RECENT DEVELOPMENTS OF THE RCNP AVF CYCLOTRON

T. Itahashi, T. Saito, N. Matsuoka, H. Sakai, A. Shimizu, K. Hosono,
I. Miura, T. Yamazaki, H. Ogata and M. Kondo
Research Center for Nuclear Physics, Osaka University, Mihogaoka, Ibaraki, Osaka 567, Japan

Abstract

The RCNP cyclotron has been satisfactorily operated for the vast demand of nuclear research experiments and other related fields. The cyclotron has worked for about 6000 hours in 1985. The beam currents of polarized proton and deuterons have been increased by the recent improvements of the polarized ion source. Protons and deuterons polarized in horizontal direction have been successfully extracted and used for the experiments. A pulsed arc power supply for PIG-type ion source has been stably operated to supply the highly charged light-heavy ions. Metal ions, lithium and calcium ions have been accelerated by using sputtering method. Negative hydrogen beam was successfully accelerated and extracted at the energy of 25 MeV.

The cyclotron cascade project will start next year and the AVF cyclotron will play an injector for the separated sector cyclotron (K=400).

Introduction

Since the last conference in 1984 (Xth International Conference on Cyclotron, Michigan) the RCNP cyclotron has delivered the beam for about 5200 hrs in 1984 and 1985. In these times, about 15% were expended for improvement and development of accelerator and experimental facilities.

Brief Description of the RCNP Cyclotron

The AVF cyclotron at RCNP is a three sector, single-dee machine. The beam energy is variable up to magnet regidity limit of 140 q^2/A MeV (designed K value was 120) for all ions except protons. The maximum energy of protons is limited to 90 MeV by the vertical focusing properties and the RF frequencies. Three types of ion sources are employed to accelerate light ions, heavy ions and polarized ions. One is a normal Livingston type for light ions installed axially in the lower yoke. In case of heavy ions, self-heated PIG source with heat insulated cathode is replaced to the light ion source. A polarized ion source is located on the second floor outside the cyclotron vault. It is the atomic beam type with ANAC ionizer. The beam is axially injected into the cyclotron through several focusing lenses. Then, the beam is inflected by 90° at the center of the cyclotron by a electric mirror inflector.

Accelerator Performance and Operation

The various kinds of particles have been accelerated in the full energy range of the designed value. In recent years, the energies of the particles except protons can be accelerated up to the higher energies correspond to the K-number of 140. Some trials for proton made a significant advance though the maximum energy is limited by both vertical focusing property and the maximum RF frequency.

Table 1 Particles accelerated and extracted in the RCNP cyclotron

Particle	Energy (MeV)	Extracted intensity	
PROTON	8, 11, 15, 19, 24, 30, 35, 40, 45, 50, 51, 52, 55, 60, 61, 65, 68, 70, 75, 80, 85	>1 μA	
H	25, 35, 50	~0.5 μA	
DEUTERON	50, 54, 56, 57, 60, 70	>1 μA	
He	26.5, 32, 40, 52, 60, 65, 70, 72, 90, 100, 105, 110, 120, 130, 140, 145, 150, 160, 165, 170	>1 μA	
ALPHA	30, 40, 47, 50, 60, 65, 70, 80, 85, 90, 100, 109, 110, 120, 130, 140	>1 μA	
POL PROTON	25, 30, 35, 40, 45, 50, 53, 55, 60, 61, 65, 66.5, 70, 75, 80, 84, 85, 87, 90	~1 μA	
POL DEUTERON	43, 45, 52, 54, 55, 56, 60, 65, 70	~0.5 μA	
$^{6}Li^{2+}$	80	>0.1 μA	*
$^{6}Li^{3+}$	125, 150, 170, 180, 210	~0.1 μA	*
$^{7}Li^{2+}$	68	>0.1 μA	
$^{7}Li^{3+}$	100, 114, 120, 132, 150, 156, 180	~0.1 μA	
$^{11}B^{3+}$	95, 100	~1 μA	
$^{11}B^{4+}$	150	~1 μA	
$^{12}C^{1+}$	87	~3 μA	
$^{12}C^{4+}$	80, 90, 100, 110, 120, 140, 160	~3 μA	
$^{12}C^{5+}$	146, 186, 215	~0.05 μA	
$^{13}C^{3+}$	54, 56, 80, 87	~5 μA	*
$^{13}C^{4+}$	98, 150, 156	~5 μA	*
$^{13}C^{5+}$	172	~0.01 μA	*
$^{14}N^{4+}$	100, 110, 115, 120, 125, 129, 130, 135, 140	~5 μA	
$^{14}N^{5+}$	135, 160, 206, 210	5 μA	
$^{15}N^{4+}$	96, 100, 120	2 μA	*
$^{15}N^{5+}$	160	~1 μA	*
$^{16}O^{4+}$	80	~1 μA	
$^{16}O^{5+}$	140, 145, 180	~1 μA	
$^{18}O^{5+}$	150, 160	~1 μA	*
$^{19}F^{5+}$	153	~0.5 μA	
$^{20}Ne^{2+}$	7.5, 8, 10	~0.01 μA	
$^{20}Ne^{4+}$	20, 22, 28, 60, 85, 88	>1 μA	
$^{20}Ne^{5+}$	110, 150	>1 μA	
$^{20}Ne^{6+}$	216, 217, 180	~0.5 μA	
$^{20}Ne^{7+}$	254	~0.01 μA	
$^{22}Ne^{3+}$	42	>1 μA	
$^{22}Ne^{4+}$	76	~0.5 μA	
$^{40}Ar^{4+}$	42	~0.5 μA	
$^{40}Ar^{5+}$	44, 73, 108	~0.5 μA	
$^{40}Ar^{6+}$	48, 108, 130	~0.1 μA	
$^{40}Ar^{7+}$	150	~0.05 μA	
$^{40}Ar^{8+}$	196, 230	~0.03 μA	
$^{40}Ca^{6+}$	108	~0.01 μA	
$^{40}Ca^{7+}$	150	~0.01 μA	
$^{41}K^{6+}$	108		
$^{41}Ca^{7+}$	150		
$^{42}Ca^{6+}$	108	~0.01 μA	
$^{84}Kr^{6+}$	61	~0.5 μA	
$^{84}Kr^{8+}$	80, 89	~0.5 μA	

* Isotopically enriched source feed

The beam intensity of polarized protons and deuterons have been progressively increased by the improvement of the polarized ion source. The advanced technique to accelerate the horizontally polarized protons and deuterons has been established by the diagonostic analysis of the accelerated beam. This technique also clarified the relation between the beam polarization and the stabilities of the magnetic field or dee voltage.

A self heated PIG ion source with a high power pulsed arc power supply have coped with the comprehensive studies using the heavy ion beams. Metal ions have been accelerated by back bombarding method.

Particles accelerated and extracted so far are listed in Table 1. The beam current is limited to 5 μA for the present to reduce the residual activities and to avoid the unnecessary damage of the machine parts.

The RCNP cyclotron is usually operated weekly. It starts at 21:00 on Monday and ends at 9:00 on Sunday. Operation statistics of the cyclotron during the past 9 years are shown in Fig. 1. In recent years, the beam time for polarized particles exceeded 50% of all beam times.

In order to meet the requests from many groups of researchers, the accelerated particles, their energies and the beam course are changed in more than hundred times as shown in Table 2.

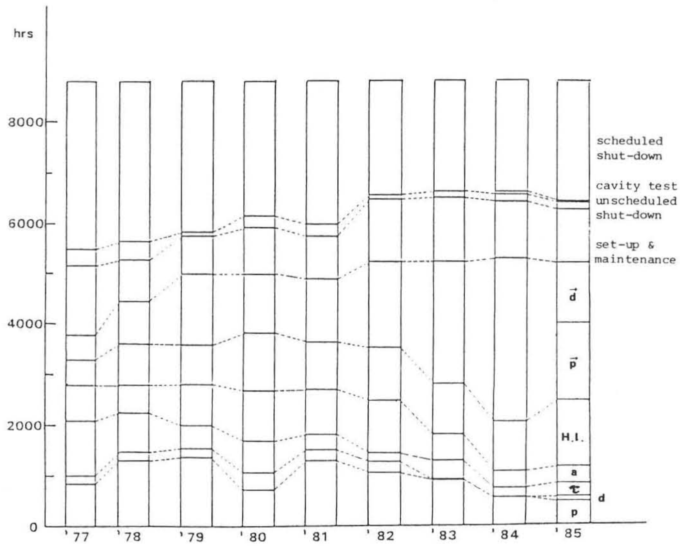

Fig. 1. Operation of the RCNP cyclotron during the last 9 years

Table 2

	particle	energy	beam course	
1979	110	140	88	8
1980	96	116	88	7
1981	103	124	88	7
1982	95	137	87	9
1983	97	136	102	9
1984	85	123	120	10
1985	100	127	84	6

In the last fiscal year, the main magnet was operated in 5817 hours and the beam time was 5139 hours in which the beam of 27 types were accelerated. The accelerator failures happened 45 times and total break down times were 148.7 hours.

Developments

Many improvements have been done in a short intervals between the experiments. About 15% of the total beam time is shared to these developments.

The maximum energy of proton and ^{3}He

Due to the results of the magnetic field measurement proton energy at about 80 MeV is near the vertical focusing limit.

In order to extend its energy as possible, a higher frequency or higher dee voltage near their design limits is required. Via following procedures, the 85MeV protons have been successfully accelerated and extracted. To overcome the lower dee voltage than that required to maintain the constant turn number, the position of the ion source and the puller has been moved slightly toward the machine center to coincide it with the accelerated orbit center. Thus, the turn number has been increased. The extraction efficiency is about 40%.

For the case of ^{3}He, there have been main difficulties in the extraction system. The higher deflector voltage may results in both the frequent discharge and the increase of the dark current. Moreover, the saturation of the magnet iron varies the beam course far from the adjustable range by the deflection magnet. To overcome these difficulties, at first, the positions of septum 1 and septum 2 must be moved with the increase of the beam energy, and the second, the saturation effect to the beam course can be weakened with the new passive element installed after the focusing magnet. These efforts make it possible to extract and transport ^{3}He beam up to 170 MeV.

Another try has been made to accelerate deuteron up to 70 MeV. The extraction efficiency is about 50%.

Time and energy resolution of the beam

Smallest and stable time width of beam is desirable to measure a time of flight of particle produced in nuclear reaction, especially, neutron. Our method is established with the phase slit and the trim coil current shifting. When a phase slit is installed at a certain radius, the time structure of beam respecting to the rf phase is divided into two, even with the same energy. The magnetic field is shifted slightly from the isochronous field by changing one of the inner trim coil current to produce the phase excursion of the beam. Adjusting the trim coil current one can make a condition that one of the beam pulse remains in an accelerating phase and the other in a decelerating phase. A beam pulse width is restricted to 2 ~ 3 ns by this procedure. To get a narrower beam pulse width, the magnetic field has to be shifted further to make a condition that only a part of the beam remains in an accelerating RF phase. In this way, a beam pulse width as narrow as 0.5 ns was obtained.

For a high resolution spectrograph (RAIDEN), it is absolutely essential to get a high intense of beam with better energy resolution. In this point, it is effective for better energy resolution to use small exit slit of the ion source. We used a slit of 0.4 mm × 5 mm. Energy resolution about 7 keV FWHM was obtained for 55 MeV proton elastic scattering though the beam intensity become finer. In recent days, moderate resolution and high transport efficiency was obtained employing the same method as the beam time width narrowing method stated above. It becomes 10^{-4} after analyzing magnet with 15 ~ 20% transport efficiency not using the small ion source slit.

Polarized Ion Source

Improvements

After the introduction of the ANAC ionizer (since 1981) and continuous efforts to improve the various parts in the dissociator, evacuating system and beam buncher, the polarized ion source was operated without serious trouble. The beam times for polarized beam were 3200 hours (1984) and 2710 hours (1985). The beam current of 5 ~ 10 μA is stably obtained at the mirror electrode of the cyclotron. The proton and deuteron beams of about 1 μA are extracted from the cyclotron. The beam polarizations are 82 ~ 86% for protons and 80 ~ 84% of the ideal values of deuterons.

Several improvements related to the ion source have been carried out. They are as follows.

1. A cryopump with a pumping speed of 1000 ℓ/s for hydrogen and 2100 ℓ/s for water was added to get better vacuum at the new ionizer column. After these improvements the polarization of the extracted protons is above 80% which is 5 ~ 10% higher than the previous value. The beam intensity is increased by a factor 3 ~ 5 as compared with the previous value. The output current is 20 ~ 30 μA at the ion source and the beam of about 1 μA is extracted from the cyclotron.

2. A beam pick off electrode and a power supply were newly installed to inject pulsed beam into the cyclotron. The electrode is placed between the electric quadrupole triplets in the injection line.

3. The power amplifier of the fundamental buncher was replaced by a wide band solid state amplifier (2 ~ 30 MHz, 500 W).

4. A new frequency doubler was made for the 2nd-harmonic buncher.

Acceleration of the Horizontally Polarized Beam

The work to get the higher horizontal polarization and the higher beam intensity has been continued, since the development using the polarization tagging method. By the recent work, the value attained for the maximum horizontal polarization $2p\overline{\sin\beta\cos\beta}$ is 0.3 and the beam intensity is 10 ~ 40 nA on target without that method. In order to improve the horizontal polarization and the beam intensity it is essential to accelerate and extract the beam from the cyclotron with a definite turn number.

The spin axis was rotated into the horizontal plane by a Wien filter in stalled just downstream the ion source. Pulsed ions were injected into the cyclotron to observe the distribution of the turn number of the extracted beam. That was observed using the signal from a plastic scintillator inserted in the beam line. By adjusting the parameters of the cyclotron, the turn number of the extracted beam was restricted and a few turns extraction was achieved. The most sensitive parameters were the dee voltage and the current of No.5 valley coil. After we searched a suitable range of dee voltage where a few turns extraction could be achieved, the beam pulsing system was turned off. Since the admixture of turn numbers is very small (less than two turns) and the spin precession angle of 56 MeV deuteron is 53.1° per turn in the cyclotron, the final polarization is expected to have a fairly large value. The average horizontal polarization $2p\overline{\sin\beta\cos\beta}$ was measured as a function of dee voltage by using the A_{xz} data of ^{1}H+d elastic scattering as shown in Fig. 2. The long term variation of this value is shown in Fig. 3. A fine readjustment of the dee voltage was made several times to maintain it as large as possible.

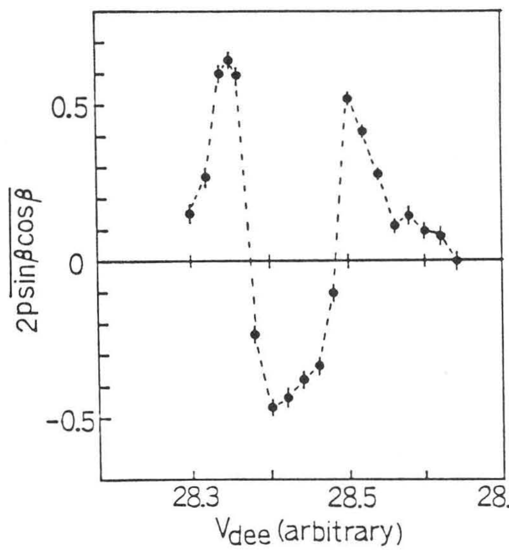

Fig. 2. Horizontal polarization $2p\overline{\sin\beta\cos\beta}$ as a function of dee voltage.

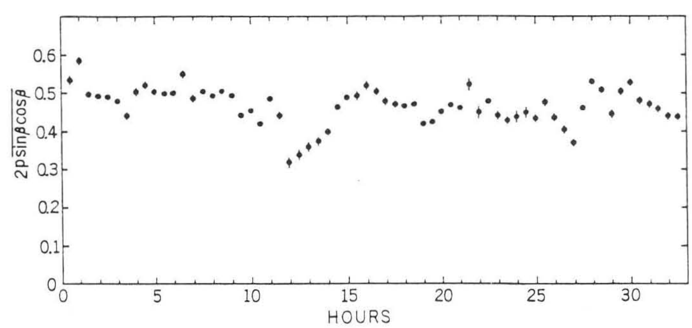

Fig. 3. An example of long term variation of horizontal polarization in an experiment.

Heavy Ion Source and Heavy Ion Acceleration

Self heated PIG ion source with the pulsed arc power supply has been operated to get the highly charged ions up to mass 40. The developments regarded as of major importance nowadays focused to produce higher charged ions near mass 40 and to increase the current of metal ions beam.

Acceleration of gaseous ions

It is very difficult to produce $^{12}C^{5+}$ or $^{20}Ne^{6+,7+}$ with the internal heavy ion source. These weak beams are simultaneously accelerated very strong beams with the lower charged ions on the higher harmonic mode. In the case of neon beam, neutrons from the bombardment of the beam probe with these high energies at extraction radius gives a good measure for the strength of each beam on the tuning process of the ion source and the cyclotron. Most optimum condition of the pulsed PIG ion source for $^{20}Ne^{6+,7+}$ ions was usually obtained in 3~4 hours after its ignition due to the degree of the cathode erosion. The extracted beam current for $^{20}Ne^{6+}$ and $^{20}Ne^{7+}$ are 350 nA and 5~7 nA (electrical ampere) respectively.

The same method to detect neutron generated at beam probe is applied to extract $^{12}C^{5+}$ beams from intense background beams of $^{12}C^{1+}$ ions on the 5th harmonic mode. The optimum arc current and voltage in peak values are 17 A and 500 V for duty factor 30% and the gas flow rate of N_2 and CO_2 are 1.00 cc/min and 1.6 cc/min respectively. The maximum extracted current is 48 nA. In order to increase the beam current of these highly stripped ions, the cathodes fixed with their holders to cool down more effectively have been tried.[4] The better performances have been obtained so far, while the cathode lifetime is much shorter than the case of the heat insulated type.

In these operations, there are some trials to optimize the anode bore of the PIG ion source for these highly stripped ions. The anode bore from 3 mm to 7 mm in 1 mm steps have been tested and of these, 5 mmϕ is the most fitted to this purpose, while the case smaller than this sometimes shows better performance and sometimes causes interrupt of the arc discharge.

A new gas feed system was prepared for corrosive or poisonous gas and can be used for BF_3 gas to accelerate B^{4+} or $F^{5+,6+}$ ions.

Acceleration of metalic ions

Another development was the acceleration of the solid element. The method (back-bombard) was the same as those developed at ORIC.[3] A single crystal of LiF (5mm×5mm×20mm) was set in a cave on the back side of the anode. This crystal was sputtered by Xe^{1+} ions returned from its 1st turn. In this method we used the larger slit of the ion source twice time as usual. Extracted beam current of $^{7}Li^{3+}$ ions reached about 300 nA after proper setting of the dee voltage and the azimuthal angle of the ion source. Using enriched ^{6}LiF crystal, $^{6}Li^{3+}$ ions with nearly the same current as $^{7}Li^{3+}$ ions was obtained.

The backbombard method was applied to produce $^{19}F^{5+}$ and $^{40}Ca^{6+,7+}$ ions with CaF_2 single crystal. Through the gas mixture of 1.1 cc/min nitrogen gas with 0.07 xenon gas, $^{19}F^{5+}$ ion was obtained with its intensity about 100 nA at the initial beam stop of the beam line.

Prior the acceleration of the calcium ions, high charge state of argon ions, $Ar^{6+,7+,8+}$ have been accelerated. By minutely adjusting the mixing ratio of argon to nitrogen gas $^{40}Ar^{7+}$ ions about 350 nA can be extracted with a efficiency of 10%. However, as for $^{40}Ar^{8+}$ ions, they are mixed with $^{15}N^{3+,5+}$ ions in the 3rd or the 5th harmonic modes. Thus, the extracted current about 50 nA should not be considered as argon ions only.

The experiments for accelerator mass spectrometry has begun with the calcium ions and it made a great progress for these ion beams.[4] About 100 nA for $^{40}Ca^{7+}$ ions can be extracted and more than 20 nA was obtained at the target.

Negative Hydrogen Beam

Negative hydrogen beam was successfully accelerated and extracted at the energy of 25 MeV using usual low voltage arc ion source. The maximum beam current more than 9 μA at the outermost radius was obtained after adjustment of both the gas flow rate and the arc current. The energies of 25-, 35- and 50-MeV have been tried and except the energy of 25 MeV was not extracted due to the abrupt increase of the dark current at the extraction electrodes.

References

1. H. Sakai et al., Nucl. Instr. and Methods (1986) to be published.
2. K. Hatanaka et al., Nucl. Instr. and Methods 217 (1983) pp.397-404.
3. E.D. Hudson, M.L. Mallory and R.S. Lord, Nucl. Instr. and Methods 115 (1974) 311.
4. T. Itahashi et al., Contribution to this conference.
5. T. Itahashi et al., Contribution to this conference.