NON-EQUILIBRIUM HEAVY GASES PLASMA MHD-STABILIZATION IN AXISYMMETRIC MIRROR MAGNETIC TRAP

A. V. Sidorov[2], P. A. Bagryansky[1], A. D. Beklemishev[1], I. V. Izotov[2], V. V. Prikhodko[1], S. V. Razin[2], V. A. Skalyga[2], and V. G. Zorin[2]

[1]*Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia*
[2]*Institute of Applied Physics, 603950, Nizhny Novgorod, Russia*

Experimental researches of the shear flows influence on the confinement in the mirror trap of the dense non-equilibrium helium and nitrogen plasma created under conditions of the electron cyclotron resonance (ECR) gas breakdown were made.

Limiter with electric potential relative to the vacuum chamber was set inside the mirror trap.

During the increasing of the value of limiter potential over Ucrit=70-100 V the considerable increasing of the full ion flux from the trap was obtained (about of 3-4 times) that is apparently indicates that the plasma density and may be electron temperature increased in the trap that can be interpreted as the transversal losses decrease that is the result of "vortex confinement" regime realization. Pointed effect was obtained in the helium and nitrogen plasma both. Azimuthal modes with m=1, m=2 dominated in spatial spectrum of plasma oscillations.

This method of "vortex confinement" regime realization for non-equilibrium heavy ions plasmas seems to be perspective for new generation of ECR heavy multicharged ion sources creation.

I. INTRODUCTION

Plasma confinement with hot electrons in open mirror traps is intensively studied because of its wide using both in scientific researches and in new technological processes. Electron cyclotron resonance (ECR) multicharged ion sources, using mirror trap for plasma, that is heated by microwave radiation under conditions of gyroresonance, confinement[1], are the one of the most striking examples. Successes in the area of the nuclear physics during last years are connected with using of ECR multicharged ion (MCI) sources as the injectors of the accelerators.

Researches aimed at the creation of the new generation of ECR ion sources with high frequency of the heating microwave radiation (up to 75 GHz) and so with high plasma density are carried out in IAP RAS. These researches are stimulated by the necessity of the high current heavy multicharged ion sources[2]. Unique experimental bench SMIS 37[3] intended for investigation of parameters of plasma, created by powerful microwave gyrotron radiation in open mirror trap, was made as result of this researches. Carried out investigations demonstrated the possibility of plasma creation with the unique parameters: high value of electron temperature enough for multiple ionization of the heavy ions, high value of plasma density provided intense multicharged ion fluxes formation[4]. That was for many reasons due to new plasma confinement regime – quasi gas dynamic – realization[5].

Development of the magnetohydrodynamics (MHD) instabilities and, as a result, plasma-wall interaction is one of the reasons that breaks stable work of the source and limits average ion charge state.

Traditional for low frequency ECR ion sources methods of MHD instabilities suppression – using of the special minimum B magnetic traps – can hardly be used for heating microwave power frequencies more then 30 GHz because of the necessity of high value magnetic fields with complicated structure creation. That is why the researches of the axisymmetric MHD stable open magnetic traps is seemed to be quite perspective.

II. "VORTEX" CONFINEMENT

Method of the so called "vortex" hot ions plasma confinement in the axisymmetric open mirror magnetic trap enabled suppression of the transversal plasma losses during the MHD instability development was successfully realized on GDT setup[6] in the Budker's Institute of nuclear physics in Novosibirsk. The essence of the method consists of differential rotation zone creation at the periphery by the radius of the plasma column. It is obtained by the creation of the special form – step-like - of the plasma potential radial profile made by the system of the special electrodes: radial limiters and bit-slice plasma receivers placed in the plasma expansion zone after the magnetic trap plug[7]. "Vortex" confinement method allows now to confine plasma with $\beta \sim 0.6$ in GDT in stationary regime with negligible level of the transversal losses.

It is important to point to the fact that, opposite to GDT, plasma of the ECR source is ion cold (it is

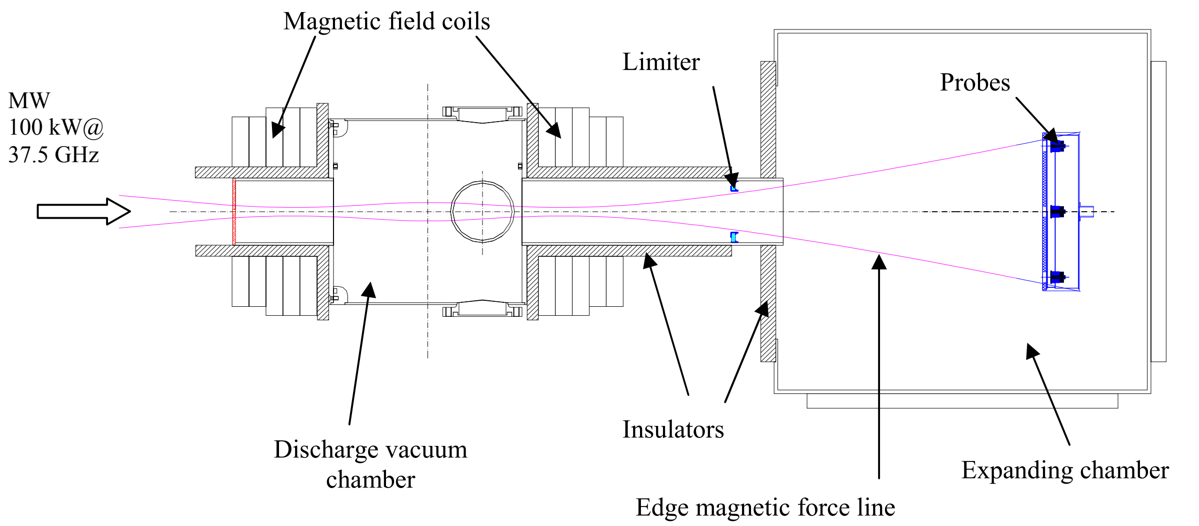

Fig. 1. SMIS 37 setup draft scheme: magnetic trap and expanding chamber are shown; limiter's position and probes location according to magnetic trap are shown too.

necessary because of the ion temperature influence on the ion beam emittance) and so the finite larmour radius (FLR) effects in the plasma of ECR ion source is negligible.

The main goal of this work was investigation of the opportunity of the using "vortex" confinement regime for plasma confined in the trap of the ECR source of the MCI.

III. EXPERIMENTAL SETUP

Experimental investigations presented in this work were carried out on the SMIS 37 setup, which was detail described in Ref. 4, and one's draft scheme is shown on Fig. 1. Gyrotron with 100 kW power at 37.5 GHz, pulse duration up to 1.2 ms and linear polarization of radiation was used as RF heating source. Plasma was confined in open mirror trap. Pulsed magnetic field was created by two groups of solenoids. Current pulse with form close to half-period of sinusoid duration was 14 ms; change of the value of the magnetic field during the RF pulse was less than 3%. Distance between the plugs was about 35 cm; mirror ratio was close to 5. The value of the magnetic field intensity was 1.8 T at the most part of experiments. Gas inlet in the vacuum chamber was made through the quartz pipe soldered in the center of the RF inlet quartz window.

Typical plasma parameters were: electron density - $10^{12}\div10^{13}$ cm^{-3}, electron temperature - 50÷100 eV, plasma chord radius ~ 1 cm.

It was constructed, manufactured and set into the vacuum chamber (Fig. 1) electrode-limiter intended for electrical potential profile control (Fig. 2). There was negative electrical potential on limiter according to the vacuum chamber with value in range of 0÷200 V.

Plasma created into the trap spread into the expanding chamber where 8 electrical probes, intended for spatial distribution of the ion flux from the plug research, were placed. Position of the probes system is shown on the Fig. 1. Probes were operated in the ion current saturation regime. One of them was placed into the center of the system, three – along the radius and

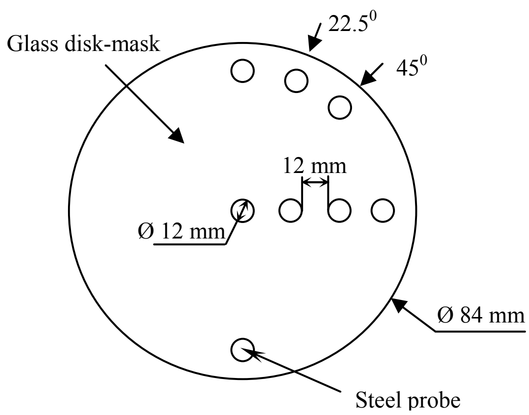

Fig. 2. Scheme of the probes positioning in the probe's system.

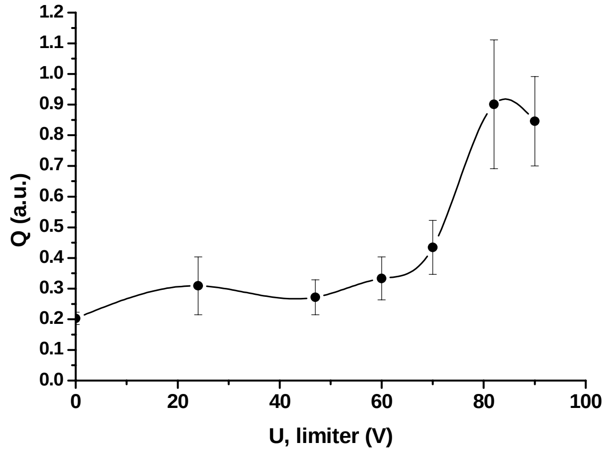

Fig. 3. Dependence of the entire charge of ions that left the trap during one working pulse on the limiter's potential for the helium plasma.

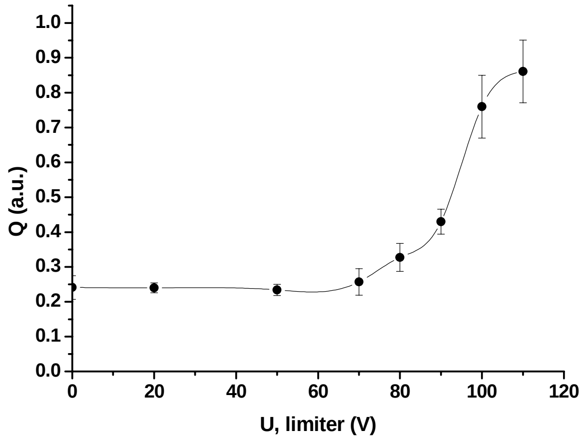

Fig. 4. Dependence of the entire charge of ions that left the trap during one working pulse on the limiter's potential for the nitrogen plasma.

another 4 – along the azimuth at the maximum radius position at the points of 22.5^0, 45^0, 90^0, and 180^0 as it shown on the Fig. 2. There were the steel mask-disk in front of the probes with 12 mm holes and the glass disk with same holes. Each of the probes was provided with measuring line and analog-to-digital converter (ADC) channel for pulse form registration.

IV. EXPERIMENTAL RESULTS AND FUTURE PLANS.

The main experiments aim was the demonstration of the opportunity of the substantial transversal losses suppression in strongly non-equilibrium plasma of ECR MCI source of quasi gas dynamic type in case of "vortex" confinement regime realization.

Dependence of the entire charge of ions that left the trap during one working pulse on the limiter's potential for the helium plasma is shown on Fig. 3. The entire charge was calculated by the following method.

1. The registration of the probe signals proportional to the ion current density was made.
2. The entire signal of the probes as the sum of the probe signals was calculated.
3. The signal proportional to the entire ion charge (integral from the entire ion current density by the working pulse time) was calculated.
4. This sequence was made for the series values of the limiter voltage.
5. The dependence of the signal proportional to the entire ion charge – Q – on the limiter voltage was constructed. For the series of the same limiter voltage values the average value of the Q was taken and the statistical error was calculated.

One can see that the potential increasing up to the values of 70÷100 V leads to substantial (in the order of 3.5÷4 times) increase of the entire ion flux form the trap that is the result of the plasma density and, maybe, electron temperature in the trap increase. So the confinement became better what can be interpreted as the substantial suppression of the transversal losses due to "vortex" confinement regime realization. Pointed effect was observed both in helium and nitrogen (see Fig. 4) plasma for various values of magnetic field and mirror ratio (in the SMIS 37 setup it was possible to change magnetic field at the plug from 1.5 T to 2 T and to change mirror ratio form 4 to 6; the "vortex" confinement regime realization was observed for the different values of the magnetic field and mirror ratio in the pointed diapasons).

Dominated modes in the spatial specter of the plasma chord oscillations were modes m=1 and m=2. Frequencies of the observed oscillations were in range of 3÷12 kHz both for "vortex" confinement regime and for the regime with substantial transversal losses.

In future it is planned to improve electrode-limiter for the opportunity to control the potential profile and to extract the ions from the plasma at the same time. In this case it will be possible to research multicharged ion creation in the plasma of ECR ion source under conditions of "vortex" confinement regime realization.

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REFERENCES

1. R. GELLER, *Electron Cyclotron resonance Ion Sources and ECR Plasmas*, Institute of physics publishing, London, UK (1996).
2. J. L. BOULY, J. C. CURDY, R. GELLER *et al.*, “High current density production of multicharged ions with ECR plasma heated by gyrotron transmitter,” *Review of Scientific Instruments*, **73**, 528 (2002).
3. S. V. GOLUBEV, V. G. ZORIN, I.V. PLOTNIKOV, S. V. RAZIN, E. V. SUVOROV, M.D. TOKMAN. “ECR Breakdown of a Low-Pressure Gas in a Mirror Confinement System with a Longitudinal Microwave Power Injection,” *Plasma Physics Reports*, **22**, 912 (1996).
4. V. SKALYGA, V. ZORIN, I. IZOTOV, S. RAZIN, A. SIDOROV, A. BOHANOV. “Gasdynamic ECR Source of Multicharged Ions Based on a Cusp Magnetic Trap,” *Plasma Sources Science and Technology*, **15**, 727 (2006).
5. A. V. VODOP’YANOV, S. V. GOLUBEV, V. G. ZORIN, S. V. RAZIN and M. A. SHILOV. “Plasma parameters of an electron cyclotron resonance discharge in a magnetic mirror in a quasi-gasdynamic confinement regime,” *Technical Physics Letters*, **25**, 588 (1999).
6. P. A. BAGRYANSKY, A. A. IVANOV, E. P. KRUGLYAKOV, A. M. KUDRYAVTSEV, Yu. A. TSIDULKO, A. V. ANDRIYASH, A. L. LUKIN and Yu. N. ZOUEV. “Gas dynamic trap as high power 14 MeV neutron source,” *Fusion Engineering and Design*, **70**, 13 (2004).
7. E. I. SOLDATKINA, P. A. BAGRYANSKY and A. L. SOLOMAKHIN. “Influence of the radial profile of the electric potential on the confinement of a high-β two-component plasma in a gas-dynamic trap,” *Plasma Physics Reports*, **34**, 259 (2008).