A PROJECT OF THE K900 SUPERCONDUCTING AVF CYCLOTRON AT JAERI

M. Fukuda, K. Arakawa, W. Yokota, S. Okumura, T. Agematsu, T. Kamiya, K. Mizuhashi, T. Nara, Y. Saitoh, Y. Ishii, T. Sakai, H. Kaneko, S. Tanaka, S. Kurashima, A. Chiba, JAERI, Takasaki, Gunma 370-1292, Japan

Abstract

A new project bringing about a breakthrough in biotechnology and materials science has been proposed at JAERI (Japan Atomic Energy Research Institute). Heavy ion beams with energy of more than 100 MeV/n are expected to contribute to remarkable progress in breeding of plants and development of new materials. Design studies of a superconducting AVF cyclotron with a K number of 900 has been started to meet requirements for the researches. A four-sector, four-dee cyclotron is being designed to cope with acceleration of both the heavy ions and 300 MeV protons.

1 INTRODUCTION

The TIARA (Takasaki Ion Accelerators for Advanced Radiation Application) [1, 2] of JAERI is a quite unique accelerator complex specialized for ion beam applications in materials science and biotechnology. The TIARA covers the energy range of keV through 27.5 MeV/n for heavy ions. The subjects of irradiation using ion beams with the energy in the MeV range are restricted to comparatively thin materials due to small range of the ions. In order to obtain sufficient linear energy transfer (LET) to induce effective interaction in the depths of the materials, the ion energy is required to be increased to 100 MeV/n and over. We have proposed a new project of advanced accelerator facilities to provide heavy ion beams in the GeV range aiming a major breakthrough in the research field of biotechnology and materials science.

A superconducting AVF cyclotron [3] is one of the best candidates for the GeV heavy ion accelerator. The superconducting AVF cyclotron has great advantages of its compactness and economy, saving construction space and operation costs. The rate of operation can be increased by using a cocktail beam acceleration technique [4] which allows the ion species and the beam energy to be changed rapidly.

The existing superconducting AVF cyclotrons specialize mainly in nuclear research [5]. Most of the superconducting AVF cyclotrons were designed to accelerate heavy ions except for the AGOR [6] at KVI. The AGOR with a K number of 600 can provide a 200 MeV proton as well as heavy ions in the GeV range. The design of the JAERI superconducting AVF cyclotron is optimized to cover a wider range of ion species and energy required for the research in biotechnology and materials science. The proposed superconducting AVF cyclotron aims at accelerating a 300 MeV proton and heavy ions with energy higher than 100 MeV/n.

2 APPLICATIONS OF HEAVY ION BEAMS IN THE GEV RANGE

2.1 Biotechnology

Relative biological effectiveness (RBE) of heavy ions in plant cells is enhanced in the LET range of from 200 to 300 keV/μm. The rate of mutations is increased by heavy ions providing the corresponding LET of this range.

An 18.8 MeV/n carbon ion is currently used for the experiment in the plant breeding at the TIARA facilities. The LET of the carbon ion in water is 100 keV/μm in the plateau region of a Bragg curve. The LET of the carbon ion is not completely adequate for the ion particle-induced mutations. In addition, the carbon ion cannot reach depths of more than 1.3 mm in water. Irradiation subjects used for the plant breeding are restricted to cells, pollens and small seeds with a size of the order of a few millimeters

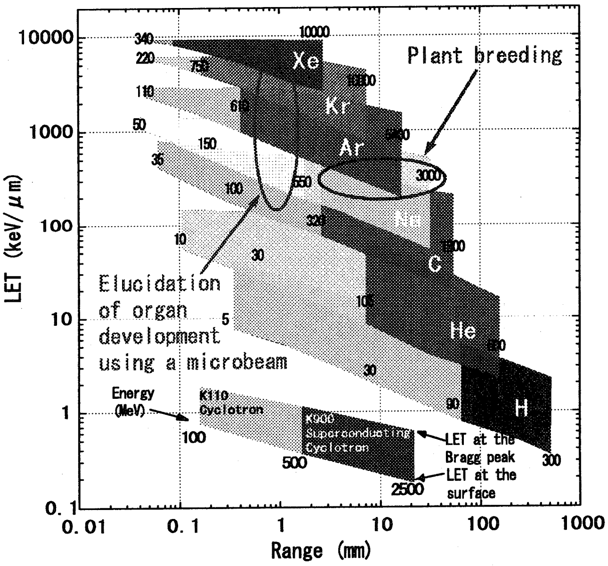

Figure 1: The LET and range in water for ions accelerated by the K110 AVF cyclotron and the K900 superconducting AVF cyclotron. The optimum regions for the research in bio-technology are indicated by ellipses.

due to the insufficient range. By increasing the energy of the carbon ion up to 100 MeV/n, the range is enlarged to 26 mm, and the irradiation subjects will be extended to tissues, petals, seedlings and large seeds.

The optimum LET and range of ions required for the plant breeding is shown in Fig. 1. The plant breeding using the carbon ion with energy above 100 MeV/n is expected to contribute production of useful plants such as UV-resistant crops, disease-resistant crops, insect-resistant crops and environment-remediable plants.

By applying the microprobe technique [7, 8] to the heavy ion beams with energy of the order of 100 MeV/n, a well-focused microbeam with a spot diameter of 1 μm will be utilized for heavy ion irradiation on specific parts of cells or tissues to elucidate animal- and plant-organ development, bio functions of cells for information transmission and apoptosis control. This research is expected to accelerate development in biology and life science that might contribute to advances in medical treatment and welfare.

2.2 Materials Science

A high-energy heavy ion can make an almost straight hole along their paths in an organic film with a very high aspect ratio. The film will be utilized to develop 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 beam will be also useful for a radiation test of fabricated semiconductor devices in an atmospheric condition to simulate single-event phenomena in space.

2.3 Requirements for the Ion Beams

Ions from carbon through krypton with energy of from 50 to 100 MeV/n have the range in water of from a few millimetres to a few centimetres. The LET at the surface of water is 100 to 400 keV/μm. The LET range 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 the studies of the single-event phenomena induced by secondarily produced particles. Heavy ions with energy higher than 100 MeV/n are useful in developing new materials.

3 DESIGN OF THE SUPERCONDUCTING AVF CYCLOTRON

3.1 Design Feature

In order to meet the requirements for the beam, we are designing 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.

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. 2. 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 [9]. The resonance limitations are under investigation.

Table 1: Cyclotron design 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

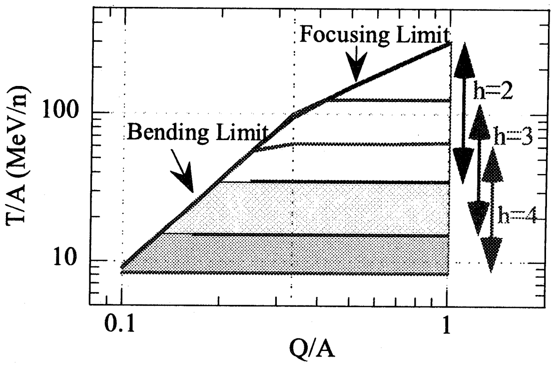

Figure 2: The energy range of the K900 superconducting AVF cyclotron using three harmonics of 2, 3 and 4.

3.2 Design 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 [6], since the ν_r of the 300 MeV protons approaches the stop band of 3/2.

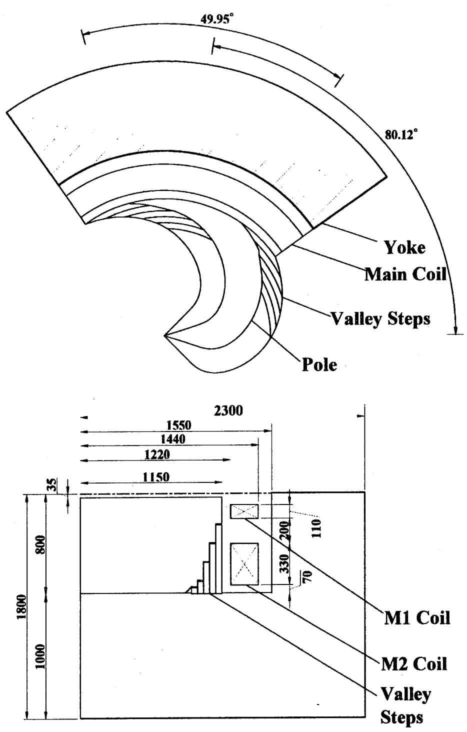

Figure 3: A schematic drawing of one of the four sectors to calculate the magnetic field.

The optimum shape of the magnetic field to accelerate protons up to 290 MeV has been found so far. Structure of the preliminarily designed cyclotron magnet is shown in Fig. 3. Two pairs of superconducting main coils are placed separately. The position and geometry of the main coils appropriate for generation of 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 flat iron field distribution.

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.

The Lorentz force between the main coils was estimated using the OPERA-3D code. The axial Lorentz force of the M1 coil close to the mid plane reaches to the maximum of 2.2 MN for the M1 current density of 27 A/mm^2 and the M2 of 0 A/mm^2 which corresponds to the excitation condition for 300 MeV proton. The axial and radial Lorentz forces of the M2 coil increase to 3.8 MN and 2.2 MN, respectively, which are obtained at the excitation of the bending limit required to accelerate 56 MeV/n $^{40}Ar^{10+}$.

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 run in close proximity to some resonance lines. Further investigation of the resonance is required for modification of the magnet design.

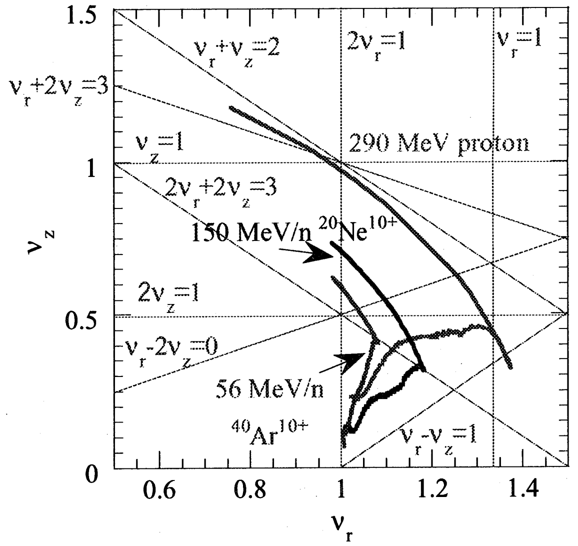

Figure 4: Working path in the (ν_r, ν_z) plane for 290 MeV protons, 150 MeV/n $^{20}Ne^{10+}$ and 56 MeV/n $^{40}Ar^{10+}$.

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