Two Approaches for H^- Ion Production with 2.45 GHz Ion Sources.

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Abstract: For few years, the accelerator community requests progress to improve the development of negative hydrogen ion sources. For spallation sources like SNS or ESS, pulsed high intensity H- beams ranging few tens of milliamperes were required with duty cycle close to 10 %. New facilities like CERN ask also high performance negative ion beams. After CEA undertook an ECR based ion source program, a European network devoted to high performance negative ion source development was created. In this group, several laboratories developing 2.45 GHz ECR sources follow different approaches to increase the extracted current. At Saclay, with a solenoidal magnetic structure based on coils, close to 4 mA of H- ion beam is now extracted in pulsed mode (2 ms/100ms). At Ecole Polytechnique, on the source Camembert III, photodetatchment measurements showed comparable H- ion creation whether the primary electrons are provided by filaments or small ECR modules inserted in the plasma chamber. Both experiments as well as future plans will be reported.

INTRODUCTION

New research areas in condensed matter physics, nuclear and particles physics, accelerator driven transmutation, testing of materials, will require in a near future High Power Proton Accelerators. These accelerators need beams of several tens of megawatts (few tens of mA at energy as high as few GeV). Among all these projects some, like Spallation Sources (ESS or SNS) or the Neutrino Factory at CERN, should use negative hydrogen ions produced in a Negative Ion Source (NIS). The negative ions produced by the source are accelerated in a LINAC and injected into compressor rings. These future machines will need long pulses of negative ions, with a reliability not yet reached at such currents. The emittance of the source should be as low as possible, in order to match the beam to the pre-accelerator (less than 0.2 pi mm-mrad rms normalized). Moreover the pulses should be perfectly reproducible and noiseless. An advance is therefore necessary in order to increase both the levels of currents delivered by the negative ion sources, and their reliability.
At present time, no NIS is able to fulfil all the requirements of the next generation of accelerators. To respond to the technical challenge given by the next generation of High Power Accelerators concerning the production of the beam and the Negative Ion Source, a group partly financed by the European Union has been constituted. A by product of these studies is the optimisation of the existing NIS in existing research infrastructures in the European Union (Rutherford Laboratory and DESY) and a better understanding of the relevant physics. Eventually, due to a better understanding of NIS operation, further progress would be possible in another domain where NIS are of importance like neutral beam injection for Nuclear Fusion. A specific website, hosted by the Dublin University regularly reports the new steps achieved by the involved laboratories as well as updated cross section database for a hydrogen discharge.
In this European network, several teams study and upgrade existing sources in terms of extracted current, reliability and pulse length as far as possible. Moreover new techniques

which have not yet been used by accelerators are under development; ECR-type Ion Sources look promising for the next generation of High Power Accelerators.
In this framework, the CEA/Saclay and Ecole Polytechnique decided to follow different ways for 2.45 GHz source developments. At Saclay, a specific test stand has been built to study a new source based on solenoïdal magnetic configuration. Whereas Ecole Polytechnique introduced a network of 7 elementary ECR plasma sources into the existing large multicusp chamber Camembert III. This article briefly presents the sources as well as the results. Material influence or mixing gas improvements are reported. Finally, the further planned developments are presented.

DESCRIPTION OF THE EXPERIMENTAL SET-UPS

At Saclay, the source based on the ECR plasma generation is operating at 2.45 GHz [1]. Two coils are used to provide the $B_{ECR} = 875$ Gauss axial magnetic field. A protected quartz window separates the standard WR 284 rectangular waveguide plasma chamber from the 1.2 kW magnetron RF source. A three ridged transition, located at the plasma chamber entrance, allows concentrated RF field on the source axis. The water cooled plasma chamber is made of copper. The 210 mm plasma chamber length has been chosen to limit as much as possible the axial magnetic field close to the extraction zone. To avoid high energy electrons in this area, a polarized metallic grid replaces the initial magnetic filter and allows separating the H- ion production zone from the ECR plasma generator. A tunable C-shape magnetic dipole (Sep) is installed in the diagnostic box to force electron dumping on the extraction electrode. The source has been designed to produce low energy beam in pulsed mode, the source typically operates 1 to 2 ms with a 5 to 10 Hz frequency leading to a duty cycle ranging from 0.5 to 2 %. The collector and the extraction system are not water cooled.

In parallel, the ECR driven multicusp H^- ion source studied at Ecole Polytechnique consists of a two-dimensional network of seven elementary ECR plasma sources operating at 2.45 GHz [2], installed on the upper flange of the multicusp chamber Camembert III (volume 40 liter). Each plasma source is made of an annular permanent magnet and a microwave applicator, representing a coaxial line parallel to the magnetization vector. The inner conductor of the coaxial line penetrates the annular magnet. Each magnet is completely encapsulated in a stainless steel envelope and is water-cooled [3]. The maximum microwave power accepted by a single source is 200 W. The plasma is produced by the electrons accelerated in the region of ECR coupling by the microwave electric field applied via the coaxial line. The fast electrons oscillate between the two mirrors in front of the opposite poles of each magnet and drift azimuthally around it. The plasma produced by the inelastic collisions of these fast electrons diffuses away from the magnet, filling the chamber Camembert III.
In this arrangement, the source contains three distinct regions: (i) a driver region, located near the network of the seven elementary ECR sources and possibly on the perimeter of the device, in the strong multicusp magnetic field); (ii) an extraction region, which extends over the central, field-free region; (iii) a weakly magnetized region with high n^-/n_e, bounded by the plasma electrode with the extraction opening. The magnetic filtering effect is provided by the magnetic field of the elementary ECR sources and possibly by the multicusp magnetic field near the wall, which confines the fast electrons.

PLASMA ANALYSIS

Diagnostics like Langmuir probe or spectrometer located behind a view port, allow plasma analysis in the negative ion production zone at Saclay. And finally, a dipole analyzer magnet placed downstream the extraction system is used to clearly identify the extracted species.

The first metallic grid made of stainless steel was installed in 2003 and this increased instantaneously the H- ion production [4]. Since then, several grid materials as well as plasma electrode materials were tested. Tantalum or Molybdenum did not lead to any new improvements [5]. On the other hand, gas mixing recently allowed slightly enhancing the extracted H- current.

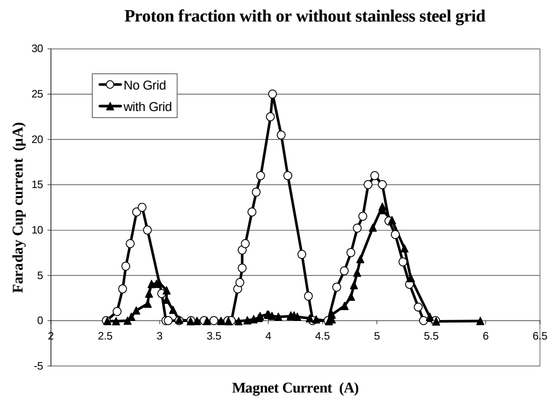

Fig. 1: Positive charge analysis (extracted current vs analyzer magnet) with or without the grid.

Langmuir probe measurements on both sides of the grid, showed significantly lower electron temperature in the H^- production zone. This electron energy reduction could explain the increase of the H^- ion current when the grid has been installed. Positive extracted charge analysis also showed the lower electron energy. The measurements indicated a very low amount of H_2^+ when the grid is installed in the chamber (Fig. 1). Like in the cold plasma where the following reaction (1) takes place, this analysis shows the H_3^+ peak becomes the highest one.

$$H_2 + H_2^+ \rightarrow H_3^+ + H + 1.71\text{eV} \qquad (1)$$

At Ecole Polytechnique, the electron temperature and density and the negative ion density (Fig. 2) were measured in the pressure range from 1 to 3 mTorr for a total applied microwave power of 1 kW (*i.e.* 140 W/antenna) and for two distances (d) from the ECR source to the probe (4.5 and 9.5 cm). Note that the electron temperature for P > 1.5 mTorr at the distance of 9.5 cm remains in the optimum range for H^- ion production, *i.e.* Te < 1 eV. The negative ion density is highest for this, larger, distance. The electron density goes up linearly with hydrogen pressure and attains, at 3 mTorr and 1 kW, 3.4×10^{10} cm^{-3}. The negative ion density also linearly increases with pressure and is not much affected by wall effects.

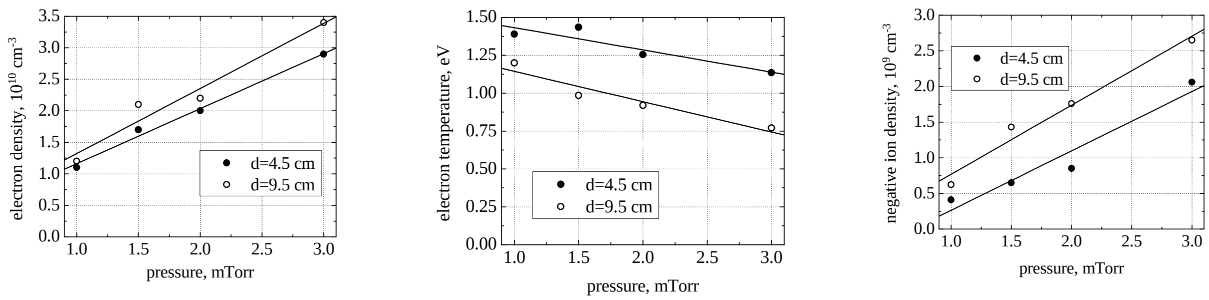

Fig. 2: Dependence of the electron temperature, electron density and negative ion density on hydrogen pressure, for two values of the distance (d) between the central minisource and the probe.

The negative ion temperature dependence on pressure is presented in Fig. 3, for the two distances d mentioned. In the case of d=9.5 cm only we found that the negative ion population contained two groups with different temperatures. The values found for these temperatures (from the two-temperature fit) are plotted in Fig. 4 versus the hydrogen pressure for an applied power of 1 kW. The average temperature (T_0) obtained from a one-temperature fit is also shown. Note that the values found for the negative ion temperature in the ECR driven source are much lower than those found in the Camembert III chamber when operated with filament discharge.

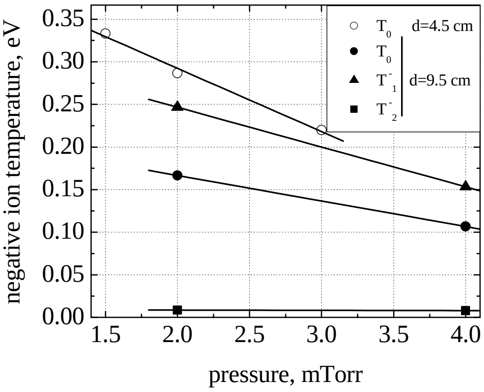

Fig. 3: Dependence on hydrogen pressure of negative ion temperature (average value) at two distances d from the ECR sources. Two temperature values found for the two H^- populations for the distance d = 9.5 cm only are also shown. Applied microwave power 1 kW.

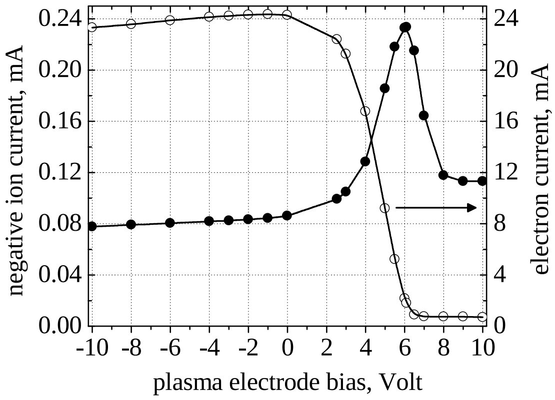

Fig. 4: Variation of the extracted negative ion current and electron current with the plasma electrode bias. Hydrogen pressure 2 mTorr. Applied microwave power 1 kW.

EXTRACTED H- IONS

There was much controversy on whether a positive or a negative plasma electrode bias was more favorable for enhancing the negative ion current. In Ref. 6 as well as in earlier reports it was shown that the negative ion current went through a maximum at a positive plasma electrode bias, approximately equal to the plasma potential. Here, at Ecole Polytechnique, we explored the operation of the source in a wide range of plasma electrode bias, both positive and negative with respect to the plasma potential (Fig. 4). Note that there is a non-negligeable negative ion current extracted even with negative bias on the plasma electrode, which is due to the effect of the positive extraction voltage. However there is no enhancement of the negative ion current compared to the value extracted at the optimum PE bias. The extracted electron current is maximum in the negative bias range. Thus, there is no advantage for this source to operate with negative plasma electrode bias.

This observation led us to consider two different modes of populating with negative ions the plasma in front of the plasma electrode.
1. In the case of negative with respect to the plasma potential PE bias the electrons oscillate in front of the plasma electrode, but are not collected by it. They produce locally negative ions, which are extracted.
2. In the case of PE bias close to the plasma potential, the electrons are collected by the plasma electrode, and the mechanism described in Ref. 6 and analyzed theoretically in Ref. 7 works: the negative ion density is enhanced in front of the plasma electrode when this region is depleted in electrons due to the positive bias and small transverse magnetic field by bringing there negative ions from the main plasma volume. The second mechanism leads under certain conditions to higher extracted negative ion currents than the first one and indeed to lower extracted electron currents.

At Saclay, we can replace the quantitative diagnostic (Faraday cup) by a qualitative one (dipole analyser) in a couple of hours. At normal pressure operation (around 2.10^{-5} Torr in the beam extraction chamber leading to around 2 mTorr in the plasma chamber) we can easily extract about 2 mA of H- ions at 6kV, collected on the Faraday cup with an entrance aperture of Ø 50 mm. The presence of H- is confirmed with the dipole analyzing magnet for the same operating tuning. The reliability of the 2 ms H- pulse is quite high and the source can operate without any human intervention for several days.

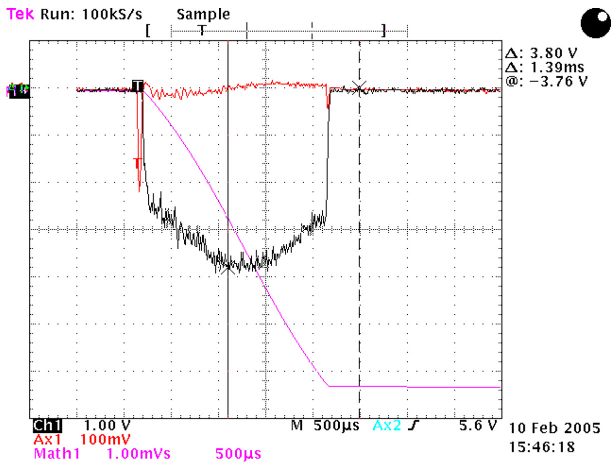

Fig. 5: Extracted pulsed beam (3.8 mA) at low pressure.

At much lower pressure 5.10^{-6} Torr in the extraction chamber, we also collected 3.8 mA of negative charges while the separator was steering the electrons (Fig. 5). At this low pressure and with the dipole analyzing magnet installed in the diagnostic chamber, we could not ignite the plasma inside the source. So we could not completely confirm so high H- ion intensity with the dipole. On the other hand the separator (C-shape dipole) was tuned on in order to deflect all electrons onto extractor electrode. We can conclude that collected negative charges are formed by negative ions which are not deflected by the Sep.

FUTURE PLANS

As in ECR sources, the cut off density is proportional to the square of the HF frequency, we can expect increasing the electronic density with a higher HF frequency and so increase collisional process that represent the first step of the H- ion production. One of the objectives of the Saclay group is to build a new NIS at 10 GHz. This new source has two main changes compared to the one in operation at present but before that we have to test those technological changes on the actual 2,45 GHz NIS.

- The present magnetic confinement realized with coils will be abandoned for a magnetic multi-cusp configuration composed by several rings of 24 permanent magnets. The magnetic configuration has been calculated and an octupole configuration has been chosen. The magnetic orientation of the magnets is perpendicular to the ring axis, thus there is no or few longitudinal magnetic component. The resonance zone at 875 Gauss lies at 32 mm from the axis. The major benefit of this kind of magnetic configuration is to reduce greatly the longitudinal magnetic field component on the source axis and thus at the extraction zone. We have designed 4 magnetic rings of different length from 20 to 50 mm long.
- In order to increase the duty cycle and eventually to work in a CW mode we need cooled beam dumps (ion collector and extraction electrode). In addition we also plan to change the actual rectangular chamber to have the possibility of changing the chamber length, in order to adapt the chamber volume to the plasma region. To fulfil all those requirements, we designed a cylindrical chamber composed of different copper rings. They include a water cooling system for higher duty cycle.

In addition, the Camembert III source will be tested in pulsed operation, in the near future, using a more powerful microwave generator. We will also test a more powerful single ECR minisource, accepting 1.5 kW cw. With the more powerful ECR minisource it will be possible to build a compact ion source useful for accelerators. Using several powerful ECR minisources it will be possible to operate a large source of interest for fusion applications.

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