A MULTI-GeV RECIRCULATING PROTON LINAC*

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Abstract

A high power GeV proton linac has many scientific applications. Recirculating RF linac as an efficient accelerator has been used and proposed to accelerate both electron and muon beams. In this paper, we study the concept of using a multi-pass recirculating RF linac to attain a multi-GeV high power proton beam. This linac consists of three types of superconducting RF cavities that accelerate the proton beam multiple times from 150 MeV to final multiple GeV energy. Such a recirculating proton linac can significantly reduce the number of RF cavities in the accelerator and lower the cost of the facility.

INTRODUCTION

A high power GeV proton (H^+/H^-) accelerator provides an important tool for scientific discovery. A number of spallation neutron sources driven by proton accelerator were built and are under construction around the world [1-5]. It was also proposed as a driver for nuclear waste transmutation in subcritical nuclear power plant [6-9], for production of tritium [10], and for high intensity neutrino physics study [11-13]. Most of those accelerators use a straight single pass linac to accelerate the proton beam to GeV energy. A proton linac is expensive in both construction and operation. Superconducting cavities were used/proposed in the main section of those facilities to accelerate the beam since those cavities can provide high accelerating gradient with little power loss on the wall. In addition, superconducting cavity also allows a larger cavity bore radius in comparison with the normal conducting cavity since the accelerating gradient of the cavity is not limited by the cavity bore radius. This helps reduce the potential proton beam losses, which is critical for all high power accelerators in order to avoid the risk of radio-activation caused by the lost particles and to allow hand-on maintenance of the accelerator.

Using a single pass superconducting linear accelerator is architecturally simple but inefficient in the use of RF cavities compared with circular accelerators such as a synchrotron, where the beam passes through the same RF cavity many times. Moreover, building and operating superconducting cavities are expensive. To minimize the construction and the operational costs, it will be beneficial to keep the number and the type of RF cavities as low as possible. For example, in the Project-X accelerator design, six types of superconducting cavities were proposed to accelerate the beam from 2 MeV to 8 GeV. A single type elliptical cavity was used to accelerate the beam from 177 MeV to 480 MeV kinetic energy, one type of cavity to accelerate the beam from 480 MeV to 3 GeV, and one type of cavity from 3 GeV to 8 GeV. In this study, we study the concept of a recirculating proton linac that was proposed before [14]. This linac takes an initial proton beam of 150 MeV from an injector and accelerates the beam to multiple GeV (e.g. 8 GeV) using three types of superconducting cavities. Each type of cavity is responsible for a single energy range. This energy range can be divided into a much smaller energy range for a single pass if one allows the beam to pass through the same cavity multiple times. This significantly saves the number of cavities needed in the accelerator and reduces the construction and the operational costs.

A MULTI-GeV RECIRCULATING PROTON LINAC

A schematic plot of the GeV recirculating proton linac is shown in Fig. 1. It consists of three sections with each section using a single type of the superconducting cavity. The first section accelerates the proton beam to a few hundred MeV, the second section accelerates the beam to 2 GeV, and the last section accelerates the beam to multiple GeV. The choice of 2 GeV energy at the exit of the second section is out of the consideration that most high power accelerator driven systems will have a final beam energy below 2 GeV [6]. For the energy between 150 MeV and 2 GeV, we will use two types of cavities with different geometric β_G. In order to determine the geometrical β_G of those cavities and the transition energy between the two sections, we define an average transit time factor as:

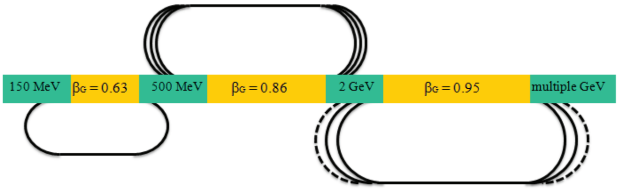

Figure 1: A schematic plot of a multi-GeV recirculating proton linac.

$$\bar{T}(\beta_G) = \frac{mc^2}{\Delta E_{\max}} \int_{\beta_{in}}^{\beta_{out}} \frac{T(\beta,\beta_G)}{(1-\beta^2)^{3/2}}\, d\beta \qquad (1)$$

where $\Delta E_{\max}$ is the energy gain through a section of cavities with 0 design phase (i.e. maximum energy gain), β_{in} is the normalized velocity at the entrance of the accelerator section, and β_{out} is the normalized velocity at the exit of the section. The maximum energy gain through the section can be written as

$$\Delta E_{\max} = qVN\bar{T} \qquad (2)$$

where N is proportional to the number of cavities used.

The first section of the linac accelerates the proton beam from150 MeV to 500 MeV. In a single pass linac, it

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*Work supported by the Director of the Office of Science of the US Department of Energy under Contract no. DEAC02-05CH11231.

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requires more than 39 cavities (assuming an average 13 MV per cavity accelerating voltage from a conservative consideration to include off-crest acceleration). In the recirculating linac proposed here, the proton beam can pass through those cavities multiple times. If we assume that the proton beam passes through this section of linac two times, this will reduce the number of cavities by half.

The first pass of the proton beam exits from this section at 325 MeV energy with a magnetic rigidity of 2.82 T-m. Assuming two Tesla bending magnets in the arc, this leads to a compact racetrack beam transport system with an arc radius of about one and a half meter. The second pass of the beam exits this section with a 500 MeV energy. This corresponds to a magnetic rigidity of 3.63 T-m. An achromatic dogleg lattice can be used to transport the beam into the second section. The second section accelerates the beam from 500 MeV to 2 GeV. For a single pass linac, this requires more than 155 cavities. If we assumes that the beam passes through this section four times, this will reduce the number of cavities in this section to 40, with 375 MeV energy gain through each pass. The third section accelerates the beam from 2 GeV to multiple GeV depending on the specific application. For an application such as the one proposed in the Project-X, this final energy can be 8 GeV. Assuming a 25 MeV energy gain per cavity (under pulsed operation mode), this will use minimum 300 cavities. On the other hand, using a recirculating linac in this section with multiple passes, e.g. six passes, the minimum number of cavities can be reduced to 50. Therefore, by using the multi-pass recirculating linac for the major energy range, the total number of cavities needed in the accelerator can be reduced by more than a factor of four. Such a reduction of the accelerating cavity number in the linac significantly lowers the construction and operational cost of the facility. Moreover, the recirculating linac also shortens the length of the total straight accelerating section. This can be important if the facility is restricted by the available straight real estate.

In a proton linac, the distance between two RF cavities is fixed as shown in Fig. 2. In the recirculating linac, a proton beam passes through the same accelerating system multiple times to save the number of RF cavities. Due to the fact that the proton beam is still non-relativistic, the velocity of the beam changes during acceleration and varies from pass to pass (especially at lower energy section). This could cause a problem for multi-pass acceleration. When the beam passes through the accelerator for the first time, the driven phase of each RF cavity can be tuned to achieve a design phase (e.g. *-30* degree) for the desired energy gain. When the beam passes through the accelerator for the second time, it has a higher energy and a larger velocity. Because the distance between accelerating cavities is fixed, at the same cavity, the proton will see a different RF phase from that during the first pass. This will not be a problem if the driven phase of the cavity can be quickly adjusted between each pass or between each bunch train for CW operation so that the desired energy gain and design phase for the beam can be achieved. However, such a fast modulation of RF driven phase normally cannot be easily attained for a superconducting cavity.

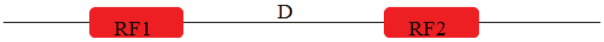

Figure 2: A schematic plot of two cavities in a section of linac.

Let t_i^m denote the time pass between two RF cavities i and $i+1$ during the m^{th} beam pass of the accelerator, t_i^n the time pass between the two cavities during the n^{th} beam pass, if the difference of the two time pass satisfies the condition:

$$t_i^m - t_i^n = \pm kT_{rf}, k = 0,1,2,3\ldots \quad (3)$$

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

For the first section two-pass recirculating linac proposed here, the above condition can be achieved through adjusting the distance between two cavities. Here, the above condition can be rewritten as:

$$l_i\left(\frac{1}{\beta_i^1} - \frac{1}{\beta_j^2}\right) = \pm kcT_{rf}, k = 0,1,2,3\ldots \quad (4)$$

where $\beta_i^1=v_i^1/c$ is the normalized velocity after cavity i during the first beam pass, $\beta_i^2=v_i^2/c$ the normalized velocity after cavity i during the second beam pass, c is the speed of light in vacuum, and l_i is the distance between the cavity i and the cavity $i+1$. Knowing the energy/velocity after each RF cavity during two beam passes, one can use above equation to determine the separation distance of two cavities to maintain the same RF phase.

Adjusting the distance between two cavities helps control RF phases during two beam passes. However, for multiple recirculating beam passes as proposed in section two and three, this will not work. Furthermore, as the proton beam energy increases, the velocity difference between two passes becomes smaller, this results in a very large separation distance in order to satisfy above condition. Another way to control the time delay (i.e. phase slippage) between multiple beam passes is to insert a phase shifter between two cavities. Such a phase shifter will control the time pass between two RF cavities for the multi-pass beam to either satisfy the condition Eq.3 or the other designed RF phase of each pass. A schematic plot of a section of accelerating cavities together with phase shifters is shown in Fig. 3.

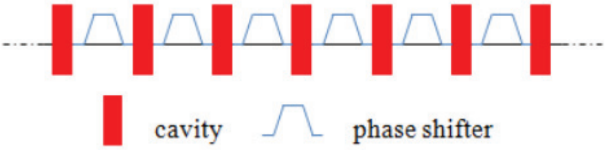

Figure 3: A schematic plot of a section of accelerating cavities with phase shifters.

Magnetic phase shifters have been used in free electron laser (FEL) light sources and electron microtrons to adjust time delay of the beam. Using an achromat magnetic chicane as a phase shifter helps preserve beam quality after the shifter and also produces different time delay for different beam energies.

The phase slippage between the proton beams with two kinetic energies passing through two neighboring cavities depends on the RF frequency of the cavity, the distance between the cavities, the first proton beam energy, and the energy jump of the second energy beam. Figure 4 shows the phase slippage as a function of the first proton beam energy in the second section of the linac assuming 1.5 meter, 2 meter and 3 meter separations of the cavities, 650 MHz RF frequency and 375 MeV energy jump after each pass.

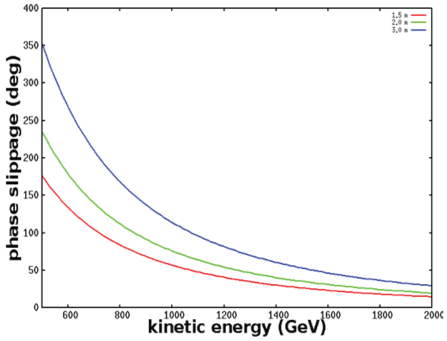

Figure 4: Phase slippage in the second section of the recirculating linac as a function of the first beam proton energy.

It is seen that second energy (higher energy) beam has a large phase slippage at lower first beam energy. A phase shifter with positive R56 can be used to make this phase slippage even larger to reach multiple integer times of 360 degree so that the fixed designed accelerating phase can be attained. This corresponds to make the higher energy particle pass through a shorter distance while the lower energy particle pass through a longer distance. As the first beam energy increases, the phase slippage becomes smaller. Figure 5 shows the phase slippage as a function of the first proton beam energy in the third section of the linac assuming 1.5 meter, 2 meter and 3 meter separations of the cavities, 650 MHz RF frequency and 1 GeV energy jump of the second beam from each pass. The phase slippage becomes much less than the 360 degrees starting with the 2 GeV first beam and becomes even smaller at higher energy. A large positive R56 phase shifter is needed in order to make the phase slippage reach 360 degrees. Instead of using a positive R56, one can also use a negative R56 phase shifter so that the higher energy particle will pass through a longer distance to reach the second cavity for acceleration. Assuming that the phase slippage is dominated by the R56 term, Fig. 6 shows the amplitude of the needed R56 as a function of the first beam energy. It is seen that at 2 GeV, it needs only 10-20 cm R56 to phase shift the high energy beam to the same fixed accelerating design phase. The requirement of the R56 amplitude becomes smaller as beam goes to higher energy.

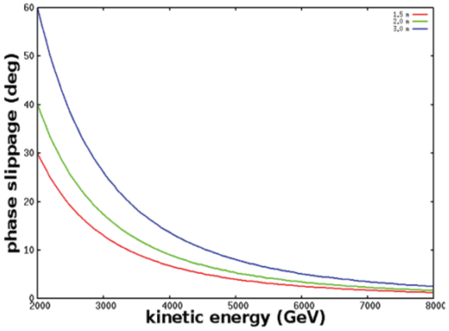

Figure 5: Phase slippage in the third section of the recirculating linac as a function of the first beam proton energy.

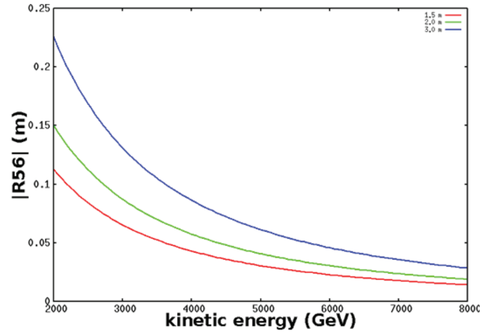

Figure 6: The R56 amplitude in the third section of the linac as a function of the first beam proton energy.

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