A PROPOSED MULTI-PURPOSE SEPARATED-SECTOR CYCLOTRON AT IPCR

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Abstract

A new research facility including an accelerator complex to provide all heavy ions up to uranium has been proposed at the Institute of Physical and Chemical Research. A separated-sector cyclotron (SSC) with K=620 MeV is being designed as a booster accelerator for a variable-frequency heavy-ion linac now under construction. For the injection of relatively light ions up to neon into the above SSC, the existing ordinary cyclotron will be converted into an AVF machine with K=90 MeV to be used as another pre-accelerator. The maximum beam energy provided by this accelerator system will range from 120 MeV/u for fully stripped ions to 15 MeV/u for very heavy ions such as uranium. Acceleration of light particles like deuterons and α particles is also possible. The basic design and some model studies of the proposed machine are described.

1. Introduction

A 160 cm ordinary cyclotron constructed in 1960 at the Institute of Physical and Chemical Research has been used as a multi-purpose facility providing heavy ions (B, C, N, O and Ne) as well as light particles to researchers in various fields. In course of time, demands for heavier ions with higher energies have grown up among many users, as clearly seen from the recent statistics that about two thirds of the total beam time has been devoted to heavy-ion experiments at nearly maximum energies (around 9 MeV/u). Although much effort has been made to improve the existing cyclotron, it became apparent even in the early 70's that the present machine could not meet the future demands satisfactorily. Therefore, extensive discussion to upgrade the facility and a design study of a new heavy-ion accelerator were initiated at that time {1}. In 1972, a separated-sector cyclotron combined with a variable-frequency linac of Wideröe type was proposed. {2} A part of this proposal (pre-accelerator section) was approved in 1974. Since the linac under construction will be completed next year, final design and model study of its booster are in progress so that construction may start in 1980 if funded.

2. Design Consideration

The main beam requirements for this facility are as follows: It should be able to accelerate beams of all elements up to uranium. The beam energy should be high enough to overcome the Coulomb barrier in the whole range of the accelerated ions, preferably over 100 MeV/u for fully stripped light ions and over 10 MeV/u for very heavy ions such as uranium. High intensity beams of protons, deuterons and α-particles of intermediate energies are also required for studies of nuclear chemistry and radiation biology as well as nuclear physics. The beam quality (mainly intrinsic energy spread and emittance) has to be as high as possible.

Among various types of accelerator complexes able to satisfy the above requirements, a separated-sector cyclotron (SSC) with an appropriate injector has been selected to be the most suitable machine from various points of view. The main advantages of the SSC are a large value of flutter in the magnetic fields to enable acceleration of energetic particles with high intensity over a wide range of ion masses and relative ease of beam injection and extraction. The simplicity of the design and construction of the SSC also inspires confidence in planning for scheduled operation and in preparing for experiments in many research fields expected at the proposed multi-purpose facility. These advantages should be compared with those of the recently developing super-conducting cyclotrons under construction or study in some laboratories. These appear to be promising machines but to still have difficulties in various technical problems.

The proposed facility consists of an SSC with four 50° sector magnets, a variable-frequency linac and an AVF cyclotron. Figure 1 shows the energy-mass capability of the proposed facility together with those of the major heavy-ion accelerators in operation or under construction in the world. The size of the sector magnets of the SSC depends on the maximum energy and mass-to-charge ratio (m/q) of the heaviest ions to be accelerated. The ratio m/q can be estimated from the work of Nikolaev et al. {3}. The maximum field product is taken to be 3400 kG·cm.

The linac presently under construction will be used as an injector for heavy ions. Details of design and performance of the linac were reported elsewhere {4}. The present classical cyclotron will be converted into an AVF cyclotron with K=90 MeV and will be used as an injector of light particles such as deuterons and α particles as well as heavy ions up to neon with final energy over 80 MeV/u.

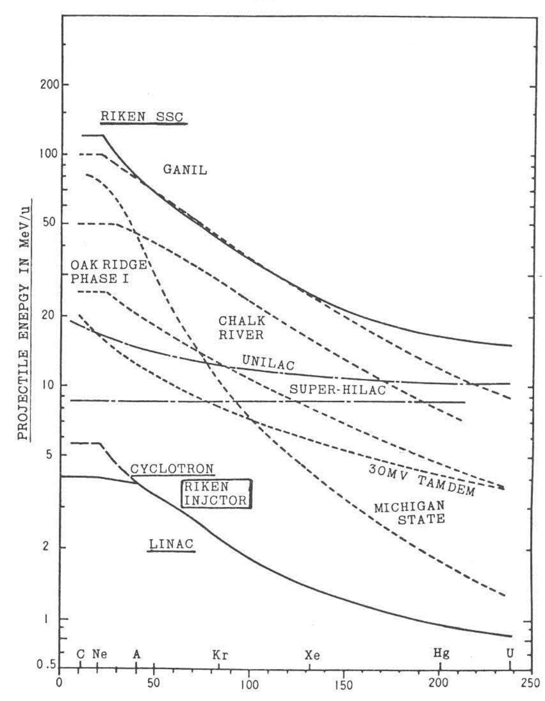

Fig. 1. Maximum beam energy vs. mass number of the proposed facility together with those of heavy-ion accelerators in operation or under construction in some other laboratories.

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3. Separated-Sector Cyclotron

Table 1 shows characteristics of the proposed SSC. The maximum beam energies are about 120 MeV/u for light ions and about 15 MeV/u for very heavy ions. The resonance condition of the SSC is shown in fig. 2. The four non-spiral sector magnets yield the required isochronous field of 17.7 kG at maximum as shown in fig. 3, where the orbit frequency of accelerating ions is chosen to be 2-9 MHz. From the matching conditions with the injectors under consideration, ions can be accelerated, in principle, with h=4, 6, 8, 10 and 12.

Table 1. Characteristics of Separated-Sector Cyclotron

Maximum energy for U^{37+},(U^{40+})	15 MeV/u
Maximum energy for C^{6+}, Ne^{10+}	120 MeV/u
Number of sectors	4
Sector angle	50°
Magnet fraction	0.555
Magnet gap	8 cm
Maximum magnetic field	18.0 kG
Main coil power	950 kW
Number of trimming coils	>40
Magnet weight	1900 ton
Injection mean radius	79 cm
Extraction mean radius	338 cm
E_f/E_i	18∿21
Number of dees	2
Dee angle	22.5°
Peak voltage	250 kV
RF power	300 kW x 2
RF frequency range	17(22)-45 MHz
Number of harmonic acceleration	4,6,8,12

The focusing properties of SSC were calculated with the modified SPYRING code [5] including the soft-edge effect on the magnetic field. In order to avoid the betatron-oscillation resonances during acceleration, we have chosen the region defined by $\nu_r>1$, $\nu_r+\nu_z<2$ and $\nu_r-2\nu_z<0$. Ions injected with energy greater than 7.0 MeV/u will cross the resonance lines of $\nu_r-2\nu_z=0$ and $\nu_r=4/3$. Detailed calculations of the beam dynamics are now in progress using the measured magnetic fields of the model magnets. Two sector magnets (approximately 1/4 scale model) have been constructed to obtain detailed information on properties of the sector magnets such as their excitation characteristics and field distribution-including the interference by adjacent magnets. Magnetic flux density at some places along the flux path has been measured to obtain a prediction of magnetomotive force for the full-scale magnet. The cross-sectional areas of the flux returns of the magnet are designed to be 10% greater than those of the pole base. Whole magnetic motive force, maximum coil power and magnet weight are estimated to be $2x10^5$ A·T, 960 kW and 1900 t, respectively.

Relative field distributions measured in steps of 1 kG in the 8-17.5 kG range are shown in figs. 4-5. The field decrease at the injection radius is 1.8% at 17.5 kG, being larger than the result calculated by a code TRIM (circular model). This is supposed to be due to large azimuthal leakage of magnetic flux near the center of the magnet.

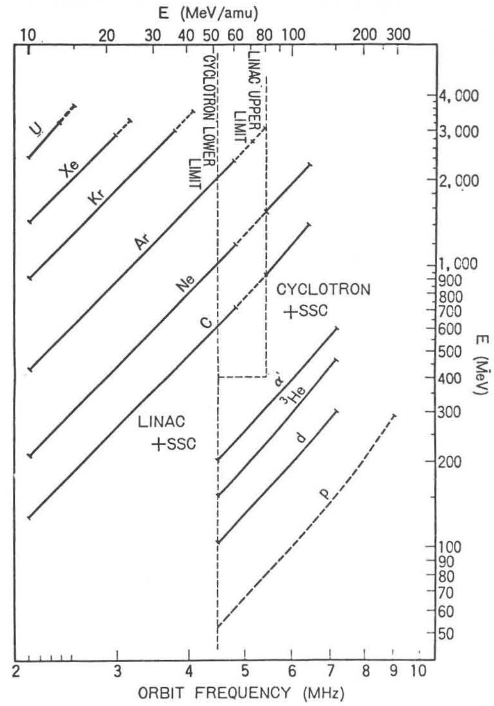

Fig. 2. Energies and orbit frequencies for various ions obtained from the proposed accelerator complex. Two vertical dashed lines indicate the lower and upper energy limits of the cyclotron- and linac-injected SSC, respectively. Solid and dashed lines for heavy ions correspond to the scheduled operation of the linac in the early stage and its expected energy increase afterwards.

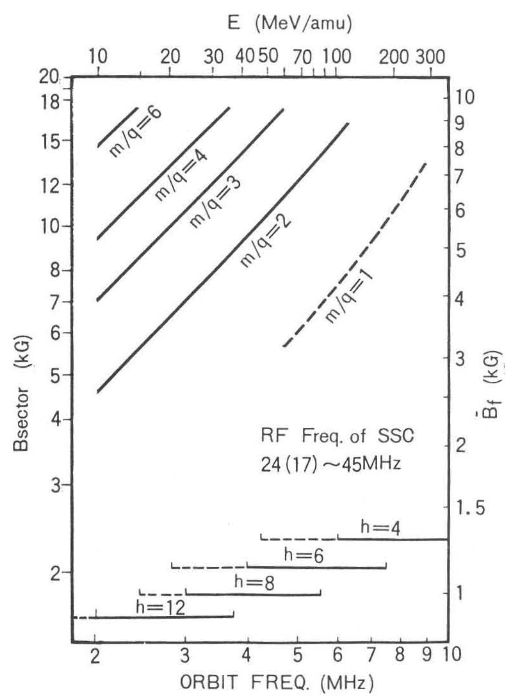

Fig. 3. Sector and average fields, particle and orbit frequencies in the proposed SSC given for several mass-to-charge ratios of beam. The designed maximum field of the sector magnet is 1.77 Wb/m². The harmonic numbers applicable to acceleration in the orbit frequency range of 2-9 MHz are indicated.

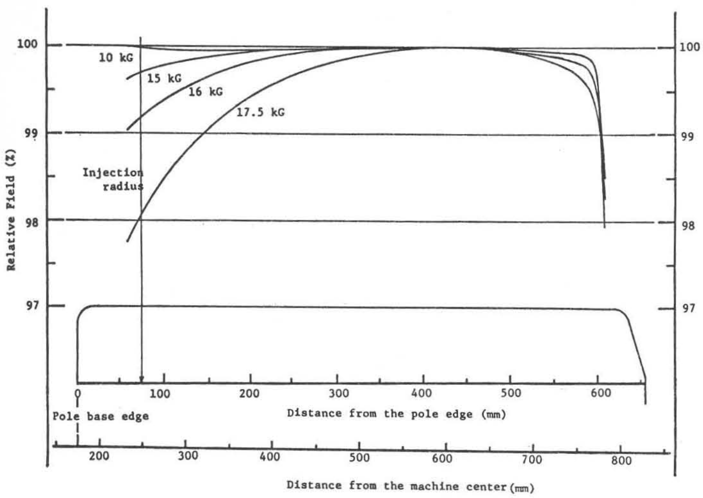

Fig. 4. Relative field distributions along the center line of the magnet. The distance between the pole base edge and injection radius corresponds to 2.5 times the pole gap.

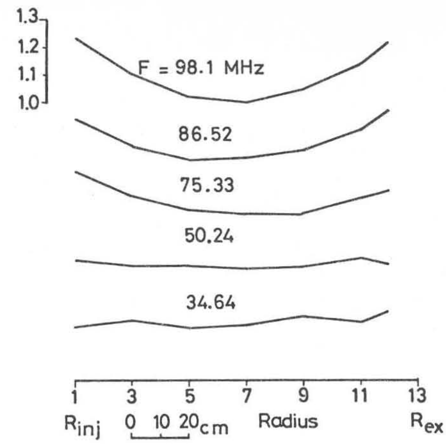

Fig. 6. Relative distributions of electrical potentials at the half-scale model cavity measured by the perturbation method.

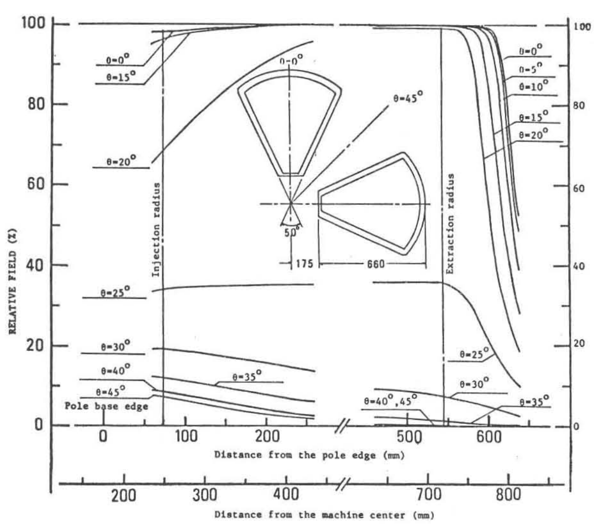

Fig. 5. Relative field distributions at 17.5 kG for various azimuthal angles.

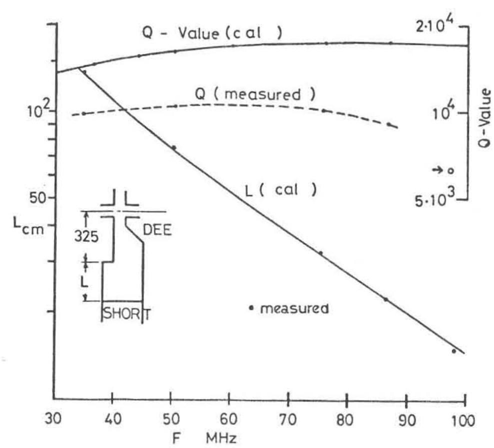

Fig. 7. Coaxial line lengths needed and Q-values at various frequencies measured for the half-scale model cavity compared with calculated ones. Relatively poor agreement between the measured and calculated Q-values is probably due to dirty surfaces and poor contact at the shorting end of the model cavity.

Ions are accelerated by two 22.5° delta-shaped dees located at opposite valley spaces between the sector magnets. The frequency range of the RF system is chosen to be 17-45 MHz to match the synchronous operation with the linac, the optimum harmonic number in acceleration becoming h=8, or h=4 in the case of injection from the cyclotron. For this purpose, a half-wave cavity resonator having coaxial structure with delta-shaped cross section has been designed. This structure of the cavity was chosen to achieve reasonable values of current density at the shorting end and of power loss in the case of maximum dee voltage (250 kV) over the whole range of frequencies.

The resonating frequencies, electric potential distributions and Q-values for the designed resonator have been tested by a half-scale model cavity of similar design already constructed. The results shown in figs. 6-7 are considered satisfactory.

An operating pressure of 1 x 10^{-7} torr is desirable in the median plane of the SSC to limit beam losses due to charge-exchange to less than about 10% in the case of very heavy ions. The cyclotron vacuum chamber (with principal outgassing loads shown in brackets) consists of 2 resonator chambers (delta resonators, copper and rubber gaskets), 2 valley chambers (stainless steel like SUS 18-8 and rubber gaskets) and 4 chambers positioned at the sector magnets (iron and trimming coils). Based on the estimated surface area of the chambers, the degas rate has been estimated to be around 5 μl/s. Two cryopumps of 25000 ℓ/s and two titanium-sublimation pumps of 5000 ℓ/s, for example, will be needed to reach the above mentioned vacuum. More detailed design of vacuum chambers and pumping systems is currently in progress.

Injector

The linac under construction at IPCR will be used as an injector of heavy ions with final energy up to 80 MeV/u. Main characteristics of the linac are shown in table 2. The linac will become operational late in 1979.

For heavy ions with final energy greater than 80 MeV/u as well as light particles such as deuteron and α particles, an AVF cyclotron has been chosen to be an appropriate injector. The maximum field of the proposed cyclotron is 17 kG, the energy constant being K=90 MeV. It is possible to accelerate p, d, h and α as well as heavy ions up to Ar with the harmonic numbers 1-3. The maximum injection energy into the SSC is limited to 5.6 MeV/u for heavy ions and 6.7 MeV/u for p, d, h and α. Main characteristics are shown in table 3. The preliminary design of the injection system is reported by Wada et al. in this conference.

Table 2. Characteristics of Injector Linac

Number of tanks	6
Number of drift tubes per tank	19∿11
Gap length	4∿9 cm
Peak voltage of gaps	180∿300 kV
Maximum total voltage gain	16(20)MV*
RF frequency range	20∿40(17∿45)MHz
Q-value of cavity	12,000∿17,000
Accelerating mode	π/3π, π/π
Duty factor (macroscopic)	100%
Mass to charge ratio	5∿20(4∿24)*
Emittance at exit	7.8 cm·mrad
Energy resolution	0.3%

Table 3. Characteristics of Injector Cyclotron

Energy constant, K	90 MeV
Number of sectors	4
Magnet gap at hill	∿20 cm
Maximum mean magnetic field	17 kG
Extraction mean radius	79 cm
Main coil power	∿250 kW
Number of dees	2
Dee angle	90°
RF frequency range	9∿20 MHz
Maximum RF voltage	50 kV
RF power	150 kW

Building

This facility will be used for research in various fields such as nuclear and atomic physics, solid-state study, material science, radiation chemistry and biology and RI production. Use for radiotherapy is also being considered. All facilities for these purposes are being planned for construction at IPCR. Fig. 8 shows proposed layout of beam lines in various experimental areas.

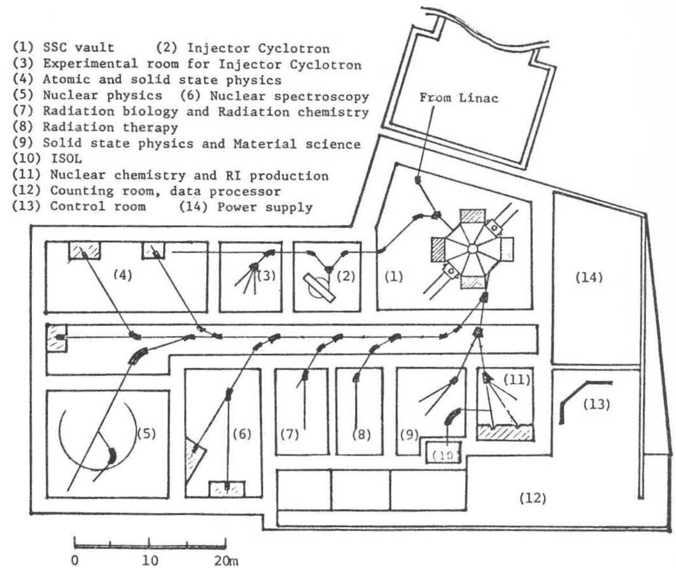

Fig. 8. Proposed layout of beam lines.

References

{1} K. Matsuda, Sci. Pap. Inst. Phys. Chem. Res., 66 (1972) 33.

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{3} V.S. Nikolaev et al., Phys. Letters 28A (1968) 277.

{4} M. Odera, Proc. of the 1976 Proton Linear Accelerator Conf., T. Tonuma, F. Yoshida and M. Odera, IEEE Trans. Nucl. Sci. NS-23, 1031 (1976).

{5} I. Miura, Private Communication.

** DISCUSSION **

H. WILLAX: If I understand correctly, this project is funded. What are the chances for final approval?

H. KAMITSUBO: Only the injector linac was funded. In the present stage, I cannot say whether or not it is possible to get financial approval for phase II of our project.