A PROPOSED MULTIPURPOSE SEPARATED-SECTOR CYCLOTRON AT IPCR

IPCR SSC Study group

The Institute of Physical and Chemical Research

Abstract

An accelerator complex consisting of a separated-sector cyclotron and two independent injectors (linac and AVF cyclotron) is proposed, which accelerates all heavy ions up to uranium. The beam energy ranges from 120 MeV/u for fully stripped ions to 15 MeV/u for very heavy ions such as uranium. Acceleration of light particles (e q., d and α) of intermediate energies is also possible. The basic design of the machine is described.

§1 Introduction

A 160 cm ordinary cyclotron at the Institute of Physical and Chemical Research has been used for multidisciplinary studies since 1966. About two thirds of the total beam time has been devoted to experiments with heavy ions (B, C, N, O and Ne) with energy up to around 9 MeV/nucleon. In course of time, demands on heavier ions with higher energies have grown up among researchers of various fields. Although extensive efforts to improve the cyclotron have steadily been made, it became apparent even in the early 70's that the present machine could not meet the future demands satisfactorily. Therefore, a design study of a new heavy-ion accelerator at IPCR was started at that time. In 1972, a separated-sector cyclotron injected from a variable-frequency linac of Widröe type was proposed.[1)] A part(linac) of this proposal was approved, the linac being under construction since 1974. In this report, the basic design of the IPCR multipurpose heavy-ion facility will be described.

§2 Design consideration

The main beam requirements for this facility are as follows : It should be able to accelerate beam of all elements up to uranium. The beam energy should be high enough to overcome the Coulomb barrier in the whole range of the accelerating ions, desirably over 100 MeV/nucleon for fully stripped light ions and over 10 MeV/nucleon for very heavy ions such as uranium. High intensity beam of protons, deutrons 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. The macroscopic duty factor up to 100% is desirable.

Among various types of accelerator complexes 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 SSC can be considered to be a large value of flutter in the magnetic field to enable acceleration of energetic particles with high intensity over a wide range of ion masses and relative easiness for the beam injection and extraction. The simpleness for the design and construction of SSC is considered also important to ascertain reaching the level of the scheduled operation rather easily and thus to facilitate preparatory works for experiments in many research fields expected at the proposed multi-purpose facility. These facts should be compared with a recently developping super-conducting cyclotron under study in some laboratories, which appears to be a promising machine in future but still to have difficulties to be solved in various technical problems. Moreover, in Japan the technology of making the large-scale super-conducting magnet has not yet been well established to apply it to a big accelerator.

The proposed facility consists of a SSC with four 50° sector magnets, a variable-frequency linac and an injector cyclotron. Some parameters of these accelerators are listed in table 1. The size of the sector magnet of 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 equation obtained by V.S. Nikoraev et al[2] for the charge distribution in the charge stripping process in solid and gaseous substances. Some calculated charge distributions in the case of a thin carbon stripper is shown in fig.1. The energy constant K of the SSC is taken to be 620 MeV.

The linac presently under construction will be used as an injector for heavy ions. Detail of design and performance of the linac were reported elsewhere.[3] The present classical cyclotron will be converted into the AVF cyclotron with K=90 MeV and will be used as an injector of light particles such as deutron and α-particles as well as heavy ions up to Ne with final energy over 80 MeV/nucleon.

§3 General description

The beam energy available from the proposed accelerator complex is shown in fig.2. The hatched and non-hatched area for the linac and linac-injected SSC show energy regions limited by the operating conditions of the linac under construction as will be described later. It should be noted that in the case of the cyclotron and cyclotron-injected SSC, only the maximum injection and final energies are indicated.

The resonance conditions of the SSC, the linac and the injector cyclotron are shown in figs. 3-5. The linac usually accelerates ions in the fundamental mode(i.e., harmonic number h=1) in the frequency range of 17-45 MHz. The injector cyclotron will be operated with h=2 in the orbit frequency range of 4.5-10MHz. Considering the matching condition of the resonance frequency between the injectors and SSC, we take the dee angle of 22.5° for SSC. Consequently, the appropriate harmonic numbers in acceleration in SSC are taken to be h=8 and 12 in the case of the linac+SSC and h=4 in the case of the cyclotron+SSC as will be described below.

SSC

Table 2 shows characteristics of the proposed SSC. The maximum beam energies are about 120 MeV/nucleon for light heavy ions and about 15 MeV/ nucleon for very heavy ions. The four non-spiral sector magnets yield the required isochronous field of 18.8 KG at maximum shown in fig.6, 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.

Fig.7 shows focusing properties of SSC calculated with the modified SPYRING code[4] 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/nucleon will cross the resonance line of $\nu_r-2\nu_z=0$. Details of beam dynamics will be calculated from 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 magnet. The preliminary field measurement has been carried out as reported in ref.5. The results are shown in figs.8-9.More detailed field measurement is now in progress.

Ions are accelerated by 22.5° delta-shaped two 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 realize the synchronous operation with the linac, the optimum harmonic number in acceleration becoming h=8, while h=4 in the case of injection from the cyclotron. Fig.10 shows an example of the designed RF resonators in the range of 22-45 MHz.

Table 1 Examples of some operating parameters at the maximum energies in the proposed accelerator complex[a)]

	LINAC					SSC								
Beam	Charge (q_1)	m/q_1	Accelerating RF freq. (MH_z)	Accelerating RF voltage (MV)	Energy per nucleon (MeV/u)	Charge[b)] (q_2)	m/q_2	B_{inj} (Wb/m^2)	B_{max} (Wb/m^2)	Orbit freq. (MH_z)	Accelerating RF freq. (MH_z)	h number	Energy per nucleon (MeV/u)
^{12}C	3+	4	40	13	3.1	6+	2	1.10	1.17	4.9	39	8	61
	3+	4	45	16.5	4			1.25	1.36	5.6	45	8	80
^{20}Ne	4+	5	40	16.5	3.1	9+	2	1.23	1.30	4.9	39	8	61
	5+	4	45	17	4			1.39	1.51	5.6	45	8	80
^{40}Ar	7+	5.7	39	18	3.0	15+	2.7	1.47	1.53	4.8	39	8	59
	8+	5	44	20	3.8			1.63	1.76	5.4	44	8	77
^{84}Kr	8+	10	31	20	1.9	24+	3.5	1.51	1.57	3.8	31	8	36
	9+	9	33	20	2.2			1.63	1.70	4.1	33	8	42
^{132}Xe	8+	17	24	20	1.2	30+	4.4	1.51	1.54	3.0	24(36)	8(12)	22
	9+	15	25.5	20	1.36			1.61	1.65	3.2	25(38)	8(12)	25
^{238}U	10+	24	19	18	0.75	37+	6.4	1.74	1.77	2.35	19(28)	8(12)	13
	10+	24	20	20	0.84			1.85	1.88	2.55	20(30)	8(12)	15

Cyclotron ($\bar{R}_{ext}$=0.794 m)

Beam	Charge	Orbit freq. (MH_z)	RF freq. (MH_z)	$\bar{B}_{ext}$ (Wb/m^2)	Energy per nucleon (MeV/u)	Charge (q_2)	m/q_2	B_{inj} (Wb/m^2)	B_{max} (Wb/m^2)	Orbit freq. (MH_z)	Accelerating RF freq. (MH_z)	h number	Energy per nucleon (MeV/u)
^{12}C	3+	6.5	13.0	1.71	5.6	6+	2	1.49	1.67	6.5	26	4	121
^{14}N	4+	6.5	13.0	1.50	5.6	7+	2	1.49	1.67	6.5	26	4	121
^{16}O	4+	6.5	13.0	1.71	5.6	8+	2	1.49	1.67	6.5	26	4	121
^{20}Ne	5+	6.5	13.0	1.71	5.6	9+	2.2	1.64	1.83	6.5	26	4	118

a) Two different values given for each beam in the case of Linac+SCC depend on the operating conditions of Linac: the upper one is taken from the initial scheduled operation of Linac corresponding roughly to the RF frequency of 20-40 MH_z; the lower is expected to be possible after some accumulation of the experience.

b) The most probable charge state after a stripper at the given injection energy.

Table 2

Characteristics of Separated Sector Cyclotron

Maximum energy for U^{37+}	15 MeV/u
Maximum energy for C^{6+}, O^{8+}, Ne^{9+}	121, 118 MeV/u
Number of sectors	4
Sector angle	50°
Magnet fraction	0.555
Magnet gap	8 cm
Maximum Magnetic field	18.8 kG
Main coil power	350 kw
Number of trimming coils	>40
Magnet weight	1800 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 MH_z
Number of harmonic Acceleration	4,6,8,12

A model cavity of the similar design for the whole range of RF frequencies (17-45 MHz) will be constructed as soon as possible. If the long stem required for the low frequency region yields serious difficulties in its mechanical structure, the frequency range will be limited to 22-45 MHz. In this case, ions with orbit frequency of 2-3 MHz can be accelerated with h=12, in which every second beam burst from the linac will be lost.

Expected beam intensities for some ions are shown in the case of the linac injector in fig.11. They are based on the ion-source data tested for the linac in our laboratory except for the case of uranium which is taken from the test data at GSI.

The operating pressure of 1 x 10^{-7} torr is desirable in the median plane of the cyclotron to limit beam losses due to charge-exchange to less than about 10% in the case of very heavy ions. The cyclotron vacuum chamber consists of 2 delta resonators(cupper and packing), 2 valley chambers(stainless steel like SUS 18-8 and packing) and 4 chambers positioned at the sector magnets(iron and shim coils), where material of each chamber together with another main source of outgassing is given in a bracket in each case. Based on the estimated surface area of each chambers, the degas rate has been estimated to be around 2.5 lus. 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.

<u>Injector</u>

The linac under construction at IPCR will be used as an injector of heavy ions with final energy up to 80 MeV/nucleon. Main characteristics and resonance conditions of the linac are shown in table 3 and fig.4, respectively. The linac will become operational in the late period of 1979.

For heavy ions with final energy greater than 80 MeV as well as light particles such as deutron and α-particles, an AVF cyclotron is 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 number of 1-3. The maximum injection energy into SSC is limited to 5.6 MeV/u for heavy ions and 6.7 MeV/u for d,h and α. Main characteristics and resonance conditions are shown in table 4 and fig.5, respectively.

Table 3 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)MH *
Q-value of cavity	12,000∿17,000
Accelerating mode	π/3π, π/π
Duty factor(macro)	100%
Mass to charge ratio	5∿20(4∿24) *
Emittance at exit	7.8 cm·mrad
Energy resolution	0.3 %

* See fig.4

Table 4 Characteristics of Injector Cyclotron

Energy constant, K	90
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 reasearches in various fields such as nuclear and atomic physics, solid-state study, material science, radiation chemistry and biology and RI production. The use for the radiotherapy is also being considered. All facilities for these purposes are being planned to be constructed at IPCR. Fig. 12 shows proposed layout of beam lines together with a plan view of SSC.

References

1) K. Matsuda, Sci. Pap. Inst. Phys. Chem. Res., 66(1972)33; M. Odera and T. Tonuma, 283, AIP 9, Cyclotrons-1972; M. Odera, I. Kohno and H. Kamitsubo, Intern. Conf. Reactions between Complex Nuclei, Held at Vanderbilt University, Nashville, Tennessee, p.63(1974).
2) V.S. Nikolaev et al., Phys. Letters 28A (1968)277.
3) 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)
4) I. Miura, Private communication.
5) S. Motonaga et al., IPCR Cyclotron Progress Report, 1977.

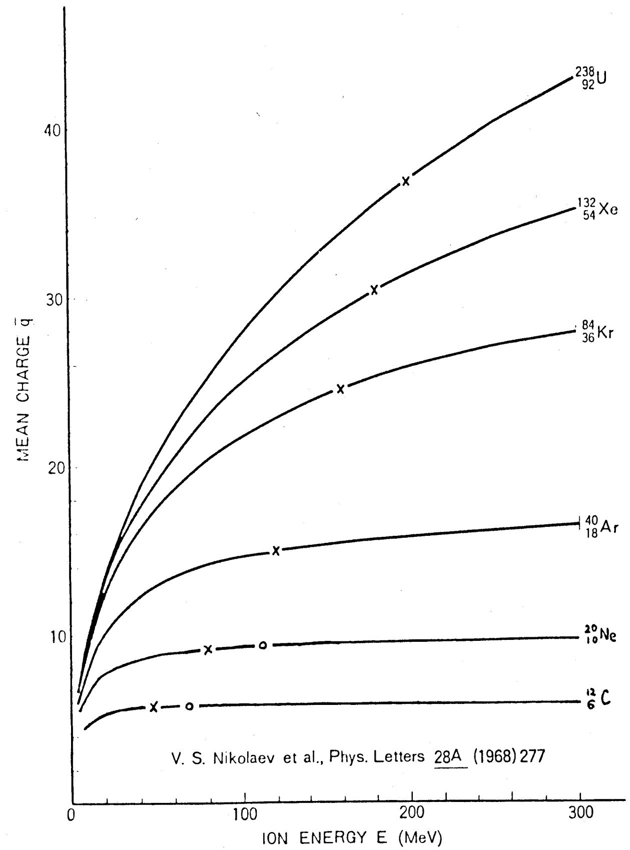

Fig.1 The most probable charge states for various heavy ions with energy up to 300 MeV expected by stripping in a thin carbon foil. They are calculated from the formula of ref.2. Crosses and circles respectively indicate the maximum injection energies from the linac and cyclotron used as injectors, respectively.

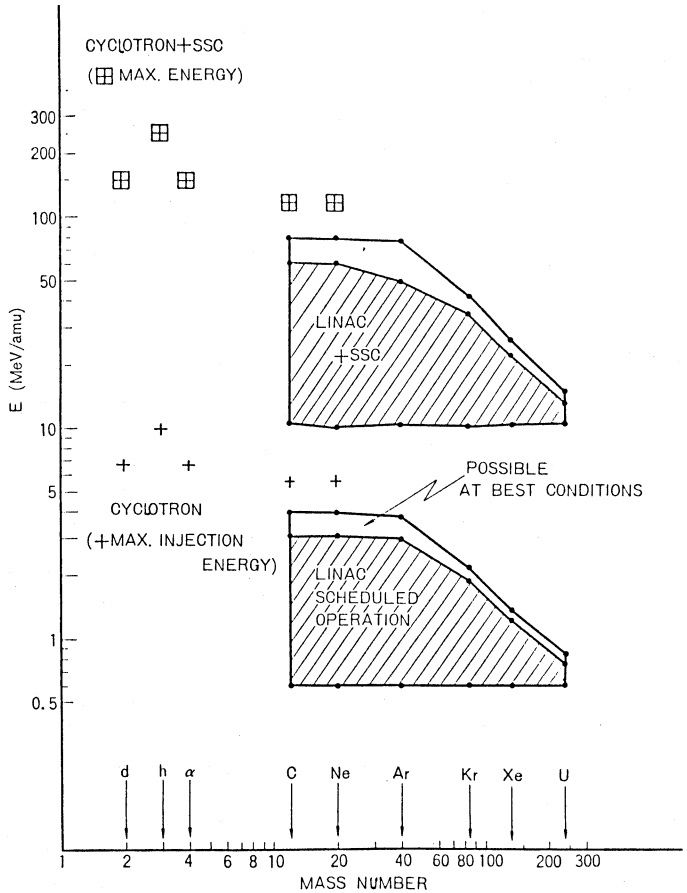

Fig.2 Energies plotted against mass numbers of beam. The hatched and non-hatched area for the linac and linac + SSC show energy regions limited by the conditions of the linac (see fig.4). In the case of the cyclotron and cyclotron + SSC, only the maximum injection and final energies are indicated.

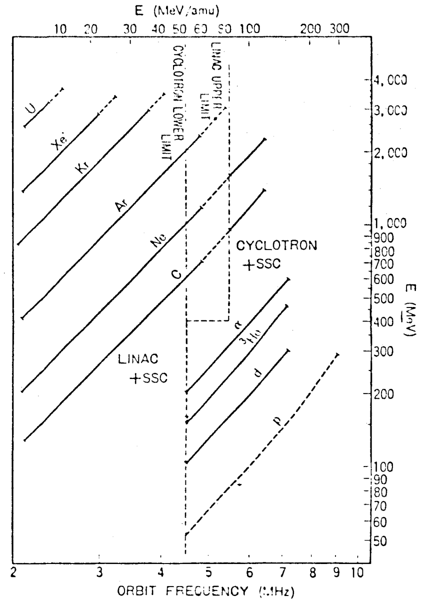

Fig. 3 Energies and orbit frequencies for various ions obtained from the proposed accelerator complex. Two vertical dashed lines indicate the lower and upper energy limits of the cyclotron- and linac-injected SSC, respectively. Heavy ions with final energy greater than 80 MeV/u and light particles such as d, h and α are injected from the cyclotron, while the linac is used as an injector in the other cases. 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 (see fig. 4), respectively.

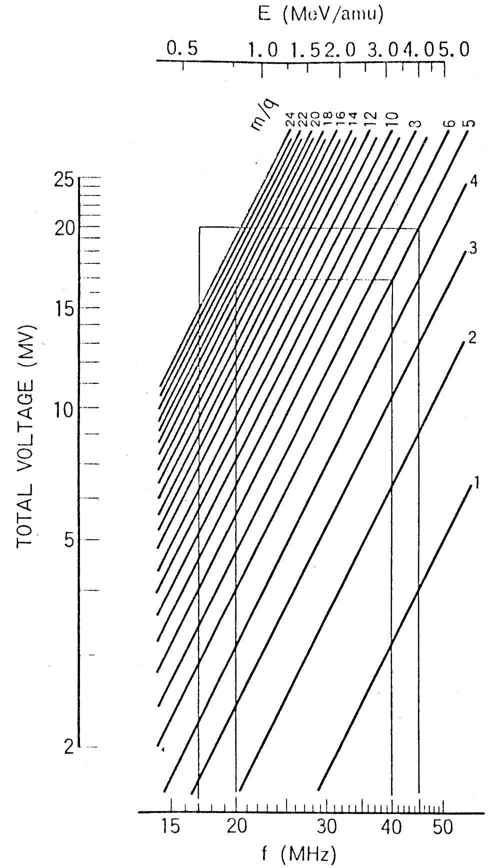

Fig.4 The resonance condition of the IPCR variable-frequency linac under construction. The inner rectangular area enclosed within solid lines indicates the approximate extent of the initial scheduled operation, in which case the maximum RF voltage is about 16 MV in the frequency range of 20-40 MHz. The outer rectangular area shows the region possible under the operation of the accelerating voltage up to 20 MV in the range of 17-45 MHz, which appears feasible from the model studies and experience in the other similar accelerators.

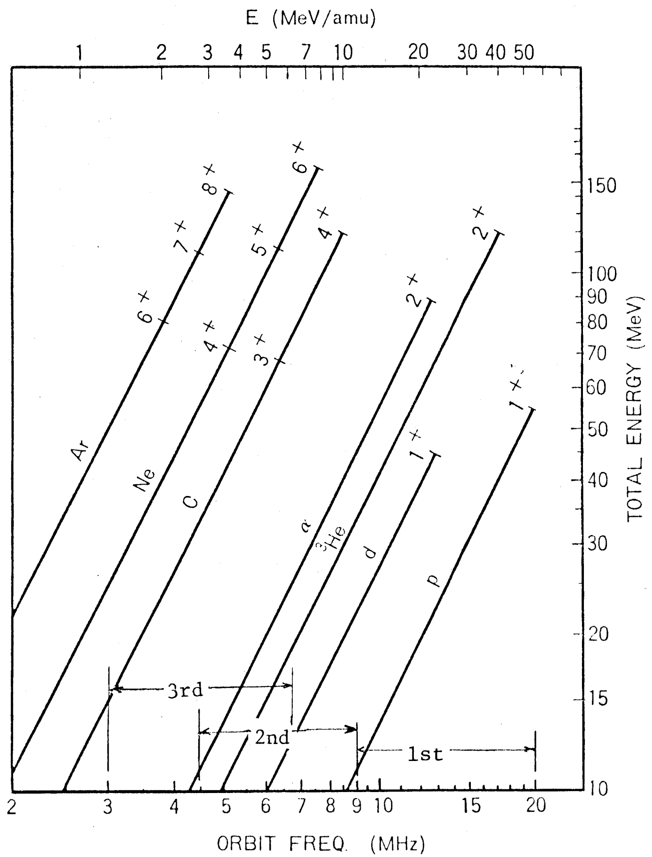

Fig.5 The resonance condition of the proposed cyclotron as an injector. The accelerating ions are indicated together with the harmonic numbers used.

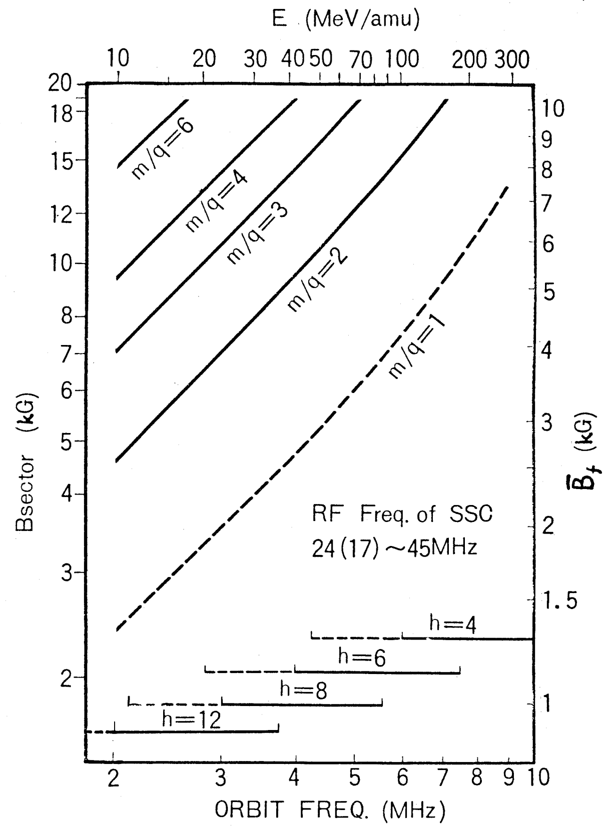

Fig. 6 Sector and average fields, particle energies, and orbit frequencies in the proposed SSC given for several mass-to-charge ratios of beam. The designed maximum field of the sector magnet is 1.88 Wb/m^2. The harmonic numbers applicable to acceleration in the orbit frequency range of 2-9 MHz are indicated.

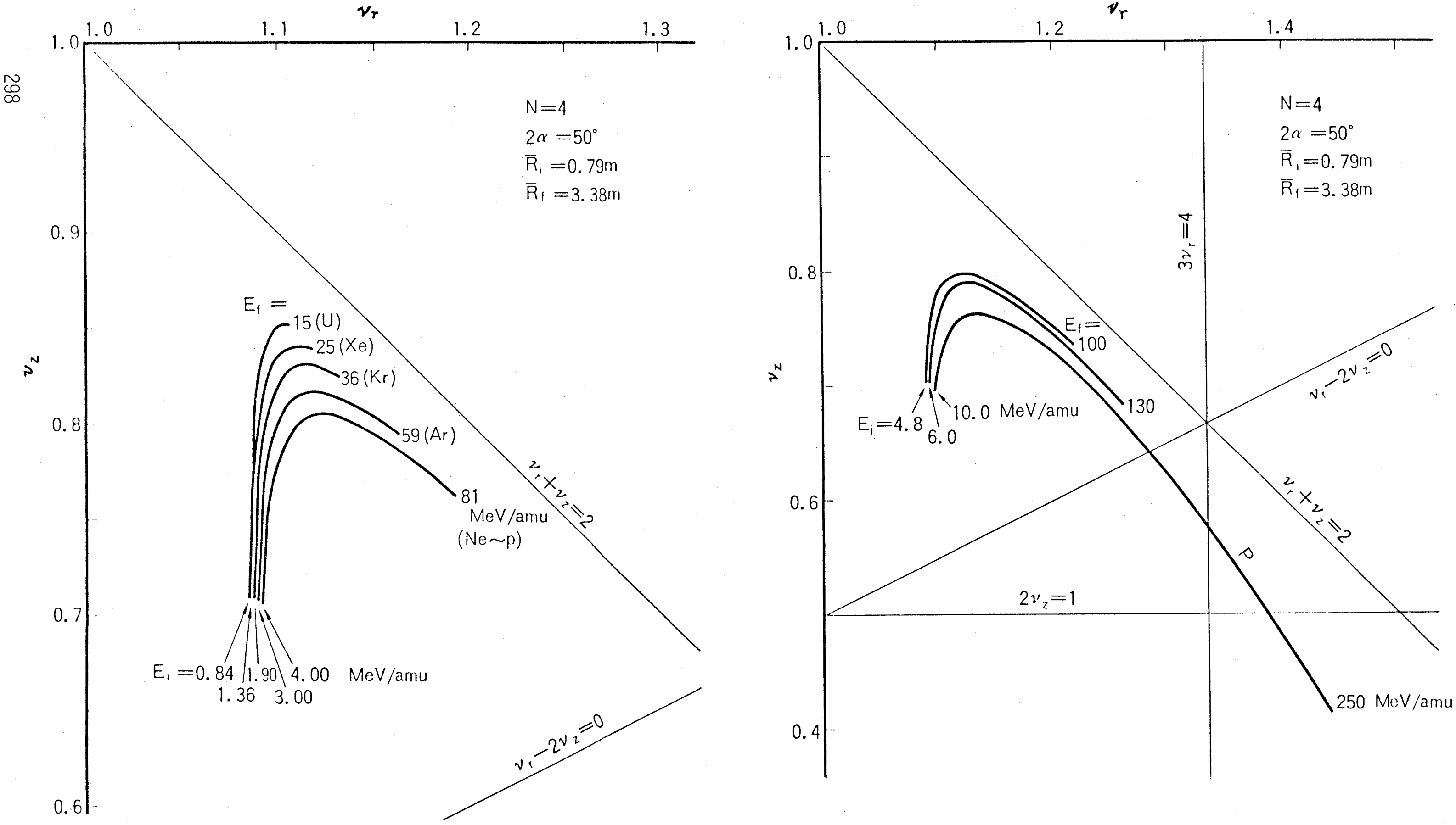

Fig.7 Focusing properties of the proposed SSC calculated with the modified SPYRING code for various injection energies.

(a) Examples in the case of the linac injector. The curves correspond to the maximum injection energies of ions (MeV/u) indicated. The final energies reached in SSC are also given.

(b) Examples in the case of the cyclotron injector. Energies at injection and extraction are indicated in MeV/u. The upper limit of the injection energy which will not cross the resonance ($\nu_r-2\nu_z=0$) is approximately 6 MeV/u.

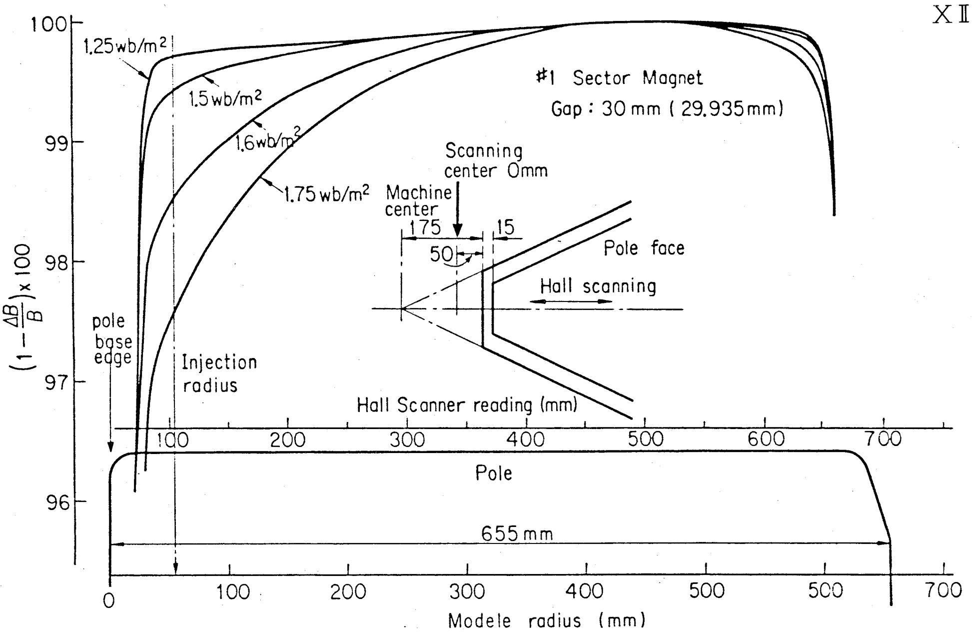

Fig. 8 Radial field distribution along the center line of the model sector magnet. Relative values are normalized to the maximum field at radius of 45 cm.

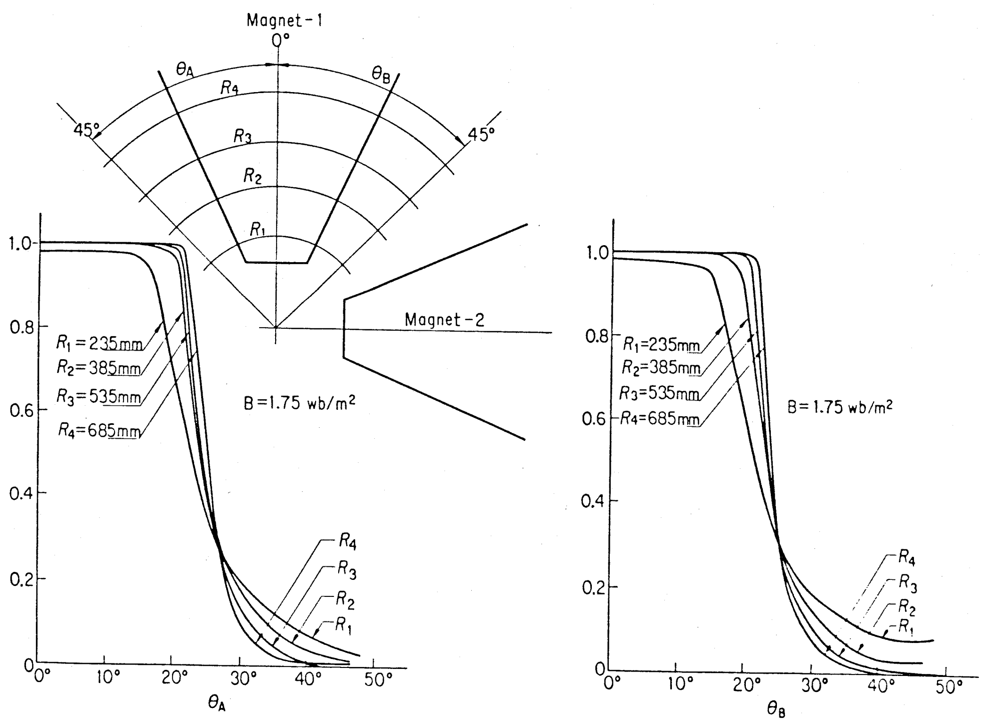

Fig. 9 Azimuthal field profiles of the magnetic field normalized to the maximum value at radius of 53.5 cm. (Q_B) and (Q_A) indicate the region with and without the effect of interference by adjacent magnets.

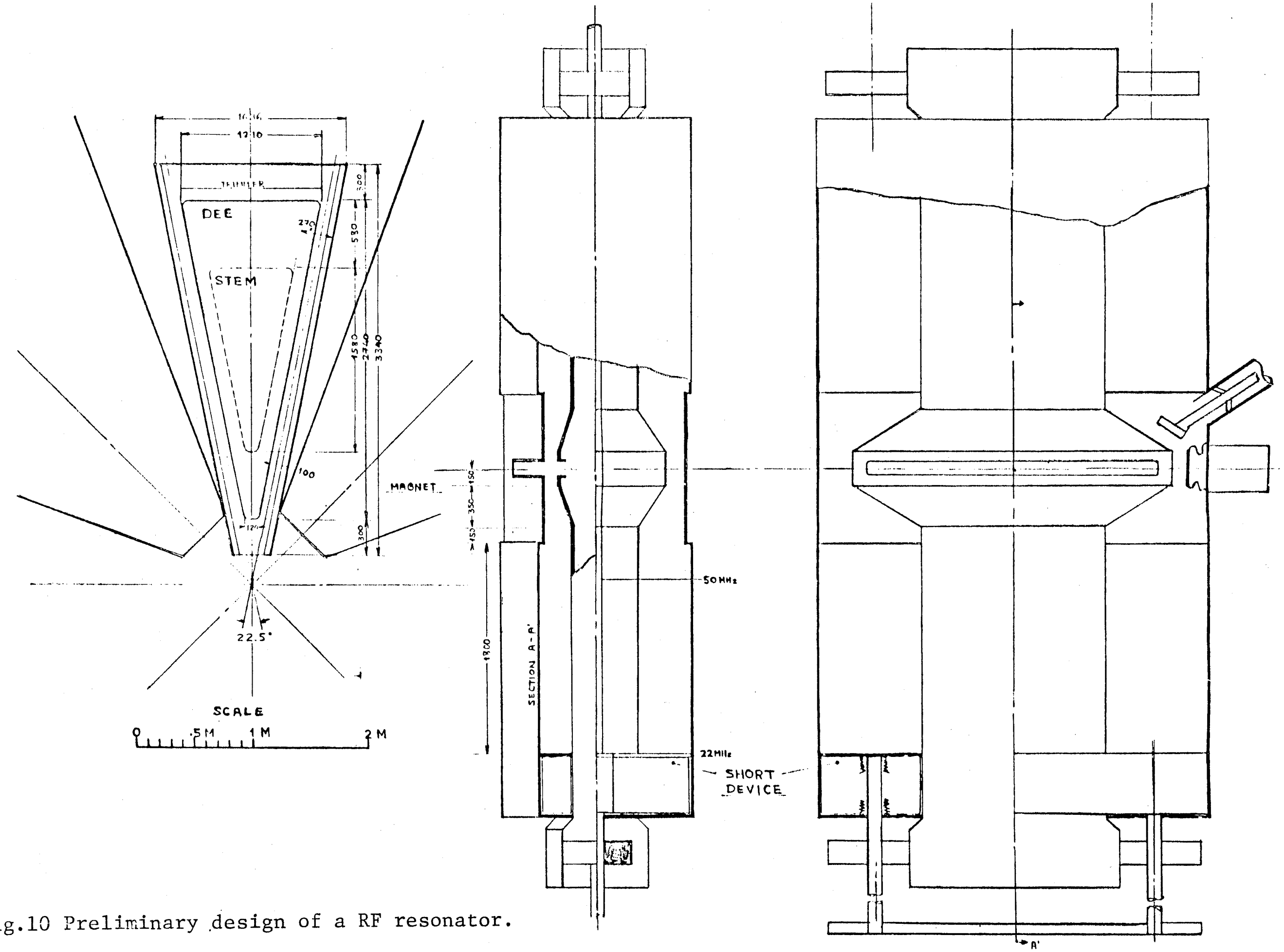

Fig.10 Preliminary design of a RF resonator.

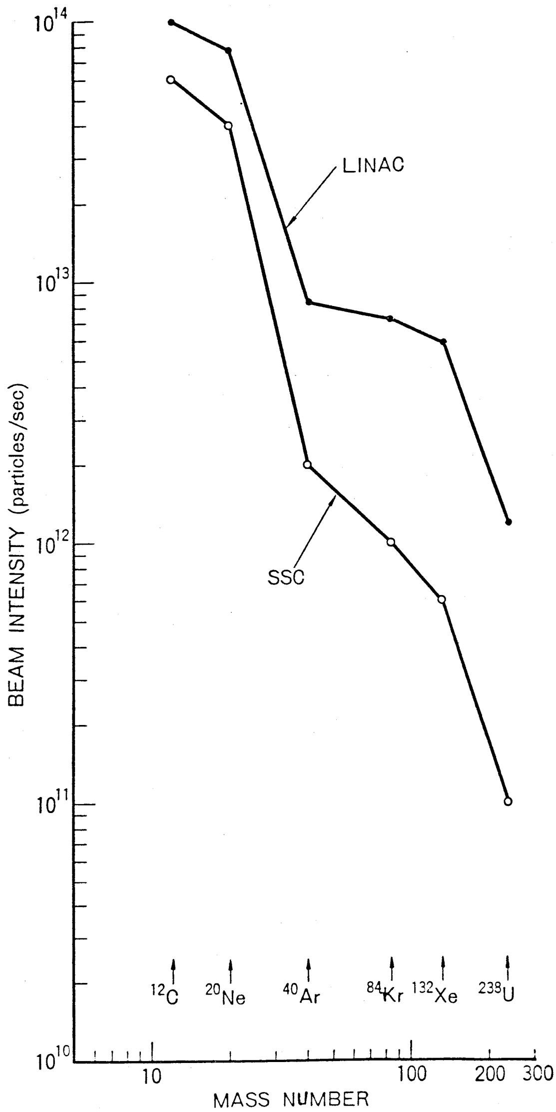

Fig.11 Expected beam intensities of the linac-injected SSC plotted versus mass numbers. They are estimated from the ion-source data tested for the linac in our laboratory except for the case of U which is taken from the test data at GSI.

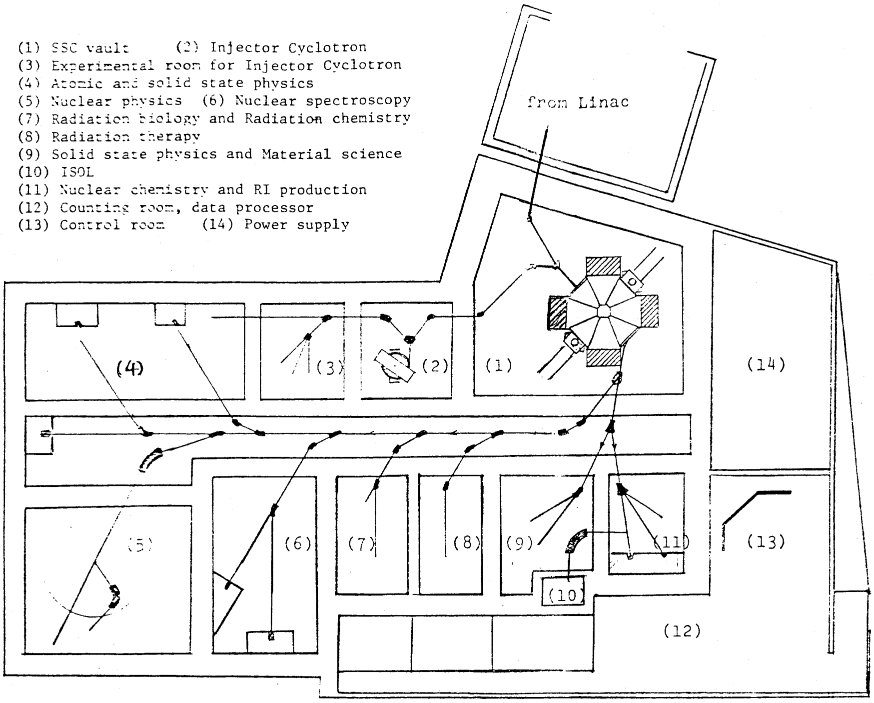

Fig. 12 Proposed layout of beam lines together with a plan view of SSC.