Status of the RIKEN AVF Cyclotron

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Abstract

The RIKEN AVF cyclotron has been in routine operation as an injector of the RIKEN Ring Cyclotron (RRC) since April 1989. The number of ion species accelerated until now amounts to 15. Beam transmission efficiency through the cyclotron is typically about 20 %. Single turn extraction is achieved and the extraction efficiency of over 75 % is routinely obtained. Polarized deuterons have been available since April 1993. Stand-alone use of the cyclotron for low-energy experiments also started in June 1993.

I. INTRODUCTION

The AVF cyclotron was completed at the end of March 1989 as one of two injectors (the other is the RILAC) of the RIKEN Ring Cyclotron (RRC).[1,2]

It has a K-value of 70 MeV, allowing us to accelerate ions whose m/q value is up to 4.5. The number of spiral sectors is 4. The extraction radius is 714 mm, which is 4/5 times the injection radius of the RRC. Beam acceleration is made, in harmonics of 2, with a couple of 85^{o} RF dees operating between 12-24 MHz. The cyclotron has external ion sources: a 10 GHz ECR ion source and a polarized proton/deuteron ion source. A beam from the ion source is injected through the upper yoke of the magnet and inflected onto the median plane of the cyclotron with a spiral inflector. A beam buncher is located 2 m upstream from the inflector. It consists of a pair of meshes; a sawtooth wave-form electric field is produced between them. The first beam (7 MeV/nucleon $^{14}N^{5+}$) was successfully extracted from the cyclotron in April 1989.[1] Since then the cyclotron has routinely been operated in a combination with the RRC, and its performance has gradually been upgraded in terms of beam intensity, transmission efficiency, extraction efficiency, stability and so on.

In this paper will be reported our operational experiences, including the acceleration of polarized deuterons. A brief description on stand-alone use of the cyclotron will also be presented.

II. OPERATIONAL EXPERIENCES

Table 1 lists the ions accelerated by the AVF cyclotron during the past four years since the first beam was obtained. We have accelerated 15 kinds of ion species. Beam intensities of several eμA are routinely extracted in recent operation. The recent one-year statistics of beam time shows that those for the following three kinds of ions exceed 50 % of the total beam time: 5.2 MeV/nucleon (95 MeV/nucleon from the RRC) $^{40}Ar^{11+}$ and 7 MeV/nucleon (135 MeV/nucleon) $^{12}C^{4+}$ and $^{18}O^{6+}$.

The performance of the 10 GHz ECR ion source has been increased in terms of beam intensity and stability by applying the plasma cathode method to its first stage.[3] Owing to this method, the beam intensities of heavy ions, in particular like Ar and Kr ions, have been greatly improved, e.g. 80 eμA of $^{40}Ar^{11+}$ and 9 eμA of $^{84}Kr^{20+}$. According to this upgraded performance, the extracted beam intensity of 5.2 MeV/nucleon $^{40}Ar^{11+}$ from the cyclotron, for example, has been increased up to about 4 eμA. The upgraded performance will allow us to accelerate 4.0 MeV/nucleon (70 MeV/nucleon from the RRC) $^{84}Kr^{20+}$ with practical beam intensity. To produce metallic ions like Mg, Al, Ni and Zr ions, we use ceramic rods of their oxides. The plasma cathode method has also remarkably been effective for these metallic ions.

A single turn extraction can be achieved by carefully adjusting the first harmonic field near the extraction and the currents of the trim coils near the cyclotron center. The beam extraction efficiency of over 75 % is routinely obtained. The beam bunching efficiency with the sawtooth buncher is 5-6. The beam transmission efficiency through the cyclotron is then typically about 20 %, though it depends on the kind of accelerated ion and in some cases drops as low as about 5 %.

In June 1992 a polarized proton/deuteron ion source was completed.[4] It is assembled about 8 m directly above the AVF cyclotron center. During the last one year effort has been made on the modifications mainly of the dissociator, the ECR ionizer and the extraction device. The beam intensity extracted from the ion source has recently increased up to 140 μA. Acceleration of a polalized deuteron beam has also been made with the AVF cyclotron (7 MeV/nucleon) as well as the RRC (135 MeV/nucleon), and the polarization has been measured. Because the AVF cyclotron cannot separate deuterons and H_2^+ ions, a charge stripper foil is used after the cyclotron to omit H_2^+ ions. Polarized dueteron beam of 300 nA and 100 nA have been obtained at 7 MeV/nucleon and 135 MeV/nucleon, respectively, with 50-60 % polarization of the ideal value. The single turn extraction available for both the AVF cyclotron and the RRC has allowed us to freely control the spin direction using a spin rotator (a Wien filter) placed downstream of the ion source, without reducing the polarization or the intensity. Figures 1 and 2 show examples of turn patterns measured for polarized deuterons inside the cyclotron and in the extraction region near the entrance of the deflector, respectively.

Beam emittances were measured before and after the

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cylotron: the emittance of the beam from the ECR ion source was about 150π mm.mrad and the emittance of the extracted beam about 6π mm.mrad. Pulse width of the extracted beam was preliminarily measured with a new type of beam phase monitor.[5] The width (FWHM) of 5.5 MeV/nucleon $^{18}O^{6+}$ ion beam was 1.6 nsec corresponding to 8.4 RF degrees. Precise measurement with the monitor will be made.

Until now, there have been serious troubles with respect to the following cyclotron components: a part of the RF contact fingers of the shorting plate were burnt and melt; and the deflector became not to work due to its unendurable leak current. In the latter case, white powder-like material containing very thin and short needle-like material was adhered to the inside of the septum along the median plane level. To remove the origin-unknown material, we had to disassemble the cyclotron four times in the recent half year.

III. STAND-ALONE USE OF THE AVF CYCLOTRON

Stand-alone use of the AVF cyclotron started in June 1993. For this three experimental ports have been provided as shown in Figure 3: at port A is installed a chamber for use in radioisotope production; at port B a scattering chamber for slow-positron experiments; at port C a scattering chamber for nuclear physics experiments. The port A is located at the end of the extraction straight line in the cyclotron vault, the port B at the end of the vertical line in E7 experimental room and the port C at the end of the horizontal line in E7. So far two experiments were made: a slow-positron experiment using 5.2 MeV proton beam at the port B and measurement of fusion cross sections using 6.7 MeV/nucleon ^{27}Al beam at the port C. The stand-alone use is made while the RRC is operated with the RILAC beam injection.

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Table 1
Ions accelerated by the AVF cyclotron from April 1989 to June 1993

Particle	Charge	RF freq. (MHz)	Energy* (MeV/nucleon)	Intensity (eμA)	Particle	Charge	RF freq. (MHz)	Energy* (MeV/nucleon)	Intensity (eμA)
p	1	19.35	9.9 (210)	5.2	^{14}N	4	13.0	4.4 (80)	3.3
	1	21.1	11.8 (270)	0.07		5	16.3	7.0 (135)	12.0
H_2	1	12.3	4.0 (70)	3.1	^{15}N	4	12.3	4.0 (70)	2.6
	1	14.0	5.2	5.0		5	15.25	6.1 (115)	1.3
	1	16.3	7.0 (135)	5.4	^{16}O	5	13.1	4.4 (80)	7.8
d	1	12.3	4.0 (70)	1.4		6	16.3	7.0 (135)	3.3
	1	13.8	5.0	2.6	^{18}O	5	12.3	4.0 (70)	5.2
	1	14.5	5.5 (100)	0.6		6	14.5	5.5 (100)	12.0
	1	16.0	6.7 (130)	0.5	^{20}Ne	7	16.3	7.0 (135)	7.4
	1	16.3	7.0 (135)	3.4	^{22}Ne	6	12.3	4.0 (70)	5.9
pol. d	1	16.3	7.0 (135)	0.3	^{24}Mg	7	14.5	5.5 (100)	0.3
^{12}C	4	13.95	5.1 (92)	0.7	^{27}Al	8	14.5	5.5 (100)	0.3
	4	14.5	5.5 (100)	0.6		9	16.0	6.7	0.5
	4	16.3	7.0 (135)	7.3	^{40}Ar	11	13.0	4.4 (80)	0.4
^{13}C	4	12.3	4.0 (70)	2.0		11	14.05	5.2 (95)	3.8

* The values in the parentheses show the energies obtained by the coupled operation with the RRC.

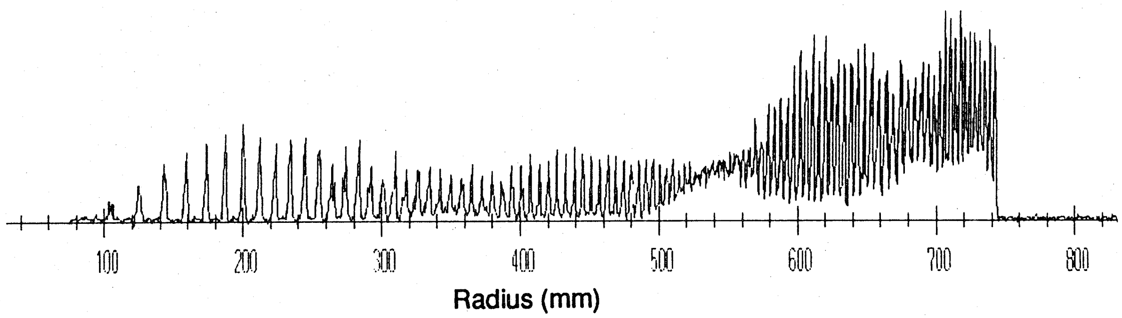

Figure 1 Example of turn pattern of 7 MeV/nucleon polarized deuterons inside the cyclotron.

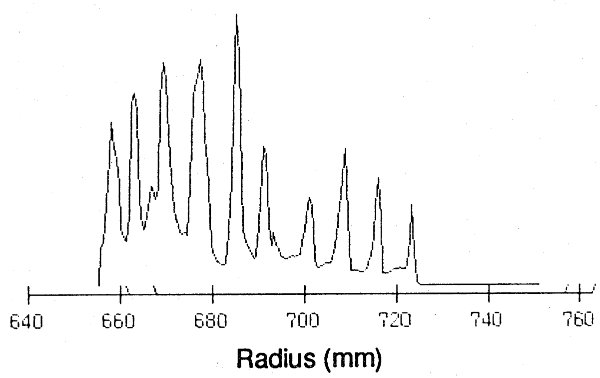

Figure 2 Example of turn pattern of 7 MeV/nucleon polarized deuterons in the extraction region near the entrance of the deflector. Turn separation is widen with the first-harmonic field perturbation.

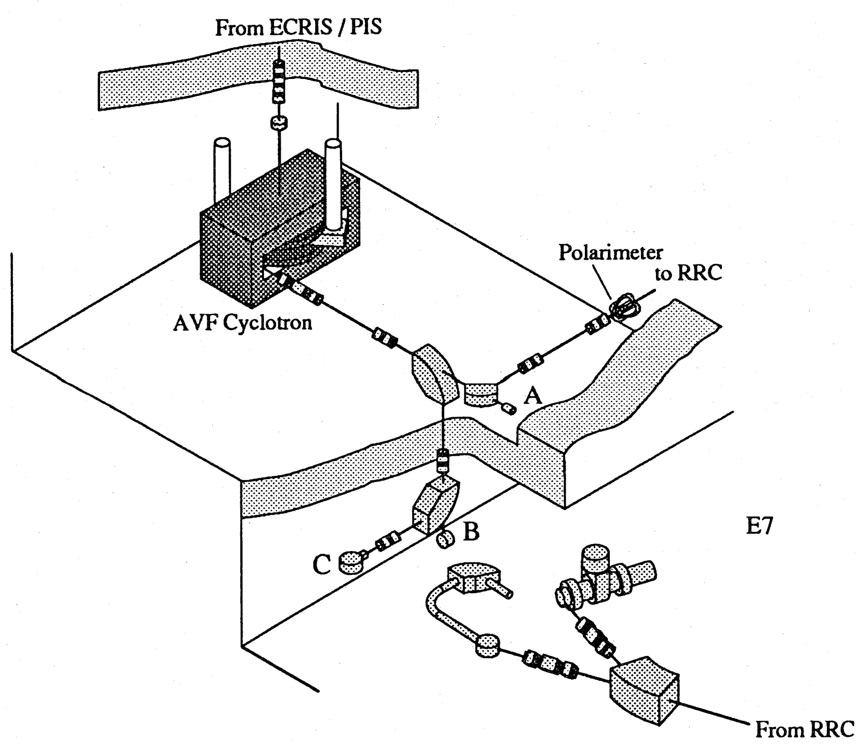

Figure 3 Schematic drawing of the arrangement of experimental ports A-C in the AVF cyclotron vault and E7 experimental room. Port A: Radioisotope production; Port B: Slow-positron experiment; and Port C: Nuclear physics experiment.