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CSR-INDUCED PROJECTED EMITTANCE GROWTH STUDY FOR THE BEAM SWITCHYARD AT THE EUROPEAN XFEL

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Abstract

Minimizing projected emittance of high brightness electron beam is important for efficient overlap between electron beam and radiation pulse in an FEL facility. Coherent synchrotron radiation (CSR) emission in a single bending section in the beam transport system usually introduces different slice energy modulation hence different slice transverse kicks in the designed dispersion-free lattice, causing projected emittance growth. Here we present theoretical and simulation study of CSR effect on the projected emittance growth in the beam switchyard arc before SASE2 undulator beamline at the European XFEL. We analyze arc optics impact on CSR effect and discuss possible schemes for emittance degradation compensation.

INTRODUCTION

Coherent synchrotron radiation (CSR) emission [1, 2] by a high brightness electron beam in bending sections usually introduces different beam slice energy modulation hence different slice transverse kicks, causing emittance degradation. For an FEL facility, this emittance dilution may degrade the overlap between electron beam and radiation pulses hence suppress the lasing performance in the downstream undulators. Suppression of CSR-driven emittance degradation is important for a better lasing scenario where the undulator system is not immediately downstream of the linac. Some methods have been proposed [3–5] to suppress CSR-driven emittance degradation by using periodic bending sections with separation of π betatron phase advance.

European XFEL is an X-ray FEL facility based on a high-electron-energy superconducting linear accelerator [6]. After the collimation section that follows the main linac, a beam switchyard arc [7–9] bends selected electron beams from a bunch train to the hard x-ray FEL beamline SASE2, where both SASE mode and self-seeding mode [10] are available. It has been experimentally observed that the FEL tuning aiming for comparable performance at SASE2 is practically more difficult than SASE1, where the undulator system is immediately downstream of the collimation section, due to limited lasing window resulted from the large slice centroid deviation introduced by the SASE2 arc CSR effect. Though a new self-seeding mode, phase-locked hard x-ray self seeding [11] can be introduced based on this unique arc kick, for nominal operation it's beneficial to mitigate the CSR effect to get a longer lasing window and hence better performance for the FEL pulse energy.

It is shown that CSR dominates over other collective effects such as space charge and wakefield influence for beam transport in this arc [12], where slice emittance growth is small. Here we present theoretical and simulation study of CSR effect on the projected emittance growth in this beam switchyard arc. We analyze arc optics impact on CSR effect and discuss possible schemes for emittance degradation compensation. With the projected emittance optimized, the overall FEL radiation pulse energy can be improved.

RESULTS

Arc Optics Impact

The designed arc optics is shown in Fig. 1. with two main bending magnet sets in horizontal (x) plane and some bending magnets in vertical (y) plane. Here we mainly focus on the x plane. There are five main quadrupoles in between the bending magnets, which correspond to the none-zero horizontal dispersion D_x turning points. The designed optics has dispersion between these bending magnets and is dispersion-free downstream. Here the shown lattice has a betatron phase advance of $\Delta\mu_x \approx 9.23$ rad and $\Delta\mu_y \approx 10.38$ rad, which are close to 3π, after which the SASE2 undulator follows.

Here, beam transport in the arc is simulated with the multi-physics software package OCELOT [13]. For simplicity, an ideal typical matched electron beam distribution with beam charge of 250 pC, electron energy of 14 GeV, initial slice geometric emittance of $\epsilon_{x0} \approx \epsilon_{y0} \approx 2.0 \times 10^{-11}$ m and all the beam slices are well aligned in both x and y direction hence the projected emittance is also the same, and gaussian distribution both in longitudinal and transverse phase space is used as input at the arc entrance. The projected emittance increases during the transport in the arc, which is shown in Fig. 2 (a), where one can see that without CSR effects included the projected emittance falls back to the original value, while when CSR effect is considered the horizontal emittance ϵ_x increases to around $2.1\epsilon_{x0}$, and $\epsilon_y \approx 1.1\epsilon_{y0}$. Figure 2 (b-d) show beam properties at the arc end with bunch head on the right side. Figure 2 (b) shows beam current profile and beam slice central energy deviation due

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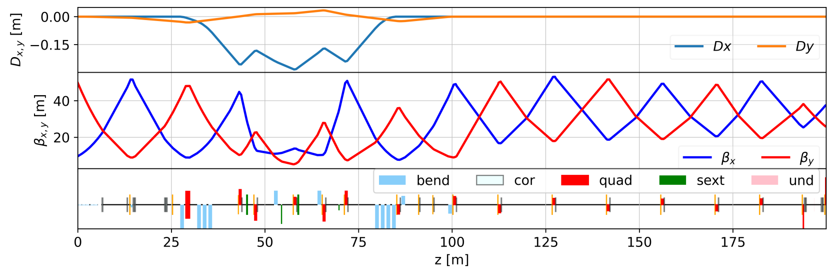

Figure 1: Nominal optics of the beam switchyard arc.

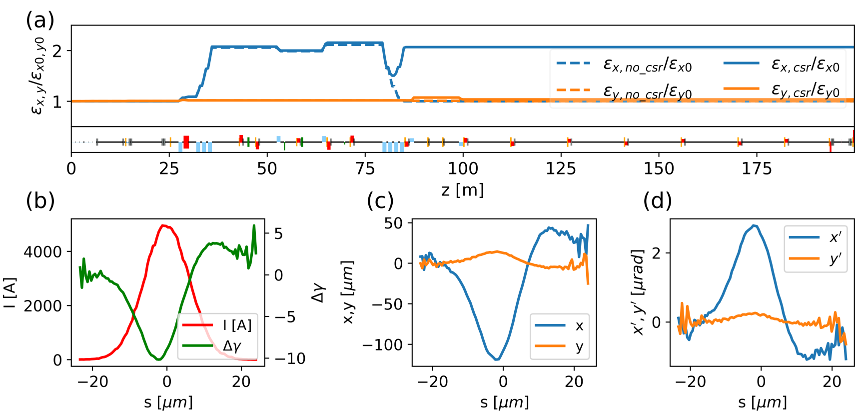

Figure 2: Projected emittance evolution with and without CSR effect (a) and beam slice properties after transport in arc (b-d) with an ideal initial beam distribution at the arc entrance. (b) beam current profile and slice central energy deviation. (c) slice transverse center. (d) slice transverse divergence.

to CSR effect. Figure 2 (c) and (d) show beam slice centroid and slice divergence.

For efficient overlap between electron beam and FEL pulse, the on-axis lasing part should have a radius approximated as $\sigma_x \sim \sigma_r \sim \sqrt{\lambda_r L_g/(4\pi)}$ and divergence as $\sigma_{x'} \sim \sigma_{r'} \sim \sqrt{\lambda_r/(4\pi L_g)}$ [14], where λ_r is the FEL resonant wavelength and L_g the gain length. Other parts of the beam will perform betatron oscillation with large amplitude and without efficient lasing due to poor overlap with the radiation field. For typical SASE2 FEL parameters this constraint requires σ_x not larger than tens of µm, which means for this ideal beam that suffers from CSR-driven emittance dilution, only part of the beam with around several µm length may lase well after aligned on axis in the undulator, which limits the lasing power to be only a fraction compared to the case where the whole beam can be aligned on axis with slice center far less than the betatron oscillation amplitude, like in SASE1 beamline.

For cases where CSR effect can be ignored, the dispersion-free optics guarantees that beam part with lower energy will get on axis again at the exit of the second bending magnets. However, with CSR effect included, the energy-deviation is introduced during the transport in the bending magnet, hence the kick angle by the bending magnet is smaller compared to the case where CSR effect is not considered, hence after bending from the second magnet, the CSR-resulted off-energy bunch part will obtain a large angle kick than on-energy part, and this kick causes projected emittance growth, as shown in Fig. 2 (a). This explanation suggests that if the quads strength in between the main bending magnets is tuned properly, this over-kick may be compensated after transport in the second magnet. This tuning will make a non-zero dispersion for the lattice, but may suppress the projected emittance value.

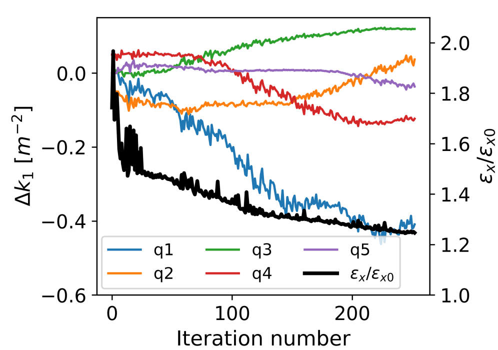

Figure 3: Normalized projected emittance evolution with quadrupole strength scan.

Figure 3 shows the emittance evolution with quads strength scan. We first scan over the five main quadrupoles in between the bending magnets separately, then do further multi variable optimization with changing their strength simultaneously. Single quad strength scan results show

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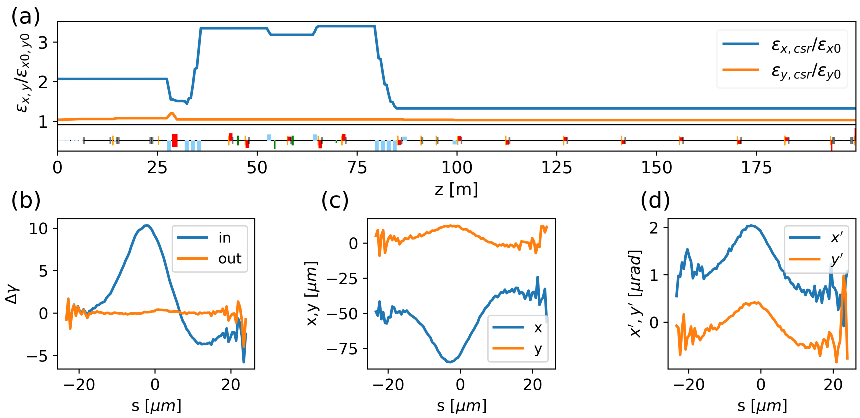

Figure 4: Projected emittance evolution with CSR effect considered (a) and beam slice properties after transport in arc (b-d). Here the input beam at the arc entrance has slice properties as in Fig. 2 (c) and (d) and inversed slice energy of Fig. 2 (b). (b) beam slice central energy deviation before (in) and after (out) transport. (c) slice transverse center. (d) slice transverse divergence.

that tuning the second and fourth quads can suppress the projected emittance growth a little bit from $2.1\epsilon_{x0}$ down to $1.9\epsilon_{x0}$, while tuning other quads seems to be not helpful. Then we start from the changed values for second and fourth quad strength to do multi variable scan to minimize ϵ_x as shown in Fig. 3. After 253 iterations with five quads strength deviation optimized to $[-0.409, 0.037, 0.119, -0.123, -0.036]$ m^{-2} compared to their values in the designed optics, ϵ_x is optimized as low as $\epsilon_x \approx 1.3\epsilon_{x0}$ (right axis of Fig. 3). With non-zero dispersion optics we have $\epsilon_y \approx 1.4\epsilon_{y0}$. This optimization may facilitate the following lasing process.

Beam Properties Impact

Another possible way for emittance degradation compensation is to control beam properties by introducing inverse modulation upstream of the arc to counteract with the CSR effect in the arc. This method is similar with the traditional one that typically utilizes DBA pairs with π betatron phase advance separated to compensate the CSR emittance dilution. here we try to manipulate beam properties in the way the first DBA (with phase advance of π upstream of the second one) does. Phase advance in the arc lattice shown in Fig. 1 is close to 3π for both x and y planes, so if we use the output beam as shown in Fig. 2 (c) and (d), the projected emittance growth modulation introduced by CSR effect by the arc lattice may compensate the initial emittance. With this new input beam one may expect emittance compensation with keeping the designed dispersion-free optics.

Figure 4 shows the case with input beam taken from Fig. 2 (c) and (d) and with inversed slice energy as in Fig. 2 (b). The projected emittance does decrease as shown in Fig. 4 (a), which has values around $\epsilon_x \approx 1.3\epsilon_{x0}$, less than the input beam, and $\epsilon_y \approx 1.1\epsilon_{y0}$ at the arc exit. Figure 4 (b) shows that with an inversed slice energy distribution one can get the output beam with nearly flattened beam longitudinal phase space. This additional energy modulation is possible due to the fact that we use the designed dispersion-free optics here, where no extra emittance growth will be introduced by the energy modulation other than the CSR effect. Slice centroid deviation and divergence shown in Fig. 4 (c) and (d) is much less than those in Fig. 2, and here with proper magnetic corrector kick the lasing window may be as large as twice of the output beam in Fig. 2.

CONCLUSION AND OUTLOOK

In conclusion, CSR-driven emittance growth in the beam switchyard arc before SASE2 at European XFEL is studied and two possible methods for suppressing the projected emittance dilution are given: tuning arc optics and manipulating beam properties upstream of the arc properly. Both methods may give smaller projected emittance, hence may result a longer lasing window for transported beam in SASE2.

For further study, theoretical model of the optics tuning may be improved and finer multi-variable optimization should be done for different input beams, such as with different current profiles and bunch charges, to see in what parameter regime the suppression is still workable. Mismatch introduced by the tuned optics with non-zero dispersion needs further optimization, where qauds downstream the second main bending magnets set may be optimized for beam matching. Start-to-end beam dynamics studies are also needed especially for controlling the beam property.

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