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Synchronization of drift waves in a DC magnetron sputtering device

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Active control of plasma electrostatic fluctuations is a line of research which has potentially important implications for fusion research, since these fluctuations are responsible for transport processes in fusion devices. For example, it has been shown in a linear machine that by driving one of the drift wave modes present in the plasma the background turbulence level can be reduced [1].

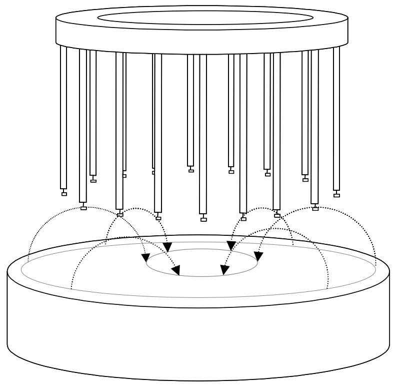

Fig. 1: Cathode and probes.

In this paper we present a first attempt of synchronizing naturally occurring electrostatic fluctuations to an externally applied resonant pattern in a low temperature magnetised plasma. The device in which the experiment is performed is a magnetron sputtering device operated in DC. In such a machine a glow discharge is produced by applying a DC voltage (of the order of 400 V) between a cathode and the chamber wall. The vacuum chamber is a cylinder 40 cm in diameter and 50 cm high. The discharge gas is argon. The cathode, which has a diameter of 10.1 cm, is equipped with permanent magnets located beneath its surface, which produce a cusp-like field (see Fig. 1). Electrons are trapped in the magnetic field, thus yielding an enhanced ionization rate and a relatively high plasma density inside the magnetic trap. Ions created by ionization events are unmagnetized and fall towards the cathode.

Previous work on this device, performed with electric probes measuring the floating potential V_f, has shown the presence of azimuthally propagating waves with azimuthal mode number m = 3÷7 and frequency of the order of 100 kHz [2,3]. They have been identified as drift-like waves, destabilized by the combined effect of electric field and density gradient.

The experimental setup of the experiment described here is the same as in ref. 3. An azimuthal array of 16 probes with a radius of 40 mm is placed at the edge of the magnetic trap, 13 mm above the cathode surface (see Fig. 1). Each probe is a cylinder with 3 mm diameter and 1 mm height, held in place by a support structure covered by a quartz tube. While in ref. 3 all the probes were used to measure the fluctuations, in this work we have used 8 probes (half of the circle) as active elements (“drivers” in the following), imposing a spatio-temporal voltage pattern on them, while the other 8 have been used to monitor the plasma response by measuring the floating potential ("sensors"). The discharge has been operated at a neutral gas pressure of 0.8 Pa, with a plasma current of 0.6 A, corresponding to a power of 260 W. In this condition the floating potential frequency spectrum exhibits two coherent peaks at 105 and 130 kHz, as shown in Fig. 2. These peaks correspond to the modes m = 4 and m = 5 respectively, as demonstrated by a wavenumber-frequency analysis (see ref. 3 for details). Also visible in Fig. 2 are two smaller peaks, corresponding to modes m = 3 (75 kHz) and m = 6 (155 kHz).

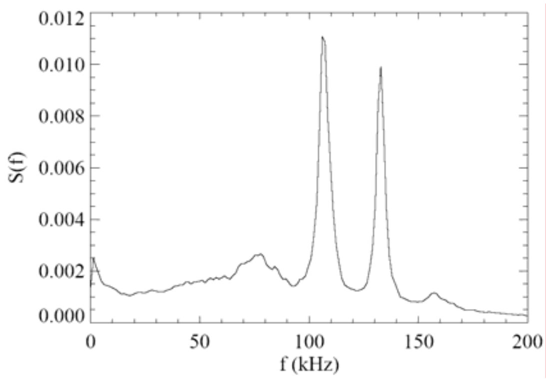

Fig. 2: Frequency specrum of fluctuations.

The strategy adopted in this experiment is to create in the 8 drivers a travelling pattern with an m = 4 azimuthal periodicity at a chosen frequency. This is performed in practice by connecting in sequence each probe to a power supply delivering a constant voltage V_d larger than the floating potential using a Mosfet. The Mosfets are controlled by a programmable function generator, so as to create the correct spatio-temporal pattern. In this way, a train of positive (i.e. from the probe to the plasma) current peaks is created, forming a perturbation with the appropriate wavenumber and frequency. The wave is clearly non-sinusoidal, and indeed this approach was chosen having recognised that only driving the probe to voltages higher than the floating potential, towards the electron part of the I-V characteristic, yields a substantial current. It is important to observe here that, due to the small collecting surfaces of the probes, only small currents (of the order of 1 mA) can be drawn, so that the applied perturbation is weak. Furthermore, it must be recognized that the perturbation is applied to only half of the circumference where the probe array lies. A counter-rotating perturbation (same frequency and wavenumber, but opposite direction) gives no effect.

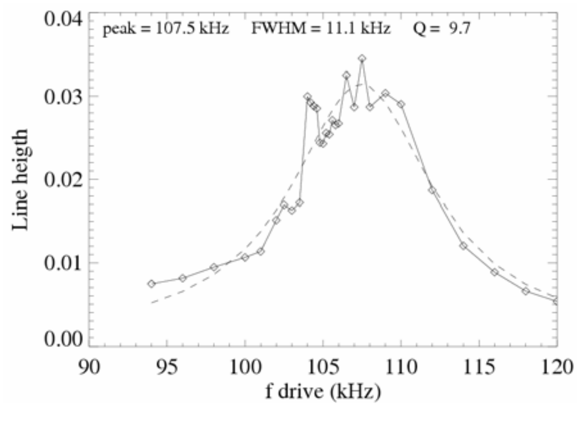

Fig. 3: Response intensity as a function of drive frequency.

The frequency spectrum of one of the sensors displays an additional sharp peak as a consequence of the application of the rotating pattern to the drivers. The height of the peak is maximum when the driving frequency is equal to that of the naturally occurring m = 4 mode, i.e. when the perturbation is resonant with the plasma. This is shown in Fig. 3, where the height of the additional peak is plotted as a function of the driving frequency. The bell-

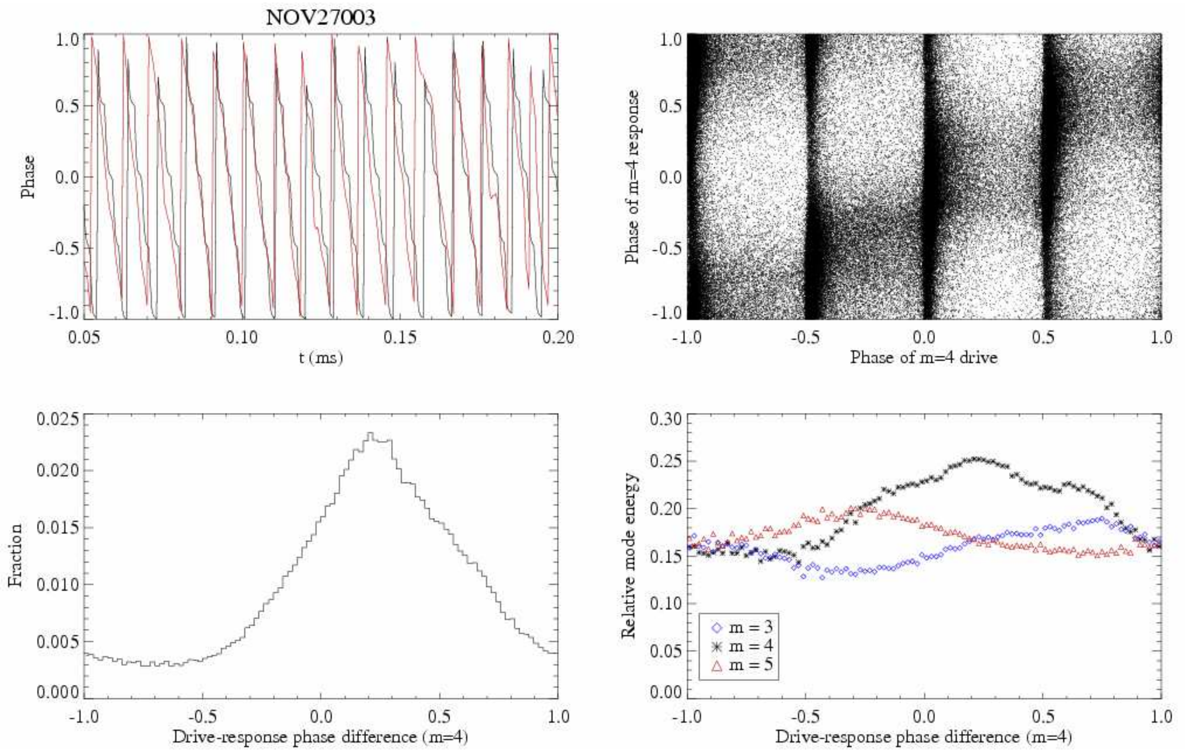

Fig. 4: Top-left: phase of m=4 drive and m=4 response; top-right: response phase vs. drive phase; bottom-left: distribution of drive-response phase difference; bottom-right: relative amplitude of m=3,4,5 modes plotted as a function of the phase difference between drive and response.

shaped curve is reminiscent of the response of a resonator. The ratio of the curve width to the peak frequency yields a quality factor $Q = \omega_0/\Delta\omega \approx 10$.

The effect of the perturbation, in the resonance condition, is displayed in Fig. 4. The top-left frame shows the phase $\alpha_{drive}(t)$ of the m = 4 mode applied to the drivers (in black) and the phase $\alpha_m(t)$ of the m = 4 mode as measured by the sensors (all phases normalized to π). It is possible to see, qualitatively, that the drive and the response are synchronized only for a fraction of the time. This is more clearly seen in the top-right frame, where the phase of the response is plotted versus the phase of the drive for the whole time record. The black vertical stripes are due to the fact that the drive phase does not vary linearly, since the drive is not sinusoidal. Apart from this effect, it is also possible to see a diagonal darker band, which shows that there exists a preferred phase relationship between drive and response. Such relationship however occurs only intermittently, so that some points are present also in other regions of the plot. Indeed, the bottom-left frame shows a probability distribution of the phase difference between drive and response. Such a phase difference clearly peaks at a value around 0.2, confirming the existence of a partial phase synchronization. Finally, the bottom-right frame of Fig 4 shows the relative mode energy (i.e. the mode energy normalized to the energy of all the modes) for the m = 4 mode, and also for m = 3 and m = 5, plotted as a function of the drive-response phase difference. It is possible to observe that when phase synchronization takes place, i.e. when the phase difference has a value around 0.2, the relative amplitude of the driven mode (m = 4) is enhanced, while that of the other two modes is increased for different phase difference values. Such a result is reminiscent of what found in Ref. 1, although it is not as strong (probably due to the drive weakness).

The occurrence of the phase synchronization, as defined by the presence of a preferred value of the drive-response phase difference, is found to depend on the drive frequency. Indeed, the phase difference distribution (bottom-left of Fig. 4) is more peaked when the drive frequency matches the that of the naturally occurring mode, and becomes more and more flat as the frequency is moved away from the resonance condition.

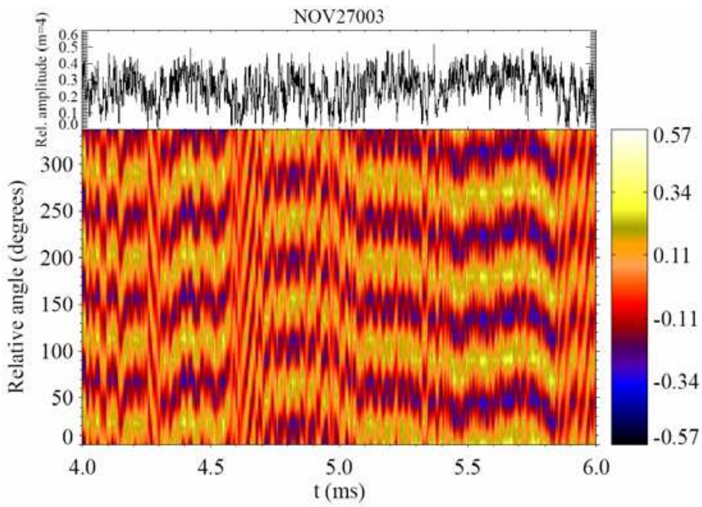

Fig. 5: m=4 mode in the reference frame of the applied perturbation (bottom), and relative amplitude of it (top).

In order to further establish the existence of a partial phase synchronization, and its effect on the mode amplitude, we show in Fig. 5 a color-coded plot of the quantity $x(\theta,t) = A_m(t)\cdot\cos[m\theta+\alpha_m(t)- \alpha_{drive}(t)]$ for m = 4, where $A_m(t)$ is the mode amplitude. This quantity is the m = 4 mode as seen in a reference frame moving with the applied voltage pattern [4]. The plot shows that a phase locking between drive and response is seen only in some time intervals, where a stationary pattern appears, and is lost in others, where the mode is found to move with respect to the applied perturbation. The top frame, showing the relative amplitude of the m = 4 mode, confirms that it increases during the phase synchronization intervals.

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