PROJECT OF THE JAERI SUPERCONDUCTING AVF CYCLOTRON FOR APPLICATIONS IN BIOTECHNOLOGY AND MATERIALS SCIENCE

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Abstract

A project for expanding TIARA (Takasaki Ion accelerators for Advanced Radiation Application) facilities of JAERI has been proposed to broaden application region of biotechnology and materials science. As a result of the investigation of TIARA facility user's request, energy increase up to more than 100 MeV/n for heavy ions and up to 300 MeV for proton are strongly required. The magnet of a superconducting AVF cyclotron with a K number of 900 has been designed to cope with acceleration of both 150 MeV/n heavy ions and 300 MeV protons. The lower limit of energies has been investigated to overlap the energy region covered by the JAERI AVF cyclotron, required to increase beam time for present users. We have designed a beam transport system to satisfy various requirements of the applications.

INTRODUCTION

An accelerator complex of the TIARA facility[1] covering the energy range from keV to 27.5MeV/n consists of the three electrostatic accelerators and the K110 AVF cyclotron[2]. Especially, the AVF cyclotron has been utilized mainly for materials science and biotechnology. As the research for ion beam application progressed, requests for the ion beams with the energy over an accelerating performance of the present AVF cyclotron have been increased in many fields. In order to survey user requests exactly, we have investigated the characteristics of the ion beam parameters. The superconducting AVF cyclotron[3] has been proposed to fulfil the beam and irradiation conditions.

INVESTIGATION OF USER NEEDS

Investigation of user needs have been carried out among the user of TIARA facility and relational scholars in Japan. A result of the investigation is listed in table 1.

In biotechnology and life science relative biological effectiveness (RBE) is enhanced in the linear energy transfer (LET) range of 200 to 300 keV/μm, such as a carbon ion beam with energy beyond 100 MeV/n, which is optimum for the ion induced mutation. By using the heavy ions with energy up to 100 MeV/n, the ion beam breeding can be applied to production of useful plants such as UV resistant crops, disease resistant crops, insect

Table 1: Investigation of user needs

Research field		Biotechnology and life science	Veterinary medicine	Materials science and radiation chemistry	Space development	RI production and radiation shielding physics
Beam condition	Ion species and energy	H < 200 MeV He < 50 MeV/n C > 100 MeV/n Ne > 100 MeV/n Fe < 200 MeV/n	H < 150 MeV C < 300 MeV/n	He~U < 50 MeV/n	H < 300 MeV C < 100 MeV/n Heavy ion < 120 MeV/n	H < 1 GeV D < 100 MeV He < 250 MeV/n
	Beam intensity	Max. several nA	Several tens Gy	< Several μA	Low fluence rate	Several μA
Irradiating condition	Direction	Vertical	Vertical / Horizontal	Vertical / Horizontal	Horizontal	Horizontal
	Unique irradiation	Large area, Uniform	3-dimension, Large area, Uniform	Pulse	Large area, Uniform	Large area, Uniform
		Microbeam	In the atmosphere	Nano-beam	In the atmosphere	Pulse
		Single ion hit	Microbeam	Single ion hit	-	-
	Beam spot size	1~1000μm	1~1000μm	1~10mm <ϕ50nm	10~150 mm	-
	Pulse beam	-	-	Interval 1μs~1s Width 1ns	-	Interval tens μs~1μs Width 1ns
	Uniform irradiation	30×30 cm^2	10×10 cm^2	-	15×15 cm^2	ϕ 40 cm
		<|5%|	<|5%|	-	<|5%|	<|5%|
Target sample		Plant cell, Tissue, Seeds and so on.	Small animal.	Solution, Organic and Molecular compound, Ceramics and so on.	Fabricated semiconductor devices.	Gases, Solutions, Solids, Radiation shielding materials.

resistant crops, environment remediable plants, new breed petals and high quality fruit crops. In addition, the heavy ion microbeam[4,5] with energy beyond 100 MeV/n is extremely helpful for research in biology and biotechnology. A well-focused microbeam with a spot diameter of 1 μm will be utilized for specific parts of cell or tissues to elucidate animal- and plant-organ development, biofunction of cells for information transmission and apoptosis control.

In materials science the heavy ions with energy up to 50 MeV/n will be utilized for the basic research of high density electronic excitation and the development of an organic film with a very high aspect ratio. A radiation test of fabricated semiconductor devices in an atmospheric condition to simulate single event phenomena in space demands both up to 100 MeV/n heavy ions and 300 MeV protons.

The requested ion species and energy are mainly heavy ions with energy beyond 100 MeV/n and protons with energy of several hundreds MeV. A superconducting AVF cyclotron was chosen to cope with both above-mentioned requests and reduction costs.

RANGE OF ACCELERATION ENERGY

Protons maximum acceleration energy

In current superconducting AVF cyclotrons[6] of three-sector type the maximum energy of protons have been limited to 200 MeV by the π-mode stop band (ν_r=N/2, where the N is a number of sectors). In order to solve this problem, we have adopted the four-sector magnet like the K250 proton therapy cyclotron designed by NSCL. So far the superconducting magnet for accelerating protons up to 290 MeV has been designed by optimizing the position and geometry of two pairs of superconducting main coils. In order to find the optimum sector shape of the magnet, the magnetic field for accelerating 300 MeV protons has been calculated by using the code OPERA-3D. Sufficient beam-focusing in the energy region more than 280 MeV can be achieved by expanding the azimuthal sector width in the radius region more than 100 cm than before. A correlation between the betatron frequencies and the accelerating energy for 300 MeV protons is shown in Fig. 1. A current density in the main coil of the median plane side is 30 A/mm^2 (726 kA/coil). A vertical betatron frequency ν_z is maintained more than 0.2 at 300 MeV.

Lower limit of acceleration energy

The utilization of heavy ion beams in biotechnology continues to grow for some years. The energy range of the JAERI superconducting AVF cyclotron should overlap with the present JAERI AVF cyclotron to improve the beam utilization efficiency.

The lower limit of energy have been estimated by closed orbit calculation for M/Q=1 to 6 with optimized field distribution of 300 MeV protons. The energy is limited mainly the ν_z=1 resonance. The estimated energy limit for the ions with M/Q=1,2,3,4,5 and 6 are listed in Table 2.

Table 2: Lower limit of acceleration energy

M/Q	Ion	Lower energy (MeV/n)
1	Proton	185
2	$^{20}Ne^{10+}$	76
3	-	27
4	$^{40}Ar^{10+}$	18
5	$^{40}Ar^{8+}$	11
6	$^{84}Kr^{14+}$	8

In case of protons, the energy at lower limit is 185 MeV. The energy can be decreased to 76 MeV/n by accelerating hydrogen molecule H_2^+. The proton on energy range of K900 cyclotron overlaps with that of the present AVF cyclotron, since the maximum energy of protons is 90 MeV. In heavy ion acceleration the energy of lower limit can be lowered to 8 MeV/n by accelerating ions with bigger M/Q, and sufficient overlapping is possible.

Tune diagram for lower energy ions from M/Q=1 to 6 is shown in Fig. 2. The more acceleration energy decreases, the more flatter increases, and the more $(\beta\gamma)^2$ decreases, the more ν_z nears 1 easily.

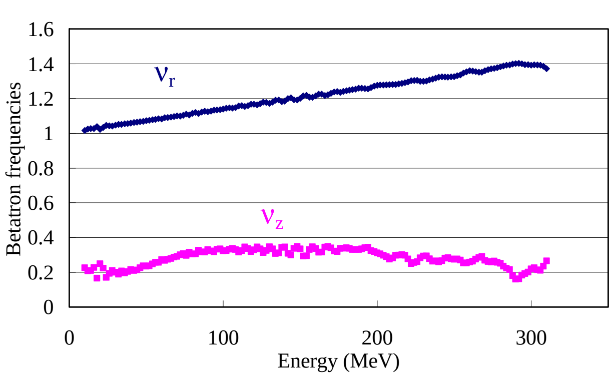

Figure 1: A correlation between the betatron frequencies and the accelerating energy for 300 MeV protons.

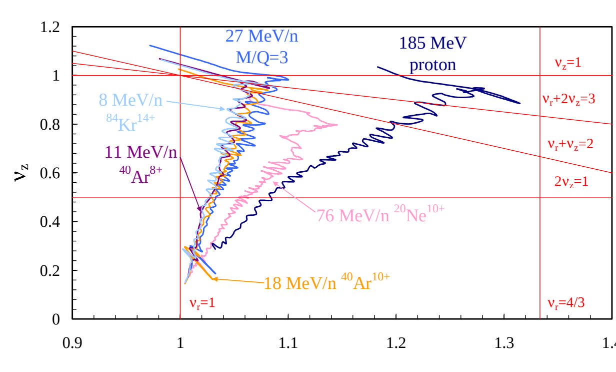

Figure 2: Working paths in the (ν_r, ν_z) for 185 MeV protons, 76 MeV/n $^{20}Ne^{10+}$, 27 MeV/n M/Q=3, 18 MeV/n $^{40}Ar^{10+}$, 11 MeV/n $^{40}Ar^{8+}$ and 8 MeV/n $^{84}Kr^{14+}$.

In order to lower the lower limit energy moreover, the sector shape has to be optimized so that the flatter is not bigger on low energy side. However the more flatter deceases, the more maximum energy decreases. Therefore the energy range needs to be determined after careful consideration based on the user requests.

BEAM TRANSPORT AND IRRADIATION

Design of the beam transport

The beam transport optics for the JAERI superconducting AVF cyclotron has been designed based on the following conditions.

1) Maximum magnetic rigidity: $B\rho = 4.5$ T • m

2) Emittance: 5 πmm • mrad

3) Momentum spread: 0.1%

Normal-conducting magnets will be adopted from the point of the cost saving and the easiness of maintenance. In order to suppress the electric power of quadrupole magnets and to save the cost, the beam divergence is reduced to small angle. The 90 degree bending magnet coil is difficult to cool by water. Therefore, we will adopt the 45 degree bending magnets.

Characteristic irradiation at the target port

As a result of the user needs investigation, various irradiation systems are required for beam utilization in the research program. As a vertical beam transport line is advantageous to fixing target samples in experiments for biotechnology, the microbeam and the uniform irradiation lines have been optimized for vertical direction. Uniform irradiation of a high-energy ion beam over a wide area, within 300 x 300 mm, will be installed for the researches in materials science.

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