Contrib. Plasma Phys. **44**, No. 7-8, 613 – 618 (2004) / **DOI** 10.1002/ctpp.200410090

2-D Experimental Study of the Plasma Parameter Variations of the Magnetically Sustained DC Discharge in Cylindrical Symmetry in Argon

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Received 15 April 2004, accepted 15 April 2004
Published online 29 October 2004

Key words Cylindrical magnetron, Langmuir probe, electron density, mean energy, radial dependence, axial dependence.
PACS 52.70.-m

Two similar experimental set-ups were used to measure axial and radial distribution of discharge plasma parameters at different magnetic fields. Both systems were cylindrical magnetrons with outer cylindrically-shaped anode and coaxially placed cathode – both the discharge vessels had diameters approximately 6 cm and they were 30 cm and 11 cm long respectively. In the longer magnetron the measurements were made using three radially movable cylindrical Langmuir probes placed at three different axial positions and in the shorter magnetron the axially movable probe was used. From the measurements there were evaluated electron density, electron mean energy, plasma potential and floating potential.

1 Introduction

Magnetically-supported dc discharges in cylindrical symmetry (cylindrical magnetrons) are used for deposition of high-temperature superconducting materials, see e.g. [1], or materials with special dielectric characteristics, see e.g. [2]. Understanding the behavior of the dc discharge in such configuration is therefore essential condition for the technological progress in this branch. The magnetron systems with cylindrical symmetry are relatively simple and thus the plasma processes in them can be simulated comparatively easy by computer models. Measurements of plasma parameters in cylindrical magnetron can thus be compared with theoretical predictions and/or calculations used for their verification.

Certain progress in study of dc discharge in cylindrical magnetron has been achieved at the University of Greifswald in Germany and at the Charles University in Prague in Czech Republic over past several years. In these studies extensive experimental investigation of the dc discharge in the cylindrical magnetron system has been performed as well as kinetic, PIC and fluid modeling. Two experimental systems have been used for these studies. The shorter magnetron system was 110 mm in length and 60 mm in diameter. The detailed description of the experimental set-ups can be found in [3,4]. There were studied following plasma parameters: electron density, electron energy distribution function, plasma and floating potentials. The measurements were compared with the numerical models. In the shorter experimental system the radial electric field computed using 1D PIC model was greater than the measured one while in the electron density and electron mean energy acceptable agreement has been achieved. This discrepancy has been initially attributed to the influence of the axial limiters, which were used to terminate the discharge axially and which were not accounted for in the 1D PIC model. In order to depress influence of the endings of the magnetron vessel a novel longer system has been developed. The longer design enabled partially the study of the axial distribution of plasma parameters, because the Langmuir probes could be placed at three different axial positions. Also, half of the cathode length was segmented to enable measurements

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of axial distribution of the discharge current. The axially movable probe has been recently added to the shorter system thus enabling measurements of axial changes of plasma parameters with good spatial resolution. In this paper we present data on the radial and axial distributions of plasma parameters in both mentioned systems. Among interesting effects observed in these dependences we can quote the axial inhomogeneity of the discharge in the longer magnetron around the center of its length at higher magnetic fields and the slightly positive plasma potential in the large part of positive column of the dc discharge at lower magnetic fields in both systems.

2 Experimental

The measurements presented here were made with two experimental set-ups, which are schematically depicted in figs. 1, 2. The experimental systems were similar, but they differed at several characteristics. The main difference consisted in the length of the discharge vessel, so that they will be called throughout this paper "the longer magnetron" and "the shorter magnetron" respectively.

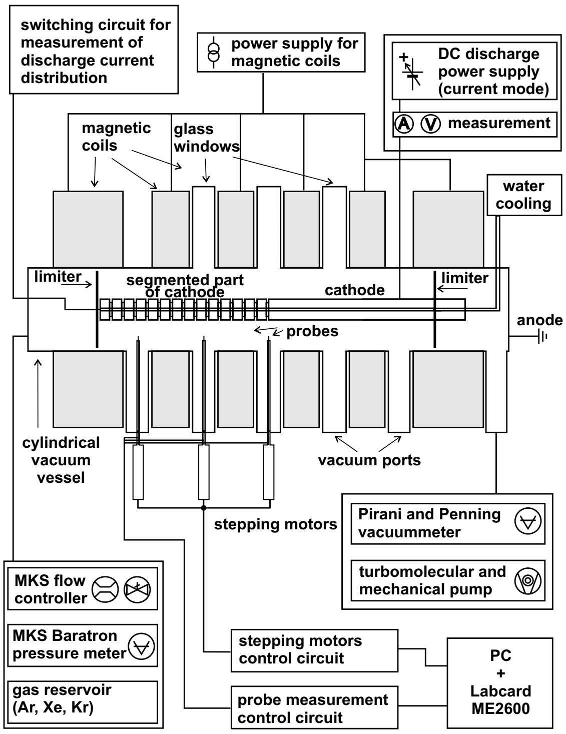

Fig. 1 The experimental set-up of the longer magnetron with three radially movable probes.

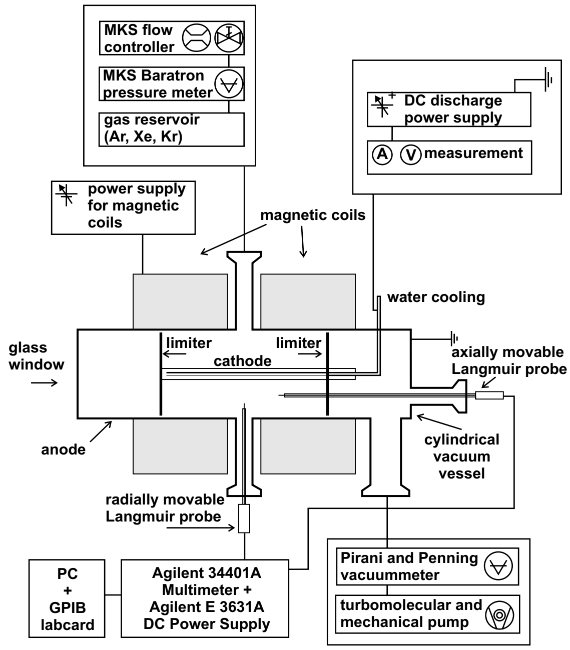

Fig. 2 The experimental set-up of the shorter magnetron with one axially and one radially movable probe.

The main part of the apparatus with longer magnetron consists of the cylindrical discharge vessel, cathode and six magnetic coils. The length of the discharge vessel is 300 mm and its inner diameter is 58 mm. It is made of stainless steel, as well as the cathode, which is placed coaxially in the vessel. The diameter of the water-cooled cathode is 18 mm and one half of its length is divided into 14 segments. Length of each segment is 10 mm and they are separated by teflon (PTFE) spacers. Arrangement like this enables measurements of axial discharge current distribution. The discharge space is axially bound by two stainless-steel limiters. During measurements presented here the limiters were connected to the cathode potential. There are eight vacuum ports to the vessel – five of them are used for Langmuir probes, which can thus monitor the discharge plasma at different axial positions. One port is used for pressure measurement and the last two serve as vacuum windows.

The vacuum system is pumped by the combination of the oil and the turbomolecular pump. This arrangement enables to achieve the background ultimate pressure lower than 10^{-3} Pa. The working gas is contained in the conventional pressurized cylinder equipped by a pressure regulator and its flow into the discharge vessel is stabilized and measured by the MKS mass-flow controller. During measurements the system is pumped from the middle of the magnetron length and the technical-grade argon is let at the both ends in. The working pressure inside the discharge chamber is possible to adjust in the range approximately from 0.3 to 6 Pa. Along the magnetron length there are six magnetic coils. The current that feeds the coils is electronically stabilized and the geometry of the coils is adapted to make the magnetic field as homogenous as possible. The homogeneity of the magnetic field $\pm 0.2\%$ has been achieved over the whole discharge vessel length.

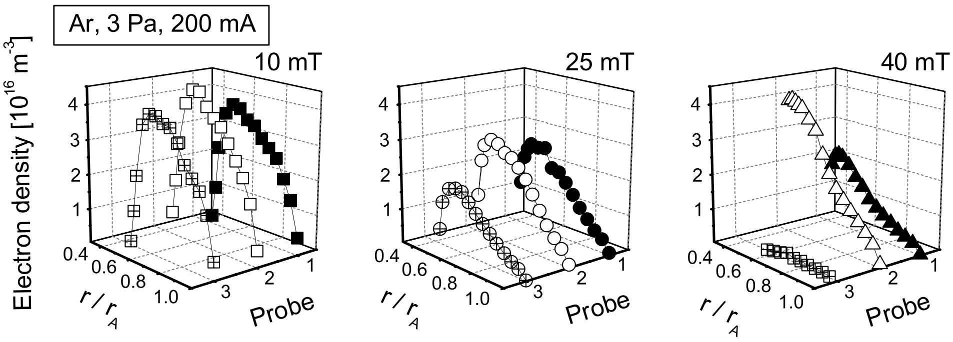

Fig. 3 Dependence of the electron density on the radial and axial position in the longer magnetron.

Three Langmuir probes were installed in present experiments with the longer magnetron. They had cylindrical tips (47 μm in diameter and 2.5 mm in length) and were radially movable by means of worm-gears driven by stepping motors. The construction of the probes was designed in a way to minimize effect of the sputtered cathode material, see [4, 5], on the probe during measurements. In all experiments the probe wires were oriented perpendicular to the direction of the magnetic field to minimize the effect of magnetic field on the probe characteristics, see [6]. The three probes were placed at different axial positions, see fig. 1. One of them was positioned in the center of the system and the two others were located 60 and 120 mm apart from it.

Presented measurements of radial and axial distribution of plasma parameters were done for magnetic fields 15–40 mT. The applied range of pressure was 1–4 Pa. The discharge current range was approximately 100 mA–400 mA. Higher discharge current induced too strong sputtering of cathode material.

The probe characteristics were measured by means of PC-controlled data acquisition system. The bias voltage generated from the D/A converter was amplified to the required level by a series of an optically isolated and high-voltage operational amplifiers. The probe current was converted to voltage via an operational amplifier connected as a current/voltage converter. The A/D converter of the computer's labcard then measured with 12-bit resolution the voltage proportional to the probe current. The probe bias voltage was not measured because the system was calibrated in such a way that the voltage set by the control program was equal to the real voltage on the probe. In order to increase the signal-to-noise ratio each measurement was repeated thousand times and the average was recorded. All the probe characteristics consisted of about 200 points. The described automated arrangement enabled to scan the radial distribution of the plasma parameters by all the three axially positioned probes in about 40 minutes with radial resolution approximately 0.5 mm.

The construction of the apparatus with shorter magnetron was similar to the one with longer magnetron. It is schematically depicted in fig. 2. In the system with shorter magnetron the magnetic field was generated by only two coils, which provided place for just one vacuum port in between of the coils in the middle of the magnetron length for positioning the radially movable probe. Apart from the radially movable probe, however, there was also an axially movable probe installed in this magnetron system, which enabled to study axial distribution of the discharge plasma parameters. Both probes were constructed in the same manner as in the apparatus with longer magnetron. The system with shorter magnetron was pumped by the combination of the dry compression piston pump (Leybold EcoDry M) and the turbomolecular pump. The discharge power circuit was similar to the one in the apparatus with the longer magnetron as well as the system of the gas flow control. Similar were also achievable ranges of working pressures in the discharge chamber and of magnetic fields.

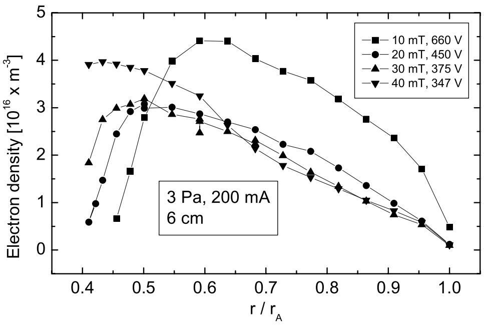

Fig. 4 Dependence of the electron density on the radial position in the longer cylindrical magnetron.

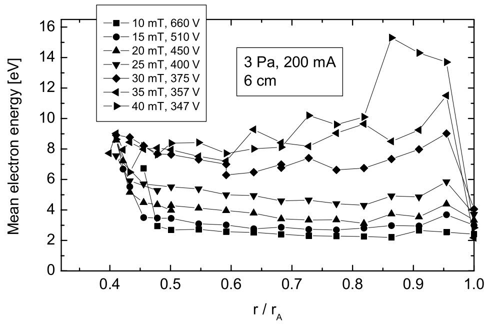

Fig. 5 Dependence of the mean electron energy on the radial position in the longer cylindrical magnetron.

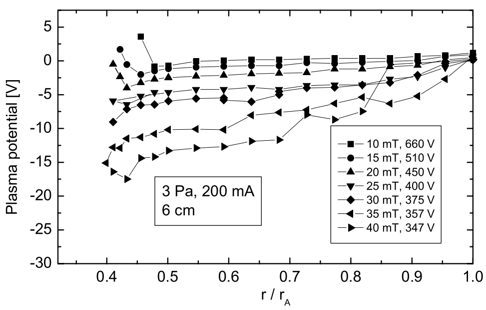

Fig. 6 Dependence of the plasma potential on the radial position in the longer cylindrical magnetron.

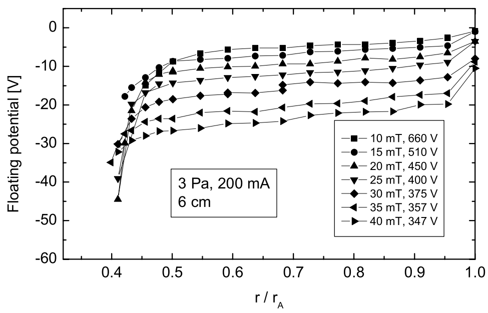

Fig. 7 Dependence of the floating potential on the radial position in the longer cylindrical magnetron.

3 Results of Measurements

The presented probe measurements with the longer magnetron were done at the magnetic field in the range from 10 to 40 mT. In fig. 3 there are depicted the results of the probe measurements made simultaneously with the set of three radially movable probes, placed at different axial positions within the magnetron. In fig. 3 the probe 1 was placed in the center of the magnetron and probes 2, 3 were at positions 60 and 120 mm apart from the center. These measurements were done at discharge current 200 mA and at pressure 3 Pa. The working gas was argon, on the x-axis there is a normalized radial distance – at the value 0.3 there is a position of the cathode surface, 1 is a position at the anode.

The plasma potential was determined as the zero-cross of the second derivative of the probe characteristics with respect to the probe voltage. Mean electron energy was computed from the integral of the electron energy distribution function. The plasma density was estimated from I_e^2 versus V_p plot (square of the probe current in the electron accelerating regime versus probe voltage). The methods used for probe data interpretation are in detail described e.g. in [7].

The radial measurements were impossible to perform up to the cathode surface because of the cathode fall. In fig. 4 there is plotted electron density vs radial distance for the probe 2, which was placed at the axial position 60 mm from the center of the magnetron. In figs. 5, 6, 7 there are radial dependences of electron mean energy, plasma potential and floating potential evaluated from the measurement with the same probe 2.

The measurements with the axially movable probe were done in the system with the shorter magnetron. The methods of plasma parameters evaluation were the same as it was described in previous paragraphs. The probe measurements were made only over one half of the magnetron length, because it was supposed, that the discharge

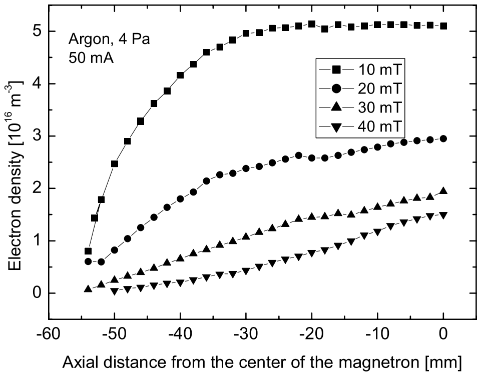

Fig. 8 Dependence of the electron density on the axial position in the shorter cylindrical magnetron.

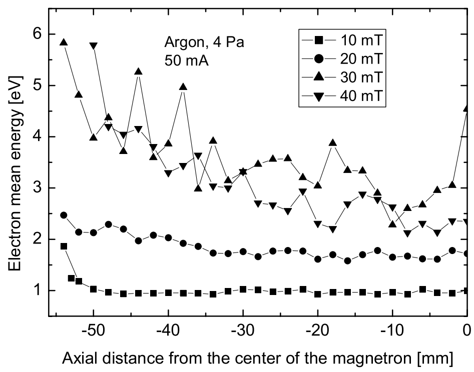

Fig. 9 Dependence of the mean electron energy on the axial position in the shorter cylindrical magnetron.

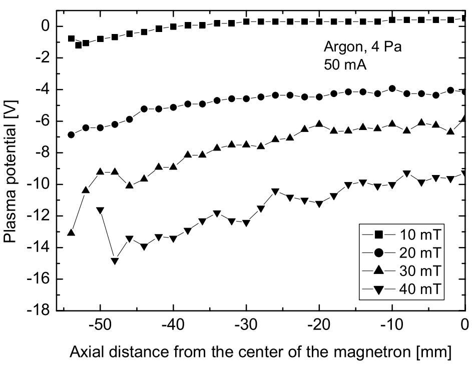

Fig. 10 Dependence of the plasma potential on the axial position in the shorter cylindrical magnetron.

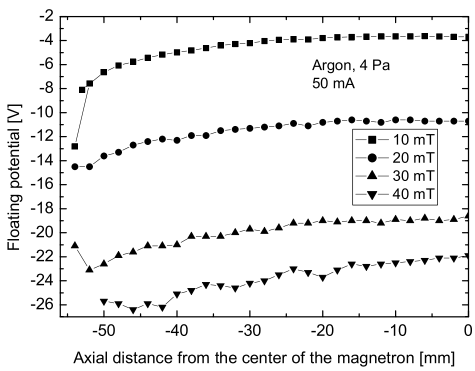

Fig. 11 Dependence of the floating potential on the axial position in the shorter cylindrical magnetron.

was symmetrical with respect to the center of the magnetron length. In figs. 8, 9, 10, 11 there are axial dependences of electron density and mean energy, plasma potential and floating potential. In all the figures 4 through 11 the measurement error can be deduced from the scatter of the presented data.

4 Discussion

At lower magnetic fields the radial profile of the measured plasma potential seems to be almost constant in a large range between cathode and anode (negligible electric field in positive column). In longer magnetron this feature is demonstrated in fig. 6 and similar attribute has been found earlier also in the shorter magnetron system, see [5]. It suggests that at such conditions plasma is created mostly in the cathode region and electrons are carried to the anode by the rest of energy that they gained in the cathode fall. Mean electron energy in the positive column amounts to ~ 1 eV. Very interesting is the slightly positive (by a few tenths of volt) plasma potential with respect to the grounded anode over most of the positive column of the discharge. This phenomenon is sometimes observed also in conventional magnetron systems. It is consistent with the fact that larger surface of the anode (roughly three times that of the cathode) serves as an efficient collector of electrons even with "anode fall" with electron-retarding field. The comparatively high mean energy of electrons in the positive column is the consequence of the fact that for electrons, which move in radial direction, the energy relaxation length with respect to elastic collisions exceeds the radius of magnetron, see [8].

With increasing magnetic field the observed electric field in the positive column of the discharge grows. The charged particles are more confined in the cathode vicinity at higher magnetic fields and also there is greater probability of electron re-capture at the cathode [9]. Consequently the average electron density in the discharge decreases when magnetic field increases. In order to maintain the pre-set discharge current the electric field in the positive column at higher magnetic fields rises.

In the plasma density profiles there is visible one more interesting phenomenon – from dependences in fig. 3 it can be seen, that for higher magnetic fields the discharge becomes axially nonhomogeneous and that there is a local maximum of electron concentration at the position 6 cm from the center of the discharge vessel length. It corresponds with fig. 4, where there are depicted radial density profiles measured with the probe placed at this position. The local maximum of the electron density shifts to the cathode, when the magnetic field increases, and the value of the maximum decreases. Above the magnetic field about 25 mT the maximum electron density increases again. These phenomena are still under study. In the shorter system similar local maximum of the plasma density located off the center of the magnetron was not detected.

The axial distribution measurements in shorter magnetron show a fall of the electron density in the direction from the center of the magnetron towards the limiters, which is accompanied by the increase of the electron mean energy. While at low magnetic field the discharge is homogeneous over most of the magnetron length at higher magnetic fields the local maximum at the center of the discharge vessel becomes more pronounced. The axial electric field is almost zero over most of the magnetron length at low magnetic field and remains below 1 V/cm at all magnetic fields used in our study except for the regions very close to limiters.

In both the investigated magnetron systems there is notable the bigger scatter of the experimental data at magnetic fields higher than approximately 20 mT. This is due to the instabilities that develop in the dc discharge and the amplitude of which at higher magnetic fields rises. Preliminary studies of the power spectra of these fluctuations [10] have shown that they can be possibly characterized as the non-linear ionization-drift turbulence of similar kind as described by Lin and Wu in [11].

5 Conclusion

We studied the radial and axial dependences of characteristic plasma parameters in two cylindrical magnetron systems. We observed two interesting phenomena – slightly positive plasma potential in the positive column at lower magnetic fields in both systems and a local miminum of the electron density at the central position in the longer magnetron. The 2D PIC modeling of both systems is in preparation.

Acknowledgements The work in Greifswald was financially supported by the Deutsche Forschungs-Gemeinschaft (DFG) in frame of the project SFB 198 Greifswald "Kinetik partiell ionisierter Plasmen". The work in Prague was partially financially supported by the Grant Agency of Czech Republic, Grant No. 202/03/0827, 202/01/D095, by the Grant Agency of Charles University, Grant No. 173/2002/B FYZ /MFF, by project COST action 527.70 and by the Ministry of Education, Youth and Sports, Research plan MSM 113200002.

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