SIMULATION STUDIES OF GENERATING ULTRA SHORT PULSES AT PITZ*

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Abstract

Generation of ultra-short electron bunches ($\leq 10fs$ bunch length) which have a small transverse phase space volume and relatively small energy spread is of great interest. Such bunches are required for fully coherent (transversally and longitudinally) FEL radiation (single spike lasing) and for plasma acceleration experiments. The Photo Injector Test Facility at DESY in Zeuthen has already demonstrated the possibility to generate and characterize high quality electron beams for a wide range of bunch charges. Currently electron bunches have a typical length of several ps. To study the possibility of producing short electron bunches at PITZ many beam dynamics simulations have been performed for 1pC bunch charge using the ASTRA code. The current PITZ beam line is supposed to be extended by a small magnet chicane. Several temporal profiles of the cathode laser pulse have been used for the simulations to produce ultra-short electron bunches with small transverse sizes. The results of the beam dynamics simulations are presented and discussed.

INTRODUCTION

The Photo Injector Test facility in Zeuthen (PITZ) is known as one of the best generators of very low transverse emittances at different bunch charges [1]. PITZ has a normal conducting 1.6 cell RF gun surrounded by main and bucking solenoids which are used to compensate the emittance growth due to space charge forces and remaining fields at the cathode. A diode pumped Yb:YAG photocathode laser system at PITZ which was developed at Max-Born Institute [2] produces up to 800 micro pulses per train with 10 Hz repetition rate. More details on the PITZ setup can be found in [3]. Under normal operation conditions gun cavity is running at ~60 MV/m max acceleration field at the cathode which provides about 6.8 MeV/c electron beam momentum after the gun running at max momentum gain phase. The second accelerating section, so-called CDS booster, provides further acceleration of the beam up to momentum value of ~25 MeV/c. Some particular measurements done during the standard thermal emittance measurements at PITZ [4, 5] have shown the possibility of transverse emittance measurements for very low bunch charges down to 1 pC. In such a case, it is of great interest to study the electron bunch compression in order to explore the possibility to produce such bunches at PITZ. The idea of creating ultra-short electron bunches which have very low charge inside was suggested a few years ago [6, 7]. The authors performed start-to-end simulations for SPARCX FEL and LCLS at 1 pC bunch charge [8]. The purpose of 1 pC charge beam was the expected ultra-short electron bunch length after the compression which will produce FEL radiation in single spike mode if the electron bunch length is on order of cooperation length. An electron beam was strongly compressed by velocity bunching after the gun at energy of 100 MeV and the magnetic compression was done at the beam energy of 1 GeV [9]. A recent numerical optimization performed at Diamond Light Source (UK) has also shown the possibility of creation of ultra-short electron bunches (below 10 fs) for 1.6 pC bunch charge at electron beam energies of a few MeV [10].

ASTRA [11] simulations have been performed to study the possibility of generating ultra-short electron bunches at PITZ for 1 pC bunch charge and for two different longitudinal laser distributions: Gaussian and a flat-top. In the simulation setup a small magnetic chicane has been added to the existing PITZ beamline to compress the electron beam longitudinally. 3 stages of the bunch compression have been applied for the PITZ compression scheme: velocity bunching [12] after the gun (~ 5.5 MeV) further compression by the CDS booster [13] (~ 16 MeV) and final compression by a magnetic chicane. For the cases of Gaussian and flat-top temporal laser profiles different pulse durations and spot sizes of the laser beam at the cathode have been considered for the simulations. For each case the magnetic strength of the main solenoid was set to the value corresponding to minimum transverse emittance of the beam before the chicane. The electron bunch length has been scanned as a function of magnetic strengths in the dipoles to have minimum bunch length after the chicane. The simulation results of the bunch compression studies are presented in this contribution.

SIMULATION SETUP: THE PROCESS OF OPTIMIZATION

A Space Charge Tracking algorithm (ASTRA) was used for bunch compression studies at PITZ. In order to get more reliable calculation results at 1pC ($6.25 \cdot 10^6$ electrons) bunch charge, $5 \cdot 10^5$ macro particles have been used in the simulation code. Thermal kinetic energy of the electrons at the cathode was 0.55 eV by default. Laser rms temporal length for the case of Gaussian temporal profile was varied from 0.6 ps to 1.4 ps with step of 0.2 ps. For each longitudinal bunch length the transverse rms laser spot size at the cathode was changed from 0.05 mm to 0.35 mm. In

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the case of a flat-top laser profile, rise and fall times of the laser temporal distribution were kept constant to 2 ps, and FWHM length varied from 5 ps to 13 ps by step of 2 ps. For each case the transverse rms laser spot size at the cathode was varied from 0.05 mm to 0.3 mm. The RF gun gradient was tuned to have $\sim$ 6.7 MeV/c momentum value downstream the gun for the on-crest gun phase. Max gradient at the second accelerating section (CDS booster) was kept constant to 20 MV/m corresponding to about 25 MeV/c maximum momentum value after the booster.

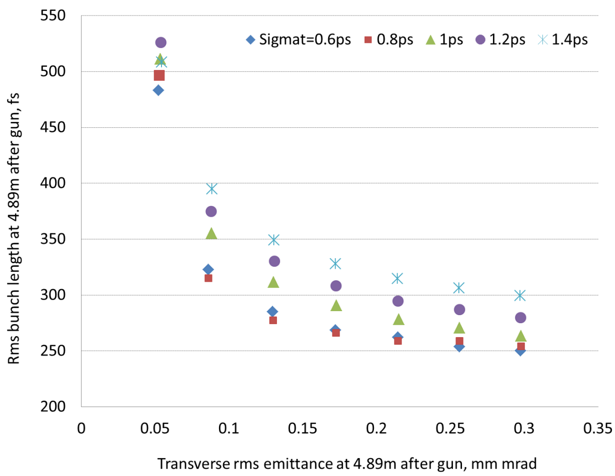

Figure 1: Rms bunch length as a function of transverse rms emittance for different beam aspect ratios (Gaussian laser temporal profile).

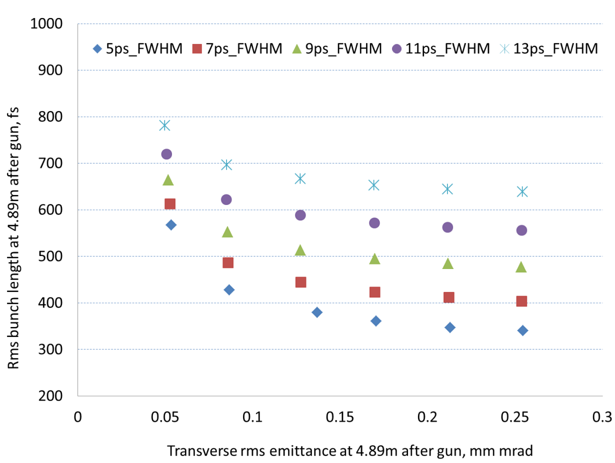

Figure 2: Rms bunch length as a function of transverse rms emittance for different beam aspect ratios (flat-top laser temporal profile).

The RF phases of the gun and the booster have been kept constant at -39 deg. w.r.t. the maximum mean momentum gain (MMMG) phase and -55 deg. off-crest correspondingly. In Figures 1, 2 the dependence of rms bunch length on transverse rms emittance after the second accelerating section and before the bunch compression (at 4.89 m after the cathode) is shown for different longitudinal and transverse sizes of Gaussian and flat-top longitudinal distributions of the laser beam. This dependence illustrates the compromise between bunch compression and transverse emittance dilution due to the space charge effect. Transverse laser spot size in the graphs changes from 0.05 mm (from the left to the right) to 0.35 mm for the case of the Gaussian profile and from 0.05 mm to 0.3 mm for the case of Flat-top laser profile.

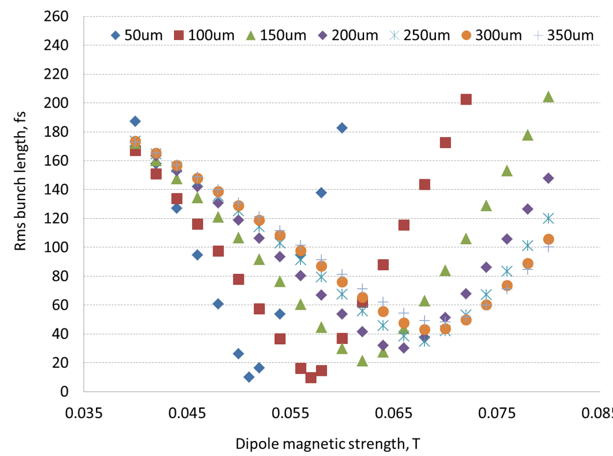

Figure 3: Rms bunch length after the chicane for different magnetic strengths inside the dipoles (Gaussian temporal laser profile).

A simple C type magnetic chicane with 4 identical dipoles was added in the simulation setup (the same length of the dipoles with the same absolute value for the strengths inside the dipoles). Position as well as the geometry of the chicane were fixed. The magnetic field distribution inside the magnets was assumed to be homogeneous (no fringe fields). The geometry of the chicane was chosen using the geometrical calculation results in [14]. The lengths of the dipoles were chosen to be 0.2 m, the distance between the second and the third dipoles was set to be 0.3 m.

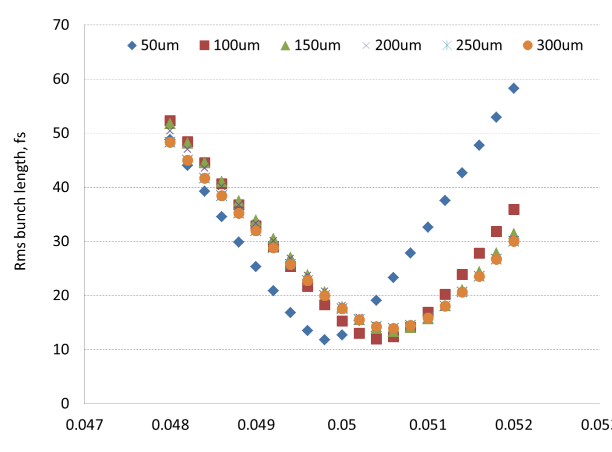

Figure 4: Rms bunch length after the chicane for different magnetic strengths inside the dipoles (flat-top temporal laser profile).

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Beam dynamics optimization has been done in two consequent phases. The first step was the tracking of the beam starting from the cathode up to 4.89 m downstream the gun using 2D space charge routine. The second step was the tracking of the electron beam through the magnetic chicane (4.9 m is the chicane starting point) including 3D space charge algorithm [15]. In Figures 3, 4 the final rms bunch length after the chicane is shown for different values of magnetic strengths in the dipoles for the Gaussian and flat-top temporal laser profiles respectively.

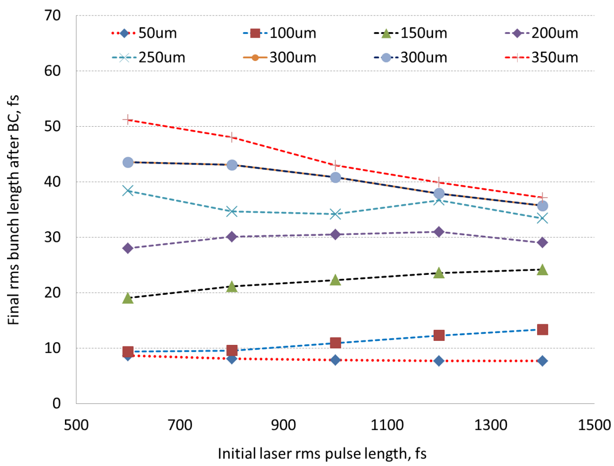

Figure 5: Rms bunch length after the compression as a function of initial rms laser pulse length (Gaussian temporal profile).

In Figures 3, 4 Gaussian laser profile was assumed to have an rms length of 1 ps, and for the flat-top case FWHM length of the laser assumed to be 9 ps, with 2 ps rise and fall time. The Figures 5, 6 illustrate the bunch compression for Gaussian and Flat-top longitudinal distributions and for different transverse rms laser spot sizes at the cathode.

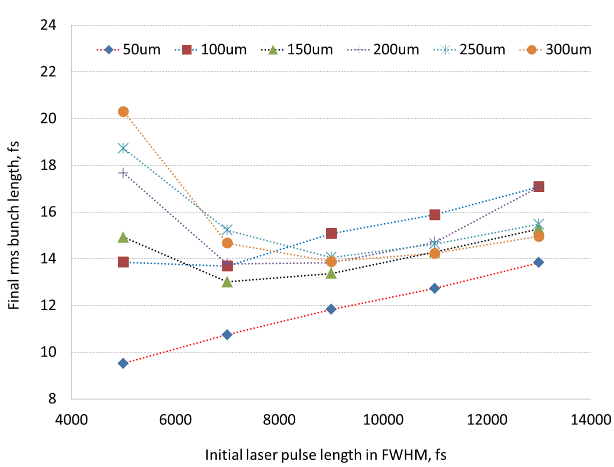

Figure 6: Rms bunch length after the compression as a function of initial laser pulse length (flat-top temporal profile).

Preliminary simulations have been performed without space charge effects (by switching off space charge routine in ASTRA) for the same simulation conditions and for the case when the laser has a Gaussian temporal distribution with 1 ps rms length and 0.05 mm transverse rms spot size at the cathode. Transverse and longitudinal properties of the beam before and after the compression are summarized in Table 1. The dependence of the final rms bunch length on the transverse laser rms spot size at the cathode for different lengths of the Gaussian and the flat-top temporal profiles is shown in Figures 7, 8. As it was expected a flat-top temporal laser profile provides with smoother compression results thought the final rms bunch length is longer in comparison to the Gaussian profile case.

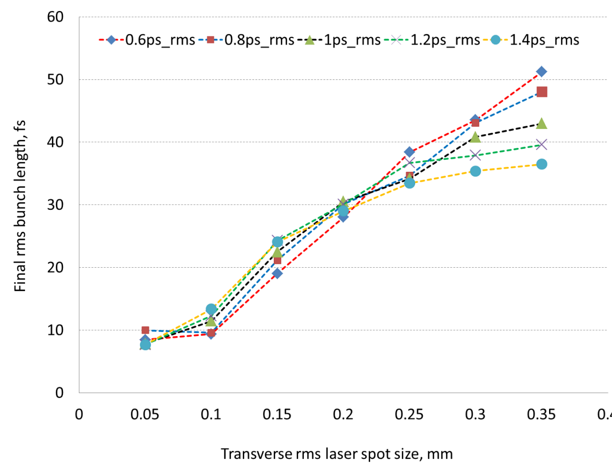

Figure 7: Rms bunch length after the compression as a function of initial transverse rms laser spot size at the cathode (Gaussian temporal laser distribution).

The case of 5 ps FWHM laser length the flat-top profile could already be treated as a quasi-Gaussian distribution with the similar trend of rms bunch length vs rms laser spot size behavior as shown in Figure 7.

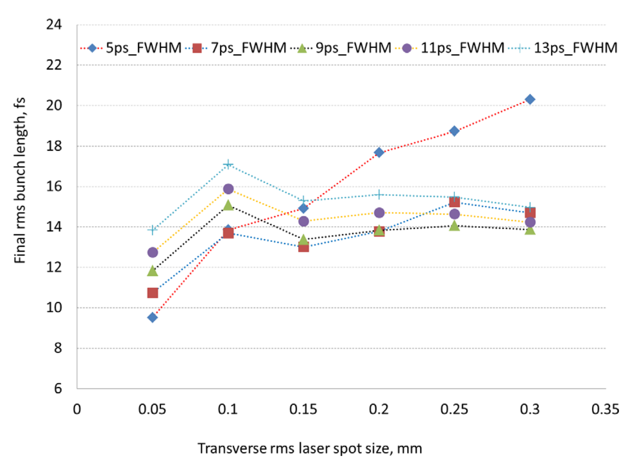

Figure 8: Rms bunch length after the compression as a function of initial transverse rms laser spot size at the cathode (flat-top temporal laser distribution).

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Table 1: The Comparison of Linear and Space Charge Included Beam Transport Before and After the Compression

Parameter	**Unit**	**Linear transport**		**Space charge included**	
		Before BC	After BC	Before BC	After BC
Hor. rms beam size, σ_x	mm	0.129	0.142	0.04	0.166
Ver. rms beam size, σ_y	mm	0.129	0.045	0.04	0.113
Long. rms beam size, σ_z	mm	0.047	0.0003	0.153	0.0023
Peak current, I	A	2.5	2000	0.6	63
RMS energy spread, dE	keV	25.09	25.09	74.05	74.05
Hor. beam emittance, ε_x	mm mrad	0.042	0.042	0.053	0.171
Ver. beam emittance, ε_y	mm mrad	0.042	0.042	0.053	0.102
Long. beam emittance, ε_z	mm mrad	0.0033	0.0073	0.126	0.142

It is important to mention that for the case of the flat-top laser longitudinal distribution the rms bunch length achieved after the compression is always smaller or equal to 15 fs for any beam aspect ratio considered in the paper. This approach can be very useful for the plasma acceleration experiments which use the electron bunches as an external injection source.

SUMMARY

ASTRA simulations have been done for the PITZ setup at 1 pC bunch charge and for two different temporal laser profiles (Gaussian and flat-top). According to the simulation results the rms bunch lengths on the order of 10 fs can be achieved after the bunch compression. No major changes are expected to be made (a small magnetic chicane to be added) with the existing PITZ beamline for the compression studies. As the beam energy is relatively low the influence of the space charge effects on the beam dynamics is still eventual. Simulations do not include any CSR effects which can be very essential for such strong compressions. A minimum value of $\sim$7.5 fs for the rms bunch length was achieved from the simulations (Gaussian profile with 1 ps rms length). Further improvements on compression and beam transport scheme could be expected by applying 3D ellipsoidal cathode laser pulses. This corresponds to more linear space charge forces and therefore to better transverse and longitudinal phase space properties of an electron beam.

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