# MODELLING OF THE SHORT BUNCH OPTICS FOR bERLinPro

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## Abstract

The Energy Recovery Linac principle allows compressing electron bunches to lengths at least two orders of magnitude shorter compared to storage rings. At bERLinPro bunch compression and decompression can be done in two stages in the injector and main arcs. Starting with different bunch lengths from the gun the distribution of compression between these two stages is subject to optimization.

Simulations show that the length and shape of the bunch in the injector and before the linac are the limiting factors for minimal bunch length. Injector simulations have to consider space charge effects, whereas coherent synchrotron radiation (CSR) effects are limiting compression in the arcs. The strength of these effects and sweet spot of compression ratios changes with different bunch charges. Optimization and simulation tools have to be chosen according to the energy regime and dominant collective effects. Current status of injector optimization and effect on the compressed bunch are presented.

## THEORY

### bERLinPro

Being a test and demonstration facility, bERLinPro ( [1], [2]) is build to explore and showcase the capabilities of the ERL technology. With the main focus on a "standard mode" set for future light source application (as listed in Fig. 1) the optics is designed flexible to allow studies of a wide range of parameters.
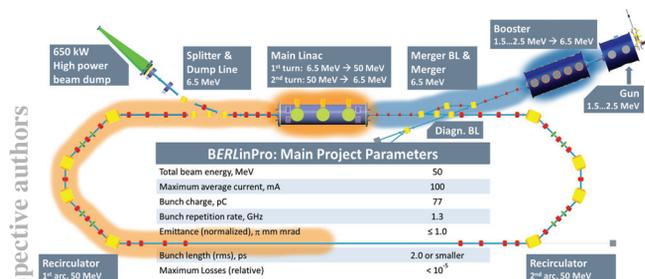


Figure 1: bERLinPro Layout.

Altering the given lattice for a short bunch mode, there are three main switches to change the bunch length. Varying the timing and laser pulse length on the cathode changes beam parameters from the start. The first compression stage uses the chicane of the dog-leg merger. The compression ratio can be adjusted by the acceleration phase in the booster cavities. After the injection into the main linac further compression is possible by adjusting linac cavity phase and the $R_{56}$ element of the arc.

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### Modelling and Optimization

Electrons in the injector are in the low energy regime (<7 MeV). Therefore space charge force has a greater effect on beam dynamics compared to the arc section (≈50 MeV). The injector of bERLinPro in standard mode was designed with a 2D-emittance compensation scheme [3]. The procedure to optimize the emittance consists of the following steps:

- Long bunches can be split into independent slices that are not interacting.
- Due to different charge densities the slice motion in phase space differs from each other in space charge dominated sections.
- Optics can be designed to align all slices at a certain point along the trajectory.
- Because of reduced influence of space charge effects at higher energy choosing a point in the main linac can maintain the slice alignment.

This model does not work for overcompressed bunches with near zero slice lengths and infinite charge densities. Head and tail slices may be omitted from the scheme if necessary. Altering the laser pulse length or compression ratio of bunches in the merger changes charge densities and strength of longitudinal and transversal space charge effects. Hence running optimizations for the injector quadrupoles is necessary for each parameter set to reapply the emittance compensation scheme.

Compressing bunches in the arc to minimal length requires inclusion of CSR into used models. Also applying a non-linear energy chirp by accelerating off-crest in the linac, spreading the bunch horizontally as well as aberrations in the arc require compensation to linearize the longitudinal phase space. Available sextupoles in the arc can compensate non linear effects of second order. For minimal bunch length this last compression stage can be done up to the point where the linear correlated energy spread vanishes. To keep the number of free parameters low and maintain the given focusing scheme of the standard mode only the linac cavity phase and sextupole strengths need to be changed.

### Simulation Tools

Optimization of the injector optics is done with a dedicated code developed on C++. It implements the emittance compensation scheme and optimizes beam parameters for a given target function. The program was only slightly changed and tweaked since its first presentation [3] and solves Eq. (1) - (7) numerically for each slice.

Used variables are:

| | | |
|---|---|---|
| $x, y$ rms sizes, | $\delta E$ | energy deviation, |
| $I$ initial current, | $\delta'$ | s-derivative of energy spread, |

$n$   bunching level,   $ct$   longitudinal coordinate,
$R$   trajectory radius,   $\epsilon(ct)$ cavity accelerating gradient,
$D$   dispersion,   $k_{x,y}$   focussing strengths,
$E_0$   beam energy,   $\gamma, \beta$   relativistic factors.

$$0 = x'' + k_x x - j\frac{1}{x+y} - \frac{\epsilon_x^2}{x^3} \tag{1}$$

$$0 = y'' + k_y y - j\frac{1}{x+y} - \frac{\epsilon_y^2}{y^3} \tag{2}$$

$$j = \frac{I}{I_0 \left(\beta\gamma\right)^3} \tag{3}$$

$$\frac{\partial n}{\partial s} = -n \cdot \delta'\left(\frac{1}{\beta^3\gamma^2} - \frac{D}{R}\right) \tag{4}$$

$$\frac{\partial \delta'}{\partial s} = \frac{\epsilon'(ct)}{E_0} - \delta'\frac{\epsilon(ct)}{E_0} - \delta'^2\left(\frac{1}{\beta^3\gamma^2} - \frac{D}{R}\right) \tag{5}$$

$$\frac{\partial ct}{\partial s} = \frac{\partial E}{E_0}\left(\frac{1}{\beta^3\gamma^2} - \frac{D}{R}\right) \tag{6}$$

$$\frac{\partial \delta E}{\partial s} = \epsilon(ct) - \epsilon(0) \tag{7}$$

Using Kapchinsky-Vladimirsky equations and linear longitudinal motion only, the code is very fast but doesn't take longitudinal interaction and space charge effects into account. Thus multiple random walks with following local minimizations are doable in reasonable time frames.

Results from the optimization are then used in Astra [4] simulations for the whole injector. Optics of the arc are optimized with Elegant [5]. Simulations with two-dimensional CSR models can be done in CSRtrack.

## SIMULATION

Our first simulations for bunch compression only used maximal compression in the arc. Elegant simulations starting with particle distributions from standard mode simulations at the linac and optimizing linac cavity phase and sextupoles for minimal bunch lengths result in a s-shape bunch in longitudinal phase space at the end of the arc. Thus decreasing the bunch length at the start of the linac can decrease energy spread after applying energy chirp and compression and also decrease length if the s-shape is maintained.

Different precompressions in the injector were tested by parameter scans over starting bunch length (by altering the "sig-clock" parameter in the Astra particle generation) and acceleration phase in the booster cavities. Parameter limits are defined by technical capabilities of the machine and reasonability for compression: $2\,\text{ps} \le \text{sig\_clock} \le 8\,\text{ps}$, $0° \le \varphi \le 12°$.

The code for emittance compensation was used to determine strengths of the four quadrupoles between booster and merger and another four between merger and linac. The two quadrupoles in the merger chicane are used to adjust the dispersion for compensation of longitudinal space charge forces. This is done by a linear approximation and requires multiple Astra runs and a correlated energy spread in the bunch.
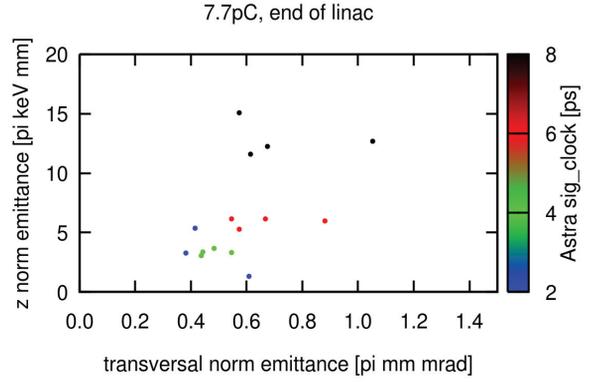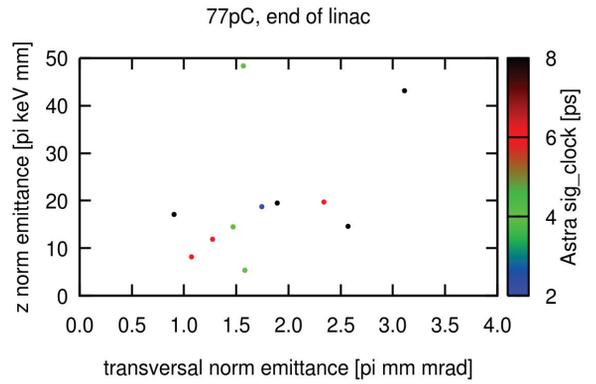


Figure 2: Injector optimization low charge.



Figure 3: Injector optimization full charge.

The optimization results were then used in Astra simulations to get the beam parameters and particle distributions for compression of the bunch in the arc. Because of the following rotation in longitudinal phase space overcompression has to be considered when rating results of the optimization. Therefore longitudinal emittance is favored over bunch length as indicator for compression, while emittance compensation is rated by transversal emittance as shown in Figs. 2 and 3.

There is a notable difference in the reliability of the optimization process to work for different bunch charges. Difficulties in compensation of longitudinal space charge forces in the dispersive section and overcompression are main reasons for emittance increases in the bunch or even complete fail of the optimization process. On the other hand overcompressed bunches at the linac also reduce the compression ratios that are possible in the arc and don't have to be considered for a short bunch parameter set.

The transition from beam parameters behind the linac to the straight section behind the first arc (see Figs. 4 and 5) is done with Elegant including a 1D CSR model. For the lower charge case best results start with the shortest generated particle distribution whereas for full charge of 77 pC the higher charge density causes growth before the booster that negates the advantage. Table 1 summarizes final
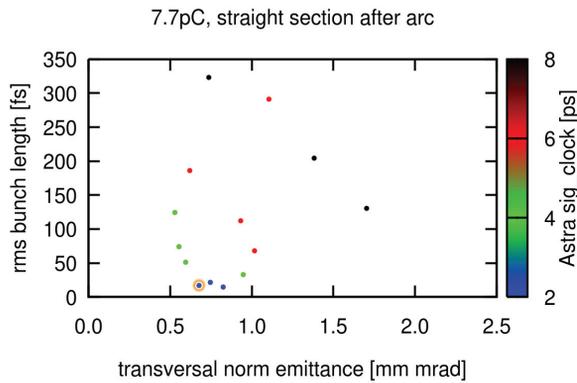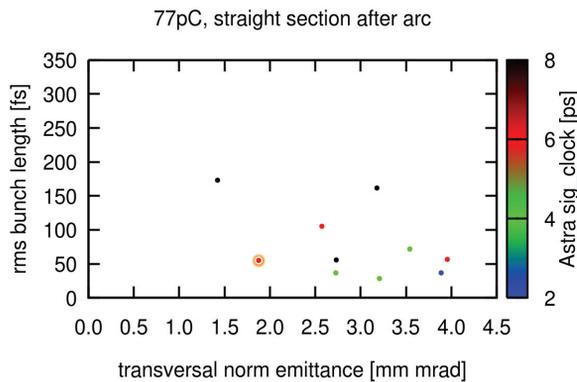
Figure 4: Arc compression low charge.



Figure 5: Arc compression full charge.



Figure 6: Longitudinal phase space low charge.
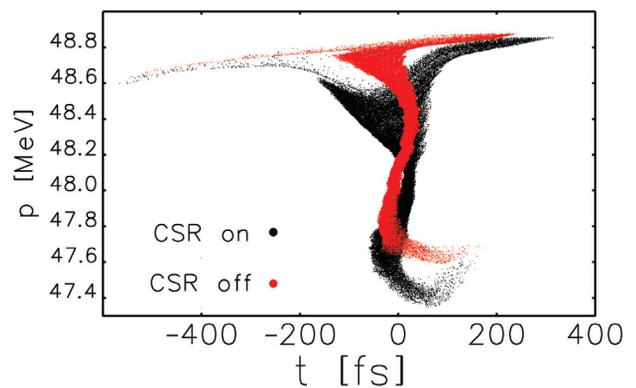


Figure 7: Longitudinal phase space full charge.

beam parameters from simulations highlighted in Figs. 4 and 5. These points are representing results with the highest peak brightness estimated as $B \sim 1/\varepsilon_x \varepsilon_y \varepsilon_z$.

To show the impact of CSR on beam parameters, associated longitudinal phase space plots are shown in Figs. 6 and 7 with CSR switched on and off. Emittance and bunch length increase when switching CSR on in simulations is at $\approx 25\,\%$.

Table 1: Beam Parameters

| Parameter | full charge | low charge |
|---|---|---|
| Booster cavity phase | $8\,°$ | $4\,°$ |
| "sig_clock" | 6 ps | 2 ps |
| Bunch charge | 77 pC | 7.7 pC |
| Bunch rms length | 55 fs | 17 fs |
| Normalized emittance | 1.9 mm mrad | 0.8 mm mrad |

## CONCLUSION

Precompressing bunches before the linac improves beam parameters if the compression ratio is below threshold for overcompression and 2D emittance compensation is accomplished. Usi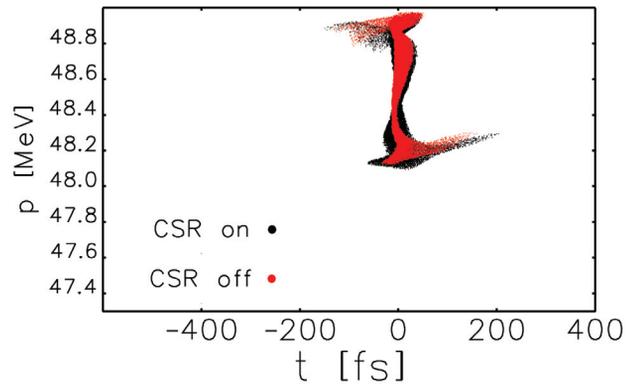ng the best performing parameter set for starting bunch length and compression ratios the final bunch length and emittance is mostly limited by coherent synchrotron radiation.

## REFERENCES

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