DATABASE EXTENSION FOR THE BEAM DYNAMICS SIMULATION TOOL V-CODE*

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Abstract

Beam dynamics simulations for long structures can be performed effectively if the involved beam line elements (BLE) do not interfere with each other. This condition permits to concentrate on a single BLE while switching only to the immediately following without keeping all nearby parts in memory. Such a procedure automatically avoids the necessity to build up a complete field description in advance. In addition, a time consuming search for contributing elements can be excluded.

Nevertheless, some devices require for a careful handling to meet those favorable properties. A typical example is given by a compact quadrupole triplet with individual magnetic fields reaching far into neighboring yokes. The beneficial assumption can still be maintained in a global sense if the whole physical device is treated as a single software unit with non-interfering fields to adjacent structures. A database which was assembled previously has to be extended according to the given requirements.

INTRODUCTION

The beam dynamics simulation tool *V-Code* [1] has been proved to be very useful in redesigning the injector layout at the superconducting linear accelerator in Darmstadt (S-DALINAC) [2]. Modifications in the beam optics are necessary because a new source providing polarized electrons should be installed in addition to the existing thermionic gun. The new 100kV source is based upon photo-emission and is supposed to complement the existing 250kV static gun on successful operation.

The beam dynamics simulations are performed with *V-Code* which is designed to handle a large amount of individual beam line elements and can therefore be used for extensive accelerator studies. The available database includes all the necessary components like solenoids, quadrupoles, rf cavities and drift spaces but as a result of their consecutive treatment overlapping external fields are not allowed.

Due to geometrical restrictions in the assembly of the new source a space-saving candidate of a quadrupole triplet violates this software-related condition if it is regarded as three separated quadrupoles. Consequently, a more general beam line element has to be created which treats the whole device as a single unit without interference of their local fields to attached cells.

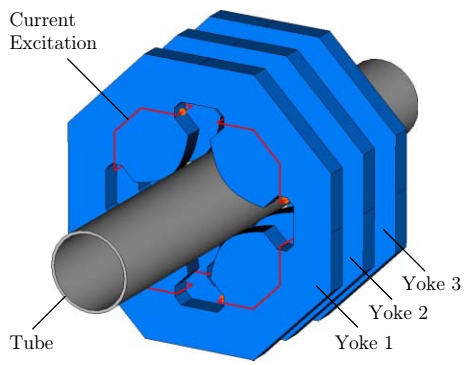

Figure 1: 3D model of a compact quadrupole triplet.

In Fig. 1 a computational model of a typical quadrupole triplet including the iron yokes, the current excitation and the beam tube is given. Further information concerning the prototype triplet in particular and the new injector layout in general together with detailed descriptions of already installed components is provided in [3].

NUMERICAL MODEL

Beam dynamics simulations including long quadrupole magnets can often be performed applying certain simplifying assumptions regarding the transition regions of the fields at the front and end face. Neglecting the actual field distribution translates in a hard edged magnet approximation. Due to the compact design of the regarded quadrupole triplet a realistic numerical model explicitly has to take the fringe fields into account. Because of the extremely narrow iron yokes a large part of the field is located in the transition region and may not be neglected. Hence it is advisable to perform a full 3D field simulation.

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Field Calculation

The magnetic field distribution for the quadrupole triplet model has been calculated using the 3D magnetostatic field solver integrated in the CST Design Environment [4]. In order to perform the simulations in an efficient way it is advisable to construct a parameterized model including the geometry and the excitation currents of each quadrupole magnet. By means of a multipole expansion the obtained field quality can be monitored and optimized.

For beam dynamics simulations only the magnetic flux density in the vicinity of the axis is required. According to the simulation model a paraxial approximation of the field gradient based on a power series expansion is sufficient for operation. Thus, the calculated 3D field information can be transferred effectively from the magnetic field simulation tool to the beam dynamics simulation program.

Ensemble Model

Charged particle beam transport is often described by means of a collision-less kinetic approach. A fast and powerful method to solve the equation arising from kinetic considerations is given by the ensemble model. The entire technique is based on the moment method and utilizes a discrete set of moments of the analyzed particle distribution instead of the particle density function f itself. First order raw moments and centralized moments of higher order in the form of

$$<\mu> = \int_{\Omega} \mu \; f(\vec{r},\vec{p}) \; \mathrm{d}r^3\mathrm{d}p^3$$

are usually used as the degrees of freedom. Here, the generally time dependent parameters μ are formulated in Cartesian coordinates such that

$$\mu \in \{x, y, z, p_x, p_y, p_z\} \qquad \text{for the first and}$$

$$\mu \in \{(x-<x>)^{l_x} \cdot (y-<y>)^{l_y} \cdot (z-<z>)^{l_z}, \ldots\}$$

for the higher order moments. The collision-less kinetic approach together with the moment method technique represents a set of first order ordinary differential equations which can be integrated supposed a consistent initial condition is provided. Details concerning the theoretical fundamentals can be found in [5, 6, 7].

Axial Quadrupoles

Starting from the MAXWELL equations in free space one can establish a functional link between the gradient dependency $A(z)$ of a quadrupole magnet and the corresponding magnetic flux density components

$$\begin{aligned} B_r &= \quad -r \; A(z) \; \cos\big(2(\phi-\phi_0)\big) \\ B_\phi &= \quad\; r \; A(z) \; \sin\big(2(\phi-\phi_0)\big) \\ B_z &= -\tfrac{1}{2} r^2 \; A'(z) \; \cos\big(2(\phi-\phi_0)\big). \end{aligned}$$

The assumptions mentioned above are always valid for a description of the static magnetic field inside the source-free region of the vacuum tube.

IMPLEMENTATION

For fast beam dynamics studies the ensemble model up to second order has been implemented into the the beam dynamics simulation program *V-Code*. Recently, an extension to the fundamental set of equations which allows to use even higher order moments has been proposed [7].

Quadrupole Triplets

Up to now, only quadrupoles with non-overlapping fields have been allowed. The modifications in the beam line layout at the S-DALINAC raised the question whether the existing database could be extended to enable also extremely compact quadrupole triplets with noticeably interfering fields.

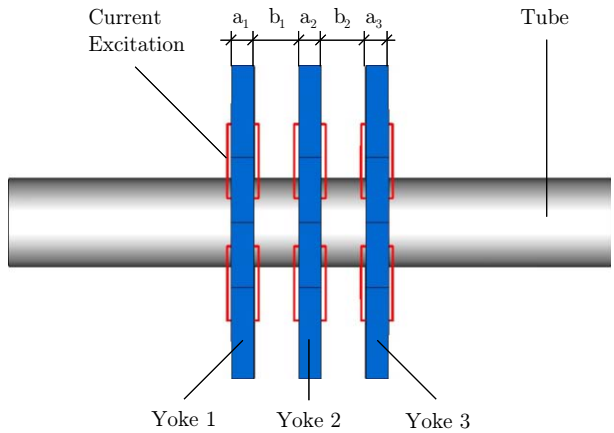

Figure 2: Side view of a compact quadrupole triplet.

In Fig. 2 the side view of a compact quadrupole triplet is shown. The iron yokes are usually designed to be identical for the whole triplet resulting in $a_1 = a_2 = a_3 = a$. In a symmetric version the gaps between the yokes are also equally spaced $b_1 = b_2 = b$ but this condition may be changed for optimization reasons.

The most flexible way to implement such a general quadrupole triplet is given when all magnets are treated independently of each other. Nevertheless, in the aimed code the whole device is designed as a single unit with adjustable current excitations within each quadrupole. A possibly intended partitioning in single independent units is not desirable due to efficiency reasons. If important parameters like the mounted angle or the total length are are not changed individually a lot of computational effort will be saved.

Data Collection

This formalism is only valid in a regime where the magnetic properties of the yokes can assumed to be linear. As a consequence, the total field is given by superimposing the fields of the discrete magnets. The weighted summation over all parts allows for handling each quadrupole independent of the chosen excitation.

Once the quadrupole strength of each individual part is determined applying zero-excitation to the remaining current pathes the overall quadrupole strength can be calculated. Step-by-step the whole data is collected while the quadrupole triplet itself remains an inseparable unit. Intrinsically, each data set belongs to a certain geometric set-up so that the same procedure has to be repeated in case of geometry changes. For a certain set of parameters b_1 and b_2 the field data can be generated and stored.

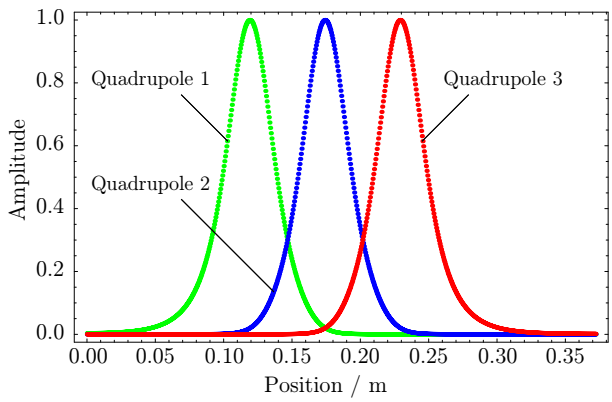

Figure 3: Normalized quadrupole strength of each individual magnet.

In Fig. 3 the normalized gradient distribution of each individual magnet along the longitudinal position is shown. The gradient information has been obtained from the original 3D field calculation in a subsequent postprocessing step. Superposition of these fields results in the overall gradient distribution. Each component can be weighted individually as the current in the excitation coils can be controlled independent from each other.

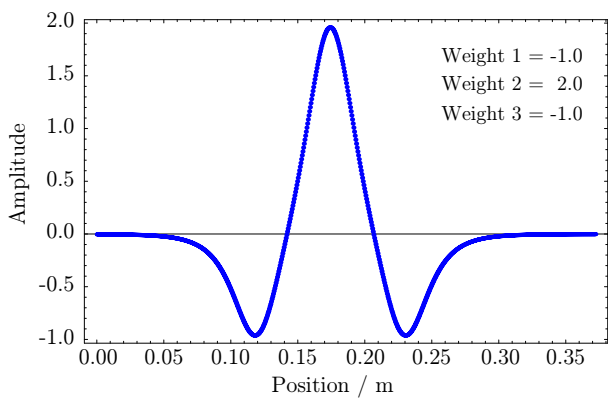

Figure 4: Normalized quadrupole strength of the whole triplet together with typical weighting factors.

In Fig. 4 a typical example for the quadrupole strength of the whole triplet is given. Dependent on the particular application the weights can vary significantly.

SIMULATION

The primary objective while implementing the compact quadrupole lens is to provide a data structure compatible to the already existing quadrupole magnets. This procedure automatically enables using the new element in a well-known software environment.

Special attention has been paid to the self-constrained condition that all field components of adjacent beam line elements should vanish in the transition locations. In Fig. 4 this fundamental behavior is documented. From the given quadrupole strength curve one can deduce the magnetic flux density components using the formulas provided above. In this context it is obvious that not only the quadrupole strength but also the derivative with respect to the longitudinal coordinate has to vanish. Therefore, a certain amount of space has to be added. In Fig. 1 this situation is illustrated graphically by means of a short beam tube.

Extensive simulations have been performed to find an optimal layout for an aspired injector redesign [8].

CONCLUSIONS

The proposed data base extension for the beam dynamics simulation tool *V-Code* allows for handling overlapping fields of compact quadrupoles like those being used at the new polarized electron source of the S-DALINAC. The design is based on already existing single quadrupole models but in the new element the functionality of the triplet as a single unit has been preserved. Special attention has been spend to keep the usage of the triplets within the program environment as user-friendly as possible. Once the data set describing the quadrupole elements is calculated they can be used as simple as separated quadrupoles.

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