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Feasibility study of a periodic arc compressor in the presence of coherent synchrotron radiation

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ABSTRACT

The advent of short electron bunches in high brightness linear accelerators has raised the awareness of the accelerator community to the degradation of the beam transverse emittance by coherent synchrotron radiation (CSR) emitted in magnetic bunch length compressors, transfer lines and turnaround arcs. Beam optics control has been proposed to mitigate that CSR effect. In this article, we enlarge on the existing literature by reviewing the validity of the linear optics approach in a periodic, achromatic arc compressor. We then study the dependence of the CSR-perturbed emittance to beam optics, mean energy, and bunch charge. The analytical findings are compared with particle tracking results. Practical considerations on CSR-induced energy loss and nonlinear particle dynamics are included. As a result, we identify the range of parameters that allows feasibility of an arc compressor for driving, for example, a free electron laser or a linear collider.

1. Motivations and work plan

The advent of sub-picosecond long electron bunches with hundreds of ampere peak current and sub-micron level energy-normalized transverse emittances, such as those driving linac-based ultra-violet, x-ray free electron lasers (XUV FELs) [1–7], Compton light sources [8–10] and linear colliders [11,12], has raised the awareness of the accelerator community to the dilution of the beam transverse emittance by emission and absorption of coherent synchrotron radiation (CSR). CSR effects are nowadays covered by a wide literature, from the theoretical [13–26], numerical [27–32], and experimental point of view [33–39]. As a consequence of CSR-induced emittance dilution, the electron beam brightness is decreased [40], and so the output radiation brilliance in light sources, and the luminosity in colliders, does.

In spite of the relatively high beam rigidity from hundreds of MeV up to multi-GeV energies, the electron beam energy-normalized projected emittance may be degraded in the bending plane at the $\sim$1 μm rad level and above, when the beam is bent in dipole magnet-chicanes that act as bunch length compressors [33–36], in multi-bend transfer lines [37] and in turnaround arcs [41–46]. Initially thought for a constant bunch length along the line [19], a specific linear optics design has recently been revisited to minimize [37] or even cancel [25] the emittance disruption in double bend achromatic (DBA) lines, and then in a periodic [26] and a non-periodic arc [47], in which the bunch length is notably compressed. Turnaround arcs have been considered as magnetic bunch length compressors for energy-recovery linac (ERL) designs, in the 0.1–1 GeV energy range [41–46]. In [43,44] some degree of optics control was exercised in order to minimize the CSR effect following the theoretical prescriptions given in [22], but in all cases the CSR effect was effectively suppressed by limiting the bunch charge below 0.15 nC. To date, turnaround arcs have not found to be suitable for time-compression of high brightness electron beams. When arcs are included in the accelerator geometry, bunch length is kept constant through them by isochronous paths [11,46], or lengthened before entering the arc (CSR effect is weaker for longer bunches), and thereby re-compressed at its end [12].

In [26], a step forward in the control of the normalized emittance at the arc's end at the 0.1 μm rad level is promised, for compression factors of up to $\sim$45, applied to a 0.5 nC beam, at 2.4 GeV. With respect to the aforementioned literature, the proposed optics solution allows larger compression factors at higher beam charges, simplifies ERL lattice designs since, in principle, a dedicated chicane is no longer needed for compression as the arc acts both as final stage of recirculation *and* compressor, and offers the possibility of new schemes for beam longitudinal gymnastic.

The aforementioned optics design, however, is not fully justified, since a special condition on the beam angular divergence in the dipoles is arbitrarily imposed (i.e., the Twiss parameter $\alpha_x=0$), which is not demonstrated yet to be the optimum choice for minimizing the CSR effect. Although the dependence of the optimum betatron function $\beta_{x,\mathrm{opt}}$ (i.e., the betatron function that

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minimizes the CSR-induced emittance) on the local compression factor (C) in the arc's cell is made explicit, no quantitative analysis of the emittance's dependence on the optics is given. Moreover, the expression provided for the emittance of the compressed beam applies to a single DBA, and there is no direct comparison of analytical predictions with start-to-end particle tracking results. Here, we intend to clarify all those points in order to understand, first, the range of validity of the linear optics analysis and, second, investigate the robustness of the proposed lattice for a wider, but still realistic, range of parameters than initially considered in [26].

In Section 2 we introduce the non-specialist reader to a physical picture that explains the projected emittance dilution due to CSR chromatic kicks, and the relationship established by the collective effect among the chromatic and the betatron component of the particles' motion. We then explain the salient differences and the approximations on which some of the recent analytical optics approaches to CSR rely. In Section 3, we expand the theoretical work in [26] to more general optics conditions, and verify the validity of the solution proposed there. Then, we study the dependence of the CSR-induced emittance (henceforth simply "CSR emittance") to the Twiss parameters in the arc's DBA cells, taking into account the evolution of the compression factor along the arc. This provides additional guidelines to the optics design of the compressor and an estimate of the CSR emittance cumulated along the lattice. In Section 4, we use particle tracking runs to study the sensitivity of the CSR emittance to beam optics, energy, and bunch charge, and compare the results with analytical expectations. In Section 5, the detailed simulation for a high charge beam is recalled from [26], and compared to a low charge beam case. In addition to this, the impact of sextupole magnets on the longitudinal and transverse beam dynamics is evaluated, and particle tracking results interpreted under the light of the analytical findings. Finally, the amount of CSR-induced energy loss is considered, being it of major importance, for example, in recirculating accelerators. Our conclusions are summarized in Section 6.

2. Linear optics model

2.1. Physical picture

A relativistic electron beam emits synchrotron radiation when it is bent in a dipole magnet. Radiation emission is coherent, that is the number of emitted photons is proportional to the square of the number of electrons, at wavelengths of the order of, or longer than, the electron bunch length. The interaction of electrons with CSR emitted in the dipole magnet can modify the electrons' distribution in the configuration and in the velocity space. Longitudinally, CSR induces a variation of the particle momentum that is correlated with the particle's longitudinal coordinate along the bunch (z) [14]. Different longitudinal portions of the bunch, henceforth called "slices", are therefore "kicked" differently. In this model, all electrons belonging to the same slice move as a rigid sub-bunch, and the slice motion is associated to that of the slice's centroid. Since CSR-induced longitudinal (i.e., energy) kicks happen in an energy dispersive region (in the horizontal bending plane), each slice centroid is instantaneously moved on a new dispersive trajectory defined by $\Delta x_\eta(s_0)=\eta_x(s_0)\delta_{CSR}$ (and analogously for the angular divergence, $\Delta x_\eta'=dx_\eta/ds$), where s is the longitudinal coordinate along the beamline, and the CSR kick happened at the coordinate s_0, η_x is the energy dispersion function, and δ_{CSR} the energy variation induced by the CSR field, relative to the beam mean energy (E). We assume that only the longitudinal component of the CSR electric field is involved in the

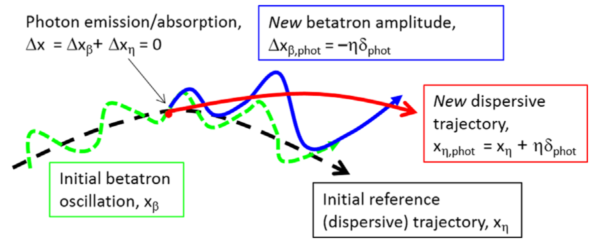

Fig. 1. Sketch of slice centroid's transverse dynamics in the presence of CSR emission/absorption. See text above for details.

process, at any point of the curved beam's path, i.e. CSR radial forces [21] are neglected. As a consequence, we do not expect any *instantaneous* change of the slices' centroid's transverse position and velocity. Since the centroid's transverse coordinate is the linear superposition of the energy-dispersive and the betatron coordinate, the sum of these two components has not to change at the CSR kick location: $\Delta x(s_0)=\Delta x_\beta(s_0)+\Delta x_\eta(s_0)\equiv 0$, that is $\Delta x_\beta(s_0)=-\eta_x(s_0)\delta_{CSR}$ (same applies to the angular divergence). In summary, after a CSR kick, each slice starts moving on a new dispersive trajectory determined by the CSR-induced energy variation. Around that trajectory, the slice oscillates with a non-zero betatron amplitude that, at the kick's location, equals the amplitude of the CSR-induced dispersive motion, as sketched in Fig.1. If the beamline is achromatic, the dispersive motion is eventually canceled out, but a non-zero betatron amplitude for the slices' centroids remains, whose value is correlated along the bunch. This way, the slice transverse emittance may be preserved, while the bunch projected emittance is not. In other words, the bunch slices' *centroids* have gained a non-zero Courant–Snyder invariant [48,49], whose magnitude is proportional to the value of η_x and η'_x (evaluated at the location where electrons–photons interaction happens) times δ_{CSR}. The rms value of the slices' centroids' invariant, averaged over all bunch slices, is the CSR-induced rms transverse projected emittance, or simply CSR emittance. According to this picture, the CSR emittance is independent from the value of the initial (unperturbed) emittance, but their product sums in quadrature in order to estimate the final beam total (i.e., projected) emittance [24,50].

The particle dynamics depicted so far is similar to that contributing to non-zero vertical emittance of electron beams stored in synchrotrons, in the presence of incoherent synchrotron radiation (see for example [49]). Unlike for incoherent emission, however, the CSR transverse effect can in principle be recovered by removal of the slices' correlation in the (z, x) and (z, x') plane [18]. A symmetric arrangement of the Twiss parameters and betatron phase advance between two identical sources of CSR emission was proposed by D. Douglas in order to remove such correlations [19]. Identical CSR kicks imply same beam properties, and in particular same bunch length, along the beamline. An optics balance, no more necessarily symmetric in the optics parameters, has then been proposed and experimented along a multi-bend achromatic transfer line [37]. Optics balance has been improved further to ensure in theory full cancellation of CSR kicks in an arbitrary DBA [25]. The revised optics balance solution has recently been extended to the case of varying bunch length in a 180° periodic arc compressor [26]. In Section 2.2, we will review the approximations adopted in those models [25,26,37], and we will verify their range of validity.

2.2. Theoretical background

Linear optics analysis in the presence of CSR kicks was introduced in [37]. It relies on three approximations. First, it considers