A STUDY OF CSR INDUCED MICROBUNCHING USING NUMERICAL SIMULATIONS

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Abstract

Microbunching due to Coherent Synchrotron Radiation (CSR) has been predicted for high density bunches and has been 'observed' in numerical simulations using the code ELEGANT, which uses a 1-dimensional model of CSR. However, there is currently a debate as to whether this microbunching is a real physical effect or is a numerical artefact introduced by the use of macroparticles in the simulation. Microbunching in ELEGANT has been studied as a function of the numerical parameters of the code for bunch parameters relevant to the proposed 4GLS facility, using up to 3M particles. The minimum length of the bunch need to transport a 1 nC bunch round the arc has been investigated for different energy spreads.

INTRODUCTION

CSR induced microbunching in high charge density bunches has been studied theoretically (see for example [1,2]). Observations of bursts of THz radiation have been attributed to CSR induced microbunching ([3] and references therein). The proposed 4GLS at Daresbury [4] requires high charge bunches for the FELs, and in the conceptual design these bunches need to be transported round a 180-degree arc. Therefore it is important to be able to predict correctly the bunch properties required to enable a high charge to be transported to the FEL without severe disruption of the bunch.

The code ELEGANT [5] has been used to simulate CSR microbunching, but the size of the microbunching can vary with the number of macroparticles used, for example as reported by Kim et al for the TESLA-XFEL bunch compressors [6]. Hence we have made an investigation of the convergence of the solutions from ELEGANT for a test bunch of relevance to 4GLS.

Secondly, we have studied the minimum bunch length needed to transport a 1 nC bunch round an arc without significant disruption to ensure that compression after the arc is feasible for the FELs.

4GLS SIMULATIONS

The model for a 4GLS arc is taken to consist of five isochronous triple-bend achromat cells with 0.5T bending magnets [7]. This transports 600MeV 1 nC bunches, which for these simulations were assumed to be Gaussian-distributed transversely, longitudinally and in energy.

Convergence Tests

A test bunch was used of rms length 256 μm (equivalent to FWHM of 2 ps), rms relative energy spread of 0.1% and normalised emittance of 1 mm-mrad. Halton sequences were used to populate the Gaussian distributions to obtain initial smooth distributions. The radices used for the phase space parameters (x,x',y,y',t,p) were mainly (2,3,2,3,2,3) with pair-wise randomisation as suggested in the ELEGANT User Guide [8]. This is denoted Halton1. Some calculations were also carried out using the radices (3,2,3,2,3,2) (Halton2) .

ELEGANT can provide the linear charge density (used to calculate CSR) at user defined locations through the bending magnets. In Figure 1 are shown three sample linear charge densities at the end of the last arc bending magnet, calculated with different numbers of macroparticles.

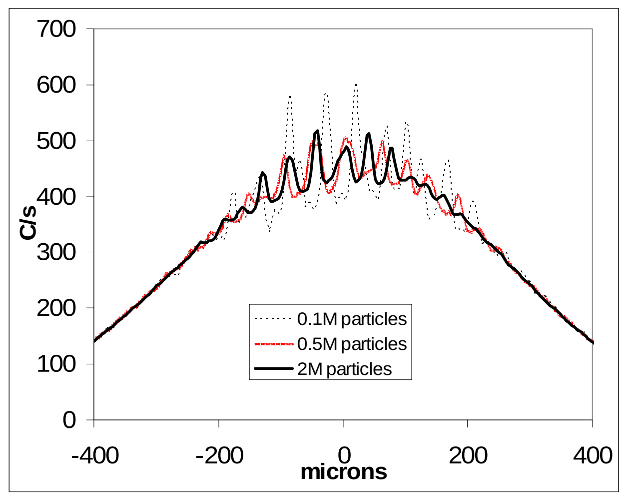

Figure 1: Linear charge density at the end of the last arc dipole for different numbers of macroparticles.

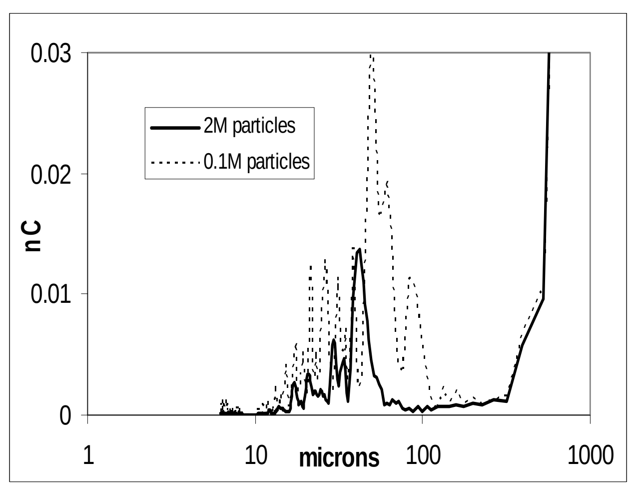

Figure 2: Power spectra of the linear density at the end of the last arc dipole as a function of wavelength for different numbers of macroparticles.

Figure 2 gives sample power spectra generated from the linear charge density, as a function of the wavelength of the bunching, again for 'Halton1' populated bunches. In order to quantify the microbunching the power spectra have been integrated from 15 to 300 μm. The integrated values have been plotted against the number of macroparticles in Figure 3.

The effect of micro-bunching in the linear charge density appears smaller at the end of the last dipole since the dispersion is basically zero. To cross-check these results, the power spectra were also calculated at the mid-point of the last bending magnet, where the dispersion is about 0.02 m. The integrated power spectra are larger but the same trends apply. Microbunching is still observed with 3 million macro-particles and – taking random errors into account - it appears that convergence has approximately been obtained by 1 million macro-particles. For the calculations in the next section, where we are looking at regimes where the micro-bunching is smaller, we have used 1 million macro-particles.

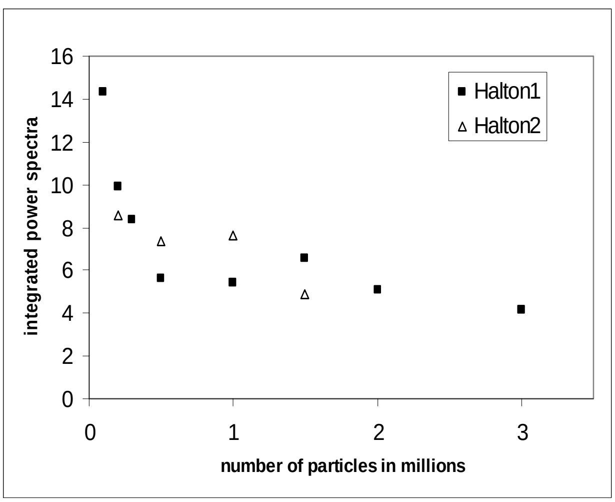

Figure 3: Sums of power spectra as a function of number of macro-particles for different type of bunch distributions.

The above calculations were carried out using 600 bins to form the histograms of linear charge density (see ELEGANT User Guide [8]). The number of bins was increased and it was found that the micro-bunching increased slightly, convergence being obtained at around 2000 bins. It is assumed that the trend with number of macro-particles is not altered when the number of histogram bins increases, and a spot check with 1 million and 1.5 million particles with 2048 bins confirms this, with the sums of the power spectra at the end of the last dipole being 11.7 and 12.8 respectively.

Figure 4 shows the horizontal displacement and relative momentum distributions at the end of the arc for the test bunch with 3 million particles. The microbunching is seen clearly in the transverse displacement.

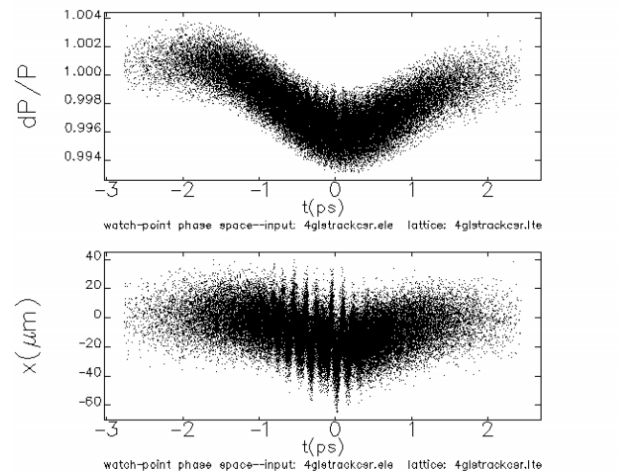

Figure 4: Distributions of horizontal displacement and relative momentum at the end of the arc for the test bunch with 3 million macro-particles.

CSR as a Function of Bunch Length and Energy Spread

The degree of microbunching has been investigated as a function of bunch length, for different relative energy spreads, using a normalised emittance of 1 mm mrad. We used 1 million particles and 2048 bins in the calculation of the linear density histograms.

The sums of the power spectra from 15 to 300 μm at the mid-point of the last dipole in the arc - where any microbunching should be more obvious - are given in Figure 5 for a range of bunch lengths and energy spreads. For comparison, calculations were also carried out with no CSR for a few cases where the micro-bunching is small – it is found that without CSR the power spectra sums at the midpoint of the last magnet were about unity. These results are summarised in Table 1. It is seen that for bunches with rms lengths of greater than 900 μm, the microbunching is small even for a relative energy spread of 0.01%.

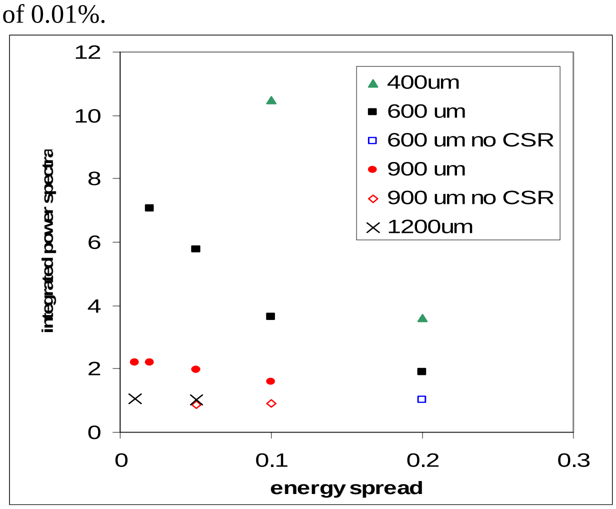

Figure 5: Sums of power spectra at the mid-point in the last arc magnet, as function of energy spread and bunch length.

Table 1: Power spectra summed from 15 to 300 µm for different bunches at the start of the first dipole, at the midpoint at the end of the last magnet.

Length µm	dE/E %	1^{st} dipole	Midpnt last dipole CSR/noCSR	End last dipole CSR/noCSR
600	0.2	0.16	1.89/1.03	0.29/0.26
900	0.1	0.12	1.59/0.9	0.24/0.22
900	0.05	0.12	1.96/0.89	0.27/0.22
900	0.01	0.17	2.21/-	0.30/-

The energy loss due to CSR was roughly independent of energy spread and varied from about 0.25% for the 256 µm bunches to about 0.03% for the 1200 µm bunches.

In reality, smooth current distributions will not be obtained from the injection system. As a first step in looking at noisy bunches we have used pseudo-random sequences to populate the distributions of a bunch with rms length of 900 µm and energy spread of 0.01%.

Figure 6 shows the current density at the start of the first dipole, at the mid-point of the last dipole and at the end of the last dipole. The sums of the power spectra from 15 to 300 µm are 1.75 at the start of the arc, 3.65 at the mid-point of the last magnet and 2.15 at the end of the last magnet. In other words, the microbunching gain is only about 20% if the dispersion is small.

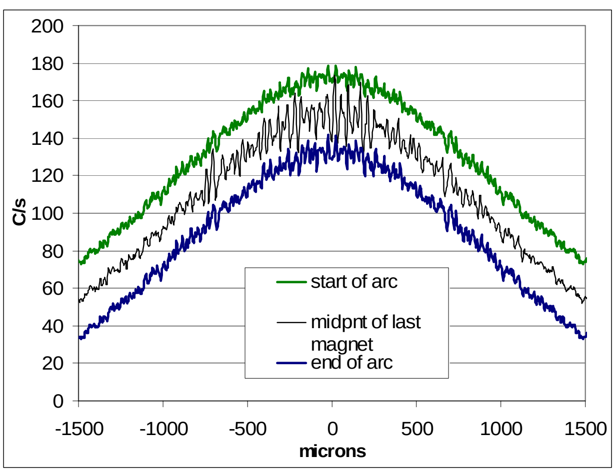

Figure 6: Current density for a bunch of rms length 900µm, initial energy spread of 0.01% rms, pseudo-random population of the bunch distributions. The upper curves have been offset for clarity - top curve start of first dipole, bottom curve end of last dipole.

CONCLUSIONS AND FURTHER WORK

The degree of CSR induced microbunching calculated using ELEGANT depends on the number of macro-particles used, but converged results have been obtained with a large number of macro-particles - in this case of the order of a million - with the microbunching still evident.

For the 0.5T isochronous arc, which is a possible model for the arcs in 4GLS, microbunching should not adversely disrupt the 1 nC bunches if the rms bunch length is greater than or the order of 1 mm. This of course needs cross-checking with realistic bunch distributions rather than ideal Gaussian bunches. The additional micro-bunching induced in any bunch compression has also to be considered.

Earlier work [7] suggested that increasing the field strength in the bending magnets decreased the effect of CSR as any increase in CSR due to the higher field was more than compensated by the shorter path length. Further work is needed to investigate the variation of microbunching with dipole field strength.

Finally, it must be remembered that the model of CSR used in ELEGANT is one dimensional and comparison with the results of three dimensional codes has not yet been possible owing to the large number of macroparticles required.

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