DEVELOPMENT OF A NEW COMPACT 5.8 GHz ECR ION SOURCE*

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Abstract

LPSC is developing a new 5.8 GHz compact ion source to produce low charge state ion beams and study their capture into the PHOENIX charge breeder plasma. The source was designed to meet criteria like stability, compactness, and low cost. It is mounted on a NW200 flange and is fully under vacuum during operation. The technology brings modularity to ease the development. It operates up to 60 kV. The plasma is heated by a 100 W solid state amplifier. The ECRIS produces 1 mA of H^+ beam with 20 W of HF power and can produce too, low charge state argon ions. It was tested under several microwave and magnetic configurations on a test bench equipped with a mass spectrometer and diagnostics. Given its good performances, this source is being installed to drive the accelerator-based neutron source, GENEPI 2, at LPSC. The developments of the source together with the results of the experiments are presented. Future plans for this ion source are also discussed.

INTRODUCTION

To characterise a charge breeder, a test bench has to be equipped with reliable and easy to install sources producing singly charged ions [1]. Such sources, regarding their performances, must ensure beam stability and quality (emittance) as well as produce the desired species with the required beam intensity. In order to study the capture of low charge state ions into the PHOENIX charge breeder plasma, one LPSC task of the EMILIE project aims to develop a new ion source targeting the specifications listed above.

Since 2013, many developments and experiments have been carried out to improve the 1^+ source. As good performances were obtained, the source was duplicated and installed in order to produce D^+ beams for the accelerator-based neutrons source operating at LPSC, GENEPI2. In parallel, developments will continue to improve the performances and to test innovative configurations.

5.8 GHz ION SOURCE DEVELOPMENT

To develop this new source, the first idea was to use a socket type connexion to obtain a compact and easy to dismount assembly. We also opted for a modular design to easily change the magnetic structure and the microwave coupling. Thus, the first configurations were based on the compact microwave ion sources technology (COMIC 2.45 GHz) [2] using a 5.8 GHz microwave (µw) frequency and with a larger plasma chamber to optimize the coaxial µw coupling. Recently, a minimum-B configuration with a waveguide coupling has been tested.

Design

The source is fixed on a NW200 flange and its length is about 400 mm (Fig. 1). The plasma chamber is water-cooled and surrounded by a container enclosing the permanent magnets. The microwave circuit passes through the flange and is axially connected to the plasma chamber. The extraction system is composed of a plasma electrode and a polarized puller allowing extraction electric field (E) tuning, a set of three electrodes (one with a negative potential inserted between two grounded electrodes) allowing space charge compensation during beam transport.

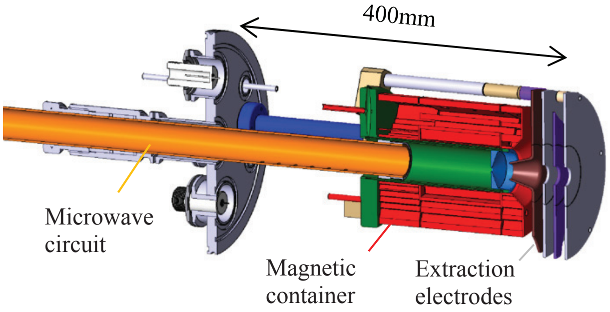

Figure 1: Cut view of the 5.8 GHz ion source modular structure.

Compact Microwave Configuration

In the compact microwave design, the goal is to produce high microwave electric field in the plasma chamber, at the ECR surface. This is done using a resonant µw structure composed of antennas and couplers with a coaxial input. The gas pressure is tuned to reach the Paschen's condition to ignite and sustain the plasma. These sources produce stable beams with a low beam emittance at low power [2].

The 5.8 GHz µw coupling assuring a high electric field at the plasma electrode hole was simulated with HFSS [3]. It is done with a 14 mm long antenna in a 41 mm inner diameter cavity. The maximum E field on the axis is 15 kV/m (Fig. 2a). Another microwave coupling using a longer antenna with 4 radial couplers has also been designed and tested. In this configuration, the µw E electric field reaches 100 kV/m on the axis, close to the plasma chamber hole, for 1 W of injected power (Fig. 2b).

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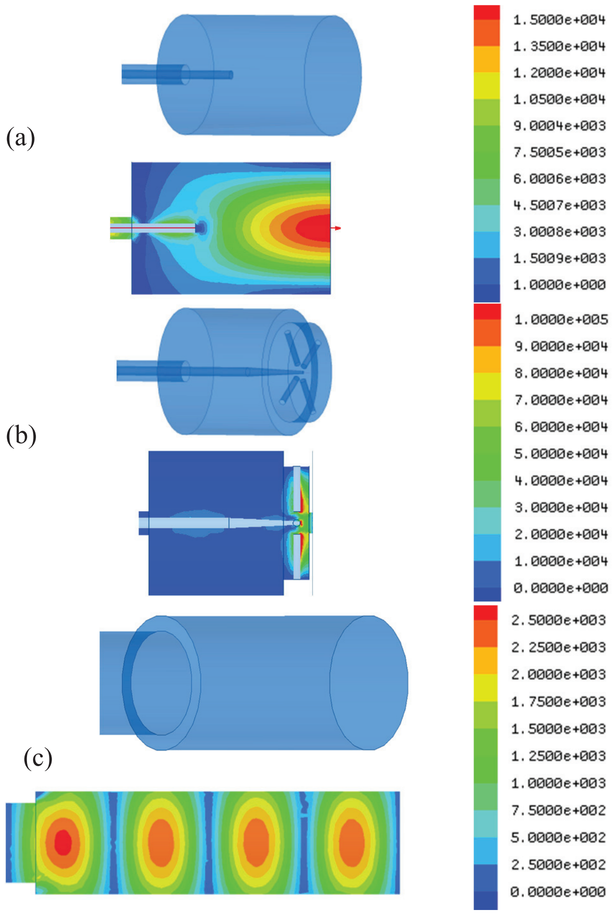

Figure 2: HFSS simulations of microwave couplings and electric field distributions (a) single antenna, (b) antenna with couplers, (c) circular waveguide.

Regarding the magnetic structure, an axial field gradient is generated by a permanent magnet ring alternating axial and radial orientation (Fig. 3). The axial peak is located at the extraction electrode, shaping one ECR resonant surfaces in the cavity while the other is in the accelerating gap outside of the source.

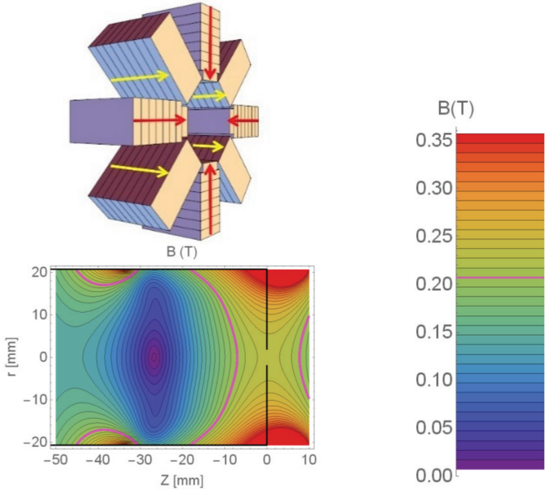

Figure 3: Gradient magnetic structure (top) and magnetic field map simulated with Radia - Mathematica (bottom).

Classical ECR configuration

A minimum-B structure has then been designed using a set of standard 12x12x12 cm^3 permanent magnets. A 0.43 T magnetic field is obtained at the injection point A, 0.24 T at the extraction point B, with a minimum of 0.15 T at point C. (Fig. 4).

The µw coupling has been replaced by a circular waveguide (TE11 mode) (Fig. 2c). A coaxial to waveguide transition has been simulated with HFSS, realized, tested, and validated before the mounting on the source.

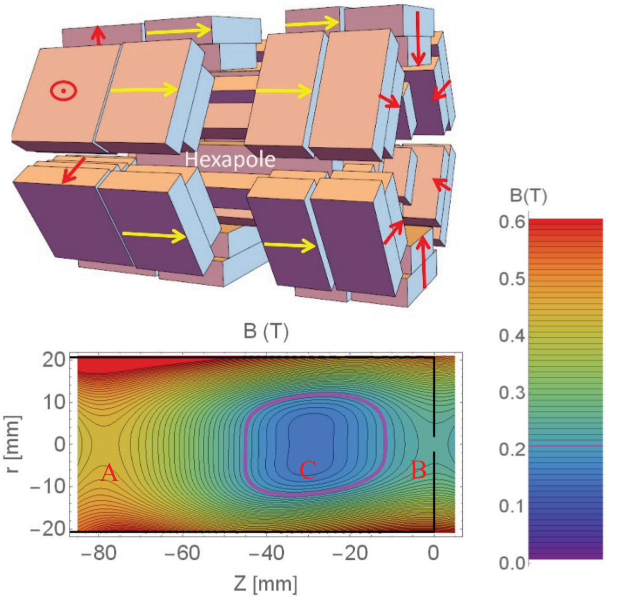

Figure 4: Minimum B magnetic structure (top) and magnetic field map simulated with Radia - Mathematica (bottom).

Results and Discussion

Table 1 presents some results in several configurations. The magnetic gradient configuration with the coaxial antenna and couplers showed very good ability to produce single charge argon beam at low power. For low charge states beams, the magnetic container was replaced by the minimum-B structure. The source generated beams up to charge 4+, the 1+ beam being predominant. The base vacuum will be improved in order to enhance the low charge state beam intensities, the plasma electrode hole will be reduced to produce some µA beams within an emittance compatible with the charge breeder acceptance.

The minimum-B magnetic configuration was also tested for the production of mA range proton beam. It was clearly noticed that more H$^+$ current could be extracted using the waveguide coupling, with less power compared to the antenna coupling. By adjusting the microwave power, the source is to produce intensities ranging from a few µA up to 1.45 mA extracted from a 4 mm hole in the plasma electrode.

To compare the two coupling efficiencies in the minimum-B magnetic structure without plasma, we computed the efficient part of the electric field on the ECR surface (B=0.207 T at 5.76 GHz).

Table 1 : Extracted Currents with a Φ=4 mm Plasma Electrode Hole

Magnetic and HF configurations	**Species**	**Current (mA)**	**HF power (W)**	**Extraction voltage (kV)**
Gradient coaxial antenna + couplers	Ar$^+$	1	25	40
MinB coaxial antenna	H$^+$	1	63	30
MinB Waveguide	Ar$^+$ / Ar^{2+} / Ar^{3+} / Ar^{4+}	0.185 / 0.142 / 0.044 / 0.01	81	30
MinB Waveguide	D$^+$	1.15	17	30
MinB Waveguide	H$^+$	1.45	45	35

As the electrons trajectories are following the magnetic field lines, the efficient part of the electric field providing ECR heating is defined as:

$$E = \frac{\vec{E}X\vec{B}}{B} \qquad (1)$$

The ECR surface is meshed with Radia-Mathematica, at each node the points coordinates and the magnetic field vectors are recorded, then the electric field is obtained using the field calculator of HFSS and imported in Radia-Mathematica to compute E.

The results are plotted on the ECR surfaces in Fig. 5 and Fig. 6, using a color scale to represent the intensity. The average value of E is also calculated to compare the two configurations.

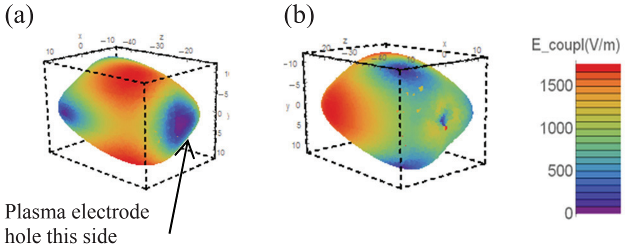

Figure 5: Front (a) and rear (b) views of the efficient E field distribution on the ECR resonance surface for the antenna coupling.

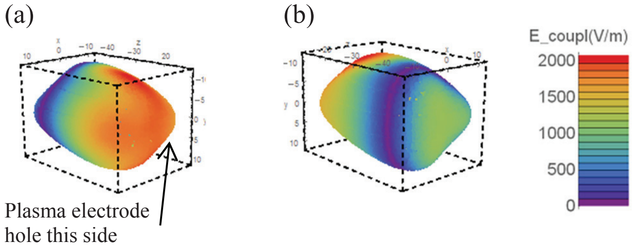

Figure 6: Front (a) and rear (b) views of the efficient E field distribution on the ECR resonance surface for the waveguide coupling.

Without plasma, in the case of the antenna, the average efficient E field is 1267 V/m and, in the case of the waveguide, it is 1072 V/m. Comparing with the experimental results, this indicates that the significant parameter is not the average coupling but rather the location on the surface, or that the plasma presence strongly affects the microwave coupling in these operating conditions. One can note that in the case of the waveguide the E intensity is much higher close to the cavity axis where the dense ECR plasma is located. While in the case of the antenna, the strongest E intensity is obtained on the peripheral part of the ECR zone (large radius), providing energy transfer to electrons playing a secondary role in ECR ion source performance.

Further simulations, including a plasma model, would be necessary to better simulate the coupling.

5.8 GHz ION SOURCE ON GENEPI2

At LPSC, GENEPI2 is an accelerator-based neutron source for multipurpose applications (nuclear physics experiments, irradiation platform, neutrons detector calibration) [4]. The neutron flux is produced by the impact of a 220 keV D$^+$ beam onto a tritium target.

Up to now, the accelerator was operated in a pulsed mode, driven by a duoplasmatron source (50 mA peak D$^+$, 700 ns pulse width, repetition rate from 100 to 4000 Hz) [5].

In order to increase the beam power and operate in CW mode, the 5.8 GHz ECR ion source has been retained to produce a 100 to 1000 μA D$^+$ beam. The source is set on a 250 kV platform (see Fig. 7). The beam is first extracted with a 35 kV potential and then accelerated through a set of 5 electrodes.

On the platform, the source socket flange is fixed on a trolley making its mounting and dismounting easy on the vacuum chamber. A 0.5 kW water chiller was also added on the platform and connected to the plasma chamber to regulate its temperature.

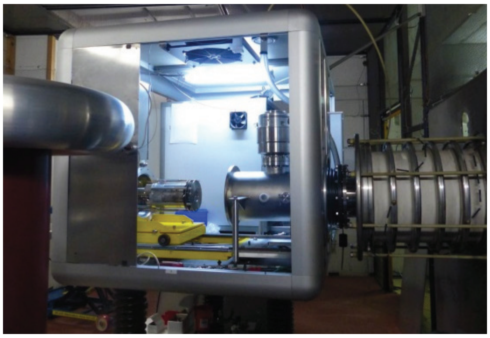

Figure 7: 5.8 GHz ion source mounted on the 250 kV platform of GENEPI2.

To start in safe conditions and qualify the accelerator operation, the extracted current was limited using a 1 mm hole diameter in the plasma electrode instead of the 4 mm one. The assembly of the source on the platform was completed in June 2016 and a 50 µA D^+ beam has been successfully accelerated in July. The plasma electrode will now be replaced to increase the D^+ current up to 1 mA.

CONCLUSION

The 5.8 GHz ion source shows a good ability to produce low charge state ion beams at low microwave power. Tuning this parameter, a wide range of intensities is achievable for H^+ and D^+. Thanks to the modular configuration and in order to improve the performances, new microwave couplings and new magnetic configurations will be tested. This could lead to configurations allowing frequency increase and therefore frequency scaling studies. To produce higher charge state currents, the vacuum and the plasma chamber pumping will also be improved.

The compactness and the simplicity of the source eased the integration of the source on the GENEPI2 high voltage platform. This reduced the time and cost required to upgrade this facility.

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