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BEAM POSITIONING CONCEPT AND TOLERANCE CONSIDERATIONS FOR bERLinPro*

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Abstract

bERLinPro is an ERL project at Helmholtz-Zentrum Berlin, with the goal to illuminate the challenges and promises of a high brightness 100 mA superconducting RF gun in combination with a 50 MeV return loop and energy recovery [1, 2]. The precision of the beam position in a single turn machine might be relaxed compared to the demands in storage rings. Still, a trajectory correction concept has to be developed and the influence of trajectory offsets on the goal parameters, its dependence on fluctuating injection parameters or effects related to the low energy of 6.5-50 MeV have to be investigated. This paper covers the initial trajectory correction studies and first tolerance scenarios of bERLinPro using the projected hardware concept.

INTRODUCTION

The motivation for beam positioning in a single pass test-facility like bERLinPro differs from that in circular user facilities. The beam lifetime, avoidance of resonances and coupling into the vertical plane are no issues in linear accelerators, whereas bunch creation- and acceleration parameters might influence the beam trajectory and have to be taken into account. The need to create reproducible machine states for experiments and machine studies is given in both cases.

For any given beam line with N error sources, the statistically expected offset of the trajectory scales with $\sqrt{N}$, i.e. in a single path device it increases with growing distance from the gun and decreases / increases with acceleration and deceleration, Figure 1.

In a storage ring, the expected amplitude is given by the equilibrium orbit, which results from the fact that the damping time largely exceeds the revolution time, so that the expected offset becomes independent of the number of turns passed since injection and therefor also of the injection parameters. In a linear machine, the trajectory does depend on injection parameters like offsets of the laser spot on the cathode, or dispersive effects due to laser or RF parameters variations. Also the achievable beam parameters like energy, emittance and bunch length are error and trajectory dependent. A priori, it is not clear in how far multi particle effects like space charge, which might lead to changes of the bunch length and central energy, have to be taken into account.

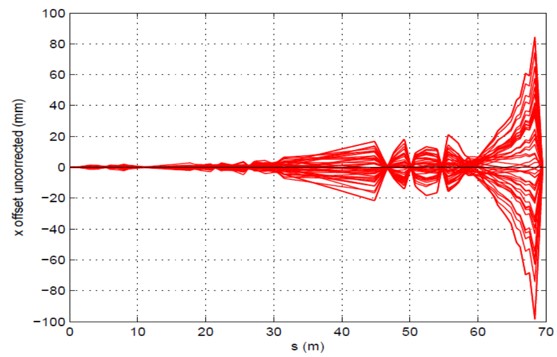

Figure 1: Horizontal trajectories in bERLinPro due to quadrupole alignment errors, the large increase beyond 60 m reflects the deceleration.

In general, only slowly varying offsets, as compared to shot-to-shot fluctuations, can be corrected by means of beam positioning. Any correction method must reflect the sequential dependence of kicks, correctors and BPMs given in single path devices, so that a method like 'single best corrector' cannot be applied.

In this paper we concentrate on the injector and acceleration part of bERLinPro until behind the linac Figure 2. At this point the maximum energy is reached, emittance compensation is achieved and space charge

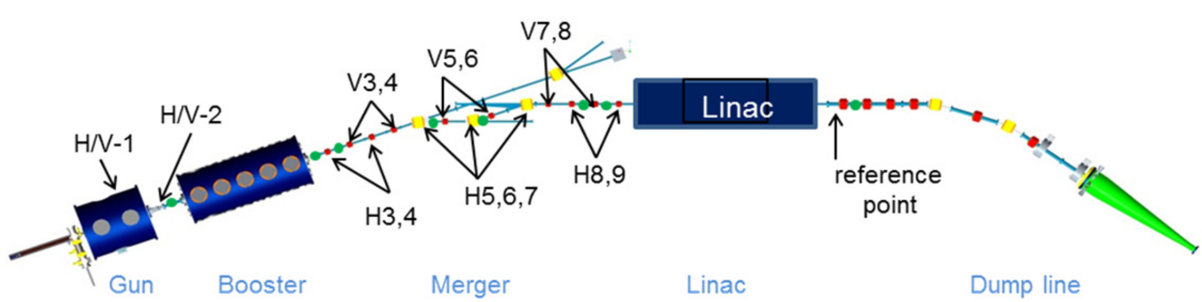

Figure 2: Distribution of H- horizontal and V- vertical corrector coils in the quadrupole (red) and dipole (yellow) magnets in the initial low energy setup of bERLinPro; green dots represent position measurement stations used in the calculations.

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effects are negligible. The impact of the bunch creation- and acceleration parameters on the trajectory of the bunch can be studied and quantified. In addition, the degradation of the design parameters due to these errors is studied.

The multi particle tracking code ASTRA [3] has been used for the calculations, to allow the investigation of space charge effects and for the correct representation of the accelerating process.

ERROR SOURCES

Table 1 lists the error sources that have been studied and their expected rms magnitude. Device offsets are generally assumed to be 250 µm rms. This value might be too small for the (poorly defined) electrical centre of the superconducting cavities, but for the lack of better data this value is used. All uncorrelated RF phase jitter is summed up under ‘synchronization’ and also includes the linac’s timing as it is fed by the same master clock. The jitter of individual cavity phases is much smaller than the jitter assumed for synchronization. Even for the gun it is negligible. The laser timing is also regarded individually because of its considerable influence on the energy of the beam, the bunch length and on the emittance. Tilts and dipole field errors have not yet been studied.

Single Parameter Studies

Investigation of the effects of single parameter deviations revealed that the trajectory is most sensitive to the solenoid position in the gun module. The rms trajectory displacement due to solenoid offsets of ~0.4 mm (~4 mm max. amplitude) (average over 250 runs) is in the order of that due to offsets of all cavities and about half of that due to all quadrupole offsets.

Table 1: Error Sources, Magnitude and Effect

parameter	rms-error	affected beam parameters
laser pulse length	0.5 ps	energy, emittance, bunch length
laser spot size	1%	emittance
laser timing	0.4°	energy, emittance, bunch length
laser trans. offset	10 µm	trajectory
bunch charge	2%	emittance, bunch length
gun Field	5e-4	energy, bunch length
solenoid field	1e-4	emittance
solenoid, cavity, quadrupole offset	250 µm	trajectory, energy, emittance
synchronization	0.1- 0.5°	energy, emittance, bunch length

The largest effect on the central bunch energy is caused by wrong laser timing (7e-4), followed by deviations in the maximum gun field or in the gun phase.

The emittance mostly depends on the laser pulse length (4% variation rms, 250 runs) and the laser timing (2%), as well as on solenoid misalignments (2%).

Also the bunch length is most sensitive to errors of the laser timing and laser pulse length (2%), so that the stability of these laser parameters plays the biggest role for the stable operation of bERLinPro. The uncertainty of the design parameters remains in the few percent region, for all single parameter variations listed in Table 1.

Multiple Parameter Studies

In a second step combinations of errors have been studied, to analyse the magnitude of target parameter variations. Applying all errors causing beam offsets, rms transverse trajectory values of 1.4 mm are reached (4 mm max. amplitude). The horizontal emittance varies by 2.5%, other effects are negligible.

Synchronization has been studied in more detail, assuming 0.1°-0.5° uncorrelated rms variation of all cavity phases and the laser timing (cut-off at 2σ). The results are displayed in Figure 3, showing the relative energy deviation and the bunch length and emittance changes as a function of the synchronization. For synchronization to better than 0.25° rms (±0.5° max), the deviation of the target parameters is comparable to that caused by other error sources, which can serve as the limiting criterion. The major contribution to the changes in emittance and bunch length stems from the laser timing as indicated by the red stars in Figure 2. The jitter of the cavity phases mostly changes the central energy of the bunch.

The effect of all errors affecting the central energy of the bunch (laser pulse length, gun field, and synchronization to 0.25° rms leads to energy offsets in the injector of 4.5e-4, which corresponds to below 200 µm

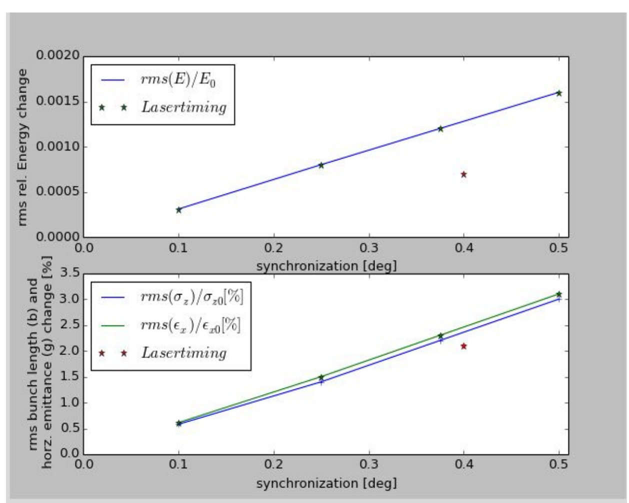

Figure 3: Central energy (top) and the emittance and bunch length (bottom) as a function of the synchronization. Red star: contribution of the laser timing.

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offsets in the merger. Behind the linac it increases to 1e-3.

Final application of the complete set of errors resulted in the values listed in Table 2. The trajectory offsets are largest at the entrance of the accelerating structures (<5 mm) and are damped thereafter due to the acceleration. The resulting uncertainty in the emittance and bunch length is in the order of a few percent. After acceleration, all trajectories show offsets of less than 2 mm at the exit of the linac and practically no divergence.

Table 2: Average rms Trajectory Offsets and rms Deviation of Beam Parameters Over 250 Runs, and after Correction (100 runs)

Parameter	Unit	Parameter Deviation	After correction
rms trajectory-x, y	mm	1.4, 1.5	0.063, 0.042
Energy		1e-3	8.7e-4
Emittance x, y	%	6.1, 3.4	4.0, 3.6
Bunch length	%	2.6	2.2

TRAJECTORY CORRECTION

In bERLinPro, all correction coils will be incorporated in the dipole magnets and in the quadrupoles, which are equipped with correction coils for both directions. Only inside and behind the gun module dedicated horizontal and vertical correctors are planned, see Figure 2.

Since the 1990s the orbit correction in most circular machines is based on the SVD-analysis of the orbit response matrix. This method is also applicable in linear machines, although the response matrix is reduced to an upper triangular matrix. Consequently, the correction must degrade towards the end of the beam line, when not enough BPMs are available to detect the response of the trajectory to errors and the corrector settings. To avoid this degradation due to the algorithm, the error sources were limited to locations upstream of the last merger dipole in the current studies.

Also in the real machine, kicks due to the misalignment of the four quadrupoles in front of the linac cannot completely be cancelled prior to the linac with the given hardware and will have to be taken care off by beam-based-alignment. Without correction, the trajectory offsets due to misalignment of these four quadrupoles alone approach 0.6 mm rms with a maximum of 2 mm at the linac entrance. Effects of misalignment of the linac cavities have to be cancelled by correctors downstream the linac, as no corrector coils are foreseen inside the cold module.

The correction algorithm applied, is taken from the BESSY II control system, large parts of which will be also used for bERLinPro.

Initially it has been verified, that the algorithm cancels individual trajectory kicks, due to errors such as laser offsets on the cathode, solenoid or booster cavities displacements by two downstream correctors. It was found, that the correction of trajectory offsets resulting from errors in the gun does depend on space charge effects being taken into account. Because the resulting trajectory offsets are small compared to other sources, usually space charge can be neglected in the calculations. Correction of 100 runs of the error set listed in Table 2 resulted in residual transverse trajectory offsets (x,y) of less than 0.48, 0.38 mm and rms trajectory offsets of 63, 42 μm on average, Figure 4.

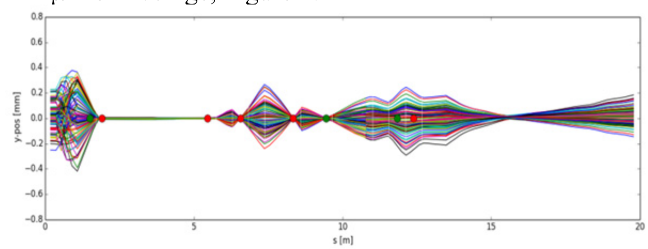

Figure 4: Corrected vertical trajectories in bERLinPro.

CONCLUSION

The presented studies show that the tolerances assumed for the misalignment of devices in the initial set up of bERLinPro as well as for the laser and accelerating parameters can be handled with the projected hardware.

Trajectory offsets can be cancelled to below 70 μm rms. In the calculations two screen monitors in the merger and in front of the linac were included, that cannot be integrated in an online trajectory correction algorithm. It has to be checked in how far their information can be used in pre-settings of correction coils, or if they have to be replaced by non-destructive BPMs .

The fluctuation of the project target parameters lies in the few percent region, even without correction, and is improved by positioning of the beam to better than 4%. This is well compatible with the expected measurement accuracy of these parameters.

The necessary degree of synchronization was determined to be 0.25° rms. Further studies of the arrival time jitter should verify the results. It was found that the stability of the laser timing and laser pulse length is crucial to achieve the goal parameters. The importance of an exact solenoid position has been accounted for by providing movers inside the gun module. The residual beam offsets in the linac need to be quantified in order to estimate potential excitation of higher order modes.

ACKNOWLEDGMENT

The programs used for the distribution of errors and the evaluation of the optics are derived from the swarm-algorithm written by M. Abo-Bakr, published in [4].

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