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SUPPRESSION OF CORRELATED ENERGY SPREAD USING EMITTANCE EXCHANGE

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Abstract

An emittance exchange (EEX) provides a precise longitudinal phase space manipulation of electron bunch. It has been studied for an easy and precise control of temporal distribution, but controls of energy distribution have not been explored. Since the energy control using EEX is under the identical principle to the temporal control, the EEX beamline can control a correlated energy spread of the electron bunch. This would benefit accelerator facilities requiring a low energy spread such as X-ray Free Electron Laser Oscillator (XFELO). In this paper, we present principle and preliminary simulation work on the suppression of correlated energy spread using the EEX beamline.

INTRODUCTION

The next generation X-ray source, X-ray Free Electron Laser Oscillator (XFELO) [1-5], can generates fully coherent X-ray pulses with ultra-narrow bandwidth. One of the challenging problems of XFELO is the energy spread requirement due to the spectral acceptance of crystal mirrors [4,5]. XFELO requires ~1E-5 rms energy spread which is significantly lower than the state-of-art XFELs. There was optimization work on the conventional linac to satisfy this tight requirement [5]. Although this simulation work showed a low correlated energy spread (~1.5E-5), this energy spread calculation only counted the core of the bunch (0.5 ps). We suggest a new approach to achieve a similar correlated energy spread from the whole bunch using double emittance exchange (DEEX) beamline.

DEEX beamline consists of two single EEX beamlines pointing opposite direction and a transverse telescope section [6] in between. The first EEX beamline exchanges the longitudinal to the transverse phase space so that any transverse manipulation can be applied to the longitudinal phase space. Following telescope section control the beam size and divergence, and this transverse beam size and divergence becomes the bunch length and energy spread by the other phase space exchange from the second EEX beamline.

This EEX based longitudinal telescoping provides two major advantages compared to conventional linac method. This method does not require an energy chirp to compress the bunch. It results in no strong requirement on linac phase, so on-crest operation would fully use RF power to accelerate the bunch. Secondly, no extra chirp control is required after the compression. Since the telescoping is imaging the longitudinal phase space with only scaling, the chirp of the bunch at the exit will be zero if the incident chirp is zero.

In this paper, we introduce two schemes of correlated energy spread suppression using a DEEX beamline Simulation to demonstrate the concept is done using ELEGANT [7], and it includes 1D CSR and wakefield from RF linac. Thin-cavity approximation is applied to transverse deflecting cavities (TDC) for simplicity. This assumption can be easily obtained by fundamental mode cavity (FMC) followed by TDC [6].

PRINCIPLE OF ENERGY SUPPRESSION

In this section, we introduce two schemes of correlated energy spread suppression using a DEEX beamline. We start with description on chicane-based conventional method. Then, we will explain two schemes using DEEX.

Chicane-based method (Fig. 1) requires a longitudinal chirp to compress the bunch. This chirp is usually generated by off-crest linac operation, and it requires harmonic cavities to linearize the longitudinal phase space. After the chicane compresses the bunch, the remained longitudinal chirp has to be separately controlled since the chicane does not control the chirp. Off-crest operation of following accelerating cavities usually de-chirp the bunch, and metallic structure based de-chirper can be used to eliminate the chirp instead of off-crest operation [8-9]. W. Qin *et al* [5] did optimization work on this conventional method to achieve the bunch satisfying XEFLO requirements. They achieved 0.5 ps of flat energy region on the final longitudinal phase space. The rms energy spread in this region was 70 keV.

As mentioned in previous section, the optimization result from the conventional method provided a flat region of only 0.5 ps. This means the rest of the beam cannot contribute on the lasing. At the same time, it requires inefficient use of linac to generate and eliminate the chirp. Also, use of harmonic cavities requires more construction and operation costs. We suggest another method to avoid the listed demerit of the conventional method using DEEX. The first scheme uses harmonic cavities to control the nonlinearity on the longitudinal phase space. On the other hand, the second scheme replaced all harmonic cavities to a single sextupole magnet.

The bunch compression via DEEX beamline does not require an initial longitudinal chirp. Instead, it requires a quadrupole to focus the beam. This transverse focusing becomes a longitudinal compression via phase space exchange. Therefore, accelerating cavities before the DEEX beamline operates on-crest to maximize the energy gain from the linac. This on-crest operation imparts quadratic

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curvature on the longitudinal phase space. As shown in Fig. 2, following harmonic cavities correct this non-linearity so that it can be very close to linear. Then, the first EEX beamline converts this longitudinal phase space to the transverse phase space. The telescope section focuses the beam for the compression purpose, it reverses the curvature orientation. This compressed and reversed curvature goes back to the longitudinal phase space via the second EEX beamline. Here the remained curvature will cancel out the RF curvature coming from the rest of the linac. This scheme can provide a low correlated energy spread for the full beam, and it does not require any off-crest operation of linac or de-chirper.

The second scheme shares the same principle as the first scheme. The major difference is how to control the non-linearity. While the first method controlled the curvature using harmonic cavities, the second scheme control this curvature using the second order components of a sextupole magnet (Fig. 3). This method even replaced harmonic cavities to a single sextupole magnet. This can be much more cost-effective way to control the beam.

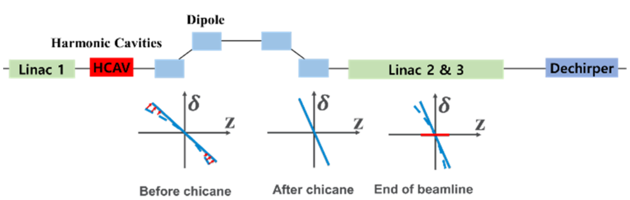

Figure 1: Schematic to explain the principle of chicane-based energy suppression with a de-chirper.

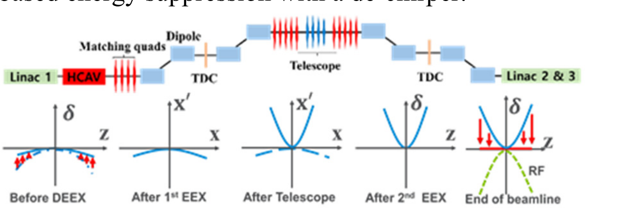

Figure 2: Schematic to explain the principle of DEEX-based energy suppression with harmonic cavities.

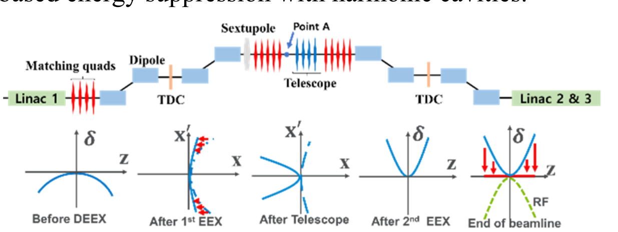

Figure 3: Schematic to explain the principle of DEEX-based energy suppression with a sextupole magnet.

Preliminarily simulation results

We demonstrated the DEEX-based method using elegant simulation. This simulation used particle distribution from LCLS II injector and its lattice file for the elegant simulation [10]. We took out both bunch compressor 1 and 2 in the original LCLS-II lattice file and located a DEEX beamline at the first bunch compressor position. The total charge is 100 pC, the emittance is 0.35 µm and the bunch is 3.3 ps long. The beam energy out of the injector is 100 MeV, and it is accelerated to 4 GeV

The linac in front of the DEEX beamline is simulated with on-crest operation. It generated expected quadratic RF curvature as Fig. 4 (a). The following harmonic cavities reduced the curvature and changed the longitudinal phase space to Fig. 4 (b). This longitudinal phase space is successfully compressed to 0.5 ps long bunch, and the orientation of the curvature is flipped to the opposite (see. Fig. 5(a)). After the acceleration to 4 GeV, the longitudinal phase space has rms energy spread of 2.2E-5 without CSR effect (Fig. 5 (b)). The emittance grew up to 0.62 µm due to the non-linear effects in the DEEX beamline. We believe this result can be further improved. We note that the compensation we expect from the rest of the beamline was not strong enough to fully cancel the remained curvature from harmonic cavities. Due to the compression, the curvature from the rest of linac was much weaker than the one from the front linac. The compensation scheme would work with higher energy.

We also made preliminary simulation result with CSR along the DEEX beamline changed the energy spread from 2.2E-5 to 2.5E-5, and corresponding longitudinal phase space images are given in Fig.5 (c) and (d).While the energy spread did not show any significant changes, emittance grew up from 0.62 µm to 4.93 µm. The transverse optics in this simulation was optimized to non-CSR simulation. Therefore, the result will be improved significantly once the beam and optics parameters match with the CSR condition on this beamline.

We also simulated a shorter bunch. Fig. 6 (a) show 0.3 ps of bunch length after the DEEX beamline. The final energy spread is 2.6E-5. Although this energy spread is little higher than the result by W. Qin et al [5], we count all beam for the energy spread calculation and the we could achieve a much longer flat region than their result using DEEX method.

Similar to previous results using harmonic cavities, we suppressed the correlated energy spread using a single sextupole magnet. In this simulation, harmonic cavities are replaced to a single sextupole magnet in the telescope section. Fig. 7 (a) shows the transvsere phase space after the first EEX beamline. This is imaged from the initial longitudinal pahse space. The sextupole magnet in between two EEX beamline suppressed this second order nonlinearity as shown in Fig. 7 (b). It generated a similar result as Fig. 5. Fig. 7 (c) and (d) show the initial and the final longitudinal phase spaces. The bunch length is compressed from 3.3 ps to 0.5 ps, and the final energy spread is 2.6E-5.

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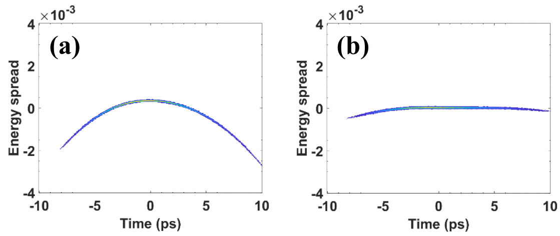

Figure 4: (a) longitudinal phase space after the injector linac. (b) longitudinal phase space after the harmonic cavities.

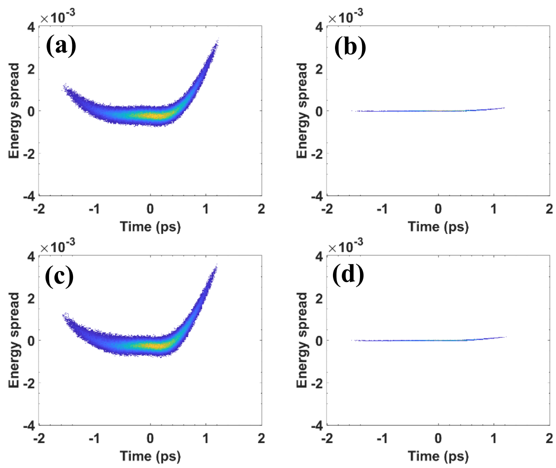

Figure 5: Longitudinal phase space after DEEX beamline (left) and after acceleration up to 4 GeV (right). CSR effect is not included in elegant simulation for top figures, and it is included for bottom figures.

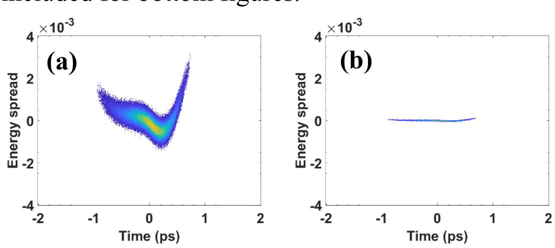

Figure 6: Longitudinal phase space after DEEX beamline (left) and acceleration up to 4 GeV (right). CSR effect is not included in this simulation. The bunch is compressed to 0.3 ps.

Conclusion

We introduced a new method to suppress a correlated energy spread to 1E-5 level using DEEX. DEEX beamline and telescope provide a bunch compression without any longitudinal chirp requirement. Non-linearity on the longitudinal phase space was suppressed using harmonics cavities and compensation scheme. Elegant simulation showed the final correlated energy spread of ~2E-5 at 4 GeV. Similarly, we achieved ~2E-5 by replacing harmonics cavities to a single sextupole magnet. This method can be alternative to the conventional method. Compared to the conventional method, DEEX can use accelerating cavities for the full acceleration only and eliminate extra element

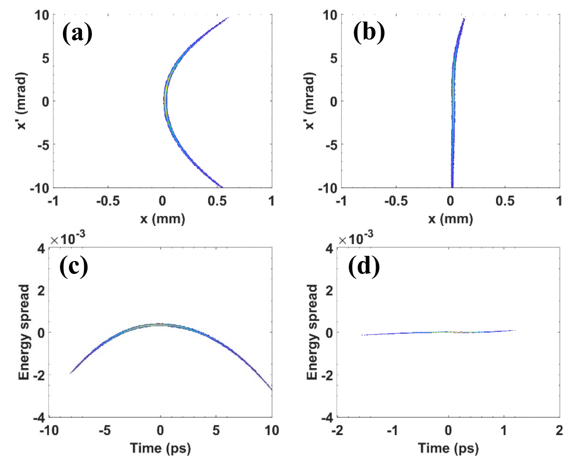

Figure 7: Horizontal phase spaces after the first EEX beamline (a) and the sextupole (b). (c) and (d) correspond to longitudinal phase space at the entrance to the DEEX beamline and after the acceleration to 4 GeV.

such as de-chirper. Also, we can take out harmonic cavities by substituting them to a single sextupole magnet. This will significantly reduce a construction and operation cost of the beamline.

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