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ECR Plasma with 75GHz Pumping

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Abstract A Simple Mirror Ion Source with 75GHz pumping (SMIS 75) has been created. The confinement system is a mirror trap with magnetic field in the plug up to 5T, variable length 15—20cm and mirror ratio 3—5. Plasma heating is performed by the microwave radiation of a gyrotron (frequency 75GHz, power up to 200kW, pulse duration up to 150μs). The first results on plasma creation, heating and confinement are presented. Gas discharge conditions and charge state distributions are investigated. The main features of the plasma are high density and short confinement time. Plasma is confined in the trap in quasi-gas-dynamic regime. This means very short rising time and very dense plasma flux.

Key words short pulse multicharged ion source

1 Introduction

Each Realization of the European Program “Beta Beam”[1] aimed at studying neutrino oscillations demands creation of powerful short pulse (from 10 to 100 μs) beams of multicharged ions (MCI) of radioactive isotopes of gas (helium, neon). Classical ECR sources are not fit for that because the time needed for gas breakdown and for plasma density to attain a steady state level is much longer than a millisecond and, hence, longer than the needed pulse duration. A possible variant of forming powerful short pulse ion beams is to use a pulsed ECR source of multicharge ions with quasi-gas-dynamic confinement, when plasma lifetime is of order 10μs[2]. Such a possibility was first noted in[3]. Detailed theoretical analysis of such a source and early experimental data on operation of a short pulse MCI source pumped by powerful electromagnetic radiation of a gyrotron at the frequency of 37.5GHz (power 100kW, pulse duration 100—1000μs) was given in[4].

In this paper we present results of experimental investigation of a short-pulse MCI ECR source pumped by gyrotron radiation at 75GHz. We demonstrate a possibility to generate current pulses having duration of about 50μs for the duration of the front 10μs and average charge of helium ions 1.5 (the HE^+ and He^{2+} ion currents are equal).

2 Description of the setup

The experiments described in this paper were conducted on the setup shown schematically in Fig. 1. Plasma was created and confined in a simple axisymmetric mirror trap under the ECR conditions. The gyrotron (1 in Fig. 1) with the radiation frequency of 75GHz, power up to 200kW, pulse duration up to 150μs and linear polarization was the source of microwave radiation in the experiments. The microwave beam was focused into the discharge chamber by means of a dielectric lens (2). The microwave power density at the focal waist in the ECR zone amounted to $100 kW/cm^2$. The mirror magnetic trap was created by a pair of impulse solenoids (3). The mirror ratio of the magnetic trap was 3.7. The reso-

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nance magnetic field intensity for the microwave radiation frequency of 75GHz was 2.7Tesla, and maximal possible magnetic field in the plug 5T. The experiments were carried out for different magnitudes of pressure in the discharge chamber ranging from 3×10^{-5} to 10^{-2}Torr.

A beam of ions generated in plasma was formed by a two-electrode grid extractor (4 in Fig. 1), with the distance between the grids being 22mm. High voltage up to 20kV accelerating ions was applied to the discharge vacuum chamber (5), and the diagnostic chamber (6) was at zero potential. To reduce plasma flux density down to the value needed for beam formation the extractor was placed at a distance of 70cm from the plug of the magnetic trap. The plasma flux density in the expansion vacuum chamber was determined by the magnitude of magnetic field that dropped about 1000-fold (as compared to that in the magnetic plug) in the extraction region.

A movable Faraday cup (7) and time-of-flight ion analyzer (8) were used to analyze the ion beam in experiments.

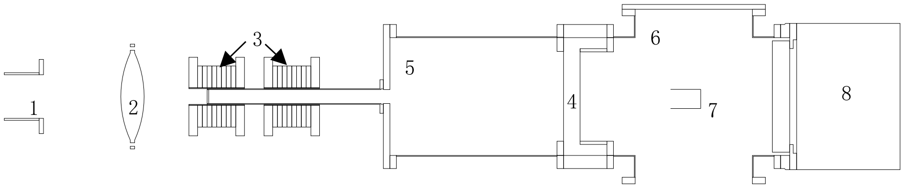

Fig. 1. Schematic of the setup: 1 – output gyrotron window, 2 – teflon lens, 3 – magnetic coils, 4 – 2 grids extractor, 5 – discharge chamber, 6 – diagnostic chamber, 7 – Faraday cup, 8 – time-of-flight ion analyzer.

3 Results of experiments

The goal of our experiments was to investigate possibilities of creating pulses with maximum short fronts and to study resulting plasma parameters.

Oscillograms of beam current at different neutral gas pressures in a discharge chamber are shown in Fig. 2. One can see that, as the pressure is increasing, the time from the beginning of the microwave pulse to the instant the beam current acquires a noticeable value, decreases, while the shape of the current–time curve remains unchanged. Experimental dependence of the reverse time of beam current registered in the Faraday cup on gas pressure is plotted in Fig. 3.

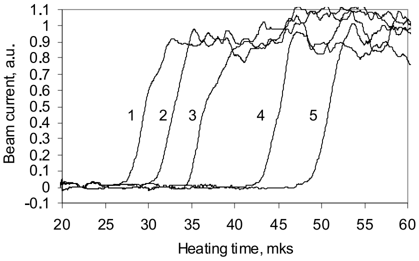

Fig. 2. Beam current oscillograms for different magnitudes of neutral gas pressure in a discharge chamber: 1 – 7.3×10^{-4} Torr, 2 – 6×10^{-4} Torr, 3 – 5×10^{-4} Torr, 4 – 4×10^{-4} Torr, 5 – 3×10^{-4} Torr.

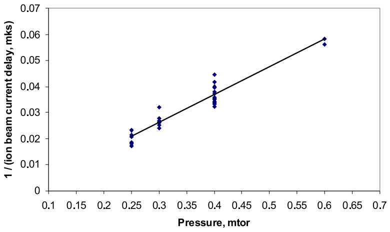

Fig. 3. Reverse time of discharge startup as a function of gas pressure.

In Fig. 4 we give an example of a pulse having a duration of 50μs. Here one can see the oscillogram for the collector current in the Faraday cup for the following parameters: trap length L=17cm, mirror ratio R=3.7, pressure 2.5×10^{-4} Torr, vacuum chamber filled with helium, magnetic field in the trap 4 Tesla, and microwave power 150kW.

It is important that in this case the discharge development time did not exceed 15μs, which is sufficient for producing pulses with a duration of 50μs and higher and meets, at least partially, requirements of the “Beta Beam” project[1]. The ion beam current density was 2emA/cm^2, and total beam current was 300emA. When calculated for the trap plug, the plasma flux density amounted to 8eA/cm^2, which is in good agreement with the theoretical predictions made at ECRIS’04[5].

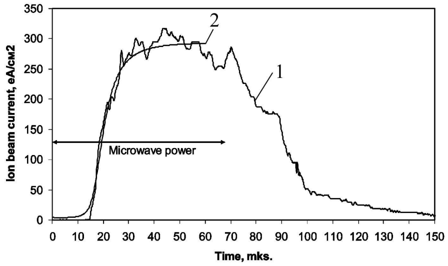

Fig. 4. Ion beam current: 1 – measured by means of the Faraday cup, 2 – calculated for the corresponding parameters.

Ion charge state distribution was also measured in the experiments. Charge state distribution of helium ions is plotted in Fig. 5; the operating conditions of the setup were the same as for Fig. 4. The He^{++} ion has e/m parameter same as the H_2^+ ion and the signals of these ions overlap in the spectrum. Results of experiments with other gases enable us to state that the hydrogen component in this coinciding peak does not exceed 10%.

Thus, our experiments demonstrate that, for the ion charge state distribution depicted on Fig. 5, it is possible to produce pulsed beams of helium ions with front duration less than 15μs.

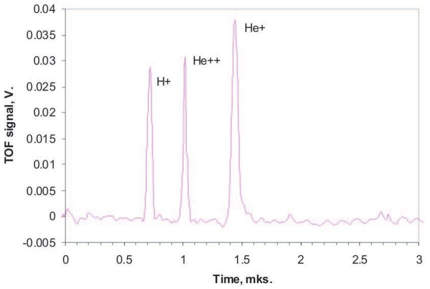

Fig. 5. Charge state distribution of helium ions.

Initial experiments showed that the time of discharge development may be further reduced by increasing neutral gas pressure above the value corresponding to the leftmost oscillogram in Fig. 2. However, such an increase of pressure in a discharge chamber leads to reduced ionization.

4 Discussion

The experimental results presented above can be readily explained in terms of theory. The model describing the process of ECR discharge development and generation of multicharge ions in a plasma confined in the trap of ECR source was described in detail in[4]. It was also shown in that work that the rate of rise of the extracted ion beam current depends on several factors:

(1) as long as $N_e \ll N_a$ (N_e, N_a is the density of electrons and ions), the rate depends on pressure; this determines the time when the magnitude of current becomes appreciable;

(2) for $N_e \sim N_a$ the current attains a steady-state value during the time on the order of the lifetime of plasma in the trap;

(3) if $N_e \ll N_a$ holds true up to the critical value of density, the current rise may be restricted by reflection of the microwave radiation when plasma density exceeds a critical value, i.e., current saturation ceases before regime (2) sets in.

It is clear from Fig. 3 that the pressure dependence of the reverse time before appearance of nonzero beam current is linear, which indicates that factor (1), indeed, determines discharge development at the stage of small plasma density when the ion beam current is almost zero. As soon as the ion beam current has become essentially non-zero, i.e., the plasma density is large enough, the process of discharge development is determined by different factors. In the region of pressures at which a steady-state regime can be attained with a high degree of ionization (in our case it is the pressure up to 10^{-3} Torr), the time needed for attaining this regime is determined by the lifetime of plasma in the trap[3]. Plasma lifetime in the quasi-gasdynamic regime of confinement is defined by the following expression:

$$\tau = \frac{R \cdot L}{2 \cdot V_s} ,$$

where R is mirror ratio, L is the length of the trap, and V_s is the ion-sonic velocity. It is apparent that it does not depend on plasma density and is determined primarily by the geometry of the mirror trap. This explains identity of time dependences of beam current in the Faraday cup at different magnitudes of gas pressure, as the experiments were carried out for constant magnetic system configuration. As was mentioned above, the quasi-gas-dynamic regime of plasma confinement is characterized by short lifetime of ions in the trap, which allowed attaining the steady-state regime in a short time. According to our estimates the lifetime was about 10μs. It should be noted, however, that the magnitude of the confinement parameter was sufficient for generation of multicharged ions ($N_e\tau \approx 4\times10^8\text{cm}^{-3}\cdot\text{s}$) due to high plasma density, which is well seen in Fig. 5.

Measurements of the spectra of ion charge state distribution and of plasma flux density from the trap allow one to judge about plasma parameters such as density and temperature. The obtained experimental results correspond to the electron temperature of 70eV and plasma density $4\times10^{13}\text{cm}^{-3}$. Modeling of the process of discharge development is in good agreement with the experiment. In Fig. 3 one can compare the oscillogram of the beam current to the Faraday cup and the calculated curve for ion beam current under these conditions.

It is clear from the expression for the plasma lifetime that by varying magnetic confinement, i.e., by changing the length and plug ratio one can change plasma confinement time in the trap and, thus, change the ion beam current rise time. However, the conditions of formation of multicharged ions will also change in this case, as a shorter time of ion confinement leads to a shorter beam current rise time but, at the same time, to a smaller average charge. We intend to investigate this dependence in detail in our further experiments.

As was mentioned above, the time of discharge development may also be reduced by a still further increase of neutral gas pressure up to the values when it is impossible to attain a steady-state regime with high degree of ionization. The point is that regime (3) is realized at large pressure (larger than 10^{-3}). The time of attaining a steady-state regime is determined by the time of exponential growth of density up to the value corresponding to the critical value for the used microwave radiation frequency. When the density attains its threshold value, the efficiency of heating drops down significantly and a steady state with low electron temperature is established.

5 Conclusion

The results presented in this work demonstrate that the gas-dynamic ECR sources with high pumping frequency are promising for creating ion beams with high current density for a rather high average charge. It is shown that using such a source it is possible to develop a system generating short pulses having duration of 50μs and more.

The results of the experiments revealed that a still further increase of the power and frequency of microwave pumping are demanded for improving characteristics of gas-dynamic ECR sources of multicharged ions.

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