OPTIMIZATION OF BEAM PARAMETERS IN APF CHANNEL*

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Abstract

A new approach based on mathematical optimization methods to obtain a synchronous phase sequence in APF linacs is suggested. The optimization problem of intensity deuteron beam parameters is discussed. As an example, the results of beam dynamics simulations are presented.

INTRODUCTION

Linear accelerators with alternating-phase focusing (APF) are admitted to be of considerable practical importance. They have found wide application in fundamental nuclear research as the initial stage in high-energy accelerators. At present there is a significant progress in the development of APF accelerators and H-resonators [1-6]. To design an initial stage of accelerator complex, such parameters as the size of linac, beam current, beam transmission, effective emittance and so on should be considered. Improvement of these parameters may be achieved by using different optimization techniques. So, design of linear accelerator on the base of optimization approach has wide practical significance.

INITIAL APF PARAMETERS

The main initial parameters of designed APF accelerator are presented in Table 1.

Table 1: Initial parameters

Input ion energy, MeV	3.45
Output ion energy, MeV	14.2
Operating frequency, MHz	433
Accelerating wave amplitude kV/cm	110
Charge number $Z=q/q_{proton}$	1
Mass number $A=m/m_{proton}$	2
Beam current, mA	10
Transversal emittance (XdX,YdY), cm·mrad	0.029π
Longitudinal emittance, keV·ns/u	1.55π
Energy spread, %	± 1

DESIGN TECHNIQUE

At the same time today we have a well-developed mathematical theory of the multiparameter optimization which can be applied to beam [7-21] and plasma dynamics [22, 23]. By using simple mathematical models at the first stage of the accelerator designing we can generate the main accelerator parameters, which determine the main characteristic of the beam. In the case of APF structure it is a synchronous phase sequence φ_S generation by using analitic representation of quality functional gradient.

The next step is to evaluate the geometry of the resonator, the lenght and aperture radii of the drift tubes and so on. Also we should realize, that using simple beam dynamics models may give an inaccurate result. So, we should conduct the final correction of accelerator parameters. In this paper we use genetic algorithm for correction lenght of accelerating cells.

GRADIENT OPTIMIZATION

The standing wave approximation of accelerating field allows to accept the following mathematical model of beam dynamics in the equivalent traveling wave [1, 2].

Let us consider the beam dynamics in following variables: β_S is the velocity of synchronous particle, $\psi = \varphi - \varphi_S$ is the phase deviation, $p = \gamma_S - \gamma$ is the energy deviation, S_{11}, S_{21}, S_{22} are the elements of the matrix $G = \begin{pmatrix} S_{11} & S_{21} \\ S_{21} & S_{22} \end{pmatrix}$, that describe dynamics of the initial ellipse G_0 in the radial plane (η, κ) where $\eta = r/\lambda$ is the radial position of particle and $\kappa = d\eta/d\tau$ (where $\tau = ct/\lambda$ is an independent variable). When

$$\frac{d\beta_S}{d\tau} = (\alpha/2)\sqrt{1-\beta_S^2}\cos(\varphi_S(\tau)), \quad (1)$$

$$\frac{d\psi}{d\tau} = \frac{2\pi(\beta_S - \beta)}{\beta_S} p, \quad (2)$$

$$\frac{dp}{d\tau} = (\alpha/2)\beta(\cos(\varphi_S(\tau)) - \cos(\varphi_S(\tau)+\psi)), \quad (3)$$

$$\frac{dG}{d\tau} = -A^T G - GA, \quad (4)$$

$$A = \begin{pmatrix} 0 & 1 \\ Q & 0 \end{pmatrix}, \quad Q = \frac{(\alpha/2)\pi(1-\beta_S{}^2)^{3/2}}{\beta_S}\sin(\varphi_S(\tau)+\psi).$$

Where $\alpha = q\lambda E_{max}/(m_0 c^2)$ is the accelerating wave amplitude parameter, $\varphi_s(\tau)$ is the synchronous phase function defined by the value $\varphi_s^{(i)}$ of each i-th accelerating cell.

To solve the problem of reducing the loss of particles and decrease of beam radius it is possible to take the following functional

$$I(u) = \int_{M_{T,u}} (c_1 F_1(\psi(T)) +$$

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$$+c_2 F_2(S_{11}(T))\big)d\psi_T dp_T dS_{11T} dS_{21T} dS_{21T},$$

$$F_1 = \begin{cases} (\psi_T + \psi_1)^2, & \text{if } \psi_T < -\psi_1, \\ 0, & \text{if } \varphi_T \in [\psi_1, \psi_2], \\ (\psi_T - \psi_2)^2, & \text{if } \psi_T > \psi_2, \end{cases}$$

$$F_2 = \begin{cases} 0, & \text{if } S_{11_T} < \bar{S}, \\ (S_{11_T} - \bar{S})^2, & \text{if } S_{11_T} > \bar{S}. \end{cases}$$

Where $c_1, c_2, \psi_1, \psi_2, \bar{S}$ are the non-negative constants, the set $M_{T,u}$ is a cross-section of the beam of trajectories at the moment $t = T$.

By using the analytic representation [1, 2, 13, 14] of the functional gradient by the $\varphi_s^{(i)}$ parameters we can construct gradient methods for optimizing the accelerator parameters.

PRELIMINARY RESULTS

At the first stage of APF linac design and optimization, we consider the problem of synchronous phase sequence (see Fig. 1.) optimization without charge particles interaction by using approach described earlier.

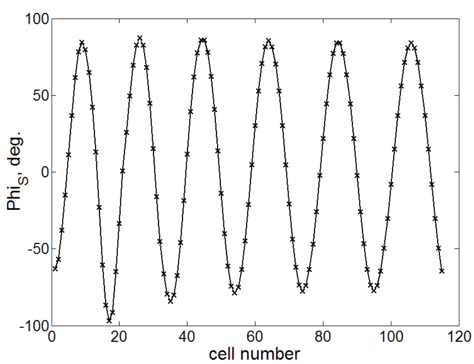

Figure 1: Synchronous phase sequence.

The results of beam dynamics simulations without interaction between charged particles by using (1)-(4) model are presented at Fig. 2, 3. There are no particle losses at this model.

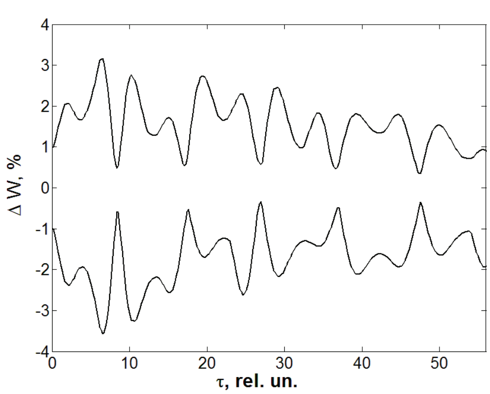

Figure 2: Beam envelopes for energy motion

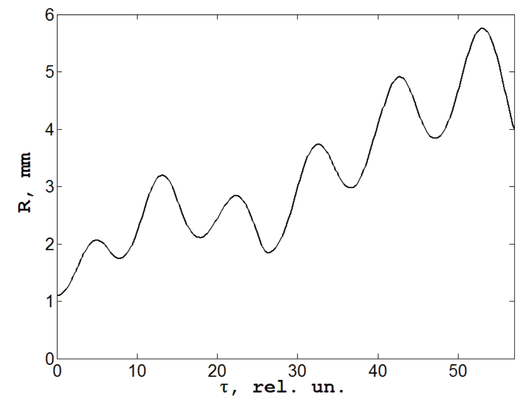

Figure 3: Beam envelopes for transversal motion

It should be noted that results of this simulations show good beam quality.

DTL STRUCTURE GENERATION

At the second stage we determine the lengths of accelerator cells by using the obtained earlier synchronous phase sequence.

We use expression for of i-th cell transit time $\tau_i - \tau_{i-1} = (\varphi_i - \varphi_{i-1} + \pi)/2\pi$ and standing wave approximation of accelerating field for iterative algorithm construction for cells lengths L_i calculation due to the synchronous phase sequence [24, 25].

The lengths of the gaps $Lgap_i$ are chosen uniformly increasing with a small amplitude modulation, depending on cells lengths. And drift tubes radii R_i are chosen by the law $R_i = 0.2 Lgap_i$.

PARAMETERS CORRECTION

At this stage we use more precise accelerating field approximation for accelerating cell [26]

$$\frac{E_z(z)}{E_{z\max}} = \frac{\operatorname{erf}\left(\dfrac{g(2z + L_{gap})}{4R}\right) - \operatorname{erf}\left(\dfrac{g(2z - L_{gap})}{4R}\right)}{2\operatorname{erf}\left(\dfrac{gL_{gap}}{4R}\right)},$$

where erf is the error function, g is a approximation parameter. Three-dimensional mathematical model, taking into account charge particles interaction by using "thick disks" method and beam envelopes dynamics is used [27-29]. Obtained from previous stage linac parameters do not provide good beam quality (see Fig. 4-6).

To solve the problem of reducing the particles losses we conduct the genetic algorithm optimization of cell lengths.

As a fitness function we use the particles loss function

$$F_{ga} = \sum_{k=1}^{N_p} F(r_k(z), W_k(z)),$$

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$$F(r_k(z), W_k(z)) = \begin{cases} 1, \text{if } \exists z \subset [0,\ L]: r_k(z) > R(z), \\ 1, \text{ if } \exists z \subset [0,\ L]: \dfrac{|W_k(z) - W_s(z)|}{W_s(z)} > 0.05, \\ 0, \text{else.} \end{cases}$$

where r_k is the radius of k-th beam envelope and, W_k is the k-th particle energy, N_p is a particles number, L is the accelerator length.

For an initial population creation we use uniform random distribution with 2 % deviation from initial cell lengths values.

Starting only from 50 element population size, genetic algorithm converges to 0 value of fitness function by the 10-20 iterations.

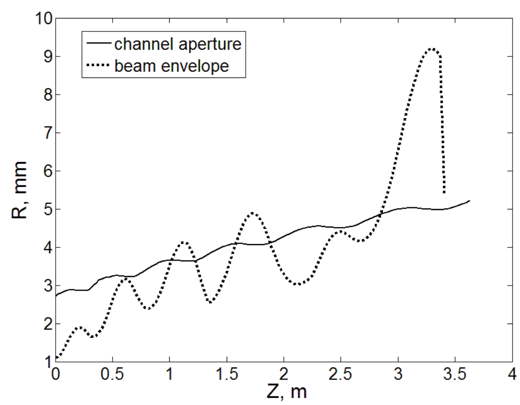

Figure 4: Beam envelope before correction

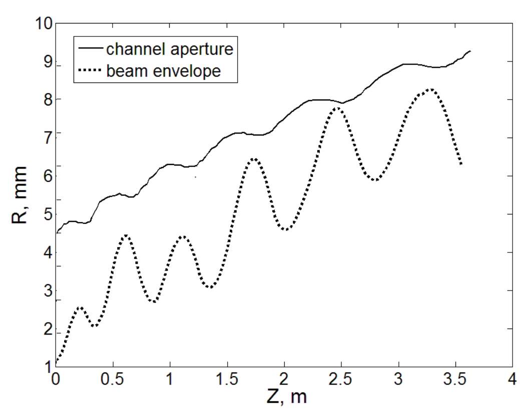

Figure 5: Beam envelope after correction

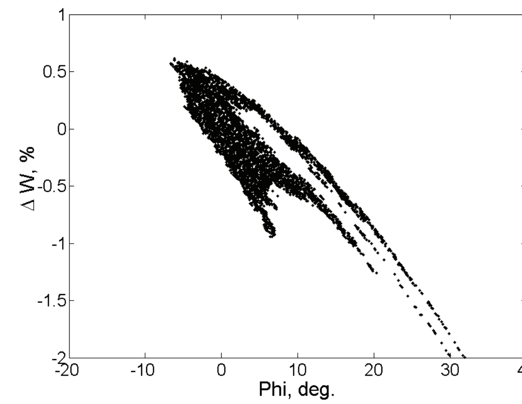

Figure 6: Output longitudinal phase – space distributions.

FINAL APF PARAMETERS

The main parameters APF accelerator are presented in Table 2.

Table 2. Final parameters

Cell number	115
Linac length, m	3.55
Transversal emittance growth, %	104
Longitudinal emittance growth, %	121
Beam transmission, %	100
Output energy spread, %	2.5

CONCLUSION

In this paper the problem of intensity beam dynamics optimization in an APF accelerator is considered. To solve this problem we propose the combination of gradient and genetic optimization methods. Proposed approach allows us to provide the numerical optimization and accelerators design taking into account other motion parameters and criteria.

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