Rotation of a nanoparticle cloud in an inductively coupled plasma induced by weak static magnetic fields

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Dust immersed in an inductive noble gas discharge gives rise to variety of plasma instabilities. Even for particles in the nanometer size range a void forms which has an asymmetric shape as minimum energy configuration. The orientation of this void inside the reactor is not stable. In particular, an external magnetic field triggers the rotation of the system void – particle cloud. This contribution investigates the influence of the external magnetic field on the plasma performance and on the rotation of the nanoparticle cloud. As diagnostics an Intensified Charge Coupled Device (ICCD) camera is used. Different modes of the rotation are characterized and a characteristic u-shaped dependency of the magnetic flux density on the circulation time is explored.

1. Experiment

In this contribution a plasma instability is investigated that occurs in an inductive noble gas discharge where nanometer-sized particles are immersed. The reactor chamber resembles the Gaseous Electronics Conference (GEC) reference cell with an extended reactor height of 6 cm. Instead of electrodes two quartz cylinders protrude into the reactor vessel from the top and from the bottom. A pancake coil is situated inside the bottom quartz cylinder and couples capacitively to the plasma at low forward power or inductively at high forward power. An external magnetic field can be applied by a pair of Helmholtz coils that wraps around the vessel.

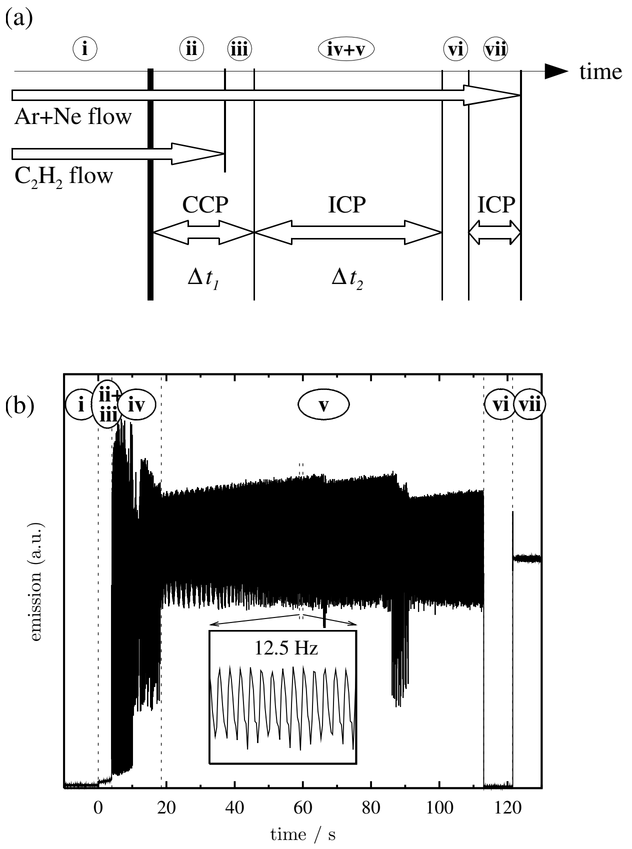

Figure 1. (a) Timing of the experiment. (b) Plasma emission during the experiment.

The experiment is carried out as follows: (i) an argon-neon-acetylene gas mixture is prepared, (ii) a discharge is ignited in the capacitive mode at low power, (iii) the acetylene supply is stopped, and (iv) the discharge is switched into the inductive mode by increasing the rf power (see figure 1). After a transient phase (iv), regular oscillations of the plasma emission with a frequency of up to several ten Hz are observed (v).

2. Rotating nanoparticle cloud

In previous publications, the phenomenon has been characterized by general observations and by Langmuir probe measurements [1] [2] [3]. In brief, carbon-hydrogenate particles are generated during (ii) which continue to agglomerate and reach their final size during (iii). The size of the particles can be varied in a range of 20 nm – 200 nm by adjusting the duration of phases (ii) and (iii) and the rf-power during particle growth. When switching to the

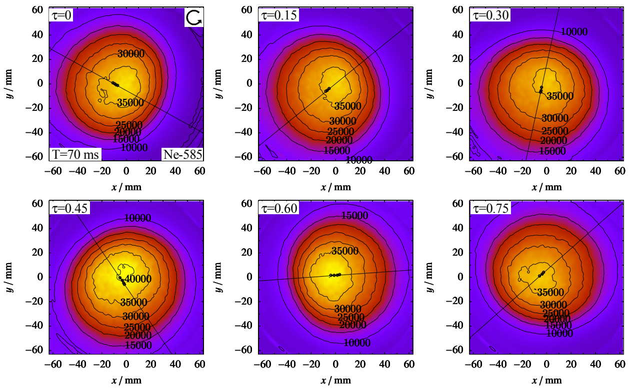

Figure 2. ICCD image sequence of the Ne-585 line at equidistant moments in phase of the plasma instability. A structure is rotating counterclockwise around the symmetry axis of the reactor.

inductive mode, the particles accumulate negative charge and stay confined in the discharge during (iv) and (v) until the plasma is interrupted.

The oscillations during (v) can be investigated spatially and timely resolved by an Intensified Charge Coupled Device (ICCD) camera that is equipped with a wavelength tunable acoustooptical wavelength filter. The camera is installed upside-down above the top quartz cylinder. Figure 2 shows an image sequence of the Ne-585 line at equidistant moments in phase. The sampling has been triggered by the signal of a photodiode that measures the modulation of the overall plasma emission. In each images a set of contour lines has been drawn. The following observations can be made from figure 2:

- The plasma consists of two distinct regions: a bright center and a surrounding area which exhibits weaker emission.
- The spot of of highest plasma emission is situated approximately in the center of the reactor.
- The contours are shifted to one side and contracted in this direction.
- The subsequent images arise from a counterclockwise rotation of their predecessors.

The bright region in the images corresponds to a particle free zone which is surrounded by dusty plasma. Obviously, the minimum energy configuration of this system is not a symmetric plasmoid in the center of the discharge. Instead, the dust cloud concentrates on one side and presses into the void. This asymmetric system rotates counterclockwise in the vessel.

3. Influence of the external magnetic field

3.1. The different modes of the void trajectory

During the experiment leading to the image sequence shown in figure 2 the Helmholtz coil has been generating a magnetic field pointing upwards in the direction of the camera at a flux density of 0.4 mT. A variation of the magnetic field shows that there exist different modes of the void trajectory:

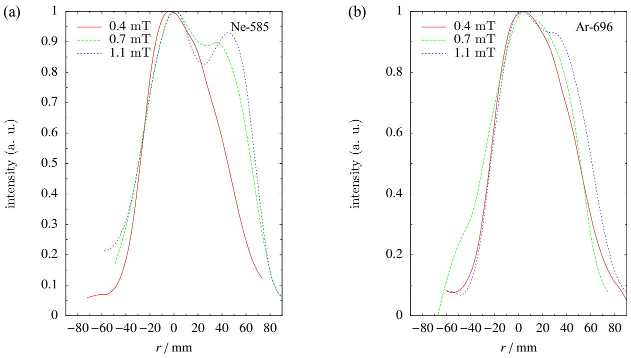

Figure 3: Emission profiles along the straight lines through the center of the ICCD images perpendicular to the contraction of the contour lines for the Ne-585 and the Ar-696 lines at different magnetic flux densities.

- Without an external magnetic field no rotation is observed. Instead the void is oscillating between the two opposite CF-160 ports.
- Starting with some magnetic flux density of about 0.3 mT an initially counterclockwise circulation establishes.
- When the magnetic flux density is increased beyond a threshold of about 0.5 mT the direction of rotation flips and the circulation time doubles.
- When further increasing the magnetic flux density the cirulation time increases spontaneously while the direction of rotation stays clockwise.
- With the direction of the magnetic field reversed the directions of rotation are directly opposed.

By the time of this writing, the physical picture behind these phenomena is not yet fully clarified. A link to the dependency of the plasma performance on the magnetic flux density can be made by considering the emission profiles along a line through the ICCD camera images which is drawn perpendicular to the contraction of the contour lines. Figure 3 shows these profiles for a neon line and an argon line at different magnetic flux densities that correspond to the different modes described above. As can be seen, the line profiles are broadened at increasing magnetic flux density which is more pronounced in the case of the neon line. This corresponds to an increased electron temperature in this region.

3.2. Dependency of the circulation time on the magnetic flux density

With respect to the adjustment of the magnetic field the mode switches are delayed by up to one minute. Within this time interval a dependency of the circulation time on the magnetic flux density can be

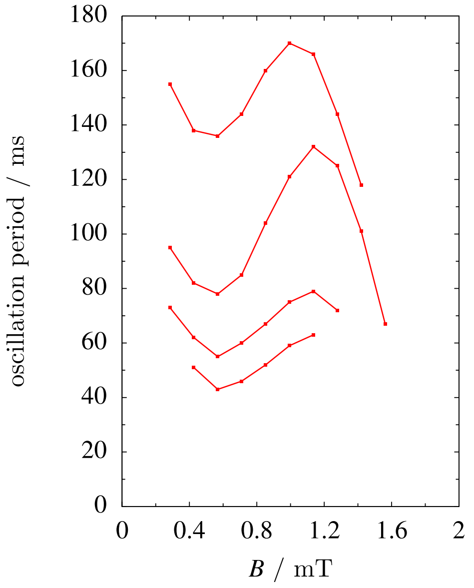

Figure 4: Oscillation period for a variation of the magnetic flux density. Several characteristics have been sampled with different particle sizes and in different modes of the rotation.

sampled as shown in figure 4. An u-shaped dependency becomes visible with a minimum at a magnetic flux density of about 0.6 mT. Beyond a flux density of 1.1 mT the circulation time is decreasing again, however, the rotation stops after after at most one minute. The minimum in the circulation time can be correlated to a maximum in electron density. This maximum can be diagnosed in the case of a stationary, particle free discharge, e.g. by the maximum in the emission profiles of the ICCD images and is confirmed by Langmuir probe measurements and Optical Emission Spectroscopic (OES) measurements of the mean EDF.

4. Acknowledgements

The authors deeply appreciate the assistance by Dr. Deborah O'Connell and Dr. Timo Gans during the measurement campaigns with the ICCD camera system. They also acknowledge the support by the German Science foundation via the SFB 591.

5. References

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