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# Efficiency investigation of a negative hydrogen ion beam production with the use of the gasdynamic ECR plasma source

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**Abstract.** Negative hydrogen ion sources are of great demand in modern physics as injectors into accelerators and drivers for neutral beam injectors for fusion devices. It has been shown earlier that the use of the gasdynamic ECR discharge provides the opportunity to extract up to 80 mA/cm<sup>2</sup> of negative ion current density. We studied experimentally the volumetric negative hydrogen ion production and vacuum ultraviolet emission in a gasdynamic ECR discharge. The high-density plasma was sustained by the pulsed 37 GHz / 100 kW gyrotron radiation in a magnetic configuration consisting of two consecutive simple mirror traps. The future prospects of the volumetric H<sup>-</sup> source based on the gasdynamic ECR discharge related to the transition from pulsed to continuous operating mode with the use of an improved magnetic confinement system are discussed. Numerical simulation of the negative hydrogen ion beam extraction at the continuous operating mode facility was performed. Optimal configuration of the extraction electrodes and the electron damping magnets was found.

## 1. Introduction

Negative hydrogen ion sources are of great demand in modern physics as injectors into accelerators and drivers for neutral beam injectors for fusion devices, such as ITER [1]. Plasma emission in the vacuum ultraviolet range (VUV) is intrinsic to the processes of H<sup>-</sup> generation and dissociation [2]. Thus, the study of the VUV emission enables evaluation of plasma parameters and volumetric rates of plasma-chemical processes to optimize the efficiency of the negative hydrogen ion source.

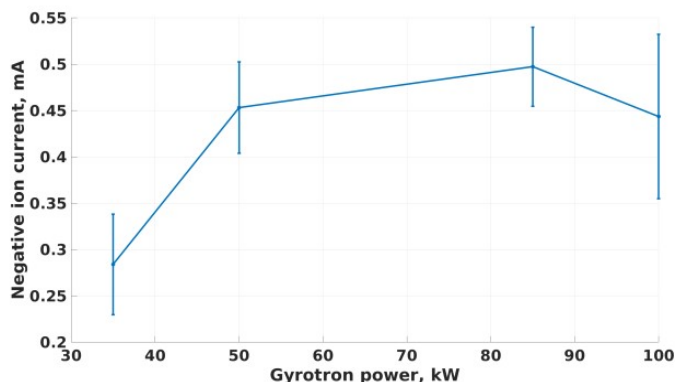
It has been shown earlier that it is possible to reach up to 80 mA/cm<sup>2</sup> H<sup>-</sup> current density with the use of the gasdynamic ECR plasma discharge at SMIS-37 facility [3], where negative ions are generated volumetrically in the two-stage spatially separated scheme. In the first stage, hydrogen molecules at high vibrational levels are produced by electronic excitation through B and C singlet states as a result of the collision with “hot” (50–100 eV) electrons. In the second stage, H<sup>-</sup> ions are generated as a result of the dissociative attachment of “cold” (≤ several eV) electrons to the vibrationally excited ground state molecules [1].



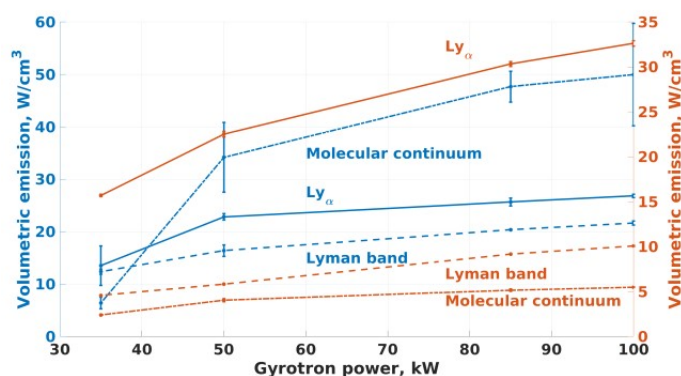
Two consecutive simple mirror plasma traps are used for the plasma confinement. The pulsed ECR discharge is sustained in the first trap by the 100 kW gyrotron radiation at 37.5 GHz, providing dense and “hot” plasma needed for the efficient electronic and vibrational excitation of hydrogen. The plasma and the excited molecules naturally flow into the second trap, where ECR heating is prohibited by the perforated plate installed between traps. In the second trap, a “cold” electron fraction is created by the ionization of the neutral gas with “hot” electrons diffused from the first trap, and negative ions are formed by dissociative attachment.

A detailed study of the VUV emission in the scheme described above was performed at SMIS-37 facility. The diagnostic apparatus for the measurement of the absolute power of the VUV plasma emission was constructed. It includes three optical filters and a calibrated photodiode (IRD SXUV5), following [4]. The filters correspond to the atomic ( $122\pm 10$  nm – Lyman alpha line) and the molecular emission ( $160\pm 10$  nm – Lyman band and  $180\pm 20$  nm – molecular continuum) of hydrogen. The plasma emission from both traps was measured, and the absolute VUV emission power density was estimated, assuming the emission is isotropic. The dependencies of the negative ion current and the VUV emission power on the system parameters were studied. As an example, the dependencies on the incident microwave power are shown in figures 1 and 2. The means for further optimization of the negative ion source derived from the comparison of the VUV-power measurements in the two traps can be found in [5].

Hereinafter, we discuss the future prospects of the volumetric  $H^-$  source based on the gasdynamic ECR discharge. We focus on issues related to the transition from pulsed to continuous operating mode and the improvement of the magnetic confinement.



**Figure 1.** The negative ion current dependency on microwave power near the optimum for  $H^-$  production.



**Figure 2.** The dependency of the VUV plasma emission on microwave power in both traps near the optimum for  $H^-$  production. The curves for the first and the second traps are shown in blue and red, respectively.

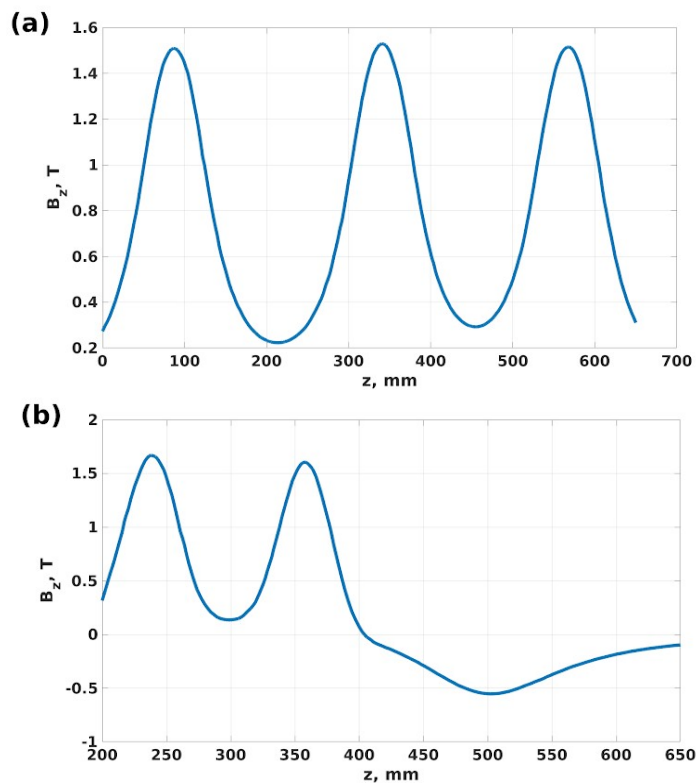
## 2. Transition to the continuous operating mode of the negative hydrogen ion source

In the above-mentioned experiments, high density ( $10^{13}$  cm $^{-3}$ ) hydrogen plasma was sustained by the pulsed microwave radiation, and the magnetic confinement system consisted of two identical simple mirror traps, as shown in figure 3(a). Each step of the two-stage volumetric  $H^-$  generation mechanism was implemented in the corresponding trap. The ion extraction system consisted of plasma

and puller electrodes with the diameters of 1.8 mm and 3 mm, respectively, placed 10 mm apart. A magnetic filter made of permanent NdFeB magnets was used for co-extracted electron deflection.

A transition to the continuous operating mode, required in many applications, is of interest due to the demonstrated efficiency of the  $H^-$  source based on the gasdynamic ECR discharge. It is thus proposed to use an all-permanent magnetic confinement system of the GISMO facility [6]. The GISMO magnetic field forms consecutive simple mirror-like and cusp traps, as shown in Fig. 3(b). The cusp field configuration would effectively prevent a direct electron transport into the second part of the trap, only leaving the diffusion process to fill the  $H^-$  formation volume with the cold plasma. At the GISMO facility, the plasma is sustained by a 28 GHz microwave radiation of a 10 kW continuous operating mode gyrotron. Similar to the previous experiments, the perforated plate will be placed between the traps to prevent ECR heating of electrons in the cusp trap. Another advantage of the GISMO facility when compared to SMIS-37 is the possibility to inject neutral gas directly into the cusp area, which presumably will enhance the plasma cooling and the  $H^-$  formation efficiency.

As the initial step, the optimal configuration for the negative hydrogen ion beam extraction at the GISMO facility and the electron magnetic filters were simulated with the IBSimu code [7].

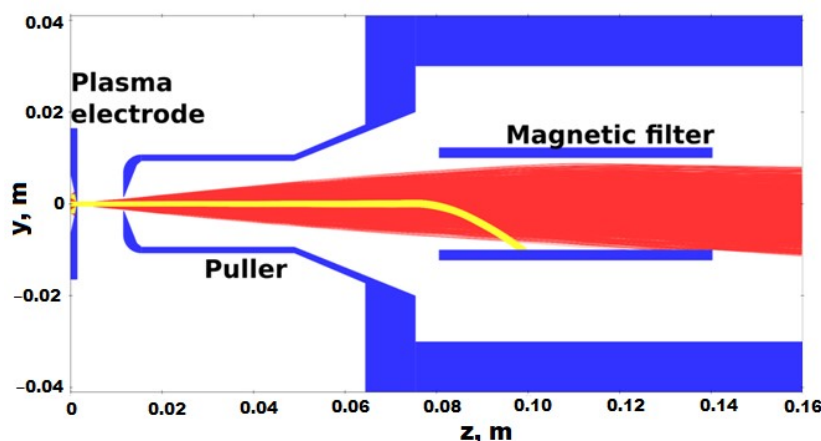


**Figure 3.** Two magnetic field configurations: (a) two identical simple traps and (b) simple magnetic trap + cusp.

### 3. Simulation results

Negative hydrogen ion beam extraction from the second (cusp) trap of the GISMO facility was simulated using the following parameters: negative hydrogen ion and electron current densities of  $24 \text{ mA/cm}^2$  and  $2.4 \text{ A/cm}^2$ , respectively, and the extraction voltage of 10 kV. The optimal configuration of the two-electrode extraction system was found to be  $D_1 = 1 \text{ mm}$ ,  $G = 10 \text{ mm}$ ,  $D_2 = 3 \text{ mm}$ , where  $D_1$  is the plasma electrode aperture,  $G$  is the distance between electrodes, and  $D_2$  is the puller aperture. The plasma electrode outlet aperture size of 1 mm is defined by the optimization of ion losses in the extraction system. The losses of the  $H^-$  beam are below 10% for the optimized configuration.

Figure 4 shows the electron (yellow) and the  $H^-$  (red) extraction for the configuration of 1–10–3 mm ( $D_1$ – $G$ – $D_2$ ). The electrons are deflected efficiently by the optimized configuration of the magnetic filter, installed 8 cm downstream the ion beam line.



**Figure 4.** The  $\text{H}^-$  extraction modeling for the 1–3–10 configuration. The beams (electrons are yellow,  $\text{H}^-$  is red) flow from left to right, the plasma electrode, the puller and the magnetic filter are blue-coloured.

#### 4. Conclusions

Features of the magnetic configuration of continuous operating mode GISMO facility, i.e. the simple mirror trap followed by the cusp trap, are presumably favorable for the  $\text{H}^-$  volume production when compared to the magnetic configuration consisting of two consecutive simple mirror traps. The concept is essentially similar to the 2.45 GHz HYBRIS  $\text{H}^-$  ion source prototype [8], with the exception of higher plasma density in the primary electron heating trap, therefore having significant potential for high-intensity applications. Negative hydrogen ion beam extraction from a plasma confined in the aforementioned magnetic trap was simulated, the optimal combination of the plasma electrode and the puller apertures together with the required interelectrode distance was found. Optimal configuration for the electron damping magnets was also found.

#### 5. Acknowledgments

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