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THREE-DIMENSIONAL RADIATIVE EFFECTS IN THE COMPRESSION OF ULTRA-SHORT ELECTRON MICRO-BUNCHES

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Abstract

Micro-bunched current profiles have recently gained traction as an alternative to bulk compression in certain free-electron laser applications. The attraction of the micro-bunched structure is owed in part to its promise to minimize deleterious effects associated with coherent synchrotron radiation (CSR) during compression. Simultaneously, these profiles push the boundaries of traditional one-dimensional CSR simulation models which assume the bunch length to far exceed the transverse beam size in the bunch rest frame - an assumption which may be violated by the sub-micron length micro-bunches. Here we present simulation studies of the impact of three-dimensional CSR effects on micro-bunching based compression schemes using the General Particle Tracer code.

INTRODUCTION

Many recent innovative approaches towards x-ray free-electron laser (XFEL) design and application have demanded the use of micro-bunched current profiles. In these XFEL architectures the beam is manipulated longitudinally so as to generate ultra-short density spikes of sub-µm length. Such density spikes have been produced experimentally at the LCLS by the XLEAP team using both a collective self-modulation process [1] as well as the inverse free-electron laser (IFEL) interaction between the beam and a 2 µm seed laser in a wiggler [2]. As for planned experimental work, two innovative XFEL designs have been proposed which would utilize micro-bunching as a means of mitigating beam quality degradation. The ultra-compact x-ray free-electron laser (UC-XFEL) would aim in its early stages to produce 1 nm soft x-ray radiation using a 1 GeV electron beam, enabled in part by its novel compression scheme whereby bulk compression is substituted by IFEL compression [3]. The matter-radiation interactions in extremes (MaRIE) project would employ a similar compression scheme at a different extreme of the XFEL parameter range: using a 12 GeV electron beam to produce 42+ keV photons [4].

With this intense interest in the applications of sub-µm micro-bunches comes a concomitant scrutiny towards the numerical methods used to study their formation. Of particular concern is the question of the validity of the one-dimensional model of coherent synchrotron radiation (CSR) effects employed by the common beamline design software elegant [5]. Traditionally the validity of the 1D algorithm is evaluated via the Derbenev criterion [6], $D = \sigma_x (R\sigma_z^2)^{-1/3} \ll 1$ where σ_x is the transverse beam size, σ_z is the longitudinal beam size, and R is the bending radius in the bunch compressor. For typical bunch compressors this rarely falls above or even close to unity, however in μ-bunched systems with $\sigma_z < 1\,\mu$m this can cease to be the case. As such, we present here a study of the impact of 3D effects during the compression of ultra-short micro-bunches in the particular context of the UC-XFEL.

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COMPRESSOR CONFIGURATION

For the purpose of these studies we will be examining the second chicane in the UC-XFEL design, which is a conventional four-dipole chicane [3]. The parameters of the chicane and the beam at the chicane entrance are listed in Table 1. Some parameters deserve some additional clarification here. The primary drift length of the chicane corresponds to that between the first and second, and third and fourth magnets which actually contribute to the momentum compaction. The secondary drift length is that between the second and third magnets which provides no momentum compaction, but will slightly modify the optics of the chicane. Furthermore, as in the UC-XFEL design we will consider a beam which is sinusoidally chirped via the IFEL mechanism [7], by which the energy distribution is modulated as $\gamma_f = \gamma_i + A\sigma_\gamma \sin(k_L s_i)$ where A is the IFEL modulation amplitude, σ_γ is the slice energy spread of the beam before modulation, and $k_L = 2\pi/\lambda_L$ is the wavenumber of the modulating laser. We will perform these studies using an ideal beam created with the rms parameters of the UC-XFEL beam at the entrance to the chicane. The reason for this is to ensure that any results we extract from

Table 1: Second UC-XFEL Chicane Parameters

Chicane Parameter	Variable	Unit	Value
Magnet Length	L_B	m	0.1
Primary Drift Length	L_D	m	1
Secondary Drift Length	L_{D2}	m	0.1
Momentum Compaction	R_{56}	mm	1.3
Input Beam Parameter	**Variable**	**Unit**	**Value**
Energy	γmc^2	GeV	1
Current	I_0	A	400
Slice Emittance	ϵ_{nx}	nm rad	55
Slice Energy Spread	$\sigma_\gamma mc^2$	keV	34
IFEL Amplitude	A	σ_γ	34
IFEL Wavelength	λ_L	µm	10

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these studies is a result of the CSR effect in general and not some particular nuance of the beam distribution. We have performed all of the simulations to follow using the General Particle Tracer (GPT) code [8], which includes a novel 3D CSR model [9, 10] which has been shown to compare well against more computationally expensive models like those employed in CSRTrack [11]. Unless otherwise specified these simulations are performed including the effects of both the velocity and radiation terms in the Lienerd-Wiechert fields. We will also use elegant for benchmarking against a 1D model, where unless otherwise specified the impact of longitudinal space charge (LSC) has been included in addition to CSR. Finally, the simulations to follow make use of 500k macroparticles within one 10 µm modulation period.

OPTICS DEPENDENCE OF EMITTANCE GROWTH

In the standard 1D approach to compressor design with CSR, the most common strategy for mitigating emittance growth is bringing the beam to a focus somewhere within the last dipole. By doing so, one maximizes the angular spread at the point where the angular kick from CSR is largest, thereby mitigating its relative impact. Here we would like to both evaluate the continued validity of this assumption and also determine the ideal entrance beta function at this ideal focusing condition. The former is studied in Fig. 1 where we have fixed the input beta function at 10 m and varied the input focusing parameter α The same trend is clear in both the elegant and the GPT results: the emittance growth is minimized when $\alpha = 4$. Indeed, this is very nearly what one would estimate by approximating the dynamics in the chicane as a drift and using the well-known expressions for the Twiss parameter evolution (see, for example, [12]):

$$\beta(z) = \beta(z_{\text{waist}}) \left[1 + \left(\frac{z - z_{\text{waist}}}{\beta(z_{\text{waist}})} \right)^2 \right] \tag{1}$$

and $\alpha(z) = -\beta'(z)/2$. Based on these, with $z - z_{\text{waist}} = 2.6$ m and $\beta(z) = 10$ m, one would estimate that the beam would reach a waist at the end of the final dipole with $\alpha = 3.7$. Additionally we see that for this input β function the estimate of the emittance growth produced by elegant is larger than that predicted by GPT across the entire range, consistent with [10].

The next question of interest is the choice of optimal input beam size, assuming that one is still focusing at the same location within the final dipole. To examine this we have shown in Fig. 2 the final maximum slice emittance as the input beta function is scanned, where in each case we have chosen α to focus at the end of the chicane for optimal emittance preservation. Here we find that when the input beam is too small, the emittance growth is dramatically enhanced. At some threshold beam size, which in our case seems to be around a beta function of 40 m, the emittance reduces to some stable value which is just a few nm rad larger than the input emittance. Simultaneously, we observe very

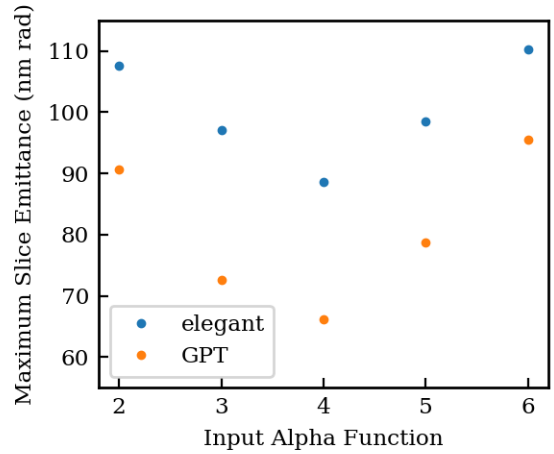

Figure 1: The dependence of the final slice emittance on the input Twiss alpha function is shown as obtained from elegant and from GPT.

good agreement between elegant and GPT at the larger beam sizes, and progressively worse agreement for smaller beam sizes. This initially seems counter-intuitive, as 1D models are more accurate when the beam size is smaller. There is no actual contradiction, however, as the emittance growth occurs primarily at the beam waist, where the beta function will be larger for smaller input beams.

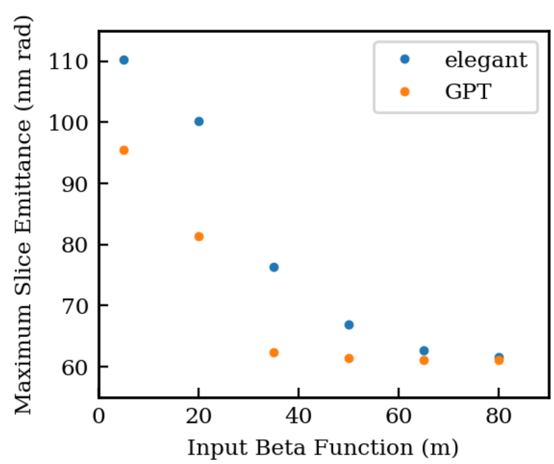

Figure 2: The dependence of the final slice emittance on the input Twiss beta function is shown as obtained from elegant and from GPT.

CLOSER MODEL COMPARISON

It is now worthwhile to examine where the source of the deviations between the 1D and 3D models lies. For this reason, we have performed simulations of the compressor using both GPT and elegant with a variety of settings employed in both. This affords us an opportunity to isolate the impact of the two collective effects at work in the chicane:

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CSR and longitudinal space charge (LSC), represented by the Coulomb contribution to the Lienerd-Wiechert fields. In GPT, one may make the simulation ignore the Coulomb term in the Lienerd-Wiechert fields, thereby amounting to a purely radiative calculation of the collective effects in the chicane. We show the slice emittance after compression for four different relevant scenarios in Fig. 3. We should note that GPT without the Coulomb term and elegant without LSC do not represent exactly the same physical scenarios on account of the model used in elegant, which includes some of the Coulomb term in its CSR calculation through the "re-normalization" procedure described in Ref. [13]. The particular case under consideration here is $\beta = 10$ m and $\alpha = 4$, chosen so as to display an obvious discrepancy that can be clearly examined.

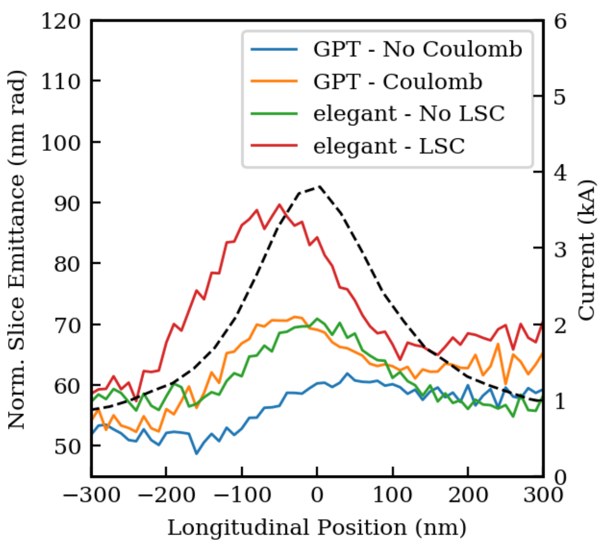

Figure 3: The slice emittance as predicted from GPT and elegant with and without their respective inclusion of Coulomb effects is plotted for $\beta = 10$ m. The black dashed line shows the current profile.

The comparison with the 1D model is consistent with the results of [10], which also found that the 1D model overestimated emittance growth effects. Interestingly, even for this large final beam size case the emittance growth due to purely radiative effects is minimal, and the larger proportion of the emittance growth is contributed by the Coulomb field. The large representation of the space-charge contribution is also realized in elegant, however it is on top of an already noticeable emittance growth from CSR. Interestingly, this case corresponds to a maximal Derbenev parameter D of just 0.2, implying that the onset of the disagreement between 1D and 3D results can be considered to begin when D is still relatively small compared to 1.

With that said, we now look in Fig. 4 at a case where the agreement is quite good, when $\beta = 80$ m at the chicane entrance, in which case the Derbenev parameter D is maximally roughly 0.08. In this case, both elegant and GPT predict similar final maximal emittance growths of 60 nm.

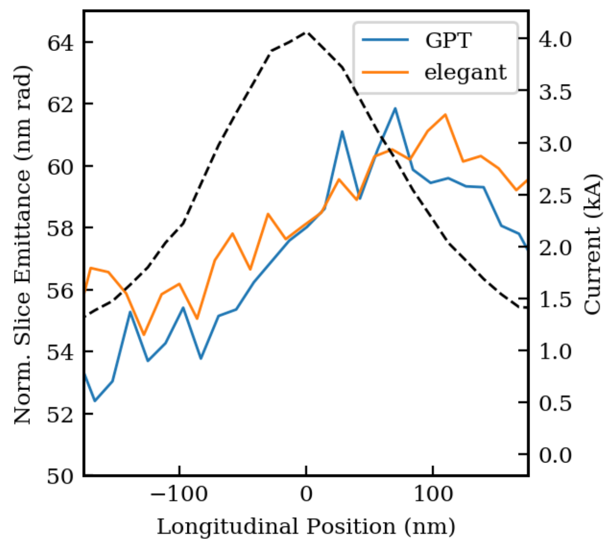

Figure 4: The slice emittance as predicted from GPT and elegant for a large input beam of $\beta = 80$ m is shown. The black dashed line shows the current profile.

As a final remark we would like to note that GPT shows an additional feature where some slices have an emittance reduced below the nominal value of 55 nm rad whereas others have increased emittance. In the presented low-emittance parameter regime the effect seems to be too small to actually benefit the final application of the beam, but it might be relevant for other cases.

SUMMARY

We have presented a study of the impact of 3D effects during the compression of ultra-short electron micro-bunches. These studies have re-affirmed that the typical design strategies employed to mitigate CSR emittance growth still hold for a 3D model, and further that the 1D model in this case tends to over-estimate the emittance growth. Some complicated slice dynamics are observed which tend to decrease the slice emittance below its nominal value at the cost of increasing the slice emittance in other portions of the beam, but appears to be quite a small effect which further does not improve the slice emittance where the beam current is largest. Nonetheless, it may be more interesting for a beam of larger initial emittance.

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