The distributions of plasma parameters in the “Magnetor” device with hot cathode discharge

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Abstract. The dipole magnetic configuration as realized in planet magnetospheres is of interest for controlled fusion plasma confinement. This type of magnetic trap is free of convective instability. Distributions of plasma parameters in “Magnetor” device with double dipole magnetic configuration that allows restrict considerable volume of confined plasma are investigated. The comparison of plasma parameters distribution inside the trap for two plasma generation methods: microwave discharge at 2.45GHz and hot cathode discharge in crossed E and B fields are made. It is shown that plasma is localized inside the magnetic separatrix for both types of discharges. To determine possible additional plasma movements caused by the presence of the electric field in the magnetic configuration measurements of plasma flows in discharge with the hot cathode in crossed E and B fields are carried out. Two directions of plasma flows with flux density $10^{16} \div 10^{17} \text{cm}^{-2}\text{s}^{-1}$ inside the magnetic trap are determined: the flow along the axis leading particles leaving from a trap through weak magnetic field region and the flow caused by plasma azimuth drift.

1. Introduction
Investigation of new magnetic configurations for thermonuclear plasma confinement is still an open problem. The main idea of such investigations is to develop magnetic configurations suppressing plasma instabilities. One of them is a dipole magnetic configuration realized in the planet magnetosphere.

A dipole magnetic configuration created by DC coil current is stable against the most hazard instability - convective instability. The criteria of convective stability was proposed in [1,2]. According to this criteria $\nabla P \nabla U < \gamma P (\nabla U)^2 / U$, where $U = -\int dL / B$ integral along magnetic field line, $P$ – plasma pressure, $\gamma$ – adiabatic index, $B$ – magnetic field, plasma is stable against interconvertible – convective disturbance, if the plasma pressure gradient lower than magnetic field pressure gradient.

Investigation of dipole magnetic configuration is carried out in the USA (CTX [3], LDX [4]) and the Japan (RT devices [5]).
A new plasma device “Magnetor” [6] with the dipole magnetic field restricted by an additional DC coil current has been created in Moscow Engineering and Physics Institute (State University) in 2003. In all these installations the plasma generated by the electron-cyclotron resonance (ECR) discharge at low pressure is investigated. Here the fast electron fraction (with energy up to hundreds keV) creates the most of plasma pressure comparable with magnetic field pressure what allows to work in high $\beta$ modes. The opportunity of obtaining the plasma configuration, in which additional density is concentrated alone magnetic surface, is of interest. The present work is devoted to the realization of plasma filling of the allocated magnetic surface via discharge with the hot cathode and to research of the key characteristics of a plasma configuration in comparison with the case of ECR plasma generation.

2. Description of the installation and plasma generation methods

The scheme of the installation is presented in the Figure 1.

![Figure 1. The scheme of “Magnetor” device: 1- the main coil, 2- the additional coil, 3- ECR surface (fundamental frequency $B_{res}=875\text{Gs}$), 4 – magnetic fields zero, 5- separatrix, 6 – magnetron, 7 – movable probe, 8 – microwave input, 9 – vacuum pumping, 10 – cathode-emitter](image)  

The magnetic system is located inside stainless steel vacuum chamber with volume of 0.12 m$^3$. It consists of the two DC current coils: the main one and the additional. These coils have the same axis and placed in one plane. The additional coil is oppositely directed to the main coil current. The magnetic field of the additional coil restricts the dipole magnetic field, created by the main DC current coil. DC currents are limited to 40 kA and -20 kA in the main and the additional coils correspondingly. There are two magnetic plugs: the first one is in the center of magnetic system ($\sim1.3$ kGs) the second is in the region between coils and its maximal magnetic field intensity ($\sim1.8$ kGs). Here, in ring region between coils with strongest magnetic field, the main coil supports are placed. Magnetic coils are isolated from the vacuum chamber.

The magnetic field has separatrix – the magnetic field surface separating magnetic field lines closed around the main coil from those being closed around additional coil. Separatrix passes through zero magnetic field points. Current values in each magnetic coil are set to create the magnetic field with the separatrix inside the vacuum chamber.

Plasma-forming gases are air and argon, working pressures range is $10^{-5}$ - $10^{-3}$ Torr.

There are two methods of plasma generation.

Primarily, plasma is created by microwave low pressure discharge using the electron-cyclotron resonance (ECR) condition. The microwave source is the magnetron with power 900W, at frequency 2.45GHz. The microwave pulse length is 10ms with 50Hz repetition frequency. The antenna loop is used for the microwave power input into the vacuum chamber. The plasma source is the resonance
surfaces crossed all magnetic lines inside the separatrix. The fundamental frequency 2.45GHz corresponds to the field strength of 875Gs. Fundamental resonant field surfaces ($B_{res}=875Gs$) have the shape similar to the disks placed at both sides of the coils plane. Higher harmonics resonant field surfaces ($B_2=\frac{B_{res}}{2}=437.5Gs$, $B_3=\frac{B_{res}}{3}=291.7Gs$ etc.) have the similar shape and are placed separately from the coils plane. As it was estimated experimentally the absorbed microwave power is about 200W (~20% of total) per each 10ms pulse.

Additionally to the microwave ECR plasma source the system of discharge with hot cathode was developed for abilities to an additional filling of one narrow magnetic surface and also for the investigation of ExB effects on the plasma confinement. The hot cathode is tungsten spiral filament of 1cm longways. It is located inside the separatrix, the anode is the vacuum chamber. The position of the hot cathode is set to get the largest plasma generation region. The power supply provides negative bias on the cathode up to the -1000 V, and current up to 5 A.

Diagnostics of plasma is carried out by the movable probes. Probes allow obtaining information on local plasma parameter and its distribution and provide adequate accuracy of relative measurements.

3. Experimental results

3.1. The electron temperature distribution and plasma concentration distribution inside the separatrix

Experiments on research of microwave discharge plasma parameters were carried out under the following conditions. The currents were in the main coil 33 kA and in the additional one 17 kA, thus the maximal value of a magnetic field in a ring plug between the coils was 1.5kGs. The plasma-forming gas was air, the working pressure was maintained at 5·10^{-5}Torr.

The plasma ignition experiments in crossed $E \times B$ fields with the heated cathode currents in coils had values 17kA for the main and 9kA for the additional, so the maximal value of the magnetic field in the trap was 780 Gs. The region of magnetic field and electric field intensity values for an opportunity of discharge ignition in crossed $E \times B$ fields was defined according to theory Haefer [7] and Redhead [8]. The voltage -780V was supplied on the cathode relative the vacuum chamber wall, the discharge current of has been limited by 300mA. The hot cathode was situated in coordinate $z=-130mm$, $r=50mm$ in the different part of magnetic trap relative to the probe system. Plasma-forming gas was air, working pressure was maintained 7·10^{-5}Torr. Attempts to ignite discharge at low pressure with the cold cathode or without imposing an electric field have come to the end with failure.

The working pressure and coils temperature were controlled during the experiments.

Double cylindrical and plate probes were used for diagnostics plasma parameters. The length of the probe was 5 mm, diameter of cylindrical probe was 0.4 mm, the width of the plate probe was 5 mm, thickness was 0.1 mm. The distance between probe electrodes was 5 mm. The criterion of double probe application possibility is an absence of probe electrode shielding one by another. This criterion is satisfied if the distance between probe electrodes more than 10 Debie radiuses.

Magnetic field inside the “Magnetor” device is strongly not uniform. It varies from from ~1 Gs to ~1.5 kGs. Therefore the ratio of the electron Larmour radius to the probe radius is changed from 0.3 to 280 (expected electrons temperature is about ~10eV). So in the region of the magnetic field value higher than 700 Gs electrons become magnetized for the probe, therefore it is possible mistake in measurement of temperature here. Ions are not magnetized in any point inside the magnetic configuration.

According to the experimental data the electron temperature is constant inside the separatrix. In the region outside of the separatrix measurements were not carried because of the low plasma concentration value. Low plasma density is the reason of overlapping electrode sheath and it is impossible to define the temperature. The value of electron temperature in the case of ECR discharge is 10 eV and in the case of the hot cathode discharge is 8 eV.

The density of plasma has been calculated from the ion saturation current measurements according to the Bohm formula in the assumption of the electronic temperature constancy. Measurements of an ion current were carried out at negative shift of -100V on a probe relative to reference electrode.
The results of plasma density distribution measurements inside the separatrix are in the figure 2. The obtained density distributions of the microwave plasma and plasma discharge in crossed ExB fields with the hot cathode are shown on figure 2 and figure 3 accordingly.

![Figure 2. Density distribution of the microwave plasma inside separatrix](image)

![Figure 3. Density distribution of the plasma discharge in crossed ExB fields](image)

It can be seen that the plasmas of these discharges are localized inside the separatrix. The reducing of the plasma density in the direction of the magnetic system axis and in a direction of magnetic field coils is observed in both cases. The reducing of microwave discharge density in the direction of magnetic field coils is connected with the presence of magnetic field lines closed on the main coil bandage. Here, at high field side, the low mirror ratio (< 3) lead to the particle losses on a surface of the main coil. The particles diffusion towards the region of high magnetic field at the hot cathode discharge is highly difficult; therefore plasma filling of this region does not occur. Also one can see that the magnetic surfaces located closely to the cathode are mainly filled.

3.2. Plasma flow investigation inside the magnetic configuration

The presence of the electric field in the magnetic configuration can lead to the additional to the diffusion directed particles and plasma movement in ExB fields (in particular – the plasma rotation). For the experimental plasma flux characterization the Mach probe technique was used. Two plane probes separated by the insulator (figure 3) must be directed normally to the plasma flux direction, so one of probes is placed at the upstream side and another one is placed at the downstream side. As the plasma source the hot cathode discharge was used.

From each probe the ion saturation currents are measured. The ratio of the upstream and the downstream currents to the probes allows to define the plasma flow velocity via formula follows from the numerical investigations [9]:

\[
\frac{J_{up}}{J_{down}} = \exp(K \frac{v_{id}}{c_i}) = \exp(KM)
\]  

(1)

\(J\) is the current density, \(K\) is the calibration factor, depending on plasma conditions, \(v_{id}\) is the plasma flow velocity, \(c_i\) is the ion sonic speed.

The formula for \(K\) factor estimation has been evaluated by Hutchinson calculations [10]:

\[
K = \frac{1}{(0.43 \cdot \sqrt{1 + \frac{T_i}{T_e}})}
\]  

(2)

where \(T_i\) and \(T_e\) are the ion and electron temperatures.

The ion temperature was not measured. It is assumed \(T_i = 0.025\mathrm{eV}\). Therefore for parameters plasma of hot cathode discharge according to (2) the factor \(K\) is about 2.34.

For the investigation of the plasma fluxes with different directions the Mach-probe system was oriented by different angles to the device axis and to the magnetic field lines.
Figure 4 represents the distribution of the ion currents ratio from probe plates inside the separatrix.

![Figure 4. Areas of measured non-zero plasma flows inside separatrix](image)

The ion currents ratio inside the separatrix mostly is about one. That indicates the absence of essential plasma flow. Only two small regions have high ion current ratio. They are numbered by 1 and 2 in the figure 4.

The first region has been found near to the magnetic system axis. The plasma flow is directed along this axis out from the magnetic trap. Magnetic field lines of paraxial region pass through the area of a weak magnetic field. The velocity of charged particles flow in this direction is about $\sim 10^5$ cm/s (M >1), the corresponding plasma flux can be estimated as $\sim 10^{16}$ cm$^{-2}$ s$^{-1}$.

The second region consists of a flow in azimuth φ-direction, i.e. around «Magnetor» axis. This flow can be driven both by particles drift due to the magnetic field lines curvature and by the crossed ExB fields azimuth motion. The plasma velocity of this flow is about $\sim 3\cdot10^5$ cm/s (M <1), and the corresponding plasma flux can be estimated as $\sim 10^{17}$ cm$^{-2}$ s$^{-1}$.

### 4. Conclusions

Density distribution of the plasma produced by both the ECR microwave discharge and the hot cathode discharge is localized inside the magnetic separatrix and isolated from the vacuum vessel walls.

The distribution of plasma density depends on a position and extent of a charged particles source.

The possibility of filling with plasmas the chosen magnetic field surface of bi-dipole magnetic configuration was demonstrated during the experiments with the discharge in crossed E×B fields. Comparison of plasma density distribution for two types of discharges allows concluding that plasma distribution depends on an arrangement and extent of a charged particles source.

There are two directions of plasma movement inside the magnetic trap were observed. The first one is the axial plasma flux, which is driven by the particles losses though the weak field regions. The second one is the azimuth flow, which can be related to the both magnetic field lines curvature particle drift and to the ExB drift. The corresponding plasma fluxes can be estimated in the range $10^{16}$÷$10^{17}$ cm$^{-2}$ s$^{-1}$.

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