Energy upgrade for biological applications

N. Fukunishi,[*1] M. Fujimaki,[*1] M. Komiyama,[*1] K. Kumagai,[*1] T. Maie,[*1] T. Hirano,[*1,*2] Y. Watanabe,[*1] and T. Abe[*1]

Energetic heavy ions have been used as an effective tool for inducing mutations of flowers, crops and microbes at RIKEN Nishina Center. Typical beams used in these applications are 135-MeV/nucleon C, N and Ne beams, a 95-MeV/nucleon Ar beam, and a 90-MeV/nucleon Fe beam. All of them are accelerated by RRC.[1)] However, the beam energies of Ar and Fe ions are insufficient to obtain nearly flat distributions of Linear Energy Transfer (LET) within thick (or in-water) irradiated samples. It sometimes causes a difficulty such that the dependence of the effectiveness of mutagenesis on LET becomes unclear. Hence an upgrade for beam energies available at the existing in-air irradiation port for biological samples (E5H) is urgently required.

Our solution to this problem is the usage of IRC.[2)] IRC is originally designed to accelerate ions up to 127 MeV/nucleon using RILAC, RRC, and IRC in series or up to 114 MeV/nucleon using RILAC2, RRC, fRC, and IRC in series. However, the maximum beam energy obtained by IRC can be increased up to 160 MeV/nucleon by employing a new acceleration scheme as follows. The injector is AVF cyclotron. It accelerates Ar ions up to 3.7 MeV/nucleon. The ions extracted from AVF are charge-stripped there, injected into RRC, and accelerated up to 66 MeV/nucleon. After RRC, additional charge stripping and energy degradation to 62 MeV/nucleon should be performed by using a thick carbon disk, which is inevitable to compensate for an energy mismatch inherent to this non-orthodox acceleration scheme.

160-MeV/nucleon Ar ions extracted from IRC are transported to the existing E5H irradiation port by extending the RIBF beam transport system as shown in Fig. 1. A beam extracted from IRC is deflected by DAKR dipole magnet in order to separate the beam from the existing SRC-injection line. The section from IRC extraction to DMR2 makes a dispersive IRC-extracted beam doubly achromatic. The beam is bended up by DMR3 and bended down by DMR4 to shift the beam vertically by 3 m to compensate for the existing floor level difference. Here, the doubly achromatic condition is also fulfilled in the vertical direction. The section from DMR5 to DMR6 forms an achromatic bending system of 90 deg. The section from DMR7 and DMR8 is also doubly achromatic. After that, the beam line is joined to the existing beam delivery fishbone at DMA1. The section immediately after DMR2 to DMR6 is not newly constructed but utilizes the existing IRC-bypassing[3)] beam line in the reverse direction. Note that the IRC-bypassing beam line was constructed to inject a beam accelerated by RRC directly to SRC in order to perform light-ion experiments. The maximum magnetic rigidity of the new branch beam line is 4.4 Tm, which covers not only 160-MeV/nucleon $^{40}Ar^{18+}$ ions but also heavier ions such as $^{56}Fe^{26+}$ ions.

Beam commissioning was made in January 2015. We extracted a 160-MeV/nucleon Ar beam in the proposed non-orthodox acceleration scheme. We found no sizable beam loss along the whole new beam transport system and confirmed that our optical design of the new branch beam line worked well. In addition, we successfully produced a uniform irradiation field of 10 cm in diameter and obtained a depth-dose curve of Ar ions as expected from numerical simulations. Details of the beam commissioning are given in Ref. 4.

One problem observed in the beam commissioning was sizable (~ 40%) beam loss during acceleration at IRC. The cause of this abnormal behavior was fixed in the additional beam test performed in October 2015. The observed beam loss was induced by a half integer resonance in the vertical betatron motion. The vertical tune at beam extraction is 0.6, which is not so close to 0.5 but strong harmonic magnetic fields induced at the beam extraction region of IRC created problems. These strong harmonic fields are effective for outer most ions accelerated in the standard acceleration schemes to secure a sufficient clearance from a baffle slit attached to the IRC chamber wall. In October, we reduced harmonic magnetic fields by rebalancing excitation currents of outer trim coils and obtained a transmission efficiency of up to nearly 100%.

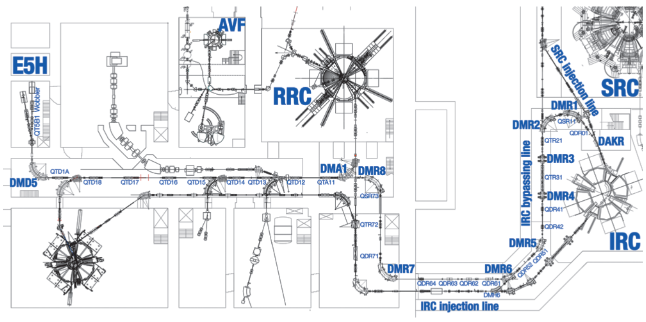

Fig. 1. Layout of RIBF beam transport system.

References

1)Y. Yano : Proc. 12th Int. Conf. Cyclotrons and their Applications, Berlin, Germany (1989) p. 13.
2) J. Ohnishi et al. : Proc. 17th Int. Conf. on Cyclotrons and Their Applications, Tokyo, Japan (2004) p. 197.
3) Y. Watanabe et al. : Accel. Prog. Rep. **42**, 111-112 (2009).
4) N. Fukunishi et al. : Proc. HIAT2015, MOPA04 (2015).

*1 RIKEN Nishina Center
*2 Faculty of Agriculture, University of Miyazaki