ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO2C2

BEAM TUNING STUDIES IN THE ESS MEBT

N. Milas*, M. Akhyani, R. A. Baron, C. S. Derrez, M. Eshraqi, Y. Levinsen, R. Miyamoto, D. Noll, R. Tarkeshian, I. Vojskovic, R. Zeng
European Spallation Source ERIC, Lund, Sweden

Abstract

The European Spallation Source (ESS), currently under construction and initial commissioning in Lund, Sweden, will be the brightest spallation neutron source in the world once its driving proton linac achieves the design power of 5 MW at 2 GeV. Such a high power requires production, efficient acceleration, and almost loss-free transport of a high current beam, thus making the design and beam commissioning of this machine challenging. During the commissioning period in 2022 a campaign for a full characterization of the ESS Medium Energy Beam Transport session (MEBT) was carried out. Both transverse optics and longitudinal parameters were measured and compared to simulations, among them: buncher cavity tuning, transverse emittance, and initial Twiss parameters. In this paper, we present the results and future plans.

INTRODUCTION

The European Spallation Source (ESS), currently shifting from construction to testing and initial beam commissioning in Lund, Sweden, will be a spallation neutron source driven by a long pulse proton linac [1]. The linac consists of normal-conducting (NC) accelerating structures and three sections of superconducting cavities, as well as three transfer-lines. The NC accelerating structures include an ion source (ISrc), a radio frequency quadrupole (RFQ), and a drift tube linac (DTL). The beam commissioning of the ESS linac is being conducted in stages [2–4]. Commissioning of the first stage, for the ISrc and LEBT, started in September 2018 and continued until early July 2019. The beam was transported through the RFQ and part of the MEBT in 2021. In the first half of 2022 beam was transported to the end of the first DTL tank (DTL1), reaching an energy of 21 MeV. Schedules of the completed commissioning steps are listed in Table 1.

This paper will highlight the studies in the Medium Energy Beam Transport section (MEBT), which follows the RFQ, performed in 2021 and 2022. The main results is an attempt of estimating the input Twiss parameters to the MEBT in all 3 planes, using the Wire Scanners and the sum signals of BPMs. A measurement of the RFQ output energy and beam based calibration of the buncher cavity amplitude will also be presented.

COMMISSIONING HIGHLIGHTS

The first part of the MEBT commissioning started in 2021 (Step 2A in Table 1), and, during this first period, the main focus was on beam transmission through the RFQ and less on the MEBT characterization. During this period, a cautious approach was taken before sending the beam to the RFQ and ramping up beam parameters. Time was spent verifying the systems critical for machine protection, such as the Beam Current Monitors (BCMs), the LEBT chopper, timing configuration [5], and machine protection systems [6]. Nevertheless, within the allocated period of five weeks, the beam was successfully accelerated with the RFQ and a stable beam with 6 mA, 50 µs, and 1 Hz was established up to the MEBT Faraday cup (FC), without any accident. The output energy of the RFQ was verified to be 3.6 ± 0.1 MeV with time-of-flight measurements (Fig. 1). In the very end of this first commissioning round some of the Wire Scanners became available for testing and preliminary measurements [7].

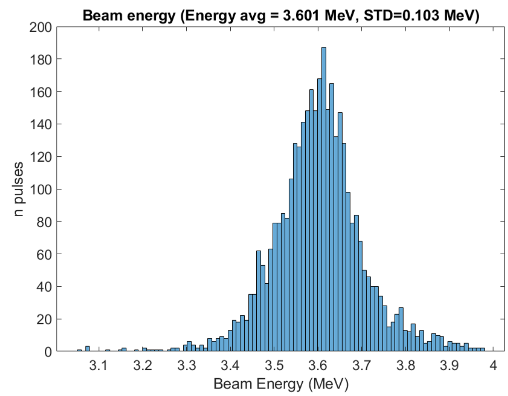


Figure 1: Histogram of the measured RFQ energy with time-of-flight.

In 2022, two additional commissioning periods with approximately nine weeks in total took place (Steps 2B and 2C in Table 1). A stable beam with the nominal 62.5 mA current was established up to the MEBT FC, with an excellent RFQ transmission of ~95%. Testing of the closed-loop operation of the low-level RF (LLRF) of the RFQ also made good progress during these periods, and the RFQ ran with both

Table 1: NC Linac Commissioning Schedule (Two additional periods were allocated for the second step.)

Step	Destination	Start	End
1	Tank after LEBT	2018-09-19	2019-07-03
2A	MEBT	2021-11-10	2021-12-17
2B	MEBT	2022-02-23	2022-03-12
2C	MEBT	2022-04-06	2022-05-23
3	DTL1	2022-05-30	2022-07-13

* natalia.milas@ess.eu

11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO2C2

the feedback and adaptive feed-forward during the following commissioning step (Step 3 in Table 1). During the first period in 2022 (Step 2B in Table 1) a series of measurements with the Wire Scanners was performed and BPMs were tested in the MEBT. The buncher cavities in the MEBT were not available until the second additional period (Step 2C in Table 1). During this period a series of phase scans and cavity tuning studies were carried out first time for the buncher cavities. The emittance measurement units (EMUs) in the MEBT, a pair of slit and grid systems, became available in the last two weeks of the commissioning step for the DTL (Step 3 in Table 1), and a few measurements were made. Unfortunately, the availability of the Wire Scanners during this second period was not stable, and we could not perform new measurements with the design optics fully set nor repeat the Wire Scanners measurements simultaneously with emittance scans.

Transport through the DTL1 was achieved in June 2022 and transport of a beam with the nominal current of 62.5 mA was first attempted on 1st of July, 2022 and established within a few hours.

THE ESS MEBT

The nominal beam parameters of the ESS linac are a peak current of 62.5 mA and pulse length of 2.86 ms at a 14 Hz repetition rate. The MEBT, designed for a beam of 3.62 MeV, is approximately 4 m long and houses a wide range of equipment needed for transverse and longitudinal beam transport and characterization. A set of 11 quadrupoles is used to match the beam in the transverse plane, and three RF buncher cavities are used to counteract debunching and to match the beam in the longitudinal plane to the entrance of the DTL1. A fast chopper, with a rise time of less than 10 ns, is also installed in the MEBT and can be used to clean up the head and tail of the beam pulse. For beam characterization a complete set of diagnostics is foreseen: 3 Wire Scanners, a pair of EMU, 7 Beam Position Monitors (BPMs), a bunch shape monitor (BSM) and a suite of current measurement devices, including one FC and two types of BCMs. Figure 2 is a schematic of the MEBT showing the positions of all diagnostics foreseen for the MEBT.

During the commissioning in 2021 (Step 2A in Table 1), the only diagnostics available in the MEBT throughout commissioning were the BPMs and the beam current monitors (FC and BCMs). The buncher cavities were installed but remained without RF power until the second commissioning period in 2022 (Step 2C in Table 1) [8], during which most of the equipment was running. Currently, the only diagnostics not yet installed in the MEBT is the BSM. The Wire Scanners and the EMUs were available and a more complete characterization of the beam was possible [7].

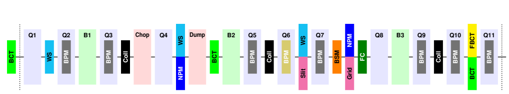


Figure 2: ESS MEBT layout.

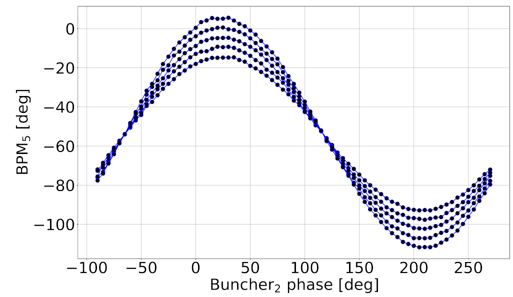


Figure 3: Example of data used for the amplitude calibration of the MEBT bunchers.

MEBT CHARACTERIZATION AND TUNING

Longitudinal Characterization and Tuning

During the commissioning of 2021 (Step 2A in Table 1) a precise measurement of the RFQ output beam energy was performed. Phase signals from two MEBT BPM were compared in the time domain and gave 3.6 ± 0.1 MeV, with meticulous calibration of cable distances and delays performed in advance [4].

All bunchers have pickups that measure the field inside but the values measured by the pickups are often less accurate than those determined by the phase scan. Figure 3 shows an example data of the phase scan of the second buncher. With the knowledge of the energy, it is possible to acquire the ratio $\chi = A_{cav}/A_{beam}$ between the cavity amplitude from the pickup measurement A_{cav} and one from the phase scan A_{beam}, which is a more direct measurement of the field experienced by the proton beam. Table 2 summarizes this calibration factor for all three bunchers. The listed values are results from many phase scans performed over several days, in order to verify stability and repeatability. Details to determine this calibration factor is described in detail in [9].

In addition to the phase and position, the BPMs also provide the amplitude signal. Once the bunchers' settings are known, the amplitude signal can provide information of the longitudinal bunch length through the following expression [10]:

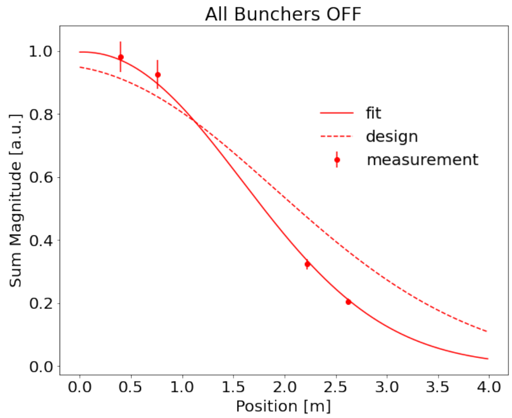
$$u(\omega, \sigma) = Q f(\omega) \exp(-\sigma^2 \omega^2 / 2) \tag{1}$$

where Q is the bunch charge, the function f is a factor related to the BPM geometry and calibration, ω is the frequency at which the BPMs perform their measurements (in the case of the MEBT BPM, it is 704.42 MHz, twice the RF frequency) and σ is the bunch length at the BPM location. Assuming

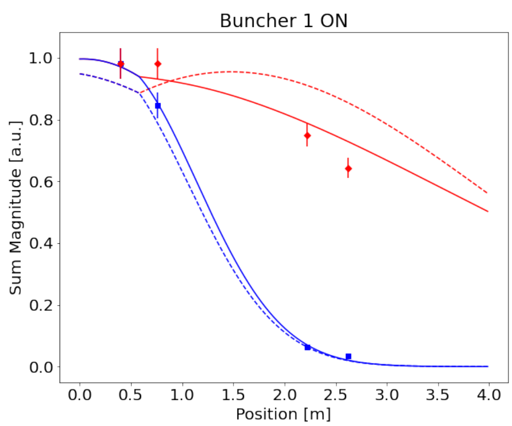
Table 2: MEBT Bunchers Amplitude Calibration Factors

Cavity	χ
Buncher 1	0.96 ± 0.02
Buncher 2	0.98 ± 0.01
Buncher 3	0.89 ± 0.01

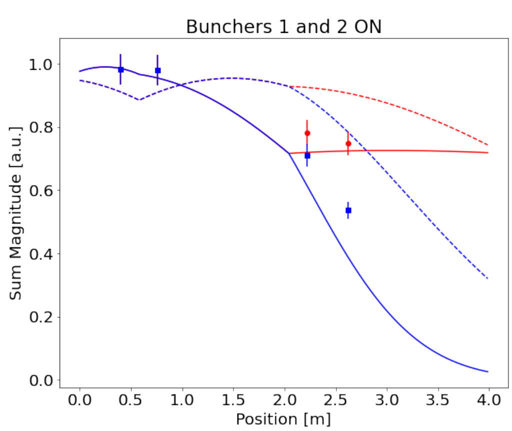
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO2C2



(a) All bunchers detuned and off



(b) Buncher 1 set to bunching (red) and debunching (blue) phases.



(c) Buncher 1 in bunching phase and Buncher 2 in bunching (red) and debunching (blue) phases.

Figure 4: BPMs amplitude signals compared to simulation. The envelope simulations use the twiss parameters listed in Table 3 as input values, full lines are the fitted results and dashed are design.

that all MEBT BPMs have a similar value for the f function, the only dependency on the amplitude signal variation lies on the bunch length.

In order to estimate the input longitudinal Twiss parameters to the MEBT, we measured the sum signals of the first four BPMs when all bunchers are turned off. In this case, the bunch length varies a lot through the MEBT, due to debunching. It was possible to estimate the values of the initial longitudinal Twiss and emittance using the amplitude signal of the first four BPMs (U_{BPM}) and to minimize its simulated value using the calculated bunch length at the BPM position from Eq. (1), according to:

$$S = \sum_{i=1}^{n} [U_{BPM,n} - u(\omega, \sigma_{sim})]^2 \qquad (2)$$

A comparison of the fitted and the design values of the Twiss parameters at the MEBT injection are listed in Table 3. Figure 4(a) shows the measurement data, used for the fitting, and two curves from simulations, where the solid curve uses the Twiss from the fits as input whereas the dashed curve uses the design values as input. Figure 4(b) shows the data and simulations for the case when Buncher 1 was turned on with the design Amplitude value and set to the bunching (red) and debunching (blue) phases. Similarly, in Fig. 4(c), Buncher 1 was on and set to default design values for amplitude and phase, while Buncher 2 was set with the design amplitude and both bunching (red) and debunching (blue) phases. For the simulation curves of Figs. 4(b) and 4(c), the same set of the input Twiss as Fig. 4(a) was used.

Table 3: Longitudinal Parameters at the RFQ-MEBT Interface for a Low Current Beam

Parameter	**Design**	**Fit**
$\varepsilon_{N,z}$ (π mm mrad)	0.287	0.18 ± 0.04
α_z	−0.255	0.2 ± 0.4
β_z (m)	0.496	0.2 ± 0.1

Transverse Emittance and Twiss

This section presents a result from 3 Wire Scanner measurements conducting during the commissioning step in 2021 (Step 2A in Table 1) as a part of extensive tests and studies of the Wire Scanners. During this measurement only the first 3 quadrupoles in the MEBT were turned on and none of the bunchers was powered. This special optics was needed to assure that the beam spot on the FC is not damaging the MEBT FC. A set of the 3 profile measurements were taken at 57 mA, close to the MEBT nominal current, and a Gaussian was fitted to each profile. The standard deviation for all profiles measured is plotted in Fig. 5. Using a simple minimizer function and an envelope model, the transverse Twiss parameters at the entrance of the MEBT were calculated and are shown in Table 4. For this fit the longitudinal twiss parameters were frozen to the values already presented in Table 3.

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO2C2

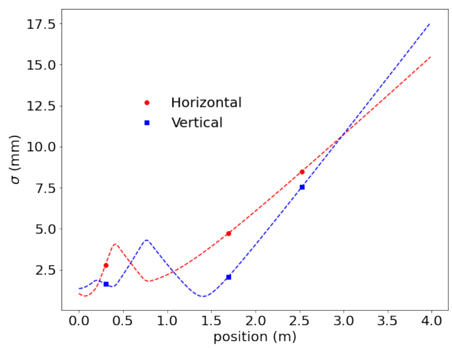


Figure 5: Measurement using all Wire Scanners in the MEBT. Bunchers are not powered and only the first 3 quads are turned on. This was a special optics setup to protect the MEBT FC. The measurements are for a beam current of 57 mA.

Table 4: MEBT Initial Transverse Twiss

Parameters	Design	Fit
$\varepsilon_{N,x}$ (π mm mrad)	0.139	0.53 ± 0.01
α_x	−0.052	0.76 ± 0.02
β_x (m)	0.281	0.26 ± 0.07
$\varepsilon_{N,y}$ (π mm mrad)	0.138	0.3 ± 0.1
α_y	−0.430	−1.0 ± 1.0
β_y (m)	0.498	0.7 ± 0.2

We also performed measurements using the EMU for both planes at the nominal current.The normalized emittance in this case for the vertical and horizontal planes are 0.23 and 0.44 π mm mrad, respectively. The values for the emittance are in agreement with the ones obtained for the Wire Scanner fit.

DISCUSSION AND OUTLOOK

Using different techniques we were able to infer the input Twiss parameters for the MEBT, given the machine configuration we used during Step 2B (see Table 1). For all the planes values were very different than ones expected from the design. For the longitudinal plane the limitation could be shortcoming from the envelope model and the fact that both the BPM sum signal or the model can describe the core of the beam but are not able to define the tails, which can have some influence, specially on the emittance value.

For the transverse plane we encountered an additional issue, during the 2021 commissioning we found out the source repeller was disconnected [4] and thus all emittance measurements from the LEBT performed in 2018-2019 period do not correspond to what we have now. Similarly the source and LEBT configuration established in that commissioning period is not also trustworthy. Unfortunately the LEBT EMUs were not operational during 2021 and 2022 and thus we had no way of optimizing the injection into the RFQ. This could be one of the reasons why the beam Twiss and emittance in the MEBT are so different. In the next commissioning period, in the second quarter of 2023, we expect to be able to re-characterize the LEBT and have a better understanding of the beam that is transported to the MEBT section.

The measurement for the EMU and wire were also never performed for the same beam conditions. The EMU results are very preliminary and require more work on both technical issues, relating to the hardware and motion control, and from the beam physics side, making sure the beam we are sending is stable enough. On particular reason that could explain the high emittances measured, specially in the horizontal plane, is that we observed during the commissioning runs that the beam position throughout the pulse is changing, which can smear the beam in both wires and EMUs measurements and result in bigger emittance values. This effect should be bigger for wires since we use longer pulses, of 20 µs, in comparison to the 5 µs pulse length using for EMU measurements.

CONCLUSION

In 2022 an extensive set of measurements in the MEBT was performed and were combined with results from the 2021 commissioning run in order to get a complete characterization of the MEBT. Estimations of the beam parameter in the RFQ-MEBT interface for all planes were presented and differed substantially from the design values. Some of the differences in the values measured and expected could be due to limitation in the envelope model, other shortcoming could come from assuming Gaussian distributions and not taking into account the beam tails, which can have a big impact on the calculation of the rms values. A new set of measurements and characterization is planned for the next commissioning run when we can perform measurement for transverse and longitudinal in parallel as well and have more control over the beam quality during the measurements, since most of the systems that were in test or commissioning stage in 2022 will be available from the beginning for the next commissioning run.

ACKNOWLEDGEMENT

The authors would like to thank the Operation and Linac teams which were heavily involved in the ESS Linac operation, hardware and beam commissioning for their continuous support and input.

REFERENCES

[1] R. Garoby *et al.*, "The European Spallation Source Design," *Phys. Scr.*, vol. 93, no. 1, p. 014 001, 2017. doi:10.1088/1402-4896/aa9bff

[2] R. Miyamoto, M. Eshraqi, and M. Munoz, "ESS Linac Plans for Commissioning and Initial Operations," in *Proc. HB'16*, Malmö, Sweden, Jul. 2016, pp. 342–347. doi:10.18429/JACoW-HB2016-TUPM5Y01

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO2C2

[3] D. C. Plostinar *et al.*, "Status of the Normal Conducting Linac at the European Spallation Source," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 2019–2022. doi:10.18429/JACoW-IPAC2022-WEPOTK001

[4] R. Miyamoto *et al.*, "Beam Commissioning of Normal Conducting Part and Status of ESS Project," presented at LINAC'22, Liverpool, UK, Aug.-Sep. 2022, paper MO1PA02, to be published.

[5] N. Milas, A. A. Gorzawski, and J. J. Jamroz, "Commissioning of the Timing System at ESS," presented at IBIC'22, Krakow, Poland, Sep. 2022, paper TUP23, this conference.

[6] S. Gabourin, M. Carroll, S. K. de Carvalho, A. Nordt, S. Pavinato, and K. Rosquist, "The ESS Fast Beam Interlock System: First Experience of Operating With Proton Beam," presented at LINAC'22, Liverpool, UK, Aug.-Sep. 2022, paper MOPORI17, to be published.

[7] C. S. Derrez *et al.*, "Wire Scanner Systems at the European Spallation Source (ESS): Tests and First Beam Commissioning Results," presented at LINAC'22, Liverpool, UK, Aug.-Sep. 2022, paper TUPOJO13, to be published.

[8] R. Zeng *et al.*, "RFQ Performance During RF Conditioning and Beam Commissioning at ESS," presented at LINAC'22, Liverpool, UK, Aug.-Sep. 2022, paper TUPOPA05, to be published.

[9] Y. Levinsen *et al.*, "First RF Phase Scans in the European Spallation Source," presented at IBIC'22, Krakow, Poland, Sep. 2022, paper TUP35, this conference.

[10] A. Shishlo and A. Aleksandrov, "Noninterceptive method to measure longitudinal Twiss parameters of a beam in a hadron linear accelerator using beam position monitors," *Phys. Rev. ST Accel. Beams*, vol. 16, p. 062 801, 2013. doi:10.1103/PhysRevSTAB.16.062801