ECR Light Ion Sources at CEA/Saclay

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Abstract. In the beginning of the 90s, T. Taylor and his collaborators demonstrated the production of intense single charge light ion beams with ECR sources operating at low frequency (i.e. 2.45 GHz). At CEA/Saclay, the SILHI source developments started in 1995. Since 1997 more than 100 mA 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 109 mA at 85 kV.

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 50 keV and 100 mA.

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 describe the recent results and present status.

Key words: High intensity, 2.45 GHz, space charge compensation

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1 Introduction

Following the Chalk River laboratory [1], several institutes or companies, 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. 2.45 GHz) using only axial magnetic structure (no multipolar radial confinement).

In France, the high intensity light ion source (SILHI) which is an ECR ion source operating at 2.45 GHz, produces high intensity (over 100 mA) proton or deuteron beams at 95 keV, (see section 2). This source has been 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. Moreover, the Spiral 2 project dedicated to radioactive beam production is based on a 40 MeV CW deuteron Linac [2]. SILHI performance encouraged us to propose a simplified source to fit in the injector of this new project. In fact, the magnetic field is provided by permanent magnets instead of coils. In addition, to produce the requested 5 mA D^+ beam at 40 keV (with rms normalized emittance lower than 0.2 π mm.mrad), the plasma electrode diameter is reduced from 9 to 3 mm (see section 3). A specific test bench dedicated to permanent magnet source studies is 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 3 GHz. The RF power is produced either by a 1.2 kW magnetron source or a 1.0 kW klystron and injected into the source via standard rectangular wave-guides with an automatic four-stub tuning system and a three-section ridged wave-guide transition. A five-electrode extraction system allows limiting beam losses and backstreaming electrons. This source was built in 1995 and now it currently produces beam intensity higher than 120 mA 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 rises close to 0.1 T in the middle of the 100 mm long plasma chamber. 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 HPPA reliability requirements (especially in the framework of ADS studies), the following technical choices were adopted to minimize the breakdown number:

- RF injection quartz window protected behind a water cooled bend.
- Electrode shape optimization to minimize the electric field and the spark rate.
- Large safety margins (> 20 %) 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.

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

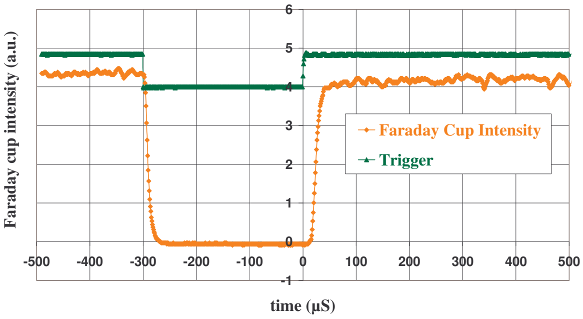

Fig. 1: 300 µs – 5 Hz short "holes" in CW mode for ADS sub-criticality control.

On the other hand, high intensity (few 10 mA) 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 non-linear space charge effects. 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 toward the walls The result is a reduction of the space charge effects. Theoretical analysis indicates the space charge compensation is greatly affected in the LEBT solenoids [4] where 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. Moreover, a small amount of heavy gas (N_2, Ar or Kr) allows minimizing the emittance [5, 6].

Such a source also produces close to 20 % of undesired particles (mainly molecular ions, H_2^+ or H_3^+, D_2^+ or D_3^+). So to avoid the injection of pollutants 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 magnetic steerers in order to improve the beam matching through the cone. Optical diagnostics based on Doppler shift effect (intensified CCD camera and spectrometer) allow species fraction analysis. Recent measurements showed only H^+ ions compose the beam analyzed downstream the cone. As a result, by using the routine, more than 85 % transmission through the cone (93 mA at the LEBT beam dump while the source exit DCCT indicated 109 mA total extracted beam) has been obtained.

3 Permanent magnet sources

For the SPIRAL 2 facility which will be built at GANIL, the neutron flow will be produced by interaction of deuteron beam with a Carbon target. The source will have to produce a CW 5 mA D^+ beam at 40 keV. So a new ECR source equipped with a 3 mm diameter extraction hole has been built with a permanent magnet assembly. Three rings made of 24 magnets provide the expected axial field in a good agreement with calculations. Appropriate magnetic shielding allows stopping Penning discharge in the extraction area. And a specific pumping system of the plasma chamber 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 7 mA. Figure 2 shows that only 700 W RF injected power is needed to get the expected 5 mA 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.

After the Spiral 2 beam characterization, in order to test the high intensity capability of such a permanent magnet source, the SILHI plasma electrode

(Φ 9 mm) has been installed on the plasma chamber. The total extracted beam intensity easily reached more than 100 mA with 90 keV energy while the source was fed with hydrogen gas. Moreover, the high reliability (only 1 beam off during 20 seconds) of such a source has been confirmed with a 216 hour test run while the source was producing 85 mA beam at 80 kV.

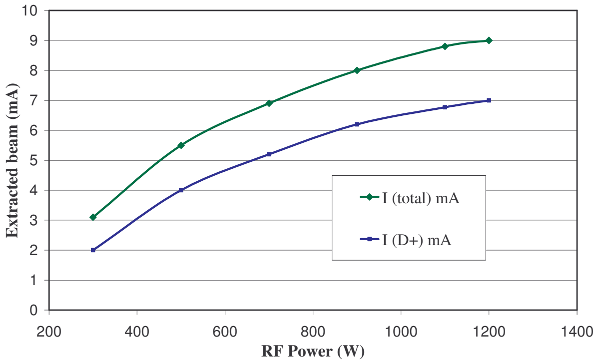

Fig. 2. D^+ and total extracted beam vs RF power

Performance of low frequency permanent magnet sources has been confirmed in several laboratories [8, 9]. At Saclay, a Test Bench for Ion Source Studies (BETSI) is under construction for such source optimization. It will allow 50 keV beam characterization (up to 120 mA) with a 104 ° dipole and diagnostics like Faraday cup, Toroids, Profiler and emittance scanner. Smaller permanent magnet structure and smaller plasma chamber will be tested as well as different RF injection systems. 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 these numerical simulations.

4 Negative ion production

Several HPPA applications using a compressor ring, like neutron sources or neutrino factories, require H- ions. In such rings, 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. For instance, 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 2.45 GHz was developed in the framework of the HP-NIS program supported by European Union. The first effective pulsed H- ion beam (1 mA – 10 keV, 2 ms at 10 Hz) 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 versus the electron steerer current. As a result, the source performance looks limited by the 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 octupolar structure, made of several rings (4, 5, 6 and 7 cm 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 that 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 15 mA to be compared with the routinely produced 120 mA beam. This proves that 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 4 mA at 10 keV [11]. As very efficient negative ion sources operating with RF antenna or filaments work with multi cusp magnetic structure, an important improvement is expected with this new magnetic arrangement.

5 Conclusion

The first Saclay ECR light ion source currently produced 100 mA 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 will start at the beginning of 2007 and then this source will be characterized on the BETSI installation. 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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