GROWTH OF DENSITY MODULATIONS IN AN ENERGY RECOVERY LINAC LIGHT SOURCE DUE TO COHERENT SYNCHROTRON RADIATION AND LONGITUDINAL SPACE CHARGE*

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Abstract

An Energy Recovery Linac (ERL) is one possibility for an upgrade to the Advanced Photon Source (APS). Such a system involves not only a long linac, but also long transport lines with many dipole magnets. Since the bunches are short, we may expect that coherent synchrotron radiation (CSR) and longitudial space charge (LSC) will have an effect on the beam dynamics. Although previous studies have shown minimal effects for an initially quiet beam distribution, the possibility of a microbunching instability seeded by initial density modulation must be evaluated. We present and discuss simulation results showing the growth of density modulations in two possible lattices for an ERL upgrade of the APS.

INTRODUCTION

The first hint that CSR could amplify initial density modulations in a beam in a single-pass system came from modeling [1] of the Linac Coherent Light Source (LCLS) with `elegant` [2]. Subsequently, theoretical analysis [3] for the TESLA Test Facility predicted an even more severe problem when LSC was included. This was subsequently confirmed by modeling with `elegant` for the LCLS [4]. What is critical in the LCLS and other similar systems is the alternation between long linear accelerators in which LSC effects accumulate and one or more bunch compression systems in which CSR effects act.

An ERL [5] upgrade to the APS promises a revolutionary improvement in x-ray properties. We have developed a concept for an "ultimate" ERL upgrade to the APS [6] that involves a long, single-pass 7-GeV linac and a large 7-GeV turn-around arc. The potential for build-up of CSR and LSC effects in such a system seems clear, due to the length of the linac and transport line, as well as the large number of dipole magnets. In addition, the bunch duration is relatively short ($\sim$2 ps rms) and the normalized emittance is very small ($\sim 0.1\ \mu$m), as is the rms fractional momentum spread ($\sim 0.02\%$). Like the LCLS and other high-performance injectors, the ERL injector is likely to be driven by a shaped laser pulse [7], which opens up the possibility that significant density ripples will be imparted to the beam at the cathode. Hence, in spite of the low charge (under 100 pC), there is reason to be concerned about potential microbunching growth.

We've investigated this for two possible optical configurations of the ERL: (1) The original "TBA" configuration [6, 8], with triple-bend-achromat (TBA) cells outside the APS and double-bend-achromat (DBA) cells inside the APS. (2) A new DBA configuration, with DBA cells throughout. A comparison of these configurations is offered elsewhere in these proceedings.

In the present work, we begin our simulations at the 10-MeV point. Full simulations starting at the cathode are obviously desirable, but beyond our scope at this time.

SIMULATION METHODS

The approach we have taken is very similar to what was done for LCLS and FERMI [9, 4, 10], where we obtained a growth curve for density modulations. We performed a series of simulations for various bunch charge, modulation wavelength, and modulation depth with CSR, LSC, and linac longitudinal wakefields. CSR was included using `elegant`'s line-charge model [11, 12], including CSR in drift spaces. This model includes the transient build-up of CSR in each dipole, but does not include shielding. Shielding will in fact have some effect on the "bulk CSR," i.e., CSR at the wavelengths related to the overall bunch length [13]. However, it will have a significantly diminished effect at the shorter wavelengths corresponding to density modulations.

LSC was included using an impedance-based method [4]. An LSC kick was added after each linac structure as well as at the center of each ID straight section. This made use of a newly-added feature in `elegant`, namely, the ability to insert an LSC kick that integrates the effect of an LSC applied over a user-specified length of the beamline. This approach is valid as long as the relative longitudinal motion of particles is not too great, which is the case when we place kicks at each ID straight section.

Control of noise is essential to getting reliable results. We followed the algorithm in [4, 10] fairly closely: 1. Choose a density modulation wavelength and depth. We used depth values between 0 and 10%, inclusive. The 0% runs are helpful in baselining the effects of noise. 2. Choose the bin size to be 1/24$^{\rm th}$ of the wavelength. This means the Nyquist frequency is 12 times the wavelength. 3. Set the low-pass noise filter cutoff to 1.5 times the modulation frequency. Combined with item 2, we smooth and interpolate features at the modulation frequency on the

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scale of the bin size. 4. Choose the number of particles such that there are at least 1000 particles per bin in the center of the distribution. This provides additional control of binning noise. 5. Generate a distribution with the desired modulation and the required number of particles. The distribution is Gaussian in the longitudinal coordinate z, with the modulation imposed by multiplying the Gaussian distribution function by $1 + d\cos 2\pi\lambda z$, where λ is the modulation wavelength and d is the modulation depth. 6. Perform tracking, recording time histograms along the system. Unlike the LCLS case, we are in principle interested in the modulation at each straight section. We recorded histograms after each set of linac structures (typically eight cavities) after each achromat in the turn-around arc (TAA), input transport line, APS, and output transport line.

The initial beam parameters were 19 pC/bunch, 0.01% rms energy spread at 10 MeV with a normalized emittance of 0.1 μm [7, 14, 15]. Gaussian distributions were used in all six phase space coordinates. For tracking, we used `Pelegant` [16], the parallel version of `elegant`. Typically 42 processors were used with up to 7.2 million simulation particles, requiring up to 24 hours for a single run. We also performed tracking with 77 pC/bunch and the same initial beam parameters, although in reality the emittance and initial energy spread would be higher.

Analysis of the simulation data used power spectral densities (PSDs) of the longitudinal histograms along the accelerator. For each location s, modulation depth d, wavelength λ, and charge q, we integrated the PSD between $0.9f_0$ and $1.1f_0$ to get a value $E(s,d,\lambda,q)$, where f_0 is the frequency corresponding to λ. The quantity $E'(s,d,\lambda,q) = E(s,d,\lambda,q) - E(s,0,\lambda,q)$ is the adjusted value, with any contribution from noise removed. The quantity $G = \sqrt{E'(s,d,\lambda,q)/E'(0,d,\lambda,q)}$ is the gain relative to the initial modulation strength.

RESULTS AND DISCUSSION

Figures 1 and 2 show the results for the all-DBA lattice, while Figures **??** and **??** show the results for the TBA lattice. What's plotted is the maximum gain seen at any location as a function of the initial modulation wavelength, for several values of the initial modulation depth. Varying the modulation depth helps ensure that results have converged and that we are in the linear regime.

The results of our analysis show the same general features as those for FEL driver linacs: low gain for long wavelengths and increasing gain for shorter wavelengths, but with a cutoff at very short wavelengths. For most cases, we don't see any significant difference as the initial modulation depth is varied. This is typical when the gain is small. However, for the all-DBA lattice with 77 pC/bunch, the gain is somewhat high and it doesn't appear that the results have fully converged. Apparently the maximum gain is $\sim$ 5, so for 1% initial modulation, the depth is only $\pm 5\%$. More work is needed to determine why this hasn't converged, since it should be in the linear regime.

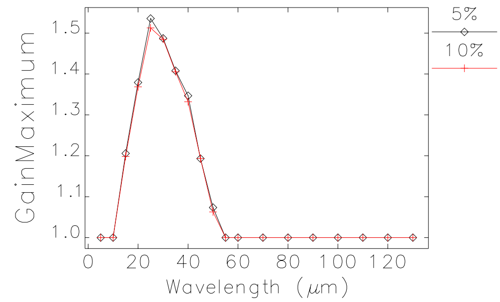

Figure 1: Maximum microbunching gain for 19 pC/bunch in the DBA lattice.

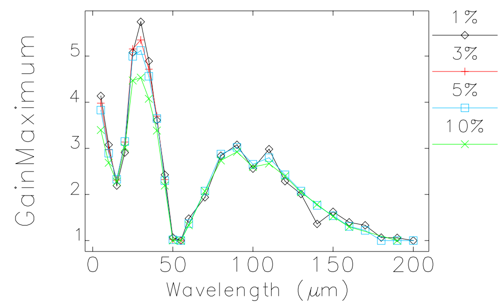

Figure 2: Maximum microbunching gain for 77 pC/bunch in the DBA lattice.

Comparing the results for 19 pC/bunch, the DBA lattice shows about 15% higher maximum gain than the TBA lattice. This is perhaps not unexpected given the larger R_{56} of the all-DBA lattice (0.57m compared to 0.24m).

For 77 pC/bunch, the results are not too different for wavelengths above 50 μm, with the DBA lattice showing about 25% higher maximum gain. However, for short wavelengths the DBA lattice is significantly worse, with maximum gain of $\sim$ 5 compared to $\sim$ 2. Note that the short-wavelength gain for 77 pC/bunch is overstated because we used unrealistically small emittance and energy spread. Exploration of this effect is in progress.

Although the maximum gain is not small, it should not degrade performance for users. For example, Figure 5 com-

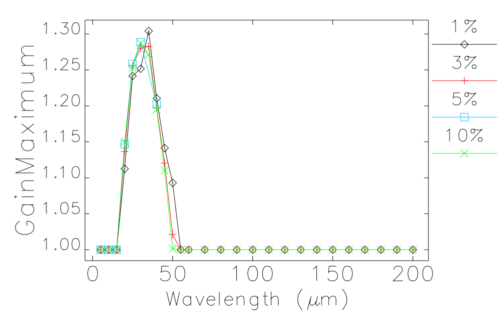

Figure 3: Maximum microbunching gain for 19 pC/bunch in the TBA lattice.

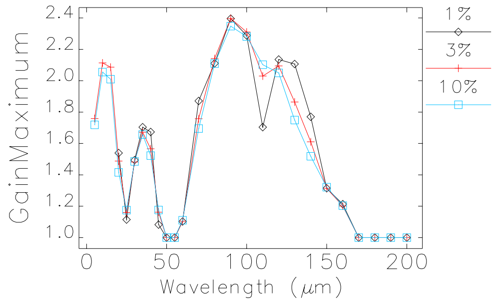

Figure 4: Maximum microbunching gain for 77 pC/bunch in the TBA lattice.

pares the normalized horizontal emittance at the ID straight sections for the DBA lattice with 77 pC/bunch for three cases: 5% and 10% initial modulation depth at 30 μm, and no initial modulation. We see that the effect is negligible.

More interesting, although still negligible, is the effect on the energy spread, shown in Figure 6. We see that the bulk CSR effect (0% modulation) results in a decrease in the energy spread in the turn around arc (TAA), followed by an increase in subsequent sections. That some decrease may occur is plausible given that the initial energy spread of the beam is dominated by rf curvature effects. Bulk CSR tends to flatten the sinusoidal distribution in time-momentum space, resulting in lower energy spread. This can't happen indefinitely and the energy spread begins to increase when the beam transits the stronger dipoles in the Transport Arc into the APS. That this effect would be stronger when a short-wavelength density modulation is present was not expected and is still surprising

Inspection of the longitudinal distribution after deceleration shows no significant effect of the initial modulation. Hence, we have no added concerns about transporting the decelerated beam efficiently.

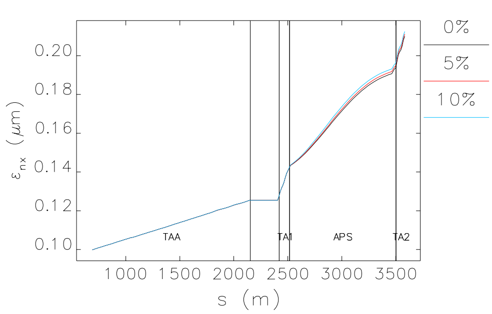

Figure 5: Effect of an initial 30-μm density modulation on the normalized rms horizontal emittance seen at the ID straight sections, for 77 pC/bunch. The line for 5% initial modulation is only slightly above that for 0% modulation. The labels refer to the TAA, input and output transport arcs (TA1 and TA2), and the APS ring.

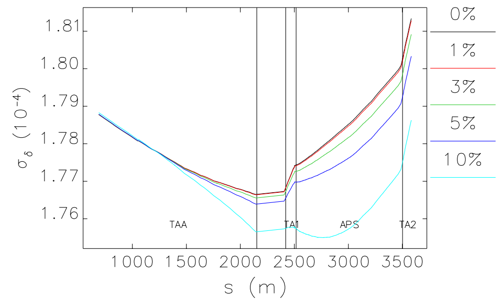

Figure 6: Effect of an initial 30-μm density modulation on the rms fractional energy spread seen at the ID straight sections, for 77 pC/bunch, for various initial modulation depths. See Figure 5 for an explanation of the labels.

CONCLUSION

We have used `Pelegant` to model the propagation of initial density modulations from the 10-MeV point in an APS ERL upgrade. Although significant gain, up to 30-fold, was found for 77 pC/bunch in the all-DBA lattice, it appears this will have little or no impact on the beam quality seen by users. Density modulation growth does not appear to be a strong reason to favor the TBA-based design over the all-DBA design. Additional modeling is needed to extend the simulations to the cathode.

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