EBLT: Electron Beam Longitudinal Tracking (forward or backward)
User Manual Version 1.0

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August 19, 2024

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1 Introduction

EBLT is a serial/parallel code for fast electron beam longitudinal forward or backward tracking through an electron linear accelerator. The accelerator includes drift, idealized RF cavities, bending magnet for zero-length chicane or user supplied R56, U566, and T5666, and zero-length marker elements. The collective effects include longitudinal space-charge effect, structure and resistive wall wakefields, and longitudinal coherent synchrotron radiation effect. Each macroparticle has three attributes: Z (m), $\Delta\gamma$, and weight (total charge /np).

To use it as a parallel code, please comment out the *use mpistub* in BeamBunch.f90, rename mpif.h as mpif.hh, and replace Makefile with Makefile_parallel.

2 Input Parameters Excluding Lattice

The following gives a line by line description of the input parameters appearing before the lattice layout used in the input file **eblt.in**. Note, *the comment line starting with* **!** *is not included in the line number.*

Line 1: np, nz, zmin, zmax, flagfwd, flagdist

np Number of macroparticles

nz Number of longitudinal grid points used to calculate collective effects.

zmin Minimum longitudinal z position

zmax Maximum longitudinal z position

flagfwd Switch for forward tracking flagfwd = 1, otherwise backward tracking from the end of the last element

flagdist Switch for different type of initial distributions
= 1; use the polynomial coefficients of current and longitudinal phase
= 2; use the Gaussian current profile and poly. longitudinal phase space
= 100; readin from EBLT particle output
= 200; readin from slice profile file with **np** lines: z(m), x1, current (A), x4, x5, dE/E_0
= 300; readin from particle file with **np** lines: x1, x2, x3, x4, ϕ (rad), -$\Delta\gamma$, x7, total charge/np (C). here, x1, x2,...x7 are not used

Line 2: $a_0, a_1, a_2, ..., a_9$ (current I coefficients)

flagdist = 1; $I(z) = a_0 + a_1 z + a_2 z^2 + \cdots + a_9 z^9$
flagdist = 2; $I(z) = a_0[\frac{a_1}{\sqrt{2\pi}a_3}\exp(-\frac{1}{2}(\frac{z-a_2}{a_3})^2) + \frac{a_4}{\sqrt{2\pi}a_6}\exp(-\frac{1}{2}(\frac{z-a_5}{a_6})^2) + \frac{a_7}{\sqrt{2\pi}a_9}\exp(-\frac{1}{2}(\frac{z-a_8}{a_9})^2)]$

Line 3: b0, b1, b2, ..., b9 (phase space coefficients)

$\Delta\gamma(z) = b_0 + b_1 z + b_2 z^2 + \cdots + b_9 z^9$

Line 4: Iavg, Ek, mass, charge, freq

Iavg: Average current = Q*freq (A)
Ek: Beam kinetic energy (eV)
mass: Particle mass (eV) charge: Particle charge in the unit of positron; charge = -1 for electron
freq: Reference RF frequency (Hz)

3 Lattice Beam Line Elements

Line 5 and beyond, describe the lattice to track through. Each line of lattice input represents one element. The general form of a lattice line is:

```
Blength, Bnseg, Bmpstp, Btype, V1  ...  V7
```

Blength The longitudinal length of the element.

Bnseg, Bmpstp Not used except for the Type less than 0, i.e. the BPM.

Btype Type of element. An integer specifying the type of element.See below for more details.

V1 ... V7 Element parameters. See below for more details.

The following are the specific parameters associated with each element type.

-2, -39, -41, -99: BPM Beam position monitor and etc. blength, Bnseg, Bmpstp, btype, V1, V2, V3, V4, ... V7.

If *btype* $= -2$, output current profile and particle phase-space coordinate information into file fort.Bmpstp and fort.Bmpstp+1 Here, 100/101 and 200/201 should be avoided since these are used for initial and final current and phase space output.

If *btype* $= -39$, increase the beam energy by V1 (eV).

If *btype* $= -41$, wakefield calculation. V1: multiplier of wakefield; V2: read-in wake function file id with name rfdataV2; V3: switch to turn on/off wakefield. (> 0 on, otherwise off)

If *btype* $= -99$ exit lattice.

0: DriftTube Drift space

```
V1: beam radius (m) used in longitudinal space-charge.
```

4: Bend Bend/chicane; if Bmpstp > 0, calculate r56, t566, u5666 for 4 dipole C chicane using bending angle V5, drift between 1st and 2nd bends V2, and blength; otherwise R56 = V2, T566 = V3, U5666 = V4.

```
V1: beam radius (m) used in longitudinal space-charge.
V7: switch for CSR ("1.01"-> IGF CSR including A and B,
"2.01" -> IGF steady state CSR, "0.0"-> no CSR
V8: switch for SC (1 on, otherwise off)
```

103: RF cavity RF cavity model

```
V1: beam radius (m) used in longitudinal space-charge.
V2: accelerating gradient (V/m).
V3: RF frequency (Hz).
V4: design phase (degree).
```

4 Output Data

fort.2 : distance, kin. energy, γ, mean Z, RMS Z, mean $\Delta\gamma$, RMS $\Delta\gamma$

fort.100 : initial current profile (3 columns) - bunch length (m), charge per cell, current (A)

fort.101 : initial particle distribution (4 columns) - z coordinate (m), $\Delta\gamma$, ptcl. weight, dE/E0

fort.50 : user specified (-2) current profile (3 columns) - bunch length (m), charge per cell, current (A)

fort.51 : user specified (-2) particle distribution (4 columns) - z coordinate (m), $\Delta\gamma$, ptcl. weight, dE/E0

fort.200 : final current profile (3 columns) - bunch length (m), charge per cell, current (A)

fort.201 : final particle distribution (4 columns) - z coordinate (m), $\Delta\gamma$, ptcl. weight, dE/E0

5 Physical Models

The physical model in this code is discussed in reference [1]. For a macroparticle transporting through the lumped RF cavity element with total length L_{acc}, its longitudinal coordinates will be updated by the following equations using a leap-frog type of approximation:

$$
\begin{aligned}
z^+ &= z_1 + \frac{L_{acc}}{2}\Delta\gamma_1/(\gamma_{01}\beta_{01})^3 &(1)\\
\gamma_0^+ &= \gamma_{01} + \frac{L_{acc}}{2}\frac{qV_{acc}}{mc^2}\cos(\phi_0) &(2)\\
\Delta\gamma_2 &= \Delta\gamma_1 + L_{acc}\frac{qV_{acc}}{mc^2}(\cos(\phi_0 - kz^+) - \cos(\phi_0)) &(3)\\
z_2 &= z^+ + \frac{L_{acc}}{2}\Delta\gamma_2/(\gamma_0^+\beta_0^+)^3 &(4)\\
\gamma_{02} &= \gamma_0^+ + \frac{L_{acc}}{2}\frac{qV_{acc}}{mc^2}\cos(\phi_0) &(5)
\end{aligned}
$$

where subscript 1 and 2 denote the quantity before and after the lumped cavity element respectively, $V_{acc} = qV_{rf}/L_{acc}$ is the accelerating gradient amplitude, k is the RF wave number, and ϕ_0 is the RF cavity design phase.

The magnetic bunch compression chicane is modeled as a thin lens element. The particle longitudinal position through the chicane is given by:

$$
z = z + R_{56}\frac{\Delta\gamma}{\gamma_0} + T_{566}(\frac{\Delta\gamma}{\gamma_0})^2 + U_{5666}(\frac{\Delta\gamma}{\gamma_0})^3 \qquad (6)
$$

where

$$
\begin{aligned}
R_{56} &\approx 2\theta^2(L_{db} + \frac{2}{3}L_b) &(7)\\
T_{566} &\approx -\frac{3}{2}R_{56} &(8)\\
U_{5666} &\approx 2R_{56} &(9)
\end{aligned}
$$

where θ is the bending angle of one of dipole magnets (assuming that all four dipoles have the same bending angle amplitude), L_b is the length of the dipole magnet, and L_{db} is the distance between the first and the second (or between the third and fourth) dipole bending magnets. From our benchmark with fully 3D element-by-element tracking using 5^{th} order transfer map for the dipole bending magnet, we need to increase the R_{56} by 0.5% in order to match the current profile after the chicane with that from the 3D model.

Collective effects such as longitudinal space-charge effect, structure and resistive wall wakefields, and coherent synchrotron radiation play an important role in the longitudinal beam dynamics and are included in this model. For the longitudinal space-charge effect, instead of using the space-charge impedance model in the frequency domain [2], we assume that the electron beam is a round cylinder with separable uniform transverse density distribution and longitudinal density distribution. The longitudinal space-charge field on the axis is given as:

$$E_z^{sc}(z) = \frac{1}{4\pi\epsilon_0}\frac{2}{a^2}\Big(\int_{z_{min}}^{z}\rho(z')dz' - \int_{z}^{z_{max}}\rho(z')dz' - \int_{z_{min}}^{z_{max}}\frac{\gamma_0(z-z')\rho(z')}{\sqrt{\gamma_0^2(z-z')^2+a^2}}dz'\Big) \tag{10}$$

where a is the radius of the cylinder, z_{min} and z_{max} denote the minimum and the maximum longitudinal bunch length positions, and ρ is the electron beam longitudinal charge density distribution.

The longitudinal wakefields from both the structure wakefields of RF cavities and the resistive wall wakefields are included in the model. The longitudinal field from the wakefields are calculated from the following convolution:

$$E_z^{wk}(z) = \int_{z}^{z_{max}} W_L(z-z')\rho(z')dz' \tag{11}$$

where $W_L(s)$ is the longitudinal wake function.

The coherent synchrotron radiation through a bending magnet can be calculated from the following integral:

$$E_z^{csr}(z) = \int_{z_{min}}^{z} W_{csr}(z,z')\rho(z')dz' \tag{12}$$

where $W_{csr}(s)$ is the longitudinal CSR wake function that includes both transient and steady-state radiations through a bending magnet following Saldin et al. (Case A-D) [3, 4] for the CSR model $flagcsr = 1$. For the CSR model $flagcsr = 2$ [5, 6], where

$$W(u(s)) = \frac{1}{4\pi\epsilon}\frac{\gamma^4}{R^2}\left\{\frac{u^2/4-1}{2(1+u^2/4)^3} + \frac{1/6-u^2/18-u^4/64}{(1+u^2/4)^3(1+u^2/12)^2)}\right\}$$

$$u(s) = (\sqrt{64+144\bar{s}^2}+12\bar{s})^{1/3} - (\sqrt{64+144\bar{s}^2}-12\bar{s})^{1/3} \tag{13}$$

and $\bar{s} = s\gamma^3/R$.

For the steady-state CSR model $flagcsr = 3$ [7],

$$\frac{dE}{cdt} = -\frac{2e^2}{4\pi\epsilon_0 3^{1/3}R^{2/3}}\int_{-\infty}^{s}\frac{1}{(s-s')^{1/3}}\frac{d\lambda(s')}{ds'}ds'.$$

Acknowledgments

This work was supported by the U. S. Department of Energy under Contract no. DE-AC02-05CH11231.

References

[1] J. Qiang, Phys. Rev. Accel. Beams 22, 094401 (2019).

[2] J. Qiang, R. D. Ryne, M. Venturini, A. A. Zholents, and I. V. Pogorelov, Phys. Rev. ST Accel. Beams, vol. 12, 100702, 2009.

[3] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkovb Nuclear Instruments and Methods in Physics Research Section A398 (2012) 373.

[4] C. Mitchell, J. Qiang, R. Ryne., Nuclear Instruments and Methods in Physics Research Section A715 (2013) 119.

[5] J.B. Murphy, S. Krinsky, R.L. Gluckstern Particle Accelerators, 57 (1997), p. 9.

[6] J. Qiang, C. Mitchell, R. Ryne., Nuclear Instruments and Methods in Physics Research Section A682 (2012) 49.

[7] M. Borland, Phys. Rev. ST Accel. Beams 4, 070701 (2001).