

# NUMERICAL CALCULATION OF MICRO-BUNCHING IN bERLinPro DUE TO SPACE CHARGE AND CSR EFFECTS \*

B. Kuske<sup>†</sup>, A. Meseck, Helmholtz-Zentrum für Materialien und Energie Berlin, Germany

## Abstract

bERLinPro is an Energy Recovery Linac Project, currently being set up at the Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany. bERLinPro is a small demonstrator for ERL technology and applications. Due to the low energy of 50, resp. 32 MeV, space charge plays a dominant role in the beam dynamics. Micro-bunching, due to unavoidable shot noise from the cathode in combination with space charge, is seen in the merger as well as in the recirculator. Coherent synchrotron radiation (CSR) can amplify this bunching, as well as micro-bunching can enhance CSR losses. With the release of OPAL 2.0 in May 2018 [1], for the first time, an open source, highly parallel tracking code is available, that is capable of numerically calculating both effects, space charge and CSR, simultaneously. The calculations are compared to earlier results, that used analytical formulas on tracked, space charge dominated bunches.

## INTRODUCTION

The goal of bERLinPro is the production of high current, low emittance cw beams, and the demonstration of energy recovery at unprecedented parameters, [2]. bERLinPro is based on superconductiv RF (SRF) technology and utilizes an SRF photon gun, an SRF booster linac with an extraction energy of 6.6 MeV and an SRF main linac module. Until the HZB module, designed for a final energy of 50 MeV is available, a module produced for the MESA project in Mainz, Germany, will be tested and used for an energy of up to 32 MeV, [3]. Micro-bunching has been studied earlier for the 50 MeV bERLinPro optics, [4]. At the time, ASTRA [5], was used to track up to 1 Mio particles on a 32x32x1024 (x, y, z) grid. Micro-bunching was calculated by taking the Fourier transform of the resulting macro-particle distribution. Analytical formulas were then used to calculate the CSR gain. The studies were confined to the recirculator and took months of computation time.

OPAL is an open source, parallel processing particle tracking code, developed at PSI. It locates electromagnetic fields arbitrarily in 3D space and is thus capable of simultaneously calculating 3D space charge effects, as well as 1D CSR effects. The high degree of parallelization enables the use of fine grids and many particles without running into computing time limits. The goal of the paper is to confirm the earlier results with more adequate means and to investigate CSR and micro-bunching effects also in the low energy injector part, and for the 32 MeV optics.

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<sup>†</sup> bettina.kuske@helmholtz-berlin.de

## THEORY & SIMULATION ISSUES

Space charge forces have a strong impact on the current profile of a bunch. At very low energies, they determine the bunch dimensions. At higher energies, and on a much finer scale, they can introduce micro-bunching structures in the bunch current profile. Unavoidable transverse, as well as longitudinal shot noise induced by the cathode laser may be converted by space charge forces to energy modulations. R56 in the lattice can translate these energy modulation to amplify or reduce micro-bunching.

The region, where the longitudinal space charge impedance, LSCI, is large, represents the range of wavelengths, where micro-bunching due to LSC can be expected. Its amplitude and wavelength both strongly depend on the bunch radius and energy. Figure. 1 shows the longitudinal space charge impedance, following [6], for bunches with different radii and for energies of 32 MeV and 50 MeV.

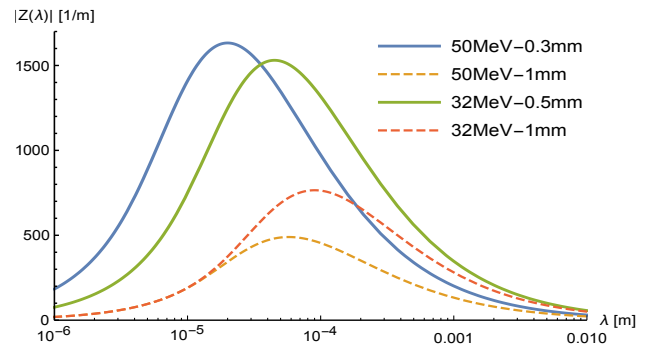


Figure 1: Longitudinal space charge impedance model for two energies and different radii.

For any phase space distribution, the bunching on specific wavelengths is determined by the bunching factor,  $b(\lambda)$ , defined as the Fourier transform of the longitudinal current profile of the bunch, Eq.(1). Furthermore, the gain,  $G(s, \lambda)$ , can be defined for parts of the lattice as the ratio between the bunching factor of a specific wavelength at the end,  $b_f(\lambda_f)$ , and the bunching factor at the beginning,  $b_0(\lambda_0)$ , whereby compression has to be taken into account, [7].

$$b(\lambda) = \frac{1}{Nec} \int I(z) e^{-\frac{i2\pi z}{\lambda}} dz; \quad G(s, \lambda) = \frac{|b_f(\lambda_f)|}{|b_0(\lambda_0)|} \quad (1)$$

The choice of the (3D) grid used in the simulation, on which space charge forces are calculated, will determine the resolution of the calculations and has to be adjusted to different bunch dimension/energy combinations in the accelerator. Table 1 lists the different grid choices. All combinations amount to  $2^{21}$  grid cells. The bunch includes 2.4 Mio macro-particles, which amounts to a sufficiently large number of

particles in the central grid cells, that contribute to space charge as well as CSR. For a uniform bunch filling and a length  $\sigma_l=1.4$  mm, each half wavelength of  $\lambda=5 \times 10^{-6}$  m would contain  $\approx 860$  particles.

Table 1: Choice of Grids / Wavelength Resolution

s	min. $\sigma_l$	energy	grid	res. - $2\sigma$
[m]	[mm]	[MeV]	-	[m]
1.5	-	2.7	128x128x128	
14.6	1.4	6.6	64x64x512	2.2e-5
26.6	1.4	32/50	32x32x2048	1.1e-5
36.0	0.6	32/50	128x16x1024	9.3e-6
54.0	0.6	32/50	64x64x512	1.8e-5
65.0	0.4	32/50	128x16x1024	6.2e-6

Figure 2 shows typical bunching curves and the gain between booster and linac in bERLinPro: Above  $\lambda=4 \times 10^{-3}$  m, the bunching factor is dominated by the bunch length. Below  $\lambda=8 \times 10^{-5}$  m, there is only noise. LSC starts to contribute at wavelengths below  $\lambda=3 \times 10^{-4}$  m, which is close to the peak wavelength of the LSCI at 6.5 MeV and a bunch radius of 1 mm. The remaining increase in the bunching factor is attributed to the bunch shape. The gain ( $>1$ ) reflects micro-bunching as well as changes in the bunch shape. Micro-bunching gain occurs for  $8 \times 10^{-5} < \lambda < 3 \times 10^{-4}$  m.

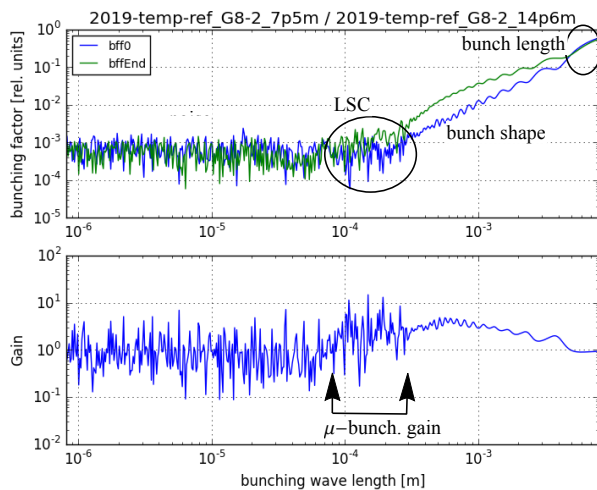


Figure 2: Top: Bunching factor at 7.5 (blue) and 14.6 m (green); Bottom: Gain; Noise, LSC effects, bunch shape and bunch length can be clearly distinguished. The micro-bunching gain is located between  $8 \times 10^{-5} < \lambda < 3 \times 10^{-4}$  m.

## RESULTS

### General Remarks

For most purposes a 3D-grid of  $32^3$  cells and  $10^5$  particles yield sufficient accuracy. Tracking with much finer grids and more particles results in moderately different lattice functions, but converge for increasing numbers grid cells. For

bERLinPro, these differences locally reach a few hundred microns in beam dimensions.

The OPAL 'emitted distribution' format is used, where no smoothing of data is applied. The statistical error is small enough, when using 2.4 Mio macro-particles. Effects of using different seeds were negligible. The initial distribution and the optics in the first 1.5 m are identical for all runs.

There are minor optics differences between the 32 MeV and the 50 MeV optics beyond 1.5 m, to compensate for different RF and fringe field focusing.

OPAL utilized the 1D CSR impedance model developed in [8]. The CSR interaction behind the dipoles is included by adding CSR-drifts. They reach up to the next dipole in the injector, and extend for 60 cm in the recirculator. The analytically estimated CSR impedance is small in the range of the micro-bunching wavelengths, and is not expected to contribute significantly to the bunching amplitudes. Its effect on wavelengths on the order of the bunch length is significant for the energy, energy spread and the emittance.

Simulations were performed for 32 MeV and 50 MeV, with and without CSR. For comparison with [4], calculations on a  $32 \times 32 \times 1024$  grid and  $1 \times 10^6$  particles have also been performed. The focus lies on the bunch parameters after the first arc, as a potential experiment would be placed there.

### LSC and CSR in the Injector

The injector of bERLinPro extends from the cathode to the main linacs entrance, at  $\approx 14$  m. The energy after the booster is 6.6 MeV. The dogleg merger consists of three, 25 cm long,  $20^\circ$  dipoles, with a bending radius of 0.72 m.

The wavelength range, where LSC is visible, shown in Fig. 2 is in good agreement with the simulations in [4], where, due to the lower number of particles, results had to be averaged over 25 runs. The magnitude of the gain, though, is  $\approx$  twice as large, which might be caused by the usage of 1D space charge model in ASTRA behind the cathode and differences in the optics, like the correct modeling of the fringe fields in OPAL.

As expected, the simulations did not show any contribution of CSR to the micro-bunching amplitudes in the merger dipoles. Furthermore, the overtaking length, i.e. the length until the radiation from the tail of the bunch can interact with the complete bunch, is larger than the length of the short merger dipoles.

The effect of CSR is seen when looking at bunch parameters. A small reduction in energy of 0.3 ‰ or  $\approx 2$  keV is detected. The horizontal emittance increases by 3.9 ‰, while the vertical emittance slightly decreases. The energy spread (including the bunch chirp) decreases slightly by 8 ‰.

After the injector, the bunch is accelerated  $8^\circ$  off crest in the main linac to imprint an energy chirp and prepare for further compression in the arc, for both energies studied. Micro-bunching is preserved during acceleration. There is a reduction though, for wavelength between  $1 \times 10^{-5} - 4 \times 10^{-5}$  m in the splitter chicane (no picture). The difference between 32 and 50 MeV is small, due to the trade off between beam radii and energy, Fig. 1.

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### LSC and CSR in the First Return Arc

Both 180° arcs of bERLinPro consist of four 60 cm long, 45° dipoles, with a bending radius of 0.76 m. In Arc1,  $R56 = -0.157$  cm at 50 MeV, resp.  $-0.182$  cm at 32 MeV. With the energy chirp imprinted in the linac, the compression factor is  $\approx 0.45$  in both cases.

**LSC** Figure 3 shows the gain after the passage through Arc1. The gain for the 32 MeV bunch peaks around  $\lambda=4 \times 10^{-5}$  m. This matches well to the maximum of the analytically calculated LSC impedance for a pencil beam with a radius of 0.5 mm, Fig. 1. The transverse beam dimension vary strongly during the passage through the arc. The average (x,y) rms beam size lies between 0.25 and 0.5 mm, disregarding the sections with large horizontal dispersion, where space charge doesn't play a significant role. On average, the bunching factor lies over 2% for  $4 \times 10^{-5} < \lambda < 1.5 \times 10^{-4}$  m, Fig. 4.

For the 50 MeV optics the average rms beam size lies between 0.16 and 0.33 mm. Also here, the wavelength, where maximal gain, resp. maximal impedance values are reached, agree fairly well, and lie around  $1.5 \times 10^{-5}$  m. The bunching factor is smaller than for 32 MeV.

**CSR** Again, CSR does not increase the micro-bunching, but results in an energy loss of 10 keV for both energies,  $\Delta p/p=2 \times 10^{-4}$  and  $3 \times 10^{-4}$  respectively, and it effects the energy spread and the emittance. Here, space charge effects have to be separated from CSR effects. Table 2 lists the changes for the horizontal emittance for the different cases. The CSR contribution at 50 MeV is only 6%, compared to an increase of 18% due to space charge. At 32 MeV the beam is space charge dominated to such an extent, that the design goal of  $< 1 \pi$  mm mrad can not be met. The vertical emittance is relatively stable with a increase below 6% to  $0.68 \pi$  mm mrad.

Table 2: Initial and Final Horizontal Emittance Values for Arc1 for Different Simulations

energy	grid	# particles	SC/CSR	$\epsilon_x / \pi \mu$ rad
50 MeV	2 <sup>15</sup>	10 <sup>5</sup>	SC	0.641-0.723
	2 <sup>21</sup>	2.4 Mio	SC	0.661-0.778
	2 <sup>21</sup>	2.4 Mio	SC + CSR	0.682-0.837
32 MeV	2 <sup>15</sup>	10 <sup>5</sup>	SC	0.599-0.719
	2 <sup>21</sup>	2.4 Mio	SC	0.705-1.420
	2 <sup>21</sup>	2.4 Mio	SC + CSR	0.740-2.050

Similar results hold for the energy spread: space charge causes the larger part of the growths, 0.6, resp. 2%. With CSR, the increase is 0.8% at 50 MeV and 2.2% at 32 MeV.

Behind the straight section, energy modulation reaches a maximum. In Arc2, the amplitudes are tilted by  $R56 > 0$ . Bunching raises to  $> 5\%$  on certain wavelengths, but beam quality is of minor interest, then.

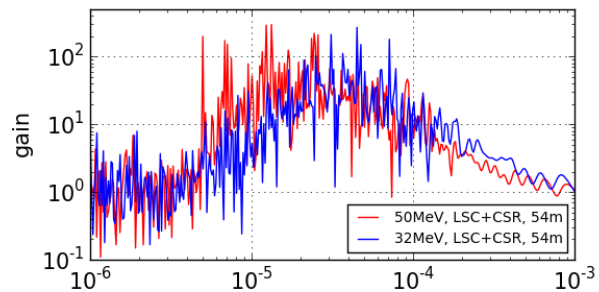


Figure 3: Gain during first 180° arc. The gain for 50 MeV (red) is shifted to lower wavelength.

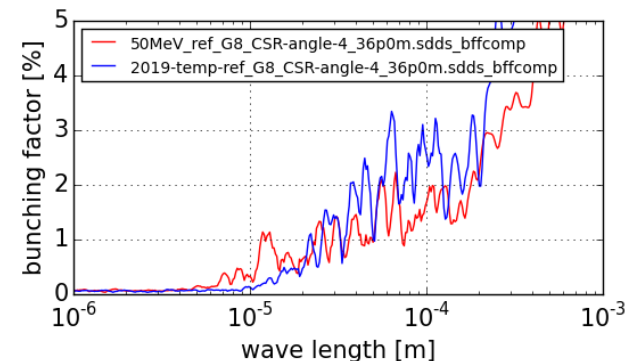


Figure 4: Bunching at the end of Arc1 (smoothed data). The bunching for 32 MeV (blue) exceeds that at 50 MeV (red).

## CONCLUSION

It could be shown, that OPAL is an adequate tool to study micro-bunching due to LSC and CSR. On the HZB cluster it took 30 min /m using 64 CPUs, for 2.4 Mio. particles and 2<sup>21</sup> grid cells. Where comparable, earlier results could be reproduced. Calculated gain wavelengths agree well with theoretical predictions. It could be shown, that the usage of the MESA linac module in bERLinPro, i.e. a reduction of the energy to 32 MeV, increases LSC effects to an extent, where the horizontal emittance goals cannot be met. It became clear, though, that, if optics could be developed with smaller transverse beam sizes in the first arc, bunching factors are in reach, that would allow for coherent emission experiments at 32 MeV.

## ACKNOWLEDGEMENTS

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