Electrostatic turbulence characterisation in a DC magnetron plasma

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Magnetron plasma sources are nowadays widely used for sputtering and film deposition applications [1]. A DC magnetron plasma is essentially a glow discharge established between a cathode and the walls of the vacuum chamber. Permanent magnets located inside the cathode create a magnetic field configuration acting as a magnetic trap for the electrons, which typically have a temperature of a few eV. A strong ionisation source is thus present in the region located in front of the cathode. Cold ions created in this region are unmagnetised, so that they are accelerated towards the cathode, causing sputtering from its surface.

A still debated problem concerning DC magnetron discharges is the process by which electrons are lost from the magnetic trap. The presence of a potential fall in the proximity of the cathode at all pressure levels has been interpreted as a proof that electron transport coefficients are non-classical [2]. Several authors have suggested that instabilities giving rise to nonlinear coherent modes or turbulence might be responsible for an anomalous cross-field electron transport. To our knowledge only one experimental investigation of low-frequency electrostatic fluctuations has been carried out in this kind of plasma [3]. In ref.3 density fluctuations of a few percent were measured by Langmuir probes, and by an indirect method these fluctuations were inferred not to be relevant for electron transport.

We report measurements of floating potential V_f and ion saturation current I_s made by Langmuir probes in a DC magnetron Ar plasma [4]. The magnetron device is cylindrical, so that the usual (r,ϕ,z) cylindrical coordinates will be used to describe it. The magnetic field has rotational symmetry around the z-axis. The vacuum chamber has a diameter of 40 cm. The magnetic field configuration in proximity of the cathode is shown in fig.1 at fixed ϕ. The cathode has a diameter of 10.2 cm and its surface is located at z = 0. The Langmuir probe system used in the present campaign is sketched in the inset of fig.1. It is made up of three electrodes, each consisting of a tungsten wire with a length of 3 mm and a radius of 0.1 mm; the distance between two nearby wires is 8 mm. Each electrode emerges from a stainless steel cylindrical pipe 150 mm long and with 4-mm diameter and is isolated from it. A 25-mm diameter cylinder supports all three pipes and is mounted on the shaft of a manipulator

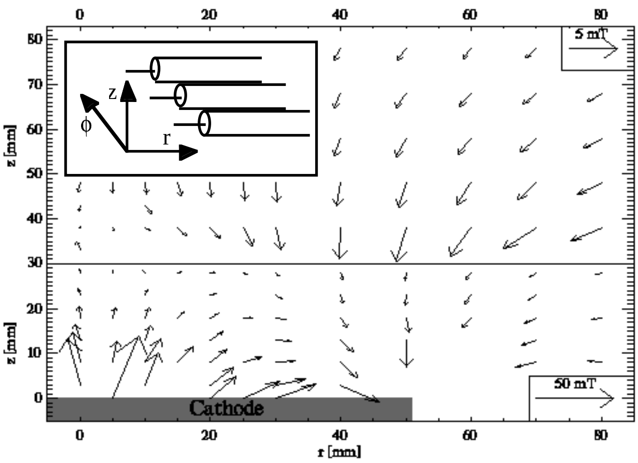

Fig.1: Magnetic field map inside the magnetron sputtering device. Two different scales are used on the two halves of the plot. r=0 is a symmetry axis. The probe layout is shown in the inset.

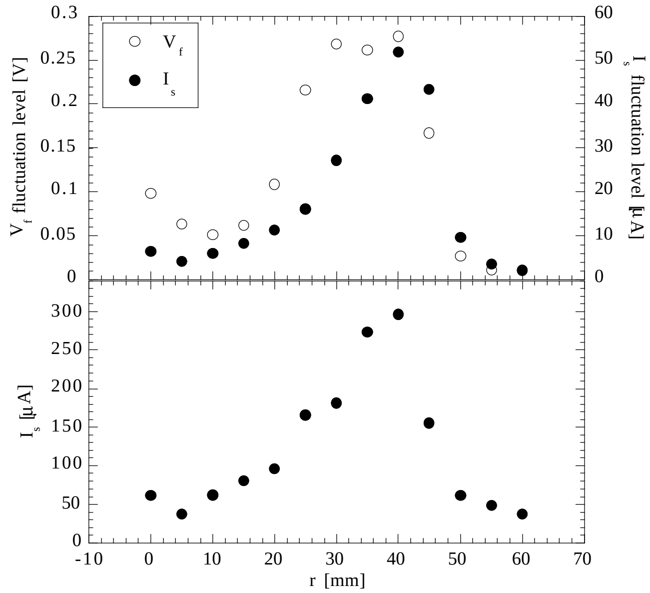

Fig.2: Top: fluctuation levels (RMS values) of V_f and I_s. Bottom: radial profile of the average I_s.

allowing horizontal translation. The two probes on the sides were left floating and were used to measure V_f. The middle one was biased at -100 V. The current flowing through it was measured by means of a transconductance amplifier (current to voltage converter) with a 500 kHz bandwidth. This current was taken as representative of I_s, although it is well known that in cold plasmas, due to the expanding sheath, it is difficult to properly determine an ion saturation current regime [5]. The probe system was located at z = 13 mm above the cathode surface. A horizontal scan of position was performed at a power level of 300 W and a pressure of 1 Pa. A power scan was also performed. For each position and power level, V_f and I_s data were recorded for 0.2 s at a sampling frequency of 1 MHz using a 12-bit digital oscilloscope. It is important to notice that these measurements were made using rectified and filtered mains voltage as power supply for the discharge. Indeed, as mentioned in ref.3, switching power supplies normally used for magnetron plasmas give rise to voltage ripples (typically at 50 kHz and higher harmonics) which are "seen" by the probes, overlapping the plasma fluctuations.

The fluctuation levels measured at P = 300 W, computed as RMS values of the raw signals, are shown in fig.2 (top). The average I_s profile is also shown in fig.2 (bottom). I_s fluctuations reach values as high as 20% of the average I_s, i.e. substantially higher than those reported in ref.3. Fluctuations of both V_f and I_s are highest around r = 40 mm, which is in the middle of the magnetic trap. The probe collection area was A = 12 mm^2. Assuming an electron temperature of 2 eV, i.e. similar to what previously measured in the same device [6], the peak density at r = 40 mm results $n = 1.4 \cdot 10^{17}\ m^{-3}$.

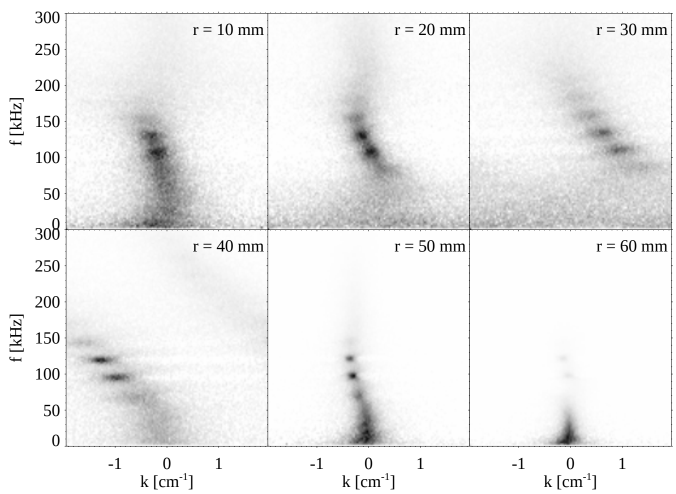

Fig.3: S(k,f) for six different radial positions.

From the two simultaneous V_f measurements made at a distance d = 16 mm the spectral density S(k,f) was evaluated, using the two-point technique commonly used for fluctuation measurements in the edge of fusion plasmas [7]. Here and in the following k is the wavenumber in the direction connecting the two probes, i.e. in the ϕ direction. Fig.3 shows S(k,f) for six radial insertions. The grayscale is such that darker regions correspond to higher power. The grayscale is different for each frame, i.e. gray levels of different frames are not directly comparable.

The most interesting feature detected in fig.3 is the presence of discrete peaks, corresponding to coherent modes. While the frequency of the peaks seems to be almost independent of r, the wavenumber is found to vary. This is confirmed by fig.4, where frequency and wavenumber of the peaks have been plotted as a function of r. The graph of k vs r suggests an aliasing effect, taking place because of the finite distance of the probes. This effect causes modes with $|k| > k_{max}$, where $k_{max} = \pi/d = 1.96\ cm^{-1}$, to be seen as having wavenumber $k' = k \pm 2k_{max}$. Some measurements made using the central tip and one of the lateral ones, i.e. a configuration which allows to detect k up to 3.92 cm^{-1}, have shown that the aliased measurements are those with $r < 40$ mm.

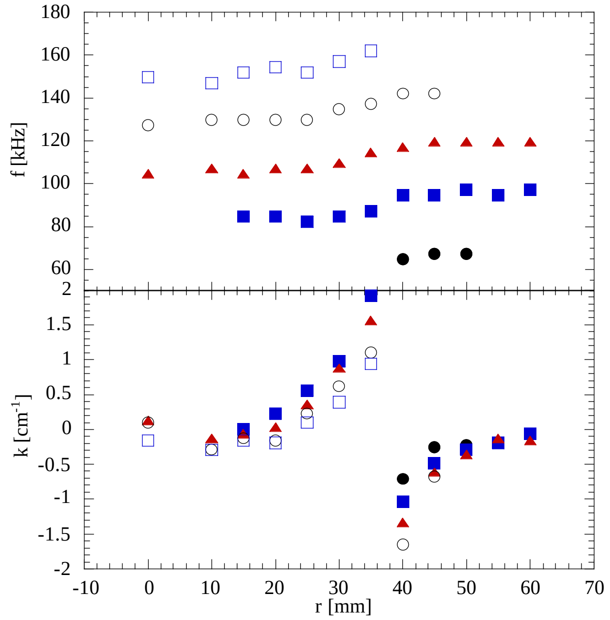

Fig.4: Frequency (top) and wavenumber (bottom) of the coherent modes. Different symbols correspond to different modes.

In fig.5 the wavenumbers corrected for the aliasing effects are plotted, together with the corresponding wavelengths. Wavelengths ranging from the size of the device (the vacuum chamber has a diameter R = 40 cm) down to something more than 1 cm are found, with a general trend to decrease going towards the center of the magnetic trap.

The scan in the discharge power has shown that frequency and wavenumber of the coherent modes are almost independent of the power level for P > 100 W. On the contrary, at P < 100 W the peaks corresponding to the coherent modes disappear from the power spectrum.

The particle flux driven in the cross-field direction by the electrostatic fluctuations has been evaluated using the two V_f measurements and the I_s measurement. The technique is the same routinely used in the edge of fusion devices [8]: the flux is evaluated in the frequency domain as the integral over all frequencies f of the quantity $-ik(f)P_{n\phi}(f)$, where $P_{n\phi}(f)$ is the cross-spectrum between density n and plasma

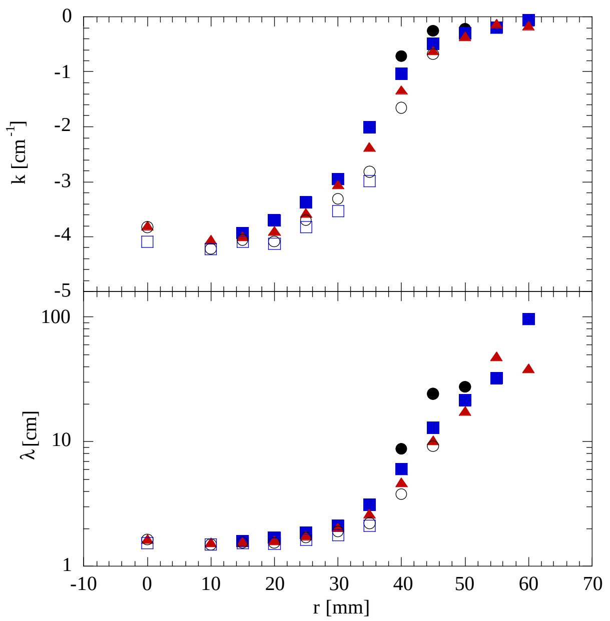

Fig.5: Wavenumber corrected for the aliasing effect (top) and corresponding wavelength (bottom).

potential ϕ. Temperature fluctuations have been neglected, by taking $\phi \approx V_f$ and $n \approx 2I_s/Ac_s$, with the ion sound velocity c_s computed assuming a constant electron temperature of 2 eV.

The particle flux measured at r = 40 mm is plotted in fig.6 as a function of the power fed to the discharge. In the same graph the current driven between cathode and vacuum chamber is also presented. The flux is mainly due to the coherent modes shown as peaks in fig.3. The measured flux is of the same order of magnitude as one could expect by considering the discharge current to be carried in equal fractions by ions and electrons, and estimating the number of electrons generated by ionisation inside the volume delimited by the magnetic surface touched by the probes. Furthermore, at powers larger than 100 W the flux is found to grow almost linearly with power, similarly to what found for the current, so that the ratio of the two is roughly constant. Although still inconclusive, these results suggest that the waves detected with the Langmuir probes could give a significant contribution to the cross-field electron transport, unlike the situation found in the device of ref.3. On the contrary, at very low power this contribution appears to be negligible, in agreement with the absence of the coherent modes in the power spectrum. Further experimental work is now required to confirm these hypotheses, and to characterise the transport driven by electrostatic fluctuations over a broader range of plasma parameters and positions.

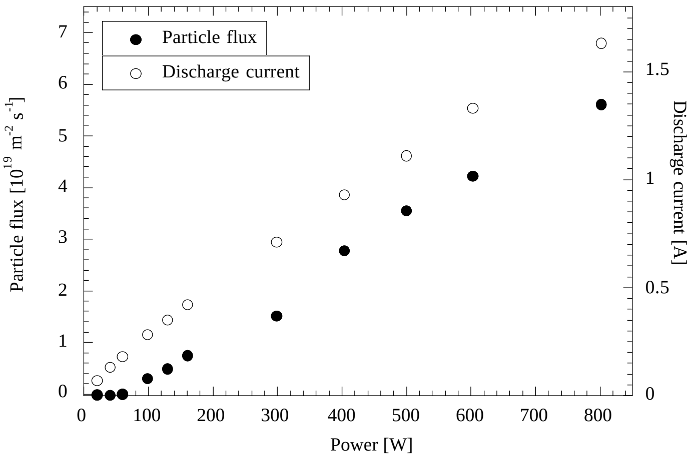

Fig.6: Particle flux at r = 40 mm and discharge current plotted as a function of the power.

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