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CONTROL OF SYNCHROTRON RADIATION EFFECTS DURING RECIRCULATION WITH BUNCH COMPRESSION*

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Abstract

Studies of beam quality during recirculation [1] have been extended to an arc providing bunch compression with positive momentum compaction [2]. It controls both incoherent and coherent synchrotron radiation (ISR and CSR) using methods including optics balance [3] and generates little microbunching gain. We detail the dynamical basis for the design, discuss the design process, give an example, and provide simulations of ISR and CSR effects. Reference will be made to a complete analysis of microbunching effects [4].

METHODS FOR CSR/ISR CONTROL

Recirculation and energy recovery are established means of cost-performance optimization. Their use for FEL drivers can be challenging because of the impact of CSR on beam quality, and the desirability of limiting machine size and complexity. Here, we describe a method providing bunch length compression and recirculation in a modest footprint (~10 m diameter at ~1 GeV) while limiting beam quality degradation due to CSR. The method is scalable to higher energy (by increasing bend radius and machine diameter).

"Conventional" Compressor Design

A FODO-based recirculation arc can be used as a compressor; as $M_{56}>0$, an incident bunch with an appropriate energy chirp will be compressed with advantages discussed elsewhere [5]. When employed as a means of final bunch compression, the impact of CSR is however dramatic and detrimental. Using a simple 1-D CSR model in DIMAD [6], we studied compression of a 150 pC, 0.5 μm-rad normalized emittance beam to ~70 fsec x 0.1% δp/p while bending through 180° at 0.71 GeV in an arc comprising eight quarter-integer FODO cells with bend radius of 2 m. The beam emittance increases as a consequence of phase space redistribution driven by the CSR interaction, but effects can be mitigated as follows:

1. Chromatically correct the lattice and compensate lattice and CSR-induced curvature in the longitudinal phase space, *i.e.*, set T_{566}. Here, this is assumed to have been done in upstream transport so as to allow compression of small relative momentum spreads while avoiding use of strong nonlinearities. We model it with a quadratic phase-energy correlation in the incoming beam (a T_{655} term).
2. Introduce lattice perturbations to suppress linear x-δp/p and x'-δp/p correlations in the beam by introducing perturbative dispersion trims.
3. Trim chromatic corrections to suppress CSR-induced nonlinear phase space distortions [7].
4. Optimize the betatron match by varying beam input parameters to minimize output emittance.

After optimization, the output emittance was ~2 mm-mrad, representing a factor of four growth in the input.

The cause of the phase space redistribution is clear: as the bunch compresses, energy modulation across the bunch due to CSR increase dramatically. As a result, the compensation described by Di Mitri et al. [8] breaks down despite the presence of desirable betatron phase and amplitude relationships inherent to the achromat. Small shifts introduced when the bunch is long are inadequate to offset the larger shifts induced when the bunch is short.

Excitation-Modulated Compressor Design

Breakdown in emittance compensation can be mitigated by redistribution of bending along the beamline and optimization as described above. The method is simple: increase the angle of bending in initial FODO cells – thereby enhancing the impact of CSR early in the beam line while the bunch is long – and decrease the bending angle in the final FODO cells, reducing the effect of CSR while the bunch is short. Initial simulation of such an excitation-modulated system shows immediate benefit. An optimized linearly declining bend (using dipoles of 40°, 35°, 30°,… 10°, 5°) presented less emittance degradation than a conventional arc. Guided by the concepts of optics balance [9] and magnifying achromats [10] (in both, upstream and downstream perturbations are balanced by the choice of the intervening lattice optics), we added a dispersion generator to provide additional control of the beam and lattice, and manually adjusted the bending pattern to minimize output emittance. Care in selection of bend angles further reduced emittance dilution; choice of bend radius managed ISR effects.

As in the conventional arc, the degraded output phase space presented correlated distortions that could be compensated by perturbing the beam line optics as described above, limiting growth of normalized emittance from 0.5 to 1 μm-rad, a factor of two lower than in the

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conventional system. Longitudinal emittance is controlled by both arcs. Further improvement in performance might be given by using more robust optimization methods [11].

Table 1 summarizes key parameters. Figure 1 shows beamline layouts for both example systems; Figures 2 and 3 illustrate optimized Twiss parameters for each case. Figures 4 and 5 give delivered 10^4 particle phase spaces for the uniform FODO and modulated compressor.

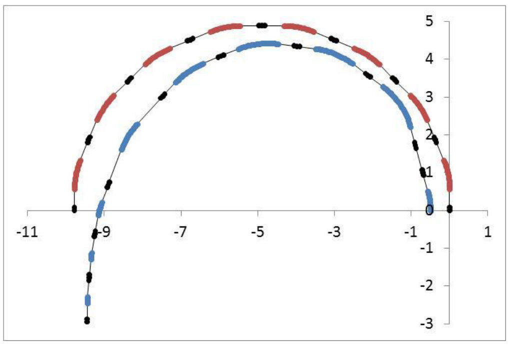

Figure 1: Conventional FO0DO and excitation-modulated compressor layouts. Quadrupoles and beam line in black; conventional line bends in brown, modulated line in blue.

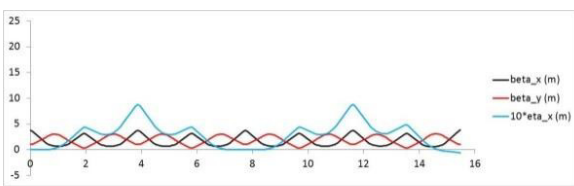

Figure 2: Twiss functions for FODO compressor.

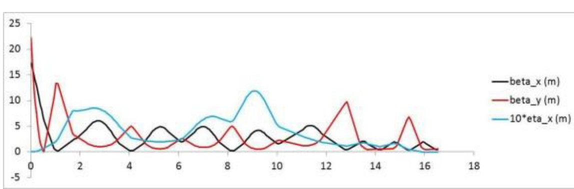

Figure 3: Twiss functions for modulated compressor.

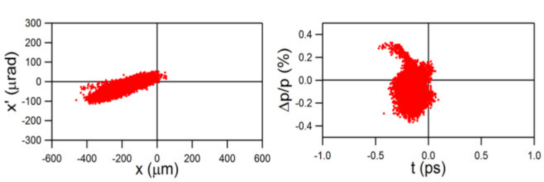

Figure 4: Bend plane (left) and longitudinal (right) phase space output from FODO arc compressor.

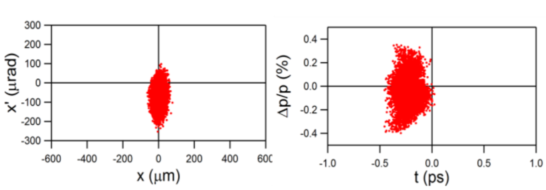

Figure 5: Bend plane (left) and longitudinal (right) phase space output from excitation-modulated compressor.

Table 1: Compressor Arc Parameters

	FODO	Modulated
Diameter	9.78 m	8.95 m
# bends	8	9
cell tune	$\nu_x,\nu_y=90^o$	$\nu_x,\nu_y=90^o$
phase advance	$\nu_x,\nu_y=2,2$	$\nu_x,\nu_y=2.4,2.5$
M_{56}	0.63 m	1.56 m
ε_x^N in/out	0.5/1.86 µm-rad	0.5/0.72 µm-rad
ε_L^N in/out	50/55 keV-psec	50/59 keV-psec

DETAILED ANALYSIS

The excitation-modulated compressor was simulated using elegant [12]. Even with a detailed physics model and a million-particle simulation, emittance growth remained modest, with growth from 0.5 to 1.0 µm-rad. The simulation found significant impact from the interaction of the forward-propagating CSR field with the bunch downstream of the bends ("csrdrift" elements in elegant), the effects of which had not been a part of the initial optimization. This effect increased the final emittance to 1.45 µm-rad. Of greater interest is that the compressor is insensitive to microbunching. Figures 6 and 7 present the output phase space with and without edge effects, and Figure 8 gives emittance evolution through the system; though emittance growth is greater with "csrdrifts", the phase space remains regular and no evidence of the µBI is apparent.

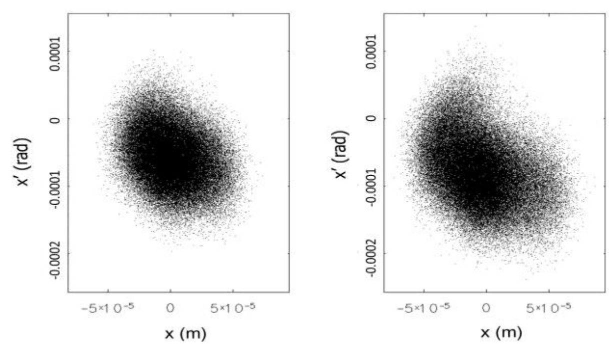

Figure 6: Horizontal phase space without (left) and with (right) CSR edge effects; 10^6 particles.

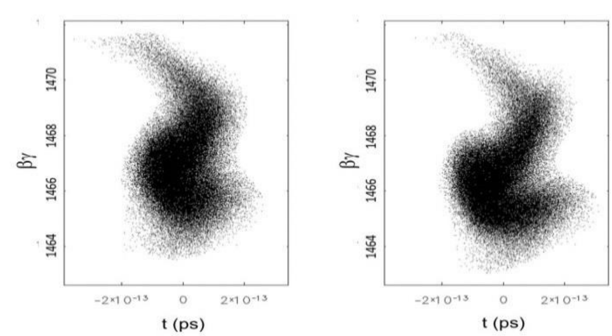

Figure 7: Longitudinal phase space without (left) and with (right) CSR edge effects; 10^6 particles

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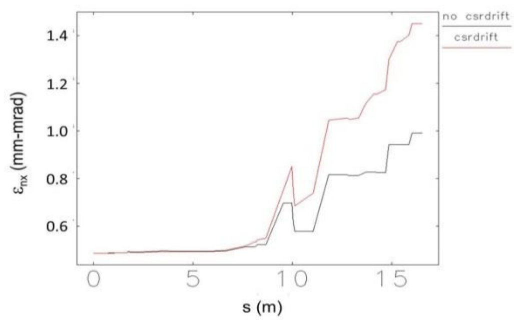

Figure 8: Emittance evolution through line without and with CSR edge effects.

A careful analysis of μBI effects confirms this observation [13]; instability gain is extremely low. Figure 9 gives the microbunching gain, and Figure 10 the spectrum, for a compressor of this type operated at 0.75 GeV with a beam of 0.75 μm-rad emittance and 70 pC. Initial bunch length was ~4 psec, uncorrelated δp/p was $1.13x10^{-5}$, and the compression factor was ~53.

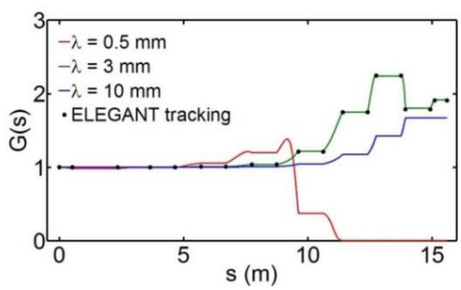

Figure 9: Microbunching gain through compressor.

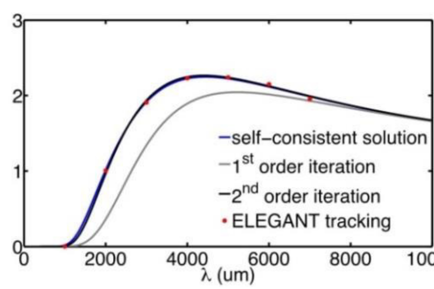

Figure 10: Gain spectrum for modulated compressor.

FUTURE DIRECTIONS

This discussion is only a demonstration of the method; the example is not fully optimized with regard to distribution of bending, choice of betatron match, edge radiation, FODO cell length, or lattice parameters. Future work will invoke such optimization, and will seek to suppress the effects of interaction of the forward-propagating CSR field with the bunch.

This method can in principle be extended to higher energy and is therefore of use in proposed short-wavelength FEL drivers [14].

CONCLUSIONS

We find that positive compaction (M_{56}>0) compression is an effective and advantageous parametric choice, as it may avoid both parasitic compressions [15] and microbunching. Optics balance can provide emittance compensation during compression (just as in well-designed chicane compressors). Wake signatures on longitudinal phase space can be managed in same way as RF curvature and lattice aberrations, by using nonlinear magnetic compensation.

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