A GeV Recirculating Proton Linac

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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 propose using a multi-pass recirculating RF linac to attain a multi-GeV high power proton beam. Besides a front-end injector, this linac consists of three type of RF cavities that accelerate the proton beam multiple times from 150 MeV to final multiple GeV energy. A new energy averaged transit time factor is defined to help choose transition energy between different sections and cavity geometry parameters in the linac design. Using superconducting recirculating linac significantly reduces the number of RF cavities in the accelerator and lowers construction and operational costs of the facility.

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I. 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 important for all high power accelerators in order to avoid the risk of radioactivation 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. Table 1 gives a list of the superconducting cavities used/proposed in some high power GeV proton linear accelerators. It is seen that in those facilities, a few types of superconducting cavities were used for major energy gain. 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. These energy ranges can each be divided into a much smaller energy range 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. In this study, we propose a recirculating proton linac that takes an ini-

TABLE I: Superconducting cavities used/proposed in some GeV H^+/H^- accelerators.

Facility	Cavity type	Freq. (MHz)	β_g	Energy (MeV)
SNS [2]	6 cell-Ellipt.	805	0.61	186-387
	6 cell-Ellipt.	805	0.81	387-1000
ESS [5]	SR	352.2	0.50	90-216
	6 cell-Ellipt.	704.4	0.67	216-571
	5 cell-Ellipt.	704.4	0.86	571-2000
Project-X [11]	HWR	162.5	0.09	2-11
	SSR	325	0.19	11-38
	SSR	325	0.43	38-177
	5 cell-Ellipt.	650	0.61	177-480
	5 cell-Ellipt.	650	0.9	480-3000
	9 cell-Ellipt.	1300	1.0	3000-8000
SPL [13]	5 cell-Ellipt.	704.4	0.65	180-643
	5 cell-Ellipt.	704.4	1.0	643-3500
APT [10]	5 cell-Ellipt.	700	0.64	217-469
	5 cell-Ellipt.	700	0.82	469 -1700
C-ADS [7]	SSR	325	0.21	10-40
	SSR	325	0.40	40-160
	5 cell-Ellipt.	650	0.63	160-360
	5 cell-Ellipt.	650	0.82	360-1500
I-ADS [8]	5 cell-Ellipt.	704.4	0.49	100-192
	5 cell-Ellipt.	704.4	0.62	192-435
	5 cell-Ellipt.	704.4	0.8	435-1014

tial proton beam of 150 MeV from an injector and accelerates the beam to multiple GeV energy using three types of superconducting cavities.

Recirculating electron linac as an efficient accelerator has operated for many years [14, 15]. It provides a cost/performance optimum between the straight linear accelerator and the circular accelerator. It was also proposed in a number of next generation light sources [16–20]. A series of workshops were dedicated to this topic [21]. Besides accelerating electron beam, it was also proposed to accelerate muon beam for neutrino factory application [22]. In hadron accelerators, recirculating induction linac was proposed to accelerate ion beam for heavy fusion application [23]. To the best of our knowledge, up to now, there is no recirculating linac that was proposed to accelerate a proton beam. In an electron linac, a single type of RF cavity is sufficient to accelerate the beam through nearly the entire accelerator since the electron velocity does not change much any more when its kinetic energy is beyond one MeV. In a proton linac, a single type of cavity is not efficient due to the phase slippage between the proton beam and the RF field during the process of acceleration. Multiple types of cavities with different cavity cell lengths are used to match the velocity change of the proton with the RF accelerating field in order to attain a good acceleration efficiency. However, as shown in Table 1 and will also be discussed in the following section, by appropriately choosing RF cavity parameters, a single type of cavity can still cover a broad range of energy for a proton beam and has a good acceleration efficiency.

The organization of the paper is as follows: in Section 2, we will present the layout of the GeV recirculating proton linac and discuss the choice of the transition energy between two sections and cavity parameters to maximize the acceleration efficiency and to minimize the number of cavities; in Section 3, we will discuss potential challenges in such a facility.

II. A GEV SUPERCONDUCTING RECIRCULATING PROTON LINAC

The design of accelerator starts with the choice of accelerating cavity parameters. In an electron linac, a single type of cavity is sufficient to accelerate the beam from a few MeV to multiple GeV, while in a proton linac, a number of types of cavities are needed to accelerate the beam to GeV with a good acceleration efficiency. A good acceleration efficiency is important in order to save the number of RF cavities needed in the accelerator. On the other hand, using too many types of RF cavities will increase the costs of designing and operating those cavities, especially for the superconducting cavities. The final choice of the RF cavity is a balance of acceleration efficiency and the type of cavities.

The acceleration efficiency can be measured by the transit time factor. For a given RF cavity, the energy gain ΔE_c of a charged particle through the cavity can be written as:

$$\Delta E_c = qVT\cos(\phi) \tag{1}$$

where q is the charge of the particle, $V = \int_0^L |E_z(0,z)|dz$ is the voltage across the cavity, E_z is the longitudinal accelerating electric field on axis, T is the transit time factor, ϕ is the design phase with respect to the maximum energy gain. From above equation, we can see that for a given design phase and voltage, in order to gain more energy, the transit time factor should be as large as possible. For a periodic RF cavity with harmonic distribution of electric field along the axis, i.e. $E_z = sin(\omega z/(\beta c))\exp(i\omega t)$, the normalized transit time factor T_0 can be given by [11, 12]:

$$\begin{aligned} T_0(\beta) \;=\; & \frac{2\beta}{\pi n}\Big(\frac{\sin(\pi n(\beta-\beta_G)/(2\beta))}{\beta-\beta_G} - \\ & (-1)^n\frac{\sin(\pi n(\beta+\beta_G)/(2\beta))}{\beta+\beta_G}\Big) \end{aligned} \tag{2}$$

where n is the number of cells in the cavity operating at π-mode, $\beta = v/c$ is the normalized particle velocity, β_G is the geometry parameter that characterizing the synchronization between the particle and the RF field inside the cavity, and $T = \frac{\pi}{4}T_0$. For a π-mode cavity, the cell length in the cavity is $\frac{1}{2}\beta_G\lambda$, where λ is the RF wavelength of the field inside the cavity. The above equation gives a good approximation to the transient factors obtained by numerical integration of actual time dependent electric field for the Project-X cavities, which are the ones proposed to be used in this study. The transit time factor depends on the velocity of the proton inside the RF cavity and the cavity parameters. Figure 1 shows a plot of the transit time factor as a function of the ratio of the particle velocity β to the cavity geometric β_G with different number of cells per cavity. It is seen that as the number of cells per cavity increases, the velocity acceptance (the range of particle velocity to attain a good acceleration efficiency) decreases. A small number of cells per cavity, e.g. $n = 3$, provides a large velocity acceptance. However, for a given energy range, this may require the use of a large number of RF cavities and the increase the system complexity. If the number of cells per cavity is too large, besides the decrease of the velocity acceptance, the fabrication of the cavity also becomes more challenge. As a compromise, in most accelerators listed in Table 1, a five cell ($n = 5$) per cavity structure was used to accelerate the proton beam energy from the 100 MeV level to the GeV level. In this study, we also propose to use such a five-cell superconducting cavity with 650 MHz frequency in the recirculating linac to accelerate the proton beam from 150 MeV to multiple GeV. The 650 MHz superconducting cavity has been extensively studied under the Project-X conceptual design at the Fermilab [11]. It can provide a high accelerating gradient (> 15 MV/m) under continuous wave (CW) operation and has also a large aperture size (~ 100 mm) for beam pass.

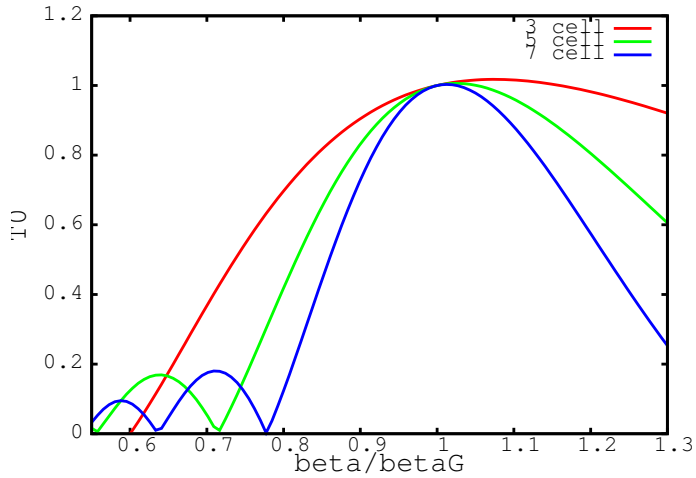

FIG. 1: Normalized transit time factor as a function of the ratio of the particle beta to the geometric beta for different number of cells in a cavity.

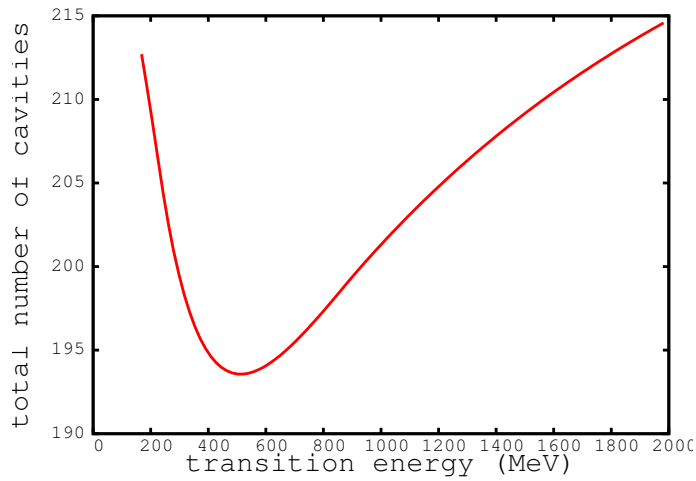

FIG. 3: The total number of RF cavities in two sections as a function of the transition energy between the section one and the section two.

A schematic plot of the GeV recirculating proton linac is shown in Fig. 2. 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 [9]. 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:

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

where ΔE_{max} is the maximum energy gain through a section of cavities, 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

$$\Delta E_{max} \;=\; qVN\bar{T} \qquad (4)$$

where N is proportional to the number of cavities used.

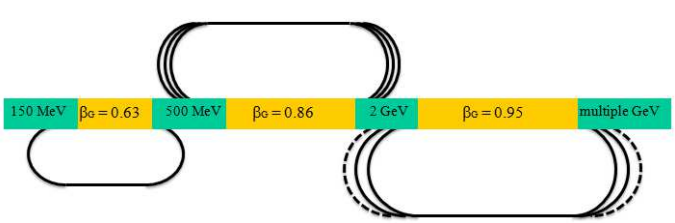

FIG. 2: A schematic plot a GeV recirculating proton linac.

For a given range of the energy, i.e. β_{in} and β_{out}, one needs to maximize the $\bar{T}$ in order to minimize the number of cavities used. For the proposed energy range (150 MeV - 2 GeV) in this study, we will use two accelerator sections, that is

$$\Delta E_{1,2max} \;=\; qV_1N_1\bar{T}_1 + qV_2N_2\bar{T}_2 \qquad (5)$$

where V_1 and V_2 are the accelerating voltage per cavity in each section, N_1 and N_2 are the number of cavities in each section, and $\bar{T}_1$ and $\bar{T}_2$ are the average transit time factor in each section. In order to minimize the total number of cavities of the two sections, we would like to minimize the $N_1 + N_2$ with respect to the transition energy, the β_{G1}, and the β_{G2} subject to above energy constraint Eq. 5. Figure 3 shows the total number of RF cavities in these two sections as a function of transition energy between the section one and the section two. Here, we assume that the average accelerating voltage per cavity is 13 MV and $V_1 = V_2$. It is seen that a transition energy at 500 MeV will result in a minimum total number of cavities. This transition energy is consistent with some proposed transition energies listed in Table 1. Figure 4 shows the average transit time factor as a function of geometric β_G in the section one and the section two. The maximum normalized average transit time factor in section one is about 0.89 with a geometric $\beta_{G1} = 0.63$, and 0.97 with a geometric $\beta_{G2} = 0.86$ in section two. In the third section, beyond 2 GeV energy, the change of proton velocity is small. We found that a 5-cell cavity with a geometric $\beta_{G3} = 0.95$ has close to 1 normalized average transit time factor for a wide range of final energy ($4-8$ GeV).

The first section of linac accelerates the proton beam from 150 MeV to 500 MeV. In a single pass linac, it requires more than 39 cavities (assuming 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 passes

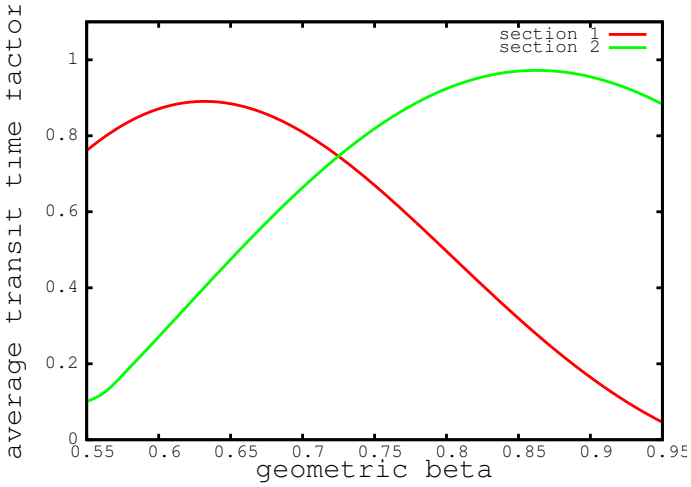

FIG. 4: The average transit time factor as a function of geometric beta in the section one and the section two of the proposed accelerator.

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 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 need to 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 the 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.

III. DISCUSSIONS

The recirculating linac is a combination of the circular accelerator and the linear accelerator. It has some advantages of the circular accelerator by passing a beam through the same RF cavity multiple times to attain large energy gain. This saves a large number of RF cavities needed in a single pass linear accelerator and the corresponding construction and operational costs. Meanwhile, due to lacking of closed orbit of the circular accelerator, the recirculating linac can avoid some nonlinear resonances in the circular accelerator. This helps accelerate high intensity beam to high energy while preserving the beam quality. The arc in the recirculating linac also provides a natural location for beam halo collimation.

The recirculating linac has a more complex accelerator architecture compared with the straight linear accelerator. It consists of not only a straight accelerating section but also arcs, merging, exiting, and straight transport systems. The same straight beam line will transport a beam with different energies. Proper design of the focusing lattice is needed to avoid significant beam mismatch in the accelerator. More advanced diagnostic system is also needed for this accelerator [24]. The proton beam traverses a longer path in the recirculating linac than that in the linear accelerator. The preservation of the beam quality to avoid transverse emittance growth and beam losses for high intensity beam with strong space-charge effects become more challenge. In the transport sections without accelerating cavity, the proton beam may be subject to debunching and the increase of energy spread due to longitudinal space-charge effects. This could be compensated with an RF bunching cavity in the straight transport section. The transverse beam break-up instability might also be an issue in the recirculating linac. However, with the proper design of RF cavity, such an instability can be avoided.

Electron recirculating linacs have been under successful operation for many years. A lot of experience in the electron recirculating linac can be reused in the proton recirculating linac. One main difference between these two linacs is that the proton beam has little coherent and incoherent synchrotron radiation through a bending magnet, which is beneficial to the preservation of beam quality. On the other hand, the space-charge effects are stronger in the proton beam than those in the electron beam with the same energy and the peak current. Special attention is needed to control those effects on proton beam quality.

In summary, in this paper, a concept of recirculating proton linac is proposed to accelerate a proton beam from 150 MeV to multiple GeV energy in three sections. A new method to determine the cavity parameter and transition energy between two sections is presented in the linac design. Some advantages of the recirculating linac and potential challenges are also discussed. In the future study, we will carry out detailed beam dynamics simulation to test this concept. The three recirculat-

ing transport systems proposed here do not necessarily represent an optimal design. Depending on the specific application, the complexity and the beam dynamics requirements of building those transport systems, fewer recirculating racetrack systems are possible. Furthermore, accelerating cavities can be installed in the straight section of the racetrack transport system if needed.

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