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Magnetic Islands Rotation in JET

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** See annex of F. Romanelli et al, "Overview of JET Results",
(24th IAEA Fusion Energy Conference, San Diego, USA (2012)).*

INTRODUCTION

The propagation of magnetic islands in tokamaks is a relevant issue both for tearing mode stability and for diagnostic applications. The latter consist in the determination of rational- q locations from the comparison between magnetic signal frequencies and plasma rotation profiles [1,2]. The former issue arises from the fact that ion inertial effects (the polarization current) can be stabilizing or destabilizing depending on the ratio between the island propagation frequency in the frame with zero radial electric field ($\omega - \omega_E$) and the ion diamagnetic frequency ω_{*i} . Here ω is the island frequency in the laboratory frame and ω_E is the Doppler shift associated with the $\mathbf{E} \times \mathbf{B}$ velocity. The linear tearing mode stability theory predicts propagation at the electron diamagnetic frequency, $\omega - \omega_E \approx \omega_{*e}$ (note that ω_{*i} is positive by definition while ω_{*e} is negative). Non-linear theoretical studies [3] give frequencies that increase from ω_{*e} to ω_{*i} for increasing ratio between the island size (w) and the ion sound gyroradius (ρ_s). Early experiments in ohmic plasmas apparently confirmed the linear theory prediction, but, since the possibility of substantial rotation in ohmic plasmas was not known at that time, the Doppler shift was neglected. More recent investigations [4] in H-mode plasmas heated by co-injected neutral beams found frequencies between $0.5\omega_{*i}$ and $1.5\omega_{*i}$. A few (8 cases in all) islands with different periodicity numbers (m poloidal and n toroidal) were studied in [4]. The main difficulty of this kind of comparison is that large error bars arise from the evaluation of ω_E and ω_{*i} at the location where $q = m/n$. In the present study, the precision of the comparison was improved by averaging over a large (149 data points) database of islands with the same m/n .

ANALYSIS METHOD

The starting point was the observation that small and persistent $m/n = 2/1$ islands are often present in the hybrid regime of operation at JET (see figure 1a). The small island size (one case only with estimated separatrix full width $w > 4\text{cm}$) ensures that there are no locking interactions with other islands nor with external error fields. The choice of using this kind of islands was motivated by the good reliability of the q - profile determination in the $q \approx 2$ region from equilibrium reconstruction constrained by motional Stark effect (MSE) measurements. It is worth noticing that the well-known big $2/1$ islands that sometimes terminate the hybrid regime appeared in some instances, but none of these events met the database selection criteria. Discharges with available MSE, charge-exchange (CX) recombination spectroscopy and high-resolution Thomson scattering (HRTS) were selected.

The CX diagnostic provides toroidal angular frequency (Ω) and temperature profiles (T_C) of CVI impurity ions. The Doppler shift is evaluated from the radial force balance neglecting density gradient and poloidal rotation,

$$\omega_E = n \left(\Omega + \frac{1}{6} \frac{dT_C}{d\psi} \right) ,$$

while, the main ion diamagnetic frequency is

$$\omega_{*i} = -n \frac{dT_c}{d\psi} ,$$

(having assumed main ions at T_c temperature) and the electron diamagnetic frequency is

$$\omega_{*e} = n \frac{dT_e}{d\psi} ,$$

ψ being poloidal flux and T_e electron temperature from HRTS. The diamagnetic frequencies are small fractions of the Doppler frequency, 10% on average and 20% at most. The island frequencies will be compared with ω_E , with the ion frequency $\omega_i = \omega_E + \omega_{*i}$ and with the “electron frequency” $\omega_e = \omega_E + \omega_{*e}$.

A data point was generated for each MSE time slice for with reliable CX and HRTS data and with a recognized 2/1 island signature. Spectral features with $n = 1$ toroidal number were recognized by cross-phase analysis of signals from a toroidal array of pick-up coils, but the available poloidal arrays did not allow a direct determination of the m number. This issue was overcome by exploiting the large difference in frequency between 2/1 islands and $m = 1$ modes associated with the $q = 1$ resonance such as fishbone instabilities, in fact the ω_i calculated at the $q = 1.5$ location proved a good discriminator. Other modes with $m > 2$ were rejected by a lower boundary at 70% of the ω_i calculated at $q = 2$ (direct calculations at $q = 2.5$ being unreliable due to edge effects). The value was subsequently determined by averaging the selected spectral points in a time interval about the MSE time slice. The procedure is illustrated in figure 1b, where the selected spectral points are highlighted in red. Reasonable variations of the frequency discriminators and of the averaging time intervals do not affect the results shown in the following.

The database spans a wide range of plasma parameters, with plasma current 1.4–2.5MA, toroidal magnetic field 1.7–2.7T, local density $2\text{--}6 \times 10^{19}\text{m}^{-3}$, normalized beta 0.5–3.5. The local plasma collisionality ranged from 0.01 to 0.1, with a few cases up to 0.2, i.e. all cases were in the banana regime.

RESULTS AND DISCUSSION

The comparison between measured frequencies and ion frequencies calculated at the $q = 2$ location is shown in Figure 2. A linear fit forced to cross the origin gives a slope of 0.99. A similar comparison with ω_E gives a slope of 1.1 (Figure 3), while a slope of 1.2 results from the comparison with ω_e . The island propagation is then in better agreement with ω_i , or equivalently the island propagation frequency in the frame with zero radial electric field equals the ion diamagnetic frequency ω_{*i} . This result confirms the validity of diagnostic applications [1,2] that exploit the presence of an (m, n) island to determine the $q = m/n$ radius as the one at which the ion frequency profile crosses the island propagation frequency. About the stability issue, the polarization current should have neutral effect on islands that propagate at ω_i .

As for theoretical implications, the results of this paper apparently agree with the prediction of non

linear theory in the large-island regime, in which the ion flow is trapped by the island separatrix and the poloidal flow is completely damped inside the island [5]. However the condition of negligible ion flow across the separatrix, $\rho_s / w \ll 1$, is only marginally fulfilled across the database, the average value of the ratio being 0.4. More theoretical progress is then needed in order to fully understand the island propagation. Two more issues raised by the present results deserve further investigation; first, are the observed 2/1 island generated by a linear instability? And second, why do they regularly saturate at low amplitude, even in plasmas with normalized beta up to 3.5?

ACKNOWLEDGMENTS.

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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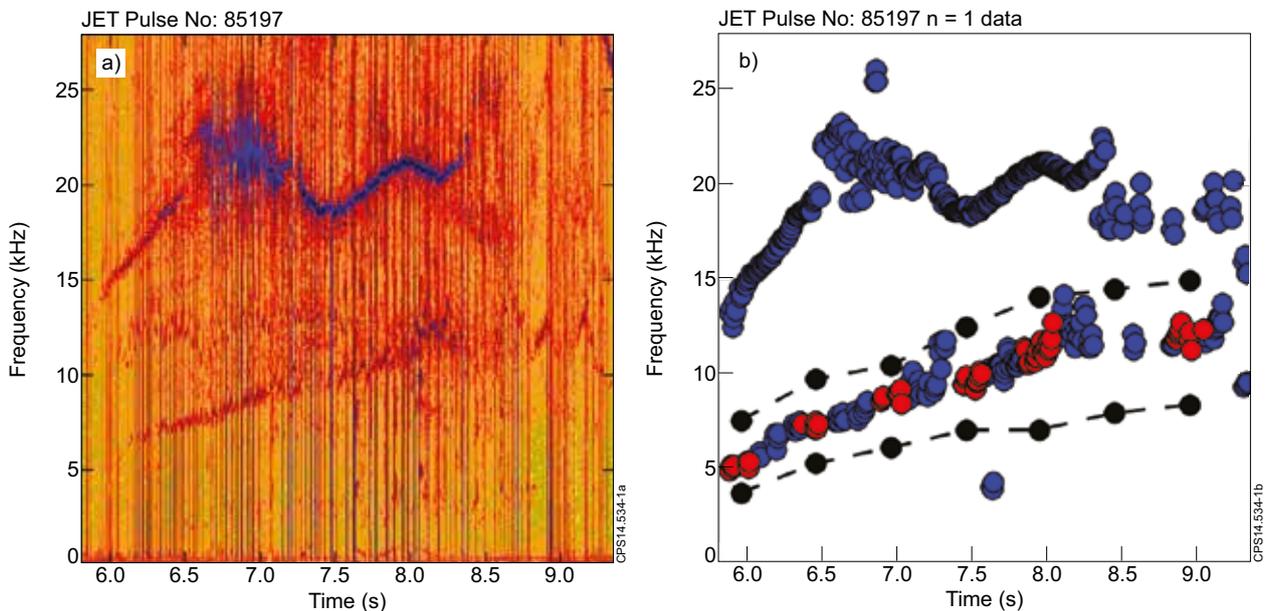


Figure 1. (a) Amplitude spectrogram zoomed in a frequency interval including signals from the 2/1 island (increasing in time from 7 to 14kHz) and from 1/1 activities (between 15 and 26kHz). (b) Spectral elements corresponding to $n = 1$ toroidal number that were extracted from the spectrogram shown on the left (red and blue symbols). The upper dashed line shows the ion frequency at $q = 1.5$, the lower one is 0.7 times the ion frequency at $q = 2$. Black dots mark MSE time slices; for each one, data lying between the dashed lines and within a time distance of 0.1s are selected (red symbols). The average frequency of each selected group is passed to the database.

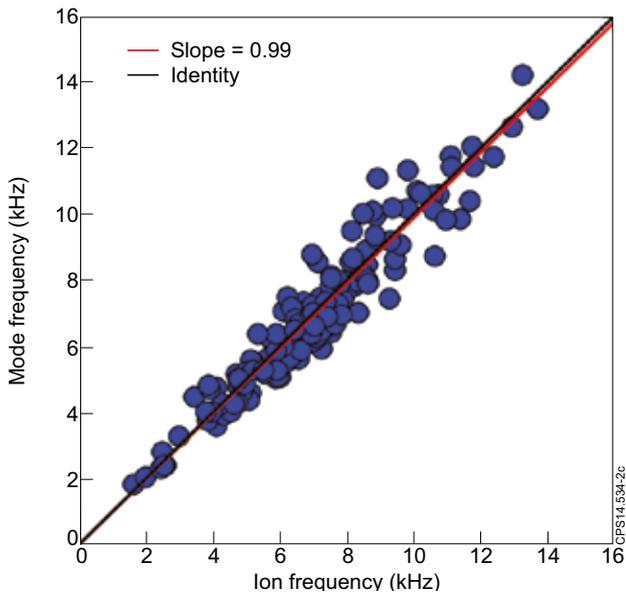


Figure 2. Comparison between measured island frequency and $\omega_E + \omega_{*i}$ (divided by 2π and scaled in kHz). The slope represented by the red line is evaluated by a linear fit forced to cross the origin.

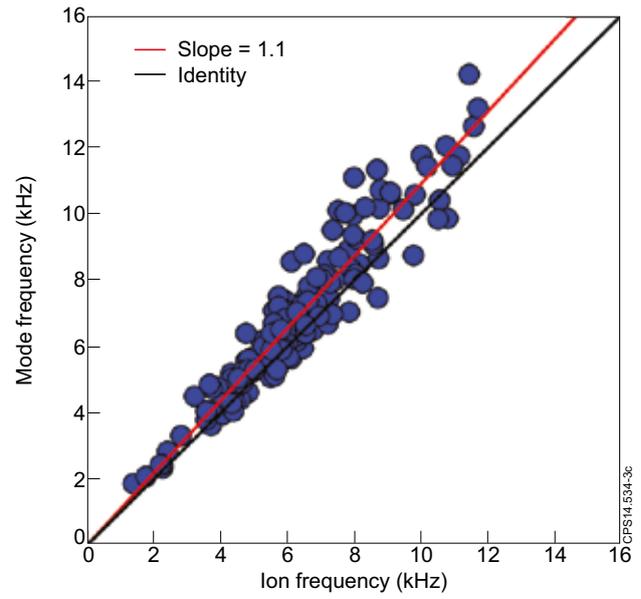


Figure 3. Comparison between measured island frequency and Doppler shift ω_E (divided by 2π and scaled in kHz). The slope represented by the red line is evaluated by a linear fit forced to cross the origin.