INVESTIGATION OF MICROBUNCHING-INSTABILITY IN BERLINPRO*

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Abstract

The Helmholtz Zentrum Berlin (HZB) is building an energy recovery linac (ERL) prototype, bERLinPro, to demonstrate the ERL principle at low emittance and high currents. As, maintaining the low emittance and energy spread is crucial for generation of high brightness synchrotron radiation, the deep understanding and control of effects degrading the emittance and energy spread are of major interest. The microbunching instability caused by the longitudinal space charge forces can lead to an increase in emittance and energy spread. In this contribution, the impacts of the microbunching instability on the beam quality and its implication for bERLinPro are discussed.

INTRODUCTION

In all types of accelerators space charge effects are present. They influence beam size, bunch length and working point. In order to describe the space charge effects, one needs to take into account that on the one hand electrons repel each other, on the other hand relativistically moving electrons represent parallel currents, leading to attracting forces. The sum of attraction and rejection lead to a reduced repelling force.

Usually, one assumes a Gaussian longitudinal particle distribution. Even on average, the “real” current profile is not smooth, it comprehends little humps. Dependent on their position the electrons inside these humps suffer different repelling forces. Electrons in the center experience a similar amount of forces from different sides. So the netto space charge force is zero for them. Electrons at the edges experience the repelling forces only from one side. Thus, these electrons are pressed out. In their case, the repelling forces lead to an acceleration or a deceleration. This way, the space charge forces lead to an energy modulation on the electrons at different wavelengths.

In accelerators, this energy modulation can be transformed to a density modulation due to the longitudinal dispersion. So the energy modulated electrons can either be replaced on top of their old hump or be replaced in between neighboured humps, creating microbunches. Thus, one obtains either an amplified or a reduced microbunching for a given wavelength. In the amplified case the microbunch gains a higher amplitude. This gain process can be discribed by [1]:

$$G \approx \frac{I_0}{\gamma_b I_A} \underbrace{\left| k_f R_{56} \overbrace{\int_0^L ds \frac{4\pi Z(k_0; s)}{Z_0}}^{energymodulation} \right|}_{microbunching} exp\left(-\frac{k_f^2 R_{56}^2 \sigma_\delta^2}{2}\right) \quad (1)$$

The exponential term in the gain formula includes the wave number k_f, the longitudinal dispersion R_{56} and the initial relative energy spread σ_δ. It damps the microbunching effect in cases where the product $k_f^2 R_{56}^2 \sigma_\delta^2$ is big. In the case of a small exponential term we achieve a strongly microbunched electron bunch, when the ratio of the bunch peak current, I_0, and the Alfven current, I_A is big. Taking into account the small energy spread expected for an ERL, one can assume that with an appropriate undulator the ERL is ideally suited for using microbunching instability to produce coherent synchrotron radiation.

In this paper results of simulation studies on the impact of the longitudinal space charge forces on the electron distribution in bERLinPro are presented.

BERLINPRO

bERLinPro’s layout is shown in Fig. 1. It is a single-pass-ERL with a 6.5 MeV injection line consisting of a superconducting RF photo-injector and a 3 × 2-cell-cavity booster section. The produced electron bunches have a very low emittance and small energy spread. The beam is merged into the superconducting main linac via a dog-leg merger where it is accelerated to 50 MeV. The corresponding electron beam parameters are given in Table 1. The linac and an optimized subsequent lattice form a closed circuit, so that the beam re-enters the linac with a 180° phase shift. Thus during the second pass, the linac decelerates the electrons and retrieves their energy. The decelerated beam is dumped in a 650 kW-beam dump at 6.5 MeV [2].

Table 1: bERLinPro Parameters

Parameter	Value	Unit
Beam energy	50	MeV
Beam current@ 1.3 GHz	100	mA
Bunch charge	77	pC
Bunch length	< 2	ps
Energy spread (rel. proj.)	0.5	%
Transverse emittance	< 1	mm mrad
Beam loss	$< 10^{-5}$	

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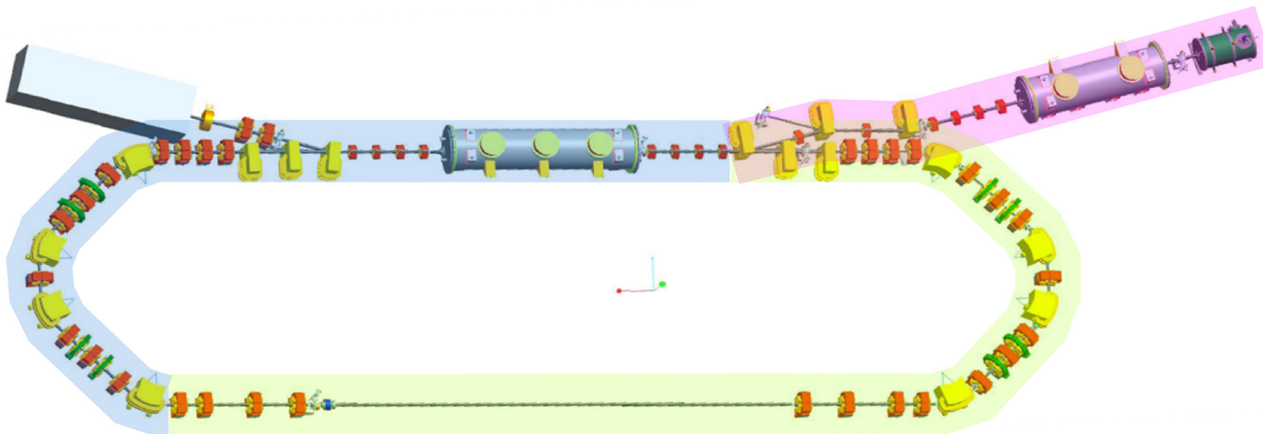

Figure 1: Scheme of bERLinPro with subdivisions in different sections [3].

Simulation code ASTRA

The utilized simulation program is ASTRA [4]. The simulations start at the gun, where electron bunches are created and they end after a recirculation directly after the second pass through the main linac. In ASTRA the quadrupole fields are limited along the moving axis (s-axis) only. This means they have infinite focusing fields perpendicular to the s-axis. Thus, while simulating a ring-accelerator a quadrupole field would appear twice, once at the intended quadrupole position and a second time as an extended field on the opposite side of the ring. Therefore, a ring-shaped transport line has to be cut in several sections, each being simulated in its own simulation run. For bERLinPro the first section ends after the dog-leg merger. The electron distribution has to be rotated about 18° before entering the recirculator. Due to the transversally infinite quadrupole fields in the simulation code, the 'simulation transport-lines' end each after a dipole. There the electron distribution is rotated about 45° before being send through the next section.

The simulations presented in this paper use the 3D space charge calculation routine in ASTRA. The algorithm is based on a fast Fourier transform. It uses a Cartesian grid in each plain. The number of grid lines is equal to 2^n [5]; where n is the number of the grid lines. For a good resolution in the simulations, the number of the longitudinal grid lines is around 256. For the simulations, electron bunches with 200,000 particles and a total charge of 77 pC are used. To ensure that the numerical noise issues do not lead to missleading effects, the simulations are repeated 20 times.

RESULTS

To present the results of the simulation studies, bERLinPro has been divided in three parts. Each part has been marked with a different background colour shown in Fig. 1. Please note, that each part is simulated as sequence of consequent simulation runs according to the discussion above. The injector has a magenta-coloured background, while the background of "Arc 1" section, which starts from the exit of the injector and ends at the exit of the first arc, is blue. "Arc 2" section includes a long drift and the second arc. It has a green background.

Injector

The injector section is about 10.71 m long. It consists of the photo injector, booster and the dog-leg merger. Figure 2 shows the longitudinal particle distribution, as well as current profile and the bunch form factor (Fourier transformation of the current profile, which shows the microbunching as a function of the wavelength) at the exit of the injector. Along the injector no higher amplitude of microbunching can be observed, as clearly indicated by the low amplitude of the Fourier transformation.

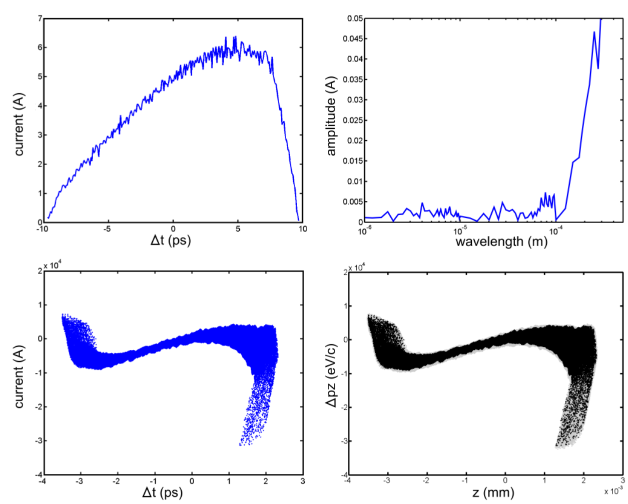

Figure 2: current profile (up left), bunch form factor (up right) and longitudinal phase space (bottom left), longitudinal phase space statistics (bottom right) at the end of injector.

Arc 1

The Arc 1 sections starts at the "merger" exit and ends after the fourth dipol of the arc. The main linac is also part of the Arc 1. Figure 3 shows the longitudinal particle distribution, as well as current profile and the bunch form factor at the exit of Arc 1. The exit shows a hint of a higher

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amplitude of the microbunching. This fact is also confirmed by analytical calculations using eq. 1.

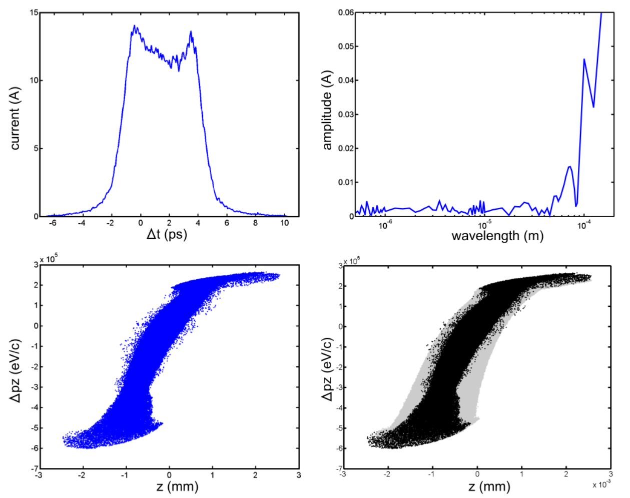

Figure 3: current profile (up left), bunch form factor (up right) and longitudinal phase space (bottom left), longitudinal phase space statistics (bottom right) at the end of Arc 1.

Arc 2

The Arc 2 section starts at the end of Arc 1, contains a long drift, the return arc and ends befor the dump. Figure 4 shows the longitudinal particle distribution, the current profile and the bunch form factor in the middle of Arc 2. The point of this subsection shows a smooth current profile. A look to the longitudinal phase space gives a clear reason. The electron bunch is located vertical in the middle of Arc 2 (Fig. 4). Along Arc 2 no higher amplitude of microbunching can be observed, as clearly indicated by the low amplitude of the Fourier transformation.

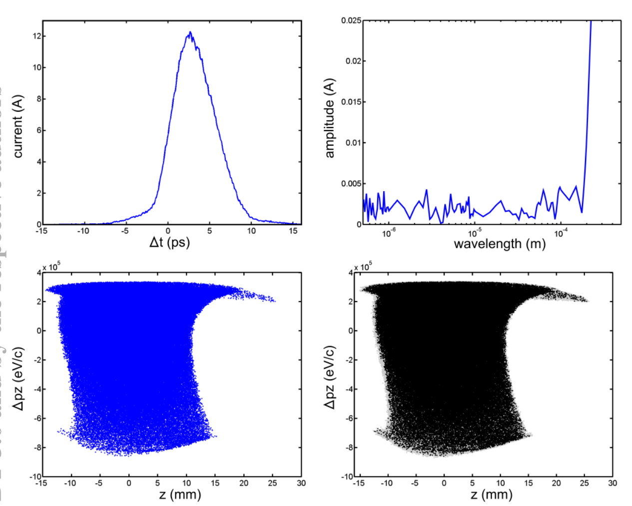

Figure 4: current profile (up left), bunch form factor (up right) and longitudinal phase space (bottom left), longitudinal phase space statistics (bottom right) in the middle of Arc 2.

CONCLUSION

The simulations of the ERL demonstrator bERLinPro shows an accelerator without microbunching instablity problems. It can be observed, that the electron bunch will smear out at the beginning of the arcs befor microbunching can develop. In addition there seems to be a hint of microbunching at the end of the first arc. This fact could be used to design a transparent microbunching amplifying optics in the following long drift, which can lead to coherent emission in the first dipole of the return arc.

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