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FIRST BEAM MATCHING AND TRANSMISSION STUDIES ON THE ESS RFQ

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Abstract

The European Spallation Source will be driven by a 5 MW, 2 GeV linear accelerator, producing 2.86 ms long proton beam pulses with a peak current of 62.5 mA at 14 Hz. Following the source commissioning in 2018 and 2019, the RFQ was successfully conditioned and subsequently commissioned with beam in 2021. In this paper, we will present results of studies on beam matching to the RFQ, both for low and high current beam modes, and will compare these results to model predictions.

INTRODUCTION

The normal-conducting part of the ESS accelerator (NCL) consists of an ion source, a low-energy beam transport section, an RFQ, a medium-energy beam transport line and five DTL tanks. The commissioning of the NCL is ongoing [1]. The RFQ has been conditioned in the summer of 2021 and first protons were accelerated to 3.62 MeV on the 26th November of 2021. After a period of tests and studies at low beam current, with a so-called probe beam with 5 µs long pulses at 6 mA and a repetition rate of 1 Hz, the beam current was increased to the design value of 62.5 mA on 12th of March 2022 using 5 µs and later 20 µs long pulses at 1 Hz.

Two solenoids in the 2.5 m-long low-energy beam transport line match the beam from the proton source to the RFQ. The solenoids are outfitted with internal steerers for trajectory correction. After the first solenoid, an iris – a set of three movable blades which form a hexagonal aperture – is installed in the LEBT [2]. Closing the iris allows an operator to change the beam current without adjusting the plasma conditions of the source. Compared to relying on adjustments of both the plasma parameters and the extraction to match the changes in space charge forces and the extracted beam distribution, this makes it easier to produce low-current beams with lower emittance compared to the full current beam. A repeller is present in front of the RFQ to prevent electrons from being injected into the RFQ.

The 4.6 m-long four-vane RFQ, designed by CEA/Saclay, accelerates the beam from an energy of 75 keV to 3.62 MeV. Its RF performance is presented in [3]. The inter-vane voltage is ramped from 80 kV at the entrance to 120 kV, requiring a forward RF power of approximately 800 kW.

The injected and accelerated beam current can be measured by three beam current monitors (BCM): one directly in front of the RFQ, one directly after the RFQ and one further downstream in in the MEBT. During all studies presented here, the beam was stopped at a Faraday Cup at the center of the MEBT. Details on the MEBT can be found in [4].

A number of studies were performed to help understand the performance of the RFQ and associated components.

VOLTAGE SCANS

The behavior of beam transmission as function of the inter-vane voltage is a good quantity to compare to model predictions to verify the expected performance of the beam dynamics of the RFQ. In simulation, for small changes in the voltage (< 10 %), output beam energy and transmission will remain relatively constant while for larger decreases, the energy spread will be large as transmission drops.

The power injected into the RFQ was scanned over the entire available range. Figure 1 shows the behavior of the transmission through the RFQ, for different matching conditions, as measured by the BCMs at the start and the end of the RFQ in comparison to the model prediction. Figure 2 shows the input distributions as predicted by a model.

The beam current for this study was approximately 6 mA. Multiple, quite different settings of the solenoid magnets were found that give beam transmission of close to 100 %. The measurements fit the expected behavior with voltage: independent of solenoid settings, the transmission remains

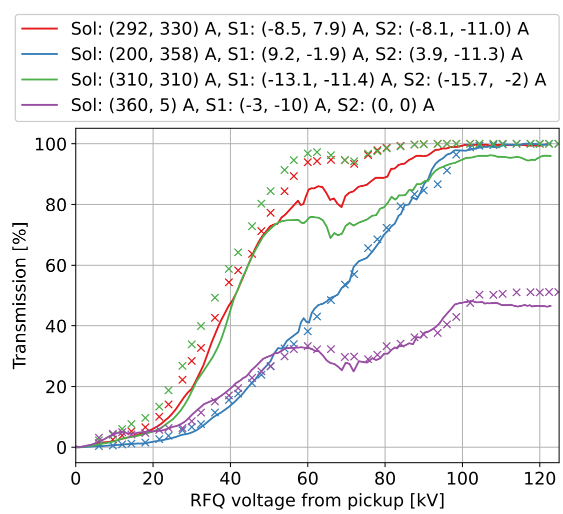

Figure 1: Beam transmission through the RFQ for different inter-vane voltages and four different LEBT configurations. The data shown as lines are measurements, the data shown as crosses are predictions by a model built upon ion source commissioning data.

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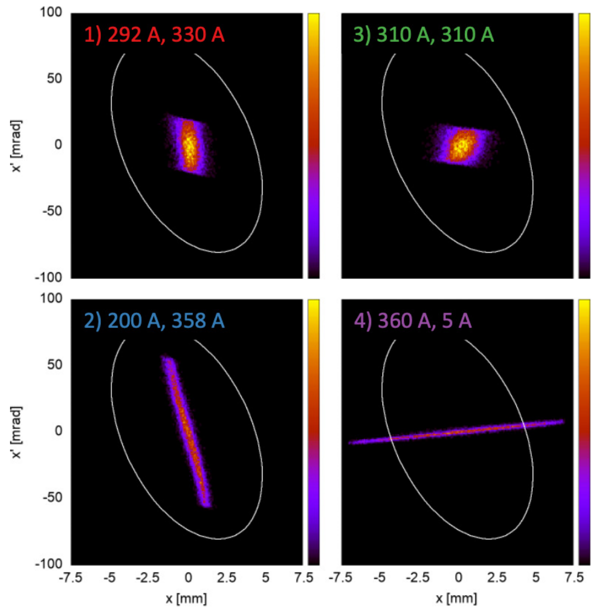

Figure 2: Transverse beam distributions at the RFQ matching plane for the different LEBT settings used to study RFQ transmission as function of inter-vane voltage in Fig. 1. The ellipses indicate the predicted zero-current acceptance.

constant for voltages above approximately 80 % nominal. For some of the matching settings, transmission does not steadily decrease, but there is a local maximum at around half the nominal voltage, 60 kV. This behavior disappears when looking at the transmission further downstream, as the beam, according to the model, only attains an energy of 400 keV and is almost entirely lost. It is also not present for curves taken when sending the full beam current.

The model is based upon data taken during the 2019 commissioning run [5]. Particle distributions were sampled from the emittance measurements which were manually cleaned from signals arising due to H_2^+ and H_3^+. These were backtracked to the source under an assumed space charge compensation level of 95 %.

The space charge contribution from heavier hydrogen molecules can have an impact on the transport. In a second simulation in forward direction, 12 % H_2^+ and 3 % H_3^+ were included with the same distribution. These were then tracked to the location of the emittance meter, building a space charge map for the next backtracking iteration. This process usually converges in 2 to 3 iterations. The resulting phase space orientation of the hydrogen molecules matches those in the measurements. The procedure could in the future be adapted to also match the fraction of these species to the intensity in the emittance measurements, providing an indirect measurement.

The resulting beam distribution from the source was then tracked to the RFQ, with the same iris setting as was used for the corresponding measurement. In case 1 and case 3, where the beam distribution at the entrance to the RFQ is well centered in the acceptance ellipse, transmission remains high for lower inter-vane voltages. In case 2, where the beam

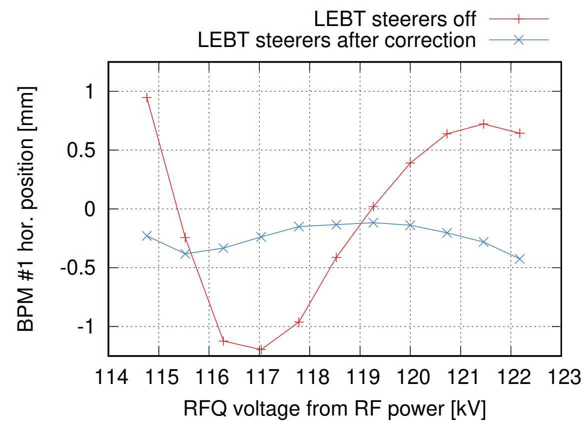

Figure 3: Oscillation of the horizontal beam position during the RFQ voltage scans, before and after correction of the trajectory in the LEBT, as measured by the first BPM in the MEBT.

is focused but aligns well with the acceptance ellipse, transmission reaches 100 % at the nominal voltage but decreases quicker than in case 1 and 3 when the voltage is reduced. The beam in case 4 was mismatched. Predictions of the RFQ acceptance show that it decreases in angular direction with voltage. Consequently, in cases 1, 3 and 4, where the angular spread is small, transmission remains higher compared to the value at nominal voltage to lower inter-vane voltages.

Between the 2021 and 2022 runs, it was discovered that a cable to the electron repeller on the source side had been left disconnected. After re-connection, through indirect studies, beam quality was found to be significantly improved [1] as a consequence of better space charge compensation behind the ion source [6]. As the emittance meter was not available in the 2021 and 2022 runs, data for the new configuration could not be taken and the model is no longer valid for data taken with the full beam current. The emittance measurements will be repeated in one of the next commissioning runs.

BEAM STEERING OF LOW-CURRENT BEAMS

While scanning the power sent to the RFQ, we observed a significant oscillation of the beam's position as measured by the BPMs in the MEBT. An example is shown in Fig. 3. This is a result of improper steering in the LEBT i.e. the beam is injected off-axis or at an angle. While with high beam current, large trajectory excursions in the RFQ will lead to a drop in transmission, this is not necessarily the case with the low-current probe beam.

The model developed above was used to predict the behavior of an off-axis beam injected into the RFQ. The beam's horizontal position is shown in Fig. 4 for different RFQ voltages and offsets at the matching plane for a range of inter-vane voltages, in a range where transmission was found to be constant. When the beam is injected at an angle or an offset, it will oscillate around the axis. As the electric field changes, the transverse phase advance in the RFQ changes.

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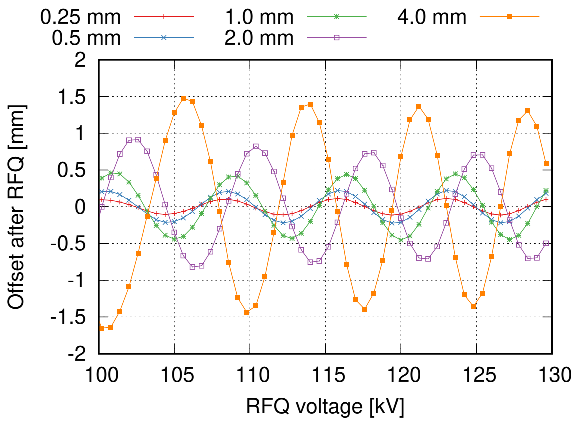

Figure 4: Model prediction of the horizontal beam offset after the RFQ as function of the RFQ inter-vane voltage in a range where transmission remains relatively constant, for different injection offsets. This was calculated using Toutatis with the first distribution shown in Fig. 2.

This leads to the oscillation of the beam center shown in Fig. 3 and Fig. 4 when changing the injected power. The same behavior is present in the vertical direction.

Operationally, the strength of the LEBT steerers was chosen by minimizing the amplitude of these oscillations. This was done using either Powell's method or the Nelder-Mead simplex method as implemented in scipy.optimize [7]. As function to optimize, the RF power was repeatedly scanned in a limited range around the nominal value and the mean squared deviation of the BPM position calculated. As shown in Fig. 3, this made it possible to reduce the oscillation from an uncorrected level of ±1 mm to ±0.15 mm.

Note that the goal of the algorithm is not to reduce the offset at the BPM but to reduce its dependence on the RFQ inter-vane voltage. The remaining 200 µm offset is not of much concern and can easily be corrected using the steering magnets in the MEBT. Some of the dependence of the beam position on the voltage remains – this implies that part of the injection angle or offset can not be corrected with the LEBT steering magnets.

IMPACT OF THE LEBT REPELLER

In front of the RFQ an electron repeller is installed that is biased to −3.5 kV by design. The same assembly also serves as a dump for the beam chopper in the LEBT and is surrounded by the BCM used to measure the beam current injected into the RFQ. The potential of the repeller is meant to prevent electrons present in the LEBT, compensating the beam's charge, from reaching the RFQ, with the dual purpose of avoiding a systematic error in the measurement of injected beam current and keeping the compensation level.

The impact of the voltage on the repeller was studied as function of beam current, reducing the beam current by closing the aperture of the iris. Figure 5 shows both beam currents measured by the BCMs in front of and after the RFQ, as well as the transmission calculated from these numbers. Below a voltage of −2 kV, the measured transmission remains constant. This is significantly more than the ~700 V estimate assuming a homogeneously charged cylinder (a 60 mA beam with ~1 mm radius in a pipe with 7 mm aperture). Note that for this study the beam was matched for the full beam and not rematched for the different injected beam currents, causing a slight decrease in transmission for the lower-current beams. As discharges on the repeller became an issue for the machine uptime and will potentially affect its lifetime, the operational voltage was reduced to −2 kV.

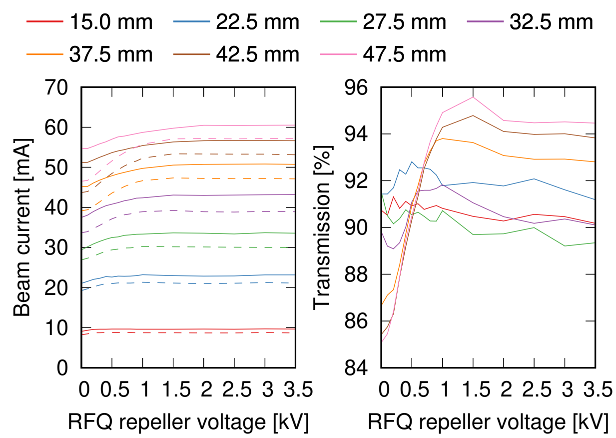

Figure 5: Impact of the voltage on the electron repeller in front of the RFQ. The beam current sent to the RFQ was changed by varying the diameter of the iris. The left plot shows the current injected (solid) into and the accelerated (dashed) current as function of the repeller voltage. The right plot shows the calculated RFQ transmission.

Around −1.5 kV, there seems to be an optimum in beam transmission for higher injected beam currents. The current out of the RFQ however does not increase. This is likely to be the result of some electrons escaping the LEBT through the BCM, reducing the measurement of injected current. Above that number, both the measurement of the injected and the extracted current drop along with the transmission through the RFQ, probably due to a reduction in space charge compensation. This loss in transmission could also not be recovered when trying to rematch the LEBT.

CONCLUSION AND OUTLOOK

The ESS RFQ, as far as could be ascertained during the early commissioning, performs according to expectations when compared to the simulation model. Beam with the full beam current was accelerated. The slit-grid emittance meter in the MEBT became available in the last days of the commissioning round to the DTL [1] and will be used in the next commissioning period (scheduled to start early 2023) for a more complete characterization of the beam quality out of the RFQ. Focusing on low-beam current operation for the initial commissioning allowed for studies with low-current, low-emittance beams (such as the study of the impact of the beam offsets at injection) that demonstrate the benefits of having an iris present in the low-energy beam transport line.

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