USE OF MICROBEAM AT JAEA TAKASAKI

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Abstract

The TIARA facilities of JAEA in Takasaki is equipped with a several-MeV light-ion and a several-dozen-MeV heavy-ion microbeam formation systems of focusing type, and a several-hundred-MeV heavy-ion microbeam formation system of collimating type. The microbeams with a spot size of 1 μm or less in diameter are extensively utilized for the research in materials science and biotechnology. An in-air micro-PIXE analysis system using a 2 MeV proton microbeam is quite useful for medical science and dentistry to visualize two-dimensional distribution of very small quantities of elements in a microscopic area like cells with very high sensitivity. A single-ion hit system using a several-hundred-MeV heavy-ion microbeam is available for medical and biological applications such as elucidations of cellular radiation response. Highly stable ion beams with energy spread less than 0.02 % are required for the microbeam production. Improvements of accelerator performance are indispensable to realize the ion beams of high quality. A flattop acceleration system and a magnetic field stabilization system have been developed for the JAEA AVF cyclotron. These accelerator technologies are also required for very precise spectroscopic studies in nuclear physics. Ultrahigh energy resolution of 0.005 % has been achieved at the RCNP cyclotron facility of Osaka University.

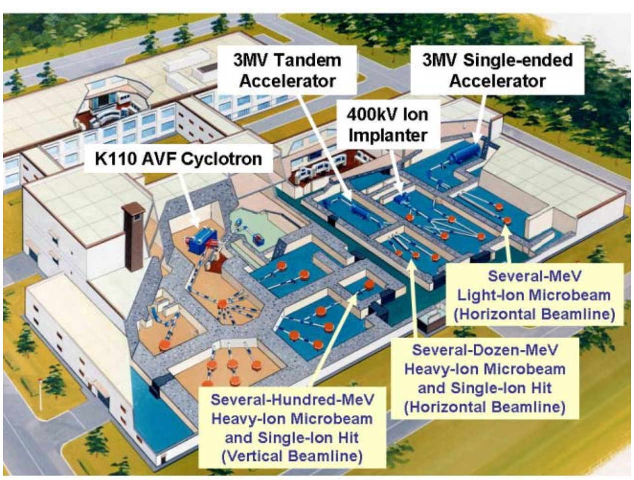

Figure 1: Bird view of the TIARA facility, equipped with four accelerators and three microbeam formation systems.

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INTRODUCTION

The ion beam irradiation research facility, TIARA (Takasaki Ion accelerators for Advanced Radiation Applications), was completed in 1993 at the Takasaki Radiation Chemistry Research Establishment of Japan Atomic Energy Research Institute(JAERI), the predecessor of the present Takasaki Advanced Radiation Research Institute of Japan Atomic Energy Agency (JAEA) [1]. Ion beam applications to the research and development in materials science and biotechnology have been fairly progressing after the full-scale operation of the ion accelerator complex facility. The bird view of the TIARA facility is shown in Fig. 1. A variety of ion beams are provided by a K110 AVF cyclotron, a 3 MV tandem accelerator, a 3 MV single-ended accelerator and a 400 kV ion implanter. The wide energy range from 20 keV through 1 GeV is covered by the accelerator complex.

Three kinds of light- and heavy-ion microbeams with a beam spot size of 1 μm or less in diameter are available at the TIARA facility. Use of the ion microbeam has greatly enhanced spatial and targeting resolutions of the ion irradiation in a finite area.

The micro-PIXE analysis has become widespread in various fields. Proton or helium ion beam with energies from 2 to 3 MeV is produced by the single-ended accelerator with acceleration voltage stability of the order of 10^{-5}. The helium ion microbeam with a spot size of 0.25μm has been produced using the high quality ion beam. The in-air micro-PIXE technique, first developed at TIARA, enables elemental analysis in cells without drastic change of the living cell condition by placing the frozen cell sample in atmosphere.

The tandem accelerator is equipped with a several-dozen-MeV heavy-ion microbeam formation system. The heavy-ion microbeam is useful for material processing and elucidation of radiation effects such as single-event upset of semiconductor devices used in space, caused by high LET(Linear Energy Transfer) irradiation. As the integration level of the semiconductor devices increases, higher spatial- and targeting-resolutions are required for the investigation of the radiation effects.

The LET range from 10 to 1000 keV/μm in water equivalent is covered by several-hundred-MeV heavy ions accelerated by the AVF cyclotron. The deposit energy is transferred in a localized area along the ion track. In case of the cell irradiation, the heavy ion causes high dose localization within the cell. A heavy-ion microbeam formation system of collimating type has been installed in a vertical beam line of the AVF cyclotron for the elucidation of cellular radiation response. Targeting precision of 5 through 10 μm has been achieved, which is sufficient to hit the cell nucleus or cytoplasm.

The quality of the ion beam provided by the accelerators directly influences the microbeam production. The microbeam spot size is determined by a gap of slits and the chromatic aberration of the beam focussing lens. The chromatic aberration originates in the energy spread of the accelerated ion beam. In case of the electrostatic accelerator, the energy spread depends mainly on the stability of the acceleration voltage. In the case of the cyclotron beam, the energy spread can be minimized by a flattop acceleration technique. The flattop acceleration for the high quality beam production is also applied to the high energy resolution experiment in nuclear physics.

PRODUCTION OF THE MICROBEAM

A microaperture with a hole of 5 to 10 μm in diameter or a precisely manufactured slit is used in the microbeam formation system of collimating type. The minimum beam spot size was limited by the size of the microaperture or the slit gap. Contamination of particles scattered at the edge of the microaperture or the slit might bring deterioration of the microbeam spot size, in some case.

A beam focusing using a multiplet of quadrupole lenses is a sophisticated technique to reduce the beam size less than 5 μm [2]. A schematic image of the focusing system for microbeam production is shown in Fig. 2. The object of the primary beam is determined by the first slits. Divergence of the beam is defined by a series of the second slits. An image of these slits can be projected at a focal plane by the focusing lenses. The microbeam spot size is determined by the demagnification factor of the lens system. Spherical and chromatic aberrations in the lens system are also taken into account to minimize the beam size.

In order to measure the microbeam spot size, the microbeam is scanned on a silicon relief pattern, and the secondary electrons emitted from the silicon relief pattern are detected. The position of the microbeam can be known from the voltage supplied to an electrostatic beam scanner. We can estimate the beam spot size from the peak width of the secondary electron distribution obtained at the edge of the relief pattern. The beam spot size of 250 nm in diameter has been achieved for 2 MeV proton and helium ion beams.

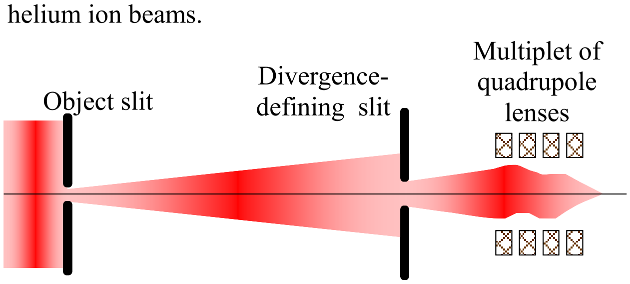

Figure 2: Image of the microbeam production.

APPLICATIONS OF THE MICROBEAMS

Several-Dozen-MeV Heavy Ion Microbeam

A heavy ion microbeam, such as a 15 MeV nickel ion accelerated by the 3 MV tandem accelerator, is utilized to investigate SEU(single event upset) of semiconductor devices used for space [3]. A single ion hit system, consisting of single-ion detectors and a fast beam switcher has been developed for observation of the SEU phenomena at a specific position of the micro device.

Several-MeV Light Ion Microbeam

The micro-PIXE analysis using the 2 MeV proton microbeam has an overwhelming advantage in analyzing very small quantities of elements in a microscopic aria with very high sensitivity. Two-dimensional distribution of elements included in cells can be visualized by the in-air micro-PIXE technique [4]. A schematic drawing of the in-air micro-PIXE system is shown in Fig. 3. A 4 μm thick Mylar film is used as a sample backing and a vacuum partition. The microbeam is focused on an experimental sample mounted on annular sample holder in the atmosphere. The X-rays emitted from the sample elements are measured by a Ge or Si(Li) detector placed upstream. The microbeam is scanned horizontally and vertically by the electrostatic beam scanner. The element species is identified by the X-ray energy. The in-air micro-PIXE system enables multi-elemental mapping of samples in atmospheric environment without drying the biological samples. The micro-PIXE analysis technique is widely applied to various research fields such as bio-medical research, dentistry, environmental science, and geology.

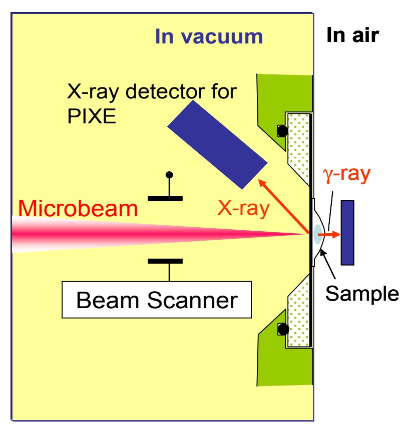

Figure 3: Schematic drawing of the in-air micro-PIXE system.

Several-Hundred-MeV Heavy Ion Microbeam

The high energy heavy-ion microbeam formation system, installed in a vertical beamline of the JAEA AVF cyclotron, is used for living biological cell irradiation. The single ion hit technique was also applied to the microbeam formation system to irradiate the specific part of individual cells [5]. Heavy ions are delivered to atmosphere through the microaperture with an inner diameter of 10 μm. A sample stage is placed just after the microaperture. Single ions are detected with a plastic scintillation counter placed downstream of the sample stage. Every time a single ion is detected, the ion injection into the cyclotron is inhibited by kicking out the ion beam with a beam switcher installed on the injection line until the single ion detection system and a data processing system become ready for the next single ion event.

The heavy ion microbeam with energy of hundreds MeV, inducing high LET in substances, is extremely useful for the research in biology and biotechnology. The high energy heavy-ion microbeam is a fine probe for the investigation of the cell response by causing great damage to DNA without destroying the whole cell. The single ion hit technique using the high energy heavy-ion microbeam is indispensable for investigation of cell-to-cell communications like bystander effects, the analysis of cellular spatial sensitivity, the interaction of damages caused by individual irradiation, the cellular repair dynamics, and the intra-cellular process such as apoptosis.

DEVELOPMENT OF A NEW HIGH-ENERGY HEAVY-ION MICROBEAM FORMATION SYSTEM

A new microbeam formation system of focusing type, using a quadruplet of quadrupole lenses in combination of a series of slits, is under development to improve the special and targeting resolutions. The new microbeam formation system has been installed in another vertical beam line of the JAEA AVF cyclotron. The system is equipped with a magnetic beam scanning system to increase the speed of the single ion hit to 600 hits/min.

The spot size of the microbeam has been estimated by measuring the distribution of the secondary electrons emitted from a copper grid with sharp edges. The position of the single ion hit has been observed using a CR-39 film. Recently the beam spot size of 1 μm has been successfully obtained [6].

UPGRADE OF THE CYCLOTRON FOR GENERATION OF HIGH QUALITY BEAMS

In order to generate the high quality beam with the energy spread of $\Delta E/E = 0.02$ %, a flattop acceleration system has been developed for the JAEA AVF cyclotron. Reduction of the energy spread has been achieved by using the flattop acceleration voltage waveform, generated by superimposing the fifth-harmonic voltage waveform on the fundamental one.

In case of the flattop acceleration using the fifth-harmonics, the magnetic field fluctuation of the cyclotron magnet is required to be less than 2×10^{-5} FW to suppress the beam phase within 16 RF degrees [7]. The magnetic field fluctuation of conventional cyclotrons is of the order of 10^{-3} to 10^{-4}. The temperature control system of the cyclotron magnet has been improved to fulfil the tolerance of the magnetic field fluctuation causing the beam phase excursion.

Development of the Flattop Acceleration System

An additional co-axial cavity, called FT cavity, has been coupled capacitively to the middle part of the transmission line of the fundamental cavity to generate the fifth-harmonic voltage. The impedance matching between the two cavities is optimized by tuning the gap between the capacitive coupler electrode and the inner tube of the fundamental cavity. The fifth-harmonic resonant frequency range from 55 to 110 MeV is fully covered by the FT cavity. The rf power for the fifth-harmonic voltage generation is fed to the FT cavity from the 3 kW wide–band amplifier.

A demonstration of the flattop voltage waveform, observed with the capacitive pickup placed at the corner of the dee electrode near the extraction radius, is shown in Fig. 4. In the practical flattop acceleration, however, the pickup signal doesn't have such a flattop waveform, because the dee electrode has a spanning angle of 86 degrees and the fifth-harmonic voltage decreases with a radius due to the voltage variation of the standing wave along the transmission line of the cavity [8]. The ratio of the fifth-harmonic voltage to the fundamental one is required to increase from the theoretical value of 1/25. The voltage ratio depends on the resonant frequency and the acceleration harmonic number.

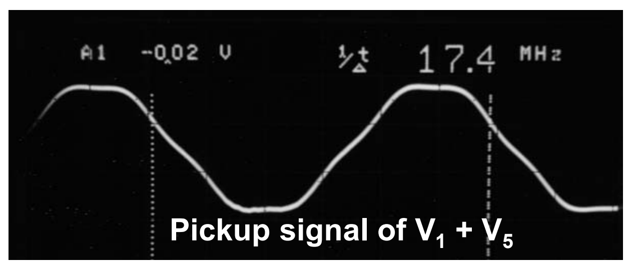

Figure 4: Flattop voltage waveform observed with the pickup of the dee electrode.

The flattop accelerated beam of 260 MeV $^{20}Ne^{7+}$ ions has been developed for the microbeam production. A clear turn pattern in the large radius region before extraction has been observed by the flattop acceleration. The energy spread of the extracted beam has been reduced to $\Delta E/E = 5 \times 10^{-4}$ or less.

Stabilization of the Cyclotron Magnet Field

The beam phase excursion out of the tolerable phase range for the flattop acceleration is caused by the error of isochronous field generation and by the fluctuation in the magnetic field. The magnetic field fluctuation originates in the temperature variation of a pole and a yoke of the cyclotron magnet.

On the basis of investigation of the correlation between the magnetic field and the yoke temperature changes, effective measures have been taken to stabilize the magnetic field. Water-cooled copper plates were installed between the main coil and the magnet yoke to control thermal conduction from the main coil to the magnet yoke. Cooling water temperatures of the copper plates and trim coils were optimized to keep the pole and yoke temperatures constant according to the excitation level. The magnetic field fluctuation has been reduced down to $\Delta B/B = \pm 1 \times 10^{-5}$ by the stabilization measures [9].

PRODUCTION OF HIGH QUALITY BEAM AT RCNP CYCLOTRON FACILITY

The techniques of the flattop acceleration and the cyclotron magnet field stabilization are common to the generation of the high quality beams for high-resolution experiments in nuclear physics. The RCNP(Research Center for Nuclear Physics) cyclotron facility of Osaka University has been upgraded to improve the beam quality and transmission to the RCNP ring cyclotron[10].

The RCNP cyclotron facility is shown in Fig. 5. The K400 ring cyclotron, equipped with a flattop acceleration system and the magnet field stabilization system, provides the high quality beam with the energy spread of the order of 10^{-4}. The magnetic field of the ring cyclotron is stabilized at the order of 10^{-6}. Ultrahigh energy resolution of $\Delta E/E = 5 \times 10^{-5}$ has been achieved with the spectrometer "Grand Raiden" by a dispersion matching method applied to the beam transport from the ring cyclotron to the spectrometer.

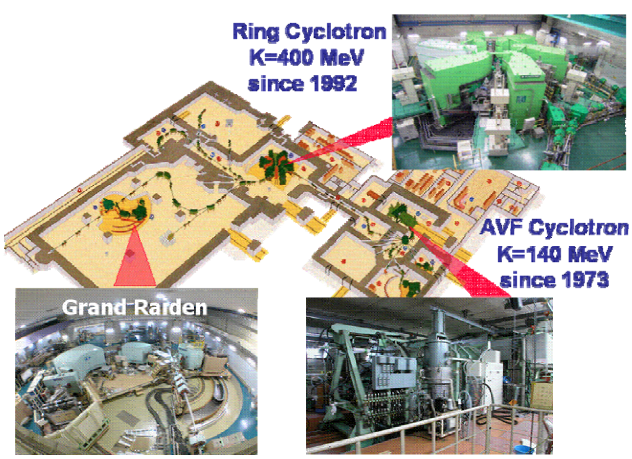

Figure 5: RCNP cyclotron facility.

A new flattop acceleration system using the fifth, seventh and ninth harmonics has been developed for the K140 AVF cyclotron to reduce the energy spread of the beam. The flattop acceleration voltage waveform has been successfully produced in the frequency range from 50 to 80 MHz. In order to improve the beam transmission to the ring cyclotron, the development of the flattop accelerated beam is now in progress.

REFERENCES

[1] R. Tanaka, et al., "JAERI AVF Cyclotron for Research of Advanced Radiation Technology", Proc. 12th Int. Conf. on Cyclotrons and Their Applications, Berlin, May 1989, p. 566.

[2] M.B.H. Breese, D.N. Jamieson, P.J.C. King, Materials Analysis Using A Nuclear Microprobe, 1996, (New York: Wiley-Interscience).

[3] T. Kamiya, N. Utsunomiya, E. Minehara, R. Tanaka, Nucl. Instr. and Meth. B 64 (1992) 362.

[4] T. Sakai, T. Kamiya, M. Oikawa, T. Sato, A. Tanaka, K. Ishii, Nucl. Instr. and Meth., B190 (2002) 271.

[5] Y. Kobayashi, M. Taguchi, T. Shimizu, S. Okumura, H. Watanabe, J. Radiat Res., 36 (4), 290 (1996).

[6] M. Oikawa, et al., "Design of a Focusing High-Energy Heavy Ion Microbeam System at the JAERI AVF Cyclotron", Nucl. Instrum. Methods B210 (2003)54.

[7] M. Fukuda, et al., "A Flat-top Acceleration System for the Variable-Energy and Multi-Particle AVF Cyclotron", Rev. Sci. Instrum., 74(2003) 2293.

[8] S. Kurashima et al., "Development of the Flat-Top Acceleration System for the JAERI AVF Cyclotron", Proc. 17th Int. Conf. on Cyclotron and Their Applications, Tokyo, Japan, 2004, p. 362.

[9] S. Okumura, et al., "Magnetic field stabilization by temperature control of an azimuthally varying field cyclotron magnet", Rev. Sci. Instrum., 76 (2005) 033301.

[10] K. Hatanaka, et al., "Upgrade Project of the RCNP AVF Cyclotron Facility", Proc. 17th Int. Conf. on Cyclotron and Their Applications, Tokyo, Japan, 2004, p. 115.