ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-THPS109

NON-DESTRUCTIVE BUNCH SHAPE MEASUREMENTS OF A NON-RELATIVISTIC ION BEAM AT RAON

Donghyun Kwak[1], Jaesung Kim[1], Geonhee Oh[1], Kyoungho Tshoo[1], Dong Geon Kim[1],
Moses Chung[2], Cheolmin Ham[1,†]
[1]Institute for Rare Isotope Science, Institute for Basic Science,
Daejeon 34000, Republic of Korea
[2]Department of Physics and Division of Advanced Nuclear Engineering, Pohang University of Science and Technology, Gyeongbuk 37673, Republic of Korea

Abstract

Characterizing the longitudinal bunch profile is crucial for understanding beam dynamics and ensuring optimal accelerator performance. To address these needs, Capacitive Pick-Up type Bunch Shape Monitors (CPU-BSMs) were developed at the Institute for Rare Isotope Science (IRIS). These devices non-destructively measure the longitudinal bunch shapes of non-relativistic and nanosecond-scale ion beam bunches.

Initial feasibility tests were conducted at a 30 MeV cyclotron to verify the performance of the CPU-BSMs. In 2024, the CPU-BSMs were employed during Nuclear Data Production System (NDPS) beam commissioning at the Rare Isotope Accelerator complex for ON-line experiments (RAON) to characterize both the longitudinal bunch shapes and the beam energy.

In this paper, we report the experimental results obtained using the CPU-BSMs during the NDPS beam commissioning at RAON.

INTRODUCTION

Nuclear Data Production System (NDPS) [1, 2] is a fast neutron experimental system at RAON [3-5]. NDPS generates neutron beams with energies up to 100 MeV using various ion beams accelerated by the SuperConducting linear accelerator 3 (SCL3). In the Low Energy Beam Transport (LEBT) line, a fast chopper and a single bunch selector can generate pulsed beam [6] for neutron Time-of-Flight (TOF) experiments at NDPS. For neutron TOF experiments, the longitudinal bunch shape of the primary ion beam must be measured to accurately evaluate the uncertainty of the neutron energy. For this purpose, Capacitive Pick-Up type Bunch Shape Monitor (CPU-BSM) was developed together with bunch shape reconstruction algorithm as described in Ref. [7]. Two CPU-BSMs were installed upstream of the neutron production target. In 2024, 16.3 MeV/u ^{40}Ar ion beams were delivered to the neutron production target at NDPS for the first time. Although the timing structure of the ion beam is not appropriate for the neutron time-of-flight measurement, we obtained the longitudinal pulse shape of the ^{40}Ar ion beam by reconstructing the measured data using CPU-BSM. Additionally, the beam energy was determined by measuring the time difference between two CPU-BSMs.

CAPACITIVE PICK-UP TYPE BUNCH SHAPE MONITOR (CPU-BSM)

For non-relativistic ion beams, the electric field generated by the beam ions spreads in the longitudinal direction. As a result, the integrated signal does not accurately reflect the actual longitudinal bunch profile. Since the electric field spreading is determined by the beam velocity, we proposed that the original bunch shape could be reconstructed from the integrated signal measured using a capacitive pick-up monitor, especially for ion beams with the nanosecond scale bunch lengths.

A Capacitive Pick-Up type Bunch Shape Monitor (CPU-BSM) was developed with a geometry similar to that of conventional phase probes used in beam energy measurements, as shown in Fig. 1. The feasibility of this approach was validated through both simulations and a proof-of-principle experiment using a 30 MeV proton beam, as previously reported [7].

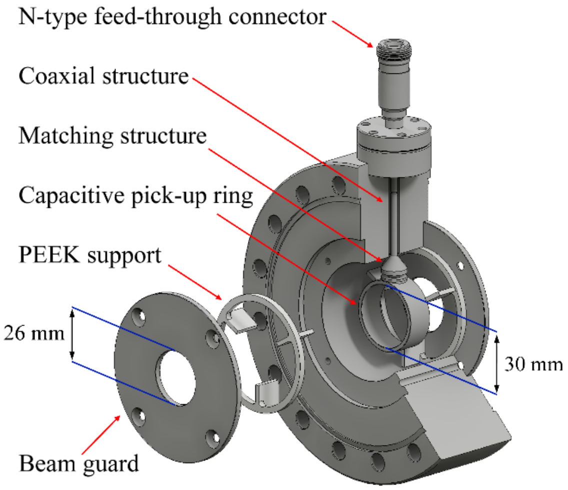

Figure 1: The 3D drawing of the CPU-BSM [7].

EXPERIMENTAL SETUP

In 2024, the first beam commissioning was performed at NDPS. ^{40}Ar^{8+} ion beams were accelerated by SCL3 and delivered to NDPS target room for the first time. The detailed beam parameters are listed in Table 1.

---

† cmham@ibs.re.kr

Table 1: Beam Parameters

Beam energy	16.3 MeV/u
Frequency	81.25 MHz
Ion type	Ar^{8+} (LINAC)
	Ar^{18+} (Target room)
Repetition rate	1 Hz
Duty	0.01 %

Prior to the beam experiment, the bunch length near the production target was calculated. At the end of SCL3, the standard deviation of the beam energy (σ_E) was calculated to be 0.01 % and that of the bunch length (σ_t) was calculated to be 0.1 ns. After traveling l through the beam transport line, σ_t can be approximated using the following relationship:

$$\sigma_t = \frac{l}{c\beta_{beam}} - \frac{l}{c(\beta_{beam}+\Delta\beta_{beam})}, \quad (1)$$

where c is the speed of light, and β_{beam} is the ratio of the average ion beam speed to c. The term $c(\beta_{beam} + \Delta\beta_{beam})$ in Eq. (1) represents the speed of beam particles that have energies higher than the average beam energy by σ_E. In this approximation, the initial bunch length (σ_t) at the end of SCL3 is neglected, since the increase in longitudinal bunch length is primarily caused by the energy deviation at SCL3. The value of $\Delta\beta_{beam}$ is given by:

$$\Delta\beta_{beam} = \sqrt{\frac{[E_{beam}(1+\sigma_E)+m_u]^2 - m_u^2}{[E_{beam}(1+\sigma_E)+m_u]^2}} - \beta_{beam}, \quad (2)$$

where E_{beam} is the average beam energy and m_u is the atomic mass unit. Assuming a Gaussian bunch profile, the bunch length near the target was calculated to be 0.6 ns in standard deviation and 1.4 ns in Full Width at Half Maximum (FWHM).

A Gaussian distribution in the time domain transforms into a Gaussian distribution in the frequency domain under a Fourier transform. With a standard deviation of 0.6 ns in the time domain, the corresponding frequency-domain distribution has a standard deviation of 0.265 GHz, implying that the dominant frequency components of the beam are located below 1 GHz. Therefore, the experimental setup focused on signals under 1 GHz.

Two CPU-BSMs were installed 8.47 m apart at the beamline of the NDPS target room. By measuring Time-Of-Flight (TOF) of the beam bunches passing through each CPU-BSM, β_{beam} and E_{beam} were calculated. Because the beam current during commissioning was expected to be relatively low, each CPU-BSM was connected to an RF amplifier via a 1 m coaxial cable. Each RF amplifier consisted of two Mini-Circuits ZFL-1000LNB+ units and one Mini-Circuits 139-VAT-8A+ attenuator.

After the RF amplifiers, 50-meter-long coaxial cables transmitted the signals to an oscilloscope (RTO64, Rohde & Schwarz) located outside the target room. During commissioning, the oscilloscope was connected to the control room via a LAN cable to enable remote data acquisition and control.

Because each combination of cable, amplifier, and attenuator exhibits a distinct frequency response, the overall gain and attenuation of each components were measured in advance using a vector network analyzer (ZND, Rohde & Schwarz). In addition, timing jitter between the two signal paths causes errors in TOF measurements. To quantify this effect, the output of a single signal generator (SMA100B, Rohde & Schwarz) was split into two paths, and the time difference between the outputs was measured using the oscilloscope. The resulting root-mean-square jitter was less than 50 ps, which is acceptable for the intended TOF measurements.

EXPERIMENTAL RESULT

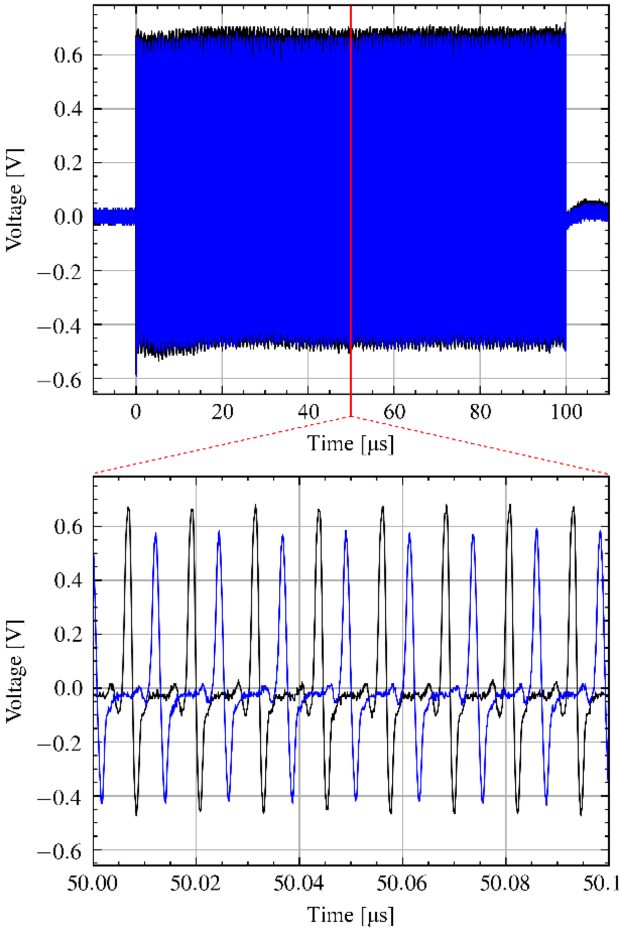

Figure 2: Measured signals of $^{40}Ar^{18+}$ ion beams obtained using the CPU-BSM1 (black) and CPU-BSM2 (blue).

Figure 2 presents a portion of the signals acquired during beam commissioning. The black line corresponds to the signal measured by CPU-BSM1 located upstream, and the blue line corresponds to the signal measured by CPU-BSM2 located downstream. Each beam bunch signal repeats at approximately 12.3 ns intervals, which aligns with the RFQ frequency of 81.25 MHz. The measured macro-pulse length of 100 µs is also consistent with the provided beam parameters specified for the experiment, as shown in Fig. 2.

The time difference between the zero-crossing points of the bipolar signals measured by each CPU-BSM is about 153.2 ns. Given that the distance between the two CPU-BSMs is 8.47 m, the beam energy was determined to be 16.3 MeV/u. Using this beam energy and Eq. (1), the estimated FWHM values at CPU-BSM1 is 1.40 ns ($l = 67.4$m) and FWHM values at CPU-BSM2 is 1.57 ns ($l = 75.9$ m).

Based on these parameters, we performed CST simulations to obtain the response function and applied it to each individual beam bunch to reconstruct its shape. Figure 3(a) shows a representative signal from CPU-BSM1 recorded on the oscilloscope, and (b) presents the corresponding reconstructed bunch profile. Similarly, Fig. 3(c) presents a representative signal from CPU-BSM2, while (d) shows its reconstructed bunch profile. In both cases, small bipolar signals appear prior to the main bunch signals. Since these smaller signals are significantly weaker than the main signals and likely arise from reflections in the 1 m cable between the CPU-BSMs and the RF amplifiers, they were excluded from the bunch shape reconstruction process.

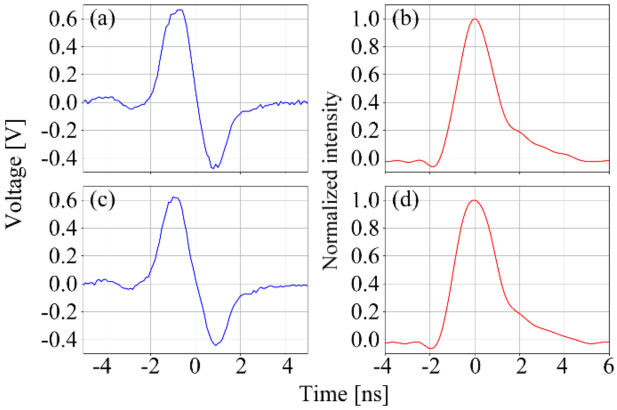

Figure 3: (a) Representative signal from CPU-BSM1 recorded on the oscilloscope; (b) reconstructed bunch profile of (a) using the inversion function; (c) representative signal from CPU-BSM2; (d) corresponding reconstructed bunch profile.

The reconstructions were also performed using only frequency components below 1 GHz, and the calculation accounted for the gain and attenuation of the cables, the attenuators, and the RF amplifiers as measured by the VNA.

Both CPU-BSM1 and CPU-BSM2 yielded reconstructed bunch shapes that are overall quite similar, resembling a Gaussian-like distribution with a tail. Figure 4 shows histograms of the FWHM values calculated after reconstructing the signals measured using (a) CPU-BSM1 and (b) CPU-BSM2. Their respective mean ± standard deviations are 1.73 ± 0.06 and 1.89 ± 0.07, which are approximately 25% larger than the simplified calculations.

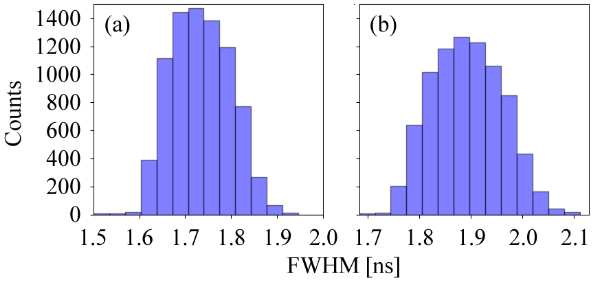

Figure 4: Histograms of the FWHM values obtained from the reconstructed bunch profiles using (a) CPU-BSM1 and (b) CPU-BSM2 signals.

CONCLUSION

To measure the beam energy and bunch length of non-relativistic ion beams during NDPS beam commissioning, Capacitive Pick-Up–type Bunch Shape Monitors (CPU-BSMs) were developed and employed. By comparing the signals from two CPU-BSMs spaced 8.47 m apart, the beam energy was measured to be 16.3 MeV/u.

The reconstructed beam bunch shapes exhibited Gaussian-like profiles with tails, and their FWHM values averaged 1.73 ± 0.06 ns (CPU-BSM1) and 1.89 ± 0.07 ns (CPU-BSM2), which are about 25% larger than the expected values. This discrepancy may stem from real beam dynamics that deviate from idealized assumptions. The transverse beam distribution was not considered in the reconstruction process. The development of a reconstruction algorithm that incorporates transverse effects remains a subject for future work.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) funded by Ministry of Science and ICT (2013M7A1A1075764 and RS-2023-00282876), and also supported by NRF grants (No. RS-2022-00154676 and No. NRF-2020R1A2C1010835).

REFERENCES

[1] C. Ham *et al.*, “Overview of nuclear data production system at RAON”, *Nucl. Instrum. Methods Phys. Res. B,* vol. 541, pp. 363-365, 2023.
`doi.org/10.1016/j.nimb.2023.05.064`

[2] C. Ham *et al.*, “Status of nuclear data production system at RAON”, *J. Korean Phys. Soc.*, published online, 2025.
`doi.org/10.1007/s40042-024-01266-6`

[3] K. Tshoo *et al.*, “Experimental systems overview of the Rare Isotope Science Project in Korea”, *Nucl. Instrum. Methods Phys. Res. B*, vol. 317, pp. 242-247, 2013.
`doi.org/10.1016/j.nimb.2013.05.058`

[4] D. Jeon *et al.*, “Design of the RAON accelerator systems”, *J. Korean Phys. Soc.*, vol. 65, pp. 1010-1019, 2014.
`doi.org/10.3938/jkps.65.1010`

[5] M. Kwon *et al.*, “RAON, Korean Heavy Ion Accelerator Facility”, *J. Part. Accel. Soc. Jpn.*, vol. 17, pp. 293-301, 2020.
`doi.org/10.50868/pasj.17.4_293`

[6] D. Kwak *et al.*, “Recent status of pre-bunching and re-bunching systems for low-energy experimental facilities at RAON”, *Nucl. Instrum. Methods Phys. Res. B,* vol. 541, pp. 385-387, 2023. `doi.org/10.1016/j.nimb.2023.05.057`

[7] D. Kwak *et al.*, “Non-destructive Bunch Shape Monitoring Method for Non-relativistic Ion Beams Based on Capacitive Pick-up type Bunch Shape Monitor”, accepted in *Prog. Theor. Exp. Phys.*, 2025.