# Observations of $\rho_i$-scale wavelength instabilities in the microtearing frequency range in RFX-mod plasma

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High frequency $\rho_i$-scale (being $\rho_i$ the ion Larmor radius) electromagnetic fluctuations, arising in presence of strong temperature gradients, are observed in the RFX-mod reversed-field pinch (RFP) plasma ($R/a=2m/0.459m$) [1]. Experimental data are compared with gyrokinetic simulations, identifying such fluctuations as microtearing modes [2], thus being the first instance of a direct evidence for these modes in a laboratory plasma.

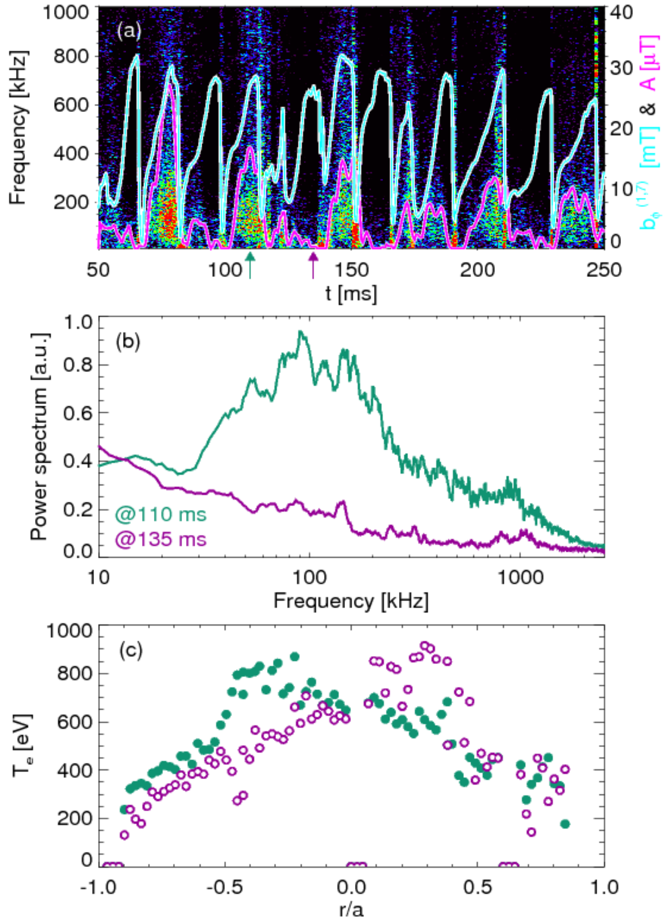

Fig. 1 a) Spectrogram of a $\dot{b}_\theta$ signal during the flat-top phase of the discharge. The cyan line is the amplitude of the toroidal component of the mode *(1,7)* (y-axis on the right in *mT*). The magenta line is the amplitude A of the high-frequency fluctuation (y-axis on the right in *μT*). Power spectra (b) and electron temperature radial profiles (c) measured at the time instants indicated by the arrows in (a).

The measurements are obtained by means of a system of in-vessel probes, capable of high time (frequencies up to *5MHz*) and space (wavelengths of few centimeters) resolution measurements of magnetic fluctuations. Three axial magnetic coils measuring the time variation of the magnetic field and located at different poloidal and toroidal positions, are used. In this analysis, we will focus on the poloidal signal $\dot{b}_\theta$, that is the quasi-parallel component at the edge of a RFP configuration, since the spectra of radial and toroidal components are largely affected by other MHD instabilities.

In the $\dot{b}_\theta$ spectrogram of Fig.1a, the time evolution of the toroidal magnetic field fluctuation $b_\phi^{(m=1,n=7)}$ at the edge (*m* and *n* being the poloidal and toroidal mode numbers) is overplotted (cyan line). It shows the typical recurrent transitions from the chaotic Multiple Helicity (MH) state to the Quasi Single Helicity (QSH) regime, characterized by a large amplitude of this mode over all the others [3]. The spectrogram appears extremely rich, with vertical lines occurring at the crashes of the dominant tearing mode *(1,7)*, signature of the reconnection of the magnetic field lines with a wide spectrum caused by localized current perturbations [4]. These phases are not discussed here, since we are mainly interested in the enhanced magnetic activity in the frequency domain between *50* and *300 kHz* observed to occur with some time correlation with the QSH phases. Indeed there are two different phenomenologies, represented in Fig. 1b by two different power spectra: the violet curve features a smooth decaying trend up to about *600 kHz* (at larger frequencies coherent peaks due to Alfvén eigenmodes appear, as discussed in [5]) and the green curve exhibits a large broad peak centered at around *150 kHz*, evidence of a quasi-coherent electromagnetic activity. The time evolution of the estimated amplitude A of the quasi-coherent component has been overplotted in Fig.1a (magenta line).

A deeper analysis shows that a necessary condition for the appearance of the peak is the existence of a proper phase relation between the O-point of the slowly rotating dominant mode and the position of the measuring magnetic probe. QSH phases produce internal thermal transport barriers (ITB) surrounding a broad portion of hot plasma (electron temperature can exceed *1 keV*) [3]. These barriers, being associated to the $m=1$ helicity of the dominant mode, are typically asymmetric across the poloidal section and rotate in time in accordance with the helical structure. In Fig.1c the electron temperature $T_e$ radial profiles, evaluated at the same two time instants used for the power spectra of Fig.1a, are shown. The toroidal position of the Thomson Scattering temperature diagnostics is such that the inner side ($r<0$) of the $T_e$ profile almost corresponds to the position along the warped helical structure where the probes are placed. The high-frequency instability is thus observed when the steepest part of the gradient is radially close to the magnetic probe.

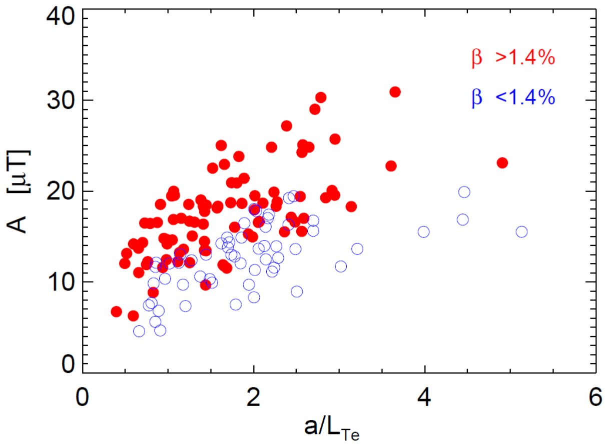

Fig. 2 Amplitude of the mode A *vs* the normalized logarithmic electron temperature gradient. Red dots and blue circles refer to different β values.

The relation between the amplitude of the mode and the electron temperature gradient has been investigated also on a statistical basis. The result is shown in Fig.2, where A is plotted versus the normalized logarithmic temperature gradient $a/L_{Te} = -a\, d(\log T_e)/dr$ at the barrier location for two intervals of $\beta$ (ratio of thermal to magnetic pressure). The amplitude of the magnetic activity is observed to grow with both the parameters $a/L_{Te}$ and $\beta$.

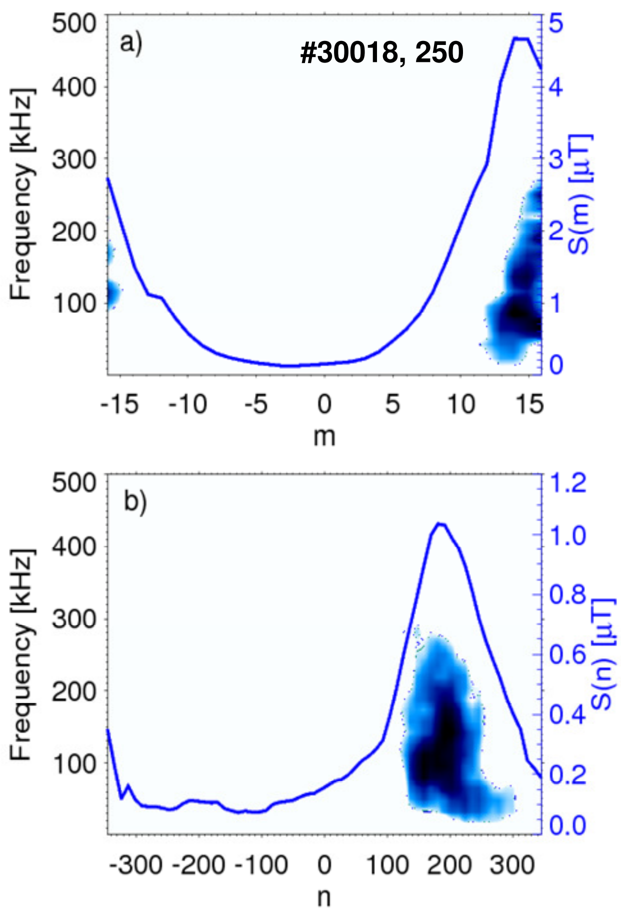

Fig. 3: *S(m, f)* (a) and *S(n,f)* (b) spectra (in a.u.) deduced by the two-point analysis. The right-hand side y-axis refers to the *S(m)* and *S(n)* spectra (blue continuous lines).

The poloidal and toroidal mode numbers associated to the instability are measured by applying the two-point technique [6] to $\dot{b}_\theta$ signals of closely spaced coils at different poloidal and toroidal positions. In Fig.3, the *S(m,f)* and *S(n,f)* spectra are shown as color-coded contours for a single discharge: the high–frequency activity is recognizable at extremely high *m* and *n* mode numbers. The *S(m)* and *S(n)* spectra (blue continuous lines), obtained by integrating over the frequency range of the peak, show that, in this case, it is centered around $(m,n)=(15,190)$, corresponding to a resonant condition $q(r_{res})=m/n$ satisfied at $r_{res}/a\approx 0.6$ in toroidal geometry, i.e. in the region of the $T_e$ gradient (black squares in Fig.4a). These wavenumbers are related to wavelengths in the centimetric range. Consequently, in order to propose a physical interpretation, we must address the kinetic problem of instabilities with $k_y\rho_i<1$ ($k_y$ being the binormal wavenumber) i.e. within the gyrokinetic formalism. Based on this consideration, a numerical investigation by means of the flux-tube code GS2 [7], dealing with the RFP configuration [9], has started. The geometry takes into account the peculiar curvature and high $\nabla B$ drifts, but the field is assumed axisymmetric. Indeed, the values of $q$, of magnetic shear and of the radial gradients considered by the code are not affected by the natural modifications caused by the helical deformation of the magnetic field, as, in particular, the flattening of the (helical) $q$ profile in correspondence to the electron temperature barrier [8]. For the electron to ion temperature ratio, the value $Te/Ti\approx 3/2$ is assumed. Fluctuations of the electrostatic potential $\phi$ and of the parallel vector potential $A_{//}$ are considered. The numerical simulation reveals the presence of microtearing modes radially localized across the electron temperature barrier. In Fig.4b the growth rates for the same shot of Fig.3 as a function of the normalized wavenumber $k_y\rho_i$ is shown. Solid symbols represent the dataset with the axisymmetric $q$ profile (red line in Fig.4a), while open symbols are obtained by artificially halving the magnetic shear, with the aim to model a $q$ profile more similar to the experiment. The measured $S(n(k_y))$ spectrum, obtained through the relation $n=rk_y/((r/R)^2+q^2)^{1/2}$ and represented by the gray solid line in Fig.4b, is compared with the gyrokinetic linear spectra, exhibiting a good agreement for the wavenumber values associated to the maximum of the curve, in particular in the halved-shear case. Both the modes of Fig.4b are identified as microtearing, since their eigenfunctions have odd symmetry in $\phi$ and even in $A_{//}$ and they propagate in the electron diamagnetic direction; moreover, the estimate of the phase velocity is in agreement with the corresponding experimental value derived from the dispersion relation of the $S(n,f)$ spectrum, $v_{ph}\sim 10^4 m/s$. A further typical feature of the microtearing modes is its dependence on some plasma parameters: as shown in [9], the growth rate gets larger for higher values of $a/L_{Te}$ and $\beta$, consistently with the results shown in Fig.2.

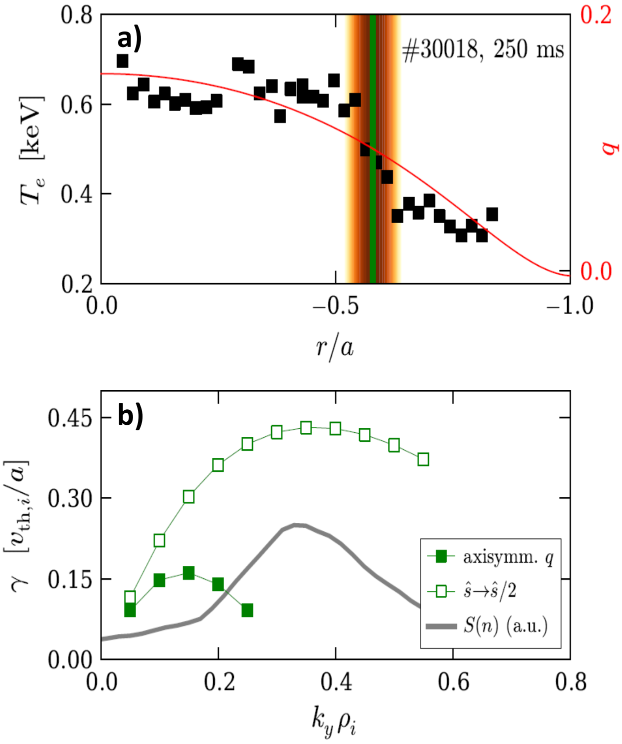

Fig.4 (a) Electron temperature (black squares) and axisymmetric $q$ (red line) radial profiles. (b) Growth rates of microtearing modes *vs* $k_y\rho_i$ at the position of the $T_e$ gradient (green line in (a)) for the axysimmetric (solid symbols) and the artificially flattened $q$ profiles (open symbols); the gray line is the *S(n)* spectrum of Fig.3.

Summarizing, an extensive experimental investigation of electromagnetic $\rho_i$-scale modes in RFX-mod is presented. All evidence points to identify them as microtearing modes, representing therefore the first direct observation ever of these modes in a laboratory plasma.

## References

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