SYNTHESIS OF OPTIMAL NANOPROBE (LINEAR APPROXIMATION)

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Abstract

High energy focused ion (proton) micro- and nanoprobes are intensively integrated as powerful analytical tools for different scientific and technological goals. Requirements for beam characteristics of similar focusing systems are extremely rigid. The value of demagnification for micro- and nanoprobes is the main optimality criteria, and as desirable value are in the range from 50 to 100 or even more. In the paper, we reconsider the basic properties of first order focusing systems from an optimal viewpoint. The matrix formalism allows us to formulate a nonlinear programming problem for all parameters of guiding elements. For this purpose there are used computer algebra methods and tools as the first step, and then some combination of special numerical methods. As a starting point for nanoprobe we consider so called ”russian quadruplet”. On the next steps, we also investigate other types of nanoprobes. Some graphical and tabular data for nanoprobe parameters are cited as an example.

INTRODUCTION

During recent years many scientists have been showing interest in ion nanoprobes, which help to create tiny particle beams about some nanometers on a target. Nanoprobes are known to be used in wide field of application by successful centers of nanoprobes (see, for example, [1]). There is rich experience for such systems development. However, in spite of this fact, review of many papers deal with nanoprobes shows that there is no quite comprehensive concept of modeling such systems in scientific literature. Four papers are presented at this conference (see also [2]–[4]), which are dedicated to different aspects of development of corresponding optimal systems. This is basic paper because general statements are formulated which are required to use for solving tasks with nanoprobes. On the basis of linear model we can create a development algorithm for optimal desired focusing systems and possible decisions with necessary illustrations about some choice reasonability.

BASIC CONCEPTS AND MODELS

Usually three or more quadrupoles are used as a focusing system for a micro- or nanoprobe. Destination and manufacturing restrictions define choice of acceptable configuration in every specific case. As the example, authors consider so-called “russian quadruplet” [5], which

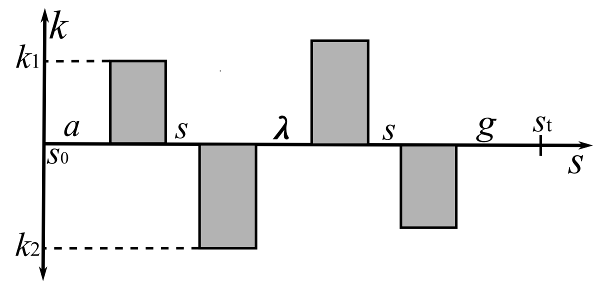

Figure 1: A “russian quadruplet” focusing system.

allows forming “high-quality” beams. Control system of quadrupoles satisfies “symmetry on power supply” condition, which can be written in the form of the following equality

$$k(s) = -k(s_t - s), \;\; s \in [s_0, s_t], \tag{1}$$

where s — a length parameter, which is measured along with optical axis of the system, s_0 — an initial point, s_t — an end point (see Fig. 1), $k(s)$ — a distribution function of gradient along the optical axis of the system. In linear approximation particle motion equations have the following form

$$\begin{aligned} x'' + k(s)x = 0, \;\; x' = dx/ds, \\ y'' - k(s)y = 0, \;\; y' = dy/ds. \end{aligned} \tag{2}$$

The solution of the system (2) could be written using so called a matrizant $\mathbb{R}(s|s_0)$ (see [6]):

$$\mathbf{X}(s) = \mathbb{R}(s|s_0)\mathbf{X}_0, \;\; \mathbf{X}_0 = \mathbf{X}(s_0), \tag{3}$$

where $\mathbf{X} = (x, x', y, y')^*$ — a phase coordinates vector. The matrizant $\mathbb{R}(s|s_0)$ is the corresponding matrix propagator of the system on components (see Fig. 1): a drift gap (“pre-distance”) with the length a, a focusing component — “objective” (with the length $s_t - s_0$), drift gap with the length g — “working distance” [5]. In this case the propagator $\mathbb{R}$ could be presented in form

$$\mathbb{R}(s_t|s_0) = \mathbb{R}_g \mathbb{M}(s_1|s_0)\mathbb{R}_a, \tag{4}$$

where partial propagators have a block-diagonal structure. Condition (1) is imposed on objective leads to contract between elements m_{ik} of the transfer matrix $\mathbb{M}$:

$$\begin{aligned} m_{11} = m_{44}, \; m_{12} = m_{34}, \\ m_{21} = m_{43}, \; m_{22} = m_{33}. \end{aligned} \tag{5}$$

It is obviously that if the condition

$$m_{11} = m_{22}, \tag{6}$$

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is correct, then we can get identical equality between transfer matrices in both planes $\{x, x'\}$, $\{y, y'\}$ from (5). It is also evidently that if the condition (6) is correct full-length propagators will be equal in mentioned planes. As the additional clause for system we consider the well known focusing condition — the focusing "from point to point". Using eq. (6) this condition can be written as $r_{12} = r_{34} = 0$, which leads to the following equation for the working distance g:

$$g = -\frac{a\, m_{11} + m_{12}}{a\, m_{21} + m_{22}}. \quad (7)$$

Parameter of the focusing quality is the value of $|r_{11}|$. If $|r_{11}| < 1$ we have condition of initial beam size compression on target and we will define it as $\mathrm{DM}_1 = r_{11}$ (demagnification in the linear case). Thereby a procedure of construction of optimal nanoprobe design task could be formulated as following:

Find control gradients of magnets, their lengths, lengths of drift gaps for ensure conditions (5), $g \geq g_{techn} > 0$ and $|r_{11}| = \gamma$. Here g_{techn} — is a technological restriction on the working distance from the bottom, γ — a desired demagnification parameter.

It is necessary to ensure condition $\gamma \leq 0.01$ for achievement tiny beam size (about some nanometers) on the target with its sufficient emittance (an object diaphragm aperture must be near 1μ). It should be mentioned that drift gap between magnets s (between each couple of magnets, first and second, third and fourth) and λ (between second and third magnets) must ensure technological conditions too. In particular these conditions are determined from solution of the task regarding fringe fields, see [3].

SOLUTION OF THE TASK

In this section we discuss the computer modeling and corresponding results. Some part of results were drawn using the well known computer algebra system — the package Maple, and some of them — using a special developed software. Similar approach allows realizing a procedure of parametric investigations of the desired focusing system as a prototype of nanoprobes. The load curves family should be constructed for this purpose (determined by (6)) in the space of magnet excitations $\varkappa_i = \sqrt{|k_i|}L_i$, where L_i — magnet length. In this paper the authors use as a normalized (scale) parameters the lens length $L_i = L$. It is convenient to put $L = 1$.

The Family of the Load Curves

Figs. 3–4 illustrate a couple of examples of load curves for various s and λ (the black lines), the graphics of $|r_{11}| = \gamma$ (the red and blue lines). On Fig.4 one can also see the plots $g = g_{\mathrm{techn}}$ (the green line and the dotted magenta). Points of intersections of referred above curves could be chosen as appropriate solutions. Modeling using symbolic procedures permits to find the whole convenient solution family with the values $\gamma \leq 0.01$ and ensures necessary conditions. It should be mentioned that optimization is required for retrieval of the values $\varkappa_1$ $\varkappa_2$, s, λ and a. Special software (the optimization package) for the solution of nonlinear programming tasks is used for this purpose in this paper. The software is based on aggregate random search methods and the so called flexible admission method [7]. This package allows us to find optimal solutions (for example, for minimization problem of the demagnification parameter).

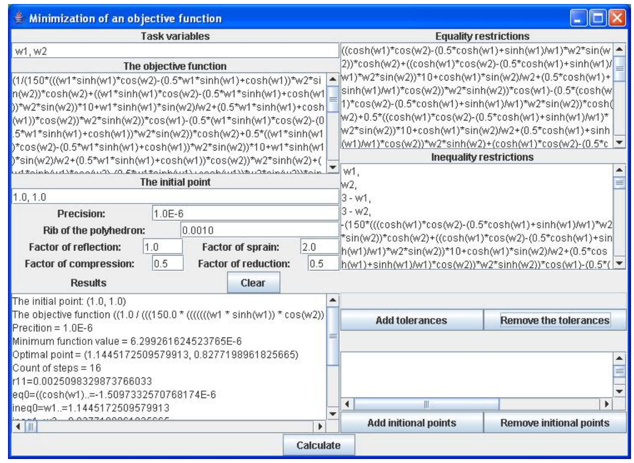

Figure 2: A screen shot of a user interface for the optimization package.

This gives us a possibility to find different points in the control parameters space, which can be of interest of practical realization of micro- or nanoprobe systems in according to our wishes. It should be noticed that only some solutions (from the quite wide family of "appropriate" solutions) must be chosen, which convenient for specified task because of its realizability and optimality for a real physical goal.

Some Examples for Optimal Solutions

On Fig. 3 one can see load curve (its part) and level surfaces for demagnification parameter. The load curve presented as dashed black line, a curve, which corresponds to $r_{11} = 0.01$ (demagnification parameter) is displayed as blue line and red line is corresponding to $r_{11} = 0.001$. These parameters are retrieved from [8] paper. If we put effective length of each lens $L = 1$, it is easy to calculate other parameters (see Fig. 1): $a = 135.5625$, $s = 3.3$, $\lambda = 5.5$ and $g = 2.34375$ could be found using (7). In order to keep circular beam it is necessary to choose point which belongs to load curve. Using desirable demagnification parameters one can construct level surfaces, and then choose convenient points in exterior of set framed by level surface.

Sometimes it is necessary to choose optimal parameters for a nanoprobe, when some of them are almost fixed or they have the strict limits. In this case an investigator can choose optimal parameters too. For example, one can put

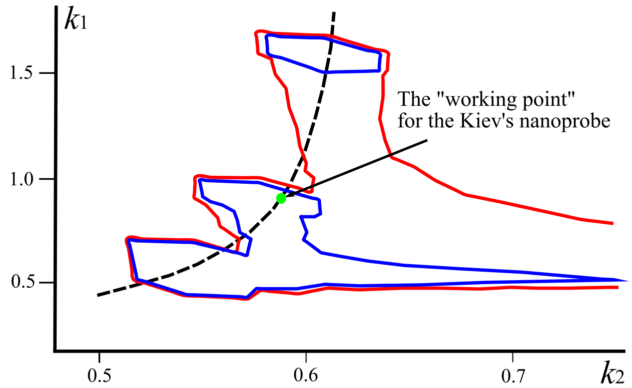

Figure 3: The load curve for Kiev's nanoprobe [8] and level curves for the demagnification. The dashed black line — the initial load curve, the blue line for $r_{11} = 0.01$, the red line for $r_{11} = 0.001$

$a = 200$, $\lambda = 3$ and do not hold fixed other parameters, so using e. g. the package Maple, it is feasible to adjust the rest of parameters to convenient. The usage of a computer algebra system (e. g. Maple) allows us to animate a number of plots in order to choose more appropriate parameters. Also it is very useful to construct level curves too. Using this technique one can track the value of g_{techn} depending on customer requirements. On Fig. 4 the green line conforms to the value of $g = 3$ and the dotted pink line — to $g = 10$ (here $s = 0.625$).

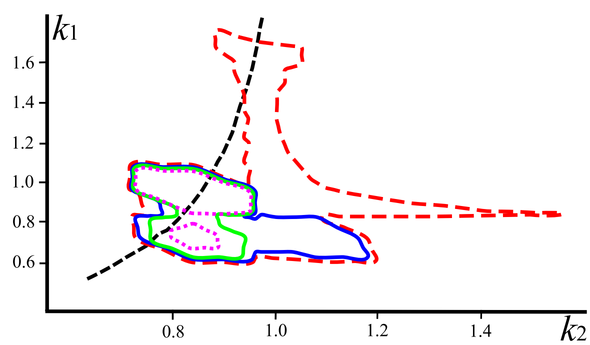

Figure 4: The load curve for a custom nanoprobe, the level curves for the demagnification and g. The dashed black line for the initial load curve, the blue line for $r_{11} = 0.01$, the dashed red line for $r_{11} = 0.001$, the green line for $g = 3$, the dotted pink line for $g = 10$.

Using the above described approach one can find different variants of nanoprobe characteristics. Combination of computer algebra methods and technologies on the one hand and numerical optimization approaches on the other hand provides the flexibility of parameters selection. If it is necessary to receive a given demagnification with round beam one can calculate g using (7) and choose convenient a, s and λ for a practical task. Many sets of optimal parameters could be found in linear model, but in order to choose the best set it is required to consider at least nonlinear effects and fringe fields effects (see [2]–[4]).

Some optimal set could be conformed to unstable system, which characteristics are instantly change with tiny deviation from optimal parameters.

CONCLUSION

The above described methodology could help to find a set of optimal parameters for nanoprobe systems under the assumption of a linear model approximation. Similar investigation is the initial step for modeling process of such kind of focusing systems. One of the next steps is based on nonlinear approximation for steering fields, and some approaches are described in [2].

With taking into account of nonlinear effects beam characteristics usually become worse than in linear model. Some correction mechanisms are reviewed in [2]. It is also required to consider fringe fields effects (see [3]), because they are intrinsic and could heavily impact on beam dynamic and beam characteristics. Comparative analysis of different effects in nanoprobe systems [4] could help to understand, what effects are most essential and require special attention.

Summarize above mentioned consequences it should be mentioned that linear model should give only rough approximation of real systems parameters. On the next steps it is necessary to verify an obtained set of optimal parameters. It helps to select a parameters subset, which satisfy completely a number of conditions of operability of the nanoprobe design concept.

REFERENCES

[1] M.C. Roco, "Government Nanotechnology Funding: An International Outlook", http://nano.gov/html/res/IntlFunding-Roco.htm

[2] S. Andrianov, N. Edamenko and Yu. Tereshonkov "Synthesis of optimal nanoprobe (Nonlinear approximation)" (in this Proceedings).

[3] Yu. Tereshonkov, S. Andrianov "Load Curves Distortion Induced by Fringe Fields Effects in the Ion Nanoprobe" (in this Proceedings).

[4] S. Andrianov and Yu. Tereshonkov "Comparative Analysis of Different Kinds of Effects in the Nanoprobe" (in this Proceedings).

[5] S.N. Andrianov, A.D. Dymnikov and G.M. Osetinsky, "Forming system for proton microbeams". Instr. and Exper. Techn., Vol. 1, P. 39–42 (1978) (in Russian).

[6] F.R. Gantmacher, "The Theory of Matrices", Chelsea Publishing Company, New York, 1984.

[7] D.M. Himmelblau, "Applied Nonlinear Programming", McGraw-Hill Book Company, New York, 1972.

[8] S.A. Lebed, "Double-mode probe forming system for modern ion nanoprobe", J. of Applied Physics, Vol. 72, 2002. P. 92–95 (in Russian).