ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL032

A VARIABLE FIELD PHASE-SHIFTER FOR RECIRCULATING PROTON LINACS*

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Abstract

The recirculating superconducting proton linac that has a potential to substantially save accelerator cost was recently proposed. It consists of three sections to accelerate the continues-wave (CW) beam to multiple GeVs. In the first section, the beam passes the linac two times. In the second and third sections, the beam goes through the linac four and six times. A phase-shifter is needed to meet the synchronous acceleration condition for multi-pass acceleration using the same RF cavity due to the phase slippage of the proton beam. Here we present the design of a variable field rectangular bend phase-shifter in which the beam goes to a different path in each pass inside the magnet to meet the synchronous condition.

INTRODUCTION

The concept of three-section recirculating superconducting proton linac that accelerates proton beams from 150 MeV to 8 GeV was recently proposed in Ref. [1]. By passing through the same superconducting linac multiple times, the recirculating proton linac can reduce the number of superconducting cavities from about 500 to about 100. This will substantially save the construction and operational costs of such an accelerator facility. The start-to-end beam dynamics design and single bunch simulations of the double-pass linac (150 MeV to 500 MeV) were carried out in Ref. [2]. The impact of space-charge effects during the CW multi-bunch overtaking collision of the first section was studied in Ref. [3]. The second section, a four-pass recirculating superconducting proton linac, consists of 40 5-cells 650 MHz superconducting cavities, which accelerate beam from 500 MeV to 2 GeV.

To obtain the desired acceleration from the Radio Frequency (RF) electric field, setting a matched driven phase is an important key to achieve the desired energy gain from each cavity. A non-periodic structure has been used in the double-pass linac to resolve the problem that the driven phase was not quickly adjusted between each pass [2]. Due to the increase of separation length between the cavities, the beam will see the same RF phase inside each cavity in the double-pass linac section.

However, for the multi-pass sections of the recirculating linac, the adjustment of separation between cavities will not be sufficient. A phase-shifter between two cavities is presented to shift time delay between multiple passes to meet the synchronous condition. The phase-shifter controls the proton beam path length and arrival time at RF cavities to satisfy synchronous condition between different passes. The phase-shifter has been used in some applications to adjust the time delay of the beam, *e.g.* Electron Microtrons [4] and Free Electron Laser Light Sources [5]. Figure 1 illustrates the schematic plot of the inserted phase-shift linac. The objective of the present study is to design the insertion device which varies the path length with the energy range in the four-pass linac section.

* Work supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
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Figure 1: A schematic plot of the inserted phase-shift linac.

THE PHASE-SHIFTER DESIGN

The simplest phase-shifter, shown in Fig. 2, includes four variable field dipole magnets and two drifts between first-second and third-fourth dipoles. Also, two one-meter spaces are reserved to add transverse focused elements between the phase-shifter and cavities.

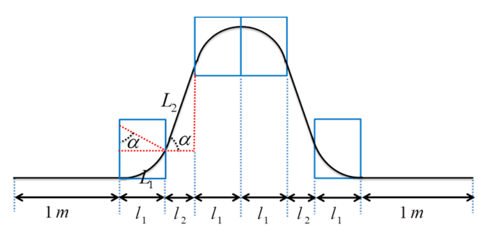

Figure 2: The layout of the phase-shifter scheme.

The total length of this device equals:

$$L = 2 + 4l_1 + 2l_2 \tag{1}$$

where l_1 is the magnet length, l_2 is the drift horizontal projected length. For the four-pass linac section, there are four energies of the beam through the phase-shifter. By varying the magnet field B in the radial direction (perpendicular to the beam path), each pass of the beam has a different bending angle and a bending radius inside the dipoles. This results in the beam from different passes going through different paths inside the phase-shifter. Therefore, it is possible for multi-pass beams to meet the synchronous phase by delaying the time. We assumed that magnet field B is the same for all pass beams at the en-

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trance of the first dipole and at the end of the fourth dipole. The total path through the phase-shifter is given by

$$\begin{aligned} L_{E_i} &= 2 + 4L_1 + 2L_2 \\ &= 2 + 4\alpha \cdot R + 2\frac{l_2}{\cos(\alpha)} \end{aligned} \tag{2}$$

Here, the path L_1 is inside the dipole, L_2 is inside the drift, and R is the bending radius. The bending angle α is given by $\alpha = \arcsin(\frac{Bl_1}{P})$. The momentum P is given by $P = BR$. Combining the bending angle and the momentum with Eqs. (2), the path through phase-shifter for a given energy E is expressed as

$$L_{E_i} = 2 + 4\arcsin(\frac{Bl_1}{P}) \cdot \frac{P}{B} + 2\frac{l_2}{\sqrt{1-(Bl_1/P)^2}} \tag{3}$$

It shows that the path is controlled by four parameters: magnet field B, dipole length l_1, drift length l_2, and momentum P. To better describe the beam energy, we introduce a two-dimension parameter E_{ij}. Where integer i denotes the beam location at cavity i and integer j denotes the pass number. Here $j=1$ shows the first pass beam. Assuming that each pass of the linac attains same energy gain 375 MeV and every five adjacent cavities is grouped into one section with 47 MeV energy gain, the range of the integer i varies from 1 to 8. Thus, the parameter E_{ij} can be calculated by

$$\begin{gathered} E_{ij} = 500 + i*47(\text{MeV}) + j*375(\text{MeV}) \\ (1 \le i \le 8, 1 \le j \le 4) \end{gathered} \tag{4}$$

Furthermore, another two parameters, separation length (H_1 and H_2) from the first and second dipole of the shifter (shown in Fig. 3), are concerned as the separation lengths decide the feasibility of such variable field dipoles. They are given by:

$$\begin{aligned} H_1 &= (R_L - l_1/\tan(\alpha_L)) - (R_H - l_1/\tan(\alpha_H)) \\ &= (P_L/B_L - l_1/\tan(\alpha_L)) - (P_H/B_H - l_1/\tan(\alpha_H)) \end{aligned} \tag{5}$$

$$\begin{aligned} H_2 &= l_2 * \tan(\alpha_L) - (l_2 * \tan(\alpha_H) - H_1) \\ &= l_2 * \tan(\alpha_L) - l_2 * \tan(\alpha_H) + H_1 \end{aligned} \tag{6}$$

Here the bending angles α_L and α_H come from the adjacent two passes j and $j+1$. As the bending angle is a positive number and less than 90 degrees, the shifter is required to satisfy the condition $B \cdot l_1 < P$. And the energy of the first pass beam is the lowest one, which means that the condition momentum P comes from the first pass. To simplify the synchronous condition, an integer N_j (the ratio of multi-pass beam time flight differences to RF period), is defined as an objective function. It is given by

$$N_j(B, E, l_1, l_2) = (L_{E_{ij}}/c\beta_{E_{ij}} - L_{E_{i(j+1)}}/c\beta_{E_{i(j+1)}}) * f \tag{7}$$

Where integer i and integer j are satisfied with $1 \le i \le 8$ and $1 \le j \le 3$. Here $j=1$ means the delayed time between the first and second pass. And the frequency f is equal to 650 MHz, c is the light speed. As the energy gain of each pass is 375 MeV, the variation of the β from j to $j+1$ pass is larger than that of the path L from *j to j+1 pass*. In the design, we would like to attain the length of the shifter as short as possible and also satisfies the synchronous condition. This can be achieved by starting from the highest energy and make the objective satisfy the equation $N_3=1$.

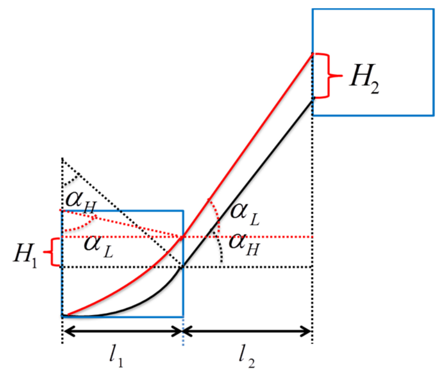

Figure 3: Separation length H_1 and H_2 inside the first and second dipoles.

RESULTS

The phase-shifter is designed in the following steps. Firstly, we set the maximum strength of the field B and dipole length l_1. After that we will copy the length of l_1 to the length of drift l_2 at the start of each cycle and use the third and the fourth passes to find the integer solution of the N_3. At this step, the filed B remains constant, and we vary the length l_1 and l_2. The shifter has to: (1) $B \cdot l_1 < P_1$; (2) $l_1, l_2 > 1\text{m}$. The step sizes of length l_1 and of l_2 are 0.01m and 0.001m. Once the length l_1 and l_2 are determined, they will remain constant. Next we would like to find the integer solution for N_2. We will reduce the field B in the second pass and use it to calculate the beam path in this pass. This path will combine with the path in the third pass to find the solution N_2. The last step is to find an integer solution N_1 by repeating the last step.

Due to the uncertainty of using room temperature magnet or superconducting magnet even both at first, the results are calculated with different maximum magnet field B, *e.g.* 2 Tesla, 2.5 Tesla, 3 Tesla and 5 Tesla. Also, we assume that the maximum dipole length is 2 meters. The computational results suggest that the increase of drift length l_2 compensate the decrease of dipole length l_1

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by choosing the higher intensity magnet field. In addition, the separation length H_2 has similar trend with l_2. Details about the parameter of different location phase-shifter at 5 Tesla and 3 Tesla are shown in Table 1 and 2.

CONCLUSION

In this paper, we present a conceptual design of the phase-shifter for the four-pass recirculating superconducting proton linac section. We compared the solutions with different maximum fields and found the parameters of the shifter. The higher maximum field reduces the total length of the phase-shifter. In the future study, we would like to carry out beam dynamics simulation through the designed phase shifters.

ACKNOWLEDGMENT

Thanks to China Scholarship Council (CSC, File No. 201604910803) to Yue Tao, financial support scholarship.

Table 1: The Phase-Shifter Parameters at 5 Tesla

i	*j*	*B* (T)	L_1 (m)	L_2 (m)	H_1 (m)	H_2 (m)
1	4 3 2 1	5 5 4.808 4.804	0.75	1.032	0.04 0.06 0.23	0.19 0.32 2.11
2	4 3 2 1	5 5 4.837 4.835	0.78	1.049	0.05 0.07 0.23	0.20 0.33 2.00
3	4 3 2 1	5 5 4.856 4.853	0.82	1.012	0.05 0.07 0.24	0.20 0.34 2.05
4	4 3 2 1	5 5 4.877 4.867	0.85	1.024	0.05 0.08 0.24	0.21 0.35 1.91
5	4 3 2 1	5 5 4.897 4.870	0.88	1.032	0.05 0.08 0.22	0.21 0.36 1.76
6	4 3 2 1	5 5 4.913 4.912	0.91	1.038	0.05 0.08 0.24	0.21 0.37 1.80
7	4 3 2 1	5 5 4.927 4.901	0.94	1.024	0.05 0.09 0.22	0.22 0.38 1.64
8	4 3 2 1	5 5 4.940 4.935	0.97	1.045	0.06 0.09 0.23	0.22 0.39 1.67

Table 2: The Phase-Shifter Parameters at 3 Tesla

i	*j*	*B* (T)	L_1 (m)	L_2 (m)	H_1 (m)	H_2 (m)
1	4 3 2 1	3 3 2.929 2.860	1.11	1.037	0.05 0.08 0.21	0.17 0.29 0.95
2	4 3 2 1	3 3 2.947 2.902	1.17	1.015	0.06 0.09 0.23	0.18 0.30 1.00
3	4 3 2 1	3 3 2.963 2.944	1.22	1.027	0.06 0.10 0.24	0.18 0.32 1.05
4	4 3 2 1	3 3 2.976 2.893	1.27	1.035	0.06 0.10 0.22	0.19 0.33 0.89
5	4 3 2 1	3 3 2.985 2.919	1.33	1.003	0.07 0.11 0.23	0.19 0.34 0.92
6	4 3 2 1	3 3 2.995 2.949	1.38	1.005	0.07 0.11 0.24	0.20 0.35 0.95
7	4 3 2 1	3 3 2.586 2.427	1.43	1.004	0.07 0.02 0.13	0.20 0.07 0.39
8	4 3 2 1	3 3 2.613 2.476	1.48	1.001	0.07 0.03 0.13	0.20 0.08 0.41

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