OPTIMIZATION AND SIMULATIONS OF BEAM DYNAMICS IN APF ACCELERATORS

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Abstract

Design problem of APF accelerator for ensure enough high quality of output beam is considered. As we know, this problem is not easy because we have to achieve stability of longitudinal and transversal motions simultaneously. One of the first significant results in this subject were obtained by V. V. Kushin [1]. In the work [2] the problems of optimizations of ion beam are considered. The optimization approaches for some beam characteristics improving (acceleration and transmission ratios) are considered. Obtained results are confirmed by particle in cell simulations.

INTRODUCTION

Linacs with focusing by an accelerating field have long been part of the composition of any modern accelerating complex. In particular, the combination of radio frequency quadrupole (RFQ) [3–5] and APF linacs [1, 2, 6, 7] is a good decision for the initial part of the accelerating channel for high energies. In this case an ion beam is bunched in the RFQ and injected into a resonator with APF. A linac with APF has a high acceleration rate and no focusing magnetic elements. Therefore, the development of these linacs and the improvement of the beam quality remain important and current problems. When a linac is developed, parameters such as the linac length, beam current, current flow, effective emittance, etc. should be taken into account. These parameters can be improved using different optimization methods. Thus, the development of a linac based on the optimization approach can be of wide practical importance.

THE MAIN STAGES

Let us give a brief description of the main stages of accelerator modelling and optimization process.

1. Synchronous phase sequence calculation. At this stage we have to obtain a first approximation of a synchronous phase sequence. For example, application of a some analytical approximation (e. g. proposed be Jameson [8]) and swarm optimization methods may give a good enough results at this stage.

2. Cell lengths calculation and Drift tube structure generation. The lengths of accelerator cells are determined by the synchronous phase sequence. The diversity of cells lengths causes the deviation from the particular value of the resonant frequency. So the distribution of accelerating field may be non-uniform. This aberration can be eliminated by the adjustment of other geometry parameters period's length, gap ratio and drift tube diameter. For calculation of gaps lengths we use approach based on the tuning of resonant frequency of each cell on the operating frequency [9]. Follow this approach we calculate preliminary the set of dependences of resonant frequency of separate accelerator cell on the main parameters of this cell (cell length, gap length, drift tubes radii). These simulations are performed using COMSOL Multiphysics using Comsol API for Matlab in automatical mode. In following using these precalculated dependences one can choose a gap length and a drift tubes radii for a arbitrary cell length in order to tune a resonant frequency of each separate cell on the operating frequency.

3. PIC simulations. Then drift tube structure is generated one can compute the distribution of electric field and simulate particle dynamics with taking into account the space charge for the beam quality evaluation. Particle-in-cell simulations can give the most accurate result. At this stage we use the DAISI code [10–14].

4. Render decision on the optimization. If after simulations one detect that beam quality is not good enough (e. g. low transmission) we can render decision on the optimization of the synchronous phase sequence.

5. Optimization can be conducted using different approaches. In this report in follow we will consider optimization based on gradient descent method.

6. After optimization one have to regenerate the drift tubes structure and repeat the PIC simulation in order to estimate optimization process advances.

GRADIENT DESCENT OPTIMIZATION

Let us denoted $\tau = ct$, $\psi = \varphi - \varphi_s$, $p = \gamma_s - \gamma$, $\alpha_{tr} = eE_{max}/(2m_0c^2)$. Here c is the light velocity; φ and φ_s is the phases of synchronous particle and beam particle; γ and γ_s is the Lorentz factors of synchronous particle and beam particle; E_{max} is the accelerating wave amplitude. The approximation of accelerating field as an cos standing wave allows to accept the following mathematical model of beam dynamics in the an equivalent traveling wave:

$$\frac{d\beta_s}{d\tau} = \frac{\alpha_{tr}}{\gamma_s}\cos(\varphi_s(\tau)),$$
$$\frac{d\psi}{d\tau} = -2\pi\frac{\beta - \beta_s}{\lambda\beta_s},$$
$$\frac{dp}{d\tau} = \alpha_{tr}(\beta_s\cos(\varphi_s(\tau)) - \beta\cos(\varphi_s(\tau) + \psi)),$$

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$$\frac{dS_{11}^x}{d\tau} = 2S_{21}^x, \quad \frac{dS_{11}^y}{d\tau} = 2S_{21}^y,$$
$$\frac{dS_{21}^x}{d\tau} = QS_{11}^x + S_{22}^x, \quad \frac{dS_{21}^y}{d\tau} = QS_{11}^y + S_{22}^y,$$
$$\frac{dS_{22}^x}{d\tau} = 2QS_{21}^x, \quad \frac{dS_{22}^y}{d\tau} = 2QS_{21}^y,$$
$$Q = -\frac{\alpha_{tr}\pi}{\lambda\beta_s\gamma}\sin(\varphi_s + \psi).$$

Here six variables $S_{11}^{x,y}$, $S_{21}^{x,y}$, $S_{22}^{x,y}$ are the elements of the matrixes $G^{x,y} = \begin{pmatrix} S_{11}^{x,y}, & S_{21}^{x,y}, \\ S_{21}^{x,y}, & S_{22}^{x,y}, \end{pmatrix}$, that describe dynamics of the initial transversal distribution ellipses $G_0^{x,y}$ in the phase planes $(y,\ dy/dt)$,$(x,\ dx/dt)$. The phase of synchronous particle is the following step-wise function

$$\varphi_s(\tau) = \varphi_{s_i} \in [-2\pi; 2\pi], \qquad \tau \in [\tau_i; \tau_{i+1}),$$
$$\tau_{i+1} - \tau_i = \lambda(\varphi_{s_{i+1}} - \varphi_{s_i} + \pi)/2\pi.$$

Thus, the set of parameters φ_{s_i} determines the beam dynamics in this approximation. For evaluation the quality of the beam we have to introduce some fitness function. For example for improving the beam transmission the following function may be used [7]

$$I = \int\limits_{M_{T,u}} (c_1F_1(\psi_T) + c_2F_2(S_{11}^{x,y})) \times$$
$$\times d\psi_T dp_T dS_{11}^{x,y}{}_T dS_{12}^{x,y}{}_T dS_{22}{}^{x,y}{}_T,$$

$$F_1 = \begin{cases} (\psi_T + \psi_1)^2, & \psi_T < -\psi_1; \\ 0, & \varphi_T \in [\psi_1, \psi_2]; \\ (\psi_T - \psi_2)^2, & \psi_T > \psi_2. \end{cases}$$
$$F_2 = \begin{cases} 0, & S_{11}^{x,y} < S; \\ (S_{11}^{x,y} - S)^2, & S_{11^{x,y}} > S. \end{cases}$$

Here c_1, c_2, ψ_1, ψ_2, S are non-negative constants, $M_{T,u}$ is the set of the beam positions in the phase space. On the base of the analytical representation presented in works [15] the representation of the partial derivatives $\frac{\partial I}{\partial \varphi_{s_i}}$ were obtained. Thus the gradient descent optimization may be constructed and applied for correction the sequence of the parameters φ_{s_i}.

RESULTS OF OPTIMIZATION

By using the proposed gradient descent optimization approach, an optimization of synchronous phase sequence was carried out for APF linac. The main resonator parameters are presented in Table 1. We assume that input bunches for APF are extracted from RFQ linac without any matching section. It is possible on the considered frequency 433 MHz. The optimized synchronous phase sequence is presented in Fig. 1. The electric field distributions calculated using electrodynamic (COMSOL) and electrostatic approximations (DAISI) are presented in Fig. 2. From Fig. 2 one can conclude that the electric field distribution is enough uniform. It has been achieved using the described above approach of the resonant frequency tuning on the design stage. The dependences of transmission ratio on input impulse current before and after optimization are presented in Fig 3.

Table 1: Main Parameters of Optimized Accelerator

Ion type	deuteron
Operating frequency, MHz	433
Input emittance (XdX, YdY), cm·mrad	0.02π
Input impulse current, mA	$0-35$
Voltage between drift tubes, kV	185
Number of cells	60
Input energy, MeV	4.1
Output energy, MeV (before optimization)	9.1
Accelerator length, m (before optimization)	1.72
Acceleration rate, MeV/m (before optimization)	2.89
$E_{max}/E_{kilpatric}$ (before optimization)	1.81
Output energy, MeV (after optimization)	8.35
Accelerator length, m (after optimization)	1.64
Acceleration rate, MeV/m (after optimization)	2.57
$E_{max}/E_{kilpatric}$ (after optimization)	1.95

From presented results one can the conclude the following observation:

1. it is possible to improve a capture ratio for the intense beam using the proposed optimization approach;

2. acceleration rate after a capture ratio optimization may rather decreases;

3. rather short gaps and drift tubes after optimization may be appears, it results in increasing the maximal electric field on the resonator surface. It is possible to eliminate this effect by increasing the length of short cells up to $1.5\beta\lambda$.

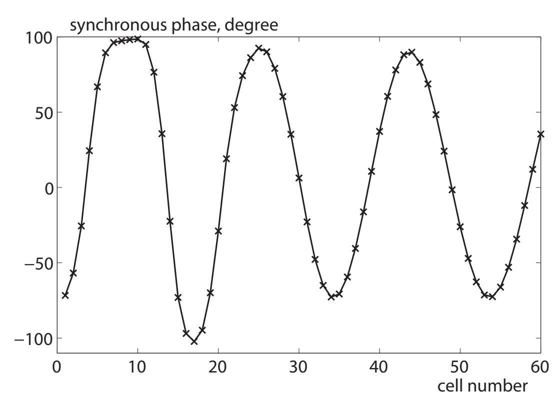

Figure 1: Synchronous phase sequence after optimization.

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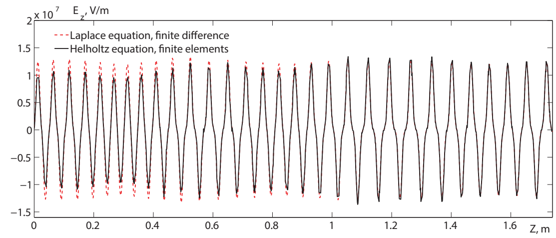

Figure 2: Electric filed distribution on the resonator axis.

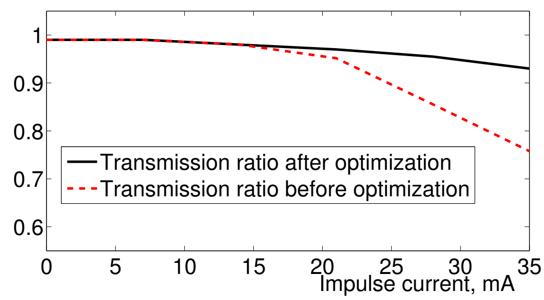

Figure 3: Transmission ratios before and after optimization.

CONCLUSION

In this paper the problem of optimizing the parameters of longitudinal and transverse motion of the beam in an APF accelerator is considered. The solution based on analyzing the beam dynamics in an equivalent traveling wave is proposed. This approach allows to provide tuning of resonator to produce the uniform field distribution. Analytic representation of the gradient of the fitness function allows us to provide the numerical optimization by different motion parameters. For instance it can be the width of the output energy and phase spectrum, the radial divergence of the beam, the effective emittance or the acceleration rate.

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