DEVELOPMENT OF AN H^- ION SOURCE BASED ON ECR PLASMA GENERATOR AT CEA/SACLAY.

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Abstract: ECR plasma generators have demonstrated their efficiency, reproducibility and long life time for the production of light positive ions like protons or deuterons. These sources generally work in CW mode. A new 2.45 GHz ECR test stand based on a pure volume H^- ion production is currently under development. This negative ion source is working in pulsed mode, 1ms at 10 Hz. The first H^- ions have been observed at the beginning of 2002 with a poor efficiency. Only a few µA were produced. To avoid negative ions destruction by non absorbed microwave close to the extraction aperture, a stainless steel grid was installed in the rectangular plasma chamber. As a result, the chamber is now effectively separated in 2 zones, the ECR plasma generator and the H^- production zone. By plotting the extracted current versus the production zone length, the H^- ion intensity reached more than 100 µA with the grid located 25 mm from the aperture. A voltage difference of the order of ten volts can be applied between the two parts of the plasma chamber in order to modify the electron energy entering the production zone. In parallel, a theoretical approach has been undertaken to improve the knowledge of electron-gas interaction.

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I. INTRODUCTION

In the framework of future high beam power accelerators, a desire exists for reliable and efficient H^- ion production. Comparatively long duty factor, high current and high quality H^- beams are required for injection into compressor rings of machines such as SNS or ESS and neutrino factories These facilities have been planned to work in pulsed mode (roughly 1 to 2.5 ms at a frequency ranging from 15 to 50 Hz). Many existing machines such as HERA, ISIS, LANCSE and others are also interested in source developments. For several years, CEA has undertaken an important R&D program on very high beam power accelerators. ECR high intensity proton source development started with the SILHI program [1]. The main objective here is to produce 100 mA proton CW beam currents at 95 keV. An electron cyclotron resonance (ECR) source has been chosen to reach these performances.

Since the SILHI source showed a good efficiency for high intensity proton beam production with a very long source life time, parallel programs are in progress. A permanent magnet deuteron source is under construction [2] for the SPIRAL 2 machine. In parallel, a new 2.45 GHz ECR source based on pure volume H^- ion production is currently under development. This negative ion source is working in pulsed mode, 1ms at 7 to 10 Hz. The H^- test stand has been already described elsewhere [3, 4].

Section II reports on experiments performed in 2002, when the first H^- ions were observed. Then recent measurements achieved with a plasma chamber separated into 2 zones are presented and discussed in Section III. A parallel effort on the electron-hydrogen gas interaction and the developed code are exposed in a companion paper [5]. This code takes into account more than 40 processes involved in electron-hydrogen gas interactions.

II. FIRST NEGATIVE IONS

At the end of 2001, modifications were made to electrically isolate the plasma chamber. It can now be biased to either positive or negative voltage. The maximum extraction voltage is 10 kV. The electron and negative ion beam separator was removed and a tunable 90° dipole analyzer magnet (DAM) with 10 mm pole gap was installed behind the 5 mm diameter hole centered on the collector plate. A Faraday cup equipped with an electrostatic secondary electron suppressor allows magnetically-analyzed beamlet measurements. With these conditions either positive or negative ion beams were analyzed. The magnetic filter was still located at its earlier position [4].

To calibrate the analyzer, positive ion measurements were made. The plasma chamber was biased to 6.4 kV while operating with hydrogen gas. A 3 mA total extracted positive beam has been produced with the following species fraction: $H^+ = 23$ %, $H_2^+ = 47$ % and $H_3^+ = 30$ %. The H^+ peak current reaches a maximum level when the DAM current is set to 2.8 A.

By reversing the DAM current and setting the plasma chamber bias to –6.4 kV, a large peak rose for a very low DAM excitation (0.15 A). This peak is attributed to electrons. Then a much lower intensity peak appeared for DAM excitation equal to 2.8 A, indicating H^- ion extraction. The same analysis with Helium plasma does not reveal any peak at 2.8 A DAM current. Both experiments prove the ability of H^- production by this source. A beam profiler was then installed and showed a beam deflection due to the Magnetic Filter (MF), which is located close to the extraction zone. By removing the MF, the e-/H- ratio was 8000. In these conditions, the total H^- ion current never reached more than 5 µA.

III SEPARATED PLASMA CHAMBER

Previous spectroscopic plasma analysis showed several lines (λ = 715.3 nm, 674.0 nm, 631.5 nm, 627.0 nm). These specific lines indicate the presence of excited hydrogen molecules which are able to produce H^- ions [5] by electron dissociative attachment.

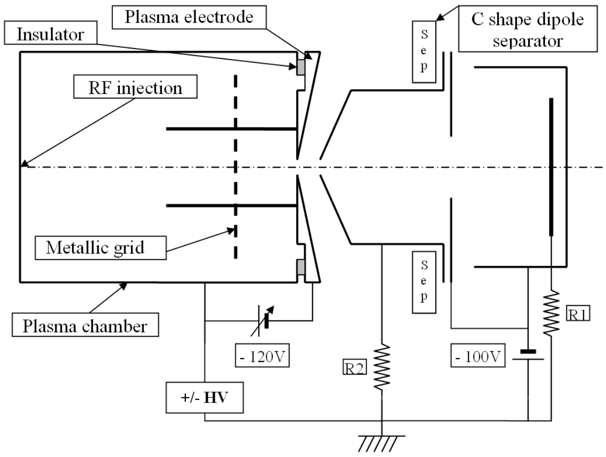

Fig 1: Experimental set up and electrode wiring.

So the small H^- ion production may be attributed to negative ion destruction close to the plasma electrode. It is possible that microwave power not completely absorbed by the plasma contributes to H^- loss. Some simulations show that a simple grid with a large transparency can stop the microwave penetration [6].

III-1 Grid location

A stainless steel grid (1mm wire diameter, 5 mm gap) has been installed in the plasma chamber. The grid is held by 2 metal rods attached to the plasma electrode. The system of grid, rods, and plasma electrode is kept at the same potential.

The plasma chamber is then physically separated in 2 zones: the microwave plasma generation zone and the negative ion production zone (Fig. 1). Electron or H^- current is measured on a 30-mm aperture Faraday cup. Electron and ion separation is done by a C-shaped dipole magnet located 80 mm downstream from the extraction aperture. The large electron-H^- current difference forced us to automatically switch resistor R1 from 10 Ω to 9 kΩ when the magnet separator is switched ON. R2 is typically equal to 10 Ω and allows extractor current measurements.

The grid was first located at 85 mm from the plasma electrode. The extracted H^- ion intensity increased instantly by a factor of 2 and reached 10 µA. The grid position has been changed in order to optimize the H^- ion production. By reducing the production zone length, the extracted current increased up to 84 µA while the grid was located at 30 mm from the plasma electrode. Then it decreased (46 µA at 20 mm). In the following experiments reported here, the grid is positioned at 30 mm from the plasma electrode.

III-2 Grid polarization

Theoretical calculations [5] confirm the influence of electron energy on the negative ion production. To test this model, the grid and the plasma electrode are biased to positive and negative voltages (Fig. 1) in the range of a few tens of volts. This procedure offers the possibility of controlling the electron energy in the production zone. By slightly polarizing the grid and plasma electrode with positive voltage, the H^- ion current decreases. At 10 keV extracted energy, current is then plotted versus the negative grid voltage. The H^- intensity continuously increases with the grid voltage up to 890 µA for - 100 V grid voltage (Fig 2).

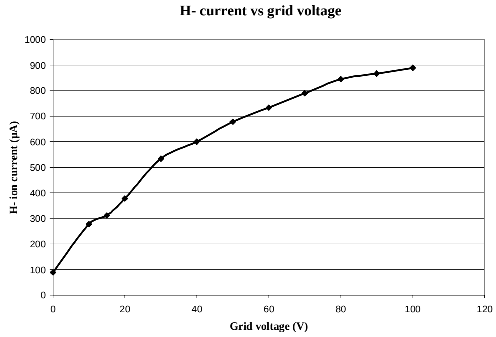

Fig 2: H^- extracted current vs grid polarization

III-3 Microwave power influence

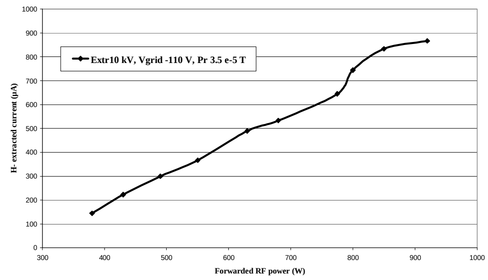

Fig.3: H^- extracted current vs forward HF power

The extracted current plotted versus the forward High Frequency (HF) power increases continuously from 140 to 850 µA when the HF power increases from 380 to 950 W (Fig 3). As no coupler has been installed yet, the reflected power is not measured. The pump box working pressure is 3.5 10^{-5} Torr and the grid is polarized at – 110 V. In these conditions, the total extracted current attains 19 mA leading to an e-/H^- ratio of 22.

III-4 Pressure dependence

The extracted H^- intensity also depends on the hydrogen gas flow. The pressure is of great influence on the plasma characteristics such as species temperature. The vacuum is implemented by a 1000 l/s turbomolecular pump. The plasma chamber is pumped through the extraction system with a 5 mm diameter plasma electrode aperture. At 950 W forward HF power, 10 kV extraction voltage and – 60 V grid polarization, the H^- intensity increases from 30 to 600 µA when the pressure in the plasma chamber increases from 1.5 to 4 mTorr.

III-5 Magnetic configuration

When the MF is removed, only 2 coils create the magnetic configuration in the plasma chamber [4]. The plasma chamber magnetic field is not influenced by the C shape electron separator located 80 mm from the plasma electrode. So by this way, the magnetic field is only due to B_r resulting from B_z decrease. For the previous measurements, the 2 coils were regularly optimized to obtain the maximum intensity with a stable signal. Axial magnetic simulations (OPERA-2D code from VectorFields) indicate a 740 Gauss maximum field on the axis and no ECR zone (875 Gauss) is noticed in the plasma chamber. New magnetic measurement will be performed to confirm this configuration which leads to the maximum H^- ion production reported in paragraph III-4.

IV DISCUSSION

To confirm the H^- ion production, helium plasma was regularly produced. With helium operation, the collected current with the separator switched ON remains equal to 0. It reaches almost 1 mA with hydrogen gas injection. Then the dipole analyzer magnet (DAM) mentioned in the section II was again installed. Positive and negative charge analyses versus DAM current are plotted for 4.5 keV beam energy (Fig. 4). This energy allows a better magnet transmission.

Positive charge analysis indicates a very low amount of H_2^+ and heavy ions (due to water) compared to the 2001 measurements [4]. The H_3^+ peak becomes the highest one. This is the typical signature of the reaction:

$$H_2 + H_2^+ \rightarrow H_3^+ + H + 1.71eV.$$

This process takes place in cold plasma. The total extracted current reaches 3.1 mA.

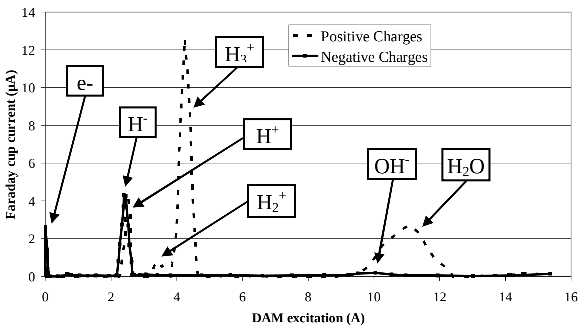

Fig 4: Both positive and negative extracted current comparison (at 4.5 keV)

Negative charge analysis shows an H^- ion peak equal to the proton one. It occurs for the same DAM excitation. The global negative charges lead to a 19 mA current. The low electron peak intensity is due to the residual magnetic field in the DAM. Moreover, a very small peak is noted for a 10 A DAM excitation, this peak seems to be due to OH^- ions.

To conclude, H^- ions are now routinely produced with this microwave source. As the magnetic simulations do not present any ECR zone in the plasma chamber, is it still an ECR source? So far the efficiency of the source is quite good (close to 1 mA/kW with a 5 mm diameter emission aperture). These different measurements are showing promising results.

The source regularly operated 5 days a week 24 hours a day in pulsed mode for a few weeks and no grid degradation has been yet observed. To definitely complete the first step of this program, future experiments will be performed as a function of gas mixing, wall and grid material. Grid and plasma electrode independent tuning will be tested. The plasma chamber volume and shape will be also investigated. A more powerful generator will allow measurements at higher RF power. As shown on Fig. 5, the rise time has to be optimized. Then, simulations will be done to define a new extraction system at higher energy, taking into account the real e^-/H^- ratio and extracted current.

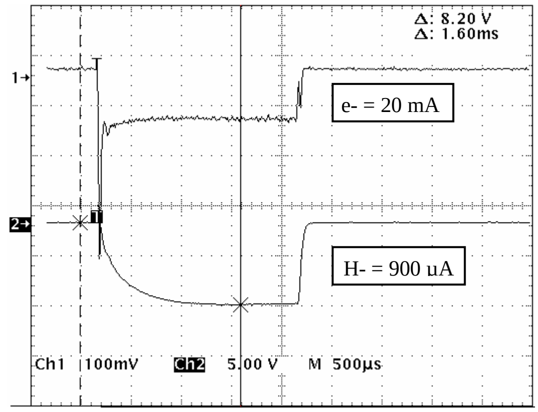

Fig 5: Separated H^- and electron extracted beams (16 pulse average)

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