Progress report of investigations on gyrotron ECR ion source SMIS 37

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PROGRESS REPORT OF INVESTIGATIONS ON GYROTRON ECR ION SOURCE SMIS 37

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Abstract

A review of experimental investigations on ion production in plasma developed on SMIS 37 source at the Institute of Applied Physics of RAS (Nizhny Novgorod) is reported. Pulsed power gyrotron with emission frequency 37.5 GHz was used for plasma creation and heating in the simple magnetic mirror trap. Magnetic field with value up to 3.5 T was created by pulsed coils. Experiments were carried out in nitrogen as operating gas. Formation of multicharged ions in dense plasma in different regimes of plasma confinement was investigated.

In this report we describe some investigations of instabilities of the plasma in the trap. Low frequency instabilities are analyzed basing on the results of plasma high-speed image registration. Also, whistler cyclotron instability was observed. Short pulses of accelerated electrons with energy about 10 keV are measured. Detected short pulses of microwave emission of the plasma characterize cyclotron instability too.

Dense plasma of singly charged ions obtained in the trap with the plug magnetic field much less than resonant value. Flux of the plasma exceeds 0,1 A/cm^2, electron temperature is about 20 eV. Such plasma seems to be interesting for surface modification.

1 EXPERIMENTAL SETUP

All the experiments were performed on the setup schematically presented on Figure 1. The source of microwaves was gyrotron. Maximum power level was 130 kW, pulse duration was 1.5 ms, and frequency was equal 37.5 GHz. Quasi-gaussian beam of microwaves was focused into the vacuum chamber placed in warm simple mirror trap. Length of the trap was 25 cm. Mirror ratio was 4. Maximum value of the magnetic field in the trap was more than 3.5 T. We used two-electrode quasi-Pierce extraction system for ion beam formation. The extractor was placed into the plug. The diameter of the hole in the plasma electrode was 1 mm. We could apply to the source up to 30 kV of extracting voltage. Extracted beam was analysed and collected by two Faraday cups. Removable Faraday cup was placed right after the puller electrode.

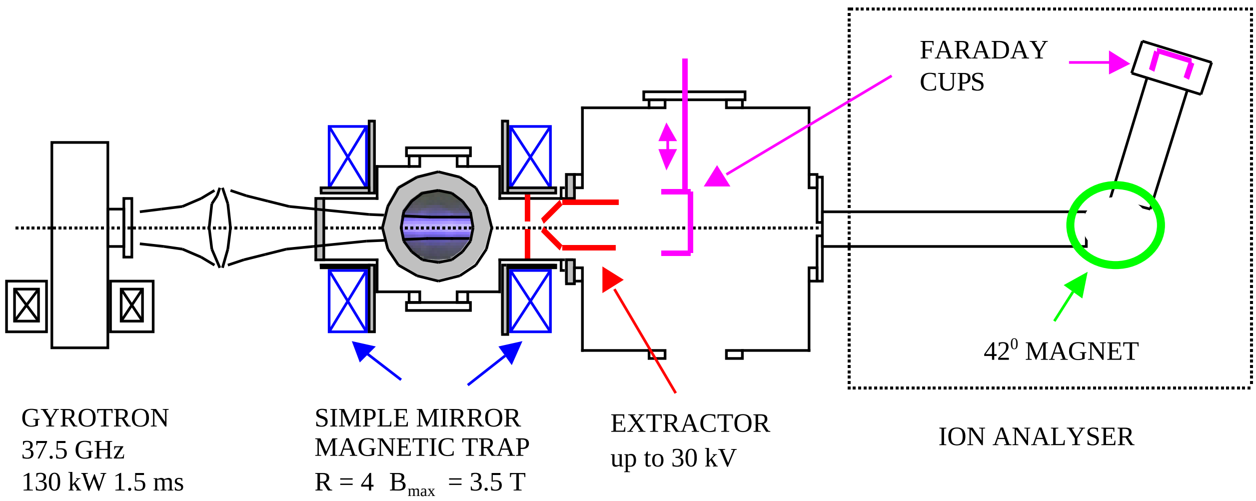

Figure 1: Schematic presentation of the setup SMIS 37

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2 ION EXTRACTION

Generally speaking ion source should produce a beam of ions with composition and flux required. Using gyrotron with frequency 37.5 GHz as a source of microwaves we can obtain plasma with rather high density ~ $5{\cdot}10^{13}$ cm^{-3} and with high flux of the plasma throw the plugs. Such dense plasma requires quite high extracting voltage being applied to produce an ion beam with good characteristics. Due to some technical problems it is possible to apply only 30 kV now. It is not enough for a good beam formation. But fine-tuning of the extraction system and control of plasma parameters makes it possible to achieve the result than 80% of extracted current with flux density of 200 mA/cm^2 reaches Faraday cup placed right after the long (33cm) puller (see Figure 2).

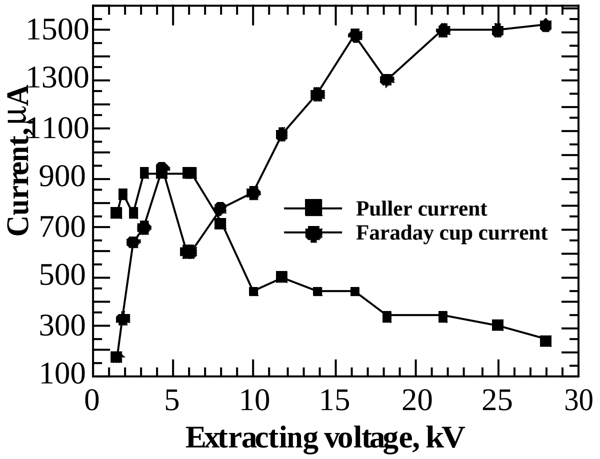

Figure 2: Faraday cup current and puller current versus extracting voltage. Extracting hole diameter is 1 mm.

3 MULTICHARGED ION FORMATION AND PLASMA STABILITY

SMIS37 is aimed to produce intense beam of multicharged ions. As it was shown above maximum achievable extracting voltage is very important factor defining the extracted beam quality. In this section some other problems limiting the performance of the source will be discussed.

Figure 3 shows the typical temporal evolution of extracted multicharged ions during the microwave pumping pulse. First 100 µs (Fig. 3a) of the discharge ions of injected gas (nitrogen) with low charges dominate, but there are some impurities already. Average Z grows up with time (Fig. 3b), but amount of impurities grows up also. Later (Fig. 3c) average Z became quite high and impurities (mainly carbon) became to be at the same level as injected gas. Later (Fig. 3d) carbon starts to dominate and this is followed by drastic change in discharge character.

3.1 Two stages of the discharge, impurities

In common case there are two stages of the discharge. First is “axial” discharge. It was called “axial” because in

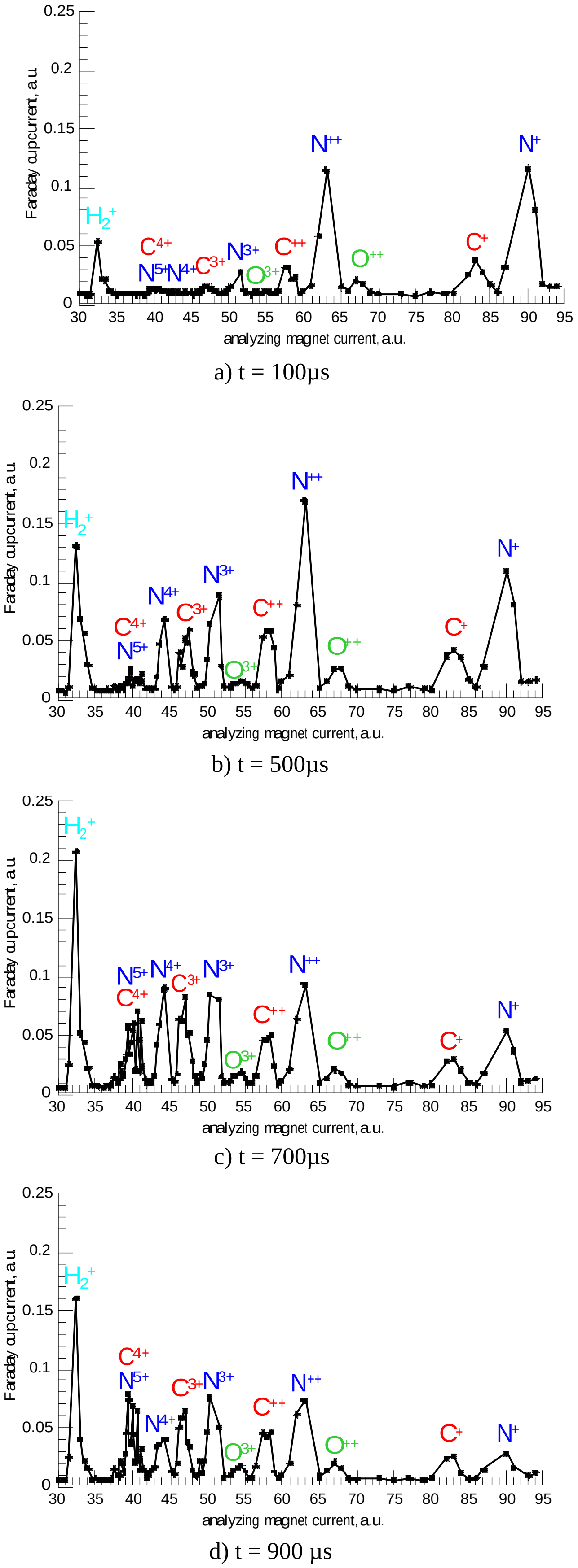

Figure 3: Typical temporal evolution of the charge state distribution in the extracted ion beam.

this case plasma looks like a column with respectively small diameter (about 1 cm). This stage is characterized by a rather good confinement time _ ~ 150 µs and respectively low extracted current density J ~ 200 mA/cm^2 (See Figure 4). The second stage of the discharge

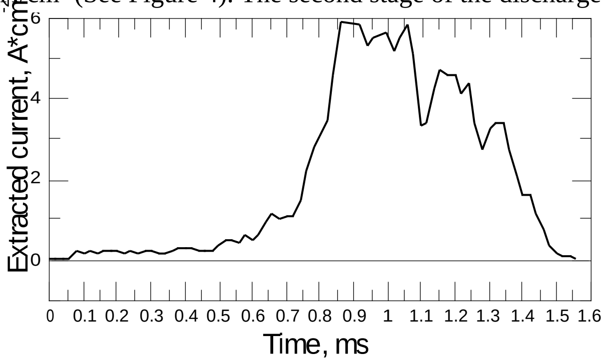

Figure 4: Oscillogram of extracted current.

is “volumetric”. In this case plasma looks like to fill all the volume of the trap. This regime characterized by poor confinement _ ~ 15 µs and very high extracted current J ~ 4 A/cm^2. The ion charge state distribution for the first stage was described above (of course when duration of the stage is long enough). Experiment shows that impurities with low charges dominate in a case of “volumetric” discharge.

3.2 Explosive instability

Such a dramatic drastic change in the source operation raises two important questions “Why one stage of the discharge changes another?” and “Where impurities come from?” Performed experiment with high-speed image register was fruitful to make the situation clearer. The optical image of the plasma in the trap was registered by the high-speed frame-mode CCD camera with shortest exposure duration about 5 µs. Image corresponding “axial” stage of the discharge is shown on Figure 5 (left image). The image remains its appearance during the first stage of the discharge. The typical image of the plasma in the “volumetric” stage of the discharge is shown on the Figure 5 (right image). In this case plasma consists of several columns, they appear and disappear at different radiuses independently. Lifetime of a columns is less than the lowest repetition period of the camera; it equals 10 µs.

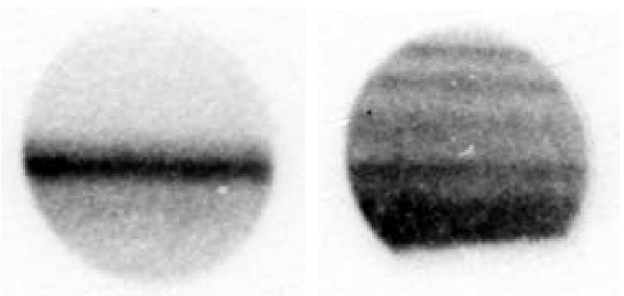

Figure 5: Typical negative image of the discharge. Left image is in “axial” stage of the discharge; right image corresponds to “volumetric” stage.

Such a small rising time of a plasma column discharge requires very intense source of neutrals. Authors suppose process of desorption of the gas from the chamber walls can play an important role. Desorbed neutrals can be taken into account in a simple zero-d model:

$$\begin{cases} \dfrac{\partial N_e}{\partial t} = k \cdot N_e N_a - \dfrac{N_e}{\tau(N_e)} \\ \dfrac{\partial N_a}{\partial t} = \alpha \cdot \dfrac{N_e}{\tau(N_e)} - k \cdot N_e N_a + F \\ \tau(N_e) = 1.5 \cdot 10^4 \dfrac{T_e^{3/2}}{N_e} \end{cases}$$

where N_e is plasma density, N_a is neutral density, T_e = 300 eV is electron temperature, $k = 2 \cdot 10^{-7}$ cm$^3 \cdot$s^{-1} is ionization coefficient, _ is confinement time, F is neutral gas inlet, _ is ion-atom secondary emission factor (desorption). Figure 6 shows the calculated densities of neutrals and plasma in time for different _. There are three parts in the curve. First part is ionization process, it lasts up to 100 µs for conditions corresponding to the experiment; there is a quasi-stable flat part of the curve and very drastic increase of the densities to the infinity at finite time – the explosive instability. The duration of the stable part of the curve depends on _ (see Fig. 6) and F and this dependence character corresponds to the experiment.

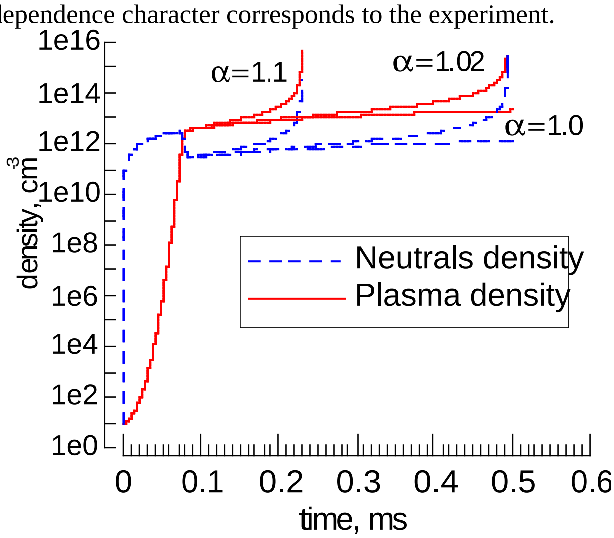

Figure 6: Calculated neutrals and plasma densities for different deadsorption coefficients.

This simple model shows the importance of the desorption process which can lead to an explosive instability of the discharge. This instability can play the main role while “volumetric” stage of the discharge changes “axial”.

3.3 Spatial instability

The spatial instability of the plasma in the simple mirror trap is the most important thing, which determines the transversal losses of the plasma. Streak camera placed in front of optical flange of the plasma chamber was used for spatial instability investigations. The most interesting results can be described with help of two photos shown on Figure 7. Upper image on the Figure corresponds to discharge with respectively low current density of the extracted beam (it was about 200 mA/cm^2). Lower image on Figure 7 corresponds to the situation when extracted current is several times higher (at the level of 2 A/cm^2). It is clear from the images that plasma in the trap is unstable in both cases but timescales differ. In first case it is about 150 μs, in the case of high current timescale of spatial instability is about 15 μs.

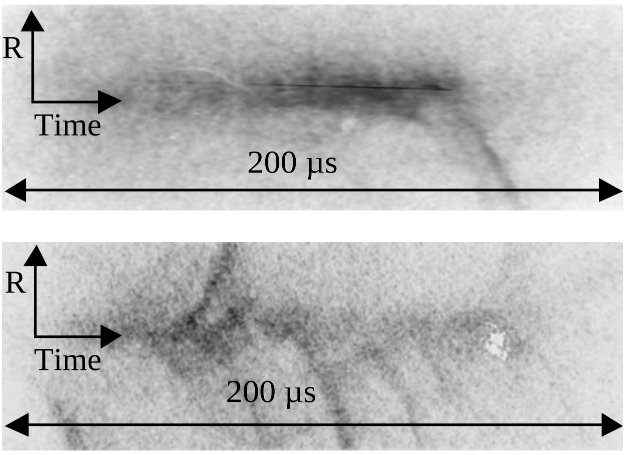

Figure 7: Negative streak camera images. Upper one is for the discharge with 200 mA/cm^2 of extracted current, lower - with 2 A/cm^2.

Spatial instability limits plasma lifetime. But using the gyrotron with emission frequency of 37.5 GHz and power 130 kW as a source of microwaves sustaining discharge provide rather high plasma density (more than $2\cdot10^{13}$ cm^{-3}), and confinement parameter N_e_ is more than $2\cdot10^9$ s$\cdot$cm^{-3} in a case of respectively low current density. This value is enough for effective production of multicharged ions with average charges. Figure 8 presents the latest result when it was possible to prolong the low current ("axial") stage of the discharge up to 1.5 ms and to avoid the explosive instability of the discharge due to desorption of the gas from the chamber wall.

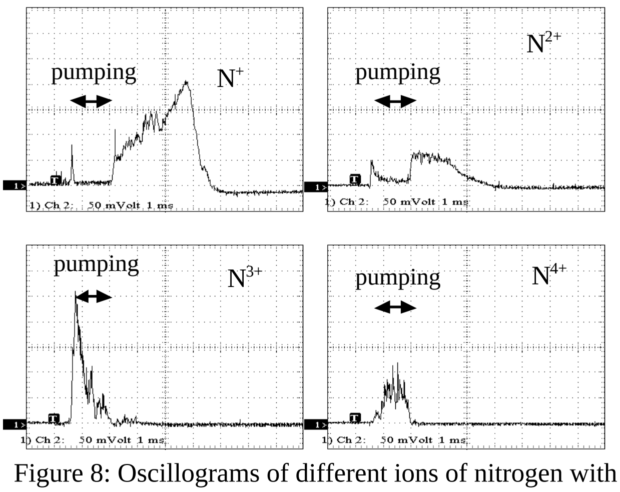

Figure 8: Oscillograms of different ions of nitrogen with oscillations due to spatial instability of the plasma.

Obviously, maximum of the charge state distribution is close to the N^{4+} during the last part of microwave pumping pulse. But these oscillograms also show the oscillations of currents due to spatial instability of the plasma in the magnetic trap.

3.4 Whistler cyclotron instability

Detailed report about whistler cylotron instability developing in SMIS 37 is presented in [1].

4 OFF-RESONANCE DISCHARGE

A very interesting and promising experimental result was obtained in a case when microwave discharge at low pressure (10^{-3}-10^{-4} torr) exist in the trap then ECR zone does not exist in the vacuum chamber (_ >> $_B$). Electron temperature (about 20 eV) of the plasma escaping from the plug was measured by Langmuir probe. Flux of the plasma through the plug was about 1 A/cm^2. The characteristic feature of this discharge is its purity. Ion charge state distribution in the off-resonance discharge is presented on Figure 9. Argon was the operating gas.

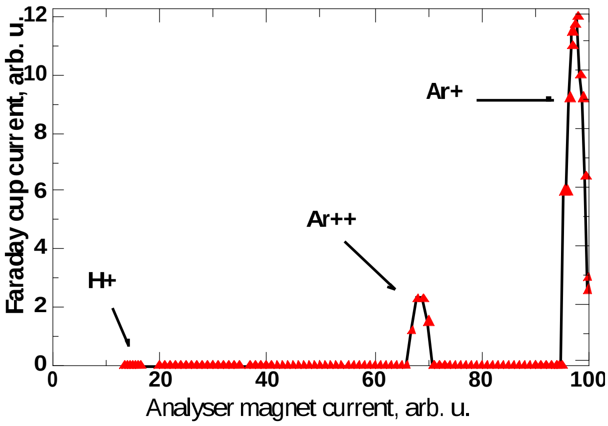

Figure 9: Ion charge state distribution in off-resonant discharge.

Second characteristic feature is the stability of the discharge. All the oscillograms are free from the oscillations and streak camera shows its spatial stability also. This off resonance discharge at such a low pressure requires two conditions. Some foreplasma should be in the trap before microwave pumping sustains it and microwave power should be high enough. This discharge seems to be interesting and promising for some applications.

5 REFERENCES

[1] A.G. Demekhov, S.V. Golubev, D.A. Mansfeld, S.V. Razin, V. Yu. Trakhtengerts, A.V. Vodopyanov, V.G. Zorin. Experimental investigation of the whistler electron microinstability in an ECR heated, mirror-confined plasma. The same proceedings.