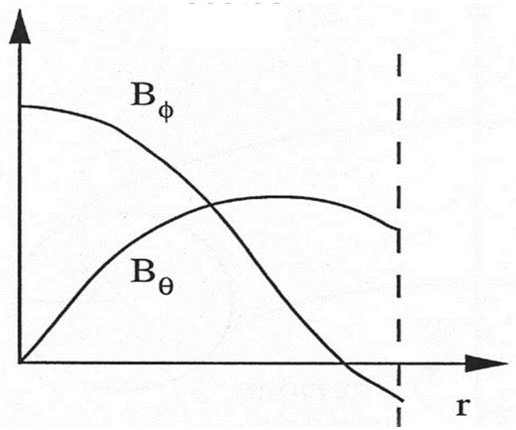
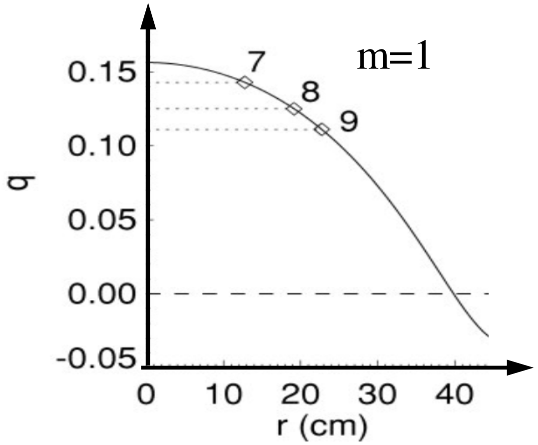
Abstract

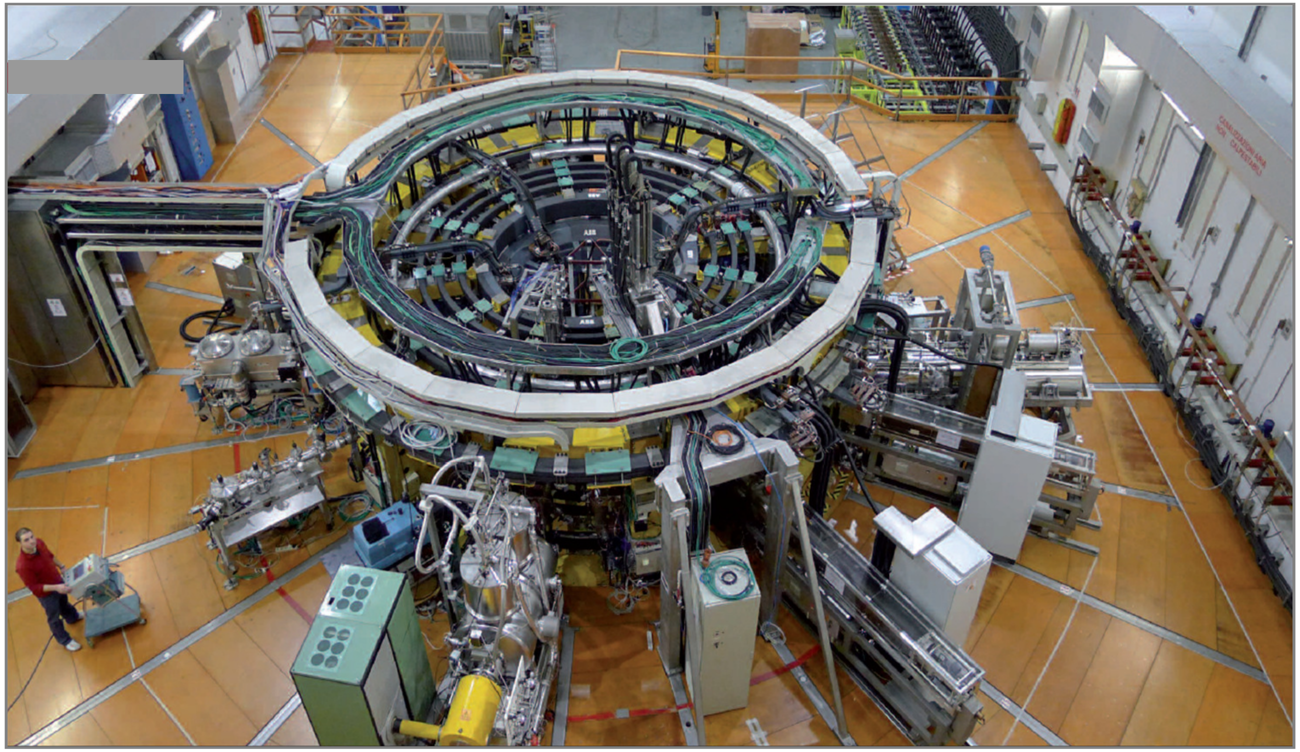
Magnetic, density and potential fluctuations up to 500 kHz at several spatial points have been observed in the core region of JIPPT-IIU tokamak plasmas using a heavy ion beam probe. The frequency spectra of the density and magnetic oscillations are found to be similar, whereas there are large differences in the phase, coherence and frequency dependences deduced from signals at adjacent sample volumes. These differences allow us to ascribe the detected magnetic fluctuations to the microtearing mode (MTM) by simple dispersion relations of the MTM in collisionless and intermediate regimes. The frequency-integrated level of magnetic fluctuations around 150 kHz (100–200 kHz) is $\tilde{B}_r/B_t \approx 1 \times 10^{-4}$, a level high enough for the ergodization of the magnetic surface and enhanced electron heat loss as derived by Rechester and Rosenbluth (1978 *Phys. Rev. Lett.* **40** 38). This level is consistent with the measurements performed using cross-polarization scattering of microwaves in the Tore Supra tokamak. Our results are the first direct experimental verification of the MTM in the core region of tokamak plasmas, which has been recently observed in gyrokinetic simulations using a very fine mesh in tokamak and ST plasmas.

The RFX-mod reversed field pinch

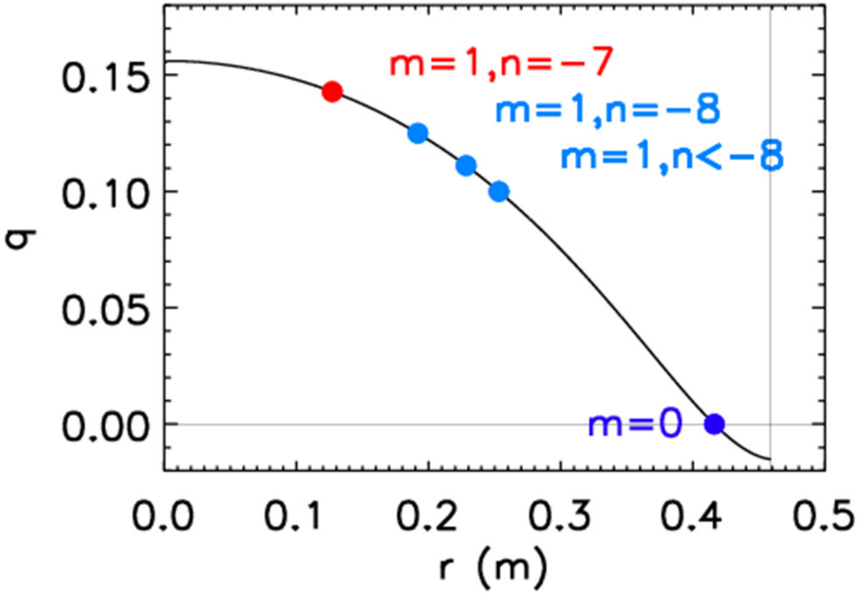
Major Radius	2 m
Minor Radius	0.46 m
Max Plasma Current	2 MA
Max Toroidal Magnetic Field	0.7 T
Pulse duration	0.5 s







- The B_ϕ profile implies that a large j_θ is flowing into the plasma.
- However, in stationary condition no E_θ is applied → who drives j_θ?
- m = 1 tearing modes give rise to an effective electric field ("dynamo field") through the nonlinear term in Ohm's law:



$$b \propto \exp[i(m\theta - n\phi)]$$

$$\mathbf{E} + \left\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \right\rangle = \eta \mathbf{j}$$

m = 1 MHD modes

resonance condition:

$$q(r) = \frac{rB_\phi(r)}{RB_\theta(r)} = \frac{m}{n}$$

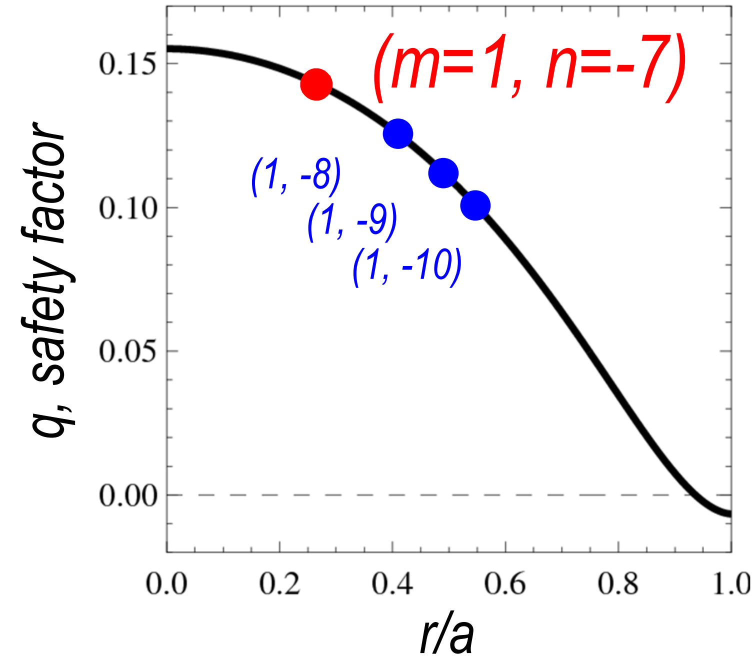
This is called Multiple Helicity (MH) condition

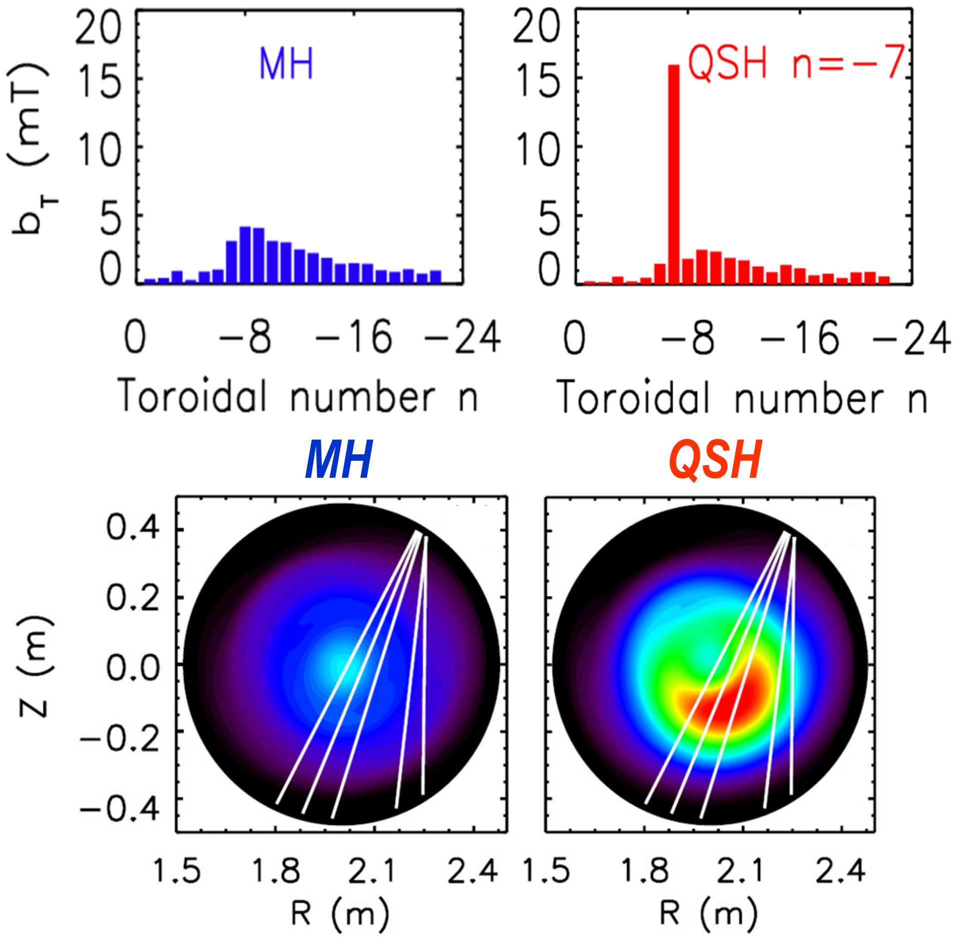
From Multiple Helicity to (Q)Single Helicity

Quasi Single Helicity (QSH) *states appear, where the most internally resonant m = 1 mode (n = 7 for RFX-mod) dominates, and the secondary mode amplitudes are reduced*

A typical feature is the appearance of a hot magnetic island.

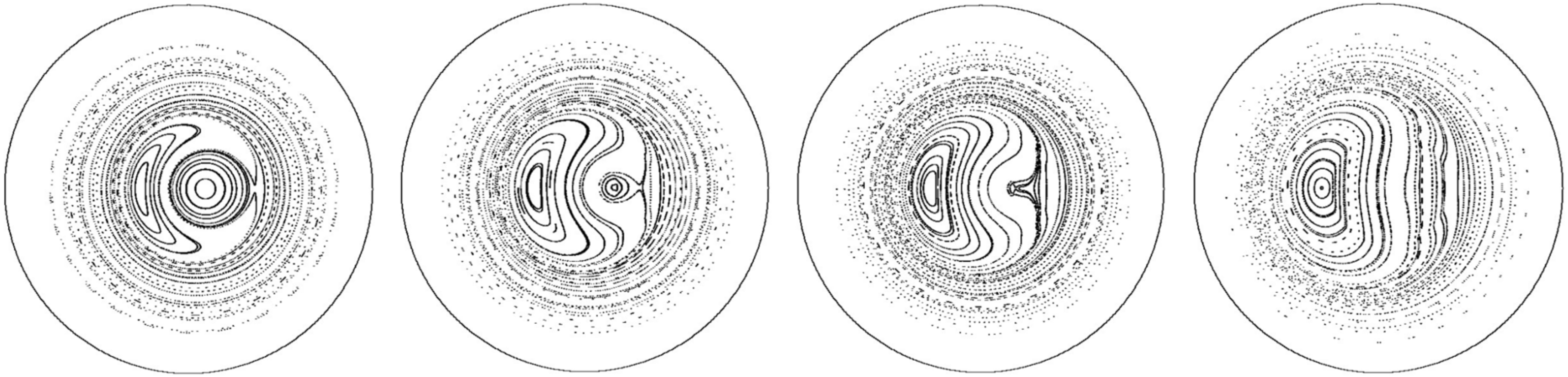
Weak m=1 secondary modes





Single Helical Axis (SHAx) states

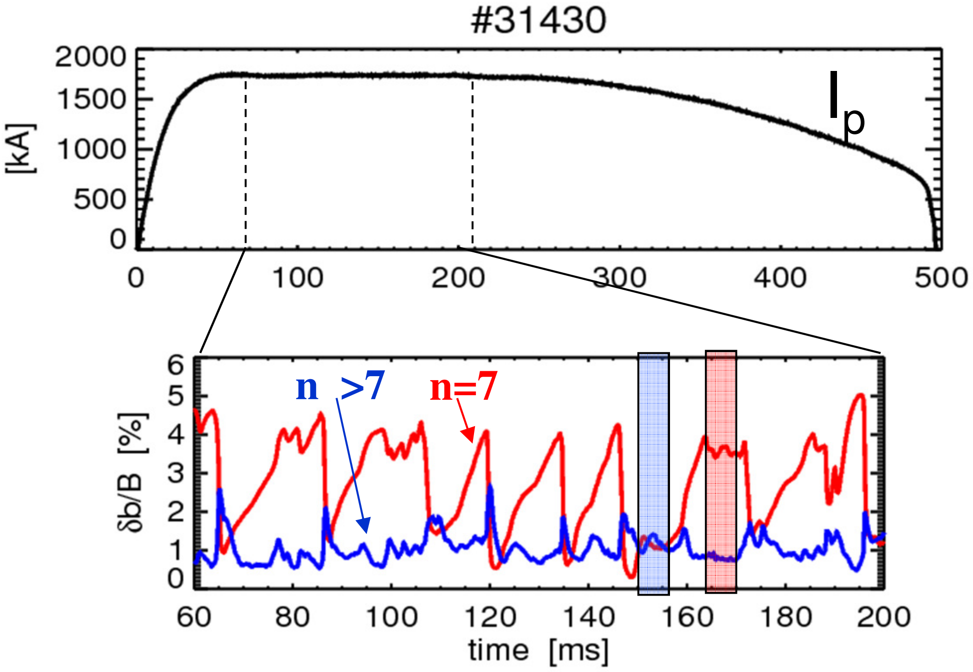
- *When the dominant mode amplitude exceeds a threshold, the main magnetic axis collapses onto the island X-point and the separatrix is expelled.*
- *The island O-point remains as the magnetic axis of a helically distorted plasma.*
- *We call this condition* ***Single Helical Axis (SHAx)*** *state,*
- *SHAx states are theoretically predicted to be* ***more resilient to chaos****.*



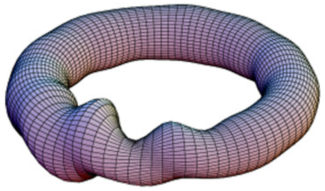
$b_\phi / B \approx 2\%$ $b_\phi / B \approx 3\%$ $\boxed{b_\phi / B \approx 4\%}$ $b_\phi / B \approx 5\%$

R. Lorenzini et al., Nature Phys. 2009
P. Piovesan, M. Zuin et al. Nucl. Fusion 2009
D.F. Escande et al., PRL 2000

Helical states and transport barriers

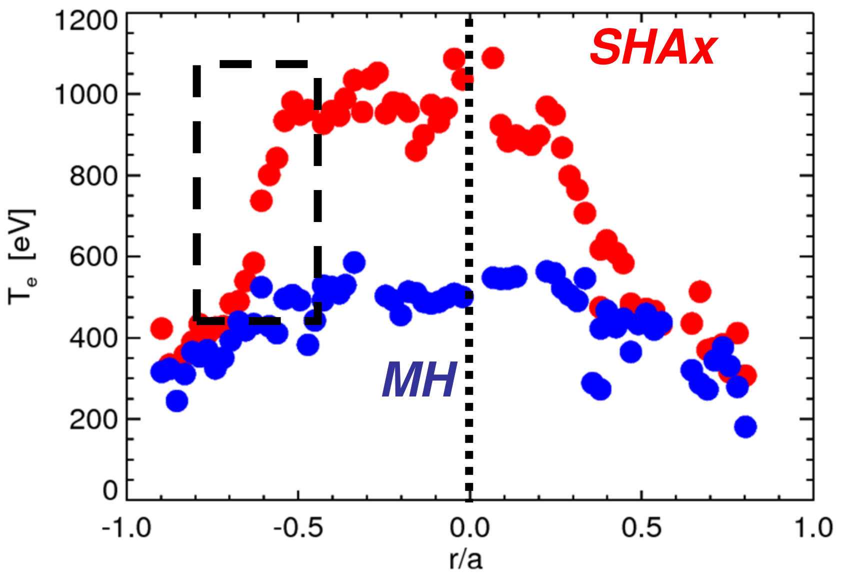


multiple helicity
MH



(deformation x 10)

single helicity
SHAx

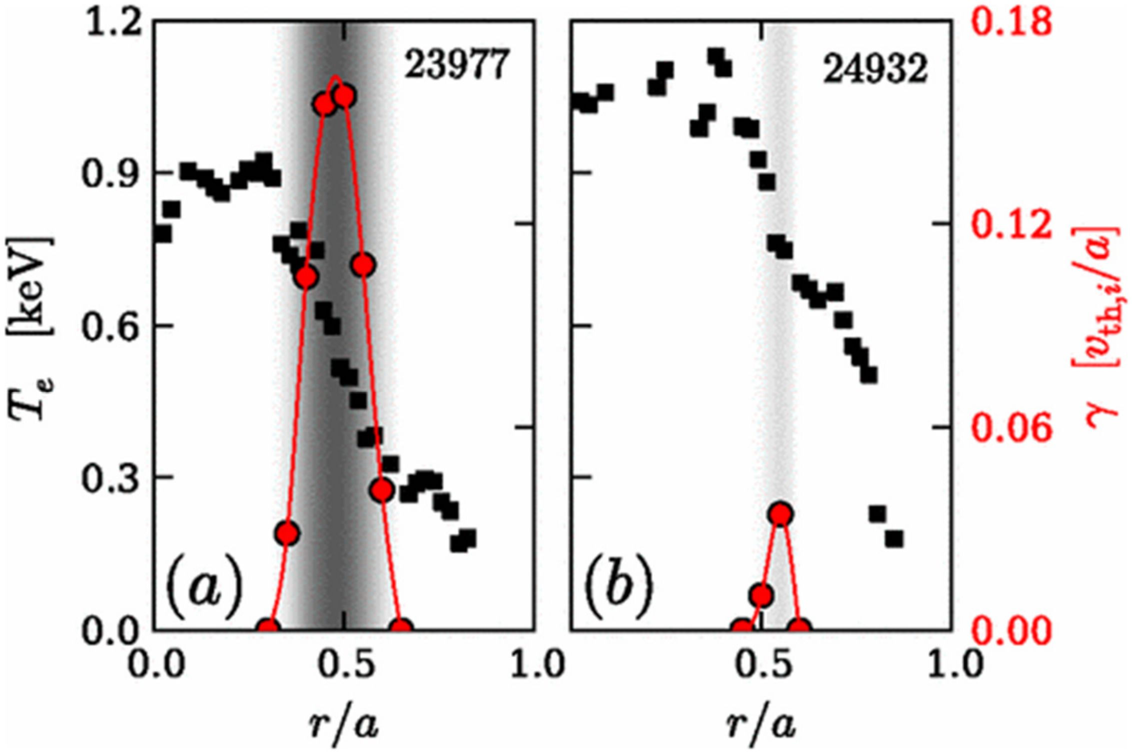


- One helical magnetic axis (SHAx, Single Helical Axis) spontaneously forms at high I_p levels (>1.5MA)
- Reduced chaos
- **<u>el. Internal electron barrier</u> eITB**

Lorenzini et al. Nature Phys. 2009

Microtearing modes predicted to become (linearly) unstable, flux tube GS2 code

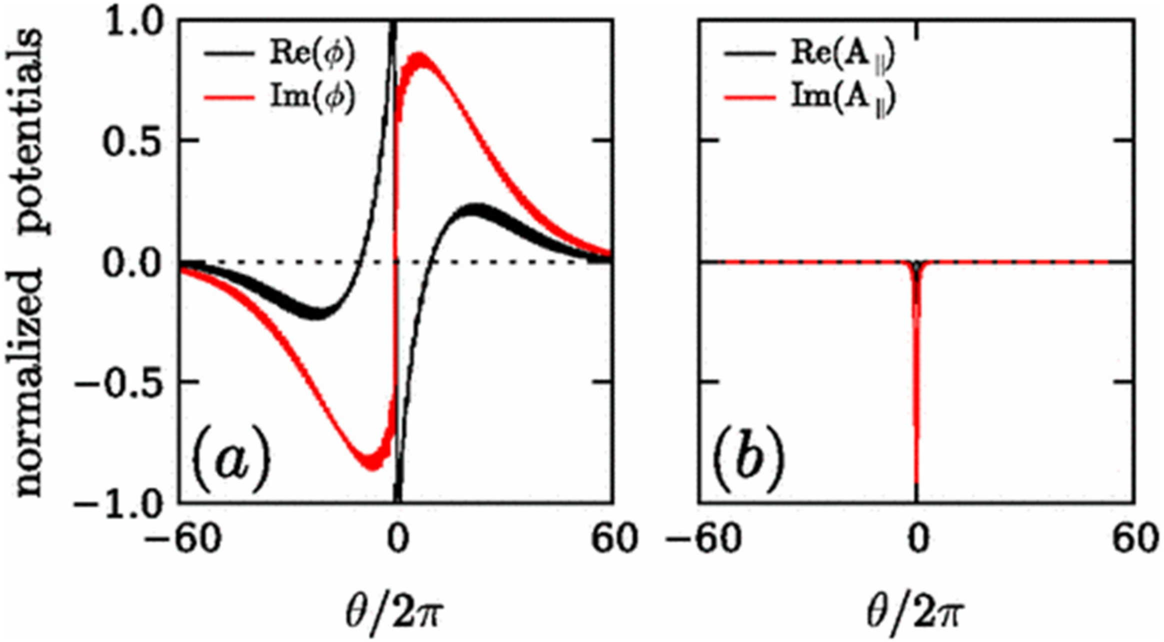
Predebon et al. PRL10

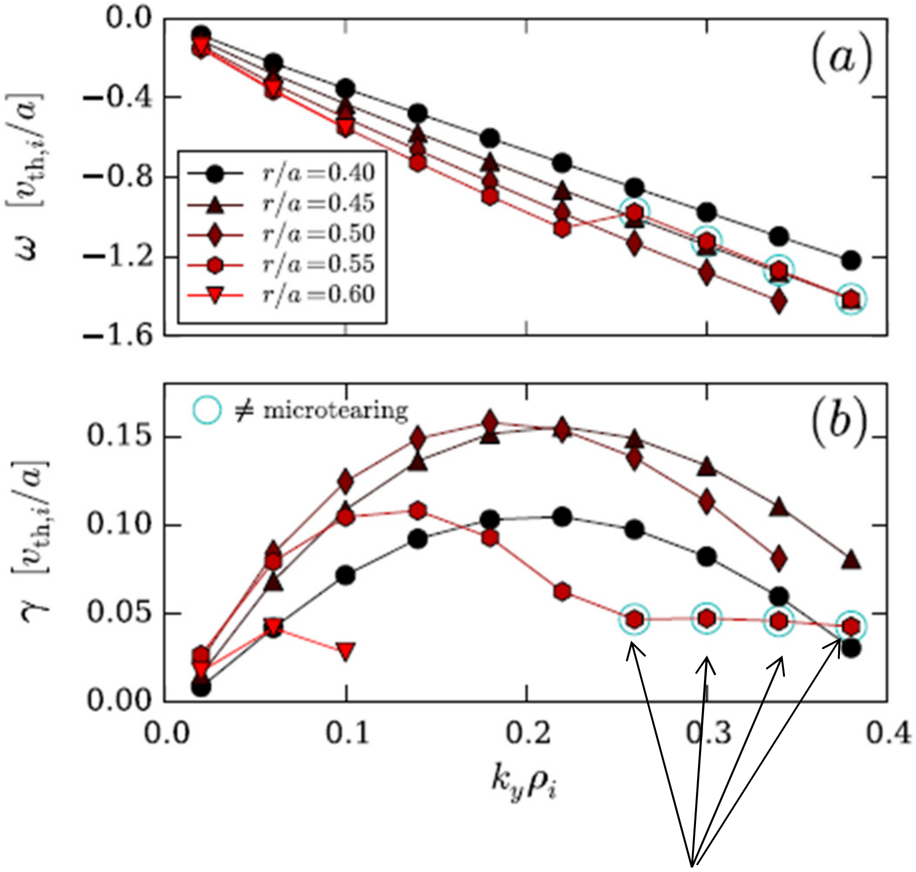


Predebon et al. PRL10

Tearing nature of such instabilities:

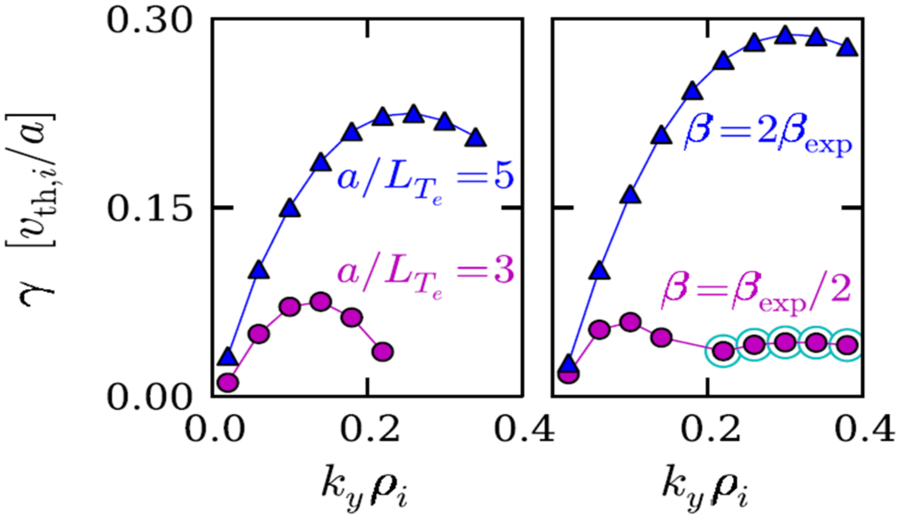
- odd parity for the electrostatic potential
- even for the parallel magnetic vector potential $A_{//}$





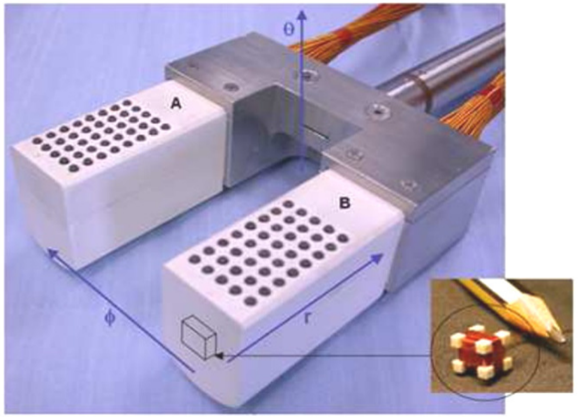
Not MT

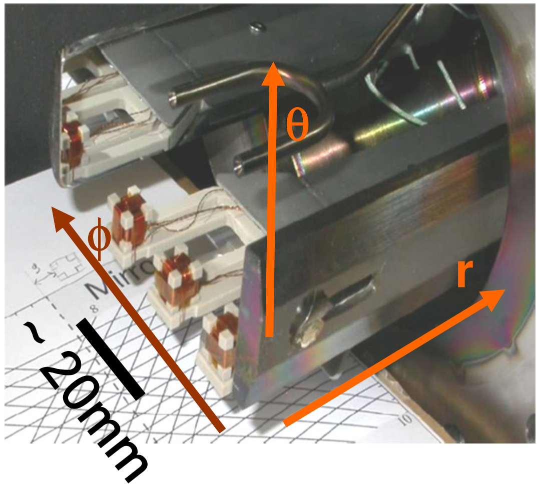
- MT modes are characterized by a propagation in the electron diamagnetic direction
- Growth rates get larger for higher values of a/L_{Te} and β.



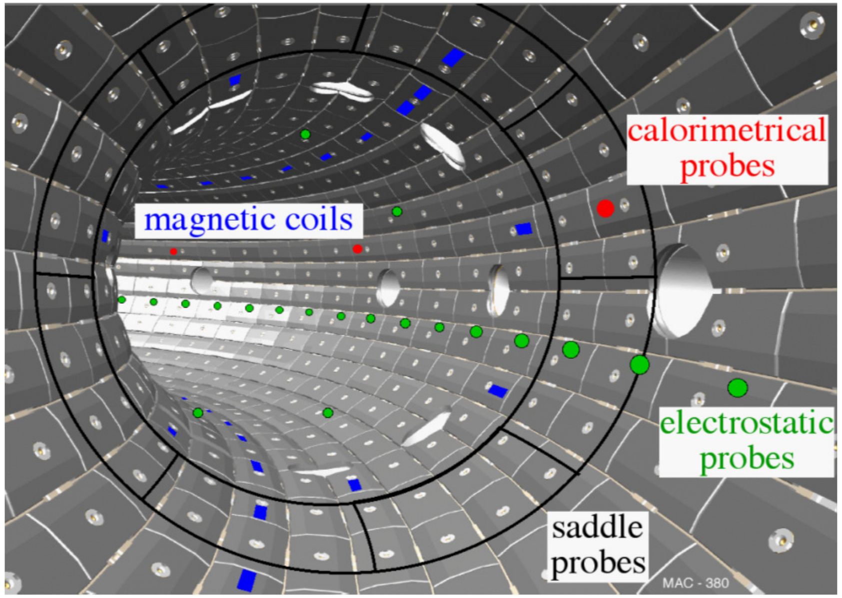
Predebon et al. PRL10

The diagnostic set-up





Systems of magnetic coils measuring the time derivative of the three components of the magnetic field ($\mathbf{b}'_r$, $\mathbf{b}'_p$, $\mathbf{b}'_t$) in various radial, poloidal and toroidal positions.



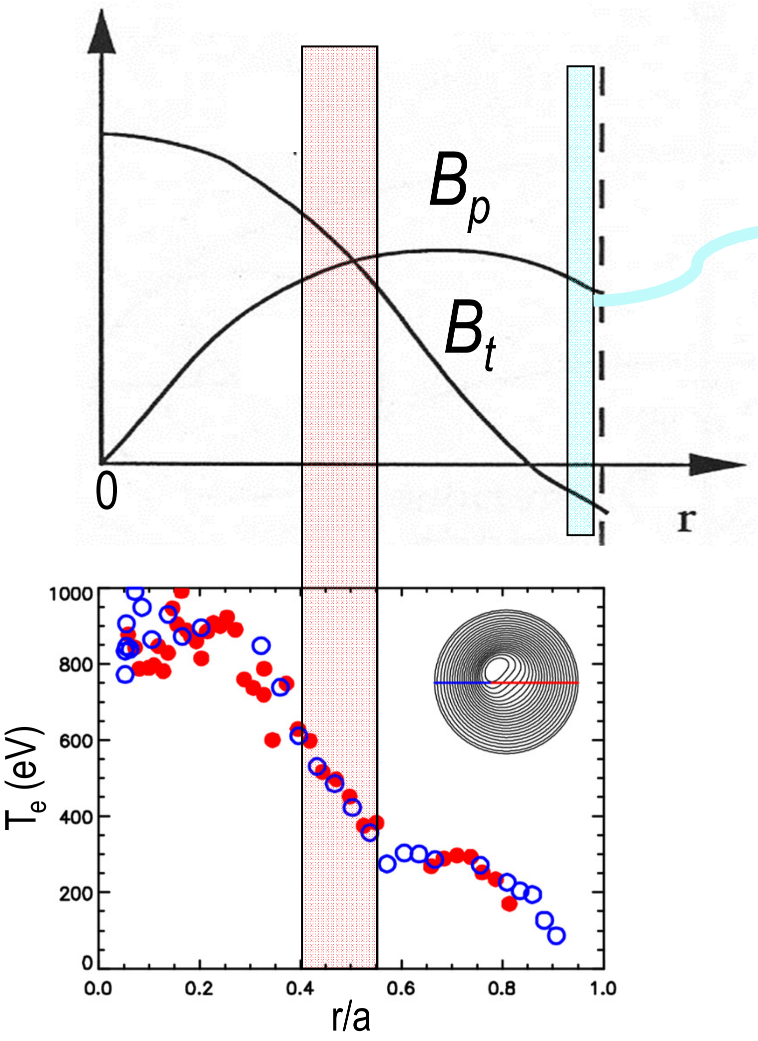
- ❖ **sampling rate:** ***up to 10 MHz***
- ❖ **probe location:** ***r/a~1***
- ❖ ***Coils distance: 20 mm***

❖ ***High mode numbers estimation:***

$$m \lesssim 16$$

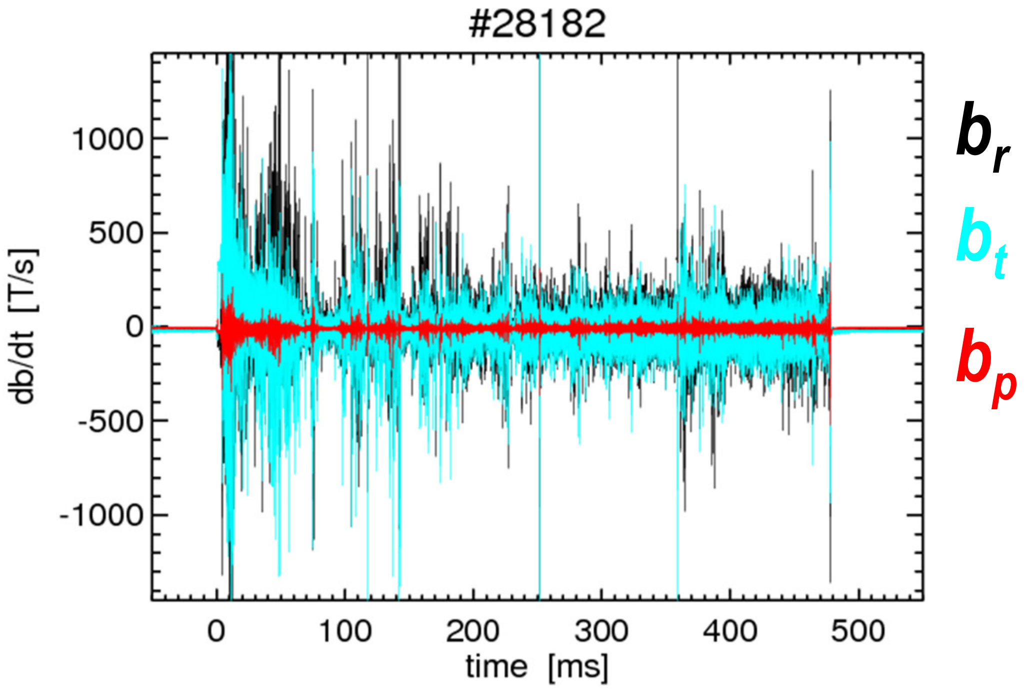
$$n \lesssim 350$$

Fluctuating magnetic components

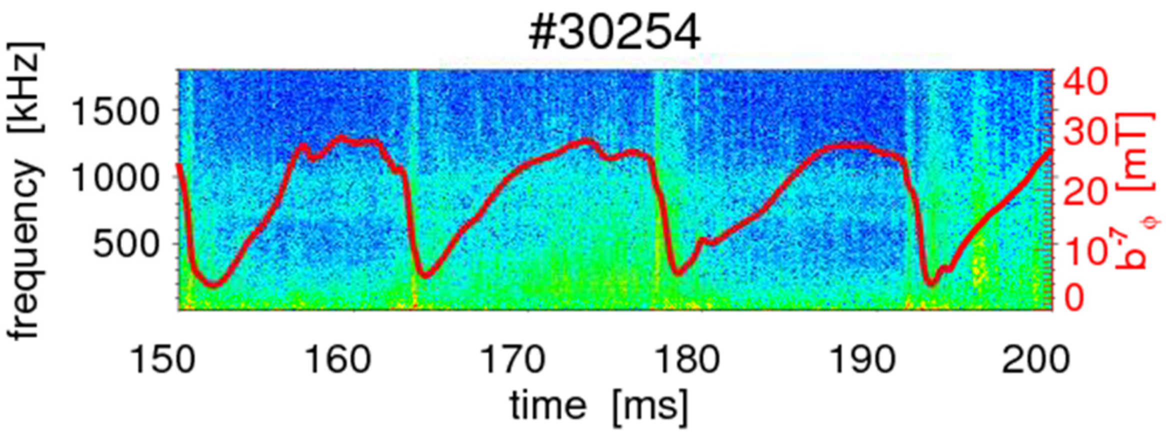


b_r (and ***b_t***) would be the perfect component to study microtearing modes, **but** edge measurements are strongly affected by edge-resonant resistive modes

b_p is much less affected by edge modes: **b_p** $\approx b_{//}$

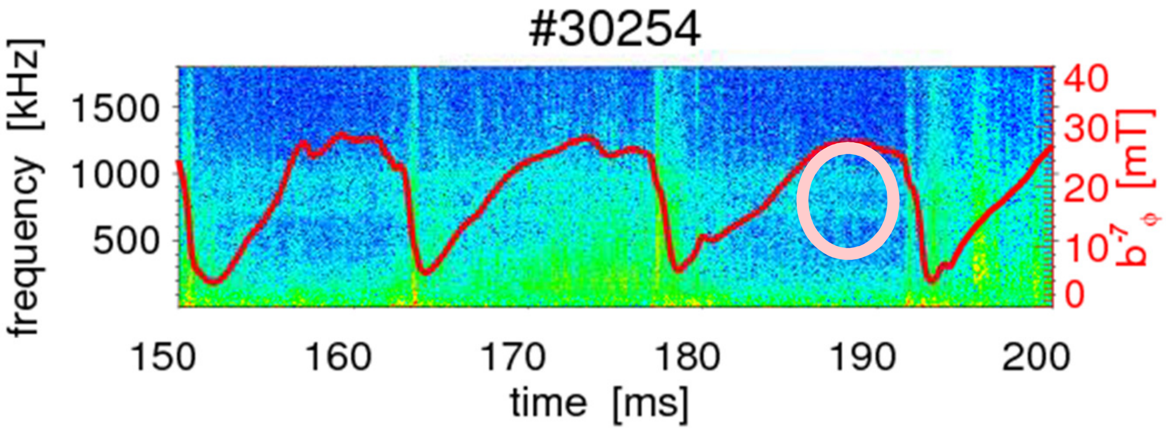


Frequency and k-space spectra

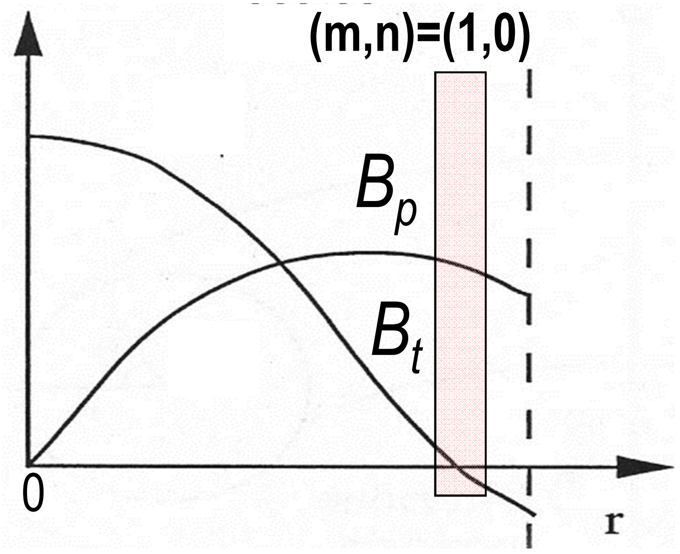


The magnetic fluctuation spectra δb_p are very reach, but the various components are well separated in Fourier space (f,k)

Frequency and k-space spectra



$$k = k_{||} \approx 2\ m^{-1}$$



non resonant

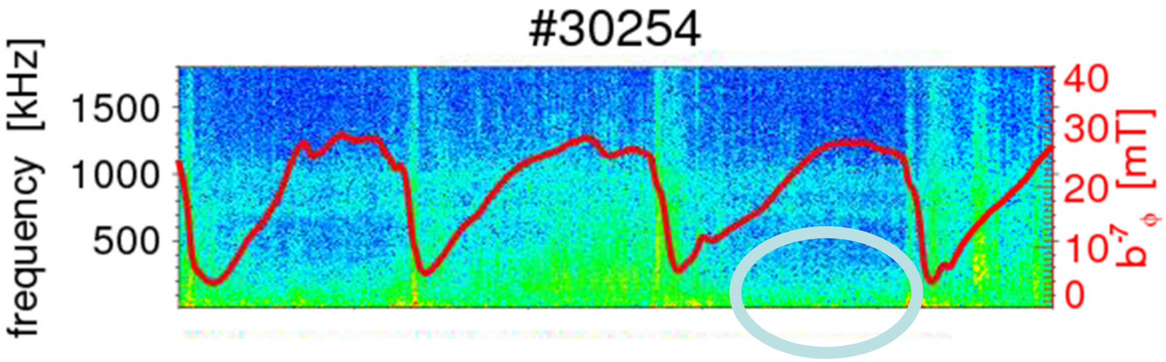
Global Alfvén modes:

$$\omega = k_{||}\, v_A$$

- *localized around q=0*
- *at a minimum of the Alfvén continuum*

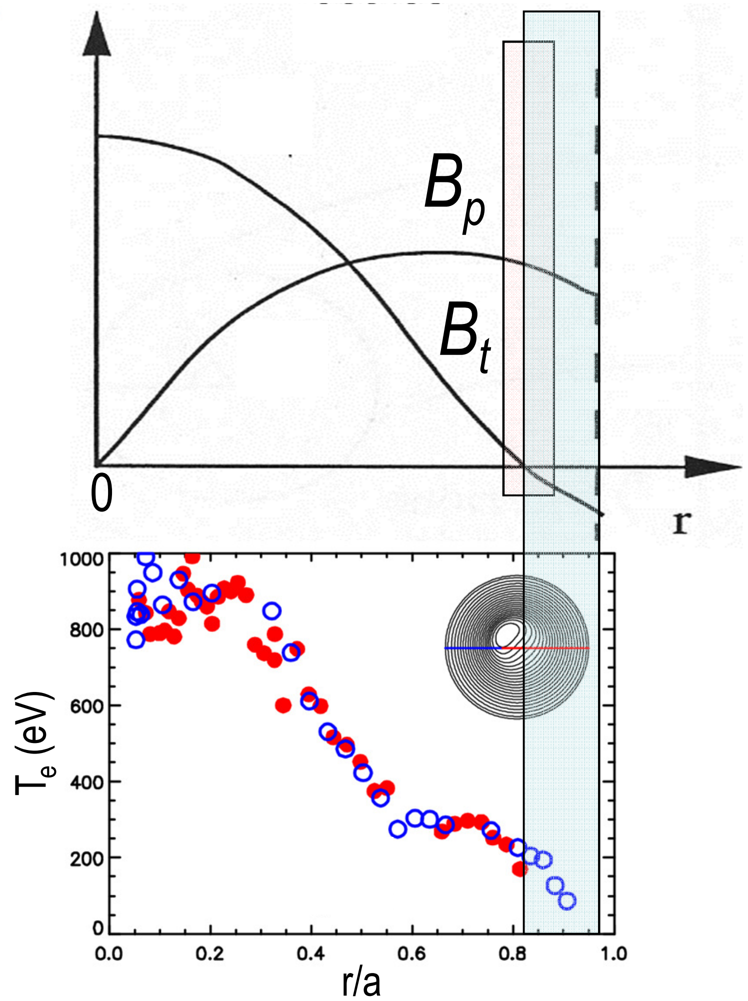
Spagnolo et al. NF 2011

Frequency and k-space spectra



m/n=(0,1)/30

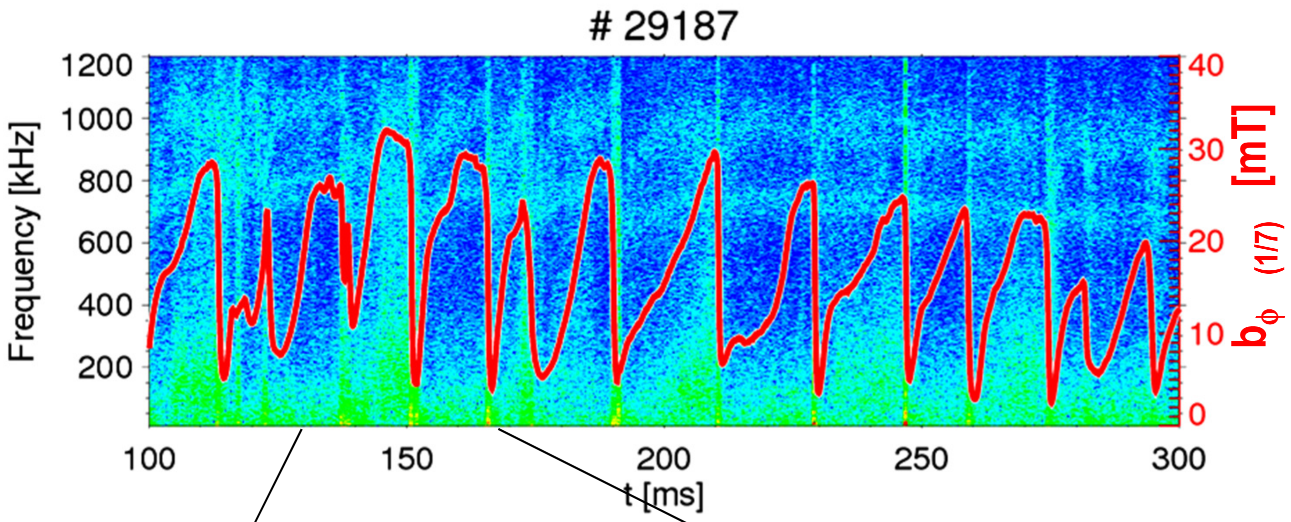
$k = k_\perp \approx 10\ m^{-1}$



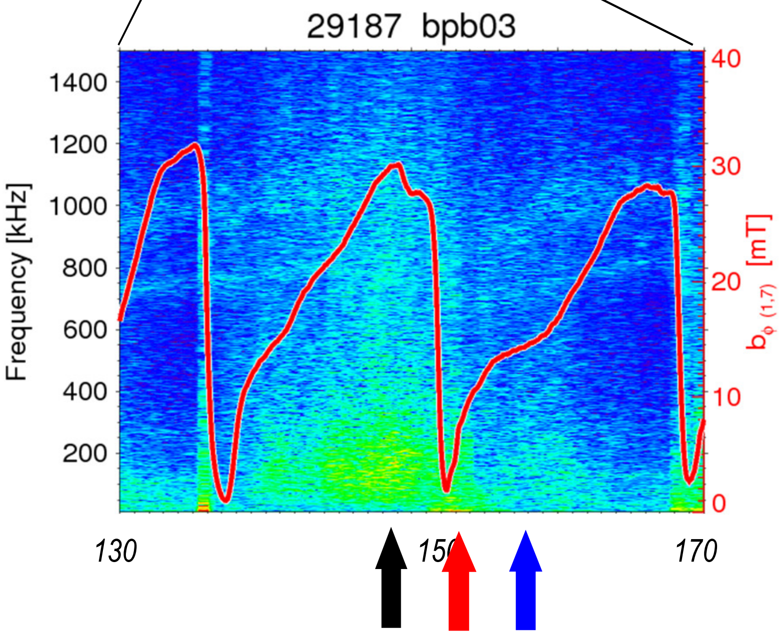
Edge <u>resonant</u> pressure driven modes

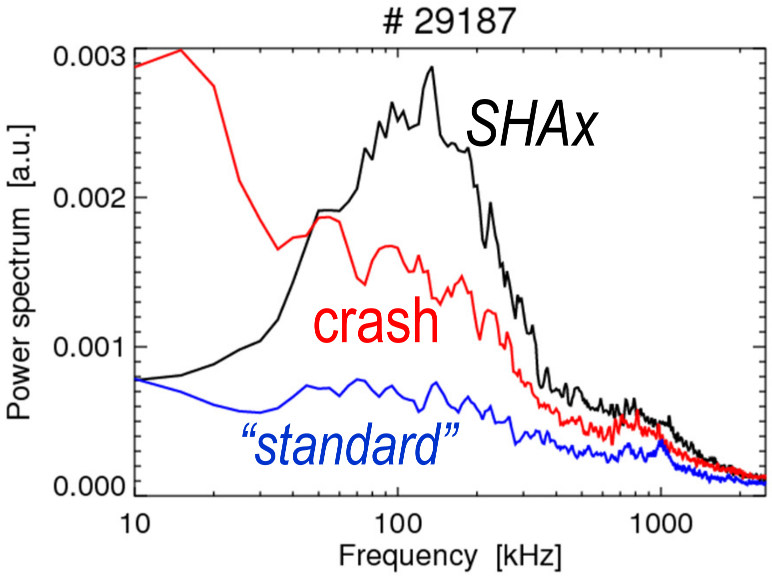
(m,n)=(0-1, 20)

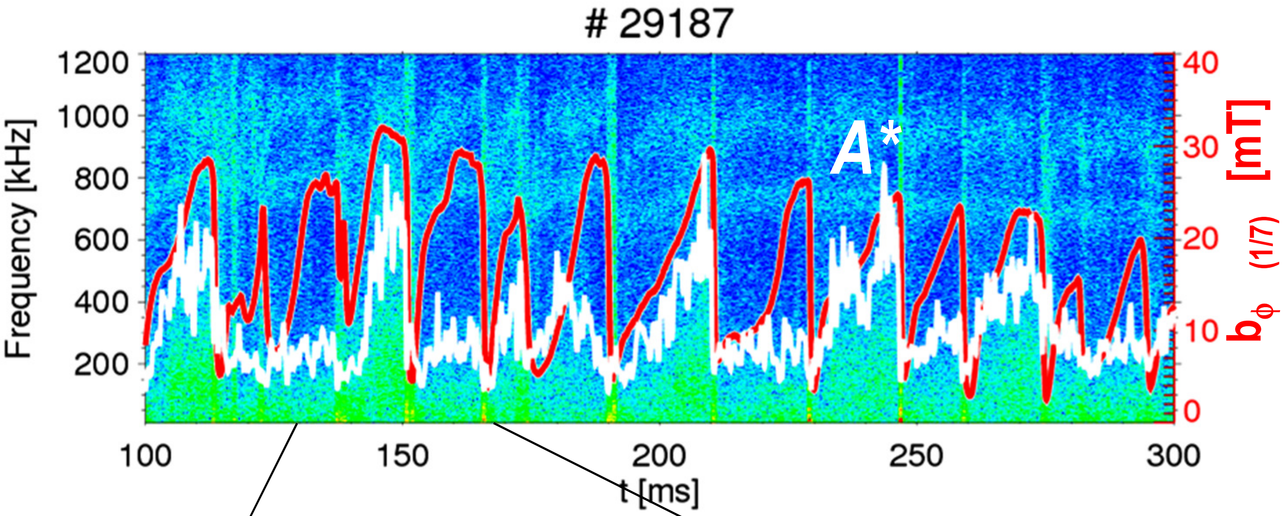
Zuin NF 2010
Paccagnella POP (2013)



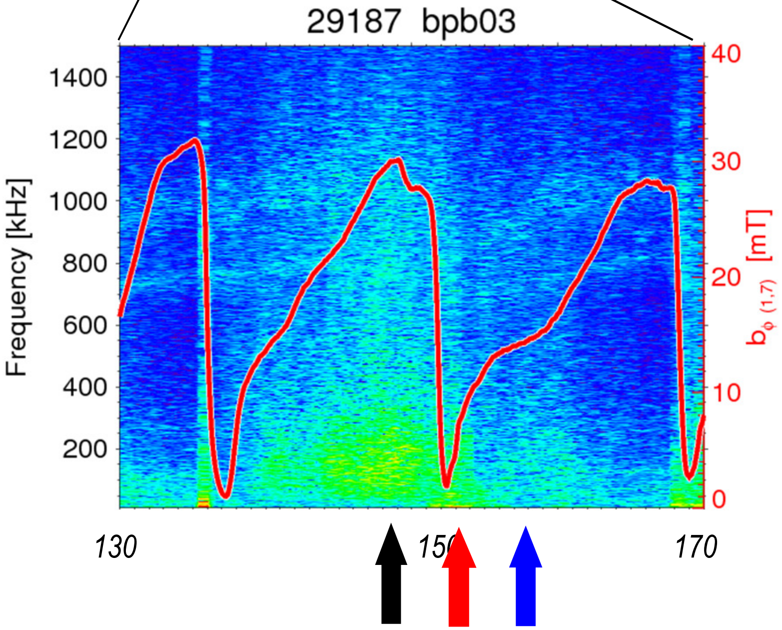
A broad peak in the power spectrum forms during some of the SHAx phases

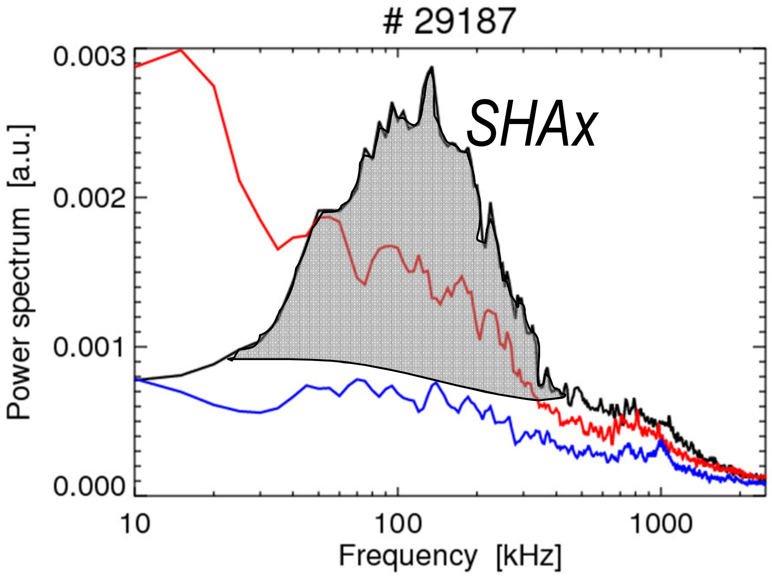




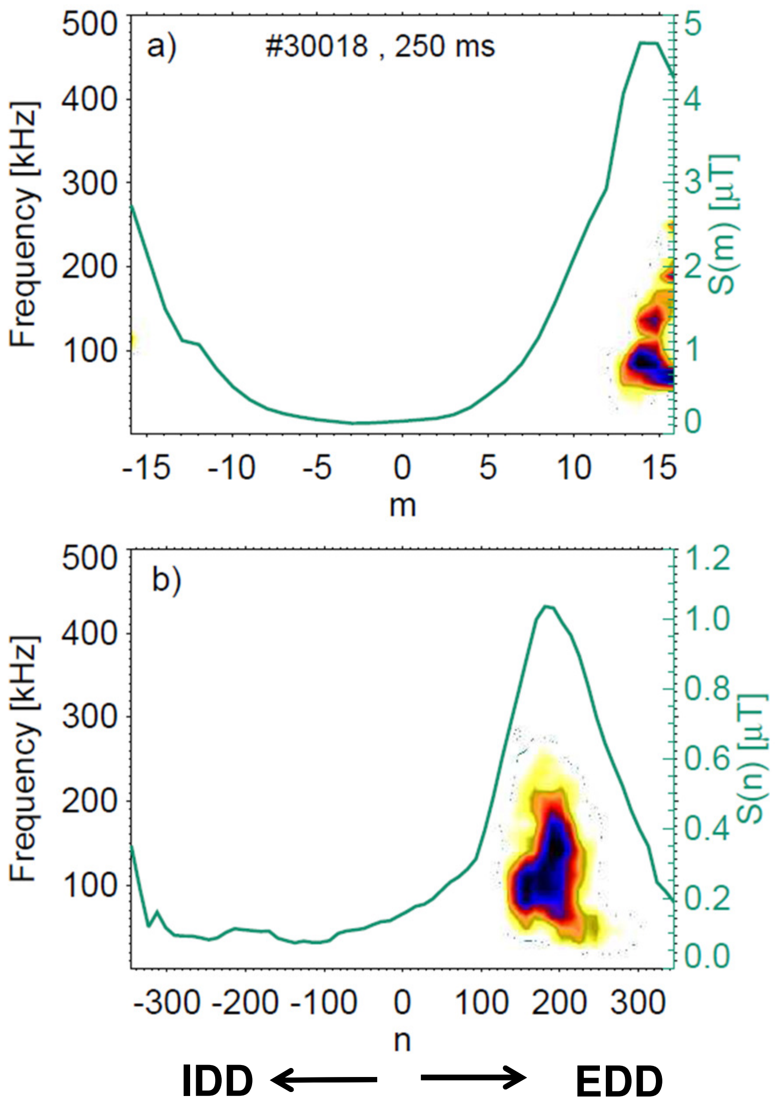


A broad peak in the power spectrum forms in *some* of the SHAx phases





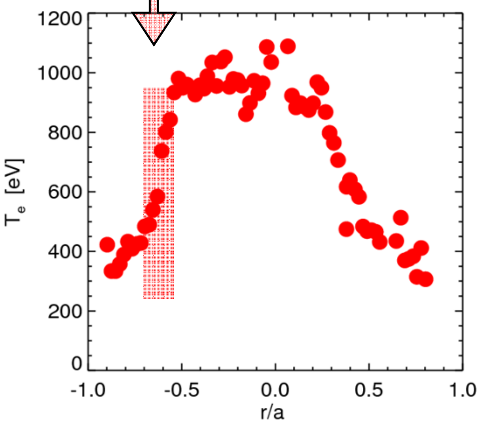
Experimental wavelength determination



By means of the 2-point technique applied on close signals we measure: ***(m,n) ~ (15,200)***
These values correspond to a resonant condition:

$$q(r_{res}) = m/n, \quad r_{res}/a \approx 0.6$$

i.e. in the region of the max ∇T_e



$$\Rightarrow \boxed{\lambda \sim 5\text{-}10\,\rho_i}$$

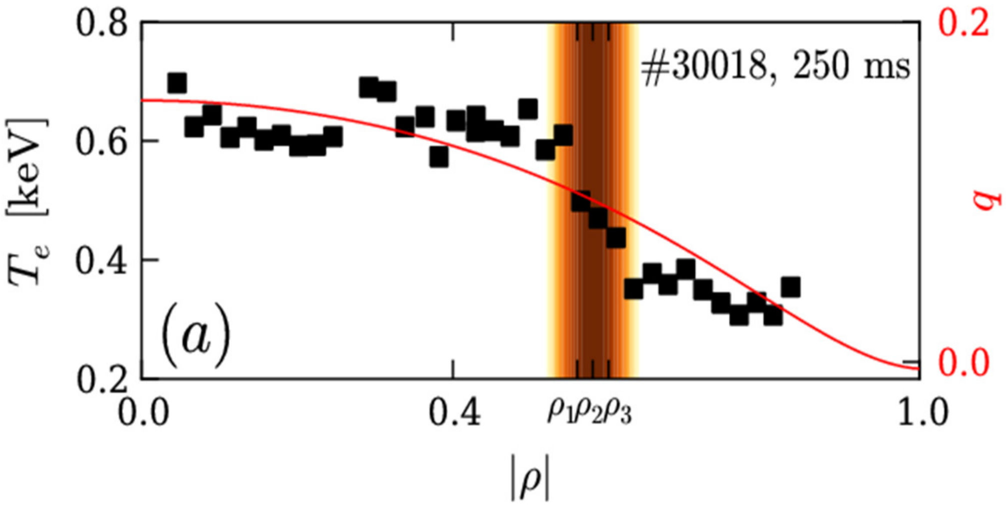
$$v_\phi = \frac{2\pi f}{n/R} \approx 10^4\,\mathrm{ms}^{-1}$$

$$v_{de} = \frac{\nabla p \times B}{e n_e B^2} \approx \frac{\nabla T_e}{B} \approx 10^4\,\mathrm{ms}^{-1}$$

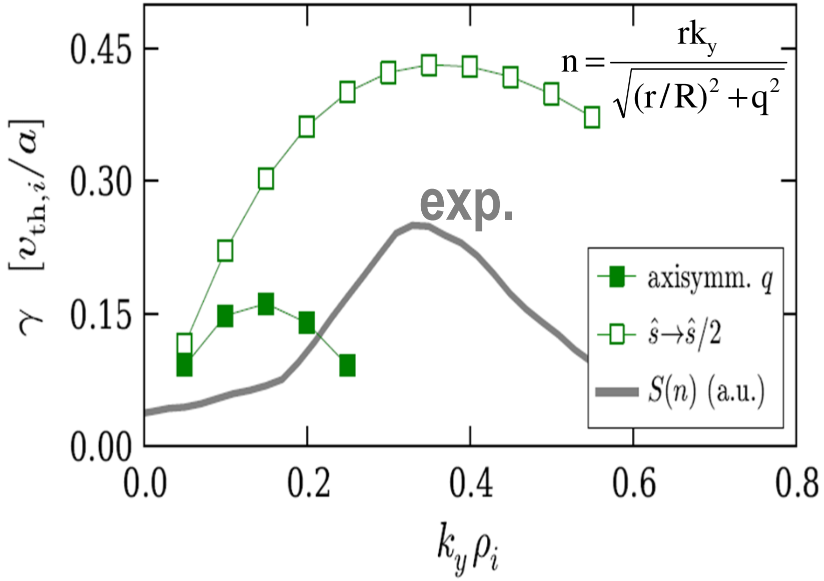
Zuin et al. PRL2014

Gyrokinetic linear stability analysis

Gyrokinetic flux-tube code GS2 [1]



Dedicated linear gyrokinetic calculations



- Microtearing modes linearly unstable
- Wavelengths (k_y) strongly depending on the shear
- **Good agreement:**

  γ spectrum - (saturated) exp. spectrum

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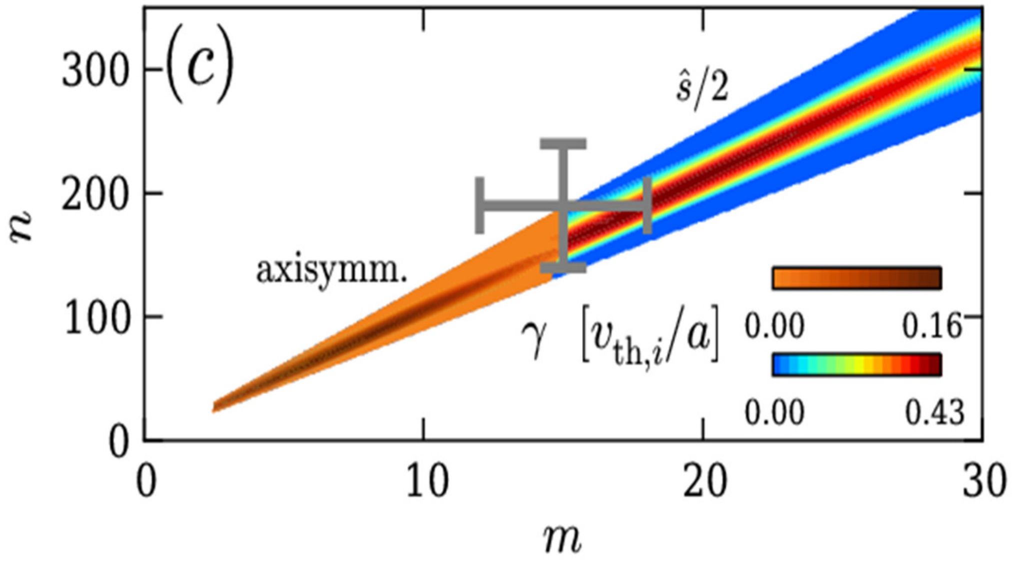
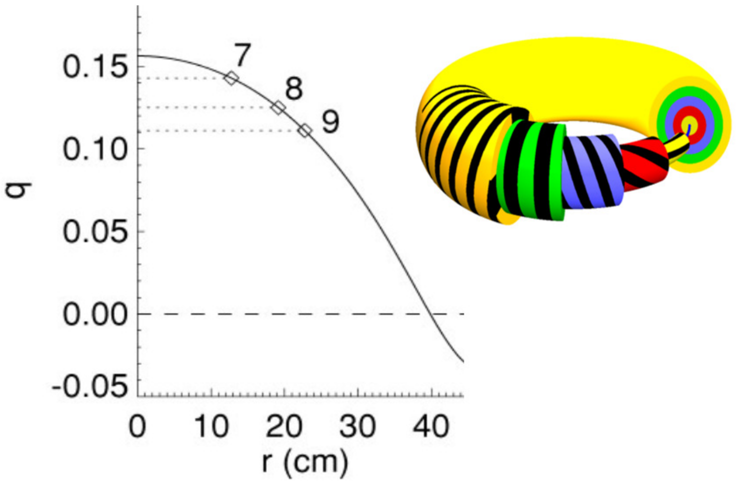
[1] http://gs2.sourceforge.net

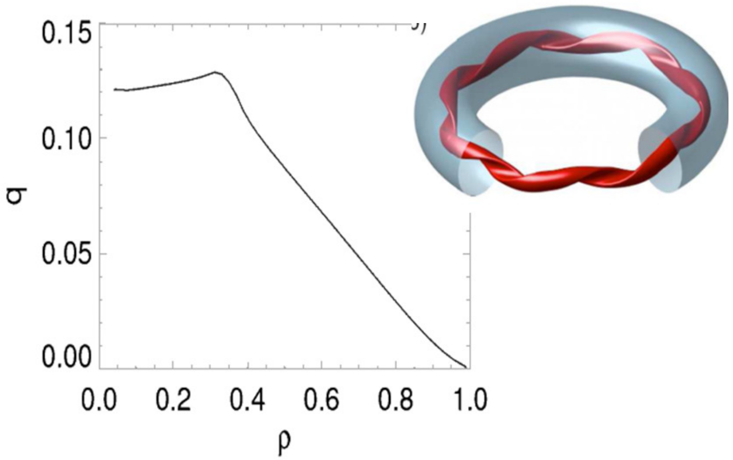
Experiment - theory



Axisimmetry

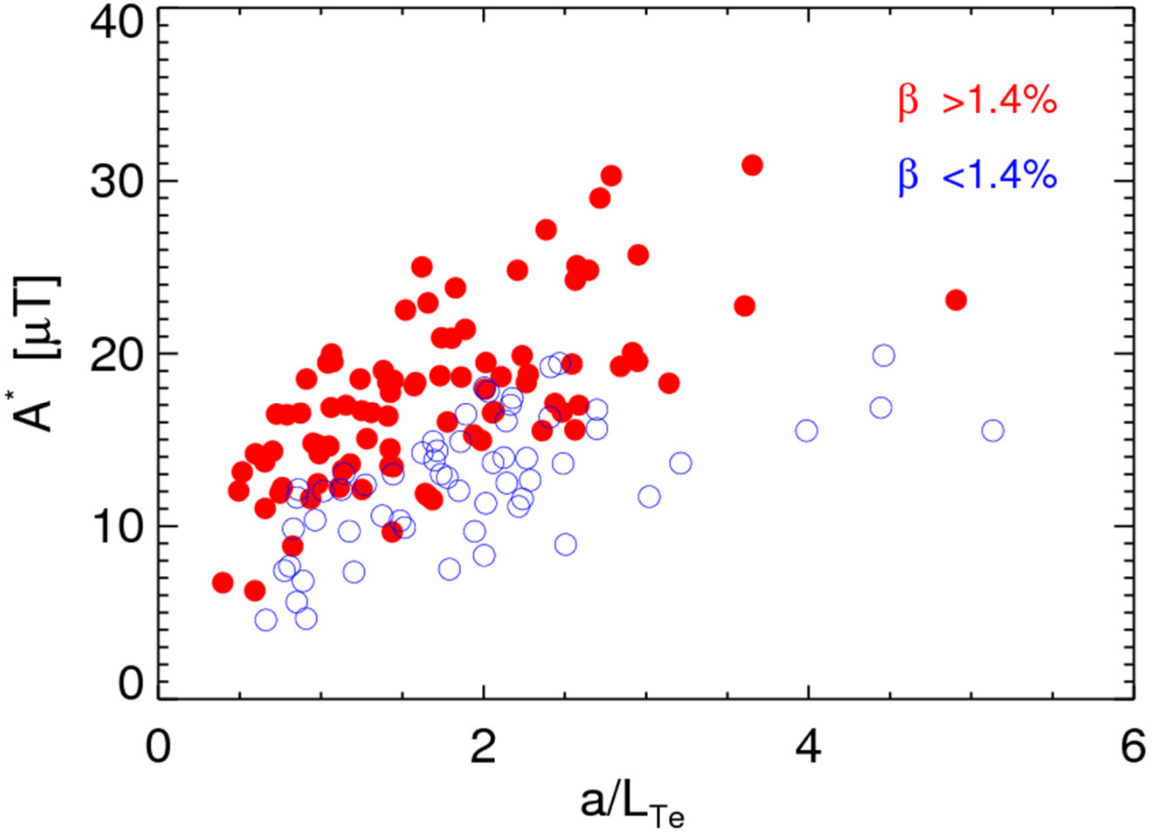


Helical symmetry



- Good agreement with the experimental data (almost same resonance condition and wavelengths), even better if a more realistic (non-axisymm.) q profile is considered

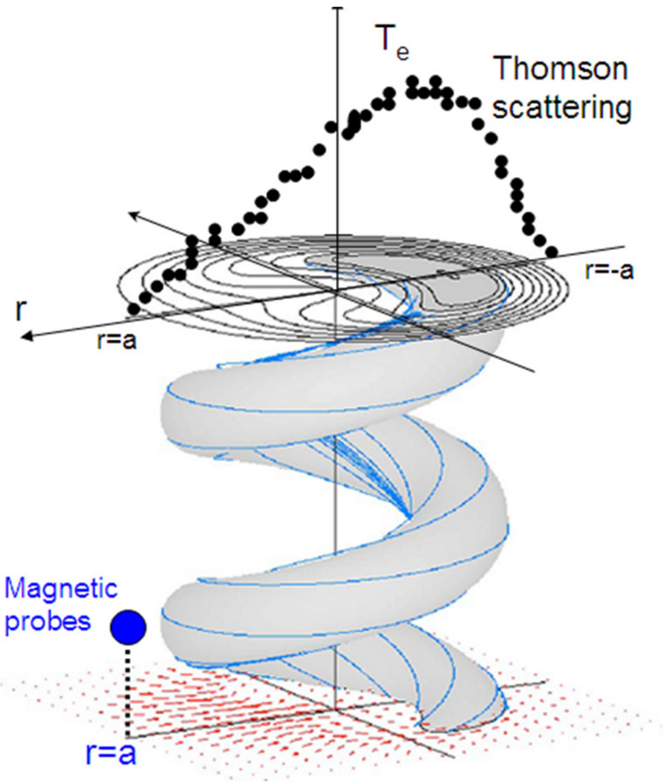
The amplitude depends on plasma parameters

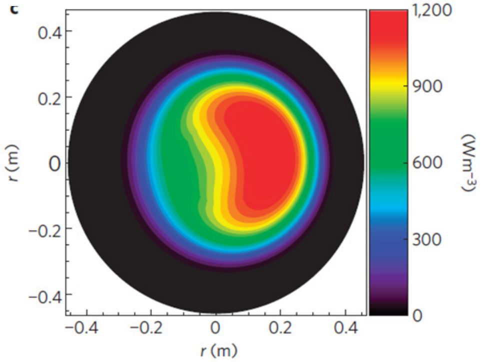


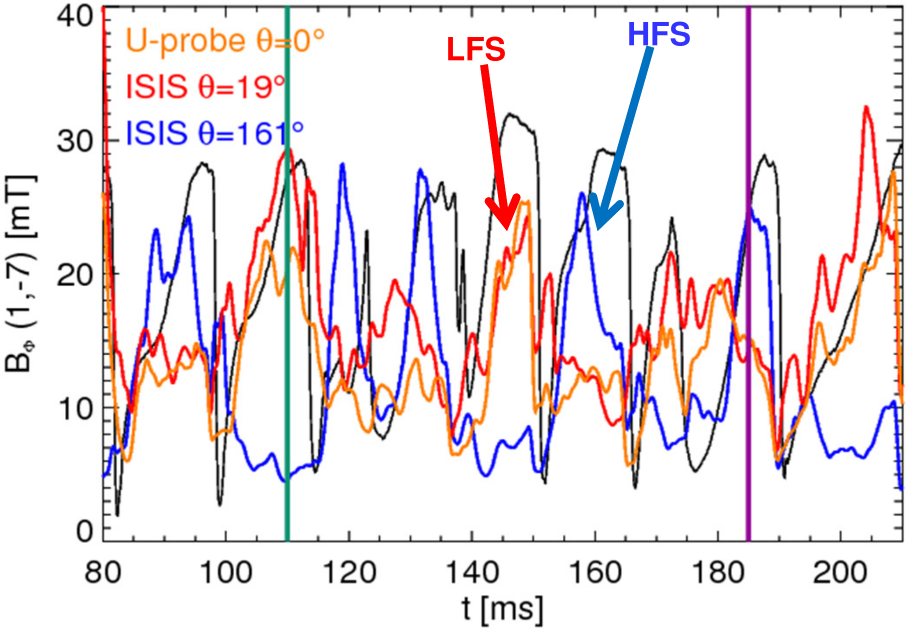
$$\beta = \frac{p}{B^2/2\mu_0}$$

- $L_{Te}=T_e/\nabla T_e$ determines the amplitude of the high frequency modes, along with β
- No clear a/L_{Te} threshold

The helical structure toroidally rotates so that the steep temperature gradient (convex side) is alternatively close and far w.r.t. the measuring probe.

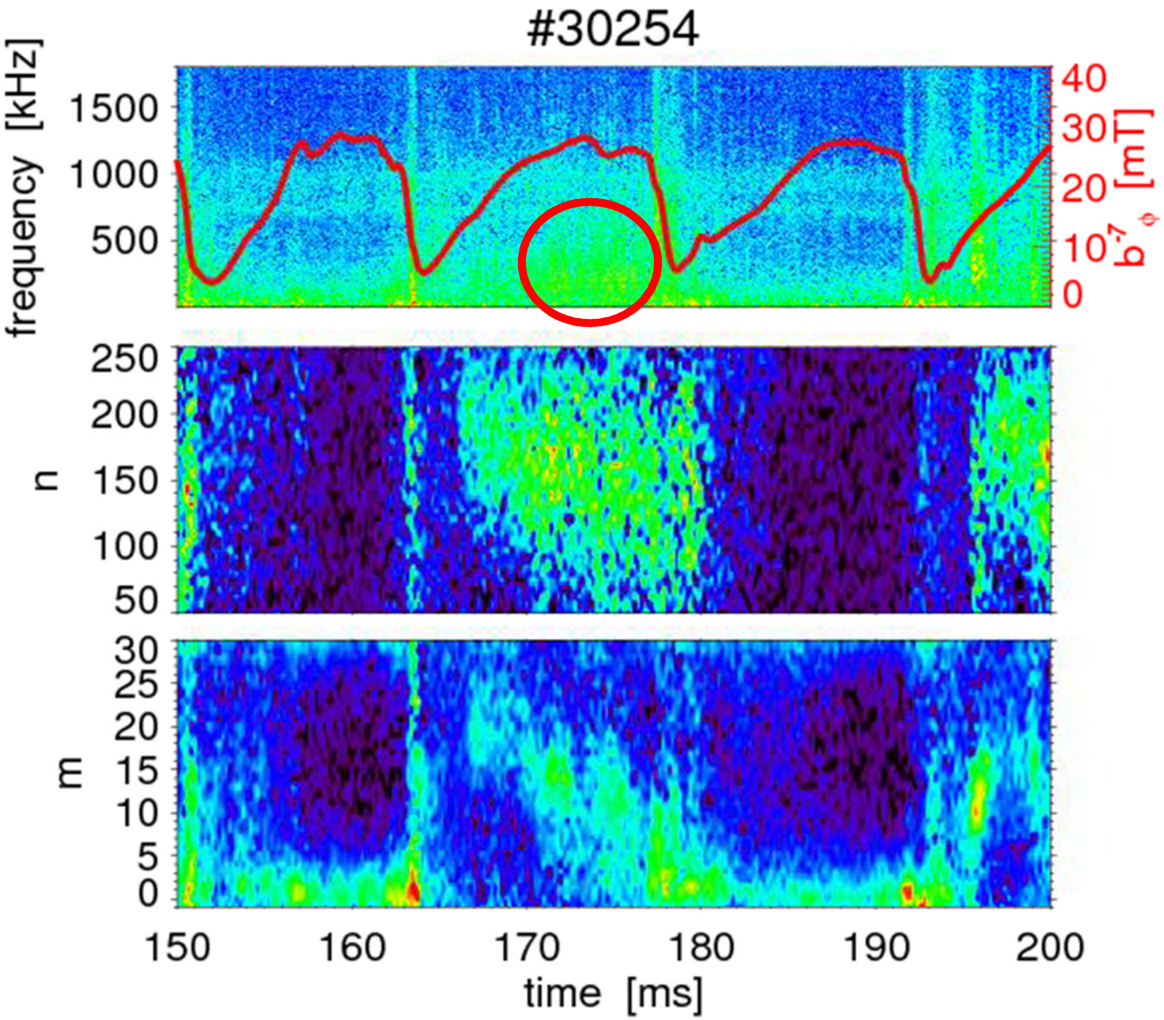




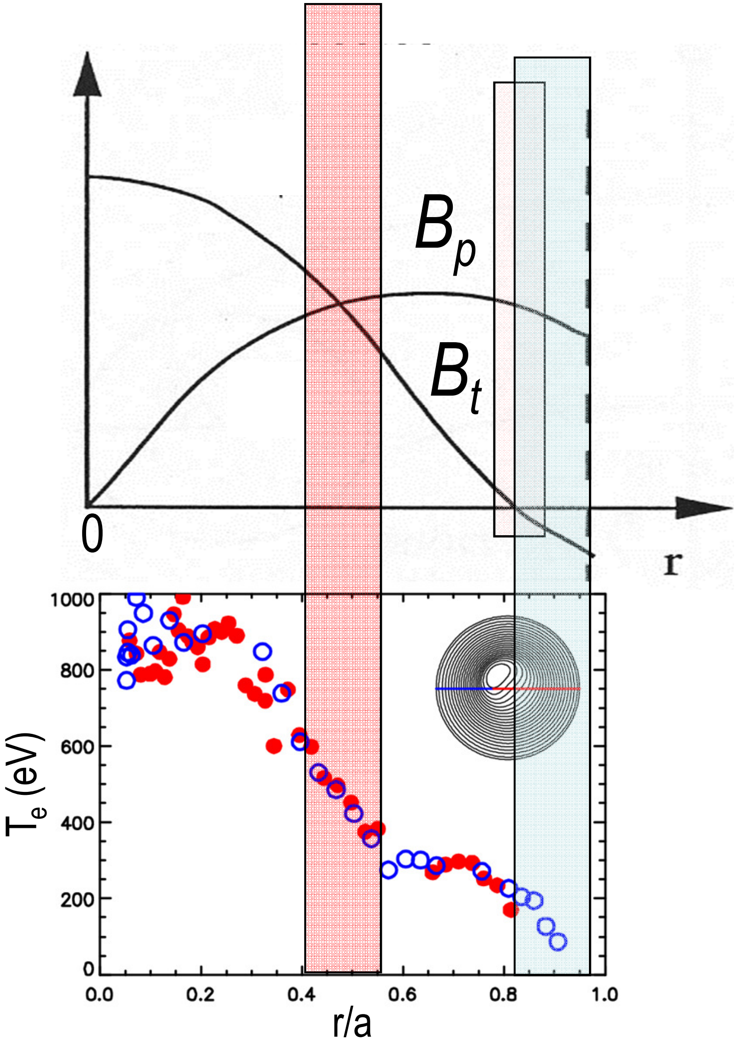


HFS and LFS anti-correlated

Microtearing spectra evolution

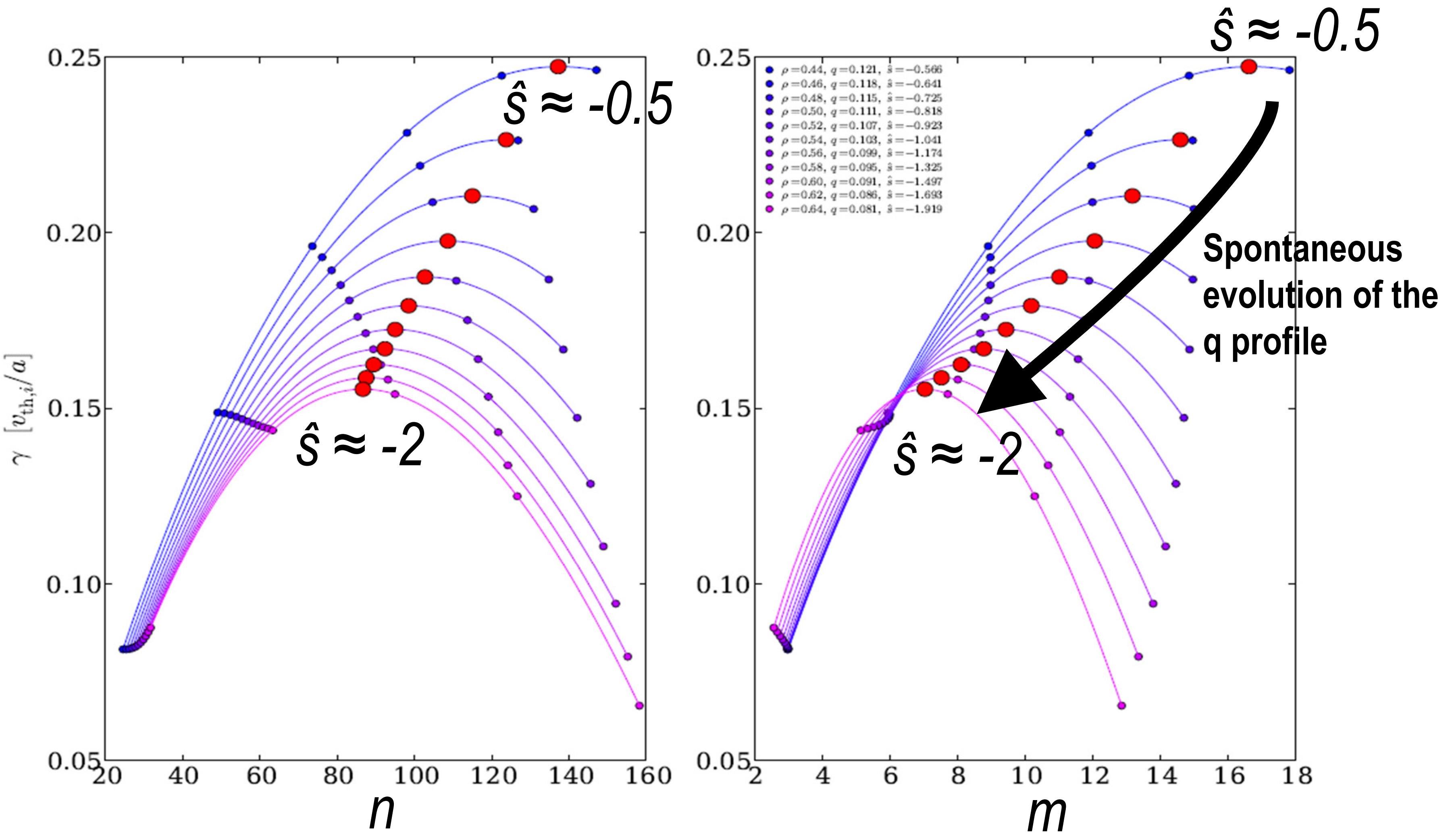


$k = k_\perp \approx 100 - 50\ m^{-1}$



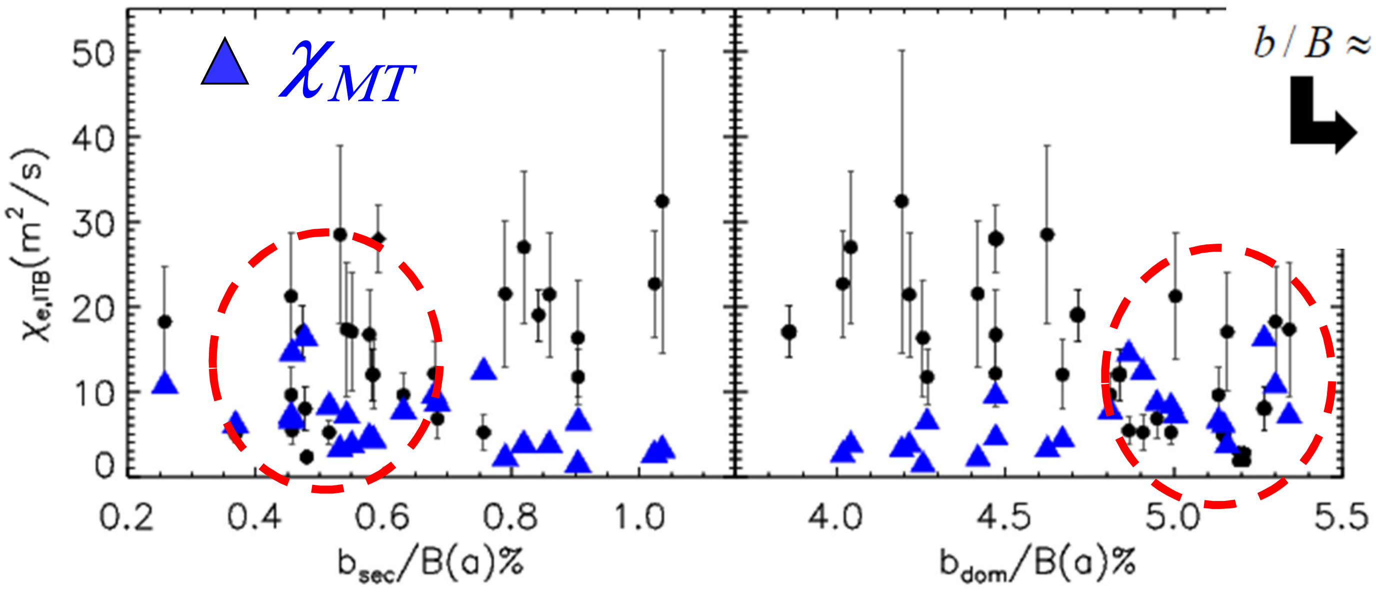
GS2: effect of the shear on MT spectra

Strong effect of the time evolution of the magnetic shear ŝ on the spectral properties of microtearing modes is predicted by gyrokinetic analysis on experimental equilibria



Spontaneous evolution of the q profile

Microtearing and heat diffusivity



$$b/B \approx \rho_e / L_{Te} = \rho_e \frac{\nabla T_e}{T_e}$$

QUASI-LINEAR UPPER ESTIMATE

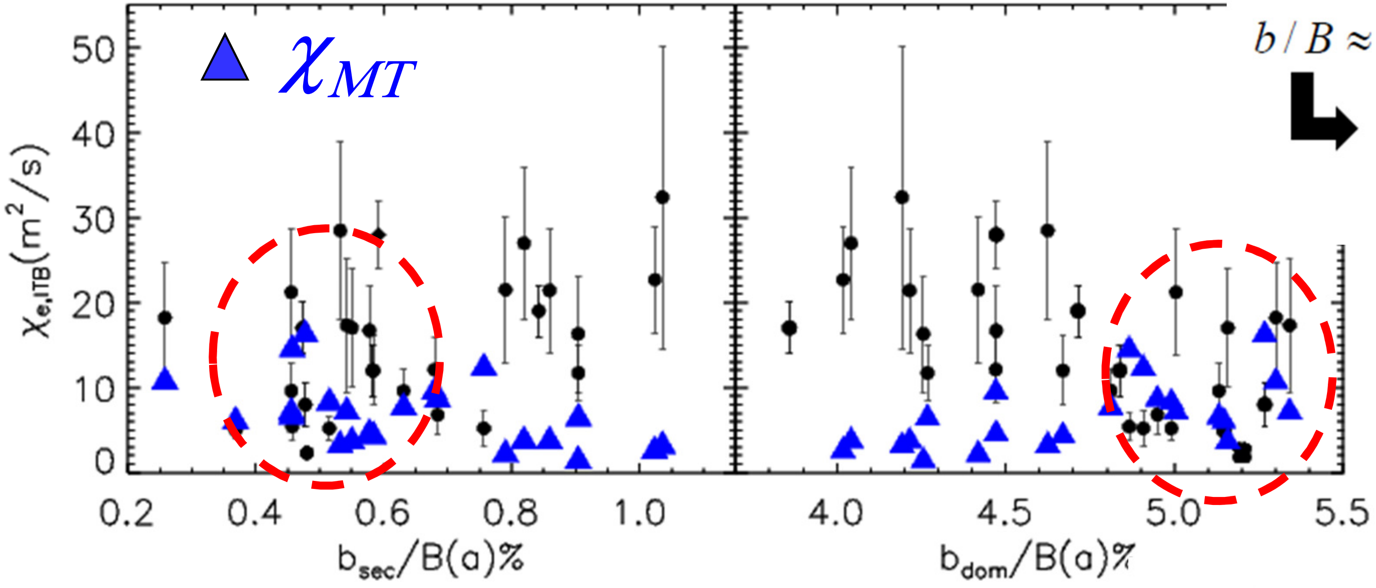
$$\chi_{MT} \approx (b/B) v_{th,e} L_C$$

Drake et al. PRL 1980

Rechester and Rosenbluth PRL 1978

High ∇Te → estimated χ_{MT} consistent with experimental findings

Microtearing and heat diffusivity



$$b/B \approx \rho_e / L_{Te} = \rho_e \frac{\nabla T_e}{T_e}$$

QUASI-LINEAR UPPER ESTIMATE

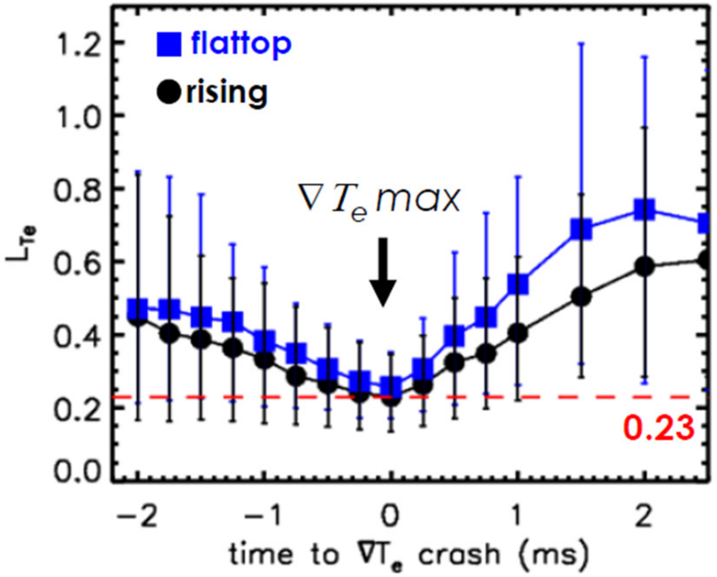
$$\chi_{MT} \approx (b/B) v_{th,e} L_C$$

Drake et al. PRL 1980

Rechester and Rosenbluth PRL 1978

$L_{Te}=T_e/\nabla T_e$

High ∇Te → estimated χ_{MT} consistent with experimental findings

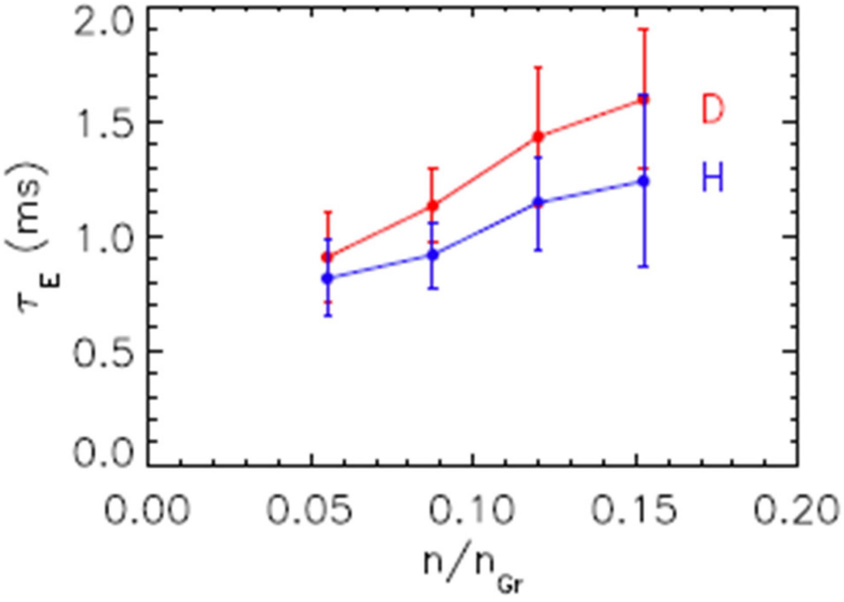


The estimated threshold for the destabilization of MT is in agreement with the observed dynamics of the eITB → marginal stability, critical gradient

This suggests a role played by MT on determining χ_e

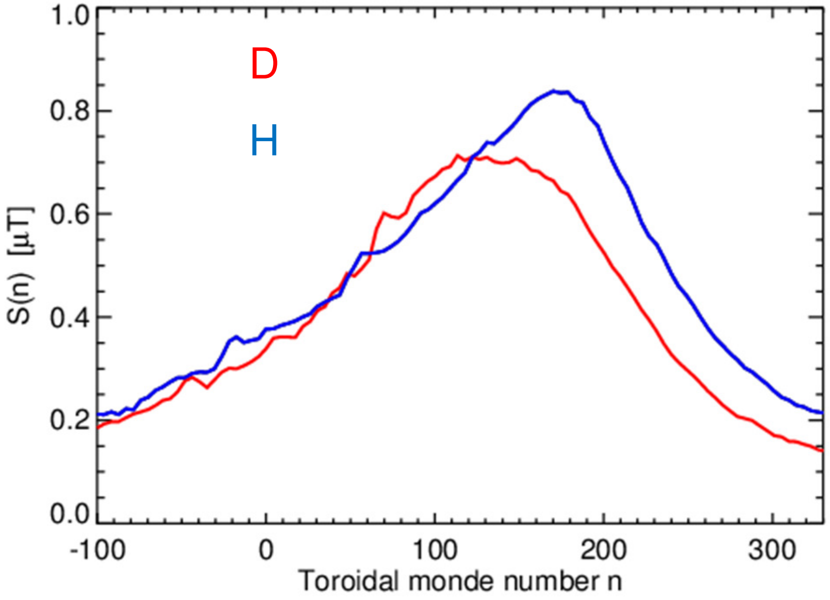
Carraro NF2013

Isotopic effect



Deuterium RFP plasmas exhibit better confinement properties wrt Hydrogen

MT spectra and amplitude seem to be also affected by the choice of the main gas

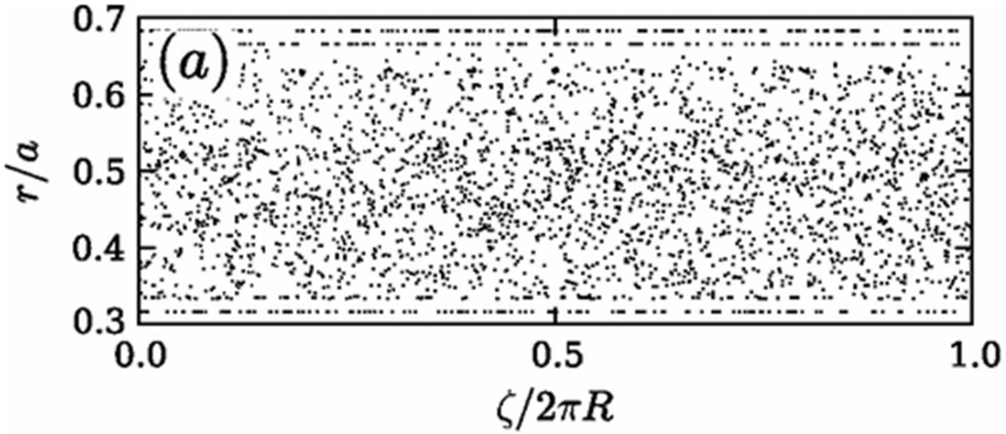


Conclusion

- Experimental observation of electromagnetic microtearing modes in the $\lambda \sim \rho_i$ range, propagating at the electron diamagnetic velocity.
- Dedicated linear gyrokinetic calculations (GS2) give predictions in good quantitative agreement with the experimental results, with particular emphasis on the effect of the magnetic shear on spectral properties.
- The quasi linear estimate of χ_e due to microtearing is in good quantitative agreement with the experimental findings in improved confinement RFP plasmas and is consistent with their experimentally measured amplitude.

Field line tracing: the overall magnetic field is built by superposing a large population of predicted MT modes.

The code allows to compute the Eulerian spatial correlation: $C(l)=\langle b(l)b(0)\rangle/\langle b^2(0)\rangle$ and then the correlation length $L_c = \int_0^\infty C(l)dl$,



Heat transport ensues only in the presence of appreciable field line stochastization.

- Chirikov criterion: $m > m_0 = q / (2 |q'| \rho_i)^{1/2} \sim 3$

.

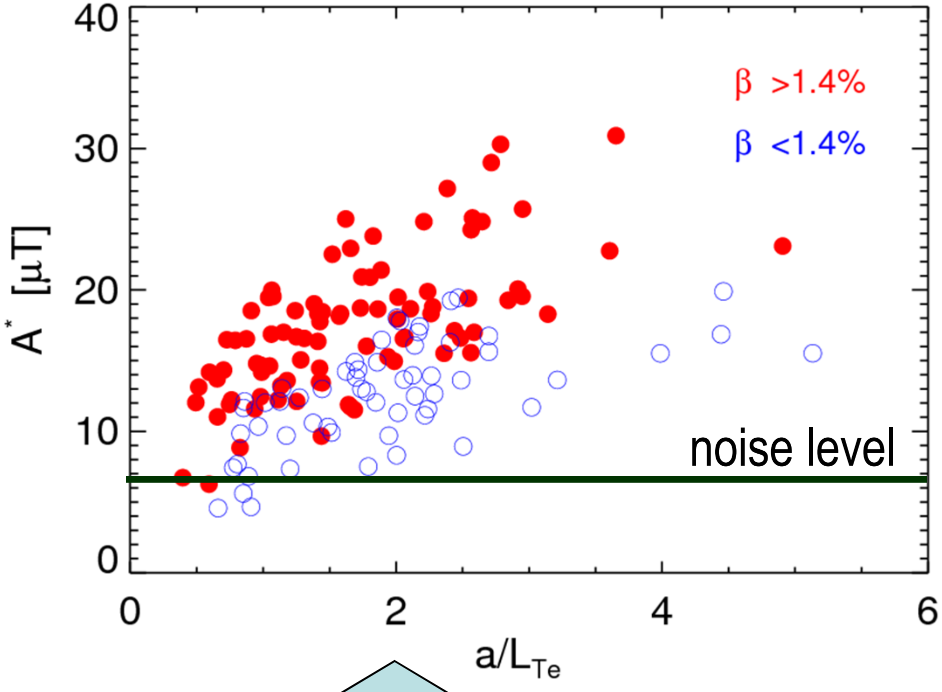
Microtearing modes are characterized by

$A_\perp \sim 0$ or, equivalently, $b_{//} \sim 0$, => $b_p \sim b_y = [1 + (r/R)^2 / q^2]^{1/2}$

with b_y binormal component of b

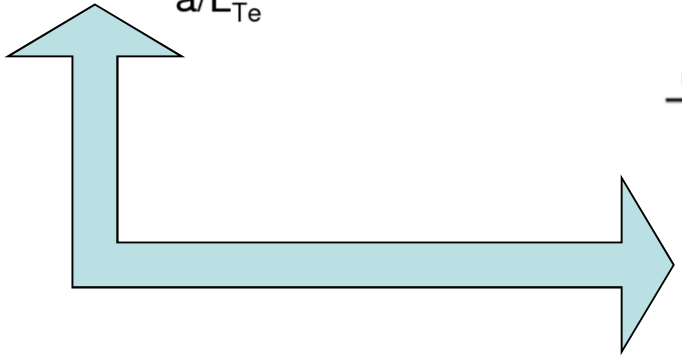
The poloidal component b_p generated around midradius, where $b_p \sim b_y/2^{1/2}$ has thus to be compared with b_p measured at the edge.

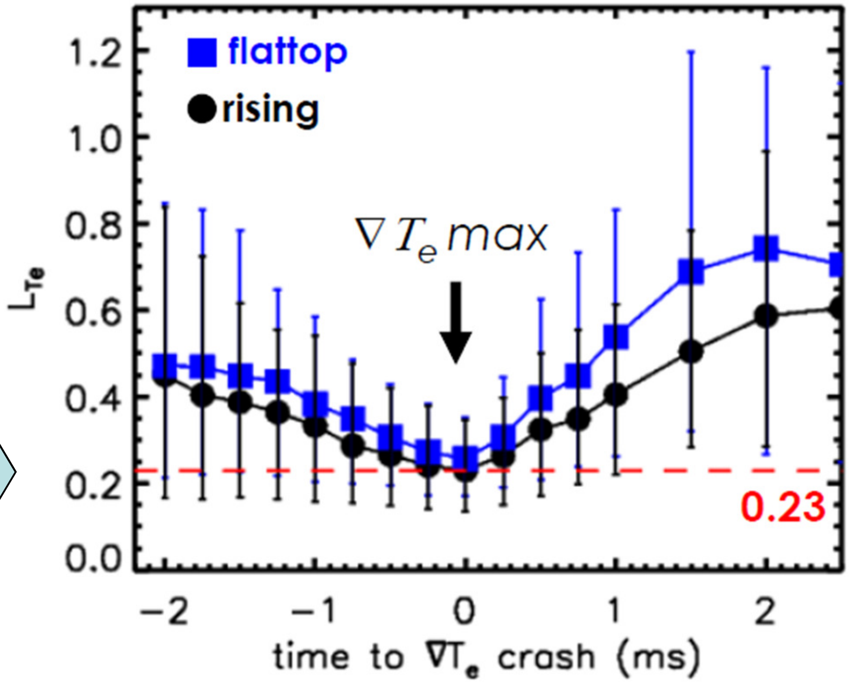
The amplitude depends on plasma parameters



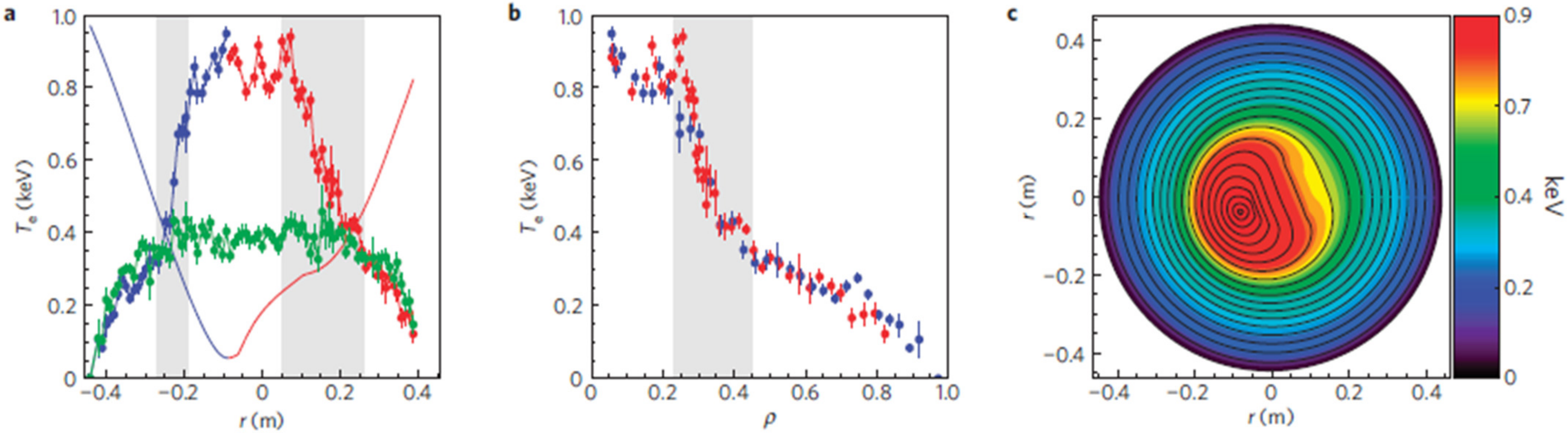
$$L_{Te} = T_e / \nabla T_e \qquad \beta = \frac{p}{B^2 / 2\mu_0}$$

- ***L_{Te}* and β** determine MT amp.
- a/L_{Te} threshold



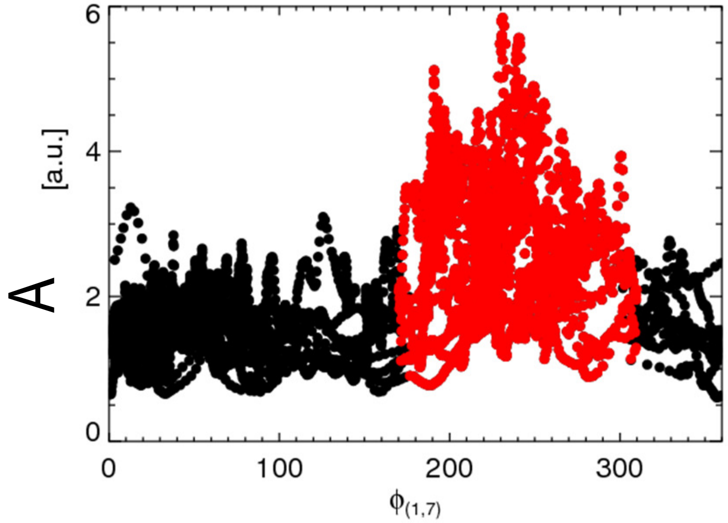


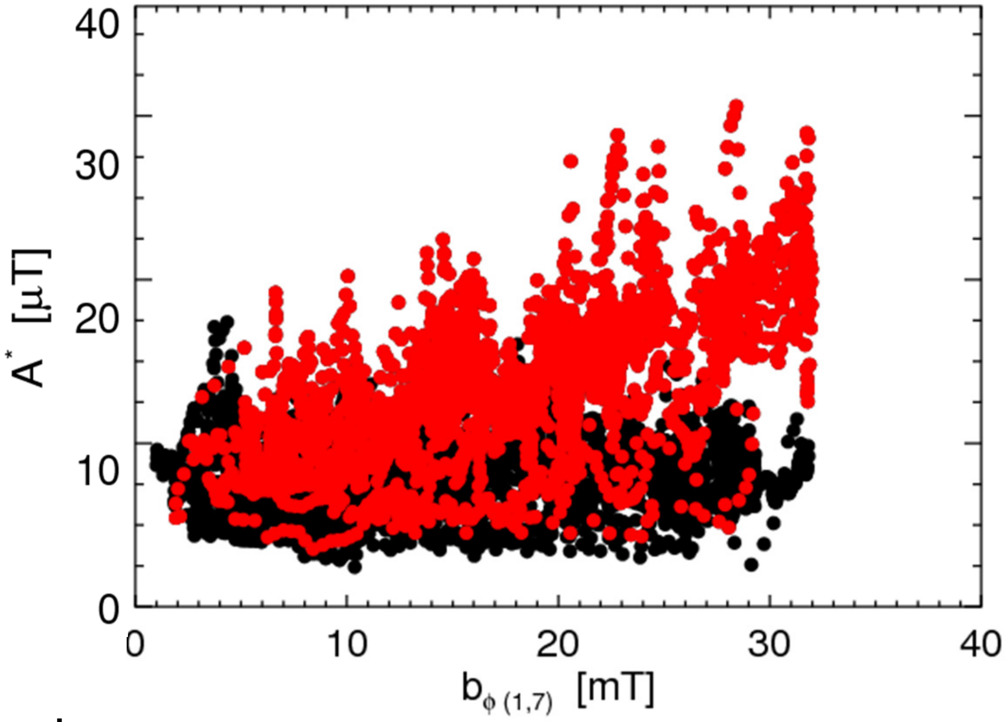
T_e turns out to be a flux function => T_e profile is not symmetric in real space



$$\rho = (\chi / \chi_0)^{1/2}$$

$\chi =$ Flux function

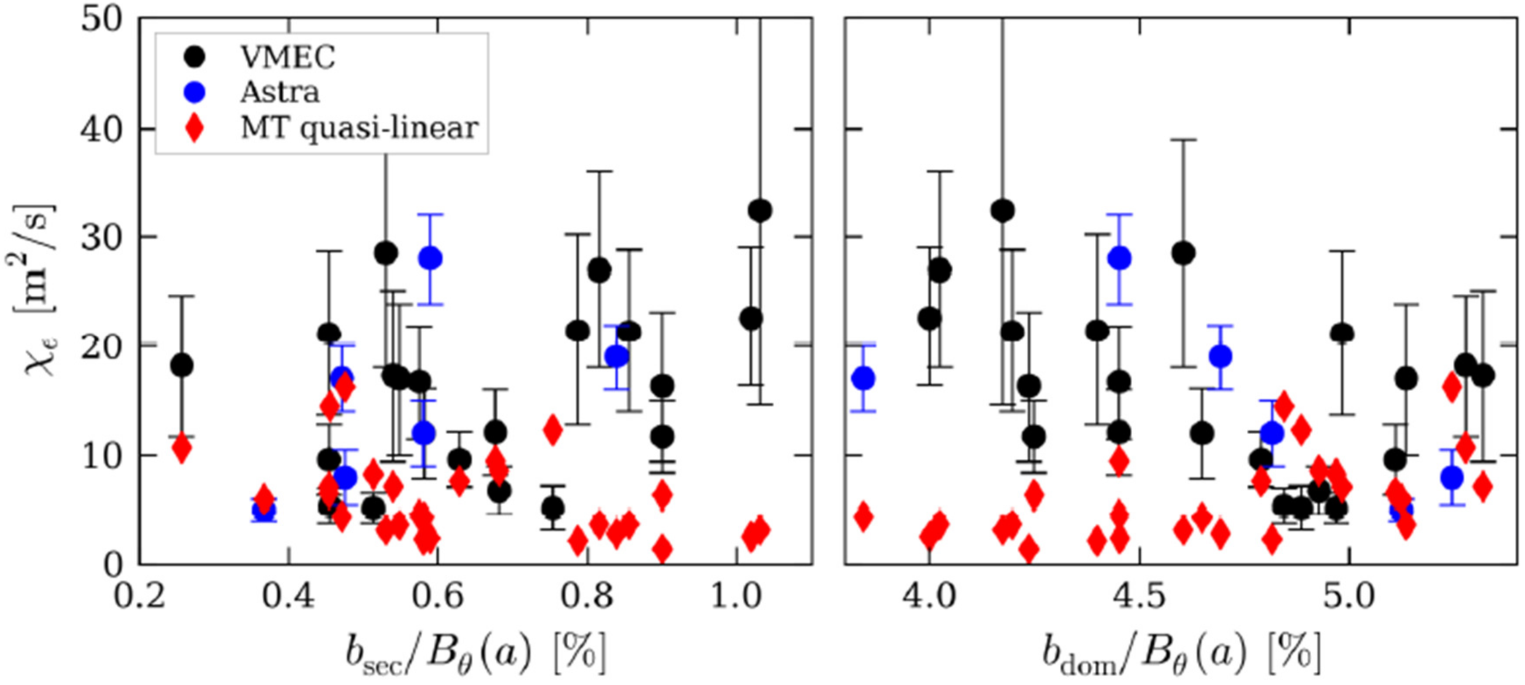




If the phase is “good”,

MT amplitude depends on the amplitude of the dominant 1/7 mode

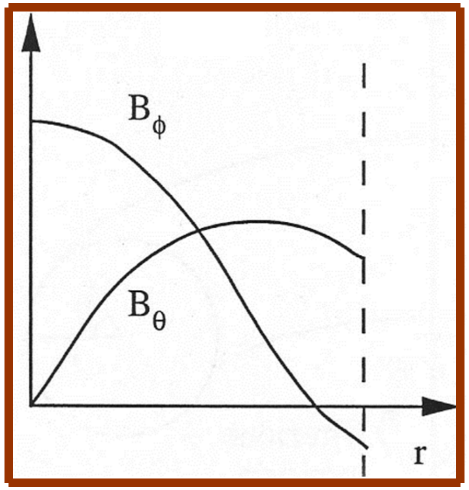
Effect on heat transport

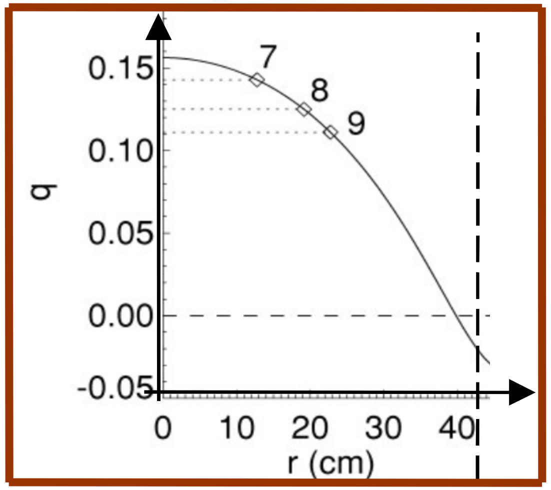


- The heat diffusivity profile χ_e in the barrier region has been evaluated during several SHAx by solving the energy transport equation in helical geometry
- Values of χ_e estimated by using VMEC and ASTRA (blue) for several SHAx cycles versus secondary mode (left) and dominant mode (right) normalized to the field at the edge B(a).
- Evaluated electron heat diffusivity due to the Microtearing modes in red.
- At the lowest secondary mode amplitudes, the spread of χ_e values suggests that microtearing could play a role in the RFX-mod plasmas.

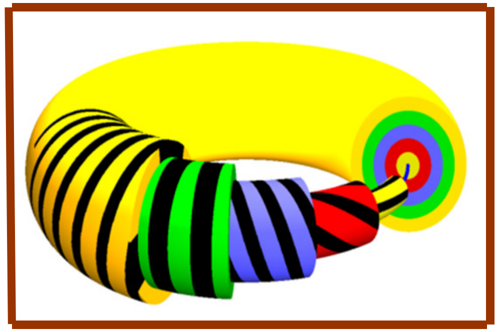
RFX-mod: toroidal and helical geometry

MH

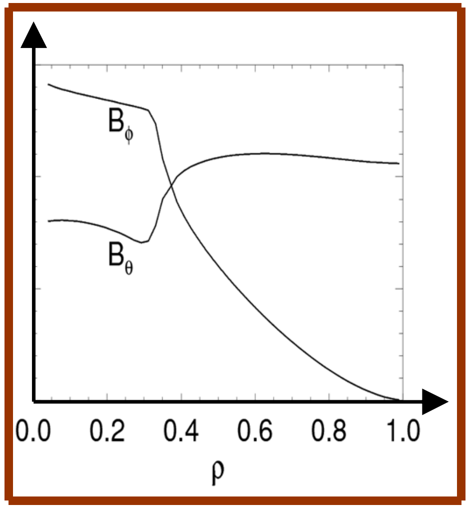


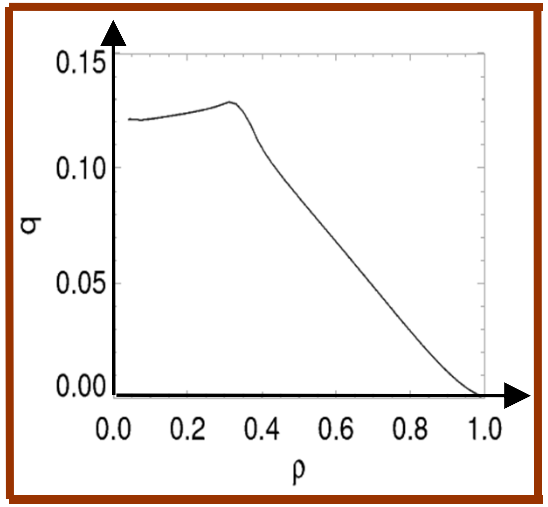


Toroidal
geometry

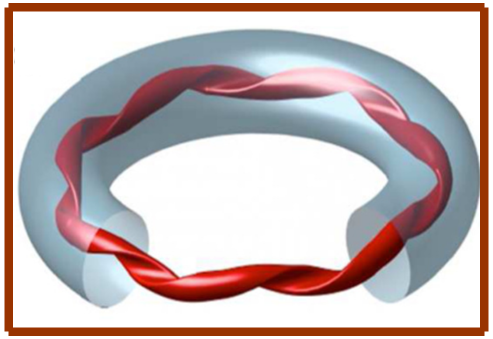


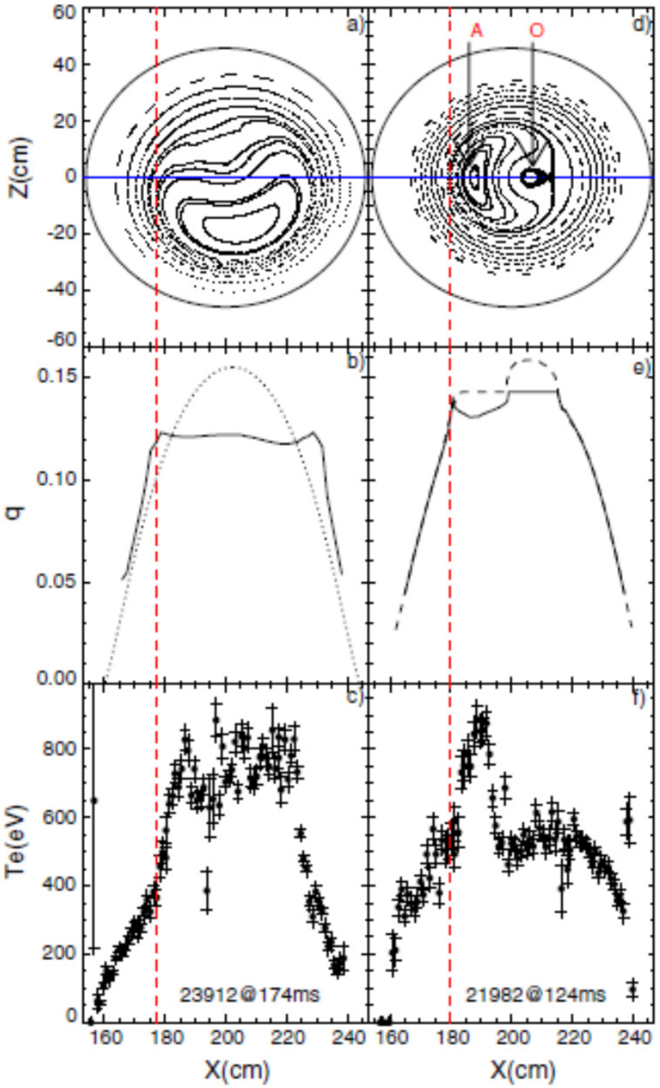
QSH



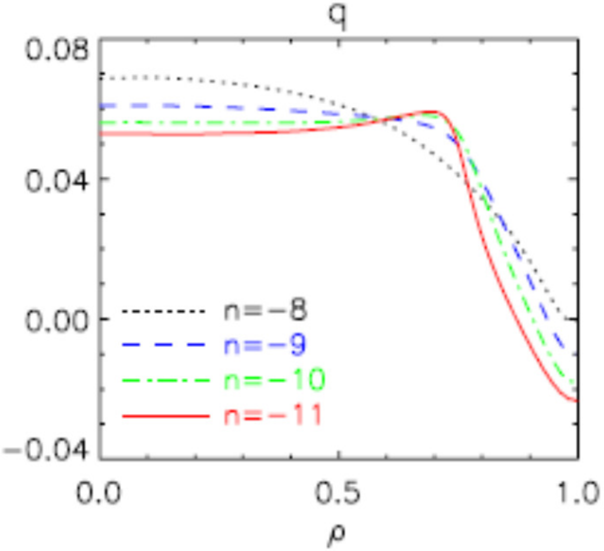


Helical
geometry

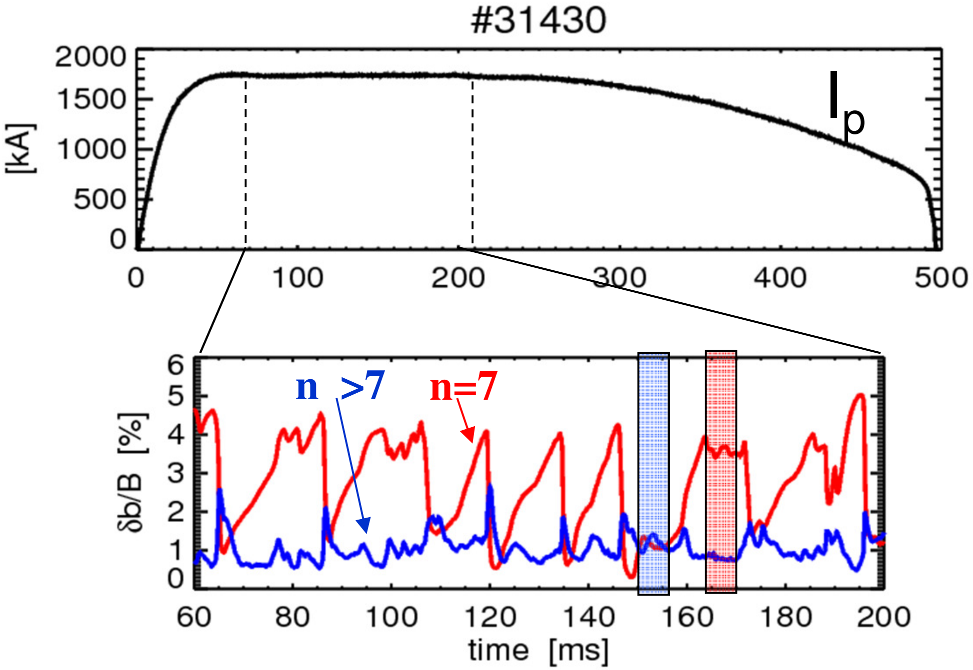




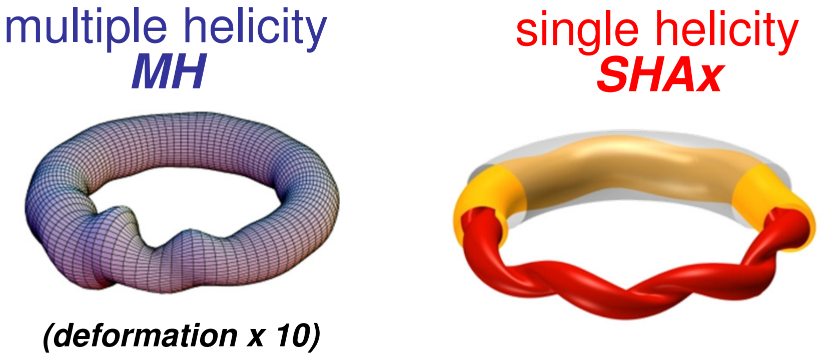
The *q* profile is indeed strongly affected by the dominant tearing mode

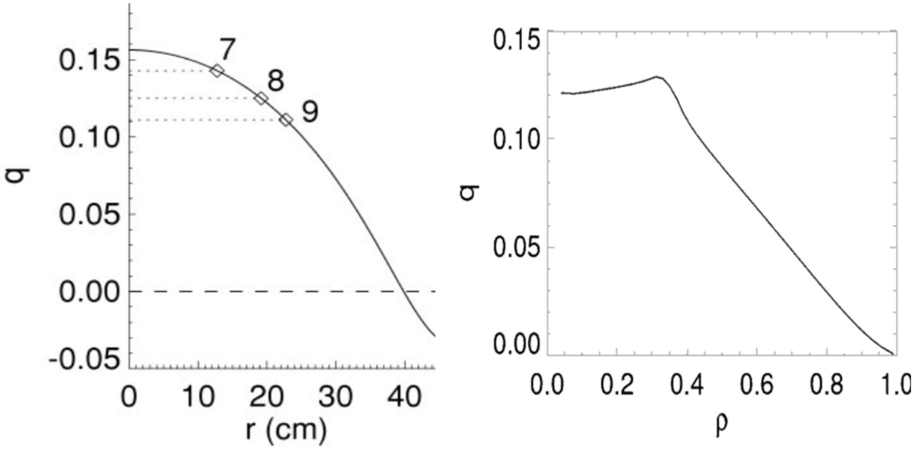


Helical states and transport barriers



- One helical magnetic axis (SHAx, Single Helical Axis) spontaneously forms at high I_p levels
- Reduced chaos





The q profile is strongly modified by the dominant mode