DYNAMION - THE CODE FOR BEAM DYNAMICS SIMULATIONS IN HIGH CURRENT ION LINAC

A.Kolomiets, V.Pershin, I.Vorobyov, S.Yaramishev, ITEP, Moscow
Ju.Klabunde, GSI, Darmstadt

Abstract

New multiparticle code DYNAMION for ion beam dynamics simulation in high current linear accelerator is presented. The code was developed to achieve the most realistic simulation results of the particle motion taking into account space charge effects. It can be used for complex linac, which consists of different types of accelerating and focusing structures. The possibility of the using measured or calculated by external code electromagnetic fields for simulations is provided. The code has been tested by comparison of simulation results carried out for wide range of linear accelerators including RFQ, DTL, IH, Wideroe accelerating structures as well as transport lines with stripper sections and bending magnets with data obtained by such well known simulation codes as PARMTEQ, PARMILA and PARTRA. Simulations made for some linacs have been compared with experimental results.

1 INTRODUCTION

Design of intense linear ion accelerators and physics of intense beams is the main direction of activity in ITEP Linac Division. The developed by founder of Division Prof. Kapchinsky theory of particle motion in linacs including space charge effects allowed to build a number of proton linacs accelerating beams with pulse current up to several hundreds of milliampers. The multiparticle code PROTON written in ITEP [1] has been successively used for study of dynamics of intense beam in RFQ and Alvarez type linacs.

However, the work on the next generation of intense linacs required developing of a tool adequate to modern tasks. It means that the code has to allow work with any accelerating and focusing structures without any exception, to take into account all nonlinearities of particle motion, caused by space charge effects, coupling between oscillations in different planes or nonlinearities of external fields. The output data of the code has to allow deep and flexible analysis of the particle motion.

The design and construction of the new ITEP linacs (RFQ injector for TWAC installation, conversion linac ISTRA-36 to a driver of ITEP Neutron Generator and development of high power proton linac for nuclear waste transmutation) and GSI High Current Injector (HSI) initiated this work. All of these linacs are the chains of different accelerating structures - RFQ, IH, Alvarez type DTL, set of single gap resonators, stripping sections with bending magnets for ion separation and beam transport lines. The accelerating structures composing linacs work at different frequencies, and beam can changes charge of particles and total current.

The above mentioned linacs have been designed by means well known codes TRACE-3D, TRANSPORT, PARMTEQ, PARTRA, PARMILLA, MIRKO. These codes are suitable for generating of structures and simulations of beam dynamics in each part independently. It leads to necessity to use some special procedures for transferring data between different codes to simulate beam dynamics along whole linac. Such method makes this work quite complicate and results not very reliable, especially for transitions from one structure to another.

Moreover, the beam dynamics in stripping sections can't be simulated directly by mentioned above codes, what does not also makes results more reliable. The common drawback of the codes is the using of simplified equations of particle motion..

However the realization of high current linac projects requires the detailed knowledge of beam dynamics because it is very important to prevent deterioration of beam parameters along full linac.

It was proposed to develop a new code for more accurate simulations. The code called DYNAMION has been written on the base of PROTON. The code has been tested by comparison with experimental study of beam parameters carried out at constructed in ITEP high current RFQ and DTL accelerators.

To adjust the code for advanced requirements it was necessary to add new features to it. The main modifications of the code are the following:

- The new subroutines allow simulate beam dynamics in any accelerating and focusing structures have been added to the code.
- Easy and flexible description of sequence of accelerating structures, transport lines etc. was introduced.
- The possibility to simulate dynamics of the beam consisting of mixture of particles with different charge to mass ratio was added.
- New subroutine has been developed for stripper section. It simulates changing of charge state of particles and its separation in bending magnets.
- New subroutine, which allows to use for accelerating and focusing elements electrical and magnetic field distributions measured or calculated by means external code have been written.
- Transport channels can consist of different elements including quadrupole lenses, bending magnets, strippers, slits and solenoids. In case of significant particle losses it is possible to breed particles for more reliable simulations.

2 DESCRIPTION OF THE CODE

The code DYNAMION was written essentially for simulation of beam dynamics and not for generation of accelerating structures like PARMTEQ. This approach determined the main properties of the code:

Coordinates and velocities of particles are calculated by time integration of motion equations in external electromagnetic fields. The particle motion equations in the code DYNAMION are used in the most general type without simplifications and with taking into account real interaction of moving particle with 3-dimensional electromagnetic field. It is especially important for beam with low energy, when transversal velocity of particles is comparable with longitudinal one. For example, in heavy ion linacs ratio between them reach up to 10%. It is clear that it considerably influences on beam dynamics. Equations of particle motion used for calculations are the following:

$$\mathbf{r} = \mathbf{r}_0 + \Delta t \cdot \frac{\mathbf{v} + \mathbf{v_0}}{2}$$

$$\mathbf{v} = \mathbf{v_0} + \Delta t \cdot \mathbf{a}$$

$$\mathbf{a} = \frac{1}{\gamma} \cdot \frac{q}{m} \cdot \left\{ \mathbf{E} - \frac{\mathbf{v_0}}{c} \cdot \left(\frac{\mathbf{v_0}}{c} \mathbf{E} \right) + \left[\frac{\mathbf{v_0}}{c} \mathbf{H} \right] \right\}$$

$$\mathbf{E} = \mathbf{E_{ext}} + \mathbf{E_{int}}$$

$$\mathbf{H} = \mathbf{H_{ext}} + \mathbf{H_{int}}$$

where $\mathbf{r_0}$ and $\mathbf{v_0}$ - initial radius-vector and velocity of particle, $\mathbf{r}$ and $\mathbf{v}$ - radius-vector and velocity of particle after Δt time interval, $\mathbf{a}$ - acceleration, q - charge, m - mass, $\mathbf{E}$ and $\mathbf{H}$ - full electric and magnetic fields, c - light velocity, $\mathbf{E_{int}}$ and $\mathbf{H_{int}}$ - space charge fields, $\mathbf{E_{ext}}$ and $\mathbf{H_{ext}}$ - electrical and magnetic external fields.

It is clear that using of the most realistic field descriptions gives the most precise results due to the absence of the inner limitation or approximation of field description in the DYNAMION code. It makes the code flexible, and allows take into account all details in field distribution, fringe fields and all nonlinear effects.

Space charge forces are taking into account by calculation of the particle to particle interaction. Unlike the codes where space charge is smoothly distributed in some volume, more realistic calculating of particle to particle interaction gives possibility to study complicate effects connected with nonuniformity of particle distribution.

$$\mathbf{r_{ij}} = \left(x_j - x_i, y_j - y_i, z_j - z_i \right)$$

$$\mathbf{v_j} = \left(v_x, v_y, v_z \right)$$

$$\mathbf{R} = \frac{1}{c} \left[\mathbf{r_{ij}} \mathbf{v_j} \right]$$

$$\mathbf{E_j} = \sum_{i=1}^{N} \frac{q_i}{\left(r_{ij}^2 - R^2 \right)^{3/2}} \cdot \mathbf{r_{ij}}$$

$$\mathbf{H_j} = \sum_{i=1}^{N} \frac{q_i}{\left(r_{ij}^2 - R^2 \right)^{3/2}} \cdot \mathbf{R}$$

Here $\mathbf{E_j}$ and $\mathbf{H_j}$ are electric and magnetic fields acting to the particle, x,y,z - coordinates of particles.

Beam dynamics in linac consisting of any sequence of accelerating and transport sections can be simulated in one run instead of using of different codes for separate calculations of RFQs, DTLs and transport lines.

Results of simulation write into file and on VMS or UNIX platforms can be analyzed and plotted by powerful graphic system PAW. PAW (Physics Analysis Workstation) is an interactive utility for visualizing experimental data in computer graphic display. PAW combines a handful of CERN High Energy Physics Library in software that processes and displays data. Thus, PAW's strong point is that it provides quick access to many facilities in the CERN library. Using of PAW gives to advanced user practically unlimited possibilities for analysis and graphical representation of simulation results.

Of course, including of all mentioned above features led to remarkable growth of processor time consumption. Nevertheless this growth is not extremely high price for increasing of simulation accuracy. More that, because results of simulation are kept in file they are available for analysis at any time without new run in contrast with codes like PARMTEQ.

3 SOME DYNAMION APPLICATIONS

3.1 Injector for the ITEP TWAC project

Constructing in ITEP new installation TWAC (TeraWatt Accumulator) [2] for heavy fusion experiments will accumulate high power heavy ion beam. The new injector for this installation capable to accelerate not less than 20 mA of $\mathbf{Co^{25+}}$ ions from laser ion source to the energy 1.6 MeV/u has been designed.

The main problem of injector design was that beam from laser ion source consists of the mixture of **Co** ions with different charge states. Because charge spectrum of **Co** is still a question, the experimentally measured spectrum of **Al** ions was used for beam dynamics simulations.

It was clear that only RFQ should be chosen as accelerating structure to reach necessary for the TWAC beam parameters. However the main RFQ input parameters could be determined only after fixing of the LEBT structure - for example, using or not particle separation leads to considerably different requirements to RFQ. DINAMION has been used for study of the question.

The simulations showed that there is no suitable possibility for particle separation before RFQ due to degradation of the beam quality in magnetic elements. Therefore the injection of the whole beam from laser source to RFQ was proposed. It allows keep beam quality but requires higher charge limit of RFQ section because accelerating of the beam consisting of mixture of the particles leads to increasing of the beam current from 20 to 70 mA.

Next question was the choice of LEBT focusing elements. Simulations were carried out for two solenoids taking into account experimentally measured magnetic field distributions. Analysis of simulation results showed significant emittance growth due to the coupling of the transversal and longitudinal motion of the low energy particles with ratio between corresponding velocities $\mathbf{v_r/v_z}$ up to 10%. Emittance increases two times in transverse planes and three times in longitudinal one. It should be mentioned that this effect can not be reliably detected by other codes which use paraxial approximation.

RFQ section has been designed by written in ITEP code ACCELL and result of simulations by DYNAMION code were used for optimization of RFQ parameters. The particle motion was simulated for the beam consisted of mixture of particles with charge states corresponding experimentally measured at laser source output for **Al**. It was shown that a particles with charge to mass ratio less than design value are not accelerated and do not form a stable bunches. Motion of ions with higher charge states is slightly mismatched, but stable and transmission of them is only few percents lower than transmission of particles with design charge to mass ratio. The detailed RFQ parameters are given in [3].

3.2 U-turn for ISTRA linac

The work on conversion of ITEP high current pulse proton linac ISTRA-36 [4] to a driver of subcritical assembly - prototype of accelerator driven installation is now in progress. The linac consists of 148 MHz RFQ section and two 297 MHz Alvarez type DTL. Due to space limitation the DTL sections must be placed at different levels, so U-turn between them has to be designed. It is a critical point of the whole project. The preliminary design made by TRACE 3D code has been optimized using DINAMION results. The found solution ensures transporting of the 10 MeV 100 mA beam without particle losses in U-turn. Parameters of the channel provide a compromise between emittance growth and beam matching to reach minimum of particle losses in DTL-2.

The simulations carried out for the full linac from RFQ input to the DTL-2 output showed the possibility of delivering of the beam with 0.5 mA average current to subcritical assembly and provide the required parameters of the installation.

3.3 HSI stripper sections

The new High Current Injector (HSI) is now under construction in GSI [5]. HSI is the sequence of very different accelerating structures (RFQ, IH, DTL, single gap resonators) and quite complicate transport channels, which include strippers, bending magnets, quadrupole lenses, slits and bunchers. Necessity of detailed study of beam dynamics in such complicate linac initiated substantially the development of described code.

The DYNAMION simulations has been made for the stripper sections where particles change their charges and total beam current increases several times. DYNAMION allows simulate processes in stripper sections in the most adequate way. The comparison with PARTRA code shows considerable difference in results of simulations taking into account space charge forces.

3.4 High power linac for transmutation

The development of high power linac is one of the main directions of research work in ITEP. The original concept of such linac has been proposed [6]. One of the main problems has to be solved is the strong requirement to the particle losses. Estimation shows that for beam with current 100 mA and energy of protons up to 1 GeV particle losses should not exceed 10^{-9} A/m to provide the handle maintenance of the linac.

The existing codes in principle can not calculate such losses directly. Nevertheless the method of small losses estimation by means of analyzing of DYNAMION simulation results calculating spectral density of correlation function of particle trajectories has been developed in ITEP [7]. The different accelerating and focusing structures were studied using this method [8]. The obtained results have been used for optimization of ITEP scheme of high power linac.

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