# IMPROVEMENT OF THE NIRS-930 CYCLOTRON FOR TARGETED RADIONUCLIDE THERAPY

Satoru Hojo†, Takashi Wakui, Ken Katagiri, Masao Nakao‡, Akinori Sugiura, Akira Noda, and Koji Noda, NIRS, QST, Chiba-shi, Japan

*Abstract*

In recent years, the production of radionuclides for Targeted Radionuclide Therapy (TRT) with the NIRS-930 cyclotron has been one of the most important activities in National Institutes for Quantum and Radiological Science and Technology (QST, NIRS).

In the production of $^{211}$At, for example, a target material with low melting point is irradiated with a high intensity helium ion beam. A vertical beam line has the advantage in irradiation with low-melting-point target. Therefore, a vertical beam line has been modified for the production of radionuclides. This line was used for neutron source with beryllium target.

The beam intensity and beam energy are important parameters for the effective production of radionuclides for TRT. In order to increase beam intensity, the acceleration phase and injection energy have been optimized by measuring beam phase. The beam energy has been measured by TOF and adjusted by tuning the acceleration frequency. Those studies and improvement are reported.

## INTRODUCTION

The NIRS-930 cyclotron was installed in 1974 for a fast neutron therapy and production of radionuclide [1]. The fast neutron therapy was terminated in 1994. At present, the NIRS-930 cyclotron is mainly used for production of radionuclides. Other purposes of the NIRS-930 cyclotron are research of physics, developments of particle detectors in space, research of biology, and so on.

Recently, the TRT has been one of the most important activities in NIRS, QST. Therefore, production of alpha emitter radionuclides for TRT is increased. The operation time for production of radionuclide at the NIRS-930 cyclotron is shown in Fig. 1. In recent five years, the operation time of helium ion beam is increasing. In 2015, the operation time of helium ion beam was increased to 479 hours, which was higher than that of proton beam and was more than 50% of that for production of radionuclides.

## VERTICAL BEAM PORT

A layout of NIRS cyclotron facility is shown in Fig. 2. The HM-18 cyclotron is only used for production of PET-radiopharmaceuticals. The NIRS-930 cyclotron has 10 beam ports, and 5 beam ports of them are exclusively used for radionuclide production. The C-1 and C-2 beam ports are used for production of PET-radiopharmaceuticals. The C-4 beam port is used for production of metal radionuclides such as $^{62}$Zn/$^{62}$Cu for SPECT. The C-9 and C-3 are vertical irradiation ports. The C-9 beam port is used for production of radionuclides with a low-melting-point solid target such as 124I and 76Br [2]. The C-3 beam port was used for fast neutron therapy, and this beam port has been modified for radionuclides production recently. This beam line has wobbler magnets for avoiding heat concentration on a target [3].

In order to produce radionuclides for TRT, the target material with low melting point is irradiated with a high intensity beam. Because an irradiation face doesn't change even if the target melts, the vertical beam port has the advantage in irradiation with low-melting-point target. Therefore, the radionuclides for TRT is produced using these two vertical irradiation ports. $^{211}$At has been produced for TRT using the C-9 beam port [4].

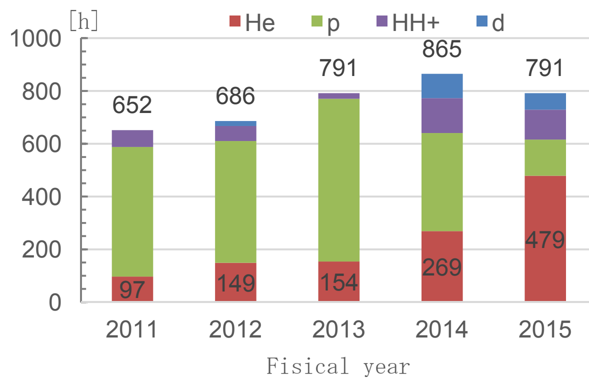


Figure 1: The operation time for production of radionuclide.

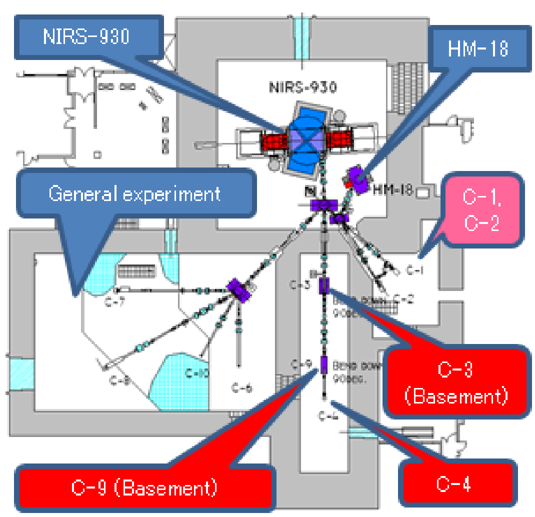


Figure 2: Layout of the NIRS-930 cyclotron. C-3: Radionuclides production using heat damageable targets; C-9: Radionuclides production $^{124}$I, $^{76}$Br, etc; C-4: Radionuclides production for SPECT; C-1, C-2: Production of PET-radiopharmaceuticals.

† hojo.satoru@qst.go.jp
‡ Present Address: RCNP, Osaka University



ISBN 978-3-95450-167-0

## REQUEST FOR BEAM IN PRODUCTION OF RADIONUCLIDE FOR TRT

The beam energy is an important parameter for producing radionuclides for TRT. A certain beam energy is required to keep contamination level low. A high beam intensity is also required, because the beam irradiation time can be shortened by the increase of production rate. Therefore, a higher injection efficiency and a higher extraction efficiency are needed for the NIRS-930 cyclotron.

### *Accuracy of Beam Energy*

In recent years, production techniques of radionuclides such as $^{211}$At have been developed and applied for studies of TRT at NIRS. In the production of $^{211}$At, the beam energy is an important factor for the quality of $^{211}$At. Cross sections of $^{209}$Bi(alpha, 2n)$^{211}$At and $^{209}$Bi(alpha, 3n)$^{210}$At are shown in Fig. 3. The incident beam energy which has a high production rate of $^{211}$At is around 30 MeV. However, when the incident beam energy exceeds 28 MeV, $^{210}$At is also produced. The decay product from $^{210}$At is $^{210}$Po, which is very high radiotoxic. In order to keep $^{210}$At level low, the control of incident beam energy is indispensable. Therefore, the beam energy was measured and adjusted at the NIRS-930 cyclotron.

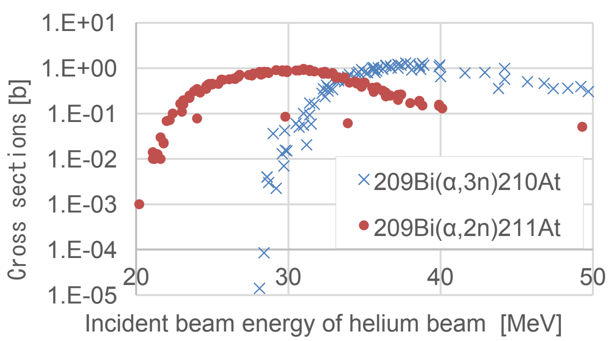


Figure 3: Cross sections of $^{209}$Bi target with helium beams. Dates are taken from EXFOR [5].

### *The Beam Energy Measurement and Adjustment*

The most preferable beam energy from the cyclotron is 34 MeV with an estimation of energy loss by the structure of the target system. The beam energy on target is then 28 MeV.

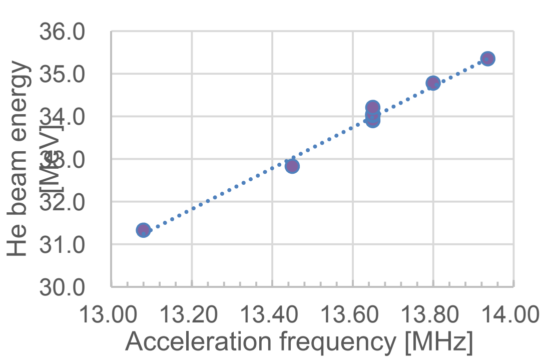


Figure 4: Measured beam energy as a function of acceleration frequency with He beam.

The beam energy was measured by the time-of-flight (TOF) system [6] and was adjusted by changing acceleration frequency. The TOF system uses two electrostatic pickup monitors. The result of the beam energy measurement by changing acceleration frequency is shown in Fig. 4. The acceleration frequency for production of $^{211}$At has been determined to 13.65 MHz from the results of this measurement.

The extraction beam energy was measured at daily operation. The difference between nominal and actual energies at daily operation of 34 MeV helium beam is shown in Fig. 5. The difference between nominal and actual energies were roughly within 0.3%.

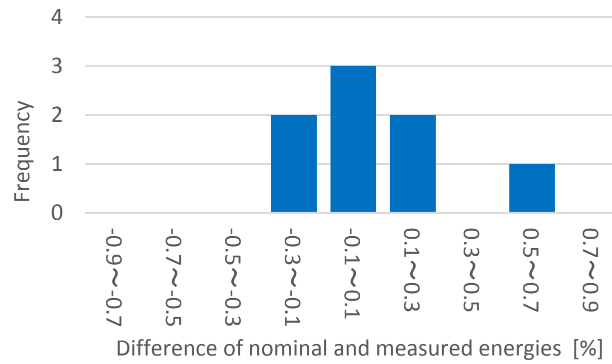


Figure 5: The difference between nominal and actual energies at daily operation of 34 MeV helium beam.

### *Extraction Efficiency*

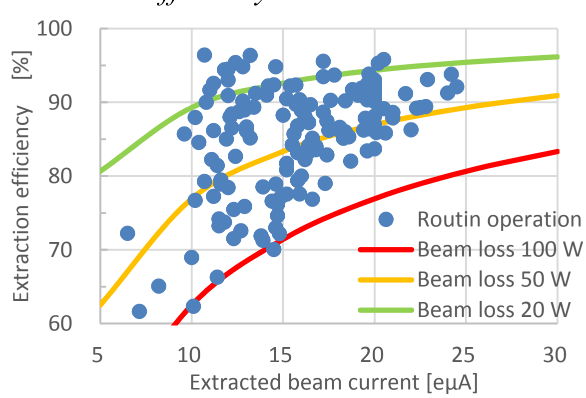


Figure 6: The extracted beam intensity as a function of extraction efficiency in routine operation.

A demand on higher beam intensity for 34 MeV $He^{2+}$ is growing in radionuclide production for TRT. Therefore beam intensity has been increased to 24.5 μA by adjusting operation parameter [7]. A higher extraction efficiency is needed for high intensity beam. Here, the extraction efficiency is the ratio of beam current at a deflector entrance and at an exit of the cyclotron. If the extraction efficiency is low, the extraction system such as a deflector are damaged and activated. The extracted beam intensity as a function of extraction efficiency in the routine operation and the lines of beam loss (100, 50, 20 W) are shown in Fig. 6. The beam loss at extraction beam intensity over 20 μA in the routine operation was below 100 W.

ISBN 978-3-95450-167-0

### *Injection Efficiency*

The injection beam current is defined as the beam current at inflector electrode when the inflector voltarge is zero volt. The injection efficiency is percentage ratio of the injection beam current and the beam current at cyclotron radius 100 mm. The injection efficiency with and without buncher as a function of injection beam current are shown in Fig. 7. The injection efficiency with buncher is declined with increasing the injection beam current.

The average injection efficiency without buncher is 22%. The beam phase width can be estimated from this injection efficiency. The average beam phase width without buncher is estimated to be 79.2 degree from the average injection efficiency.

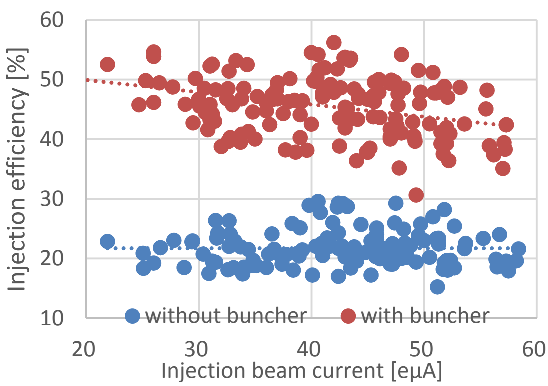


Figure 7: Dependence of injection efficiency with buncher and without buncher on injection beam current.

The dependence of a beam bunch length on the beam intensity was simulated by SPUNCH [8] to confirm the buncher gain and one-dimensional longitudinal space charge effects. In this calculation, the injection beam current at inflector ranges from 30 to 60 eμA. The results are shown in Fig. 8. The beam bunch length becomes wider by increasing the injection beam current.

The buncher gain is defined as the ratio of the beam current with and without buncher at cyclotron radius of 100 mm. The buncher gain in routine operation is shown in Fig. 9. The buncher gain tends to decline with increasing the beam current. We also calculated the buncher gain by SPUNCH using the beam phase width of 79.2 degree. The results of the calculation for the injection energy of 10.8, 12.8, and 14.8 keV are also shown in Fig. 9. The buncher gain is declined with increasing the injection beam current as with the injection efficiency. It was confirmed the decline in the buncher gain by space charge effects of injection beam was the cause of the decline in the injection efficiency. From Fig. 9, the calculated buncher gain becomes larger with increasing energy. Thus, the buncher gain can be increased with the higher injection energy. It is suggested that a modification of the central region such as an inflector electrode is needed to increase the beam current of 34 MeV $He^{2+}$.

## CONCLUSION

The NIRS-930 has been used for production of radionuclide for TRT. The energy of extracted beam was measured and adjusted. The difference between nominal and actual energies were to be roughly within 0.3% in the routine operation. In the beam extraction, the beam loss was less than 100 W. For the beam injection, a modification of the central region to increase the injection energy is needed to suppress the space charge effect.

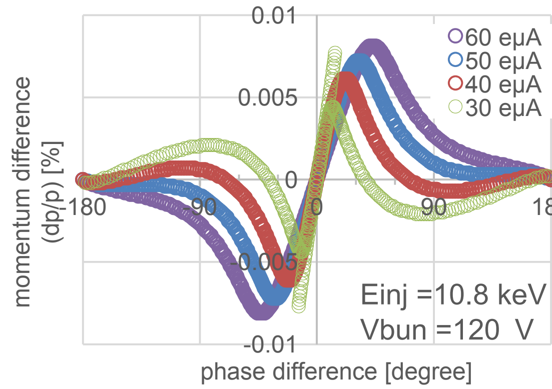


Figure 8: The calculation of the bunch length at the inflector by SPUNCH. The dependence the injection beam current of 30 to 60 eμA. Einj: Injection energy to the cyclotron, Vbun: buncher voltage.

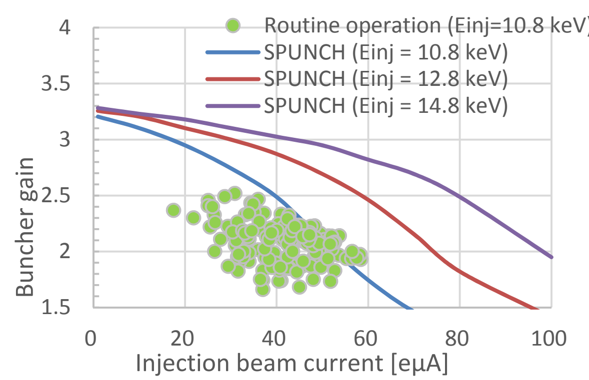


Figure 9: The buncher gain at cyclotron radius 100 mm.

## REFERENCES

[1] H. Ogawa, *et al*, IEEE Trans. Nucl. Sci. NS-26, No.2 (1978) p. 1988.

[2] K. Nagatsu *et al*., "Fully automated production of iodine-124 using a vertical beam", Applied Radiation and Isotopes 69 (2011) 146–157.

[3] K. Katagiri, *et al*., "Design of beam transport lines for radioisotope production systems in NIRS cyclotron facility"in *Proc. IPAC'2014*, Dresden, Germany, June 2014, paper WEPRO088, pp 2162-2164.

[4] K. Nagatsu, *et al*., "Production of $^{211}$At by a vertical beam irradiation method" Applied Radiation and Isotopes 94 (2014) 363–371.

[5] EXFOR `http://www.jcprg.org/exfor/` Hokkaido University Nuclear Reaction Data Centre (JCPRG).

[6] S. Hojo, *et al*., "A beam energy measurement system at NIRS-930 cyclotron" in *Proc. Cyclotrons'04*, Tokyo, Japan, October 2004 p. 407.



ISBN 978-3-95450-167-0

[7] S. Hojo, *et al*, “Progress on the upgrade for TRT at NIRS Cyclotron Facility” in *Proc. HIAT2015*, Sept. 2015, paper MOPA07, p. 48.

[8] R. Baartman, “SPUNCH - A space charge bunching computer code”, in *Proc. Cyclotrons’86*, Tokyo, Japan, Oct. 1986, p. 238.

ISBN 978-3-95450-167-0