ERROR ANALYSIS OF THE PEFP 100 MEV LINAC*

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Abstract

The 100 MeV Linac of the Proton Engineering Frontier Project (PEFP) consists of an ion source, a low energy beam transport (LEBT), a 3 MeV radio frequency quadrupole (RFQ), and an 100 MeV drift tube linac (DTL). The DTL is separated into two parts. The first part includes 4 tanks which accelerate 20 mA proton beams up to 20 MeV. The medium energy beam transport (MEBT) follows the 20 MeV accelerator in order to match the proton beams into the next linac as well as to extract and supply 20 MeV proton beams to the user facilities. The second part of the DTL consists of 7 tanks to accelerate proton beams to 100 MeV. This work focuses on an error analysis of the designed 100 MeV linac in order to study the steering magnets which control the beam fluctuations and reduce the potential beam loss.

INTRODUCTION

The quadrupole magnets in a DTL are essential elements for a beam control in the transverse directions. However it's impossible to perfectly manufacture and install the magnets in the linac. Two main source of the errors are a displacement and rotation of the magnets. The displacement errors generate a betatron oscillation of a beam centre in the lattice structure of the linac. An oscillation is a source of an emittance growth and then the beam quality becomes worse. The particles can be lost if the oscillation amplitude becomes larger. The rotation errors should couple the horizontal and vertical beam properties.

The lattice structure of the PEFP DTL is FFDD where there is no empty drift tube for diagnostics or a beam steering[1]. Because the inter-tank distances of the low energy part (3 ~ 20 MeV) of the linac are too short to install steering magnets, we studied the steering effects under the condition that the magnets will be installed between the DTL tanks in the high energy part (20 ~ 100 MeV) of the PEFP linac system. The schematic plot of the PEFP linac is given in Figure 1.

We also evaluated beam steering methods by using an error calculation code[2] which treats errors as a first order perturbation [3]. Then we determined the specifications of the steering magnets in order to control the beam fluctuations which are generated by the displacement and rotation errors.

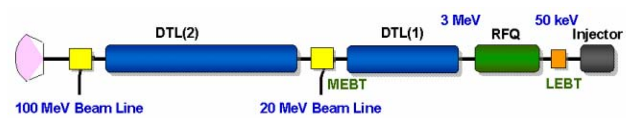

Figure 1: PEFP Linac system.

BEAM STEERING METHOD

We can control the beam oscillation by using steering magnets which are small dipole magnets. These magnets have two roles. One is shifting a beam's center to the accelerator axis at a specific point. The other is changing the divergence of the trajectory of the beam center to be zero at the same point. These purposes can be achieved by four steering magnets, two for the horizontal direction and the others for the vertical direction. The information on the beam trajectories can be obtained by two beam-position monitors (BPMs) in both transverse directions.

In order to determine the positions of the steering magnets, we calculated the zero current phase advance between the DTL tanks. We used $\mu_{12} = \sin^{-1}(m_{12}/\sqrt{\beta_1\beta_2})$ where μ_{12} and m_{12} represent the phase advance and transfer matrix element between two points, respectively. The parameters, β_1 and β_2, are the values of the beta function at those points. The results are summarized in Table 1. If the phase advance is much smaller or larger than 90 degrees, the magnitude of the magnetic field becomes larger for the same beam steering effects. Based on these results, we choose two steering sets where each set consists of four dipole magnets and two BPMs. The schematic plot of the steering scheme of the PEFP linac is given in Figure 2.

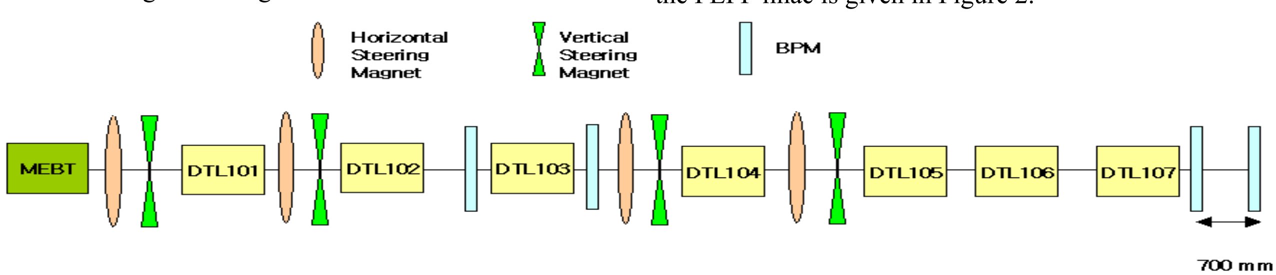

Figure 2: Beam steering in the PEFP linac.

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Table 1: Phase advance between two points before and after DTL tanks.

DTL	Phase Advnace (degree)
DTL101	-55.0
DTL102	21.4
DTL103	69.8
DTL104	60.1
DTL105	38.3
DTL106	1.3
DTL107	-11.1

Steering algorithm

We evaluated a steering algorithm for two cases by comparing beam centres before and after a turning of the steering magnets. The error values of the displacement and rotation of the quadrupole magnets are randomly generated under a specified limit. In the first case, we considered a displacement error only. The maximum error value is 100 μm. The propagation of a beam centre through the PEFP linac is given in Figure 3. The steering magnets are summarized in Table 2 in this case. We found that the steering algorithm generally works well. However there may be some fluctuations in the fifth and sixth tanks. In the second case, we studied the error effects of a displacement and rotation with the maximum displacement errors of 50 μm and rotation errors of 17 mrad which is about 1 degree. Since the quadrupole magnets are rotated about a stem position or the centre of magnets in the longitudinal direction, the dipole kicks before and after the pivot point are cancelled. That is why the fluctuation of a beam centre is relatively insensitive to the rotation errors. Figure 4 shows the propagation of a beam centre. Table 2 includes the magnetic fields of the steering magnets in unit of ampere-turn. We found that the steering algorithm works very well.

Table 2: Steering magnets in ampere-turn under the displacement error whose maximum value is 100 μm.

Steerer (ampere-turn)		Horizontal	Vertical
Set 1	First	1020	945
	Second	510	-1249
Set 2	First	-397	524
	Second	-702	235

Table 3: Steering magnets in ampere-turn under the displacement and rotation errors whose maximum values are 50 μm and 17 mrad.

Steerer (ampere-turn)		Horizontal	Vertical
Set 1	First	887	935
	Second	1196	902
Set 2	First	351	-533
	Second	-324	697

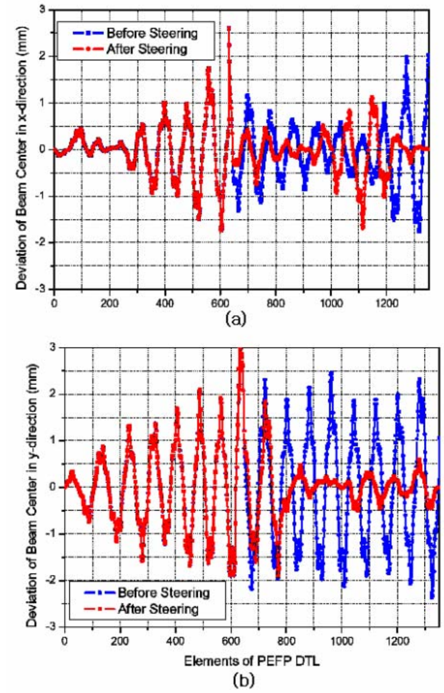

Figure 3: Propagation of beam centre in the (a) horizontal and (b) vertical directions under the displacement error whose maximum value is 100 μm: Blue and red lines represent before and after turning on the steering magnets.

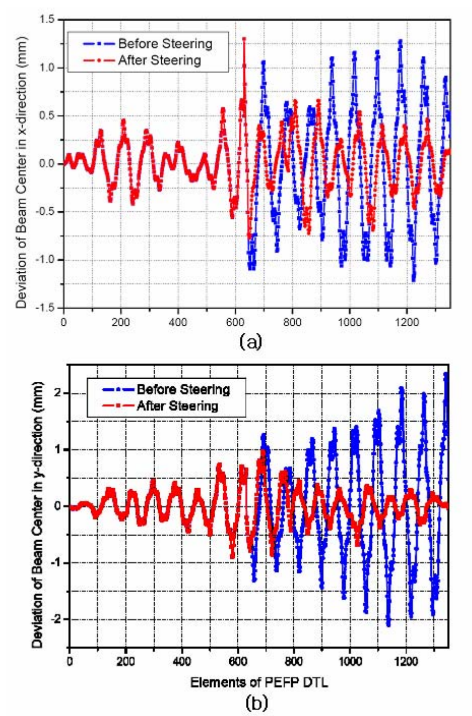

Figure 4: Propagation of beam centre in the (a) horizontal and (b) vertical directions under the displacement and rotation errors whose maximum values are 50 μm and 17 mrad: Blue and red lines represent before and after turning on the steering magnets.

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Steering magnets and beam size

We obtained the maximum beam size, which is given by the displacement of a beam centre with three times the rms beam size, in the high energy part of the DTL tanks. The maximum values of the displacement and rotation errors are 50 µm and 17 mrad, respectively. The results are given in Figure 5 where the data is obtained by choosing a 99% value of 1000 simulation results. We found that the beam size is limited to 5 mm after a steering.

In order to obtain the required magnetic field of the steerers for controlling a beam fluctuation, we calculated them under the condition that the maximum displacement errors are varied from 25 µm to 100 µm with a fixed maximum rotation error of 17 mrad. The results are given in Figure 6 for two steering sets where they are obtained by choosing a 99% value of 1000 simulation results. The required magnetic field of the steering magnets is about 2300 gauss-cm for the 50 µm case. We found that the magnetic field values of the first steering set are larger than the second one. Figure 7 shows the variation of the required magnetic filed when we choose the data of a 90 % or 99% value of 1000 simulations.

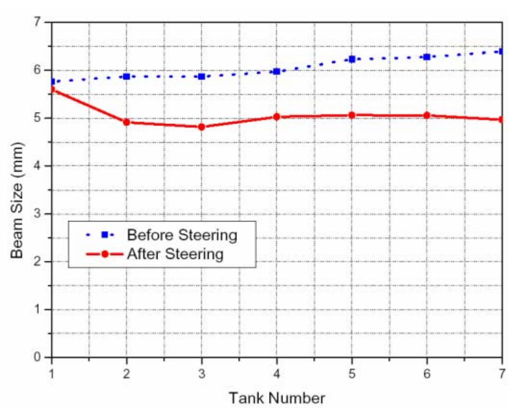

Figure 5: The maximum beam size in the seven tanks after 20 MeV: blue (dotted) line before steering and red (real) line after steering.

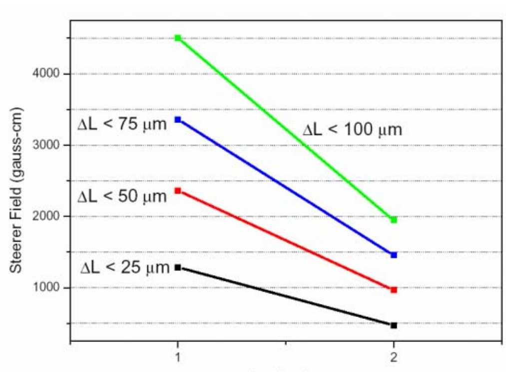

Figure 6: The required magnetic field of the two steering magnet sets: Each case is for different maximum values of the displacement errors (25, 50, 75, and 100 µm) with a common maximum value of the rotation error of 17 mrad.

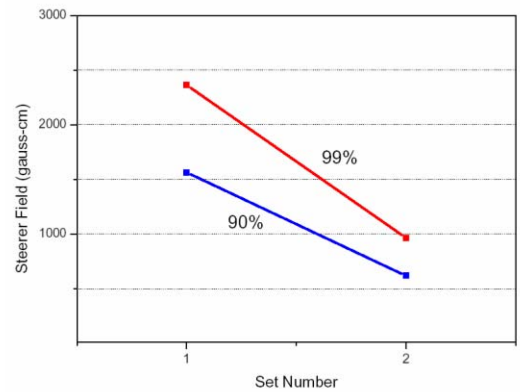

Figure 7: The required magnetic field of the two steering magnet sets: Each case is for 90% and 99% values (The maximum values of the displacement and rotation errors are 50 µm and 17 mrad.).

DISCUSSION

This work is related to an error analysis of the PEFP linac in order to obtain the information on a beam steering. We choose the positions before and after the DTL101 and DTL104 for installing the steering magnet sets because the phase advances between these two points before and after the tanks are relatively larger. For the maximum displacement and rotation errors of 50 µm and 17 mrad, the required magnetic field is about 2300 gauss-cm in order to control the beams against displacement and rotation errors.

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