ACCELERATION OF POLARIZED DEUTERON BEAMS WITH RIBF CYCLOTRONS

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Abstract

We have recently performed experiments with polarized deuteron beams at the Radioactive Isotope Beam Factory (RIBF). Tensor- and vector-polarized deuterons were produced using the RIKEN polarized ion source (PIS) [1], which is an atomic-beam-type ion source equipped with an electron cyclotron resonance (ECR) ionizer, and were accelerated to 190 MeV/u, 250 MeV/u, and 300 MeV/u with a cyclotron cascade. To measure the various spin observables, the spin orientation of the deuteron beams was freely directed by using a Wien filter. The advantage of this method is that since the velocity of the deuteron is low the size of a magnet required for the spin rotation is very compact. On the other hand it is crucial to realize strict single-turn extraction for each cyclotron because the cyclotron magnetic field causes precession of the deuteron spin resulting in a deviation between its spin orientation and the beam propagation direction. This paper describes the acceleration of the polarized deuteron beams by the RIBF accelerators and the method to confirm single-turn extraction.

INTRODUCTION

The mission of the Radioactive Isotope Beam Factory (RIBF) accelerator complex is to expand the availability of rare isotope beams. The RIBF accelerator complex was designed to provide various heavy ions with energies of up to 400 MeV/u. The versatility of the primary beams is one of the key advantages of RIBF. The acceleration mode is chosen according to the species, energies, and required intensities. Until now, 345 MeV/u beams of ^{48}Ca and ^{70}Zn, 320 MeV/u beam of α and 345 MeV/u beams of ^{78}Kr, ^{124}Xe, and ^{238}U, have been produced at RIBF using the RIKEN heavy-ion linac (RILAC) injector [2] in variable-energy mode and the RILAC2 injector [3] in fixed-energy mode, respectively. In addition, light ions d (190, 250, 300 MeV/u), ^{12}C, ^{14}N,^{16}O (250 MeV/u), and ^{18}O (230, 250, 294, 345 MeV/u) have been accelerated using the light-ion mode of the azimuthal varying field (AVF) cyclotron as an injector to the RIKEN ring cyclotron (RRC) and superconducting ring cyclotron (SRC), as shown in Fig. 1. While RIBF can provide intense heavy-ion beams for the production of radioactive isotope beams, light-ion beams are also available for physics experiments requiring high precision. Among them, a polarized deuteron beam with an intermediate energy of 100–300 MeV/u is one of the most powerful probes to study spin-dependent interactions, such as three-body-force of nucleon interactions [4]. Required turn purity was more than 99% for these experiments.

POLARIZED DEUTERON BEAMS

Production of Polarized Deuteron Beams

The RIKEN polarized ion source (PIS) is an atomic-beam-type ion source. It is a copy of one developed at Triangle University Nuclear Laboratory (TUNL) [5], and was modified at the Indiana University Cyclotron Facility (IUCF) [6].

A schematic illustration of RIKEN PIS is shown in Fig. 2. First, D_2 gas produced from heavy water in a water electrolyzer is dissociated and formed into atomic beams in a dis-

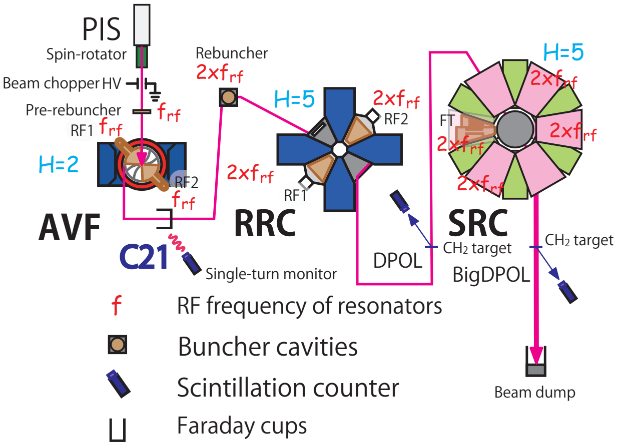


Figure 1: Setup of accelerators and monitors for polarized deuteron acceleration utilizing azimuthally varying field (AVF) cyclotron, RIKEN ring cyclotron (RRC) and superconducting ring cyclotron (SRC).

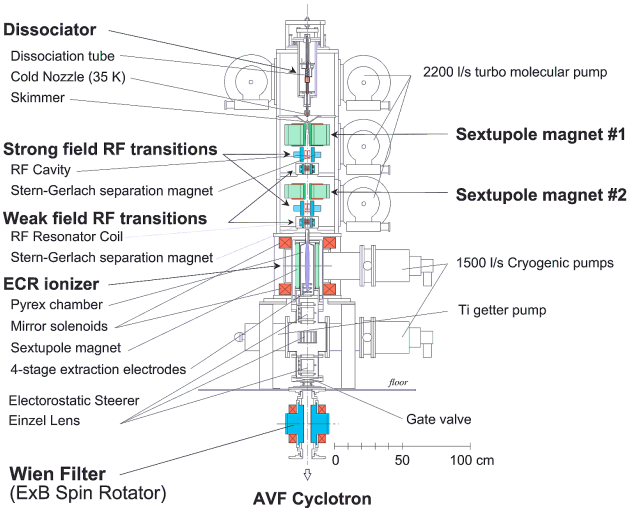


Figure 2: Schematic illustration of RIKEN polarized ion source.

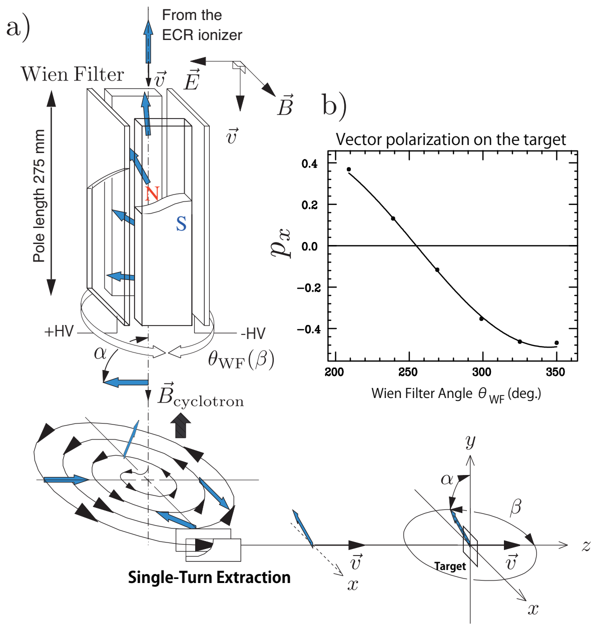


Figure 3: Method of spin-orientation control using a Wien Filter.

sociator. Next, the electron spin of the deuterium atoms is selected by passing the beam through sextupole magnets. The subsequent RF transition apparatus flips the deuteron spins using Stern-Gerlach separation magnets. RIKEN PIS is equipped with a two-stage spin selector so that any deuteron spin state represented by vector and tensor polarizations can be obtained. Spin-selected deuterium atoms are then ionized by the ECR ionizer, and the intensity of the resulting ion beam is < 100 μA. The polarization of the deuteron beam is typically 80% of the theoretical value. The orientation of the polarization of the deuteron beams, which is in the vertical direction after the ionizer, can be controlled using a so-called Wien filter installed downstream of the ECR ionizer before injection to the AVF cyclotron [7] (see Fig. 2). Using a magnetic field, the deuteron spins are tilted without changing their direction of the motion by the $\vec{E} \times \vec{B}$ field, and are rotated azimuthally by rotating the Wien Filter. The tilt and rotation angles were calibrated by observing the vector polarization, as shown in Fig. 3b.

Why Single-turn Extraction?

During acceleration by the cyclotrons, the cyclotron magnetic field causes the deuteron magnetic moment $\vec{\mu}_d = g\vec{S}_d$ (g is g-factor defined as a ratio of magnetic moment to spin) to precess according to the following equation.

$$\frac{d\vec{\mu}_d}{dt} = \gamma \vec{\mu}_d \times \vec{B}_{\mathrm{cyclotron}}$$

Here γ is a Lorentz factor.

Controlling the spin orientation by tilting the spin prior to injection to the cyclotrons was considered unsuitable, since when the deuteron spin was tilted into the horizontal plane, the spin orientation with respect to the beam propagation direction differs turn-by-turn by an angle of $\Delta\beta = 360\times\gamma(g-1)$ degrees (g=0.8477 for a deuteron). If the deuterons have different turn numbers, i.e., if different spin orientations are simultaneously extracted, from the deuteron polarization amplitude will be reduced. To overcome the problem, single-turn extraction and maintaining the same turn number for the extracted beam was required for all these cyclotrons. Therefore, a real-time monitoring system for single-turn extraction that measures the purity of the turn is indispensable.

Table 1: Characteristics of AVF, RRC, and SRC

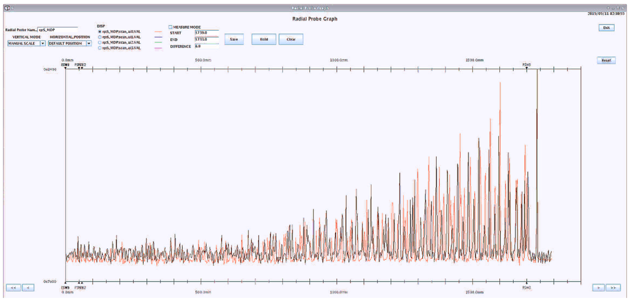
Cyclotron	**AVF**	**RRC**	**SRC**
K [MeV]	70	540	2600
R_{inj} [m]	inflector	0.89	3.56
R_{ext} [m]	0.712	3.56	5.36
Number of Sectors	4	4	6
Sector Angle [deg.]	50	50	25
RF Resonators	2	2	4+FT
Number of gaps [/res]	2	2	1
Dee Angle [deg.]	85	23.5	-
Harmonic Number	2	5	5
Frequency [MHz]	12–24	18–38.2	18–38.2
V_{acc} [MV/turn]	<0.2	0.4–0.5	1.5–2

Table 2: Accelerated Beam Energy $E_d(\equiv E_{\mathrm{total}}/\mathrm{A})$, RF frequency ($f_{\mathrm{rf}}$), RF voltage ($V_{\mathrm{rf}}$), Turn Separation ($\Delta\bar{R}_{\mathrm{ext}}$) for Acceleration of Deuterons with an Energy of 190, 250, and 300 MeV/u.

Energy [MeV/u]		**190**	**250**	**300**
AVF	E_d [MeV]	4.0	4.9	5.5
H=2	f_{rf} [MHz]	12.3	13.7	14.5
	V_{acc} [kV/turn]	89	92	107
	$\Delta\bar{R}_{\mathrm{ext}}$ [mm]	4.0	3.3	3.4
RRC	E_d [MeV]	70.4	89.9	102.5
H=5	f_{rf} [MHz]	24.6	27.4	29.0
	V_{acc} [kV/turn]	581	655	795
	$\Delta\bar{R}_{\mathrm{ext}}$ [mm]	6.6	5.7	5.9
SRC	E_d [MeV]	187.5	252.3	298.5
H=5	f_{rf} [MHz]	24.6	27.4	29.0
	V_{acc} [kV/turn]	1403	1482	1461
	$\Delta\bar{R}_{\mathrm{ext}}$ [mm]	7.6	5.5	4.3

Acceleration by a Cyclotron Cascade

As mentioned above, the deuterons were accelerated by the cyclotron cascade shown in Fig. 1 utilizing the AVF [7], RRC [8], and SRC [9]. The main specifications of these three cyclotrons are listed in Table 1. Table 2 lists the acceleration parameters for the deuterons with energies of 190, 250, and 300 MeV/u. The AVF cyclotron, which consists of an H-type magnet with four spiral sectors and two frequency-tunable RF resonators, was designed as a light-heavy ion injector to the RRC. The vector- and tensor-polarized deuteron beams provided by the polarized ion source were injected to the



Radial Probe Nam... rpS_MDP

VERTICAL MODE: MANUAL SCALE

HORIZONTAL_POSITION: DEFAULT POSITION

START 1739.0

END 1733.0

DIFFERENCE 6.0

Figure 4: Beam turn patterns of the SRC with (red line) and without (black line) flat-topping, as measured by a radial probe.

AVF cyclotron after passing through an electrostatic inflector, which only changes the direction of the beams. To obtain a sufficient turn separation at the extraction region, a so-called phase slit was used to reduce the longitudinal emittance at the beam injection. The RRC is a separate-sector cyclotron with four sector magnets and two double-gap RF resonators. Since the injection radius of the SRC was designed to have an identical radius to the extraction radius of the RRC (see Table 1), light-ion beams, which have a fairly large charge-to-mass ratio can be directly injected to the SRC with the same harmonic number. The SRC, which has a K-number of 2600 MeV, is capable of providing 345 MeV/u $^{238}U^{86+}$ ions with an average magnetic field of $\bar{B} = 1.5$ T. The six-sector magnet, which utilizes superconducting technology [10], produces magnetic fields of up to 3.8 T. A deuteron energy (E_d) of 190 MeV/u requires a magnetic field of $\bar{B} = 0.77$ T, which is below the lower limit originally intended for the SRC. Owing to the fairly high acceleration voltage produced by the four acceleration resonators (see Table 1), a sufficient turn separation was obtained at the extraction region. Furthermore, flat-top acceleration by imposing the third-harmonic RF during the deceleration phase on fundamental acceleration RF field was crucial for accepting the beams from the RRC without using a re-buncher. Figure 4 shows the beam density distributions in the case of $E_d = 190$ MeV/u when the third-harmonic resonator was on and off, as measured using a radial probe. The turn pattern indicated by a red line obtained with flat-topping acceleration exhibits sharp peaks and a larger separation between the tail parts of consecutive two turns compared to the black one which was taken by turning off the flat-top resonator.

SINGLE-TURN MONITORS

In the case of single-turn extraction, beam bunches are extracted through an electrostatic-deflection-channel (EDC) after N times circulation. If some portion of the bunch was not extracted at the right time, it slipped into other bunches. Therefore, single-turn extraction can be confirmed by observing the time structure of the extracted beams.

For the AVF, the time structure of beam bunches chopped using a fast electrostatic chopper system [11] was useful for measuring the turn mixing rate [12]. Since the harmonic number of the AVF was even (two), the portion extracted with 1-turn delayed ($N + 1$) or 1-turn advanced ($N - 1$) extraction appeared at the timing indicated by the arrows in Fig. 5b and Fig. 5c, respectively. An example of the time structure of the beam bunches is shown in the right panel of Fig. 5. The single-turn monitor shown in Fig. 1, which is a plastic scintillation counter, measured the timing of the detected gamma-rays from beam stopper C21 (Faraday Cup) inserted into the transport line. In this case, no turn mixing was found, as indicated by the blue and red arrows in Fig. 5.

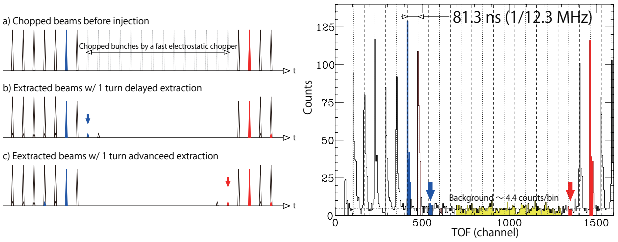


Figure 5: Left: Schematic illustration of the time structures of bunched beams before injection and after extraction. Right: Measured time structure of the extracted beams.

For the RRC and the SRC, whose RF resonators operate at the second harmonic of that of the AVF resonators (i.e., $f_{\mathrm{rf}}^{\mathrm{RRC,SRC}} = 2 \times f_{\mathrm{rf}}^{\mathrm{AVF}}$) with an odd harmonic number of 5, a degree of turn mixing can be obtained by observing a bunch frequency of the extracted beams. An example of the measured time structure of the beams extracted from the SRC is shown in Fig. 6a. The figure shows the timing of the recoiled protons with a CH_2 target in reference to an RF signal with a frequency of $f^{\mathrm{beam}}/2$, as measured using the BigDPOL deuteron polarimeter (see Fig. 1). While the beam frequency (f^{beam}) is the same as the RF frequency of the AVF resonators, beams extracted at the wrong timing appear among the timings of f^{beam}, as indicated by the red arrows in Fig. 6a. In this case, the observed mixing rate was 0.07%. Figure 6b is a histogram of the time difference between scattered and recoiled particles detected in coincidence. The overall time resolution of the monitor, as estimated by the width of the peak, was 0.75 ns. The length of the beam bunches at the target position was roughly estimated from the width shown in Fig. 6a to be as short as 0.58 ns by subtracting the time resolution of the monitor estimated

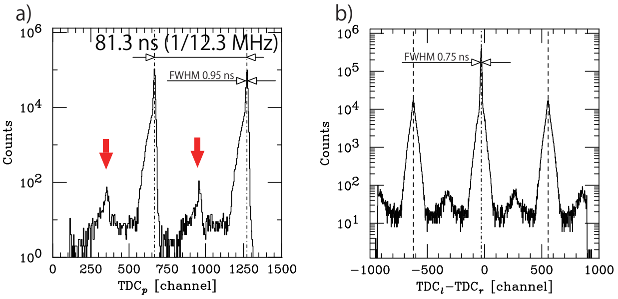


Figure 6: Measured time-of-flight and time difference between a deuteron counter and a proton counter.

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from Fig. 6b, which corresponds to ± 2.6 deg. in phase of $f_{\mathrm{rf}}^{\mathrm{SRC}}$. The single-turn operation was stable and extracted turn was successfully maintained during the measurements for 2–3 days and the obtained turn purity was much more than 99%.

SUMMARY

Polarized deuteron beams with energies of 190, 250, and 300 MeV/u were used in deuteron-proton elastic scattering experiments [4]. Single-turn operation was feasible for this series of experiments, even in the case of 190 MeV/u and $\bar{B}$ = 0.77 T, which was below the lower limit originally intended for the SRC. The purity of the single-turn was satisfactory, and the accelerators were stable enough to perform the experiments.

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