BENCHMARK AND SIMULATION DESIGN OF A LOW ENERGY BUNCH COMPRESSOR

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Abstract

In the electron beam slicing method [1], a low energy bunch with very short and focused beam size is required to interact with the storage ring bunch. We have designed a low energy bunch compressor with BNL photo-cathode electron RF-gun [2] by applying simulation code PARMELA [3].

In this paper, in order to confirm the simulation result, we benchmark the simulation result from PARMELA with that from IMPACT-T [4] for our compressor with BNL RF-gun. In order to increase the repetition rate of the electron beam slicing system, and change the compressor's RF gun from BNL RF-gun to LBNL's VHF gun [5] to redesign the compressor by applying IMPACT-T with both space charge effects and CSR effects considered. The benchmark between PARMELA and IMPACT-T has produced excellent agreement. The comparison of the CSR effects also shows the bunch can be compressed and focused to our desired size after optimization using code IMPACT-T with CSR effects turned on. The new compressor with high repetition rate still works in space charge dominated domain and the bunch with a negative energy chirp at the entrance of the chicane is compressed by a chicane with positive R_{56}. After the optimization, we have achieved a low energy bunch with the 128 fs RMS bunch length, 42 μm and 25 μm RMS beam size in the vertical and horizontal directions respectively, at 22 MeV with 200 pC charge.

INTRODUCTION

The electron beam slicing method [1] generates ultra-short x-ray pulses using focused short low energy (~20 MeV) electron bunches to create short slices of electrons from the circulating electron bunches in a synchrotron radiation storage ring. When a low energy electron bunch crosses from top of a high energy storage ring electron bunch, its Coulomb force will kick a short slice from the core of the storage ring electron bunch. The separated slices, when passing through an undulator, will radiate ultra-short x-ray pulses at about 100 fs. In order to minimize the cost of the electron beam slicing system and to explore the lower limit of the compressor's bunch energy, a low energy bunch compressor [2] without acceleration after the RF-gun exit has been designed to achieve the desired bunch compression and focusing. The RF gun used in this compressor is BNL RF-gun and the simulation code applied is PARMELA with space charge effects considered. Some optimized results for the BNL RF-gun compressor are given in Table 1.

In this paper, to verify the simulation results, we benchmark the simulation results from PARMELA with the results from IMPACT-T for the low energy compressor with BNL RF-gun. To study the coherent synchrotron radiation (CSR) effects, we compare the simulation results when CSR effects is turned on with those when CSR is turned off in IMPACT-T. In order to increase the repetition rate of the electron beam slicing system, we change the compressor's RF gun from BNL RF-gun to LBNL's VHF gun [5] and redesign the compressor by applying IMPACT-T with both space charge effects and CSR effects considered.

BENCHMARK AND CSR EFFECTS

Both Linac tracking codes PARMELA [3] and IMPACT-T [4] can track relativistic particles taking into account space charge effects in the 6D space, whereas the space-charge solver is 2D r-z or 3D depending on the code. IMPACT-T also considers the coherent synchrotron radiation (CSR) effects which are not included in PARMELA.

To verify our simulation results from PARMELA, taking the compressor of case 3 in Table 1 as an example we benchmark the results with PARMELA against those with IMPACT-T. By applying IMPACT-T, we also discuss CSR effect which is not considered in code PARMELA. The CSR effects are related to the bunch energy, bunch charge and bunch length. To check the CSR effects, we compare the simulation results when CSR effects being turned on with the results when CSR effects being turned off in IMPACT-T. The results of the benchmark and comparison is shown in Table 2, Fig. 1 and Fig. 2.

Data in Table 2 show the RMS bunch length difference between PARMELA and IMPACT-T with CSR off is less than 6%. The difference of the transverse RMS beam size between the two codes is larger than 20% when all the results are calculated for 90% particles, with 10% longitudinal tails cut-off. If the transverse RMS beam size are calculated for 100% particles as shown in Fig. 1, the difference of those between the two codes decrease to ~10%. Fig. 1 show the 6-D phase space at the final focus point for the three simulation results: PARMELA (the 1st row), IMPACT-T with CSR effects off (the 2nd row) and IMPACT-T with CSR effects on (the 3rd row). The color bar indicates the particle density.

Due to the space charge forces the particle energy is no longer constant, and the dispersion function and beta functions both lose their original meaning. We redefine the equivalent dispersion and the equivalent beta functions as described in [1]. To show the agreement between the two codes and the difference of the calculations with and without the CSR effects considered, we plot the evolution of the newly defined beta functions and the dispersion function along the dispersive chicane section of the compressor for the three simulation results in Fig. 2. Although the exact

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Table 1: Performances of Compressors with Different Charge and Different Energy

compressor[a] case	RF-gun	accelerate cavity	length [m]	Charge [pC]	Energy [MeV]	σ_L[b] [fs]	σ_H[c] [μm]	σ_V[d] [μm]
1	BNL	no	6.75	50	5	166	31	28
2	RF-gun	yes	6.75	100	12	110	34	31
3		yes	6.75	150	12	145	35	24
4	LBNL	yes	8.5	150	18	130	47	28
5	VHF-gun	yes	8.5	200	20	148	46	25
6		yes	8.5	200	22	128	42	25

[a] The simulation results for the BNL RF-gun compressor come from PARMELA with CSR effects ignored. The simulation results for the LBNL's VHF gun compressor come from IMPACT-T with CSR effects considered.
[b] the longitudinal RMS bunch length at final focal point
[c] the horizontal RMS beam size at final focal point
[d] the vertical RMS beam size at final focal point

value of these functions in Fig. 2 lose their original meaning with space charge effects increasing, these function curves still can be used to compare the simulation results.

The simulated results of IMPACT-T with CSR off (green curve) show good agreement with those of PARMELA (red curve) with slightly difference in the newly defined RMS beam size. The agreement between the two codes (the red and green curve) in the newly defined dispersion is excellent. The green curves (CSR off) and the blue curves (CSR on) are completely overlapped before the chicane's third bending magnet which is located at 4.6 m of the beamline. The green and blue curves appear separated after the third dipole. The separation indicates the CSR effects and also shows the CSR effects mainly take place at the 3rd and 4th dipole of the chicane. Analysis show the bunch length is significantly compressed from 800 fs to 300 fs when passing through the 3rd dipole and the bunch length has been compressed to 235 fs at the entrance of the 4th dipole. Although the CSR effects induce some minor difference, the results in Table 2 indicate it is promising that the final bunch can be further optimized.

The benchmark between PARMELA and IMPACT-T has produced excellent agreement. The comparison of the CSR effects also shows the bunch can be compressed and focused to our desired size after optimization using code IMPACT-T with CSR effects turned on.

Table 2: Benchmark Results of PARMELA Against IMPACT-T and Comparison of CSR Turning Off with CSR Turning On in IMPACT-T

code	CSR effects	σ_L[a] [fs]	σ_H[a] [μm]	σ_V[a] [μm]
PARMELA	off	145	35	24
IMPACT-T	off	137	45	32
IMPACT-T	on	157	41	26

[a] σ_L, σ_H, σ_V are the longitudinal RMS bunch length, the horizontal RMS beam size, the vertical RMS beam size at the final focal point respectively.

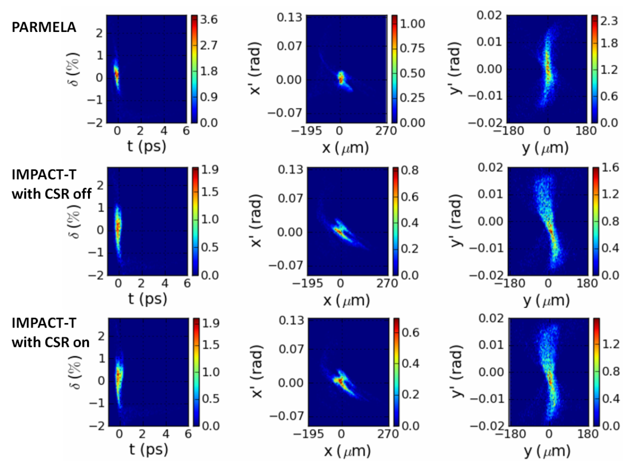

Figure 1: The histograms of bunch's 6-D phase space at the final focus point of the compressor. Data come from different simulation codes for the same compressor of case 3 in Table 1: PARMELA (the 1st row), IMPACT-T with CSR off (the 2nd row), IMPACT-T with CSR on (the 3rd row). The color bar shows the particle density.

HIGH REPETITION RATE LOW ENERGY COMPRESSOR

In order to increase the repetition rate of the electron beam slicing system to increase the photon flux, we change the RF gun of the compressor from BNL photo-cathode RF gun to LBNL's VHF gun which operates at 186 MHz with repetition rate of 1 MHz [5] and redesign the compressor by applying simulation code IMPACT-T with both space charge effects and CSR effects considered.

Matching by Manual Adjustment

We use the simulation result for the benchmarked compressor with BNL RF gun at 13 MeV as a starting point to study the compressor with VHF gun. First, we keep the same magnet sections as those of the benchmarked compressor which include the matching magnets, chicane magnets and final focusing magnets. We change the gun from BNL RF

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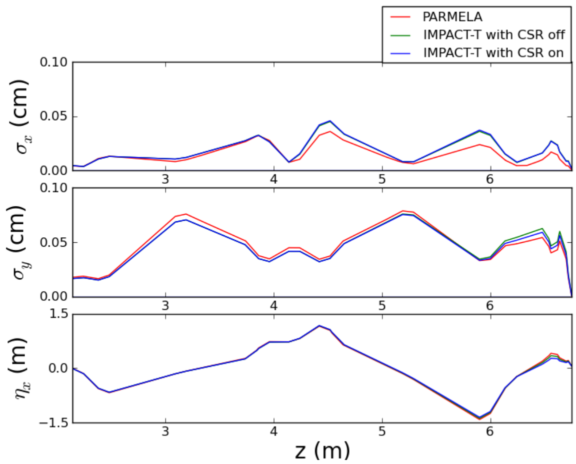

Figure 2: The evolution of the newly defined beta functions and the newly defined dispersion function along the dispersive section of the compressor. The red, green and blue curves correspond to the simulation results by PARMELA, IMPACT-T with CSR off, IMPACT-T with CSR on respectively.

gun to LBNL VHF gun and we also add several RF cavities between the gun and the matching magnets to accelerate the bunch. Then with the space charge effects turned on, we adjust the gun and the accelerating section to make the bunch's energy chirp and the transverse beam size after the acceleration to match with those at the entrance of the first matching quadruple of the benchmarked compressor.

At the photocathode, we set the bunch longitudinal distribution as flat-top with linear ramp at two ends and the total length from head to tail is 8 ps. The bunch transverse distribution is a uniform ellipse with hard cut edge and the diameter of the ellipse in x and y is 1.5 mm. The 3-D momentum distribution of the bunch is Gaussian. The bunch charge is set at 150 pC. Simulation shows the beam energy after LBNL's VHF gun is 730 keV. In order to avoid large betatron oscillation and beam blowing up, we move the accelerating cavity very close to the photocathode gun.

While keeping the bunch energy at 13 MeV after acceleration, we adjust the phases and gradients of the RF cavities manually to match the energy chirp of the bunch after acceleration with the energy chirp at the entrance of the first matching quadruple of the benchmarked compressor. At the same time, We adjust the intensity of focusing coils manually to make the bunch's transverse beam size match with those at the entrance of the first matching quadruple of the benchmarked compressor. We iterate the adjustments of the focusing coils and the RF cavities to optimize the matching. After the matching, the total length of the compressor system consisting of the LBNL's VHF gun, two focusing coils, two RF cavities and the matching, dispersive and focusing magnets section is 8.5 m. At the entrance of the first matching quadruple, the bunch's energy spread is increased to ±9% and the longitudinal bunch length is about 25 ps.

Global Optimization by Genetic Algorithm

With the previous matched compressor of LBNL VHF gun, we carry out a multi-objective optimization procedure [6] using a genetic algorithm to optimize the compressor with the bunch energy fixed at 13 MeV. After optimization, the RMS bunch length is still larger than 1 ps and the transverse RMS beam size are also very large around 150 μm. Analyzing the longitudinal phase space of the final focused bunch colored by the initial emmitance after acceleration and the initial energy spread after acceleration shown in Fig. 3 (I,II), we find the bunch length increase is not directly related to the initial emmitance, but is related to the initial energy spread. If we artificially cut off those bunch particles with the initial energy spread larger than ±2%, the RMS bunch length at the final focal point decreases from 1.26 ps to 0.38 ps as shown in Fig. 3 (III).

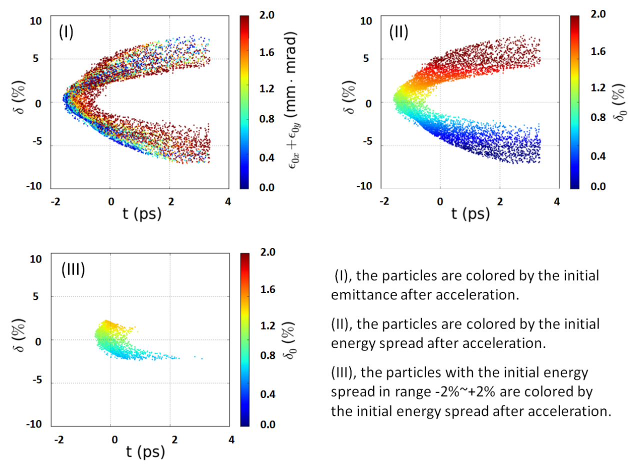

Figure 3: The longitudinal phase spaces at the final focal point for one optimized result of the VHF-gun compressor at 13 MeV. Simulation code is IMPACT-T with both space charge effects and CSR effects being turned on.

Based on the previous observation, in order to reduce the final bunch length, we increase the bunch energy to decrease the relative energy spread after the RF cavity acceleration. At the same time, in order to increase the kick angle and shorten the slice width in electron beam slicing method [1], we also increase the bunch charge. Using IMPACT-T with CSR effects turning on, we iterate to carry out the global optimization and gradually increase the bunchŠs charge and energy. Some optimized results are shown in Table 3. For example in Table 3, the 22 MeV, 200 pC charged bunch is longitudinally compressed from 6.8 ps head to tail bunch length at photocathode to 128 fs RMS bunch length by the 8.5 m compressor. The transverse beam size are focused from the diameter ellipse of 2 mm at photocathode to 42 μm and 25 μm for horizontal and vertical RMS beam size respectively. Figure 4 shows the histograms of 6-D phase space at the final focus point of the 22 MeV compressor with the color bar indicating the particle density.

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Table 3: Performances of the 8.75 m LBNL's VHF Gun Compressor

bunch performance	initial bunch	focused[a] bunch
longitudinal bunch length [fs]	6783[b]	128[c]
horizontal beam size [μm]	1994[b]	42[c]
vertical beam size [μm]	1971[b]	25[c]
energy spread [%]	0.0014[d]/0.98[e]	1.38
average kinetic energy [MeV]	0.73[d]/22[e]	22
horizontal emittance [μm]	59[d]/0.143[e]	0.71
vertical emittance [μm]	58.5[d]/0.142[e]	0.19
charge [pC]	200	200
current [A]	30	1563

[a] be calculated for 90% particles, with 10% longitudinal tails cut-off.
[b] at cathode
[c] RMS value
[d] at gun exit
[e] after RF acceleration

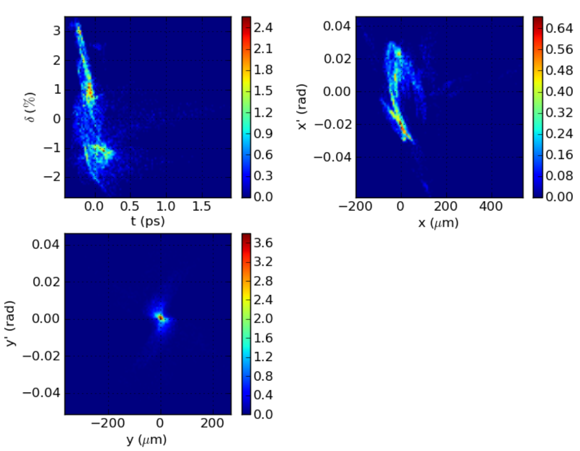

Figure 4: The histograms of 6-D phase space at the final focus point of the 22 MeV compressor with VHF gun. The color bar shows the particle density. Simulation code is IMPACT-T with both space charge effects and CSR effects being turned on.

CONCLUSION

The benchmark between PARMELA and IMPACT-T has produced excellent agreement. The comparison of the CSR effects also shows the bunch can be compressed and focused to our desired size after optimization using code IMPACT-T with CSR effects turned on. Our simulation shows that electron bunch with high charge can be compressed to very high current bunch at very low energy with both space charge effects and CSR effects included. This low energy compressor with repetition rate about 1 MHz significantly increases the repetition rate of the electron beam slicing system, and hence increases the photon flux of the ultrashort x-ray source.

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