Performance of the OEDO beamline

J W Hwang¹, S Michimasa¹, K Yamada², S Ota¹, M Dozono¹, N Imai¹, K Yoshida², Y Yanagisawa², K Kusaka², M Ohtake², M Matsushita¹, D S Ahn², O Beliuskina¹, N Chiga², K Chikaato³, N Fukuda², S Hayakawa¹, E Ideguchi¹, K Iribe⁶, C Iwamoto¹, S Kawase⁶, K Kawata¹, N Kitamura¹, S Masuoka¹, H Miyatake⁷, D Nagae², R Nakajima¹, T Nakamura⁸, K Nakano⁶, S Omika², H Otsu², H Sakurai², P Schrock¹, H Shimizu¹, Y Shimizu², T Sumikama², X Sun², D Suzuki², H Suzuki², M Takaki¹, M Takechi³, H Takeda², S Takeuchi⁸, T Teranishi⁵, R Tsunoda¹, H Wang⁶, Y Watanabe⁶, Y X Watanabe¹, K Wimmer⁹, K Yako¹, H Yamaguchi¹, L Yang¹, H Yoshida⁵ and S Shimoura¹

¹ Center for Nuclear Study, the University of Tokyo, Wako, Saitama 351-0198, Japan
² RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan
³ Department of Physics, Niigata University, Niigata, Niigata 950-2181, Japan
⁴ Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
⁵ Department of Physics, Kyushu University, Nishi-ku, Fukuoka 819-0395, Japan
⁶ Department of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka 816-8560, Japan
⁷ Wako Nuclear Science Center, IPNS, KEK, Wako, Saitama 351-0198, Japan
⁸ Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 158-8551, Japan
⁹ Department of Physics, the University of Tokyo, Bunkyo, Tokyo 113-0033, Japan

E-mail: jw.hwang@cns.s.u-tokyo.ac.jp

Abstract. The OEDO (Optimized Energy Degrading Optics for RI beam) beamline has been developed to obtain low-energy (10 – 50 MeV/u) RI beams by slowing down the secondary beams at RIBF, RIKEN. Such beams are useful probes to investigate nuclear structure by means of nucleon transfer and Coulomb excitation reactions. The beamline is designed to produce a well-focused beam of small energy spread with the help of the angle-tunable wedge degrader and the radio-frequency deflector. The commissioning and first physics experiments using the OEDO beamline were carried out in 2017. OEDO successfully provided the energy-degraded beams of Se, Zr, and Pd. Its performance including the optics and transmission was evaluated using those experimental data and it functions properly as designed. We expect that our novel beamline shed a light on the experimental approaches involving nuclear reactions at several tens of MeV/u to expand our knowledge of nuclei far beyond the line of stability.

1. Introduction

A radioactive isotope (RI) beam, the essential tool of the modern nuclear physics, is mainly produced by the two different ways: the isotope separator on-line (ISOL) and the in-flight (IF) methods. In the ISOL method, fission or spallation reactions of beams of light particles (e.g. $e^-$, $p$, $d$) with a heavy element target such as uranium are used. It is efficient with high production rate but it cannot be employed for exotic nuclei. Produced beams have very low energies, a
few MeV/u, including the re-acceleration procedure. In the IF method, RI beams are produced by using fission or fragmentation of primary beams in the production target (e.g. Be). While the intensity is not so high as the ISOL method, it is applicable to nuclei in the vicinity of the driplines. Produced beams have similar energies per nucleon with the primary beams, typically more than 50 MeV/u.

Regarding the beam energy, RI beams with an intermediate energy (10 – 50 MeV/u) are difficult to be reached by both the ISOL and IF methods. Those beams are appropriate to study shell structure and the correlation among nucleons in nuclei by inducing transfer reactions of a nucleon or a pair of them such as \((d,p)\) and \((p,t)\). They are also helpful to investigate astrophysical issues, in particular, nucleosynthesis processes through experimental approaches to the structure and responses of RIs involved in the processes. Other reactions that are active in that energy range such as Coulomb excitation and resonance scattering can provide different experimental evidences in the study of exotic nuclei.

To produce such RI beams, we have established a new beamline called OEDO [1], which stands for ‘Optimized Energy Degrading Optics for RI beams’. It has been designed for low-energy RI beams with the energy of 10 – 50 MeV/u by slowing down higher-energy RI beams provided by BigRIPS [2] at RIBF. This paper reports the essential principle and performance of the OEDO beamline.

2. Design and principle

The OEDO beamline was constructed in the RIBF in RIKEN as a part of the renovation of the High-resolution beamline [3, 4]. As shown in Fig. 1, the OEDO beamline is one of the branches following the BigRIPS beamline, and is operated in cooperation with it. Once the RI beam is produced between F0 and F3, the beam is purified and slowed down during passing through the section from F3 to FE11. The final part from FE11 to S0 serves to tag the beam for reactions at the final focal plane S0. Note that FE11 can be the final focus depending on the experimental conditions. To obtain the well-focused slowed-down beam with the suppressed energy spread, the two key components are introduced into the beamline: the angle-tuneable degrader at FE9 for reducing and bunching the beam energy and the radio-frequency deflector (RFD) at FE10 as a time-dependent ion-optical element for focusing.

2.1. Angle-tuneable degrader

The angle-tuneable degrader consists of a pair of aluminum sheets having quadratic cross sections and their overlap functions as a typical wedge degrader. We can adjust the wedge angle by changing the relative position of the two sheets (for details of the mechanism, see Ref. [5]).

The degrader system has a fixed central thickness of 3 mm and the varying wedge angle from 0 to 40 mrad. If necessary, we can increase the total central thickness by placing an additional flat degrader behind the system. As shown in the inset of Fig. 1, the system includes two guides for each degrader sheets, which are mounted on the horizontal rails for parallel movement. Two linear stepper motors independently drives each guide along the corresponding rail by remote control.

To obtain a monoenergetic beam with an expected energy, the system is installed at the dispersive focus (FE9) and optimized by tuning its wedge angle and total thickness. The wedge angle is determined to vanish the dispersion of a beam for compression of its energy distribution. Fortunately, we can use the real-time data for fine-tuning thanks to remote control. In addition, the total thickness at the beam center can be adjusted precisely by moving both degrader sheets in the same direction.
Figure 1. Schematic layout of the total beamline including the BigRIPS separator, OEDO beamline, and SHARAQ spectrometer. The insets describe the designs of the angle-tuneable degrader and the RFD, respectively. Note that the final focus can be either FE11 or S0 depending on the experimental conditions.

2.2. Radio-frequency deflector
The RFD is used for time-dependent focusing unlike the general ones used to purify secondary RI beams by removing unexpected contaminants. The system consists of a coaxial cavity resonator, a power amplifier, and parallel electrodes. The specifications are determined by considerations of the required bending power, transmission, and physical constraints (for details, see Ref. [1]).

The electric field with a radio frequency is applied in the horizontal direction between the electrodes \( V(t) = V_0 \sin(\omega t + \phi) \), and a beam is horizontally deflected according to its arrival timing and velocity. Because the RFD is synchronized with the superconducting ring cyclotron, the final step of the acceleration process of the primary beam, by fixing the frequency \( \omega \), every bunch of RI beams show the same behavior in the RFD. The phase \( \phi \) and amplitude \( V_0 \) are optimized to obtain the well-focused beam at the final focal plane.

2.3. Ion optical principle
To describe the principle of the OEDO beamline, we introduce the transfer matrix method [6]. Here, we consider the phase space only with the horizontal dimension, \((x, a, \ell, \delta)\). \(x\) and \(a\) are the horizontal position and angle, respectively. \(\ell\) and \(\delta\) correspond to the difference in flight length \(\ell = -v_0(t - t_0)/\gamma_0^2\) and the momentum deviation \((\Delta p/p)\) of the reference particle with respect to the central trajectory, respectively.

A general in-flight separator consists of two ion-optical sections, the initial achromatic focus to the intermediate dispersive focus (F0 – FE9 in OEDO) and the dispersive focus to the final achromatic focus (FE9 – FE11(S0)). A wedge-shaped degrader is placed at the dispersive focus (FE9). If we set \(M_1, M_2,\) and \(D\) to be the matrices for the first (F0 – FE9), second sections (FE9 – FE11(S0)) of the beamline, and the angle-tuneable degrader at FE9, respectively, they
can be described by
\[
\mathcal{M}_{1(2)} = \begin{pmatrix}
(x|x)_{1(2)} & 0 & (x|\ell)_{1(2)} & (x|\delta)_{1(2)} \\
(a|x)_{1(2)} & (a|a)_{1(2)} & 0 & (a|\delta)_{1(2)} \\
(\ell|x)_{1(2)} & (\ell|a)_{1(2)} & 1 & (\ell|\delta)_{1(2)} \\
0 & 0 & 0 & 1
\end{pmatrix}, \quad \mathcal{D} = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
(\delta|x)_{\text{D}} & 0 & 0 & (\delta|\delta)_{\text{D}}
\end{pmatrix},
\]

where \(\mathcal{M}_{1(2)}\) is the general form for point-to-parallel (or parallel-to-point) optics and \(\mathcal{D}\) is that for a wedge degrader with \((\delta|\delta)_{\text{D}} = (1 - t_{\text{D}}/R)^{-1}\) and \((\delta|x)_{\text{D}} = -(\tan \alpha_{\text{D}}) \cdot (1 - t_{\text{D}}/R)^{-1}\) for the given central thickness \(t_{\text{D}}\), wedge angle \(\alpha_{\text{D}}\), and range \(R\) \([6, 7]\).

The best energy-bunching can be achieved by vanishing the \((\delta|\delta)\) term of the transfer matrix of \(\mathcal{M}_m = \mathcal{D} \mathcal{M}_1\), which is \((\delta|x)_{\text{D}}(x|\delta)_1 + (\delta|\delta)_{\text{D}} = 0\). This monoenergetic condition is satisfied using an appropriate wedge angle \(\alpha_{\text{D}}\) of the degrader according to the momentum dispersion \(((x|\delta)_1)\) at the dispersive focus, \(\text{FE}9\).

Typical optics of an in-flight separator consisting of time-independent elements are designed to be symmetric with respect to the degrader, \(\mathcal{M}_2 = \mathcal{M}_1\), with \((x|\ell)_{1(2)} = 0\). Then, the momentum dispersion of the total beamline under the above monoenergetic condition is calculated to be \((x|\delta)_{\text{T}} = (x|x)_{\text{D}}(x|\delta)_1\). In such optics, the best energy compression \(((x|\delta)_{\text{T}} = 0)\) and spatial focusing \(((x|a)_{\text{D}} = 0)\) at the final focal plane cannot be accomplished simultaneously, because vanishing both \((x|x)_{\text{D}}\) and \((x|a)_{\text{D}}\) is impossible in principle within the phase space restricted to \(x\) and \(a\).

Due to the existence of the RFD, the time-dependent ion-optical element, however, the \((x|\ell)_{2}\) term is not zero and the new longitudinal dimension \(\ell\) is introduced to the phase space exploited in the ion optics. Then, the above conditions for energy compression and focusing become
\[
(x|a)_{\text{T}} = (x|\ell)_{\text{D}}(\ell|a)_{1} = 0, \quad (2a)
\]
\[
(x|\delta)_{\text{T}} = (x|x)_{\text{D}}(x|\delta)_1 + (x|\ell)_{\text{D}}(\ell|\delta)_1 = 0. \quad (2b)
\]

Both conditions are practically satisfied by the very small \((x|\ell)_{2}\) and the two right-hand-side terms in Eq. (2b) complementary to each other. In the case of obtaining a \(^{77}\text{Se}\) beam of 40 MeV/u from 170 MeV/u, for example, the beamline satisfies both of the conditions simultaneously, \((x|a)_{\text{T}} = -0.033\) and \((x|\delta)_{\text{T}} = 0.001\), with the operation of the RFD. In terms of ion optics, therefore, the OEDO beamline can achieve its main purpose, producing a well-focused low-energy beam by the slowing-down method with the suppressed energy spread through a phase-space transformation in the extended space with the extra dimension of \(\ell\) using the time-dependent ion-optical element in the beamline.

3. Performance

The performance of the OEDO beamline was verified through the first experimental campaign after the completion of its construction on 2017. In the campaign, OEDO provided several RI beams of \(^{77,79}\text{Se}\) at 19.5 and \(\sim 50\) MeV/u, \(^{93}\text{Zr}\) at 34.3 MeV/u, and \(^{107}\text{Pd}\) at 29.5 and 32.0 MeV/u using the primary beam of \(^{238}\text{U}\) at 345 MeV/u with the Be target for the in-flight fission-fragmentation. To measure the position and angle of a beam for experimental evaluation of the optics of the beamline, two parallel-plate avalanche counters \([8]\) or two low-pressure multi-wire drift chambers \([9]\) were installed at each focus from F3 to S0. For the time-of-flight measurement to reconstruct an energy of a beam, a plastic scintillation counter and a polycrystalline chemical vapor deposition diamond detector \([10]\) were also placed.

3.1. Energy degradation and bunching

Figure 2(a) shows the result of energy degradation and bunching performance in the production of the \(^{79}\text{Se}\) beam of 45 MeV/u from the 170-MeV/u one. The kinetic energies of the beams
without and with the degrader were measured to be 172.8 ± 3.4(σ) and 46.3 ± 2.7(σ) MeV/u, respectively. This result verifies that a monoenergetic low-energy beam is produced as expected with the suppressed energy spread through energy degradation by our degrader system. In particular, we confirm that the angle-tuneable feature operated by remote control helps us to deal with the discrepancy between the design of the ion optics and the actual setting by the fine-tuning of the wedge angle and thickness.

3.2. Beam focusing
The performance of focusing is shown in Fig. 2(b) by comparing the horizontal position distribution of the 50-MeV/u $^{77}$Se beam at FE11 in operation of the RFD to that without operation. For the $^{77}$Se beam, the FE11 focus was designed to be the final focal plane. The RFD was optimized to have the best focusing with the high voltage ($V_0 = 280$ kV) and the phase matched to the arrival timing of the beam. The distribution becomes narrower with the width of 13.5 mm in FWHM when the RFD is in operation, which is three times smaller than the width without operation, 43.9 mm in FWHM. The result shows that the focusing performance of the OEDO beamline is successfully achieved by using the time-dependent ion optical element, RFD.

3.3. Transmission
The transmission of the OEDO beamline was experimentally evaluated from F3 to FE9, FE11, and S0 as tabulated in Table 1. The transmission is defined as the relative intensity with respect to that at F3. The typical distributions of a beam profile are 5 mm in $x$, 15 mrad in $a$, 4 mm in $y$, 30 mrad in $b$, and 2% in $δ$ (all values in FWHM). Consequently, the OEDO beamline provides not only well-focused but also high-intensity RI beams by slowing down intermediate-energy RI beams to a few tens of MeV/u. Note that the poor transmission between FE11 and S0 is due to the small bore diameter of the quadrupole magnet installed in this section.

4. Summary and perspectives
The OEDO beamline has been established at RIBF, RIKEN in 2017, as an upgrade of the High-resolution beamline, to provide a low-energy RI beams of 10 – 50 MeV/u of high quality by slowing down a beam produced by the IF method. Both energy bunching and spatial focusing
Table 1. Transmission of the OEDO beamline with respect to the intensity at F3. This was evaluated for the expected secondary beams, used in the experiments, in the range of 30 – 50 MeV/u.

| Focus | F3 | FE9 | FE11 | S0 |
|-------|----|-----|------|----|
| Transmission (%) | 100 | 61  | 54   | 18 |

are simultaneously accomplished thanks to the monoenergetic degrader that can be precisely optimized by its angle-tuneable feature and the radio-frequency deflector, the time-dependent ion-optical element that can bring in another dimension to the phase space for focusing after energy degradation. For evaluation of the performance of the OEDO beamline, the experiments were carried out to obtain a low-energy beam of $^{77,79}$Se, $^{93}$Zr, and $^{107}$Pd with the energies of several tens of MeV/u and the energy compression and focusing work well as expected. In the OEDO beamline, the beam energy and its spread were reduced from $172.8 \pm 3.4$ to $46.3 \pm 2.7$ MeV/u in $\sigma$, and a horizontal width of the beam was shrunk to be $13.5$ mm in FWHM at the final focal plane, FE11. The beam transmission was evaluated to be 54% at FE11 and 18% at S0.

The produced RI beams for the evaluation of the performance were also used for the physics theme, the spallation reaction of Zr and Pd on a proton/deuteron and the $(d,p)$ surrogate reactions for $^{77,79}$Se [11]. However, the OEDO beamline exhibits its potential when it produces a low-energy beam of exotic nuclei. Many experimental themes such as the systematic study of octupole collectivity on neutron-rich Zr using $(p,p')$ and the $(d,p)$ surrogate reaction for investigation of r-process are being prepared as a future work at OEDO. Obviously, OEDO is open for any experimentalists, and we expect to perform novel experiments to explore nuclear territories far from the $\beta$ stability line.

Acknowledgments
We appreciate the efforts by the staffs in the RIKEN Nishina Center and the Center for Nuclear Study, the University of Tokyo for the successful test of the beamline. This work was funded by ImPACT Program of Council for Science, Technology, and Innovation (Cabinet Office, Government of Japan). S. M. and S. S. acknowledge support by JSPS KAKENHI Grant Number JP16H02177 in Japan.

References
[1] Michimasa S et al 2019 Prog. Theor. Exp. Phys. 2019 043D01
[2] Kubo T et al 2012 Prog. Theor. Exp. Phys. 2012 03C003
[3] Uesaka T et al 2012 Prog. Theor. Exp. Phys. 2012 03C007
[4] Michimasa S et al 2013 Nucl. Instrum. Methods Phys. Res., Sect. B 317 305
[5] Hwang J W et al 2019 Prog. Theor. Exp. Phys. 2019 043D02
[6] Wollnik H 1987 Optics of Charged Particles (Academic Press Inc.)
[7] Shimoda T et al 1992 Nucl. Instrum. and Methods Phys. Res., Sect. B 79 320
[8] Kumagai H et al 2001 Nucl. Instrum. Methods Phys. Res., Sect. A 470 562
[9] Miya H et al 2013 Nucl. Instrum. Methods Phys. Res., Sect. B 317 701
[10] Michimasa S et al 2013 Nucl. Instrum. Methods Phys. Res., Sect. B 317 710
[11] Imai N et al 2018 Proc. 2017 Symp. on Nuclear Data, JAEA-Conf2018-001 (Japan Atomic Energy Agency)