SOFTWARE COMPLEX "DYNPART" FOR THE CALCULATION OF SELF-CONSISTENT BEAM DYNAMICS IN DIELECTRIC WAKEFIELD ACCELERATING STRUCTURES

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Abstract

Dielectric waveguide structures are a basis for development of new generation of accelerators on the basis of a wakefield method of the charged particle acceleration, beam manipulation, and also free electron lasers. A self-coordinated dynamics of relativistic particle beams in a single layer cylindrical waveguide with dielectric filling is investigated. The computer code is developed based on mathematical expressions for the analysis of the radial dynamics. The possibility of modelling interaction of different types of particles in a bunch is realized. Influence of both own wake fields and external fields of focusing and deflection systems on bunch dynamics is analyzed.

INTRODUCTION

Wakefield acceleration principle is based on a generation by high-current charged particles bunch in the waveguide structure of an electromagnetic wave with a longitudinal component of the electric field up to 100 MV/m. This wake field is used to accelerate a following low-current bunch of high energy. In free electron lasers electromagnetic wave generated by high-current electron bunch is extracted from the waveguide and structure is used as an electromagnetic radiation source.

Dielectric wakefield accelerating structures are single or multilayer dielectric cylindrical waveguides with outer metal covering and vacuum channel along the axis. Along with the longitudinal fields there are transverse fields, leading to bunch deflection from the axis of the waveguide and subsidence of particles on its wall.

Development of new methods of acceleration based on principle of wakefield acceleration, requires a detailed analysis of the self-consistent beam dynamics taking into account both own and external focusing and deflecting fields.

Nowadays, wakefield accelerators often use light particles, electrons, as driving bunch, to generate the wakefield for acceleration of another electron bunch (which is usually called “witness”) like it is organized at AWA/APS accelerator complex in Argonne National Laboratory (USA) [1]. Wakefield acceleration of heavier particles, like protons, is not used because of traditional cyclic accelerators like synchrotrons are more effective for acceleration of heavy particles. Nevertheless wake field generated by driving electron bunch in the wakefield structure can be used for energy modulation of long proton bunch [2].

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At the same time wakefield acceleration with its high acceleration gradient would be promising in case of muons acceleration which can live in their self-reference system only 2.2 μs.

Effectiveness of wakefield acceleration is limited by “Wakefield’s theorem”. In accordance with "Wakefield's theorem" in the accelerator, where the electron bunches move along the same line, in the case of symmetric driving electron bunch accelerated bunch cannot increase its energy more than twice the value of electron energy of the driving bunch. This limit can be overcome by using a proton beam accelerated in synchrotron as a driver and electron or muon bunch as a witness.

SPECIALIZED SOFTWARE

For the analysis of the radial beam dynamics in the accelerating structure, methods of computational experiment are used. Specialized software, like CST Particle Studio [3], has been developed to aid in accelerator modelling; however, these codes based on particle-in-cell solver being universal are rather slow. Some special codes like BBU-3000 developed for self-consistent beam dynamics in wake fields uses numerical methods for differential equation solving. We decided to take a different approach and develop a software complex that uses strict analytic solutions to dynamics equations to calculate particle coordinates [4, 5].

DYNPART SOFTWARE COMPLEX

Analysis of the beam dynamics in the developed software is based on the method of macroparticles. In this method charge distribution function is realized by generating an array of particles with a given distribution in space, and field calculation is organized by summation of field generating of each macroparticle over the array. In case of high-current relativistic beams electrostatic approximation inapplicable to determine the Cherenkov wake field. Our algorithm for calculating wake fields is based on dot charge field expansion in series on waveguide eigenfunctions. That requires for the self-consistent beam dynamics calculation using the "particle – particle" method. The number of operations in this method increases with the square of the number of macroparticles that increases the calculation time and thus imposes restrictions on their accuracy. For accelerating of calculations an analytical solutions of the equations of relativistic dynamics and optimized for calculation speed algorithm for finding wake fields based on expansion on waveguide eigenfunctions were used (Fig. 1).

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Developed software allows to:

1. Calculate of parameters of the cylindrical waveguide with single layer dielectric filling.
2. Simulate dynamics for any number of bunches in waveguide.
3. Solve the self-consistent equation of dynamics in 2D, and 3D models.
4. Choose parameters of alternating-gradient focusing and weak focusing.
5. Observe the transformation of the beam shape when it moves in the waveguide in the process of calculating (Fig. 2).
6. Display the field distribution in the space inside and outside the beam, and construct a vector diagram fields.
7. Identify the flight range to prevent beam touching the waveguide wall.
8. Perform optimization of the parameters of the waveguide and the beam focusing system for maximization of flying range and energy extraction from the beam.
9. Perform parallel computing based on OpenMP for shared memory systems. The result is a substantial increase in performance of about 8 times compared with the linear calculations.

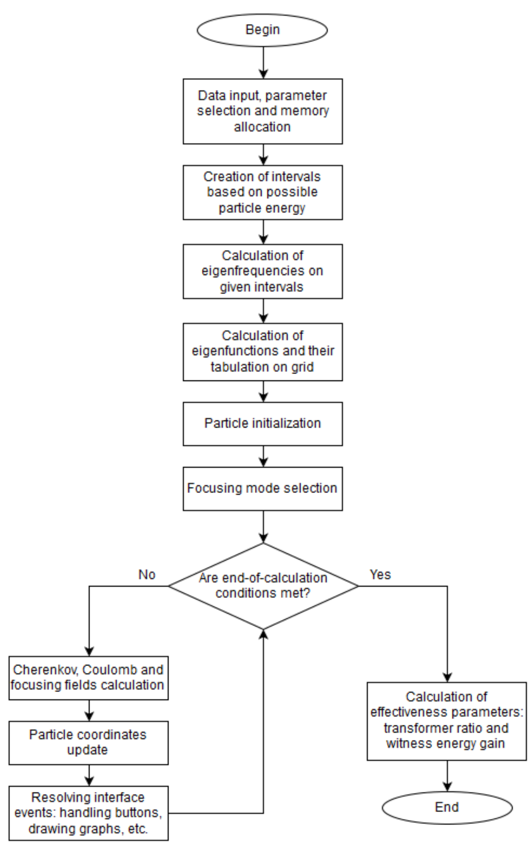

Figure 1. A workflow chart for the primary calculation process of DynPart.

New features and code optimizations

"DynPart" program [6], developed for study of beam dynamics in wakefield accelerating structures, has been revised and expanded to this day. Some parts of the code have been optimized to increase computing speed, and new features were added.

The primary feature of the new version is the ability to calculate beams made of different particles. The beams being studied can now include bunches contain different particles (see Fig. 2). Supported particles are protons, electrons, muons and their antiparticle counterparts.

New graphs are plotted, including the energy distribution within a bunch (see Fig. 3) and phase-space impulse graph.

This expanded functionality allows us to study the wakefield accelerators. Testing data shows to be consistent with real-world results obtained by Argonne National Laboratory, which leads us to the conclusion that the code developed is correct and can be used for further research.

For increasing speed of calculations optimization algorithm for wake fields calculating was developed. On the first step an array of waveguide eigenvalues and eigenfunctions is created, correspondent to different bunches with different types of particles, different charge energies and charge positions. In the course of calculation of bunch dynamics wake fields are found by the choice of an array element corresponding to type, energy and the position of a particle.

Additionally, the code is now based on Cartesian coordinates and uses them to move data between modules; the only conversion to cylindrical coordinates is made within a field calculation module for cylindrical geometry.

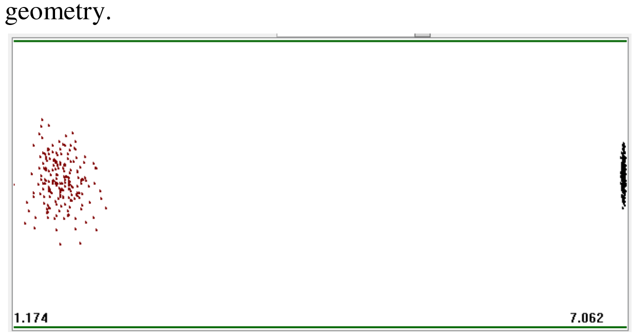

Figure 2. A screenshot illustrating an example simulation of different particles in an accelerator; painted red being the protons, and black – the electrons.

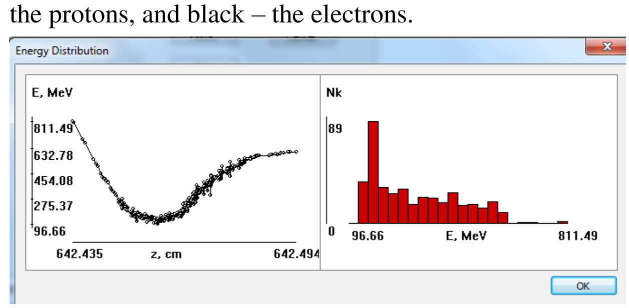

Figure 3. Driver bunch energy distribution

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Perspectives

New code architecture is developed to meet the new requirement of easy expandability. The new architecture is supposed to be modular and, therefore, easily modifiable. We will be able to combine various sequences of wave guides with dielectric filling of different geometry and the focusing and rotary elements. We will also try to perform a platform abstraction – in other words, create a platform-independent program that uses a platform-dependent API for low-level operations. Primary target platforms include Windows and Linux, therefore, using Qt appears reasonable for resolving this task, as it includes features such as platform-independent multithreading and graphics.

DYNPART IN RESEARCH

DynPart code was used for calculation of beam dynamics for Argonne Wakefield Accelerator / Argonne Photon Source (AWA/APS), investigation of interaction of FODO focusing with dielectric loaded wakefield waveguides [1, 4-6]. DynPart code has also been used to calculate of electron driver beam dynamics and creating of appropriate energy modulation for an mm-wavelength proton high energy microbuncher developed in collaboration with CERN AWAKE experimental group [2].

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