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LINAC4 SOURCE AND LOW ENERGY EXPERIENCE AND CHALLENGES

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Abstract

At the end of Long Shutdown 2 (LS2), in 2020 Linac4 became the new injector of CERN's proton accelerator complex. The previous version of the Linac4 H^- ion source (IS03), produced an operational pulsed peak beam current of 35 mA, resulting in 27 mA after the Radio-Frequency Quadrupole (RFQ). This limited transmission was mainly due to the extracted beam emittance exceeding the acceptance of the RFQ.

A new geometry of the Linac4 source extraction electrodes has been developed with the aim of decreasing the extracted beam emittance and increasing the transmission through the RFQ. The new source (IS04) has been studied and thoroughly tested at the Linac4 source test stand. At the start of the 2023 run, the IS04 was installed as operational source in the Linac4 tunnel and is being successfully used for operation with 27 mA peak current after the RFQ. During high-intensity tests, the source, the linac, and the transfer-line to the Proton Synchrotron Booster (PSB) were also tested with a peak beam current of up to 50 mA from the source resulting in 35 mA at the PSB injection.

This paper discusses the recent developments, tests, and future plans for the Linac4 H^- ion source.

INTRODUCTION

Linac4 is the proton beam injector for CERN's accelerator complex, including the Large Hadron Collider (LHC). It accelerates negative hydrogen ions, H^-, to 160 MeV and transfers them to the Proton Synchrotron Booster (PSB). The ions are stripped of their two electrons during the charge exchange injection process into the PSB. The low-energy part of Linac4 consists of a 45 keV ion source, a low-energy beam transport (LEBT), and a radio-frequency quadrupole (RFQ) that accelerates the beam to 3 MeV.

The previous Linac4 source version, the IS03 [1], produced a beam current of 35 mA, which resulted in 27 mA after the RFQ. Attempts to run with a higher intensity from the source did not result in a higher intensity out of the RFQ. This was mainly due to the extracted beam emittance exceeding the acceptance of the RFQ. The IS03 extraction design could work with a much higher co-extracted electron current, which allowed the source to operate without caesium. Now that caesiation is routinely used for surface H^- production, a new geometry of the Linac4 source extraction electrodes has been developed and optimised for higher beam currents, with the aim of decreasing the extracted beam emittance and increasing the beam current and transmission through the RFQ. The new source type, the IS04, has been studied in simulations and thoroughly tested at the Linac4 test stand [2].

NEW EXTRACTION SYSTEM

The IS04 ion source is composed of a ceramic (Al_2O_3) plasma chamber with an external five-turn RF antenna. Hydrogen gas is injected via a pulsed valve and a 2 MHz RF amplifier provides 100 kW maximum power to ignite and sustain the plasma. The source is operated in surface H^- production mode, with a continuous caesium injection at 65 °C; during the source start-up process, initial caesiation is usually done at higher temperatures and can take up to a few days. In routine operation at Linac4, the ion source produces beam pulses with a length of 850 µs at a repetition rate of 0.83 Hz and is typically providing 35 mA of beam at 45 keV energy with about 30 kW of forward RF power.

The IS04 source extraction system has a simplified design [3] compared to IS03, with only three electrodes (see Fig. 1): plasma, puller, and ground, which makes the extraction region 6 cm shorter than in the IS03. The puller-dump and einzel lens causing undesired emittance growth were eliminated. The design voltage of the puller electrode is -22.5 kV. Co-extracted electrons are disposed of at 45 keV onto a dedicated dump after deflection by a permanent dipole magnet housed at the base of the dump itself. The dump can be biased with a voltage of up to +1 kV to contain secondary electrons produced on the dump and create a potential barrier for the positive compensation particles collected in the beam in the low-energy beam transport section.

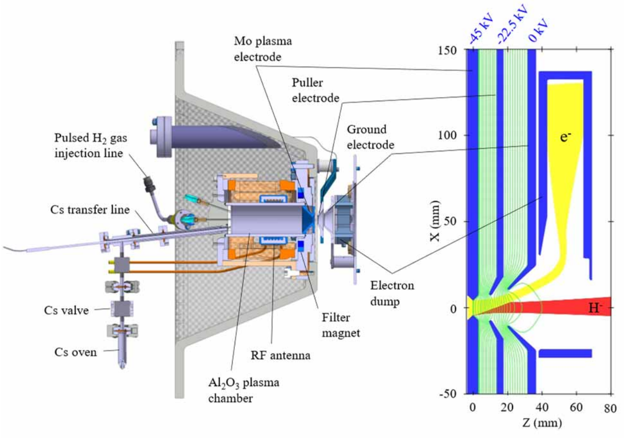

Figure 1: IS04 source 3D model (left) and extraction simulation model in IBSimu (right).

SIMULATIONS

Simulations have been carried out to characterise and improve the performance of the source, LEBT, and RFQ, as well as to help analysing the measurement results. Two simulation codes have been used. IBSimu [4], which is a computer simulation package for ion optics, plasma extraction and space charge dominated ion beam transport, is mainly used to model the plasma, and simulate ion beam

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extraction and electron dumping. TRAVEL [5], which is a particle-tracking program including space charge effects and electromagnetic field maps, is used with an external input beam distribution, e.g., from IBSimu, and electromagnetic field maps to simulate the beam transport from the ion source extraction through the LEBT and the RFQ.

The plasma extraction model in IBSimu is known to underestimate the charge density near the plasma sheath due to approximations made by neglecting the magnetic field and collisional effects near the plasma sheath region [6]. Therefore, for the IS03 source, plasma parameters and simulation mesh size in IBSimu have been varied to match the measured beam emittance [1]. The plasma density has been scaled up by 30% and the mesh size around the plasma meniscus has been reduced to 10 μm (to resolve the plasma Debye length) to reproduce the measured beam emittance in the LEBT. For the IS04 source, despite having the same plasma generator as the IS03, the same plasma parameters and mesh size in IBSimu did not result in a good agreement between the measured and simulated beam emittance, which is 5-8 times smaller and unrealistic.

As a different approach, the beam distribution generated in IBSimu at the plasma electrode has been used as an input to simulations in TRAVEL, using electromagnetic field maps for the extraction system and for the solenoid field. Simulations are done for a stabilised beam with full space-charge in the extraction system due to the electric fields and with a fully space-charge compensated beam in the LEBT. This assumption represents the situation after the first 200 μs transient. The emittance obtained from these simulations is considerably larger than that from IBSimu but still about 30% lower than the measured value in the LEBT (see Fig. 2) for the same 50 mA beam and the first solenoid magnet powered with 125 A current. Emittances in the solenoid field map (0.053-0.653 m) are not shown, and the emittance decrease in TRAVEL is due to beam losses.

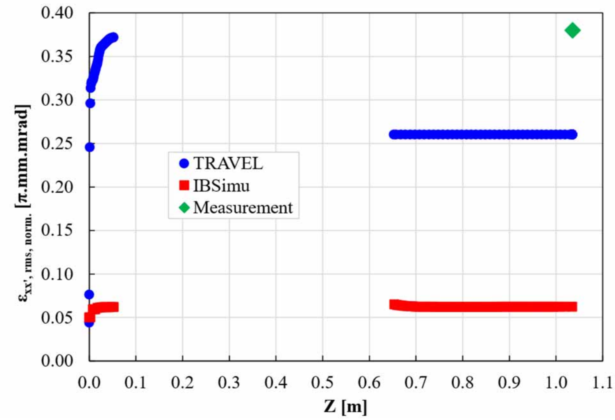

Figure 2: Normalised rms emittance from source plasma electrode to the emittance meter in the LEBT.

In TRAVEL simulations, most of the emittance increase happens in the first few millimetres of the extraction. Comparing the electric fields computed in IBSimu and in Superfish [7], the radial component of the electric field in the first 10 mm of the extraction, between the plasma and puller electrodes, is considerably different between the two codes computed for the same extraction system geometry. Further study is ongoing to correctly assess if this difference comes from the boundary conditions used at the plasma meniscus and extraction bore region or if the space-charge has been correctly considered.

Studies of H$^-$ beam formation [8] with the IS03 source show an asymmetry in the density distribution of the charged particles in the extraction region induced by the filter magnet field, which influences the meniscus shape and the extracted beam parameters. This too can have an important impact on the emittance of the extracted beam.

Plasma Electrode Angle

The plasma electrode geometry, in combination with the puller voltage, directly affects the shape of the plasma meniscus and the initial focalization of the beam. The angle of the plasma electrode, defined in Fig. 3, influences the strength of the transverse (focusing) electric field component. For a smaller electrode angle, the electric field equipotential lines in the extraction region are straighter and hence produce a weaker transverse electric field with less focusing. In this case, higher plasma electrode angles should focus the beam better and hence improve the emittance. Based on this assumption, plasma electrodes of 25° and 45° were simulated and compared to the nominal 35° with the aim of achieving a lower emittance.

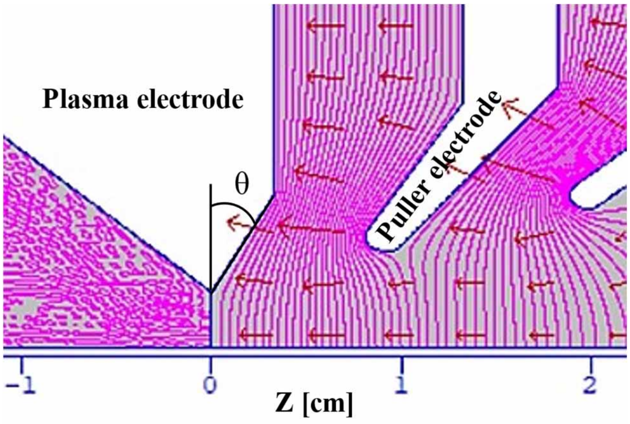

Figure 3: Plasma electrode angle and electric field lines computed in Superfish without beam.

Particle tracking simulations were done in TRAVEL, using field maps generated in Superfish and input beam generated in IBSimu for 50 mA. Both simulated and measured beam emittances were up to 20% lower with 45° plasma electrode and therefore it was retained for all further studies and measurements reported here.

Puller Voltage

For a given distance between the plasma electrode and the puller electrode, the puller voltage affects the plasma meniscus shape and therefore, the divergence of the extracted beam, hence the emittance. The effect of the puller voltage on the beam emittance at the location of the emittance meter for 35 mA beam current and the first solenoid powered with 125 A is shown in Fig. 4. The simulations show 7% improvement in the emittance for -20 kV applied voltage on the puller, whereas the measurements show smaller emittances for puller voltages between -24 kV and -26 kV. The beam transmission through the RFQ, measured during the 2021 tests in the Linac4 tunnel, was the highest for the puller voltage of -24 kV.

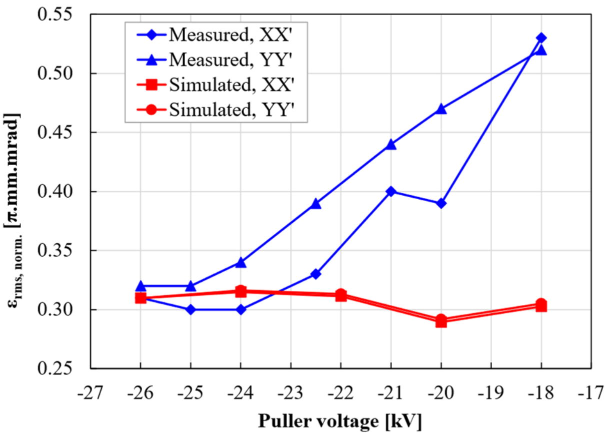

Figure 4: Normalised rms emittance vs puller voltage.

Simulations are a valuable tool to study and optimise the effect of different source and LEBT parameters on beam properties. However, optimisation of a single parameter of the source or the LEBT that improves the beam emittance, does not necessarily result in an improved beam transmission through the RFQ and improved beam quality downstream. A more holistic approach and overall optimisation of the beam extraction and beam optics through the low energy front-end is required already at the design stage.

Backtracking

Due to a high beam divergence and long distance between the source extraction and the emittance meter slit, it is currently not possible to measure the beam distribution directly after the source. Therefore, the beam distribution measured at the emittance meter has been backtracked to the entrance of the first solenoid field map and used as an input beam in simulations. We assume no space charge compensation (SCC) through the extraction system, but the SCC degree in the LEBT is unknown. Therefore, the backtracking is also used to assess an effective beam current, assuming a constant and uniform SCC in the LEBT, both longitudinally and transversally. The backtracking of the beam could in principle be done through the electric field map of the extraction system too, but TRAVEL code does not seem to be suitable for tracking a very low energy decelerating beam through a field map.

Once the input beam is obtained, it is tracked forward through the LEBT, while optimising the solenoid strength to maximise the beam transmission through the RFQ or the RFQ acceptance mask. The RFQ acceptance mask [9] is a simple device made of four consecutive plates with square apertures of different sizes, which represents the transverse acceptance of the RFQ, and is installed at the end of the LEBT at the Linac4 source test stand and is also modelled in the simulations.

Backtracking has been done for both 35 mA and 50 mA beams, using measured beam distributions with three different solenoid strengths to improve the convergence, while varying the degree of the SCC and minimising the mismatch factor [10] between the pairs of beam distributions. For a given beam current, the minimum mismatch factor was found for very different SCC degrees in the horizontal and vertical planes, which is not what is expected. This discrepancy is probably because with the slit-grid emittance measurement method we do not measure the correlation between the beam distributions in each transverse plane, which exists due to the beam rotation in the solenoid field. Therefore, a different feature of the beam distribution, namely the 4D emittance, has been compared, assuming it should be the same at the entrance of the solenoid for all three measured beam distributions. The difference of the 4D emittance for the pairs of the backtracked beams at the entrance of the solenoid was calculated and then combined in the following way:

$$\Delta E = \sqrt{\Delta e_{12}^2 + \Delta e_{23}^2 + \Delta e_{13}^2},$$

where Δe_{ij} is the 4D emittance difference between two pairs of beam distributions measured and simulated for three different solenoid strengths. A minimum for this combined 4D emittance was found at SCC of 84% for 35 mA beam and 97% for 50 mA beam. The beam distributions at the entrance of the solenoid obtained with this method are shown in Fig. 5 for both 35 mA and 50 mA and have a transverse normalised rms emittance of 0.36 π.mm.mrad and 0.49 π.mm.mrad, respectively.

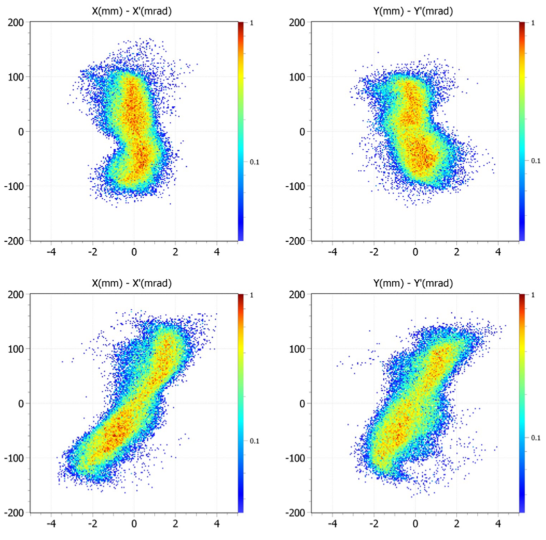

Figure 5: Backtracked beam distributions at the solenoid entrance for 35 mA (top) and 50 mA (bottom).

RFQ

The backtracked beam distributions are used to simulate the beam transport through the LEBT and matching to the RFQ. To compare the simulations to the measurements at the test stand, the RFQ acceptance mask has been modelled in the simulations and the beam transmission through it has been maximised by varying the strength of the solenoids, which is expected to correspond to matching the beam to the RFQ. Comparing the solenoid settings from simulations to those used at Linac4, the differences are less than 3%. The simulated beam distributions at the RFQ matching plane are shown in Fig. 6 and have a normalised rms emittance of 0.47/0.36 π.mm.mrad in XX'/YY' plane for 35 mA and 0.46/0.38 π.mm.mrad in XX'/YY' plane for 50 mA.

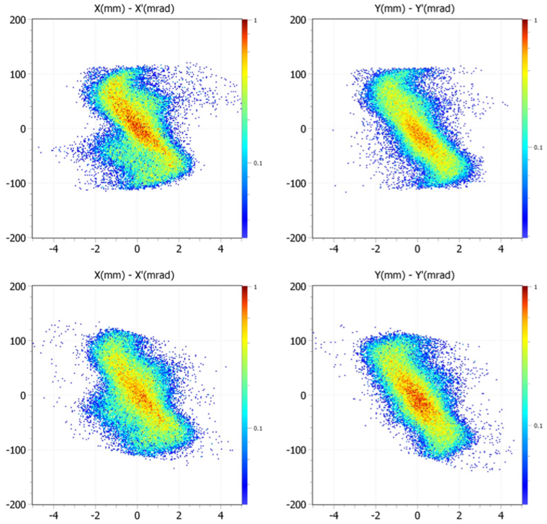

Figure 6: Matched transverse beam distributions at the RFQ matching plane for 35 mA (top) and 50 mA (bottom).

The matched beam distributions were tracked through the RFQ field map in TRAVEL and the effect of the RFQ vane voltage on the beam transmission has been studied, where 103% voltage scaling (dashed line) in Fig. 7 corresponds to the design voltage of 79 kV. At the design vane voltage, the simulated beam transmission through the RFQ is 86% for 35 mA and 85% for 50 mA. To reach the nominal beam energy of 3 MeV at the end of the RFQ, the vane voltage must be at least at 95% of the design value, while for higher than the design voltage values the beam energy starts to plateau. The transmission improves with a higher vane voltage, but it also starts to plateau for higher values than the design voltage.

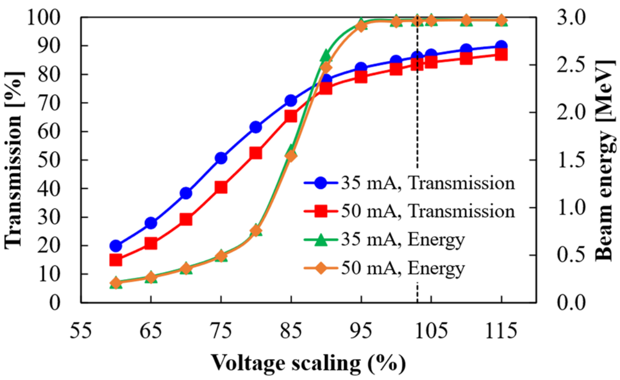

Figure 7: Simulated beam transmission and mean energy at the RFQ exit as a function of the RFQ vane voltage.

The results from simulations and measurements with the RFQ acceptance mask at the test stand and the RFQ at Linac4, are summarised in Fig. 8. As the RFQ acceptance mask only discriminates in the transverse planes and does not account for the longitudinal acceptance, the measured beam transmission through the RFQ at Linac4 is lower compared to the simulations or measurements at the test stand with the acceptance mask. The operational vane voltage of the RFQ at Linac4 was carefully RF calibrated during tuning and commissioning, but a lower than expected amplitude would also explain the differences in beam transmission. Simulated transmission with acceptance mask for 35 mA and 50 mA beam matches the corresponding measurements, while the simulation with 50 mA beam through the RFQ at nominal voltage (field map scaling 1.03) matches the measurement with the RFQ voltage 5% higher than the operational 3.2 MV.

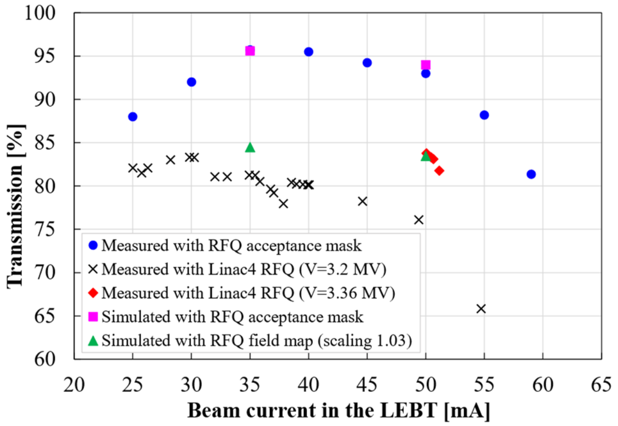

Figure 8: Simulated and measured beam transmission through RFQ acceptance mask and Linac4 RFQ.

MEASUREMENTS AT THE TEST STAND

The Linac4 source test stand is used for developing and testing H$^-$ sources, validating Linac4 spare source units, and also serves as a low-energy material irradiation facility. The setup shown in Fig. 9 includes the H$^-$ source, a LEBT with two solenoid magnets and a pair of steerer magnets, two beam current transformers (BCT), a diagnostics tank with a slit-grid emittance meter, and an RFQ acceptance mask at the end. A gas injection system in the LEBT is used to influence the space charge compensation of the beam.

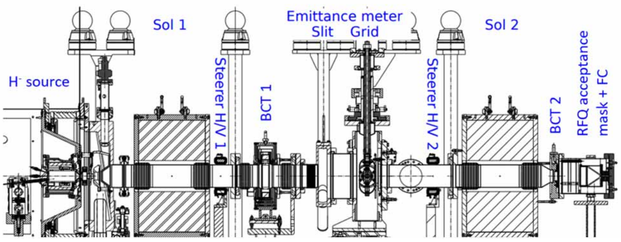

Figure 9: Source and LEBT layout at the Linac4 test stand.

The tests with the IS04 ion source at the Linac4 test stand started in April 2021, but the main test plan was carried out in 2022. The goal of the measurements was to validate and characterize the source for its installation for operation at Linac4. All measurements have been done with a continuously caesiated source.

Emittance Measurements

The emittances were measured for beam current in the range 25-60 mA for three different settings of the first solenoid magnet. For the beam to be fully captured by the emittance meter, which has a measurement range of ±35 mm, the nominal solenoid settings (107-110 A) used to match the beam to the RFQ cannot be used. Therefore, a higher solenoid current of at least 120 A is required to produce a beam size small enough to measure. However, due to the transverse phase-space coupling introduced by the solenoid, the measured emittances do not necessarily represent the emittance at the RFQ matching plane for the matched beam optics. Nonetheless, these emittance measurements, combined with the beam transmission through the RFQ acceptance mask, were essential for comparing and optimising different source and LEBT configurations.

The emittance values measured at the test stand for different beam currents and different solenoid settings are shown in Fig. 10. The optimum beam current range, for which the source extraction design has been optimised, is 35-50 mA, where the emittance values are the lowest and are in the range of 0.3-0.5 π.mm.mrad depending on the beam current and the solenoid strength.

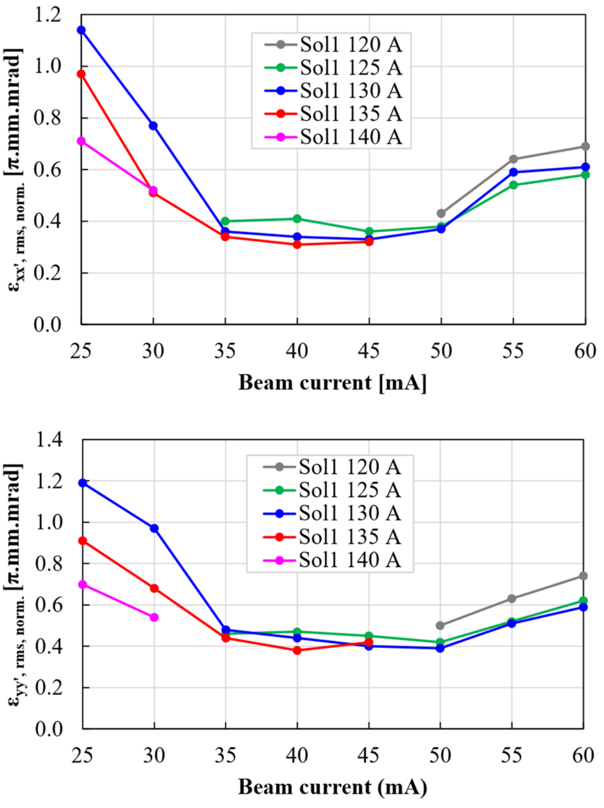

Figure 10: Measured normalized rms emittance as a function of the beam current for different solenoid settings.

Typically, the emittance measurement data has been analysed by first applying a general threshold to the measured signal, manually removing the H_0 beam signal and calculating the emittance in PlotWin [11]. The resulting emittance value depends on the interpretation of the noise, which is not always simple to differentiate from the beam signal and even more complicated in presence of low-density tails, especially for low beam currents. For this reason, an emittance analysis application (EAS) [12] based on SCUBEEX method [13] has been developed to facilitate the interpretation of the measured data. The application also includes a tool to select and remove the H_0 beam.

Tests with the RFQ at Linac4

As part of its validation process, the new IS04 source was installed in the Linac4 tunnel for short tests in November 2021. The transmission through the RFQ, from the BCT in the LEBT to the BCT in the MEBT, was measured for different source beam currents. Most of the measurements were done with the operational RFQ voltage of 3.2 MV. On the last day of the tests, the RFQ voltage was increased by 5% (to a value higher than allowed for operation), which resulted in 10% increase in beam transmission and is an indicator that the operational voltage should be further studied (see the simulations section). A summary of these measurements and a comparison to the IS03 source is presented in Fig. 11.

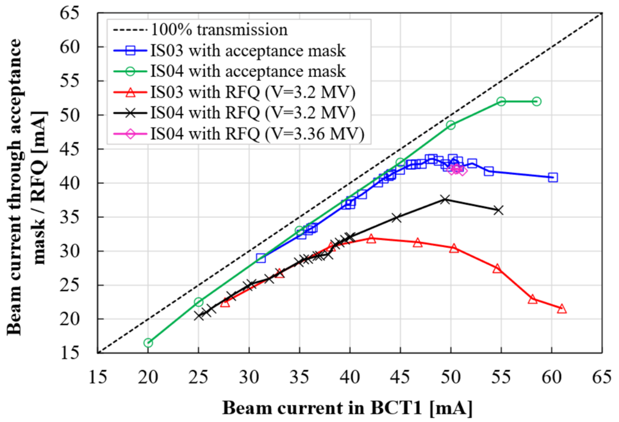

Figure 11: Measured beam current through the RFQ acceptance mask and RFQ as a function of the beam current in the LEBT BCT. Dashed line defines 100% beam transmission. The puller voltage was set to -24 kV.

The beam transmission through both the RFQ acceptance mask and the RFQ itself is higher for higher currents with the IS04 source compared to the IS03, which confirms a smaller emittance out of IS04. For a given beam current, the beam transmission through the RFQ acceptance mask is higher than through the RFQ itself since the mask does not discriminate the beam longitudinally. Nevertheless, the acceptance mask has been a valuable tool for characterising and optimising the source and for finding LEBT settings for beam matching to the RFQ.

The effect of the solenoid polarity on the beam transmission through the RFQ was tested too. Changing the polarity of the two solenoids from (- -) to (+ +) combination (other combinations were tested too) improved the beam transmission through the RFQ by 11% for the 50 mA beam current and operational RFQ voltage. This may be due to the steering on the beam which originates from the source filter and electron dumping magnetic fields, as well as source misalignment, which steers the beam off axis when entering the solenoid. Depending on the solenoid polarity, this steering is then either compensated or enhanced by the beam rotation introduced by the solenoidal field, affecting the transmission. Similarly, the rotation introduced by the first solenoid may partially be compensated by the second one. Additionally, solenoid field aberrations close to its aperture may be minimized depending on the polarity. These effects need to be studied and quantified.

OPERATION AND HIGH-INTENSITY TESTS AT LINAC4

Following the measurement campaign at the Linac4 test stand, including a reliability run, and a short test with the RFQ at Linac4, the IS04 ion source was installed as operational source at Linac4 at the start of 2023 run and was successfully validated with the operational 27 mA peak current after the RFQ, providing similar beam characteristics along the linac as with the outgoing ion source. The transverse emittances measured at the end of the linac and at the end of the transfer line to PSB with 25 mA peak beam current are 0.26/0.25 π.mm.mrad (XX'/YY'). The pulse-to-pulse beam stability from the source is typically in the order of 0.5-0.7% (rms) and the source availability so far is above 99%.

It was demonstrated that IS04 can reliably produce up to 50 mA beam with improved beam characteristics. However, for now, the operational beam current from the source remains 35 mA, as this fully covers the present beam intensity needs of the entire CERN proton chain. Nevertheless, there is an interest from the Physics Beyond Colliders Working Group at CERN to explore the capabilities of the injector complex, particularly in terms of a higher beam intensity for future needs and flexibility in beam production schemes. High-intensity tests were done at Linac4 and its transfer line to PSB during dedicated machine development time with the aim of verifying the existence of possible beam transmission bottlenecks, testing the low-level RF system and assessing the available RF power margin of the cavities, as well as preparing for future high-intensity tests in PSB. With 52 mA from the ion source and 40 mA out of the RFQ with operational voltage of 3.2 MV, 35 mA beam has been transported up to the PSB injection line without any rematching in the linac above 3 MeV. After the RFQ, the main bottleneck is the chopper line at 3 MeV, and there were no beam losses observed in the rest of the machine. The transverse emittances measured with 35 mA in the diagnostics line before the PSB injection were 0.27/0.26 π.mm.mrad (XX'/YY'). The measured longitudinal beam phase spread is similar to the nominal one and indicates a similar energy spread. With this peak beam current, the available RF power for the cavities was on the limit and a beam chopping was needed at 3 MeV.

FUTURE PLANS

In terms of Linac4 operation needs, the focus of the source development is now mostly on further improving the pulse-to-pulse beam stability, reliability, and availability, which is today, after more than 15 years of development, mainly dictated by the gas injection system and the pulsed valve stability. Additionally, a flexible pulsing of the source with a variable cycle period of 0.9-2.5 s is being considered in view of increasing the beam availability and accelerator complex efficiency for different users, which is challenging for the source stability. Therefore, a continuous gas injection and different plasma ignition methods are being considered. Continuous gas injection would also be beneficial for source availability in view of its potential use for a muon collider with a high repetition rate of 50 Hz.

Certain aspects discussed throughout this note need to be further studied and understood, both through simulations and measurements. There is an ongoing effort to improve the IBSimu simulation model of the source extraction as well as to couple TRAVEL with other codes capable of simulating plasma conditions and providing more realistic beam distributions as an input. The effect of the solenoid polarity on the beam transmission and emittance should be further analysed. The transverse beam distribution from the source is asymmetric due to the filter magnet field and depending on the polarity and the strength of the solenoids, may introduce additional emittance growth due to the exchange between the two transverse planes. The space charge compensation and its effect on the emittance along the LEBT is another area of interest.

The simulations have shown the importance of having an emittance measurement right after the source for a better understanding of the beam distribution from source and to decouple it from the effects introduced by the solenoid. It would also be helpful to measure the emittance in the LEBT and at the RFQ matching plane with the nominal optics. Therefore, a redesign of the emittance meter is currently ongoing.

Finally, both simulations and measurements have shown that the RFQ vane voltage may not be the optimum and that the typical beam transmission plateau above the nominal voltage has not been reached. So far, the RFQ operational field level is maintained to limit the number of high voltage sparks. This could possibly be further analysed at the test stand with the spare Linac4 RFQ.

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