SUB-fs ELECTRON BUNCH GENERATION USING EMITTANCE EXCHANGE COMPRESSOR*

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Abstract

Sub-fs electron bunch has been pursued in the last decade using several different methods. These methods rely on one of the velocity difference or path length difference to compress a long bunch to sub-fs bunch. Here, we introduce a new method to generate the compression. Emittance Exchange (EEX) beamline makes transverse-to-longitudinal exchange of phase space. In this beamline, a transverse focusing at the upstream introduces a longitudinal compression at the downstream due to the exchange. Since this exchange scheme does not rely on the velocity or the path length differences, it does not require any longitudinal manipulation (e.g. chirp), and it could generate a short bunch with well-controlled nonlinear effects using nonlinear magnets. We present preliminary simulation results of EEX based bunch compression and sub-fs bunch generation.

INTRODUCTION

Sub-fs long electron bunch is required in many modern accelerators. Since the sub-fs bunch can only be generated by the bunch compression, several different bunching scheme and their combinations were explored [1]. Here we introduce EEX based compression method for the sub-fs bunch which provides the longitudinal manipulation over the transverse control via the phase space exchange [2]. It is possible to achieve sub-fs bunch length when the strong enough focusing is applied to the low emittance beam. We investigated the linear principle the EEX compression method and limiting factors such as thick cavity effect, higher order effect and collective effects.

In this paper, we are going to present simulation results for the sub-fs bunch generation using EEX beamline. Simulations are done using ELEGANT [3] including 1D CSR. 6D Gaussian beam is generated at the entrance to the EEX beamline to simulate the sub-fs feasibility. We discuss the linear dynamics of the EEX bunch compression. Second, higher order suppression is demonstrated using sextupole magnets. Finally, we show the CSR effect on the bunch compression and the emittance growth along the beamline.

LINEAR DYNAMICS IN EEX BEAMLINE

When we define the 4D particle coordinate as $\mathrm{X} = (x, x', z, \delta)$, the beam transport through the beamline can be described as,

$$\mathrm{X_f} = R\mathrm{X}_i, \tag{1}$$

where subscripts indicate the entrance and the exit to the beamline, and R is the linear transfer matrix. Here the longitudinal position at the exit which is related to the final bunch length can be expressed as,

$$\mathrm{z_f} = R_{51}x_i + R_{52}x_i' + R_{55}z_i + R_{56}\delta_i. \tag{2}$$

In the case of the EEX beamline, R_{51} and R_{52} are the dominant terms while R_{55} and R_{56} originated from thick-cavity effect are close to zero [4]. Since these additional terms increase the final bunch length, one can use fundamental mode cavity (FMC) to eliminate this thick cavity effect (see Fig. 1) [5].

When the thick-cavity effect is fully eliminated, the final bunch length can be minimized when the horizontal slope satisfies the condition,

$$\frac{\sigma_{xx'}}{\sigma_x^2} = -\frac{R_{51}}{R_{52}}. \tag{3}$$

The final bunch length can be calculated from Eq. (3) and (4), and it can be expressed as,

$$\sigma_{z,f} = R_{52}\frac{\varepsilon_x}{\sigma_{x,i}}, \tag{5}$$

where ε_x is the horizontal rms emittance and $\sigma_{x,i}$ is the initial horizontal rms beam size.

NUMERICAL SIMULATION FOR SUB-fs BUNCH GENERATION

Previously, we discussed about basic principle of EEX bunch compressor. In this section, we carry out the ELEGANT simulation to generate sub-fs bunch under the nonlinear limiting factors. The beamline and initial beam parameters are given in Table 1.

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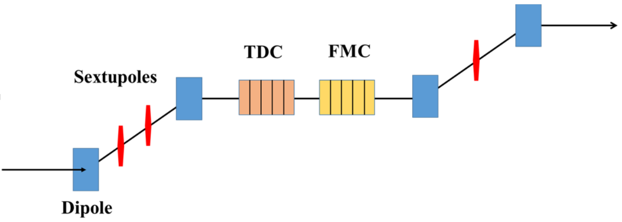

Figure 1: Layout of EEX bunch compressor. The beamline consists of two doglegs, transverse deflecting cavity, fundamental mode cavity and sextupole magnets.

Table 1: Beamline and Beam Parameters for ELEGANT Simulation

Beamline Parameters	**Values**
Bending angle	5 (degree)
Dipole-Dipole	5 (m)
Dispersion of dogleg	-0.47 (m)
TDC kick strength	2.13 (m^{-1})
FMC voltage	-718 (kV)
1^{st} sextupole geometry strength	1309.51 (m^{-3})
2^{nd} sextupole geometry strength	-1138.23 (m^{-3})
3^{rd} sextupole geometry strength	17.68 (m^{-3})
Beam Parameters	**Values**
Energy	100 (MeV)
Charge	2 (pC)
σ_z	0.167 (ps)
$\sigma_{xx'}/\sigma_x^2$	-0.97
$\sigma_{yy'}/\sigma_y^2$	0
$\sigma_{zz'}/\sigma_z^2$	-0.0393
ε_{nx} (RMS)	0.05 (μm)
ε_{ny} (RMS)	0.05 (μm)
ε_{nz} (RMS)	0.1 (μm)

According to Eq. (5), the beam size at the entrance to the EEX beamline is the key parameter since the emittance is not a tunable factor. A large initial beam size generates a small bunch length at the exit in the linear regime, but it generates strong higher orders effects. In Fig. 2, we scan the initial beam size and compared corresponding final bunch length from Eq. (5) to ELEGANT simulations under different conditions to investigate the limiting effects. Case (a) in Fig. 2 is the simulation result with higher order effects but no CSR. Case (b) uses sextupole magnets to suppress the higher order effects (see Fig. 1) and there is no CSR yet. Case (c) is the simulation with sextupole magnets and CSR effects.

When initial σ_x is less than 0.1 mm, analytical calculation and case (a) shows good agreement while the bunch length above this range rapidly increases due to the strong higher order effects from the beam size. To suppress the higher order effects, we introduced three sextupole magnets to the EEX beamline as shown in Fig. 1. The sextupole setting is optimized for the initial σ_x of 0.1 mm, and Fig. 2 shows that the bunch length curve for case (b) is clearly lower than the case (a).

When CSR is introduced to the simulation, it normally increases the bunch length. However, the bunch length growth is ignorable with the beam and beamline parameters in Table 1 which has a low peak current and a small bending angle. The final bunch length with all physics is 0.9 fs for 0.1 mm of initial σ_x, and it can be reduced further if we increase σ_x little more (0.14 mm provides 0.72 fs).

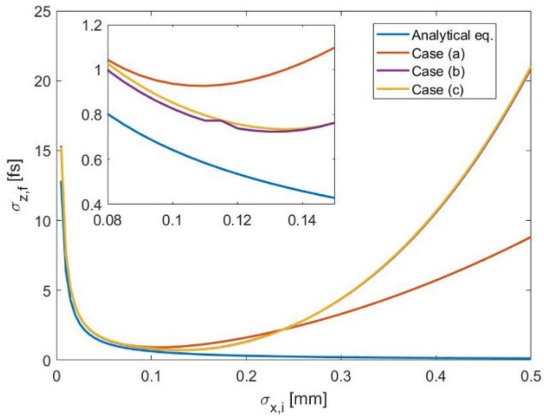

Figure 2: Final bunch length from different initial horizontal beam size. Blue line is the bunch length from Eq. (5). Case (a) is ELEGANT result without higher order magnets and CSR effect. Case (b) is ELEGANT result with sextupole magnet for the higher order suppression but no CSR effect. Case (c) is ELEGANT result with the sextupoles and CSR effect.

EMITTANCE GROWTH FROM EEX BUNCH COMPRESSOR

The limiting factors, higher order effects and CSR effects, increase the bunch length and the emittance at the same time. Figure 3 shows the emittance evolution along the EEX compressor. At the entrance to the beamline, the horizontal emittance is 0.05 um and the longitudinal emittance is 0.1 um. Due to EEX, the final horizontal and longitduinal emittance should be 0.1 um and 0.05 um if there is no emittance growth. However, the higher order effect increased the longituidnal emittance to 0.061 µm (see Fig. 3 a). This emittance growth from the higher order effect is suppressed when sextupoles are introduced. The final longitudinal emittance is 0.054 µm in this case (Fig. 3 b).

In the previous section, we found that the CSR effect is negligible to the final bunch length. However, the emittance is sensitive to the CSR effect. When CSR is applied to the simulation, the longitudinal emittance increases to 0.066 µm (Fig. 3 c). Among all cases, the final horizontal emittance is well preserved.

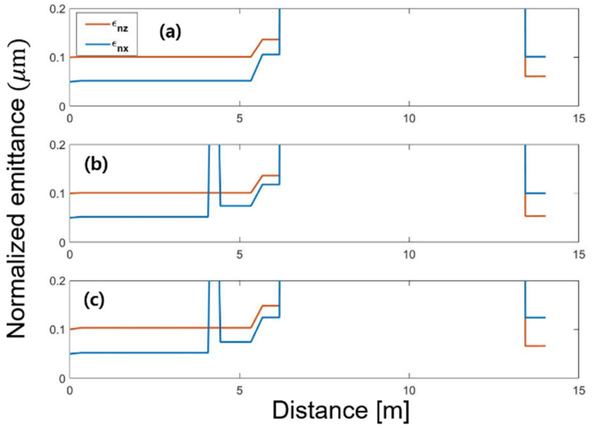

Figure 3: Emittance evolution along the EEX bunch compressor with initial σ_x of 0.1 mm. Simulation setup is the same as Fig. 2. Red and blue lines are normalized longitudinal and horizontal emittances, respectively. (a-c) correspond to Case (a-c) in Fig. 2. In case (a), final ε_{nx} and ε_{nz} are 0.1 and 0.061 µm. In case (b), final ε_{nx} and ε_{nz} are 0.1 and 0.054 µm. In Case (c) final ε_{nx} and ε_{nz} are 0.1 and 0.066 µm.

NEXT STEP FOR SUB-fs EEX BUNCH COMPRESSOR

We achieved the final bunch length of less than 1 fs with 1D CSR effect. The minimum bunch length was 0.72 fs, and it can be reduced further if we can use a larger initial beam size with appropriate sextupole setting. Once we go to the larger beam size, third order effects start to effect on the bunch length. It may end up with few more sextupole magnets and octopole magnets to achieve a 0.1 fs or shorter.

CSR effect was not a significant issue for the sub-fs generation, but it has to be mitigated to preserve the emittance. The method to suppress the emittance growth from CSR is underway.

So far, the simulation used 6D Gaussian beam, but we are going to extend the work to the simulation with realistic beam. To include the injector simulation, we will use ASTRA [6] or OPAL [7].

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