Two approaches for H^- ion production with 2.45 GHz ion sources

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Abstract

Over the last few years, the accelerator community requested the development of improved negative hydrogen ion sources. For spallation sources, like SNS or ESS, pulsed high intensity H^- ion beams of a few tens of milliamperes, with a duty cycle close to 10%, are required. New facilities like CERN also ask for high performance negative ion beams. Since CEA undertook an electron cyclotron resonance (ECR)-based ion source programme, a European network devoted to high performance negative ion source development has been created.

In this group, several laboratories developing 2.45 GHz ECR sources follow different approaches to increase the extracted ion current. At Saclay, with a solenoidal magnetic structure based on coils, close to 3 mA H^- ion beam is now extracted in pulsed mode (2 ms/100 ms). A metallic biased grid separates the plasma bulk from the H^- ion production zone and significantly improves the H^- extracted current. At Ecole Polytechnique, the source Camembert III operates in continuous wave and pulsed modes. Photodetachment measurements in continuous wave mode show considerable H^- ion density (10^9–10^{10} cm^{-3}), whether the primary electrons are provided by filaments or small ECR modules inserted into the plasma chamber. Similarities and differences between the ECR-driven and the filamented source are discussed. Representative experimental results from the sources of the two laboratories as well as future plans are reported here.

1. Introduction

New research areas in condensed matter physics, nuclear and particles physics, accelerator driven transmutation, testing of materials, etc will require high power proton accelerators in the near future. These accelerators need beams of several tens of milliamperes. Among all these projects, some, like Spallation Sources (ESS or SNS) [1,2] 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 Linear Accelerator (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 ought to 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 must be perfectly reproducible and noiseless. An advance is, therefore, necessary in order to increase both the levels of currents delivered by the NISs and their reliability.

At the present time, there is no NIS able to fulfil all the aforementioned requirements for the next generation of accelerators. In order to respond to the technical challenge posed by the next generation of high power accelerators, concerning the specifications of the beam and the NIS, a group partly financed by the European Union has been constituted. A by product of these studies is the optimization of the NIS installed at existing research infrastructures in the European Union (Rutherford Laboratory and DESY [3]) 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 is of great importance, like neutral beam injection for nuclear fusion. A specific website [4], hosted by the Dublin University, regularly reports the new steps achieved by the involved laboratories as well as updated cross section database for hydrogen discharge.

In this European network, several teams study and upgrade existing sources in terms of extracted ion current, reliability and ion current pulse length. Moreover, new techniques which have not yet been used by accelerators are under development; electron cyclotron resonance (ECR)-driven ion sources look promising for the next generation of high power accelerators.

In this framework, the CEA (Saclay) and Ecole Polytechnique (Palaiseau) 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 solenoidal magnetic configuration, while at Ecole Polytechnique a network of seven elementary ECR modules was introduced into the existing large multicusp chamber Camembert III. This paper briefly presents the sources and summarizes the representative results. Finally, further future plans are presented.

2. Description of the experimental set-ups

At Saclay, the source based on the ECR plasma generation operates at 2.45 GHz [5]. Two coils are used to provide an axial magnetic field $B_{\mathrm{ECR}} = 875$ G (see figure 1(*a*)). In this field the value of the electron cyclotron frequency ω is equal to the microwave (MW) frequency ($B_{\mathrm{ECR}} = m_{\mathrm{e}} \times 2\pi \times \omega/e$, where m_{e} is the electron mass and e the electron charge). Thus, the electrons are able to be accelerated and increase their kinetic energy. A protected quartz window separates the standard WR284 rectangular waveguide plasma chamber from the 1.2 kW magnetron MW source. After the windows a three ridged transition, located at the plasma chamber entrance, allows to concentrate the MW field on the source axis. The plasma water-cooled chamber is made of copper. A length of 210 mm has been chosen for the plasma chamber in order to limit, as much as possible, the axial magnetic field close to the extraction zone. The magnetic coils are located around this chamber. To avoid high energy electrons in this area, a polarized metallic grid replaced an initial magnetic filter and allows the separation of the H^- ion production zone from the ECR plasma generation zone. The grid is connected to the plasma electrode (PE) and both are negatively biased with respect to the plasma chamber which is connected to the negative high voltage (figure 1(*b*)). 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 at 1 to 2 ms at a frequency between 5 and 10 Hz, leading to a duty cycle ranging from 0.5 to 2%. The collector and the extraction system are not water cooled.

On the other hand, the ECR-driven multicusp H^- ion source studied at Ecole Polytechnique consists of a two-dimensional network of seven elementary ECR plasma modules operating at 2.45 GHz (figure 2(*a*)) [6], installed on the upper flange of the multicusp chamber Camembert III (40 l) [7] replacing the previously used filaments (figure 2(*b*)) [8]. The MW, produced from a single 1.2 kW generator, is applied to the seven modules via a divider and coaxial cables. Each ECR plasma module is made of an annular permanent magnet and a MW 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. The maximum MW power accepted by a single module is 200 W. The plasma is produced by the electrons accelerated in the region of ECR coupling by the MW 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 seven elementary ECR modules and possibly near the cylindrical wall, 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 PE with the extraction opening. The magnetic filtering effect is provided by the magnetic field of the elementary ECR modules and possibly by the multicusp magnetic field near the cylindrical wall, which confines the fast electrons.

The extraction system (lower part of figure 2(*b*)) essentially consists of three electrodes. The first PE (plasma electrode) in contact with the plasma has a circular extraction aperture 0.8 cm in diameter. The second electrode (extractor) is located 0.62 cm from the PE and also has an opening of 0.8 cm in diameter. A pair of Sm–Co magnets is located in the extractor just behind the opening and creates a transverse magnetic field (300 G) on the beam axis, strong enough to deflect the accelerated electrons onto the extractor, as long as the extraction voltage does not exceed 5 kV. The H^- ions are barely affected by the presence of this field, which causes only a small lateral displacement of the H^- ion flux reaching the collector (the third electrode). The entire extractor is made of soft iron in order to minimize the stray magnetic fields. The plasma in front of the PE is magnetized by a weak magnetic field produced by the magnets in the extractor and due to this and to a small positive bias of the PE, large densities of volume-produced negative ions concentrate in this region [9]. The absence of electron leakage through the extractor onto the collector was verified by extracting negatively charged particles from argon plasma, which does not contain negative ions. No current was measured to the collector in this case.

The main plasma parameters are measured using a microcomputer-controlled electrostatic probe (0.5 mm diameter and 15 mm long) made of tungsten. The H^- ion density is measured by the photodetachment technique reviewed in detail in [10]. The H^- negative ion temperature was measured using the two-laser photodetachment technique. The negative ion temperature kT^- is determined from the negative ion density recovery curve after the negative ions have been destroyed by photodetachment in a small cylindrical region. The fitting technique allows us to determine the respective temperatures ($T_1^- > T_2^-$) and the fractions of the two negative ion populations [11] or an average temperature of the two populations (T_0^-), as previously reported [8, 10].

3. Plasma analysis

A Langmuir probe and an optical emission spectrometer allow plasma analysis in the negative ion production zone at Saclay. Furthermore, a dipole analyzer magnet placed downstream in the extraction system is used to identify the extracted species. A first metallic grid made of stainless steel was installed in 2003 (see figure 1(*b*)). The mesh of this grid is small enough to stop the MW propagation. It is negatively biased at the same potential as the PE. These combined features instantaneously increased the H^- ion production [12] because the negative

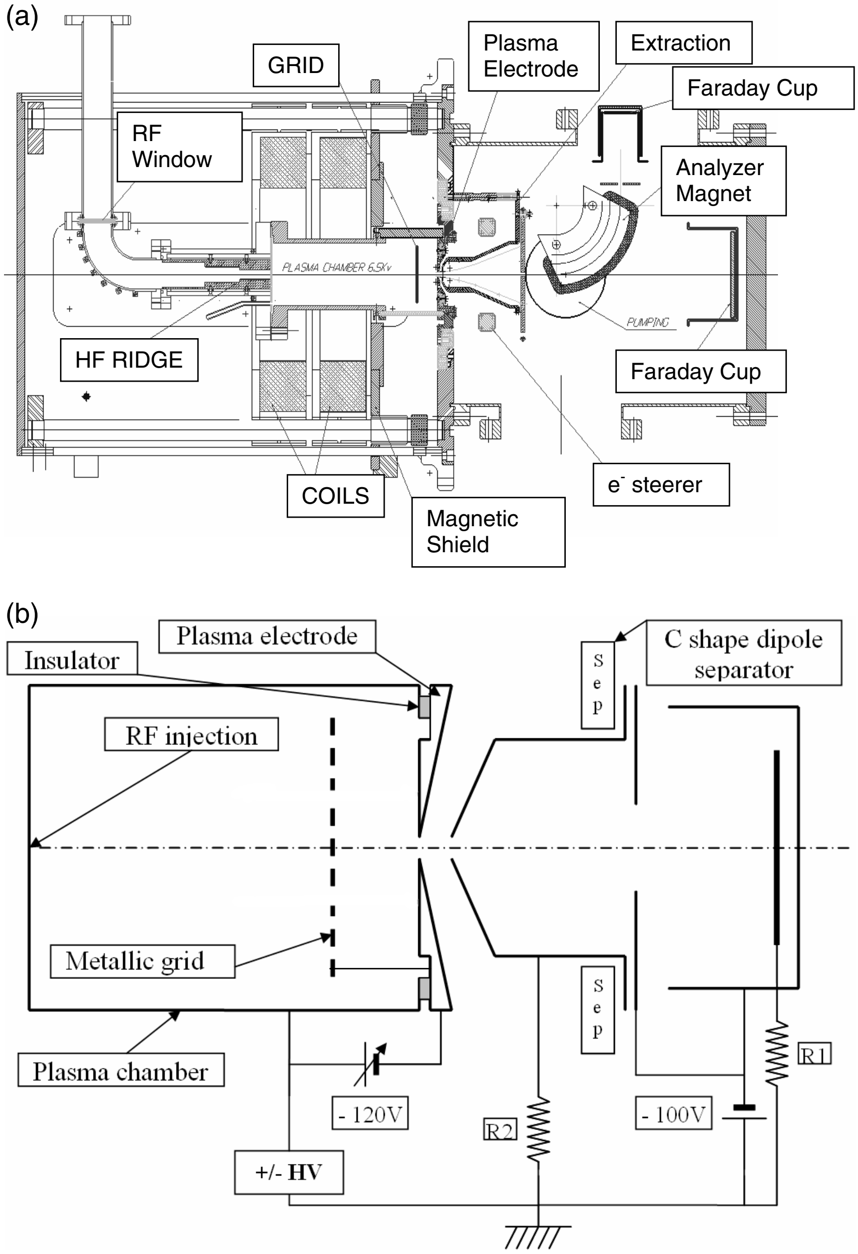

Figure 1. (*a*) General view of the ECR H^- ion source at Saclay. (*b*) Bias and connections.

bias reduces the electron kinetic energy and increases the dissociative attachment (DA) process which leads to the H^- ions formation. Since then, several materials for the grid, as well as for the PE, have been tested. Tantalum or molybdenum did not lead to further improvements [13]. On the other hand, gas mixing recently allowed slight enhancing of the extracted H^- current.

Langmuir probe measurements on both sides of the grid indicate lower electron temperature in the H^- ion production zone [5]. The derived electron temperature was measured as 6.7 eV before the grid and ranges from 3.5 to 5.3 eV in the production region behind the grid. These comparative measurements are realized in the fringe magnetic field of the coils and, consequently, the probe measurements indicate only the tendency of the plasma parameters. This electron energy reduction could explain the increased H^- ion current in the presence of the grid. Positive extracted charge analysis also indicates low electron energy. The measurements indicate a very low amount of H_2^+ when the grid is installed in the chamber (figure 3). Like in the cold plasma, where the following reaction (1) takes place, this analysis shows the H_3^+ peak becoming the highest one.

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

At Ecole Polytechnique, the electron temperature and the electron and negative ion densities (figure 4) were measured in the pressure range between 1 and 3 mTorr for a total applied MW power of 1 kW (i.e. 140 W/antenna) and for two distances d (4.5 and 9.5 cm) between the ECR source and the probe. 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,

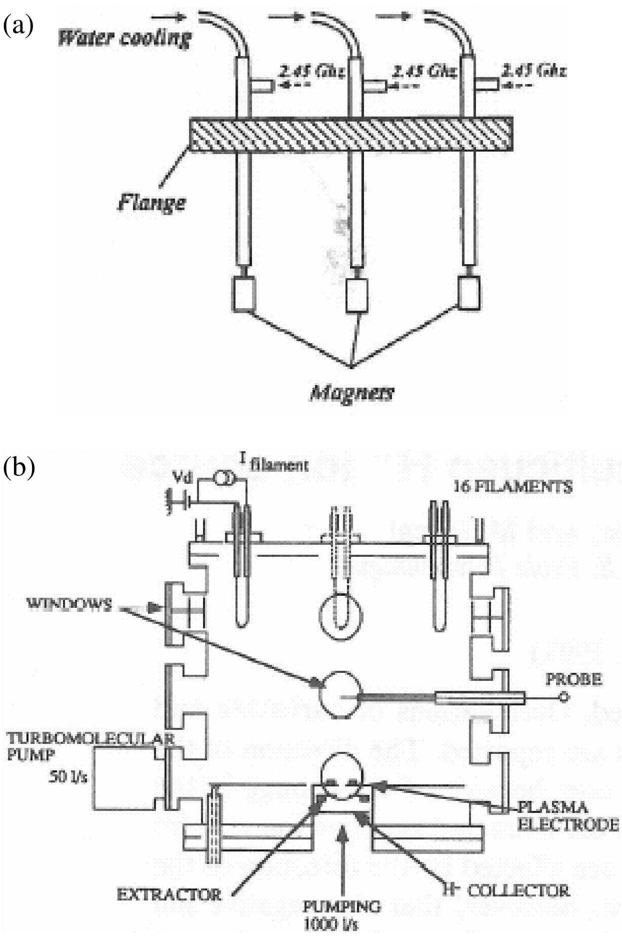

Figure 2. (*a*) General view of the upper flange of the H^- ion source at Ecole Polytechnique housing the elementary ECR modules. (*b*) General view of the chamber Camembert III at the filamented version of the source and the extraction system (lower part).

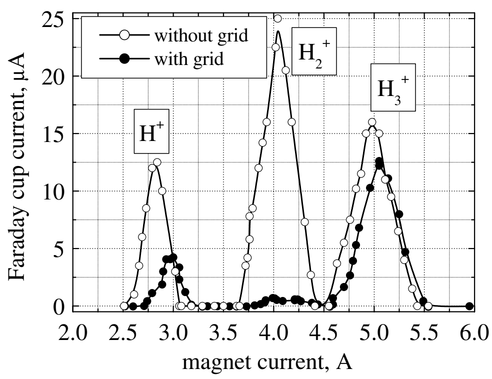

Figure 3. Positive charge analysis (extracted current versus analyzer magnet current) with/without the metallic grid at Saclay source.

i.e. $kT_e < 1$ 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, 3.4×10^{10} cm^{-3}. The negative ion density also linearly increases with pressure up to 3 mTorr and is not much affected by the modification of the wall surface state by the deposition of a fresh tantalum film (which we designate as *wall effect*). Further pressure increase leads to a maximum negative ion density, obtained at a pressure of 4–5 mTorr. This value is somewhat higher than observed in the filamented Camembert III, where this optimum pressure was only 2 mTorr [8], under similar power conditions. The negative ion temperature dependence on pressure is presented in figure 4(*d*), for the two distances mentioned. In the case of $d = 9.5$ cm two negative ion groups with different temperatures are present. The values found for these temperatures (from the two-temperature fit) are plotted versus the hydrogen pressure in figure 4(*d*) for an applied power of 1 kW. The average temperature (T_0^-) obtained from the one-temperature fit is also shown. Note that the values found for the temperature of both populations in the ECR-driven source are lower than those found in the Camembert III chamber operated as a filamented source in the same pressure range ($kT_1^- \sim 0.5$ eV and $kT_2^- \sim 0.05$ eV [7]). When $d = 4.5$ cm, only a single negative ion population is found.

4. Extracted H^- ion currents

There was much controversy on whether a positive or a negative PE bias is more favourable for enhancing the negative ion extracted current. In [9], as well as in other reports, it is shown that the negative ion current goes through a maximum at a positive PE bias, approximately equal to the plasma potential. At Ecole Polytechnique, the operation of the source in a wide range of PE bias, both positive and negative with respect to the plasma potential, has been explored (figure 5). Note that there is a non-negligible negative ion current extracted even with negative bias on the PE, which is due to the effect of the positive extraction voltage. However, there is no enhancement of the negative ion current compared with 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 PE bias.

This observation led us to consider two different modes of populating the plasma with negative ions in front of the PE:

1. In the case of negative, with respect to the plasma potential, PE bias the electrons oscillate in front of the PE, 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 PE, and the mechanism described and analysed theoretically in [9, 14, 15] takes place: the electron density in front of the plasma grid is depleted by the positive PE bias and the small transverse magnetic field. Negative ions diffuse into this region from the main plasma volume and enhance the local negative ion density.

Unlike the negative ion density in the centre of the source, the extracted negative ion current is affected by the *wall effect* [16–18], mentioned in section 3 and described in section 5.

At Saclay, the quantitative diagnostic (Faraday cup) can be replaced by a qualitative one (dipole analyzer) in a couple of hours. At normal pressure operation ($\sim 2.10^{-5}$ Torr in the beam extraction chamber corresponding to ~ 2 mTorr in the plasma chamber) about 2 mA of H^- ions at 6 kV can easily be extracted. These ions are collected on the Faraday cup through an entrance aperture of Ø 50 mm. The presence of H^-

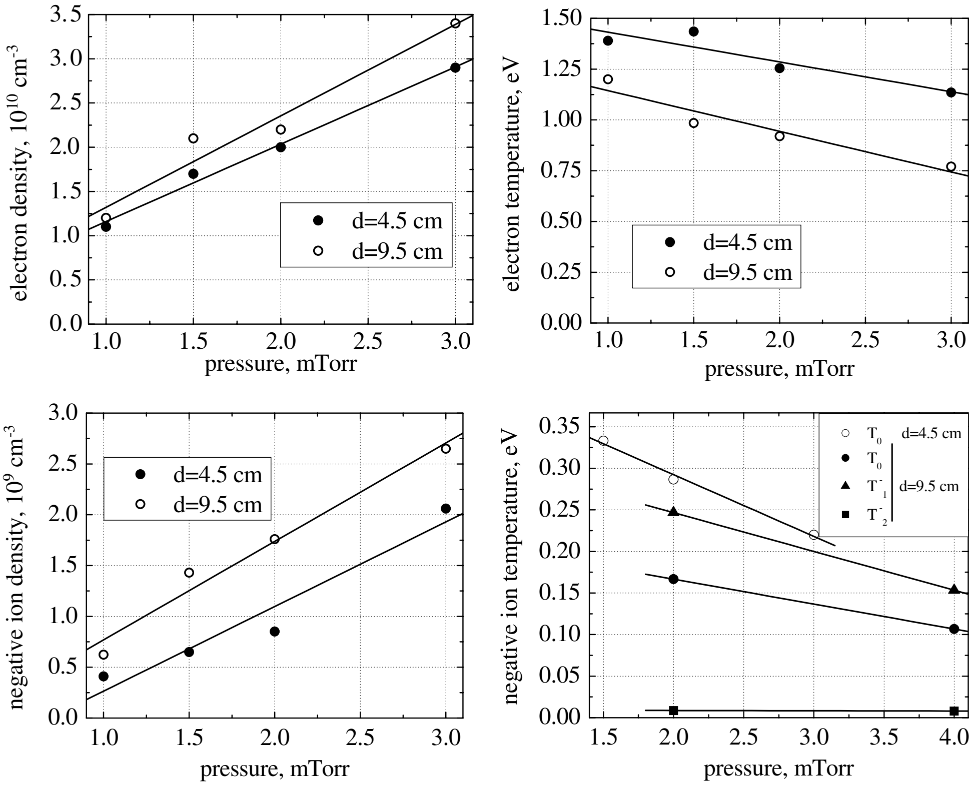

Figure 4. Dependence of the (*a*) electron density, (*b*) electron temperature, (*c*) negative ion density and (*d*) negative ion temperature on the hydrogen pressure, for two distances *d* between the central elementary ECR module and the electrostatic probe at Ecole polytechnique source. Two temperature values for the two H^- populations were found only for the distance of 9.5 cm.

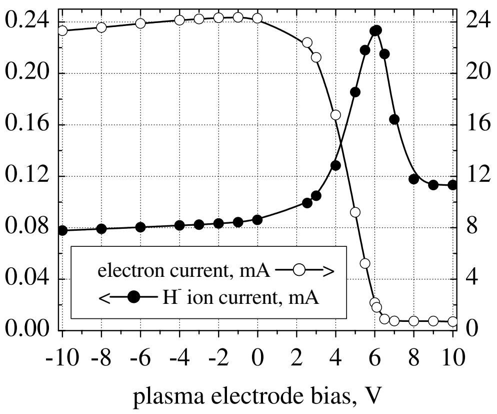

Figure 5. H^- ion and electron extracted currents at Ecole Polytechnique source versus the PE bias (2 mTorr, 1 kW, 2 kV extraction voltage).

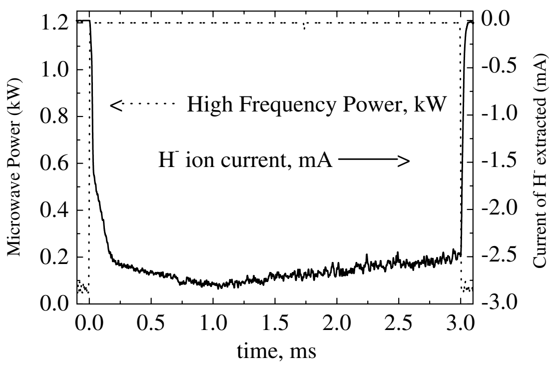

Figure 6. H^- ion extracted current at Saclay source during 3 ms MW pulse ($\sim 5.10^{-3}$ mTorr, 1.2 kW, 9 kV extraction voltage, pulse period 100 ms).

is confirmed with the dipole analyzing magnet under the same conditions. The source reliability has been checked in pulsed mode (2 ms with a repetition rate of 100 ms) during five days and a continuous operation without any human intervention has been achieved.

At much lower pressure in the extraction chamber ($\sim 5.10^{-3}$ mTorr), 2.8 mA of negative charges are collected (figure 6), while the separator steers the electrons. At this low pressure, and with the dipole analysing magnet installed in the diagnostic chamber, the ignition of the plasma inside the source is not possible. Thus, the high H^- ion intensity cannot be confirmed using the dipole analyzer. On the other hand, the separator (C-shape dipole) is tuned on in order to deflect all electrons onto the extraction electrode. We assume that the collected negative charges are formed by negative ions which are not deflected by the separator.

5. Discussion

The operation of Camembert III has several general features, independently or whether operated with filaments or with the present ECR modules.

(i) The required applied discharge power and MW power to obtain the same negative ion density is similar.

(ii) The electron temperatures are similar, for equal applied power and gas pressure.
(iii) The phenomena near the PE in the presence of the same weak transverse magnetic field are similar, i.e. optimum negative ion current is obtained for a positive PE bias, close to the plasma potential.

Several differences can be mentioned.

(i) The operation with filaments has the advantage, in the case of volume production operation, of renewing the metal film deposited on the walls. This enhances considerably the negative ion density in the centre of the source (the *wall effect*) [17], probably due to recombinative desorption of vibrationally excited molecules [18]. However, this is a major disadvantage in the case of surface production, since the fresh metal deposit covers the cesium film.
(ii) A higher optimum gas pressure was observed with the ECR modules. This may be related to the lower gas temperature, without the hot filaments, leading to lower V–T transfer destruction of vibrationally excited molecules.
(iii) A lower negative ion temperature was observed with the ECR modules. The lower temperature of the hot population is probably related to the lower sheaths[3] around the ECR modules, compared with those around the filaments. A more detailed investigation of these sheaths, as well as of the gas temperature, has to be performed to verify these explanations.

6. Future plans

As in the ECR sources the cut off density is proportional to the square of the high frequency ω_{HF} multiplied by the electronic temperature ($n_e \approx T_e \times \omega_{HF}^2$), one expects increased electronic density with a higher frequency and, thus, increased collisional process that represents 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 will have two main differences compared with the one being in operation at the present time. These technological modifications are as follows and, first of all, have to be tested on the present 2.45 GHz NIS.

1. The present magnetic confinement, obtained with coils, is to be replaced by a magnetic multicusp configuration composed of several rings, each of which contains 24 permanent magnets. Solenoid coils produce a too high longitudinal magnetic field at the extraction region. The new magnetic configuration has been calculated and an octupole configuration has been chosen. The magnetic orientation of the magnets corresponds to a Halbach configuration perpendicular to the ring axis. The major benefit of this kind of magnetic configuration is the important reduction of the longitudinal magnetic field component on the source axis and, thus, at the extraction zone.

2. In addition one plans to change the present rectangular chamber (WR284 guide) to have the possibility of changing the chamber length, in order to adapt the chamber volume to the plasma region.

[3] The sheath is a non-neutral structure at the plasma border which allows to preserve the neutrality inside the plasma by regulating the fluxes at its periphery.

To fulfil all these requirements, a cylindrical chamber, including a water cooling system for higher duty cycle, has been designed.

At Ecole Polytechnique, the ECR-driven version of the Camembert III source will be tested in pulsed operation up to 6 kW. A more powerful ECR module, capable of supporting 1.2 kW in continuous wave operation, is tested. This ECR module is similar to that being used now. In order to achieve higher power operation, the MW are applied using a WR340 standard guide instead of the coaxial cables used with the present, smaller (200 W) modules. This ECR module, or a network of them, could be installed into accelerator or fusion ion sources in a compact design avoiding the use of filaments. Finally, the extracted H^- current and the negative ion density near the PE, in the ECR-driven Camembert source III, will be compared, as has been done in the filamented version of the source [9, 15].

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