A 5.3 MeV/U, 200MHz APF DTL FOR CARBON IONS AS AN INJECTOR OF MEDICAL SYNCHROTORN*

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Abstract

A new low energy medium frequency DTL for 12C5+ with alternative phase focusing method (APF), which has the advantage in compact space and low cost, was designed as an injector of medical synchrotron. There are no conventional focusing elements in the APF DTL, and instead, the transversal focusing is realized by means of using RF field which changes correspondently with the synchronous phase. The envelopes of beam size are presented and the emittance change of six-dimension phase space is shown. The simple method proposed by Y. Iwata was employed to create synchronous phase array. Since the motion between transversal and longitudinal planes is coupled, the longitudinal acceptance of the DTL is not large.

Introduction

Alternative phase focusing (APF) refers to a method to design a DTL. There being no such conventional focusing elements as quadrupoles and solenoids, which would lead to higher shunt impedance, forms the main feature of an APF DTL. Since transversal focusing relies only on RF electric field which changes in accordance with the synchronous phase, the method is more suitable for lower energy machine.

Alternative phase focusing (APF) was first proposed in 1953[1]. Initially, the method was not widely used because of transversal defocus contributed by small phase interval [2]. The introduction of asymmetry of phase array which increases the freedom number led to a widened phase interval, and asymmetric alternating phase focusing (AAPF) found practical applications [3]. Previously, the APF tended to be studied by combination of linear maps [4], but now it is more convenient to research and design with computational method.

Owing to the fatal weakness that the longitudinal acceptance and the current limit are small, this method was not taken into consideration in ion accelerators, especially in those pursuing high intense beam, until the cancer therapy machine was built in HIMAC [5].

With the development of medical synchrotron, the compact space and low cost rather than high intense beam are concerned; and this makes the APF DTL become a better choice as a linac injector. HIMAC in Japan has built a medical machine with an APF DTL injector, and professor Iwata proposed a formula to get the synchrotron phase array [6]. At first, the same synchrotron phase array was used in my design.

PSO Method

Particle swarm optimization (PSO) refers to a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality [7].

There are two keys to introduce PSO into accelerator design. One is to choose appropriate learning factors and inertia factors to avoid local optimal solution; the other is to construct a proper fitness function to restrict the best solution and restrain the movements of particles, in which penalty function method is used.

To increase the total point, two types of restraint, hard boundary conditions and envelope control, are concerned while the total point is the smaller the better. For those solutions whose size is bigger than the tube radius or those whose energy increase is minus or those whose initial beta function is less than zero, the total point is given a high mark which is proportional to the number of cells in which the particles experience hard boundaries.

Since the betatron motion and synchrotron motion are seriously coupled by RF field in APF gaps, the minimum of beam transversal size corresponds to the maximum of longitudinal size; meanwhile, in order to limit the maximum of transversal size, the minimum cannot be too small. Thus, three types of fitness are tried: the square of maximum of transversal size, the sum of the squares of maximum of both transversal and longitudinal beam sizes with different proper coefficients, and the variance of the difference between beam size achieved and that given. It has to mention that the horizontal ordinate is cell number rather than the length of cavity.

In addition, the first synchrotron phase is restrained around -80 degree so that a larger longitudinal acceptance was obtained.

Manual Result Relying on Iwata's Formula

Iwata proposed a function to describe the synchrotron phase array as follows [7]:

$$\Phi_s(n) = \Phi_0 \exp(-a \cdot n) \sin\left(\frac{n - n_0}{b \cdot \exp(c \cdot n)}\right), \quad (1)$$

where n is the cell number. Iwata gave a good set of parameters, Φ_0=90(deg), n_0=-5.8, a=0.006, b=1.42 and c=0.0043. Blue stars in Figure 1 illustrate the synchrotron phase array as a function of cell number for those parameters, while the blue curve shows the general profile of the phase array.

Based on Iwata's phase array, an APF was manually designed and the transmission efficiency is less than 75%. The kinetic energy is 0.6 MeV/u at input end, and longitudinal envelop is not well controlled. The input longitudinal emittance is 160 degKeV, and the transversal normalized emittance 0.717 πmm mrad.

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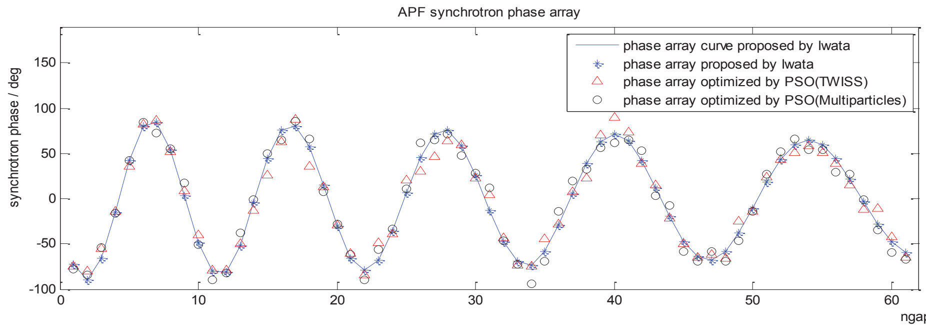

Figure 1: The general profile of synchrotron phase array generated from the formula proposed by Iwata is shown in blue curve, and phase array is shown in blue star. The red Δ represents the synchrotron phase array optimized by PSO using TWISS transformation, black o by PSO using multiparticle track.

Firstly, effective gap voltages are adjusted until the transversal beam size is less than tube radius to ensure that all particles could get through the tube, that is to say, this step is to guarantee that the particle lose must not happen in transversal plane. And then in consideration of transversal envelop, effective gap voltages are adjusted to decrease longitudinal phase width to the greatest extent. Lastly, try to match the structure by changing input Twiss parameters.

However, the two sides of half phase width around the synchrotron particle, a quarter superperiod behind the asymmetry of momentum dispersion results from non-linear effect in synchrotron motion, are seriously asymmetry, which contributes to the longitudinal particle lose.

Twiss Maps with PSO Method

To be simplest, RF gap is considered as "Thin gap", using a similar method to that of quadruple study, while the difference is that the value of RF gap maps is less than 1 because of the energy gain in accelerating process. The RF gap maps used in this paper are as follows [8]:

$$k_t = \frac{-\pi q E_0 T L \sin\varphi_s}{m_0 c^2 \bar{\gamma}^2 \bar{\beta}^2 \lambda}, \tag{2}$$

$$k_l = \frac{2\pi q E_0 T L \sin\varphi_s}{m_0 c^2 \bar{\beta}^2 \lambda}, \tag{3}$$

$$\mathrm{M}_t = \begin{bmatrix} 1 & 0 \\ \frac{k_t}{(\beta\gamma)_f} & \frac{(\beta\gamma)_i}{(\beta\gamma)_f} \end{bmatrix}, \tag{4}$$

$$\mathrm{M}_l = \begin{bmatrix} 1 & 0 \\ \frac{k_l}{(\beta\gamma)_f} & \frac{(\beta\gamma)_i}{(\beta\gamma)_f} \end{bmatrix}. \tag{5}$$

Eqs.(2-5) are fixed with coordinate X(x[mm],x'[mrad], y[mm],y'[mrad], z[mm], Δp/p[mrad]). Here cos(φ) was expanded in Taylor method and only one-order approximation is taken, thus, the non-linear motion in RF gaps disintegrates to be linear motion. Firstly, a manual result was achieved under the condition that the synchrotron phase array proposed by Iwata was used, and then it is used as one initial seed in PSO method to obtain a better one with a smother envelop curve illustrated in Figure 2 and a shapely beam size curve illustrated in Figure 3. Actually, with the energy increasing, the same geometric length of beam corresponds to a smaller phase width. Thus, a reasonable increase of beam size in longitudinal phase space is more preferable to achieve a larger acceptance. The result is achieved while the transversal and longitudinal emittances are 20 π mm mrad and 35 π mm mrad respectively.

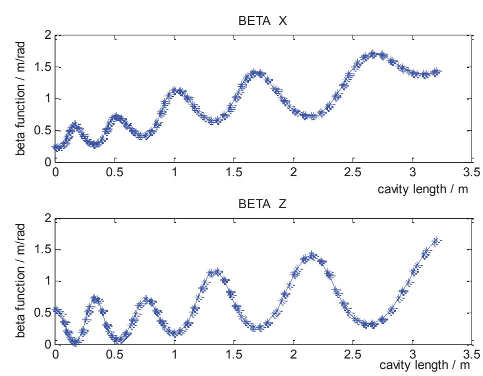

Figure 2: Betatron function in both transversal and longitudinal planes, showing excellent smoothness.

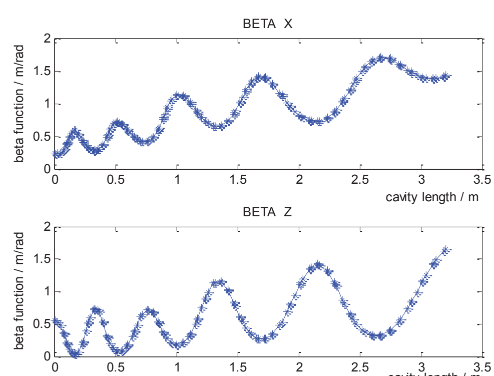

Figure 3: Beam sizes in both transversal and longitudinal planes, which are controlled absolutely well.

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In the process of optimization with PSO method, there are 2n+4 parameters, which means it is an optimization of 2n+4 dimensions, where n is the gap number. The main hard boundaries set in the code are as follows:

- The n effective voltages must be more than 0.
- The n absolute values of synchrotron phases must be less than 90 degree.
- The maximum of transversal beam size must be less than tube radius.
- The input 2 betatron functions must be more than 0.
- The imaginary part of all values must be equal to 0.
- The first synchrotron phase should be as close as possible to -90 deg at its larger side.

Using penalty function method, the total point is fixed according to the times that the beam touches the boundaries. The three control options of beam size are:

- The square of the maximum of transversal beam size.
- The sum of the two squares of the maximum of beam size both in transversal and longitudinal planes with two proper changeable coefficients.
- Although the periods become sparse along cavity length in Figure 2 and Figure 3, there is a similar profile to synchrotron phase curve if the cavity length changed to be gap number, which is used to restrain the curve shape.

The optimized synchrotron phase array is represented by red Δ in Figure 1.

Putting the result into multiparticle tracing code, a transmission efficiency of less than 80% was obtained. Obviously, there is a long tail where particles are lost illustrated in Figure 4. One factor contributing to it is multiparticle track is different from Twiss transformation; the other factor is that the non-linear effect is involved in multiparticle tracing code.

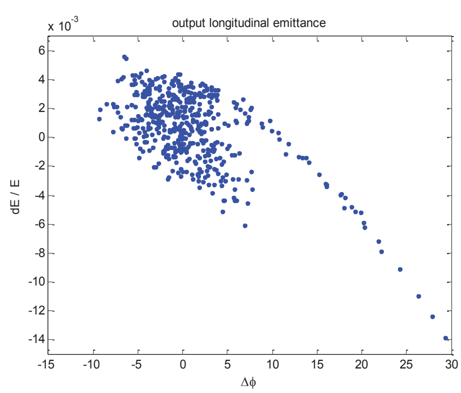

Figure 4: The beam has a long tail with non-linear effect, which lead to a low transmission efficiency of less than 80%.

Particle Multiparticle Track with PSO Method

PSO method was used similarly to Twiss maps, and the good result optimized with Twiss maps was set as one initialized seed as well. The result is pretty good. Output kinetic energy is 5.38 MeV/u shown in Figure 5, and the transmission efficiency 100%, cavity length 3.184 m

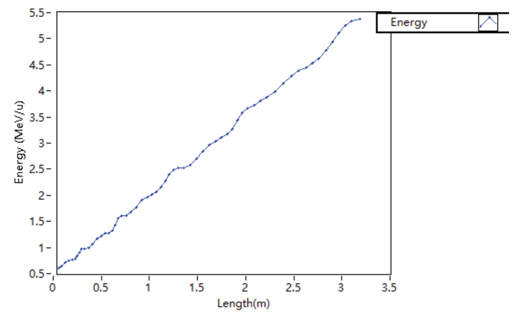

Figure 5: Kinetic energy as a function of cavity length.

No matter in transversal or longitudinal plane, the beam size is well controlled, which is shown in Figure 6 and Figure 7. In Figure 6, the red curve is overlapped with the blue one owing to rotational symmetric beam. It is a diverging beam at the output end in longitudinal plane; nevertheless, the phase width is controlled in the interval of -20 and 25 degrees.

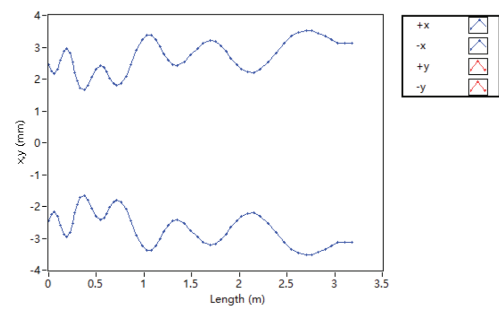

Figure 6: Transversal beam envelop.

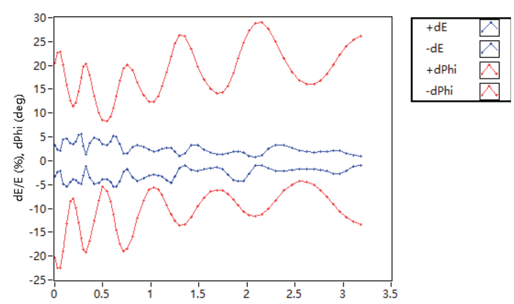

Figure 7: Longitudinal beam envelop.

The emittances at input end and output end in three planes are shown in Figure 8. And six dimension beam sizes are shown in Figure 9, in which one step represents one cell.

The main parameters are listed in Table 1. The optimized synchrotron phase array is illustrated in Figure 1 by black circle.

Conclusion

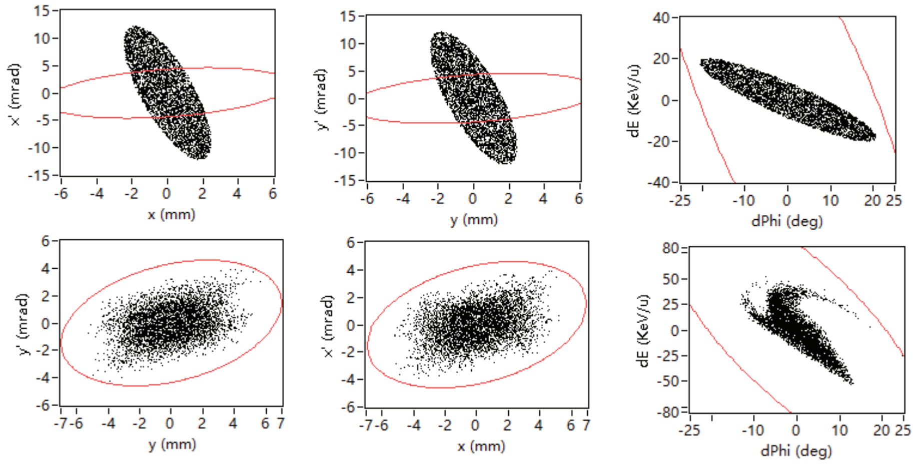

Figure 8: The emittances at input end in three phase space is shown in the upper three figures respectively, and emittances at output end is shown in lower three figures. The initial input is KV distribution.

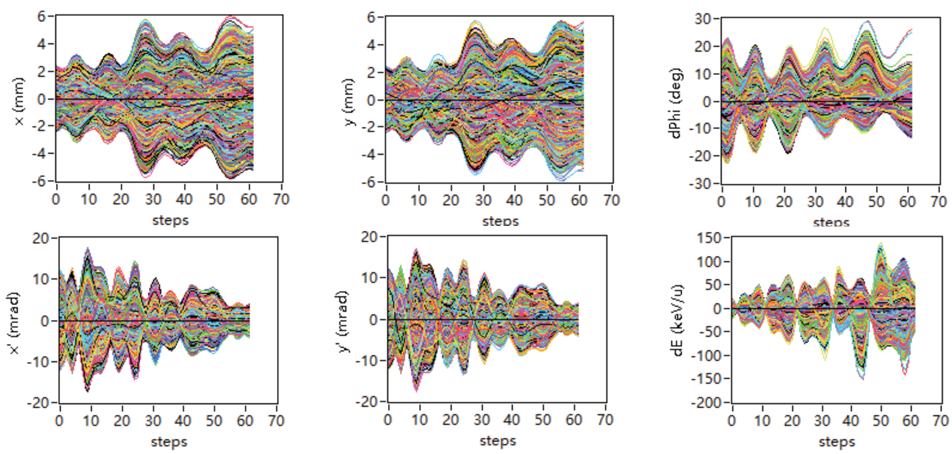

Figure 9. Six dimension beam sizes are shown as a function of cell number. One step in figures represents one cell. The beam size is controlled so well that all of 5000 particles is get through the cavity without particle lose; The longitudinal beam size and energy spread are small as well.

Table 1: Main parameters of APF

PARA	Value
Input energy	0.6MeV/u
Average RF field	19.2513 Mv/m
RF frequency	200MHz
Tube radius	6 mm
Norm- emittance T	0.71796 π mm mrad
Emittance L	180 deg keV
Beta T	0.3 m/rad
Beta L	2.37 deg/KeV
Alpha T	1.1
Alpha L	2.08

It is known that transversal focusing realized by Rf field is in both APF and RFQ, "the region of parameter space that is most advantage for APF is the same as for the RFQ [9]". The latter is of superiority in large longitudinal acceptance and RF focusing, so APF could not find applications widely.

The beam dynamics is much sensitive to structure and phase array, and the modulated tubes and gaps are a problem in cavity design and process. Meanwhile, in order to utilize the high shunt impedance resulting from relatively empty cavity without focusing elements, IH structure is used, which would introduce dipole mode field breaking the rotational symmetry and leading to distortion of transversal beam dynamics. Therefore, stability margin should be taken into consideration at first design.

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REFERENCES

[1] M. L. Good, "Phase-reversal Focusing in Linear Accelerators", Physics Review, Vol.92, p. 538 (1953).

[2] N. Wells, "Radio-frequency quadrupole and alternating phase focusing methods used in proton linear accelerator technology in the USSR," Interim report, 1985.

[3] B.P. Murin et al., "Proton Linear Accelerator with alternating phase focusing," proceeding, Vol.1, p. 330 (1978).

[4] I. M. Kapchinskiy, "Theory of resonance linear accelerators", p. 184 (1985).

[5] Y. Iwata et al, "Alternating-phase-focused IH-DTL for injector of heavy-ion medical accelerators", NIMA, 569, p. 685 (2006).

[6] Y. Iwata et al, "Beam Dynamics of Alternating-PHASE-Focused Linacs for Medical Accelerators," proceedings of APAC, 2004, Gyeongju, Korea.

[7] http://en.wikipedia.org/wiki/Particle_swarm_optimization.

[8] K. R. Crandall, "Trace 3-D documentation", p. 16(1997).

[9] T. P. Wangler, "RF linear accelerators", p.405 (2007).