INTERMEDIATE COMMISSIONING RESULTS OF THE 70 mA/50 keV H^+ AND 140 mA/100 keV D^+ ECR INJECTOR OF IFMIF/LIPAc

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Abstract

The LIPAc accelerator aims to operate 125 mA/CW deuteron beam at 9 MeV to validate IFMIF's accelerators that will operate in CW 125 mA at 40 MeV. The different subsystems of LIPAc have been designed and constructed mainly by European labs and are being installed and commissioned in Rokkasho Fusion Center. The 2.45 GHz ECR injector developed by CEA-Saclay is designed to deliver 140 mA/100 keV CW D^+ beam with 99% gas fraction ratio. Its LEBT presents a dual solenoid focusing system to transport and match the beam into the RFQ. Its commissioning continues in 2016 in parallel with the RFQ installation. The normalized RMS emittance at the RFQ injection cone is to be within 0.25π mm·mrad to allow 96% transmission through the 9.81 m long RFQ. In order to avoid activation during commissioning, an equal perveance H^+ beam of half current and half energy as nominal with deuterons is used. In this article, the commissioning results with 110 mA/100 keV D^+ beam and 55 mA/50 keV H^+ beam are first reported.

INTRODUCTION

IFMIF (International Fusion Materials Irradiation Facility) is a projected ADS neutron source for qualifying fusion reactor materials. Its design performance will break through present accelerator technological frontiers with 125 mA/CW deuterium ion beam up to 40 MeV [1]. It is presently in its EVEDA (Engineering Validation and Engineering Design Activities) phase before construction. The validation of IFMIF accelerator is based on a challenging 125 mA/9 MeV CW deuteron accelerator called LIPAc (Linear IFMIF Prototype Accelerator) which is being assembled, commissioned and will be operated in Rokkasho [2, 3]. LIPAc has been designed and constructed mainly in European labs with participation of JAEA in the RFQ couplers. It is composed of an injector delivered by CEA-Saclay [4], a RFQ [5] delivered by INFN on April 2016, a superconducting Linac designed by CEA-Saclay [6], RF power, Medium and High Energy Beam Transfer lines and a beam dump designed by CIEMAT.

The injector is composed of a 2.45 GHz ECR ion source based on the CEA-Saclay SILHI source design [7] and a LEBT line that will transport and match the beam into the RFQ thanks to a dual solenoid focusing system with integrated H/V steerers. Its commissioning started in 2015 and will continue in 2016 interleaved with the RFQ installation in order to optimize the project schedule. Simulations show that to have less than 10% losses in the RFQ, the injected D^+ beam must be 140 mA/100 keV CW with a normalized RMS emittance of no more than 0.30π mm·mrad [8] (target of 0.25π mm·mrad for 4% of losses).

Commissioning activities use an equal perveance H^+ beam of half current and half energy as deuterons at nominal conditions to allow hands-on maintenance activities since the activation power of 50 keV protons is negligible. Moreover, an electrostatic chopper has been implemented in-between the two solenoids to provide sharp beam pulses of short length (~ 50-100 μs) for machine protection system in view of the RFQ commissioning.

Injector commissioning is divided into three phases. In phase A1, the emittance was measured between the two solenoids while it is measured just downstream the RFQ injection cone during phase A2 (this can only be possible in the absence of the RFQ from its positioning). In phase A3, we plan to measure the emittance just downstream the 5-electrode beam extraction system in order to characterize the source itself. The realization of this last phase is still under discussion. Results obtained during phase A1 have already been reported [9]. This paper presents thus the results of the injector commissioning performed during phase A2 with a first part devoted to the H^+ beam commissioning of 55 mA/50 keV in March 2016 (two weeks) and a second part to the D^+ beam commissioning of 110 mA/100 keV in December 2015 (one week). Commissioning was done with short beam pulses (use of the chopper) up to CW operation. To characterize the beam, several beam diagnostics were used [10].

SOURCE TUNING AND SPACE CHARGE

Broad experience has been gained in the tuning of plasma source parameters during the last year of beam commissioning. It was observed that several discrete

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plasma states exist which can strongly influence beam parameters such as emittance and the fraction ratio of species, i.e. mainly D^+, D_2^+ and D_3^+ (or H^+, H_2^+ and H_3^+) generated by the source and measured with a deported spectrometer and a fiberscope installed currently in-between the two solenoids of the LEBT.

RF power can be increased in order to increase the total extracted current and thus the current at the end of the LEBT measured by the beam stop (BS). Subsequently, it leads to a higher space charge which induces emittance growth and beam losses along the injector (inducing thus a decrease of the BS current). A compromise is required.

H^+ BEAM 55 mA/50 keV

Beam Characterization at 10% Duty Cycle

Up to now, the highest BS current obtained was of 55 mA with a total extracted current of 85 mA and a H+ fraction ratio of 73%. The current transmission of the H+ beam was thus high, i.e. of 89% along the LEBT up to the BS. To avoid a large beam divergence due to space charge, the first accelerating gap of the 5-electrode beam extraction system was set to a quite high value, i.e. 37 kV. Systematic measurements were performed to carefully characterize the best working point found up to now.

First, the BS current was measured as a function of the coils currents of the two solenoids (named SOL1, SOL2) in order to locate the area of maximum current transmission along the LEBT, see Fig. 1.

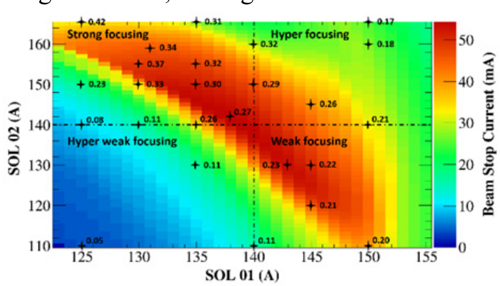

Figure 1: BS current and emittance measured as a function of SOL1&2 at the best working point found up to now.

Emittance was then measured at 25 couples of SOL1 & SOL2 (see values in π mm·mrad on Fig. 1) and Fig. 2 overlaps the results with an emittance contour plot (crosses indicate measured points). The BS current lines are added in Fig. 2 from data of Fig. 1. Both simulations and measurements show that the emittance is the highest in the strong focusing area and that it decreases from the strong to the weak focusing area. The boundary delimiting an emittance of 0.30π mm·mrad was found and is plotted in Fig. 2. According to extensive simulations [11], the Twiss parameters should be the best matched for the RFQ somewhere in the strong focusing area. For an ideal machine (e.g. with a perfect alignment), simulations predict that the Twiss parameters are the best matched in the upper left zone of the strong focusing area. In the real life, there are however uncertainties about the accurate location of the best matched Twiss parameters inside the strong focusing area. There may be thus a compromise between a low emittance, well matched Twiss parameters and high BS currents. However, new simulations are on-going based on these extensive measurements (including beam potential measurements) to determine more accurately the area of well-matched Twiss parameters.

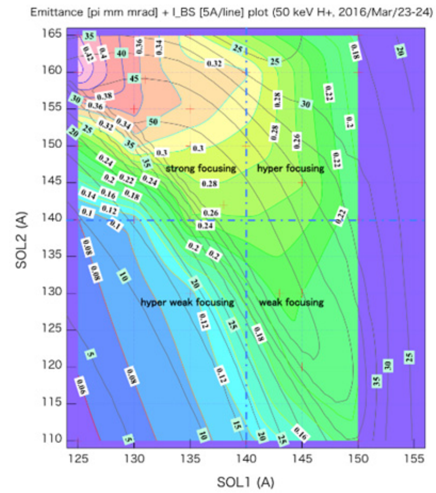

Figure 2: Emittance contour plot from the emittance values shown on Fig. 1 + BS current lines from data of Fig. 1.

Study at High Duty Cycle up to CW Operation

The duty cycle was increased step by step up to CW operation. By keeping constant the RF power at each step, it was observed that the emittance and the H^+ fraction ratio was degrading with the increase of duty cycle. The plasma needs probably more RF power to keep the same characteristics when the duty cycle is increased. In the near future, the RF power will be increased while the H_2 gas flow will be adjusted consequently to find an equilibrium in the plasma. In this way, it is hoped that the plasma conditions will not change. Moreover, Krypton gas will be injected at high duty cycle to observe if the emittance decreases due to a better space charge compensation.

D^+ BEAM 110 mA/100 keV

Operation from 10% to 50% Duty Cycle

Fine tunings of the injector parameters were performed at 20% duty cycle and the best beam parameters obtained up to now are reported on Table 1 for a given beam focalization (SOL1= 277 A; SOL2= 270 A). The duty cycle was then increased up to 50% and the source parameters were slightly tuned to get a stable extracted current. Especially, D_2 gas flow and RF power were increased. The results at 50% duty cycle are also reported on Table 1. It was not possible at this time to go higher in duty cycle due to technical problems but a complete beam characterization will be performed this year up to CW operation.

Measured fraction ratio of D^+ is very high at least at 20% duty cycle, which confirms that the injector design is very well optimized for deuteron.

For a BS current of around 110 mA, the emittance is under specifications at 20% and 50% duty cycle even though it was higher at 50% duty cycle. BS currents higher than 110 mA were reached by increasing the RF power, but the emittance was then growing due to space charge.

Table 1: Best Beam Parameters Measured at 20% and 50% Duty Cycle for SOL1= 277 A and SOL2= 270 A

Duty cycle [%]	**20**	**50**
Extracted current [mA]	150	158
BS current [mA]	112	108
Norm. ε [π mm.mrad]	0.23	0.31
D^+ / D_2^+ / D_3^+ ratio [%]	92 / 5 / 3	Not measured

BS current was measured as a function of SOL1 & SOL2 at 10% duty cycle, see Fig. 3. The area of maximum current transmission along the LEBT was large with a highest current of 115 mA. Recent simulations predicted that the Twiss parameters are the best matched somewhere in the strong focusing area but the emittance was measured at that time in the weak focusing area (see Fig. 3). Measurements will be thus repeated this year at several couples of SOL1&2 to define a safe range of solenoids coils currents in view of the RFQ commissioning.

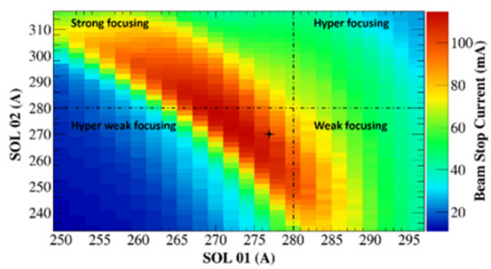

Figure 3: BS current measured as a function of SOL1 & SOL2 at 10% duty cycle; Highest current of 115 mA.

Chopper Operation with Beam Pulses of 100 µs

The chopper was operated to provide beam pulses of 100 µs for a source pulse of 2 ms (repetition rate of 60 ms). The BS current was measured with and without Krypton gas injected in-between the two solenoids of the LEBT, see Fig. 4. The first 10 µs of rising time corresponds to the one of the high voltage power supply of the chopper plates but the rising time of beam pulses is then long, of around 200 µs. Injection of Krypton gas slightly reduced its slope which suggests that it corresponds to the transient time of space charge compensation (SCC). In fact, inside the second diagnostic chamber where the emittance meter and the BS is installed, the vacuum level is around ten times lower than upstream (~10^{-7} torr) and the time of SCC corresponds to few hundreds of µs, compared to few tens of µs upstream. Modifications will be given in order to be able to inject this year Krypton gas in the second diagnostic chamber and to improve SCC. A much shorter rising time of beam pulses is thus expected.

At SOL1= 292 A and SOL2= 250 A, the emittance of the chopped beam of 100 µs was then measured with and without Krypton gas injected in-between the two solenoids for different delays of the chopper gate along the source pulse of 2 ms, see Fig. 5. The emittance increased by 11% along the source pulse and was lowered by 6% to 10% with Krypton gas. Since the emittance was measured probably during the transient time of SCC, the injection of Krypton gas inside the second vacuum chamber may lead to a lower emittance. More beam time will be allocated this year to continue the operation with the chopper.

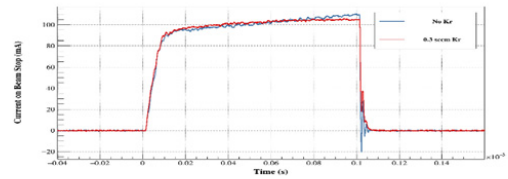

Figure 4: BS current of a chopped beam of 100 µs (source pulse of 2 ms) with and without Krypton gas injection. (SOL1&2 = 292&250 A).

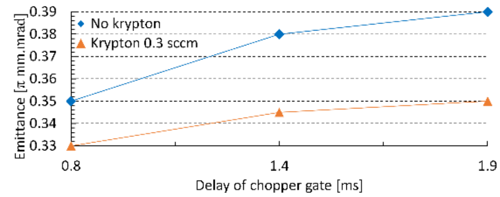

Figure 5: Emittance of the chopped beam of 100 µs with and without Krypton gas for different delays of the chopper gate along the 2 ms source pulse (SOL1&2= 292&250 A).

CONCLUSION

During the two weeks of H^+ beam commissioning in March 2016 (phase A2), high BS currents up to 55 mA could be obtained. A working point was found at 10% duty cycle with eventually a compromise between a low emittance, well matched Twiss parameters and high BS currents. A study up to CW operation suggested that the source parameters should be re-optimized with the increase of duty cycle in order to keep the same plasma conditions. More time will be devoted for CW operation.

D^+ beam commissioning performed during one week in December 2015 (phase A2) gives very encouraging results since the emittance was under specification at 20% and 50% duty cycle for high BS currents of 110 mA. These results should however be confirmed from chopper operation up to CW operation in the area where the Twiss parameters should be the best matched for the RFQ.

The LIPAc injector has been designed for producing high intensity 100 keV D^+ beam. Operating this one with H^+ beam at half current and half energy leads to largely lower plasma density and explains the difference between H^+ and D^+ beam extraction and transport at low energy.

So, H^+ and D^+ beam commissioning will continue in 2016 from chopper operation up to CW operation with the ambition to reach BS currents up to 70 mA for H^+ and up to 140 mA for D^+ while keeping the emittance below 0.30π mm·mrad with well-matched Twiss parameters.

REFERENCES

[1] J. Knaster et al, Nuclear Fusion 55 (2015) 086003.
[2] P. Cara et al, Proc. IPAC 2016, MOPOY057, Busan.
[3] A. Mosnier et al, IPAC 2012, THPPP075, New Orleans.
[4] R. Gobin et al, Proc. IPAC 2013, THPWO003, Shanghai.
[5] M. Comunian et al, Proc. LINAC 2008, MOP036, Victoria.
[6] H. Dzitko et al, Proc. IPAC 2015, THPF006, Richmond.
[7] R. Gobin et al, Rev. Sci. Instrum., 79 (2008) 02B303.
[8] M. Comunian et al, IPAC 2011, MOPS031, San Sebastián.
[9] Y. Okumura et al, Rev. Sci. Instrum., 87 (2016) 02A739.
[10] B. Bolzon et al, Proc. IBIC 2015, TUPB008, Melbourne.
[11] L. Bellan et al, Proc. LINAC 2016, 2041, East Lansing (to be published).

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