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Observations of toroidicity-induced Alfvén eigenmodes (TAE) in a RFP plasma

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Plasma confined in a Reversed Field Pinch (RFP) configuration are characterized by a relatively high amplitude of magnetic fluctuations (typically of the order of 1% of the average field). Most of the fluctuation power is concentrated in the low frequency range dominated by several tearing modes resonating in the core region [1]. The higher frequency of the spectrum has usually deserved less attention as it was thought to give a smaller contribution to the confinement properties of the configuration. Among the causes for the magnetic fluctuations in that frequency region, Alfvén waves merit a special mention. Turbulence induced by Alfvén waves has been indicated as a possible spontaneous mechanism for anomalous ion heating [2] or as a current drive method in RFP's [3]. In particular toroidicity-induced Alfvén eigenmodes (TAE) are commonly observed in Tokamaks [4, 5] while first evidences of Alfvén eigenmodes (AE) in RFP devices have been presented in previous works [6, 7]. A TAE is a normal mode of a toroidal plasma. In an axisymmetric cylindrical single ion species plasma of length $2\pi R$, shear Alfvén waves have a continuum spectrum given by $\omega^2(r) = k_\parallel^2(r)v_\mathrm{A}^2(r)$, where $v_\mathrm{A} = B/\sqrt{\mu_0\rho}$ is the local Alfvén velocity, $k_\parallel = (m+nq)B_\theta/rB$ the parallel component of the wave vector to the local magnetic field and $\rho = m_\mathrm{i}n_\mathrm{i}$ is the mass density [8]. All perturbations belonging to the Alfvén continuum suffer a strong damping due to wave phase mixing. Where the Alfvén cylindrical continua of two resonant surfaces with subsequent poloidal mode numbers ($|\Delta m| = 1$) and same toroidal mode number n have a crossing point, corrections for toroidicity, expressed in terms of the inverse aspect ratio $\epsilon = a/R$, resolve the degeneracy, coupling the two modes and creating a frequency gap in the spectrum [8]. Inside the gap Alfvén waves can develop discrete frequency eigenmodes, TAE, which do not suffer any *continuum damping* [9]. The TAE frequency is approximately the one of the crossing point obtained in the cylindrical geometry therefore it can be estimated writing down the degeneracy condition [2, 7] as it follows:

$$k_{\parallel,m} = -k_{\parallel,m-1} \Rightarrow m + nq(r_\mathrm{gap}) \approx \pm\frac{1}{2} \tag{1}$$

The condition (1) fixes the value of the parallel wave number $k_{\|,\text{gap}} \simeq \pm B_\theta/2Br$. As a consequence the TAE frequency $f_{\text{TAE}} \simeq k_{\|,\text{gap}} v_{A,\text{gap}} \simeq B_\theta/4\pi r\sqrt{\mu_0\rho}$ does not strongly depend on the poloidal m and toroidal n mode numbers but different subsequent ($|\Delta m| = 1$) resonant surfaces have the gap located at different radii. In this work magnetic measures, performed at the edge of Extrap-T2R RFP device are presented and interpreted as experimental evidences of TAE modes in a reversed field pinch. Extrap-T2R is a torus of major radius R=1.24 m, and minor radius a=0.183 m. The typical discharges performed, during our campaign, had plasma current I_p ranging from 60 to 80 kA, core density $n_e \simeq 1 \cdot 10^{19}$ m^{-3} and pinch parameter $\Theta = B_\theta(a)/ < B_\phi >$ between 1.6 and 2.4. Magnetic signals were collected by two groups of three Mirnov (magnetic) coils measuring the time-derivative of magnetic flux through three mutually perpendicular areas ($\partial B_r/\partial t$,$\partial B_\theta/\partial t$,$\partial B_\phi/\partial t$). The two groups were placed inside a single boron nitride case at two closely spaced toroidal positions ($\Delta x = 1.2$ cm being the distance) and at the same radial and poloidal position. The signals were sampled at a frequency of 2 MHz. The probe was placed on the outboard of the machine, outside the limiter (r/a=1.06), on the equatorial plane. A third group of three Mirnov coils was placed at the same toroidal and radial position but on the upboard of the machine, and in this case measurements have been performed at 4 or 8 MHz. In fig. 1 the Fourier spectra of the three components of magnetic field for the shot 13915 are shown. The spectra are characterized by two peaks. The lower frequency ($f \sim 70$ kHz) is the effect of the tearing modes rotation. The second peak at higher frequency ($250 \leq f \leq 600$ kHz) is observed only on the toroidal components while it is absent on the poloidal and radial one. Thus the high frequency fluctuation is polarized on a direction perpendicular to the poloidal magnetic field and this is consistent with what is expected for an AE localized at the edge of an RFP. Indeed a shear Alfvén fluctuation does not compress the plasma, the parallel component of perturbed magnetic field is given by the perpendicular pressure balance $\mu_0\delta p + B\delta B_\| = 0$ while the other two components are $\delta\mathbf{B}_\perp \simeq (\mathbf{B}/B) \times \nabla\delta A_\| \simeq (\hat{\theta}\frac{B_\phi}{B} - \hat{\phi}\frac{B_\theta}{B})\frac{\partial\delta A_\|}{\partial r} + i\hat{\mathbf{r}}(\frac{nB_\theta}{RB} - \frac{mB_\phi}{aB})\delta A_\|$, where $\delta A_\|$ is the parallel component of potential vector [10]. Thus at the RFP edge the toroidal component

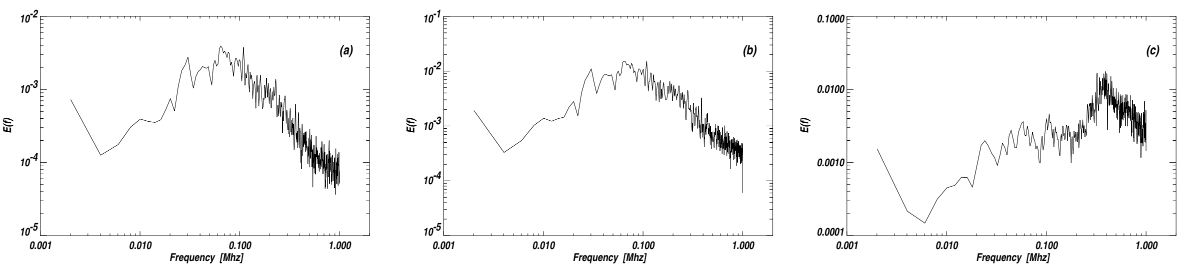

FIGURE 1. (a),(b),(c) Fourier power spectra for the shot 13915 of three components of magnetic field $\partial B_r/\partial t$, $\partial B_\theta/\partial t$, $\partial B_\phi/\partial t$, respectively.

should be high with respect to the poloidal because of the smalleness of the average toroidal field. By the correlation between signals measured at different toroidal positions we could estimate the toroidal wave number $k_\phi = n/R$ of fluctuations. In fig. 2 the spectra $S(k_\phi, f)$, as function of toroidal wave number and frequency obtained for the toroidal components (panel (a)) and for the poloidal ones (panel b), are shown. As expected the two spectra exhibit different frequency ranges. All the high frequencies $0.2 < f < 0.6$ MHz of the toroidal $S(k_\phi, f)$ spectrum correspond to a toroidal wave number $\mathrm{n} \cong \mathrm{k}_\phi(\mathrm{R} + \mathrm{a}) \cong -30$. The $S(k_\phi, f)$ of the poloidal component shows only the tearing mode rotation frequency related to a lower toroidal periodicity $\mathrm{n} \simeq 10$. In fig. 2 panel (c) the Alfvén continua of the (m=2,1,0,-1 & n=-30) resonant surfaces are plotted in the cylindrical approximation (dashed lines) together with the hydrogen ion-cyclotron frequency profile which establishes an upper limit to the shear Alfvén continuum. The estimated n=-30 number has been used. The m number was not measured but, as mentioned before, the mode polarization point towards an edge resonant mode and only negative m have degeneracy outside the reversal ($r/a \simeq 0.8$). Therefore the toroidicity corrected Alfvén spectra for the couple (m=0,-1 & n=-30), were superimposed (full lines). Toroidicity opens a gap in the spectrum at $r/a \simeq 0.9$ with a frequency $f_{\mathrm{TAE}} \simeq 500$ kHz comparable to the observed peak. In fig. 3 it is clearly visible that the mode is excited during global relaxation events because the high frequency peak appears in the spectrogram when the $F = B_\phi(a)/ < B_\phi >$ parameter suddenly drops. Therefore discharges with higher average Θ have been performed and a long-lived excitation of the mode frequency was observed. This is shown in fig. 4 where the spectrograms of toroidal magnetic component for two high Θ discharges with similar plasma parameters ($\mathrm{I_p} \simeq 75$ kA, $n \simeq 1.5\ 10^{19}\ \mathrm{m}^{-3}$, $\Theta \simeq 2.2$) have been plotted. The discharge 13461 was performed with hydrogen plasma while the shot 13322 was with deuterium. In both cases the mode lasts longer than in the usual Θ discharges and the frequency of the deuterium

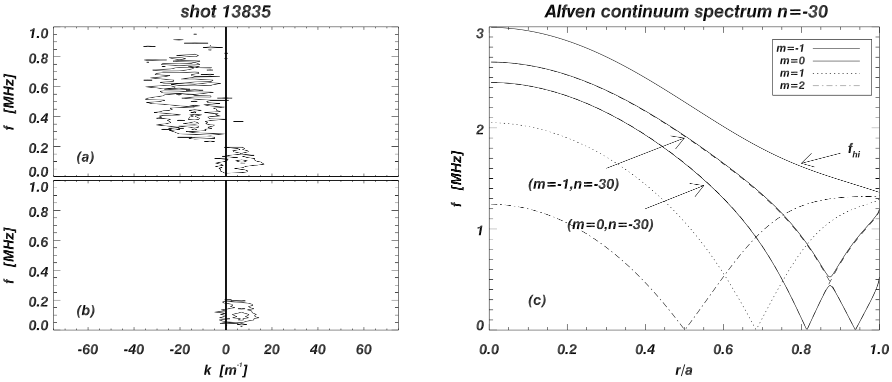

FIGURE 2. The $S(k_\phi, f)$ spectrum for $\partial B_\phi/\partial t$ fluctuations is plotted in the panel (a), while $S(k_\phi, f)$ for $\partial B_\theta/\partial t$ is plotted in the panel (b). Alfvén continuum spectrum of Extrap-T2R averaged RFP magnetic and density profiles for $Ip = 70$ kA discharges is plotted in the panel (c)

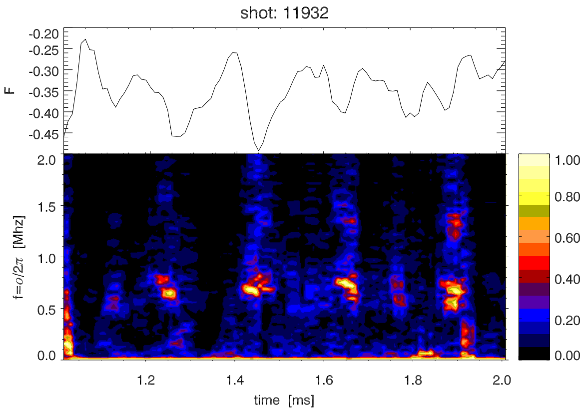

FIGURE 3. (Upper panel) Time evolution of the parameter F during the shot 11932 ($\Theta \simeq 1.8$). (Lower panel) Spectrogram of $\partial B_\phi/\partial t$ for the same shot.

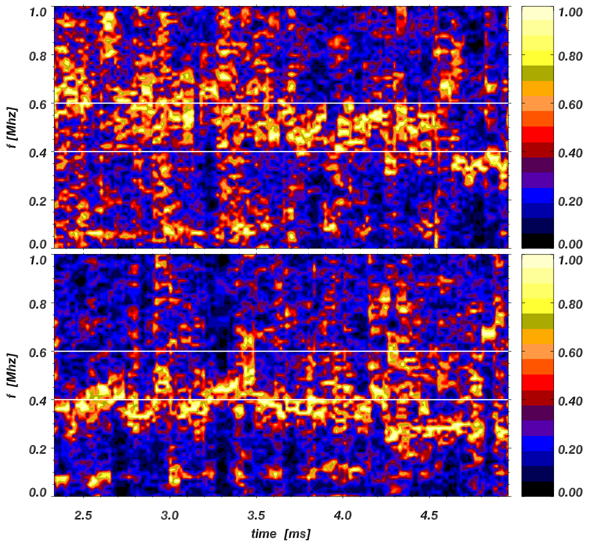

FIGURE 4. Spectrograms of the toroidal magnetic field component for the hydrogen shot 11461 (upper panel) and deuterium one 13322 (lower panel)

shot is almost a factor of $1/\sqrt{2}$, lower than the hydrogen one. In conclusion, an high frequency mode which shows mass scaling, frequency, polarization and phase properties of a TAE eigenmode has been observed at the edge of the Extrap-T2R reversed field pinch device. The same kind of phenomenon is expected in the other RFP devices.

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