IMPLEMENTATION OF FRINGE FIELD DIPOLE MAGNETS INTO THE V-CODE BEAM DYNAMICS SIMULATION TOOL[*]

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Abstract

Fast online beam dynamics simulations can advantageously assist the machine operators at various particle accelerator machines because they provide a more detailed insight into the actual machine status. Based on the moment approach a fast tracking code named V-Code has been developed at TEMF. Within the SFB 634 project the V-Code beam dynamics simulation tool is supposed to be employed at the control system of the Superconducting Darmstadt LINear ACcelerator S-DALINAC. In order to be able to simulate the entire beam line of the re-circulating linear accelerator, an implementation of fringe field dipole magnets is mandatory.

INTRODUCTION

The beam dynamics simulation tool V-Code has been developed to model the motion of bunched particle beams in the vicinity of the design orbit of linear accelerators. Its database structure is build up in a way to handle even an extremely long beam line which may consist of a large amount of individual beam line elements. This is achieved with minimum requirements to the computer memory by means of loading each contiguous description data from the hard disk drive if required. Even though the original intention was focused on the linear motion this design enables also curved particle trajectories if a curved design orbit is provided.

The beam dynamics simulation for the recirculating electron accelerator S-DALINAC naturally requires a proper handling of dipole magnets including the fringe-fields for accurate modeling. Unlike a hard edged field approach the fringe fields influence the beam focusing and its inhomogeneity results in a non-circular bunch motion. For a precise reproduction of the transverse motion specialized techniques to obtain and to handle the reference path in V-Code together with the 3D-field data along the curved trajectory had to be developed.

NUMERICAL MODEL

The evolution of the phase space distribution in time is modeled on the basis of the VLASOV equation whereas the space charge effects are taken into account as external forces. The fundamentals of the numerical model are already stated in [1] with details concerning efficient practical implementations given for example in [2].

The resulting ordinary differential equations with the discrete moments of the phase space distribution function as degrees of freedom can be integrated in time provided proper initial conditions are given and all essential external forces are known. These forces can be determined with the help of the LORENTZ equation when the electric field strength and the magnetic flux density are known.

Because one need to determine those fields only in the immediate vicinity of the particle distribution a compact and simple way to provide all components is given by a TAYLOR series expansion of the external fields with respect to the design orbit. Depending on the utilized order of moments to describe the particle distribution a suitable amount of series coefficients has to be provided.

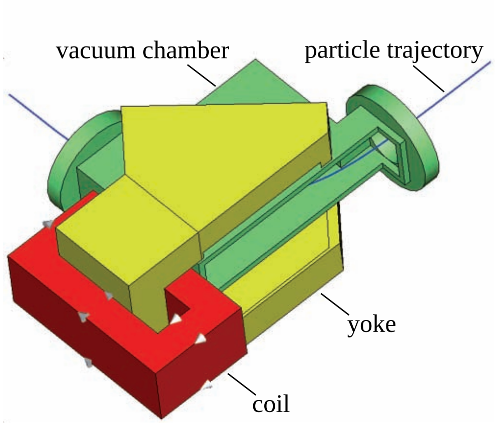

Figure 1: Schematic computational model of a dipole magnet including the excitation coil and the high permeable yoke. For visualization reasons the front part of the vacuum chamber and the magnet yoke is removed. Additionally, a typical particle trajectory is specified as the design orbit.

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Magnetic Field Calculation

Before the TAYLOR series expansion coefficients can be stated a fully three dimensional magnetic field calculation has to be performed. This can be done for example with the help of the magneto-static solver integrated into the CST Design Environment [3]. For optimization reasons the whole dipole magnet is modeled in a parameterized fashion including all geometrical details and material properties. Particular emphasis is put on the proper location of the yoke edges as they directly influence the focusing behavior.

Reference Path

Because the magnetic flux density is needed only in the vicinity of the particle distribution it is sufficient to evaluate the proposed series expansion exclusively along the reference path of the dipole magnet. Due to the inhomogeneity of the field this line is not known a priori and has to be determined individually. Within the CST Design Environment this can be accomplished by tracking a single particle with proper initial conditions using the built-in particle solver. In Fig. 1 the computational model of a typical dipole magnet together with the calculated particle trajectory is shown.

Field Along Reference Path

In case that the reference path is a straight line the full field is usually split into individual multipole components as described for example in [4]. The correct superposition of all multipole parts can be accomplished by specifying the local multipole strength along the longitudinal coordinate and determine the corresponding transversal fields with the help of MAXWELL's equations. The same holds true for the local coordinate system in case of a curved reference path. To illustrate the functional behavior of the essential y-component of the magnetic flux density the calculated field along the curved line is shown in Fig. 2. From the specified curve the effect of shimming is noticeable.

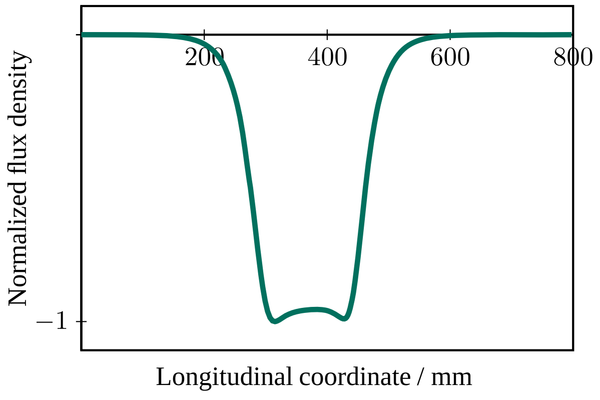

Figure 2: Vertical component of the magnetic flux density along the curved reference path normalized to the absolute maximum. Geometric details are specified in Fig. 1.

Directional Derivative

If the magnetic flux density is distributed in a way that the local multipole expansion can not be immediately performed along the reference path direction then the deviation of the local orientation with respect to the specified path has to be determined first.

Within the CST Design Environment a flexible postprocessing tool enables the evaluation of the vertical magnetic flux density component along multiple auxiliary circles situated along the specified reference path. Each data block belonging to an circle within the horizontal plane can be further processed to determine the local gradient information including both the absolute value of the derivative as well as the corresponding directional information.

The detailed knowledge of the directional derivative can then be used to set up a local multipole expansion which enables the recovery of all magnetic field components. Once the orientation is determined a reliable procedure known from the straight-line-case can be applied without major changes. For this reason the force calculation as well as the subsequent beam dynamics studies follow right from previous considerations. Within the specified coordinate system all necessary field components are given and the aimed beam dynamics studies can be performed.

In Fig. 3, a top view of the bend magnet setup is displayed. Beside the sketched magnetic yoke the reference path ranging from bottom left to the top center approximately in form of a quarter circle is included. Along the path the extracted directional derivative is displayed in terms of a colored vector. The marked arrows demonstrate the local gradient direction where a color code is used to identify the corresponding amplitude information. From the design point of view both the orientation of the local field as well as the amplitude can be controlled by a proper shape of the applied magnetic yoke.

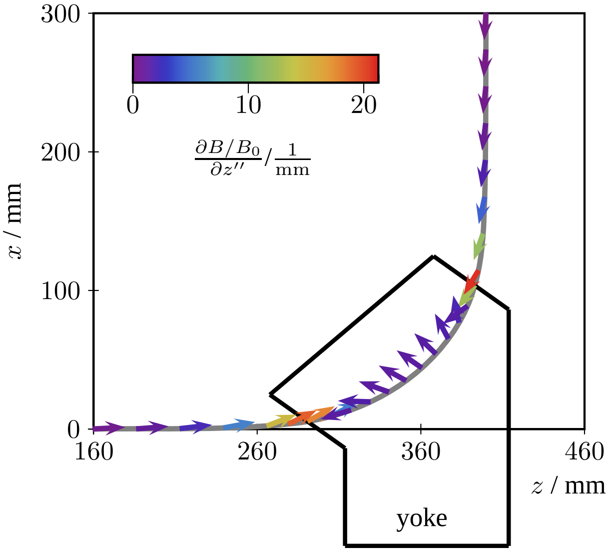

Figure 3: Directional derivative with amplitude scaling for the vertical magnetic flux density component along the reference path in the 90° bend magnet specified in Fig. 1.

IMPLEMENTATION

Because of different requirements to the local coordinate systems during the recovery of all magnetic field components, the time evolution of utilized bunch parameters as well as visualization aspects relative to the reference path a variety of coordinate transformations is involved during the beam dynamics simulation of a magnetic dipole element. An overview of the utilized systems is shown in Fig. 4. Corresponding to the actual bunch position (z_1, x_1) its normal projection (z_s, x_s) onto the reference path is determined. This uniquely defines the longitudinal position as well as the orientation of the primed system and can be use for the local transversal coordinates.

As seen above the curved trajectory and the effects caused by edge focusing lead to different gradient directions of the vertical magnetic flux density along the reference path. The gradient direction is reproduced in the double-primed coordinate system where the field components can be reconstructed. For accuracy reasons the calculation of the bunch evolution is done in the global unrotated coordinate system in order to prevent multiple coordinate rotations which give rise to the accumulation of round-off errors. Following this approach only one rotation at the very end of the simulation has to be performed.

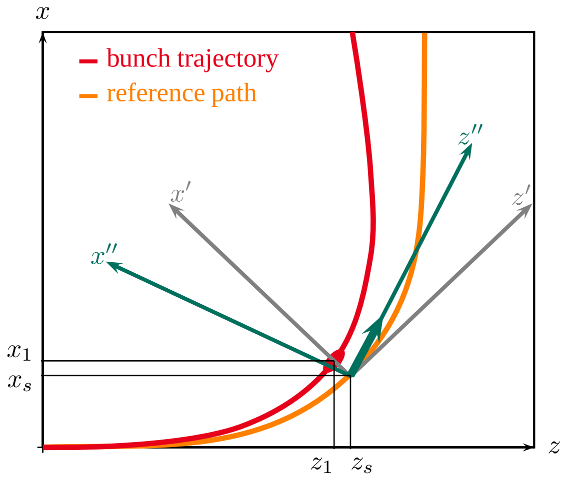

Figure 4: Typical projected bunch trajectory and the reference path for the dipole setup specified in Fig. 1. Three coordinate systems for the beam dynamics, the field calculation and the visualization are involved in the overall computations.

SIMULATION

In order to determine the practical applicability of the implementation the V-Code simulation results are compared with simulation results obtained by the particle tracker integrated in the CST Design Environment. The simulated focusing behavior of the dipole magnet is shown in Fig. 5 and Fig. 6. From the CST Design Environment the data were obtained by tracking a bunch of particles through the dipole magnet while using the implemented particle monitors for bunch dimension information.

In V-Code the transversal dimensions are determined from the global coordinates by means of coordinate transformation using the primed system. This automatically leads to the proper bunch dimensions as well as the right offsets. In the provided figures one can observe that not only the center of mass but also the transversal beam dynamics are modeled precisely. The effect of edge focusing is clearly visible.

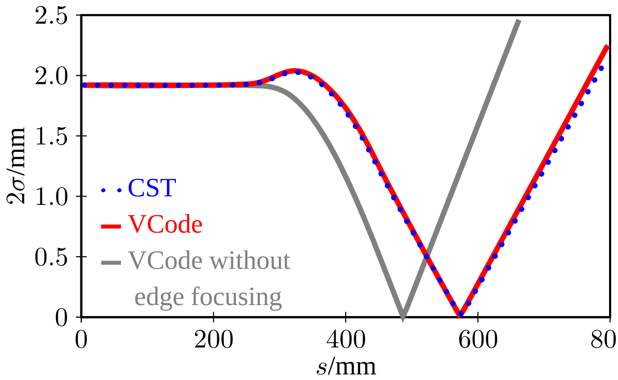

Figure 5: Simulation of the horizontal focusing effect within the dipole magnet.

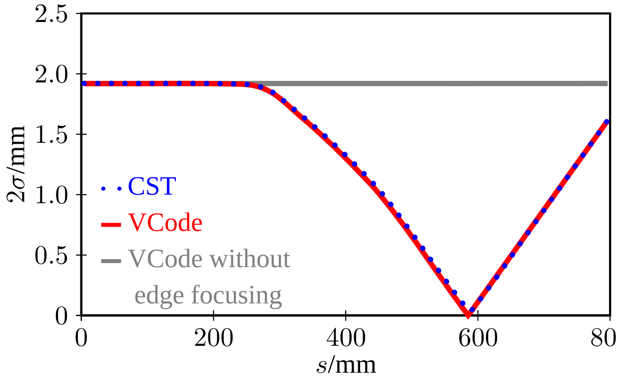

Figure 6: Simulation of the vertical focusing effect within the dipole magnet.

REFERENCES

[1] P. J. Channell, The Moment Approach to Charged Particle Beam Dynamics, *IEEE Trans. Nucl. Sci.*, NS-30, No. 4, Page 2607, 1983.

[2] W. Ackermann, T. Weiland: Data Base Extension for the Ensemble Model using a Flexible Implementation, presented at the 2005 Particle Accelerator Conference (PAC05), Knoxville, Tennessee, USA, May 16-20,2005, 19.05.2005.

[3] CST - Computer Simulation Technology, Bad Nauheimer Str. 19, D-64289 Darmstadt, Germany, http://www.cst.com.

[4] W. Ackermann, W.F.O. Müller, T. Weiland, J. Enders, H.-D. Gräf, A. Richter: Database Extension for the Beam Dynamics Simulation Tool V-code, Proceedings of the 10th European Particle Accelerator Conference (EPAC 2006), June 01.07.2006, pp. 2176-2178.