Design optimization of the APF DTL in the SSC-linac*

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Abstract A linear accelerator as a new injector for the SSC (Separated Sector Cyclotron) of the HIRFL (Heavy Ion Research Facility Lanzhou) is being designed. The DTL (Drift-Tube-Linac) has been designed to accelerate $^{238}U^{34+}$ from 0.140 MeV/u to 0.97 MeV/u. To the first accelerating tank which accelerates $^{238}U^{34+}$ to 0.54 MeV/u, the approach of Alternating-Phase-Focusing (APF) is applied. The phase array is obtained by coupling optimization software Dakota and beam optics code LINREV. With the hybrid of Multi-objective Genetic Algorithm (MOGA) and a pattern search method, an optimum array of asynchronous phases is determined. The final growth, both transversely and longitudinally, can meet the design requirements. In this paper, the deign optimization of the APF DTL is presented.

Key words APF linac, phases optimization, MOGA, pattern search method

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1 Introduction

According to the current design of the SSC-linac, ions of $^{238}U^{34+}$ generated from an ECR ion source will first be delivered to a Radio Frequency Quadruple (RFQ) linac through Low Energy Beam Transport (LEBT). Then the beam will transported to the DTL by Middle Energy Beam Transport (MEBT), which consists of a pair of quadruple triplets and a rebuncher. The layout of the SSC-linac is shown in Fig. 1.

The beam with energy 0.54 MeV/u will be extracted from the APF DTL. The requirements of the extracted beam quality are as fellows: the extraction energy is 0.54 MeV/u, the normalized emittance in the x and y directions is 0.8 πmm·mrad in both cases, the energy spread ($\delta E/E$) is 1% and the phase spread $\delta\phi$ is 25°.

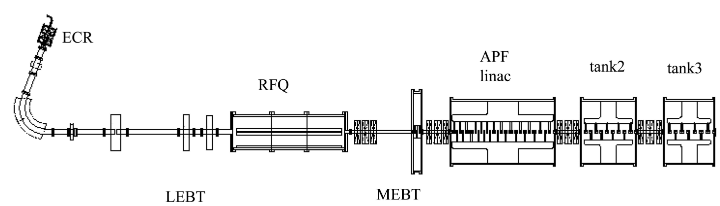

Fig. 1. The layout of the SSC-linac.

2 The principle of APF

There are two methods to maintain both the longitudinal and the transverse stability. The first is to keep the synchronous phase at negative value and use external focusing elements. The second is to use a RF field with alternating synchronous phases, which is the APF method. In designing the first accelerating

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tank, the approach of APF as an alternative design is investigated.

The principle of the APF linac was proposed in the early 1950s [1]. It is based on periodic changes of the sign of RF filed synchronous phase to maintain the longitudinal and transverse beam stability simultaneously. When accelerated ions pass through the RF electric field in an acceleration gap, the RF defocusing force $\Delta_{\rm RF}$ acts to accelerate the ions as follows,

$$\Delta_{\rm RF}=\frac{\pi e\xi VT\sin\phi}{2E\beta\gamma^3\lambda}, \tag{1}$$

where ξ is the ratio of charge to mass, ϕ is the acceleration RF phase, E is the ion energy per nucleon, V is the voltage, T is the transit time factor, β is the normalized velocity and γ is the relativistic mass factor. It is obvious that ions are focused when the RF phase ϕ is positive in transverse motion, and defocused when it is negative. In the longitudinal motion, the inverse situation occurs. Due to the principle, the APF linac can utilize the focusing and defocusing force provided by the RF field without additional focusing elements. That means a more compact and easily adjusted linac can be designed according to the theory. At present, there are a few APF linacs being constructed all over the world [2–5].

Since the focusing of the beam mainly depends on the RF defocusing force, the beam dynamics are very sensitive to the array of synchronous phases. To get an optimized array of synchronous phases is a very time-consuming and painstaking task. Maybe this is why the APF linac has not been adopted widely.

3 Optimization method

In this paper, a method to search an optimized array of synchronous phases is proposed. In this method, the beam optics code is combined with an optimization algorithm to adjust the parameter automatically and get an optimized phase array.

LINREV is a beam optics code, developed for the design of the RILAC booster at RIKEN [6]. It is a FORTRAN program based on matrix methods. It can build a lattice of DTL and trace each ion in 6 dimensional phase space. Some modifications have been carried out to allow it to work with the optimization software.

The DAKOTA [7] (Design Analysis Kit for Optimization and Terascale Applications) toolkit developed by the Department of Energy's Sandia National Laboratories is free open-source optimization software, which integrates several optimization packages, such as COLINY, CONMIN and JEGA. It contains a variety of gradient-based and non-gradient-based optimization methods. What is more, DAKOTA provides a flexible and extensible interface to third part codes.

LINREV is linked to DAKOTA through the use of script languages (Bourne shell and Perl). The flowchart of the optimizing iteration is shown in Fig. 2.

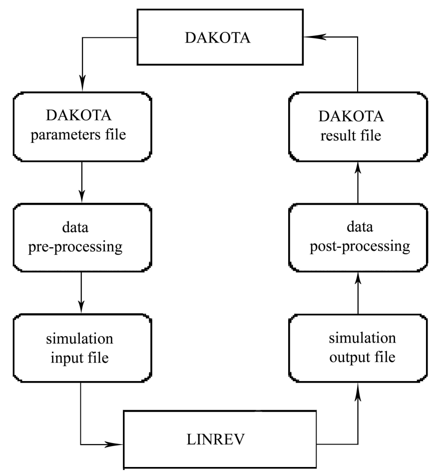

Fig. 2. The loosely coupled interface between DAKOTA and the simulation code LINREV.

4 Design optimization of the APF linac

1000 ions are initialized as a Gaussian distribution in the transverse direction and homogeneous distribution in longitude with the Twiss parameters listed in Table 1.

Table 1. The Twiss parameters of the initial ion distribution.

	alpha	beta
x-direction	4.67	2.48 mm/mrad
y-direction	2.38	1.69 mm/mrad
longitude	0.271	0.372 (°)/(keV/u)

The phase space and x-y distribution of the initial beam is shown in Fig. 3.

In the optimization of the APF DTL design, we want to yield small emittance and large beam transmission by optimizing the phase array. The problem is treated as an optimization problem. Four beam parameters (ϵ_{xf}, ϵ_{yf}, $\delta E_{\rm f}$- $\delta\phi_{\rm f}$ emittance and transmission) are taken as objectives, and twenty six phases are set as variables. Each phase is limited to a certain scope. The optimization problem is expressed as

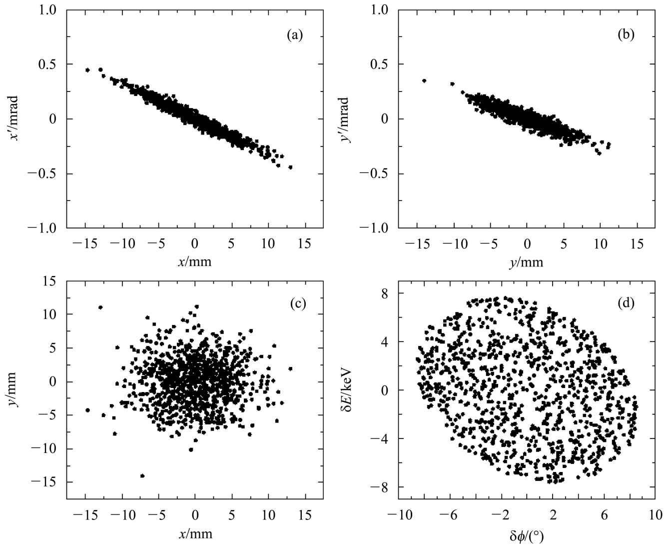

Fig. 3. Phase space and x-y distribution of the injected beam. (a) The phase space distribution of the initial beam in the x direction. (b) The phase space distribution of the initial beam in the y direction. (c) The distribution of the initial beam in the x-y plane. (d) The phase space distribution of the initial beam in the longitudinal direction.

$$\text{Minimize:}\quad \epsilon_x = f(\phi 1, \phi 2, \cdots, \phi 26), \tag{2}$$

$$\epsilon_y = f(\phi 1, \phi 2, \cdots, \phi 26), \tag{3}$$

$$\epsilon_{\delta W-\delta\phi} = f(\phi 1, \phi 2, \cdots, \phi 26), \tag{4}$$

$$\text{Maximize:}\quad \text{transmission} = f(\phi 1, \phi 2, \cdots, \phi 26), \tag{5}$$

$$\text{Subject to:}\quad -90^\circ \leqslant \phi 1, \phi 2, \cdots, \phi 5 \leqslant 90^\circ, \tag{6}$$

$$-60^\circ \leqslant \phi 6, \phi 7, \cdots, \phi 26 \leqslant 60^\circ, \tag{7}$$

$$0.535 \leqslant E_{\rm f} \leqslant 0.545. \tag{8}$$

Eqs. (2)–(5) are goals functions. In Eqs. (6) and (7), the synchronous phases of each cell $\phi 1, \phi 2, \cdots, \phi 26$ are limited to a certain range. The first five phases are limited to the range of $\pm 90^\circ$ in order to produce a focusing force on the beam; the others are selected in a $\pm 60^\circ$ range to accelerate the beam. Eq. (8) is added to achieve the extracted energy of about 0.54 MeV/u.

A hybrid optimization strategy combining a global optimization method MOGA with a local optimization method pattern search method [7, 8] is adopted. The objective functions converge to goal values after 22486 iterative simulations. The total time spent is about 750 seconds on a HP workstation XW8600.

5 Result

The final phase array is plotted in Fig. 4. In this way, the beam is mainly focused in both the transverse and longitudinal directions in cells whose synchronous phase amplitude is large, and mainly accelerated in the others.

All the 1000 ions are injected into the APF linac, and 971 ions are extracted, corresponding to the transmission of 97.1%. The energy of the extracted ions is 0.542 MeV/u with 26 cells, and the total length of the APF linac is 2.0 m. The phase space and x-y distribution of the extracted beam are shown in Fig. 5.

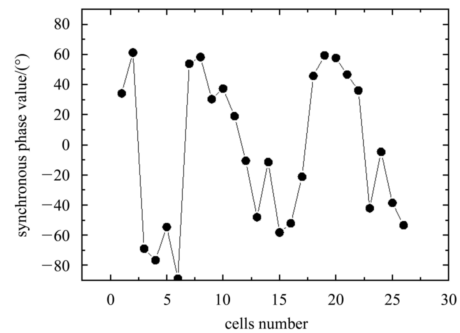

Fig. 4. The array of synchronous phase in the APF DTL.

As shown in Fig. 5, the energy spread of the extracted beam is about ±4 keV/u, corresponding to 0.7% for the central energy 0.542 MeV/u. The $\delta\phi$ is about ±25 degrees. In the transverse direction, the normalized emittance grows by about 25.7% in the x direction and 8.4% in the y direction. The emittance growth in the x direction is larger than in the y direction. This is due to a mismatch between the injected beam eclipse in Table 1 and the focusing structure in the x direction. So the ion distribution of the injected beam to the APF DTL must be the same in the x and y directions in order to match the focusing structure in both directions. The parameters of the extracted beam meet the requirements.

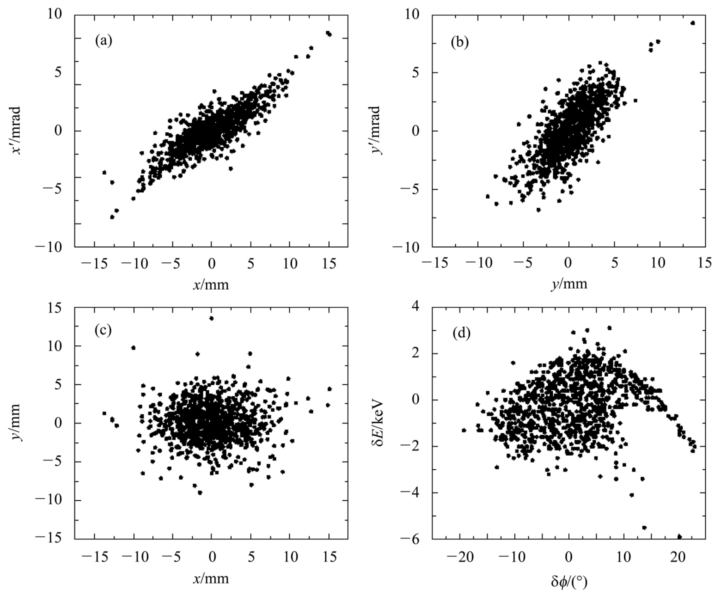

Fig. 5. Phase and x-y distribution of the extracted beam from the APF linac. (a) The phase space distribution of the extracted beam in the x direction. (b) The phase space distribution of the extracted beam in the y direction. (c) The distribution of the extracted beam in the x-y plane. (d) The phase space distribution of the extracted beam in the longitudinal direction.

Table 2. Summary of parameters.

parameters	value
injection energy/(MeV/u)	0.140
extraction energy/(MeV/u)	0.542
operation frequency/MHz	52.0
ϵ_{nxi}/(πmm·mrad)	0.6
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δE_i-$\delta\phi_i$ emittance/(π·keV/u·(°))	20
number of gaps	26
tank length/m	2.0
acceleration rate/(MV/m)	2.567
inner radius of drift tubes/mm	18
ϵ_{nx} growth	25.7%
ϵ_{ny} growth	8.4%
$\delta E_{\rm f}/E_{\rm f}$	±0.7%
$\delta\phi_{\rm f}$/(°)	±25

The major parameters of the beam and the designed APF linac described in this paper are listed in Table 2.

6 Summary

The optimization design of an AFP linac is presented. The parameters of the extracted beam are comparable with the design requirements and can be accelerated further.

By integrating the optimization software DAKOTA and the beam optics calculation code LINREV, the optimum phase array could be obtained easily and quickly. In the future, the sensitivity analysis of the structure will be performed.

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References

1 Good M L. Phys. Rev., 1953, **92**: 538

2 Iwata Y, Yamada S, Murakami T et al. Nuclear Instruments and Methods in Physics Research A, 2006, **569**: 685–696

3 Kushin V V, Nesterov N A, Parshin I O et al. http:// epaper.kek.jp/p93/PDF/PAC1993_1798.PDF, In Proc. of the 1993 PAC, 1993, **3**: 1978–1800

4 Matsui S, Hattori T, Hayashizaki N et al. Nuclear Instruments and Methods in Physics Research B, 2000, **161–163**: 1178–1181

5 Hattori T, Matsui S, Hayashizaki N et al. Nuclear Instruments and Methods in Physics Research B, 2000, **161–163**: 1174–1177

6 Kamigaito O, Kase M, Sakamoto N et al. Review of Scientic Instruments, 2005, **76**: 013306

7 http://www.cs.sandia.gov/DAKOTA/documentation.html, DAKOTA Version 4.2 User's Manual

8 http://www.cs.sandia.gov/DAKOTA/documentation.html, DAKOTA Version 4.2 User's Reference Manual