DEUTERON BEAM COMMISSIONING OF THE LINEAR IFMIF PROTOTYPE ACCELERATOR ION SOURCE AND LEBT

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Abstract

During the EVEDA (Engineering Validation and Engineering Design Activities) phase of the IFMIF (International Fusion Materials Irradiation Facility) project, a 125 mA/9 MeV prototype accelerator (LIPAc) has to be built, tested an operated in Rokkasho-Mura (Japan). Involved in this project for several years, CEA/Saclay designed the injector of this accelerator which is composed by an ECR ion source, delivering a 140 mA deuteron beam at 100 keV, and a low energy beam transport (LEBT) line to match the beam for the injection into the RFQ. In this paper, the components of the LIPAc injector are described. The commissioning of the ion source and LEBT with beam started in November 2014. The different phases of the commissioning are explained and some noticeable experimental results obtained with a D^+ beam at 100 keV are presented.

1. INTRODUCTION

The International Fusion Materials Irradiation Facility will produce a high flux (10^{18} n.m^{-2}.s^{-1}) of 14 MeV neutrons dedicated to characterization and study of candidate materials for future fusion reactors. A solution based on two high power cw 175 MHz accelerator drivers, each delivering a 125 mA deuteron beam at 40 MeV to a liquid lithium target, is foreseen [1]. Before building such challenging machines, a first phase, called EVEDA, was planned to develop and test a 125 mA cw/9 MeV deuteron Linear IFMIF Prototype Accelerator (LIPAc) which is being assembled, tested and operated at Rokkasho-Mura, in Japan [2]. This accelerator is first composed by an ECR ion source and a low energy beam transport (LEBT) line that are both described in the next section. Then, a 175 MHz Radio-Frequency Quadrupole (RFQ) [3] bunches and accelerates the beam to 5 MeV. A Medium Energy Beam Transport section [4] is designed to optimise the D^+ injection into a superconducting radio-frequency (SRF) linac (based on Half Wave Resonator cavities) that will accelerate the beam to 9 MeV [5]. Finally, a high energy beam transport line [6] will drive the beam though a diagnostic plate, to fully characterise it, and will send it to a beam dump.

2. LIPAC ION SOURCE AND LEBT LAYOUT

The purpose of the ion source and the LEBT [7] (also called "injector") is to produce a 140 mA/100 keV deuteron beam and to transport and match it for its injection into the next accelerating section which is a RFQ. At the end of the LEBT, the transverse normalized RMS emittance has to be lower than 0.3π mm.mrad (with a target value of 0.25π mm.mrad) in order to reach the optimal beam transmission through the RFQ.

The LIPAc injector (see Fig. 1) was built and tested at CEA-Saclay and then was shipped to Japan in 2013 where it was more extensively commissioned.

2.1. Ion Source

The LIPAc Electron Cyclotron Resonance ion source, based on the SILHI design, is operated at 2.45 GHz. This source has been optimized to extract, at 100 keV, a total beam intensity from 150 mA to 175 mA in order to meet the required 140 mA of D^+, as D_2^+ and D_3^+ are also produced by the ECR plasma. The ion source has also to provide a 50 keV/70 mA proton beam (same perveance as the above mentioned D^+ beam) that will be used to perform the commissioning of the RFQ and the SRF-linac while minimizing the machine activation.

A five electrodes extraction system has been designed to minimize the beam divergence while keeping a maximal electric field below 95 $kV.cm^{-1}$ in order to reduce possible high voltage breakdown. The first electrode is called plasma electrode, is located at the end of the plasma chamber and consequently is at the same potential of the ion source (100 kV). The diameter of its extraction hole can be modified from 6 mm to 12 mm depending on the total beam intensity that has to be extracted.

Then, a so-called intermediate electrode is used to extract the beam from the plasma chamber. The voltage applied on this electrode can be finely tuned in order to adjust the potential difference in first extraction gap (from 14 to 40 kV) to optimize the beam divergence. The role of this electrode is critical for the beam formation and its subsequent transverse properties.

The third electrode is a grounded one (called ground electrode 1) in order to achieve the beam extraction at its final energy. Then, a repelling electrode polarized at around -4 kV is placed. It induces a moderate negative potential barrier (around -150 V on the axis) that prevents the electrons produced in the source extraction region to be attracted and accelerated toward the plasma chamber. The last electrode is also grounded (ground electrode 2) and bring back the electrostatic potential to zero, before entering the LEBT.

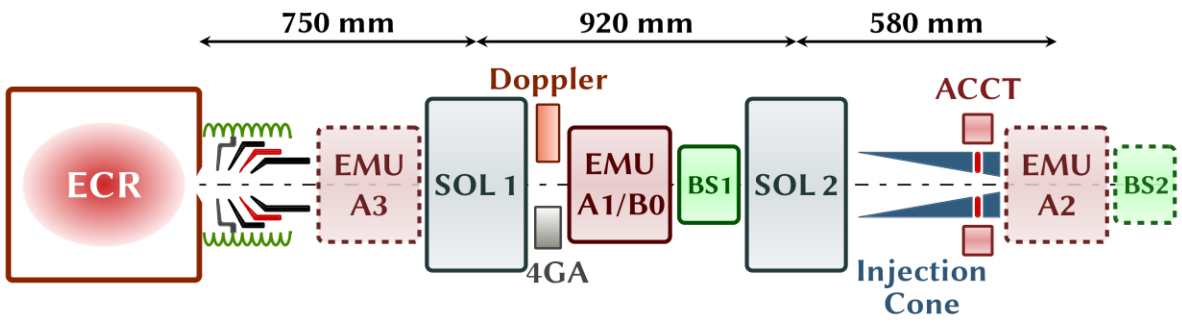


FIG. 1. LIPAC ion source and LEBT set-up. Different positions of the emittancemeter are shown for the different phases of the beam commissioning.

2.2. LEBT

The LEBT uses a dual solenoid focusing scheme to transport the beam and to match it into the RFQ. In order to save space horizontal and vertical magnetic steerers have been inserted into each solenoids to provide an adequate dipolar correction to compensate possible beam misalignments.

A low energy beam combined with a very high intensity implies high space charge forces that may lead to a delicate transport through the line with a possible emittance growth and eventually beam losses. Hopefully, magnetostatic focusing and steering in the LIPAC LEBT allows to transport the beam in space-charge compensation (SCC) regime [8]. SCC or space-charge neutralization occurs when a beam is propagating through the residual gas (or some additional gas) of the low-energy beam line and subsequently induces ionization of the molecules of this gas. The secondary particles produced by ionization (i.e. electrons or ions), which have an opposite polarity to the particles of the beam, are trapped by the potential created by the beam itself until a steady state is reached. Thus, the low-energy beam can be considered as a plasma that creates a focusing effect that counteracts the space-charge effect.

The total length of the beam line, from the plasma electrode to the internal face of the RFQ entrance flange, is 2.05 m. At the end of the LEBT, a cone with a half-angle of 8° is located just before the RFQ to allow the injection of the beam of interest (D^+)while stopping the other beam species (i.e. D_2^+ and D_3^+) to prevent their injection into the RFQ, that would cause subsequent beam losses. The RFQ entrance flange hole is 12 mm diameter. A circular electrode negatively polarized, is located 20 mm before the end of the cone. This electrode creates an electric field that repels the electrons created in the cone and prevents them to be attracted by the RFQ field; that way, these electrons can contribute to the space charge compensation of the beam in the RFQ injection zone.

A slow chopper, composed by two parallel electrostatic plates fed by high voltage power supplies (10 kV) can also be inserted between the two solenoids. It is used to define short beam pulses (hundreds of µs) that will be used to limit the beam power injected into downstream elements like the RFQ and the SRF-linac during their commissioning phases. One has to note that the rise time of the pulses defined by this chopper cannot be shorter than a few tens of µs for a physical reason: it is the time that it takes to establish space charge compensation in the beam line.

2.3. Beam Diagnostics

Before its injection into the RFQ, the beam produced by the injector needs to be characterized as much as possible. Consequently, either during the commissioning or operation phases, several beam diagnostics have been foreseen and have been installed along the LEBT in order to measure different physical values relative to the beam. The main beam diagnostics are briefly presented here but a detailed description can be found in [9].

2.3.1. Beam Intensity Measurement

First, the total beam intensity (I_{Tot}) extracted from the ion source is given by the current output of the main high-voltage power supply.

An insulated beam stopper, located between the two solenoids (BS1), gives an order or magnitude of the beam intensity transported through the beam line. Nevertheless, the value given by this beam stopper is overestimated as secondary electrons, which are emitted from its surface when D^+ particles are impacting it, are not repelled by any electrostatic or magnetic device.

An AC Current Transformer (ACCT) is installed at the end of the injection cone to measure the beam intensity just before its injection into RFQ. The same type of ACCT is located just downstream the RFQ in order to measure the RFQ transmission. The ACCTs can measure pulsed beams above some tens of microseconds.

During the source and LEBT commissioning phases, as the RFQ was not yet installed, a second insulated beam stopper (BS2) was placed after the injection cone. The beam intensity measurement on BS2 is more precise than on BS1 as a dipolar magnetic field higher than 100 G is applied in front of it to repel the secondary emitted electrons. This electrical measurement of the beam intensity given by BS2 has been confirmed by a calorimetric one (not biased by secondary electrons).

2.3.2. Emittance Measurement

The Emittance Measurement Unit (EMU) that has been chosen is an Allison scanner [10]. This device records the projection of the beam distribution in the (yy’) phase space (vertical plane) from which the beam emittance and its Twiss parameters are calculated. In principle, the EMU can be operated in the (xx’) plane as well, by mounting it horizontally in its chamber. The beam size and divergence range that can be measured with this apparatus are respectively [-40 mm, 60 mm] and [-120 mrad, 120 mrad] for a beam energy of 100 keV.

As shown on Fig.1, the Allison scanner can be mounted at several locations of the injector during the beam commissioning. In operation, the EMU is normally located between the two solenoids.

2.3.3. Optical Measurements

Considering the high beam power that can be extracted from the ion source (from 500 W at low duty cycle to 15 kW in CW operation), non-interceptive diagnostics, when possible, have been favoured. For example, beam profilers based on the fluorescence of residual gas have been chosen. The beam profile can be recorded by CCD or CID cameras. CCD cameras provide a better image and were used during injector commissioning. Nevertheless, they can hardly be used in standard operation as their performance degrades quickly under a high neutron and gamma flux that can occur in the IFMIF-LIPAc vault (20 Gy/hour is foreseen in CW operation). Consequently, CID cameras even if they are less sensitive to light than CCDs, were chosen as they can be operated in a high radiation environment. In order to improve their signal to noise ratio, custom image-intensified CID cameras, using multichannel plate, were tested during the last phase of the source and LEBT commissioning [11].

It is also possible to determine the proportions of the different species composing the beam using Doppler-shifted spectroscopy. A CCD camera is installed at the focal plane of a spectrometer with an angle of 20° relatively to the beam direction [12]. A 20-m long radiation hardened fiberscope is used to transport the fluorescence light from the CDD camera to the spectrometer that can be operated outside the accelerator vault. The species fraction measurements were mainly performed between the two solenoids of the LEBT.

3. BEAM COMMISSIONING PHASES

In 2012, during the few months of beam commissioning that was performed at CEA-Saclay, the deuteron beam intensity transported at the end of the LEBT reached an unprecedented value of 140 mA at 100 keV. Emittance measurements that were carried out at low duty cycle (10%) showed promising results [13].

The source and LEBT were dismounted and then remounted in Rokkasho-mura. The beam commissioning started again in Japan in 2014. It was decided to divide the injector commissioning in several phases for which beam diagnostics (mainly the EMU) could be positioned at different locations of the LEBT. The goal is to perform beam measurement after the source, between the two solenoids and at the end of the LEBT.

During the first phase of the injector commissioning called A1 phase, the EMU was installed in the first diagnostics chamber between both solenoids. This will be the EMU position during LIPAc operation, when the whole accelerator will be assemble.

In the second commissioning stage called A2 phase, the EMU and an intensity measurement device (BS2) were placed in a second diagnostic chamber, designed and built specifically for the beam commissioning, which was installed around 300mm after the injection cone. Several experimental campaigns have been achieved in this configuration.

In the commissioning phase A3 held in July 2017 the configuration of the injector was modified to characterize the intrinsic beam parameters as close as possible to the ion source extraction system. The diagnostic box, containing the EMU, BS2 and optical profilers has been placed just after the ion source.

Finally, after these 3 phases, the RFQ was connected to the LEBT in 2017, starting a new phase B dedicated to the RFQ commissioning. Nevertheless, it is still possible to perform measurements between the two solenoids, with the same experimental setup as in A1 phase. This is called B0 phase and a measurement campaign has been carried out with deuteron beam at the end of 2017.

4. EXPERIMENTAL RESULTS

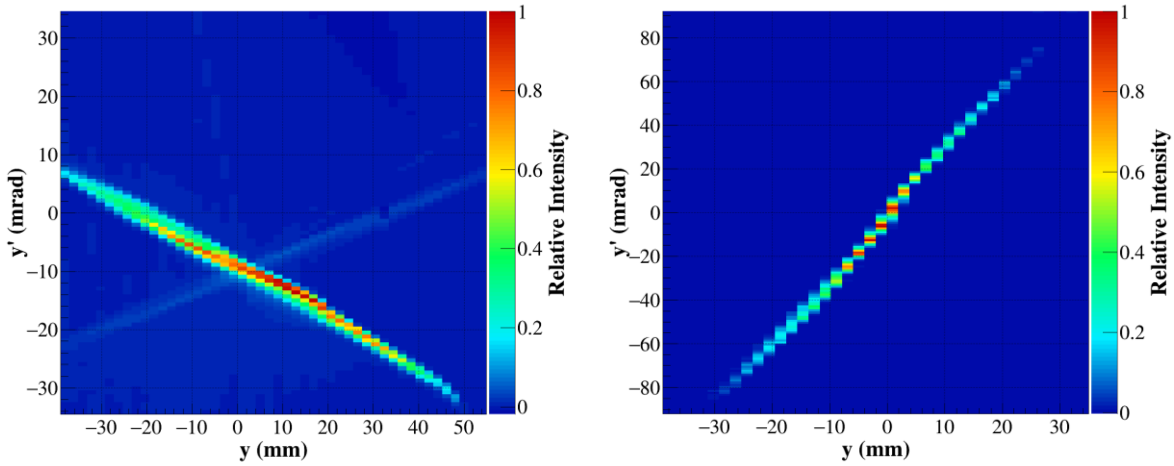
In the present paper, we will focus on experimental results that have been obtained in the last two years while the ion source was mainly operated at low duty cycle (3 to 5 %).

4.1. Phases A1 and A2

Only a few results of the A1 and A2 phases are presented here, as more comprehensive reports were published in previous papers [14, 15].

The raw data of a measurement of the beam distribution in the (yy’) phase space plane (called “emittance measurement” in the rest of the paper) performed with the EMU installed between the two solenoids (A1 phase setup), is presented on Fig. 2(a). This measurement has been done with a pulsed D^+ beam (duty cycle: 3%) of 140 mA at 100 keV (total beam current extracted from the source = 166 mA). On Fig 2(a) it can be seen that a quite high background is present in the data; furthermore, several beam contributions seem to be present on the plot. To explain this last point one has to consider that not only D+ are produced by the ECR ion source but also molecular ions like D_2^+ and D_3^+. All the ion species are extracted at the same energy, 100 keV in our case; consequently, they don’t have the same magnetic rigidity because they have different masses. As the first solenoid of the LEBT is inducing a static magnetic field that optimise the transport of the beam of interest (i.e. D^+), the species which have a different rigidity will simply experience a different focusing. During the A1 phase, the emittance measurements were performed after the first solenoid, so the different species composing the total beam show different projections on the space charge space. Consequently, in order to calculate the emittance and Twiss parameters of the desired specie, its signal needs to be isolated to obtain a reliable value. For that reason, a dedicated code has been written to analyse the data produced by the EMU [16].

First, this code has to detect and remove the measurement background produced by secondary emission (electrons and ions) in the Alisson scanner. Indeed, in order to achieve proper measurements of low energy beam of intensities above 100 mA one has to seriously consider and subtract the background that is produced by a considerable amount of secondary particles. Then, the data analysis code detects and separates the signal contribution of the different species and computes the emittance value of the most intense specie; the proportion of the different beam components can also be derived. The species fraction ratios obtained with the EMU and our algorithm have been compared with direct measurements performed with Doppler-shifted spectroscopy with a good agreement for a 100 keV deuteron beam [17]. In the present case of Fig 2(a), the D^+, D_2^+ and D_3^+ proportions were respectively 92%, 7% and 1%.



(a) (b)

FIG. 2. Beam distribution measurement in the (yy') phase space of a 140 mA D^+ beam at 100 keV at two positions of the LIPAc LEBT (a): A1 phase measurement – (b): A2 phase measurement

Fig. 2(b) represents the result of an emittance measurement that was recorded during the A2 phase with a pulsed D^+ beam (duty cycle: 3%) of 140 mA at 100 keV and under identical experimental conditions as the measurement describe above (shown on Fig. 1(a)). Here only the signal from the D^+ beam is observed, as the molecular ions are lost upstream of the LEBT, particularly in the injection cone. The D^+ beam is transported with almost no losses through the LEBT and it has to be focused efficiently in order to pass through the 12 mm diameter hole of the end of the injection cone (the beam size is approximately 50-70 mm diameter in the second solenoid). So, the A2 phase measurements are performed after a beam waist, that's why a divergent beam is observed on Fig 2(b).

As two solenoids are used as focusing elements in the LEBT, it is possible to transport the beam and guide it through the cone, while keeping an optimal transmission, with different focusing optics. In other words, an almost 100% transmission can be maintained with different set of solenoids tuning but the resulting beam Twiss parameters at the EMU location will be different. The effect of different solenoids tuning points on the beam emittance is presented in Table 1. The emittance quantities given in this paper are always RMS normalized values.

TABLE 1. Beam emittance values (ε) recorded during A1 and A2 phases for different sets of magnetic field applied by the two solenoids.

SOL1 / SOL2 (T)	0.354 / 0.428	0.368 / 0.409	0.382 / 0.379	0.396 / 0.349
ε phase A1 (π mm.mrad)	0.230	0.222	0.213	0.200
ε phase A2 (π mm.mrad)	0.307	0.269	0.247	0.290

For our experiment, the beam focusing is considered "strong" for high second solenoid (SOL 2) values, as the beam waist at the end of the injection cone will become smaller as SOL 2 increases. Consequently, in Table 1, the focusing is becoming "weaker" from left to right.

An emittance increase is observed in all the cases between the middle (phase A1 measurement) and the end (phase A2 measurement) of the LEBT. This can be caused by the beam waist that occurs after the cone. At the beam waist location, the beam density becomes necessarily higher which induces stronger space charge forces. Besides, it was observed during the A2 phase that the space charge compensation was not optimal in the diagnostic box located after the cone. Indeed, the pressure in it was a decade lower than in the LEBT. A lower space charge compensation, especially where a beam waist occurs, can lead to emittance increase.

It has to be mentioned that the major emittance increase in the LEBT occurs when the beam passes through solenoid magnetic field nonlinearities. The bigger the beam diameter in a solenoid, the more emittance increase. Consequently, in this set of data, it makes sense to observe an emittance increase between A1 and A2 measurements as the beam is passing through the second solenoid with a noticeable diameter.

In fact, the required focusing to inject optimally the beam into the RFQ is even stronger than the ones presented in Table 1. During phase A2, an extensive work has been carried out to minimize the beam emittance in the diagnostic box at the end of the LEBT with a strong focusing. The ion source and the intermediate electrode voltage have been carefully tuned in order to optimize the extracted beam. Indeed, the beam divergence at the source output is a crucial criteria as it triggers directly the beam size in the first solenoid and the subsequent emittance increase. For a low duty cycle, a very stable and reproducible working point has been found with a total extracted beam intensity of 155 mA. The best emittance that was recorded at the end of the LEBT, for a 135 mA D^+ beam intensity, was $\varepsilon = 0.25\ \pi$ mm.mrad. But this value was obtained with a focusing (SOL 1 = 0.324 T / SOL 2 = 0.45 T) that may not lead to the lowest beam mismatch (under 10%) regarding to its injection into the RFQ. The emittance obtained for a D^+ beam that would have the optimal Twiss parameters (determined by simulation) from the RFQ transmission point of view is 0.34 π mm.mrad (SOL 1 = 0.309 T / SOL 2 = 0.469 T). Even if this value is slightly above the required one, it has to be recalled that the emittance measurement is performed after a beam waist that could lead, as said before, to an emittance increase; in the case of an injection into the RFQ, that would not happen, because the beam would be immediately focused by the quadrupolar electric field.

4.2. Phase A3

During phase A3, beam profile and emittance measurements were performed as close as possible to the extraction system of the ion source. The same stable source operating parameters that were found in phase A2 have been applied to extract reliably a total beam intensity of I_{Tot} = 155 mA. The main interest of this commissioning phase A3 was to study the evolution of the beam size and emittance as a function of the intermediate electrode voltage. The result of this systematic measurements is presented on Fig 3. The quantity V_{IE} is the potential difference between the plasma and the intermediate electrode.

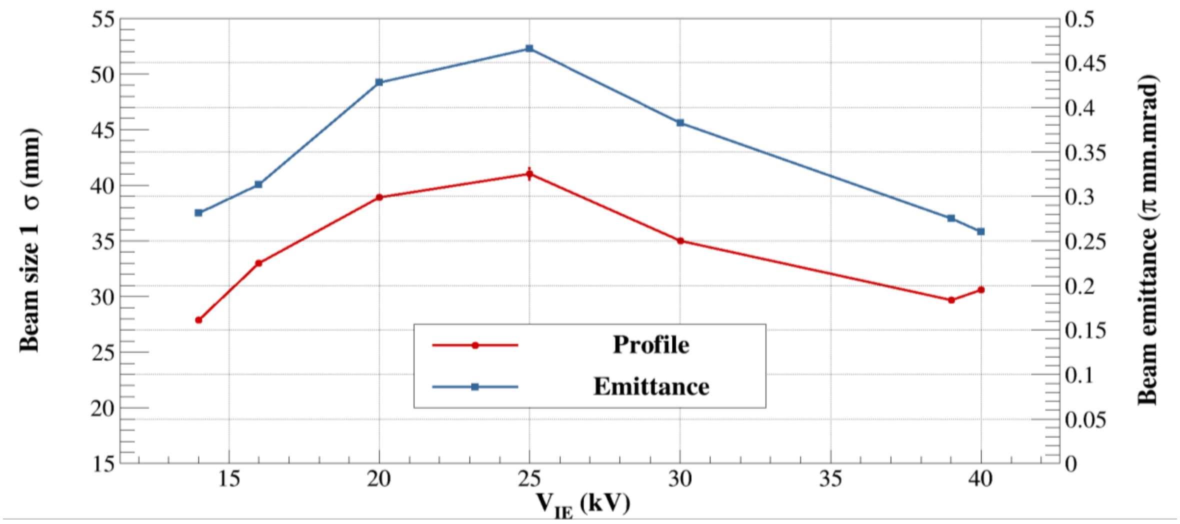


FIG. 3. Beam size (1σ) and emittance versus intermediate electrode voltage.

A decrease of the intermediate electrode voltage down to 14 kV improves the beam emittance and size. During the A1 or A2 phase, it was not possible to apply a potential difference in the first extracting gap below 20 kV.

Before the A3 phase, the ion source extraction system has been carefully scrutinized and cleaned; the high voltage platform grounding has also been improved. If it would have been possible to decrease that much the intermediate electrode voltage, the beam emittance values measured during the previous commissioning phases may have been improved.

The measured emittance values seem quite high, by respect to the ones found after the first solenoid or at the end of the beam line (see section 4.1). However, the EMU data are not easy to analyse as the different extracted species cannot be separated in the phase space plane with our experimental setup. Here, the emittance of the total extracted beam is measured. Around 10% of D_2^+ and D_3^+ beam contribute to this measurement and may increase the emittance value that would have been found with a D^+ beam only. Moreover, some beam halo may increase the emittance close to the source when it is not detectable further in the LEBT, because of losses or beam scrapping.

4.3. Phase B0

Before the beam experiments of the B0 phase at the end of 2017, the ions source extraction system has been dismounted and measured with a 3D coordinate measuring machine. Some discrepancies were found with respect to the reference design, the most critical inconsistencies being the gap lengths between the extraction electrodes. All the extraction system has been dismantled and electrodes have been cleaned or even replaced. After a new assembly and adjustment of mechanical shims, the gaps between electrodes have been found in good agreement with the reference design.

During phase B0, beam emittance and profiles were recorded in the middle of the beam line, after the first solenoid, as the LEBT was already connected to the RFQ. Consequently, the measurements performed during phase A1 are directly comparable to the ones obtained during the present phase. Such a comparison is shown on Fig. 4 with all the parameters of the source and LEBT remaining equal (I_{Tot} = 165 mA). An emittance improvement of around 30% has been observed for the considered solenoid 1 focusing fields.

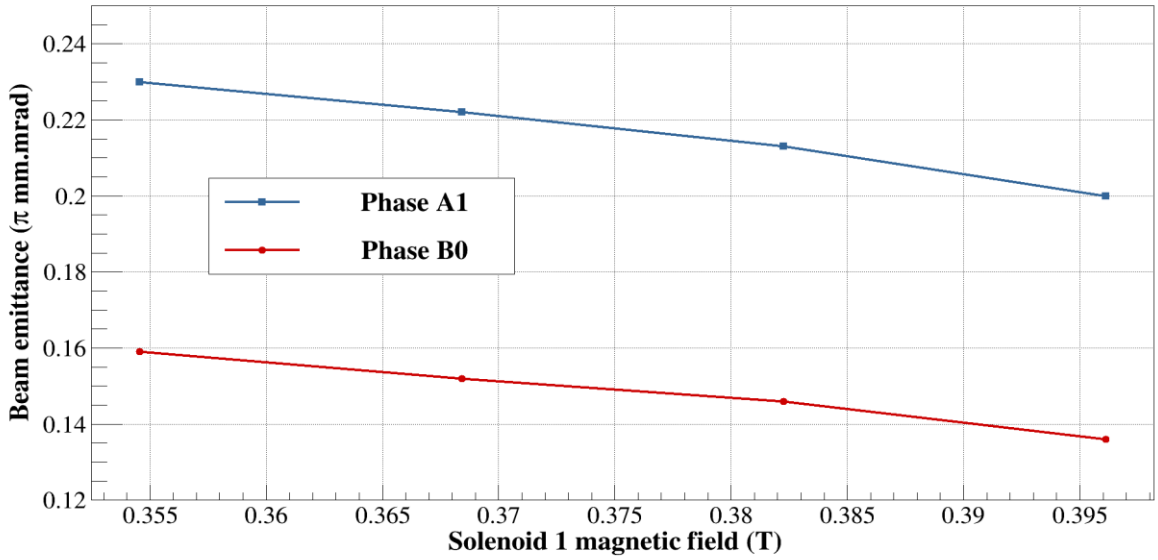


FIG. 4. Beam emittance versus magnetic field applied by solenoid 1. Comparison of phase A1 and B0 measurements.

For a total extracted beam intensity of 155 mA (which corresponds to around 140 mA of D^+ considering the measured species fraction), optimized ion source parameters and the solenoid 1 magnetic field required for RFQ optimal injection (SOL 1 = 0.309 T), the measured emittance was $\varepsilon = 0.145\ \pi$ mm.mrad. This last result implies promising perspectives in order to obtain better beam emittance values at the RFQ entrance. More generally, phase B0 results emphasize the critical role played by the beam formation in the ion source extraction system for the beam quality in the whole LEBT.

5. CONCLUSION

During the last years, intensive experimental activities have been achieved in the framework of the D^+ beam commissioning of the LIPAc ion source and LEBT. At low duty cycle operation, the ion source has shown to be stable and reliable while extracting a 155 mA total beam. The pulsed D^+ beam intensity and emittance seem to be relevant for a proper matching into the RFQ especially since the realignment of the ion source extracting system.

In parallel to this experimental work, important simulation activities have been performed in order to reach a better understanding of the physics of the high intensity ion beam in LEBT and to be able to predict more precisely the beam behaviour and its injection into the RFQ [18,19].

In a near future, more work is still ahead to reach reliable and reproducible ion source operation conditions for the extraction of a continuous beam of at least 150 mA of total intensity. This CW beam will also have to be transported through the LEBT, to be characterised thoroughly and to be matched for its injection into the RFQ.

DISCLAIMER

The views and opinions expressed herein do not necessarily reflect those of the European Commission or of Fusion for Energy, or of the authors' home institutions or research funders.

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