AVF-CYCLOTRON AS AN INJECTOR FOR RIKEN RING CYCLOTRON

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An AVF cylotron has been designed as an injector for RIKEN Ring Cyclotron. The $K = 70$ *Mev* cyclotron is able to accelerate nuclei with mass to charge ratio of less than 4. Matching conditions between the two cyclotrons have been taken into account. The cyclotron is also designed to be equipped external ion sources like an ECR source, polarized ion sources and so on. Design parameters of the cyclotron and its injection system will be described here.

INTRODUCTION

The RIKEN Ring Cyclotron, which has just completed, is planed to have two injectors. One is a variable frequency linac RILAC, which was completed in 1980, and the other an AVF cyclotron which will be constructed from 1987.

The linac, which is operated in the same radio frequency with that of the ring cyclotron, is designed so as to accelerate all nuclei of $A/q<28$ over an energy range of *0.6 - 4.0 Mev/u*.[1]

It is known that a linac is suited for the acceleration of heavy ions because of easiness of beam extraction, and that a cyclotron, on the other hand, is favor of accelration of light and light heavy ions up to higher energies. Then the two injectors are used not only independently but also complementally to each other.

AN INJECTOR CYCLOTRON

In designing the AVF cyclotron, following points were taken into account: 1) the cyclotron must be matched precisely to the post accelerator in view of beam optics; 2) it should be adaptable to external ion sources; 3) it will be used mainly as an injector.

Matching conditions between the two cyclotrons include the constansy of a longitudinal distance between beam pulses, of a beam velocity, and of a particle rigidity. For the first condition, we have an expression

$$n_a \cdot r_a \cdot h_s = n_s \cdot r_s \cdot h_a,$$

where n_a and n_s are simple integers, and h_a and h_s harmonic numbers in the AVF and ring cyclotrons, respectively. The r_a and r_s are effective extraction radius of the AVF cyclotron and effective injection radius of the ring cyclotron.

Table 1 Design characteristics of the AVF cyclotron.

K value	70 Mev
No of secotor	4
Extraction radius	0.714 m
Mean magnetic field	0.5 - 1.7 T
Gap width	315(V), 133(H) mm
Max. magnetmotive force	3.2×10^5 AT
No of trim coils	9
No of harmonic coils	4
No of dees	2 ($\lambda/4$ type)
No of cavities	2
Dee angle	85 °
RF range	12 - 24 MHz
Dee voltage	70 kV
Harmonic nos	2, 1
Pressure	5×10^{-8} Torr
Emittance	6π mm · mrad
Ion sources	external

Table 2 Beam energies obtainable at the AVF cyclortron. B_e and f_p mean magnetic field strength at the exit and orbital frequency, respectively.

A/q	Typical nuclei	h_a	E(Mev/u)	B_e(T)	f_p(MHz)
1	p^+	2	15.1 - 6.1	0.78 - 0.50	12.0 - 7.7
		1	60.6 - 15.1	1.57 - 0.78	24.0 - 12.0
2	α^{++}, $^{12}C^{6+}$	2	15.1 - 3.8	1.57 - 0.78	12.0 - 6.0
		1	17.8 - 15.1	1.70 - 1.57	13.0 - 12.0
3	$^{12}C^{4+}$	2	7.9 - 3.8	1.70 - 1.18	8.7 - 6.0
4	$^{20}Ne^{5+}$	2	4.4 - 3.8	1.70 - 1.56	6.5 - 6.0

For the second condition, we can get

$$f_a \cdot r_a = f_s \cdot r_s,$$

in which f_a and f_s are orbital frequencies in respective cyclotrons. For particle rigidities between before and after charge stripping, the relation is given by

$$q_a \cdot B_a \cdot r_a = q_s \cdot B_s \cdot r_s,$$

where q_a and q_s are numbers of charge of ions before and after a charge exchange, and B_a and B_s mean magnetic field strengths on an outermost equilibrium orbit of the AVF cyclotron and an innermost one of the ring cyclotron, respectively.

From the first condition, we can obtain some parameter sets which are available for an injector cyclotron. The parameters of $r_a = 0.714$ *m*, $n_a = 1$, $h_a = 2$, $r_s = 0.893$ *m*, $n_s = 2$, and $h_s = 5$ were employed in consideration of the magnet size and the frequency range. The cyclotron, therefore, will be operated in half frequency with the ring cyclotron. Minimum energies for nuclei of less than $A/q = 4$ have been placed at about *4 Mev/u* which is the maximum energy feasible by the linac. Selected parameters employed under the above conditions are listed in Table 1. Relation among energy per nucleon, magnetic field strength, and radio frequency together with frequency ranges corresponding to $h = 1$ and 2, is shown in Fig 1 for some mass to charge ratios and typical ions. The maximum mass to charge ratio is taken to be *4*. Thus charge states of more than *10*, for example, are desirable for a ^{40}Ar beam. Design characteristics are summarized in Table 2.

In order to obtain highly charged ions, good quality beams, or polarized ion beams, various ion sources will be installed in an ion source room which is situated above the cycloton vault. Beams from these sources are guided to the magnet median plane via. an injection beam line and an inflector.

INJECTION AND INFLECTION SYSTEMS

In order to accelerate various types of ions, the cyclotron must be adaptable for external ion sources. An ECR-source and a duoplasmatron are scheduled to be equipped with the cyclotron. Other kinds of ion sources will be also equipped from now on. For this purpose, beam transport lines between ion sources to the cyclotron and a beam inflection system to the median plane of the cyclotron have been designed. The beam line must have functions not only to guide beams to the cyclotron but also to be capable of adjusting optical properties of the beam.

A design of the beam transport system has been made using the TRANSPORT code.[2] A preliminary beam transport line is shown in Figs. 2 and 3. Five ion sources will be capable of being installed in the ion source room. It may be seen in Fig. 2, for example, that a quadrupole triplet immediately after the ion source 2 focuses the beam to a double waist at the object point of a doubly achromatic 90° bending section. The quadrupole length is *20 cm* and the total length of this section *200.0 cm*. It is also considered to use electric quadrupoles in place of the magnetic ones for this purpose. The bending section consists of two 45° dipole magnets and three quadrupole magnets between them. The bending radius and quadrupole lengths are *30 cm* and *20 cm*, respectively. A telescopic system which consists of two *15 cm* solenoids is placed subcequently. The total length is *207.6 cm*. At the focusing point, the same phase space ellipse will be formed in spite of the position of ion sources. The charge state analysing section is of mirror symmetry having the configuration of a telescopic and achromatic cell of quadrupole doublet + dipole + quadrupole doublet in the half system. In this case we can achieve the charge resolution of $dQ/Q=1/40$. A phase space matching section composed of 4 quadrupoles will be installed subsequently.

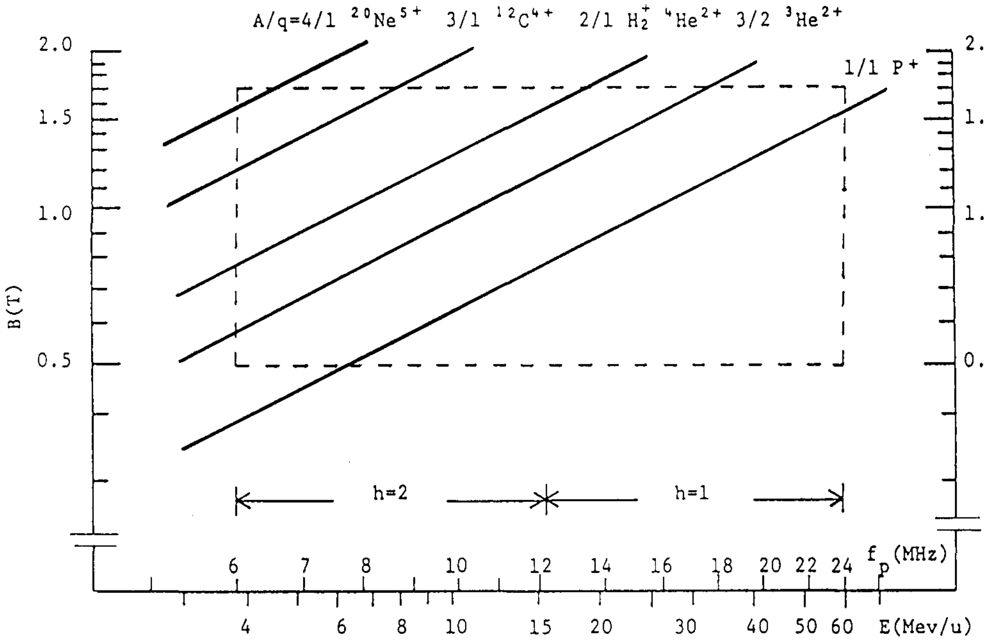

Fig.1 Relation among energy per nucleon, magnet field, and RF frequency. The number on each line is the mass to charge ratio.

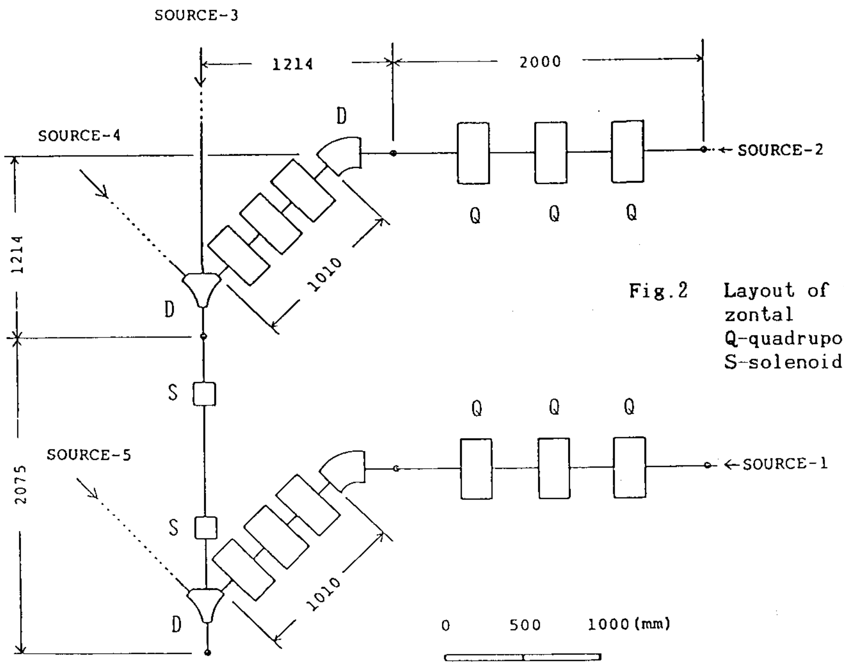

Fig.2 Layout of the injection system. Horizontal beam transport line : Q-quadrupole magnet; D-dipole magnet; S-solenoid.

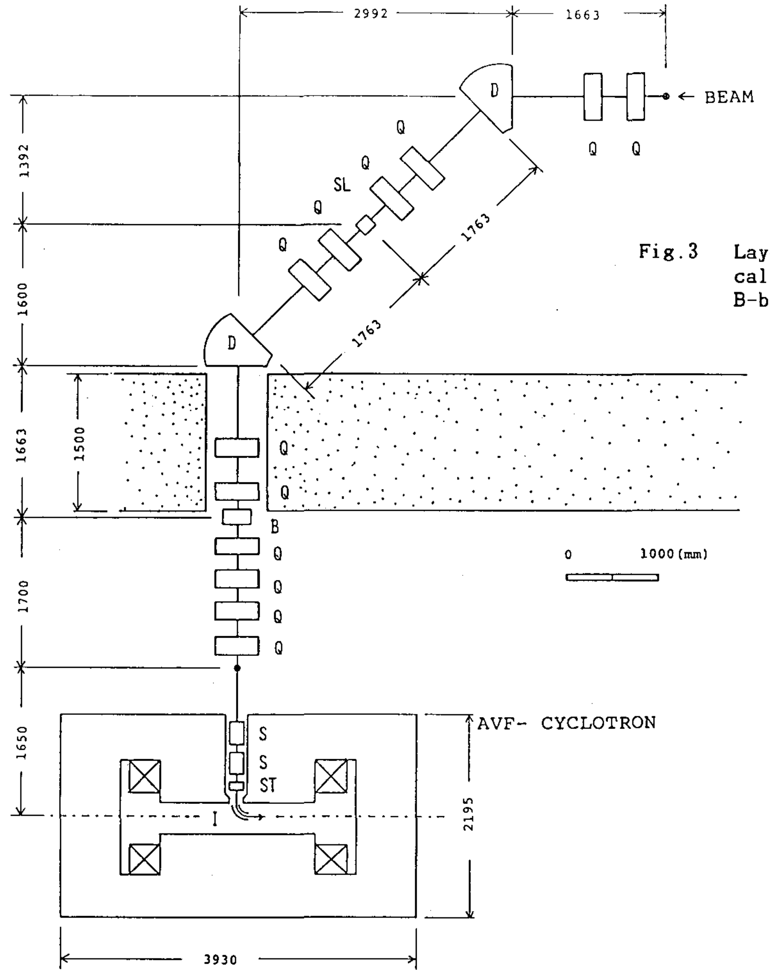

Fig.3 Layout of the injection system. Vertical beam transport line : SL-slit; B-buncher.

The system makes the beam match the focusing conditions at the exit of an inflector. In the axial hole of the cyclotron, the beam receives focusing and rotating actions due to the stray field. In order to correct the unwanted rotation of the optical axis, a beam rotating system has to be provided. The design of the matching and rotating sections is in progress.

It is known that there are three types of beam inflectors from the axial beam line to the magnet median plane. Because of its flexibility, small volume, and low electric power, we employ a spiral inflector. Its shape projected on the median plane is determined from a value of $K = R_e/2R_m$, where R_e and R_m are the electric and magnetic radii at the exit of the inflector, respectively.[3] Figure 4 shows the K dependences of the distances from the entrance of the inflector to its exit and that of the distance from the rotation center at the exit to the cyclotron center, and the radial gradient of the beam at the exit. Calculation has been performed for on-axis beams in an assumed magnetic field in order to optimize the inflector parameters and examine optical properties of beams in the central region of the cyclotron. Particles will be accelerated on constant orbits for harmonic numbers of $h = 1, 2$, and the orbit center must converge to the machine center after a certain number of rotation. Typical examples are shown in Figs. 5-a,b for the each acceleration mode. A tentative result has been obtained of $K = 1.38$, $R_e = 2.3$ *cm*, and $R_m = 0.83$ *cm*. For different accelration modes, optimization of the acceleration condition has to be made by movement of the puller and the rotation of the inflector with respect to the machine axis.

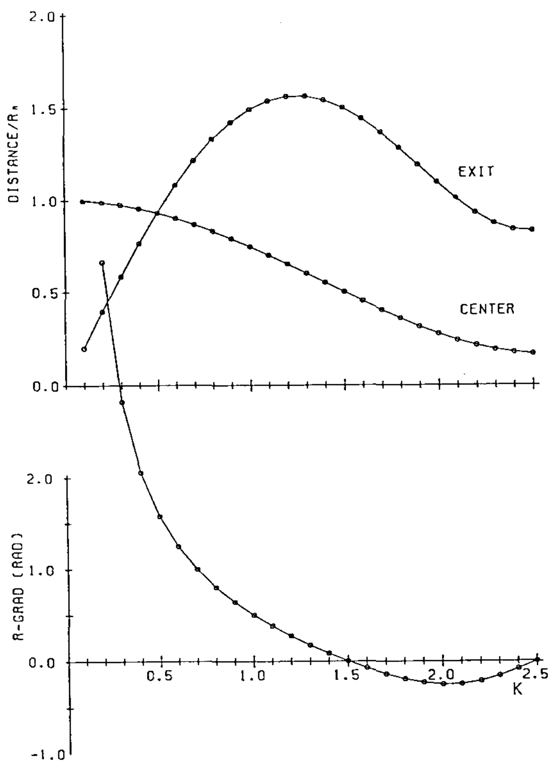

Fig.4 K dependence of the distances from the entrance of the inflector to its exit, and the rotation center of beams at the exit(top), and the radial gradient of the beam at the exit versus K(bottom).

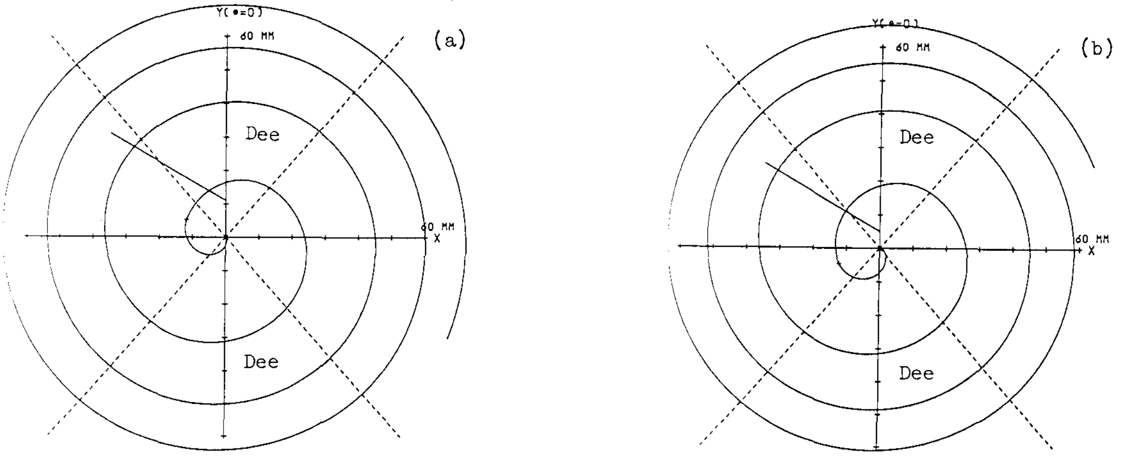

Fig.5 Typical beam orbits in the central region of the cyclotron. Broken lines show the central lines of accelerating gaps, and a thick line a front of the puller. (a)A C^{4+} beam is injected with *20.4 kev* and accelerated up to *7 Mev/u* in a mode of $h=2$. (b)A proton beam is injected with *6.4 kev* and accelerated up to *50 Mev* in a mode of $h=1$.

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2) K.L.Brown et al. : SLAC Report, No 91(1974)
3) J.L.Belmont et al. : IEEE Trans. Nucl. Sci., NS-13,191(1966).