HIGH INTENSITY HELIUM BEAM AT CEA/SACLAY

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Abstract

The Spiral 2 injector will be first built, installed and tested at CEA Saclay before its transfer to Caen. The RFQ has been designed to accelerate different particles: protons, deuterons and q/A = 1/3 heavy ions. The A-Phoenix ion source developed and tested at LPSC Grenoble will be directly transferred to Ganil. So to test the q/A = 1/3 ions acceleration with the RFQ built at Saclay, the light ion ECR source has been thought capable to produce $^3He^+$ ions. Moreover, high intensity ^3He ion beam accelerator applications are possible in other domains such as astrophysics or neutrino factory.

The SILHI source has been fed with natural helium (^4He) gas for several days. Beam intensity as high as 20 mA (110 mA/cm^2 through 4.8 mm diameter aperture) has been extracted from the source with energy of 95 keV. Extensive experiments have been done with the 9 mm diameter nominal plasma electrode to characterize the He^+ extracted beam. With the same extracted beam density, total beam intensity in the range of 100 mA seems reachable. In addition, simulations of the beam extraction will be done to estimate electrode modifications in order to improve the beam transport.

INTRODUCTION

CEA/Saclay, in the framework of High Power Proton Accelerator (HPPA) researches, develops intense light ion sources [1] for several projects such as Iphi or Spiral 2 [2]. Up to now, developments were focused on proton or deuteron beam production with ECR ion sources. As a result, for 10 years, Silhi (High Intensity Ligth Ion Source) is capable to regularly produce more than 100 mA proton beam with energy as high as 95 keV. The magnetic configuration is provided by 2 coils. More recently, a permanent magnet ion source has been developed to produce “low intensity” deuteron beam for the Spiral 2 project which is now under construction in different places before its final installation at Ganil in Caen. Both ECR sources operate at 2.45 GHz and the RF power is fed to the plasma chamber via standard rectangular waveguides.

The Spiral 2 project aims to accelerate up to 40 MeV, deuteron beams with intensity ranging from 0.15 to 5 mA and q/A = 1/3 heavy ion beams (like $^{18}O^{6+}$ or $^{36}Ar^{12+}$) with intensity as high as 1 mA. To answer the Spiral 2 demands, 2 different ECR sources will be installed: a Silhi like source for deuteron production equipped with permanent magnets and the A-Phoenix source developed by LPSC in Grenoble [3].

The Spiral 2 injector will be first built, installed and tested at CEA Saclay before its transfer to Caen. But the A-Phoenix ion source will be directly transferred to Ganil. So to test the q/A = 1/3 ions acceleration with the RFQ built at Saclay, the light ion ECR source has been thought capable to produce $^3He^+$ ions. Moreover, high intensity ^3He ion beam accelerator applications are possible in other domains such as astrophysics or neutrino factory. For example, CLAIRE project [4] in Berkeley proposes to install a light ion ECR source on a 300 keV HV platform to produce 100 mA helium beams. Interaction of helium ions beams (> 100 mA, 17 MeV) with oxygen gas target has also been proposed for ^{18}Ne beam production (for the Beta Beam experiment).

In a first step, the Silhi plasma chamber, equipped with a 4.8 mm extraction hole, has been fed with ^4He gas. Beam intensity as high as 20 mA (870 Am^{-2}) have been extracted from the source with energy of 95 keV. Species fraction analysis and emittance measurements are reported in section 2. Then the classical 9 mm diameter plasma electrode aperture has been installed. This electrode generally allows the 100 mA H^+ production. To minimize extraction electrode temperature increase, the source was operating in pulsed mode with 0.3 duty cycle. A 100 kV – 104 mA total beam has been produced for a very short time. The helium beam characterization with ^4He and ^3He gas injection is reported in section 3. In section 4, simulations of the beam extraction are presented and possible electrode modifications are discussed in order to improve the low energy beam transport.

FIRST He$^+$ BEAM ANALYSIS

As the Silhi source extraction system has been designed to produced high intensity proton beams (in the range of 100 mA), in order to verify the helium beam production capability, the plasma chamber has been first equipped with a small extraction hole (diameter 4.8 mm). Beam intensity of about 20 mA was expected.

Emittance and beam profile have been analyzed, with the SILHI Emittance Measurement Unit (EMU) [x], 0.53 m downstream the extraction hole with a 95 kV - 17 mA extracted intensity (RF power 750 W) as a function of the intermediate electrode voltage.

The evolution of the beam profile (Fig. 1) demonstrates the influence of the intermediate electrode voltage. The potential of this electrode has been tuned from 75 to 61 kV with respect to the ground potential. The beam profile changes from a hollow beam towards a peak shape beam. Figure 1 also shows the beam diameter increases from 30 to 40 mm. In the same time, the rms normalized emittance value (0.047 π.mm.mrad) did not change for the 3 values of the electrode potential.

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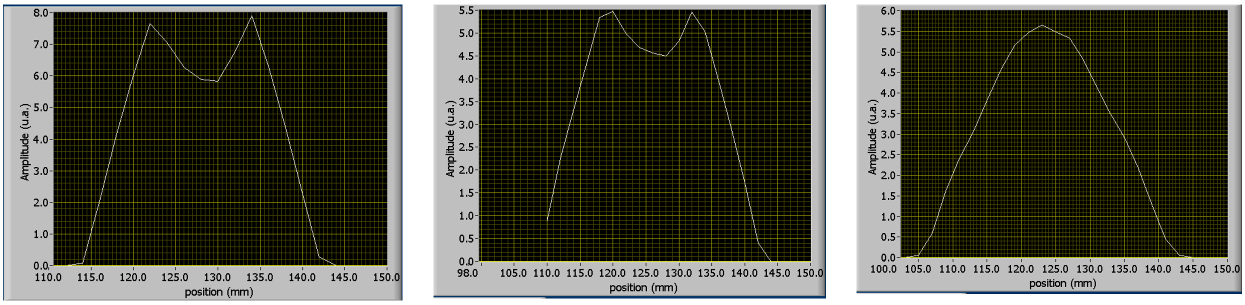

Fig. 1 : Beam profile analysis vs intermediate electrode voltage
(a) HTEI = 75 kV (b) HTEI = 67 kV (c) HTEI = 61 kV

The SILHI EMU equipped with a Wien Filter also allows species fraction measurements. Figure 2 shows the $^4He^+$ ions (98 %) are only accompanied by a small amount of impurities (2 %). One could note no multi-charge ions ($^4He^{2+}$) are produced. As the Wien filter is made with permanent magnets, the $^4He^{2+}$ peak should be on the right side of He^+ peak (at 4.81 kV on the white curve).

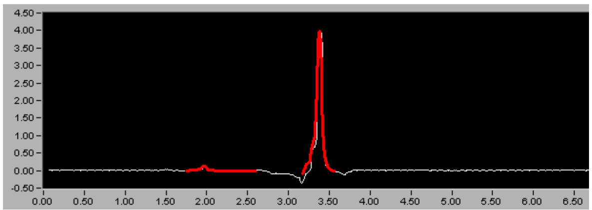

Fig. 2 : Species fraction analysis with ^4He injection

The maximum total extracted beam reached 20 mA at 95 kV leading to 110 mA/cm^2 beam density. Such density produced through a 4.8 mm diameter aperture should lead to close to 100 mA total beam with the 9 mm plasma electrode aperture which generally equips the SILHI source.

HIGH INTENSITY He^+ BEAM PRODUCTION

As the extraction system is not well adapted, difficulties have been encountered to correctly extract continuous high intensity beam with the 9 mm plasma electrode. As the beam diverges a lot, electrode temperatures increase and the spark rate becomes important. Moreover, in these conditions, even after source extraction tuning, the LEBT transmission was very low (as low as 10 %).

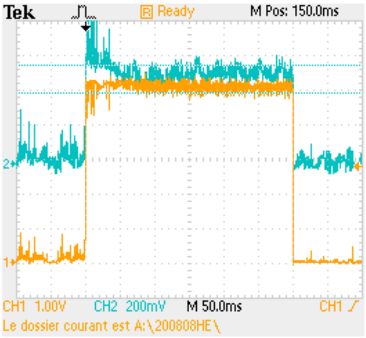

Fig. 3 : 104 mA $^4He^+$ beam (orange curve, 20 mA/cc) measured at the source exit.

As a result, to extract high current (in the range of 80 to 100 mA) with the existing electrodes, the source has been tuned in pulsed mode with a long duty cycle, 300 ms pulse length and 1 Hz repetition rate (dc = 0.3).

In these conditions, the maximum extracted current (measured with the DCCT located inside the accelerator column) reached 104 mA (Fig. 3, orange curve) with energy of 100 keV. The first gap of the 5 electrode system has been increased a lot by biasing the intermediate electrode at 56 kV. Despite such values, the transmission through the first LEBT solenoid was as low as 12 % (Fig. 3, blue curve with 4 mA/cc) and the grounded electrode temperatures increased. So, the beam has been stopped after only few minutes.

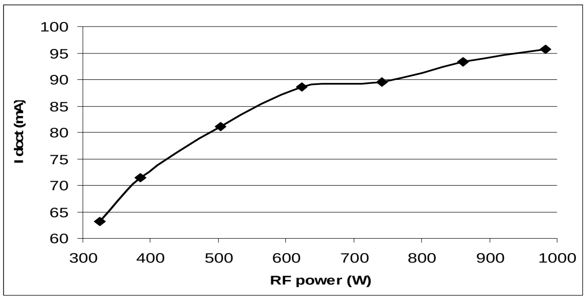

Fig. 4 : Extracted $^4He^+$ beam vs injected RF power

Despite such difficulties, the total extracted beam has been plotted as a function of the injected RF power (Fig. 4). The extraction conditions have been continuously adapted to minimize the temperature increase. The current increases continuously from 63 to 96 mA while the RF power increases from 325 to 980 W. The species fraction analysis (measured at 94 mA) indicates $^4He^+$ reaches more than 98 %. No $^4He^{2+}$ ions are extracted and only very small amount of heavy ions due to impurities are observed.

To produce the beam with quite stable conditions (no electrode temperature increase and reasonable spark rate) the extracted current has been limited at 94 mA with an energy of 95 keV (the intermediate electrode was biased at 48 kV).

Due to the high price of ^3He isotope gas, the source plasma chamber has been fed with, for only few days. Figure 5 presents the total extracted beam versus the injected RF power. For these measurements, the extraction conditions (gas flow, magnetic field and electrode voltages) remained constant all along the experiment. Stable beam (with 95 keV energy) has been produced with intensity as high as 95 mA with no electrode temperature increase. In the same time, the 1st part LEBT transmission (downstream the 1st solenoid) decreased from 83 to 17 %. The pulse shape (Fig. 6) shows 100 ms are needed to reach a plateau.

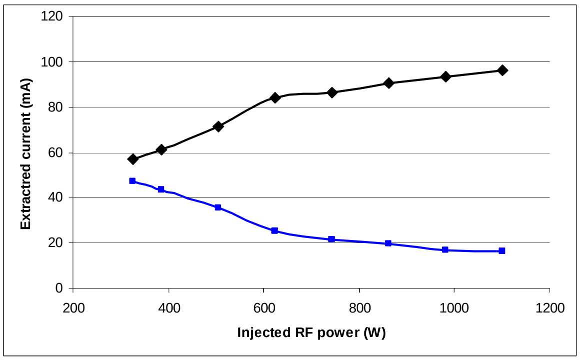

Fig. 5 : ^{3}He^{+} beam measured with DCCT (black curve) and Faraday cup (blue curve) vs injected RF power

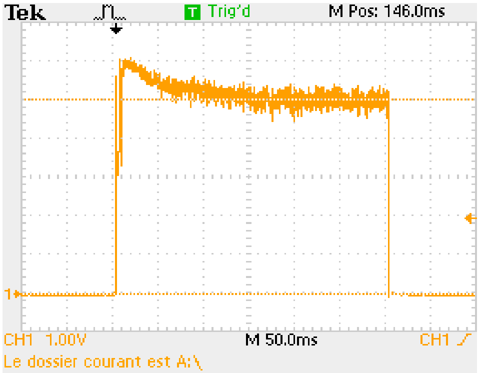

Fig. 6 : 100 mA ^{3}He^{+} beam (20 mA/cc) at the source exit.

The species fraction analysis (Fig. 7), measured with a 94 mA beam, shows ^{3}He^{+} reaches more than 98 %. Like for ^{4}He^{+}, no multicharged ions have been observed (nominal location: 5.5 kV).

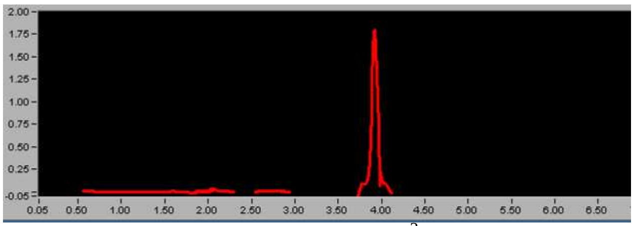

Fig. 7 : Species fraction analysis with ^{3}He injection

He^{+} BEAM EXTRACTION SIMULATIONS

The main challenge for an accelerating column is to extract with the lowest emittance ions from the plasma, ie the smallest beam size with the lowest divergence. The high voltage and the extraction electrode bias potentials can be adjusted to lower the emitance, but sometimes it is also necessary to change the shape of some electrode.

In our case we have chosen to change the shape of the plasma electrode.

In the simulations, done with Axcel code, we have fixed the plasma density at 148.6 mA/cm^2 with a 9 mm extraction hole. High voltage and plasma electrode potentials are fixed respectively at 95kV and 47kV with respect to the ground potential. The gaps between electrodes are constant for all simulations. And the space charge compensation has been set at 96.5 % downstream the electron repeller. Only the plasma electrode angle (θ) has been modified varying from 45° to 60° (Fig. 8).

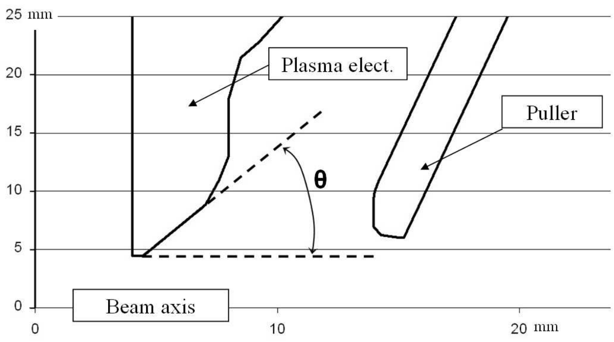

Fig. 8 : Scheme of the plasma electrode showing θ angle

To summarize the preliminary results obtained with the different simulations, one could note:

- the extracted current is a little bit higher for ^{3}He^{+} beam current than for ^{4}He^{+} (Fig. 9). For both ^{3}He^{+} and ^{4}He^{+} the intensity increases when the plasma electrode angle increases
- the ^{3}He^{+} beam rms normalised emittance decreases from 0.12 to 0.06 π.mm.mrad while the θ angle varies from 60 to 45°.

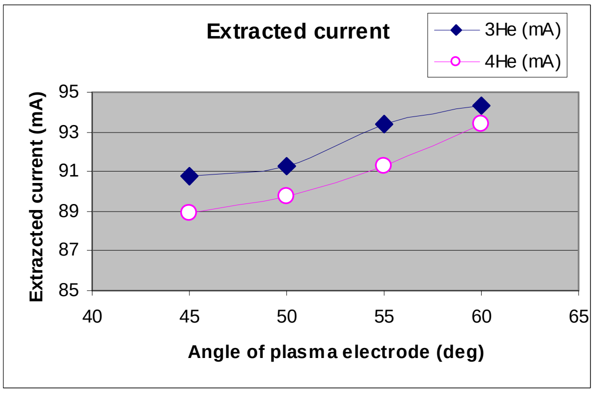

Fig. 9: Extracted current versus plasma angle electrode for both Helium isotope

CONCLUSION

Both ^{4}He and ^{3}He gas have been injected in the SILHI source for several days. This short period test demonstrated the extracted ^{3}He^{+} beam density as well as ^{4}He^{+} beam density can reach 150 mA/cm^{2} with an energy close to 100 keV. Important beam losses and high spark rate proved the existing extraction system is not adapted for high intensity helium beam production. The divergence of the beam is really too high. Moreover the very poor low energy beam line transmission confirms the necessity of a new extraction system design.

Preliminary simulations also show the present system is not adapted. They indicate changing the plasma electrode angle could lead to a lower beam emittance. But the high divergence pushes toward more fundamental evolutions. New simulations, taking onto account realistic space charge compensation effects, will have to be done in the near future before to envisage the electrode modifications.

This experiment demonstrates the needs of the Spiral 2 project (1 mA at 60 keV) could be easily overcome. But it will be challenging to reach the beam characteristics for the projects which need high $^3He^+$ beam intensity (in the range of 100 mA).

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