DOUBLE-HORN SUPPRESSION IN EEX BASED BUNCH COMPRESSION

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Abstract

Nonlinearities on the longitudinal phase space induce a double-horn current profile when the bunch is compressed strongly. Since this double-horn can degrade the performance of FELs due to the CSR it makes, the suppression of the double-horn is one of important beam dynamics issues. Emittance exchange (EEX) can be interesting option for this issue due to its longitudinal controllability. Since EEX exchanges the longitudinal phase space and transverse phase space, higher order magnets such as octupole can control the nonlinearity. In this paper, we present simulation results on the suppression of the double-horn current profile using EEX based bunch compression. We use a double EEX beamline installed at the Argonne Wakefield Accelerator facility for the simulation.

INTRODUCTION

XFELs require a bunch length of ~10 fs to generate ultrafast X-ray pulses [1-4]. This strong compression sometimes introduces a bad feature called double-horn in the current profile [5, 6]. This double-horn possibly degrades the lasing quality when it generates an intense CSR acting with the core of the bunch [6]. Naturally, how to suppress the double-horn feature is one of important beam dynamics issues to improve the X-ray quality.

Emittance exchange (EEX) is an interesting option to provide a strong bunch compression with a correction on the double-horn profile. EEX exchanges horizontal and longitudinal phase spaces [7, 8], thereby any horizontal manipulation controls longitudinal properties [9, 10]. This means that a horizontal focusing compresses a bunch [1-13] and nonlinear correction on the transverse plane corrects longitudinal nonlinearities. Similarly, this exchange based compression has two advantages compared to chicane compressors. The first advantage is that the compression does not require a specific longitudinal chirp. It releases a constraint on the operating phase of accelerating cavities. On-crest operation would be more efficient to operate the machine. Secondly, the EEX compressor can control the longitudinal chirp at the downstream of the beamline using quadrupole magnets due to the exchange again [10].

Although the exchange of phase space enables a new way to compress the bunch, it also increases the transverse emittance due to an exchange with an initially large longitudinal emittance. We use a double-EEX (DEEX) beamline to avoid this issue. DEEX beamline consists of two EEX beamlines pointing opposite directions and transverse manipulation section in between. The first EEX beamline exchanges longitudinal and horizontal phase spaces and following manipulation section control the transverse phase space using quadrupole magnets. The second EEX beamline exchanges these phase space and the transverse manipulation from quadrupoles becomes longitudinal control.

In this paper, we present progress on simulation work to support upcoming experimental demonstration of the concept. We firstly describe a possible source of double-horn formation. Next, we introduce a simple method to suppress the double-horn formation from this source using a single octupole magnet. Finally, we demonstrate the concept using IMPACT-T [14] simulation.

SOURCE OF DOUBLE-HORN FORMATION

Particle's longitudinal position and momentum usually have a correlation due to both external field applied to the bunch and self-field such as space-charge field. One of the possible source of double-horn formation is included in this longitudinal correlation. To confirm this source, we need to understand how the correlation affect on the final profile.

Bunch's final profile can be written as below due to the charge conservation

$$g(z_i) = f(z_i)\,(dz_i/dz_f), \qquad (1)$$

where $f(z_i)$ and $g(z_i)$ are initial and final current profiles, respectively. Here the derivative term can be derived from the particle transport through the beamline. In the DEEX beamline, the particle's final longitudinal position can be written as

$$z_f = R_{55}z_i + R_{56}\delta_i\,, \qquad (2)$$

where R_{55} and R_{56} are elements of the linear transfer matrix of a DEEX beamline. Note, quadrupoles in between two EEX beamlines control these linear coefficients.

If δ and z do not have any correlation, dz_i/dz_f term will be a constant and there will be no double-horn. However, correlations can make denominator zero which generates a spike on the profile. If we expand the longitudinal correlation using polynomial, the fractional momentum (δ) and longitudinal position (z) can be written as

$$\delta_i = h_1 z_i + h_2 z_i^2 + h_3 z_i^3, \qquad (3)$$

where index of i corresponds to particle's initial location, and fourth order or higher are ignored in this discussion since the first three terms dominantly determine the correlation in most of case. By plugging in Eq. (2) and Eq. (3) to Eq. (1), denominator can be written as

$$\frac{dz_i}{dz_f} = \frac{1}{(R_{55} + R_{56}h_1 + 2R_{56}h_2 z_i + 3R_{56}h_3 z_i^2)}. \quad (4)$$

This equation will have two points where the denominator becomes zero. If these two points are sitting in the domain of the final current profile, they make two spikes. This is the double-horn we usually observe [5-6].

SUPPRESSION OF DOUBLE-HORN USING OCTUPOLE MAGNET

In the double EEX beamline, there is transverse beam manipulation section in between two EEX beamlines (see Fig. 1). Since the first EEX beamline send all longitudinal properties to the transverse phase space, the transverse manipulation in this middle section controls the all longitudinal properties at the end of the beamline. This process enables a new capability to control a nonlinearity on the longitudinal phase space. As described in the earlier section, any third-order correlation on the longitudinal phase space can induce a double-horn profile. Since this correlation sits on the transverse phase space after the first EEX, one can use well-known solution for transverse third-order correction, octupole magnet.

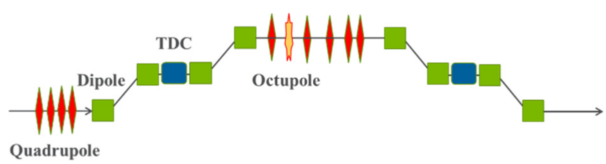

Figure 1: Configuration of a DEEX beamline.

To determine the octupole's strength for the cancellation, we need to understand how particle behave in the beamline and the octupole's impact on it. For simplicity, we ignore effects from the cavity thickness.

The particle's horizontal position and divergence before the octupole magnet can be expressed as

$$\begin{aligned} x_1 &= R_{15}^{(1)} z_i + R_{16}^{(1)} \delta_i, \\ x'_1 &= R_{25}^{(1)} z_i + R_{26}^{(1)} \delta_i, \end{aligned} \quad (5)$$

where z_i and δ_i are longitudinal position and energy spread before the EEX beamline, respectively. $R^{(1)}$ is the linear transfer matrix from the entrance to the EEX beamline to the octupole magnet. Similarly, particle's position and momentum after a thin octupole can be written as

$$x_2 = x_1, \qquad x'_2 = x'_1 - \frac{1}{6} K (x_1^3 - 3x_1 y_1^2), \quad (6)$$

where subscript 2 represents the particle coordinate after the octupole magnet, and K is the integral strength of the octupole magnet. Note, a quadrupole magnet is located in front of the octupole magnet (see Fig. 1). This quadrupole magnet minimizes the vertical beam size so that the octupole gives a pure third-order kick horizontally.

The final longitudinal position z_f can be written as Eq. (5), and plugging Eqs. (1), (5), and (6) into this final transport gives the final equation we need.

$$\begin{aligned} z_f &= R_{51}^{(2)} x_2 + R_{52}^{(2)} x'_2 \\ &= \left(R_{51}^{(2)}\left(R_{15}^{(1)} + R_{16}^{(1)} h_1\right) + R_{52}^{(2)}\left(R_{25}^{(1)} + R_{26}^{(1)} h_1\right)\right) z_i + \\ &\quad \left(R_{16}^{(1)} R_{51}^{(2)} h_2 + R_{26}^{(1)} R_{62}^{(2)} h_2\right) z_i^2 + \left(R_{52}^{(2)} R_{26}^{(1)} h_3 - \right. \\ &\quad \left. R_{52}^{(2)} K \left(R_{15}^{(1)} + R_{16}^{(1)} h_1\right)^3 / 6 + R_{16}^{(1)} R_{51}^{(2)} h_3\right) z_i^3, \end{aligned} \quad (7)$$

where $R^{(2)}$ is linear transport matrix after the octupole.

Appropriate choice of K can eliminate all z_i^3 terms in Eq. (7). This would provide a bunch compression without double-horn formation. The cancellation condition can be easily found from Eq. (7), and the required K is,

$$K = 6h_3\left(R_{16}^{(1)} R_{51}^{(2)} + R_{26}^{(1)} R_{52}^{(2)}\right) / R_{52}^{(2)} \left(R_{15}^{(1)} + R_{16}^{(1)} h_1\right)^3, \quad (8)$$

Another interesting thing to note is that the current profile will not contain any spikes when h_2 is small enough to have the large solution in Eq. (4). On the other hand, a large h2 can generate a single spike in the current profile. In this case, a sextupole magnet in between two EEX beamlines would control the second order effects making spikes.

NUMERICAL SIMULATION FOR DOUBLE-HORN SUPPRESSION

We demonstrate this suppression using octupole magnet using IMPACT-T simulation. The simulations use the beamline at Argonne Wakefield Accelerator facility (AWA) [15-16].

For the demonstration of the concept, we firstly checked the beam's behaviour without CSR effect. This simulation agrees well with the expectation. We generated the beam which has strong third-order correlation from AWA linac (see Table 1 and Fig. 2a). Third order polynomial fitting on the longitudinal phase space of Fig. 2a provided the first, second and third order correlation coefficients (see. Eq. (3)). Without octupole magnet correction, the DEEX beamline compresses the bunch from 1.39 ps to 0.20 ps as shown in Fig. 2b. Due to the initial third order correlation, this compression introduced a clear double-horn feature in the current profile.

Table 1: Beam Parameters before the DEEX Beamline

Parameters	**Values**
Charge	200 pC
Energy	43 MeV
First order chirp (h1)	2.7 m^{-1}
Second order chirp (h2)	-562.1 m^{-2}
Third order chirp (h3)	2.70E6 m^{-3}

Required octupole magnet strength is calculated using the coefficients we found from Fig. 2a and Eq. (8). Calculated strength K is -2422.8 m^{-3}, and corresponding simulation result is shown in Fig. 2c. The longitudinal phase space is unfolded and an S-shape in Fig. 2b disappeared. Here the final bunch length is 0.34 ps which is little longer than no correction case. Octupole worked a little bit stronger than expected, and it pushed particles further than the spot for linearization as one can see from Fig. 2c.

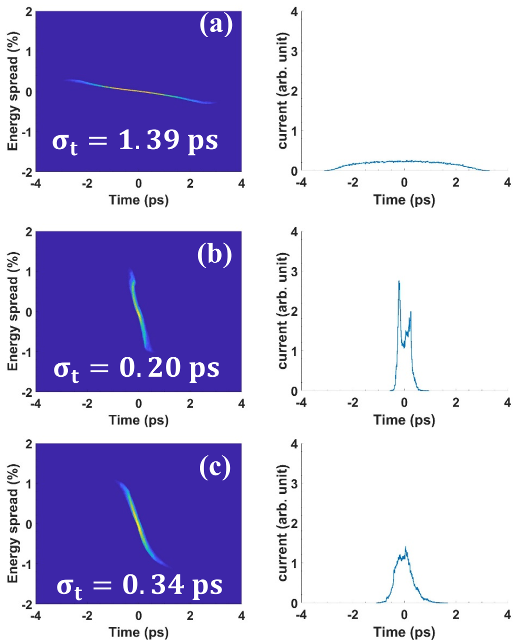

Figure 2: Longitudinal phase spaces and corresponding current profiles without CSR. (a) corresponds to before the DEEX beamline while (b) and (c) corresponds to after DEEX beamline. Octupole correction is not applied to (b) while (c) is the simulation result with octupole correction.

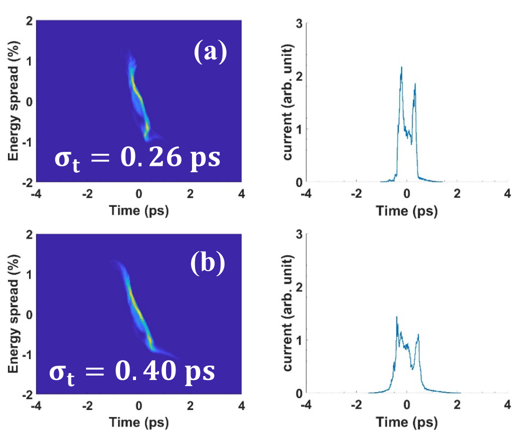

Figure 3: Longitudinal phase spaces and corresponding current profiles with CSR. (a) and (b) corresponds to after DEEX beamline. Octupole correction is not applied to (a), (b) is the simulation result with octupole correction.

For the experimental demonstration, CSR effect should be considered for the simulation. Figure 3 shows the simulation results with CSR effect. The double-horn feature is clear without octupole magnet (Fig. 3b), and it is suppressed by octupole magnet (Fig. 3c). Although this single case shows a reasonable result, CSR can adjust the beam transport described in the previous section. Eq. 8 may require major modification depending on the CSR strength and optics. We need further optimization of experimental setting to clearly observe the effect of the octupole magnet on double-horn formation.

CONCLUSION

We confirmed third-order correlation in longitudinal phase space generates a double-horn in current profile. This feature can be easily correct using an octupole magnet in DEEX beamline. Required octupole strength is calculated from the beam transport in the DEEX beamline, and the particle tracking simulation proves its feasibility. Further study is underway to find optimized experimental setting including CSR effect. AWA group plans to demonstrate this double-horn suppression experimentally using the DEEX beamline installed at the AWA facility.

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