DOI: 10.15669/pnst.7.388

Progress in Nuclear Science and Technology
Volume 7 (2025) pp. 388-394

ARTICLE

Development status of the accelerator system for transportable compact neutron source RANS-Ⅲ

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At RIKEN, a transportable compact neutron source (RANS-III) is under development for on-site nondestructive inspection of the degradation of old concrete and reinforced steel structures. The accelerator system for RANS-III comprises a 500 MHz radio-frequency quadrupole (RFQ) linear accelerator (linac), four sets of semiconductor amplifiers, a proton ion source, a low nergy beam transport (LEBT) system, and a high-energy beam transport (HEBT) system. The 500 MHz RFQ linac mainly comprises three components: a measure vane and two minor vanes. Because the resonance frequency of the cavity was selected as 500 MHz, the cavity diameter and weight of the linac were lower than those of the conventional four-vane RFQ linac (RANS-II RFQ). The RF system comprises an Low Level Radio Frequency (LLRF), four sets of semiconductor amplifiers, coaxial tubes, and RF couplers; it can inject up to 300 kW of RF power into the 500 MHz RFQ linac. We developed a permanent-magnet electron cyclotron resonance (ECR) ion source and an LEBT system with a double-Einzel lens. The ECR ion source comprises a 2.45 GHz magnetron, plasma chamber, neodymium magnets, and suppressor electrode. We conducted a beam property test of the ECR ion source and Einzel lens using an analytical beamline comprising a Faraday cup and bending magnet. First, the beam current and proton fraction were measured as a function of the hydrogen gas flow rate using a DC high-voltage power supply and ECR ion source. Next, short-pulse proton beam generation in the order of microseconds was demonstrated using the ECR ion source and a pulsed high-voltage power supply to generate a short-pulse neutron beam.

Keywords: ECR ion source; proton linac; transportable neutoron source

1. Introduction

Neutron beams are often used as probes for material analyses owing to their high transmission and light element discrimination performance; such beams are generated in nuclear reactors or large accelerator facilities. Recently, accelerator-driven compact neutron sources have been developed for each application [1-3]. At RIKEN, for in situ use at manufacturing factories and nondestructive inspection of infrastructure, such as bridges, accelerator-driven compact neutron sources, namely RANS and RANS-II, have been developed [4, 5]. Several nondestructive inspections have been developed using neutron beam generated by RANS, including an analysis of the salt content in concrete by performing a prompt γ-ray analysis [6]. On the other hand, neutron scattering imaging using pulse neutron beam by RANS-II was realized for the nondestructive inspection of the inside of infrastructure, such as bridges [7], which is possible to identify and visualize water and voids mixed in concrete, respectively.

In addition to RANS and RANS-II, RANS-III, a transportable accelerator-driven compact neutron source (see **Figure 1**), is being developed. As portable neutron souses, radioactive isotopes (RI) and the DD reaction are generally considered. However, neutron intensity from them is not insufficient for the neutron scattering imaging with pulsed operation. Considering about Neutron generators using the DT reaction, although the neutron intensity is sufficient, the neutron energy is so high that the shielding becomes too large for portable neutron source. Therefore, the configuration of RANS-III is similar to that of RANS-II: an ECR ion source, a 2.49 MeV RFQ linac, an RF system, a high-energy beam transfer (HEBT) system, and a target station with a lithium target. Because RANS-III is to be installed in an automobile for the in situ nondestructive inspection of infrastructure, downsizing of the accelerator system is important. The inner diameter of the RFQ linac is inversely proportional to the resonant frequency. Focusing on this property, a 500 MHz RFQ linac has been developed for RANS-III, downsizing to approximately half and one-third, respectively, compared to those of RANS-II. Using a 3D electromagnetic simulation software and a beam tracking cord, an RFQ cavity was designed, which can accelerate a proton beam with a current of 10

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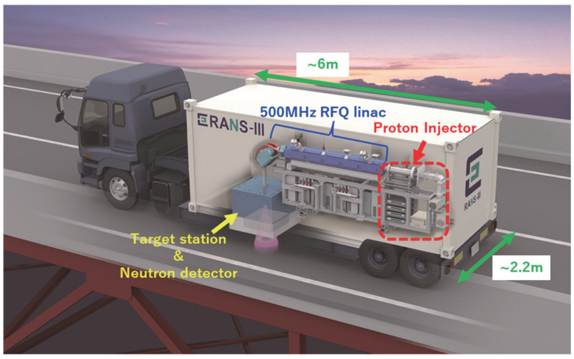
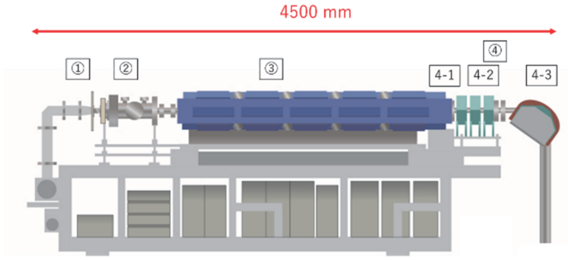


(a) Image of RANS-III



(b) 500 MHz RFQ linac.
① ECR ion source, ② LEBT line, ③ 500 MHz RFQ,
④ HEBT (4-1: a steering magnet,4-2: a doublet Q magnet,
4-3: 90° bending magnet)

Figure 1. RIKEN transportable compact neutron source (RANS-III).

mA up to 2.49 MeV with a duty cycle of 3% [8]. The RFQ cavity was fabricated based on design evaluations. The three-piece RFQ fabrication method was adopted to fabricate the RFQ cavity [9]. The resonant frequency, unloaded quality factor Q, and electric field strength distribution of the RFQ cavity were measured by conducting a low-power test. The electric field strength deviation was tuned from approximately 50% to approximately 20% using eight fixed tuners. After the tuning, the resonant frequency was 498.8 MHz, and the unloaded quality factor Q was 73% of the design value. An RF system was constructed to input RF power to the RFQ cavity. Because the coupler port of this cavity is small (diameter: 46 mm), the voltage near the coupler port may become high, causing discharge. To input nominal RF power (approximately 300 kW) to the RFQ cavity, the RF voltage around the coupler ports was reduced by developing four RF systems with an RF power of 75 kW per system. Using the four RF systems, 100 µs of RF power at 300 kW with a repetition frequency of 10 Hz was injected into the RFQ cavity [10].

To accelerate a proton beam with an average beam current of 100 µA at a duty cycle of 3%, an ion source and a low-energy beam transport (LEBT) line are required to generate a proton beam with a peak current range of 3.3–10 mA and to focus the proton beam to φ2 mm at the input tip of the RFQ electrodes. RANS-III is mounted on a vehicle and used on-site, which requires a limited footprint, load capacity, and power supply. Therefore, the ion source system should be lightweight and have as low an operating power as possible. We developed an LEBT system with a permanent-magnet ECR ion source and a double-Einzel lens as the ion source system for RANS-III.

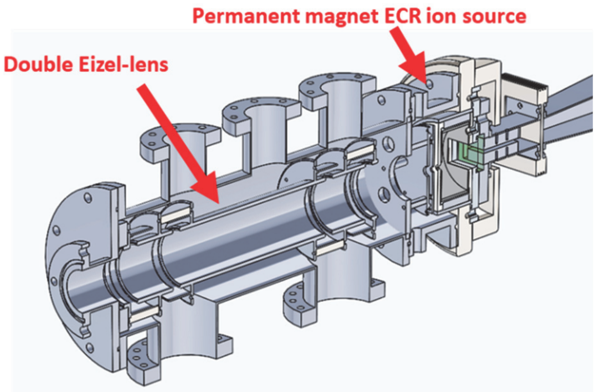
The rest of this paper is organized as follows. In Section 2, we describe the configuration and design of the ion source and LEBT line. In Section 3, the characteristics of the beam, such as the peak current and proton ratio produced by the permanent-magnet ECR ion source and the double-Einzel lens, are measured, and the ion source conditions suitable for injection into the RFQ linac are described. A short-pulse-beam extraction test from the ECR ion source with a high-voltage power supply was performed for neutron scattering imaging that can enable a nondestructive inspection of the inside of infrastructure. In Section 4, we draw our conclusions and outline future plans.

Table 1. Parameters of an accelerator-driven compact neutron source RANS-III.

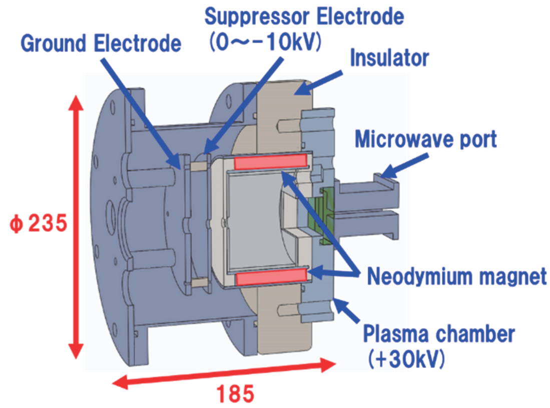
Resonant frequency [MHz]	500
Input beam energy [keV]	30
Output beam energy [MeV]	2.49
Peak beam current [mA]	≦10.2
Input emittance (RMS, nom) [π mm mrad]	0.1
Twiss parameter α	0.61
Twiss parameter β	3.0
Maximum duty cycle [%]	3.0
Average beam current [µA]	≦100
Power loss [kW, 100% Q]	183.3
Unloaded Q	8730
Cavity length [mm]	2370
Cavity outer diameter [mm]	~300
Cavity weight [t]	0.7

2. Development of the proton ion source system for RANS-Ⅲ

Figure 2 shows the ion source and LEBT system used for RANS-III. To reduce the power consumption during operation, we chose a permanent-magnet ECR ion source and a double-Einzel lens-type LEBT line. The ECR ion source comprises a 2.45 GHz magnetron, ridge tuner, RF window, plasma chamber, neodymium magnet, and extraction electrode system. The diameter of the ion source chamber was 235 mm, and the total length was 185 mm. Boron nitride was installed on the inner wall of the plasma chamber to increase the proton ratio, and 26 sets of neodymium magnets (5 mm × 5 mm × 50 mm) were placed on the sides of the plasma chamber. A 2.45 GHz microwave propagates from the magnetron to a WR-430 directional coupler, to a three-stub tuner, to an E-corner, and to a WR-284 reducer, in that order, to feed into the plasma chamber. The plasma chamber was operated at 30 kV to extract the ion beam from the ECR plasma. The

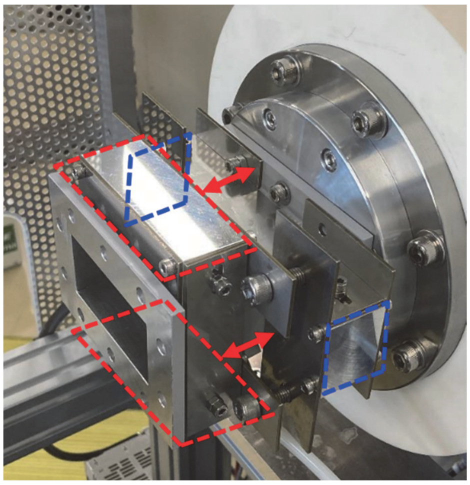


(a) ECR ion source and LEBT system

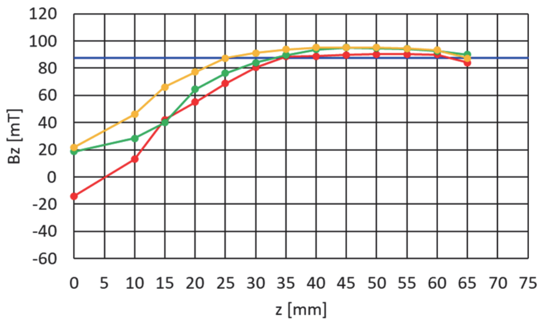


(b) Configuration of the permanent magnet ECR ion source

Figure 2. Configuration of the permanent magnet ECR ion source and the double-Einzel-lens-type LEBT.



(a) Additional magnet on the ECR ion source



(b) Magnetic distribution on axis

(z = 0: RF window, z = 65: extract electrode)
Red: without additional magnet
Green: with additional magnet, maximum spacing
Yellow: with additional magnet, minimum spacing
Blue: ECR condition

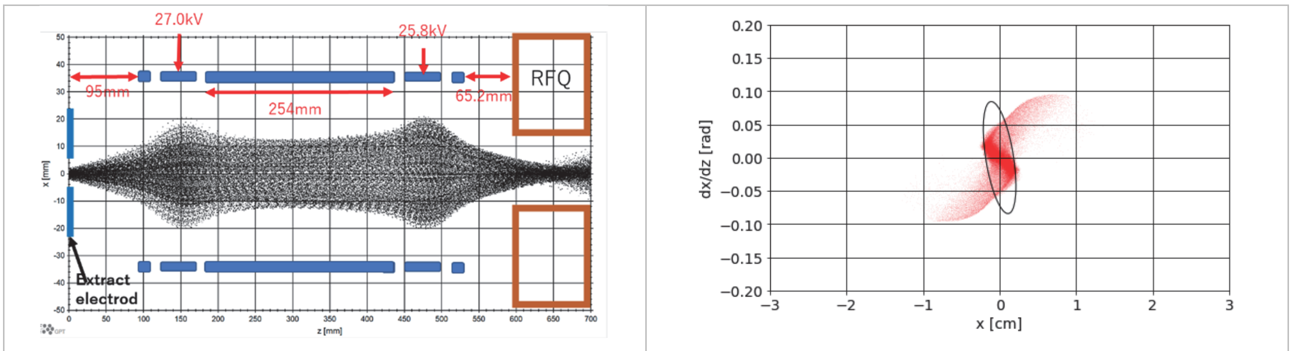
Figure 3. Additional pure magnets and magnetic field distribution.

extraction electrode array comprised a plasma electrode, suppressor electrode, and ground electrode. The plasma electrode was made of iron, and the suppressor and ground electrodes were made of stainless steel (SUS304). To stabilize the plasma sheath surface during beam extraction and suppress electrons from the downstream side, the suppressor electrode can apply a suppression voltage of up to −10 kV. The plasma chamber has a 5 mm diameter aperture and a 13.5 mm gap between the plasma chamber and the suppression electrode. Therefore, according to the Child Langmuir law, the maximum beam current is estimated about 25 mA at a extraction voltage of 30 kV and a suppression voltage of 0 V.

On the other hand, the LEBT line comprises two sets of deceleration–acceleration-type Einzel lenses and drift electrodes. Each electrode is supported by an alumina rod. The LEBT chamber has 152 ICF vacuum ports and is equipped with a 220 L/s turbomolecular pump. There are nine ports in total where high-pressure feed device, vacuum gauge, Residual Gas Analyzer (RGA), etc., are installed.

Twenty-six neodymium magnets were installed on the sides of the plasma chamber, and iron electrodes were placed at both ends of the plasma chamber to generate a magnetic field inside the chamber. Two sets of neodymium magnets were installed around the ridge tuner to adjust the magnetic field. Adjusting the spacing between the two sets of neodymium magnets, the position of the ECR conditions on the microwave port side will change without opening the ion source to make plasma ignition easily. The magnetic field was adjusted slightly by changing the distance between each magnet pair. **Figure 3** shows the measured magnetic field along the axis of the plasma chamber. By moving the additional magnets, the magnet field can be changed likely to the yellow and the green dot. The results show that there are two regions in the plasma chamber that satisfy the ECR condition.

In addition, because RANS-III is mounted on a vehicle and used on-site, the power consumption should be kept as low as possible; however, if a solenoid magnet is used in the LEBT line, the power consumption required for the solenoid coil will increase to several kilowatts. Therefore,



(a) Beam simulation in the double-Einzel lens

(b) Beam emittance at the RFQ electrode

Figure 4. Double Einzel-lens-type LEBT system.

we developed a double-Einzel lens to efficiently inject the proton beam from the ion source into the RFQ linac.

The shape of each electrode was based on that of the Einzel lens for RANS-II. The double-Einzel lens comprises two lens electrodes (inner diameter: 70 mm, length: 60 mm) for beam focusing, two ground electrodes (inner diameter: 70 mm, length: 11.5 mm), and one drift electrode (inner diameter: 70 mm, length: 254 mm) with a gap of 11.6 mm between each electrode. Each electrode was then fixed using an alumina rod. To maintain a small LEBT line, the rods were placed 45 mm from the beam axis. To avoid charge-up of the rods, metal sleeves were installed at each electrode gap. A positive voltage was applied to the lens electrode, and the beam was focused via a deceleration–acceleration mechanism.

To inject the ion beam into the RFQ linac efficiently, we optimized the conditions of the Einzel lens (lens configuration and voltage). First, we calculated the electric field distribution of the Einzel lens using the 2D electric field simulation software POISSON [11]. Subsequently, using the electric field distribution data, the particle trajectory from the ion source extraction electrode to the entrance of the RFQ electrodes was calculated using the beam simulation software General Particle Tracer [12]. From the calculation results, we obtained a beam current that matched the acceptances of the RFQ linac of RANS-III. To maximize the matched beam current, we optimized each parameter using the Nelder–Mead method: 1) distance between the drawer and ground electrode ①, 2) drift electrode length, 3) distance between ground electrode ② and RFQ electrode, 4) voltage at lens electrode ①, and 5) voltage at lens electrode ②.

Figure 4(a) shows the beam simulation of the optimized Einzel lens. The beam from the extraction electrode passes through the 95 mm ground electrode ①, is decelerated and accelerated by the lens electrode at 27.0 kV, and passes through the drift electrode (total length: 254 mm) as a parallel beam. In addition, the beam is focused by the lens electrode ② applied at 25.8 kV and injected to the RFQ linac 145 mm downstream. The diameter of the beam in the Einzel lens was maintained within approximately 2/3 of the inner diameter of the lens to minimize the spherical aberration in the Einzel lens as much as possible. **Figure 4(b)** shows the beam emittance shape injected into the RFQ. The solid ellipse is the acceptance of the RFQ linac of RANS-III. The emittance shape is fragmented owing to the aberration of the Einzel lens and space-charge effect. However, the beam matching rate with the acceptance is 70%, which means that an ion beam with a current of 14 mA can be injected into the RFQ linac.

3. Beam extraction test of the ECR ion source

3.1. Beam current and proton fraction measurements

To evaluate the characteristics of the ion beam produced by the ion source system, we conducted a beam-property test using a test bench. The test bench of the ion source is shown in **Figure 5**. The test bench was arranged in the following order from the ion source: double-Einzel lens, Faraday cup 1(FC1), bending magnet(BM) and Faraday cup 2(FC2). FC1, which has an inner diameter of 10 mm, measures the peak current and pulse waveform of the beam extracted from the ion source by suppressing the secondary electrons using the suppression electrode. Beam slits are placed in front of FC1 and FC2, and their width is set to 2 mm when analyzing ion species. The ion species were separated by the bending magnet and slit, and the current of the separated ions was measured using FC2. The beam current for each ion species was obtained by normalizing the measured ion species ratio by the beam current measured in FC1.

The ion beam current and ion species of the ECR ion source with respect to the gas flow rate were measured using a test bench. The magnetron output was 1000 μs RF power at 2000 W, with a repetition frequency of 10 Hz.

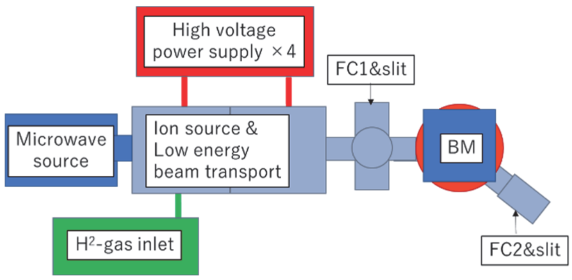
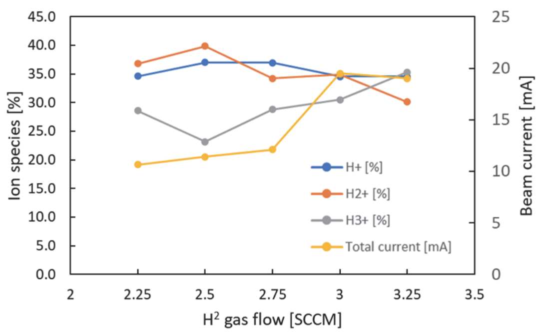
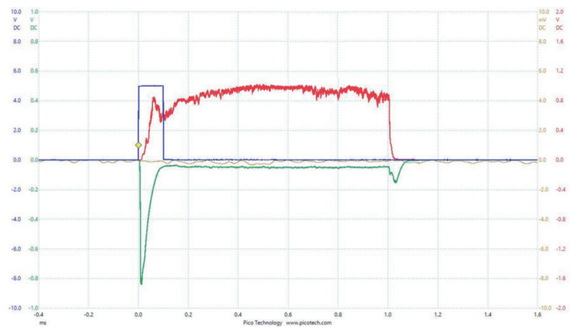


Figure 5. Testbench of the ion source.



(a) Total beam current and ion species as a function of the hydrogen gas flow



(b) Beam pulse shape for a hydrogen gas flow of 3.00 SCCM (Blue: microwave timing signal, Red: Ion beam pulse, Green: Reflected wave).

Figure 6. Beam measurement resalts.

The additional magnets are spaced as minimum (Figure 3 (b) yellow). Under each gas flow rate condition, the three-stub tuner was adjusted to minimize microwave reflection from the ECR ion source. **Figure 6(a)** shows the beam current and ion species relative to the gas flow rate. With the increase in the gas flow rate, the beam current increases, reaching a maximum of 20 mA at 3 SCCM. However, the ratio of the proton beam does not change significantly with the hydrogen gas flow rate and is approximately 35%. **Figure 6(b)** shows the pulse shape of the ion beam with a microwave energy of 2000 W and a gas flow rate of 3.00 SCCM. The three-stub tuner was adjusted to minimize the reflection power after generating the ECR plasma; thus, most of the microwaves were reflected during the period when the plasma was not ignited for several tens of microseconds after the microwaves were transmitted, and the reflected microwaves almost disappeared after the plasma ignition. The ion beam current level reached its maximum value about 500 µs after microwave oscillation. These results indicated that a proton beam with a current of 7 mA was generated at a hydrogen gas flow rate of 3.0 SCCM.

3.2. Short pulse beam extraction test with ECR ion source

In neutron scattering imaging, backscattered neutrons from the concrete are detected using the time-of-flight method to obtain information on the position of voids or water in the concrete. Therefore, to improve the signal-to-noise ratio of the image, the pulse width of the fast neutron beam injected into the concrete must be as short as possible. Because RANS-III does not have a neutron chopper, the pulse width of the proton beam from the accelerator must be reduced to shorten the pulse width of the neutron beam. However, a filling time of several tens of microseconds is required before the acceleration voltage is applied to the accelerating cavity. Therefore, in the method of shortening the RF pulse width injected into the accelerator, when the beam pulse width becomes shorter than 10 µs, the flat-top fraction of the accelerated proton beam pulse decreases, and the peak current decreases. Because the fraction of molecular ions from plasma ignition is high up to several hundred microseconds, the amount of accelerated proton beam current is reduced when the beam pulse width is reduced by shortening the plasma ignition time of the ECR ion source. A commonly used method for generating short-pulse beams is to incorporate an electric field beam chopper into the beamline immediately after the ion source or the RFQ linac. In this case, the beam chopper must be integrated into the beamline, making the accelerator longer and unsuitable for RANS-III, which has a limited site area. A pulsed high-voltage power supply is required for the chopper. Therefore, we have investigated a method of extracting a short pulse beam by applying a pulsed voltage to the plasma chamber.

Figure 7 shows the schematic of the ECR ion source using the pulsed extraction method. The pulsed high-voltage power supply system for extracting the ion beams from the generated ECR plasma comprised a DC high-voltage power supply (Matsusada, HBB-40P50), a high-speed switching power supply (BELKE, HTS441-10-

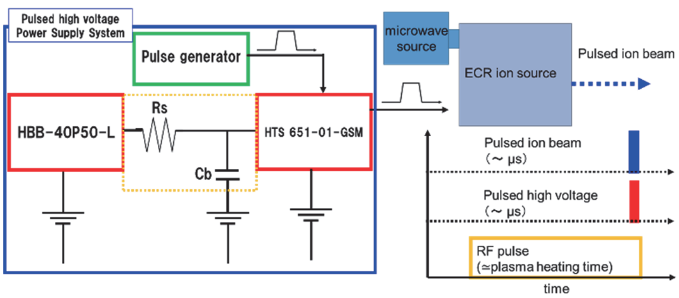
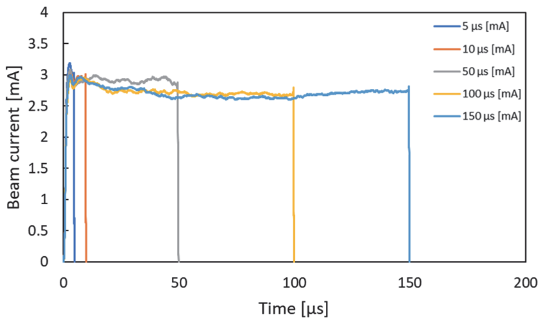
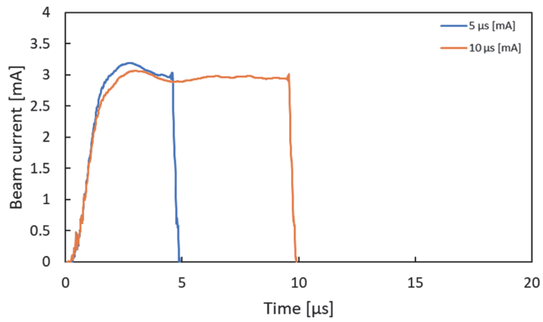


Figure 7. Schematic of the pulse extraction ECR ion source.



(a) Extraction voltage ON time: 5–150 µs



(b) Extraction voltage ON time: 10 µs, 5 µs

Figure 8. Total beam pulse measured at FC1 by the pulse extraction voltage.

GSM), and a pulse generator. A 9 nF capacitor (Cb) was incorporated between the DC high-voltage power supply and the high-speed switching power supply, and electrical energy was provided to the capacitor by a DC high-voltage power supply. A high-voltage pulse is generated by switching the high-speed switching power supply with respect to the pulse width of the signal input from the pulse generator. The capacitance of the ECR ion source is estimated to be approximately 50 pF.

The ion beam generated by the pulse-extraction voltage was measured at FC1. **Figures 8(a)** and **(b)** show the ion-beam pulses with respect to the pulse width of the extraction voltage. However, for the withstand voltage of the capacitor (Cb), the extraction voltage was up to 12 kV (Voltage, plasma chamber, 12 kV; voltage, suppressor electrode, 0 V). Other conditions of the ion source were as follows: microwave power, 2000 W; microwave pulse width, 1000 µs; voltage, Einzel lens 1, 10.5 kV; and voltage to Einzel lens 2, 8.5 kV. The delay time of the extraction voltage was set to 1,000 µs considering the total delay time and pulse length. The peak beam current measured at FC1 was 3 mA, which is the same as that extracted under a DC extraction voltage of 12 kV. The pulse width of the ion beam was shortened on the basis of the pulse width of the pulsed high voltage, and beam extraction with a minimum beam pulse width of 4 µs could be confirmed. Thus, it is expected that pulsed neutron beam shorter than 10 µs is generated if a proton beam extracted by this method can be accelerated. To accelerate the beam in the accelerator, the capacitor must be replaced with a capacitor with a higher breakdown voltage to enable operation at extraction voltages of 30 kV or higher.

4. Conclusions

A 500 MHz RFQ linac system for a transportable accelerator-based neutron source, called RANS-III, was developed. A permanent-magnet ECR ion source and a double-Einzel lens-type LEBT system were developed as the RANS-III ion sources. From the ion source test result, a proton beam with a peak current of 7 mA was obtained.

We demonstrated the generation of short-pulse beams from an ECR ion source using a pulsed extraction voltage system. A minimum beam duration of approximately 4 µs was possible at an extraction voltage of 12 kV. We plan to increase the withstand voltage of the capacitor and other components to more than 30 kV to generate a short-pulse beam of 30 keV, which is the injection energy of the RANS-III RFQ.

In the future, A beam acceleration test will be performed on the RFQ linac in combination with the ion source system. Currently, construction of the test bench, which consist of the RFQ linac, the ion source system, and the RF system and a Faraday cup. We plan to optimize the operating conditions of the accelerator to maximize the output beam current from the RFQ linac, and measure the energy of the output beam using a combination of 90° bending magnets and slits. In addition, construction of an HEBT line and beam commissioning will be done to transport the beam from the RFQ linac to the lithium target with the desired beam shape.

Acknowledgements

This work has been supported by Grant in Aid for JSPS Fellows Grant No. 20K20111.

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