DESIGN STUDIES OF THE K900 JAERI SUPERCONDUCTING AVF CYCLOTRON FOR THE RESEARCH IN BIOTECHNOLOGY AND MATERIALS SCIENCE

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Abstract

A new project aiming for a breakthrough in biotechnology and materials science has been proposed at TIARA (Takasaki Ion Accelerators for Advanced Radiation Application) facilities of JAERI. Heavy ion beams with an energy of more than a hundred MeV/n will contribute to remarkable progress in breeding of plants and development of new materials. We have started designing a new superconducting AVF cyclotron with a bending limit of 900 and a focusing limit of 300. The cyclotron magnet is being designed to cope with acceleration of both the heavy ions and 300 MeV protons.

1 INTRODUCTION

The TIARA is very unique facilities designed for utilization of ion beams for the research in biotechnology and materials science[1]. The present accelerators cover the energy range of keV through 27.5 MeV/n. The ion beam applications are expected to be enormously broadened by increasing the energy beyond 100 MeV/n.

Relative biological effectiveness(RBE) of heavy ions in plant cells is enhanced in the linear energy transfer(LET) range of 200 to 300 keV/μm. The rate of mutations induced by ion beam irradiation is increased in the LET range, which is the optimum condition for the plant breeding. An 18.8 MeV/n carbon ion accelerated by the K110 AVF cyclotron[2] is commonly used for the experiment in the plant breeding at TIARA. The LET of the carbon ion in water is around 100 keV/μm in the plateau region of a Bragg curve. The LET is insufficient for ion particle-induced mutations. In addition, the carbon ion cannot reach depths of more than 1.3 mm in water. Subjects of ion beam irradiation for the plant breeding are restricted to cells, pollens and small seeds due to the insufficient range of the order of a few millimeters. By increasing the energy of the carbon ion up to 100 MeV/n, the range is enlarged to 26 mm, and the optimum LET for the ion particle-induced mutations can be obtained in the depths of the subjects. Using the carbon ion beam with an energy beyond 100 MeV/n, the subjects of the ion beam irradiation will be extended to tissues, petals, seedlings and large seeds. The ion-beam breeding can be applied to production of useful plants such as UV-resistant crops, disease-resistant crops, insect-resistant crops and environment-remediable plants, which will contribute to security of food resources and conservation of global environment.

By applying the microprobe technique[3,4] to the heavy ion beams with an energy of the order of 100 MeV/n, a well-focused microbeam with a spot diameter of 1 μm will be utilized for irradiating the heavy ions on specific parts of cells or tissues to elucidate animal- and plant-organ development, biofunctions of cells for information transmission and apoptosis control. This research will result in fruitful development in biology and life science that might contribute to advances in medical treatment and welfare.

The high-energy heavy ions can make an almost straight hole along their paths in an organic film with a very high aspect ratio. The film will be utilized for developing newly functioned devices such as a precise filter for selecting atoms and molecules, and an organic semiconductor device with which ultra-fast data processing might be possible. The heavy ion beams will be also useful for a radiation test of fabricated semiconductor devices in an atmospheric condition to simulate single-event phenomena in space.

2 DESIGN CHARACTERISTICS OF THE SUPERCONDUCTING AVF CYCLOTRON

2.1 Requirements for the Beam

Heavy ions from carbon through krypton with an energy of 50 to 100 MeV/n have a range of a few millimetres to a few centimetres and the LET of 100 to 400 keV/μm in water, which fulfils the requirements for the research on the ion-beam breeding. A 120 MeV/n krypton ion has an optimum range in silicon for the radiation test of semiconductor devices in the atmosphere. A 300 MeV proton is required for studying the single-event phenomena induced by secondarily produced particles. Heavy ions with an energy of more than 100 MeV/n are useful for developing new materials. A high - intensity heavy ion beam is required for the research in radiation chemistry.

The beam time of the present K110 cyclotron requested by users far exceeds the annually scheduled

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one. In order to make up for the deficiency of the beam time, the low energy region of the new accelerator needs overlapping with the energy region of the present K110 cyclotron.

A superconducting AVF cyclotron[5] is the best choice for our new project. The superconducting AVF cyclotron has great advantages of compactness and economy, saving costs for construction and operation. The operation efficiency can be enhanced by using cocktail beam acceleration technique[6] which enables a rapid change of the ion species and the beam energy.

2.2 Main Design Feature

In order to meet the requirements for the beam, we have adopted the superconducting AVF cyclotron with a bending limit of 900 and a focusing limit of 300. The major cyclotron parameters are listed in table 1.

Table 1: Cyclotron parameters

Bending limit K_b	900
Focusing limit K_f	300
Pole diameter	2300 mm
Number of sectors	4
Minimum hill gap	70 mm
Maximum average magnetic field	4.5 T
Extraction radius	1050 mm
Number of dees	4 in valleys
RF frequency range	24 to 64 MHz
Operating harmonics	2, 3, 4
Peak dee voltage	100 kV

An RF operating range of 24 to 64 MHz using three harmonics modes of 2, 3 and 4 is chosen to cover the wide range of beam energy as shown in Fig. 1. The upper limits of the energy for each harmonics are determined by the bending and focusing limits, and the conditions restricted by the geometry and electric field limitation of a spiral inflector. We currently assume that a minimum magnetic field radius of the inflector, R_m, is 13 mm, a maximum electric field radius, R_e, 30 mm, and a maximum electric field 25 kV/cm. The lower boundaries of each harmonics region are temporarily defined by the minimum RF frequency of 24 MHz. As the magnetic field is decreasing, flutter is getting higher, resulting in an increase of focusing frequency ν_z. The lower boundaries might move upwards due to a low field limit imposed by a resonance[7]. The resonance limitations are under investigation.

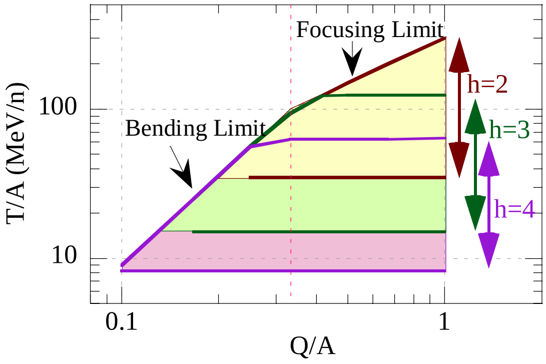

Figure 1: The energy range of the K900 superconducting AVF cyclotron using three harmonics of 2, 3 and 4.

3 DESIGN OF THE MAGNET

3.1 Structure of the Magnet

A cyclotron magnet is being designed to cope with acceleration of both the heavy ions and the protons. A four-sector magnet has been adopted to avoid the forbidden $\nu_r = N/2$ resonance, where the N is a number of sectors, to accelerate protons up to an energy of 300 MeV. The resonance becomes a serious problem for a three-sector cyclotron[8], since the ν_r of the 300 MeV protons approaches 1.5.

Structure of the preliminarily designed cyclotron magnet is shown in Fig. 2. Two pairs of superconducting main coils are placed separately[8]. The position and geometry of the main coils appropriate for generating various isochronous fields with different gradients have been investigated to cover a wide range of energy. The shape of the valley regions has been adjusted by adding several steps to produce the optimum iron field for generating the isochronous field.

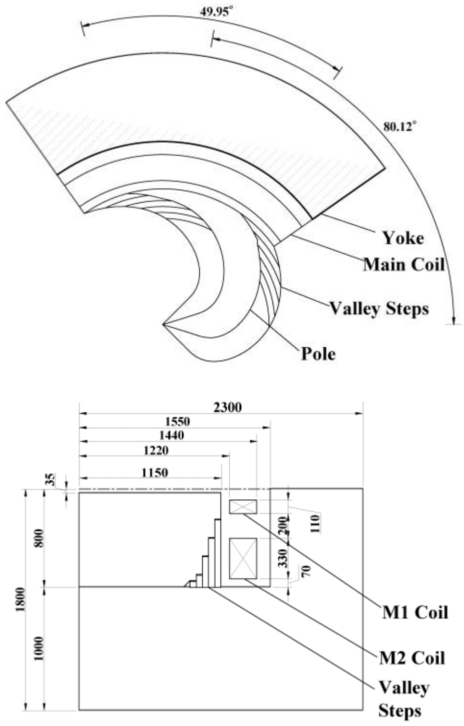

Figure 2: A schematic drawing of one of the sectors to calculate the magnetic field.

3.2 *Magnetic Field*

The magnetic field has been calculated using the code OPERA-3D. The optimum shape of the magnetic field for accelerating protons up to 290 MeV has been found so far. The average field for the acceleration of 290 MeV protons and contribution of iron to the field are shown in Fig. 3. Almost flat distribution of the average field produced by iron has been obtained. Trim coil fields to correct the average field for isochronism are estimated to be less than several hundreds gauss. The correction fields need to be reduced as low as possible to minimize the power of the trim coils, since thermal conduction to the magnet pole should be avoided to stabilize the magnetic field.

Working paths in the (ν_r, ν_z) plane for the 290 MeV protons, 150 MeV/n ^{20}Ne^{10+} and 56 MeV/n ^{40}Ar^{10+} are shown in Fig. 4. The paths runs in close proximity to some resonance lines. Further investigation of the resonance is required for modification of the magnet design.

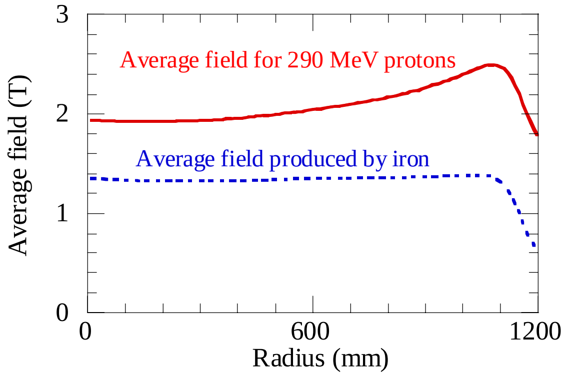

Figure 3: Average field for accelerating 290 MeV protons.

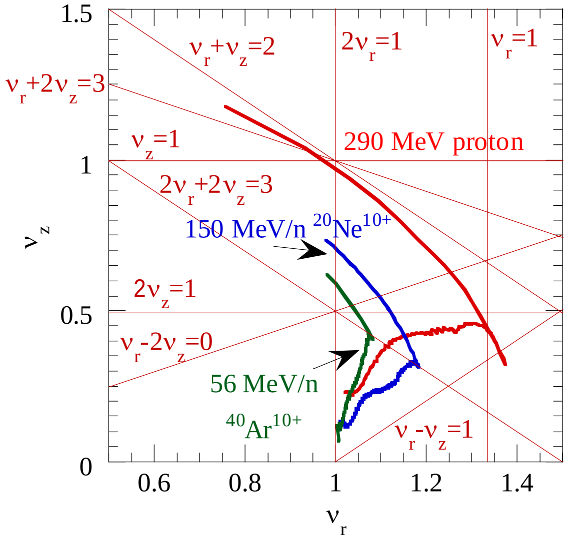

Figure 4: Working path in the (ν_r, ν_z) plane for 290 MeV protons, 150 MeV/n ^{20}Ne^{10+} and 56 MeV/n ^{40}Ar^{10+}.

4 DOUBLE-STAGE ACCELERATION

A feasibility study of a double-stage acceleration using the present K110 cyclotron as an injector has been carried out to boost the energy of heavy ions of which higher charge states are difficult to produce using an ECR ion source. A lower limit of a stripping ratio, Q_{K900}/Q_{K110}, is defined by the condition that the ions accelerated by the K110 cyclotron can reach to a stripping foil placed in the center region of the K900 cyclotron. By consideration of the injection velocity and a stripping efficiency, the beam energy of the K110 cyclotron is found to be increased two or three times by the K900 cyclotron. The same beam energy as the boosted one can be also obtained by a stand-alone acceleration mode of the K900 cyclotron using heavy ions with higher charge state produced by a current ECR ion source. In this case, the double-stage acceleration mode has not so much advantage in the energy boost.

5 PROJECT STATUS

The conceptual design of all the systems are in progress now. The research programs in biotechnology and materials science using the K900 cyclotron are being devised in parallel. We propose to start installation of the new facilities in 2004 and expect to extract the first beam in 2007.

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