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SACM

SERVICE DES ACCELERATEURS DE CRYOGÉNIE ET DE MAGNÉTISME

N/RÉF : DSM/DAPNIA 03-72

OBJET : IFMIF KEP

CEA-DSM-DAPNIA-SACM contribution to the IFMIF KEP phase

June 2000 to December 2002

1 Introduction and Background

The International Fusion Materials Irradiation Facility (IFMIF) requires generation, by a linear accelerator (linac), of 250 mA continuous current of deuterons at a nominal energy of 40 MeV, with provision for operation at 30 MeV and 35 MeV. The basic approach is to provide two linacs modules, each delivering 125 mA to a common target. This approach has availability and operational flexibility advantages.

The accelerators begin with a deuteron ion source and a low-energy beam transport to a radiofrequency quadrupole (RFQ), buncher and preaccelerator up to ~5 MeV. A high-energy beam transport from the accelerator to the lithium target must perform a variety of functions, complicated by the presence of strong space-charge forces within the beam. A very low beam loss along the accelerator and transport lines is required in order that maintenance can be performed without requiring remote manipulators.

The "Key Element Technology Phase" (KEP) was initiated in 2000 with the objective of reducing some key technology risk factors. The risks were identified as those needed to achieve a CW deuterium beam with the desired current in the accelerators, to verify relevant component designs on a laboratory scale both in the lithium target system and test cell system, and to validate design codes.

The activities defined here concentrate on key engineering development items of the Accelerator Facility system. Consequently, the task can be structured into

- D+ Source (deliverables 1,2,9,10),
- RF system (deliverable 5),
- RFQ accelerator (deliverables 3,4),
- DTL accelerator (deliverables 6-10),

The IFMIF KEP is carried out at the CEA in the framework of a considerably larger activity presently undergoing in the field of high-intensity linear accelerators [1,2]. The activity specific to IFMIF has been concentrated on:

- Deliverable 1: Source
- Deliverable 4: 4-vanes RFQ design
- Deliverable 5: RF (Radio Frequency) System
- Deliverable 6: DTL design
- Deliverable 9: high power diagnostics

We report here the results obtained accordingly with the task schedule. The major intermediate report were:

DSM/DAPNIA/SEA 01/41, "CEA-DSM-DAPNIA-SEA contribution to the IFMIF KEP phase. Step report – June 2001". 35 pages. [3]

DSM/DAPNIA/SEA 02/09, "CEA-DSM-DAPNIA-SEA contribution to the IFMIF KEP phase. Step report – June to December 2001". 25 pages. [4]

IFMIF international team, "IFMIF key element technology phase, interim report", JAERI-Tech 2002-22. [5]

IFMIF KEP Report, IFMIF international Team JAERI-Tech 2003-005, march 2003 [6]

2 Source and LEBT (TTMI01 D01)

2.1 Introduction

SILHI ("Source d'Ions Legers Haute Intensité") is in operation at CEA-Saclay [7]. It delivered its first proton beam in July 1996. This ECR (Electron Cyclotron Resonance) source is designed to produce continuous high-intensity proton and deuteron beams. Calculations for deuteron operation have been specifically done to reach the IFMIF requirements (for example, a 100 kV-200 mA high-voltage power supply). The present deliverables concentrate on the ECR source long run test, the beam transport and beam analyses (RAMI, beam quality, performances). It includes

1a Long run of ECR source

1b Beam Analyses produced by the ECR source

1c Performance of ECR source (Proton and deuteron production)

1d Layout of LEBT

The reliability-availability is one of the most important goals. So the source has to be as reliable as possible and 6 long run tests have been done to analyse its behaviour in continuous operation.

The extraction system has been improved in the past to minimize beam losses at higher extracted beam current and the source command and control system was completely updated with the EPICS system. This new configuration should allow us to extract higher intensity deuteron beam after conditioning, a second long run reliability test has been performed for 1 month in October 2001.

2.2 Long run of ECR source – Subdeliverable 1a.

2.2.1 *Summary of the first run tests*

In December 1997 the source has been continuously operated during 5 days (103 hours) with a 100 mA CW proton beam at 80 keV. The global reliability reached 94.5 % with 53 shutdowns mainly induced by HV sparks. The second test has been performed in May 1999 with a 75 mA CW beam at 95 keV, the availability reached 98 % for a continuous operation of 106 hours. The beam has been interrupted 24 times.

In October 1999, after improvements, a new 5 days test run was done with a 75 mA extracted beam at 95 keV. **Only one beam trip occurred during the 104 hours run test for 2'30" and 103 hours uninterrupted running time have been achieved. The reliability reached 99.96 %.**

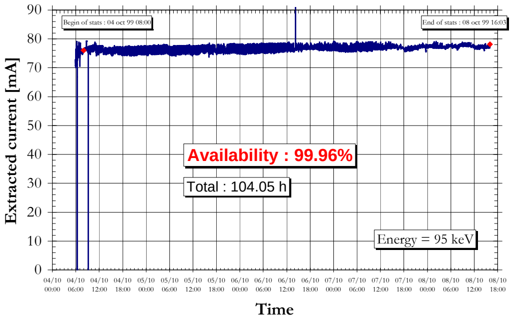

Figure 1 : 1999 104 h test.

Reliability tests [8].

2.2.2 *Four weeks reliability test*

Long run tests often benefit the knowledge of the source behaviour and component failure. A four weeks run test has been decided following the remote control exchange and the installation of the new extraction system.

To limit beam losses in the extraction zone, a new set of electrodes has been designed and assembled on the installation in October 2000; it allows us to extract up to 150 mA total extracted beam with a LEBT transparency (up to the future RFQ matching point) higher than 90 %.

Then the source was stopped for 2.5 months (mid of November 2000 to end of January 2001) to completely change the remote control system. The old one, based on Visual Basic and PCs, controlled all the power supplies and was associated with a Selectron PLC for vacuum control. The SILHI became the development test bench of this EPICS system. It was also the only way to make a 4 weeks run and with accurate beam characteristics measurements. It includes much better automatic recovery system. After few months' tests, all the SILHI wiring has been changed including the PLC, which has been replaced by an industrial Siemens device. Now workstations replace PCs. At the end of January, the beam was again extracted and weeks have been spent to improve the control system, specifically the automatic procedures. These procedures allow us to leave the source working without any operator and allow long distance control through modem connections.

For the new long run test, all beam characteristics were checked: beam intensity, proton fraction, emittance and beam noise. To avoid LEBT activation, the tests are made with protons. Unfortunately, as the EMU was located at the extraction column exit, the sampler melted (due to too high power density). So the EMU was installed at the end of the LEBT with a new sampler. Emittance measurements are not possible at this location, since the beam size is too large there. But we were able to measure the proton fraction and the beam noise. Since that time, the EMU is improved and is still under improvements.

The 4 weeks run started on Monday March 19, 2001 with the beam parameters reported in Table 1.

Parameters	**Requests**	**Run Status**
Energy [keV]	95	95
Proton extracted beam [mA]	100	≈ 97
Total extracted beam [mA]	110	118
Proton fraction [%]	> 90	≈ 84
Extraction aperture [mm]	9	9
Extracted beam density [mA/cm²]	156	185
Forward RF power [W]	Up to 1200	1000
Duty cycle [%]	100	100
Hydrogen mass flow [sccm]	< 10	5.3
Beam noise (rms) [%]	< ± 1	± 0.95 max

Table 1 : SILHI long run requirements and March-April 2001 run test parameters

After 24 H while already 3 beams off occurred, the beam intensity slowly reduced to 107 mA and the proton fraction dropped to 75 %. To recover the initial current with a better proton fraction, the source magnetic configuration was slightly modified. Then the proton fraction reached 82 % and stayed stable for 48 H. During this period, the rms beam noise was also stable around ± 0.6 %. Unfortunately the breakdown rate increased to 9 breaks in 2 days. To keep the extracted beam constant, a servo control loop was then programmed and installed without operation stopped. It works by measuring the DCCT current and adjusting the RF power accordingly.

During the first weekend, 4 new beam off occurred; 3 of them necessitated external intervention for the source restart and the last one with an automatic restart. A 25 H uninterrupted beam was obtained. For all the weekend, the RF power progressively increased and on Monday morning the proton fraction was again dropped to lower than 75 %.

The experiment has been still lengthened for 2 days in the same conditions and the beam characteristic degradation still continued. On Wednesday March 28 the proton fraction was as low as 63 %. During the last day, some residual gas analyses were done in the beam line. A possible explanation has been found, concerning an oil contamination, which could come from the end part of the LEBT. Finally in the 9 first days of the test, 28 breakdowns occurred (Figure 2) and the MTBF turned out to be lower than 8 hours.

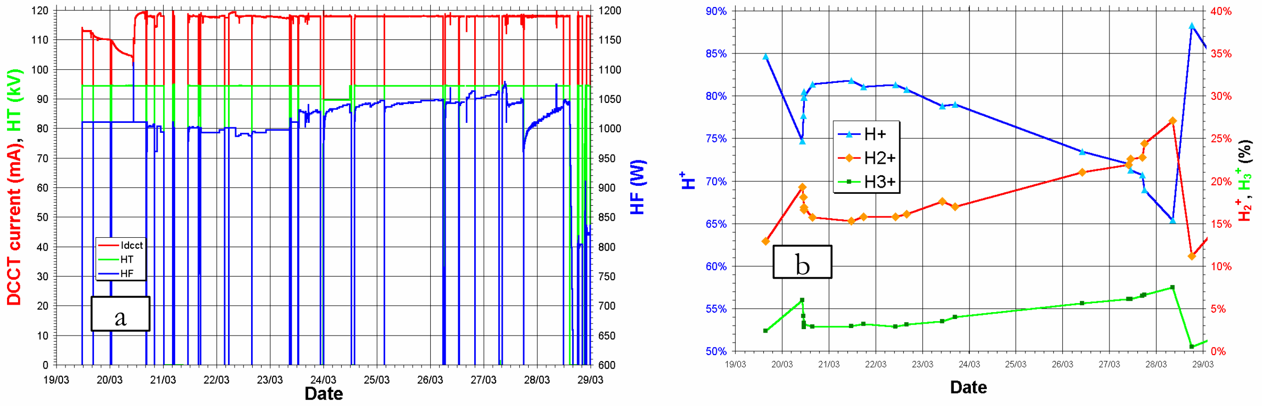

Figure 2 : Total extracted beam, (a) HV source and forward RF power, (b) Species evolution versus elapsed run time of the first 9 days of the test run.

On Wednesday afternoon, a 23 mA-75 keV cleaning Oxygen beam has been produced for 3 hours and was also considered as a beam stop for the "factory". Just after the production of the new hydrogen plasma, the proton fraction reached 88 % (see the H^+ jump on Figure 2-b on March 28). On Thursday morning, it came back to 83 % and remained quite stable for 4 days. During this period, the RF power was adjusted to maintain the total extracted current at nominal value. The rms beam noise also remained stable at ± 0.6 %. As a result of the possible diagnostics of oil contamination coming from the LEBT end part, the intermediate valve was maintained closed except for proton fraction and beam noise measurements. Moreover the spark rate increased and almost 25 unacceptable beam off occurred from Wednesday March 28 to Monday April 02 (Figure 3) leading to a 4.1 hour MTBF.

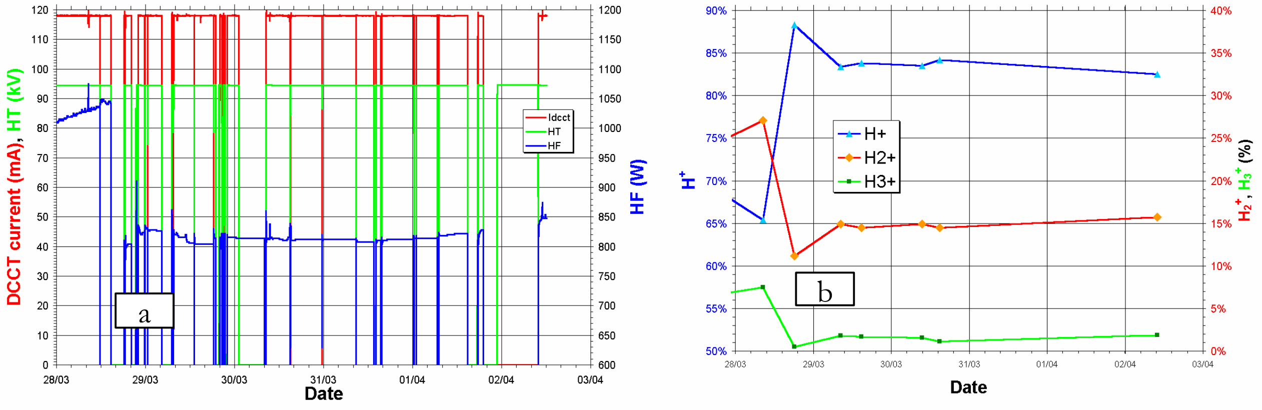

Figure 3 : Total extracted beam, (a) HV source and forward RF power, and (b) Species evolution, both versus elapsed run time from March 28 to April 02

Seeing all these problems like proton fraction degradation and important spark rate, we decided to stop the run at that time. In order to understand the source behaviour, a new experiment was planned.

A 6 hours cleaning Oxygen beam has been performed on Tuesday morning before to start a new 75 mA beam run for 7 days in order to compare with the 1999 tests. Following the O_2 cleaning beam, a 120 mA extracted proton beam has been analysed. The proton fraction reached 90 % with an rms noise as low as ± 0.5 %; 24 H later, the proton fraction came back to 84 %. Then the intensity has been voluntary decreased to 75 mA on Wednesday April 04 in the afternoon. The source worked in these conditions (75 mA at 95 kV) for 5 days with a proton fraction stabilized around 82 % but with a very high beam off rate. 21 beam stops occurred during this 110 H long period (MTBF = 5.2 hours).

The experiment has been definitely interrupted on Monday April 09 in the morning for a complete check-up of the accelerator column.

2.2.3 Comments on the first 4-weeks run

Unless what was expected, we were not able to run with a satisfactory source behavior. The events are deeply explained in the June 2001 step report [3]. Even if this reliability test did not reach the expected results, it gave us lots of information summarized hereinafter.

- Beam line pollution leads to rapid beam quality degradation. The LEBT design has to clearly take this into account
- The O_2 cleaning beam seems very efficient to improve the proton fraction but unfortunately after the cleaning, the spark rate increased. The improvement of proton fraction after ion source conditioning with oxygen plasma is similar if not identical to Los Alamos LEDA injector performance.
- The automatic restart procedures have to be adapted to all the situations. Improvements allows us to automatic restart in about 1 minute with a 1 second scan period but can be reduced with a faster scan or an hardware solution.
- The new EPICS control system allowed us to work without any operator locally and to operate with home connection via Internet network if needed. Only few hardware failures obligate us to come back to the source to repair. Despite this good control system, spark during week-end and night implied very long beam stop. It necessary decreased the beam availability. A better operability could be obtained with 24 h a day in-situ control.
- The servo control loop, which maintains a constant extracted beam current, works well.
- The beam noise was never over ± 0.95 % and often in the ± 0.5 to ± 0.7 % range (Figure 4). This noise was mainly due to the 20 kHz spaced-lines transferred to the plasma from the magnetron RF switched power supply. It may then disappear with the Klystron installation. Our knowledge at that time on beam noise did not allow us to describe it with more precision. Since that time we prefer to describe it as a total number (x%) instead of a ±x% value (see §2.3.2 page 15).

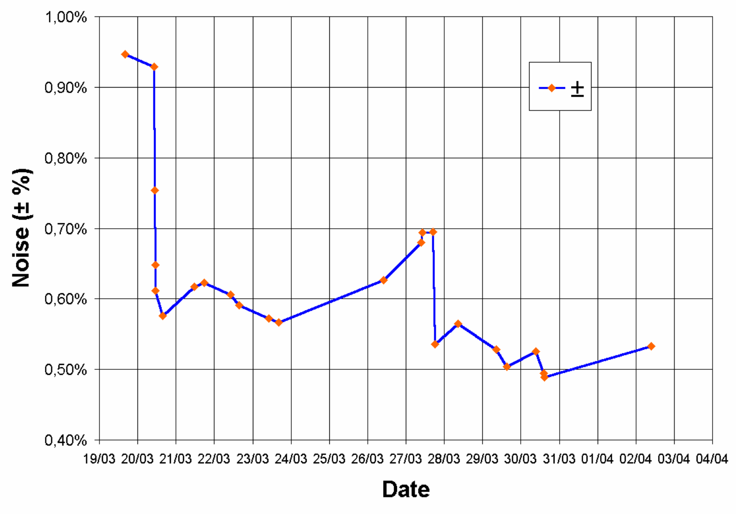

Figure 4 : Beam noise measurements versus the elapsed run time of the first 14 days of the run

The dismounting of the accelerator column gave us new information:

- Lots of spark traces have been observed between the intermediate electrode and the first grounded electrode but also at the inner surface of the main insulators.
- Carbon traces have also been found at the surface of the electrodes, showing that the beam was off-axis on the electron repeller.

All the pieces (insulators, electrodes, flanges, screens) have been chemically cleaned following specific process for each material before to reassemble the accelerator column. A precise alignment and a serious HV conditioning were then done.

Compare to the 1999 tests, the main differences came from current increased and the new electrodes. With the new set of extraction electrodes, 100 mA proton beam are transported up to the future RFQ matching point and more than 150 mA total beam was extracted. The new set of electrodes increases by 10% the electric field at the surface. This may be one of the reasons of the spark rate increase. Of course, the pollution observed (carbon traces) is also very important for HV column reliability.

This 4-week reliability run test did not show the expected results for several reasons, including oil contamination.

2.2.4 New long run

Soon after the failure of the first 4-weeks run, and after improvements on the command/control system and the source itself, a new long run was started in order to verify the overall system. Slightly more than a week time was then available, given about 160h of source availability. The results shown in Figure 5 give back the very good results of the October 1999 test.

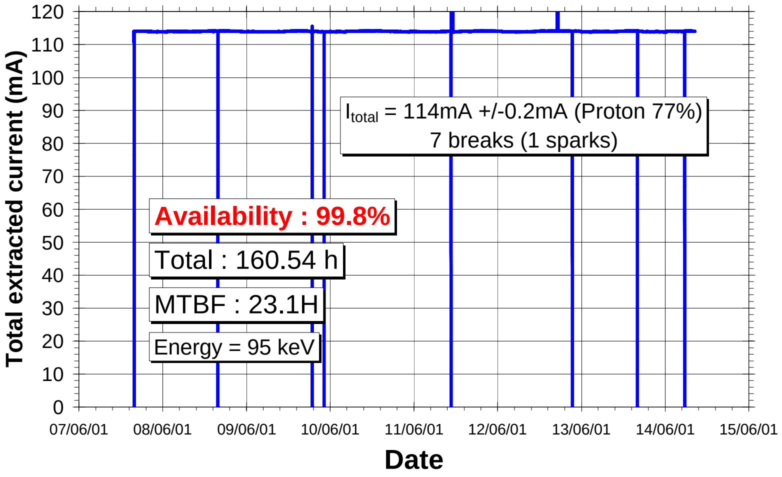

Figure 5 : New long run test.

The major difference was then the total beam current of 114 mA. We had about one spark par day. The MTBF was about 23 hours and the MTTR was about 2.5 min. Five of the seven beam trips were due to plasma interruption and not a real spark in the HV column. The control was modified to ensure a faster restart in such a case.

The most important point is that it reflected the "common" source behaviour. This meant that our feeling is that the present source configuration gives us about 1 spark a day, with no hardware destruction.

2.2.5 The second 4-weeks run

A four weeks run test has been started in October 5, 2001, according to the decision taken in March 2001, with the beam parameters reported in Table 2. It last in fact for a full 1 month through November 6 (744 hours).

For the new long run test, all beam characteristics were checked: beam intensity, proton fraction, emittance and beam noise. Again, in order to avoid LEBT activation, the tests are made with protons.

Parameters	Requests	Run Status
Energy [keV]	95	95
Proton extracted beam [mA]	100	≈ 96
Total extracted beam [mA]	110	120
Proton fraction [%]	> 90	≈ 80
Extraction aperture [mm]	9	9
Extracted beam density [mA/cm²]	156	185
Forward RF power [W]	Up to 1200	800
Duty cycle [%]	100	100
Hydrogen mass flow [sccm]	< 10	5.7
Beam noise (rms) [%]	< ± 1	± 0.95 max

Table 2 : SILHI long run requirements and run test parameters

233 sparks were recorded. The availability was equal to only 95%. One big problem occurs in the beginning: A non-foreseen stop occurs on the VME during the weekend and nobody was present to restart the source. 15 hours of down time results of that specific problem. The availability would have increase to 97% without this 15 hours down time.

	With the VME problem	Without the VME problem
Availability	95.0%	97.0%
MTBF	03:01:52	03:06:30
MTTR	00:09:34	00:05:44

Table 3 : SILHI source availability

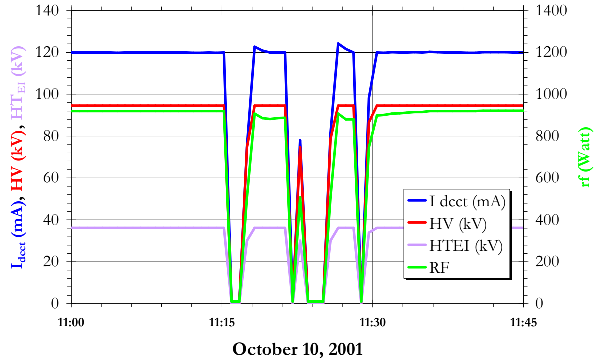

Figure 6 : classical multi-spark occurring during the 1 month run. The problem has been solve

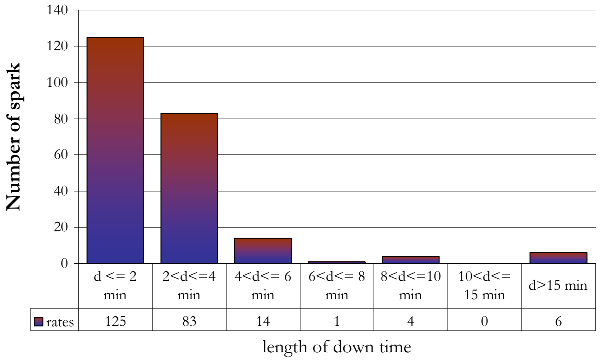

Figure 7 : Down time repartition

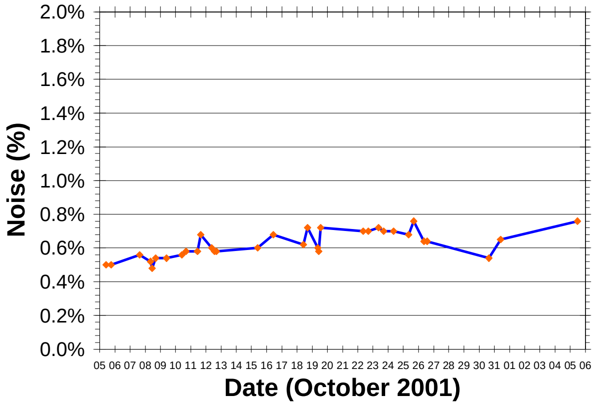

Figure 8 : Beam noise evolution during the 1 month run.

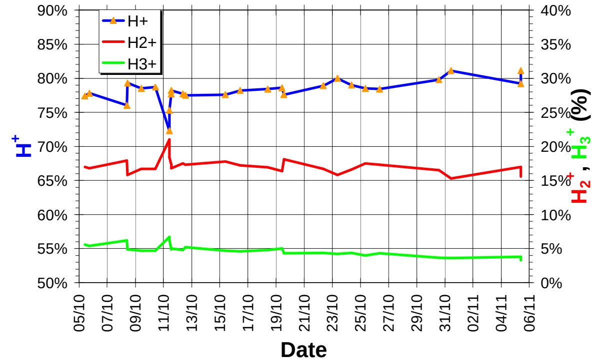

Figure 9 : Species fraction evolutions during the 1 month run.

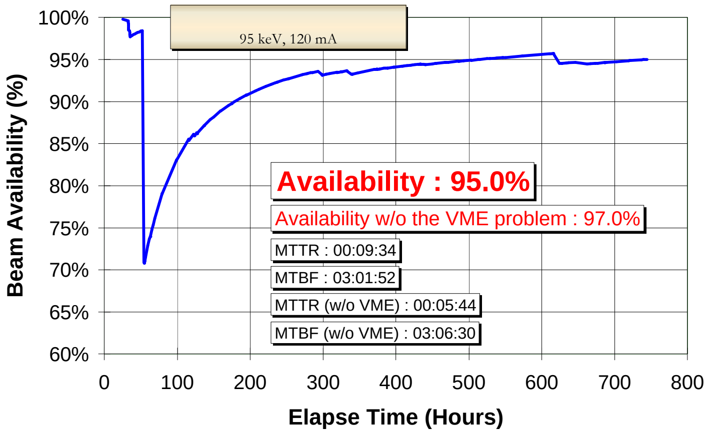

Figure 10 : Availability during the 1 month run.

2.2.6 Conclusions of the second 4-weeks run

Very good beam noise was achieved, but some concerns may still exist on the species fraction. We are working on that problem.

2.3 Beam Analyses produce by the ECR source – Subdeliverable 1b

2.3.1 Beam emittance

2.3.1.1 Emittance unit

The emittance measurement unit (EMU) is a single device able to handle up to 15kW of beam power on a 4 cm diameter spot. It is composed of a single aperture which defines the small beamlet (tantalum piece, ϕ=0.2mm). This beamlet is analyzed in angle on a wire about 10 cm behind through a Wien filter. This wire is equipped of a secondary electron suppressor.

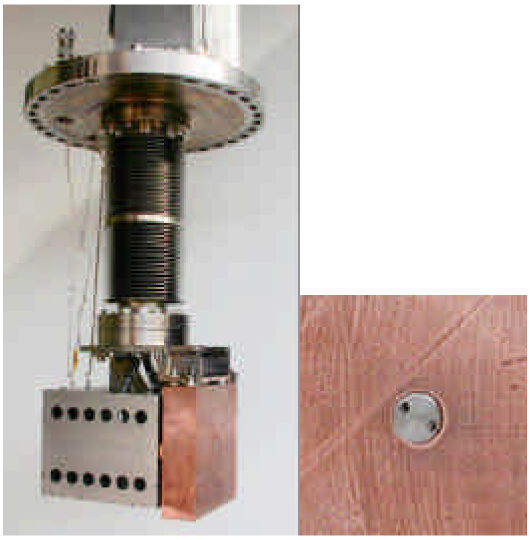

Figure 11 : EMU, and a zoom on the aperture.

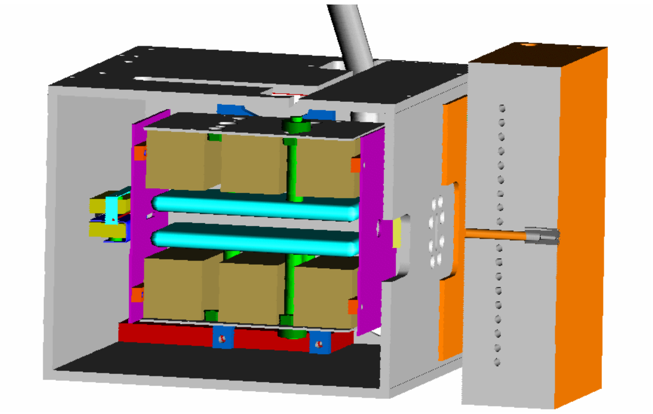

Figure 12 : 3D view of the Wien filter

The Wien filter allows measuring the proton or deuteron only emittance (or the D_2^+ or the D_3^+).

The principle of the measurement gives an r-r' result and not an x-x'. This choice was made in order to have better analyses of the emittance beam tail. Unfortunately we cannot easily calculate the x-x' value from the r-r' measurement. Some symmetry assumption has to be made in the x-y plane (easily verified with the CCD camera) and x'-y' plane (no measurement). The relation between the 2 measures is $2\times e_{x-x'} \geq e_{r-r'} \geq \sqrt{2}\times e_{x-x'}$. In every case, the x-x' value is smaller than the r-r' value.

2.3.1.2 Emittance measurement

The emittance can be measured at two locations. The first one is located just after the extraction system before the first solenoid (53 cm downstream the aperture). The second one is down the line at about the RFQ matching point (slightly further), 4.4 m downstream the aperture.

To characterize the SILHI proton beam, a 2 week emittance measurement campaign has been performed. The EMU also allows us species fraction measurements. So, proton fraction has been characterized for these emittance measurements. This campaign has been done with a 97 mA proton beam (120 mA total).

Emittance at the source exit

First, the emittance has been analyzed after the extraction system, as a function of the intermediate electrode voltage which modifies the extraction electric field configuration (Figure 13).

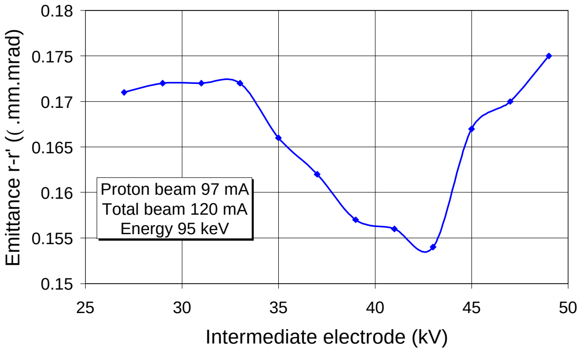

Figure 13 : Source emittance vs intermediate electrode voltage (1st puller electrode).

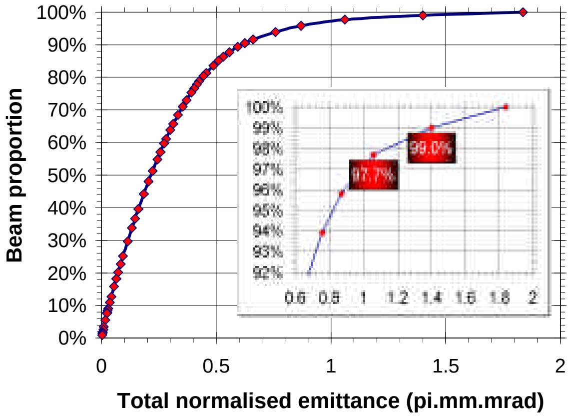

Figure 14 : Beam brightness.

Extraction simulations indicated a minimum emittance value for a 40 kV first gap extraction voltage which has been confirmed by the measurement. The r-r' rms normalized emittance value varies from 0.175 to 0.15 π.mm.mrad while the intermediate electrode voltage is going from 27 to 49 kV. The minimum value has been obtained for 43 kV.

From the RFQ point of view, total emittance is more important than rms emittance. The beam tail could results in more beam losses, even if the rms emittance value is within the required value. The beam brightness was calculated from the emittance value, and allows us to verify that 99% of the beam is included in 1.4 π.mm.mrad normalized (Figure 14). This value is below the 1.5 π.mm.mrad required for IFMIF.

Beam profile

The EMU can be used to reconstruct the beam profile. It is then a precise electrical measurement that can be compared with the CCD camera images. The Wien filter included in the EMU allow to extract the H^+ profile from the H_2^+ and H_3^+ profiles.

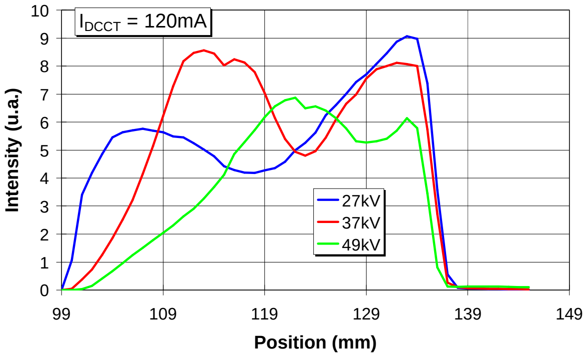

Figure 15 : Beam profile at the source exit as a function of the intermediate electrode settings.

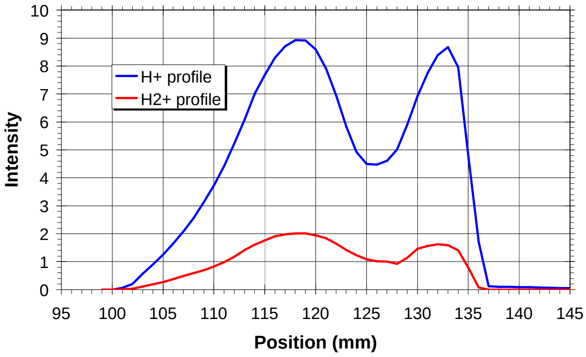

Figure 16 : H^+ and H_2^+ profile at the source exit.

It clearly appears that the beam is a hollow beam (donuts shape). This is also independent of the species.

Emittance at the LEBT exit

Then the EMU was moved to the second location. Emittance measurements were performed by tuning the intensity, the LEBT magnetic configuration and the intermediate electrode voltage. According the settings, the proton fraction ranged from 65 to 85 % and the total extracted current increased from 55 to 140 mA.

One of the main observation was that a badly tune LEBT leads to a big emittance growth. This kind of error are obtain with a strong cross-over in-between the 2 solenoids (Figure 17).

The beam emittance at the end of the LEBT depends dramatically on the LEBT solenoids values (Figure 19 and Figure 20) and looks quite stable by varying the extraction electric field configuration (Figure 18). This indicates a low influence of the extraction configuration. A minimum value of 0.23 π.mm.mrad has been observed downstream a cross over located at the future RFQ entrance for 70 mA transported proton beam.

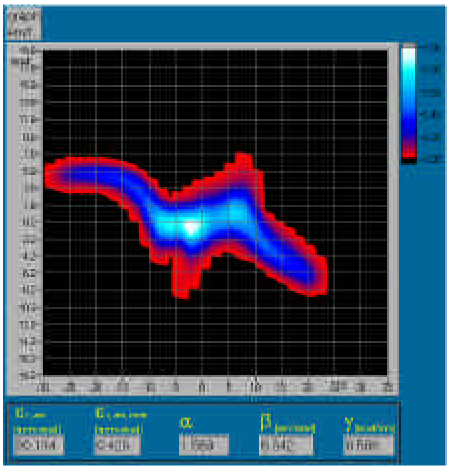

Figure 17 : Emittance after an extremely bad tuned LEBT