SPACE CHARGE EFFECTS OF CATCH-UP COLLISION IN A CW DOUBLE-PASS PROTON LINAC*

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Abstract

Recirculating superconducting proton linac has an advantage to reduce the number of cavities and the resulting accelerator construction/operation costs. Beam dynamics simulations were done recently in a double pass recirculating proton linac using a single bunch. For continuous wave (CW) operation, the high energy proton beam bunch during the second pass will catch up and collide with the low energy beam bunch during the first pass at a number of locations inside the superconducting linac. In this paper, we report on the study of the space-charge effects during a collision on both beams through the rest of linac.

INTRODUCTION

The existing recirculating superconducting electron linac has been stably operated for many years, which proves that recirculating linac is an effective way to reduce the number of cavities and to save the operation cost [1, 2]. The concept of a recirculating proton linac that accelerates proton beams from 150 MeV to 8 GeV using three sections of recirculating superconducting linac was recently proposed in Ref. [3]. In the first section, the initial beam is accelerated to 500 MeV by passing through the linac twice. The start-to-end beam dynamics simulation of this section had been carried out in Ref. [4].

A schematic plot of the double-pass superconducting proton section is shown in Fig. 1. It consists of a section of superconducting linac, two arcs and a beam transport line which has 4 bunching cavities to keep the beam longitudinally bunched. During the second pass, the high energy proton beam bunch catches up the low energy proton beam during the first pass at several locations. Thus, the Coulomb force comes not only from the particles in the bunch itself, but also from the other bunch. The purpose of this paper is to investigate the space charge effects during collisions on both beams and the rest of linac using the particle-in-cell code IMPACT [5].

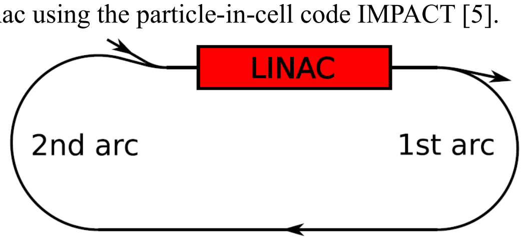

Figure 1: A layout of the double-pass proton linac [4].

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THE FOUNDATION OF PHYSICS

During the catch-up collision interaction, defocusing electric forces and focusing magnetic forces play an important role for the particle motion. The attractive magnetic forces, which depend on the velocities, tend to compensate the defocusing from electric forces. For example, when the particles of the low energy bunch are in the RF fields, the radial Lorentz force is given by:

$$F_r = q(E_r - \beta_L c B_\theta)\,. \tag{1}$$

where q is the charge of the particle, E_r and B_θ are the electric and magnetic field from the high energy bunch at the collision interaction time, c is the speed of the light in vacuum, β_L is the velocity of the low energy bunch. The relationship between a radial component E_r and an azimuthal component B_θ is expressed as

$$B_\theta(r) = \frac{\beta_H}{c} E_r(r)\,. \tag{2}$$

where β_H is the high bunch velocity. Combining Eqs. (1) and (2), the effects of the catch-up collision can be obtained by the following equation

$$F_r = qE_r(1-\beta_L\beta_H)\,. \tag{3}$$

The electric fields for a three-dimensional uniform ellipsoid to describe a typical linac bunch are given by [6]

$$E_{sx} = \frac{3I\lambda(1-f)}{4\pi\varepsilon_0 c(r_x+r_y)r_z}\frac{x}{r_x}\,. \tag{4}$$

$$E_{sy} = \frac{3I\lambda(1-f)}{4\pi\varepsilon_0 c(r_x+r_y)r_z}\frac{y}{r_y}\,. \tag{5}$$

$$E_{sz} = \frac{3I\lambda f}{4\pi\varepsilon_0 c r_x r_y}\frac{z}{r_z}\,. \tag{6}$$

The r_x, r_y and r_z are the semi-axes of the ellipsoid which are related to the root mean square (RMS) beam sizes a_i by $r_i = \sqrt{5}a_i (i=x,y,z)$, f is an ellipsoid form factor and equals $1/3p$ which $p = \gamma r_z / \sqrt{r_x r_y}$ if 0.8 $<p<$ 5.

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Assume that E_{si} is a constant, the momentum change from the integral of F_r within the interaction time can be given by $\Delta P = F_r \cdot t$.

The ratio of the momentum change between the catch-up collision effects and the space charge effects within the bunch itself depends on the RMS beam size and the interaction time. The average RMS beam sizes of the low and high energy bunch at different interaction time are shown in Table 1. Comparing results in the same direction but different interaction results, the difference of the two bunch Lorentz force F_r is similar as the RMS beam sizes difference is small. It suggests that the interaction time should be the main contribution to the momentum change. Simulation results show that the interaction time from the catch-up collision is 7e-11 seconds, while in the fourth cavity total interaction time is 4.915e-9 seconds. The low energy bunch momentum change ratios due to the catch-up collision to the space-charge effect in x, y and z directions are 0.0182, 0.0240 and 0.0101. Following the same procedure, the corresponding values of the high energy bunch are 0.0120, 0.0179 and 0.0226, respectively. The catch-up collision effects are less than the space charge effects from the bunch itself.

Table 1: Average RMS Beam Sizes at Different Interaction Time

Time		Low Bunch (e-2 m)	High Bunch (e-2 m)
Collision	X	0.22481	0.17328
	Y	0.15014	0.13126
	Z	0.12042	0.19008
Total	X	0.22565	0.17442
	Y	0.14836	0.13063
	Z	0.12239	0.19047

SIMULATION RESULTS

The double-pass recirculating superconducting proton linac optimization results in a focusing-focusing-defocusing-defocusing (FFDD) lattice, with each cell of this lattice containing four cavities [4]. There are five catch-up collision locations and the linac includes 17 650 MHz 5-cells superconducting elliptical cavities. The first collision occurs inside the drift, and the rest four collisions are different from the first one and are inside the RF cavities, such as the fourth cavity, the eighth cavity and so on. Taking the second collision which collides inside the fourth cavity as an example, we will show the simulation results during the catch-up collision and the rest of linac.

Catch-up Collision Simulation

The parameters of the two Gaussian bunches at the entrance of the fourth cavity are shown in the Table 2. In order to investigate the catch-up collision effects, single bunch simulation of the low and of the high energy bunch, which shows the space charge effects from bunch itself, has been conducted to compare with two bunch catch-up collision results. Touse the IMPACT-T code to simulate two bunches together (combined bunch simulation), the rf phase of the two bunches should be the same [7]. It is important to simulate single low energy bunch through a short distance and get a new combined low energy bunch distribution so that the low bunch's rf phase added 291 times 2π is same as the high's rf phase in the combined beam. The low energy bunch velocity in this simulation is assumed to be a constant due to the short length at the beginning of cavity. For combined bunch simulation, the total simulation time for two bunches is same, so low bunch still inside the cavity when the high bunch is outside of the cavity as IMPACT-T code stopped when the central of the combined bunch arrives at the end of cavity. Then, there is another short distance for the low bunch simulation to make the combined low energy bunch arrive at the end of the cavity.

Table 2: The Parameters of Low and High Bunches

	Low Bunch	High Bunch
Energy	165.86 MeV	341.36 MeV
Phase	85.90 Radian	1916.94 Radian

The two bunch catch-up process in the combined beam simulation is shown in Fig. 2. At the beginning, two bunches have same phases but at different locations. After a while, near the location of 0.45 meters, high energy bunch catches up the low energy bunch and overtakes it. The simulation results of RMS beam size and emittance of the single and combined low and high bunch in transverse and longitudinal direction are shown in Figs. 3 and 4. Comparing the single and combined results, the relative difference of the RMS beam size and emittance growth are less than 1% which is in agreement with the analytical estimation.

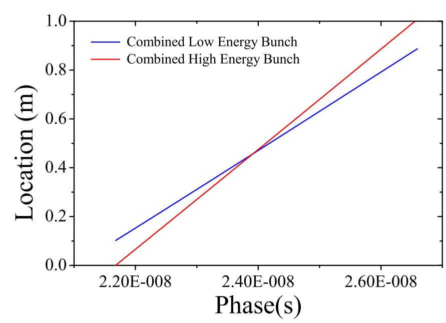

Figure 2: The catch-up process of combined bunches.

The Rest of Linac Simulation

The single and combined low and high energy bunches at the end of the fourth cavity need to be converted into the IMPACT-Z code distribution and to simulate through the rest of linac lattice. The simulation results are shown in Figs. 5 and 6. The ratios of the RMS beam size and emittance growth with catch-up collision to those without collision through the rest of linac simulation are also less than 1%.

CONCLUSION

The impact of space charge effects due to catch-up collision on beam quality in the CW double-pass re-circulating superconducting proton linac was studied. With an initial Gaussian distribution, we simulated single

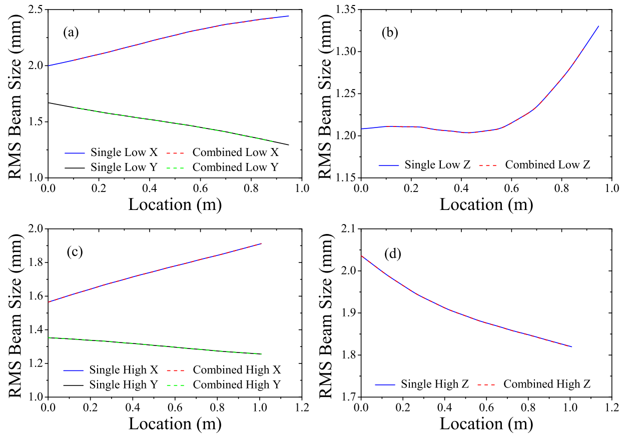

Figure 3: Single and combined low and high bunches RMS beam size of catch-up collision simulation results. (a) and (b) are low energy bunch results in transverse and longitudinal; (c) and (d) are high energy bunch's results.

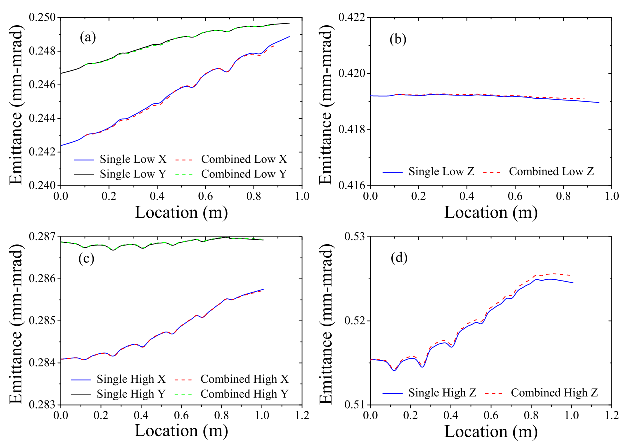

Figure 4: Single and combined low and high bunches emittance of catch-up collision simulation results. (a) and (b) are low energy bunch compared results in transversal and longitudinal; (c) and (d) are high energy bunch's.

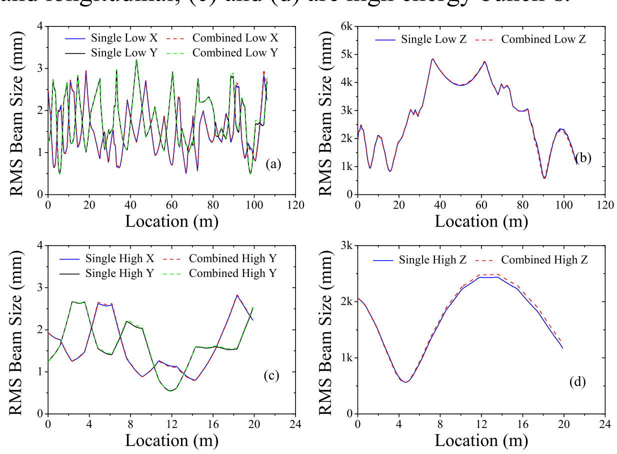

Figure 5: The RMS beam size results in rest of linac simulation. (a) and (b) are compared low energy bunch results in transversal and longitudinal; (c) and (d) are compared high energy bunch's.

bunch and combined two bunches including catch-up effects using the IMPACT-T and -Z code through the rest of linac. The simulation results clearly show no particle losses during the collision and through the rest of linac. The relative differences of the RMS beam sizes and emittance growth between the separate single bunch results and the combined two bunch results are less than 1%, which is in consistent with the analytical estimation from the foundation of physics theory.

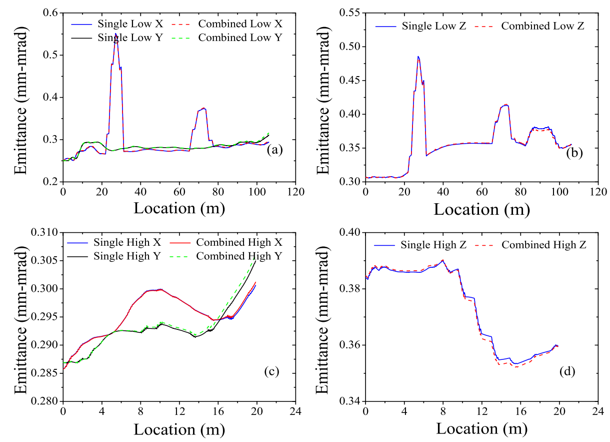

Figure 6: The emittance results in rest of linac simulation. (a) and (b) are compared low energy bunch results in transversal and longitudinal; (c) and (d) are compared high energy bunch's.

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