SNOP – BEAM DYNAMICS ANALYSIS CODE FOR COMPACT CYCLOTRONS

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Abstract

The SNOP program complex intended for particle dynamics simulations in a compact cyclotron from the injection line to the extraction system is described. The main features of the SNOP are usage of 3D electric and magnetic field maps, beam space charge effect calculation, and analysis of the beam losses on the structure elements of the facility under consideration. The optimal usage of modern computer capabilities and graphic libraries for visualization is a key issue in the SNOP development. The beam dynamics modeling results for various cyclotrons are presented.

INTRODUCTION

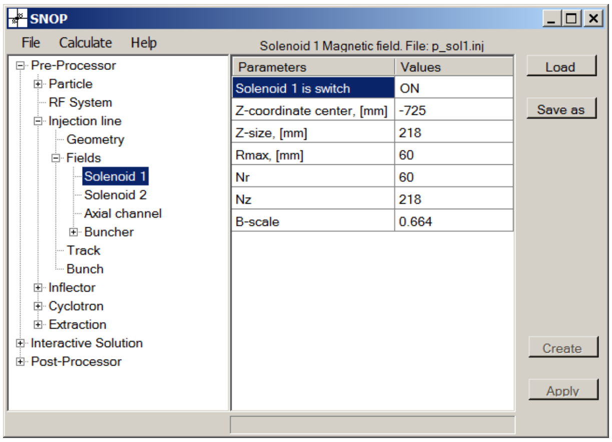
Recently, compact cyclotrons are widely used for solution of fundamental and applied problems. Noticeable expenses that are needed for the design and operation of the cyclotrons impose stringent requirements on the accuracy of the simulations conducted to select the facility parameters and to assess the beam dynamics peculiarities. There are a number of available codes such as TRANSPORT [1], MAD [2], TRACE3D [3], and COSY [4] based on the matrix formalism for the design and study of beam-optics systems. Some of them include detailed beam space charge calculations. However, none of these codes provides a full description of the peculiarities of beam dynamics in a compact cyclotron. The other group of the programs is prepared for special accelerating facilities [5, 6]. It is problematic to use these codes for the beam dynamics analysis in the cyclotron as a complete setup, from the injection line to the extraction system. This situation appeals to preparation of programs that can be easily applied to any cyclotron facility, operate with 3D (spatial) electric and magnetic field maps, take into account the beam space charge effects, and most effectively use resources of modern computers. The program complex SNOP that is produced at JINR and intended for simulation of beam dynamics in a compact cyclotron complies with all the above-mentioned requirements. The SNOP is a qualitative extension of the CBDA code described in [7].

PROGRAM COMPLEX DESCRIPTION

The main features of the SNOP are usage of 3D electric and magnetic field maps, beam space charge effect calculation, and analysis of the beam losses on the structure elements of the facility under consideration. The optimal usage of the modern computer capabilities is a key issue in the SNOP development.

Complex Structure

The program complex is convenient to use due to its user-friendly interface (see Fig. 1). The SNOP is structured in such a way that there are dedicated blocks responsible for real units in the beam transport line and accelerator itself. There are also separate menus to control parameters of acceleration particles and setting parameters for the equation of particle motion including beam space charge effects.



Solenoid 1 Magnetic field. File: p_sol1.inj

Parameters	Values
Solenoid 1 is switch	ON
Z-coordinate center, [mm]	-725
Z-size, [mm]	218
Rmax, [mm]	60
Nr	60
Nz	218
B-scale	0.664

Figure 1: SNOP main window.

The program complex shell permits one to control parameters of the electromagnetic devices for the beam acceleration and focusing, such as the dee electrode, solenoid, electrostatic inflector, magnetic and electrostatic quadrupole, magnetic channel, electrostatic deflector, and main, trim and harmonic coils.

The SNOP shell is prepared in such a way that it is possible to modify available parameters without editing any files manually.

The tooling for the magnetic field analysis permits full-size calculations of the magnetic field characteristics. The mean magnetic field, flutter, betatron tunes, amplitudes of radial oscillations, etc can be calculated using analytical formulas and closed equilibrium orbit computation.

There is a possibility of using such systems as MathCAD and AutoCAD, with which data exchange can be carried out. MathCAD is applied at the initial data generation and for analysis of the results. AutoCAD permits one to specify geometry of the objects when calculating particle losses and to depict the positions of the accelerated and lost particles against the background of the real geometry of the facility (see Fig. 2).

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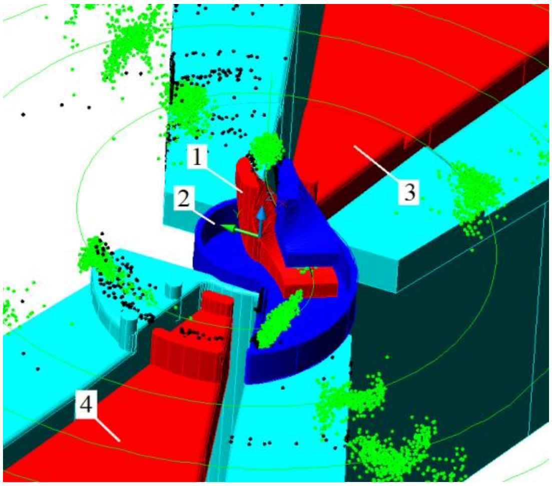

Figure 2: AutoCAD visualization of the central region of a cyclotron: (1) inflector, (2) inflector RF shield, (3) dee 2, (4) dee 1.

The SNOP allows using graphical libraries for visualization of the calculated results. This makes t possible to plot on the screen some physical process that happen in the facility simultaneously with the simulation progress. The simultaneous motion of a set of the macroparticles can be visible against the background of the chosen geometrical structure of the facility under investigation to understand an impact of various selected parameters of the acceleration regime on the particle behavior.

Equations of Particle Motion

The Cartesian coordinate system is used in the program complex as most generally applicable to definition of electromagnetic fields of the structure elements. The SNOP calculates trajectories of macroparticles in the electromagnetic fields, solving a complete system of the equations of motion without any simplification. It uses the classical fourth order Runge-Kutta method to solve the system of the equations.

Usage of the Electromagnetic Field Maps

The SNOP supports beam dynamics calculations using 3D (spatial) maps of electric and magnetic fields. Import of the field maps calculated in the OPERA/TOSCA program [8] is an option provided. For user's convenience there is a possibility of analytical field distribution for some of the structure elements at the stage of initial selection of the facility parameters. Along with application of the static field maps there is a possibility of using time-dependent electromagnetic fields, e.g., buncher and acceleration dee fields.

Calculation of Beam Space Charge Effects

There are two possibilities of considering particle self-fields in the SNOP: direct calculation of the Coulomb particle interactions and the PIC (Particle-In-Cell) method [9]. The latter is one of the methods used to solve a certain class of partial differential equations. In this method, individual particles in a Lagrangian frame are tracked in continuous phase space, whereas moments of the distribution such as densities and currents are computed simultaneously on Eulerian (stationary) mesh points. A larger number of macroparticles in the calculation is ensured by application of the PIC method compared to the former method.

Particle Losses on the Structure Elements of the Facility

In the SNOP there is a possibility of detecting loss of particles when they cross the surfaces of the accelerator structure elements. One of the options is description of the structure geometry by analytical surfaces. This permits fast estimation of the particle losses in the facility regions where this geometry input is valid. For more accurate calculation of losses the geometry can be imported from the CAD program with sufficiently detailed presentation of the mechanical model. It can be used in those parts of the facility where the geometry is more complex and cannot be described by analytical surfaces. Fast algorithms for determining the particle intersection with the surfaces of the bodies are used to decrease the required computer time for the calculations in the SNOP. The graphical capability of the program complex permits visualization of the lost particles on various surfaces of the facility.

BENCHMARKING

As was mentioned above, the predecessor of the SNOP is the CBDA code. The results obtained with the CBDA were many times cross-checked with such well known programs as Trace3D and SPUNCH and were confirmed by the experiments with the beam at the RIKEN AVF Cyclotron (Japan).

Let us consider some examples of the SNOP application to the modeling of newly developed and operational accelerating facilities.

The HITFiL cyclotron (IMP, China) [10] is under construction to be employed as an injector to a synchrotron for hadron therapy of tumors. The synchrotron should accelerate carbon ions with the energy 400 MeV/nucl. The cyclotron is designed to accelerate $^{12}C^{5+}$ ions up to the energy 7 MeV/nucl.

As the starting point, the preliminary cyclotron technical project was adopted. The main purpose of the simulations was analysis of the beam dynamics and overall functioning of the injection, acceleration, and extraction systems. The results of the simulations were taken as a basis for modification of practically every element of the machine in the final version of its technical project. Estimation of the overall beam transmission efficiency through the whole cyclotron was a key issue of the study.

The activity was focused on substantial improvement of the extraction system functionality. The main results emerged from the calculations were substantial modernizations of the extraction system elements and, which is most important, installation of a new element, namely, the gradient corrector of the cyclotron fringe field along the extracted beam trajectory. The calculations showed that the proposed upgrade of the extraction system would lead to drastic improvement of the extracted beam characteristics.

The corresponding calculations performed for the newly formulated machine structure (after all the modifications offered by the calculations) showed that the beam transmission efficiency through the accelerator units increased and the total transmission increased by a factor ~5 times (see Fig. 3).

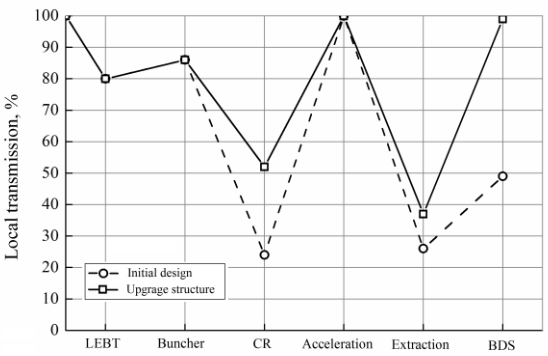

Figure 3: Beam transmission efficiency at various structure elements of the cyclotron.

Computer-aided modeling for the RIKEN AVF cyclotron (Japan) [11] was also performed. As one of the results, a new method was emerged [12] to substantially suppress particle energy spread in a compact cyclotron. The viability of the method was demonstrated experimentally by the beam tests. The new inflector geometry and the optimized central electrode structure have been formulated for the upgrade of the AVF cyclotron.

The SNOP was applied to multicomponent beam (15 various ions) dynamics simulations of the FRIB Front End line [13]. Space charge calculations were performed with 10^6 macroparticles.

The recent application of the SNOP was modeling of the NIRS-930 cyclotron [14]. Computer representation of the machine was prepared, including the area from the axial injection line to the outlet window of the cyclotron. A comparison of the calculations with the experimental data shows that the constructed model agrees with the reality very well. Here one of the key points is the beam transmission efficiency though the cyclotron (see Table 1).

Table 1: Transmission, %

	Calculation		Experiment
Range	No space charge effects	Space charge effects included.	
Central region	35	31	29
Acceleration	89	85	89
Extraction	52	49	49
Total	16	13	12

Optimization of the operational parameters for typical beams in the whole performance area of NIRS930 is the next step in the simulations, which is expected to improve the transmission through the cyclotron and the beam quality.

CONCLUSIONS

The program complex SNOP is a convenient tool for the beam dynamics analysis in a compact cyclotron. The SNOP is user-friendly and permits conducting calculations for a wide class of facilities. It is handy for construction of the computer model of a cyclotron. The program complex is very useful and has a high potential for computer simulations of accelerators.

The SNOP was applied for the beam dynamics analysis in a number of operational and projected accelerator facilities with favorable comparison to the beam measurements.

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