GASDYNAMIC ECR ION SOURCE FOR NEGATIVE ION PRODUCTION

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Abstract

H[-] ion sources are needed in various areas of accelerator technology, such as beam injection into cyclotrons and storage rings and as a part of neutral beam injectors for plasma heating in experimental facilities studying thermonuclear fusion. It was recently demonstrated that gasdynamic ion source based on ECR discharge in a simple mirror trap is very efficient for proton beam production [1]. Here we use the gasdynamic plasma source as the first stage driver of volumetric negative ion production through dissociative electron attachment (DEA) [2]. Experiments were performed with a pulsed 37 GHz / up to 100 kW gyrotron radiation in a dual-trap magnetic system, which consists of two identical simple mirror traps. The first trap was used for the plasma production under ECR condition. Dense hydrogen plasma flux from the first trap flows into the second trap through a perforated plate, which prevented the propagation of microwaves into the second one. The configuration helps to separate plasma volumes with "hot" and "cold" electrons. We present recent experimental results on this topic. A negative ion current density of 80 mA/cm^2 through 1 mm plasma electrode was demonstrated.

INTRODUCTION

The first attempt to use a gasdynamic ECR discharge for a volumetric negative ion production was performed in 2017 [3]. It was shown that it is possible to achieve total negative ion current of 0.2 mA through 5 mm extraction aperture by optimizing the gas injection scheme, but with high level of impurities caused by residual water. In the present work we demonstrate results of the next stage experiments, in which measures have been taken to reduce the level of impurities.

EXPERIMENTAL SCHEME

We used 37 GHz / up to 100 kW gyrotron radiation for plasma production in a dual-trap simple mirror magnetic system (plug magnetic field ranging from 1 to 2.5 T). In the first trap the plasma was created under ECR condition. Dense hydrogen plasma flux from the first trap was allowed to flow into the second trap through a perforated conducting plate, acting as a microwave reflector preventing electron heating in the second trap. Presumably, that allowed to produce two electron

fractions: "hot" electrons in the first chamber with the energy of about 50 – 100 eV and "cold" electrons in the second chamber, with the energy below 15 eV. The "hot" electrons effectively ionized the gas and excited high vibrational states of hydrogen molecules through excitation to B and C singlet states. These molecules then propagated into the second trap and produced H[-] ions there as the result of dissociative electron attachment (DEA) with "cold" electrons. Such approach is similar to the one suggested in [4] where 2.45 GHz ECR discharge was used as a plasma cathode producing "hot" electrons. The scheme of the experimental facility is presented in Fig. 1. We used an extraction system consisting of plasma and puller electrodes to form a beam of negative particles and a magnetic filter made of two pairs of rectangular permanent magnets placed after the puller for electron dumping. Both magnet pairs produced a magnetic field transverse to the extracted beam and had the opposite magnetization directions to compensate each other's influence on the ion trajectories. In the first experiment we investigated the influence of the neutral gas injection scheme on the negative ion current. Various gas injection schemes were used: continuous, pulsed and their combination. The pulsed injection was realized with an electromagnetic valve connected to a buffer vessel with pressure of 0.05 - 1 bar.
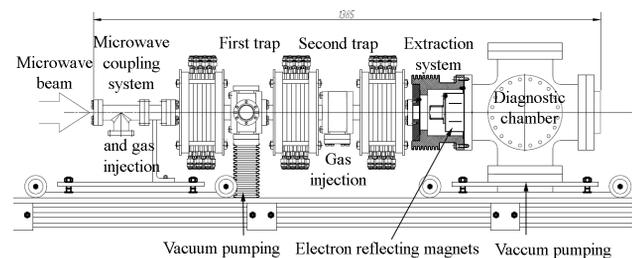
Figure 1: The scheme of the experimental facility.

Various diagnostic tools were used: a magnetostatic analyzer, a Faraday cup and a quadrupole mass spectrometer. The analyzer was used for the measurement of the ion beam spectrum, determination of the impurity level and investigation of the dependence of the H[-] current on various parameters. The analyzer was used to measure the relative quantity of negative ions, as the significant beam line losses make absolute measurements obscure. Meanwhile, the Faraday cup placed right after the extraction system and electron deflection magnets was used for the measurement of the total current of negative ions. The quadrupole mass spectrometer was used in a diagnostic chamber to determine the composition of the injected gas.

RESULTS

The first stage of the experiments was performed with an extraction system consisting of a 5 mm aperture plasma electrode and a 10 mm aperture puller electrode separated by 11 mm. The following scheme of gas injection was used: constant flow of H_2 into the first chamber and pulsed injection into the second chamber. The background pressure in the diagnostic chamber was 10^{-6} Torr, gyrotron power up to 80 kW, extraction voltage 12.4 kV. The total current of negative ions measured with the Faraday cup was 0.2 mA and the duration of the pulse was 100 us.

The second stage of experiments was conducted with pulsed gas injection into the second chamber only. In that case the gas diffused into the first chamber, where the hot plasma was generated. The maximum total negative ion current was measured to be 2 mA obtained at 12.4 kV extraction voltage. The dependence of the total negative ion current on the delay between the leading edges of the gas injection and microwave pulse is shown in Fig. 1. The gas injection scheme described above seemed to be the most effective, so it was used hereafter.

The negative ions current ratio was measured with the magnetostatic analyzer and is shown in Table 1.

Table 1. Negative ion current ratio

Ion	OH^-	H^-	O^-	O_2^-
Relative quantity in analyzer	0.5	1	0.2	2

The dependence of the negative ion current on the magnetic (mirror) field strength is shown in Fig. 2. The most probable way of fragile H^- destruction is an interaction with "hot" electrons [2]. Their density increases as the magnetic field increases. The current saturation at B > 2.5 T is supposedly related to this fact.

The measured negative ion spectrum is shown in Fig. 3. H^-, OH^-, O^-, $^{19}F^-$, O_2^-, H_2O^- and an unknown ion with an atomic mass of 25-27 u were detected. The "mystery ion" could be Al^- from the ceramic (Al_2O_3) clamping of the perforated plate placed between the magnetic traps. After the dismantling of the facility it was found out that the PTFE insulation of the grid ground wire was damaged, so that unknown negative ion could also be CN^-, although C^- was not detected.
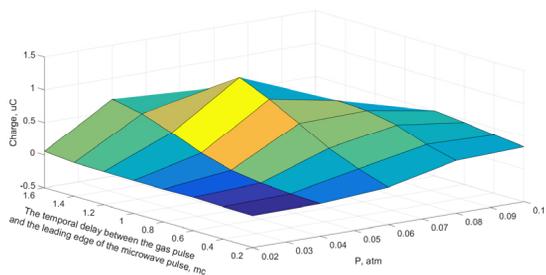
Figure 1: The dependence of the extracted negative ion charge on the temporal delay between the gas pulse and the leading edge of the microwave pulse and gas feed line pressure with 5 mm extraction aperture
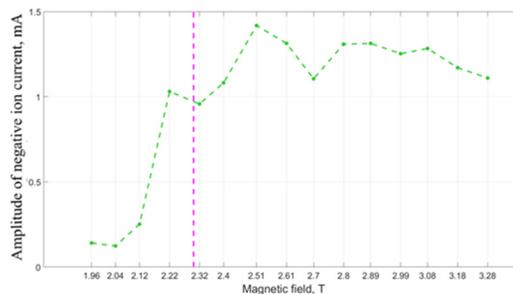
Figure 2: The dependence of extracted on Faraday cup negative ion signal on the strength of the magnetic field with 5 mm extraction aperture. The border of ECR regime is shown with purple line
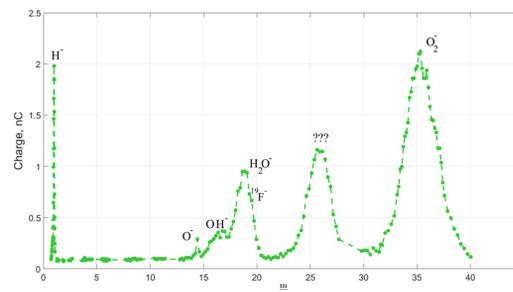
Figure 3: Negative ion spectrum with 5 mm extraction aperture

With the use of the quadrupole mass spectrometer we detected a significant amount of water in the residual gas (see Figs. 4 and 5), which was reduced by means of long-term heating and pumping. The H^-/O_2^- ratio was found to be 2/3 after conditioning of the plasma chambers.
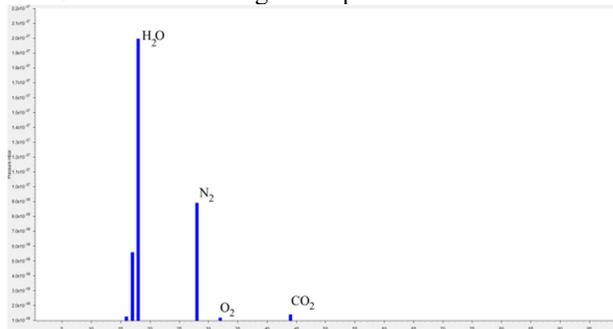
Figure 4: The spectrum of residual gas before final pump out
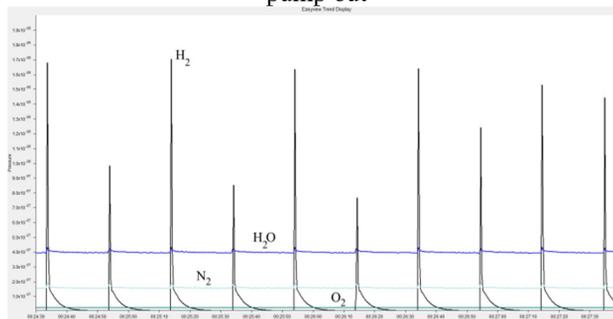
Figure 5: The gas spectrum in the diagnostic chamber during pulsed H_2 injection after the final pump out

Next stage of the experiments was performed with the plasma aperture of 1 mm andpuller aperture of 3 mm spaced 11 mm apart. By tuning the extraction voltage and the gas pressure (both time delay and upstream pressure) a total negative ion current of 0.8 mA was achieved at U_{extr} = -20.4 kV. The dependence of the negative ion current on the extraction voltage for two pressures is shown in Fig. 6. It was shown that after the above-mentioned measures the percentage of impurity ions substantially decreased (see Fig. 7).
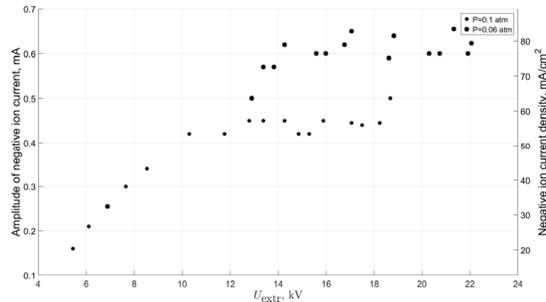
Figure 6: The dependence of the negative ion current and current density on the extraction voltage for several values of pressure in the gas feed line with 1 mm extraction aperture
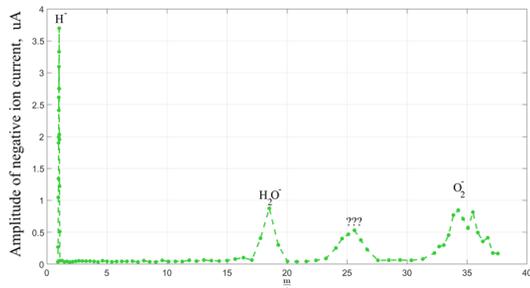
Figure 7: Negative ion spectrum with 1 mm extraction aperture

It is known that the conditions for H_2^+ generation and for the first stage of H^- generation, i.e. populating high vibrational levels through electronic excitation, are similar. As can be seen from Fig. 8, which depicts the spectrum of positive ions extracted from the plasma, there was a presence of such positive ions: the ratio of H^+ / H_2^+ is about 7-8 times, which implies a significant difference between the achieved and optimal conditions for H^- production. We plan to use the ratio as an indicator for future optimization of our experimental conditions.

The next stage of the experiments was performed with 3 mm plasma electrode aperture and 5 mm puller aperture spaced 11 mm apart. A 1.5 mA total current of negative ions was achieved at U_{extr} = 24.7 kV (see Fig. 9). Decreasing the distance between the electrodes by 5 mm provided the maximum total current of negative ions of 1.1 mA - this can be seen in Fig. 10, where the dependence of the current on the voltage for different values of pressure upstream of the valve for this extraction system is depicted.
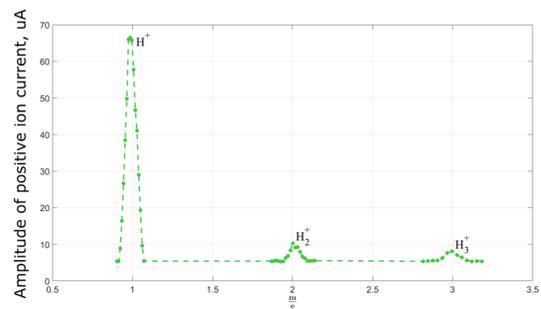
Figure 8: Positive ion spectrum with 1 mm extraction aperture
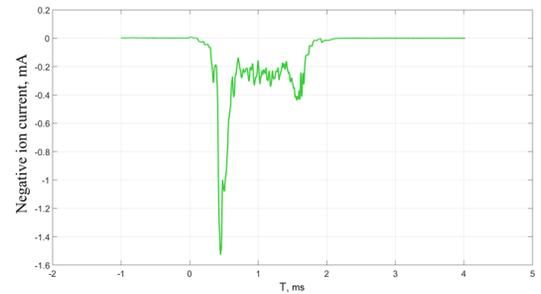
Figure 9: A typical negative ion oscillogram with 3 mm extraction aperture
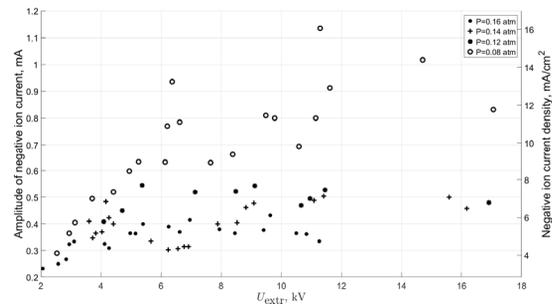
Figure 10: The dependence of the negative ion current and current density on the extraction voltage for several values of pressure in the gas feed line with 3 mm extraction aperture

CONCLUSIONS

We measured dependencies of the negative ion current on various parameters of the two chamber high-frequency gasdynamic ECRIS, leading to the optimization of the extraction system and the gas feed line pressure. A negative ion current density of 80 mA/cm^2 through 1 mm plasma electrode was demonstrated.

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