BEAM TUNING STUDIES FOR THE RAON LINEAR ACCELERATOR*

Dong-O Jeon†, Ji-Ho Jang, Yujung Ahn, Institute for Basic Science, Daejeon, South Korea

Abstract

Various studies have been conducted and validated to tune the RAON linear accelerator. The RF set-points of the superconducting cavities and buncher cavities are determined with phase scan technique with 2 BPMs. With the BPM calibration, the beam energy is quite accurately determined with accuracy of tens of keV/u. We check the beam energy from phase scan with dipole scan method. With measured beam parameters, transverse optics can be controlled routinely and matching between sections of the linac is done.

INTRODUCTION

The RAON facility consists of the injector and superconducting linac SCL3 [1]. Beam commissioning of the RAON injector section started since August 2021 with various ion beams, including proton, helium, oxygen, neon, and argon. The low-energy beam transport (LEBT) delivers the beam from the ion source to the RFQ. Various diagnostics are installed for machine tuning and operation. Figure 1 shows the layout of the injector and the first QWR cryomodule along with beam diagnostics.

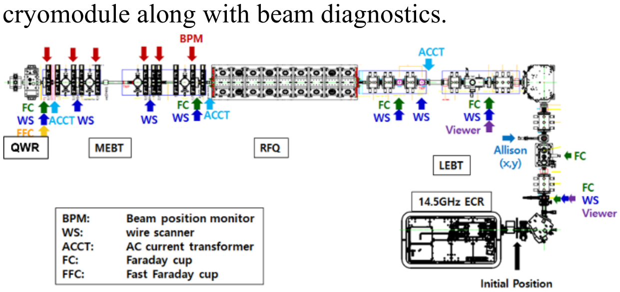

Figure 1: Layout of the injector and the first QWR cryomodule along with beam diagnostics.

Beam accelerated by the RFQ is transported to the superconducting linac through the medium-energy beam transport (MEBT), which provides transverse matching using magnetic quadrupoles and longitudinal matching using four buncher cavities.

In the QWR section, one cavity is installed in each cryomodule, whereas in the HWR section, two cavities are installed in each HWR-A module and four in each HWR-B module. Quadrupole doublets installed in the warm sections provide beam focusing. In addition, beam diagnostics such as beam position monitors (BPMs) and wire scanners are placed in the warm sections. To date, three beam-commissioning campaigns of the superconducting linac SCL3 have been conducted using argon and neon beams, starting with $^{40}Ar^{9+}$ beam followed by two subsequent campaigns of $^{40}Ar^{8+}$ beam and $^{22}Ne^{6+}$ beam.

This paper reports the beam tuning study results of the RAON injector and the superconducting linac. The injector commissioning results are presented primarily for $^{40}Ar^{8+}$ beam, with results from other ion species included as necessary, while the superconducting linac commissioning results are reported for $^{40}Ar^{8+}$ beam.

BEAM TUNING STUDIES

In operating an accelerator, various beam tuning measurements are needed to set the accelerator to the design state: RF set-points of cavities, beam profile measurements for tuning the proper optics, beam current measurements for transmission, orbit correction, etc.

With measured rms beam sizes, beam parameters such as rms emittance, Courant-Snyder parameters are determined. Utilizing these, the beam can be adjusted for better beam transmission and better matching to the downstream accelerator.

RF Set-Points

RF cavities of the RAON are superconducting cavities (QWR and HWR) and normal conducting buncher cavities. Their RF set-points are determined by using the phase scan technique with two downstream BPMs, and a physics application called CAPS has been developed and routinely used. Phase scan can determine the cavity RF set-point and the input beam energy pretty accurately to the accuracy of tens of keV/u. Figure 2 illustrates a typical phase scan result displaying the difference of two BPM phases.

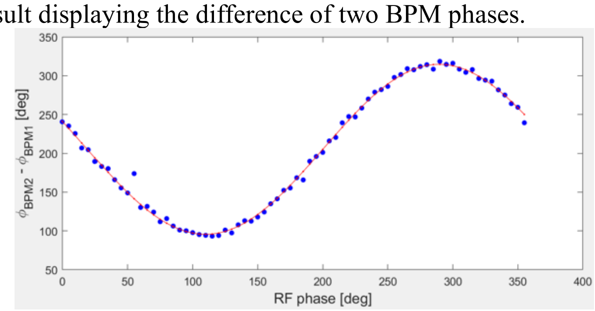

Figure 2: Plot of phase scan with two BPMs.

BPMs had been calibrated, and the beam energy obtained from phase scan has become quite accurate. Beam energy is also checked against beam energy obtained from dipole scan. For instance, $^{40}Ar^{9+}$ beam energy from phase scan (dipole scan) is 21.01 (20.92) MeV/u, and $^{22}Ne^{6+}$ beam energy from phase scan (dipole scan) is 24.50 (24.47) MeV/u. Figure 3 depicts $^{40}Ar^{8+}$ beam energy of the linac obtained from phase scans and TRACK code simulation for $^{40}Ar^{8+}$ beam. They show good agreement.

There are about ten cavities which are turned off for various reasons and rephasing nearby cavities are done to compensate their mismatch effect. Transmission of linac is

* supported by the Institute for Basic Science (IBS-I001-D1)
† jeond@ibs.re.kr

about 95% and we are looking into this because halo monitors do not show concrete beam loss signal above noise level.

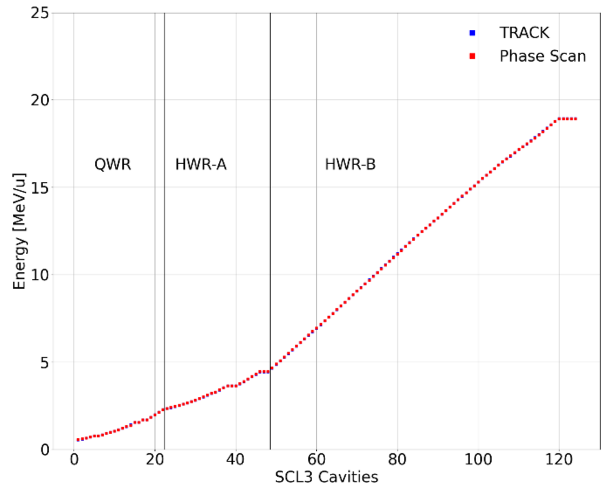

Figure 3: $^{40}Ar^{8+}$ beam energy comparison: phase scan results and TRACK code simulation. They agree well with each other.

Transverse Optics and Matching

Transverse optics of the linac is controlled by using a physics application with measured beam parameters. Beam parameters are measured with 3 or 4 wire-scanners or with Allison scanners.

Functions of the LEBT are to transport the beam from the ECR ion source and to match to the RFQ. With Allison emittance scanners and four wire-scanners, we are able to control the LEBT optics and to maximize the beam transmission. Figure 4 shows a typical emittance measurement from the Allison scanners. Figure 5 illustrates the beam size fitting method to obtain beam parameters using rms beam sizes from wire-scanners, and Fig. 6 the quad scan method to obtain beam emittance. Generally quad scan method takes about two hours. Table 1 lists the LEBT rms emittances obtained from the Allison scanners and quad scan method. They show reasonable agreement. Y emittance difference is due to a prominent beam tail of the measured beam in Y phase space, as shown in Fig. 4.

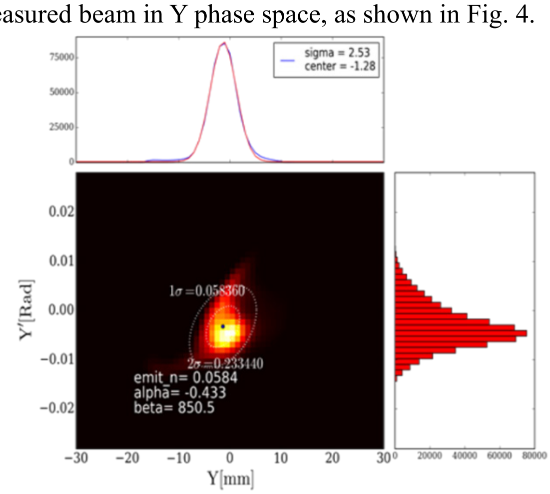

Figure 4: Example of Y emittance scan.

Table 1: LEBT rms Emittance Measurements

	ε_x [mm-mrad]	ε_y [mm-mrad]
Allison scanner	0.048	0.067
Quad scan	0.041	0.038

Through transverse studies, we realized that there are a few limiting apertures such as ACCT in the LEBT that reduces LEBT beam transmission. These will be remedied in the future. Tomography reconstruction using 4 wire-scanners are tried and compared with the Allison scanner data [2]. It shows a good agreement.

RF set-point of the RFQ is determined by comparing measured transmission with simulation as displayed in Fig. 7. for various ion beams, RFQ transmission is generally in the range of 90% ~ 97%. Light ion beams have higher beam emittance and their RFQ transmission tends to be low.

We also note that on-axis injection to the RFQ is crucial [3]. Off-axis injection results in significant increase of emittance and beam tail, as displayed in the measured beam profile of Fig. 8. Only Y beam profiles are displayed, but the same pattern is observed in X beam profiles as well. Proper matching to the RFQ reduces the RFQ output beam emittance measured in the MEBT and output beam has little beam tails as portrayed in Fig. 9.

Proper matching to the next section of the linac reduces beam loss and increases beam transmission. Figure 10 portrays the beam envelope in the MEBT and in the QWR section of the superconducting linac. Using the four wire-scanners in the QWR section of the linac, rms beam sizes are obtained and are used to match the beam from the MEBT to the QWR section, as displayed in Fig. 10. Table 2 compares the rms emittances obtained from different methods.

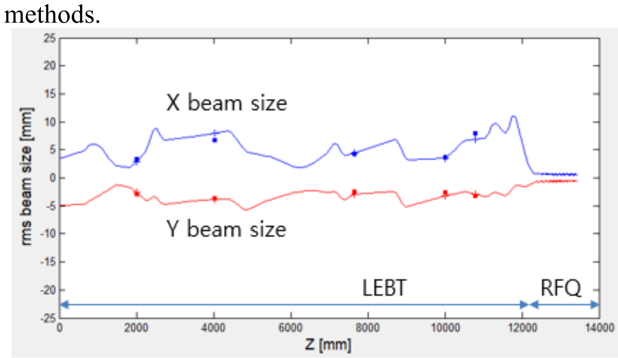

Figure 5: LEBT beam profiles from the ECR Ion Source (left) to the RFQ (right). This is based on beam size fitting method. Solid squares represent rms beam sizes from measurements using wire-scanners and Allison emittance scanners.

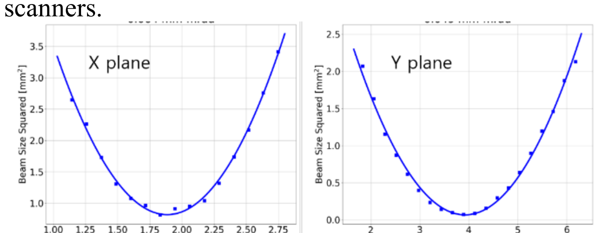

Figure 6: Quad scan method to obtain beam emittance.

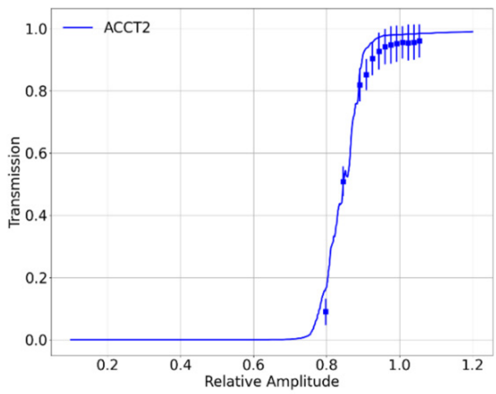

Figure 7: Plot comparing measured RFQ transmission and simulation. Relative amplitude 1 corresponds to the design set-point.

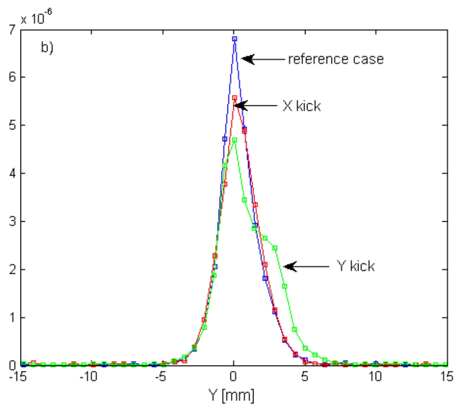

Figure 8: Y beam profiles measured with a MEBT wire-scanner. RFQ output beam has little beam tail with on-axis injection and matching (reference case). Y kick before the RFQ clearly generates Y beam tails, while X kick does not induce Y beam tails. X kick generates X beam tail.

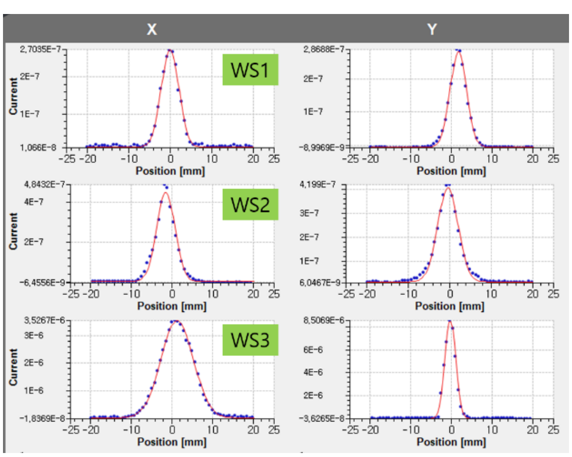

Figure 9: MEBT beam profiles of wire-scanners with on-axis injection and matching to the RFQ. It is observed that beam profiles show little beam tails.

Table 2: MEBT rms Emittance Measurements

	ε_x **[mm-mrad]**	ε_y **[mm-mrad]**
RFQ output	0.064	0.053
Quad scan	0.096	0.069
Beam size fitting	0.086	0.065

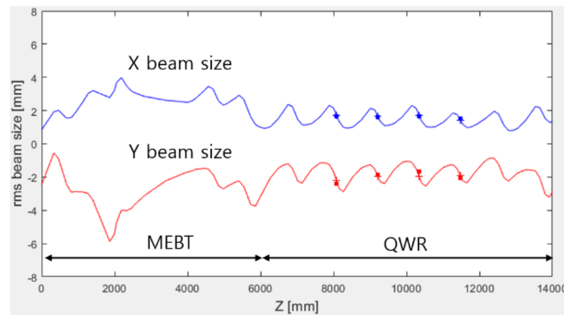

Figure 10: MEBT to QWR section beam profiles. It shows that proper matching to the QWR section is achieved. Solid squares are rms beam sizes obtained from wire-scanners.

CONCLUSION

Physics applications have developed and been applied to set the linac to the design state. Phase scan application has been developed and applied to set the RF set-points of cavities and reasonably high beam transmission of about 95% has been achieved. We are looking into this beam loss, because halo monitors do not show concrete signals above noise level. We have demonstrated that we can control the transverse beam optics of the injector and the SCL3. Matching has been performed improving the beam transmission. Through tuning studies, we came to understand the machine better. Results of tomography reconstruction is presented in a separate paper during the conference.

ACKNOWLEDGEMENTS

This work is supported by the Institute for Basic Science (IBS-I001-D1).

REFERENCES

[1] D. Jeon et al, "Design of the RAON Accelerator Systems", *J. Korean Phys. Soc.*, vol. 65, No. 7, pp. 1010, 2014. doi:10.3938/jkps.65.1010

[2] Dong-O Jeon *et al.*, "Transverse phase space tomography and comparison with Allison scanner data in the RAON heavy ion accelerator", *Nucl. Instrum. Methods Phys. Res. Sect. A,* vol. 1082, pp. 171005, 2026. doi:10.1016/j.nima.2025.171005

[3] Dong-O Jeon, Ji-Ho Jang, Hyunchang Jin, Hyung-Jin Kim, "Effects of off-axis beam injection to RFQ", *Nucl. Instrum. Methods Phys. Res. A*, vol. 1052, pp. 168250, 2023. doi:10.1016/j.nima.2023.168250