LIGHT ION ECR SOURCES STATE OF THE ART FOR LINACS

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Abstract

Since the middle of the 90's development of high intensity light ion injectors are undertaken at CEA-Saclay. The first 100 mA proton beam has been produced by the SILHI ECR source in the framework of the IPHI project. Ever since, more than 100 mA of protons or deuteron beams, with high purities, have been regularly produced in pulsed or continuous mode, and with very good beam characteristics analyzed in dedicated beam diagnostics. CEA-Saclay is currently involved in several high intensity LINAC projects such as Spiral2, IFMIF-EVEDA and FAIR, and is in charge of their source and LEBT design and construction.

This article reports the latest developments and experimental results carried out at CEA-Saclay for the 3 projects. In addition, a review of the developments and beam results performed in other laboratories worldwide are also presented.

INTRODUCTION

For several decades numerous projects are based on high intensity beam interaction with different targets, either for industrial applications or research facilities. High intensity light ion beam projects are often ranked in the HPPA (High Power Proton Accelerator) family. Table 1 gives a list of worldwide research facility projects based on positive ions. One could note, numerous projects based on negative ion production (mainly H-) also exist and are not listed here.

Table 1: List of several HPPA around the world

	Particles	Intensity	Pulse length	Repetition	Duty Factor	Emittance
	p/d/H-	mA	ms	Hz	%	π mm.mad
LEDA	H^+	100	CW	-	100	0.25
IPHI*	H^+	100	CW	-	100	0.25
TRASCO	H^+	30	CW	-	100	0.2
SARAF	H^+, D^+	2	CW	-	100	0.2
IFMIF*	D^+	140	CW	-	100	0.25
Spiral2*	H^+, D^+	5	CW	-	100	0.25
PEFP	H^+	20	2		8-20	
MYRRHA	H^+	10/25	CW	-	100	0.25
Chinese ADS	H^+	10	CW	-	100	
FAIR*	H^+	100	1	4	0.4	0.3
ImPUF	H^+, D^+	5	CW	-	100	
ESS	H^+	60/90	2.9	14	4	0.3

Like for all ion accelerators, the general lay out (fig. 1) shows the first element of such HPPA is the ion source. The ion source has to provide the requested beam with characteristics giving the best conditions to inject the beam into the1st accelerating cavity. Thus the source has to be designed to minimize the beam emittance. The 1st accelerating cavity is generally an RFQ (Radiofrequency Quadrupole) which bunches and accelerates the beam up to few MeV. A LEBT (Low energy Beam Transport), follows the source and allows matching the beam at the entrance of the RFQ. As shown in table 1, the requested rms normalized emittance value turns out to be 0.25 π.mm.mrad at the RFQ entrance. As a consequence, for an HPPA, while designing an injector, one has to consider not only the source but the ion source, the extraction system and the LEBT as a whole[1].

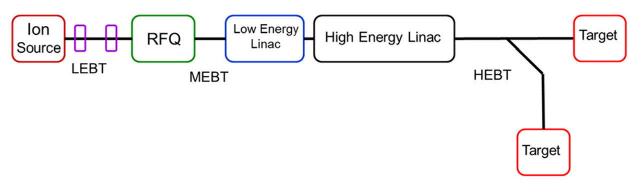

Figure 1: Schematic lay out of a high intensity Linac

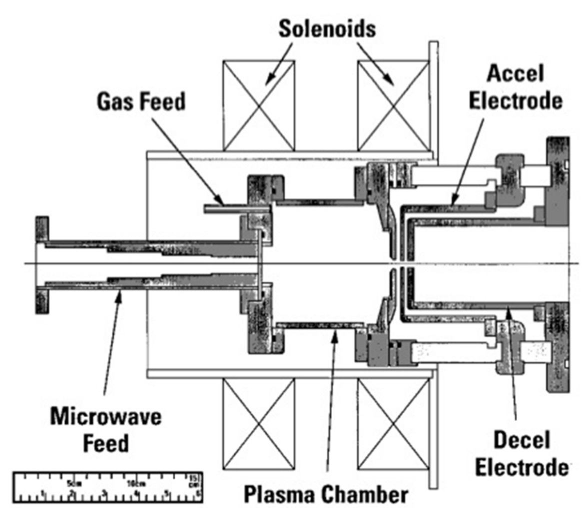

Figure 2: 1st ECR ion source dedicated to HPPA, developed in Chalk River

Then, after the RFQ, the main part of the accelerator consists of a long string of cavities (generally superconducting cavities) separated by matching sections and equipped with well-adapted diagnostics.

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One of the main requests for the HPPA, mainly for ADS (Accelerator Driven System) is the reliability and the reproducibility. Such demands push injector designers to use well-known reliable sources which are ECRIS (Electron Cyclotron Resonance Ion Source). An ECRIS source has to satisfy the equation:

$$\omega = e B / m$$

where: ω = pulsation, e = electron charge, B = magnetic field and m = electron mass.

The 1st ECR ion source dedicated to high intensity proton facility has been developed in Chalk River by Taylor and Mouris [2] at the beginning of 90's. One can consider now such a source as an "ECR ion source" as it has been demonstrated the plasma density is increased with an ECR zone into the plasma chamber. Few years later, the Chalk River source has been moved to Los Alamos where a new version has been developed for the LEDA project. This new source, equipped with a 4 electrode extraction system, allowed injecting and accelerating a 75 mA - 6.7 MeV beam after the RFQ.

GENERAL ASSESSMENTS

Since then, the Chalk River source has often been taken as reference for the design of the new sources around the world.

The source design is generally based on a 2.45 GHz frequency generator which transfers the RF power to the plasma chamber via waveguides and RF window. For such a frequency, the electron resonance occurs when the magnetic field reaches 875 Gauss in the plasma chamber.

A multi-electrode (3, 4 or 5 electrodes) system (accel – decel) is used for the beam extraction. Different codes allow simulating particles trajectories in the extraction system and minimizing the emittance at the very beginning of the accelerator. For beam transport at low energy, codes have also to take into account the space charge compensation.

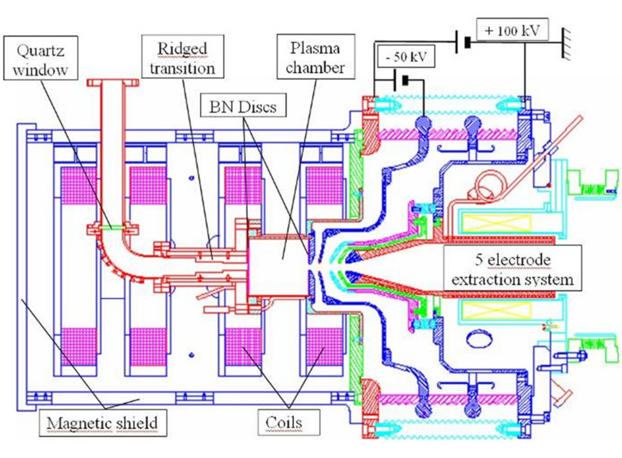

Figure 3: SILHI source design with BN disks, Electron repeller, Window protected by a bend, Ridged waveguide transition

Numerous modifications have been done worldwide by the different groups developing high intensity light ion beam injectors. And now, one can say several key points are of most importance for an injector design.

- Extraction system with electron repeller allows minimizing electron backstreaming from LEBT
- Hardening and/or protection of the RF window (from backstreaming electrons produced in extraction system) is needed for longer lifetime. In order to help thermal dissipation, aluminium nitride window can be used. Other solution for longer window life time is to protect it with some ceramic shielding made of alumina or boron nitride. Finally it is possible to protect the window behind a bend.
- A ridged or tapered transition allows increasing the electromagnetic field at the entrance of the plasma chamber.
- Installing ceramic disks at both extremities of the plasma chamber permits to increase the plasma density resulting from production of secondary ions.
- The localisation of one ECR resonance at the entrance of RF into the plasma chamber (just at the surface of the ceramic disk) greatly improves the plasma density and as a consequence, the extracted beam intensity. Positioning 1 ECR resonance zone on both sides of the plasma chamber allows other performance enhancement [3].
- In the accelerator column, the shielding of the negative triple junction (ceramic, vacuum and flange) is important to minimize the ignition of sparks [4].
- Reducing the length of the LEBT (and first between the source and the first focussing solenoid) helps to minimize the emittance growth in the beam line [5, 6].
- Injecting amount of heavy gas into the beam line also allows reducing the emittance growth by improving the space charge compensation [7].

The SILHI source [3] presents several of these key points (Fig. 3) which allowed obtaining a robust and efficient design. Figure 4 presents the emittance gain while injecting nitrogen gas into the beam line [8].

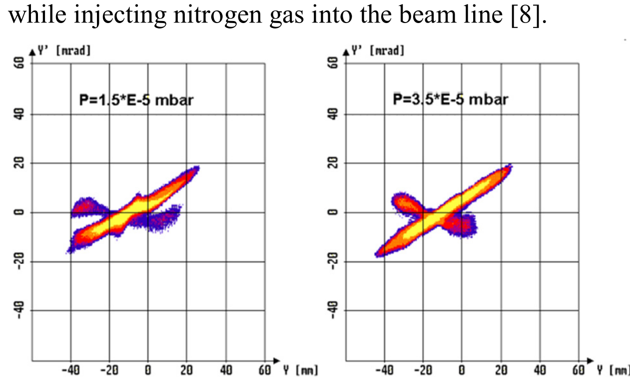

Figure 4: Emittance gain by injecting N_2 gas into the SILHI beam line.

WORLWIDE OVERVIEW

Since the beginning of 90's, several laboratories as well as several private companies develop and operate this kind of sources.

After the pioneers already mentioned (in Chalk River (Fig. 2) and Los Alamos), we can report the work done in Europe by CEA/Saclay with SILHI source and INFN/LNS in Catania with TRIPS source and very long high voltage DC break [9]. In parallel, works were carried out in China at IMP Lanzhou and Peking University [10].

Since then, with the large number of facilities demanding high intensity light positive ion beams, such sources are developed and designed all over the world. Important work is done to minimize the source size and also to provide the most efficient magnetic configuration. The magnetic configuration can be provided by pure permanent magnets [5] (Fig. 5a), by a mix of permanent magnets and iron pieces, by permanent magnets associated with coils or by coils and iron pieces [10]. New design is proposed for ESS source; a third coil biased with opposite current will be added in order to obtain a minimum B magnetic configuration into the plasma chamber [11] (Fig. 5b).

Concerning the plasma chamber size, work has been first carried out at the early 90's [2] and then with permanent magnet sources in order to limit the volume of permanent magnets. Other experiments are in progress with variable length of the plasma chamber, in addition with different diameter chamber.

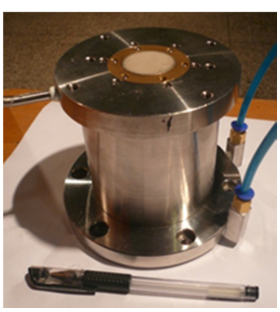

Figure 5a: all permanent magnet PKU source

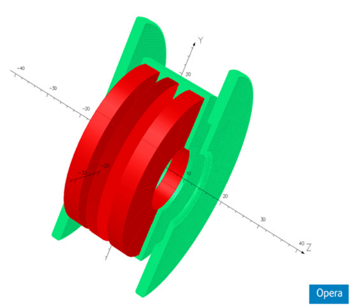

Figure 5b: ESS source design with 1 inversed coil

FOCUS ON SPIRAL 2, IFMIF AND FAIR INJECTORS

For the IPHI (High Intensity Proton Injector) project [13], CEA/Saclay designed the SILHI source in the middle of the 90,s and developed it in order to reach more than 100 mA H^+ continuous beam at 95 keV energy with high reliability. Since then CEA is participating in several HPPA project injectors such as Spiral 2, IFMIF [14] and FAIR.

SPIRAL 2 Injector

For Spiral 2, CEA/Saclay participated first to the design of the proton and deuteron source (Fig. 6). As the requested current of H^+ and D^+ is equal to 5 mA, the source design has been based on permanent magnets. Preliminary source tests were done on the Silhi experimental beam line at 40 keV. Then, in the recent years, the whole light ion Spiral 2 injector has been built and tested at CEA/Saclay [13].

Before moving the whole injector to Ganil at the end of 2O12, beam characterization has been done in several locations along the LEBT. Of course beam intensity and species fractions were checked. The first dipole allows demonstrating the source is producing more than 80 % of H^+ or D^+ depending on the selected gas injected into the plasma chamber. Then emittances have been measured in both plans after both dipoles. Emittance values are 0.22 π mm.mrad for 20 keV H^+ beam and 0.18 π mm.mrad for 40 keV D^+ beam after the second solenoid. Recently, emittances have been analysed just at the entrance of the RFQ location.

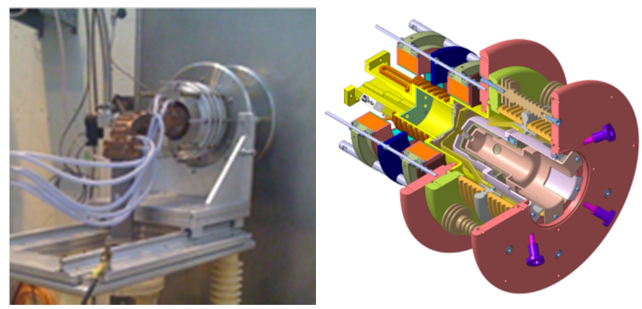

Figure 6: Picture and 3D view of the Spiral 2 ion source with permanent magnets and 5 electrode extraction system.

IFMIF Injector

The IFMIF injector performance is very challenging with a 140 mA of D^+ continuous beam demand at the entrance of the 176 MHz RFQ. To reach such high intensity, it has been decided to keep a magnetic configuration which allows online tuning during conditioning and operation. For this, the magnetic configuration of the source (Fig. 7) is based on 2 coils like the SILHI source. Of course, the extraction system has been initially optimised for such high intensity deuteron beam [15] with 4 electrodes.

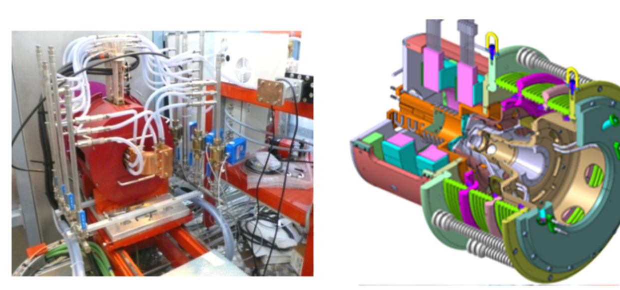

Figure 7: Picture and 3D view of the Spiral 2 ion source with coils and initial 4 electrode extraction system.

The first hydrogen plasma and the first beam were produced in May 2011 in pulsed mode. Then up to 75 keV continuous beam has been extracted with intensity of about 100 mA through a 10 mm diameter aperture. In

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parallel, diagnostics able to characterize high power beams have been installed and commissioned. An Allison emittance scanner has been especially developed with a highly water cooled entrance slit.

Recently, a pulsed Deuteron beam (125 mA) has been produced at 100 keV with a 1% duty cycle. Up to now, with D^+ beam, the duty cycle is limited for neutron production and activation reasons.

As preliminary results demonstrated a quite high spark rate, the addition of a 5th electrode (as grounded electrode between puller and electron repeller) is presently underway.

FAIR Injector

The FAIR injector demands high intensity (100 mA) pulsed beam at 9 keV, with pulsed as short as few 10 µs. After, preliminary experiments done with the SILHI source several years ago [8], FAIR project asked for a copy of SILHI source. Therefore, CEA is presently designing the FAIR proton injector.

Then, this injector will be installed and tested at Saclay before moving to GSI. A slow chopper will be designed by GSI and installed just before the RFQ entrance in order to get a very short rise time.

CONCLUSION

For more than 20 years, numerous projects of HPPA demand reliable high intensity (from few mA to more than 100 mA) light ion beam, either in pulsed or continuous mode. Such demands pushed the ion source community to develop robust and reproductive ion injectors. Important work has been done worldwide on ion sources based on the ECR principle operating at 2.45 GHz low frequency.

Of course, such sources are not only used for Linear accelerator. They are also used as Cyclotron Injector. For example, this one of these sources is installed on the proton-therapy facility in Bloomington (Indiana University). This example proves the high reliability of the source.

In addition, one can note such sources are also able to produce single-charged heavy ions with high efficiency.

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