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A PHASE SHIFTER FOR MULTI-PASS RECIRCULATING PROTON LINAC*

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Abstract

The multi-pass recirculating proton linac can significantly improve the usage efficiency of RF superconducting cavities by passing the proton beam through the same cavity multiple times. However, in order to achieve the multiple acceleration, synchronous conditions in phase have to be satisfied. In this paper, we propose a fixed field superconducting magnet system as a phase shifter to meet the synchronous conditions.

INTRODUCTION

Superconducting proton linacs have been constructed or proposed as a driver for high energy neutrino physics study [1], for production of spallation neutron sources [2, 3] and tritium [4], and for nuclear waste transmutation and energy production [5, 6]. However, those linacs are expensive due to the inefficient usage of superconducting RF cavities with single pass of the proton beam. Recently, we proposed a concept of recirculating superconducting proton linac that has a potential to substantially save those accelerator project costs by reusing each section of the superconducting linac multiple times to accelerate the beam to multiple GeVs [7, 8]. A schematic plot of a multi-GeV recirculating proton linac is shown in Fig. 1.

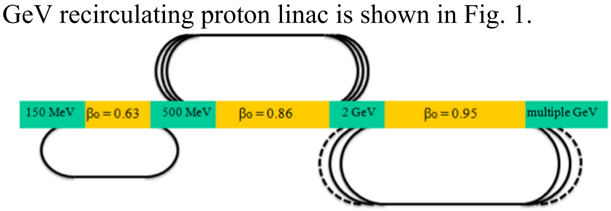

Figure 1: A schematic plot of a GeV recirculating proton linac [7].

Here, the proton beam is accelerated in three sections using three types of superconducting RF cavities separately. In the first section, the proton beam is accelerated from 150 MeV to 500 MeV in a double pass linac. A total of 17 cavities is needed in this section, instead of 34 cavities in a single pass linac. In the second section, the proton beam is accelerated from 500 MeV to 2 GeV in 4 passes, using 39 cavities instead of 156 cavities. In the third section, the proton beam is accelerated from 2 GeV to 8 GeV in 6 passes, using 50 cavities instead of 300 cavities. This new concept drastically reduces the number of superconducting cavities needed to reach the final 8 GeV beam energy from near 500 to around 100. It also avoids the potential intensity and repetition rate limits of the Rapid Cycling Synchrotron.

The electron recirculating accelerator has been built and operated for many years [9]. For proton beam, there exist unique challenges due to the phase slippage between different energy proton beams passing through a fixed distance. The recirculating proton beam passing through the same cavity might see different RF phase from the previous passes. Let t_i^m denote the time elapse between two RF cavities i and i+1 during the mth beam pass of the accelerator, t_i^n the time elapse between the two cavities during the nth beam pass, if the difference of the two time elapses satisfies the following synchronous condition:

$$t_i^m - t_i^n = \pm k\, T_{rf}\,, \quad k = 0, 1, 2, \ldots \qquad (1)$$

where T_{rf} is the oscillation period of the RF field inside the cavity, the proton beam will see the same design phase of the cavity during multiple passes of the accelerator.

Beam dynamics design studies [10, 11] have been done for the first section of proposed multi-GeV recirculating linac using the IMPACT code [12, 13]. The separation between superconducting cavities is adjusted to satisfy the above synchronous condition so that proton beams with two different energies can be accelerated using the same RF cavity. However, for multiple passes (>2), the slippage in phase can no longer be corrected by spacing between cavities and requires a new approach. An energy dependent path length change using magnetic phase shifters during recirculation is one option, but this requires high magnetic fields due to the large magnetic rigidity of the proton beam at GeV energy. An additional challenge for the design of phase shifting magnets comes from CW operation. In such a mode it is not possible to ramp the magnetic field fast enough, requiring that the magnets have a momentum acceptance large enough to cover the full range of energies in the recirculating section with fixed magnetic field. In this paper, we propose a fixed field achromatic superconducting magnetic system that can provide synchronous phase shifts for different energy beams.

FIXED FIELD PHASE SHIFTER USING SUPERCONDUCTING MAGNETS

In the previous study, a chicane-like phase shifter concept using three bending magnets was proposed for multi-pass recirculating proton linac [14]. However, that concept requires discontinuous change of magnetic field profile, which is not practically achievable. In this study, we propose using two bending magnets as a phase shifter between two RF cavities. The field profile inside the bending magnet varies continuously in the direction perpendicular to the magnet entrance edge. A schematic plot of the new fixed field phase shifter is shown in Fig. 2. Here, the proton beam passing through the RF cavity will enter the magnet with 45 degrees with respect to the magnet's entrance edge. In the middle plane of the magnet, there is only vertical component of the field that varies only as a function of x, the distance perpendicular to the entrance edge. There is no z dependency of the vertical magnetic field in the middle plane. From this symmetry, the proton beam will exit the magnet with another 45 degrees with respect to the entrance edge. The entire magnet provides 90 degree bending of the proton beam.

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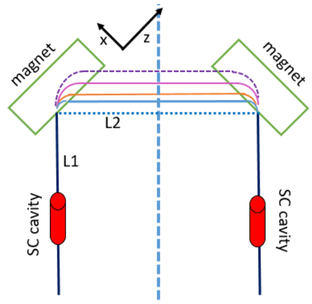

Figure 2: A schematic plot of the fixed field phase shifter.

Using the symmetry as shown in the dashed line of the above plot, another bending magnet with the same field profile bends the beam another 90 degrees and transports the beam into the straight section of the next RF superconducting cavity (SC). Different energy proton beams coming out the RF cavity in the first straight section and entering the bending magnet travel different paths inside and between the magnets. Due to the symmetry, these different energy beams all come back to the straight section and enter the next superconducting cavity. These two 90 degree bending magnets form an achromatic system for different energy beams. This approach using the symmetry of bending magnets to achieve large momentum acceptance has also been used for electron accelerators [15], and has recently been considered for superconducting gantries for proton therapy [16]. By appropriately designing the field profile along the direction perpendicular to the entrance edge, i.e. By(x), the time differences of multiple passes of the proton beam through this phase shifter can be made to satisfy the synchronous condition.

The second section of the proposed multi-GeV recirculating proton linac accelerates the proton beam from 500 MeV to 2 GeV in four passes. The energy gain through each pass is 375 MeV. We designed the magnetic field profile of the phase shifter for two group of energies. The first group of energy is at the entrance of this section with kinetic energy varying from 500 MeV, to 875 MeV, to 1250 MeV, and to 1625 MeV through four passes of the linac. The phase shifter for this group of energy is called entrance phase shifter. The second group of energy is at the exit of the linac with kinetic energy increasing from 875 MeV, to 1250 MeV, to 1625 MeV, to 2000 MeV. The phase shifter for this group of energy is called exit phase shifter. In order to satisfy the synchronous conditions for all four beam passes, starting with an initial magnetic field profile By(x), we adjust the length of L1 and L2 in Fig. 2 so that the time difference between the first pass and the second pass satisfies the synchronous condition. Here, L1 is the distance from the cavity to the entrance point of the magnetic field edge, and L2 is the distance from that point to the central middle plane. The magnetic field edge is the starting location of magnetic field and includes the fringe field of the bending magnet. Next, we adjust the vertical magnetic field profile By(x) with fixed L1 and L2 so that the time differences between the third pass and the second pass, and the time difference between the fourth pass and the third pass satisfy the phase synchronous conditions. Using the new field profile By(x), we readjust L1 and L2 so that the time difference between the first and the second pass satisfies the synchronous condition. Using the new L1 and L2, we adjust the By(x) again so that the time differences between the second, the third, and the fourth pass satisfy the synchronous conditions. This process is repeated for a number of times until all the time differences between the first, the second, the third, and the fourth pass satisfy the synchronous phase conditions. In this way, all four recirculating proton beams passing through the fixed field phase shifter will see the same RF phase and will be accelerated following the designed energy gain.

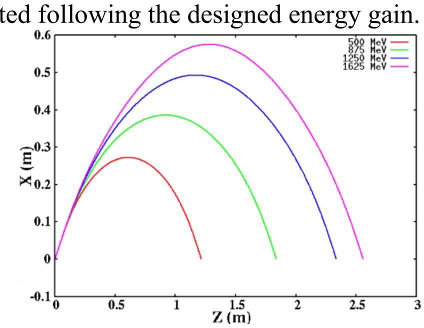

Figure 3: Trajectories of proton beam with four energies inside one bending magnet of the entrance phase shifter.

Figure 3 shows the trajectories of proton beams with four energies inside one bending magnet of the entrance phase shifter. Here, each energy beam denotes the beam from each pass at the entrance of the second section of the proposed GeV recirculating proton linac. It is seen that the four trajectories are widely separated with a minimum separation about 30 cm at the exit of the magnet. This large separation between different passes is helpful for inserting transverse focusing element, e.g. quadrupole, in the drift between the two bending magnets of the phase shifter.

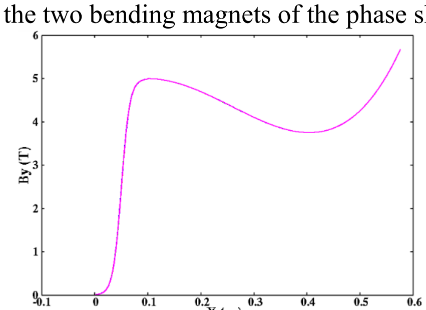

Figure 4: Middle plane magnetic field profile inside the bending magnet of the entrance phase shifter.

Figure 4 shows the magnetic field distribution profile at the middle plane of the bending magnet of the entrance phase shifter for the four proton beam passes after the optimization. The L1 is 0.28 meters and the L2 is 2.58 meters after the optimization. This field can be written as

$$By(x) = \begin{cases} 2.5(\tanh(20\pi(x-0.05))+1), \quad x \le 0.1 \\ 5 - 36.78(x-0.1)^2 + 64.83(x-0.1)^3 + 37.93(x-0.1)^4 \\ +3.2(x-0.1)^5, \quad x > 0.1 \end{cases}$$

Here, we assumed that the magnetic field can be approximated by a hyperbolic function in the fringe field region and a polynomial function inside the bend. We also assumed the peak of the field as 5 Tesla by using superconducting magnet technology.

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Figure 5 shows the trajectories of four energy proton beams inside one bending magnet of the exit phase shifter. Here, each energy beam denotes the beam from each pass at the exit of the second section of the proposed GeV recirculating proton linac.

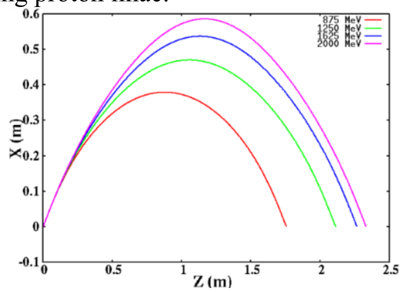

Figure 5: Trajectories of proton beam with four energies inside one bending magnet of the exit phase shifter.

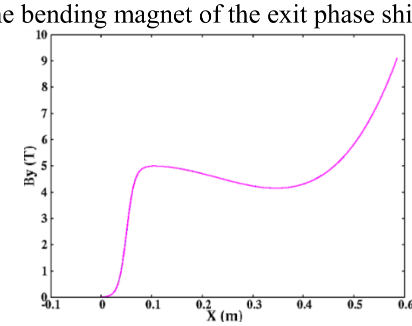

Figure 6: Middle plane magnetic field profile inside the bending magnet of the exit phase shifter.

Figure 6 shows the magnetic field profile at the middle plane of the bending magnet of the exit phase shifter for the four proton beam passes after the optimization. The L1 is 0.32 meters and the L2 is 1.73 meters after the optimization. This field can be written as

$$By(x) = \begin{cases} 2.5(\tanh(20\pi(x-0.05))+1), \quad x \le 0.1 \\ 5 - 37.45(x-0.1)^2 + 78.45(x-0.1)^3 + 68.02(x-0.1)^4 \\ +6.69(x-0.1)^5, \quad x > 0.1 \end{cases}$$

In the above examples, we have assumed a short fringe field region with 0.1 m length. Initial superconducting magnet design studies have shown allowing a larger fringe field region reduces the complexity of the magnet design. For this reason, we have also explored a scenario with a larger fringe field region of 1.2 m. In this scenario the spacing between magnets (and distance of beam entry and exit from the magnet ends) must be kept large enough such that the fringe field overlap is sufficiently small and entrance and exit fields sampled by the beam are symmetric.

Figure 7 shows the trajectories of four energy proton beams inside one bending magnet of the entrance phase shifter using the larger fringe field region. The four trajectories are widely separated at the exit the magnet, which is helpful for independent transverse focusing.

Figure 8 shows the middle plane magnetic field profile of the entrance phase shifter after the optimization. The L1 is 1.16 meters and the L2 is 4.59 meters from the optimization. The field inside the magnet can be written as

$$By(x) = 5 - 35.58(x-0.1)^2 + 53.7(x-0.1)^3 + 17.42(x-0.1)^4$$
$$+ 46.26(x-0.1)^5, \quad x > 1.2$$

Using the large fringe field, we also calculate four pass trajectories and field distribution inside the bending magnet for the exit phase shifter. Figure 9 shows the trajectories of four energy proton beams inside one bending magnet of the exit phase shifter with a larger fringe field region.

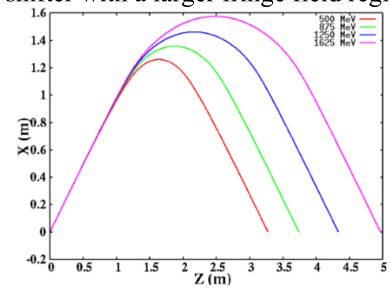

Figure 7: Trajectories of proton beam with four energies inside one bending magnet of the entrance phase shifter with large fringe field region.

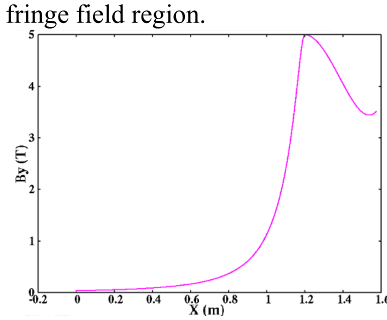

Figure 8: Middle plane magnetic field profile inside the bending magnet of the entrance phase shifter.

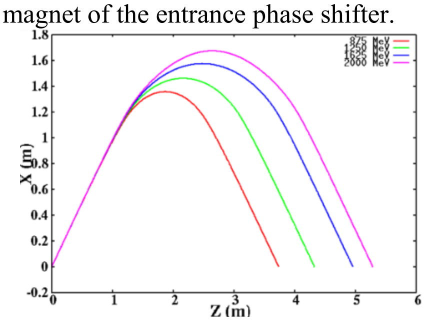

Figure 9: Trajectories of proton beam with four energies inside one bending magnet of the exit phase shifter with large fringe field region.

Figure 10 shows the middle plane magnetic field profile of the exit phase shifter after the optimization. The L1 is 1.13 meters and the L2 is 4.61 meters from the optimization. The field inside the magnet is given as

$$By(x) = 5 - 35.65(x-0.1)^2 + 53.7(x-0.1)^3$$
$$+ 27.48(x-0.1)^4 + 20.75(x-0.1)^5, \quad x > 1.2$$

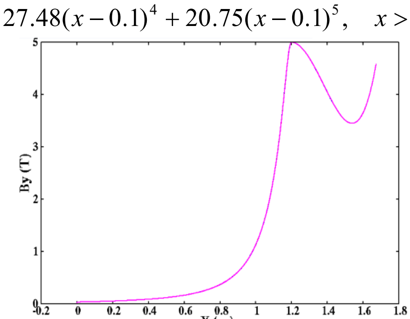

Figure 10: Middle plane magnetic field profile inside the bending magnet of the exit phase shifter.

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