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# HIGH BEAM CURRENT OPERATION WITH BEAM DIAGNOSTICS AT LIPAc

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*Abstract*

The Linear IFMIF Prototype Accelerator (LIPAc) is under commissioning in Rokkasho Fusion Institute in Japan and aims to accelerate 125 mA D+ at 9 MeV in Continuous Wave (CW) mode for validating the IFMIF accelerator design. To ensure a fine characterization and tuning of the machine many beam diagnostics are installed spanning from Injector to the beam dump (BD). The beam operations in 1.0 ms pulsed D+ at 5 MeV was successfully completed with a low power BD (Phase B) in 2019. Despite the challenges posed by the pandemic, the crucial transition to a new LINAC configuration was also finalized to enable operation in 1.0 ms – CW D+ at 5 MeV with the high-power BD (Phase B+). The 1st beam operation of Phase B+ was carried out in 2021. The experiences and challenges encountered during the beam operations we obtained at the last beam operations will be described.

## INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) is a fusion neutron source for the material irradiation test of the plasma-facing components in fusion reactors. The data expected from the IFMIF is used to understand the effect of the high energy neutron flux to determine and develop new advanced materials [1]. Through a first decision to start the IFMIF project in 1994, and the conceptual design studies had been carried out by four main members, Russia, the EU, the US and Japan [2]. To pursue a successful engineering design activity, the IFMIF Engineering Design and Engineering Validation Activities (EVEDA) project has been started under the Broader Approach (BA) Agreement between the EU and Japan. One of the activities of the project is the completion of the engineering validation of the Accelerator Facility of IFMIF [3]. The Linear IFMIF Prototype Accelerator (LIPAc) is under commissioning in Rokkasho Fusion Institute of National Institutes of Quantum Science and Technology (QST) in Japan. European institutions such as CEA, CIEMAT, INFN, and SCK-CEN were responsible for the design, manufacture, and testing of the majority of accelerator components: injector, Radio Frequency Quadrupole (RFQ), Low/Medium/High Energy Beam Transport Lines (LEBT/MEBT/HEBT), Superconducting RF (SRF) LINAC, RF systems, Local Control Systems and Beam Diagnostics. QST (former Japan Atomic Energy Agency, JAEA) provides buildings, main auxiliaries systems, the RFQ coupler, MEBT Extension Transport Line (MEL) and Central Control System [4]. Figure 1 shows the final configuration of the LIPAc and each contribution. The LIPAc aims to test the scientific and technical feasibility of the accelerator through a full scale of prototype from the injector to the first cryomodule. Table 1 summarized the goal of the beam characterizations of LIPAc.

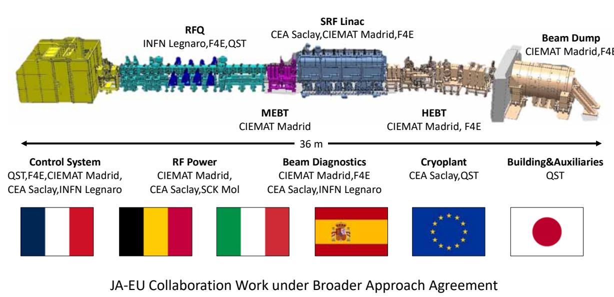


Figure 1: The final configuration of LIPAc.

Table 1: Goal of the LIPAc Beam Operation

| Parameter | Values | Units |
|---|---|---|
| Duty factor | CW | - |
| Ion type | D+ | - |
| Beam Current | 125 | mA |
| Beam Energy | 9 | MeV |
| RF Frequency | 175 | MHz |
| Beam Power | 1.125 | MW |
| Target of Beam Stop | Cu | - |

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In addition, for earlier realization of the neutron source for the material irradiation test, Fusion Neutron Source Design (FNSD) activities such as IFMIF/DONES in Granada, Spain and A-FNS in Rokkasho, Japan have been started [5-6]. Thus, all the results, experiences and lessons learned and to be learned from the LIPAc will be used for those accelerator designs as well.

In this paper, we describe the experiences and challenges encountered during the beam operations at Phase B+, particularly the findings from the interceptive devices to measure the beam profile and emittance using tungsten wires rackets, SEM-grid. We also discuss the quick results on other beam diagnostics from the beam operation toward the high duty cycle (HDC), which are currently being conducted in this Summer 2023.

## PHASE B+ OPERATION

The beam operation of LIPAc has been performed conducting accelerator components installation phases step by step. Figure 2 shows all the beam operation phases of LIPAc. The beam operations in 1.0 ms pulsed D+ at 5 MeV was successfully completed with a low power BD (LPBD) as called Phase B in 2019 [7]. Since August of 2019, we had moved to Phase B+ with the new LINAC configuration, dismantling the LPBD, installing MEL, HEBT, a high power BD and changing the location of D-Plate to between the first triplet and the second doublet quadrupoles. In the initial operation plan, the Phase B+ operation would start after the winter maintenance period, March 2019, and finish before the SRF installation around June 2024.

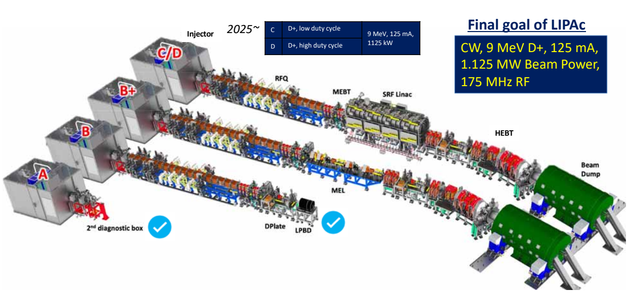


Figure 2: LIPAc beam operation phases.

Despite the challenges and unforeseen delays posed by the pandemic for almost two years, the crucial transition to the new configuration was also finalized to enable operation in 1.0 ms – CW H+ at 2.5 MeV and D+ at 5 MeV. The maximum beam power is expected 625 kW in the BD. The Phase B+ beam operation is separated by three sub-phases as shown in Table 2.

Table 2: Main Beam Characteristics of Phase B+.

| Sub-phase | Characteristics | |
|---|---|---|
| Stage 1 | H+, 10 mA<br>D+, 20 mA | < 0.1% duty cycle |
| Stage 2 | H+, 60 mA | < 1% duty cycle |
| Stage 3 | D+, 125 mA | High duty cycle |

The Stage 1 of Phase B+ was successfully carried out, leading to an evolution of the beam operation structure. This evolution included the separation of two control rooms, with full support from remote participants, including EU experts. We used an individual video meeting tool for all operators and a remote access computer to share real-time operation results in both July and December 2021 [8]. However, there were two major failures of RFQ components, RF circulator and RF couplers at the beginning of 2022 [9-12].

After those failures were overcome through the hard and supportive work of the whole team around for 1.5 years, we have started the Stage 2 of Phase B in August 2023. A few remarkable results we obtained just before the 2.5 weeks of summer maintenance are shown at the latter section of this paper.

Note that the regular summer maintenance period is set two months (August and September) including an annual inspection. This time, the short period was determined to overcome unexpected delays from the pandemic and some failures.

## BEAM DIAGNOSTICS AT PHASE B+

The primary goal of LIPAc beam diagnostics is to ensure the proper transport and acceleration of the beam from the ion source to the dump, while also comprehensively understanding and measuring all beam characteristics during operation. It covers to measure the characteristics such as beam current, position, phase, energy, transverse profile, emittance, and beam losses from exit of the RFQ to the BD as shown in Fig. 3. Since the Phase B configuration, we added 1 additional ACCT in the HEBT, 7 additional Beam Position Monitors (BPMs), 13 Beam Loss Monitors (BLoMs) in the MEL and the HEBT, another SEM-grid, 1 Ionization Profile Monitor (IPM), 2 Fluorescence Profile Monitors (FPMs) and 1 slit in the HEBT. In addition, a full of beam dump instrumentation (BD Inst.) was installed including 6 ionization chambers (ICs) and 3 accelerometers.

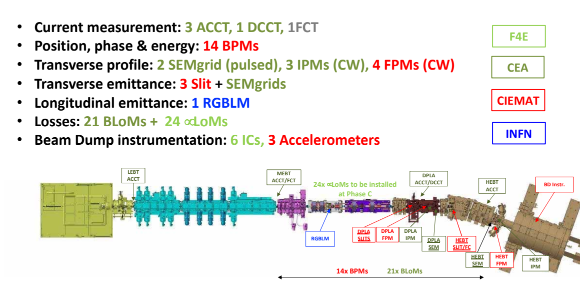


Figure 3: General information of LIPAc beam diagnostics.

## INTERCEPTIVE PROFILER: SEM-GRID

Two Secondary Emission Monitor (SEM) grid units are installed respectively in the D-Plate (DSG) and in the HEBT (HSG). SEM-grids are array of tungsten wires that are directly inserted in the beam path. The currents resulting from the interaction of the beam with the wires are read by integrating FEE, and the beam profile is recovered. Figure 4 shows a brief structure from the wires to the FEE of

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the DSG. The DSG is also used for the emittance measurements with a slit and a steerer magnets. The DSG has 47 wires, with d=20 μm, unevenly spaced over an aperture of 100*100 mm$^2$, while the HEBT one has 47 wires, with d=100 μm, unevenly spaced over an aperture of 150*150 mm$^2$. And two wire planes are set at 90º for the both SEM-grids. Table 3 summarizes the uneven spacing between the wires in DSG and HSG.

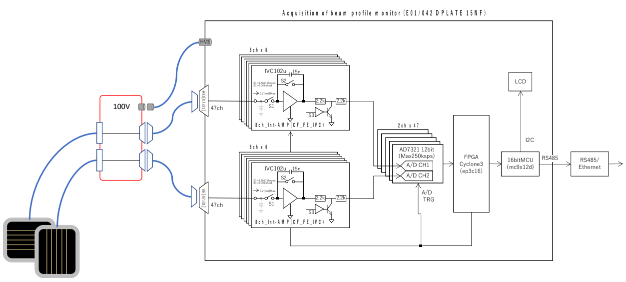


Figure 4: Structure from the SEM-grid wires to the FEE.

Table 3: Spacing between Wires in DSG and HSG

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **D-Plate SEMGRID (DSG)** | | | | | | | |
| Wire # | 1-5 | ~15 | ~32 | ~42 | ~47 | | |
| Gap (mm) | 3 | 2 | 1 | 2 | 3 | | |
| **HEBT SEMGRID (HSG)** | | | | | | | |
| Wire # | 1-5 | ~11 | ~17 | ~30 | ~36 | ~42 | ~47 |
| Gap (mm) | 4.5 | 3 | 2.5 | 2 | 2.5 | 3 | 4.5 |

The SEM-grid measurements are limited by thermal capabilities of the wires. Overall, when the limitations are respected, SEM-grid is a straightforward solution for profile measurements. Still few issues were found, first thin wires can break easily especially during venting as shown in Figure 5. Also, the destruction of FEE has been observed after important sparking events in ion pumps close by as shown in Fig. 6.

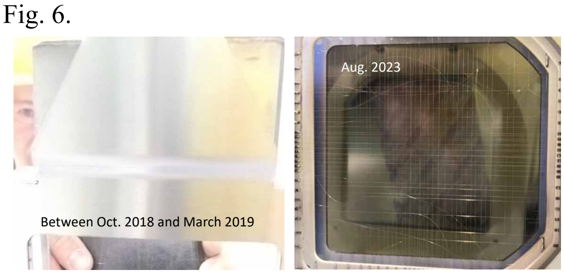


Figure 5: Broken wires during venting in the D-Plate.

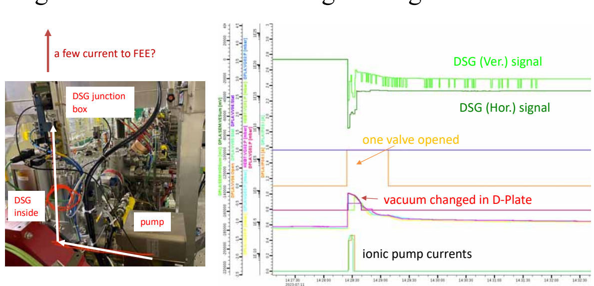


Figure 6: Possible spark event to destruct the DSG FEE.

Also, the degradation of the wire over long times is not well understood and under investigation, however, we have proposed a gain correction from analysis of emittance measurement for future beam operations [13]. Figure 7 shows an example of profile with the gain correction, we confirmed that it could make better match to the beam simulation expectation.

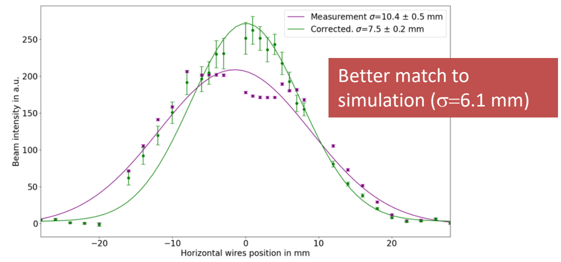


Figure 7: Example of beam profile before and after the gain correction.

## INTERCEPTIVE DEVICES: SLITS AND FARADAY CUP

Two slits are located about 1.5 m upstream of the SEM-grid in the D-Plate for each axis (horizontal and vertical), as called DSL, to measure the beam emittance. The DSLs are made by copper which has water cooling line implemented and mounting graphite layers as shown in Fig. 8. In the HEBT, another slit (HSL) for the energy spread measurement made by tungsten alloy with the HSG and the faraday cup unit (HFU) are located upstream of the HEBT dipole. The HFU is the only one beam stopper from the LEBT to the bended beam line before the last triplet in the HEBT. Since these interceptive devices are actuated by a stepping motor with high precision <1.0 μm, they could introduce a reliable combination using with the ACCTs for a quick beam size scanning and with the SEM-grid for the emittance measurement.

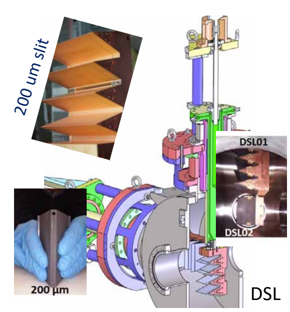


Figure 8: The structure of D-Plate slit (DSL).

## CURRENT MEASUREMENT: CURRENT TRANSFORMER

In the beam line, 4 ACCTs (1 in-air and 3 in-flange model of Bergoz) are installed at the exit of LEBT, at the exit of RFQ, at the middle of D-Plate and in front of the BD for the pulsed beam operation. Table 4 summarizes a role of the CTs and characteristics. They allow to check the correct transmission between the different LINAC sections.

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Table 4: Characteristics of LIPAc CTs

| Location | Type | Band Width |
|---|---|---|
| LEBT | ACCT | 5 Hz – 326 kHz |
| MEBT | ACCT | 2.4 Hz – 350 kHz |
| MEBT | FCT | 14 kHz – 266 MHz |
| D-Plate | ACCT | 2.8 Hz – 340 kHz |
| D-Plate | DCCT | 0 – 12.6 kHz |
| HEBT | ACCT | 2.7 Hz – 330 kHz |

## LOSS MEASUREMENT: BLOM & NEUTRON DETECTOR

In the beam line, we have 21 BLoMs from the exit of the RFQ to the end of HEBT. They provide an interlock signal in less than 10 us to the Machine Protection System (MPS) to avoid irremediable damages of the machine due to high energy particles produced during the beam operation. The BLoM was designed based on the LHC Ion Chambers and calibrated the response by gammas from $^{60}$Co source and neutrons (3.0 and 14.7 MeV). In addition, 6 He-3 neutron detectors were installed critical locations considered to detect neutron produced by 5 MeV deuterons and device materials near bunchers, scrapers, interceptive devices and the entrance of BD based on the experiences at the previous Phase B operation [14]. The neutron detector is covered a polyethylene block to reduce the background neutrons as much as possible. Figure 9 shows the all the position of those BLoMs and neutron detectors.

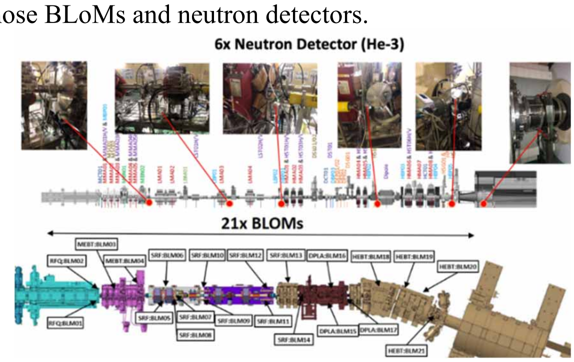


Figure 9: Positions of BLoMs and neutron detectors.

## POSITION, PHASE AND ENERGY: BPM

The BPMs is devoted to the measurement of the transverse centroid position and phase. Figure 10 shows a system of BPM with real pictures of LIPAc BPMs. The signal through the pickups on 4 pole electrodes (0º, 90º, 180º and 270º on the vacuum flange) goes to the analogue front developed by CIEMAT. Then IF signal transfers to the digitizer which is DAQ, FPGA implanted synchronizing with the RF and timing system by the digital white rabbit [15].

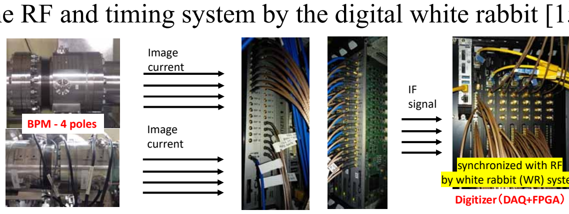


Figure 10: The BPM system and signal transfer structure.

## NON-INTERCEPTIVE PROFILER: FPM

The goal of the LIPAc beam operation is the stable 125 mA, CW, 9 MeV D+. Thus, it is difficult to use the direct profile monitor to intercept in the beam line like the SEM-grid by the thermal capabilities of the wire during higher duty cycle aiming the CW operation. The fluorescence profile monitor (FPM) based on a linear photomultiplier (PMT) array coupled to a lens was installed to satisfy the requirement of the goal [16]. Since it is based on the residual gas fluorescence originated, it is sensitive on the vacuum level, light, and radiations. In the beam line, 2 FPMs in the D-Plate (DFP) covering thin metal foils for the light shielding and another 2 FPMs in the HEBT (HFP) covering the metal foil and a few lead sheets for light and radiation shielding are located. Each FPM can measure the charge from the collecting light by the reaction between photon and gas molecules or atoms for both beam projections, horizontal and vertical as shown in Fig.11.

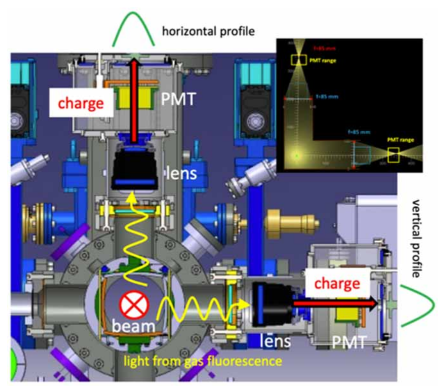


Figure 11: Schematic view of the inside of FPMs.

## OTHERS: IPM, RGBLM AND BD INSTR.

Though the current duty cycle is too low thus the signal cannot be detected properly by the beam diagnostics below, however, they have been prepared for the HDC with conditioning.

Another non-interceptive device is the IPM, it relies on the collection of ionization of residual gas by the beam, using a strong electrical field. The ionization by products is then collected on a segmented strips readout [17]. Finally, a FEE is used to integrate the charge signal. Two IPMs (X and Y planes) are installed in the D-Plate, and one in the HEBT (X plane only, due to lack of space).

The residual gas bunch length monitor (RGBLM) was and tested to measure bunches of about 300 ps with a frequency of 175 MHz. The 100*100 mm$^2$ aperture device have 3 steps HV electrode to accelerate the secondary electron emitted by the ionization and bend it to the sensing MCP stage. The insulation and conditioning study have been performed toward HDC operation [18].

To monitor the beam stopped by a copper cone of the BD, we have two kinds of diagnostics as the BD instr.: ICs for ensuring that the beam remains within the BD design limit and the accelerometer for detecting the localized heating by incorrect alignment [19].

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## BEAM DIAGNOSTICS OPERATION

In this section, we describe that a typical beam diagnostics routine in LIPAc for the beam operation together with a few remarkable results we have obtained at the Phase B+ so far. Note that an experimental programme for LIPAc nominal beam perveance is signed and approved before the start of the new beam operation phase. It is an internal document covering the goals of sub-systems, experimental setup, and plans for the operation Stages. The beam diagnostics shall be ready to provide all necessary data respecting the programme.

### *Step A. Transmission and Waveform*

We check the beam transmission from the upstream LEBT to the downstream HEBT and each waveform using the ACCTs. Figure 12 shows the one of the results we achieved in September 2023, the high beam current 125 mA (repetition rate 1 Hz, around 90% of transmission) with beam pulse 60 us and 150 us (injector chopper gate width), respectively. The waveform at LEBT and MEBT are adjusted by injector such as Kr gas flow and RF/RFQ parameters such as cavity voltages based on the experience points obtained during the long-time conditionings in advance.

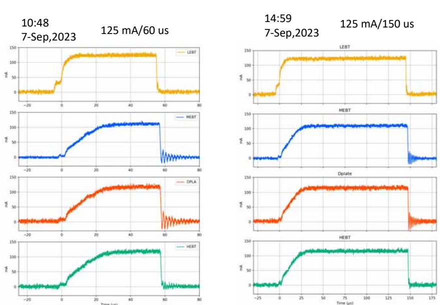


Figure 12: Beam transmission and waveform by ACCTs, from upstream (LEBT) to downstream (HEBT).

### *Step B. Size and Stability*

Then we move to the slit scanning with ACCTs to check the beam size and stability. The interceptive devices OPI on the left and the beam current at ACCTs (mA) or on HFU (uA) on the right are shown in Fig. 13. Note that the reason of the narrow beam shape on the HFU in the figure is that the two same directional (vertical) slits are inserted at the scanning. The scanning could give the quick view of the beam size and its stability before we move to the emittance measurement. The HFU signal is set by a specific gain (1E6 V/A at the measurement, and 1000 V of repeller voltage) setting to avoid a damage of the signal plate.

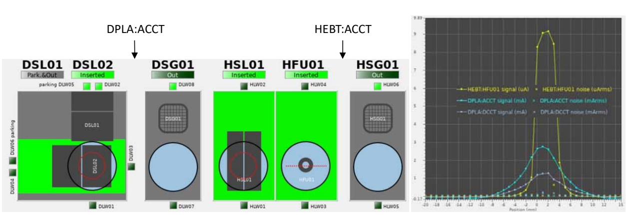


Figure 13: A typical scanning result with the slit and ACCTs (and/or HFU).

### *Step C. Emittance Measurement*

For tuning up the accelerator, we measure the emittance using slit, the SEM-grid and the exclusive steerer. Note that since our SEM-grid has the large wire gaps which often larger than the beamlet as shown in the Table 3 above, thus, it is not possible to use a normal technique of the emittance measurement without a steerer or a deviator. Figure 14 shows the one example of the emittance measurement obtained during the latest HEBT steering tuning at the Stage 2 of Phase B+. Then we compare the results with the simulation calculated by TraceWin as shown in Fig. 15.

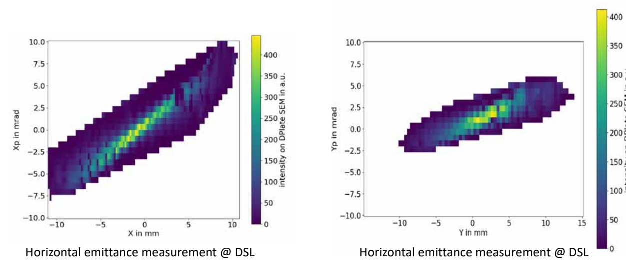


Figure 14: Emittance measurement with DSL and DSG during HEBT steering tuning.

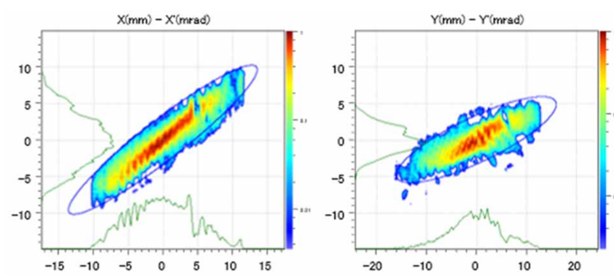


Figure 15: Result of the TraceWin simulation of the emittance using the parameter measured.

### *Step D. Profile Measurement*

When the simulated beam size, the current and the energy are respected the limitation of the maximum pulse length based on the theoretical hypothesis of the thermal capability, the full profile measurement is performed with the SEM-grids. Figure 16 shows one of the results obtained at the DSG. In addition, the HFPs showed a clear profile with a specific magnet setting conditions at the last beam operation. Figure 17 shows the horizontal profile obtained on HFP and HSG. Further comparison between the different profile measurements will be continued.

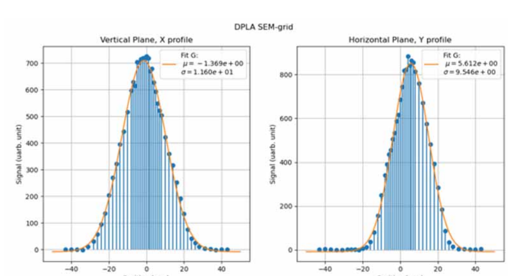


Figure 16: Full beam profile on the DSG.

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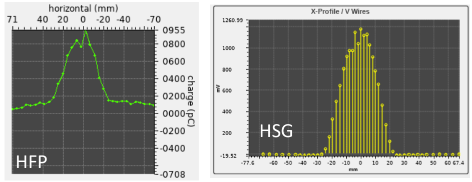


Figure 17: Horizontal profiles on HFP and HSG.

### *Step E. Measurement of Position and Loss to Optimize the Beam Parameter*

When the beam is stably extracted and accelerated, we move to the dedicate measurements of the Beam Based Alignment (BBA) [16] to adjust the proper alignment offset of main magnets in the transport line from MEBT to HEBT nearby BPMs. Figure 18 shows a typical measurement result during the BBA which the quadrupole in the MEL. It carefully performed to monitor the beam losses and the beam position.

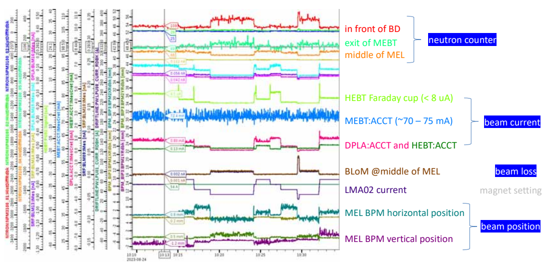


Figure 18: BBA performed with the magnet current adjustment and monitoring the beam.

## SUMMARY

The LIPAc beam operation Phase B+ has been started overcoming unexpected difficulties on human activities and failures on the components. We already reached a kind of our goal, the high current beam operation (~125 mA) at the low duty cycle. Most of the beam diagnostics installed has been somehow working, even though it has small and large issues. However, all the results, failures, experiences and lessons learned (and to be learned) will be used effectively not only for our further beam operation, but also for other accelerator design activities.

From now on, we expect to increase the beam pulse toward to the high duty cycle keeping the high beam current through Stage 3 in Phase B+. And the work on the LIPAc beam diagnostics is ongoing to provide all useful information.

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