Available online at www.sciencedirect.com
SCIENCE DIRECT®
Nuclear Instruments and Methods in Physics Research A 558 (2006) 325–328
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

BETACOOL program for simulation of beam dynamics in storage rings

A.O. Sidorin*, I.N. Meshkov, I.A. Seleznev, A.V. Smirnov, E.M. Syresin, G.V. Trubnikov

Joint Institute for Nuclear Research, Dubna 141980, Russian Federation

Available online 28 November 2005

Abstract

The BETACOOL program developed by the JINR electron cooling group is a package of algorithms based on a common format for input and output files. The program is oriented to simulation of the ion beam dynamics in a storage ring in the presence of cooling and heating effects. The version presented in this report includes three basic algorithms: simulation of RMS parameters of the evolution of the ion distribution function over time; simulation of the distribution function evolution using a Monte-Carlo method; and a tracking algorithm based on a molecular dynamics technique. General processes to be investigated with the program include intrabeam scattering in the ion beam, electron cooling, and interaction with the residual gas and the internal target.

PACS: 34.70.+e; 36.10−k; 29.27.Bd

Keywords: Storage ring; Beam cooling; Electron cooling

1. Introduction

Electron cooling is widely used for ion-beam parameter control in storage rings. At present there are approximately 20 storage rings in operation and under construction that are equipped with electron cooling devices. The BETACOOL program developed for simulation of electron cooling processes [1] is actively used for the design and simulation of electron cooling systems in several research centers: JINR, ITEP, Jülich-FZ, GSI, RIKEN and BNL [2–6]. BETACOOL is programmed with an object-oriented method using the C++ language. The interface with the Windows operating system was developed on the basis of a BOLIDE system (Builder Object Library & Interface Development Environment), which is dedicated to fast elaboration of the physics and mathematics applications.

The general goal of the BETACOOL program is to simulate long-term processes (in comparison with the ion revolution period) leading to variation of the ion distribution function in six-dimensional phase space. The ion beam motion inside the ring is supposed to be stable and is treated by a linear approximation.

The structure of the program allows simulation of the evolution of the ion distribution function using a few independent numerical algorithms. Each algorithm simulates the ion beam dynamics for the same input beam and ring parameters and uses the same set of effects acting on the beam distribution function in simulations.

This report discusses the latest version of the BETACOOL program, which includes three algorithms for beam dynamics simulation and takes into account the following processes: electron cooling, intrabeam scattering, ion scattering on residual gas atoms, and interaction of the ion beam with the internal target, among others.

2. BETACOOL algorithms

Three basic algorithms for simulation of the evolution of the ion distribution function are now included in the program:

- RMS dynamics simulation;
- simulation of distribution function evolution using a Monte-Carlo method (model beam algorithm); and
- multi-particle tracking based on a molecular dynamics technique.

*Corresponding author.
E-mail address: sidorin@jinr.ru (A.O. Sidorin).

0168-9002/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2005.11.041

The physical model used in the RMS dynamics simulation is based on the following general assumptions:

(1) The ion beam has Gaussian distribution over all degrees of freedom, and is not changed during the process.
(2) The algorithm for analysis of the problem is considered as a solution of the equations for RMS values of volumes of the beam phase space for three degrees of freedom.
(3) The maxima of all the distribution functions coincide with the equilibrium orbit.

The evolution of the ion beam parameters during its motion inside the storage ring is described by the following system of four differential equations:

$$\frac{dN}{dt} = N\sum_j \frac{1}{\tau_{\mathrm{life},j}}, \quad \frac{d\varepsilon_h}{dt} = \varepsilon_h \sum_j \frac{1}{\tau_{h,j}},$$
$$\frac{d\varepsilon_v}{dt} = \varepsilon_v \sum_j \frac{1}{\tau_{v,j}}, \quad \frac{d\varepsilon_{lon}}{dt} = \varepsilon_{lon} \sum_j \frac{1}{\tau_{lon,j}} \qquad (1)$$

where N is the particle number, and ε_h, ε_v and ε_{lon} are the RMS values of the horizontal, vertical and longitudinal beam emittance, respectively. Characteristic times are functions of all three emittance values and the particle number and have a positive sign for a heating process and a negative sign for a cooling process. A negative sign for the lifetime corresponds to particle loss and the sign of the lifetime can be positive in the presence of particle injection, when the particle number increases. Index j in Eq. (1) indicates the number of processes involved in the calculations. The algorithm structure is designed in such a way that allows the inclusion of any process into calculation that can be described by cooling or heating rates. The numerical solution of Eq. (1) is performed using a Euler method with automatic step variation. The result of the simulation gives the time dependence of the emittance and the particle number. An ion ring optic structure is necessary only for intrabeam scattering (IBS) simulation. The IBS growth rates are calculated in accordance with an analytical model using ring lattice functions imported from the output file of the MAD program [7].

Step of the integration of Eq. (1) over time is determined by the characteristic times of the effects investigated and the calculation speed can be very fast. However, in some cases the basic physical model cannot provide realistic simulation, mainly due to basic assumptions about the Gaussian shape of the ion distribution function. This assumption is more or less realistic in an equilibrium state of the ion beam, when the equilibrium is determined by many processes of a stochastic nature. If equilibrium does not exist due to fast particle loss or in the initial stage of beam cooling, the ion distribution function can be far from Gaussian. The same situation occurs in an experiment with internal targets for which the dimensions do not coincide with the ion beam dimensions. In addition, the ionization energy losses of the ion beam in the target cannot be correctly calculated within the framework of this model.

Investigation of the ion beam dynamics for an arbitrary shape of the distribution function is performed using multi-particle simulation within the framework of the model beam algorithm. In this algorithm the ion beam is represented by an array of model particles. The heating and cooling processes involved in the simulation lead to changes in the particle momentum components and particle number, which are calculated in accordance with the dynamics simulation step over time. Each effect is located at some position of the ring characterized by the ring lattice functions. Transformation of the beam inside the ring is carried out using a linear matrix for random phase advance between the effect locations. The simulation results can be presented both as a beam profile evolution over time or as the time dependence of the beam emittance and particle number.

The real ion-ring optic structure is only necessary for IBS diffusion power calculation. The change in particle momentum due to IBS is calculated on the basis of one of the analytical models, as in the case of RMS dynamics simulation.

For simulation of the IBS process through Coulomb interaction between ions, the tracking algorithm is used. One of the goals of this algorithm is to simulate the formation of a crystalline state of the ion beam. In this crystalline state, the IBS process cannot be treated within the framework of analytical models, which are based on the assumption of an ion distribution function of Gaussian shape. To speed up calculations in the tracking algorithm, IBS simulations are performed using a molecular dynamics technique. In this case the motion equations are solved for a small number of particles located inside a short cell. The influence of all other particles is taken into account through periodic boundary conditions in the longitudinal direction for the particle distribution function, and the use of Evald's sum for calculation of the Coulomb forces. Therefore, this algorithm can only be used for a coasting beam.

Within the framework of the tracking algorithm, the particle motion equations are integrated in the real optical structure of the ring. The ring structure is imported from the MAD input file. Each cooling or heating effect involved in the calculations, together with the IBS, is located in some optical element. Calculation of the variation of particle co-ordinates due to any effect is achieved using the MAP effect. The effect position in the ring is described in the MAD input file using special marks.

The structure of basic objects in the BETACOOL program, namely, the models of the ion ring and the ion beam, are developed in such a way that allows realization of all three algorithms with the same input parameters. The heating and cooling effects are realized on the basis of a common standard and the same parameters can be used in each algorithm.

3. Structure of the effects

In the present version of the program, the ion beam dynamics can be investigated taking into account one or a few effects from the following list:

(1) Electron cooling;
(2) Intrabeam scattering;
(3) Scattering on residual gas;
(4) Interaction with the internal target;
(5) Collisions with another beam in the collider mode of the ring operation; and
(6) External heating of the ion beam.

Algorithms for simulation of beam–beam effect, stochastic and laser cooling are under development.

The effect structure permits the uniform use of each effect in all basic algorithms. For this purpose, each effect is represented by three models: a transformation map, a kick of the ion momentum, and characteristic time calculation.

The effect used as a transformation map is associated with some optical element of the ring and its position is marked in the input file. The map transforms the particle co-ordinates from the entrance to the exit of the element and calculates the particle loss probability.

On the basis of the transformation map for each effect the procedures for calculation of the particle momentum kick and of the characteristic time are developed. Calculation of the momentum kick is used in the model beam algorithm and characteristic times are necessary for RMS dynamics simulation.

4. Electron cooling simulation

The structure of the effects can be illustrated in an example of an electron cooler model.

Usually the action of electron cooling on the ion dynamics inside a storage ring is described using a few standard simplifications:

(1) Angular deviation of the longitudinal magnetic field line is substantially less than the ion beam angular spread.
(2) Ion transverse displacement inside the cooling section is substantially less than the electron beam radius.
(3) The ion beam temperature is substantially greater than the electron temperature and ion diffusion in the electron beam can be neglected.
(4) The electron beam has a round cross-section and a uniform density distribution in the radial direction.

Under these assumptions and using an asymptotic of the analytical friction force, formulae were obtained for the characteristic times for the emittance and momentum spread decrease on electron cooling [8]. In the first version of the BETACOOL program, electron cooling was simulated in accordance with this model [1]. This model is also used in a few programs dedicated to electron cooling simulation. However, this model cannot cover all possible versions of electron cooling designs.

Recently, modifications of the usual configuration of the electron cooling system were proposed. To avoid instability of the ion beam related to the extremely high density of the cooled beam, use of a so-called "hollow" electron beam—a beam with low density in the central part—was proposed. Extension of the electron cooling method in the region of electron energy of a few MeV is related to RF acceleration of the electrons. In this case a Gaussian distribution of the electrons can be expected in the radial plane and, if the electron bunch is shorter than the ion bunch, in the longitudinal direction too. Calculation of the cooling times in this case requires modification of both the electron beam model and the base physical model.

Another expected peculiarity of a medium-energy cooling system is the great length of the cooling section of up to approximately 20–50 m. To obtain very high accuracy of the magnetic field is a difficult technical task and the cost of the cooling system will strongly depend on the required level of accuracy. Therefore, before design of the cooling section solenoid, the influence of the magnetic field line curvature on the cooling process needs to be investigated. All the effects can be taken into account by numerical solution of the ion equations of motion in the cooling section.

To solve all the problems related to simulation of the cooling process, a hierarchy of objects was developed within the framework of the BETACOOL program. The structure of the electron cooler presentation allows the extraction of procedures of different levels and their inclusion in calculations for cooling processes in other programs. The cooling simulation is based on a friction force calculation in the particle rest frame. The friction force can be calculated in accordance with an analytical model from a library or using results of numerical calculations imported from an external file. The next layer of the simulation is related to a cooler representation as a map, transforming particle coordinates from the entrance to the exit of the cooling section and calculating the ion loss probability due to recombination with electrons. Calculation of the cooler map is based on a model of the electron beam that provides transformation of the ion velocity to the frame related to the electron beam and takes into account the real geometry of the cooler. Currently, BETACOOL has three electron beam models available for simulations: a uniform cylinder, a Gaussian cylinder and a Gaussian bunch. A model of a hollow beam will be realized in the near future. The cooler model takes into account variation of the magnetic field in the cooling section. For this aim the co-ordinates of the electron beam trajectory inside the cooling section are input from an additional file and the ion equations of motion inside the cooler are solved numerically.

The map of the cooler can be used directly within the framework of the molecular dynamics algorithm or another tracking procedure. On the basis of the map, the kick in ion momentum after crossing the cooling section can be calculated, which is necessary for simulation of the ion distribution evolution in the model beam algorithm. The map of the cooler is also used for the cooling rate calculation necessary for RMS dynamics simulation. The cooling rate calculation can be carried out using two models of the ion beam: the cooling rates for "rms particles", or cooling rates for an ion beam with Gaussian distribution in all degrees of freedom.

5. Software structure

The BETACOOL program is a part of the software developed for electron cooling simulation. The software is divided into two independent parts: a physical code, which is written using only standard C++ syntax; and an interface, which is an executable program working under the Windows environment. Connection between the two parts of the program is provided using three types of files: input, output and files used for control of the calculation process. On one hand, such a structure allows the program to be used on a PC to control the calculation process and analyze results during simulations. On the other hand, the physical part of the program can be compiled for a UNIX operation system and used for calculations independently of the interface. The interface in this case can be used for preparation of the input file and result visualization after completion of the calculations. All input and output files are in text format. The parameters in the input file are divided into groups according to the structure of the BETACOOL objects.

The interface part of the software consists of an executable file (Bolide.exe), *.dfm files containing information about the BETACOOL exterior, and input files for post-processing of the calculated data. Development of the BETACOOL exterior is possible without recompilation of the Bolide.exe file. The interface is also used to work with the file structure on disc.

The physical part of the software consists of the executable file Betacool.exe compiled for Windows or a UNIX operation system and files of input parameters. For intrabeam scattering calculation, use of a file of lattice parameters is required, for instance, a MAD file. Additional input files are used for electron cooling simulation under friction force calculated by other programs and for input of magnetic field errors in the cooling section.

The source code of the physical part of the software consists of three relatively separate parts:

- The interface, which supports the format of input and output files common to the Bolide system;
- A library of base numerical algorithms, including the description of dimensional variables, templates of the program self-counters, procedures for matrix algebra, and algorithms for the numerical solution of differential equations; and
- Physical codes describing the objects of the program and procedures for them.

The structure of the BETACOOL program exterior corresponds to the structure of general objects in the source code and correspondingly to the structure of the input file.

Acknowledgements

This work was supported by RFBR Grant #02-02-16911 and INTAS Grant 03-54-5584.

References

[1] A. Lavrentev, I. Meshkov, The computation of electron cooling process in a storage ring, Preprint JINR E9-96-347, 1996.
[2] A. Smirnov, A. Sidorin, E. Syresin, I. Meshkov, T. Tanabe, T. Katayama, Computer simulation of ECOOL and IBS process in ACR and DSR using BETACOOL program, RIKEN-AF-AC-21, April 2000.
[3] E. Syresin, N. Alekseev, V. Bykovsky, D. Koshkarev, Y. Korotaev, I. Meshkov, et al., Phys. Sci. T104 (2003) 160.
[4] V.A. Mikhailov, A.V. Butenko, I.B. Issinsky, I.N. Meshkov, et al., Progress in the nucleotron booster design, in: Proceedings of EPAC 2002, Paris.
[5] I.N. Meshkov, R. Maier, et al., Electron cooling application for luminosity preservation in an experiment with internal targets at COSY, JINR, Dubna, 2001, Jul-4031.
[6] I.N. Meshkov, A.O. Sidorin, A.V. Smirnov, E.M. Syresin, G.V. Trubnikov, P.R. Zenkevich, Simulation of electron cooling process in storage rings using BETACOOL program, in: Proceedings of Beam Cooling and Related Topics, Bad Honnef, Germany, 2001.
[7] F. Christoph Iselin, The MAD Program. Physical Method Manual, Geneva, Switzerland, September 1994.
[8] I. Meshkov, Phys. Part. Nucl. 25 (6) (1994) 631.