MODELING OF MATCHING CHANNELS FOR ACCELERATOR COMPLEXES*

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Abstract

Practically modern accelerator facility can be considered as a composite machine. Therefore it is necessary to consider special matching channels to joint all accelerator components together. For such channels advance various requirements, which can be formulated in the form of criteria sets. In this paper considered a global optimization concept allows to find appropriate solutions sets. This approach is demonstrated on the problem of modeling the matching channels for NICA accelerator complex.

INTRODUCTION

Matching channels modeling is an important problem for accelerator design. Such matching systems (see, for example, [1]) are part of any modern accelerator complex and realize beam lines transportation with lattice functions matching.

Known that a beam particles motion has a nonlinear nature and described by large number of control parameters with corresponding criteria set. Therefore, beam evolution modeling can be formulated as an optimization problem. The choice of appropriate mathematical tools for both dynamics simulations and optimization procedures plays a significant role.

In this paper matrix formalism [2] used as an instrument for beam lines modeling. This formalism allows to design different transportation systems from linear to nonlinear models. This step-by-step concept is well represented in the paper [3]. Also, in this paper evolutionary algorithms used as an optimization tool for beam lines design (see, for example [4, 5]). The efficiency of this approach is considered on the matching channels modeling problem for NICA (Nuclotron-based Ion Collider fAcility) accelerator complex [6].

BEAM LINE MODELING

Usually, on the first step a researcher considers linear approximation of motion equations:

$$\frac{d\mathbf{X}}{ds} = \sum_{k=1}^{\infty} \mathbb{P}^{1k}(s)\mathbf{X}^{[\mathbf{k}]}, \tag{1}$$

where $\mathbf{X}$ – vector of the phase space, $\mathbf{X}^{[k]} = \mathbf{X}\otimes\ldots\otimes\mathbf{X}$. The symbol "$\otimes$" means Kronecker product, s – the global reference orbit, $\mathbb{P}^{1k}(s)$ – matrix of the k-th derivatives.

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Solutions of the motion equations (1) can be written in the form:

$$\mathbf{X}(s) = \sum_{k=1}^{\infty} \mathbb{R}^{1k}(s|s_0)\mathbf{X}_0^{[k]}, \tag{2}$$

where $\mathbb{R}^{1k}(s|s_0)$ – beam propagator. This approximation case and nonlinear motion equations presented in [3].

In this article considered *envelope formalism description* of the beam in the terms of envelope $\mathbb{S}(s)$ – matrix dimension $n\times n$. The most popular form of this matrix is described in terms of rms (root–mean–square) values [7]:

$$\mathbb{S}(s) = \int\limits_{\mathfrak{M}(s)} f(\mathbf{X})\mathbf{X}\mathbf{X}^* d\mathbf{X}, \tag{3}$$

where $\mathfrak{M}(s)$ – a current phase manifold occupied by beam particles, $f(\mathbf{X})$ – a distribution function.

The transverse manifold occupied by beam particles can described by $\mathbb{S}(s)$–matrix (i. e. rms-envelope matrix). Besides the rms-envelope matrix we can introduce another envelope matrices (see, for example, [2]). For all forms of envelope matrices can be written from (3) in the following form of the matrix dynamical equation :

$$\mathbb{S}(\boldsymbol{s}) = \mathbb{R}(s|s_0)\mathbb{S}_{\mathbf{0}}\mathbb{R}^*(s|s_0),$$

where $\mathbb{S}_0$ – the initial envelope matrix, $\mathbb{R}(s|s_0)$ – beam propagator, which symbolic presentation described in [5].

This matrix contains information about the main characteristics of the beam and allows to represent different functional types. The matrix formalism mentioned above has the following advantages:

- All calculations are realized with two-dimensional matrix which allows to use all effective algorithms of linear algebra (including parallel algorithms in contrast to the tensor calculus).
- The most optimization criteria can be written in terms of the elements of the matrices (from nonlinear equations (2)) without phase coordinates.
- Allows to use symbolic algebra methods and store relevant information in the form of standard symbolic expressions [9].

Thus, for each control element construct a sequence nonlinear matrices $\mathbb{R}^{1k}(s|s_0)$ from (2). These matrices can be evaluated in symbolic forms and kept in a special data base or knowledge base. This matrix sequence corresponds to standard control elements (such as dipole, quadrupole, sextupole, octupole and so on).

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MATCHING CHANNEL REPRESENTATION

This article discusses optimal parameters searching for the different matching channels types. Introduce the following types of matching channels, depending on the geometrical properties and functional performance requirements of the beam inside the channel and in particular at its exit:

- *Initial matching channels*. Realize primary transportation of beam particles into the accelerator [1].
- *Complex matching channels*. Realize beam particle transportation from one accelerator component to another.

The first type describes the matching channels of initial injection into the accelerator. The beam characteristics described by its weak conditions on the lattice functions. The main functional requirement for this type of channels is continuous particles injection.

The second type of channels include other channels, which main objective is to transfer from one component of the particle accelerator complex to another with more stringent conditions on the lattice functions. Also there are some control elements in this type of channels, which allows to improve the beam properties.

For example, for NICA Project one of these channels connects the Booster and Nuclotron [8] (see Fig. 1), where

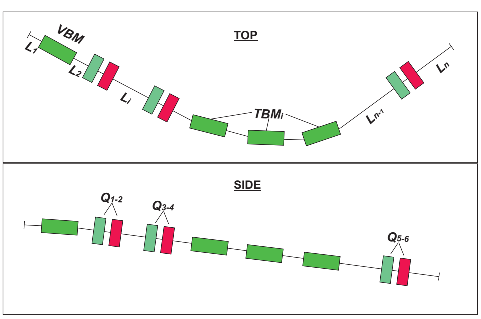

Figure 1: Booster–Nuclotron matching channel.

Q_i – quadrupole lenses, VBM – vertical dipole magnet, TBM_i – horizontal dipole magnets, L_i – free gaps between control elements.

The general form of matching channel types described above is shown schematically in Fig. 1 in terms of the matrix formalism, where i – schematic representation of i-th control element of channel lattice, $\mathbb{R}_i^{jk}(s|s_0)$ – matrix formalism lattice presentation.

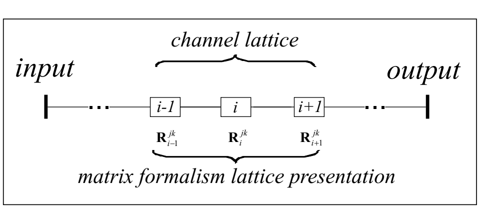

Figure 2: Matching channel scheme.

The main problem of matching channels is to transport the beam particles without energy loss. It requires to use various mechanisms of global optimization research in the problem parameter spaces.

OPTIMIZATION PROCEDURE

Recently, the beam lines modeling by evolutionary methods attract more interest among developers. In most papers on this subject are considered simple beam lines [4] consisting of a small number of controls. However, even in such small systems the process of searching for the optimal solutions is complicated by large number of control parameters, which requires to solve the global optimization problem [5].

In general case for both matching channels types integral functional can be represented in the following form:

$$\mathrm{J}[\mathbf{A}] = \int\limits_{s_0}^{s_T} \int\limits_{\mathfrak{M}(s)} g_1(\mathbf{A}, \mathbf{X}, \tau) d\mathbf{X} d\tau + \\ + \int\limits_{\mathfrak{M}_T} g_2(\mathbf{A}, \mathbf{X}, T) d\mathbf{X},$$

where $\mathfrak{M}$(s) – a current phase set, occupied by beam particles. The function g_1 describes the functional criteria distribution inside the channel, function g_2 – the terminal beam requirements.

Often, the first integral is represented as a finite sum in the form:

$$\mathrm{J}[\mathbf{A}] = \sum_{i=1}^{p} \alpha_i \mathrm{J}_i[\mathbf{A}],$$

where $\mathrm{J}_i[\mathbf{A}]$ — partial functional responsibility for certain characteristics of the beam, α_i — weight coefficients determining the contribution of a functional, i. e. its importance.

Consider linear model restrictions in matrix form:

- focusing point to point: $r_{12} = r_{45} = 0$;
- dispersion restrictions:

$$\|r_{13}, r_{23}| \leq \varepsilon_x, |r_{46}, r_{56}| \leq \varepsilon_y.$$

Nonlinear model restrictions can be divided in two types:

- geometrical aberrations (i.e. spherical aberrations);
- dispersion aberrations k-th order ($k \geq 2$).

Additional functional conditions are used in the case of intense beam, which can be described using a set of distributed points, occupy the given volume; a distribution function $f_0(\mathbf{X}) = f(\mathbf{X}, s = 0)$ and other functional restrictions.

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COMPUTATIONAL RESULTS

In this paper consider computational results obtained using the developed software package GOA (Global Optimization Approach [5]), which allows to create different structures. Computational process divides into three stages:

- *Initial stage*. Construction of the linear approximation of the control particles beam structures relying on developers personal experience and preference [1].
- *Mathematical modeling stage*. Calculation (or extraction from the special data space) linear and nonlinear matrices correspond to the lattice with functional requirements and constraints.
- *Optimization stage* redefine the functional requirements and constraints in term of GOA (Global Optimization Approach [5]). Realize computational procedures using GOA for preliminary results evaluation and implement appropriate solution selection.

The third step is performed accordingly for linear and nonlinear models. Construction of transport channels (matching channel) is realized in graphical module of GOA package (see in Fig. 3), where red and blue curves correspond to

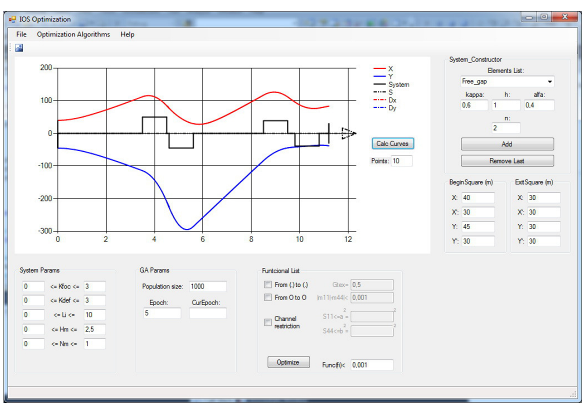

Figure 3: Global Optimization Approach.

the maximum values of the envelopes matrix in the x and y planes.

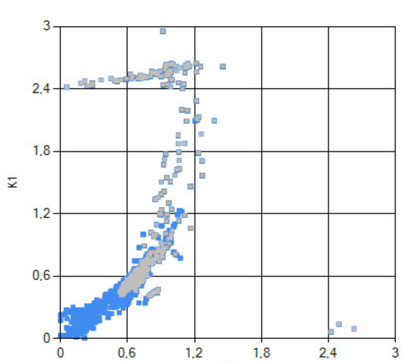

Figure 4: Appropriate solutions.

For example, considered simple transport structure consisting of two quadrupole doublets with non-zero distance between the lenses [5]. This structure has a set of appropriate solutions in the space $k_1 \times k_2$ of lens gradients (see in Fig. 4)).

This optimization complex allows researcher to make the modeling process flexible and manageable. The corresponding applied software allows to find appropriate solutions sets and will demonstrate on the problem of modeling the matching channels for NICA accelerator complex.

SUMMERY

In the paper there is described the global optimization approach linear and nonlinear beam lines based on the matrix formalism. GOA is an universal program complex. This approach allows to solve different problems of searching for a set of optimal solutions. The corresponding addition possibilities (for example, graphical presentation) permits an investigator to research appropriate solutions. This ideology implies to use distributed and parallel technologies for necessary computing and will be integrated in the virtual accelerator concept.

REFERENCES

[1] O. Kozlov, A. Eliseev, I. Meshkov, V. Mikhaylov, A. Sidorin, N. Topilin, G. Trubnikov, A. Tuzikov, "Transport Beam Lines for NICA Accelerator Complex," IPAC'11, San Sebastian, September 2011, THPS046, p. 3526.

[2] S. Andrianov, "A Matrix Representation of Lie Algebraic Methods for Design of Nonlinear Beam Lines," AIP'97, 391, p. 355.

[3] S. Andrianov, "Step-by-Step Optimization for Beam Lines," Nuclear Instruments and Methods in Physics Research, 2004, Vol. 519, 1-2, p. 28.

[4] L. Yang, D. Robin, "Global Optimization of the Magnetic Lattice Using Genetic Algorithms," EPAC'08, Genova, June 2008, THPC033, p. 3050.

[5] E. Podzyvalov, S. Andrianov, A. Ivanov, "Methods and Instruments for Beam Lines Global Optimization," Physcon'11, Leon, September 2011, `http://lib.physcon.ru/doc?id=bb024d809268`

[6] A. Sidorin, A. Kovalenko, I. Meshkov, G. Trubnikov, "Project of the Nuclotron-Based Ion Collider Facility (NICA) at JINR," IPAC'10, Kyoto, May 2010, MOPD011, p. 693.

[7] A. Chao, M. Tigner, *Handbook of Accelerator Physics and Engineering*, (Singapore: World Scientific, 1999), 650.

[8] A. Tuzikov, V. Mikhaylov, "Booster-Nuclotron Beam Line for NICA Project," Physics of Particles and Nuclei Letters, 2010, Vol. 7, 7, p. 478.

[9] N. Kulabukhova, A. Ivanov, V. Korkhov, A. Lazarev, "Software For Virtual Accelerator Designings," ICALEPCS'11, Grenoble, October 2011, WEPKS016, p. 816.

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