

TRANSIT CODE FOR BEAM DYNAMIC SIMULATION

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Abstract

Multiparticle computer code TRANSIT for simulation of intense ion beams in linacs and transport systems is presented. The code is based on experience in design of ion linacs in ITEP. TRANSIT summarizes the most actual and modern methods and algorithms for integration of motion equations including space charge forces. It is being used in ITEP for design and simulation of conventional RFQs, spatially periodic RF focusing linacs, beam transport systems, RF deflectors, etc. The paper presents general description of TRANSIT code and some achieved results.

INTRODUCTION

Development of codes for beam dynamic simulation in ITEP has been started in the early 80s [1]. It was concerned with design of first RFQ proton linacs in ITEP [2]. The simulation code was a tool for study of high intensity beam dynamics in RFQ linacs. It had to describe motion of beam particles accurately and in the most natural approach. Initially external field of RFQ channel was approximated by 2-term 3-D potential, but self-field of the beam was calculated by combined "particle-particle" (PP) and "particle-in-cell" (PIC) method. It was expected as the most adequate method for beam interaction solver, but it was replaced by conventional PIC method in following versions due to technique difficulties. Coulomb field of each macroparticle was expressed by Lienard–Wiechert potentials. The beam had initial truncated normal (gaussian) distribution of space charge density as the most natural. Macroparticle motion solver was operated on predictor-corrector scheme. This code was called PROTON.

Further upgrades of the code allow user to choose PP or PIC methods, simulate multi-component ion beams with different charge-to-mass ratios in different elements of the channel: RFQ cells, quadrupoles, drift spaces, drift tube linacs, etc. External fields can be based on 3-D interpolation of data from ASCII files. The code POLE [x] was used to simulate 3-D field in RFQ cells and the code ALFIL - to simulate 3-D field in DTL cells. These upgrades were caused by application of the code for simulations of UNILAC [3]. This upgraded code was called DYNAMION. Thus it was able to simulate beam dynamics from plasma border inside the ion source up to the end of the linac.

Further versions of the code have been developed in GSI [4] and ITEP independently due to separate applications. To avoid a confusion the code developing in ITEP was called TRANSIT. This paper presents general description of TRANSIT code and some achieved results.

MOTION SOLVER

Motion Equations

One of the most important effect in linear accelerators is emittance growth of accelerated ion beam. It is mainly expressed by redistribution of space-charge density of the beam and halo formation due to nonlinear external and self fields. Unfortunately finite difference approximation of particle motion can produce the artificial emittance growth. The rate of artificial growth is defined by resolution of finite difference approximation (i.e. integration step) and order of numeric method. There are methods that doesn't cause the artificial growth - symplectic methods [5]. The most simple and natural one is "symplectic Euler method", which is used in TRANSIT. Symplectic Euler methods is shown below:

$$\begin{aligned}\vec{v}_{i+1} &= \vec{v}_i + \Delta t \cdot \vec{A}(\vec{v}_{i+1}, \vec{r}_i), \\ \vec{r}_{i+1} &= \vec{r}_i + \Delta t \cdot \vec{v}_{i+1}, \\ \vec{A} &= \frac{q}{m} \sqrt{1 - \frac{v^2}{c^2}} \left\{ \vec{E} + \frac{1}{c} [\vec{v} \vec{H}] - \frac{1}{c^2} \vec{v}(\vec{v} \vec{E}) \right\}.\end{aligned}$$

Here \vec{v} is vector of particle velocity, \vec{r} - radius-vector of a particle, \vec{A} - acceleration vector, q - particle charge, m - particle mass, E and H - vectors of external and self electromagnetic field, c - speed of light.

In addition elementary transfer matrices of every particle are evaluated for each integration step during simulation. The multiplication of elementary matrices defines common transfer matrix of focusing lattice. It provides the analysis of beam dynamics proposed in [6].

Beam frame

TRANSIT is able to simulate beam dynamics through the channel consisted from various number of elements. Element is a part of a channel with specifically defined field distribution (3-D mapping, series, etc.) or drift space. Length and aperture radius (especially for self-field calculations) have to be defined for each element.

To reduce calculating time for multi-element channel the moving frame has been proposed for TRANSIT. Beam frame is 3-D space domain around the reference particle. Frame has length of $\beta\lambda$ and transverse sizes equal to aperture radius. Frame moves with reference particle during simulation. Beam frame can include only part of all elements. of a channel at every moment of time. Special algorithm of interaction between lost particles and beam frame has been proposed for accurate and authentic simulation.

External Fields

One of the most important feature of TRANSIT code is 3-D mapping of external field from ASCII file. Motion

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solver performs 3-D quadratic interpolation of imported field in turn. Files with external field distribution can be exported from any code of electrostatic or microwave simulation. Measured 3-D field distribution can be used for simulation as well.

A package of additional 3D electrostatic solvers has been developed for the most demanded linacs to provide field maps for TRANSIT. PreRFQ is a code for calculating field in RFQ cells with sinusoidal or trapezoidal modulation. PreRFQ builds the cell from two halves with different parameters as shown in Figure 1.

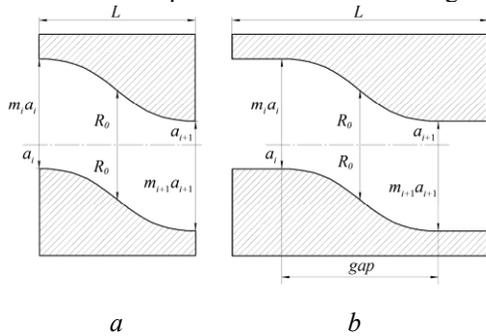


Figure 1: RFQ cell (a - sinusoidal, b - trapezoidal) geometry for PreRFQ code.

ALFIL code is used to simulate field in DTL cells with round drift tubes with or without quadrupole lenses. TUBE-RFQ code is used for spatially - periodic structures where accelerating gaps are formed between RF quadrupoles and cylindrical drift tubes (Figure 2). All these codes export 3D distribution of field or potential to ASCII files.

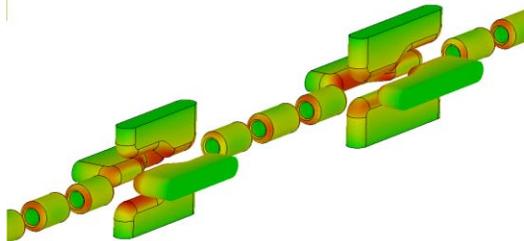


Figure 2: Spatially - periodic structure.

Self-field

Like most beam dynamics codes TRANSIT uses conventional PIC method [7] for self-field calculation. Charge weighting scheme used in PIC method is volume weighting or so-called Cloud-in-Cell (CIC) which is 1st order scheme.

Self-field of the beam is calculated from 3-D charge density distribution with fast Fourier transformation (FFT) algorithm.

Upgrade of PIC method to combined PIC and PP method (called "Particle-Particle - Particle-Mesh" or P³M [7]) is scheduled in following versions of the code.

Initial Distribution

TRANSIT has an external random generator for initial distribution of macroparticles. Binomial algorithm used in

this generator can simulate various kinds of distributions: KV, waterbag and truncated normal (gaussian) distribution with specified truncation parameter. For the most applications truncated normal distribution with truncation parameter 2.5σ (full emittance is $2.5^2 = 6.25$ RMS emittance) is useful.

Graphical User Interface

One of significant difference of TRANSIT code from DYNAMION is presence of Graphical User Interface (GUI). GUI is a single window application with several tabs (Figure 3):

- initial beam parameters,
- phase-plots of input and output beam,
- linac structure,
- transverse envelopes,
- phase-space density of the beam,
- log & project files.

Moreover GUI is able to show field distribution along the linac, modify parameters of the main solver and run the simulation, calculate emittance values and Twiss parameters of the beam, export plots into graphical files, etc. For example, phase-plots in Figure 3 correspond to exit of the structure shown in Figure 2 as well as electric field along the structure near the longitudinal axis is shown in Figure 4.

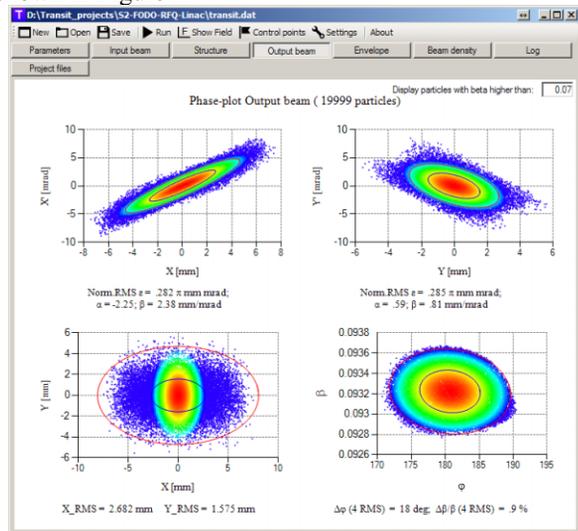


Figure 3: Main window of TRANSIT GUI.

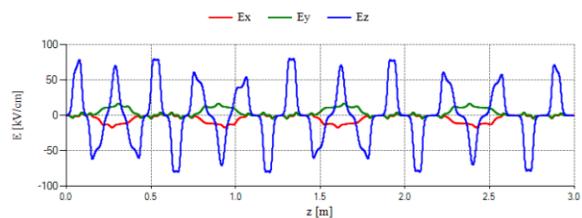


Figure 4: Field distribution along the linac.

TRANSIT solver operation is displayed as beam phase-plots and transverse envelopes online during simulation (Figure 5, that corresponds to simulation of the structure shown in Figure 2).

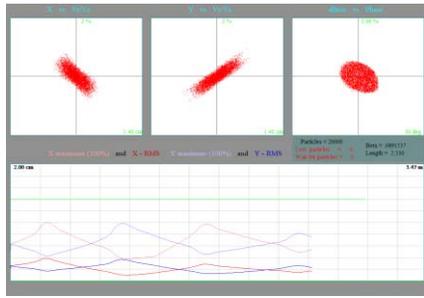


Figure 5: Phase-plots and transverse envelopes during simulation.

POSTPROCESSING

TRANSIT calculates only main beam parameters. For detailed analysis of beam dynamics TRANSIT is able to export coordinates and velocity components of beam particles to ASCII file at any position along the linac or periodically through several integration steps. It allows user to analyze and plot results at any time without new run with special programs, like PAW (Physics Analysis Workstation) [8], Gnuplot [9], PlotWin [10], etc.

Figure 6 illustrates PAW histograms for transverse phase advance of particles in 352 MHz DTL section with FOFODODO focusing lattice. Figure 6a presents phase advance distribution for lattice without accelerating field and zero beam current. Figure 6b present phase advance distribution of accelerating beam with zero current, and figure 6c - phase advance distribution of accelerating beam with 40 mA current.

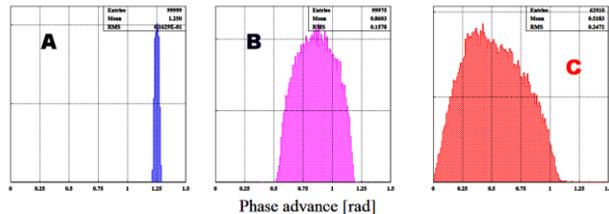


Figure 6: Transverse phase advance distribution. *a* - no acceleration of beam with zero current, *b* - accelerating beam with zero current, *c* - accelerating beam with 40 mA current.

APPLICATION OF THE CODE

TRANSIT code is being used in ITEP for design and simulation of conventional RFQs, spatially periodic RF focusing linacs, beam transport systems, RF deflectors, etc. List of some applications of the code is presented below.

- Ion RFQ injector for ITEP-TWAC project [11],
- Some variants of second section of ion injector for ITEP-TWAC project [12, 13, 14],
- High intensity proton 7.4 MeV RFQ with trapezoidal modulation [15],
- RF deflector for hollow beam formation [16],
- Single frequency high intensity high energy normal conducting hadron linac [17],
- Compact proton injector for synchrotrons [18].

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