

# RECENT DEVELOPMENTS IN IMPACT AND APPLICATION TO FUTURE LIGHT SOURCES\*

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## Abstract

This paper discusses two recently added capabilities of the IMPACT suite that are relevant to modeling electron linacs, namely the new 1D coherent synchrotron radiation (CSR) modeling capability and the integrated Green's function (IFG) algorithm for modeling high aspect ratio beams. In addition, we present initial results of application of the enhanced version of IMPACT-Z to high-fidelity modeling of the microbunching instability in a realistic light source lattice.

## INTRODUCTION

The Integrated Map and Particle Accelerator Tracking (IMPACT) code suite was originally developed to model beam dynamics in ion linear accelerators [1]. It has been greatly enhanced and now includes a linac design code, a 3D rms envelope code and two parallel particle-in-cell (PIC) codes: IMPACT-T, a time-based code, and IMPACT-Z, a z-coordinate based code. Presently, the code suite has been increasingly used in simulations of high brightness electron beams for future light sources. These simulations, performed using up to 100 million macroparticles, include effects related to nonlinear magnetic optics, short-range longitudinal and transverse RF structure wake fields, 3D self-consistent space charge, and coherent synchrotron radiation (at present a 1D model). We present illustrations of application for a simulation of the microbunching instability. We conclude with plans of further developments pertinent to future light sources.

## NEW MODELING CAPABILITIES

### Modeling High Aspect Ratio Beams

IMPACT's recently added capabilities were developed to meet the needs of modeling electron linacs. In particular, having a parallel, 3D, self-consistent space charge modeling capability is crucial for modeling the longitudinal space charge-driven microbunching instability in high peak current machines. As shown in Fig. 1 for a "typical" test system, simulations without space-charge effects included can miss entirely the onset and growth of the instability.

Another aspect of modeling high-intensity beams is that there is often a need to model systems that have very high aspect ratios. For example, very high aspect ratios are seen in the beam frame of ultrarelativistic electron beams traveling at  $\gamma \sim 10^2 - 10^3$ . At the same time, simulations have to resolve ultra-low beam loss and be able to model beam

stability and halo formation. The development of the (fully 3D and self-consistent) integrated Green's function

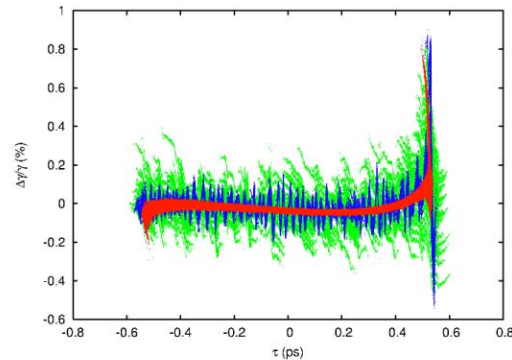


Figure 1: Microbunching instability seen in the longitudinal phase space of the bunch in simulations with 2M particles (green) and 100M particles (blue) with CSR turned off, compared with the no-space-charge, no-CSR result (red).

approach [2] has allowed to increase effective performance of such simulations by two orders of magnitude, as compared to simulations using the standard FFT-based approach to achieve the same level of resolution (Fig.2).

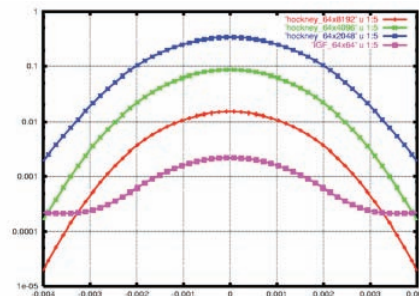


Figure 2: Electric field error (vertical axis) as a function of the position  $x$  (horizontal axis) along the line  $y=0$  inside the Gaussian bunch. Note that IGF on a 64x64 grid (purple) is more accurate than a standard calculation using 64x2048 (blue), 64x4096 (green), and 64x8192 (red).

### 1D CSR Modeling in IMPACT

A new capability that has recently been added to IMPACT is a routine for computing CSR in bend magnets. The CSR is modeled as a one-dimensional longitudinal wakefield. The model implemented in the

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current version is a 1D (zero transverse emittance), steady-state (long magnet, no transient effects) result of Ref. [3], where the change in energy due to CSR is given by

$$\frac{dE}{cdt} = -\frac{2e^2}{3^{1/3} R^{2/3}} \int_{-\infty}^s \frac{ds'}{(s-s')^{1/3}} \frac{d\lambda(s')}{ds'}$$

Numerical evaluation of this expression is complicated by the fact that the integral operator kernel is weakly singular, and the linear charge density  $\lambda(s)$  it operates on is contaminated by numerical noise. Magnitude of this noise depends both on the number of simulation particles and number of grid points, which in practice, for reasons of limited computing resources, almost never can be chosen so as to bring the noise down to the level found in the physical system being modeled. Although the process of deposition of charge onto a grid using the linear (cloud-in-cell) deposition scheme acts as a smoothing filter, yet in our experience the smoothing it provides is insufficient.

Our approach is based on a combination of integration-by-parts, use of custom-designed filters, and treating differently--for the purposes of numerical integration--the regions near and far from the singularity of the integral term's kernel. Specifically, away from the singularity we formally integrate by parts, then numerically evaluate

$$I_1 = C_1 \int_{-\infty}^{s-h} \lambda(s') \frac{ds'}{(s-s')^{4/3}} + C_2 \frac{\lambda(s-h)}{h^{1/3}}$$

where  $C_1$  and  $C_2$  are constant pre-factors, and  $h$  denotes the spacing of the mesh. In doing so we carry out explicit low-pass filtering of the charge density and utilize a low-order numerical integration scheme. For explicit denoising we use filters that come with transfer functions uniformly approaching zero for  $\omega$  close to the Nyquist frequency and which are designed to conserve total charge and guarantee the non-negativity of the resulting filtered distribution density. They also should be computationally inexpensive to apply. An example of filter that satisfies the above criteria and that also performed well in our tests is given by (1/96)[7 24 34 24 7]. (We also use “multilevel” filtering which is beyond the scope of this paper.) It is also advantageous in numerically integrating noisy integrands to use a low-order integration scheme such as the trapezoidal rule which, viewed as a filter, amplifies the near-Nyquist frequency content of the signal to a lesser extent than any of the higher-order integration schemes. Finally, within one mesh spacing,  $h$ , of the singularity we replace  $\lambda(s)$  with a second-order polynomial fit to the smoothed density, and then evaluate the integral over  $[s-h, s]$  analytically.

The resulting CSR routine was tested by simulating the passage through a single bend magnet of two model distributions, one a flat-top density as a function of  $z$  (Fig.3), the other having a sinusoidal charge density

modulation in the  $z$ -direction (Fig. 4). Both were composed of 2M macroparticles and had no initial slice energy spread. In both cases, the agreement is seen to be quite good.

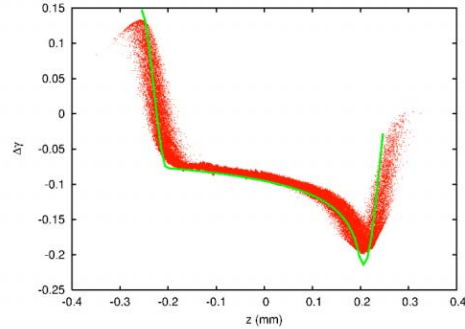


Figure 3: Testing the CSR routine on a single-magnet, flat-top distribution model: analytical result (green) vs. the computed distribution in the longitudinal phase space.

It was confirmed in separate tests that in both these simulations the local energy spread in the final distribution is due to non-zero transverse emittance of the initial distribution and not to residual sampling noise and discreteness of the mesh, whose contribution to the final slice energy spread is negligible by comparison.

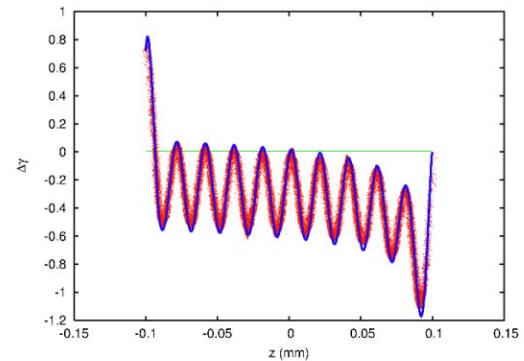


Figure 4: Same as Fig. 3, except a sinusoidal density modulation is superimposed on the flat-top initial distribution. Numerical result (red), analytical prediction (blue), and the initial distribution (green) are shown.

## LIGHT SOURCE MODELING WITH IMPACT

The newly added capabilities allowed us to apply IMPACT to modeling electron linacs for 4<sup>th</sup> generation light sources. Here we present initial results of modeling the LSC-driven microbunching instability in a model linac lattice consisting of two bunch compressors and four linacs totalling 15 RF cavities. The 0.8 nC electron bunch of length  $\sim 1$  ps, initially at  $\sim 100$  MeV, is compressed by a factor of 10 and accelerated to approximately 1 GeV as it goes through the lattice.

Of interest to us were the details of two phenomena, one physical, the other numerical. The physical effect we aimed to model was the suppression of the instability by introducing an uncorrelated energy spread relatively early in the beamline (which in practice can be done, for example, by means of a laser heater [4]). However, numerical simulations of the growth of the instability are easily muddled by a distinct, but closely related numerical effect, namely the amplification of sampling noise during the course of the simulation by the beamline, which acts as an amplifier “unaware” as to whether the input microstructure is physical or numerical in origin. This creates obvious difficulties in interpreting simulation results. While qualitatively it is clear that the smaller the number of simulation particles the less “trustworthy” the results, the details do matter, and the quantitative exploration had until now remained out of reach.

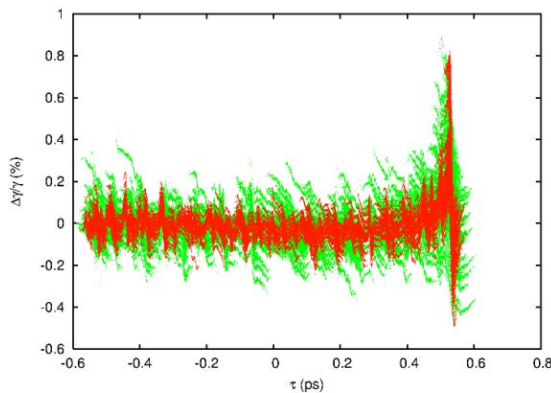


Figure 5: Results of IMPACT simulations of a model linac lattice with varying number of particles sampling the same initial distribution: 2M (green) vs. 20M particles (red). The final distribution’s footprint in the longitudinal phase space of the bunch is shown.

Fig. 5 illustrates the effect of increasing the number of simulation particles from 2M to 20M (a  $64 \times 64 \times 2048$  Cartesian grid was used for all simulations in this paper). The initial slice energy spread of 7.7 keV introduced to mimic the presence of a laser heater grows to  $\sim 940$  keV and  $\sim 530$  keV, respectively, with no indication that saturation should be close at hand. Fig. 6 superimposes the final footprints in the longitudinal phase space for the 20M- and 100M-particle distributions, with the initial local energy spread of 7.7 keV as before. Although the final rms spread is only  $\sim 360$  keV in the 100M-particle run, the combination of the above results and runs

performed with intermediate numbers of particles was found insufficient to draw quantitative conclusions about limiting behavior, if any, that would emerge were the number of macroparticles to approach that in an actual system ( $5 \cdot 10^9$ , in this case). There is no doubt, however, that a simulation with a number of particles of the order of several million or less would grossly exaggerate the magnitude of the instability for relatively low values of the initial slice energy spread.

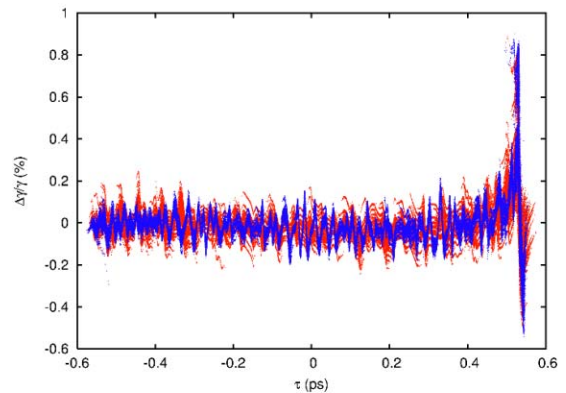


Figure 6: Same as Fig. 5 for 20M particles (red) and 100M particles (blue).

A thorough discussion of this and other related work will be given in an upcoming publication. Our current work and future plans include enabling start-to-end simulations of light sources, as well as adding improved CSR models (transition regions and a 3D model) and the ability to model beam slices with increased precision by using simultaneously two different spatial scales.

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