Direct Observation of a Cross-Field Current-Carrying Plasma Rotating Around an Unstable Magnetized Plasma Column

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Abstract

The low-frequency instability of a magnetized plasma column and the anomalous radial plasma convection are shown to be linked with the existence of a radial cross-field current along a plasma channel rotating around the central magnetized plasma. The direct observation of the rotating plasma is obtained using an ultra-fast intensified camera. The ionizing electrons injected along the axis of the plasma column contribute to the accumulation of negative charges when the axial collector is at floating potential. The required neutrality leads to the continuous radial expulsion of energetic electrons and to the formation of a rotating plasma channel (m=1 unstable wave).

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The problem of anomalous transport in magnetized plasmas has been investigated during the last twenty years. Historically, the evidence that plasma diffusion at the edge of a magnetized plasma column is anomalous dates from the early sixties. The Russian research in confinement of hot plasmas [1] reported first the fact that plasma filaments escape from the central magnetized plasma and reach the wall, leading to the degradation of the quality of the confinement. This has been later mentioned by Kadomtsev [2] and also by Chen [3] with emphasis on the problem of the leakage of fusion devices. During the last fifty years, many investigations have been devoted to the identification of the various mechanisms leading to the destabilization of a magnetized plasma column. In fact, the most efficient mechanisms involve the creation of an azimuthal separation of charges at the edge of a magnetized plasma [4]. Various phenomena can lead to this situation such as centrifugal effects, the curvature of the field lines, or the collisional slow electric drift of the ions. Moreover, finite ion Larmor radius effects have to be taken into account when the magnetic field is low.

We have investigated the cross-field transport of the plasma in the edge of a magnetized plasma column and we have obtained the experimental evidence that the plasma detected around the plasma column is not convected directly from the central plasma. We have observed for the first time a rotating plasma around a magnetized plasma column using an ultra-fast intensified camera and we conclude that the plasma is locally created by the ionizing electrons drifting outside the central column through electric drift. We show also that the existence of a radial electronic current across the rotating plasma channel is the key parameter for the destabilization of the plasma column. In fact, when the impedance of the axial collector is high, the non-exact balance between axially injected electrons and axially collected electrons determines in return a radial current that is made possible through radial electric drift inside the large azimuthal electric field of an unstable wave.

To the best of our knowledge, this situation involving a non-exact balance between the injected flux of negative charges and the collected axial current has not been yet carefully investigated. Our experimental situation is very similar to the experiments by Chen and Cooper on instabilities in a reflex discharge [5, 6] where the turbulent radial current towards the cylindrical anode was necessary to operate the discharge. More recently, Rypdal et al. [7] have shown that ion polarization current was necessary to establish a fluctuating equilibrium in a toroidal magnetized plasma. Cross-field currents are also often involved in the description of intermittency and transient events in space plasmas, in solar physics [8, 9],
and also in the case of plasma thrusters [10]. Finally, due to charge injection, our experiment has similarities with the experiments in non-neutral plasmas exhibiting the diocotron instability [11]. Our findings could lead to a different analysis of the anomalous transport in collisional laboratory and fusion plasmas.

The results reported here are obtained in the magnetized plasma produced in the MIS-TRAL device [12, 13]. A thermionic discharge with 32 hot tungsten filaments is operated in a large source chamber connected to a cylindrical vessel (40 cm in diameter, 1 meter in length). The vessel is inserted inside a solenoid made of 20 water-cooled coils equally spaced along the cylindrical vacuum chamber. The maximum magnetic field strength is 0.03 T. The potential of the anode inside the source plasma determines the plasma potential inside this plasma. This potential is the reference value for ionizing electrons produced inside the source chamber and entering the plasma column. A very fine mesh grid at the entrance section of the column allows an electric insulation between the source plasma and the target plasma. The grid is kept at floating potential. Only energetic electrons overcome the potential of the grid (typically -15 volts) and enter the column through a 8 cm circular aperture. A linear magnetized plasma column is produced (8 cm diameter, 90 cm length) inside the cylinder. The vacuum chamber is evacuated at a pressure of about $10^{-6}$ mbar. The collector at the end of the plasma column is made of a copper plate that can be replaced by a fine metallic mesh grid allowing optical measurements along the axis of the device. The plasma column is surrounded by an insulated collecting cylinder -20 cm in diameter- divided into two separate half-cylindrical parts. Each half-cylinder can be biased independently and the temporal evolution of the collected current is recorded. The evolution of the transverse current is measured when several parameters are changed i.e. the potential of the axial collector that is varied from floating to collecting polarization, the working gas pressure and the potential of the anode. The radial density profile is almost gaussian with a central density in the range $10^{15}$ to $10^{16} m^{-3}$. The electron temperature ranges from 2 to 4 eV depending on the working gas pressure [13], ranging from $10^{-5}$ to $10^{-3}$ mbar in argon. Several Langmuir probes consisting in 2 mm tips protruding outside a semi-rigid coaxial cable are used for radial scan of the plasma density, the plasma potential and the electron temperature. The electron density fluctuations are recorded by three digital scopes and the power spectrum of the fluctuations is monitored using a spectrum analyzer.

The radiation from the plasma is used as a fast and efficient diagnostic [14]. The camera
is a fast gated and intensified model. The intensifier incorporates a S25-type photocathode that is sensitive to the bright near-infrared line at 810 nm of the excited argon atoms. The axial probing by Langmuir probes has shown that the density fluctuations are uniform along the axis of the plasma column. This flute character of the instability allows the axial imaging of the whole plasma. The central part of the magnetized plasma column is very bright and a disk is inserted to mask this region of the plasma. When a coherent unstable wave is established, a trigger signal is built by using the density fluctuations recorded by a Langmuir probe located at the edge of the central plasma column. A variable delay is added before triggering the camera in order to produce a stroboscopic analysis of the rotating plasma.

The second specific diagnostic used in our measurements is based on a radially movable electrostatic energy analyzer (Retarding-Field Analyzer, RFA) that can be oriented in order to face the source plasma or alternately to face the end-plate. Measurements perpendicular to the B-field are not possible due to the strong magnetization of the electrons. The electron parallel velocity distribution function is obtained using this RFA that is made of a small collector (14 mm in diameter) behind two high transparency grids. The first grid is kept at a potential slightly higher than the plasma potential. The second grid is the selecting grid. It is swept in polarization from -50 volts to +10 volts. The collector of the RFA is grounded through a resistor allowing to measure the collected current and hence the energy distribution of the electrons along the direction parallel to the magnetic field. After rotation of one half-turn, the direction of analysis can be reversed from the parallel upstream direction to the parallel downstream. This gives very valuable information on the asymmetry of the distribution function.

The column is most often unstable when the plasma discharge is switched on. The magnetic field is 0.017 T corresponding to a cyclotron frequency of 6.46 kHz for argon ions. Previous studies have shown that the polarization of the collector is an important parameter for the destabilization of the plasma column [15, 16] though a definitive explanation of the destabilization has not yet been obtained. The pressure is fixed at $2 \times 10^{-4}$ mbar. The frequency of the instable wave is about 4 kHz. At a fixed gas pressure, two crucial parameters are identified: the biasing of the source plasma and the impedance of the end-plate. A larger flux of ionizing electrons is injected when the potential of the source anode is lower. On the other hand, a low impedance of the end-plate connected to the ground across a variable
resistor would lead to a quasi complete collection of the primaries.

On the contrary, a high impedance of the collector leads to the build-up of a negative sheath and to the floating potential of the collector. We note that changing the load of the collector from short-circuit (stable plasma) to high impedance (unstable plasma) fully controls the onset of the instability. This particular point leads to the possibility to make a fruitful analogy between our experiment and experiments in non-neutral plasmas [17]. Indeed, inside a Penning trap, the diocotron instability is recorded due to the reflexion of the electrons at each end of the trap and to the existence of the modulated self-consistent radial electric field.

We have chosen to set the experiment into the most unstable regime which is obtained with a floating collector. The potential of the anode in the source plasma is $V_a=-5\,\text{V}$. The time-series of the density fluctuations recorded by the Langmuir probe at the edge of the central plasma column is shown in Fig. 1(a). The shape of the signal resembling to a cnoidal wave indicates the strongly nonlinear state. This is confirmed by spectral analysis. The study of the correlation with an other probe located at a different angular position exhibits clearly the $m=1$ structure of the mode. The relative fluctuation level is maximum at the edge of the plasma column. The frequency of the unstable mode is always below the ion cyclotron frequency and increases with decreasing the potential of the anode of the source chamber, i.e. increasing the flux of the ionizing electrons entering the cylindrical magnetized target plasma.

The optical probing using the fast camera gives a very valuable insight on the structure of the instability. We have measured that the most intense radiation is produced by near-infrared atomic lines. Successive frames are recorded with an increasing delay after local detection by the probe of the maximum of the plasma density. A video file is obtained exhibiting the rotation of a bright plasma channel around the central magnetized plasma column. The plasma channel has a large extension along the plasma column and establishes a connection between the central plasma and the wall. A series of successive frames is depicted in Fig. 2 where the bright central part of the column is masked. If the collector is grounded, the rotating plasma channel suddenly disappears and the central plasma is stable.

The measurement of the temporal evolution of the current collected by the two half-cylinders at the wall is also highly instructive: Fig. 1(b) shows the current (electron current) collected by one of the half cylinders. The square shape of the signal corresponds
to the successive collection by the half-cylinders. It is in complete agreement with the frames depicted in Fig. 1(a). The time-series of the second cylinder is opposite in phase and is therefore not displayed. The most important conclusion is that a negative current is continually drawn radially from the central magnetized plasma column. Obviously, this current is part of the axial current across the first section of the plasma column. The required global neutrality implies a radial flux of negative charges. However, it is important to note that the mechanism for this cross-field current is not so obvious. It is highly probable that the azimuthal electric field across the m=1 structure leads to the radial ExB drift of the electrons present in the edge of the plasma column, including the ionizing electrons. In return, this ExB convection builds a plasma channel because ionizing electrons are convected. Finally, the plasma channel connects electrically the core plasma to the wall. This localized plasma sheet is ExB rotating around the central column under the global influence of the radial electric field.

The radial current flowing transversally is measured. It is varied by changing the flux of the axially injected ionizing electrons or by collecting or not the ionizing electrons at the end of the plasma column. The crude estimation of the collisional transverse current is far below the measured value of the current density across the magnetic field.

The experiment shows that the collisionality is an important factor but more measurements have to be conducted in order to get a better understanding. For instance, we measure that the plasma potential inside the central column increases from -8 volts to -2 volts when the potential of the collector is continually changed from floating potential to ground. The frequency of the unstable mode decreases and a turbulent state is obtained. To summarize, the flux of ionizing electrons with incomplete collection on the axis leads to a coherent unstable wave with transverse current. Decreasing the flux of injected negative charges or increasing the parallel collection leads to the decrease in frequency and to a lower radial current.

At first glance, one could estimate that no ionization process exist in the shadow of the limiter. This is not the case as it is seen by measuring the velocity distribution of the electrons is measured in that region. The presence of ionizing electrons around the core plasma, i.e. in the shadow of the limiter (SOL), is investigated using the RFA in various conditions and at several radial locations from the wall to the edge of the central plasma column. In the SOL the data acquisition is performed only when the rotating plasma channel
FIG. 1: Temporal evolution of the density and radial current: (a) Plasma density recorded by a Langmuir probe located behind the limiter, normalized to the density on the axis of the plasma column; (b) Electronic current recorded on one of the collecting half-cylinders. The current is present when the plasma channel rotates in front of the corresponding cylinder.

FIG. 2: Axial view of the plasma column whose bright central part has been masked. The successive frames recorded by the ultra-fast intensified camera exhibit the rotation of the plasma channel establishing the electrical connection between the central plasma and the collecting cylinder. The rotation is counter-clockwise and it is consistent with the measured inward radial electric field.

is at the location of the analyzer. Moreover, the Electron Energy Distribution Function (EEDF) is measured upstream and downstream. In the latter case, electrons reflected by the floating axial collector can be detected. The results are summarized in Fig. 3. At first, when the axial collector is grounded, the measurement of the EEDF is performed on the axis of the central magnetized plasma column. With the RFA facing the source plasma (upstream) the solid line in Fig. 3(a) exhibits a large distribution in energy of the collected
FIG. 3: Integrated energy distribution of the electrons obtained from the energy analyzer with grounded (a, b) or floating collector (c,d), in the central plasma (a,c) and behind the limiter near the wall (b,d). Solid line: RFA oriented toward the source. Dash-dot line: RFA oriented toward the collector. It is clear that energetic electrons are detected outside the core plasma only when the collector is floating. We note that a large number of electrons flowing upstream is also observed in the case of floating collector.

electrons (the EEDF would be obtained from the first derivative of the collected current for potentials lower than the potential corresponding to the saturation current) and a large ionizing tail beyond 20 eV. With the RFA facing to the collecting end-plate, a cold low-density distribution is recorded. The central plasma column is stable and quiet. When the RFA is located near the wall, a very cold and tenous plasma is detected [Fig.3(b)].

On the other hand, with a floating collector, the situation is quite different. The integrated EEDF is displayed in Fig. 3(c) with the RFA located in the center of the plasma column. When the RFA collects electrons coming directly from the source plasma (solid line), the integrated EEDF is somewhat similar to the case with grounded collector, but when the RFA is oriented toward the collector, an energetic tail is still recorded (dashed line). In fact, the end-plate at floating potential reflects a large part of the electron distribution as seen in Fig. 3(c). The most important point is that changing the radial location of the RFA to the edge of the cylinder (2 cm from the wall), the measurement of the EEDF
shows in Fig. 3(d) that a large number of energetic electrons are still present and that the distribution is similar upstream and downstream. This explains the existence of the plasma channel across the magnetic field. To the best of our knowledge, this observation is quite new.

In the case of a laboratory plasma with a low ionization degree and rather high collisionality, the plasma detected transiently outside the column is due to the local ionization by drifting energetic electrons. In evaluating the final transformation of the parallel current into transverse current, the detailed mechanisms of the axial collection of ions and electrons have to be taken into account, as well as the recombination processes inside the plasma. This detailed experimental study is important for a better understanding of the transport of plasma across the magnetic field.

In summary, we have presented an experimental study of a low-frequency instability in a magnetized plasma column leading to the evidence that it is due to the necessity to evacuate radially the axially injected negative charges following a mechanism very similar to the diocotron instability. In fact, the electrons are ejected due to the build-up of a large amplitude $m=1$ deformation of the column. The ejected energetic electrons create a transverse plasma channel around the core plasma. In parallel, the radial electric field is still effective inside the plasma channel and it leads to the azimuthal ExB drift of the electrons and hence to the rotation of the structure. In conclusion, the key parameter is the radial electric field, but the effective parameters are the pressure of the gas (collisionality) and the potential at the collector determined by an external polarisation or alternately by its impedance. More precisely, the impedance of the axial collector defines the balance between injected and axially collected charges. This determines in return the radial electric field and the radial current when the nonlinear instability has saturated into the rotating plasma channel. This experiment could be proposed as a test-experiment for the analysis of the stability of collisional magnetoplasmas created by electron beams, in particular when turbulent states are studied. In that case, the understanding of the equilibrium of the magnetoplasma has to take into account the intermittent expulsion of negatively charged plasma filaments.

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