SIMULATION DESIGN OF A LOW ENERGY BUNCH COMPRESSOR WITH SPACE CHARGE EFFECT *

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Abstract

We study a low energy (5MeV) bunch compressor design to produce a short (<200 fs) and small size (~30 μm) bunch for the electron beam slicing project [1]. In order to lower the cost of our system, we have designed a bunch compressor using only a BNL photo-cathode electron RF-gun and a four-dipole chicane with several matching and focusing quadruples. Because there is no acceleration after the RF-gun exit, the compressor works in space charge dominated domain and the bunch has a negative energy chirp due to space charge effect at the gun exit. To provide compression for the negative energy chirped bunch, the chicane has positive R_{56}. After the optimization, we have achieved a low energy bunch with the 166fs RMS bunch length, 28 μm and 31 μm RMS beam size in vertical and horizontal direction separately, at 5 MeV with 50 pC charge. This result meets the basic required beam parameters for the electron beam slicing scheme.

INTRODUCTION

In the electron beam slicing method [1], we use one short and focused low energy bunch to cross the high energy bunches in a synchrotron radiation storage ring to kick a short slice of the high energy electrons. The separated slice when passing through an undulator, can radiate ultra-short x-ray pulses at about 150fs. In this paper, we discuss the simulation design of one compressor to obtain the required short focused low energy bunch. Short pulse bunch is required in many systems, for example, FEL systems or collider systems which need the bunch to reach very high peak current. Many magnetic bunch compressors have been designed to compress the bunch to reach several hundred femtosecond [2-5]. In these compressors, in many FEL systems or collider systems, the final bunch has to be compressed longitudinally to reach very high peak current (i.e., 2.5 kA for TTF-FEL). Many magnetic bunch compressors have been designed to compress the bunch to reach several hundred femtosecond [2-5]. In order to avoid the space charge effects, the bunch is usually accelerated to energies where the space charge forces are weakened sufficiently by the $1/\gamma^2$ scaling, and then is compressed longitudinally to increase the peak current [6-7]. The bunch accelerated at an off-crest RF accelerating system usually has a positive energy chirp (correlated energy spread along the bunch length) i.e., the head particles have lower energy than the tail particles'. When the positive energy chirped bunch traverses a dispersive section with a negative R_{56}, the flight time is shorter for the tail particles than it is for the head particles, then the bunch will be longitudinally compressed. In our case [1], in order to minimize the cost, we try to design a compressor with no acceleration after the RF-gun to achieve the desired bunch compression and focusing [1]. Therefore we design an unconventional compressor at low energy (5MeV) and space charge dominated regime to compress and focus the bunch. This magnetic chicane has positive R_{56} to compress the bunch with negative energy chirp. We use OptiM and ElEGANT to perform the initial linear design of the positive R_{56} chicane and the final focusing system, ignoring space charge effects at first. With this starting point from OptiM and ELEGANT, we apply PARMELA to consider the space charge effects by gradually turning on the charge. We carry out a multi-objective optimization procedure using the genetic algorithm [8] to perform the global optimization for 23 variables. For the final result, our 5m long compressor can compress a 5MeV low energy bunch with 50pC charge from 2ps to 166fs RMS longitudinal bunch length and 28 μm, and 31 μm for horizontal and vertical RMS beam size respectively at focal point.

LINEAR DESIGN OF THE POSITIVE R56 CHICANE

Negative Energy Chirp and Positive R56

In linear approximation, the compressed rms bunch length σ_1 is simply scaled from its original rms bunch length σ_0 as [6]

$$\sigma_1 \approx \sqrt{\left(1+hR_{56}\right)^2 \sigma_0^2 + R_{56}^2 \sigma_\delta^2},$$

where h is the energy chirp, σ_δ is the rms relative intrinsic energy spread. To maximized compression, the chicane R_{56} should make $1+hR_{56}=0$.

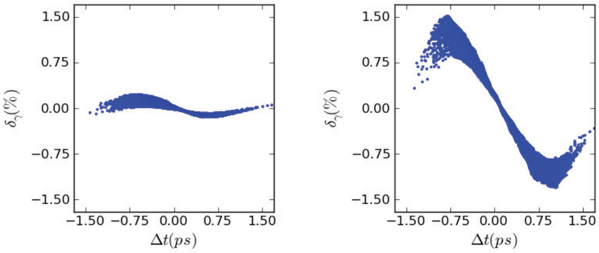

Figure 1: Energy chirp at photocathode RF-gun exit (left) and at the entrance of the chicane (right).

By simulation, we confirm that the energy chirp from the photo-cathode electron RF-gun is small and negative due to the space charge effects, i.e., the head particle with

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higher energy as shown in the left of Fig. 1 with energy chirp -0.25% per ps, i.e., $1/h=-120mm$. To compress such a negative chirped bunch, the chicane must have positive $R_{56}=120mm$ such that the higher energy particles go through a longer path length than the low energy particles. After the chicane the electrons at the tail with lower energy will then be able to catch up with the particles at the head of the electron bunch. In ELEGANT, the drift space induced $R_{56}=-s/\gamma^2$ is not included. For our 5MeV low energy compressor with 5m long chicane, the drift space induced $R_{56}=-50mm$ must be included. Therefore R_{56} for the chicane, required in the ELEGANT calculation, is 170mm. The large R_{56} requirement leads to large dispersion function, large beta functions and large beam size which will induce large betatron oscillation. And the large betatron oscillation leads to long path length and hence longer bunch length. Our analysis shows that we have a rather restricted condition for the compressor: we need to control beta functions within 10m, and require dispersion function to be less than 12cm. Therefore, we need to reduce R_{56}. For this we find that we need to increase the energy chirp to near or larger than 1%. To reduce the R_{56} of chicane, instead of avoiding space charge forces, we focus the electron beam and utilize this effect to increase the energy chirp to $-1.5\%/ps$, $1/h=-20mm$ before entering to the chicane as shown in the right of Fig. 1. Thus, the required chicane R_{56} is greatly reduced to 70mm from 170mm.

Positive R56 Chicane

The schematic layout of our positive R_{56} chicane is shown in Fig. 2. It is constructed by four rectangular dipoles each with 20º bending angle. Between the dipoles, we set several quadruples to flip the particle trajectory so that higher energy particle's path length is longer than the lower's. Chicane's R56 except drift space mainly comes from the dipoles' dispersion by $R56=\int\frac{\eta}{\rho}ds\sim\eta\theta$. To increase the R56 of dispersion without increasing the maximum of η, we move quadruples very close to the dipoles so that η does not continue to increase once the beam passes through the dipole, i.e., η reaches its maximum at the ends of the dipoles . We obtain the linear lattice bunch length of 100fs at the focal point with space charge effects neglected. The twiss parameters of the chicane at its beginning are matched to the twiss parameters of the beam at the exit of the RF-gun using OptiM and ELEGANT with space charge effects ignored. The lattice functions are shown in Fig. 3 (bottom).

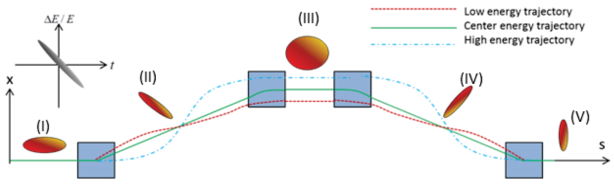

Figure 2: Particle trajectory in positive R_{56} chicane.

NONLINEAR OPTIMIZATION WITH SPACE CHARGE EFFECTS

Dispersion Function and Beta Functions in Space Charge Regime

The space charge effects simulation study of the whole compressor system consisting of only a BNL photo-cathode RF-gun and a compressor chicane with a matching section is carried out by the code PAMELA. We assume the field gradient is 100MV/m at the cathode and fix the laser spot size at radius of 2mm. At first, at the entrance to the chicane, we turn off the space charge effect for the calculation inside the chicane. This is because when we turn on space charge effect in the chicane, the 3-D simulation blows up: the beam size increases from 30μm to 500μm, and the bunch length increases from 100fs to 1ps. Due to the space charge forces the particle energy is no longer constant, and the dispersion function and beta function both lose their original meaning. We redefine the equivalent dispersion by averaging the trajectory in selected initial energy ranges and the equivalent beta functions using RMS beam size in selected initial emittance range. As we gradually increasing the charge in the chicane, by try and error we adjust the quads to restore the 'dispersion function' and 'beta functions' to be approximately the same as the case without space charge effects. This procedure allows us to gradually increasing charge to 30 pC without blowing up the beam, without losing particles. Fig. 3 shows the linear lattice functions along compressor without space charge effects from the code OptiM (bottom) and the nonlinear newly defined functions with space charge effects from code PARMELA (up). It's seen that the effective dispersion function and beam size are restored to the similar forms as the linear functions. It shows the chicane

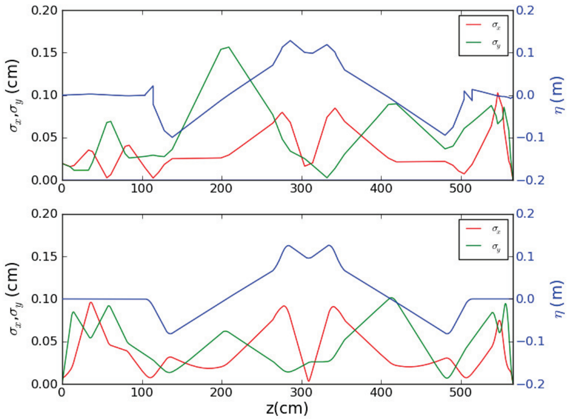

Figure 3: RMS beam size and dispersion with space charge effects from PARMELA (up) and without space charge effects from OptiM (bottom).

still has the symmetrical behaviour in space charge forces dominated regime approximately. Even though the bunch length is still very large (about 700fs), this provision makes it possible to carry out optimization by genetic algorithm without losing particles during the tracking.

Global Optimized Results

We carry out a multi-objective optimization procedure using a genetic algorithm [8]. The variables are the laser pulse length, laser phase relative to RF phase, solenoid strength, field strengths of quads and dipoles in the chicane, field strengths of matching quads. The optimized objects are the bunch length and the sum of transverse RMS beam sizes. When we use the genetic algorithm, we iterate by alternating optimization with adjustment of the limits of variables reduced parameter scanning phase space, and we also gradually increase charge from 30pC to 50 pC by genetic algorithm. At 5MeV with 50pC charge and a 5 m compressor chicane, the optimization leads to 166 fs RMS bunch length with 28 µm, and 31 µm for horizontal and vertical RMS beam size respectively at the focal point. The optimized results are given in Table 1. The RMS bunch length is calculated for 90% of particles, with 10% tails cut off. When number of simulation particles is 10000, the result is convergent. Estimate on CSR effect shows that its effect on energy spread and emittance is negligible in this low energy compressor.

Table 1: Optimized Results of the Compressor

		Initial bunch	**Focused bunch**
Longitudinal bunch length [fs]	σ_z	1270 (cathode)	166
Horizontal beam size [µm]	σ_x	2000 (cathode)	31
Vertical beam size [µm]	σ_y	2000 (cathode)	28
Energy spread [%]	ΔE/E	0.09 (gun exit)	0.93
Average energy [MeV]	E	4.69 (gun exit)	4.69
Horizontal Emittance [µm]	ε_x	0.177 (gun exit)	1.02
Vertical Emittance [µm]	ε_y	0.189 (gun exit)	0.84
Charge [pC]	Q	50	50

Analysis of One Optimized Example

The evolution of longitudinal phase space during bunch compression is shown in Fig. 4(I-V): after the focal point following the RF-gun exit (I), inside the chicane (II-IV) and after the chicane (V). In these figures, the particles are coloured according to the initial energy at the focal point before chicane. The bunch energy chirp rotates from negative to positive (shown in (I-IV)), then, after the chicane, in the final focusing section, rotates reversely to reach a very short bunch length (shown in (V)). Before the middle of the chicane, the head particle has higher energy. In the middle of the chicane, the bunch length reaches the maximum. To overcome the drift space's negative R_{56}, we need to over compress the bunch at the third dipole in the chicane in Fig. 4(IV). At this position, the initial head becomes the tail, and the energy spread starts to decrease. At the end of compressor, we obtain a compressed and focused bunch in Fig. 4(V). Fig. 4(VI) shows the longitudinal phase space at the same position as in Fig. 4(III)'s, but the particles are colored according to the particles' initial horizontal position. Fig. 4(VI) indicates the longitudinal path length spread is due to different initial horizontal position. The optimized result shows the structure of our chicane and the bunch behaviours in the chicane are partially symmetric relative to the centre of the chicane.

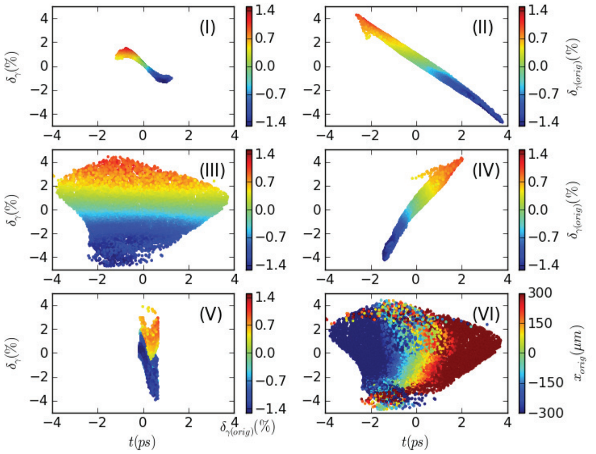

Figure 4: Evolution of longitudinal phase space during bunch compression; Particle is coloured according to the initial energy spread in (I-V) and the initial transverse horizontal position in (VI).

CONCLUSION

Our simulation shows the low energy compressor can compress the bunch length to about 150fs and focus the RMS bunch size to about 30 µm at 5MeV with 50pC charge in space charge dominated domain. This compressed and focused bunch can be used in the electron beam slicing project [1].

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