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SOFTWARE-COMPUTING SYSTEM FOR NUMERICAL MODELLING OF BEAM DYNAMICS IN ACCELERATORS

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Abstract

The spectrum of software packages for the physics of charged particles beams is extremely wide. From most popular and effective systems can be allocated such programs as COSY Infinity [1], MAD X [2], Polymorphic Tracking Code (PTC) [3], MARYLIE [4]. Heterogeneous individual formats of input and output data, the lack of a common and user-friendly interface and the narrow specialization of these programs pose a number of challenges for the modern researchers. It significantly reduces the effectiveness and quality of corresponding computational experiments. In this article, we present a universal tool for automation and increase in computing efficiency of computing experiments. The authors consider a method for developing the concept and prototype of a corresponding software package that would combine the advantages of existing (first of all non-commercial) program packages. This software is based on unifying the input and output data format for corresponding programs, visualize the information in various ways, including reference and training information for "beginners". The results obtained within the developed framework will be a significant contribution both to the development of numerical and symbolical methods for solving evolution nonlinear equations.

INTRODUCTION

Modern research in the physics of charged particle beams are based on expensive, resource-intensive and highly technological processes. Over the past decades, in the field of beam physics, many software packages and libraries have been developed that can be divided into several types.

Some packages describe the ray tracing (OXRAY, RAYTRACE, TURTLE), determine particle trajectories through a system of control elements both internal and external electromagnetic fields using first of all numerical integration. Programs of a different kind serve to describe the evolution of beam particles in phase space (COSY Infinity, MAD, MARYLIE and so on). In these programs, the elements of transition matrices of optical systems are calculated, which gives us a more detailed picture of the system under study.

Some programs for modeling the dynamics of beam physics use methods of differential algebra, which allows replacing the computation of derivatives in terms of traditional difference schemes by algebraic relationships, see, first of all, COSY Infinity. Despite the high enough computational efficiency, a common drawback of such solutions is that the corresponding algorithms are poorly parallelized (with the exception of paralleling over particle trajectories). This is primarily due to the fact that the ideology of differential algebra is based on a step-by-step mapping of the trajectory dynamics of the beam particles, which does not allow the construction of mappings generated by both the control system and the beam itself (the self-field of the beam).

First of all, the existing programs differ in approaches to solving the charged particles transporting problems. Some of them, as a result, is provided by a set of separately taken trajectories (one-particle approach), others are based on the construction of the operator of beam evolution (operator approach). The first group includes such programs as OXRAY, RAYTRACE, TURTLE, and others. The bright representatives of the second group are MARYLIE, MAD X, COSY Infinity, and also TRACEIO, TRACE 3D, IONBEAM program packages.

It can be argued that the set of software packages for the physics of charged particle beams is wide and varied. But we should be noted that most of them are highly specialized and developed mainly for specific classes of tasks. Virtually all of them do not have a single user graphical interface and are designed for use by experienced professionals. Each program has its own format of input and output data, which often makes it impossible to share them with third-party software.

Thus, it can be stated that today it is to develop a universal software package that will allow to combine various software tools and methods, unify the input and output data formats, visualize and compare the results. Similar program complex can not only automate, significantly accelerate and improve the efficiency of computing experiments but can be used in training students in accelerator physics.

A SOFTWARE COMPLEX BUILDING

In the development of the software complex, the ideology of the virtual accelerator is used as the basis. It is a set of programs that allows to predict the behavior of a real accelerator using various numerical simulation methods, and, depending on the experiment, evaluate the necessary adjustments of the control system to achieve the required beam particles. The description of this concept is provided in the following papers [5, 6].

The Methods of Modeling Used

Taking into account the analysis of qualitative properties and relevance of the existing packages, the following numerical simulation methods were implemented in this project: Cosy Infinity, MAD X, OptiM, Matrix Formalism (MODE) [7].

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Cosy Infinity. This program is used to simulate and analyze the charged particles beams dynamics of arbitrary orders. This package implements also support for symplectic integration. It allows us to construct the so-called matrix mappings of arbitrary orders of nonlinearity. The COSY Infinity features:

- The solution of equations is based on the method of automatic differentiation.
- The solution of ODE systems.
- The module of the FOX language for calculations with arbitrary accuracy.
- COSY-GO package for global optimization, based on Taylor models and interval methods.
- Modeling of control elements is allowed taking into account fringe fields.

MAD X. One of the most popular and high-quality programs for simulation of particle dynamics in magnetic optics, the development of the European Organization for Nuclear Research (CERN). This program allows calculations and processing of data for both large-scale accelerator systems (LHC) and small accelerators. At the moment, MAD X uses its own implementation for the fourth order of nonlinearity, based on the construction of the Lie maps, and the TRANSPORT program for displaying the second order of nonlinearity.

It should be noted that in the presence of a wide and effective functional the package MAD does not have a single user interface, data input and output only provides through the creation of the specialized files, which, of course, makes it difficult to use. As a consequence, this program is cannot be used as a program for learning and rather difficult for novice users.

OptiM. This software package designed to analyze the structure of storage rings and linear accelerators. With this program, one can quickly build beta functions, variances, calculate vibration frequencies, and investigate the structure of resonance phenomena and so on. Although OptiM allows numerical simulation of non-linear dynamics (based on step-by-step integration), its main application is the analysis of the structure of a storage ring based on a visual display of parameters of interest to researchers.

To construct the beta function and dispersion, OptiM uses the linear approximation of the corresponding particle motion equations. To calculate the beta function and dispersion, OptiM uses step-by-step integration of the particle motion. Coordinate values are displayed at each integration step.

The OptiM software package has a graphical interface for constructing various graphs, for example, graphs for the beta function, dispersion, etc.

MODE. This development of the St. Petersburg State University is an integrated development environment (IDE), which includes a project management system, code editor and libraries that implement the business logic of matrix integration of the spin-orbit dynamics equations.

The basis of this program is the matrix formalism [8]. This method allows us to represent the solution of the system under study in the following form:

$$X = \sum_{i=0}^{k} R^{1i}(t) X_0^{[i]} \qquad (1)$$

here R^{1i} — matrices corresponding to nonlinearities of the i-th order, which can be calculated both in numerical and symbolic (formulas) forms.

It is important to emphasize that the matrix formalism ideology is effectively realized with the parallel computing architecture (for example, using graphics processing units (GPU) [9]), as in this case all the computations are reduced to matrix multiplication.

The main fundamental difference of the matrix formalism for the representation of the motion equations in the form of differential equations or Hamiltonian systems is that we operate with two-dimensional matrices instead of multidimensional tensors, as in MAD, COSY Infinity, TRANSPORT, etc. The matrix formalism can be used as an successive approximations approach for the various models of beam dynamics.

Beamline and Optical System Simulator (BOSS)

In the scope of our research the Beamline and Optical System Simulator (BOSS) was developed (Figure 1). This software package has the following functionality:

- An interactive building of the system model from control elements.
- Providing a choice of calculation methods (COSY Infinity, MAD, OptiM, matrix formalism).
- Automatic generation of the configuration file for the chosen program.
- Data visualization in various ways (results can be saved as a png-image).
- User-friendly interface.
- Providing the reference and training information for beginners.

FUNCTIONALITY VALIDATION

For the functionality validation of the developed program two systems were considered. The first one is a simple system consisting of three quadrupole magnets and four shifts. The second system is a part of the OSC [10] (Optical Stochastic Cooling) project of the Fermi National Accelerator Laboratory.

With using of the BOSS program we have built the models for the mentioned systems, generated the correct configuration files for the COSY Infinity and OptiM programs, performed calculations and visualized the results (Figure 2, 3, 4).

The calculation results of the COSY Infinity and OptiM differ in some points, which is explained by the different mathematical approaches implemented in this packages.

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CONCLUSION

The analysis of existing software for the beam particle dynamics in accelerators revealed the strengths and weaknesses of available tools, approaches and research methods. Furthermore, the modern requirements for physical accelerators and numerical experiments results lead to the need to solve one and the same problem by different ways and methods.

With this in mind, the BOSS program complex was developed as a prototype of the universal tool for automating and accelerating of the computational experiments execution.

To validate the developed software product, a numerical experiment was performed. The results of the experiment proved the correct operation of the program.

Currently, this software is being actively developed for carrying out computational experiments in the scope of the large-scale NICA (Nuclotron-based Ion Collider fAcility) [11] project of the Joint Institute for Nuclear Research (JINR, Dubna, Russia).

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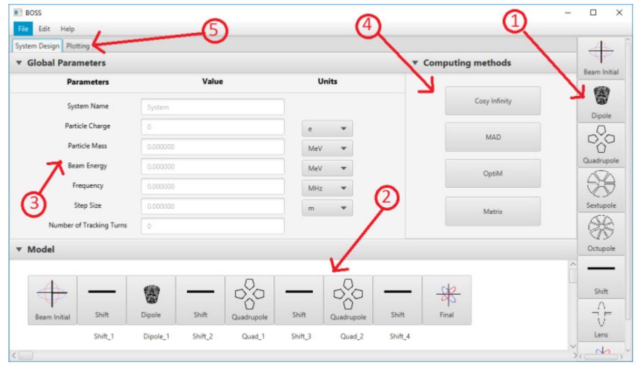

Figure 1: The main window of the BOSS program: 1 - the palette of the control elements, 2 - the system modeling area, 3 - the system global parameters bar, 4 - the software package selection bar, 5 - the data visualization.

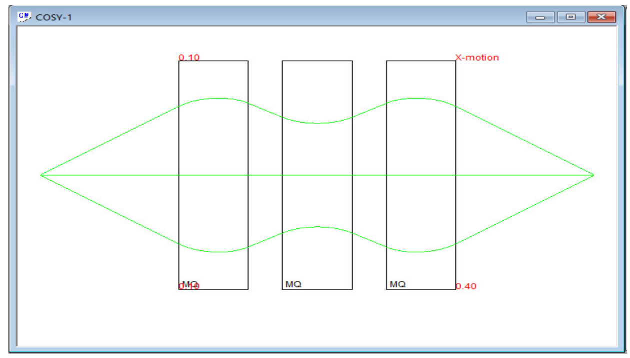

Figure 2: The first system dynamics visualization in the Cosy Infinity.

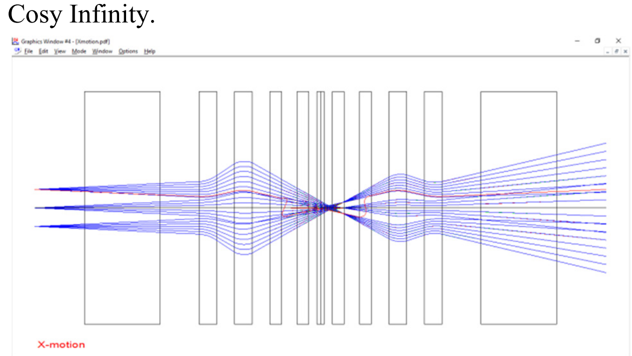

Figure 3: The beam particle dynamics visualization for the second system in the Cosy Infinity.

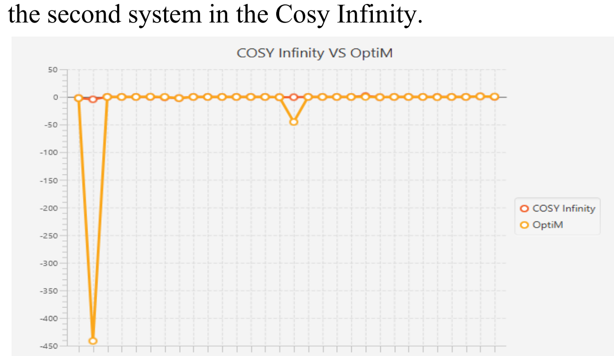

Figure 4: The combined visualization of the COSY Infinity (red) and OptiM (yellow) calculation results in the BOSS program.