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First observation of electron fishbones associated to the double-kink mode in Tore Supra

P. Maget, G. Huysmans, G. Giruzzi, F. Imbeaux, X. Garbet, J.-L. Ségui, V.S. Udintsev,
V. Basiuk, D. Mazon, Ph. Moreau, Y. Peysson
Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache, F-13108 St Paul-lez-Durance, France

We report here the observation of MHD modes identified as electron fishbones in Tore Supra discharges using Lower Hybrid (LH) waves for generating most of the plasma current. Fishbone modes are marginally stable ideal modes, which are destabilised by trapped suprathermal particle, via wave-particle resonance at the toroidal precession frequency. Ion fishbone modes are driven by deeply trapped ions, and they destabilise the internal kink [1], as well as the double-kink modes [2]. This latter form of ion fishbone has been observed in JET Optimised Shear scenario [3]. The mechanism for electron fishbone is similar, except that the ideal mode is destabilized by barely trapped electrons. Up to now, electron fishbone modes have only been observed associated to the internal ($q = 1$) mode, in discharges heated at the Electron Cyclotron frequency [4] [5] [6], or with LH waves [7]. But it is natural that, in reversed magnetic shear plasmas with a suprathermal electron population, electron fishbone can exist in association with the double-kink mode. This is what we observe in Tore Supra for the first time, where the electron fishbone mode is observed in association with the double-kink mode on $q = 2$ and $q = 3/2$.
The Tore Supra tokamak [8] is equipped with two LH antennas capable of delivering about 3 MW for long duration (best present result is 3 MW for 370 s). Electron fishbone modes are observed in fully non-inductive discharges using LH, but also in other LH discharges with non-zero loop voltage, some of them having in addition a fast ion population driven by Ion Cyclotron Resonance Heating (ICRH) system.
Detection of MHD modes is provided by the measurement of electron temperature profile by means of a 32 channels Electron Cyclotron Emission (ECE) radiometer (sampling rate 1-86 kHz) [9], and by a recently installed Correlation ECE diagnostic [17]. Magnetic probes are limited to the detection of mode frequency lower than 10 kHz, and unfortunately they are not sensitive enough to detect inner MHD modes such as the ones considered here.
The plasma current driven by LH waves is determined from Hard X-ray tomography reconstruction, using the 38 chords of the horizontal camera. The current profile due to LH waves is calculated by dividing the bremsstrahlung emission from suprathermal electrons in the range 60-80 keV by the local electron density. The result is then renormalized to the expected LH

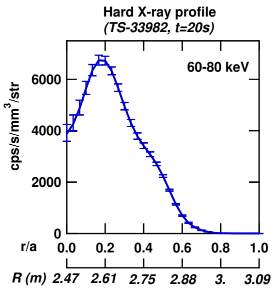

Figure 1: Hard X-ray profile

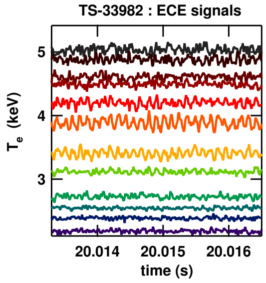

Figure 2: ECE time traces

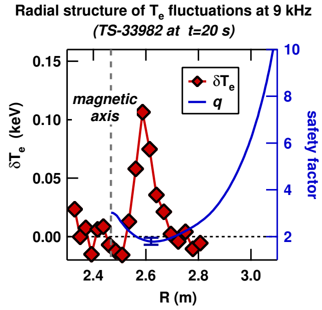

Figure 3: Radial structure

driven current, corresponding to a global current drive efficiency of about $0.610^{19}AW^{-1}m^{-2}$, which is more precisely adjusted so as to reproduce the experimental loop voltage. The LH contribution to the non-inductive current is used as input in the integrated code CRONOS [10] (where the bootstrap current is calculated with the NCLASS code [11], for a consistent reconstruction of the magnetic equilibrium). LH current drive in Tore Supra has a hollow profile, as evidenced by Hard X-ray tomography (figure 1, where error bars materialize the upper and lower values in the period t=19-20s). For this reason, non-inductive discharges using LH are characterized by a negative magnetic shear in the plasma core, which is favourable to low electron heat transport [12], but is also prone to the triggering of double-tearing modes [13].

Electron fishbone modes are often detected in fully non-inductive discharges, where LH current represents about 90% of the total current, the rest being provided by the bootstrap current. As a first example we consider a discharge at a magnetic field $B = 3.7T$ and a total plasma current $I_p = 0.51MA$. In several phases of this discharge, fluctuations of the electron temperature at about 9 kHz are observed in the region R=2.55-2.65 m, which corresponds to an off-axis region r/a=0.1-0.3 (figure 2). The radial structure of the mode is determined from the Morlet wavelet transform of the ECE signal by: $\delta T_e = A(f)cos\Phi(f)$, where $A(f)$ and $\Phi(f)$ are the amplitude and phase of the wavelet transform at the frequency where the spectrogram is maximum. The mode structure exhibits an off-axis maximum which is consistent with the hollow safety factor, and points towards a double-resonant mode on $q = 2$ (figure 3).

From experimental measurements, one can deduce the energy of electrons participating in the fishbone destabilization, which is: $E_{eV} = rRB\omega/q$, where the energy is expressed in eV, B is the magnetic field, R the major radius, r the minor radius, q the safety factor, and ω the mode frequency, equal to the toroidal precession frequency. For the example of figure 3, we find $E \simeq 40keV$. Electrons of this energy belong to the suprathermal tail driven by LH. Indeed, the energy at which starts the deviation from a Maxwellian distribution is [14]: $E_1 \simeq 5T_{e,keV}$, that is to say $E_1 \simeq 20keV$ in the same example. This evaluation supports the interpretation of the high frequency mode as an electron fishbone destabilized by fast electron tail driven by LH waves.

Hollow safety factor profiles are prone to the excitation of double-tearing modes, as observed in Tore Supra fully non-inductive discharges [13], but the observation of an electron fishbone alone is possible when the minimum of the safety factor is close enough to the rational. Indeed, the $n = 1$ mode is then stable, as shown on fig. 4 (CASTOR code [15] is used here; the growth rate is normalized to the Alfven time $\tau_A = R\sqrt{\mu_0 \rho_M}/B$, where ρ_M is the mass density, and the resistivity is normalized to $\mu_0 R^2/\tau_A$, so that η is the inverse Lundquist number $\eta = \tau_A/\tau_R = 1/S$; the scan in q_{min} is performed by rescaling the equilibrium).

The transition from fishbone to tearing mode has only been observed during a particular form of the O-regime with Giant Oscillations [16]. Since the equilibrium safety factor in such regime is expected to oscillate close to the magnetic axis (which is confirmed by recent observation of unstable Toroidal Alfven Eigenmodes (TAE) at the location of electron fishbone in similar discharges with ICRH [17]), this experimental observation does not reproduce the simple shift down of the safety factor profile shown in fig. 4. Instead, it appears to change from a double-resonant configuration in the case where the electron fishbone is present, to a single or triple resonant case as deduced from the tearing mode structure (fig. 5). There is in fact a possible impact of electron fishbone mode on magnetic equilibrium that could explain . Indeed, this instability should in principle redistribute part of the fast electron population, and in the case where the same population is also driving the plasma current, one would expect an impact of the mode on the magnetic equilibrium itself. There is actually a possible implication of the electron fishbone mode on the O-regime phenomenon, since the amplitude of the mode is sometimes observed to follow electron temperature oscillations. However, whether this a cause or a consequence is still to be assessed. If so, electron fishbone modes could have important impact in the Advanced Scenario envisaged for a Fusion Reactor in the presence of a high energy electron population, through a partial redistribution of the plasma current in the MHD-unstable region.

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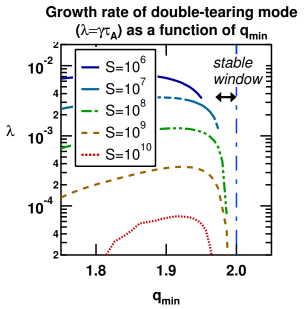

Figure 4: Linear stability of double-tearing mode

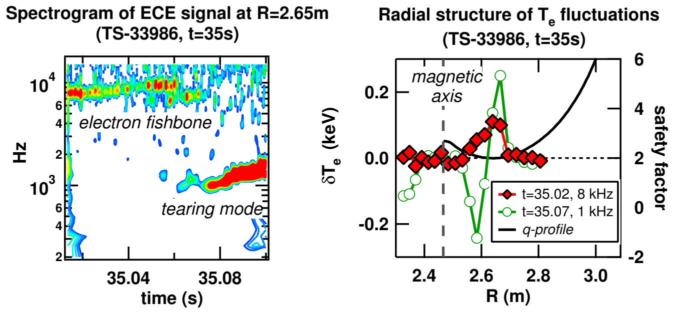

Figure 5: Transition from fishbone to tearing

References

[1] Chen L., White R.B. and Rosenbluth M.N., Phys. Rev. Letters **52**, 1122 (1984)

[2] Helander P. et al, Phys. Plasmas **4**, 2181 (1997)

[3] Huysmans G.T.A. et al, Nuclear Fusion **39**, 1489 (1999)

[4] Wong K.L. et al, Phys. Rev. Letters **85**, 996 (2000)

[5] Ding X.T. et al, Nuclear Fusion **42**, 491 (2002)

[6] Valovic M. et al, Nuclear Fusion **40**, 1569 (2000)

[7] P. Smeulders, et al, Proc. 29th EPS Conference on Plasma Phys. and Contr. Fusion, Montreux [ECA 26B, D-5.016 (2002)].

[8] Main parameters: major radius R=2.4 m, minor radius a=0.72 m, magnetic field B<4T, circular cross-section.

[9] Ségui J-L et al, submitted to Review of Scientific Instruments (2005)

[10] Basiuk V. et al, Nuclear Fusion **43**, 822 (2003)

[11] Houlberg W.A. et al, Phys. Plasmas **4**, 3230 (1997)

[12] Litaudon X. et al, Plasma Phys. Control. Fusion **38**, 1603 (1996)

[13] Maget P. et al, Nuclear Fusion 45, **69** (2005)

[14] P.T. Bonoli, IEEE Trans. on Plasma Science 12, **95** (1984)

[15] W. Kerner et al, J. Comp. Phys. **85**, 1 (1989)

[16] G. Giruzzi et al, Phys. Rev. Lett. **91**, 135001 (2003); F. Imbeaux et al, Proc. IAEA, EX P6-16 (2004); This conf. G. Giruzzi et al **I1.006**, ; F. Imbeaux et al, **P1.034**

[17] Udintsev V.S. et al, submitted to Review of Scientific Instruments (2005); this conf. **P1.037**