HIGH INTENSITY ECR ION SOURCE (H^+, D^+, H^-) DEVELOPMENTS AT CEA/SACLAY.

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Abstract. The SILHI (Source of Light Ions with High Intensities) source has been producing proton beams since 1996. The first aim is to produce up to 100 mA cw beams at 95 keV for IPHI (Injector of Protons for High Intensity) demonstrator. This prototype is developed by a CEA/DSM – CNRS/IN2P3 collaboration for applications such as Accelerator Driven Systems for nuclear waste transmutation, production of radioactive ion beams or secondary particles. To measure installation reliability, continuous five-day long runs have been performed. In October 1999, a 99.96 % availability was achieved with a single short beam off and a 103 H uninterrupted beam. A new extraction system leads to lower beam losses and higher LEBT transparency. SILHI now produces 95 keV - 130 mA total beam with a proton fraction higher than 80 %. An up to 157 mA (247 mA/cm^2) total CW beam has been extracted. The new EPICS control system, EMI-hardened devices and automatic control procedures now allows us to do longer runs. To analyze the reliability of these upgrades, a 4-week test was planned. In the framework of the IFMIF project CEA participation, 135 mA-95 kV deuteron pulsed beams were produced. Extraction simulations and recent SILHI results are also presented. In addition, a new test bench has been recently developed to analyze H^- beam production.

I. INTRODUCTION

For several years, CEA and CNRS have undertaken an important R&D program on very high beam power accelerators such as Accelerator Driven Transmutation of Waste (ADTW), new generation of exotic ion facilities and neutrino and muon production. The CEA is also implied in projects such as ESS (European Spallation Source) and IFMIF (International Fusion Material Irradiation Facility).

The SILHI main objective is to produce 100 mA proton or 140 mA deuteron CW beam currents at 95 keV with rms normalized emittances lower than 0.2 π mm.mrad. An electron cyclotron resonance (ECR) source has been chosen to reach these performances for its high reliability – availability. SILHI is developed to be the source of the IPHI prototype[1]. The 95 keV proton beam will be accelerated up to 5 MeV by a 8 m long RFQ and up to 10 MeV by an Alvarez type DTL. Experiments with SILHI are also devoted to the production of deuterons for IFMIF and a new test bunch is under study for H- ion production.

Since 1996, SILHI has been regularly producing proton beams, in cw or pulsed mode, with performance close to the request [1]. A new extraction system has been designed to minimize beam losses on the extraction electrodes by reducing the initial divergence. It was recently installed and beam of more than 150 mA total current were extracted (see section II). New reliability tests were performed to analyze EMI-hardened device improvements as well as automatic procedures. In April, the source performance degradation forced an interruption to the 4 week continuous run. Since then, a new 162 hour test has been successfully achieved; the beam availability reached 99.8 %. In section III, the first deuteron pulsed beam measurements are reported and discussed. And then, the new test bunch for the H^- ion production, based on the ECR plasma generation, will be briefly presented.

II. PROTON SOURCE PERFORMANCE

SILHI is an ECR ion source operating at 2.45 GHz. The RF power is produced by a 1.2 kW magnetron source and is fed to the source via standard rectangular wave-guides with a four stub automatic tuning system and a three section ridged wave-guide transition.

II-1. New extraction system

The first set of the 5 extraction electrode system led to beam losses and limited the LEBT beam transmission. Some enhancements were obtained by reducing the distance between electrodes but unfortunately, aberrations increased. So, a new extraction system has been designed using Axcel and MultiPart codes. The main differences with the previous setup are:
- a new 9 mm diameter plasma electrode with a 45 ° angle instead of 8 mm diameter and 60.5 ° angle,
- a new reduction of both accelerator gaps leading to a global accelerator length of 21.5 mm instead of 23.8 mm.

As a result, the initial divergence decreases from 58 to 24 mrad and leads to a maximum beam radius of 29 mm in the first LEBT solenoid. Previously the maximum beam radius was 63 mm. The maximum electric field increases 10 % up to 110 kV/cm. Calculations indicate a slight aberration increase but the global proton beam emittance decreases of about 10 %.

This new system has been installed and beams with more than 130 mA total extracted current are easily produced with a 80 % proton fraction.

II-2 Reliability – availability tests

Three 100 hour long runs have been performed with the previous extraction system to analyze the source reliability. The source was continuously operated for 5 days and the reliability-availability respectively reached 94.5 %, 97.9 % and 99.96 %. In October 1999, only one beam trip occurred at the beginning of the 104 hour test for 2.5 min, and 103 hours uninterrupted running time was achieved.

In the framework of the CEA participation to the IFMIF program, a new long CW test was planned for a 4 week duration. Since the source remote control is completely updated with the EPICS system, automatic procedures and home internet network connections allow us to leave the source working without any operator locally. The run began with a 97 mA proton beam (118 mA total and 84 % proton fraction) extracted at 95 kV. During the first nine days, 28 breakdowns occurred and the mean time between failure (MTBF) turned out to be lower than 8 hours. In the same time, the servo control loop which keeps constant the extracted beam progressively increased the RF power, indicating changing beam characteristics. The proton fraction dropped from 84 to 63 %. Beam line residual gas analysis revealed an oil contamination coming from the end sectionof the LEBT.

A 23 mA-75 keV cleaning oxygen beam was produced for 3 hours to simultaneously remove hydrocarbon impurities and increase proton fraction [3]. Just after, the proton fraction reached 88 % and then decreased to 83 %. It remained stable for 4 days as the beam was contained in the first part of the LEBT, with the intermediate vacuum valve closed. During this period, the spark rate increased and 25 beam offs occurred leading to a 4.1 hour MTBF. A new cleaning O_2 beam was produced for 6 hours and then a 120 mA beam was analyzed. The proton fraction jumped to 90 % and then decreased again to 84 %.

During the beam test, the beam noise was never over 1.9 % and currently in the 1 to 1.4 % range (Fig. 1). This noise was mainly due to the 19 kHz coherent oscillations transferred to the plasma from the magnetron RF switched power supply.

Even though this reliability test did not reach the expected results, it gave us valuable information summarized here.

- Beam line pollution leads to rapid beam quality degradation.
- The O_2 cleaning beam seems very efficient to improve the proton fraction but unfortunately after the cleaning, the spark rate increased.
- The automatic restart procedures which take 2.5 min, were not completely adapted to all the situations especially if a spark occurs during the restart period.

The accelerator column was completely disassembled and chemically cleaned. Many spark traces and carbon deposition were observed on the surface of the electrodes and insulators.

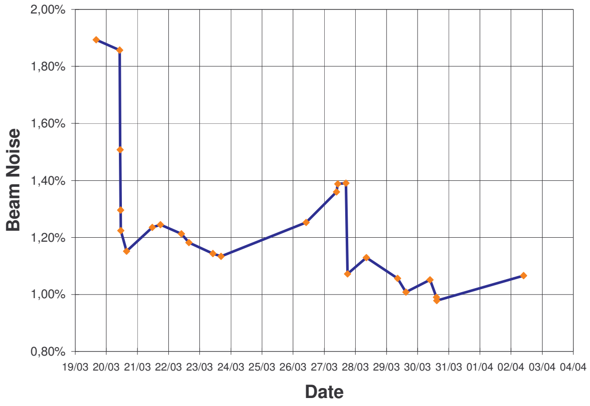

Fig. 1: Beam noise measurements versus the elapsed run time.

After conditioning, a 114 mA (+/- 0.2) - 95 keV beam was produced for 162 hours with a 77 % proton fraction. Seven beam offs occurred mainly due to plasma extinction (only one spark). The 7 restarts were automatically operated and took 2.5 min each. The availability reached 99.8 %. Automatic restart procedure enhancements now allow beam off for as short as 20 seconds before recovering more than 95 % of the beam current.

Space charge compensation and emittance improvements have already been described [4,5]. The emittance measurement unit (EMU) has been modified to allow emittance analysis at the exit of the source. Preliminary experiments indicated a slight EMU acceptance limitation and did not allow us measurements at the source exit.

An up to 157 mA (247 mA/cm^2) total beam was extracted. Nominal SILHI proton performances, in CW mode, are summarized in table I. The emittance value reported in the table was previously done in the second part of the LEBT.

TABLE I : SILHI requirements and present status.

Parameters	Request	Status
Energy [keV]	95	95
Intermediate electrode voltage [kV]	65	48
Proton extracted beam [mA]	100	108
Total extracted beam [mA]	110	130
Proton fraction [%]	> 90	83
Extraction aperture [mm]	10	9
Extracted beam density [mA/cm^2]	140	204
Forward RF power [W]	< 1200	850
Duty cycle [%]	100	100
Hydrogen mass flow [sccm]	< 10	~5
Beam noise [%]	< 2	< 1.9
r-r' rms norm. emittance (LEBT) [π.mm.mrad]	0.2	0.11 @75 mA

III SILHI DEUTERON PRODUCTION

The IFMIF project is a 40 MeV material irradiation facility for the fusion community. It will accelerate 2 X 125 mA CW D$^+$ beam. For this program SILHI has been tuned to analyze deuteron beam characteristics. To minimize structure activation, the deuteron beam has been produced in pulsed mode (2ms / s) by modulating the 2.45 GHz magnetron power. This experiment has been done using the 120 mA proton beam extraction system. So a good transport line transparency was not expected.

Beam characteristics (intensity, deuteron fraction, beam noise) were checked for a 135 mA – 100 keV total extracted current and summarized in table II. The LEBT transparency reached 75 % (Fig. 2), between the DCCT located 25 cm downstream from the plasma electrode (hollow squares) and the beam stopper 3.5 m away (hollow circles). The 6 MHz bandwidth ACCT (black triangles), placed between the 2 solenoids and behind a 80 mm diameter collimator, indicates a 1.25 % rms beam noise (1.34/108.1). Like for protons, the noise was also mainly due to the 19 kHz spaced-lines induced by the magnetron power supply.

TABLE II : SILHI deuteron production.

Parameters	Status
Energy [keV]	100
Intermediate electrode voltage [kV]	50
Deuteron extracted beam [mA]	129
Total extracted beam [mA]	135
Deuteron fraction [%]0	96
LEBT transparency [%]	75
Extraction aperture [mm]	9
Extracted beam density [mA/cm²]	212
Forward RF power [W]	900
Duty cycle [%]	0.2
Deuterium mass flow [sccm]	~1
Beam noise [%]	1.25

The deuteron fraction was analyzed by using the EMU Wien filter. The different species measurements indicated more than 96 % of D$^+$ and less than 4 % of D_2^+. No D_3^+ and heavy masses were observed. A total beam current as high as 166 mA (261 mA/cm^2) was extracted with a lower LEBT transparency.

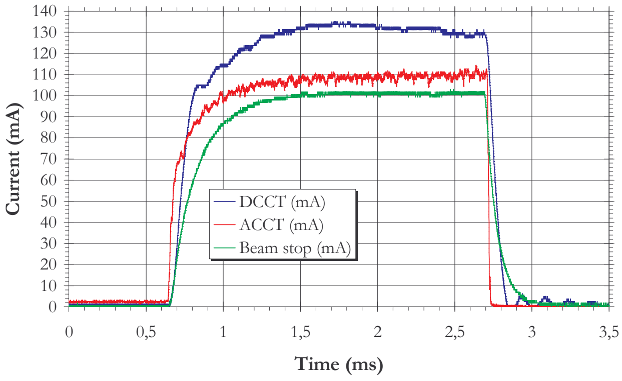

Fig. 2: LEBT transparency for 135 mA total deuteron beam.

During the deuteron beam experiment, high energy neutron production was checked with a specific probe (Bertold LB 6411). The activation level progressively increased to reach 11.5 µSv/h after 2 hours. This activation was mainly induced by the (d, D) reaction at the surface of the copper target which produces 2.45 MeV neutrons. The maximum level was not obtained as the experiment was done on a short period (2 days) with lots of voluntary breaks to minimize the activation. This value was achieved with a very low duty cycle, longer pulses experiments could only be done with appropriate shielding.

As a result, the SILHI source looks as well adapted for deuteron production as for protons. The performance in term of species fraction is a little bit higher with deuterons.

IV. HYDROGEN NEGATIVE ION SOURCE

Reliable high-intensity H- ion source development is now part of the CEA/Saclay work in the field of high-intensity linear accelerators. A 2.45 GHz ECR H- ion source and test bench have been built [6]. The first step is to study the pure volume negative ion production. The source has been designed taking into account our SILHI experience. The high-energy electrons created in the ECR zone are trapped by a dipole magnetic filter. A rectangular 200 mm long plasma chamber and an intermediate iron shield are used to minimize the axial magnetic field close to the plasma electrode. In the up to 10 kV extraction system, electrons and negative ions should be magnetically separated. To reduce the electron/H- ratio, the plasma electrode could be biased by a few volts power supply. Pulsed hydrogen plasma is currently produced. And the first extracted beam analysis did not allow us to clearly demonstrate H^- ion production. Preliminary experiments (beam analysis and plasma characterization) are presented in a companion paper and possible evolutions are also discussed [7].

ACKNOWLEDGMENTS

Many thanks to the whole IPHI team members for their contributions, especially P-E. Bernaudin, R. Duperrier, and N. Pichoff. The authors would also like to thank the CEA-Grenoble source team, the Los Alamos LEDA-AAA group and the Catania TRIPS group for their fruitful collaboration and valuable discussions during the last 6 years.

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