NEW HIGH-ENERGY BEAM TRANSPORT LINE DEDICATED TO BIOLOGICAL APPLICATIONS IN RIKEN RI BEAM FACTORY

N. Fukunishi#, M. Fujimaki, M. Komiyama, K. Kumagai, T. Maie, Y. Watanabe, T. Hirano, T.Abe
Nishina Center for Accelerator-based Science, RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan

Abstract

The existing beam transport system of the RIKEN RI Beam Factory has been extended to deliver higher energy beams to the existing irradiation port for biological applications in order to breed seaweed using an ion-beam breeding technique widely used for flowers and crops. The maximum magnetic rigidity of the new branch beam line is 4.4 T-m. As a result, a 160-MeV/nucleon argon beam is available for seaweed breeding experiments. The new beam line was commissioned in January 2015 and we confirm that the design specifications have been met.

INTRODUCTION

Heavy-ion beams are widely used for biological applications thanks to their high biological effectiveness. The RIKEN Nishina Center has used energetic heavy ions as an effective tool inducing mutations of flowers, crops, and microbes [1]. Selective breeding is conducted from irradiated samples and many commercially useful plants have been produced. The beams used in these experiments are 135-MeV/nucleon carbon, nitrogen and neon beams, a 95-MeV/nucleon argon beam and a 90-MeV/nucleon iron beam. These are obtained from the RIKEN Ring Cyclotron commissioned in 1986 [2]. Linear Energy Transfer (LET) is proportional to the second power of the ion's charge for the ions having the same velocity. Hence we can control damage to the sample by changing ion species. The LET dependence of biological effects has been demonstrated by modern genetic analysis in which the pattern of gene deletion was shown to differ among ion species [3].

The difference between our method and cancer therapy is that the Bragg peak region is not used because too much damage leads to a low survival rate of irradiated samples and would be less effective for obtaining useful new breeds. Using the Bragg peak region would also create a further difficulty. In these breeding experiments, the LET-dependence of the mutation effectiveness should be precisely determined to develop a database, essential for efficient breeding. But an ion's LET changes greatly within the sample irradiated if we use the Bragg peak region of the ion. The only exception is the irradiation of very thin samples, but these are not always available.

The effectiveness of ion-beam breeding has been established for a wide variety of plants. Based on this success, a new project has started, in which ion-beam breeding is applied to seaweeds, such as wakame (*Undaria pinnatifida*) and kombu (*Saccharina japonica*). Wakame is a special product of the Tohoku region in Japan, which was seriously damaged by a big earthquake in 2011. In applying this technique to seaweed, heavier ions, such as argon and iron, were expected to be more effective than lighter ions; but these ions do not have sufficient energies to form nearly flat LET distributions. To solve this problem, we decided to use a higher-energy cyclotron: the Intermediate-stage Ring Cyclotron (IRC) [4]. The bending limit of the IRC is 980 MeV, much higher than that of the RRC (540 MeV). The maximum beam energy of the IRC for medium-heavy ions is 160 MeV/nucleon, also much higher than the 95 MeV/nucleon of the RRC. This energy upgrade results in a nearly 3-fold increase of the ion range in the assumed experiments with argon ions. However, the existing beam delivery system of the RIBF cannot deliver a beam extracted from the IRC to the existing irradiation port where a fully automated irradiation system is installed [1]. Hence, the existing beam delivery system has been extended to meet this demand.

#fukunisi@ribf.riken.jp

HIGH-ENERGY BEAM LINE

Beam Line Description

The relevant part of the RIBF beam delivery system is shown in Fig. 1. A beam extracted from the IRC is deflected by the DAKR dipole magnet in order to separate the beam from the existing SRC-injection line. The SRC (Superconducting Ring Cyclotron) is the final-stage accelerator of the RIBF. The section from IRC extraction to DMR2 makes the dispersive IRC beam doubly achromatic. The beam is bent up by DMR3 and bent down by DMR4 to shift the beam vertically by 3 m to compensate for the floor level difference. Here, the beam is doubly achromatic in the vertical direction. The section from DMR5 to DMR6 forms an achromatic bending system of 90°. The section from DMR7 and DMR8 is also doubly achromatic. After that, the beam line is joined to the existing beam delivery fishbone at the DMA1. The section from just after the DMR2 to DMR6 is not newly constructed but uses the existing IRC bypassing beam line in reverse. The IRC bypassing beam line was constructed to inject a beam accelerated by the RRC directly into the SRC, skipping the IRC, in order to perform light-ion experiments, especially polarized deuteron experiments. Faraday cups are added to the IRC bypassing beam line to adapt it for the present purpose.

The ion optical design was made by using TRANSPORT code. The maximum magnetic rigidity was 4.4 T-m, slightly smaller than the maximum magnetic rigidity of the IRC (4.57 T-m). The beam envelopes

ISBN 978-3-95450-131-1

obtained are shown in Fig. 2. No special ion-optical requirements are necessary for the section from IRC extraction to the confluent point DMA1 because the beams are used for irradiation experiments and a system dedicated to producing a uniform irradiation field of 10 cm in diameter already exists. However, to make beam tuning easier, point-to-point and waist-to-waist imaging is imposed from the point just after the IRC to the final irradiation point.

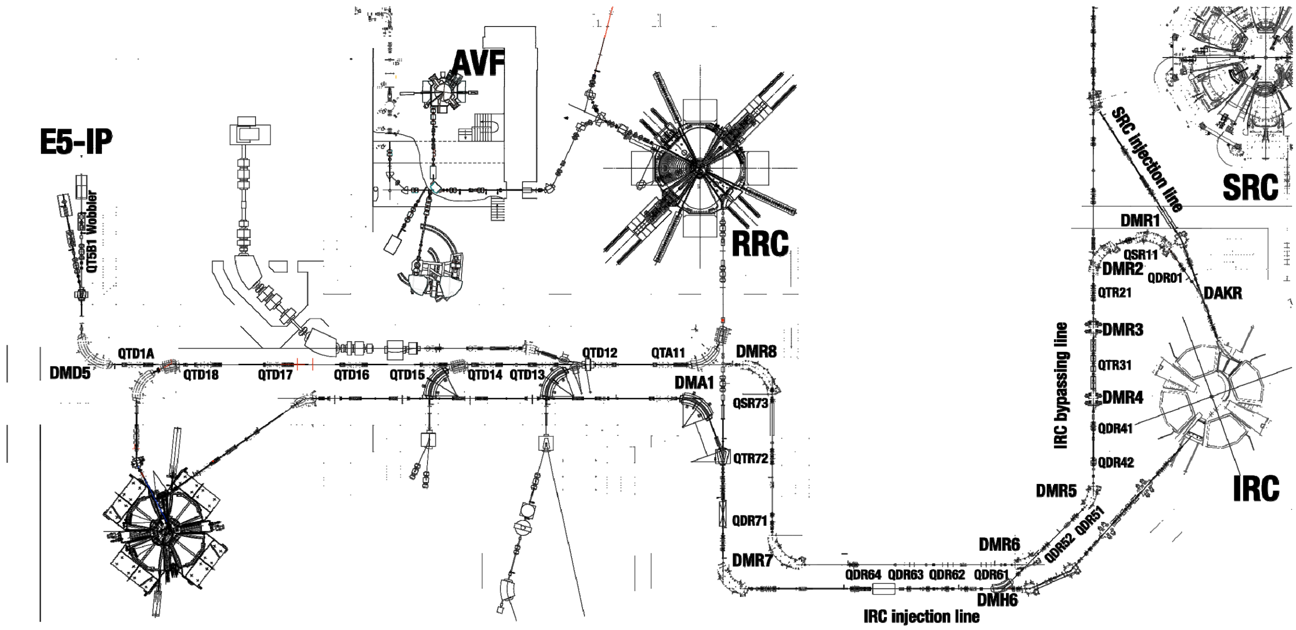

Figure 1: Layout of the RIBF beam transport system. Beams extracted from the IRC are transported to DMA1 via a new beam line and the existing IRC bypassing line. Beams are then transported to the existing irradiation port (E5-IP) through the existing beam delivery fishbone.

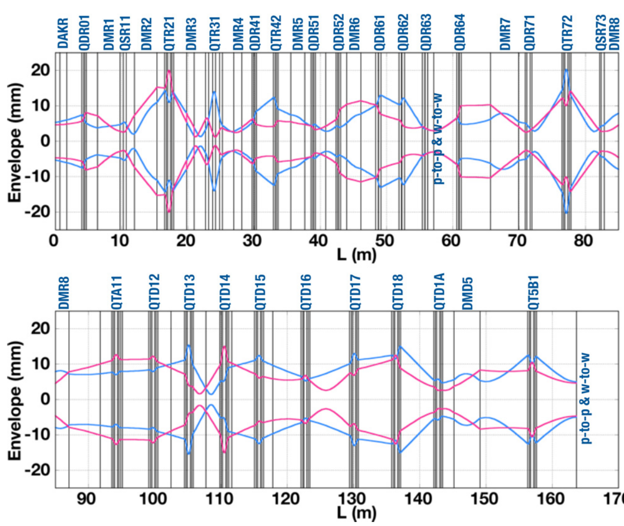

Figure 2: Beam envelopes of the high-energy beam line. Blue and magenta lines indicate horizontal and vertical beam envelopes, respectively, for a beam with $\varepsilon_{H,V} = 5\pi$ mm-mrad.

Subsystem

The specifications of the magnets are summarized in Tables 1 and 2. All of them are conventional normal conducting magnets. To reduce costs, old magnets are reused here as much as possible. In addition, some quadrupole and steering (correction) magnets are temporarily moved from one of the neighboring beam lines. The power supplies exciting the magnets used in the new beam line are not newly fabricated because we can use the sufficient number of existing power supplies that are free from exciting the magnets used in the new beam line. Beam vacuum is obtained using turbo molecular pumps with a pumping speed of 220 L/s, supplemented by rotary pumps. The beam monitors are Faraday cups for beam intensity measurements and wire scanners for beam profile measurements. These monitors are newly designed taking cost reduction and maintainability into account. Two kinds of vacuum chamber have been newly designed for vacuum pumping and beam monitoring. These devices are all controlled remotely and the control system of the new beam line was integrated into the existing EPICS-based RIBF control system.

Table 1: Specifications of dipole magnets used in the high-energy beam line.

Magnet	Bending radius (m)	Bending angle (deg.)	Gap (cm)	B_{max} (T)	Edge angle (deg.)
DAKR	4.0	15	6	1.5	7.5
DMR1, 2	2.7	72.5	6	1.65	25
DMR3, 4	2.7	25	6	1.64	12.5
DMR5, 6	2.7	45	6	1.64	15
DMR7, 8	2.7	90	6	1.65	25
DMD5	2.5	90	6	1.78	26.5

ISBN 978-3-95450-131-1

Table 2: Specifications of Quadrupole Magnets

Magnet type	Length (cm)	Bore diameter (mm)	Field Gradient (T/m)
Q220	22	70	16
Q420	42	70	16
2.5-inch Q	36	63.5	15

BEAM COMMISSIONING

Beam commissioning was on January 24 and 25, 2015. A 160-MeV/nucleon-argon beam was obtained using a non-orthodox three-stage acceleration mode in which energy degradation between the RRC and the IRC was necessary because such a beam was not part of the original RIBF design. The injector is the AVF cyclotron [5], which accelerates argon beams up to 4 MeV/nucleon. The beam extracted from the AVF is charge-stripped there and injected into the RRC. After the RRC, a thick carbon disk induces additional charge stripping and energy degradation. The efficiency of this process is 100%, although there is sizable emittance growth. However, this is not important because the irradiation experiments use faint beams and we can select as small a part of the emittance as we like.

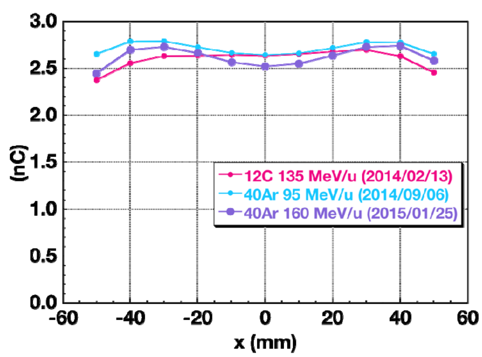

Figure 3: Uniformity of irradiation field for a 160-MeV/nucleon argon beam. X=0 corresponds to the center of the irradiation field.

After extracting a 160-MeV/nucleon argon beam from the IRC, the commissioning of the beam line was begun. Pre-determined magnet excitation currents worked well and the beam was transported to the confluent point (DMA1) within 30 min. Beam tuning improved the transmission efficiency from IRC extraction to the irradiation port to 100%. After that, we formed a uniform irradiation field using two wobbler magnets and a beam scatterer made of a gold film. Figure 3 shows the uniform irradiation field obtained in comparison with two widely used beams. The depth-dose curve of the 160-MeV argon ions was obtained using a calibrated ionization chamber with various beam energies degraded by a set of aluminum plates with various thicknesses that are used for the routine dose calibration. The results are shown in Fig. 4 compared with the result of the PHITS [6] simulation. The measured ion range in the aluminum degrader is slightly shorter than the PHITS simulation. This difference cannot be explained by the estimated uncertainty in the beam energy (~1%) of the IRC and a direct energy measurement is necessary to fix this small discrepancy.

In conclusion, we have successfully transferred the high-energy argon beam to the existing irradiation port as expected and, just after commissioning, wakame and kombu samples were irradiated with the high-energy argon beams.

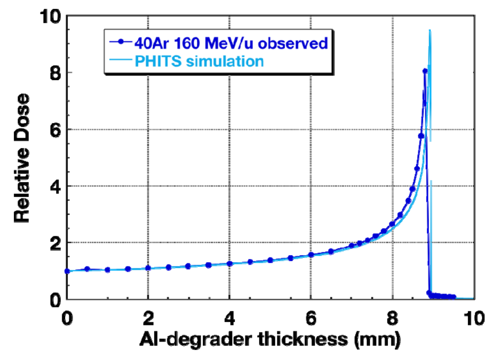

Figure 4: Depth-dose curves for a 160-MeV/nucleon argon beam.

ACKNOWLEDGEMENTS

We would like to thank the accelerator operators of SHI Accelerator Service Ltd. for their dedication in installing many beam line components. A part of the present work was supported by the Tohoku Marine Science Center project from MEXT.

REFERENCES

[1] T. Abe, H. Ryuto and N. Fukunishi, "Ion beam radiation mutagenesis", Plant Mutation Breeding and Biotechnology, edited by Q.Y. Shu, the Joint FAO/IAEA Programme, pp. 95 – 102. (2010).
[2] Y. Yano, Proc. 12th Int. Conf. Cyclotrons and their Applications, Berlin, Germany (1989) p. 13.
[3] T. Hirano et al., "Molecular nature of mutations induced by high-LET irradiation with argon and carbon ions in *Arabidopsis thaliana*", Mut. Res. **735**, 19-31 (2012).
[4] J. Ohnishi et al., Proc. 17th Int. Conf. on Cyclotrons and Their Applications, Tokyo, Japan (2004) p. 197.
[5] A. Goto et al., Proc. 12th Int. Conf. Cyclotron and their Applications, Berlin, Germany (1989) p. 51.
[6] T. Sato, K. Niita, N. Matsuda, S. Hashimoto, Y. Iwamoto, S. Noda, T. Ogawa, H. Iwase, H. Nakashima, T. Fukahori, K. Okumura, T. Kai, S. Chiba, T. Furuta and L. Sihver, Particle and Heavy Ion Transport Code System PHITS, Version 2.52, J. Nucl. Sci. Technol. **50**:9, 913-923 (2013).

ISBN 978-3-95450-131-1