A RECIRCULATING PROTON LINAC DESIGN*

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Abstract

The acceleration efficiency of the recirculating RF linear accelerator was demonstrated by operating electron machines. The acceleration concept of recirculating proton beam was recently proposed and is currently under study. In this paper, we present a 6D lattice design and beam dynamics tracking for a two-pass recirculating proton linac from 150 MeV to 500 MeV, which is the first section of the three acceleration steps proposed earlier [1]. Issues covered are optimization of simultaneous focusing of two beams passing the same structure and achromatic condition under space-charge potential.

INTRODUCTION

The recirculating electron beam of superconducting linear accelerator (LINAC) is proven to be efficient due to high construction/operation cost of the superconducting RF cavities [2, 3]. The synchronization of the multi-pass RF phases is less important factor for the relativistic electron beam due to nearly frozen longitudinal velocity. The proton beam, on the other hand, experiences relatively large velocity change through the accelerating structure, and requires strong restriction on RF phase synchronization for multiple passes. Especially, when the beam passes LINAC only twice, Ref. [1] showed that such a synchronization can be achieved by proper choice of the separation length between the cavities. It can be understood by the following condition.

$$L(1/v_1 - 1/v_2) = n T_{RF} \tag{1}$$

where v_1 and v_2 are the longitudinal beam velocities of the 1st and 2nd passes respectively, T_{RF} is the RF time period, n is an integer number, and L is the separation length. Note that the separation length becomes larger and larger as the beam is accelerated. Such a non-periodic structure may alleviate the beam halo formation but makes the design of the focussing channel difficult.

Table 1: Parameters

Item	Value	Description
Bunch Current	20 mA	Averaged over RF period
Transverse emittance	0.23 mm-mrad	Normalized
Longitudinal emittance	3.2 deg-MeV	Normalized
SCRF Freq.	650 MHz	5 Cell

* 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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Another important issue of the recirculating proton LINAC is the relatively strong space-charge. Especially, the achromatic condition of the splitter and merger system can be easily violated by the space-charge induced dispersion [4].

The purpose of this paper is to assert the feasibility of the multi-pass scheme for efficient proton beams acceleration. We address the above two issues by a conceptual (but rigorous in terms of particle dynamics with full 3D space-charge simulation) design of double-pass recirculating LINAC. We adopt the input parameters similar to Project-X as shown in Table 1. The layout of the double pass recirculating LINAC is shown in Fig 1.

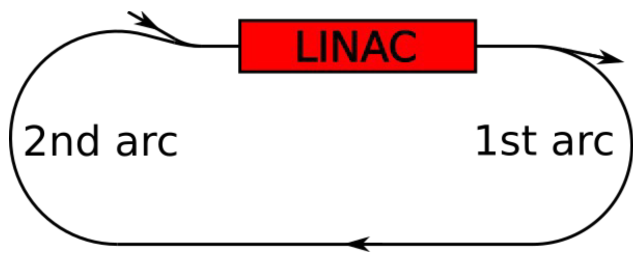

Figure 1: Layout.

LINAC

The LINAC consists of 17 superconducting RF cavities and the separation length between the cavities are chosen according to Eq. (1). The energy gains for each cavity are shown in Fig. 2 where the cavity number i and 17+i are pointing physically the same cavities. Passing the same structure twice, the beam is accelerated from 150 MeV to 500 MeV. All the RF phases, except the 2nd and the 4th cavities, are synchronized to -30 degree. Further phase optimization can make the energy gain even more efficient.

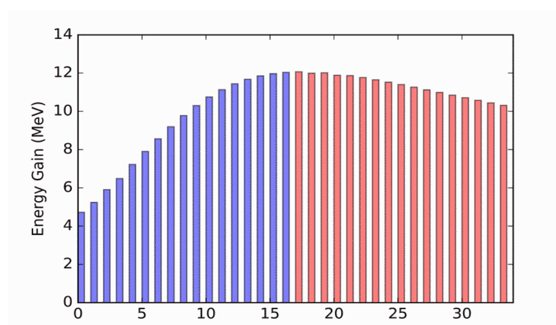

Figure 2: Energy gain of each cavities.

Focusing Channel

Figure 3 shows the separation length between cavities in regard of Eq. (1). In order to overcome the space-charge and RF defocusing and lack of the space for quadrupoles,we synchronize the RF phases of the 2nd

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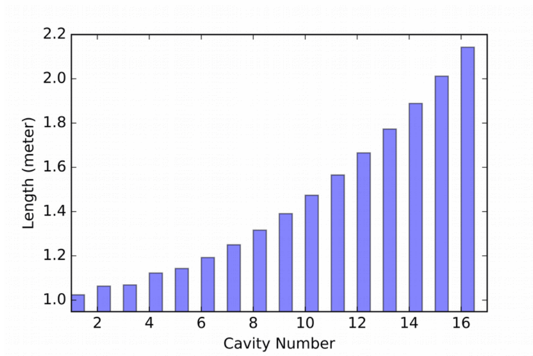

Figure 3: Separation length from the i-th cavity entrance to the next cavity entrance.

and the 4th cavities to +30 degree. Usual design procedure of periodic LINAC structure is to find the periodic solution of a proper phase advance of the first cell, then optimize the quadrupole strengths near the periodic solution for the rest of cells. Such a procedure can make the design of the focussing channel simple.

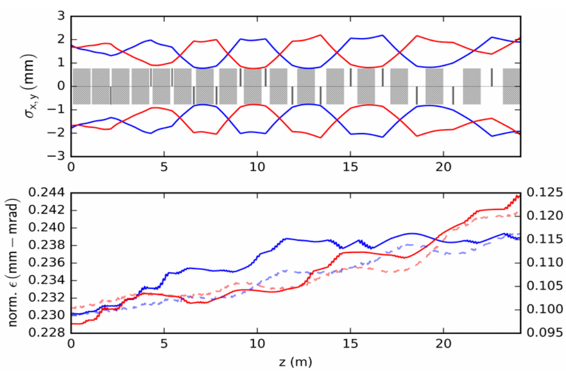

Figure 4: 1st pass LINAC with 6D waterbag distribution. RF cavities are represented by shadowed boxes, and the F/D quadrupoles are represented by up/down rods. The blue/red curves are horizontal/vertical. The dashed curve represent $1-\epsilon_{95}/\epsilon$ where ϵ_{95} is the emittance of the 95% inner most particles of Courant-Snyder circle.

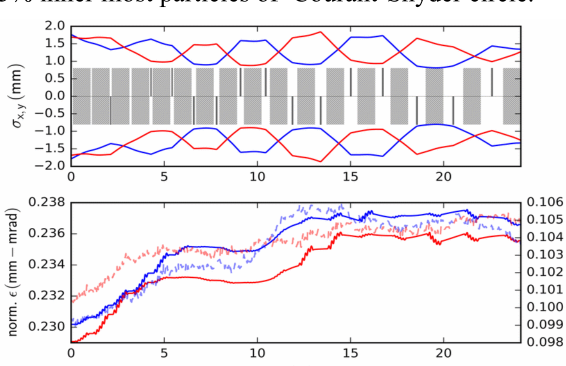

Figure 5: 2nd pass LINAC with 6D waterbag distribution.

However, periodic structure may not be the best solution. Especially, a non-periodic structure may alleviate beam halo formation. In case of phase synchronized double-pass LINAC, the length of each cell increases non-linearly. Therefore, we use numerical optimization for the focussing channel design.

The number of optimization knobs we used are total 22 including the initial optics functions for the 1st and the 2nd pass of the beam and the the strength of the quadrupoles installed between each cavities except after the 1st and the 3rd cavities. We used IMPACT [5] for 3D space-charge tracking, and differential evolution algorithm [6] for global optimization. The cost function is weighted mainly for smooth beam envelope and emittance near the exit of the LINAC. The 6D waterbag initial distribution was used during the optimization so that the resulting focusing channel is general and insensitive to tail distribution of the beam which, usually, is not predictable [7]. Figure 4 shows the resulting rms beam envelope of the 1st pass on top of optimized focusing channel. Figure 5 is the 2nd pass through the same structure. Interestingly, the optimized focusing channel is a FFDD lattice which makes the lattice looks periodic with each cell containing 4 cavities.

However, the periodic solutions of optics for each cells are not matched to each other as it is resulted from purely numerical optimization from scratch. Some of the cells does not even have periodic optics solution. Nevertheless, since every cells are different and initial optics is optimized to a mismatched one, the beam is stable throughout the structure as well as the initial optics is well matched to the optimized one. In addition, optimizing the emittance can make the apochromatic condition [8] to be satisfied as much as possible. Figures 6,7 present the simulation of 6D Gaussian initial distribution on the same structure for a comparison. The dashed line corresponds to the normalized rms emittance of 95% particles innermost of the Courant-Snyder circle. The growth of the ratio between the 95% and 100% rms emittance can be interpreted as an indication of the beam halo formation.

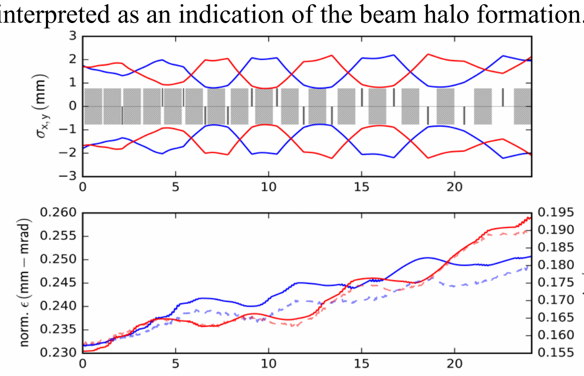

Figure 6: 1nd pass LINAC with 6D gaussian distribution.

ARC

Another expected concern of the recirculating proton LINAC is the achromatic condition under the space-charge influence. In addition to the zero-current achromatic condition, the following conditions can be used to reduce the space-charge induced dispersion [4]

$$\int_{-L/2}^{L/2} \frac{M_{12}(s)}{\rho(s)} s\, ds = 0 \qquad (2)$$
$$\int_{-L/2}^{L/2} \frac{M_{11}(s)}{\rho(s)} s\, ds = 0$$

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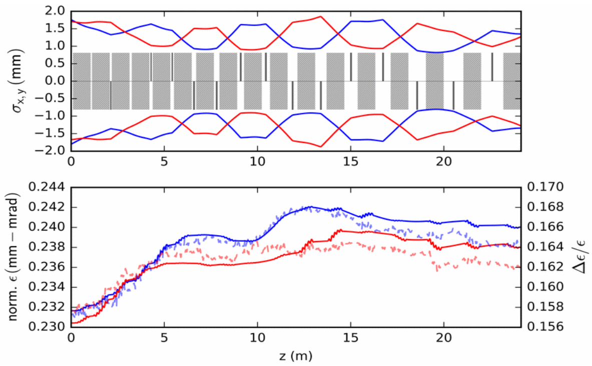

Figure 7: 2nd pass LINAC with 6D gaussian distribution.

where L is the length of the arc, ρ is the bending radius and M_{ij} is the transport matrix map. Depending on lattice geometry, the solution may not exist. Instead, we find a numerical solution which satisfy Eq. (2) as much as possible. Figures 8,9 shows the numerically optimized arcs and the transverse beam envelope with 6D waterbag initial distribution. At both arcs, little horizontal emittance growth is observed with 20mA bunch current.

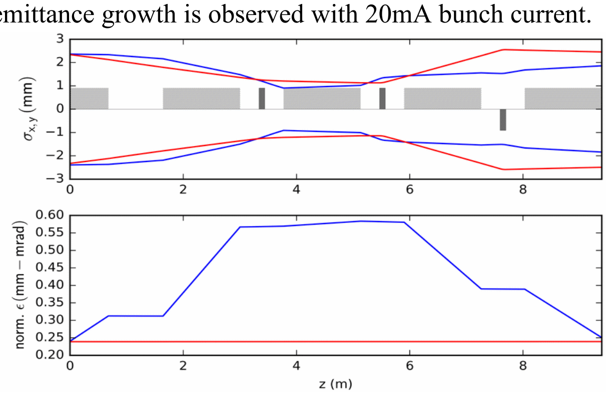

Figure 8: Transverse beam at the 1st arc. Bending magnets are represented by shaded boxes.

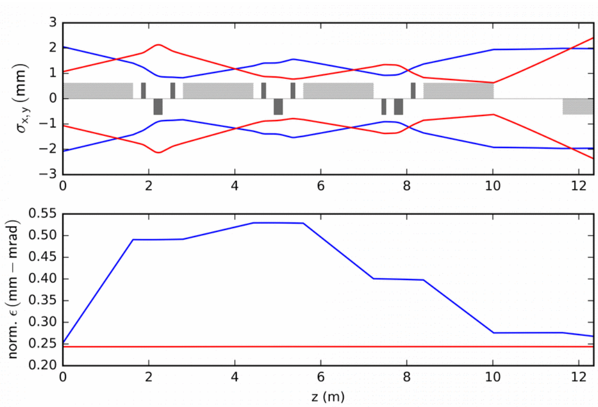

Figure 9: Transverse beam at the 2nd arc. The downward shaded box represent negative angle bending magnet.

Finally, Figure 10 shows 6D space-charge tracking from the 1st pass LINAC entrance to 2nd pass LINAC exit after additional end to end optimization of quadrupole strengths. The normalized emittance growth the entire structure was 13%, 6.5% and 10% for horizontal, vertical and longitudinal motion respectively. It is worth point out that the RF phases are synchronized but not optimized to produce smooth longitudinal envelope. It can be further optimized for better beam quality for higher current.

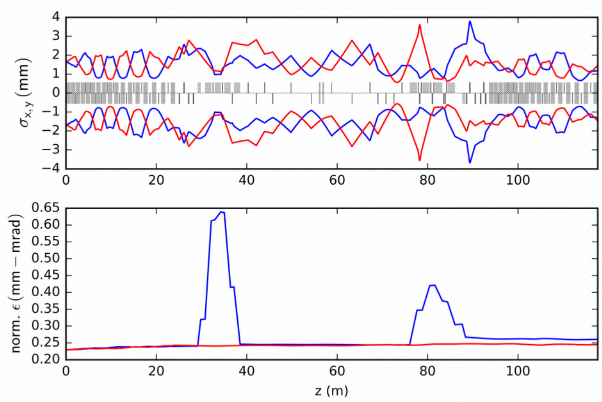

Figure 10: Transverse beam envelope from the 1st pass LINAC entrance to 2nd pass LINAC exit.

CONCLUSION

We have presented a conceptual design of non-periodic focusing channel for double-pass LINAC channel and achromatic arcs under space-charge influence. 6D space-charge tracking with IMPACT on the conceptual design proves the feasibility of the recirculating proton LINAC.

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