Magnetic island rotation in TJ-II plasmas

B. J. Sun, D. López-Bruna, M. A. Ochando, M. A. Pedrosa

Laboratorio Naciónal de Fusion, Ciemat, 28040-Madrid, Spain

Introduction

In order to confine hot plasmas, magnetic-confinement fusion (MCF) devices rely on the establishment of nested flux surfaces. Their breakup to form islands or stochastic regions can degrade plasma confinement and induce disruptions. For these reasons tearing mode studies have been a continued concern, especially in tokamak technology. Over the years, however, there has been accumulating evidence that magnetically resonant regions (prone to open islands) confer also interesting properties to MCF plasmas. It is known, for example, the relation between low order rational values of the safety q-profile (typically $\iota = 1/q$ in currentless devices) and the establishment of transport barriers.

The destructive effects of magnetic islands in stellarators are mitigated because the current density shear is much smaller than in tokamaks, thus providing less drive for tearing mode instabilities. Additionally, due to negative magnetic shear, the bootstrap current is believed to be stabilizing [1]. Locked magnetic islands can exist due to error fields and plasma effects, but they do not necessarily grow to threaten confinement. In many cases, the basic dynamics of magnetic islands in stellarators is related to their rotation in the plasma frame. Island rotation is easy to detect, and it may convey important information for plasma control. This work is devoted to magnetic island rotation in plasmas of the TJ-II stellarator and its relation with confinement properties, notably the creation and destruction of transport barriers.

Phenomenologycal overview

TJ-II is a Heliac-type stellarator with low magnetic shear within a large range $\iota \sim$ 1–2. ECRH and NBI are used to heat the plasma up to ~ 1 keV electron temperatures. Average electron densities, $\bar{n}$, are on the order of 10^{19} m^{-3}. Low frequency coherent modes are found independently of heating regime, and the mode positions and numbers are often related with some dominant rational surface in the near edge region ($0.4 < \rho < 0.9$, where ρ is a normalized radial coordinate). Typical phenomenology in relation with island rotation is exemplified in figure 1, which corresponds to discharge #33847 in a magnetic configuration such that $\iota = n/m = 8/5$ locates at $\rho \approx 0.76$. During the ECRH phase (Fig. 1(b)) a coherent mode labelled 1 in Fig. 1(a) starts ($t \approx 1110$ ms) with 5 kHz, increases frequency as $\bar{n}$ does, and drops when the gas puffing (not shown) is cut at $t \approx 1140$ ms. The ECRH switches off at $t \approx 1160$ ms provoking about 10 ms of plasma cooling. When the co-NBI is coupled to the plasma the coherent mode re-appears (labelled 2), initially with 21 kHz, slightly increasing frequency with density. After $t = 1220$ ms (dashed vertical line) the frequency increases but also loses coherence and intensity. This process is related with reductions of edge H_α light and magnetic fluctuations, which are typical signatures of plasma preparation for an L-H transition.

The phase indicated with label 3 in figure 1(a) has given rise to much literature because of its rich dynamics. Figures 1 (c) and (d) are just a zoom in this time window for the same discharge. As of $t = 1129$ ms (vertical dashed line), the initially coherent mode undergoes a pulsed activity accompanied by H_α peaks. The H_α becomes larger on average and each pulse separates short phases of rapidly decreasing frequency in the spectrogram. When possible, mode number analyses indicate that modes 1–2–3 share the same poloidal number m, always corresponding to a low order rational in the magnetic configuration. Bolometers confirm that the oscillations locate around the expected position of the $\iota = n/m$ resonance. In general, mode 3 can be sustained for long times despite its being the threshold between L- and H-mode confinement regimes [2]. The following sections give more detailed descriptions of steady and bursting modes, and reveal the link to island dynamics.

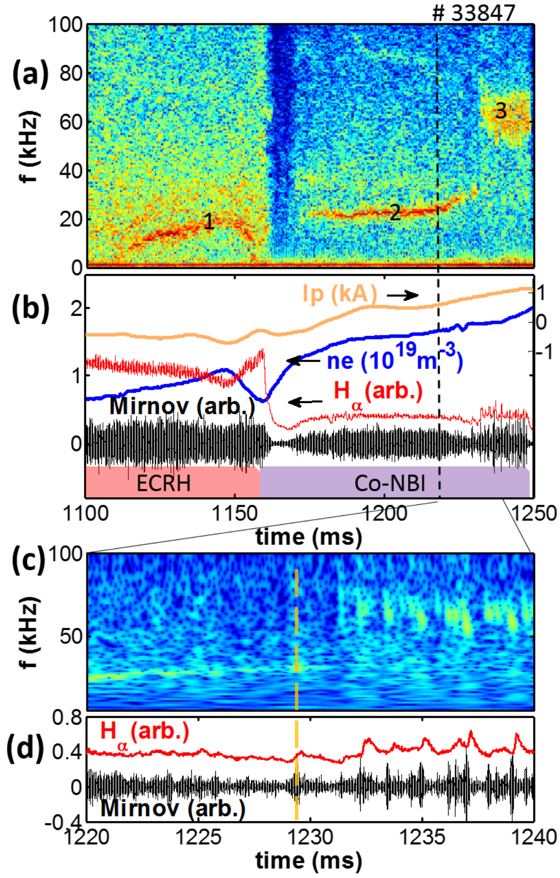

Figure 1: *TJ-II discharge #33847. (a) Power spectrum of Mirnov coil signal; (b) plasma current* I_p*, line average density* $\bar{n}$*,* H_α *signal, and raw Mirnov data. Zoom in view: (c) wavelet power spectrum of Mirnov; (d)* H_α *and Mirnov coil data.*

Steady island rotation mode

Steady island rotation, like modes 1 and 2 in Fig. 1(a), is normally seen in low-density ECRH or in NBI plasmas with peaked density profiles, as is typical in L-mode of confinement; and generally with the low order rational surface located around $0.5 < \rho < 0.9$. As expected from rotating islands, the mode frequency scales linearly with m and the slope is compatible with ExB rotation frequency $f_{E\times B} = v_{E\times B}/(2\pi a\rho)$ [3]. Here a is the average minor radius.

Further proof of island rotation is given in figure 2, corresponding to a discharge started and sustained with co-NBI at low density ($\bar{n} = 0.7 \times 10^{19}$). The start-up with NBI causes a negative current ~ -3 kA that carries the surface $\iota = 3/2$ to $\rho \approx 0.5$. The 10 kHz coherent mode detected by ECE radiometers shows a clear phase inversion between channels ECE4 ($\rho = 0.45$) and ECE3 ($\rho = 0.53$), indicating a modulation of the average T_e gradient in that region. Steady island rotation can show harmonics, especially for low m rationals. For example, up to the 5th harmonic has been detected for the 3/2 island.

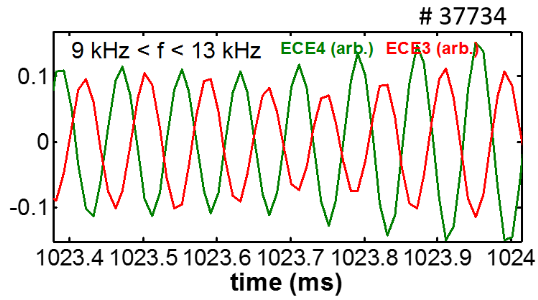

Figure 2: *TJ-II #37734. Electron temperature fluctuation within the 9–13 kHz frequency band for ECE channels #4 ($\rho = 0.45$) and #3 ($\rho = 0.53$).*

Bursty island rotation mode

Chirping frequencies (Fig. 1, mode 3) substitute the steady rotation when the plasma approaches the L-H transition. Figure 3 shows time traces of a $\bar{n} = 0.8 \times 10^{19}$ m^{-3} plasma heated and fueled with co-NBI ($I_p \approx 1$ kA) in which $\rho_{8/5} \approx 0.5$. In the shady region, the innermost ECE4 ($\rho = 0.45$) shows a continued increment of electron temperature while the outer ECE3 ($\rho = 0.53$), and more clearly the outermost ECE2 ($\rho = 0.65$), decrease: a transport barrier has developed between the ECE4 and ECE3 locations. Then, a sudden burst on the Mirnov signal coincides with a quick drop of temperature according to ECE4; but ECE3 and ECE2 rise, as expected from the sudden breaking of the barrier. The process is repeated on a ms time-scale.

The correlation between the flattening/steepening of profiles (e.g. electron temperature) around the resonant location and the envelope magnetic fluctuations has been also detected with bolometry and is always associated with a break-up/build-up of transport barriers owing to continuous heating and fueling. This provokes a kind of limit cycle oscillation and flux-surface wide perturbations on many plasma magnitudes.

The amplitude and characteristic times between bursts (e.g. in magnetic or H_α signals) depend mainly on the order of the rational. For higher orders, such as $\iota = 8/5$, the unstable rotation has usually repetition lags about 0.5–1 ms and there are no obvious changes in global plasma parameters, quite like in tokamak grassy ELMs. For the lower order 3/2, each MHD burst can last for several ms causing decrements in $\bar{n}$ and temperatures. Sometimes, clear drops in plasma current and large H_α pulses are found, resembling more closely giant tokamak ELMs.

The frequency of unstable rotation modes also varies linearly with m and can show harmonics for the lowest m values. Frequencies per mode number have been found in the ranges $f/m = 8$–16 kHz ($\iota = 8/5$), 7–12 kHz (5/3) and 8–20 kHz (3/2). The lower f/m boundary is quite robust, while the upper limit seems to depend on island size and local plasma parameters.

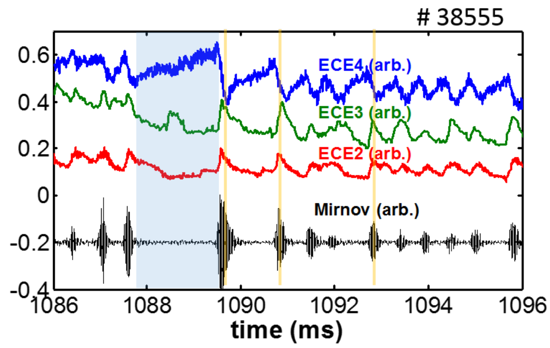

Figure 3: *TJ-II discharge #38555. ECE signals around the* $\iota = 8/5$ *resonance, and Mirnov coil data.*

Discussion and conclusion

Low order rational surfaces are singular in MHD equilibrium. They can give birth to magnetic islands that interact non-linearly with the plasma fluid via resistivity, local gradients and plasma flows. These are common elements of L-H transition theories, which makes the rotation of magnetic islands naturally sensitive to the transition threshold, and also viceversa according to TJ-II literature. Such strong link between island dynamics and the formation of transport barriers justifies the existence of a sustainable threshold state, which is the bursty island rotation mode above. The corresponding repetitive creation and breaking of transport barriers provides signatures that are typical of zonal-flow dynamics (e.g. predator-prey cycles, long-range correlations, strong relation with the L-H transition, intermediate modes...) commonly associated to turbulent self-organization. Whether the latter is relevant or not to interpret the experiments, magnetic island dynamics is a mandatory ingredient in TJ-II plasmas. Similar behaviors can be seen in other experimental devices pointing to common physics, and we suggest that information on the presence of possible magnetic resonances be always given (e.g. the q-profile).

In conclusion, magnetic islands can rotate steadily with plasma flow in general TJ-II plasmas. Unstable island rotation, characterized by chirping frequencies and bursts in magnetic activity and plasma transport, is found at the threshold for the L-H transition. The phenomenology resembles typical tokamak activity, suggesting very basic and common physics in MCF plasmas.

References

[1] Carrera R et al. 1986 Phys. Fluids **29** 899

[2] López-Bruna D et al. 2013 Nucl. Fusion **53** 073051

[3] Sun B J et al., 41st EPS Conf. on Plasma Physics, Berlin 2014, ECA Vol. 38, P2.090