PRESENT STATUS OF JAEA AVF CYCLOTRON FACILITY

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Abstract

In order to supply ion beam stably we have recently constructed an all-permanent-magnet type ion source. Ion beams such as H, O and Ne were produced stably. A beam attenuation system with metal meshes has been improved. By using new meshes with denser hole arrangement and lengthening the space of meshes, beam intensity can be controlled more precisely with maintaining the beam profile. The power supplies of the magnet coils used in the cyclotron were modified to stabilize the coil current with the stability $\Delta I/I$ of the order of 10^{-6}. In addition, developments of new irradiation techniques such as quick change of microbeam by cocktail beam acceleration technique and large-area uniform beam irradiation using multipole magnets are in progress.

INTRODUCTION

The JAEA AVF cyclotron with a *K* number of 110 MeV accelerates various ions, 5 to 90 MeV protons and 2.5 to 27 MeV/n heavy-ions at TIARA (Takasaki Ion accelerators for Advanced Radiation Applications) facility. TIARA is a very unique accelerator facility established for utilization of ion beams exclusively for the research in the field of biotechnology and materials science; for example, estimation of radiation hardness of space-use devices and plant breeding using ion-induced mutation. We have been developing ion sources, acceleration techniques and beam irradiation techniques for providing useful irradiation fields to researchers.

MACHINE OPERATION

Scheduled irradiation experiments were completely accomplished in fiscal year 2006 and 2008 without any serious troubles. Integration of operation time since the first beam in 1991 reached 60,000 hours on May 2010. Table 1 shows the detail of the cyclotron operation in fiscal year 2009. We usually operate the cyclotron from Monday morning to Friday evening through day and night, and the yearly operation time amounted to 3148.3 hours. The number of switching ion species, energy, or beam course amounts to 547 times, the number of changing acceleration harmonics 56 times. The number of machine troubles including minor breakdowns was 130 times. The severest trouble in 2009 was a breakdown of a high voltage power supply of the RF system. Cancellation of experiments in fiscal 2009 resulted from only this trouble.

Table 1: Statistics for cyclotron operation in fiscal 2009

Beam time	2461.8 h
Machine tuning	620.9 h
Beam development	65.6 h
Total operation time	3148.3 h
Switches of particle and/or energy	238 times
Change of beam course	309 times
Change of harmonic number	56 times
The number of experiments	633
Experiment cancelled due to machine trouble	2(8.5h)

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NEW ION SOURCE

The AVF cyclotron has three external ion sources; Multicusp ion source for H^+ and D^+, OCTPUS (ECR) for gaseous heavy ions, and Hyper nanogan (ECR) for highly- charged heavy ions including metal ions. In addition to them, a new ECR ion source has been developed to provide highly-stabilized beams [1]. Since this source is of all-permanent-magnet type, fluctuation of beam current intensity is less than that of ECR ion sources with room temperature coils, which cause considerable heat transfer to the plasma chamber and the sextupole magnets. The mirror magnetic field distribution of the new ECR ion source is adjustable by radially moving the permanent magnets in order to form the magnetic field suitable for various ion species. Highly stable ion beams such as H, O and Ne can be produced by this ion source. Figure 1 shows the stability of the $^{16}O^{6+}$ beam intensity, which is better than 3.2% for 8 hours.

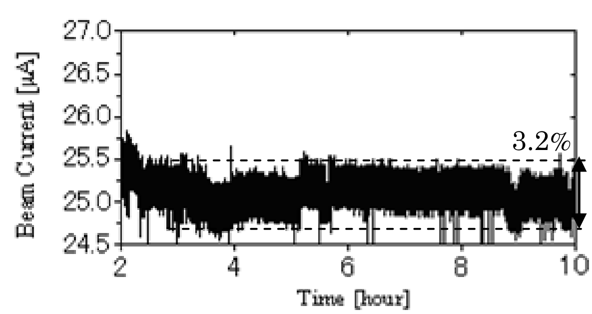

Figure 1: Stability of the $^{16}O^{6+}$ beam intensity produced by the all-permanent-magnet ECR ion source. The long-time stability of the beam is better than 3.2%.

BEAM ATTENUATOR IMPROVEMENT

A beam attenuation system using thin metal meshes, which have many regularly-arrayed holes, is installed in the injection line for quick attenuation of beam intensity with the beam size and the emittance almost maintained. Each metal mesh has the opening ratio of 1/2, 10^{-1}, 10^{-2} or 10^{-3}. However, when single mesh with low opening ratio of 10^{-2} or 10^{-3} or combined meshes were used for high beam attenuation, the beam profile changed or vanished at the target point, as shown in Fig. 2 (a) and (b). The cause of this phenomenon is thought that the beam was not attenuated uniformly due to the scattering distribution of the mesh holes and/or the too-short installation interval of meshes.

The beam attenuation system has been improved. By using a new meshes with denser hole distribution and lengthening the maximum interval of meshes from 120 mm to about 1100 mm, beam intensity can be controlled more precisely with maintaining the beam profile [2]. As a result, the beam profile on the target barely changes even by use of combined meshes. Figure 2 (c) shows the effect of new meshes; the beam profile was maintained.

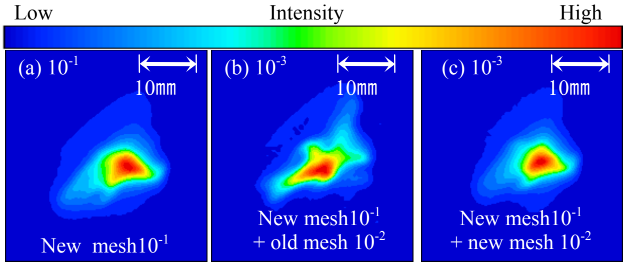

Figure 2: Comparison of beam intensity profiles on the target with a previous short interval of meshes: (a) standard for comparison with only a new mesh of opening ratio of 10^{-1}, (b) added an old mesh of opening ratio of 10^{-2} (ϕ 0.1 mm), (c) added a new mesh of opening ratio of 10^{-2} (ϕ 0.01 mm). These profiles were obtained from the optical density of irradiated radiochromic films, GAFCHROMIC films (HD-810, International Specialty Products) [3].

STABILIZED POWER SUPPLIES

A number of developments of acceleration technique are in progress. For production of a focused heavy-ion microbeam [4], an energy spread of the beam has to be reduced to $\Delta E/E = 2 \times 10^{-4}$ to diminish the effect of chromatic aberration at the lens which focus beam to a micrometer in diameter. The energy spread is reduced by introducing a flat-top (FT) acceleration system [5]. A highly-stabilized magnetic field of the cyclotron with a stability $\Delta B/B$ within 10^{-5} is also indispensable to realize FT acceleration because slight change of the magnetic field strength has significant influence on beam phase and trajectory in the cyclotron.

The required stability of the magnetic field was achieved by keeping temperature of the magnet constant [6]. In addition, the power supplies of the magnet coils used in the cyclotron were modified to stabilize the coil current with a stability $\Delta I/I$ of the order of 10^{-6}. The current feedback circuits with a digital-to-analog converter (DAC) are mounted in thermostatic chambers, temperature in which was formerly kept at 50 ±1°C by an electric heater. However, such high temperature precipitates degradation of electric parts in the DAC. The heater was therefore replaced with a Peltier device to keep temperature of the circuit at 27 ±1°C in ambient temperature over around 30°C. Moreover, the DAC circuit with Peltier device for main magnet coil was put in a incubator, a high-precision temperature controlled bath at 20 ±1°C, because of the high contribution to the magnetic field strength, while the other DAC's put on power supplies were at room temperature. The shunt resistance to measure the main magnet coil current for feedback control in the power supplies were replaced with direct current current transformer (DCCT). Figure 3 shows a change of the main magnet coil current. The stability ΔI/I was within $\pm 1.5 \times 10^{-6}$.

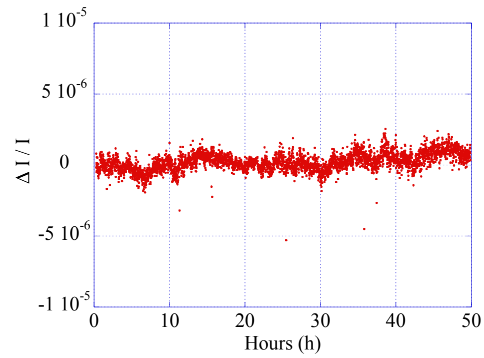

Figure3: Stability of main magnet coil current measured by DCCT.

QUICK CHANGE OF HEAVY-ION MICROBEAM

A microbeam of 260 MeV $^{20}Ne^{7+}$ with a spot size of 1 μm in diameter is available. Users of the microbeam require irradiating at plural values of linear energy transfer (LET) in one experiment. To do so, we have to change the ion species and/or kinetic energy of the microbeam in short time. Forming the microbeam, however, takes about 8 hours or more because the ion source, the cyclotron, and the focusing lenses must be tune very carefully. A microbeam of one species is provided in a beam time for this reason.

On the other hand, a cocktail beam acceleration technique is often used to change the ion species quickly. In this technique, beams of cocktail (mixture of plural species) having almost the same mass to charge ratio (M/Q; M is ion mass in the atomic mass unit, Q ion charge state) are injected into a cyclotron simultaneously, and one of them is extracted by slightly shifting the acceleration frequency. The magnetic rigidity of extracted beams is the same; therefore, lens parameters in the beam transport line do not need to be changed in principle.

This technique with microbeam formation has enabled

Table 2: Series of the cocktail beam with M/Q ≈ 2.85

Ion	M/Q	RF (MHz)	Energy (MeV/A)	LET in water (keV/μm)
$^{11}B^{4+}$	2.75178	18.1337	14.01	90.71
$^{14}N^{5+}$	2.80007	17.8210	13.54	186.6
$^{20}Ne^{7+}$	2.85551	17.4750	13.01	387.2
$^{28}Si^{10+}$	2.79714	17.8397	13.56	684.7
$^{40}Ar^{14+}$	2.85391	17.4848	13.03	1143

us to change microbeam from 260 MeV $^{20}Ne^{7+}$ to 520 MeV $^{40}Ar^{14+}$, which have M/Q ≈ 2.85, within 30 minutes. In the near future, $^{11}B^{4+}$, $^{14}N^{5+}$ and $^{28}Si^{10+}$ as shown in Table 2 will be added to the series of the 'cocktail microbeam' with M/Q ≈ 2.85 [7].

FORMATION OF LARGE AND UNIFORM BEAM PROFILE

The raster scanning method is widely used for large-area uniform irradiation of beams. In TIARA, the beam is swept at 50 Hz in one direction and 0.25~2.5 Hz in the other so as to obtain a uniform field. Irradiation time much longer than the scanning period is necessary to achieve a good uniformity. That is, this method is less suitable for short-time irradiation or low-fluence irradiation. Therefore, we have been developing a multipole-magnet beam profile uniformization system, MuPUS, based on the nonlinear focusing method as a new large-area and uniform irradiation technique [8].

The system can form a uniform beam by folding the tail part of the beam profile using the nonlinear magnetic field of octupole magnets. This method needs a simple and smooth profile such as a Gaussian or parabolic one as a precondition. Therefore, the beam from the cyclotron, which usually has a complicated profile, is multiply-scattered by a thin foil to form the profile close to Gaussian. Figure 4 (a) shows a quasi-Gaussian profile of the scattered beam on the target, measured by GAFCHROMIC film. The quasi-Gaussian profile was transformed to a uniform profile by octupole magnets of MuPUS as shown in Fig. 4 (b). A uniform beam of 10-MeV H^+ was successfully formed over 6 cm square, and is already supplied to research experiments.

At present, the uniform beam is extracted into the air through a 30-μm-thick titanium foil for quick change of target samples. The uniformity of the beam is affected by scattering and energy loss in the air. Thus, distance from the titanium foil to the target must be as short as possible.

REAL TIME MEASUREMENT SYSTEM OF BEAM PROFILE AND UNIFORMITY

MuPUS can form a stationary and broad uniform profile on the target, while the beam spot is moving fast in the raster scanning method. We have to confirm the large-area profile and the uniformity on the target before the beam is supplied to users. However, measurement of the profile using radiochromic films takes time to scan and analyze the irradiated films. Therefore, a real-time measurement system is being developed using a fluorescent screen.

A few kinds of Tb-doped Gd_2O_2S fluorescent screens called DRZ (Mitsubishi Chemical Co.) are used in this system. Compared with an Al_2O_3 fluorescent screen, the DRZ screen has much shorter decay time of light emission and higher sensitivity to ion beams. The light emitted from the DRZ screen on the target is detected by a CCD camera, and the fluorescent signal is analyzed by a LabVIEW (National Instruments Co.) system on a Windows PC. Figure 5 is a screen shot of the measurement program, which can show relative 1D and 2D beam profiles and uniformity of the irradiation area in real time. The uniformity is calculated as the root-mean-square (rms) error of the average beam intensity in arbitrary regions of interest. We have confirmed that the rms uniformity of the fluorescent has a similar tendency to that of GAFCHROMIC films. In order to monitor the uniformity of a large-area beam precisely, the installation location of the camera has been optimized.

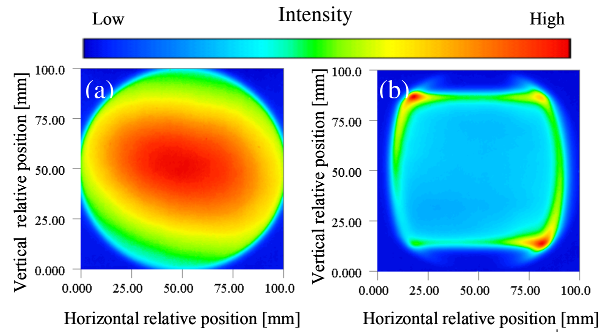

Figure 4: 2D intensity distributions of a 10 MeV H^+ on the target. (a) A quasi-Gaussian beam. (b) A uniform beam.

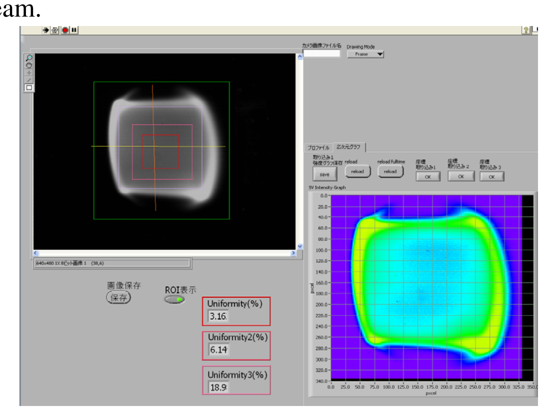

Figure 5: An image of the beam profile measured by the real-time measurement system. The uniformities of three different areas can be calculated automatically. Note that the deformation of the beam profile is because the light emitted from the screen is monitored from the approximately 27° direction.

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