ECR Light Ion Sources at CEA/Saclay *

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Abstract In the beginning of the 90s, T. Taylor and his collaborators demonstrated ECR sources operating at low frequency (i.e. 2.45GHz) are able to produce very intense single charge light ion beams.

At CEA/Saclay, the SILHI source developments started in 1995. Since 1997 more than 100mA proton or deuteron beams are routinely produced in pulsed or continuous mode. To comply with ADS reliability constraint, important improvements have been performed to increase the installation reliability. Moreover, to optimize the beam transport in the low energy beam line, the extraction system was carefully designed and space charge compensation studies were undertaken. An important step has been reached in 2005 with the development of a permanent magnet source able to produce a total beam of 109mA at 85kV.

A new test bench named BETSI, especially dedicated to permanent magnet source developments, is presently under construction. It will allow analysing positive or negative extracted beams up to 50keV and 100mA.

In addition, for several years work has been done to optimize the production of negative hydrogen ion beam with such an ECR source. Recent analysis pushed towards the construction of a new set up based on a multicusp magnetic configuration.

After a brief overview of the CEA/Saclay source developments, this article will point out on the recent results and present status.

Key words high intensity, 2.45GHz, space charge compensation

1 Introduction

Following the Chalk River laboratory[1], several institutes or companies, all around the world, are presently working on production of intense light ion beams. These positive beams (CW or pulsed) are mostly extracted from ECR sources operating at low frequency (i.e. 2.45GHz) using only axial magnetic structure (no multipolar radial confinement).

In France, the Spiral 2 project dedicated to radioactive beam production is based on a 40MeV CW deuteron Linac[2]. Moreover, the high intensity light ion source (SILHI) which is an ECR ion source operating at 2.45GHz, produces high intensity (over 100mA) proton or deuteron beams at 95keV, for several years (see section 2). This source was developed in the 90's, in the framework of High Power Proton Accelerator (HPPA) studies. At that time, CEA and CNRS decided to build the IPHI (High Intensity Proton Injector) low energy beam demonstrator. The obtained SILHI performance encouraged us to propose a permanent magnet source based on the same principle to fit in with the injector of the Spiral 2 project. To produce the requested 5mA D^+ beam at 40keV (with rms normalized emittance lower than 0.2π·mm·mrad), the plasma electrode diameter was

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reduced from 9 to 3mm (see section 3). A specific test bench dedicated to permanent magnet source studies is presently under construction.

In parallel, a negative ion source, also based on ECR plasma generator, has been built at CEA/Saclay. Presently, few mA of hydrogen negative ions are now regularly extracted in pulse mode (section 4).

2 SILHI: high intensity light ion source

SILHI is an ECR ion source operating at 2.45 or 3GHz. The RF power is produced either by a 1.2kW magnetron source or a 1.0kW klystron and injected into the source via standard rectangular wave-guides with a four stub automatic tuning system and a three section ridged wave-guide transition. A 5-electrode extraction system allows beam losses limitation and the source currently produces beam intensity higher than 120mA with a proton fraction close to 85%. As demonstrated by T. Taylor[1], the higher plasma density is observed when ECR resonance zones occur at both extremities of the plasma chamber (on the boron nitride disks)[3]. In this case, the maximum magnetic field reaches close to 0.1T. To optimize the beam stability, the SILHI source routinely runs with only one ECR zone located at the RF entrance in the plasma chamber, the second ECR zone being located in the extraction system.

In order to comply with HPPAs reliability requirements (especially in the framework of ADS studies), the following technical choices were adopted to minimize breakdown number:

- Quartz window protected behind a water cooled bend

- Electrode shape optimization to minimize the electric field and the spark rate

- Large safety margins on all Power Supplies (HV and others)

- Optimization of Power Supplies air or water cooling

- Separate cable path and shielding for signals and power

- Galvanic insulation of analog and digital signals

- Use of EMI hardened devices especially for all sensitive electronics and PLC

- Development of beam current feedback

- Development of EPICS automatic start/restart procedures

- Development of specific beam diagnostics.

Such choices allowed reliability as high as 99.8% obtained during a continuous 162 hour long run test while the source was producing 114mA total current. Otherwise, for ADS program, sub-criticality reactor measurements should require frequent short beam “holes”. While the SILHI source was producing 80mA beam at 95keV, in CW mode, 300μs beam “holes” have been obtained with 1Hz and 5Hz repetition rates. As shown on Fig. 1, the fall time and rise time turn out to be 20 to 30μs.

On the other hand, high intensity (few 10mA) beam transport has to be carefully studied in order to fulfill the beam characteristics required at the following accelerator cavity entrance. The complexity of high intensity beam dynamics is mainly due to nonlinear space charge effects. When such beam interacts with residual gas, space charge compensation occurs. When H^+ beam interacts with hydrogen residual gas, electrons and H_2^+ ions are produced. In transit gaps, where no magnetic or electric field influences the particles, electrons are trapped in the beam and positive ions are repelled to the walls As a result, reduction of space charge effects occurs. Theoretical analysis indicates space charge compensation is greatly affected in the LEBT solenoids[4]. In the solenoids, both secondary ions and electrons are confined in the beam. And in the fringe field of solenoids, electrons are attracted toward the solenoid centre whereas the secondary ions tend to be repelled toward the pipe. As confirmed by experimental measurements (emittance analysis or space charge measurement with 4 grid analyzer), the theoretical study shows the beam potential remains important in some areas. SILHI LEBT space charge compensation measurements also showed the important contribution of secondary electrons. These secondary electrons are mainly produced by means of beam losses on the walls, interceptive diagnostics or gas adding. For example, a small amount of heavy gas (N_2, Ar or Kr) allows better space charge compensation and allows minimizing the emittance[5, 6].

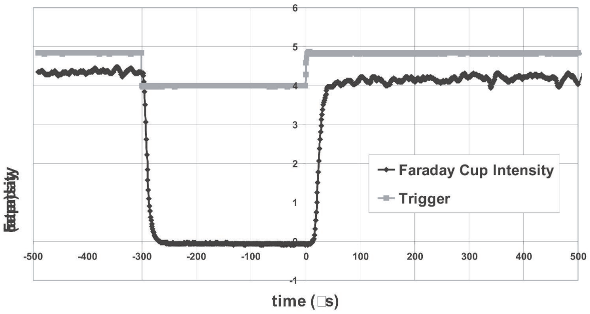

Fig. 1. 300μs – 5Hz short “holes” in CW mode for ADS sub-criticality control.

Such a source, producing more than 80% of H+ or D+ fraction species, also produces close to 20% of undesired particles (mainly molecular ions, H_2^+ or H_3^+). So to avoid impurities enter into the RFQ, a special cone, shaped with angle equal to the H^+ beam theoretical convergence has been designed. This cone is now installed close downstream the second solenoid and a home made routine, allows tuning solenoids and steerers in order to improve the beam matching through the cone. Optical diagnostics using Doppler shift effect (intensified CCD camera and spectrometer) showed only H^+ ions compose the beam analyzed downstream the cone.

3 Permanent magnet sources

For the SPIRAL 2 facility which will be built at GANIL in Caen, the neutron flow will be produced by interaction of deuteron beam with a Carbon target. The source will have to produce a cw 5mA D^+ beam at 40keV. So a new ECR source equipped with a Φ3mm extraction hole has been built with a permanent magnet assembly. 3 rings made of 24 magnets provide the expected axial field in good agreement with calculations. Appropriate magnetic shielding allows stopping Penning discharge in the extraction area. And a specific plasma chamber pumping system helps to minimize unexpected impurities. Then the source was installed on the Silhi accelerator column and the extracted deuteron beam was characterized in the 2 solenoid LEBT. The source performance[7] fully satisfies the Spiral 2 injector requirements with a maximum D^+ beam close to 7mA. Fig. 2 shows only 700W RF injected power is needed to get the expected 5mA D^+ beam. As Spiral 2 installation plans to also accelerate heavy ions, a long LEBT is under study. It will be composed of 1 solenoid, 2 dipoles and several quadrupoles. Classical diagnostics (Faraday cups, profilers, emittance measurement unit) will allow beam transport and matching at the entrance of the RFQ.

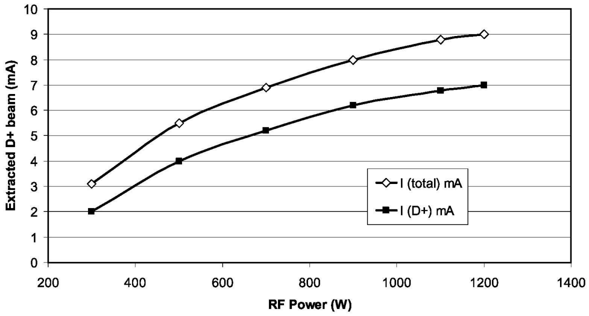

Fig. 2. $D^+$and total extracted beam vs RF power.

After the deuteron beam characterization, to test the high intensity capability of such a permanent magnet source, the Silhi plasma electrode (Φ9mm) has been installed on the plasma chamber. The total extracted beam intensity easily reached more than 100mA with 90keV energy while the source was fed with hydrogen gas. Moreover, the high reliability (only 1 beam off of 20s) of such a source has been confirmed with a 216 hour run test while the source was producing 85mA beam at 80kV.

Performance of low frequency permanent magnet sources are now confirmed in several laboratories[8, 9]. At Saclay, a specific test bench (Fig. 3) named BETSI is under construction for such source optimization. It will allow 50keV beam characterization (up to 120mA) with a 104° dipole and diagnostics like Faraday cup, Toroids, Profiler and emittance scanner. Smaller permanent magnet structure and smaller plasma chamber different RF injection systems will be tested. Moreover, a theoretical study of the injected RF power and plasma interaction is presently in progress. Experimental plasma and beam analysis are planned to validate the numerical simulations.

4 Negative ion production

Several HPPA applications using compressor ring, like neutron sources or neutrino factories, require H- accelerated ions. The injection efficiency is largely higher with negative ions than with positive ions. These installations operate in pulse mode. As the future machine goals are largely higher than the performance of the existing ones, important developments are presently in progress all around the world. For example, CEA/Saclay has undertaken a specific program on H- ion source development. For several years, the ECRIN source, built with SILHI spare parts and operating at 2.45GHz was developed In the framework of the HP-NIS program supported by European Community. The first effective pulsed H- ion beam (1mA — 10keV, 2ms at 10Hz) was produced when the original magnetic filter has been replaced by a polarized grid inserted in the plasma chamber. Then several tunings and tests (grid and plasma electrode material, gas mixing, production zone geometry with and without collar) have been performed in order to improve the negative ion beam. Moreover, negative extracted charge current (electrons and H- ions) has been analysed while the electron steerer was plotted. As a result, the source performance looks limited by transverse magnetic field simultaneously provided by coils and steerer[10], as confirmed by magnetic measurements. Such observation pushed us to study a permanent magnet multipolar structure in Halbach geometry to replace the source coils. To enlarge source tuning possibilities, an octupuar structure, made of several rings (4, 5, 6 and 7cm long) has been chosen and a modular plasma chamber will also be tested. This will allow varying independently the plasma chamber and the magnetic structure length. Recent magnetic measurements confirmed the ECR zone is located at $r = 33$mm. Moreover, this magnetic structure has been installed around the SILHI plasma chamber, replacing the coils. The positive extracted intensity only reached 15mA to be compared with the routinely produced 120mA beam. This proves the plasma density is low on the axis of the source and looks promising for H- production.

As the BETSI test bench presently under construction will allow positive and negative ion extraction, this negative ion source will be tested in the near future. The dipole will greatly help the characterisation of the negative ion beam. Of course a specific extraction system will allow electron separation at low energy. Up to now, with the ECRIN source, the maximum H^- extracted current reached 4mA at 10keV[11]. As very efficient negative ion sources operating with RF antenna or filaments work with multi cusp magnetic structure, important improvement is expected with this new magnetic arrangement.

5 Conclusion

The first Saclay ECR light ion source currently produced 100mA of H^+ beam for several years with good performance in term of reliability, stability, beam noise, emittance... The proton beam, guided in the 2 solenoid LEBT, is now ready to be injected into the IPHI RFQ. Moreover, recent developments allow us to produce such high intensity beams with a permanent magnet source. The BETSI test bench, presently under construction, will allow improving the magnetic structure and RF injection. For the Spiral 2 project, the D^+ source construction and transport beam line will start at the beginning of 2007. On the other hand, high intensity H^- ion beam production looks difficult with this kind of source but few mA are routinely produced in pulsed mode. Future developments, specifically theoretical and experimental RF injected power and plasma interaction study, will allow a better understanding of the different sources and help for the design of new installations. To conclude, such ECR light ion sources are really powerful and efficiently fit in with the HPPAs requests.

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