BUNCH COMPRESSION IN THE SDL LINAC*

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Abstract

Electron bunch compression is critical to achieving the high peak currents required for efficient short wavelength FEL operation, but its success may depend sensitively on a number of parameters. From energy spectra of uncompressed bunches, we can characterize the longitudinal phase space (including bunch length, energy spread and energy chirp) of these bunches as a function of the injector parameters. These data serve as initial conditions in our simulations, which are then compared to our measurements of compressed bunches made using the chicane bunch compressor in the SDL at the NSLS (BNL).

1 INTRODUCTION

The Deep-Ultra Violet Free Electron Laser (DUV-FEL) is under development in the Source Development Laboratory (BNL). The goal of the project is to generate UV radiation at 100 nm wavelength and below. The adopted FEL scheme is based on High Gain Harmonic Generation (HGHG) scenario [1]. The accelerator [2] consists of a BNL/SLAC/UCLA type electron gun driven by a Ti:Sa laser, four SLAC-type linac tanks and a four magnet chicane. A 4.5 MeV electron beam leaves the gun, is accelerated up to 70 MeV in two linac sections, compressed in the magnetic chicane, and accelerated up to 140 MeV (200 MeV maximum) in the last two linac sections.

The RF gun currently can produce 2 ps (RMS) bunches with 300 pC of charge and 2-4 π mm-mrad normalized emittances [3]. The peak current required for successful FEL operation is on the order of 350 A. Therefore the compression of the electron beam is critical.

Currently the RF gun is capable to generate up to 600 pC of charge at 30 degrees RF phase. In our case it is determined by the available laser power, because the gun commissioning showed that even at 600 pC we are still on the linear part of the charge dependence versus laser power curve. Transverse emittance and bunch length, as well as peak current, are very sensitive to the amount of charge in the bunch. For the optimization of the FEL performance we need to be able to vary the amount of charge and, in turn, the compression ratio. So for every value of laser power we must adjust the compressor set-up. We need to quickly determine the initial longitudinal bunch parameters as input to calculations for compression optimisation.

In this paper we discuss a new approach to determine the initial bunch parameters at the entrance of linac tank 2, where the beam receives the energy chirp. It is necessary to measure these initial properties to be able to calculate the proper settings for longitudinal transport line optics: phases in the accelerator cavities and chicane magnetic strength. A similar problem exists for transverse beam optics where one needs to obtain initial Twiss parameters. In the transverse case several experimental techniques are available, e.g. “quadrupole scan” [5]. For the longitudinal dynamics, in order to obtain initial values of bunch length, energy spread and energy chirp before compression, we developed a fast method to measure the energy and energy spread versus RF phase.

2 THE COMPRESSION SCENARIO AND METHOD

The layout of the accelerator is shown on Fig. 1. The second linac tank is used to provide the energy chirp in the electron beam. A four-magnet chicane installed after the second linac tank converts this energy modulation into a spatial modulation. Tank 3 is used to remove the residual energy spread. Tank 4 serves for: a) acceleration of the electrons up to the nominal energy of 140 MeV; b) bunch length measurements using the “zero-phasing” technique [4]. The electron energy spectrometer consists of a quadrupole triplet, calibrated dipole and YAG screen monitor.

Assume electron bunch accelerated only the first two tanks (chicane and all other tanks are OFF). In the absence of the wakes, the final energy for the electron located at a distance z relative to the bunch centre is:

$$E_f(z) = E_i + E_2 \cdot \cos\left(\varphi_2 + \frac{2\cdot\pi\cdot z}{\lambda_{RF}}\right),$$

where E_i is the initial energy (at the exit of the first tank), E_f is final energy (after the second tank), E_2 and φ_2 are the energy gain and phase of the second tank. Defining initial and final energy deviation of an electron as:

$$\delta_i = \frac{E_i - E_{i0}}{E_{f0}}, \qquad \delta_f = \frac{E_f - E_{f0}}{E_{f0}},$$

where “0” index corresponds to the bunch center, we may write for the energy deviation along the bunch:

$$\delta_f(z) = \delta_i + \frac{E_2}{E_{i0} + E_2\cdot\cos(\varphi_2)} \cdot \left(\cos\left(\varphi_2 + \frac{2\cdot\pi\cdot z}{\lambda_{RF}}\right) - \cos(\varphi_2)\right)$$

Expanding the right side we get:

$$\delta_f(z) = \delta_i + \frac{E_2}{E_{i0} + E_2\cdot\cos(\varphi_2)} \cdot \sum_n \left(\frac{2\cdot\pi\cdot z}{\lambda_{RF}}\right)^n \cdot \left[\frac{\partial^n}{\partial\varphi^n}(\cos(\varphi))\right]_{\varphi_2} \quad (1)$$

For initial Gaussian distribution in time-energy coordinates one can get the following expression for the energy spread after the second tank:

$$\sigma_{\delta f}(\varphi_2) = \sqrt{\sigma_{\delta i}^{\ 2} + (k(\varphi_2)\cdot\sigma_{zi})^2}, \quad (2)$$

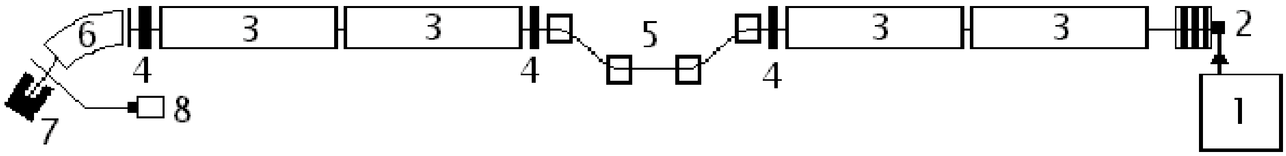

Fig 1. The layout of SDL accelerator. 1 – Laser system, 2 – RF gun, 3 – 2.856 GHz, SLAC type linac structures, 4 – triplets, 5 – magnetic chicane, 6 – spectrometer, 7 – beam dump, 8 – YAG monitor.

where $k(\varphi_2) = -\frac{2\cdot\pi}{\lambda_{RF}}\cdot\frac{E_2\cdot\sin(\varphi_2)}{E_{i0}+E_2\cdot\cos(\varphi_2)}$,

$E_{i0} = E_{GUN} + E_{T1}\cdot\cos(\varphi_1)$

where E_{GUN} and E_{T1} are RF gun output energy and tank 1 maximum energy gain correspondingly.

Expression (2) corresponds to the linear term in the expression (1) and depends on the initial bunch length and energy spread at the entrance of the tank 2. To determine the initial energy spread and bunch length we measure dependence of the final energy spread versus tank 2 phase (chicane, tanks 3 and 4 are off) and fit expression (2) to the measured data (Fig. 2). The initial energy chirp "r" depends on the phase difference Δφ between the maximum of the energy curve and minimum of the energy spread curve (denoted C on Fig. 2):

$$r = \frac{dE_{chirp}}{dt} = E_2\cdot\omega_{RF}\cdot\sin(\Delta\varphi)$$

The minimum of the fit determines the initial uncorrelated energy spread $\sigma_{\delta i}$=A, the slope of the fit (B) is proportional to the bunch length. Near the phase corresponding to a minimum of right hand side of Eq. (2) we drop the initial energy spread in Eq. (2) and linearize $k(\varphi_2)$:

$$B = \frac{\omega_{RF}}{c}\cdot\frac{E_2}{E_f}\cdot\sigma_{zi}$$

Once we have initial conditions defined we can calculate correct settings for a given compression ratio.

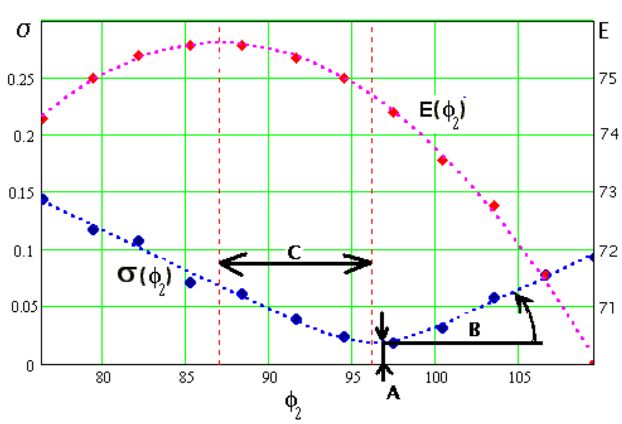

Fig 2. The energy (MeV) and energy spread (%) dependencies versus phase (degrees) of tank 2. The initial energy spread, bunch length and energy spread are the functions of A, B and C respectively.

3 RESULTS

Before the compression we have calibrated the energy gain in every linac tank. For the current RF set-up (RF gun and first two tanks are powered by one klystron) we cannot simply switch ON and OFF every

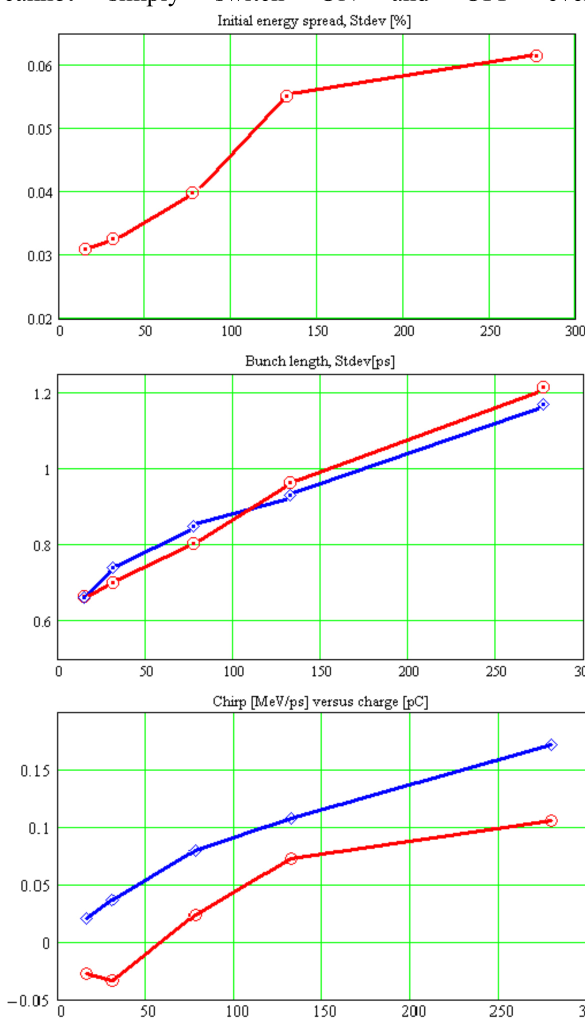

Fig 3. Energy spread (%), bunch length (ps) and energy chirp (MeV/ps) dependencies versus bunch charge (pC).

tank and measure the differences in final electron beam energy. Therefore, we measured final energies of an electron beam, changing the phase of the tank. Fitting dependence $E_{FINAL}(\varphi_i) = E_0 + E_i\cdot\cos(\varphi_i)$ to the data, we have determined the following maximum energy gains as follows: G_{tank1}= 32.8 MeV, G_{tank2}= 37.5 MeV, G_{tank3}= 62 MeV and G_{tank4}= 63 MeV.

We performed measurements of the energy and energy spread for different amounts of laser power.

Fig. 2 shows the dependencies and fits with the use of discussed method for 250 pC of charge. The calculated values are: bunch length is equal to 1.1 ps, energy spread is 0.035 %, and chirp is 0.053 MeV/ps at 39.1 MeV. The dependencies of energy spread, bunch length and energy chirp versus charge are shown on Fig 3. These measurements were performed at a laser pulse length equal to 1.2 ps (RMS). The low charge region of the plot demonstrates ballistic compression of the electron bunch in the gun. As charge increases the bunch length increases due to space charge effect (red data points on Fig. 3). We have also measured bunch length using the "zero-phasing" method (blue data points on Fig. 3) and found good agreement. We also see, the energy chirp is changing according to the charge (Fig. 3). Well-known S-band wake effect [6] has been used to compute the wake-induced chirp for all four linac sections. The result of the calculation (blue ponts on the bottom picture of Fig. 3) shows that the observed initial chirp is mainly due to the wake effect in the linac structures. The constant offset of the data with respect to the calculated values is, probably, due to beam dynamics in the gun and tank 1.

Using measured data we have simulated the compression process and compared it with the measurement. For simulation we used simple a 1D model of the longitudinal motion for the tracking of individual particles. We have found good agreement with the measured beam parameters. For the particular case of 250 pC, the measured RMS bunch length after compression is equal to 0.52 ps, the energy spread is 0.13 % (compression ratio is 3.5). This agrees well with the calculated values of 0.45 ps and 0.114 % for bunch length and energy spread respectively. At the higher compression ratios the strong modulation, arising in the compression process [7,8], affects the longitudinal beam phase space distribution, so the discussed technique cannot be used.

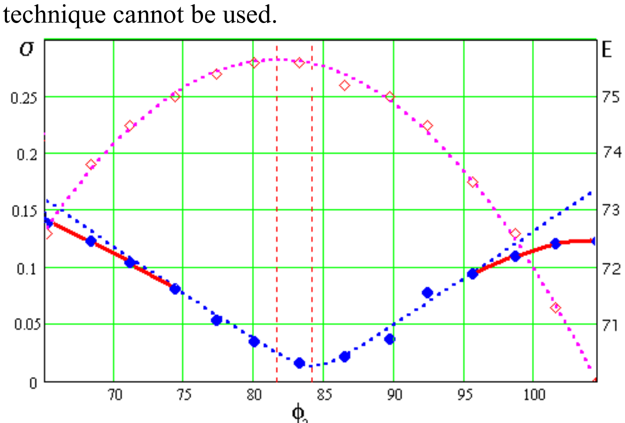

Fig 4. Measured energy (pink) and energy spread (blue) versus tank 2 phase data. The blue dotted curve which is a fit of data to eq. (2) deviates from measurements at phases far from the energy spread minimum.

4 CONCLUDING REMARKS

In the process of measurements we assumed that the initial distribution was close to a Gaussian in both time and energy coordinates. We also compared the experimental data with different types of particle distribution in the bunch. We used "top hat", parabolic and linear distributions and found that the calculated bunch parameters do not differ significantly for different types of distributions.

The wake effect, which is not included in expression (1) can be important for high peak current. For our case (σ_t>0.5 ps, I_{peak}<500 A) the calculation shows that, although, the presence of a wake will introduce an error in our estimation of the initial chirp of the bunch, this error is not very significant for compression, because it can be easily adjusted in the compression process. For a higher peak current one must include wake into expression (1).

A puzzle is the dependence of the measured energy spread on phase far from the minimum (see Fig. 4). One finds that expression (2) gives a good fit to measured data in the region of about +/- 15 degrees around the minimum. However, at larger phases there is a systematic deviation of the fit with respect to the data. In order to attempt to explain this we considered several possible reasons:

1) Nonlinearity of the spectrometer could introduce a spurious dependence. However, the estimates of the high order transport terms show they are negligible.

2) One might think that wakes in the linac could lead to this effect, but, because of the relatively long wake characteristic wavelength, it can only change the chirp of the bunch.

3) Correlations in the bunch structure may affect the particle distribution and lead to this type of effect. Further estimates are needed.

Investigation of this puzzle continues.

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