

IMPACT-T User Document Version 1.6

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LBNL-62326, 2007

May 17, 2010

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

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1 Introduction

IMPACT-T is a fully three-dimensional program to track relativistic particles taking into account space charge forces and short-range longitudinal and transverse wakefields. IMPACT-T is one of the few codes used in the photoinjector community that has a parallel implementation, making it very useful for high statistics simulations of beam halos and beam diagnostics. It has a comprehensive set of beamline elements, and furthermore allows arbitrary overlap of their fields, which gives the IMPACT-T a capability to model both the standing wave structure and traveling wave structure. It is also unique in its use of space-charge solvers based on an integrated Green function to efficiently and accurately treat beams with large aspect ratio, and a shifted Green function to efficiently treat image charge effects of a cathode [1]. It is also unique in its inclusion of energy binning in the space-charge calculation to model beams with large energy spread. IMPACT-T has a flexible data structure that allows particles to be stored in containers with common characteristics; for photoinjector simulations the containers represent multiple slices, but in other applications they could correspond, e.g., to particles of different species. Together, all these features make IMPACT-T a powerful and versatile tool for modeling beams in photoinjectors and other systems.

2 Five Steps to Run the IMPACT-T Code

- prepare input files (rfdatax or 1Tx.T7) for cavity, solenoid or bending magnets.
- set up IMPACT-T input file, ImpactT.in.
- run phase scan (a python script file) to set up the RF initial phase to match the desired energy gain using a single particle on axis.
- run the IMPACT-T tracking code.
- check the simulation results.

3 Pre Processing

There are three preprocessing programs. The **RFcoefext** takes the discrete field data on axis in `rfdata.in`, extends the data to make a symmetric data, and generates the Fourier coefficients for these extended data and stores them in `rfdataxxx` file for IMPACT-T input use. This file is used when only half of field in the injector is given. *Note, the user should use the output file `rfdata.out` to check whether the input Fourier mode number is sufficient or not by comparing the plot of col. 2 vs. col. 1 with those from `rfdata.in`. Basically, `rfdata.out` contains the reconstructed and extended RF field and its derivatives using the Fourier coefficients.*

The **RFcoefcls** takes the discrete field data, generates the Fourier coefficients of these data directly and stores them in `rfdataxxx`. It also generates a shifted field data in `rfdata.tmp` based on these coefficients. This file will be used to regenerate a Fourier coefficients for the shifted field data, which will be used to model traveling wave field using the summation of two standing wave fields (one field is the shift of the other field). The file `rfdataxx` will be used in the beam line element such as SolRF. The output file `rfdata.out` is the field reconstructed using those Fourier coefficients. This will be used as a good check of the accuracy of Fourier expansion approximation.

A Python scripting program, **ImpactTphase.py**, scans through initial driven phase of the RF cavity in `ImpactT.in` file. It can also be used to scan through other parameters. The user needs to go into the

code to specify the exact location of the parameter. For the phase scan, the output of this scripting file is Engout with column one the driven phase, column five the final energy.

4 Input Parameters Excluding Lattice

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

Line 1: Npcol, Nprow

Npcol Number of columns of processors, used to decompose domain along Y dimension.

Nprow Number of rows of processors, used to decompose domain along Z dimension.

Line 2: Dt, Ntstep, Nbunch

Dt Time step size (secs).

Ntstep Maximum number of time steps. IMPACT-T will stop after Ntstep time steps or the center of the bunch goes beyond the end of the lattice whatever is first.

Nbunch During the simulation of the rf photoinjector, when the laser pulse length is long and the rf acceleration gradient is high, this could cause the electron beam out of the cathode with a significantly large energy spread. In this case, the single Lorentz transform from the beam frame to the lab during the calculation of the space-charge forces is not sufficient. To do this more accurately, the initial distribution of the bunch can be divided into longitudinally into **Nbunch** slices. The Lorentz transformation can be done for each slice/bunch and the total space-charge are summed up. More slices mean better accuracy but at the cost of increased computational time. The computation time increases approximately linearly with Nbunch. When **Nbunch** > 1, more input files named **ImpactT2.in**, **ImpactT3.in**, ...**ImpactTNbunch.in** have to be provided. These input files can have independent definition of the particle information. The total current is distributed among different bunch files. However, the external lattice layout has to be the same. Since each bin/bunch has independent parameters, the IMPACT-T code can be used to simulate a beam with multiple species.

Line 3: Dim, Np, Flagmap, Flagerr, Flagdiag, Flagimg, Zimage

Dim Phase space dimension. Must be set to 6.

Np Number of particles to track.

Flagmap Type of integrator. Currently must be set to 1.

Flagerr Error study flag. 0 - no misalignment and rotation errors; 1 - misalignment and rotation errors are allowed for Quadrupole, Multipole (Sextupole, Octupole, Decapole) and SolRF elements. This function can also be used to simulate the beam transport through rotated beam line elements such as skew quadrupole etc.

Flagdiag Diagnostics flag: 1 - output the information at give time, 2 - output the information at the location of bunch centroid by drifting the particles to that location, 3 or more - no output.

Flagimg Image charge flag. If set to 1 then the image charge forces due to the cathode is included. The cathode is always assumed to be at $z = 0$. To not include the image charge forces sets imchgF to 0.

Zimage z position beyond which image charge forces are neglected. Set z small to speed up the calculation but large enough so that the results are not affected.

Line 4: Nx, Ny, Nz, Flagbc, Xrad, Yrad, Perdlen

Nx Ny Nz Number of mesh points in x , y , and z . For the open boundary condition, currently, they have to be a **power of 2** due to the FFT algorithm used here. In the future, this will be generalized to arbitrary integer number.

Flagbc Field boundary condition flag: Currently must be set to 1 which corresponds to an open boundary condition.

Xrad, Yrad, Perdlen Size of computational domain. Xrad and Yrad define the transverse size, Perdlen defines the longitudinal size. Here, Perdlen has to be greater than the beam line lattice length.

Line 5: Flagdist, Rstartflg, Flagsbstp, Nemission, Temission

Flagdist Type of the initial distribution. This is a number between 1 and 21:

- 1 Uniform - 6d uniform distribution
- 2 Gauss3 - 6d Gaussian distribution
- 3 Waterbag - 6d Waterbag distribution
- 4 Semigauss - 3d Waterbag distribution in spatial and 3d Gaussian distribution in momentum space
- 5 KV3d - transverse KV distribution and longitudinal uniform distribution
- 15 GaussDouble - two 6d Gaussian distribution with same center but different sigmas. The sigmas of each distribution are controlled by two parameters and are defined in subroutine GaussDouble_Dist of the file Distribution.f90.
- 16 Read - read in an initial particle distribution from file **Partcl.data**.
- 17 CylcoldZ - uniform cylinder distribution in spatial with transverse Gaussian and longitudinal half Gaussian in momentum space.
- 18 CylGaussTest - transverse uniform cylinder with longitudinal linear ramp on both ends and a flat top in the longitudinal direction;
In momentum space, transverse Gaussian distribution and longitudinal half Gaussian distribution.
- 19 CylDbGauss - transverse uniform cylinder with longitudinal double Gaussian distribution; 0 initial momentum spread
- 20 UniformChain - N pulse of uniform box distribution in spatial and momentum, and an interval between each pulse
- 21 Streakcam - N pulse of spatial uniform and thermal velocity distribution and an interval between each pulse.
- 22 ParobGauss - transverse parabolic and longitudinal Gaussian distribution in spatial, and transverse Gaussian distribution and longitudinal uniform distribution in momentum.
- 23 CylGauss - transverse uniform and longitudinal Gaussian distribution in spatial, and transverse Gaussian, longitudinal half Gaussian in momentum.
- 24 readParmela - read in Parmela particle format.
- 25 readElegant - read in Elegant particle format.
- 26 CylIsoGauss - uniform cylinder in 3D spatial and semi-Gaussian distribution
- 27 CylcoldZSob - uniform cylinder with longitudinal density modulation in spatial, and Gaussian distribution in momentum space.

The detailed input parameters for each type of initial distribution are define in lines 6-8. See the description of Line 6 - 8 for more information.

Rstartflag If *restartflag* = 1, restart the simulation from the previous check point. If *restartflag* = 0, start the simulation from the beginning.

Flagsbstp Not used.

Nemission There is a time period where the laser is shining on the cathode and electrons are being emitted. *Nemission* gives the number of numerical emission steps. More steps gives more accurate modeling but the computation time varies linearly with the number of steps. Typically *Nemission* is between 10 and 20, depending on laser pulse length. If *Nemission* < 0, there will be no cathode model. The particles are assumed to start in a vacuum.

Temission Laser pulse duration (sec.) *Note, this time needs to be somewhat greater than the real emission time in the initial longitudinal distribution so that the time step size is changed after the whole beam is a few time steps out of the cathode.*

Line 6 - 8 These three lines give the initial distribution parameters in x-px plane, y - py plane and z-pz plane. These lines, along with **distType** as given in line 5, is used to form the initial distribution.

There are 21 parameters for the initial distribution except the read option, which read in the particle data directly from the external file. The parameter names are:

sigx(m), sigpx, muxpx, xscale, pxscale, xmu1(m), xmu2,
 sigy(m), sigpy, mupy, yscale, pyscale, xmu3(m), xmu4,
 sigz(m), sigpz, muzpz, zscale, pzscale, xmu5(m), xmu6

Here, *xscale* and *pxscale* are multipliers for *sigx* and *sigpx*. They are used when the *sigx* and *sigpx* numbers are derived from a match to the lattice and *xscale* and *pxscale* are then used to mismatch the initial distribution. If not used, *xscale* and *pxscale* should just be set to 1. *xmu1-6* define the center offset of the initial distribution. The phase space density is generally written as

$$\rho(\tilde{x}, \tilde{p}_x, \tilde{y}, \tilde{p}_y, \tilde{z}, \tilde{p}_z) = \rho_x(\tilde{x}, \tilde{p}_x) \rho_y(\tilde{y}, \tilde{p}_y) \rho_z(\tilde{z}, \tilde{p}_z) \quad (1)$$

With the phase space coordinates being

$$\begin{aligned} \tilde{x} &= x - xmu1 \\ \tilde{p}_x &= p_x - xmu2 \end{aligned} \quad (2)$$

with similar equations for the other four coordinates.

1 Uniform

$$\rho_x(\tilde{x}, \tilde{p}_x) = \begin{cases} \text{const} & |\tilde{x}| < \frac{\sqrt{3}\tilde{\sigma}_x}{\sqrt{1-\text{muxpx}^2}} \text{ and } |\tilde{p}_x| < \sqrt{3}\tilde{\sigma}_{px}(1 - \frac{\text{muxpx}}{\sqrt{1-\text{muxpx}^2}}) \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where $\tilde{\sigma}_x = \text{sigx}$ and $\tilde{\sigma}_{px} = \text{sigpx}$. For *muxpx* = 0, in (\tilde{x}, \tilde{p}_x) phase space, the distribution is a rectangle of constant density.

2 Gauss3

The form of the density function is

$$\rho_x(\tilde{x}, \tilde{p}_x) \propto e^{-f_x} \quad (4)$$

where

$$f_x(\tilde{x}, \tilde{p}_x) \equiv \frac{\tilde{x}^2}{\tilde{\sigma}_x^2} + \frac{2\tilde{x}\tilde{p}_x\text{muxpx}}{\tilde{\sigma}_x\tilde{\sigma}_{px}} + \frac{\tilde{p}_x^2}{\tilde{\sigma}_{px}^2} \quad (5)$$

with similar forms for ρ_y and ρ_z .

3 Waterbag The form of the density function is

$$\rho_x(\tilde{x}, \tilde{p}_x) = \begin{cases} \text{const} & f_x(\tilde{x}, \tilde{p}_x) < \sqrt{8} \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

where f_x is given in Gauss3. The density is a constant inside of an ellipse.

4 Semigauss Essentially a Waterbag distribution in $(\tilde{x}, \tilde{y}, \tilde{z})$ space and a Gaussian distribution in $(\tilde{p}_x, \tilde{p}_y, \tilde{p}_z)$ space.

5 KV3d $\delta(f_x, f_y)$ -function transversely and uniform longitudinally. Here the transverse distribution is a self-consistent solution of the Poisson-Vlasov equation for a coasting beam. Not a realistic model but good for diagnostic checks.

15 GaussDouble The form of the density function is

$$\rho_x(\tilde{x}, \tilde{p}_x) \propto Ae^{-f_x^1} + Be^{-f_x^2} \quad (7)$$

where f_x^1 and f_x^2 are defined in Gauss3 with different sigmas and A and B are hard wired in the source code, and similar forms for ρ_y and ρ_z .

16 Read Read distribution from an external file. called `partcl.data` Here the file `partcl.data` has the format:

```
nptot
x, px, y, py, z, pz
```

where, nptot is number of lines (i.e. particles) in the file, and $x(m)$, px/mc , $y(m)$, py/mc , $z(m)$, pz/mc are six phase space coordinates. Note: these coordinates will be shifted by the centroid parameters defined in lines 6-8.

17 CylcoldZ Transversely uniform elliptical and uniform longitudinally. Here, sigx and sigy define the transverse edge of the cylinder, sigz defines the half length of the cylinder. The transverse momentum follows a Gaussian distribution with sigpx and sigpy. The longitudinal momentum follows a Semi-Gaussian distribution ($p_z^3 \exp(-\frac{p_z^2}{2sigppz^2})$).

18 CylGaussTest Transversely uniform elliptical distribution with sigx and sigy defining the edge of the distribution. Longitudinal linear ramp for the head and tail with flat top in the middle. The length of flat top is set by pzscale, length of linear ramp is set by zscale, The distribution has Gaussian transverse and longitudinal half Gaussian in momentum space.

19 CylDbGauss Transversely uniform elliptical distribution with sigx and sigy defining the edge of the distribution. Longitudinal double Gaussian distribution with each distribution having half of the particles and same sigmas given by sigz. The central separation of the two Gaussian distributions is given by zscale. The distribution has 0 transverse and longitudinal temperature.

20 UniformChain Generate a chain of longitudinal square wave like distribution with each pulse corresponding to a uniform distribution defined in equation (5). The interval between each pulse is given by sigz*sqrt(3). The number of pulse is given by zscale.

21 Streakcam Generate a chain of longitudinal square wave like distribution with each pulse corresponding to a uniform distribution defined in equation (5). The interval between each pulse is given by sigz*sqrt(3). The number of pulse is given by zscale. The velocity distribution is generated from a distribution,

$$f(E) \propto \frac{E}{(E + W_k)^4} \quad (8)$$

$$f(\theta) \propto \sin(2\theta) \quad (9)$$

$$f(\phi) \propto \text{uniform} \quad (10)$$

where $0 \leq \theta \leq \pi/2$ and $0 \leq \theta \leq 2\pi$, kinetic energy $0 \leq E \leq E_{max}$ (eV), and W_k is the work function in eV. The E_{max} is given by the input parameter `sigpz` and W_k is given by the input parameter `pzscale`.

- 22 ParobGauss** Transversely $\sqrt{1-(r/\text{sigx})^2}$ and Gaussian longitudinally. Here, `sigx` define the transverse edge of the cylinder, `sigz` defines the rms length of the cylinder. The transverse momentum follows a Gaussian distribution with `sigpx` and `sigpy`. The longitudinal momentum follows a uniform distribution with `sigpz*sqrt(3)` as one side edge.
- 23 CylGauss** Transversely uniform and Gaussian longitudinally. Here, `sigx` and `sigy` define the transverse edge of the cylinder, `sigz` defines the rms length of the cylinder. The transverse momentum follows a Gaussian distribution with `sigpx` and `sigpy`. The longitudinal momentum follows a half-Gaussian distribution.
- 26 CylIsoGauss** Uniform cylinder in 3D spatial (`sigx` and `sigy` are the radial edges, `sigz` is the half bunch length), and isotropic semi-Gaussian distribution ($p^3 \exp(-\frac{p^2}{2\text{sigpz}^2})$) in three momentum space.
- 27 CylcoldZSob** Uniform cylinder with longitudinal density modulation in spatial, and Gaussian distribution in momentum space. Here, the relative modulation amplitude is "muzpz", the modulation wavelength is "zscale (m)".

Line 9: Bcurr, Bkenergy, Bmass, Bcharge, Bfreq, Phsini

- Bcurr** Beam current in Amps.
- Bkenergy** Initial Beam Kinetic Energy in eV.
- Bmass** Mass of the particles in eV.
- Bcharge** Particle charge in units of proton charge.
- Bfreq** Reference frequency in Hz.
- Phsini** Initial reference phase in radians. Not used

5 Lattice Beam Line Elements

Line 10 and beyond, describe the lattice to track through. Each line of lattice input represents one element. Elements may overlap longitudinally. The general form of a lattice line is:

`Blength, Bnseg, Bmpstp, Btype, V1 ... V23`

Note, even though the IMPACT code allows the overlap of element field, the maximum length of the computational domain is set by the starting location of the last element plus the length of the last element.

- 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 ... V23** Element parameters. See below for more details.

The rf E field is parameterized by

$$\text{field} = f(x, y, z) \cos(2\pi ft + \theta_0) \tag{11}$$

Some of the element parameters are:

zedge Longitudinal position of the entrance face of the element.

scale This can be used to scale the field amplitude. Normally set to 1.

RF frequency Frequency of the RF field in Hz.

theta0 Initial phase in degree.

file ID ID number of the external file to open to read in field data.

radius Aperture radius. Not currently used in the calculation.

x misalignment error Used in Quadrupole, Multipole (sextupole, octupole, decapole) and SolRF beam lineelements.

y misalignment error Used in Quadrupole, Multipole (sextupole, octupole, decapole) and SolRF beam lineelements.

rotation error x Used in Quadrupole, Multipole (sextupole, octupole, decapole) and SolRF beam lineelements.

rotation error y Used in Quadrupole, Multipole (sextupole, octupole, decapole) and SolRF beam lineelements.

rotation error z Used in Quadrupole, Multipole (sextupole, octupole, decapole) and SolRF beam lineelements.

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

-1, -2, -3, -4, -5, -6, -7, -9, -11, -99: BPM Beam position monitor and etc. blength, Bnseg, Bmpstp, btype, V1, V2, V3, V4, ... V8. *Note: the location of the first "-1,-2,-3,-4" line should be put after the initial beam distribution.*

If *btype* = -1, steer the transverse beam centroid at given location V3(m) to position x offset V4(m), Px ($\gamma\beta_x$) offset V5, y offset V6(m), and Py ($\gamma\beta_y$) offset V7.

If *btype* = -2, output particle phase-space coordinate information at given location V3(m) into filename fort.Bmpstp with particle sample frequency Bnseg. Here, the maximum number of phase-space files which can be output is 100. Here, 40 and 50 should be avoided since these are used for initial and final phase space output.

If *btype* = -3, output particle phase-space and prepare restart at given location V3(m) into filename fort.(Bmpstp+myid).

If *btype* = -4, change the time step size from the initial Dt (secs) into V4 (secs) after location V3(m). The maximum number of time step change is 100.

If *btype* = -5, switch the simulation from azimuthal symmetry to fully 3d simulation after location V3(m). This location should be set as large negative number such as "-1000.0" in order to start the 3D simulation immediately after the electron emission.

If *btype* = -6, turn on the wake field effects between location V3(m) and V4(m). If *Bnseg* is greater than 0, the longitudinal and transverse wake function will be read in from file "fort.Bmpstp". If *Bnseg* \leq 0, the code will use analytical function form described as follows. For analytical wake functions, the wake function parameters (iris radius) *a* = V5(m), (gap) *g* = V6(m), (period) *L* = V7(m). Here, the definition of these parameter can be found from SLAC-PUB-9663, "Short-Range Dipole Wakefields in Accelerating Structures for the NLC," by Karl L.F. Bane. This will be updated in the future since the parameters *a*, *g*, *L* might change from cell to cell within a single

structure. For the backward traveling wave structure, the iris radius "a" has to be set greater than 100, gap "g" set to the initialization location of BTW. For backward traveling wave structures, the wakes are hardwired inside the code following the report: P. Craievich, T. Weiland, I. Zagorodnov, "The short-range wakefields in the BTW accelerating structure of the ELETTRA linac," ST/M-04/02. For external supplied wake function, The maximum number data point is 1000. The data points are assumed uniformly distributed between 0 and V7(m). The V6 has to less than 0. Each line of the fort.Bmpstp contains longitudinal wake function (V/m) and transverse wake function (V/m/m).

If *bytpc* = -7, merge the multiple bins into only one bin at given location V3(m) in order to save computing time.

If *bytpc* = -9, output slice-based information at given location V3(m) into file "fort.Bmpstp" using "Bnseg" slices.

If *bytpc* = -11, collimate particles at given location V1(m) with transverse aperture defined by V2(m) (xmin), V3(m) (xmax), V4(m) (ymin), V5(m) (ymax).

If *bytpc* = -99, stop the simulation at given location V3(m).

0: DriftTube Drift space

V1: zedge
V2: radius Not used.

1: Quadrupole Quadrupole

V1: zedge
V2: quad gradient (T/m)
V3: file ID
If > 0, then include fringe field (using Enge function) and
V3 = effective length of quadrupole.
V4: radius (m)
V5: x misalignment error (m)
V6: y misalignment error (m)
V7: rotation error x (rad)
V8: rotation error y (rad)
V9: rotation error z (rad)
If V9 != 0, skew quadrupole
V10: rf quadrupole frequency (Hz)
V11: rf quadrupole phase (degree)

2: ConstFoc 3D constant focusing beam line element.

V1: zedge
V2: x focusing gradient: $kx0^2$
V3: y focusing gradient: $ky0^2$
V4: z focusing gradient: $kz0^2$
V5: radius

3: Sol Solenoid.

V1: zedge
V2: Bz0 (T)
V3: file ID
V4: radius
V5: x misalignment error Not used.

```

V6: y misalignment error  Not used.
V7: rotation error x      Not used.
V8: rotation error y      Not used.
V9: rotation error z      Not used.

```

The discrete magnetic field data is stored in 1Tv3.T7 file. The read in format of 1Tv3.T7 is as following:

```

! the input range units are cm
  read(14,*,end=33)tmp1,tmp2,tmpint
  this%RminRft = tmp1/100.0
  this%RmaxRft = tmp2/100.0
  this%NrIntvRft = tmpint
! the input range units are cm
  read(14,*,end=33)tmp1,tmp2,tmpint
  this%ZminRft = tmp1/100.0
  this%ZmaxRft = tmp2/100.0
  this%NzIntvRft = tmpint
  n = 0
50  continue
    read(14,*,end=77)tmp1,tmp2
    nn = n+1
    j = (nn-1)/(this%NrIntvRft+1) + 1
    i = mod((nn-1),this%NrIntvRft+1) + 1
    this%brdatat(i,j) = tmp1
    this%bzdatat(i,j) = tmp2
!    write(15,100)float(i-1),bzdatat(i,j)
    n = n + 1
    goto 50
77  continue

```

4: Dipole Dipole bending magnet element. In the IMPACT-T code, the bending magnet is described by four linear functions to characterize the pole face and starting and ending face of the fringe field. Here, the coordinate system is a Cartesian coordinate X-Z with origin before the bending magnet. Here, X is the horizontal direction, and Z is the longitudinal direction. The particles are tracked in this X-Z Cartesian coordinate with external B field given in this coordinate. The space-charge forces are calculated by transforming the particle coordinates into a rotated coordinates of bunch centroid. The space-charge forces are calculated in that rotated coordinate including relativistic effects. Then, the space-charge forces are transformed from the rotated coordinates to the X-Z coordinate to push the particles. At the exit of the bend, all the particle coordinates are transformed to the new X-Z coordinate of the next beam line element. The four functions which characterize the face is: $z1 = k1*x1+b1$, $z2 = k2*x2+b2$, $z3 = k3*x3+b3$, $z4 = k4*x4+b4$. The region between $z1$ and $z2$ is the fringe field region for entrance, $z2$ and $z3$ is the region of constant By field, $z3$ and $z4$ is the region of fringe field for exit. Here, the parameters, $k1$, $b1$, $k2$, $b2$, $k3$, $b3$, $k4$, $b4$ are stored in the input file rfddataV4 (from 3-10). "V4" is the input parameter as described below. The first two parameters in the rfddataV4 is face-ID (not used) and gamma for the reference particle. So far, we have assumed a linear function on the middle plane ($y=0$) for the field in the fringe field region.

```

V1: zedge
V2: x field strength (T)
V3: y field strength (T)
V4: file ID          file ID to contain the geometry information of bend.

```

V5: radius (m) half of gap width.
 V6: x misalignment error Not used.
 V7: y misalignment error Not used.
 V8: rotation error x Not used.
 V9: rotation error y Not used.
 V10: rotation error z Not used.

Here, the input file `rfdatav4` contains 22 lines. The first line contains the switch flag for 1D csr wakefield. The csr wakefield will be included for a value greater than 0. The second line contains the γ of the beam. Line 3 to 10 contains $k_1, b_1(m), k_2, b_2(m), k_3, b_3(m), k_4, b_4(m)$, the geometric description of the pole faces at the entrance and the exit. Line 11 is the twice of the shift z_0 (m) at the entrance fringe field region. Line 12 is the twice of the shift z_0 (m) at the exit fringe field region. These two lines are used to determine the shift used in the Enge function fitting. The shifts are half of those values. Line 13 to 20 contains 8 coefficients in the Enge function. Here, we have assumed that the entrance and the exit have the same Enge function coefficients. Line 21 is the effective starting location along the arc of the bend in meter. Line 22 is the effective ending location along the arc of the bend in meter. These two numbers are used in the calculation of transitive effects of the CSR wake. Normally, these two numbers are the mid locations of the fringe region. However, if the transitive effect at the exit is important, the total length of the bend may include a section of drift.

Note, the length ($Blength$) in the dipole element input line should contain the arc length of the reference particle inside the fringe fields and the dipole field region.

5: Multipole Multipole (See Quadrupole for Quadrupole)

V1: zedge
 V2: pole type: sextupole (2), octupole (3), decapole (4)
 V3: field strength (T/mⁿ)
 V4: file ID If > 1e-5 then read in the fringe field
 V5: radius Not used.
 V6: x misalignment error
 V7: y misalignment error
 V8: rotation error x
 V9: rotation error y
 V10: rotation error z

101: DTL Drift tube linac

V1: zedge
 V2: scale
 V3: RF frequency
 V4: theta0
 V5: file ID
 V6: radius
 V7: quad 1 length
 V8: quad 1 gradient
 V9: quad 2 length
 V10: quad 2 gradient
 V11: x misalignment error for Quad 1
 V12: y misalignment error for Quad 1
 V13: rotation error x for Quad 1
 V14: rotation error y for Quad 1
 V15: rotation error z for Quad 1

V16: x misalignment error for Quad 2
 V17: x misalignment error for Quad 2
 V18: rotation error x for Quad 2
 V19: rotation error y for Quad 2
 V20: rotation error z for Quad 2
 V21: x misalignment error for RF cavity
 V22: y misalignment error for RF cavity
 V23: rotation error x for RF cavity
 V24: rotation error y for RF cavity
 V25: rotation error z for RF cavity

102: CCDTL Coupled-cavity-drift-tube-linac. See 105:SolRf for more details. V12 (Bz0) is not used here.

103: CCL Coupled-cavity-linac. See 105:SolRf for more details. V12 (Bz0) is not used here.

104: SC Superconducting cavity. See 105:SolRf for more details. V12 (Bz0) is not used here.

105: SolRF Solenoid with embedded RF field.

V1: zedge
 V2: scale of RF field
 V3: RF frequency
 V4: theta0
 V5: file ID
 V6: radius
 V7: x misalignment error
 V8: y misalignment error
 V9: rotation error x
 V10: rotation error y
 V11: rotation error z
 V12: scale of solenoid B field. [Only used with SolRF element.]

Here, the rfdDataV5 file contains the Fourier coefficients for both E fields and B fields. The first half contains E fields, and the second half contains B fields. The following is an example of the rfdDataV5 file:

```

7.0 /# of Fourier coef. of Ez on axis
-0.0616710037 /distance before the last elem.
0.0616710037 /distance after the last elem. This is the real length used in the simulation.
0.1233420074 /length
1.26367829640838925 /Fourier coefficients of Ez on axis.
0.403913638991465318
-0.154151286798631891E-08
-0.148620139078017188
-0.460805472944262358E-0
0.863984014678981088E-01
0.369511645542406301E-09
7.0 /# of Fourier coef. of Bz on axis.
-1.04665 /distance before the last elem
0.95335 /distance after the last elem. This is the real length used in the simulation.
2.0 /length of total field
0.980347705847995596E-04 /Fourier coefficients of the Bz on axis.
0.723873881539517666E-04
  
```

0.297047022969352459E-10
0.400457811524145360E-04
0.905081032754064534E-10
0.202293442430655808E-04
0.933729888398092589E-10

110: EMfld Read in discrete EM field data as a function of (x,y,z) or (r,z) or analytical representation of EM field data. This element is not used in the IMPACT-T code but used in the z based IMPACT code.

111: EMfldCart Read in discrete EM field data, E_x , E_y , E_z , B_x , B_y and B_z , as a function of (x,y,z) representation of EM field data.

V1: zedge
V2: scale of RF field
V3: RF frequency
V4: theta0
V5: file ID
V6: radius not used yet
V7: x misalignment error not used yet
V8: y misalignment error not used yet
V9: rotation error x not used yet
V10: rotation error y not used yet
V11: rotation error z not used yet

The discrete field data is stored in 1Tv3.T7 file. Some read-in FORTRAN codes are as following:

```

! the input range units are m
read(14,*,end=33)tmp1,tmp2,tmpint
this%XminRfgt = tmp1
this%XmaxRfgt = tmp2
this%NxIntvRfgt = tmpint
read(14,*,end=33)tmp1,tmp2,tmpint
this%YminRfgt = tmp1
this%YmaxRfgt = tmp2
this%NyIntvRfgt = tmpint
read(14,*,end=33)tmp1,tmp2,tmpint
this%ZminRfgt = tmp1
this%ZmaxRfgt = tmp2
this%NzIntvRfgt = tmpint
n = 0
50 continue
   read(14,*,end=77)tmp1,tmp2,tmp3,tmp4,tmp5,tmp6
   n = n+1
   k = (n-1)/((this%NxIntvRfgt+1)*(this%NyIntvRfgt+1))+1
   j = (n-(k-1)*(this%NxIntvRfgt+1)*(this%NyIntvRfgt+1)-1)/(this%NxIntvRfgt+1) + 1
   i = n - (k-1)*(this%NxIntvRfgt+1)*(this%NyIntvRfgt+1) - &
      (j-1)*(this%NxIntvRfgt+1)
   this%Exgridt(i,j,k) = tmp1
   this%Eygridt(i,j,k) = tmp2
   this%Ezgridt(i,j,k) = tmp3
   this%Bxgridt(i,j,k) = tmp4
   this%Bygridt(i,j,k) = tmp5
   this%Bzgridt(i,j,k) = tmp6

```

```

77          goto 50
           continue

```

112: EMfldCyl Read in discrete EM field data $E_z(MV/m)$, $E_r(MV/m)$, and $H_\theta(A/m)$ as a function of (r,z) of EM field data (from SUPERFISH output).

```

V1: zedge
V2: radius
V3: RF frequency
V4: theta0
V5: file ID
V6: radius                not used yet
V7: x misalignment error  not used yet
V8: y misalignment error  not used yet
V9: rotation error x      not used yet
V10: rotation error y     not used yet
V11: rotation error z     not used yet

```

The discrete field data is stored in 1Tv3.T7 file. Some read-in FORTRAN codes are as following:

```

! the input range units are cm
read(14,*,end=33)tmp1,tmp2,tmpint
this%ZminRft = tmp1/100.0
this%ZmaxRft = tmp2/100.0
this%NzIntvRft = tmpint
! the input range units are cm
read(14,*,end=33)tmp1
read(14,*,end=33)tmp1,tmp2,tmpint
this%RminRft = tmp1/100.0
this%RmaxRft = tmp2/100.0
this%NrIntvRft = tmpint
n = 0
50  continue
    if(mod(n,2).eq.0) then
        read(14,*,end=77)tmp1,tmp2,tmp3 !Er, Ez, Etheta (MV/m)
        nn = n/2+1
        j = (nn-1)/(this%NzIntvRft+1) + 1
        i = mod((nn-1),this%NzIntvRft+1) + 1
        this%ezdatat(i,j) = tmp1*1.0e6
        this%erdatat(i,j) = tmp2*1.0e6
        n = n + 1
        write(15,100)float(i-1),this%ezdatat(i,j),this%erdatat(i,j)
    else
        read(14,*,end=77)tmp1 !Htheta
        nn = (n+1)/2
        j = (nn-1)/(this%NzIntvRft+1) + 1
        i = mod((nn-1),this%NzIntvRft+1) + 1
        !convert from H (A/m) to Tesla
        this%btat(i,j) = tmp1*mu0
        n = n + 1
    endif
    goto 50
77  continue

```

113: EMfldAna Discrete EM field data as a function of analytical representation of EM field data.

V1:	zedge	
V2:	radius	
V3:	RF frequency	
V4:	theta0	
V5:	file ID	
V6:	radius	not used yet
V7:	x misalignment error	not used yet
V8:	y misalignment error	not used yet
V9:	rotation error x	not used yet
V10:	rotation error y	not used yet
V11:	rotation error z	not used yet

6 Output Data

fort.18:

1st col: time (secs)
2nd col: distance (m)
3rd col: gamma
4th col: kinetic energy (MeV)
5th col: beta
6th col: Rmax (m) R is measured from the axis of pipe
7th col: rms energy deviation normalized by MC²

fort.24, fort.25: X and Y RMS size information

1st col: time (secs)
2nd col: z distance (m)
3rd col: centroid location (m)
4th col: RMS size (m)
5th col: Centroid momentum normalized by MC
6th col: RMS momentum normalized by MC
7th col: Twiss parameter
8th col: normalized RMS emittance (m-rad)

fort.26: Z RMS size information

1st col: time (secs)
2nd col: centroid location (m)
3rd col: RMS size (m)
4th col: Centroid momentum normalized by MC
5th col: RMS momentum normalized by MC
6th col: Twiss parameter
7th col: normalized RMS emittance (m-rad)

fort.27: maximum amplitude information

1st col: time (secs)
2nd col: z distance (m)
3rd col: Max. X (m)
4th col: Max. Px (MC)

5th col: Max. Y (m)
6th col: Max. Py (MC)
7th col: Max. Z (m) (with respect to centroid)
8th col: Max. Pz (MC)

fort.28: load balance and loss diagnostic

1st col: time (secs)
2nd col: z distance (m)
3rd col: min # of particles on a PE
4th col: max # of particles on a PE
5th col: total # of particles in the bunch

fort.29: cubic root of 3rd moments of the beam distribution

1st col: time (secs)
2nd col: z distance (m)
3rd col: X (m)
4th col: Px (MC)
5th col: Y (m)
6th col: Py (MC)
7th col: Z (m)
8th col: Pz (MC)

fort.30: square root, square root of 4th moments of the beam distribution

1st col: time (secs)
2nd col: z distance (m)
3rd col: X (m)
4th col: Px (MC)
5th col: Y (m)
6th col: Py (MC)
7th col: Z (m)
8th col: Pz (MC)

fort.34, fort.35: X and Y output information in dipole reference coordinate system (inside dipole ONLY)

1st col: time (secs)
2nd col: z (m)
3rd col: x or y (m)
4th col: xrms or yrms (m)
5th col: Centroid momentum normalized by MC
6th col: RMS momentum normalized by MC
7th col: correlation parameter
8th col: normalized RMS emittance (m-rad)

fort.36: Z output information in dipole reference coordinate system (inside dipole ONLY)

1st col: time (secs)
2nd col: z (m)
3rd col: rms (m)
4th col: Centroid momentum normalized by MC
5th col: RMS momentum normalized by MC
6th col: correlation parameter
7th col: normalized RMS emittance (m-rad)

fort.37: maximum amplitude information in dipole reference coordinate system (inside dipole ONLY)

1st col: time (secs)
2nd col: z distance (m)
3rd col: Max. X (m)
4th col: Max. Px (MC)
5th col: Max. Y (m)
6th col: Max. Py (MC)
7th col: Max. Z (m) (with respect to centroid)
8th col: Max. Pz (MC)

fort.38: reference particle information in dipole reference coordinate system (inside dipole ONLY)

1st col: time (secs)
2nd col: x distance (m)
3rd col: Px/MC
4th col: y (m)
5th col: Py/MC
6th col: z (m)
7th col: Pz/MC

fort.40: initial particle distribution at $t = 0$. Particle coordinates are dimensionless as defined before.

fort.50: final particle distribution projected to the centroid location of the bunch.

fort.60 output file for slice information of the initial distribution: 1st col: bunch length (m) 2nd col: number of macroparticles per cell 3rd col: current profile 4th col: x slice emittance (m-rad) 5th col: y slice emittance (m-rad) 6th col: energy spread per cell without taking out correlation (eV) 7th col: uncorrelated energy spread per cell (eV)

fort.70 output file for slice information of the final distribution:

7 Physical Models

The general equations of motion used in the IMPACT-T code are:

$$\dot{\mathbf{r}} = \frac{\mathbf{P}}{m\gamma} \quad (12)$$

$$\dot{\mathbf{p}} = q(\mathbf{E} + \frac{\mathbf{P}}{m\gamma} \times \mathbf{B}) \quad (13)$$

where, $\gamma = 1/\sqrt{1 - \beta^2}$, $\beta_i = v_i/c$ with $i = x, y, z$, c is the speed of light, m is the rest mass of particle, q is the charge of particle. The electric field, \mathbf{E} , and the magnetic field, \mathbf{B} , include the contributions from the external focusing and accelerating fields and the space-charge fields of intra-particle Coulomb interactions.

Given electric and magnetic fields, the equations of motion are solved using a second-order leap-frog algorithm: the particles are drifted half time step; the particles are collected and deposited onto a three-dimensional grid; the Poisson equation is solved in the beam frame; the electric and magnetic fields are obtained in the laboratory frame through the Lorentz transformation; the particle momenta are updated using both the space-charge fields and external fields for one time step according to Eq. 2; the particles are drifted another half time step. This procedure is repeated for many time steps until the beam is out of the computational domain of beam line elements.

7.1 Internal Coordinates of Particle

The coordinates of particle used inside the IMPACT-T are dimensionless variables:

$$x/dz, p_x/mc, y/dz, p_y/mc, z/dz, p_z/mc \quad (14)$$

where the scale length $dz = c dt$ with dt being the initial time step size, the momentum $p_k = \gamma\beta_k$ for $k = x, y, z$, $\beta_k = v_k/c$, v_k is the velocity in each direction and c is the speed of light.

7.2 Particle Emission from Cathode

The emission process of electrons from the photocathode is simulated by generating a 3D particle distribution behind the cathode. The longitudinal bunch length is determined by the laser pulse length Δt and longitudinal velocity associated with the initial averaged kinetic energy of the beam. This particle distribution is moved out of the cathode using $N_{emission}$ steps within Δt seconds. Here, $\Delta t\beta C$ gives the full length of the beam. During the emission, both the external fields and the space-charge effects are taken into account in the simulation. The image charge effects from the cathode can be included depending on the material property of the photocathode. If $N_{emission} < 0$, the emission model is turned off. The simulation will start as if there is no cathode.

7.3 Space-Charge Effects

For a beam with input current > 0 , the space-charge effects will be included in the simulation. (0 current means no space-charge effects.) By default, the code assumes that the beam has an azimuthal symmetry. This allows the use of less number of macroparticles in simulation which reduces the computational time significantly. For a fully 3d beam, an input line with type a code “-5” should be inserted in the input file, ImpactT.in (see more explanation in the beam line element section). This line starts the 3d simulation after a given location in the input file. To turn on the 3d space-charge effects right at the beginning, that location needs to be set < 0 . The electron beam out of the cathode can have a large energy spread. In this case, the quasi-static approximation using one reference frame might not be sufficient. Multiple reference frames (also called energy bin) can be used so that within each reference frame the energy spread is small. The total space-charge forces are summation of contributions from all reference frames. In the current version of IMPACT-T, the multiple reference frames are modeled as multiple bunches. For modeling the beam dynamics in photoinjector, the initial distribution can be divided into multiple slice longitudinally so that each slice after the emission will have a small energy spread. These slices can be merged together after some distance when the total relative energy spread becomes small (see BPM -7 for usage).

The space-charge forces are calculated by solving the 3D Poisson equation with open boundary conditions using an integrated Green function method. The image charge effects of the conducting cathode are also included using a shifted Green function method. A detailed description of the space-charge solver can be found in reference [1].

7.4 Short Range Longitudinal and Transverse Wakefields

Besides the space-charge forces, the short range longitudinal wake field (monopole) and transverse wake field (dipole) are also included. To include the wakefield effects, the element type “-6” needs to be used (see the BPM explanation). (Note: the wakefield module works correctly only for one bin/slice model. To turn on the wakefields, the multiple bins have to be merged into one bin by using BPM “-7” function.)

The effective forces from the wake fields are given as:

$$F_x(s) = q \int_s^{\infty} W_T(s' - s)x(s')\lambda(s')ds' \quad (15)$$

$$F_y(s) = q \int_s^{\infty} W_T(s' - s)y(s')\lambda(s')ds' \quad (16)$$

$$F_z(s) = q \int_s^{\infty} W_L(s' - s)\lambda(s')ds' \quad (17)$$

where W_T is the transverse wake function, W_L is the longitudinal wake field function, and λ is the line density function of the beam. To compute the effective forces from wake fields more efficiently, we extend the above integrals into a full domain convolution as:

$$F(s) = \int_{-\infty}^{+\infty} G(s' - s)\rho(s')ds' \quad (18)$$

where

$$G(s) = \begin{cases} W(s) & \text{for } s \geq 0 \\ 0 & \text{for } s < 0 \end{cases} \quad (19)$$

$$\rho(s) = \begin{cases} x(s)\lambda(s) & \text{for transverse wake} \\ y(s)\lambda(s) & \text{for transverse wake} \\ \lambda(s) & \text{for longitudinal wake} \end{cases} \quad (20)$$

The above convolution is calculated using an FFT-based method on a doubled computational domain.

The transverse and longitudinal wake functions can be calculated following some analytical expressions or be read in from external files. For analytical representation, the transverse and longitudinal wake functions for the SLAC $2\pi/3$ DDS structure is given by [2]

$$W_T(s) = \frac{4Z_0cs_0}{\pi a^4}\phi(s)(1 - (1 + \sqrt{s/s_0}\exp(-\sqrt{s/s_0}))) \quad (21)$$

$$W_L(s) = \frac{Z_0c}{\pi a^2}\phi(s)\exp(-\sqrt{s/s_{00}}) \quad (22)$$

with

$$s_0 = 0.169 \frac{a^{1.79}g^{0.38}}{L^{1.17}} \quad (23)$$

$$s_{00} = \frac{g}{8} \left(\frac{a}{\alpha(g/L)L} \right)^2 \quad (24)$$

$$\alpha(s) = 1 - \alpha_1\sqrt{s} - (1 - 2\alpha_1)s \quad (25)$$

with $\alpha_1 = 0.4648$. Here, the structure parameters are iris radius a , gap g , period L , and $Z_0 = 120\pi$, $\phi(s)$ is a step function of s ($\phi(s) = 1$ for $s > 0$, 0 for $s < 0$). For the BTW accelerating structure at the ELETTRA linac, the transverse and longitudinal wake functions are [3]

$$W_T(s) = 2.8 \times 10^{16}\phi(s)((1 - (1 + \sqrt{s/1.2 \times 10^{-4}}\exp(-\sqrt{s/1.2 \times 10^{-4}}))) + 0.5\sqrt{s}) \quad (26)$$

$$W_L(s) = 1.0 \times 10^{12}\phi(s)(1226\exp(-\sqrt{s/3 \times 10^{-4}}) + \frac{0.494}{\sqrt{s}} + 494\sqrt{s}) \quad (27)$$

For read-in external wake function option (see “-6” of BPM), the data has to be uniformly distributed between 0 and L with maximum data number 1000.

7.5 Longitudinal CSR Wakefield

The longitudinal CSR wake can be included in the simulation together with the 3D space-charge calculation if the first line input parameter in the input rfdata file is greater than 0. Under the ultra-relativistic approximation, the rate of change of energy in the bunch is given by [4, 5]

$$\frac{dE(s, \phi)}{cdt} = -\frac{2e^2}{4\pi\epsilon_0 3^{1/3} R^{2/3}} \left(\int_{s-s_L}^s \frac{1}{(s-s')^{1/3}} \frac{\partial\lambda(s')}{\partial s'} ds' + \frac{\lambda(s-s_L) - \lambda(s-4s_L)}{s_L^{1/3}} \right) \quad (28)$$

where R is the bend radius, ϕ is the angle into the bend, s is the relative position within the bunch, t is time, $s_L = R\phi^3/24$ is the slippage length. The first term is normally called steady-state wake when the slippage length becomes longer than the bunch length. The second term denotes the entrance transient wake.

For a bunch moving out of the bend, the CSR wake function under ultra-relativistic approximation are given by [6]

$$W(s) = \begin{cases} -\frac{4}{R} \frac{1}{(\phi_m + 2x)} \lambda(s - \frac{R}{6} \phi_m^2 (\phi_m + 3x)) & \text{for source in front of the bend} \\ \frac{4}{R} \left(\frac{\lambda(s - \Delta s_{max})}{(\phi_m + 2x)} + \int_{s - \Delta s_{max}}^s \frac{1}{\psi + 2x} \frac{\partial\lambda}{\partial s'} ds' \right) & \text{for source inside the bend} \end{cases} \quad (29)$$

where dimensionless x ($x/R > x$) is the distance from the observation point to the exit of the bend magnet, ϕ_m is the total bend angle of the magnet, ψ is related to $s - s'$ through the equation

$$s - s' = \frac{R\psi^3}{24} \frac{\psi + 4x}{\psi + x} \quad (30)$$

and the Δs_{max} is defined by

$$s - s' = \frac{R\phi_m^3}{24} \frac{\phi_m + 4x}{\phi_m + x} \quad (31)$$

In the IMPACT-T code, the line density function λ and its derivatives are smoothed using a first-order Savitzky-Golay filter [7]. The first derivatives of the density function is further smoothed using a customer designed local filter to calculate the second derivative [8].

7.6 RF Fields in Standing Wave Structures

For an RF linac, under proper gauge ($\phi = 0$), the external electromagnetic fields in a cylindrically symmetric accelerating structure can be obtained from [9]:

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} \quad (32)$$

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (33)$$

where the vector potential \mathbf{A} is given by

$$A_x = \frac{1}{\omega} x \sum_{n=0}^{\infty} \frac{1}{2(n+1)} e'_n(z) r^{2n} \sin(\omega t + \theta) \quad (34)$$

$$A_y = \frac{1}{\omega} y \sum_{n=0}^{\infty} \frac{1}{2(n+1)} e'_n(z) r^{2n} \sin(\omega t + \theta) \quad (35)$$

$$A_z = -\frac{1}{\omega} \sum_{n=0}^{\infty} e_n(z) r^{2n} \sin(\omega t + \theta) \quad (36)$$

with $r^2 = x^2 + y^2$ and

$$e_{n+1}(z) = -\frac{1}{4(n+1)^2} (e_n''(z) + \frac{\omega^2}{c^2} e_n(z)) \quad (37)$$

where $e_0(z)$ is the electric field on the axis, ω is the RF angular frequency, θ is the initial phase of the RF field with respect to global time zero, and the superscript prime denotes the derivative with respect to z . In the current version of the IMPACT-T code, n is up to 1 in the above equations' summation so that only second order and third order nonlinearity are included for off-axis fields.

If RF cavity does not have a cylindrical symmetry, the fully three-dimensional electromagnetic fields are read in from external data files.

7.7 Traveling Wave Structures

The electromagnetic fields in a traveling wave structure can be viewed as having the form of standing wave around the entrance and the exit of the structure, and a traveling wave in most cells between. In the IMPACT-T code traveling wave are modeled using a superposition of two standing waves. Here, the forwarding traveling wave field on the axis is given by [10]:

$$E_t(z, t) = \frac{1}{\sin(\beta_0 d)} (E_s(z) \cos(\omega t + \beta_0 d - \pi/2 + \theta) + E_s(z + d) \cos(\omega t + \pi/2 + \theta)) \quad (38)$$

where, $E_s(z)$ is the electric field of a standing wave, d is the length of a single cell, $\beta_0 = \omega/c$, and θ is the initial driven phase of the wave, which is the same as that in the entrance and exit standing wave fields. For backward traveling wave, the field on the axis can be written as:

$$E_t(z, t) = \frac{1}{\sin(\beta_0 d)} (E_s(z) \cos(\omega t + \beta_0 d - \pi/2 + \theta) + E_s(z - d) \cos(\omega t + \pi/2 + \theta)) \quad (39)$$

7.8 Solenoid

In the IMPACT-T code, by using type code "3", the magnetic fields of solenoid B_r and B_z are read in from an external file containing discrete data on $r-z$ plane. By using type code "5", the magnetic fields of the solenoid can be obtained from the on-axis field data described by Fourier coefficients as

$$B_x = -B_0' x/2 + B_0''' x(x^2 + y^2)/16 \quad (40)$$

$$B_y = -B_0' y/2 + B_0''' y(x^2 + y^2)/16 \quad (41)$$

$$B_z = B_0 - B_0''(x^2 + y^2)/4 \quad (42)$$

where B_0' , B_0'' , B_0''' are the first, the second and the third derivatives of field on axis.

7.9 Bending Magnet

The bending magnet in the IMPACT-T code is modeled as a constant vertical field region and two fringe field regions on both ends of the magnet. At the entrance of the bending magnet, a Cartesian coordinate is set. A schematic plot of the layout of a bending magnet in this local coordinate system is shown in Fig. 1. The pole faces of the bending magnet at the entrance and the exit are described by four linear

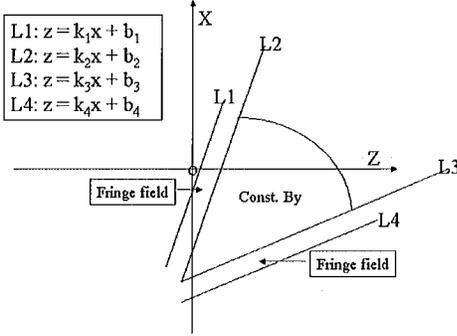


Figure 1: A schematic plot of the layout of a bending magnet in a local Cartesian coordinate system.

equations:

$$z = k_i x + b_i \quad (43)$$

where i is from 1 to 4 corresponding to the four edge lines defining the fringe field and center field region in the figure. The mid-plane field inside the fringe region of exit is assumed to be an Enge function [11]:

$$B_y(0, 0, z)/B_{y0} = \frac{1}{1 + \exp(c_1 + c_2 s + c_3 s^2 + c_4 s^3 + c_5 s^4 + c_6 s^5 + c_7 s^6 + c_8 s^7)} \quad (44)$$

where $s = (z - z_0)/g$, g is the full gap width, z is the distance measured perpendicular to the pole face L_3 . Here, the shift in z_0 is the half of the input parameters 11 and 12 inside the rfddata file. The coefficients (absolute values) of the Enge function for the fringe field at the entrance is assumed to be the same as the exit ones except that the shift is controlled by the input parameter 11. The coefficients c_1 to c_8 are from the least square fitting of the measured data profile.

A reference particle is defined with only initial longitudinal components from the centroid of the beam in the local coordinate system. Inside the bend, both simulated macroparticles and the reference particle are advanced using the dipole magnetic field. To calculate the space-charge forces or CSR forces, we transform the macroparticles coordinates into a coordinate system originating at the reference particle through rotation. A momentum kick is done inside the reference particle coordinate system and transformed back to the local coordinate system. When the beam is out of the bending magnet, all macroparticles are rotated again into the reference particle coordinate system. This gives the macroparticles local coordinates in the next beam line element. Here, we have assumed that the reference particle will move through the axis of the bending magnet and into the axis of the next element.

7.10 Quadrupole

The magnetic fields in the IMPACT-T code for constant quadrupole are:

$$B_x = B_g y \quad (45)$$

$$B_y = B_g x \quad (46)$$

$$B_z = 0 \quad (47)$$

where B_g is the constant field gradient. If the fringe field is included (see the input lattice description), the magnetic fields are

$$B_x = B_g y - B_g'' y^3 / 6 \quad (48)$$

$$B_y = B_g x - B_g'' x y^2 / 2 \quad (49)$$

$$B_z = B_g' x y \quad (50)$$

where B_g' and B_g'' are first and second derivatives of field gradient with respect to z . In the current version of the IMPACT-T code, the fringe field function is assumed to be

$$B_g(0, 0, z) / B_{g0} = \frac{1}{1 + \exp(c_1 + c_2 s)} \quad (51)$$

where $s = (z - z_0) / g$, g is the diameter of aperture, the shift $z_0 = (\text{total length} - \text{effective length}) / 2$, and $c_1 = -0.00004$, $c_2 = 4.518219$ in current version. The values of c_1 and c_2 are hardwired into the code but can be modified according to the real quadrupole fringe field profile. For the current values of c_1 and c_2 , the fringe field region is about $3g$. The effective length will be the total length subtracting the fringe field region width.

The skew quadrupole can be modeled with a rotation angle error of above quadrupole magnet.

7.11 Multipole

In the IMPACT-T code, the multipole element includes sextupole, octupole and decapole. For sextupole,

$$B_x = B_0 x y \quad (52)$$

$$B_y = B_0 (x^2 - y^2) / 2 \quad (53)$$

For octupole,

$$B_x = B_1 (3x^2 y - y^3) / 6 \quad (54)$$

$$B_y = B_1 (x^3 - 3x y^2) / 6 \quad (55)$$

For decapole,

$$B_x = B_2 (x^3 y - x y^3) / 6 \quad (56)$$

$$B_y = B_2 (x^4 - 6x^2 y^2 + y^4) / 24 \quad (57)$$

where B_0 , B_1 , and B_3 are input parameters.

8 Recently Added Features

- Quadrupole element: If v9 (rotation angle with respect to z) is nonzero, this is a skew quadrupole. If v10 (rf frequency) and v11 (phase) are nonzero, this is an rf quadrupole.
- collimation function at given z location by using "-11".
- output slice-based information (current, uncorrelated energy spread, slice emittances, correlated energy spread) at given z location using "-9". The slice information for the initial distribution and the final output distribution is stored in file fort.60 and fort.70.

- modified the structure wakefield calculation so that the code can use both analytical expressions and read-in transverse and longitudinal wake function from external files.
- particle coordinates for initial read-in distribution are $x(m)$, P_x/mc , $y(m)$, P_y/mc , $z(m)$, P_z/mc .
- particle coordinates for output phase distribution at given location are $x(m)$, P_x/mc , $y(m)$, P_y/mc , $z(m)$, P_z/mc .
- switch flag for cathode (Nemission > 0 , flagcathode = 1, cathode exists, otherwise, 0 no cathode model).
- 1D csr wake module including the transient effects at the entrance and the exit of dipole bend magnet.

9 Others

IMPACT-T has a sister program called IMPACT which also does tracking with space charge forces. The difference between the two is that the independent variable in IMPACT is the longitudinal position z while IMPACT-T uses the time t as the independent variable. The advantage of IMPACT-T over IMPACT is that space charge forces need to be evaluated at constant t . This allows IMPACT-T to more accurately model the space charge forces. This difference between IMPACT-T and IMPACT is most noticeable at low energy. That is, with particles near the gun. When there are external fields (solenoid field, RF field, etc.) then potentially IMPACT-T has to do more work to find the external fields for each individual particle location. This makes it slower than the z -based IMPACT code. It should be noted that at the end of the calculation IMPACT-T stops at some time t so that the particles will have different z .

Acknowledgments

We would like to thank Dr. D. Sagan of Cornell University for making the first LaTeX draft of this document after his visit to LBNL. We would like to thank Dr. A. Adelman for working on the HDF5 part of the IMPACTcode, Dr. I. Pogorelov for writing a steady-state CSR wake function, and a localized filter function, Drs. R. Ryne, S. Lidia, and C. Limborg for the development of the numerical algorithms and benchmark studies of the code. We would also like to thank all of our collaborators and users for comments, suggestions, and feedbacks to improve this code and for exercising this code on real physical problem studies. This work was supported by the U. S. Department of Energy under Contract no. DE-AC02-05CH11231, and by a Scientific Discovery through Advanced Computing project, “Advanced Computing for 21st Century Accelerator Science and Technology,” which is supported by the US DOE/SC Office of High Energy Physics and the Office of Advanced Scientific Computing Research.

References

- [1] J. Qiang, S. Lidia, R. D. Ryne, C. Limborg-Deprey, Phys. Rev. Special Topics - Accel. Beams 9, 044204, (2006).
- [2] K. L.F. Bane, “Short-Range Dipole Wakefields in Accelerating Structures for the NLC,” SLAC-PUB-9663, 2003.

- [3] P. Craievich, T. Weiland, I. Zagorodnov, "The short-range wakefields in the BTW accelerating structure of the ELETTRA linac," ST/M-04/02.
- [4] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, Nucl. Instrum. Methods Phys. Res., Sect. A398, 373 (1997).
- [5] M. Borland, Phys. Rev. Special Topics - Accel. Beams 4, 070701 (2001).
- [6] G. Stupakov and P. Emma, "CSR Wake for a Short Magnet in Ultrarelativistic Limit," SLAC-PUB-9242, 2002.
- [7] W. Press, S. Teukolsky, W. Vetterling, and B. Flannery, *Numerical Recipes in FORTRAN*, Cambridge University Press, New York, 1992.
- [8] I. Pogorelov, J. Qiang, R. D. Ryne, M. Venturini, A. Zholents, R. Warnock, "Recent Developments in IMPACT and Application to Future Light Sources," in Proceedings of 9th Intern. Comp. Accel. Physics Conf., p. 182, 2006.
- [9] P. L. Morton, Particle Dynamics in Linear Accelerators, Ph. D. Thesis, Midwestern Universities Research Association, The Ohio State University, 1963.
- [10] G. A. Loew, R. H. Miller, R. A. Early and K. L. Bane, SLAC-PUB-2295 (1979).
- [11] H. A. Enge, Rev. of Sci. Instr. 35, 278, (1964).