STATUS REPORT ON JAERI-AVF CYCLOTRON

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The JAERI AVF cyclotron has been used for experiments since January 1992. The routine operation of the cyclotron began in September 1992. The total operation times amounted to 10,000 hours in February 1995. Twenty-five ion species for ranging from hydrogen through xenon with energies of 10 - 520 MeV have been used for experiments, so far. This paper reports status on the performance and operation of the cyclotron and recent developments.

1 Introduction

The TIARA (Takasaki Ion accelerators for Advanced Radiation Application) facilities have been constructed at the Takasaki Radiation Chemistry Research Establishment of Japan Atomic Energy Research Institute (JAERI) since 1987 for a materials science using various ion beams in a wide range of acceleration energy. The facilities consist of an AVF cyclotron and three different types of electrostatic accelerators: a 3MV tandem accelerator, a 3 MV single-ended accelerator and 0.4 MV ion implanter.

Large AVF cyclotrons , so far, have been used mostly for fundamental nuclear physics and medical application to radiation therapy and radioisotope production. Our cyclotron[1, 2] is mainly applied for R&D in materials science and other irradiation purposes. These applications of the cyclotron require that many kinds of light and heavy ions can be accelerated in a wide range of energies. To meet the requirement, continuing efforts have been made on new beam development, improvement of beam extraction and transmission, etc.

The operation of the AVF cyclotron for experiment was started from 1992 in daily operation mode on a trial base. The weekly continuous operation was started from September 1992. The total operation times amounted to 10,000 hours in February 1995.

2 Present Status

2.1 Operation

The yearly operation time is divided into three beam-time periods, each of which consists of 11 weeks of beam-times and allocated to experiments by Program Advisory Committee. Three weeks for maintenance and additional beam-times and about two weeks of operation intervene between the programmed beam-times. The experiment plan and beam-times are allotted for each period. The weekly operation is usually carried out continuously from Monday morning till Friday evening. Regular over-haul is carried out for 4 weeks in the summer.

Operation statistics of the cyclotron during past 4 years are shown in Fig. 1. The percentage of time in last two years used for experiments, beam developments and tuning were about 82%, 8% and 10%, respectively. The accelerated particles and their beam time are also shown in Fig. 2.

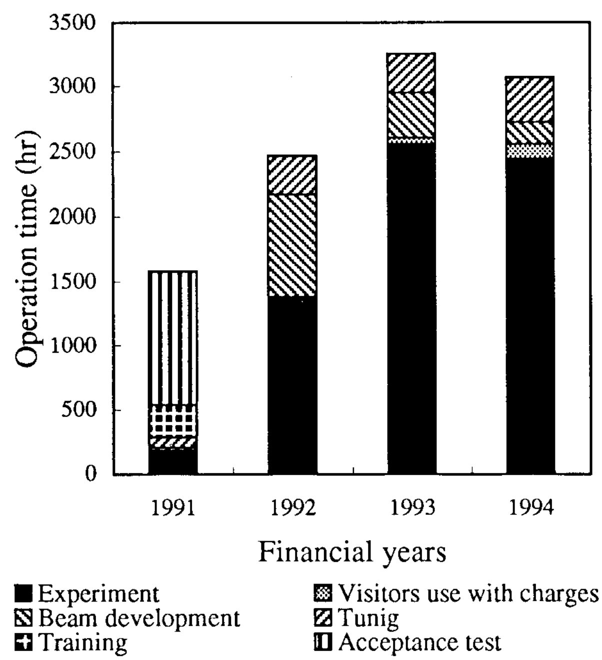

Fig. 1 : Statistics of the cyclotron operation from 1991 to 1994.

2.2 Maintenance

The beam extraction system consists of an electrostatic deflector and a magnetic channel and also of a gradient corrector to focus the beam horizontally. The positions of the deflector and the magnetic channel can be controlled remotely. However, the position of the gradient corrector of a passive type was adjusted manually. In 1993, the gradient corrector was replaced by remote driving type one for easily optimizing to focus the beam horizontally from the cyclotron. A RF amplifiers (EIMAC 4CW800B and 4CW50000E) were also replaced by new ones in the yearly overhaul.

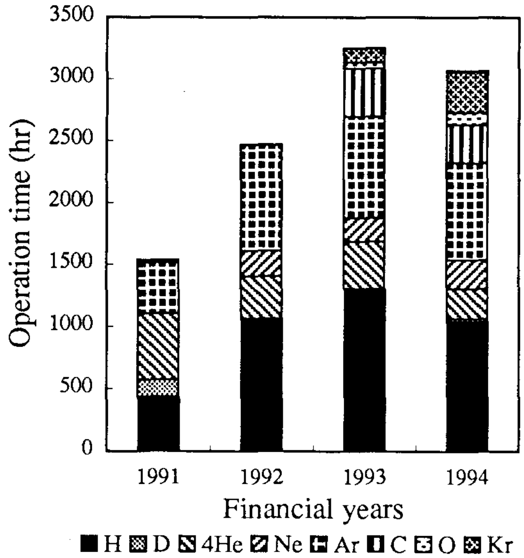

Fig. 2 : Statistics of the beam time from 1991 to 1994.

In 1994, a baffle slit system at the extraction hole of the acceleration chamber was replaced by remote driving one to easily control the slit width. We added a plate to this system in order to measure the total beam current. To measure the beam profile from the cyclotron, the single-wire profile monitor was installed just after the gradient corrector.

The accumulation of induced radioactivity in the acceleration chamber is making it more difficult to conduct maintenance work inside the cyclotron. The strongest source of radiation is the electrostatic deflector. The septum electrodes of the deflector were replaced by new ones.

The accelerator system troubles happened 751 times for four years from 1991 to 1994. The aluminum rotor wings and stator ones of the turbo-molecular pump were destroyed completely last year. The fine broken pieces of aluminum were scattered in the ducts of the beam transport lines. More than 100 hours of time loss was due to this trouble and we had to cancel or reschedule the beam time for repair.

3 Beam Development

3.1 Extracted Current and Transmission

Particles accelerated and extracted so far are listed in Table 1. The extraction efficiency is defined by the ratio of the beam current measured with the main probe at r=900 mm to that with a Faraday cup (FC) just after cyclotron. The average extraction efficiencies for harmonic 1, 2 and 3 are 56.0%, 65.5% and 56.3%, respectively.

The overall transmission efficiency is defined by the ratio of the beam current with a FC just after an analyzing magnet at the injection line to that with a FC just after cyclotron. The average transmission efficiencies for harmonic 1, 2 and 3 are 13.6%, 17% and 12.7%, respectively. The best extraction and overall transmission efficiency was 86% for 330 MeV $^{40}Ar^{11+}$ and 26% for 20 MeV H^+, respectively. The maximum beam currents of heavy ions such as C, O, Ne, Ar, Kr and Xe mainly depend on the ability of the ECR ion source.

Table 1 : Results of extracted intensity and overall transmission.

Ion	Energy (MeV)	Extracted Intensity (eμA)	Extraction Efficiency (%)	Overall Transmission (%)
H^+	10	12	68	13
	20	5	77	26
	30	5	67	22
	45	30	79	14
	50	5	44	14
	60	5	57	22
	70	5	42	12
	90	10	48	7.7
D^+	10	11	39	7.4
	35	41	59	4.6
	50	21	49	7.2
$^4He^{2+}$	20	5.5	69	11
	50	20	62	17
	100	10	62	10
$^{12}C^{5+}$	220	0.25	77	22
$^{16}O^{5+}$	100	1.7	34	8.1
$^{16}C^{6+}$	160	1.9	58	21
$^{16}O^{7+}$	225	0.2	54	10
$^{20}Ne^{6+}$	120	1.6	53	18
$^{20}Ne^{7+}$	260	0.33	70	19
$^{20}Ne^{8+}$	350	1.5	63	23
$^{36}Ar^{8+}$	195	2.5	63	13
$^{36}Ar^{10+}$	195	0.30	43	11
$^{40}Ar^{8+}$	175	3.0	73	15
$^{40}Ar^{11+}$	330	0.6	86	20
$^{40}Ar^{13+}$	460	0.1	63	24
$^{84}Kr^{20+}$	520	0.045	72	20
$^{129}Xe^{23+}$	450	0.20	72	11

3.2 Single Pulse Extraction

The beam chopping system consists of a pulse voltage chopper (P-chopper) and a sinusoidal voltage chopper (S-chopper)[3]. The P-chopper was made to chop DC beams from the ion sources into pulse beams in the injection line. The S-chopper was made to extract a single beam pulse after the exit of the cyclotron. The single pulses were successfully extracted for 70 MeV H^+ and 175 MeV $^{40}Ar^{8+}$ ions using the chopping system as shown in Table 2.

Table 2 : Results of single pulse extraction.

particle	$^{40}Ar^{8+}$	H^+
energy	175 MeV	70 MeV
pulse interval	3.3 μs 4.75 μs	2.11 μs 1.27 μs
pulse width	-	1.95 ns
charge	$7*10^{-14}$ C/pulse	$2*10^{-15}$ C/pulse
detector	SSD	Scintillator

3.3 *Measurement of Absolute Beam Energy*

The energy of ion particles has been measured absolutely by using the crossover technique[4] which is based on scattering kinematics, in particular the variation with the angle of the energy of the particles scattered by elastic and inelastic processes from different target nuclei. A 10 MeV proton was chosen since the crossover angle is relatively large and it is easy to detect the particles at backward angles. A 2.78mg/cm^2 polyethylene film was used as the target including hydrogen and carbon nuclei to use the 4.439 MeV excited state in carbon. To detect scattered particles around the crossover angle, a semiconductor detector was mounted on a movable arm.

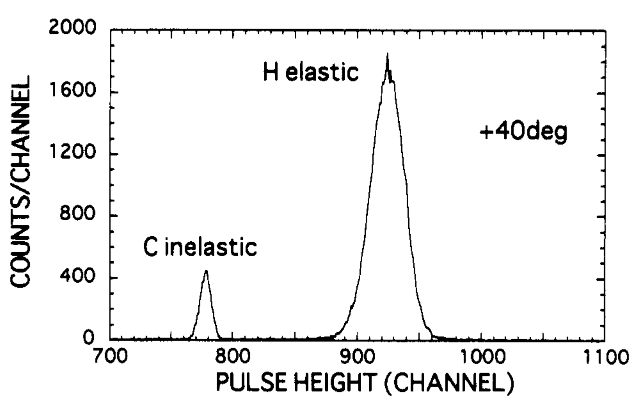

Fig. 3: Pulse height spectrum at an scattering angle of 40 deg. for a nominal 10 MeV proton.

Figure 3 shows a typical pulse height spectrum obtained in an scattering chamber. The left peak is inelastic scattering on carbon nuclei and the right one is elastic scattering on hydrogen nuclei. The relationship between the scattered angles and the pulse heights in the both interactions is shown in Fig. 4. The crossover angle was evaluated from the crossing point of the interpolating lines. To compensate an asymmetric factor of the scattering geometry, left and right angle measurements were carried out. The average value of the crossover angle obtained from both angles was 44.3° and the absolute beam energy was evaluated at 9.9 MeV. The uncertainty of the measurement is under estimation.

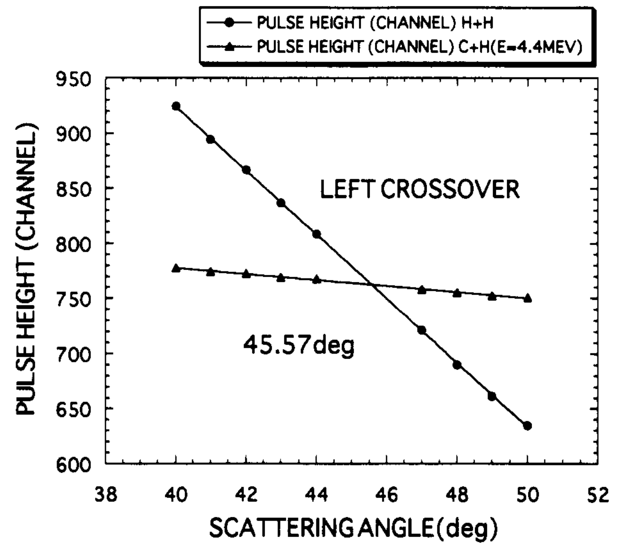

Fig. 4: Relationship between the scattering angle and the pulse height for the elastic scattering and the inelastic scattering.

4 Recent Developments

4.1 *Beam Attenuator*

Extremely low beam currents below 1 nA are required in various experiments. The beam attenuators were installed in the injection line to adjust the beam intensity drastically without changing the cyclotron parameters. A beam attenuator consists of two or three stainless steel meshes, each of which has an opening ratio of 10^{-1}, 10^{-2} or 10^{-3}. Very low opening ratios less than 10^{-4} can be achieved by combining the meshes in each attenuator. The beam attenuation ratios in the range of the opening ratio from 10^{-1} to 10^{-15} were obtained by measuring the attenuated beam intensity. The beam attenuation ratios are in agreement with the total opening ratios of the meshes in the order of magnitude.

4.2 *Beam Scanner*

The beam scanner[5] for uniform irradiation of a large area (100 x 100 mm^2) by high-energy intense beams is used for various purposes of materials science. It is composed of a set of electromagnets for horizontal and vertical deflections. The beam is scanned by the magnetic fields varying in triangular waves in a frequency of 50 Hz in the horizontal direction and 0.5 - 5.0 Hz in the vertical one. The relative fluence distribution of the scanned beam was measured by cellulose triacetate (CTA) film dosimeter. At first, the uniformity of the two-dimensional fluence distribution of ion beams was ±15 %, because of the wave form distortion of the excitation current for the scanning electromagnet. An improvement of the power supply of the scanner resulted in a good fluence uniformity within ±4%, as shown in Fig. 5.

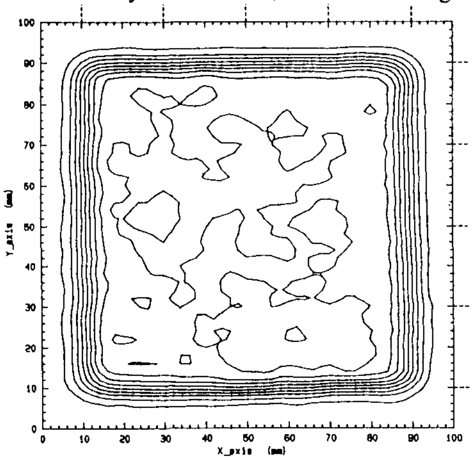

Fig. 5 : An example of fluence distribution of 175 MeV Ar^{8+} beam measured by CTA film dosimeters after modification of the beam scanner.

4.3 Beam Pulse Monitor

The beam pulse monitor provides a fast timing signal of the beam pulse by detecting secondary electrons and photons emitted from a target inserted into the beam[6]. A foil target, having a large interaction area with the beams, has been adopted for detection of high-energy light ion beams.

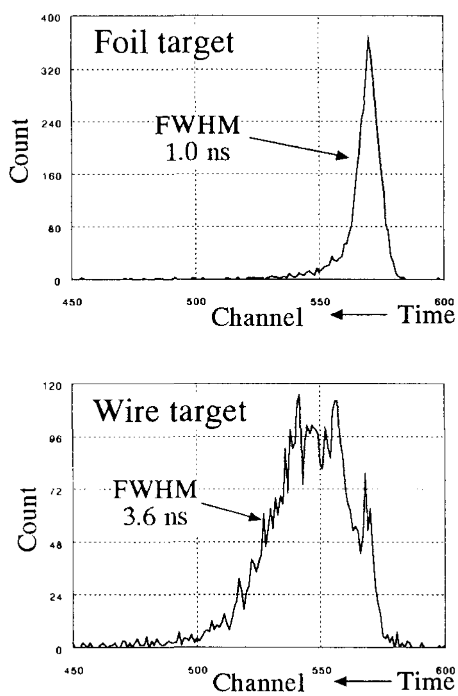

Fig. 6 : Time spectra measured with the foil target and the wire target at the collection voltage of -4 kV for 260 MeV $^{20}Ne^{7+}$ beam. The values of FWHM were evaluated on the assumption of the Gaussian distribution.

A wire target was also mounted for detection of low-energy heavy ion beams so as to minimize the degradation of the beam.

The foil target is a 3 mm thick aluminum-foil strip with 5 mm width, and the wire target is a tungsten wire 0.3 mm in diameter. The foil and wire targets are placed in front of a micro-channel plate (MCP) at a distance of 50 mm and 94 mm, respectively. The foil target is tilted at an angle of 45 degrees to the beam axis for efficient detection of secondary electrons and photons emitted from the foil surface.

Secondary electrons are collected into a MCP (F4655-10, Hamamatsu photonics Ltd.) through a slit using an electrostatic field. The operational voltage of the MCP is -2.4 kV, a recommended maximum voltage. Time spectra for 260 MeV $^{20}Ne^{7+}$ beams at a collection voltage of -4 kV is shown in Fig. 6. In this arrangement of the targets, the foil target is superior to the wire one in time resolution.

4.4 18-GHz ECR Ion Source

The 18-GHz ECR ion source was constructed at JAERI and is now in test operation by generating Ar ions since June, 1994. The source performance has been improving with vacuum in the plasma chamber, and the charge states up to Ar^{13+} have been observed so far. The optimum current of the solenoid coil, mounted between the mirror coils to vary the mirror ratio, shows a tendency to increase with charge states. Further investigation is necessary for an appropriate explanation on a rule of the solenoid. The source performance will still improve by further optimization of the magnetic field, the position of the extraction hole and the improvement of the pressure in the plasma chamber. After a goal performance is attained by using Ar ions, metallic ions will be generated in the next stage.

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