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FIRST RF PHASE SCANS AT THE EUROPEAN SPALLATION SOURCE

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Abstract

The installation and commissioning of the European Spallation Source is currently underway at full speed, with the goal to be ready for first neutron production by end of 2024. This year we accelerated protons through the first DTL tank. This included the RFQ, 3 buncher cavities in the medium energy beam transport as well as the DTL tank itself as RF elements. At the end of the DTL tank we had a Faraday cup acting as the effective beam stop. This marks the first commissioning when RF matching is required for beam transport. In this paper we discuss the phase scan measurements and analysis of the buncher cavities and the first DTL tank.

INTRODUCTION

The European Spallation Source (ESS) is designed as the world brightest neutron source, driven by a 5 MW proton beam that is accelerated to 2 GeV. The proton linac driver consists of a normal conducting (NC) front end that brings the beam energy to around 90 MeV, followed by a super conducting (SC) section and finally a beam transport to the rotating tungsten target wheel. The linac features a very long beam pulse length of 2.86 ms, with a 14 Hz repetition rate. The NC radiofrequency (RF) and hence beam bunch frequency is at 352.21 MHz. The two last SC families operate at twice that frequency, 704.42 MHz.

The first beam commissioning of the ESS linac commenced in 2018-19, including the ion source (IS) and the low energy beam transport (LEBT) [1, 2]. The second stage of commissioning started in the fall of 2021, included the radiofrequency quadrupole (RFQ) and the medium energy beam transport (MEBT). This run continued with some minor interruptions until the next step which sent beam through the first drift tube linac (DTL) tank, starting at the end of May 2022 and continuing until mid July. For this stage the buncher cavities in the MEBT were also made available, which marked the first time beam-based RF matching was possible and necessary.

In this paper we will discuss the initial experience in matching the RF phase and amplitude using the phase scan technique primarily for the buncher cavities and also for the first DTL tank. A more general overview of the MEBT characterisation is presented in [3]. Prerequisites for this work is also to have good diagnostics [4], and a well functioning timing system [5]. For the bunchers, the primary signal to look at is the beam position monitor (BPM) phase response. For the DTL we have transmission scans as well as the response signals of the internal BPMs in the tank.

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SIMULATIONS

Our primary simulation software is TraceWin [6], as well as OpenXAL [7] meant primarily for online modelling though usable for any simulation where an envelope model is sufficient. That essentially translates to effects where a linear space charge model is sufficient. In both cases, each gap in the bunchers and DTL is modeled as a drift-kick-drift.

RF phase scans are performed by modulating the amplitude and phase of an RF element, and monitoring the Time of Flight (ToF) of the beam downstream of the element. In general the absolute value of the ToF is not known, so most commonly one then instead looks at the change in BPM phase signal(-s) and compares with model expectation.

For modelling RF cavities one often refers to the transit time factor (TTF), which follows

$$T=\frac{1}{\int E_z dz}\left[\int E_z \cos\omega t dz - \tan\phi \int E_z \sin\omega t dz\right]. \quad (1)$$

Here E_z is the longitudinal on-axis field amplitude that generally depend on z, and ω is the RF frequency. V_0 is the integrated field amplitude E_z. ϕ is the relative phase arrival of the particle. The time t is a function of z through the speed of the particle. Through the TTF we can then get the simple formula for the the net energy gain traversing the cavity, which becomes

$$\Delta W = qV_0 T\cos\phi, \quad (2)$$

where q is the charge of the particle, and V_0 is the integrated field (denominator of (1)). For $\phi=0$ we then have what we call "on crest" acceleration, which gives the maximum energy gain, but then with no longitudinal focusing. In fact there is even defocusing on half of the bunch, since particles arriving early (or late) and would need a higher energy kick to "catch up" instead get a lower energy kick falling further behind the synchronous particle.

Buncher cavities run at $\phi = -90°$, which provides no acceleration but maximum longitudinal focusing. These are rather simple cavities generally speaking, providing sine-like signatures in phase space downstream that are relatively easy to analyse (differing for example from DTL signatures). As we can understand from Eq. (1), even if the net energy gain is zero, the transit time still depends on the amplitude of the cavity. This can be understood from the fact that the cavity has a finite size and the particle is travelling slower than the speed of light. If $\phi=-90°$, the particle arrives at the entrance of the cavity early and experience a slight deceleration. In the middle of the cavity there is no acceleration, while in the second half there is a comparatively positive acceleration

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which nets out as 0 acceleration. However the particle will have travelled on average with a slightly lower energy through the cavity than if it was turned off. This is why one commonly looks at the phase variation between 2 downstream BPMs rather than just a single BPM. The RF relative phase is found when there is no amplitude dependency on the phase between the two downstream BPMs.

In the commissioning run presented here, we have no downstream BPMs of the DTL to look at, so we are left with analysing the transmission and the signature curves of internal BPMs.

Buncher Cavities

There are 3 buncher cavities in the MEBT to focus the beam longitudinally and match to the DTL following. The first buncher stops the rather strong debunching arizing from space-charge forces out of the RFQ to maintain a reasonable beam size through the transport section, and would ideally be placed more or less as close to the RFQ exit as possible. The second maintains stable longitudinal envelope and operates at about half the strength of the two other bunchers. The last is primarily responsible for matching to the DTL and would again ideally be placed as close to the DTL entrance as possible. This last buncher operates quite close to the maximum field possible with these bunchers.

All bunchers operate at −90° from the accelerating phase, which means that the centroid is unaffected. The head of the bunch (arriving early) will experience a deceleration kick, and the late tail of the bunch will experience an accelerating kick.

The −90° is conceptually quite easy to find for such a cavity. It is essentially the phase where the downstream ToF does not depend on the cavity amplitude. However, the transit through a finite length cavity at this phase, the beam initially experience some decelaration, in the middle of the cavity zero acceleration, and then some acceleration again at the end of the cavity again to reach the net acceleration of zero. This means the transit time through the cavity does depend on the amplitude at the correct phase. This is the motivation for measuring the ToF between two downstream BPMs rather than just one. A BPM far downstream would be showing an intersection point very close to −90°, as the variation in transit time becomes small in comparison to the variation in ToF.

In Fig. 1 we demonstrate how the single BPM fit would look for our first MEBT buncher. The intersection of the curves from a given BPM is not exactly at −90°, and the discrepancy is strongest for the closest BPM2, while for the other 2 BPMs we are close to the expected measurement errors in this example. It is still preferred to use 2 BPM for ToF since it is fully model independent, but single BPM fit can be useful to improve statistical understanding of the fit.

A secondary effect here is that if we do a sine fit of each phase curve to find the −90°, the relative effect of the transit time increases somewhat. It was found in simulations that this effect is well below the measurement uncertainties we are working with in the data for this commissioning round.

When we later in the paper quote a single BPM fit, we then subtract the offset expected from a simulated fit using our field map model.

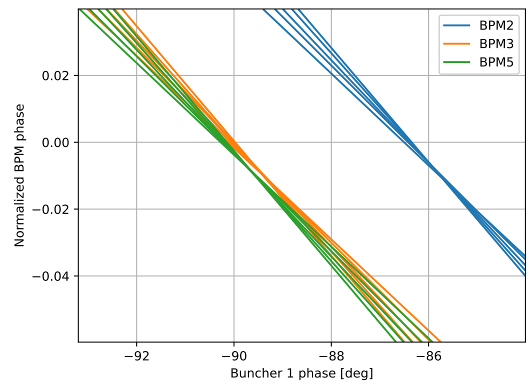

Figure 1: Simulated phase curves of BPMs as a function of buncher RF phase for varying buncher field amplitude. The colours represent different BPMs and the different curves of same colour are for different amplitudes. The point where curves intersect represent the cavity phase where this signal is amplitude independent.

DTL

Figure 2 show the simulated phase signatures of the internal BPMs to the DTL tank. Interesting to note is that the first BPM should follow a rather simple sine-like signature, with a minima close to $\phi = 0$. The first BPM will also have a good transmission for a larger range of RF phases. On top of that it should be added that unwrapping the signals of the later BPMs requires a very fine grained phase scan, as well as accurate BPM signals. For example BPM4 in simulation shows a phase variation of over 5000° in phase during the full 360° scan. BPM1 shows 80° variation.

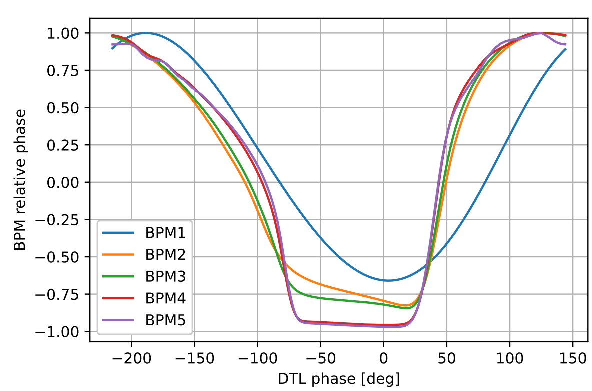

Figure 2: The simulated phase signatures of the 5 first internal BPMs in the DTL tank. The 6th BPM signal seems unstable for several phases, so it is excluded from this plot. Each signal is divided by the maximum so all signatures can be compared in the same plot.

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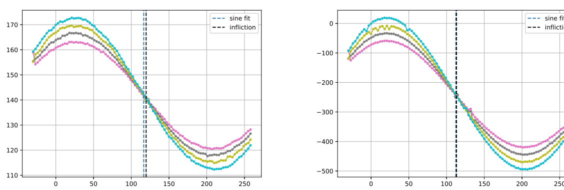
Table 1: Phase set points for buncher 1, from analysing different BPM and/or BPM pair signals from a specific RF phase scan. For the intersect method the median of all curve intersects is used, for sine fit the mean of the phase from each amplitude curve is used.

BPM	**Intersection** median	error	**Sine-fit** mean	error
BPM2	110.92	3.93	111.48	0.39
BPM3	112.56	0.26	112.82	2.22
BPM5	109.04	0.43	111.21	3.00
BPM2 - BPM3	112.66	0.33	110.52	0.11
BPM2 - BPM5	108.53	0.64	107.39	0.62



(a) BPM2 (b) BPM3 - BPM2

Figure 3: Phase scan curves for buncher 1, for two of the BPM responses evaluated.

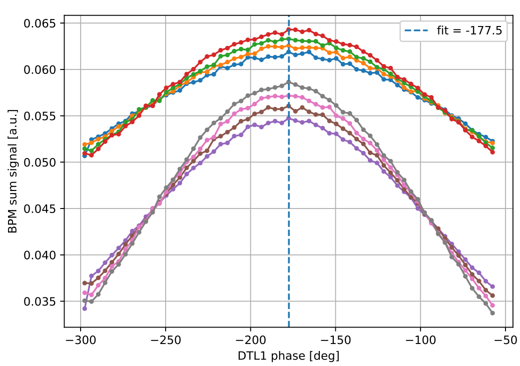


Figure 4: The sum signals from 2 BPMs during a phase scan of the second buncher. The maximum of the curve fit should indicate the −90° phase.

RESULTS

Bunchers

Figure 3 show scan curves for buncher 1, both single BPM and difference signal between two downstream BPMs. We see that ta large both signals seem similar and clean enough to analyse. The vertical lines show the estimated -90° operating phase by using sine fit as well as averaging the intersections of the lines. We see that the two methods overlap quite well. Table 1 lists a complete overview of fit results for the signals considered for matching buncher 1.

In Fig. 4 we show data of the BPM sum signal from the 5th and 6th BPM during a phase scan of the second buncher. A maximum from a fitted line of these curves are found to be −177.46°±1.54°. This can be compared to −180.4° from the sine fit of the phase signals mentioned earlier.

Table 2: Summary of the matched amplitude and phase set points for the 3 bunchers in the ESS MEBT. For evaluating phase the sine fit was chosen.

Cavity	**Amplitude** [kV]	**Phase** [°]
Buncher 1	131.81±0.78	112.61±0.30
Buncher 2	62.85±0.20	−180.45±1.39
Buncher 3	163.98±0.66	31.72±0.39

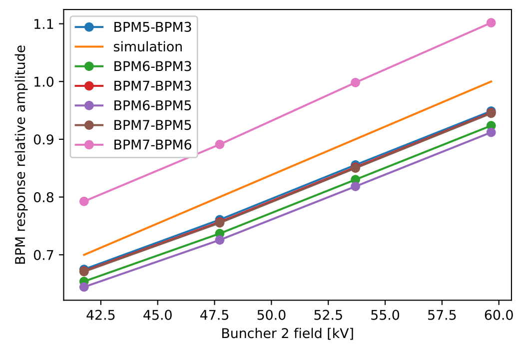


Figure 5: Buncher 2 amplitude fit to model. The curves show the relative amplitude, so 1.0 for the nominal 59.66 kV would imply no correction.

The amplitude we evaluate by comparing the amplitude of a sine fit to the simulation. In Fig. 5 we show an example of such a fit for buncher 2. In this example we see that 3 BPMs agree very precisely to a correction of about 5.3%, while any pair involving BPM6 do not fit to this correction.

In Tab. 2 we have summarised the obtained matched parameters for phase and amplitude of the three bunchers. Here we can add that the stability of phase is worse than the error of the measurement indicates, typically we would get consistent results from multiple scans within 1-2 degrees but not less. The error reported is the sum of squared errors of the individual curve fits and the variation of the values obtained from each individual curve.

For the third buncher we find a fit which gives a higher amplitude set point than the design maximum of 160 kV. Various measurement and fitting methods so far has found results in the range of 10-13% increase necessary. We conclude for now that the 3rd buncher most likely will need to run very close to the maximum possible field. Before we have beam transport through a larger part of the linac it is challenging to conclude on how accurate these fits are.

DTL

The main goal for the DTL commissioning with beam in this run was to get the beam through the cavity and secondly to get the full current through. Both of these were achieved shortly after we had the green light for the respective beam modes [8]. Additionally a full RF conditioning, getting to the nominal RF pulse was a main goal for the DTL [9].

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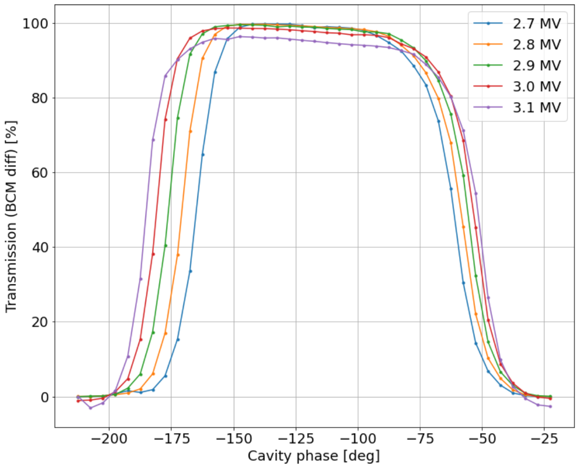
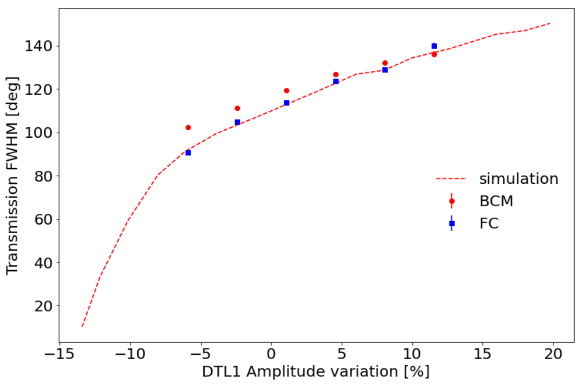


(a) Transmission



(b) FWHM fit

Figure 6: Transmission curves (a) during an RF phase scan of the DTL at different amplitudes, and a fit of the FWHM of the transmission (b) to the simulations as a way to find the amplitude correction.

DTL Transmission and Amplitude Set Point

We succeeded to obtain a few phase scan sets of the DTL, however we encountered some technical obstacles with signal processing, and (apparent) noise from strong harmonics of the RF source at the operating frequency of the diagnostics, which is twice the RF frequency in these sections of the linac.

The transmission was measured with a beam current monitor (BCM) at the end of the tank, as well as a Faraday cup (FC) that was placed shortly after the tank as an effective beam stop for this commissioning run. In Fig. 6a we show the transmission measured with the BCM. At a glance this corresponds reasonably well to what is expected from simulations.

In Fig. 6b we look at the FWHM of each transmission curve, and compare that to the model predictions. In simulations [10] we have found that this method should be less dependent on e.g. input beam parameters. The FWHM fit provides an estimate for the amplitude correction, and in this scan we found that 2.9 MV/m should be the closest match for the design 3.0 MV/m transmission signature. This is within the estimated RF calibration error.

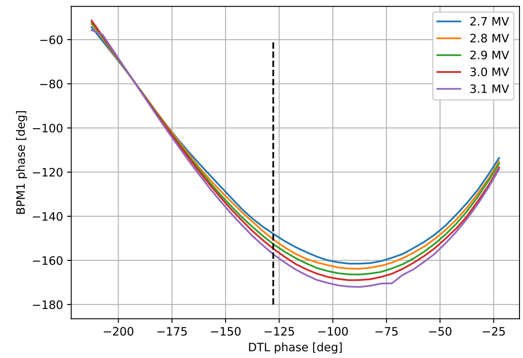


Figure 7: Measured phase signal of the first BPM in the tank as a function of the DTL phase signal, for different amplitudes. The working point from the fit is marked with dashed black line.

DTL BPM Signals and Phase Set Point

As discussed earlier, the first BPM in the tank should be an interesting candidate for finding the correct phase for the DTL. In Fig. 7 we see that during these scans there is indeed a similar curve, and the minima of each curve should be close to the 0° phase of the cavity. If we look closer at the simulation data, we find that the minima should be around 3.5-4° for the nominal field, and slowly increasing as the field increases. In our measurements we find instead a slowly reducing minima phase, from −88.7° at 2.7 MV m^{-1} to −89.5° at 3.1 MV m^{-1}. If we assume that the average of these curves should follow the simulated offset of 3.61°, and subtract the 35° operating point (from design), we land at an operating phase of −127.8°.

SUMMARY AND OUTLOOK

During the 2022 commissioning run of the ESS front-end, we successfully sent beam through the RFQ, MEBT and the first DTL tank. This was the first time we performed beam-based RF matching. We found a reasonably good set of reference amplitude and phase points for the bunchers and DTL1, and decent consistency between measurements and methods. A complete evaluation of the quality of the longitudinal beam transport will probably not be possible before a larger part of the linac is installed. Going more in details, there are still inconsistencies between the discussed fitting methods as well as diagnostic signal processing that needs to be ironed out or accounted for before the goal of an automated setup procedure could be materialised.

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