Controlling Noise and Choosing Binning Parameters for Reliable CSR and LSC Simulation in `elegant`

—

OAG-TN-2005-027

—

Michael Borland—9/27/2005

—

APS Operations Division, Advanced Photon Source

1 Introduction

A frequent question from `elegant` [1] users is how to select binning parameters for coherent synchrotron radiation (CSR) and longitudinal space charge (LSC) simulation. This brief note attempts to address this issue. The method is also discussed briefly in Appendix A of [2].

Usually, this question arises in the context of simulating instability gain in a linac FEL driver. In such simulations, one deliberately imposes a density or energy modulation on a beam at the input to the system. One wants to determine the gain in the density and energy modulation as a function of the wavelength of the initial modulation.

2 Creating the Initial Distribution

A number of `elegant` users make use of the script `smoothDist6` [3] to generate the density or energy modulated initial beam from the output of a photoinjector simulation. Here, we discuss the method used by this script. The script was fine-tuned to work well for the 200k particle LCLS beam, but should work well for other cases.

1. Make a 1000-bin histogram of t, the time coordinate. Smooth this histogram with a 5-point linear Savitzky-Golay filter, iterated 50 times. To this histogram is added any density modulation the user has requested.

2. Sample this time histogram using a quiet-start method to generate t coordinate values for the requested number of particles. At the same time, generate a quiet normally-distributed coordinate $z_n (n = 1, 2, 3, 4, 6)$ for subsequent creation of x, x', y, y', and δ, respectively, for each t. Note that we will be imposing locally gaussian distributions in the transverse plane and in energy offset.

3. Fit a 12-term polynomial to the (t, p) data, to get $p_{Residual} = p - p_{Fit}$. Compute the average of p_{Fit} and the standard deviation of $p_{Residual}$ vs t for slices of 1000 consecutive particles.

4. Compute the normalized emittances vs t for slices of 1000 consecutive particles. This data is not smoothed. Also, we ignore the variation in beta and alpha from slice to slice.

5. Using these tables of emittances, average momentum, and rms momentum spread vs time, plus the user's values for energy modulation and the desired beta functions, compute x, x', y, y', and δ for each particle created in step 2.

3 Noise Control in LSC and CSR Simulations

The most important part of noise control, particularly for LSC, is proper use of a low-pass filter. For CSR, one can get away without using this feature, but for LSC it is absolutely essential.

One may question whether use of smoothing is workable instead of a low-pass filter. Experience shows that it is not. Typical smoothing algorithms (e.g., nearest neighbor or Savitzky-Golay) are essentially notch filters when seen in frequency space. Because they don't suppress all high frequencies, they can't control noise as well as a low-pass filter.

One may also ask whether one should simply decrease the number of bins for a fixed number of particles, instead of using a low-pass filter. After all, in a sense the low-pass filter just throws away the information content in the closely-spaced bins. However, the low-pass filter gives us an interpolated particle density at the chosen bin spacing, with noise eliminated above a certain frequency. If we simply reduce the number of bins, we are then left with the difficult problem of how to interpolate inside the bins in a way that represents the modulation frequency well. Using the low-pass filter method neatly eliminates this difficulty.

This feature is built into elegant's LSC and CSR algorithms, but it is turned off by default. Turning it on requires setting the `HIGH_FREQUENCY_CUTOFF0` and `HIGH_FREQUENCY_CUTOFF1` parameters. One must set these parameters in such a way that we cut off high frequencies that are not of interest in our simulation, without affecting the signal from, say, a deliberately imposed density modulation on the incoming distribution. Note that in doing so, we are deliberately ignoring anything that might happen with higher frequencies. Depending on how the cutoff frequency is set, this may include, for example, harmonics of the imposed frequency.

The method of choosing the number of bins, number of particles, and cutoff frequency is as follows:

1. Determine the initial full bunch duration B.
2. Choose the minimum initial duration M to simulate. This would correspond, for example, to one's chosen modulation wavelength.
3. Choose the number of bins to be $N = F * B/M$, where $5 \leq F \leq 10$. A higher value for F is generally better, as it determines how well the wake will be interpolated.
4. Choose the number of particles to be $P = R * N$, where $1000 \leq R \leq 3000$. Again, higher is better.
5. Set the cut-off frequency so that it is above the frequency that corresponds to the minimum length scale. The Nyquist frequency corresponds to $F_c = N/(2 * B)$, while the frequency for the minimum length scale is $1/M = N/(F * B)$, giving the ratio of the two as $2/F$. For $F = 10$, the cut-off frequency must be greater than 0.2. In order to simulate the second-harmonic of $1/M$, one must choose a cutoff-frequency greater than 0.4.

Here is a practical example:

1. Assume $B = 4ps$.
2. Assume $M = 0.1ps$.
3. Choose $F = 10$, giving $N = 400$ bins.
4. Choose $R = 3000$, giving $P = 1.2 \times 10^6$ particles.
5. Choose a cutoff of 0.3.

Note that `elegant` requires two cutoff values, `HIGH_FREQUENCY_CUTOFF0` and `HIGH_FREQUENCY_CUTOFF1`. The cutoff filter falls linearly from one to zero starting at the first value and ending with the second. In practice, these may be set to the same value.

References

[1] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000.

[2] Z. Huang *et al*, "Suppression of microbunching instability in the linac coherent light source," Phys. Rev. ST Accel. Beams, **7**, 074401 (2004).

[3] M. Borland, unpublished program.