FAST PARTICLE TRACKING CODE*

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Abstract

This paper presents a fast particle tracking (FPT) code for linac beam dynamics. It includes wake fields, coherent synchrotron radiation (CSR) and longitudinal space charge. We systematically benchmark the FPT with ELEGANT with different physics aspects: pure optics, wakefields, CSR and space-charge forces.

MODEL

The FPT code is originally developed to study the collective effects, including wakefields and CSR. There are two models for CSR: 1D CSR in free space [1] and 2D CSR with resistive wall beam pipe. In the 2D case, the CSR is calculated by another Finite Element Method (FEM) code based on the paraxial equation [2] and input it to FPT. Currently, the transverse collective effect is off. We are able to simply turn on/off different collective effects. These features make the code much fast compared other detail codes, meanwhile it includes the main physics we are interested.

The longitudinal spacing charge (LSC) has been recently added. It includes analytical methods for both round Gaussian and uniform beam model and numerical LSC module. The LSC impedances of a round Gaussian and uniform beam are

$$\frac{Z_{||}^{gau,free}(k)}{L} = i\frac{1}{4\pi\varepsilon_0}\frac{k}{\gamma^2\beta c}e^{-\frac{k^2\sigma_r^2}{2\gamma^2}}Ei(-\frac{k^2\sigma_r^2}{2\gamma^2}) \,, \quad (1)$$

$$\frac{Z_{||}^{rd,free}(k)}{L} = i\frac{1}{k\pi a^2\varepsilon_0\beta c}[1-\frac{ka}{\gamma}K_1(\frac{ka}{\gamma})]. \quad (2)$$

where E_i is the exponential integral function and K_1 is the modified Bessel function of the second kind. Note that the LSC impedance of the Gaussian beam can be approximated as the one of uniform beam with $\sigma = a/\sqrt{2}$ and $\sigma = a/\sqrt{3}$ at short and long wavelength regime, respecttively. But there is no simple approximation at the frequencies near $\frac{ka}{\gamma}{\sim}1$ as shown in Fig. 1. The LSC impedance for arbitrary transverse beam shape with arbitrary beam pipe can be calculated numerically with FEM method [3].

In the following sections we benchmark FPT with ELEGANT with different physics aspects: pure optics, wakefields, CSR and space-charge forces. The collective effects are added step-by-step. In the benchmark we use LCLS-II linac. The initial beam has ideal Gaussian distribution in longitudinal direction with *rms* beam size of 1.0 mm and energy spread of 1.0 keV. The initial beam energy is 100 MeV. The particles are tracked through the linac and we compare the beam after the second bunch compressor (BC2).

WITHOUT COLLECTIVE EFFECTS

To compare different collective effects, it is important to study a case when all collective effects are turned off. This means the wake field, CSR and space charge are not included. The main parameters of the linac set-up are: the rf phase at L1, linearizer and L2 are –12.7, –150 and –15.5 degree, respectively. Figure 2 shows the phase space and current profile after BC2. There is an excellent agreement. The beam energies are 250 MeV and 1.60 GeV at BC1 and BC2, respectively. If we increase the energy at BC2 to 1.647 GeV (we use this energy for the rest of comparisons), the peak current reduced to 1.0 kA due to the reduction of relative energy chirper as shown in Fig. 3. There are excellent agreements for both beam energies when the collective effects are turned off.

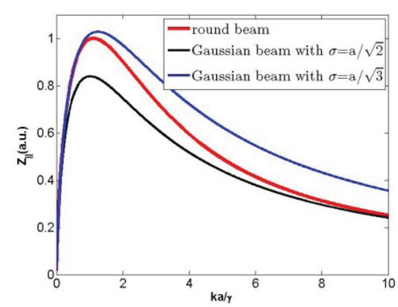

Figure 1: Comparison of the longitudinal space charge impedance of a round uniform and Gaussian beam.

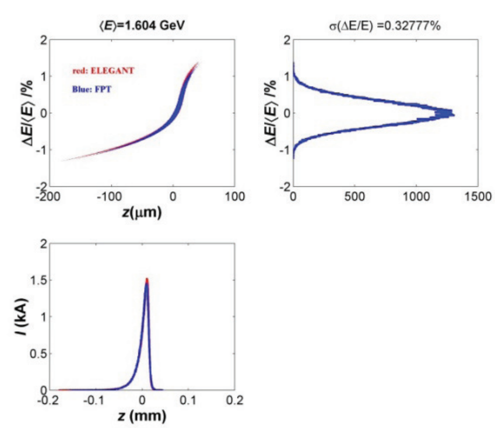

Figure 2: Longitudinal phase space at the end of BC2 without collective effects, beam energy at BC2 is 1.6 GeV. ELEGANT (red); FPT (blue).

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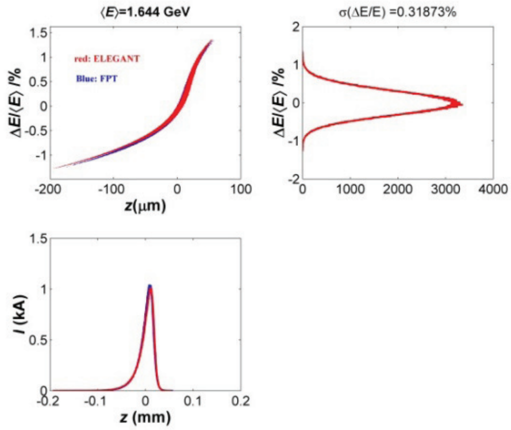

Figure 3: Longitudinal phase space without collective effects. Beam energy at BC2 is 1.644 GeV. ELEGANT (red); FPT (blue).

WAKEFIELDS ONLY

In this case the geometric wake of rf structure and the resistive wall wake are included. We will use a new superconducting linac composed of TESLA-like RF cavities (1.3 GHz) in continuous wave (CW) operation, in order to accelerate a 1 MHz electron beam to 4 GeV. Those wakefields de-chirp the bunch and therefore reduce the final peak current from 1.0 kA (Fig. 3) to 0.8 kA (Fig. 4). There is a 2 km long bypass beamline after the rf linac, the strong resistive wall wake of the beam pipe continue de-chirp the beam and make the phase space flat without changing the peak current. This is typical scheme for LCLS-II to control the energy chirp. Again, Fig. 4 shows excellent agreemens.

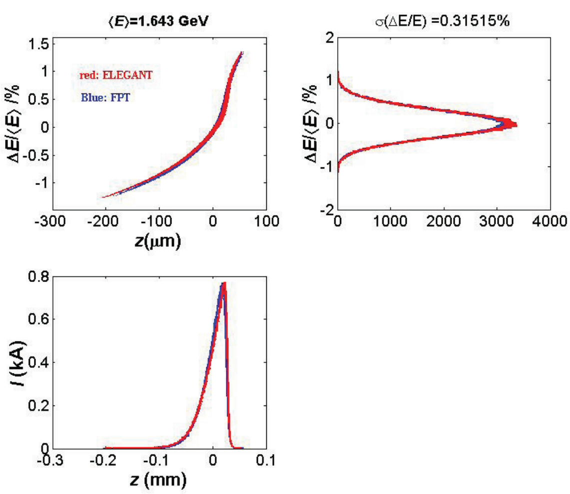

Figure 4: Longitudinal phase space with geometric wake and resistive wall wake effects. ELEGANT (red); FPT (blue).

WAKEFIELDS + CSR

1D free space CSR is used in both codes for this comparison. Similar as wake field effect, the CSR can de-chirp the beam in the longitudinal phase space and therefore can change the beam current profile. This is typical CSR effect in LCLS-II. The CSR in the third bend of BC2 de-chirp the bunch and change the peak current due to the non-zero dispersion there. Although the last bend has stronger CSR and therefore larger energy kicker, it has negligible effect on the current profile due to the very small dispersion there.

Figure 5 shows the phase space at the end of the last bend magnets at BC2. Again the agreement is very good. In our case the CSR in the drift regime after the last bending magnet is not smaller and even larger than the CSR inside the magnet.

2D CSR will be compared with the 1D model late to check the shielding effect. The shielding effect is small for very short bunch. Figure 6 shows the CSR in the last dipole magnet for a wave number k=1e6 [1/m]. The shielding starts to be effective with smaller aperture <8 mm. The actual aperture in LCLS-II design is larger (~40 mm). With such large aperture, the shielding effects on the CSR seen by the beam are small.

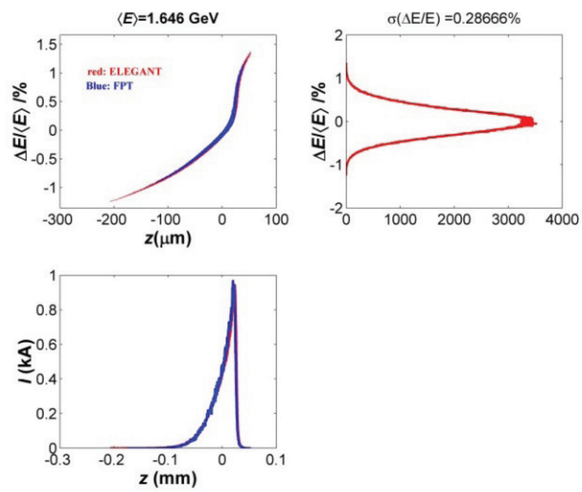

Figure 5: Longitudinal phase space with geometric wake, resistive wall wake and CSR. ELEGANT (red); FPT (blue).

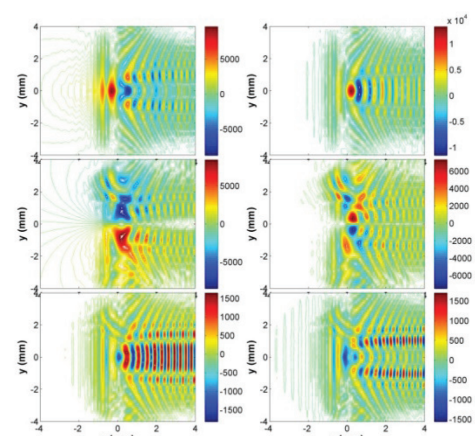

Figure 6: CSR field at the end of last bending magnet for wave number k=1.0e6 [1/m]. The horizontal field (top), vertical field (middle), and longitudinal field (bottom) are shown. Positive x represents outside direction.

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WAKEFIELDS+CSR+LSC

The longitudinal space charge (LSC) effect is finally included. Both codes use 1D space charge model for this comparison. The LSC kicker in FPT is benchmarked with analysis. However the micro-bunching instability has large sensitivity to the numerical issue, such as noise (number of particles used in the simulation, grid size, etc.). ELEGANT uses 50 million macro-particles in the simulation, while FPT uses only 8 million.

Since the shot noise is proportional to the square root of the number of particles, we manually add one window on the LSC impedance by a factor of $\sqrt{N_{sim}/N_{real}}$. Where N_{real} and N_{sim} represents the real number particles and the number of particles used in the simulation, respectively. Note that we only apply this trick before the first bunch compressor (BC1). The results are shown in Fig. 7. The overall de-chirp due to LSC is very similar for both codes because the LSC impedance at Linac 2 (L2) (after BC1) is much larger than that before BC1. So the trick effectively reduces the noise at L2. FPT has smoother current profile simply due to the noise reduction trick at L1. At this moment it is not sure whether this is a proper way to treat the initial noise with less number particles because it is complicated by the grid size used in the simulation.

The bunching factor (Fig. 8) shows a modulation wavelength around 2~3μm. The START-to-END simulations from IMPACT-T/Z and ELEGANT always shows similar spectrum even at the end of linac [4]. This indicates the micro-bunching at that wavelength range is amplified along the downstream of the linac. In theory the simulated wavelength of micro-bunching (resolution) has strong dependence on the slice number, instead of the number of particles.

The micro-bunching instability is complicated by the initial noise and numerical parameters. We shall do further detail studies, such as reducing the initial noise with less number of macro-particles and more damping with 2D LSC. The energy spread due to 2D LSC provides additional damping to the instability. Figure 9 shows the LSC field of a uniform beam. The LSC field over the beam is not uniform. The field has a much larger spread for a Gaussian beam compared to a uniform beam. The spread over a Gaussian beam increases at short wavelength and the 2D effect becomes stronger.

Similar as CSR, LSC may add chirp to the beam and change the overall current profile. The peak current increases when LSC is added (comparing Fig. 5 with Fig. 7). If we are interested in this de-chirp effect, instead of the micro-bunching instability, we can simplify the LSC model to do fast computation: add high frequency pass filter to include the overall de-chirp effect from the LSC as shown in Fig. 10. In this case the requirement for the number of particles is largely reduced.

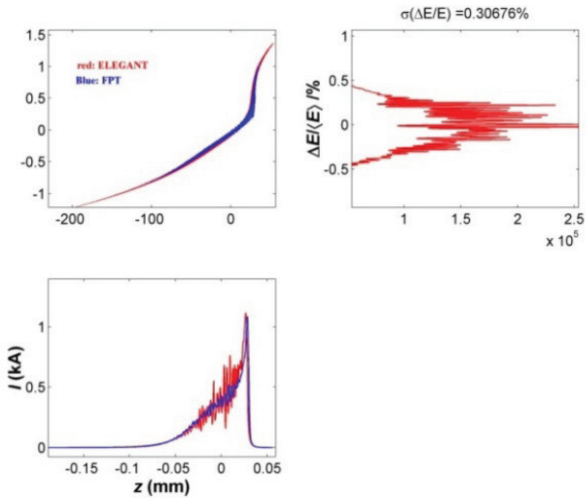

Figure 7: Longitudinal phase space at the end of BC2 with geometric wake, resistive wall wake, CSR and LSC. FPT applies noise reduction trick at L1 and uses 8 million particles, while ELEGANT uses 50 million particles.

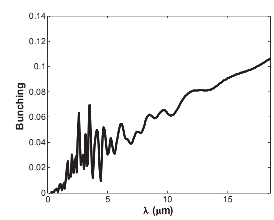

Figure 8: Bunching factor of beam.

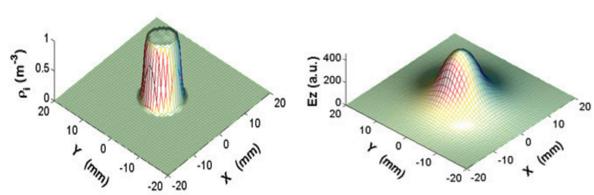

Figure 9: A uniform beam (left) and the LSC electric field (right) in a free space at $\frac{ka}{\gamma} = 1$.

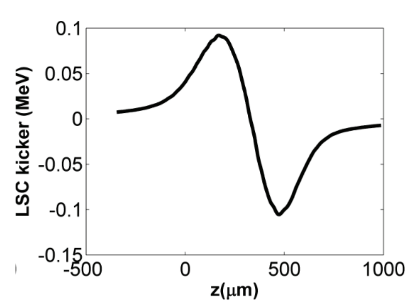

Figure 10: Example the LSC kicker along a Gaussian bunch, bunch head to the left.

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SUMMARY

FPT model with different physics aspects is discussed and it is benchmarked with ELEGANT. There are excellent agreements between FPT and ELEGANT codes for different effects: pure RF linac, wake fields and CSR. There is also good agreement for LSC wake. We will continue to study the micro-bunch instability with better noise reduction schemes and reduced number macro-particles in the simulation. 2D effect of CSR and LSC will be studied.

ACKNOWLEDGEMENTS

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