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ERRORS STUDY OF A DOUBLE-PASS RECIRCULATING SUPERCONDUCTING PROTON LINAC*

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Abstract

The concept of recirculating superconducting proton linac was recently proposed. Beam dynamics simulations were carried out in a double-pass recirculating proton linac using a single bunch. Although all the beam line elements should be installed following the designed values, in reality, there exist machine imperfections that will cause beam off-centering and even particle losses. In this paper, we report on the study of the static and dynamic errors from RF cavities and magnetic focusing elements in the double-pass recirculating proton linac.

INTRODUCTION

The concept of the three-section recirculating superconducting proton linac that accelerates proton beams from 150 MeV to 8 GeV was recently proposed in Ref. [1]. This linac has potential to reduce the total number of superconducting cavities by a factor 5 and save the construction and operational costs of the accelerator facility. The first section of the proposed linac shown in Fig. 1 consists of a superconducting linac, two arcs and a straight beam transport line. The proton beam is accelerated from 150 MeV to 500 MeV by passing through 17 5-cells 650 MHz superconducting cavities two times. The start-to-end beam dynamics design and single bunch simulations of the double-pass linac were carried out in Ref. [2]. And the impact of space-charge effects during the CW multi-bunch overtaking collision of the first section was studied in Ref. [3].

The reference design of the linac assumes perfect elements from the requirements. It is necessary to verify the robustness of this design under realistic imperfect conditions. The errors from alignment, RF jitters and variations give rise to beam off-centering, which may lead to direct beam loss or significant emittance growth. The beam off-centering from most of static errors can be corrected by a proper correction scheme that employs a number of correction magnets together with some beam position monitors (BPM). However, the dynamic field and alignment errors will result in emittance growth or halo formation. Here we present the static and dynamic errors from RF cavities and magnetic focusing elements in the double-pass linac. In this study, we consider three important factors: beam-loss power, root mean square (RMS) of beam size and emittance growth in the linac design.

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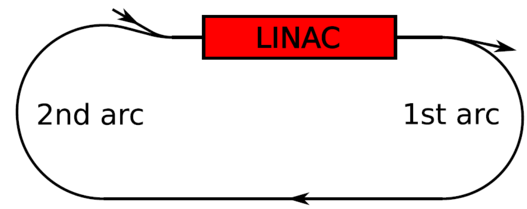

Figure 1: A layout of the double-pass proton linac [2].

ERROR DEFINITION

To evaluate the beam losses arising from the beam transport in a real linac, two families of errors are considered.

- Static errors: can be detected and cured with appropriate diagnostics and correctors. A correction scheme is established to correct these errors.

- Dynamic errors: the time dependent jittering. The amplitudes of this defect are set to one order of magnitude lower than the static errors. The effect of uncorrected errors is simulated by adding them after the correction of the static errors.

The dynamic errors used in the superconducting linac will be different during the double passes. For both static and dynamic errors, a uniform distribution is chosen with estimated maximum error amplitudes of ± A. The RMS value is given by $A/\sqrt{3}$ [4]. The amplitudes of the cavity and the quadrupole errors in the error studies are presented on the Table 1 and 2 [4-6].

Table 1: Amplitudes of the Cavity Errors used for the Error Studies

Cavity	Static	Dynamic
Gradient [%]	± 1	± 0.5
Phase [deg]	± 1	± 0.5
Displacement (x,y) [mm]	± 0.5	± 0.01
Rotation (x,y) [mrad]	± 2	± 0.02

Table 2: Amplitudes of the Quadrupole Errors used for the Error Studies

Quadrupole	Static	Dynamic
Gradient [%]	± 0.5	± 0.05
Displacement (x,y) [mm]	± 0.1	± 0.002
Rotation (x,y,z) [mrad]	± 2	± 0.02

CORRECTION SCHEME

A correction scheme was used to correct the misalignments and filed errors of the focusing elements and the

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superconducting cavities in the simulation. According to the lattice design, nine pairs of BPM and corrector are attached to quadrupoles in the straight beam transport line of the double-pass linac and are responsible for the orbit correction.

ERROR STUDY

The error studies with corrections were performed by using the 3D particle-in-cell (PIC) code IMPACT-Z [7]. In the simulation, we used 100,000 macro particles and 64 x 64 x 64 numerical grid points. The aperture diameter sizes of elements are 8.3 cm, which is the same with Project X's [8]. The inevitable installation errors include translational errors, rotation errors, and field errors. All errors are randomly generated and uniformly distributed between the negative and positive maximum values.

A set of 1000 linacs was simulated with all the errors and corrections in the following steps. Firstly, we generate the random errors and add them to the reference design lattice. For the same location cavity or quadrupole of each linacs, the static errors for the first and for the second pass are set as the same random error at the first step. While the dynamic errors are different. The second step is to run the linacs. To make sure the lattice with errors work well under the reference design, we calculate the delta energy gain from the field error and minus it at the end of the first pass. The last step is to turn on the correction scheme and run with correction scheme linacs. Assume that the difference of the BPM and corrector location are negligible. Also, the difference of the corrector location between inside and at the end of the quadrupole is neglected. The BPMs and correctors are listed at the end of the quadrupoles in our error study simulations. The value of corrector was calculated by the centroid location length combined with the random BPM error. The amplitude of the random BPM error was chosen to be 0.02 mm based on the measurement accuracy.

Figure 2-7 present the RMS emittance and RMS beam size evolution with errors and correctors in the transverse and longitudinal directions. Also, we compared the reference results with the 1000 seeds average results at the end of the linac (Table 3).

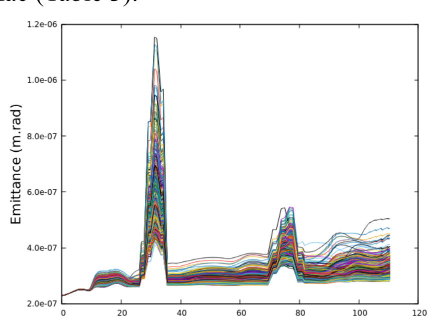

Figure 2: The X direction emittance results in the errors and correction scheme study.

The results show that the horizontal and longitudinal RMS emittance growths are 6.67 %, 10 % and 2.78 %, respectively, with errors and correctors for the basic design. And the RMS beam size growths are 10.14 %, 6.45 % and 7.5 %. All particle losses occur during the second pass between the 16th and 17th cavities. The total losses at different positions are shown in Fig. 8. The average lost beam powers along the double-pass linac are given in Fig. 9. The average particles loss is 3.4e-5 % and the maximum average loss power is about 1.76 W at the entrance of quadrupole.

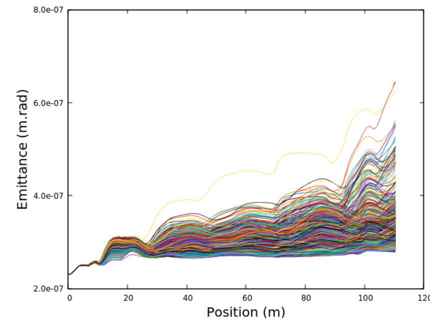

Figure 3: The Y direction emittance results in the errors and correction scheme study.

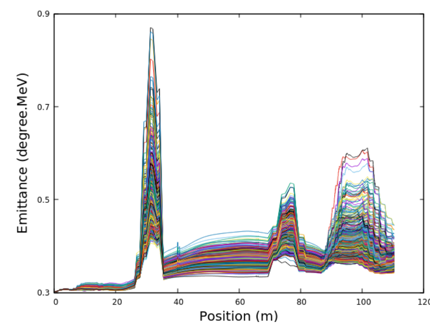

Figure 4: The Z direction emittance results in the errors and correction scheme study.

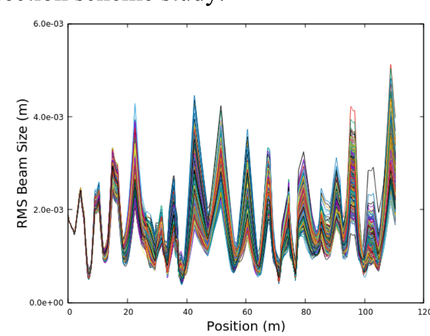

Figure 5: The X direction rms beam size results in the errors and correction scheme study.

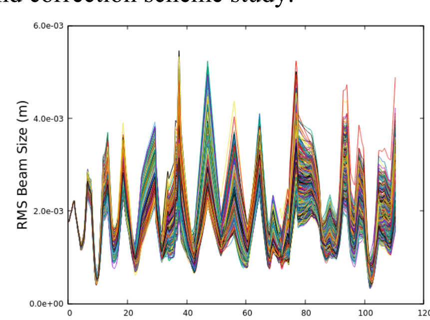

Figure 6: The Y direction rms beam size results in the errors and correction scheme study.

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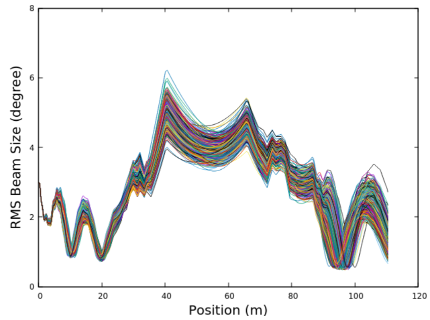

Figure 7: The Z direction rms beam size results in the errors and correction scheme study.

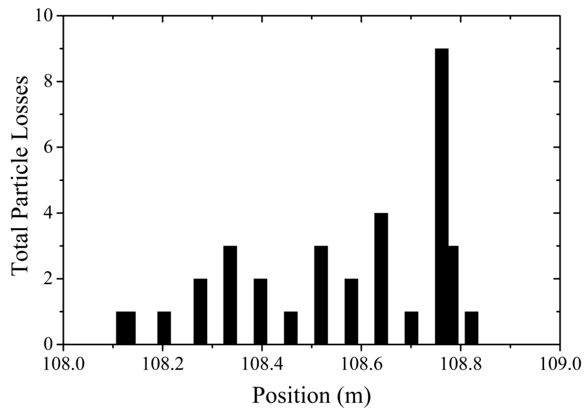

Figure 8: The total particle losses during 1000 linacs shown in different position.

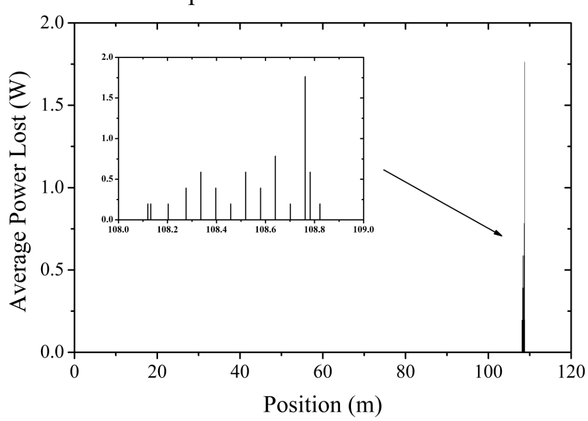

Figure 9: The average loss power along the linac and zoom in plot around the particle loss region.

Table 3: The Reference Linac Results and 1000 Linacs Average Results Show at the End of the Linac

		Reference Linac	1000 Linaces (average)
Emittance	X	0.30	0.32
(mm.mrad)	Y	0.30	0.33
(degree.MeV)	Z	0.36	0.37
RMS Size	X	2.17	2.39
(mm)	Y	2.48	2.64
(degree)	Z	1.20	1.29
Max Size	X	1.94	1.99
(cm)	Y	1.03	1.07
(degree)	Z	4.18	6.46

CONCLUSION

The error study with a correction scheme for the double-pass recirculating superconducting proton linac was carried out. The average particle losses are 3.4 x 10^{-7}, which verifies the robustness of the design. The beam quality is good because the emittance growth for all the errors with correctors is less than 10 %.

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