The 11th Symposium on Accelerator Science and Technology, Harima Science Garden City, 1997

Heavy Ion Microbeam Project in RIKEN Ring Cyclotron

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Abstract

The RIKEN Accelerator Research Facility has contributed to bio-science taking advantage of a variety of heavy-ion beams. To make further contribution to bio-science, we are planning to construct the new beam course which provides microbeams. As a first step, we design here a beam course for a 50-μm microbeam. We employ the beam collimation method in producing a microbeam. We also introduce a position-sensitive detector and a microscope to adjust a sight. The schedule of the first beam is the end of this fiscal year.

1 Introduction

The heavy-ion beam is high linear-energy-transfer(LET) radiation and produces a great biological effect on an organism. Hence, heavy-ion beams have played an important role for studies of bio-science, for example heavy-ion therapy and heavy-ion-induced mutations. Bio-science is one of the major research subjects in the RIKEN accelerator research facility(RARF). Beam service time for bio-science was about 400 hours in 1996. In experiments performed in the RARF, a target is irradiated uniformly by heavy ions. Such a uniform irradiation experiment is very useful when we investigate statistical aspects of a phenomenon, for example the survival rate of cells irradiated by heavy ions.

Besides the uniform-irradiation experiment, biologists suggest a new type of experiments in which we irradiate specified cells or organs with heavy ions. To irradiate a small part of an organism selectively, we need a heavy-ion beam, the beam size of which is several micrometers on a target. Such a fine beam is called a microbeam. The microbeam is useful to elucidate complex communication between cells or groups of cells(bio-crosstalk) and to make surgical operations on a cell using heavy ions(cell-surgery). In order to promote these programs, we are now planning to construct the new beam course which provides microbeams.

Heavy-ion microbeams are now available in several facilities. For example, the Takasaki Radiation Chemistry Research Establishment provides various types of microbeams including sub-micrometer beams[1]. Compared with these facilities, the RIKEN Ring Cyclotron(RRC) covers a wide energy range. Hence, we will extend the energy frontier of the microbeam in this project. The final goal of this project is to produce heavy-ion beams with the beam size less than 10 μm. As a first step to this goal, we design here a 50-μm microbeam course because slight modification of the existing beam line is sufficient to realize it.

In this report, we will introduce characteristic features of heavy ions accelerated by the RRC in Section 2. We will illustrate the design of the new beam course in Section 3. We will briefly summarize the present status of our project in Section 4.

2 Heavy-ion Beams in RRC

One of the remarkable features of the RRC is that it provides heavy-ion beams over the whole atomic mass range and a wide energy range from 0.6 MeV/nucleon to 135 MeV/nucleon. In the case of the heavy-ion beam, the LET is proportional to the square of the charge of the ion and is inverse proportion to the energy of the ion. We summarize in Table 1 the energy and the LET of the heavy ions which we use frequently to study bio-science in the RARF. Note that the lower value of the LET corresponds to the maximum energy for each ion. On the contrary, we observed the higher value with a range shifter.

Table 1
Properties of the RRC beams

Ion	Energy (MeV/u)	LET (keV/μm)	Range in Water (mm)
$^{12}C^{6+}$	135	23~290	40
$^{20}Ne^{10+}$	135	61~680	23
$^{40}Ar^{17+}$	95	280~1500	8.2
$^{56}Fe^{24+}$	90	620~3500	4.3

Another important feature is that the heavy ion accelerated by the RRC has a long range because of its high energy. We also tabulate the ranges in water in Table 1. Because of this long range nature, irradiation experiments in the air are easily performed. Moreover, this property makes it possible to investigate the inner part of an organism without undesired damages on a surface region.

Taking advantage of a wide variety of the LETs and long range nature of heavy ions, many experimental studies have been performed in the RARF. For example, characteristics of heavy-ion-induced mutations, effectiveness of the DNA repair system in response to high-LET radiation and an effective mutation method for plants have been studied with the present irradiation system[2].

3 Design of Microbeam Course

In producing a microbeam, we may employ either (both) of the following two methods. The first one is to focus heavy ions strongly at the target position with magnets. This method is suitable for a small-emittance beam. The second one is to use a collimator with extremely small aperture. In this beam collimation method, a high-intensity beam is necessary.

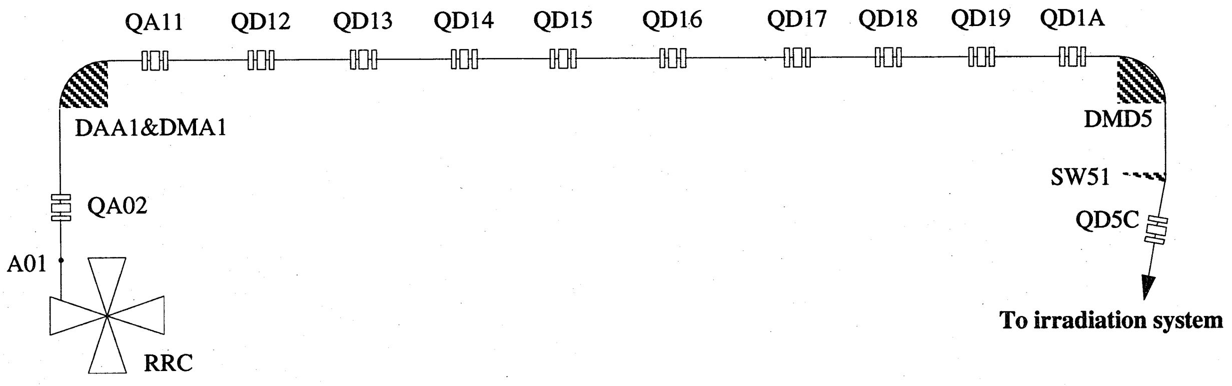

Fig. 1 Configuration of magnets in the E5C line. A box(semi-circle) shows a quadrupole(dipole) magnet.

We adopt here the second one because the beam current of the RRC is sufficiently high and insertion of few devices into the present beam line realizes a 50-μm microbeam. To avoid the divergence of the beam on the target, it is important that we make a parallel beam at the collimator and set a target just behind the collimator.

3.1 Beam transport system

We use a branch of the beam distribution system of the RRC, which we call the E5C course, as a microbeam line. We do not change the configuration of magnets illustrated in Figure 1 because other beam lines use same magnets except for the last triplet of quadrupole magnets. In spite of this, we have sufficient number of adjustable parameters, i.e., field gradients of quadrupole magnets.

Making use of these degrees of freedom, we design the beam transport system which satisfies the following requirement. The requirement is to reduce a beam loss at the collimator because a great beam loss may cause a serious problem for the radiation protection. To this end, we insert two sets of slits in the upper stream of the beam line. One set of slits works for both horizontal and vertical directions. We determine positions of slits as these slits also work to define the emittance of the beam.

It is easy to find solutions to satisfy the requirement. We illustrate here the beam envelope of a typical solution in Figure 2. In this solution, we suppress strongly the divergence of the beam below the last quadrupole magnet. Due to this property, we can choose freely the position of the collimator and the end-point of the beam line where we extract heavy ions into the air.

Here, we will explain more detailedly properties of this solution. Following the first-order beam optics theory, the position(x) and the angle(θ) of heavy ions are given using a transfer matrix as

$$\begin{pmatrix} x \\ \theta \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_0 \end{pmatrix}.$$

Here, x_0 and θ_0 mean the position and the angle at the A01 point, respectively. The A01 point is the object point. We adopt the point-to-parallel transport to suppress the beam divergence, and consequently m_{22} is zero. The maximum angle of heavy ions depends on the values of m_{21} and x_0. In this solution, heavy ions which fulfill the condition as -0.08 (mm) $< x_0 < 0.08$ (mm) can pass through the first set of slits. We choose m_{21} as -0.05 mrad/mm for both horizontal and vertical directions at the exit of the last quadrupole magnet. Consequently, the maximum angle of heavy ions is 4 μrad. The transmission efficiency is $1.35 * 10^{-9}$, and the resulting current of the microbeam is 840 ions/second for a 100 pnA heavy-ion beam. Finally, the achromaticity is fulfilled in this case.

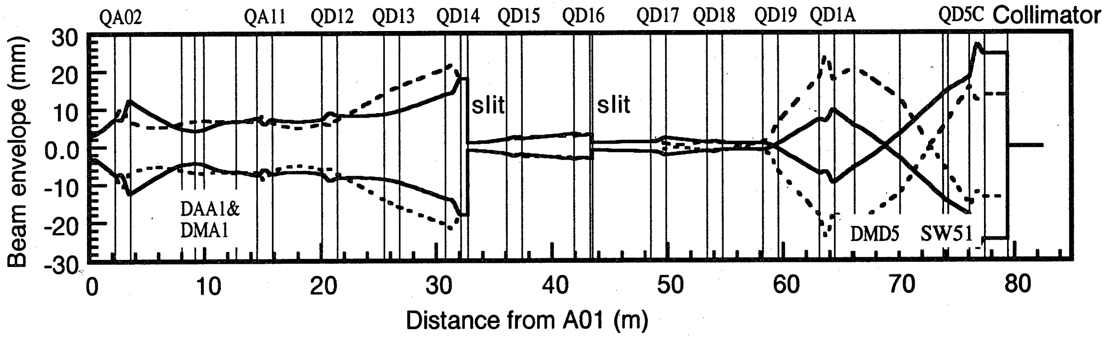

Fig. 2 Beam envelope in the E5C course. A solid(dashes) line is the horizontal(vertical) component. The A01 point is the object point of the beam optics. Vertical lines show positions of magnets, slits and the collimator.

3.2 Collimator and Irradiation System

Figure 3 shows the conceptual design of the irradiation system. First, we need a collimator with aperture of 50 μm to produce a microbeam. The thickness required is 10 mm when we use a heavy metal, because the energy of heavy ions is quite high. It is difficult but technically possible to make such a narrow and thick collimator[3] and a test bench of the collimator is in course of production. In Figure 3, we plan to use another collimator placed in the upper stream(left one in Figure 3). The aim of this collimator is to select an essential part of a beam beforehand.

In addition, we use a position-sensitive detector(PSD) to resolve the beam axis. We employ a microscope to determine the target position. We fix the target to a movable stand. We drive the stand using a stepping motor and choose the minimum step as 50 μm. Utilizing these apparatuses, we set the target precisely on the beam axis. The scintillation counter placed above the target numerates heavy ions. We also prepare a range shifter in order to vary the LET. We set all devices on the same table which defend them from vibration. A beam profile monitor and a Faraday cup are for beam tuning and we set them off the beam axis during experiments.

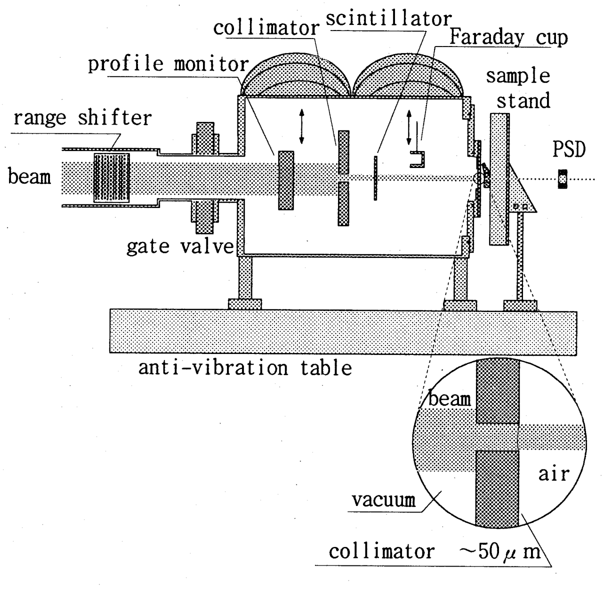

Fig. 3 Conceptual design of the irradiation system.

4 Present Status of Project

In the preceding section, we outlined the design of our new beam course. We mention here the present status of the project. As stated previously, it is in progress to make the collimator, which is the key ingredient of our project. It will be completed in this fall. We will test it and produce the first microbeam in this fiscal year. At the same time, we will study the beam transport and examine the position-sensitive detector. In producing a microbeam, a new beam profile monitor is necessary because the beam intensity is very low. Recall that we plan to insert two sets of slits in the beam line. A small fraction of the beam, 0.02 % in the example mentioned in Section 3, can pass through these slits. Hence, the maximum current is 0.2 pnA. To measure the beam profile for such a low-density beam, members of our group developed a new profile monitor. The profile monitor is designed to work effectively for a small current[4]. In addition, we should refine the design of the irradiation system. We plan to finish the detailed design till the next spring. The first irradiation experiment is scheduled in 1998.

References

[1]T. Kamiya, N. Utsunomiya, E. Minehara, R. Tanaka and I. Ohdomari, Nucl. Instr. and Meth. **B64** (1992) 362.
R. Tanaka and T. Kamiya, Nucl. Instr. and Meth. **B79** (1993) 423.
T. Kamiya, T. Suda and R. Tanaka, Nucl. Instr. and Meth. **B104** (1995) 43.

[2]Studies of bio-science in the RARF are reported briefly in RIKEN Accelerator Progress Report. Examples listed in the text are included in vol.30(1996) and references are therein.

[3]M. Anzai, private communication.

[4]A. Yoneda et al, in proceeding of this conference.