START-TO-END CALCULATIONS AND TRAJECTORY CORRECTION FOR bERLinPro*

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Abstract

bERLinPro is an ERL project under construction at the 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]. Latest changes to the optics code OPAL [3, 4] allow for the first time to perform start-to-end tracking studies including space charge in a single run, without switching between codes. This opens the way to apply correction schemes to displaced trajectories in the complete machine and to study the effect of jitter sources, including the space charge dominated injector, on the machine performance parameters. Trajectory correction is discussed. Jitter is studied with respect to its potential impact on the recovery process and parameter changes before the dump.

INTRODUCTION

Start-to-end simulations for single pass devices usually combine ASTRA [5] or PARMELA [6] calculations in the low energy, space charge dominated regions of the machine, and elegant [7] calculations in the high energy parts of the machine, where CSR effects have to be taken into account, and space charge can be neglected. This approach becomes tedious, when error studies are pursued and sophisticated interfacing procedures between codes have to be developed.

OPAL is an open source tool for charged particle optics in large accelerators. It is built 'ab initio' as a parallel application, includes a 3D space charge routine as well as short range wake fields. Much effort has been invested to modify the 'flavour' OPAL-T to meet bERLinPro simulation demands, which resulted in the new OPAL-3D version of OPAL-T, introduced in this conference [4]. The changes include a complete rewriting of the dipole implementation, arbitrary placement of fields in 3D space and error statistics to name a few. CSR has yet to be transferred to the new version.

The correct representation of the dipoles turned out to be the crucial point in benchmarking elegant and OPAL. bERLinPro will incorporate eight 45° dipoles in the recirculator, with a length of 0.6 m and a gap of 0.052 m. The shape of the fringe field makes a sophisticated representation necessary, using 8 Enge-coefficients [8]. elegant offers the usage of up to 3 Enge-coefficients for an element that provides tracking through a dipole magnet, ASTRA uses one. By reducing the integrated

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fringe field parameter, 'FINT', of the elegant SBEND representation of dipoles by 10%, acceptable agreement between the matrix formalism and tracking results could be achieved.

The comparison of the two codes revealed, that space charge is again in effect in the recirculator after the final bunch compression to 2 ps: The emittance and the bunch length increase. So far, space charge has not been taken into account during optimization of the dump line, where the transverse bunch size is already enlarged. The discrepancies to space charge calculations turned out too large, so efforts are ongoing to re-optimize the dump line with space charge. Therefore, the current calculations stop behind the linac after deceleration.

The work presented in this paper is a continuation of the work presented in IPAC'14 [9]. At the time, tolerance studies and trajectory correction have been studied only for the initial part of the machine, until full energy is achieved in the main linac. After the completion of the changes in OPAL the studies have now been extended to the recirculator, currently still without CSR. elegant calculations show an energy loss of 0.02% due to CSR and negligible modifications of the longitudinal phase space.

The purpose of trajectory correction in an ERL is threefold: secure transportation of the beam to the dump, alignment of the beam at the SRF modules to preserve an optimum position with respect to minimal excitation of transverse HOMs (1-2 mm), and the preservation of the relevant beam characteristics at a potential experiment.

Jitter studies are used to verify or tighten the demanded precision i.e. of the laser parameters or synchronization. Here the arrival time jitter before re-entry into the linac, the variation of the bunch parameters in front of the dump line and the stability of the bunch parameters at the experiment are of interest.

JITTER AND OFFSETS

In the studies in [9] it could be shown, that only the offsets and jitter sources listed in Table 1 show significant impact on the trajectory or the bunch characteristics. The error levels have been set to 'state of the art' values. The value for 'synchronisation', i.e. all uncorrelated jitter of RF phases and laser timing was determined so that the resulting parameter degradation is in the order of magnitude of other unavoidable error sources. The laser timing jitter has been reduced to 0.3 ps (0.5 ps) in the laser specifications.

Table 1: RMS Error Levels Assumed in the Simulations

parameter	rms-error / (ref. value)
laser pulse length	0.5 ps / (7 ps)
laser timing	0.3 ps*
gun Field rel.	5e-4 / (30 MV/m)
synchronization	0.25°, 0.5ps
solenoid, cavity, quadrupole transverse offset	250 μm

*: Value reduced compared to [9]

TRAJECTORY CORRECTION

The correction coils in bERLinPro are incorporated in other magnets. Each quadrupole can be powered to either vertical or horizontal steering; correction coils in dipoles steer only horizontally. Additionally, two individual steering coils are installed within the gun module and between gun and booster.

Due to the double passage of the beam through the linac straight, there is a ~10 m long passage between the start of the linac until the dump chicane, where offsets in the accelerated beam cannot be corrected, as there are no correctors inside the linac module, and the 4 adjacent correctors serve to direct the decelerated beam into the dump. Respectively, the high energy beam cannot be controlled between the merger chicane and the end of the linac. These are regions of special interest for the trajectory compensation.

The correction algorithm applied is the SVD-analysis of the orbit response matrix, commonly used in storage rings [10]. In single pass devices, the response matrices are of upper triangular form. The benefit of the method is that it can be directly applied to the real machine and is model independent; actually, the algorithm for these calculations is taken from the BESSY control system.

100 randomized simulations were executed up to 76 m (shortly passed the linac), with alignment errors generated from a 1.6-sigma Gaussian distribution (250 μm rms, 400 μm max.).

With these values, the uncorrected offsets of the beam are uncritical in the horizontal plane (<10 mm), but could reach the physical aperture (20 mm) vertically already in the first arc.

In a first attempt, the SVD algorithm was applied using all 23 BPMs in front of the dump line and a scheme of alternating horizontal (25) and vertical (20) quadrupole correctors and 10 singular values in each plane. The results are displayed in Figure 1. The standard deviation of 100 corrected trajectories at the BPMs generally lies below 1 mm, except at 4 horizontal and 2 vertical BPMs, where <1.7 mm are reached. Uncorrected displacements are reduced by a factor of ~10. The remaining offsets at the second passage through the linac are amplified by the

RF-defocussing during deceleration to few mm at the end of the linac in numerous cases. This could lead to unacceptable losses to HOMs, and needs further improvement. For individual error sets, better corrections can be reached by using different numbers of singular values.

In all 100 corrections scenarios 7 horizontal and 6 vertical correctors show rms kick strengths of less than 5% of the average kick values. These correctors could be eliminated from the correction scheme. Few BPMs are located at places where all steerer trajectories have a zero crossing, i.e. they will not contribute information to the correction scheme.
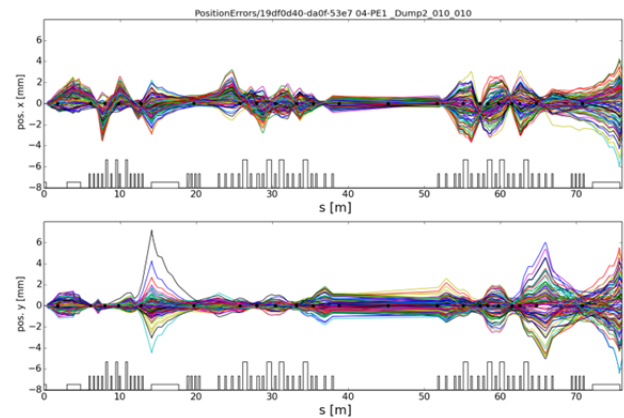

Figure 1: 100 corrected horizontal (top) and vertical (bottom) trajectories. BPMs are indicated with black dots.

The evaluation of the bunch parameters at the potential experiment the centre of the straight section (45 m) for these 100 runs (10.000 tracked particles) is displayed in Table 2. They lie within the measuring accuracy of the parameters.

Table 2: RMS Variation of Beam Parameters for 100 Corrected Trajectories at the Centre of Straight Section

Parameter	Unit	rms value 100 runs
Trajectory-x, y	mm	0.2, 0.5
Beam size	%	1.7, 4.4
Bunch length	%	4.6
Emittance x, y	%	6.2, 5.7

JITTER STUDIES

Three different combinations of jitter sources were simulated, for 100 randomized cases each. See Figure 2 (top) for the resulting rms arrival time jitter along the machine, and the related jitter of the central bunch energy (bottom). The effect of the laser timing jitter (0.3 ps rms, blue curve) has been calculated separately, as former investigations had shown the importance of this effect (for
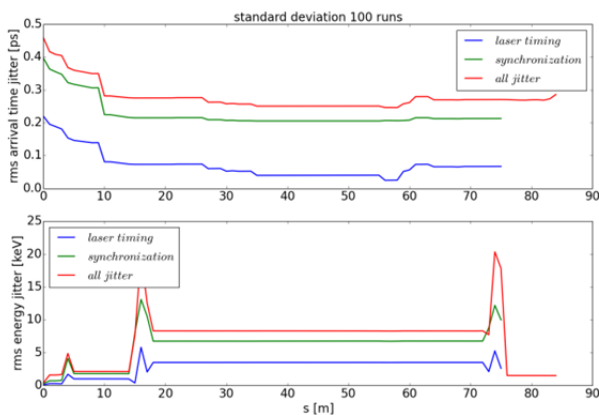
Figure 2: Top: spread of 100 randomized jitter simulations of the arrival time along the machine, considering laser timing (blue), synchronization (green) and all jitter sources (red). Bottom: spread of the bunch energies for the same simulations.

a larger value of 0.5 ps rms). The effect of synchronization errors, i.e. uncorrelated rms variation (0.5 ps) of all cavity phases and the laser timing is displayed in green. The red curve shows the combined effect of jitter in laser timing, synchronization, laser pulse length (0.5 ps) and gun field amplitude (5e-4). In all cases the initial jitter is largely compressed in the SRF gun. The first booster cavity is set to zero crossing, to imprint a chirp on the bunch for bunch compression. This also causes compression of the timing jitter in the booster (~4 m) in the merger (~10 m). The correlation between time and energy related to the laser timing jitter, present in the blue and red case, leads to further compression in parallel with the bunch compression in the first arc (25-35 m) and at the beginning of the second arc (~57 m). The overall arrival time jitter before re-entry to the linac is ~270 fs or 0.13°, which is well within the acceptance of the LLRF system.

The largest contribution is that of the synchronization errors with ~64%, followed by gun amplitude and the laser pulse length jitter (~30%). The contribution of the

Table 3: RMS Value of the Beam Parameters at the First BPM in the Dump Line and at the Centre of the Straight Section for 100 Random Jitter Simulations

Parameter	Unit	rms value of 100 runs	
		@ dump	@experiment
Trajectory-x, y	mm	0.01, 0.0	0.01, 0.0
Bunch length	%	2.2	2.2
Beam size-x,y	%	3.4, 2.7	2.1, 1.9
Energy	%	0.022	0.017
Energy spread	%	6.2	3.7
Emittance x, y	%	6.0, 4.6	5.5, 5.7

laser timing (~6%) is rather small for the reduced value of 0.3 ps rms. The associated absolute energy jitter is displayed in Figure 2 (bottom). It is less than of 10 keV (2e-4 relative) before deceleration and 2.2e-4 rel. after deceleration, much smaller than the energy acceptance of the dump. The associated standard deviation of the bunch parameters at the first BPM in the dump section for 10.000 tracked particles are listed in Table 3, together with the values at the position of a potential experiment. They lie all in the few % region and seem uncritical for the dump process as well as for an experiment.

CONCLUSION

Start-to-end simulations for bERLinPro were performed for the first time in a single run using a new, yet unreleased version of the code OPAL-T. The benchmarking between OPAL and elegant brought up several crucial beam dynamic issues, we have not been aware of before. First attempts were reported to correct the trajectory, distorted due to misalignment, applying SVD on the steerer response matrix. As the simulations start at the cathode, space charge has to be taken into account when the variation of bunch parameters is of interest. This makes any statistical investigations extremely time consuming. There are two difficulties related to applying SVD in single pass machines: the decreasing information available on the corrector impact towards the end of the structure, and the big impact an early corrector has at the later BPMs, due to the large trajectory offsets caused by the RF-defocussing during deceleration. The setting of the correctors in the injector is thus influenced by the dump BPMs. Repetitive corrections might solve this problem, or corrector specific weights for the BPMs. Still, even a single correction leads to quite satisfactory results, considering initial offsets of up to 20 mm. Simulation allowing for jitter in all parameters of major impact show little disturbance of the beam parameters and small arrival time jitter <300 fs.

ACKNOWLEDGMENT

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