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Double Emittance Exchanger as a Bunch Compressor for the MaRIE XFEL electron beam line at 1GeV

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Abstract. We demonstrate an alternative realization of a bunch compressor (specifically the second bunch compressor for the MaRIE XFEL beamline, 1GeV electron energy) using a double emittance exchanger (EEX) and a telescope in the transverse phase space. We compare our results with a traditional bunch compressor realized via chicane, taking into account the nonlinear dynamics, Coherent Synchrotron Radiation (CSR) and Space Charge (SC) effects. In particular, we use the Elegant code for tracking particles through the beam line and analyze the eigen-emittances evolution to separate the influence of the CSR/SC effects from the nonlinear dynamics effects. We optimize the scheme parameters to reach a desirable compression factor and minimize the emittance growth. We observe dominant CSR-effects in our scheme resulting in critical emittance growth and introduce alternative version of an emittance exchanger with a reduced number of bending magnets to minimize the impact of CSR effects.

INTRODUCTION

Once Linac Coherent Light Source (LCLS) turned on its first photon beam in 2009 we entered a new era of 4th generation light sources [1]. Since then, many light source facilities have been planned and built, such as FLASH at DESY, SACLA at SPRING-8, and FERMI at ELECTRA, and some are still in the design stage.

Scientists at Los Alamos National Laboratory have been dreamt of building a light source with extreme capabilities such as ultrashort wavelength 0.03 *nm*, high Brightness, high repetition rate and much more as a part of Matter-Radiation Interactions in Extremes Facility (MaRIE). Finally in 2016 the project got approved as CD-0. Such extreme capabilities for a hard X-Ray light source can be realized only as a Free Electron Laser, which will require a short undulator period of 1 *cm* and beam energy of 10 *GeV* according to the scale $\lambda_{x-ray} \sim \lambda_u/(2\gamma^2)$. In addition, due to the electron beam emittance limitation for a free electron laser, $\epsilon_{n_x,n_x} \leq \beta\gamma\lambda_{x-ray}/4\pi$, and the scaling from state- of-art high brightness photo-injectors, $\epsilon_{n_x,n_x} \sim 1\mu m(q/nC)^{1/2}$, to reach high current per pulse one would have to compress the beam ($q = 100\ pC$, $\epsilon_{n_x,n_x} \sim\ 0.15\ mm\ mrad$) to a bunch length of $\sim 12\ fs$, hence an advanced bunch compressor is needed, which would have to be inserted somewhere in the accelerator beam line, and ideally would preserve the input beam quality and moreover would not effect the beam quality at the entrance of the undulator.

Typical bunch compressors are realized as a multi stage compression modules: chirper, chicane, dechirper, placed at different locations along the beam line, and as a result at different energies of the electron beam. The multi stage scheme is defined by the fact that often high compression ratio ∼ 100 is required and it is almost impossible to realize it as a single chicane type bunch compressor. There are several factors destroying the quality of an electron beam traveling through a bunch compressor, such as Coherent Synchrotron Radiation (CSR), CSR induced micro-bunch instabilities, Space Charge (CS) effects, which are all collective effects in their nature. At lower energy $\sim\ 10\ MeV$ space charge effects are dominating while at energies of $\sim\ 100\ MeV - 10\ GeV$ CSR effects are taking place. To mitigate SC effects and satisfy specific design needs it was planned to have two Bunch Compressors for the MaRIE XFEL electron beam line at 250 MeV and 1 GeV. Preliminary studies showed that a standard chicane-type bunch compressor at 1 GeV destroys the electron phase-space and as a result increases emittance, slice-emittance due to CSR effects, also micro-bunch instability effects were observed. In finding an alternative solution we proposed realizing a second bunch compressor as a Double Emittance Exchanger (EEX) and a Telescope. Previously, schemes based on a single EEX were proposed which would switch the longitudinal and transversal phase space of the beam to reach a desired bunch size. However, the transverse phase space quality of an electron beam for a Free Electron Laser is not less critical than longitudinal bunch size, and also the fact, that initial (from the cathode) transverse and longitudinal emittances are quite different quantities, destroyed the chances of this scheme to improve on the standard chicane-type bunch compressor. In our proposed design the initial phase spaces are preserved in the approximation of ideal exchange, while the longitudinal bunch size is compressed by applying transverse optics elements in the telescope between two EEX. If CSR emittance growth effects would be comparable with standard chicane-type design results, then our alternative method spreads micro-bunch instabilities over 6-dimensional phase space and thereby is an improvement over existing techniques. Finally, there are almost no limitations on the transverse optics, that is why such a scheme may reach high compression ratio and substitute both compressors at once.

STANDARD DESIGN

Emittance Exchange (EEX) was introduced in 2002 by M. Cornacchia and P. Emma [2]. Various schemes can be used to flip transverse and longitudinal phase space. The exact (in the first order) EEX is realized as two same direction doglegs and a transverse deflecting cavity between them. Such a configuration would shift the beam from its original trajectory and some mechanism would be required to return it. Therefore, an alternative EEX, realized as chicane type doglegs (up-down or down-up) was studied, however such a scheme gives non-exact exchange in the linear order and would require nonlinear optics to correct the phase space. Originally, the first double EEX with a telescope as a bunch compressor was proposed by A. Zholents and M. Zolotorev in 2011 [3]. Using chicane type EEX modules with correction elements was assumed. For the MaRIE second bunch compressor as a Double EEX we want to have an exact exchange. At the same time, if we invert the second EEX direction, the electron beam will go back to its original path. For this configuration the phase space has to be flipped ($x \longrightarrow -x$) in the telescope, which is easy to realize. In addition we want to avoid any beam correction elements in the EEX part and add it in the advanced telescope design if needed. Summarizing the above, we get the design represented in Fig. 1, where EEX Up/Down

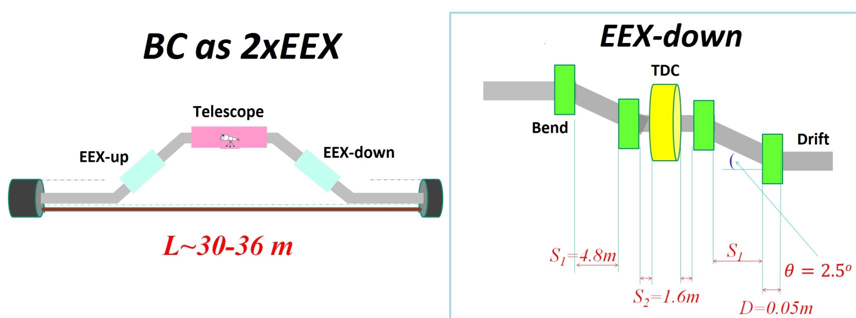

FIGURE 1. Scheme of the Bunch compressor at 1GeV for the MaRIE XFEL electron beam as the Double Emittance Exchanger

and Telescope modules are presented as matrices in $xx'zz'$-representation (only drift in yy'- phase space is assumed):

$$EEX_{up/down} = \mp \begin{pmatrix} 0 & 0 & \frac{L_{eff}}{\eta} & \frac{L_{eff}}{\eta} - \eta \\ 0 & 0 & \frac{1}{\eta} & \frac{\epsilon}{\eta} \\ \frac{\epsilon}{\eta} & \frac{L_{eff}}{\eta} - \eta & 0 & 0 \\ \frac{1}{\eta} & \frac{L_{eff}}{\eta} & 0 & 0 \end{pmatrix} \qquad T = \begin{pmatrix} m - \left(\frac{1}{m} + m\right) q & L_{eff}(-1+q)\left(\frac{1}{m} + m\right) & 0 & 0 \\ \frac{\left(\frac{1}{m}+m\right) q}{L_{eff}} & \frac{1}{m} - \left(\frac{1}{m} + m\right) q & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

and the parameters for EEX are defined according to the relations:

$$\epsilon = -2D\,\theta\,Csc[\theta] + Sec[\theta]\left(2D + S_1 Tan^2[\theta]\right); \tag{1}$$

$$\eta = (D + S_1 + S_1 Cos[2\theta])\,Sec^3[\theta]\,Tan[\theta/2]; \tag{2}$$

$$L_{eff} = (D + S_1 + DCos[2\theta])\,Sec^3[\theta] + S_2]; \tag{3}$$

where D and θ are bending magnet length and angle, S_1 and S_2 are separations between two magnets and magnet - deflecting cavity respectively, and cavity parameter $k = -1/\eta$. Telescope parameters are:

$$q = L_{eff}\epsilon/\eta^2 \quad and \quad m = compression\ factor \tag{4}$$

Such a telescope configuration can be realized using drifts, focusing and defocussing lenses, and in our design it is constructed as the combination of two triplets (negative drifts) and a "superlens". The final Double EEX bunch compressor scheme is described by a first order transport matrix, derived as a multiplication product of its elements:

$$BC = EEX_{down} \cdot T \cdot EEX_{up} = \begin{pmatrix} 1 - \frac{2L_{eff}\epsilon}{\eta^2} & 2L_{eff}\left(1 - \frac{L_{eff}\epsilon}{\eta^2}\right) & 0 & 0 \\ -\frac{2\epsilon}{\eta^2} & 1 - \frac{2L_{eff}\epsilon}{\eta^2} & 0 & 0 \\ 0 & 0 & 1/m & 0 \\ 0 & 0 & 0 & m \end{pmatrix} \tag{5}$$

and is approximately $30 - 36$ meters long for a realistic set of parameters.

EIGEN EMITTANCE FORMALISM

Usually the beam quality in linear accelerators is described by its emittances or normalized emittances, beam sizes and divergences, twiss parameters, as well as an energy spread. These quantities are great characteristics of a beam if its Σ-matrix is block diagonal. However, advanced analysis is needed to optimize work a complicated beam line such as an EEX, because in the process of exchange, transverse and longitudinal phase spaces are mixed and a lot of correlations between them appear, which means the Σ-matrix is far from being block diagonal. In the case of an ideal exchange one may claim that at the beginning and a the end of the beam line the electron beam matrix is block diagonal and there is nothing to worry about. However, there is nothing ideal in the accelerator world and an exact exchange is just a myth ignoring nonlinear effects, CSR effects and much more. Hence, a special technique is needed to describe beam propagation through the advanced schemes such as any type of a bunch compressor. Fortunately, Alex Dragt presented to the accelerator community eigen emittances: "The Hamiltonian motion of a beam has three conserved moments, which can be chosen as the quantities known as the eigen-emittances λ_j [4, 5]":

$$Det\left(J\Sigma - i\lambda_j I\right) = 0, \tag{6}$$

where I is a Identity Matrix and J is the unit block-diagonal antisymmetric symplectic matrix. Eigen emittances are invariants under the linear beam dynamics and define the minimum of rms emittances. The minimum is reached once Σ-matrix is block diagonal. In the case of EEX scheme design one would have to compare eigen emittances with a real emittances under assumption of linear dynamics - to make sure the design is correct in the first place; then add higher order effects and analyze if rms emittances are still matching with eigen emittances - if both are growing then high order elements, such as sextupoles, octupoles, etc. are needed to correct high order dynamics of the beam line, if only emittances are growing but eigen emittances are remaining the same then nonlinear effects destroy the ideal exchange configuration or mismatching electron beam and beam line twiss parameters and it might be possible to fix it by adjusting the first order elements, such as quads, bends, drifts, etc without significant modification of the scheme. In the next step, one would have to turn on CSR and CS effects in the simulations and analyze eigen/rms emittances dynamics through the beam line. In the case of only rms emittance growth, twiss parameters adjustments have to be repeated. In the case of increasing eigen emittances one would have to correct specific elements depending on which effects are dominating and where. In the worst case scenario one would have to redesign the scheme completely and start all over. Finally, eigen emittances make the understanding of a magical EEX straightforward. Beam optics in the process of the ideal exchange is flipping the projection directions of eigen emittances (invariants of a linear beam dynamics) to the rms emittances.

SIMULATION RESULTS

Simulation studies were performed using Elegant tracking code by Michael Borland [6]. Simulation results for the Double EEX design are presented on Fig. 2 for the case of linear dynamics. It is clear that ideal exchange is perfectly

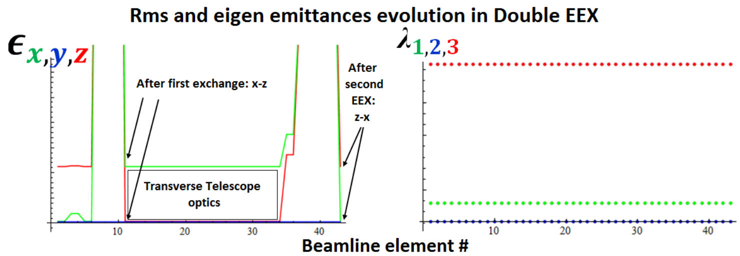

FIGURE 2. RMS (a) and Eigen (b) Emittances evolution through the Bunch Compressor (BC) Beamline

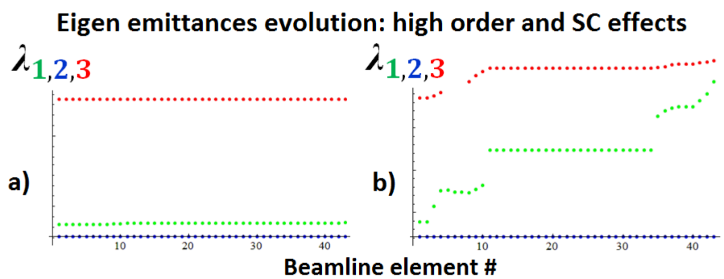

FIGURE 3. Eigen Emittances evolution through the BC: a) high order effects and b) high order effects + space charge: $q = 100pC$

executed in this design and appropriate compression ratio is reached. Nonlinear dynamics practically do not effect the exchange and high order elements are not needed in the scheme (Fig. 3 a). However once we turn on the CSR effects in Bends and Drifts, eigen emittances start growing extremely fast trough the beam line (Fig. 3 b). The determinant of the electron Σ-matrix, characterizing the phase space volume, grows roughly 16000 times, and normalized emittance ϵ_x grows 60 times, which makes the beam going through such compressor not appropriate to use for the MaRIE XFEL. The ratio (~ 1.5) between Multiplying Emittance Product (MEP) and Σ-matrix determinant confirms that the exchange is close to ideal (rms emittances are matching with Eigen emittances) but collective effects (CSR) in the process totally destroy the phase space, therefore significant modifications of the design are required to mitigate it.

DESIGN MODIFICATIONS

Using two unsymmetrical EEXs can significantly improve the result. Optimum configuration for the multiple parameters were found for the short time (4) using A. Scheinker Extremum Seeking algorithm [7]. Normalized emittance ϵ_x growth in such configuration is ~ 7, which is significantly smaller than in the previous symmetrical configuration, however it is still not appropriate for the MaRIE XFEL electron beam.

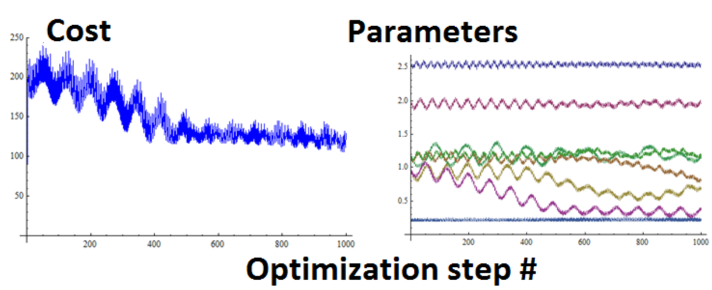

FIGURE 4. Optimization search output using Extremum Seeking algorithm: "Cost" evolution - the Σ-matrix determinant growth, is on the left and parameters evolution - such as bending magnets angles and drifts, is on the right

In parallel, the alternative configuration of an EEX is proposed as a solution. It is realized via use of two deflecting cavities, negative drift and one dogleg (5) instead of the standard configuration of two doglegs and one deflecting cavity. The number of bending magnets, active sources of CSR effects, is reduced from four to two. The preliminary studies of this configuration (single EEX) show the significant Σ-matrix determinant growth ∼ 33, which, most likely, makes it not appropriate to use in the Double EEX Bunch Compressor.

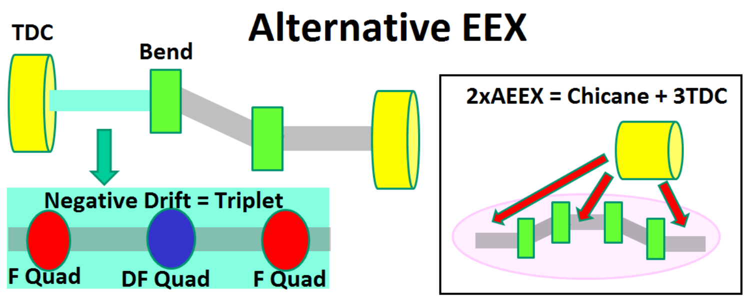

FIGURE 5. Alternative Emittance Exchanger configuration with reduced number of bending magnets. Scheme is similar to the Chicane configuration with inserted Transverse Deflecting Cavities (TDC) in the case of a double EEX bunch compressor

CONCLUSION

Simulation studies have shown dramatical emittance growth in the Double EEX bunch compressor caused by CSR effects in bending magnets. Eigen emittance evolution has been analyzed to understand weak spots in the original scheme and nature of the problems. Two solutions have been proposed to minimize CSR effects. First - using unsymmetrical EEXs, has been realized using fast extremum search algorithm. Significant improvements have been observed. Second - using alternative EEX configuration with reduced number of bending magnets, has not shown sufficient improvements. Further optimizations of the scheme are planned to reduce CSR effects via keeping the longitudinal bunch size along the Double EEX beam line as big as possible and compressing it in the last few elements.

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