BEAM DYNAMICS OF ALTERNATING-PHASE-FOCUSED LINACS FOR MEDICAL ACCELERATORS

Y. Iwata*, T. Furukawa, T. Kanai, M. Kanazawa, N. Kanematsu, M. Komori, S. Minohara, T. Murakami, K. Noda, S. Shibuya, M. Torikoshi, and S. Yamada
Department of Accelerator Physics and Engineering, National Institute of Radiological Sciences (NIRS), 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan
V. Kapin
Radiative Acceleration Center, Moscow Engineering Physics Institute (MEPhI), Kashirskoe sh. 31, Moscow, 115409 Russia

Abstract

A simple method to find an array of synchronous phases for alternating-phase-focused (APF) linacs is presented. The phase array is described with a smooth function having free parameters. With a set of the parameters, a simulation on the beam dynamics was made and distributions of the six-dimensional phase spaces were calculated for each set of the parameters. The parameters were varied, and numbers of the simulations have been performed. An optimum set of the parameters were determined so that the simulations of the beam dynamics yield large acceptances and small emittances of the extracted beams. Since the APF linac can provide both axial and radial stability of beams just with the rf acceleration-field, no additional focusing element inside of drift tubes are necessary. Comparing with conventional linacs having focusing elements, it has advantage in construction and operation costs as well as its acceleration rate. Therefore, the APF linacs would be suited for an injector of medical synchrotrons. A practical design of the APF linac for an injector of a medical accelerator is presented.

INTRODUCTION

A synchronous phase of the rf acceleration-field for conventional drift-tube-linacs such as the Alvarez structure is usually chosen to be negative value of around ϕ_s=-30 degrees to obtain axial beam stability as well as a large acceptance. Due to the negative synchronous phase, beam particles would be radially defocused during the acceleration. To compensate the radial defocusing, magnetic quadrupoles are usually installed inside of drift tubes. Because of these quadrupoles, the size of drift tubes may not be small and would limit the injection energy and operation frequency of the rf field. Consequently, those limits affect the entire size of the linac as well as its construction and operation costs.

In early 50's, the principle of an alternating-phase-focused (APF) linac has been proposed. According to the principle, the negative or positive synchronous phase is alternatively chosen at each gap. The negative (positive) synchronous phase provides axial (radial) focusing and radial (axial) defocusing. By analogy with the principle of strong focusing, both the axial and radial stability would be obtained just with the rf acceleration-field. Hence, no additional focusing element is necessary for the APF linac. This feature would make the construction and operation costs lower than those of conventional linacs, and therefore is attractive for an injector of medical accelerators, because the costs as well as the size of accelerators are crucial for local medical institutes.

Because of its attractive feature, number of studies has been made for the beam dynamics of the APF linacs [1-4]. Since the focusing of the beam relies only on the rf acceleration-field, the beam dynamics of the APF linac depends strongly on a choice of the alternating synchronous phases. Thus, a major task of those studies was devoted to optimize an array of the synchronous phase to obtain large acceptances as well as low emittances of extracted beams. Although number of studies has been made, there is no straightforward method to find the array of the alternating synchronous-phase, which will provide the reasonable acceptance and emittance of the beam. In this paper, we propose a simple method to find the array of the alternating synchronous-phase. Finally, the practical design of the APF linac for medical injectors was presented.

ARRAY OF ALTERNATING PHASE

In contrast to conventional linacs, entire characteristic of the beam dynamics for the APF linac depends strongly on an array of the synchronous phase. Thus, a choice of the phase array plays a key role in designing the APF linac. For the APF method, the focusing force depends on a period of the alternating phase, N_p. In the simplest case, the alternating phase having N_p=1 is $\phi_s=\phi_0,-\phi_0$. As compared with the Alvarez structure, the focusing force, provided by the rf field, would be insufficient as a velocity of the beam increases. To compensate its weak focusing force at the higher beam-velocity, one may use the higher period, *e.g.* N_p=2; $\phi_s=\phi_0,\phi_0,-\phi_0,-\phi_0$. However, a sudden change of the period during the acceleration would cause a mismatch which will induce the considerable emittance growth. Thus the period needs to be changed adiabatically to keep the beam emittance low over entire drift tubes. To accomplish this, we employed the following function to describe the phase array:

* Corresponding author: y_iwata@nirs.go.jp

$$\phi_s(n) = \phi_0 \exp(-a \cdot n) \sin\left(\frac{n - n_0}{b \cdot \exp(c \cdot n)}\right), \quad (1)$$

where *n* is the cell number. The first exponential describes an attenuation of the phase amplitude, and the alternating phase is expressed with the sine function A change of the period is described with the exponential in the argument of the sine function. The function has the five free-parameters of ϕ_0, n_0, *a*, *b*, and *c*. With a set of the parameter, a cell table can be generated, and a simulation on beam dynamics is made. The parameters were varied, and numbers of these simulations were performed. A good set of the parameters was determined to obtain the large acceptances and small emittances.

PRACTICAL DESIGN

According to the current design of the medical accelerator, carbon ions of 12C4+ generated from an ECR ion source will firstly be delivered to a RFQ linac. Injection energy of the RFQ linac will be 8 keV/u. Then the carbon beam will be bunched and accelerated up to 600 keV/u with the RQF linac. The resonant frequency of the RFQ linac will be chosen to be 200 MHz to reduce the cavity radius as well as its length. Then the emittance of the extracted beam will be matched with the acceptance of the APF linac using a matching section consisting of a quadrupole triplet installed in between the RFQ and APF linac. The phase space distributions of the extracted beam from the RFQ linac were calculated with PARMTEQ. Five hundreds of particles were tracked, and 96% of them (482 particles) were reached to the last cell and extracted. The calculated phase space and X-Y distributions after the matching section is shown in. Figure 1. All of 482 particles are plotted in the figures.

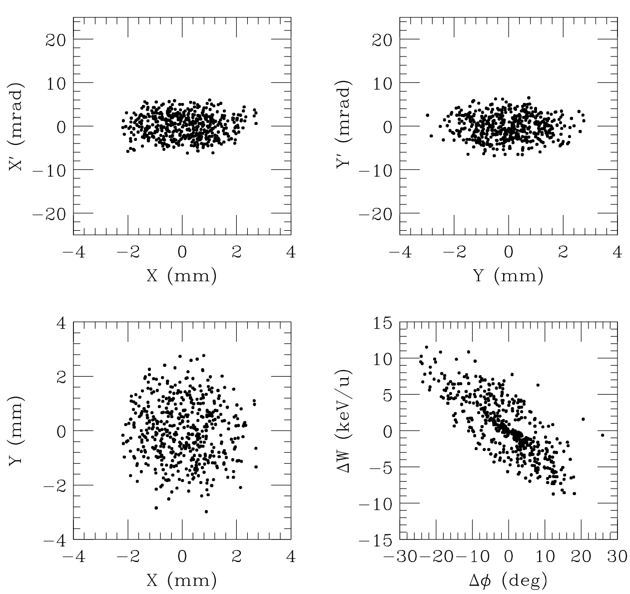

Figure 1: Phase space and X-Y distributions after the matching section. All the 482 particles extracted from the RFQ linac are plotted in the figures.

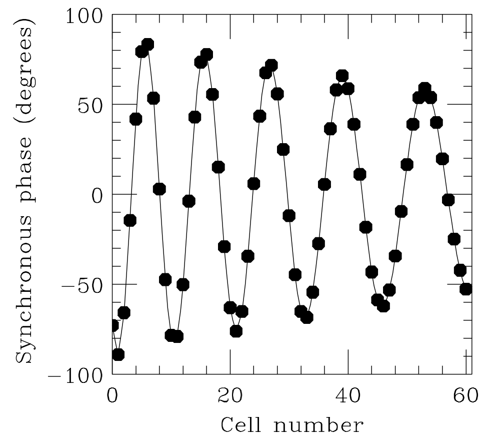

Figure 2: Array of synchronous phase as a function of the cell number.

The carbon beam having *E/A*=600 keV will be injected to the APF linac. The extraction energy of the APF linac was determined to be 4 MeV/u, so that the energy is sufficiently high enough to strip all electrons from $^{12}C^{4+}$ with a thin foil made of carbon. Then the fully-stripped carbon beam will be injected to a heavy-ion synchrotron and accelerated up to 400 MeV/u. Finally the carbon beams having *E/A*=400 MeV will be extracted and transported to a treatment room.

The operation frequency of the APF linacs was chosen to be 200 MHz, which is the same as that of the RFQ linac. Considering possible voltage breakdown between the gaps, the gap voltage for each cell was determined so that the maximum surface field along the drift tubes was kept to be ~235 kV/cm, corresponding to 1.6 of the Kilpatric limit, E_{Kilpat} (=147 kV/cm for 200 MHz). To estimate the surface field for each cell, electric field calculations using the two-dimensional field solver, POISSON, were made.

With above conditions and the phase space distributions of the matched beam shown in Figure 1, a parameter search with the function described as Eq. (1) was performed. As a result of the parameter search, good transmission of the beam and rather small emittances were obtained with the set of parameters, ϕ_0=90 (deg), n_0=-5.8, *a*=0.006, *b*=1.42, and *c*=0.0043. The phase array as a function of cell number for the above parameters is plotted in Figure 2. The energy of particles reached to be *E/A*=4 MeV with 60 cells, and the total length of the linac is 2.8m.

The calculated distributions of the phase space for the extracted beam are shown in Figure 3. All the 482 particles in Figure 1 were tracked through the APF linac, and 479 particles were extracted, corresponding to the transmission of 99%. Calculated energy spread of the extracted beam is about ± (15keVu)/(4MeV/u)~±0.38 %, which may be comparable to the acceptance of synchrotrons.

Table 1: Summary of parameters.

Quantity	Value	Unit
Injection energy	600	keV/u
Extraction energy	4	MeV/u
Operation frequency	200	MHz
Number of gaps	60	-
Tank length	2.8	m
Maximum gap voltage	440	kV
Maximum surface field	~235 (1.6E_{Kilpat})	kV/cm
Inner radius of drift tubes	6	mm
Transmission	99	%
X-X' emittance	7.2	π•mm•mrad
normalized emittance	0.67	π•mm•mrad
emittance growth	63	%
Y-Y' emittance	6.7	π•mm•mrad
normalized emittance	0.62	π•mm•mrad
emittance growth	44	%
ΔW-Δφ emittance	1.2	π•keV/u•ns
Energy spread	±0.38	%

Figure 4 shows the calculated beam envelopes for outmost particles. The oscillations of the beam envelopes corresponding to that of the phase array were seen. At the injection, the beam size is approximately ±2mm. The beam size starts to increase around 30th cell, and reaches up to ~5mm.

The major parameters of the current design described in this paper are summarized in Table 1. It was told that the emittance growth of the radial component would be large for the APF method. The emittance growth in the radial component was calculated to be about 63% for X-X' and 44% for Y-Y' which are comparable to those reported in ref. [4]. On the other hand, almost no emittance growth was observed for the axial component.

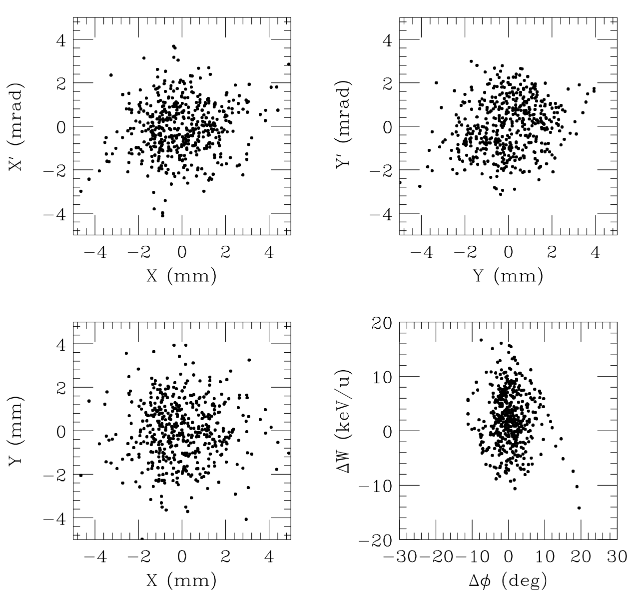

Figure 3: Phase space and X-Y distributions for the extracted beam from the APF linac. The 479 particles out of 482 were extracted. The corresponding transmission was 99%.

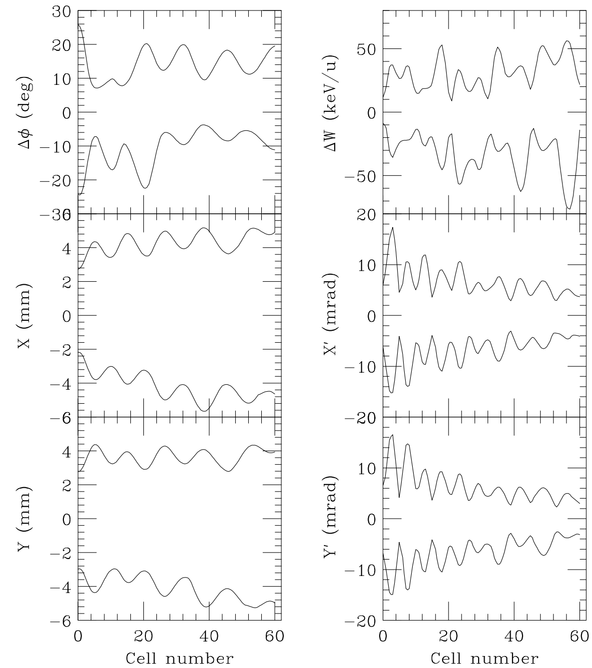

Figure 4: Beam envelopes for outermost particles as functions of the cell number.

SUMMARY

A simple method to find the array of the synchronous phase was presented. Since the radial and axial beam stability was obtained just with the rf accelerating-field, the focusing force would be insufficient as beam particles accelerate. To compensate the weak focusing force, the period of the array needs to be increased. To avoid the mismatch in changing the period during the acceleration, the smooth function having the free parameters was employed. By performing numbers of the simulations on the beam dynamics, a good set of the parameters was determined.

With the method described in this paper, a practical design of the APF linac for an injector of a medical accelerator was presented. With the required parameters, a search for the parameters of the function was performed, and a good set of the parameters was determined for the medical injector.

REFERENCES

[1] D. Swenson, Particle Accelerators, **Vol. 7**, 61 (1976).

[2] V.V. Kushin, Proceedings of the 1994 International Linac Conference, **Vol. 2**, 957 (1994).

[3] H. Okamoto, Nucl. Instr. and Meth. B **284**, 233 (1989).

[4] S. Minaev *et al.*, Proceedings of the 1999 Particle Accelerator Conference, New York, p. 3555 (1999)