

SIMULATIONS FOR BEAM-BASED MEASUREMENTS IN bERLinPro*

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Abstract

bERLinPro is an energy recovery linac project whose goal is to establish the accelerator physics knowledge and technology needed to produce 50 MeV beams with high current, low normalized emittance, and low losses [1]. Precise measurements of beam parameters are essential for demonstrating the achievement of performance goals. In this paper we present simulations for measurements of energy, energy spread, and bunch length using the tracking code Astra [2].

INTRODUCTION

Commissioning of bERLinPro will be done in several phases, beginning in autumn of 2018 [3]. A primary purpose of bERLinPro is to demonstrate high-current (100 mA), low normalized emittance ($<1 \pi$ mm mrad), low-loss ERL operation, so careful measurement of beam parameters is of high importance. This paper details the results of Astra simulations for beam-based measurements of longitudinal beam parameters. The simulations presented here focus on the first phase of commissioning, during which the maximum beam momentum will be 3 MeV/c.

Layout of Diagnostics Line

The diagnostics line is shown in Fig. 1. This line is located downstream of the booster, continuing in a straight path from the gun after the main beam path has been steered towards the linac and recirculator. It includes two quadrupoles, a transverse deflecting cavity (tcav), a spectrometer magnet, a stripline beam position monitor (BPM), two YAG:Ce view screens (FOMs), and Faraday cups in the dumps at the ends of both the straight and the spectrometer lines. There are also four more quadrupoles downstream of the Booster which can be used for adjusting optics in the diagnostics line.

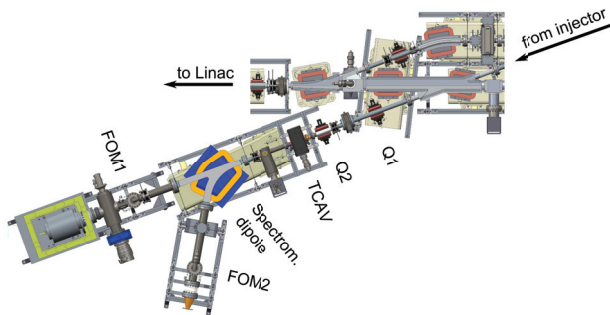


Figure 1: Layout of the diagnostics line.

ENERGY AND ENERGY SPREAD

The longitudinal phase space distribution of a bunch depends heavily on the phase of the gun cavity relative to the laser arrival time. Figure 2 shows the mean and RMS momentum offsets relative to a reference momentum ($\frac{p-p_0}{p_0}$) of a distribution of particles as a function of cavity phase. A cavity phase of zero is defined to be the phase that results in maximum energy gain. Energy spread is minimized when the cavity phase is -5° .

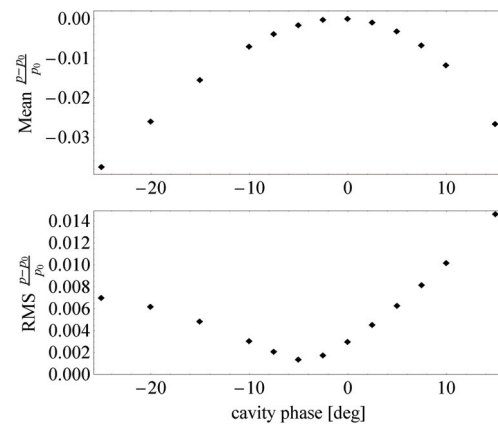


Figure 2: Mean (top) and RMS (bottom) relative momentum offset of a particle distribution tracked through the gun cavity in Astra vs. cavity phase.

Gun Cavity Phasing

When the machine is first turned on, the relative phasing between the laser and the gun cavity will not be precisely known; a beam-based method is needed for determining the relative phasing.

The two cold mass steerers in the gun cryomodule are capable of delivering a combined angular kick of ~ 16 mrad, and the resulting transverse beam offset can be observed at a FOM about 0.9 m downstream of the kickers. The resolution of the energy measurement using these kickers is limited by the size of the FOM, which has a full width of 25 mm; only a very small kick can be given or else the beam will be displaced beyond the edge of the FOM or even strike the vacuum chamber wall.

Figure 3 shows the results of Astra simulations in which a bunch is tracked from the cathode to the FOM with varying cavity phase, with the steerers on. The estimated measurement resolution for beam centroid position with the FOM would be as small as $\sim 2 \mu\text{m}$ in the case of a Gaussian beam, but we do not expect the transverse beam profile to be Gaussian so estimating the measurement resolution is less straightforward. We will use the FOM pixel size ($20 \mu\text{m}$) as

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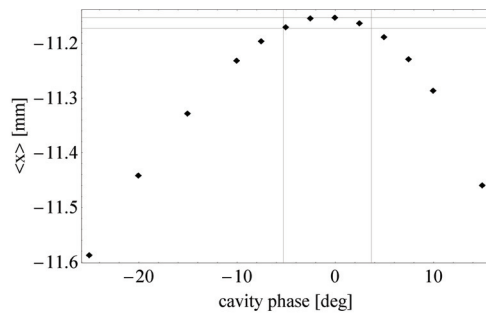


Figure 3: Simulations of phase scan beam deflection measurements using steerers in the gun module. The estimated beam centroid measurement resolution of 20 μm would correspond to a cavity phase resolution of $\approx \pm 5^\circ$ (gray lines).

a rough estimate of position measurement uncertainty. That measurement error corresponds to a cavity phasing error of about 5° or a mean momentum error of about 1.5×10^{-3} (see Fig. 2). If the measurement resolution turns out to be much worse, for example 0.1 mm, we could still expect to find the cavity zero phase to within about 10° .

Diagnostics Line Spectrometer

More precise energy and energy spread measurements can be made once the beam has been threaded downstream to the diagnostics line. For Astra simulations of the spectrometer line, the magnet was defined analytically rather than using a field map because no field measurements have been made. The quadrupole Q2 (see Fig. 1) was set to focus the beam on FOM2 horizontally. The dispersion function (~ 0.91 m) was calculated by tracking an ensemble of particles with momentum offsets through the spectrometer magnet to FOM2 and then fitting horizontal position vs. momentum.

Figure 4 shows the phase space in $(z, \delta \equiv \frac{p-p_0}{p_0})$ coordinates of the ensembles of particles just before the spectrometer and the (δ, x) coordinates of the particles at the spectrometer screen. Here p_0 is a “reference” momentum for which a particle is bent by exactly 60° . Each ensemble was tracked from the cathode through the spectrometer using a different cavity phase. The particles all lie roughly along the black line whose slope is the dispersion function, but they do not lie exactly along the line because the transfer matrix between the entrance and exit of the spectrometer has some dependence on initial (x, x') coordinates in addition to initial momentum. This is a systematic source of measurement error that we cannot eliminate because we have no way of measuring (x, x') before the spectrometer. However, the error introduced by this is small.

Figure 5 shows the difference between the mean and RMS relative momentum offset of the ensemble of particles in the Astra simulation, as well as the values calculated using the approximation $x = D \frac{p-p_0}{p_0}$. The difference between the simulated and calculated values is primarily due to the betatron component of beam spot size on the screen. Note that in these simulations the “measurements” were all made with the same quadrupole settings, which properly focus

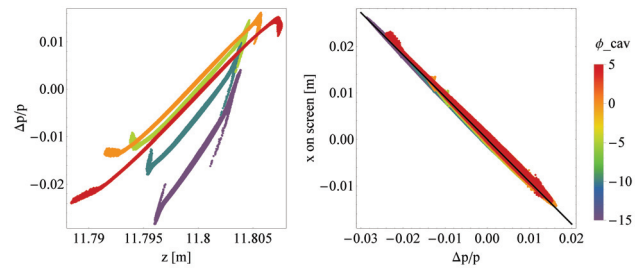


Figure 4: Longitudinal (z, δ) coordinates of a simulated particle distribution before the spectrometer (left) and (δ, x) coordinates on the spectrometer screen (right) for bunches tracked from cathode through spectrometer in Astra with varying cavity phase.

the beam on the screen when the gun cavity phase is at its design value of -5° . The transverse optics depend on the gun phase, so measurement error could be reduced by adjusting the quads each time the gun phase is changed so that the beam is re-focused on the screen. When the optics is well matched to focus the beam spot on the screen, the calculated values for relative mean momentum offset agree with the simulation values to within a few per mil.

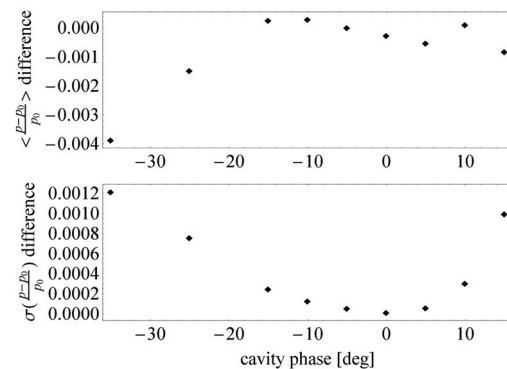


Figure 5: Difference between mean and RMS relative momentum offset of particles in Astra simulation and calculated values based on simulated beam spot on spectrometer screen, reflecting systematic error in the measurement.

The major source of uncertainty in energy measurements will be the calibration of the spectrometer magnet’s field. Measurements of absolute beam momentum will be less precise than relative momentum shifts because the field of the spectrometer magnet has not been measured, so the calculation of integrated field strength for a given current is only approximately known. In addition, this magnet was designed to be used with 20 MeV/c beam in a different machine. For the low fields needed to bend 3 MeV/c beam the residual fields in the magnet may lead to a field error of about 2.5%, so we could expect a similar uncertainty in our calculation of the absolute (“reference”) momentum of the beam. Fortunately it may be reasonable to assume that the peak energy produced by the gun will not change after it is measured with a well-calibrated spectrometer in GunLab.

BUNCH LENGTH

A transverse deflecting cavity (tcav) will be used for bunch length and slice emittance measurements in bERLinPro. The results of first simulations of bunch length measurements are given here.

The 1.3 GHz Cornell-designed deflector [4], adjusted to the requirements of HZB, is currently under construction at Research Instruments. It is specified to have a shunt impedance of 5.3 MΩ and will be supplied with a maximum of 10 kW of RF power during the initial commissioning phase of bERLinPro. The tcav will be placed downstream of the two quadrupoles in the diagnostics beamline, as shown in Fig. 1. The vertically deflected beam will then be imaged onto a screen (FOM1) in the diagnostics straight line.

All simulations were performed using Astra [2] with a 3D map of the deflector fields. The simulations correspond to the initial commissioning phase, during which the Booster is not installed so the beam energy is limited to 2.7 MeV. Figure 6 shows the RMS beam size in horizontal and vertical direction along the beamline [5].

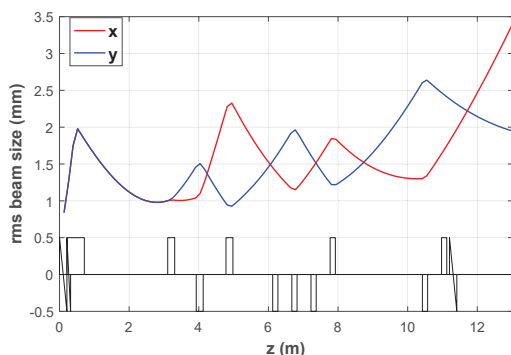


Figure 6: Horizontal and vertical RMS beam size along the diagnostics beamline with the tcav switched off.

In a first step, the streak factor of the tcav was determined by simulation. This was done by tracking particles with varied z positions with respect to the bunch center through the deflector and then observing their respective y offset at the screen. The tcav phase was chosen such that the center of the bunch is not influenced by the deflector. The streak factor is then given by the slope of the linear dependence between those coordinates.

For the measurement simulation, the cavity was switched off first to find the RMS beam size on the screen $\sigma_{y,0}$. The optics was not optimized for a minimum vertical beam size for these preliminary simulations. With the tcav switched on, the deflecting voltage was adjusted to match the beam size to the size of the screen. Using the streak factor found before, the longitudinal beam profile can be calculated from the y -profile at FOM1. Figure 7 shows a comparison of the longitudinal profiles at the entrance of the tcav taken directly from Astra simulation and as calculated from the screen image. As expected, a similar characteristic is found. The difference between the curves is still to be investigated.

The RMS bunch length σ_z was calculated from the vertical

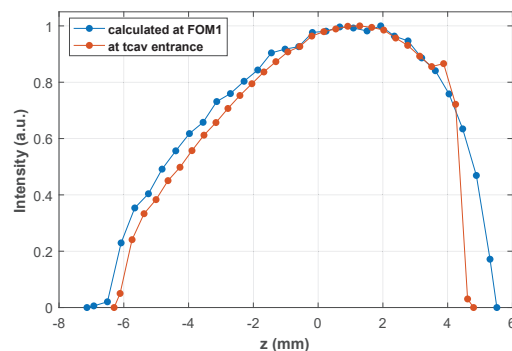


Figure 7: Comparison of the longitudinal profiles at the entrance of the tcav and those calculated from the deflected beam image at FOM1.

beam size induced by the deflector $\sigma_{y,tcav}$, which in turn was found from the total size at FOM1 $\sigma_{y,total}$ corrected by the beam size without deflection $\sigma_{y,0}$ according to the relation

$$\sigma_{y,total} = \sqrt{\sigma_{y,0}^2 + \sigma_{y,tcav}^2}$$

The simulated value of σ_z at the entrance of the tcav is 2.68 mm whereas the calculation results in 2.72 mm, giving an accuracy better than 2%. Hence, the procedure is suitable for measurements. For further studies the optics will be optimized to achieve lower values of $\sigma_{y,0}$, which will improve the resolution of the measurements.

CONCLUSION

Detailed Astra simulations for measuring longitudinal beam parameters have been presented. Rough energy measurements for cavity phasing will first be done using cold mass steerers in the gun module, and then more precise measurements of mean energy and energy spread will be made using the spectrometer in the diagnostics line. Bunch length measurements will also be made in the diagnostics line using the transverse deflecting cavity.

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