BEAM DYNAMICS

APPLICATION OF OPTIMIZATION TECHNIQUES FOR RFQ DESIGN

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Optimization approach to the beam dynamics optimization in RFQ accelerators is considered. A statement of the optimization problem and its solving methods are described. As an example, an optimization of 47.2 MHz RFQ for the acceleration of heavy ions (A/Z=20) is discussed. From the start version up to the final one the BDO-RFQ and the LIDOS RFQ associated codes are used.

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INTRODUCTION

RFQ accelerator is used as the initial part of large linacs for industrial and medical purposes. There are many methods and codes to design a RFQ channel. Below we show how mathematical optimization methods can be used in the practical design of a RFQ accelerator [1 - 11].

Accelerating and focusing processes in RFQ accelerators are controlled by the smooth changing of the four parameters: vane modulation, intervane voltage, synchronous phase and aperture. These parameters define the length of the modulation period. According to the experience of RFQ designs, the total channel can be divided by three conventional parts: a gentle buncher for bunching and the small beam acceleration in a weak accelerating field when the synchronous phase is near -90^0, a forming section when the synchronous phase and the vane modulation are increased to their nominal values and a last part which is the accelerating one [5 - 8, 12].

As a rule designer chooses the lengths and plots of the parameters manually: change parameters – view results, change parameters depending on the previous results – view the results again and so on. The duration of this process mainly depends on its initial version – how far is the start version from the final result.

At the same time today we have a well-developed mathematical theory of the multiparameter optimization which can be applied to beam dynamics and plasma problems and formally give us a possibility to optimize any accelerating or focusing channel [13 - 26].

Mathematical optimization consists of the criteria choice, the control parameters and the directional movement from the previous version to a better one. The goal of this movement is to achieve a minimum deviation from the accepted optimization criteria. The minimum channel length when the transmission is no less than some accepted value can be a possible optimization criteria for the RFQ channel. It is usual to consider the parameters of each cell (vane modulation, intervane voltage, synchronous phase and aperture) as the control ones. Theoretically we can find optimal plots of the cell parameters, using methods of mathematical optimization.

Nevertheless the theoretically possible result cannot be achieved in practice. To solve the above "trivial" statement of the optimization problem we need to vary thousands of control parameters. But the time required for the calculation of a single set of parameters can be rather significant. Taking into consideration that, as a rule, the number of calculated scenarios is times larger than the number of the control parameters and it is necessary to avoid local minimums, we can conclude that optimization in such statement is impossible in practice.

So it is necessary for the practical optimization to develop acceptable simplified mathematical models of the beam dynamics and to create directional optimization methods based on the analytical approaches.

PROBLEM STATEMENT

References [27 - 29] concern the basis of the simplified modeling of beam accelerating and focusing in a RFQ channel. In spite of simplifications, this model describes the dynamics of a real beam quite accurately. In brief it is focused on solving of the phase motion equation (1), which is based on a traveling wave approximation, together with the equation of the synchronous particle motion (2) and constraints on tension of an accelerating field and beam parameters (3), (4).

$$\psi'' + 2\frac{\Omega_0}{\omega}\eta\frac{W_n}{W}\cos\phi_s\psi' + \left(\frac{\Omega_0}{\omega}\frac{W_n}{W}\cos\phi_s\eta' + \right.$$
$$\left. + \frac{\Omega_0}{\omega}\eta\frac{W_n}{W}(\cos\phi_s)' - (\frac{\Omega_0}{\omega}\eta\frac{W_n}{W}\cos\phi_s)^2\right)\psi - \quad (1)$$
$$-\eta\frac{W_n}{W}(\cos\phi_s - \cos(\psi+\phi_s)) - \frac{ek^2}{W_0\Omega_0^2}\frac{\partial U_c}{\partial\psi} = 0;$$

$$\left(\frac{W}{W_n}\right)' = 2\frac{\Omega_0}{\omega}\eta\cos\phi_s; \quad (2)$$

$$A_{def} = 2\left(\frac{\Omega_0}{\omega}\right)^2\eta\frac{W_n}{W}\left|\sin\phi_s\right| \le A; \quad (3)$$

$$\frac{d\langle\Delta\varphi\rangle^2}{d\zeta} \le 0. \quad (4)$$

Here W_n and W are the initial and the current beam energy, $\omega = 2\pi/\lambda$ is the RF-field frequency, $k = 2\pi/L$, L is the acceleration period length, $\Omega_0^2 = \frac{2\pi e(UT)_{\max}}{W_n\lambda^2}$, U is the intervane voltage, T is the acceleration efficiency, depending on the vane modulation and the ratio of the aperture to the acceleration period length; $\eta = \dfrac{UT}{(UT)_{\max}}$; the maximum value $(UT)_{\max}$ is the initial data. The last term in the phase motion equation corresponds to a space charge field.

Constraint (3) concerns the defocusing parameter, usually $0.01 \le A \le 0.02$. Constraint (4) concerns with the monotonic decrease of the phase length rms value $\Delta\varphi$. It is necessary for space charge dominated beam acceleration.

So we need to find plots $\eta(\zeta)$ and $\varphi_S(\zeta)$ to provide bunching and acceleration of a beam. To solve this problem we need to introduce some functional [12, 13, 27, 30, 31], describing the capture of an accelerated particles and other needed beam parameters at the output of the channel. Constraints (3), (4) are included also.

After that we solve the problem of a beam focusing optimization.

OPTIMIZATION AND DESIGN TECHNIQUES FOR RFQ CHANNEL

Optimization of the longitudinal motion of particles was carried out using the BDO-RFQ code developed at the Saint-Petersburg State University [32]. As a result of the optimization the functions $\eta(\zeta)$ and $\varphi_S(\zeta)$ have been identified, providing desired characteristics of the output beam. Since there are external force oscillations with frequency ω it is enough to fix several points on the graph to set these functions, the rest values in the intermediate points can be obtained by interpolation (linear in the simplest case). Practice shows that it is sufficient to use 20 points or less.

Thus, the optimization of the longitudinal motion reduces to finding the values of functions $\eta(\zeta)$ and $\varphi_S(\zeta)$ in a number of selected points in order to solve the equations (1) and (2) with the restrictions (3) and (4) to get an option that satisfies your criteria. It should be noted that the choice of the direction of minimization is based on an analytic representation of the gradient of the investigated functional and does not depend on the number of points of the approximating the functions $\eta(\zeta)$ and $\varphi_S(\zeta)$.

After optimization of the phase motion, given the specified intensity values $E = U / R_0$ and focusing parameter $Q \sim U / R_0^2$, the average aperture radius R_0 and the intervane voltage can be determined, then the efficiency T is determined, which unambiguously corresponds to the modulation of the electrodes m. The correspondence between the variable ζ and the cell number n is set by $n = 2\zeta / \kappa$ where $\kappa = \Omega_0 / \omega$. Thus all the necessary dependencies are defined $U(n)$, $m(n)$, $R_0(n)$ and $\varphi_S(n)$ for the initial approximation.

The proposed technique is implemented in the software package BDO-RFQ code [32]. The initial data array [$U(n)$, $m(n)$, $R_0(n)$, $\varphi_S(n)$], obtained on the basis of the found optimized laws $\eta(\zeta)$ and $\varphi_S(\zeta)$ then used to convert them into the format of the initial data of the LIDOS RFQ Designer code [33, 34]. The latter is used for the final correction and selection of the channel parameters, taking into account the real shape of the electrodes, their possible sectioning for mechanical processing and electrodynamics settings, etc.

The problem of the shape optimization of the radial matching section for RFQ channel can be considered separately. The optimization criterion in the BDO-RFQ code is the specified initial beam divergence [35 - 37].

SIMULATIONS RESULTS

Below we represent the results of the beam dynamics simulations and main parameters of the heavy ions (A/Z=20) linac.

The initial beam and the RFQ channel parameters are presented in Table 1.

Table 1

Initial RFQ parameters

Input ion energy, MeV	0.12
Output ion energy, MeV	2.0
Operating frequency, MHz	47.2
Kilpatrick factor E/E_{kilp}	2.0
Charge number $Z=q/q_{proton}$	1
Mass number $A=m/m_{proton}$	20
Beam current, mA	10
Emittance, cm·mrad	0.03π

Control functions $\eta(\zeta)$ and $\varphi_S(\zeta)$, obtained by the BDO-RFQ code are shown in Figs. 1, 2.

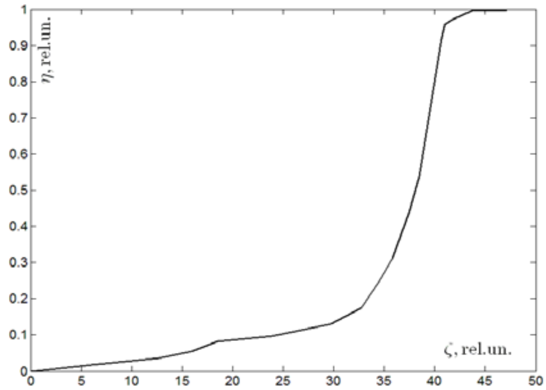

Fig. 1. $\eta(\zeta)$ control function

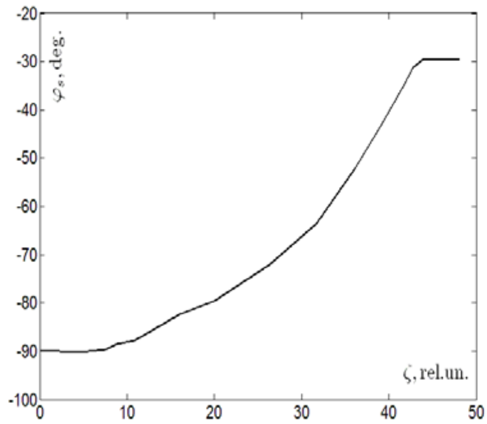

Fig. 2. $\varphi_S(\zeta)$ control function

To estimate the beam parameters, simulations with the LIDOS RFQ Designer code were carried out. Simulation results are presented in Figs. 3-5 for the real electrodes shapes and in Table 2 for the real and the ideal electrodes shapes. The optimal matcher profile is presented in Fig. 6.

Table 2

Simulation results

Beam parameters	Real	Ideal
Transmission	1.0	1.0
X emittance growth	1.1	1.0
Y emittance growth	1.0	1.0
Accelerator length, m	2.974	

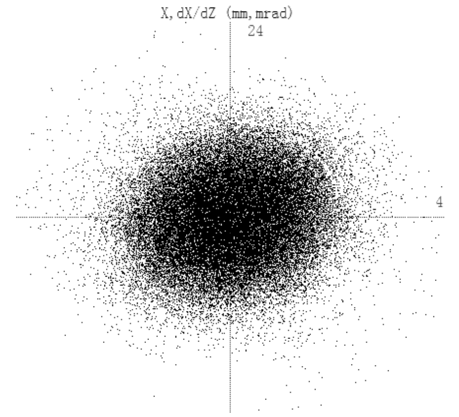

Fig. 3. Output transversal emittance

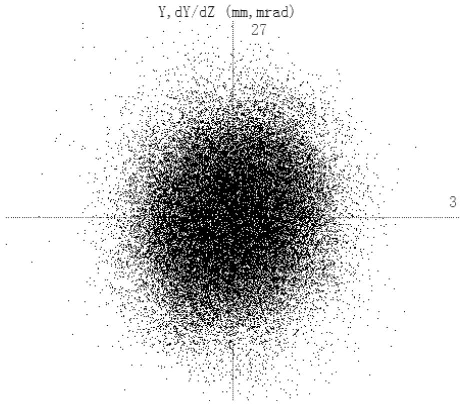

Fig. 4. Output transversal emittance

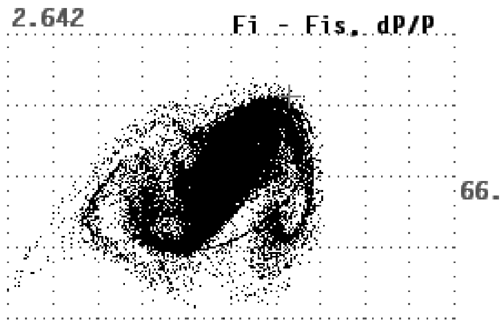

Fig. 5. Output longitudinal emittance

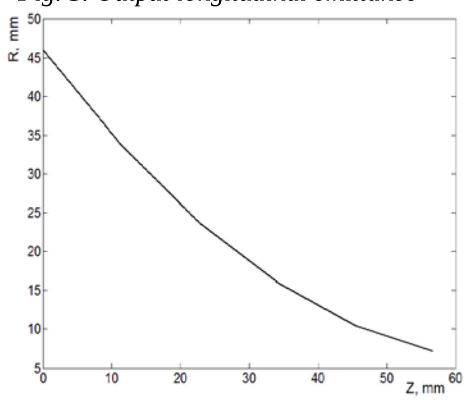

Fig. 6. RFQ matcher profile

CONCLUSIONS

Developed optimization approach to a RFQ channel design leads to good results for the beam transmission and output beam parameters. It requires small correction to obtain optimal parameters taking into account the real shape of the vanes, possible vanes sectioning and the real space charge distribution. Also this optimization approach has high efficiency of the parameters calculation for other channels, for example for an APF accelerator [38 - 41]. Suggested analytical representation of the functional variation can be used for tolerance calculation in various accelerating and focusing systems [13, 42].

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ПРИМЕНЕНИЕ ОПТИМИЗАЦИОННЫХ ПОДХОДОВ К РАЗРАБОТКЕ УСКОРИТЕЛЕЙ С ПОКФ

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Рассматривается оптимизационный подход к расчету параметров канала ПОКФ. Описываются постановка оптимизационной задачи и методика ее решения. Приводятся результаты реализации этой методики на примере оптимизации ускорителя RFQ тяжелых ионов (A/Z=20) на частоте 47,2 МГц. От первоначальной до финальной версии проекта ускорителя используются программные комплексы BDO-RFQ и LIDOS RFQ.

ЗАСТОСУВАННЯ ОПТИМІЗАЦІЙНИХ ПІДХОДІВ ДО РОЗРОБКИ ПРИСКОРЮВАЧІВ З ПОКФ

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Розглядається оптимізаційний підхід до розрахунку параметрів каналу ПОКФ. Описується постановка оптимізаційної задачі і методика її рішення. Приводяться результати реалізації цієї методики на прикладі оптимізації прискорювача RFQ важких іонів (A/Z=20) на частоті 47,2 МГц. Від первісної до фінальної версії проекту прискорювача використовуються програмні комплекси BDO-RFQ і LIDOS RFQ.