Reliability Tests of the High Power Proton Source SILHI at CEA/Saclay

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Abstract: In France, the IPHI demonstrator project (Injector of Protons for High Intensity) is developed by a CEA/DSM – CNRS/IN2P3 collaboration for several applications based on the use of High Power Proton Accelerators. The IPHI RFQ is designed to accelerate a 100 mA proton beam from 95 keV to 5 MeV. The construction of the segmented 8-m long RFQ is under progress. The particles are injected from the SILHI (High Intensity Light Ion Source) ECR source. SILHI has been producing intense beams since 1996. A new extraction system and new control system led to large improvements in term of intensity, beam line transmission, stability. Moreover, automatic restart procedures allow to minimize the beam off time. More than 130 mA are now routinely produced at 95 keV with a proton fraction higher than 80 %. Several long run tests have been performed to measure the source reliability and to improve the mean time to repair. This article will report a summary of the reliability tests pointing out the influence of the lasts improvements. The source will be installed on the IPHI site within the next months.

I - INTRODUCTION

CEA and CNRS have undertaken an important R&D program on very high beam power light-ion accelerators (MW class) for several years. The two French research agencies are interested among others by applications such as Accelerator Driven System (ADS), new generation of exotic ion facilities or neutrino and muon production for high-energy particle physics. The R&D program is essential since the performances requested by these projects are one to two order of magnitude higher than those achieved by the most powerful existing accelerators. Severe beam loss limitations are necessary to allow hands-on maintenance. The necessity to achieve a very high availability with a reduced number of beam trips add new constraints which make the R&D effort even more indispensable to have a realistic view of the new generation of high-power accelerators.

The strategy carried by the CEA–CNRS collaboration has been to restrict the R&D program to a limited number of essential subjects with a maximum overlap on the different projects. The R&D effort is then concentrated on three topics : 1) IPHI a prototype of linac front end up to 10 MeV with beam currents up to 100 mA CW, 2) Construction and test of $\beta<1$ superconducting cavities, 3) Improvement of the codes for accurate beam dynamics calculations.

IPHI is foreseen to be the front part of a high power proton accelerator (HPPA) [1]. It includes an ECR source, a RFQ and a DTL to provide beam energies up to 10MeV. Since 1996, SILHI has been regularly producing intense proton beams, in cw or pulsed mode, with performance close to the request [2]. A new extraction system has been designed to minimise beam losses on the extraction electrodes by reducing the initial divergence. New reliability tests were performed to analyse EMI-hardened device improvements as well as automatic procedures. In 2001, a 162 hour test has been successfully achieved; the beam availability reached 99.8 %.

II - IPHI GENERAL LAYOUT

The figure 1 represents the general layout of the IPHI prototype. The ions are produced at 95 keV by the ECR ion source located on a HV platform. The 2 LEBT solenoids allow the beam matching at the 5 MeV RFQ entrance. The DTL (not yet funded) will increase the energy up to 10 MeV. The diagnostics line will be first installed at the RFQ exit to characterize the beam at intermediate energy.

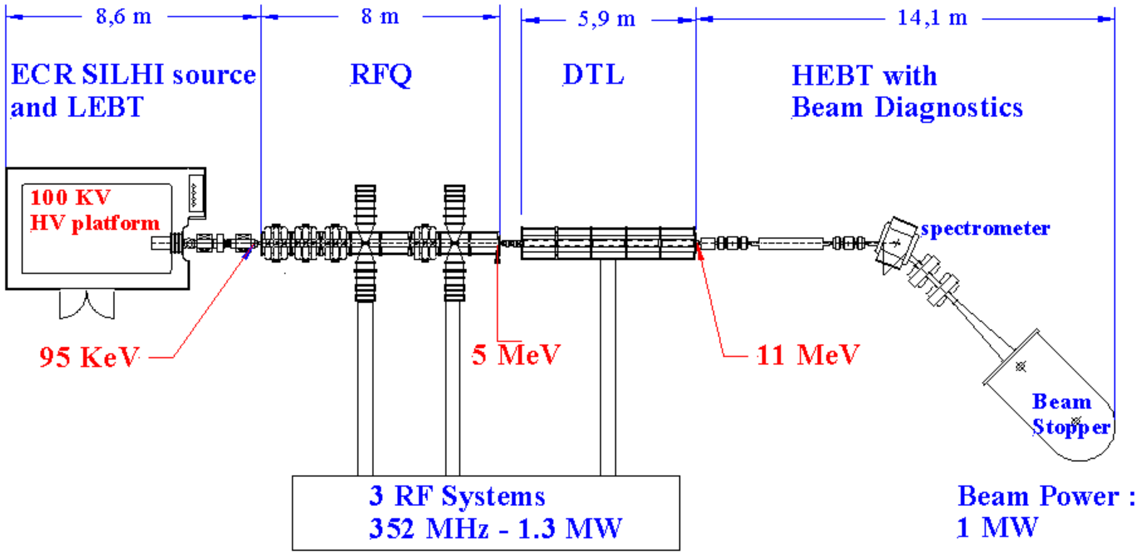


Fig.1: General layout of the IPHI project

The IPHI site in now ready to receive the different parts of the prototype. Two 352 MHz klystrons are already arrived from CERN to power the RFQ (construction under progress). The first RFQ segment is under mechanical and RF tests after brazing. The seven other segments will be built within less than 2 years. The SILHI experiments stopped at the end of April and the source will be installed on the IPHI site within few months.

III - 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. A new set of the 5-electrode extraction system allows beam losses limitations and the source is now currently producing beam intensity higher than 120 mA with a proton fraction close to 85 %.

The emittance measurement unit is an aperture-slit method made of a 0.2 mm diameter Tantalum sampler and a Wien Filter. It allows species beam emittance analysis at the exit of the accelerator column (0.53 m from the plasma electrode) or at the end of the LEBT (4.5 m from the plasma electrode). The r-r' rms normalized emittance values turn out to be lower than 0.2 π.mm.mrad at the exit of the source for a 100 mA proton beam. A significant emittance growth has been observed at the end of the LEBT (nominal values of 0.3 π.mm.mrad). This emittance growth did not depend on the extraction configuration. The critical parameters seemed to be the beam focussing depending on the solenoid current.

To minimize possible breakdown and to optimize the reliability, different developments and technical choices were adopted. The following list presents several items developed in this framework:

- 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

LEBT space charge compensation analysis indicated the significant contribution of secondary electrons by means of beam losses on the walls, interceptive diagnostics or gas adding. A small amount of heavy gas (Ar or Kr) allow a better space charge compensation.

Source reliability tests

Three 100-hours 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-hours test for 2.5 min, and 103 hours uninterrupted running time was achieved.

Table 1 summarizes the 5 run reliability tests performed since the source produced its first beam in 1996.

Parameters	**Déc. 97**	**Mai 99**	**Oct. 99**	**March 01**	**June 01**
Energy (keV)	80	95	95	95	95
Intensity (mA)	100	75	75	118	114
Duration (h)	103	106	104	336	162
Beam off number	**53**	**24**	**1**	**53**	**7**
MTBF (h)	**1.75**	**4**	**n. appl.**	**≈ 6**	**23.1**
MTTR (mn)	**6**	**5.3**	**2.5**	**≈ 18**	**2.5**
Uninterrupted beam (h)	**17**	**27.5**	**103**	**25**	**36**
Availability (%)	**94.5**	**97.9**	**99.96**	**95.2**	**99.8**

This table shows the reliability-availability can reach higher than 99.5 % with a very low number of beam off within a whole week. The mean time to repair is largely too long for continuous injection in a ADS and improvements will have to be again achieved to match the requests. As a bad running gives more information than a good one, the following paragraphs comment the March 2001 test where the availability only reached 95.2 %.

In the framework of the CEA participation to the IFMIF program, a new long CW test was planned for a 4 weeks 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. Too many breakdowns occurred. In the same time, the servo control loop which keeps constant the extracted beam current 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.

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

- Beam line pollution leads to rapid beam quality degradation.
- The O_2 cleaning beam seems very efficient to improve the proton fraction but after the cleaning, the spark rate did not decrease.
- 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.

After cleaning of the accelerator column and new conditioning, a 114 mA (+/- 0.2) - 95 keV beam was produced for 162 hours with a 77 % proton fraction (Fig. 2). Seven beam off 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 %.

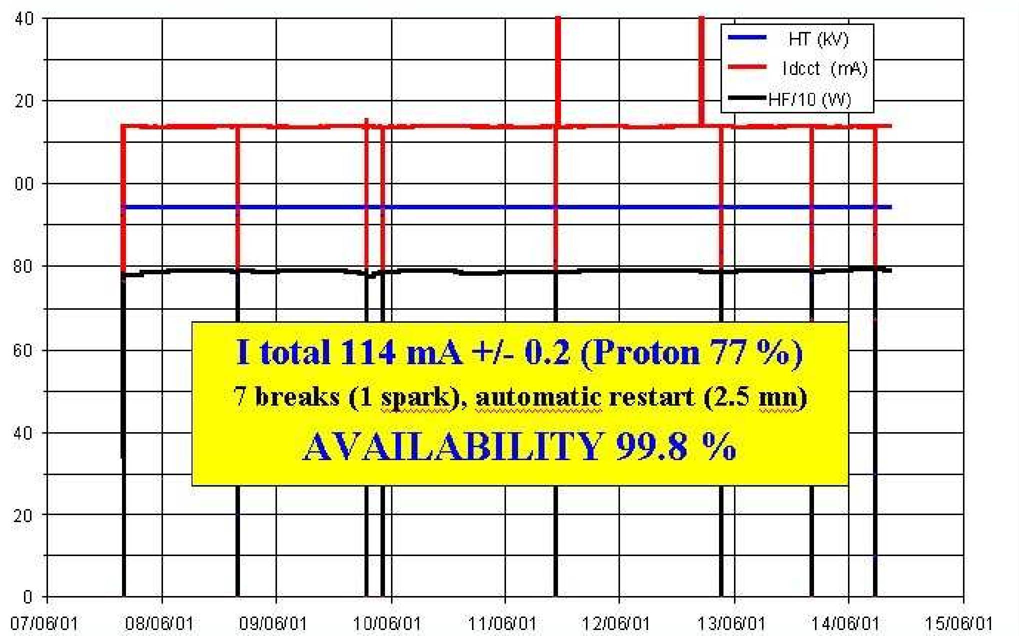
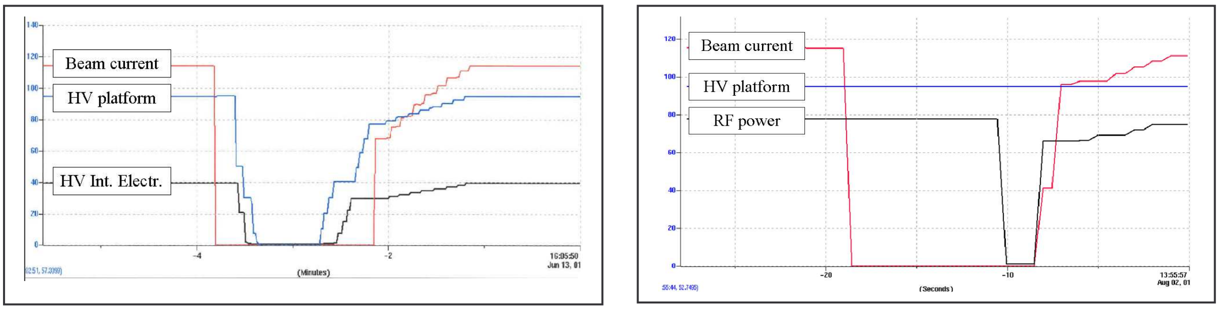


Fig. 2: 162 hour long run

After automatic procedure improvements achieved with the EPICS control system, beam off for as short as 20 seconds occur when only plasma extinguishes. The figure 3 shows 2 different automatic restarts: a) the beam stop is due to a HV spark and the HV power supplies switched down; b) the beam stop is only due to plasma extinction and switching down and up the RF power allow us to recover the beam.

A fast analog feedback should be developed to again minimize the beam off duration in case of plasma extinction. Less than few hundred ms duration could be expected. At present time, spark very often lead to power supplies switch down and do not allow faster restart than 2.5 minutes.

The beam noise is in the 1 to 1.4 % range. This noise was mainly due to the 19 kHz coherent oscillations transferred to the plasma from the magnetron RF switched power supply. A 3 GHz klystron will be tested to minimize the beam noise. The non Gaussian distribution of the noise do not allow any more to speak of a +/- range but in a full range beam noise.



a) b)

Fig 3: Automatic restart: a) after spark(2.5 min beam off)
After plasma extinction (20 s beam off)

IV- CONCLUSION

To summarize the SILHI reliability analysis, the different tests have been performed with a higher intensity than expected by the ADS HPPA. More than 800 hours of continuous operations gave us lots of information to optimize the source behavior. Several weak points have been discovered and solved.

No spark occurs without beam after specific accelerator column conditioning. The use of EMI hardened devices enhanced dramatically the source performance. Sparks now do not lead to power supplies failures or PLC reboots. Moreover short experiments indicated a lower spark rate with a lower beam intensity as well as with pulsed beam. These results will have to be confirmed by specific runs planned after the move of the source on the IPHI site.

The SILHI beam characteristics are close to the RFQ requests and the first 5 MeV beam is expected in 2004.

Table 2 summarizes the SILHI source performance. In deuteron, the duty factor was limited by neutron production.

Particles	**PROTON**		**DEUTERON**	
Parameters	Requests	Status	Request	Status
Energy [keV]	95	95	95	100
Intermediate Electrode [kV]	55	56	?	50
Proton , Deuteron Current [mA]	100	108	140	129
Total Current [mA] **(I max)**	110	130 **(157)**	155	135 **(166)**
Proton, Deuteron Fraction [%]	> 90	83	> 90	96
Plasma electrode diameter [mm]	-	9	-	9
Current Density [mA/cm²]	140	204	243	212
Availability [%]	AHAP	> 99	AHAP	-
RF Forward Power [W]	< 1200	850	< 1200	900
Duty Factor [%]	100	100	100	0.2 *
H_2 , D_2 Gas Flow [sccm]	< 10	5	< 10	1
Beam Noise rms. [%] rms normalized emittance [π.mm.mrad]	2 0.2	1.2 0.11 @75 mA	2 0.2	1.2 -

References

1) PY Beauvais et al. "Status report on the Saclay High Intensity Proton Injector Project (IPHI)", EPAC 2000 Conference proceedings, Vienna, Austria.
2) R. Gobin et al. "High Intensity ECR ion source (H+, D+, H-) development at CEA/Saclay", ICIS 2001 Conference, Rev. Scien. Instr., volume 73 n° 2 (922).