INTERMEDIATE COMMISSIONING RESULTS OF THE REQUIRED 140 mA/100 keV CW D^+ ECR INJECTOR OF LIPAC, IFMIF'S PROTOTYPE

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Abstract

The LIPAc accelerator aims to operate in Rokkasho Fusion Institute a 125 mA/CW deuteron beam at 9 MeV to validate the concept of IFMIF's accelerators that will operate in CW 125 mA at 40 MeV. The 2.45 GHz ECR injector developed by CEA-Saclay is designed to deliver 140 mA/100 keV CW D^+ beam with 99% D^+ fraction ratio. Its LEBT relies on a dual solenoid focusing system to transport and match the beam into the RFQ. The normalized RMS emittance at the RFQ injection cone is required to be within 0.25π mm·mrad to allow 96% transmission through the 9.81 m long RFQ. An equal perveance H^+ beam of half current and half energy as nominal with D^+ is expected to be used to avoid activation during commissioning. The injector commissioning at Rokkasho is divided into three phases to characterize the emittance between the two solenoids of the LEBT (A1) and just downstream the RFQ injection cone (A2) and the extraction system of the source (A3). Phase A1 has been achieved and phase A2 continues in 2016 in order to reach the required beam parameters and to match the beam into the RFQ. This paper reports the commissioning results of phase A1 and the intermediate ones of phase A2 for H^+ and D^+ beams.

INTRODUCTION

IFMIF (International Fusion Materials Irradiation Facility) is a projected accelerator-driven-type neutron source for qualifying fusion reactor materials. It is characterised by its beam current frontier accelerator producing two sets of 125 mA/CW deuterium ion beams up to 40 MeV [1]. The current EVEDA (Engineering Validation and Engineering Design Activities) phase is developed to validate the IFMIF accelerator with a challenging 125 mA/9 MeV CW deuteron accelerator called LIPAc (Linear IFMIF Prototype Accelerator). LIPAc was designed and constructed mainly by European laboratories with the participation of QST in the RFQ couplers and the control system. It is being assembled, commissioned and will be operated at Rokkasho [2, 3]. It is composed of an injector delivered by CEA-Saclay [4], a RFQ [5] delivered by INFN on April 2016, a superconducting SRF 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 to transport and match the beam into the RFQ using a dual solenoid focusing system with integrated H/V steerers. Its commissioning started in November 2014 at Rokkasho and continues in 2016 interleaved with the RFQ installation to optimize the project schedule. It has to deliver to the RFQ 140 mA/100 keV CW D^+ beam to meet LIPAc requirements. Moreover, simulations showed that the normalized RMS emittance at the RFQ injection cone has to be no higher than 0.30π mm·mrad [8] with well-matched Twiss parameters in order to minimize losses to less than 10% in the RFQ (target of 0.25π mm·mrad for 4% of losses).

Commissioning program plans to use an equal perveance H^+ beam of half current and half energy as deuterons at nominal conditions to avoid activation and ease maintenance activities. However, it has to be stressed that the injector design has been optimized to produce high intensity 100 keV D^+ beam. In terms of beam extraction and transport at low energy, the performance of the injector can thus be lower by operating this one with 70 mA/50 keV H^+ beam due to lower plasma density.

The injector commissioning is divided in different phases. During phase A1, the emittance was measured in the first diagnostic chamber located between the two solenoids of the LEBT while it is measured in the second diagnostic chamber located downstream the RFQ injection cone at phase A2 (for both phases, the RFQ cannot be placed at its final position). The realization of a third phase A3, where the emittance is measured just downstream the 5-electrode beam extraction system to characterize the source itself, is still under discussion.

This paper presents the results of phase A1 with D^+ beam (completed at the beginning of September 2015) and the intermediate ones of phase A2 with D^+ and H^+ beams. In view of machine protection system during the RFQ commissioning, the injector was operated at low duty cycle with sharp beam pulses down to 100 µs length (use and test of an electrostatic chopper) up to CW operation. The different diagnostics of the injector used to characterize the beam are described in [9].

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PHASE A1 WITH 100 keV D^+ BEAM

Plasma Electrode of 10 mm Diameter

Phase A1 commissioning started with the use of a plasma electrode of 10 mm diameter to limit the maximum current that can be extracted as a first step.

After enough ion source conditioning at high duty cycle with a beam, the ECR coils currents (COIL1, COIL2) and the tuners of the source can be optimized to maximize the plasma efficiency, i.e. the extracted current for a given RF power. Figure 1 shows the measured extracted current which increased with the increase of ECR coil 1 current for a RF power of 700 W. Plasma discharges appeared at higher coil 1 currents but the operation range of the coils currents allowing a stable plasma became wider day after day with high duty cycle conditioning of the ion source.

By adjusting also carefully the flow rate of D_2 gas injected into the ion source chamber, the extracted current can increase linearly with the injected RF power, see Fig. 5. Beam currents up to 113 mA were extracted at 1000 W of injected RF power with a very similar plasma efficiency at low (40%) and high duty cycle (91%). This corresponds to 158 mA for hydrogen (113 mA × $\sqrt{2}$), which is very similar to the plasma efficiency obtained during the proton beam operation at 100 keV.

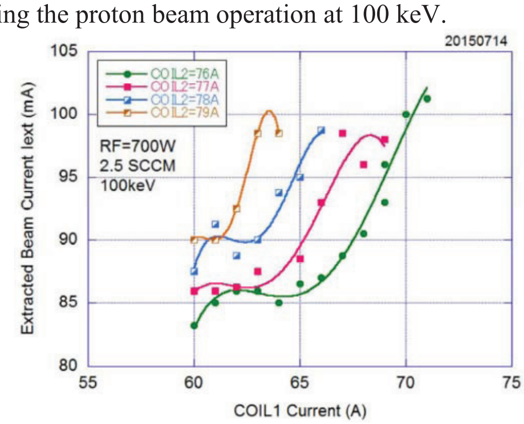

Figure 1: Optimization of the ECR coils currents in order to maximize the plasma efficiency for D^+ beam operation.

The voltage of the first accelerating gap (VIE) of the 5-electrode beam extraction system has to be optimized in order to minimize the beam divergence at the exit of the extraction system, and to avoid thus emittance growth. It exists an optimum VIE for a given extracted current. For instance, the emittance could be minimized down to 0.11π mm·mrad with VIE around 30-35 kV and for an extracted current of 105 mA (9.5% duty cycle), see Fig.2.

The D^+ fraction ratio was measured with two diagnostics, the Doppler-shifted spectroscopy and the Allison scanner (Emittance Measurement Unit - EMU). With this last device, the D^+ fraction ratio is estimated by integrating the emittance diagram of each ion species (mass separation measurement) [9]. With both diagnostics, it was shown experimentally that the D^+ fraction ratio increases usually with the extracted current or the plasma density in the ECR ion source [10]. It reached already a high value of 93% (mass separation measurement) for the extracted current of 105 mA at 9.5% duty cycle, which confirms that the injector design was well optimized for 100 keV D^+ beam.

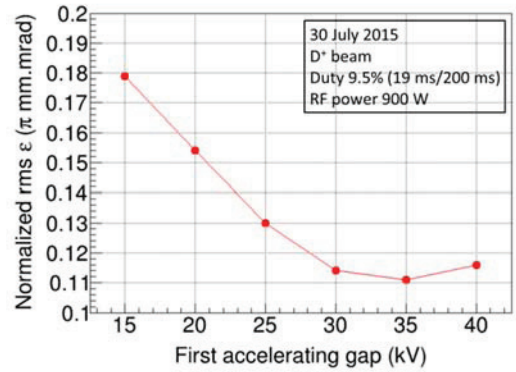

Figure 2: D^+ beam emittance as a function of the first accelerating gap voltage for an extracted current of 105 mA.

The duty cycle was increased step by step up to CW operation with an extracted current of around 65-75 mA to study if the beam characteristics remain the same while keeping the same injector parameters. Emittance increased significantly with the duty cycle when the flow rate of D_2 gas injected into the ion source chamber was kept low. However, the emittance degradation up to CW operation was reduced when the gas flow rate was increased, see Fig. 3. This trend of emittance growth with the duty cycle may be connected to various experimental conditions (including starting conditions).

The emittance could be improved at high duty cycle (only) by injecting Krypton gas between the two solenoids of the LEBT, see Fig. 3. Moreover, space potential measurements of the beam plasma were performed with the 4-Grid Analyzer (FGA) device located between the two solenoids of the LEBT. Measurements were performed at 9.5% and at 80% duty cycle where it was observed a significant degradation of the emittance. The D_2 gas flow rate was kept to 2.1 sccm for both duty cycles. The extracted current was lower at 80% duty cycle, i.e. 72 mA compared to 85 mA at 9.5% duty cycle. The space charge potential was centred on 11 eV at 10% duty cycle. It increased to 16 eV at 80% duty cycle but it decreased to less than 10 eV with Krypton gas injection, see Fig. 4. Space charge was thus compensated at high duty cycle.

A study of neutrons yield from D-D reactions in the LEBT is reported in [11] as a function of the duty cycle.

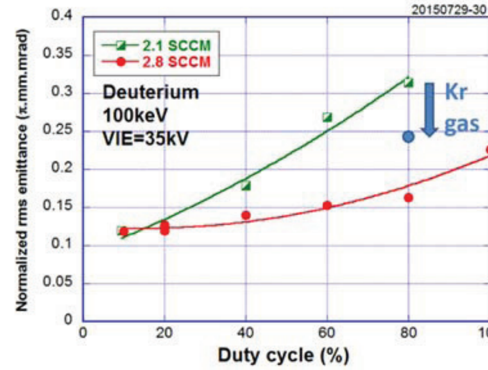

Figure 3: Emittance of D^+ as a function of duty cycle for two different D_2 gas flow rates and with Krypton injection.

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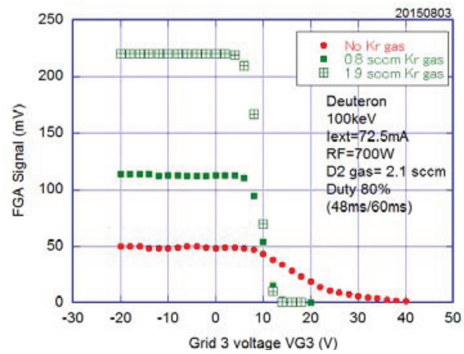

Figure 4: Measured Faraday cup signal in the FGA showing the space potential of the beam plasma (D^+ beam) with and without Krypton gas injection at 80% duty cycle.

Plasma Electrode of 12 mm Diameter

After enough experience taken on the injector behaviour, a plasma electrode of 12 mm diameter was installed.

From a plasma electrode of 10 mm diameter to one of 12 mm diameter, the extracted current should increase following the extraction surface factor (i.e. 1.44). After optimizing the plasma source parameters, currents as high as 186 mA could be extracted with an injected RF power of 950 W at 9.8% duty cycle, which is more than 1.44 times higher than the currents obtained with the plasma electrode of 10 mm diameter at 91% duty cycle. In Fig. 5, the extracted current was measured as a function of the injected RF power for a plasma electrode of 10 mm and of 12 mm. For a plasma electrode of 12 mm diameter, the measurements were done at three different dates, showing that the plasma efficiency was improving with ion source conditioning.

For an extracted current of 153 mA at 9.5% duty cycle, the emittance was minimized down to 0.27π mm·mrad between the two solenoids of the LEBT (VIE= 40 kV). This measurement was performed by maximizing the beam current transmission through the RFQ injection cone with the coils currents of the two solenoids of the LEBT (SOL1= SOL2= 280 A). Under this condition, D^+ ion beam is focused while D_2^+ and D_3^+ ion beams are divergent, see Fig. 6. The analysis of emittance data with the presence of three ion species is described in [9]. The D^+ ratio was of 90% (mass separation measurement) and the current measured on the Faraday cup (located between the two solenoids) was of 134 mA.

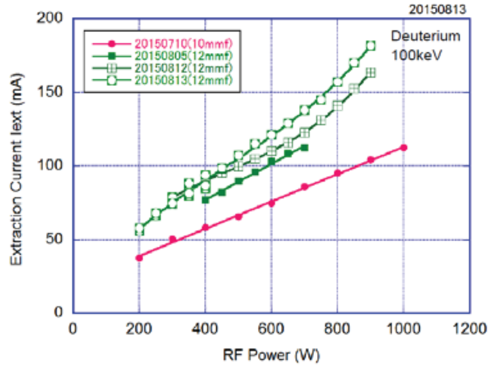

Figure 5: Extracted current as a function of the injected RF power for a plasma electrode of 10 mm and of 12 mm (D^+).

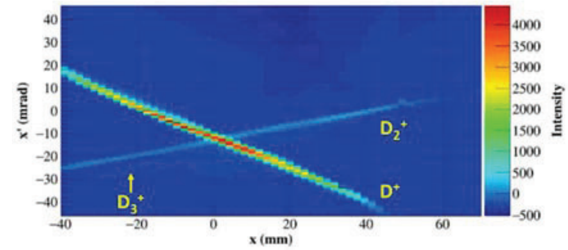

Figure 6: Raw emittance data of D^+, D_2^+ and D_3^+ beams for an extracted current of 153 mA at 9.5% duty cycle.

PHASE A2: IMPROVEMENTS TO BRING

Space Charge Compensation After RFQ Cone

A study of space charge compensation was done with 50 keV H^+ beam at 10% duty cycle (extracted current of 86 mA) in the second diagnostic chamber. In fact, the vacuum level is more than ten times lower at this location than in the first diagnostic chamber. By increasing the pressure inside the second diagnostic chamber (shutdown of the turbomolecular pump of this chamber), the emittance decreased of 20%. This study was performed for three very different beam focalizations to confirm the reproducibility of the results. Compensation of space charge thus occurred at least partially. In Fig. 7 and Fig. 8, the measured emittance diagrams are plotted (background subtracted) with respectively low pressure and higher pressure (SOL1= 134 A and SOL2= 145 A).

Unfortunately, this test was done very recently and all the other measurements were performed with low vacuum level in the second diagnostic chamber. The results presented in this paper can be thus most probably improved simply by increasing this vacuum level. In fact, the emittance has to be within specifications at the RFQ entrance and the EMU is placed ~300 mm downstream from it. For the next commissioning campaign in October 2016, modifications will be done in order to be able to inject D_2 / H_2 gas and Krypton gas directly into this diagnostic chamber and to know the real emittance value at the RFQ entrance.

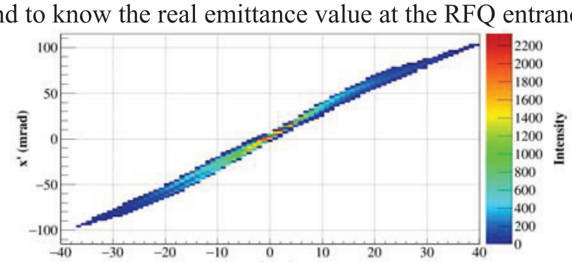

Figure 7: Emittance data without space charge compensation in the second diagnostic chamber (50 keV H^+ beam).

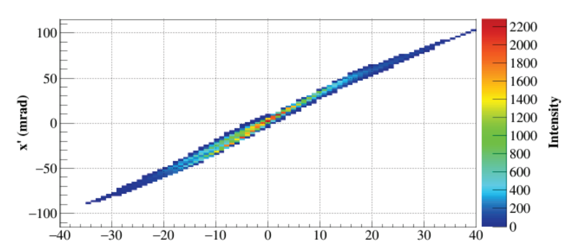

Figure 8: Emittance data with space charge compensation in the second diagnostic chamber (50 keV H^+ beam).

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Improvement of Current Measurement on BS

In this article, results of currents measured on the beam stop (BS) are from electrical measurements (same principle as for a Faraday cup), which can be tricky with such an injector. Although a repeller electrode for electrons is located just upstream the end of the RFQ cone, the results of currents may be underestimated due to secondary electrons hitting the self-biased BS. These electrons can be generated by the interaction of the beam with the end of the cone and with the second diagnostic chamber [9]. In addition, autopolarisation of the BS leads to the modification of the electron trapping in the second diagnostic chamber. A magnetic secondary electrons suppressor will be thus added for the next commissioning campaign.

A calorimetric measurement system at the BS was available but modifications were needed to get sufficient resolution especially at low duty cycle. In the next campaign, the improved calorimetric measurement system will be commissioned [12] and results will be cross-checked with the ones of electrical measurements.

PHASE A2 COMMISSIONING

Commissioning with 100 keV D^+ Beam

Commissioning of phase A2 with 100 keV D^+ beam was performed with a plasma electrode of 12 mm diameter in order to extract enough current and to reach the requirements at the entrance of the RFQ.

For an extracted current of 150 mA, the BS current was measured at 10% duty cycle as a function of SOL1 & SOL2 after adjusting finely the injector parameters (see Fig. 9). The emittance was measured at three settings of SOL1 & SOL2 (with the same injector parameters) in the weak focusing area at 10% duty cycle (VIE= 43 kV). It was under specifications while the BS current was of 104-112 mA, see Fig. 9 which reports the emittance values in π mm·mrad. However, the Twiss parameters should be the best matched for the RFQ somewhere in the strong focusing area according to recent simulations [13]. In the next commissioning campaign, the emittance will be measured also in this area with as objective to keep it within specifications. With the Doppler-shifted spectroscopy, D^+ ratio was measured to be of 92%, D_2^+ ratio of 5% and D_3^+ ratio of 3%. D^+ ratio measurements give the same results with the Doppler-shifted spectroscopy and the EMU (mass separation measurement) at 100 keV (see the results reported for phase A1 with the same extracted current of ~ 150 mA). This gives thus confidence on these results.

A study at high duty cycle was also performed. The emittance was measured at 50% duty cycle (SOL1= 277 A and SOL2= 270 A) and was of 0.31π mm·mrad for an extracted current of 158 mA (BS current of 108 mA). Unfortunately, HV breakdowns occurred at that time and prevent to continue this study. High duty cycle operation will be done in the next campaign up to CW operation.

Experimental data show that the emittance tends to increase with the extracted current. Higher BS currents were obtained with higher extracted currents but the emittance was over specifications. These experiments need to be however repeated in the next campaign with calorimetric measurements (and electrical measurements using a magnetic secondary electrons suppressor) and with D_2 or Krypton gas injection into the second diagnostic chamber.

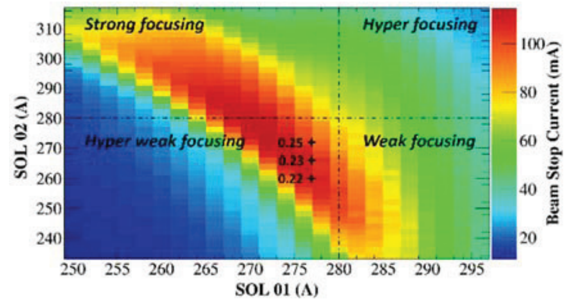

Figure 9: BS current as a function of SOL1 & SOL2 and emittance measured at 3 settings of SOL1 & SOL2 (D^+).

The electrostatic chopper was operated to provide sharp beam pulses of 100 μs for source pulses of 2 ms (repetition rate of 60 ms). Figure 10 shows the chopped beam current measured on the BS, the source pulse, the voltage supplied to the chopper plate and the chopper gate signal.

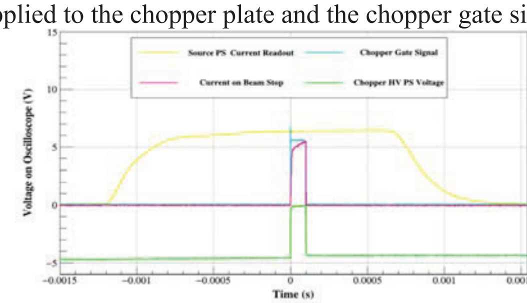

Figure 10: Chopped beam current of 100 μs measured on the BS (purple curve), source pulse of 2 ms (yellow curve), voltage supplied to the chopper plate (green curve) and signal of the chopper gate (blue curve).

Commissioning with 50 keV H^+ Beam

Commissioning with 50 keV H^+ beam used a plasma electrode of 10 mm diameter since only half of the current is required compared to 100 keV D^+ beam.

The highest currents obtained on the BS were of 55 mA (10% duty cycle) but these results have to be cross-checked with calorimetric measurements (and electrical measurements using a magnetic secondary electrons suppressor). To maximize BS currents, extracted currents had to be set to values no higher than 85 mA to avoid beam losses due to large beam divergence. Also, the plasma parameters were carefully tuned in order to obtain a quite high H^+ fraction ratio of 73%. Note that this measurement was done with Doppler-shifted spectroscopy, which gave a lower H^+ fraction ratio at 50 keV respect to the 100 keV. Investigations are on-going about that.

The emittance was measured at 10% duty cycle for an extracted current of 85 mA and was under specifications in the weak focusing area (VIE= 37 kV). However, the emittance increased from the weak to the strong focusing area as predicted by simulations and it was below 0.30π mm·mrad in only half of the strong focusing area. Figure 11 summarizes these results with the BS current

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measured as a function of SOL1 & SOL2. On the same plot, the results of emittance measured at 25 settings of SOL1 & SOL2 are reported with as units π mm·mrad. In Fig. 12, the results of emittance are overlapped with an emittance contour plot (measured points are indicated by crosses) and the boundary delimiting an emittance of 0.30π mm·mrad is plotted. By injecting H_2 or Krypton gas into the second diagnostic chamber, the emittance can be probably reduced and may be within specifications for any settings of SOL1 & SOL2. During the RFQ commissioning, there will be in this case no limitations to find the best matched Twiss parameters which should be located in the strong focusing area as reported previously.

A study up to CW operation showed that the emittance and the H^+ fraction ratio were degrading with the increase of duty cycle. However, the emittance may be recovered at least partially at high duty cycle by injecting Krypton gas into the first diagnostic chamber as it was observed for D^+ beam in phase A1. Krypton gas injection into the second diagnostic chamber at high duty cycle may also help to recover the emittance obtained at low duty cycle.

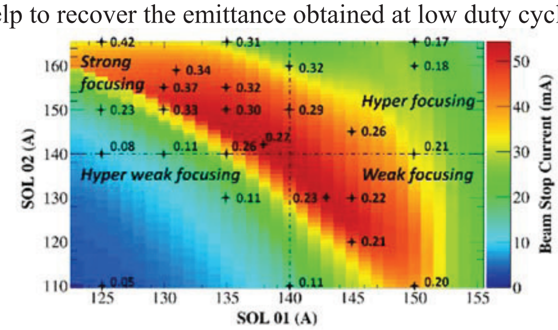

Figure 11: BS current as a function of SOL1 & SOL2 and emittance measured at 25 settings of SOL1 & SOL2 (H^+).

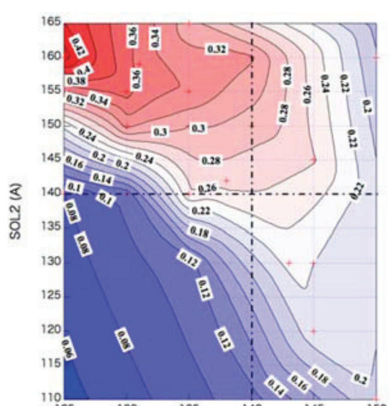

Figure 12: Emittance contour plot as a function of SOL1 & SOL2 from the emittance values reported on Fig. 11 (H^+).

CONCLUSION

Intermediate results of phase A2 commissioning of 100 keV D^+ and 50 keV H^+ beams reported an emittance within specifications for BS currents of 110 mA and 55 mA respectively (electrical measurements) at 10% duty cycle. For H^+ beam, these results were valid for any settings of SOL1 & SOL2 maximizing the current transmission except in half of the strong focusing area (best matched Twiss parameters for the RFQ according to recent simulations). For D^+ beam, the emittance was measured only in the weak focusing area and BS currents higher than 110 mA were obtained by increasing the extracted current but the emittance was then over specifications.

Very recent experiments showed that by increasing the pressure in the second diagnostic chamber, the emittance decreased by 20% due to space charge compensation. The results reported in this article can be thus improved. In fact, it is to be stressed that the EMU is placed ~300 mm downstream from the RFQ entrance, where the emittance values are to be within specifications.

The emittance and the H^+/D^+ fraction ratio were degraded with the increase of duty cycle. However, commissioning results of phase A1 with D^+ beam showed that the emittance was improved at high duty cycle by injecting Krypton gas between the two solenoids of the LEBT. Injecting Krypton gas (or D_2 / H_2 gas) into the second diagnostic chamber at high duty cycle may also help to retrieve the emittance obtained at low duty cycle.

The LIPAc injector has been designed to produce 100 keV D^+ beam of high intensity. H^+ beam operation at half current and half energy can lead to lower plasma density and can explain the difference of extraction and of transport at low energy between H^+ and D^+ beams.

In October 2016, commissioning of H^+ and D^+ beams will thus continue with the objective to reach the requirements at the RFQ entrance from chopper operation up to CW operation with well-matched Twiss parameters. To achieve this goal, injection of Krypton gas (or D_2 / H_2 gas) into the second diagnostic chamber will be possible to learn the real emittance value at the RFQ entrance. Also, a calorimetric BS measurement system of high resolution is now available and a magnetic secondary electrons suppressor will be added to the electrical BS measurement system. Results of electrical and calorimetric measurements will be compared in the next campaign.

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