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Modification of electrostatic fluctuations by externally imposed radial electric fields

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Abstract. This paper concerns experiments on the turbulence of a toroidal magnetoplasma in the presence of a radial electric field. The possibility of reduction of turbulence through the application of an external biasing potential has been evaluated by measuring the electrostatic fluctuations and main plasma parameters.

1. Introduction

Investigations of possible improvements in plasma confinement are closely connected to research on plasma turbulence and anomalous particle fluxes.

Previous work (e.g. Chiueh et al. 1986; Biglari et al. 1990) suggested that the creation of a radial electric field in the plasma edge could decorrelate electrostatic fluctuations and reduce anomalous particle transport. According to this work, if the macroscopic variation of the plasma poloidal velocity along a radial correlation length is larger than the spatial decorrelation velocity of the instability, electrostatic fluctuations can be decorrelated and thus suppressed as shown by Craddock et al. (1994).

Moreover, some preliminary experiments performed in large and small devices Chiueh et al. (1986) and Groebner et al. (1990), and particularly those conducted in the toroidal device BETA by Chaube and Jain (1996) and Jain (1996), have shown that the application of radial electric fields can lead to a decrease in turbulence and an improvement in plasma confinement.

The main purpose of our experiments is to study the effects of an electric field imposed externally by means of a biased limiter on electrostatic fluctuations in a steady-state magnetized plasma produced in the Thorello device (Alba et al. 1993). The analysis includes measurements of the plasma profile modifications as well as the spectral properties of fluctuations. The electrostatic fluctuations are measured through a digital correlation technique applied to multiple electrostatic probes.

2. Experimental set-up

We have carried out the experiments in the Thorello device, described in detail by Alba et al. (1993), which produces a hydrogen plasma in a torus (major radius $R = 40\,\mathrm{cm}$, minor radius $a = 8\,\mathrm{cm}$), confined magnetically with a field of up to $2.5\,\mathrm{kG}$.

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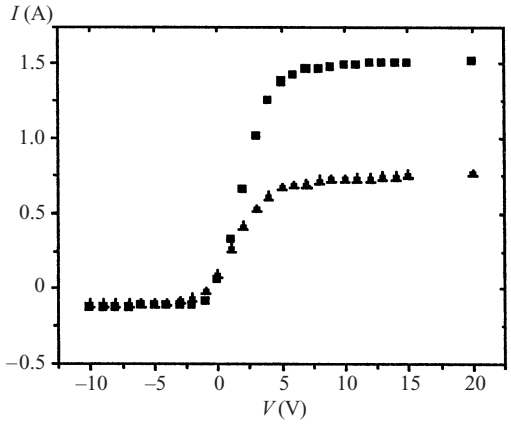


Figure 1. Current/potential characteristic curve of the half-moon-shaped limiter, for two different magnetic field configurations of $B = 333\,\mathrm{G}$ (▪) and $B = 1000\,\mathrm{G}$ (△).

The experiments are performed in hydrogen gas at a pressure of about 4×10^{-4} mbar at a discharge current of about 4 A and a magnetic field of 333 G. For these discharge parameters, the typical plasma parameters, obtained by means of a Langmuir probe diagnostic, are electron temperature T_e = 1–3 eV, edge plasma density of order $10^9\,\mathrm{cm}^{-3}$, and core plasma density of order $10^{11}\,\mathrm{cm}^{-3}$. There is neither a toroidal current nor a poloidal magnetic field imposed on the plasma, and hence no poloidal transform exists.

An half-moon-shaped limiter, called a *lunetta*, is placed in the vacuum chamber, and can be biased in order to apply radial electric fields in the plasma edge. Its characteristics are described in the following section.

Electrostatic fluctuations are estimated using the digital correlation technique developed by Levinson et al. (1984) and Beall et al. (1982), by means of Langmuir-probe arrays developed for this specific purpose. Signals collected by the probe pins are acquired simultaneously by a four-channel digital oscilloscope with 8-bit resolution, using sampling times of $10\,\mu s$ and $5\,\mu s$ (which allow one to observe frequencies less than 50 kHz and 100 kHz, respectively). Once acquired, data are processed by means of a Fortran program that performs a statistical analysis.

3. The half-moon limiter

In our experiment, the radial electric field is imposed by DC-biasing a half-moon-shaped limiter that is positioned at the edge of the vacuum chamber.

Our first measurements were focused on characterisation of the limiter, in particular its particle-collection properties, and on the selection of the polarisation parameters and the magnetic field. The current/potential limiter characteristic was obtained by applying a different biasing potential to the limiter itself and measuring the current collected. As we expected from the theory, we found that the properties of the collection current of the limiter are very similar to those of a Langmuir probe, characterized by two different saturation regimes, and an intermediate region, described by an exponential growth of the collected current with increasing biasing potential, as can be seen in Fig. 1.

The biasing potential range was chosen in order to work in the transition region

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of the current/potential limiter curve (between the two saturation regimes, with a polarization between −2 V and +6 V), because in this way we could characterize the behaviour of the imposed electric field for different values of the collection current of the limiter, and observe the gradual changes of the plasma as the biasing potential increased smoothly.

For the confining magnetic field, instead, we decided to observe the plasma behaviour for low magnetic field ($B = 333$ G), principally because, as can be seen from Fig. 1, we found that, for lower magnetic fields, the current range flowing into the limiter is quite wide, as is the biasing potential. In contrast, for higher magnetic fields, the electron saturation regime is reached even for low biasing potential, and it is quite short (typically, the current saturation regime for $B = 333$ G is about 1.5 A, while for $B = 1000$ G, it reaches at most values of 0.6 A, for the same applied polarization $V = +15$ V). Moreover, as we shall see in the next section, the biasing modifies the plasma profiles, especially in the edge region, where the limiter is located: for lower magnetic fields, the plasma extends into the edge chamber region, because it is less confined, and it is possible to modify its parameters in a more efficient way than for higher magnetic fields.

4. Plasma density and radial electric field

Plasma parameters are estimated by the Langmuir probe method, with associated error bars of the order of 30%.

One of the most interesting features in the plasma profiles is the behaviour of the plasma density (Fig. 2a), estimated from the ion saturation regime: as the biasing potential becomes more positive with respect to the vacuum chamber, the plasma density in the limiter's magnetic shadow decreases rapidly, while the core density increases. This is very similar to what is observed in the presence of a stronger confining magnetic field, and can be interpreted in terms of positive biasing contributing to an improvement in plasma confinement, since the plasma column appears to be shifted towards the centre of the vacuum chamber.

Measurements of the radial electric field (Fig. 2c) obtained by taking the derivative of the plasma potential (Fig. 2b), with respect to the radial coordinate, according to the equation $\mathbf{E}_r = -\boldsymbol{\nabla}_r V_{pl}$) play a very significant role, since one of the most important aims of our research was to study the external modification of the radial electric field and its shear, and its effect on electrostatic fluctuations and anomalous transport.

The radial electric field in the absence of external biasing appears to be characterized by low positive values, which are fairly constant along the radial coordinate; thus, without biasing, no electric field shear is present. The application of a negative potential to the limiter provokes no significant changes in the electric field profile or in its shear; instead, as an increasing positive bias is imposed on the plasma edge, the edge electric field reaches higher and higher values (even 3 V cm^{-1} for a polarization of +4 V); we also observe the creation of electric field shears, especially in the outer plasma zone, where the electric field curve becomes steeper and steeper as the polarization increases.

We note how the radial field profile shows the presence of two inversion points of the electric field, i.e. two positions where the sign of the radial field changes; as we shall see, it is possible that at these points, an inversion of the poloidal rotation of the plasma due to the creation of a radial electric field from outside takes place.

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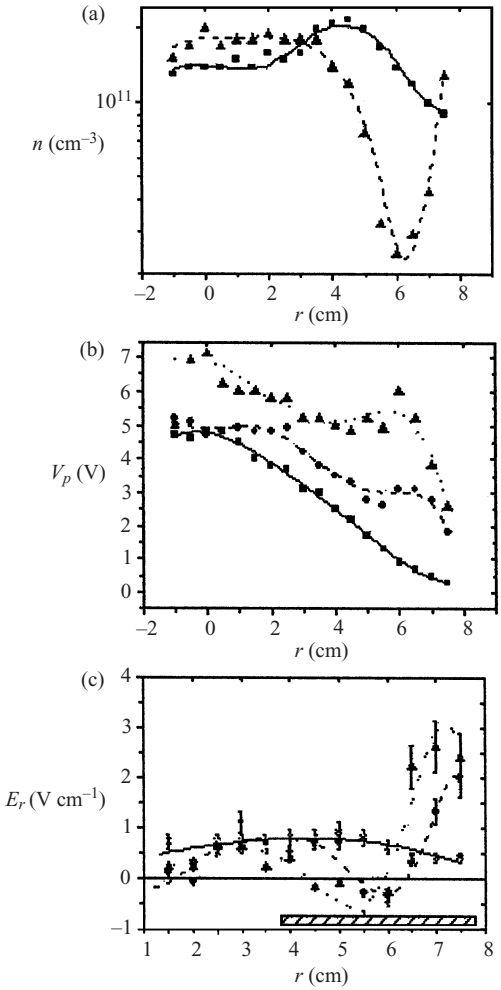


Figure 2. Radial profiles of plasma density (a), plasma potential (b) and radial electric field (c) in Thorello, for the following parameters: $B = 333$ G, $P = 10^{-4}$ mbar, $I_b = 4$ A. The error bars, which are of the order of 20% in the case of the electron temperature and of 30% in the other cases, are shown only in (c); some fitted curves are shown instead in (a) and (b). The curve (■) is relative to a floating limiter (i.e. without polarization), (●) and (△) refer to polarizations of +2 V and +4 V respectively. The plasma centre is at $r = 0$, the cathode is at $r = -4$ cm, the limiter edge is at about $r = 4$ cm, and the vacuum chamber edge is at $r = 8$ cm. In (c), the extension of the limiter is also given.

Trying to understand in a more accurate way the effect of poloidal rotation of the plasma due to the radial electric field, we estimate the value of the so-called $\mathbf{E}_r \times \mathbf{B}$ velocity (Fig. 3). In the absence of externally imposed polarization, the poloidal velocity is characterized by fairly constant, always negative, and low values; this means that the plasma poloidal rotation is characterized by the absence of those inversion points of rotation that seem to be responsible for the decorrelation of the electrostatic fluctuations, as reported in Chiueh et al. (1986) and Biglari et al. (1990).

When various positive polarizations are applied to the limiter (in Fig. 3, we show,

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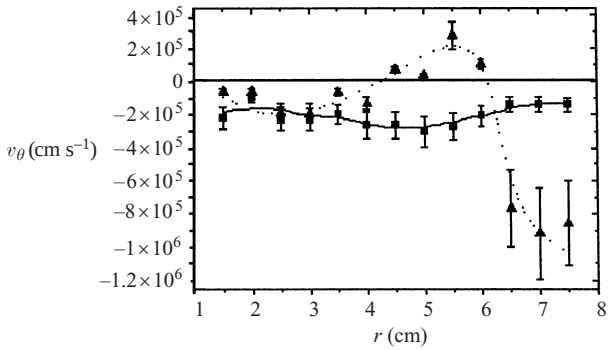


Figure 3. Radial profile of $\mathbf{E}_r \times \mathbf{B}$ poloidal velocity of the plasma column for $V_p = 0$ (▪) and $V_p = +4$ V (△). Fitted curves are also shown for both cases.

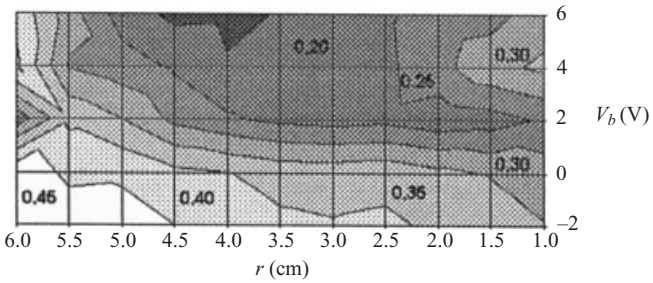


Figure 4. Plasma density fluctuations normalized to the mean plasma density, versus polarization and radial coordinate.

for an example, the case of a biasing potential of +4 V), the poloidal velocities become more and more intense, and a strong shear is observed, especially in the edge plasma region (as a consequence of the generation of a radial electric field shear, as we have seen previously). Thus, the plasma poloidal rotation in the edge region is characterized by high rotation velocities, with strong variations of both signs and values, which may have important effects on the electrostatic fluctuations.

It is even possible to find a range of frequencies that can be decorrelated by polarization if we calculate the shear rate of the electric field; for the positive biases observed in our experiments, it appears to be of the order of about 50 kHz, which corresponds exactly to the frequency range where electrostatic fluctuations appear to be strongly reduced (further measurements of anomalous transport Riccardi et al. (2000) seem to confirm this result).

5. Electrostatic fluctuations

One of the subjects of our research was the study of the behaviour of plasma fluctuations in the presence of constant externally induced electric fields (and their shear).

In Thorello, electrostatic fluctuations are characterized by very high levels, with a very important role being played by density fluctuations, which seem to describe the general plasma behaviour better than the plasma potential fluctuations. Further details are reported in Riccardi et al. (1997, 1998). In Fig. 4, a surface level

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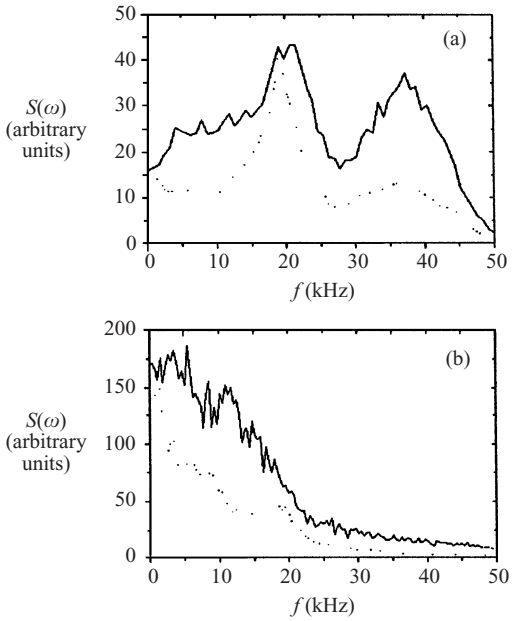


Figure 5. Electrostatic fluctuation spectra of plasma potential (a) and plasma density (b) relative to polarizations of $V_p = 0$ (full lines) and $V_p = +2$ V (dotted lines).

plot describes the radial profile of the plasma density fluctuations, normalized to their mean values, with respect to the vacuum chamber radius and the externally imposed polarization. In our experiments, we observe that when a positive bias is applied to the limiter there is a drastic reduction of density fluctuations (even of the order of 50%, in the case of the highest polarizations); this effect seems to increase with the polarization amplitude, and appears, in a less remarkable way, even for the plasma potential fluctuations.

Moreover, it should be noted that this reduction of electrostatic fluctuations has not been observed for negative biasing, since the density fluctuation profile does not change significantly. This behaviour is very similar to what we have seen in plasma parameters measured by the Langmuir probe technique, where we have observed no significant changes in any of the plasma parameters for negative applied polarizations.

A spectral analysis conducted on plasma potential fluctuations through the digital correlation technique gives many interesting results. In Fig. 5 a comparision between the electrostatic fluctuations without polarization and in presence of a positive polarization is shown, for plasma potential (Fig. 5a) and plasma density (Fig. 5b) fluctuations.

Plasma potential spectra in the absence of an externally imposed electric field are characterized by a two-peak structure – one in the frequency range of about 20 kHz, and the other at about 40 kHz. When a positive biasing potential is imposed, the width of the first peak greatly decreases, while the higher-frequency contribution is suppressed. It should be noted that this behaviour of high-frequency turbulence reduction has been predicted from calculations of the radial electric field shear rate, which has shown that suppression of high-frequency fluctuations may occur owing to the presence of a radial electric field like the one that we have produced.

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Plasma density spectra, shown in Fig. 5(b), exhibit quite different behaviour: both in the absence of polarization and in the presence of polarization, spectra are characterized by an exponential decrease of the power for higher frequencies: in this case, the application of an external biasing potential acts mainly with a reduction in the frequency range between 5 and 20 kHz.

6. Conclusions

An experimental investigation of the effects of an externally induced electric field on electrostatic plasma fluctuations has been conducted in the Thorello device.

On analysing the plasma parameters, we observe that as the applied polarization becomes more and more positive, stronger and stronger electric field shears are created, especially in the plasma edge; moreover, the plasma confinement appears to increase, since the plasma column is shifted towards the centre of the vacuum chamber.

Electrostatic fluctuations are greatly reduced along the whole radial coordinate, and their mutual coherence degree also decreases, when a positive bias is applied to the limiter; even plasma potential spectra seem to become less turbulent.

Finally it should be noted that these results are obtained only for a positive applied bias: when the polarization is negative, the plasma parameters remain the same, and there is no change in the electrostatic fluctuations.

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