ESTIMATION AND CORRECTION OF THE UNCONTROLLED BEAM LOSS DUE TO THE ALIGNMENT ERROR IN THE LOW-ENERGY LINEAR ACCELERATOR OF RAON

Ji-Gwang Hwang, Eun-San Kim*, Dept. of Physics, Kyungpook National University, Daegu, Korea
Dong-O Jeon, Hyung Jin Kim, RISP, IBS, Daejeon, Korea

Abstract

RAON(Rare isotope Accelerator Of Newness) mainly consists of the front-end system, ISOL system, re-accelerator for ISOL system, charge stripper section and main linear accelerator(linac) for ECR ion source [1]. Since the beam energy at the down-stream of the front-end system is low, $0.3 \sim 0.5$ MeV/u, the trajectories of the beam is very sensitive to the alignment error of the magnets and cavities at the entrance of the main linac. It can cause the uncontrolled beam loss due to the large amplitude of the trajectory. The effect of the alignment errors of the magnets and cavities was estimated and corrected by using analytical model which is based on analytical model and code TRACK [2]. The calculation result based on the analytical model agrees very well with the simulation by using the TRACK code. Using the analytical model, the position and number of the corrector and Beam Position Monitor(BPM) in low energy linac was determined to compensate the amplification of the beam trajectory under 400 um. We will present the result of the estimation of the alignment error and the correction using steering magnet with strip-line Beam Position Monitor (BPM) in a low energy section.

INTRODUCTION

Main target of the Rare Isotope Science Project(RISP) is to construct the high power heavy-ion accelerator that is a key research facility allowing ground-breaking investigations into numerous facets of basic science, such as nuclear physics, astrophysics, atomic physics, life science, medicine, and material science [3]. The heavy-ion accelerator mainly consists of the front-end system, ISOL system, re-accelerator and superconducting main linear accelerator(linac). The driver linac consist of the ECR ion source, LEBT (Low-Energy Beam Transport) line, RFQ accelerator, MEBT (Medium-Energy Beam Transport) line and main SCL that is shown in Fig. 1 [4].

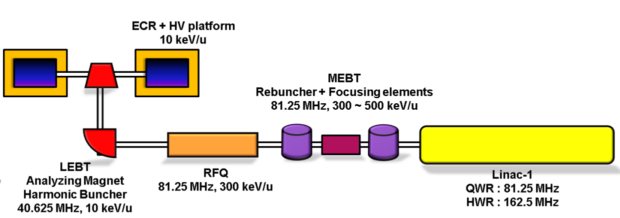

Figure 1: Schematic layout of the driver linac.

Especially, the trajectories of the ion beam center, which is called beam orbit, in the low energy part of the main linac from 0.5 MeV/u to a few MeV/u is very sensitive to the alignment and strength errors of the magnets and cavities. It can cause the uncontrolled beam loss due to the amplification of the trajectory of the ion beam center by the interference of the errors. The low energy part of the main linac consist of 22 superconducting QWR(Quarter Wave Resonator) cavities with a doublet quadrupole magnet per cell. The layout for two periodic cell of low energy linac is shown in Fig. 2.

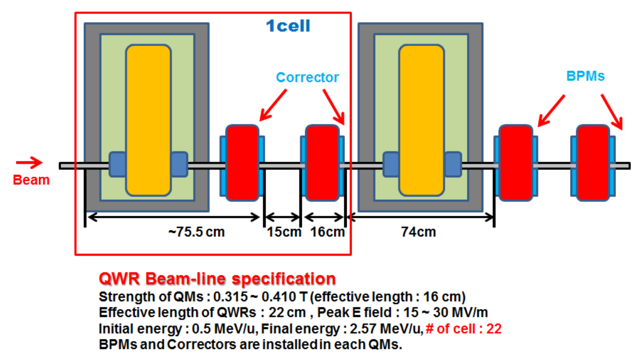

Figure 2: Schematic layout of two cell of the low energy linac.

The effect of the alignment and strength errors of the magnets and cavities was estimated and corrected using TRACK code based on the scheme studied by using analytical model that is based on the transfer matrix of the elements. The calculation result based on the analytical model agrees very well with the simulation by using the TRACK code. We will present the result of the estimation of the alignment and field strength errors in the low energy linac of RAON, the result of the orbit correction using steering magnet with strip-line Beam Position Monitor (BPM), and the analytical method for the orbit correction.

BASIC THEORY

In the low energy part of the heavy-ion linac, which consists of the quadrupole magnet, beam diagnostic device and QWR cavities, the trajectory of the ion beam is sensitive to the alignment errors of the components [5]. The trajectory of the ion beam center is changed by the kick due to the alignment error as shown in Fig. 3.

The read-back of the i th BPM which measures the centroid of the transverse position of the ion beam at locations

* eskim1@knu.ac.kr

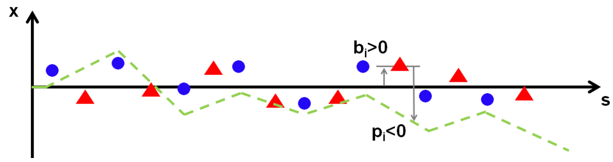

Figure 3: Scheme of the kick due to the alignment error of the elements.

i along a low energy linac can be written as [6]

$$p_i = \sum_{j=1}^{i} k_j C_{ij} - b_i \pm r_i \tag{1}$$

where k_j is the kick angle at location s_j ($s_j < s_i$) due to a transversely misaligned quadrupole magnet and QWR upstream of BPM-i, C_{ij} is the transfer coefficient which maps a beam angle at point j to a position at point i, b_i is the read-back offset of BPM-i , and r_i is the resolution of BPM-i. The amplitude of the kick due to the alignment error of the elements is depend on the displacement between the center of the ion beam(x_{ci}) and center of the element(x_{ce}), $k_j \sim \Delta x$ where $\Delta x = x_{ci} - x_{ce}$.

QWR Cavity

The kick by the QWR cavity is caused by the electric field on the vertical plane produced by an asymmetry structure of the cavity. The vertical electric field of QWR cavities was well explained by following analytical model [7]:

$$E_y = -y\frac{9}{32}k^2 V_{stem}(\cos(kz) - \cos(3kz))\sin(\omega t + \phi) \tag{2}$$

where $\omega = 2\pi f_{hf}$, $k = \frac{2\pi}{\beta_0\lambda}$, $\lambda = \frac{c}{f_{hf}}$, h_{hf} is a frequency of the cavity, β_0 is geometrical beta of cavity, ϕ is phase of cavity and c is a speed of light. Hence the energy gain in the transverse direction is given by

$$\Delta W_y = qLT(\beta)\cos\phi \int_{-L}^{L} E_y(z)\,dz \tag{3}$$

where $T(\beta)$ is transit time factor, $\sin\left(\frac{\pi g}{\beta\lambda}\right)/\left(\frac{\pi g}{\beta\lambda}\right)$. Therefore the amplitude of the kick due to the transverse field of QWR cavity can be expressed by $\Delta W_y/(W_z + \Delta W_z)$. Since the transverse electric field has dependency on the position of beam(y), the strength of the kick is depend on the incident position on transverse direction, $k_{QWR} \sim (y + \Delta y_{QWR})$ where Δy_{QWR} is the amplitude of the alignment error of the QWR cavity.

Quadrupole Magnet

The kick by the quadurupole magnet can easily explained by the transfer matrix. The trnsfer matrix of the quadrupole magnet is given by

$$\begin{pmatrix} \cos\phi & \frac{1}{\sqrt{k_0}}\sin\phi & 0 \\ -\sqrt{k_0}\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{4}$$

where k_0 is normalized strength of the quadrupole magnet, $\phi = \sqrt{k_0}l$ and l is length of the quadrupole magnet. Hence the kick by the quadrupole magnet is inversely proportion to vertical position of the beam at the entrance of the magnet, $k_{QM} \sim (x + \Delta x_{QM})$. The angle change in the quadrupole magnet is $\Delta x' = -\sqrt{k_0}\sin\phi(x + \Delta x_{QM}) + (\cos\phi)x'$.

ANALYTICAL MODEL

The analytical model for the orbit jitter, which is based on the transfer matrix of the elements, is used to define the positions of the BPMs and correctors are well define to reduce the orbit jitter in the low energy linac. The trajectory of the ion beam orbit is well explained by the the first order matrix of the transfer matrix. The orbit of the ion beam with error of the magnets and BPMs was calculated that is shown in Fig. 4.

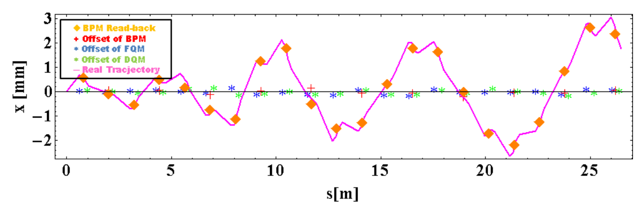

Figure 4: Beam orbit in the low energy linac with error of the elements.

As shown in Fig. 4, the orbit of the ion beam was amplified since the displacement between the center of the quadrupole magnet and ion beam was increased. Hence the orbit correction is one of the critical issue for a long linac. The several combination of the BPMs and correction for orbit correction was investigated to compensate the orbit amplification as small as possible. In this calculation, the resolution of the BPMs and alignment error of quadrupole magnet were given by 100 μm and 150 μm, respectively. When two cell was merged with one section for orbit correction, the orbit was down to about 1 mm that is shown in Fig. 5.

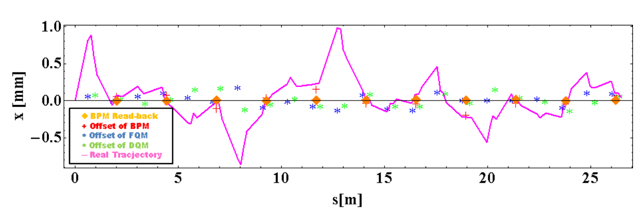

Figure 5: Scheme of the kick due to the alignment error of the elements.

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NUMERICAL CALCULATION

The scheme for orbit correction which was investigated by the analytical model in previous section was simulated using code TRACK to confirm the performance in the realistic situation with 3D field map of the cavities and space charge calculation. Information of the error level of each component which is used in the tracking simulation using code TRACK is listed in Table 1.

Table 1: Error Levels for the Simulation

Equipment	Quantity	Error Level
QWR Cavity	Alignment(Δ_{xy})	0.5 mm
	Alignment(Δ_z)	0.5 mm
	Tilit	5 mrad
	Voltage, Phase	1 %, 1 deg
Quadrupole magnet	Alignment(Δ_{xy})	200 & 300 μm
	Alignment(Δ_z)	200 & 300 μm
	Tilit	5 mrad
	Field strength	1 %

The alignment error levels of the cold component will be installed in the cryomodule and warm component will be installed in room temperature are assumed to 0.5 mm and 0.15 mm, respectively. The amplitude of the field of magnet and cavities are also assumed to 1 %. The orbit of the ion beam without the correction is computed using code TRACK to compare the result with the analytical model that is shown in Fig. 6.

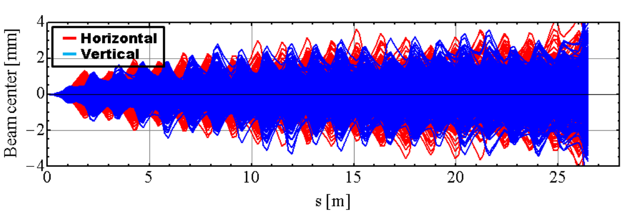

Figure 6: Scheme of the kick due to the alignment error of the elements.

The jitter of the orbit without the correction is also amplified and about 4 mm at the maximum. Based on the scheme which is studied using analytical mode, the correction of the orbit was performed using code TRACK. The result of the computation is shown in Fig. 7.

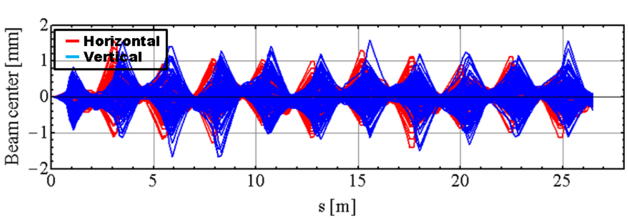

Figure 7: Scheme of the kick due to the alignment error of the elements.

As shown in Fig. 7, the orbit of the ion beam is about 1 mm at the maximum. The orbit near the BPM position is also less than 0.3 mm. The calculation result of the tracking simulation by using code TRACK agrees very well with the result of analytical model is shown in previous section.

CONCLUSION

The study of the effect of the alignment and field error of the components are performed by using the code TRACK and analytical model based on the first order transfer matrix of the elements. The calculation results of two methods shows a good agreements. And the amplification of the beam orbit in the low energy linac was compensated by below the 1 mm in the both analytical calculation and the tracking simulation using code TRACK. The orbit correction with the lattice, which consists of 2 BPMs with 2 corrector per 2 cell is one of the accommodation for orbit correction for low energy part of the linac which consist of the QWR cavities with doublet magnet. Since it has enough space between the corrector and BPMs, the strength of the correction in the orbit correction was also can be reduced.

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