VARIABLE FREQUENCY LINAC RILAC, AS AN INJECTOR OF A SEPARATED SECTOR CYCLOTRON

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Summary

A heavy ion linear accelerator in RIKEN, RILAC, is the first linac of which accelerating frequency is tunable according to charge to mass ratio of ions to be accelerated. It was designed as a new type pre-stripper accelerator of a two-stage heavy-ion facility. The construction of the linac was started in 1975 and the first beam acceleration through the whole six cavities was achieved in 1981. RILAC has accelerated successfully the various ions ranging from proton to gold. It is now providing useful beams of various ions of elements between helium and gold to experimental groups. The post-stripper accelerator, which is a separated sector cyclotron, was approved in 1980 and is under construction. In this report, we describe the design and performance of the RILAC as the planned multi-particle and variable energy injector of the cyclotron.

1. INTRODUCTION

In 1971, we proposed to construct a two-stage heavy ion accelerator complex with a linac and a separated sector cyclotron. Its preliminary design was presented at the Sixth International Cyclotron Conference[1] in 1972. RILAC is the pre-stripper linac of it and is the first linac of which accelerating frequency is tunable in a wide range, between 17 and 45 MHz. In this report, design and performance of the RILAC as an injector of the cyclotron are presented.

There are two motivation to adopt this frequency variable design: One is to secure acceleration of ions of almost all the elements in the periodic table. The other is to match the accelerating condition between the pre-stripper linac and the post-stripper separated sector cyclotron.

The construction of RILAC was started in 1975 and the first beam acceleration through the first resonator was obtained in 1979 and through the whole six accelerating structures in 1981. It has accelerated ions of various elements ranging from hydrogen to gold at different accelerating frequency depending on the charge-to-mass ratio of ions. The energy per nucleon of the accelerated ions is 0.6 MeV at the lowest and 4.0 MeV at the highest frequency. RILAC is by itself being actively used for atomic physics and material science.

The magnetic rigidity of the ions after stripping at the exit of the linac remains below 800 kG-cm. The energy of the ions is multiplied by a factor of 17 by the next stage separated sector cyclotron which is under construction since 1980. Its design and status are given in separate papers in this proceedings.

2. Design

Frequency tunable linac as injector of SSC

When we choose a heavy ion injector of a separated sector cyclotron from various types of accelerator, we must consider some requirements. As is well known, ion source technology for multiply-charged heavy ions is developing rapidly. New accelerator system of heavy ions should be able to utilize the advantage of such a future development. We judged that an accelerator type which can be injected from an external ion source is favorable in this respect. We thought that a high vacuum should be necessary in the path of the highly-charged ions, at least in the region where velocity of ions is small. We chose a drift tube linac as the prestripper accelerator.

When a linac is operated as a multi-particle accelerator, some problems arise from large difference in charge-to-mass ratios of ions produced by a source for light and heavy elements. In a fixed frequency linac, the velocity of ions at a given position in the accelerator should be independent of the charge and mass of the ions in order to synchronize the acceleration of ions at the drift tube gaps. Therefore, a higher accelerating voltage is necessary for heavy ions with a small charge-to-mass ratio. Required voltage is proportional to A/q, where A is the mass number and q is number of charge of the ions. In our estimation of charge state available in the ion source technology at 1970, ratio of A/q between ions of element heavier than carbon was more than 7. Power consumption, which is proportional to the square of the voltage, changes almost by a factor of 50.

If the resonant frequency of the accelerating structure is adjustable, for instance as $f \propto (q/A)^{1/2}$, it is not necessary to use a very high voltage for the acceleration of heavy ions. Power ratios can be reduced drastically down to 4 in this case.

As an injector of the separated sector cyclotron, matching condition of acceleration parameters between both accelerators has to be considered. Since the orbit frequency of the ions in a cyclotron is variable according to q/A and magnetic field, the accelerating frequency of the injector is desired to be tunable as well. If the same acceleration frequency is used in the injector and the cyclotron, it should be easy to tune the whole accelerator system, and particularly to transfer the beam by bunch to bunch. Good match of the cyclotron with the new type linac may be expected when combined.

Note that the maximum energy-per-nucleon in this frequency variable scheme is proportional to q/A of ions to be accelerated. The relation is similar to that of acceleration by a DC accelerator. Therefore, increase of charge of ions directly leads to increase of accelerated energies. On the other hand, energies of ions remain same for any charge state in the ordinary fixed frequency linacs.

The magnetic rigidity of the accelerated beam is proportional to $(A/q)^{1/2}$ for the variable frequency scheme, whereas it is A/q for the fixed frequency scheme. Requirement for the range of magnetic field adjustment is more gentle in the variable frequency scheme than in the fixed frequency case.

Since the separated sector cyclotron is developed to work continuously (CW operation), its injector is also required to work in the CW mode. When the variable frequency scheme is used for the linac, the acceleration voltage can be set to modest values for any ion and a CW operation is possible. The energy per nucleon for lighter ions is much larger than that for heavy projectiles in this scheme.

Accelerating frequency range

The range of the accelerating frequency was determined considering the circulation frequency of the ions in the separated sector cyclotron on one hand and limitation imposed by RF problems on the other hand. The former in turn, depends on the maximum magnetic field in the pole gaps and the angle of the sector magnets and the accelerating electrodes. The latter includes accuracy to keep field pattern along the linac axis for a large resonant frequency variation, availability of high power wide band amplifiers etc.. Some compromises together with developmental works were necessary. Frequencies between 17 and 45 MHz were chosen as the range of operation for ions having q/A between 1/28 and 1/4. This charge to mass ration is thought to cover ions of any element produced using conventional and well-proven PIG type ion source.

Resonator

Figure 1 shows the resonator schematically. Six such resonators are necessary for the RILAC and each must be tuned with accuracy within 100 Hz of the given frequency. It is a quarter wave coaxial structure having a race-track shaped cross section. A shorting device is used for the wide frequency tuning. The capacity compensators are used for the fine frequency tuning required and also for automatic resonant frequency restoration during operation.

Drift tubes are located at the open end of the quarter wave resonator enlarged in the direction of acceleration. Quadrupole magnets for beam focusing are sealed in the drift tubes supported by the outer conductor. The length of every drift tube cell is made so that the phase of RF field changes by π during transit of ions through it. However, in the first resonator where a high focusing field is necessary, the length of drift tubes sections containing the quadrupoles is made longer so that the phase changes by 3 π.

Maximum current density at the shorting contacts of the shorting device is expected to be 50 A/cm at the highest voltage at 45 MHz. Until now, condition which requires such a high current has not been used yet.

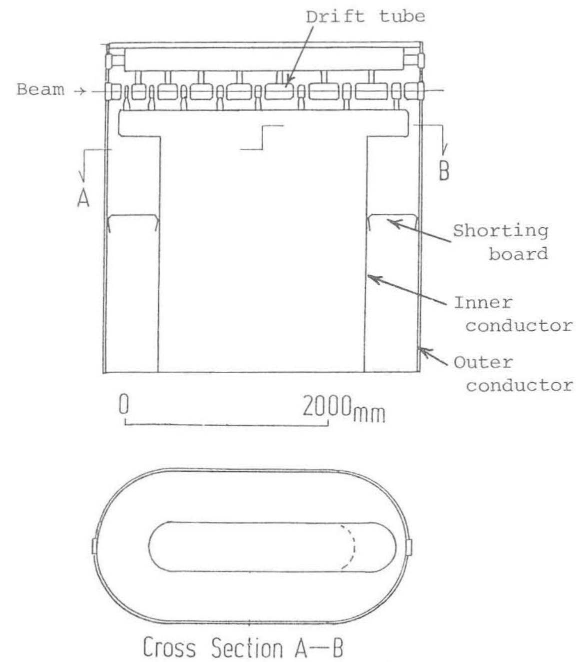

Fig.1 Symplified drawing of the deformed coaxial structure which has race-track cross section.

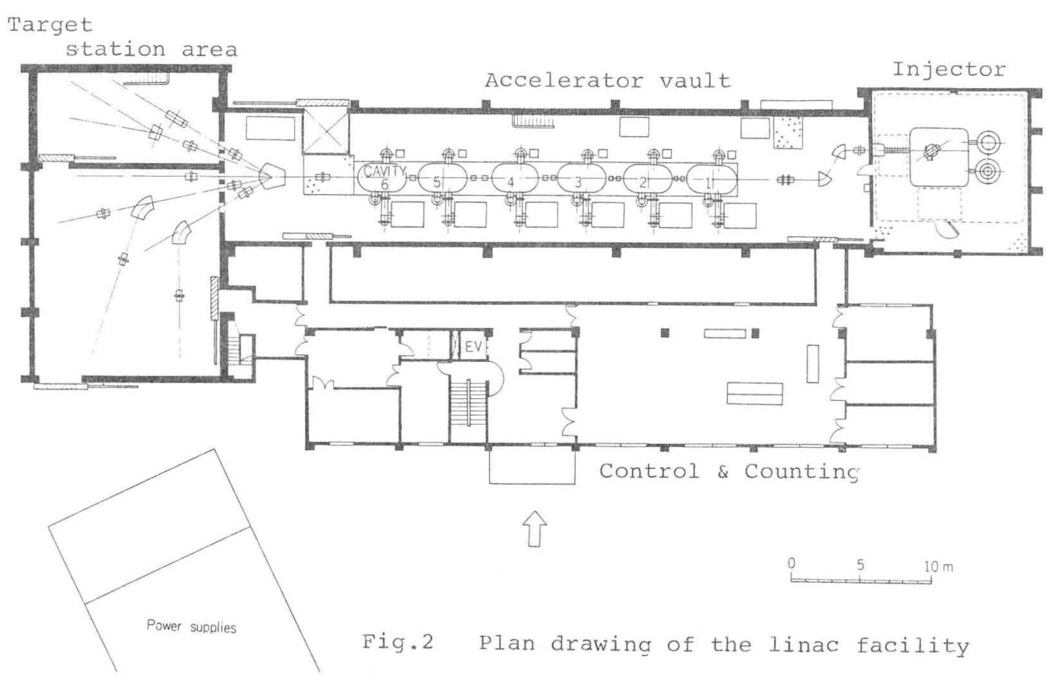

Fig.2 Plan drawing of the linac facility

Layout

Layout of the RILAC facility is shown in Fig. 2. The ion source terminal has floor area of 4 m x 4 m and is at the 500 kV potential at maximum. At present, several PIG sources with bombarded cathode are used for production of the multiply charged heavy ions. Ions of metallic elements are produced by use of a sputtering electrode. Mass and charge state are roughly analyzed in the source magnet and separated precisely by a couple of bending magnets of r = 0.6 m after acceleration by the injector voltage.

A buncher is installed after the second bending magnet.

The RF acceleration part is composed of six resonator tanks with the same size. Each resonator is excited by a power amplifier independently. It is evacuated by turbo molecular pumps and the vacuum pressure in it is kept below 3×10^{-7} torr during operation.

Charge stripping scheme is not used to date.

Fig. 3 is photograph of the RILAC seen down stream from the injector side. The specifications of RILAC are summarized in table 1.

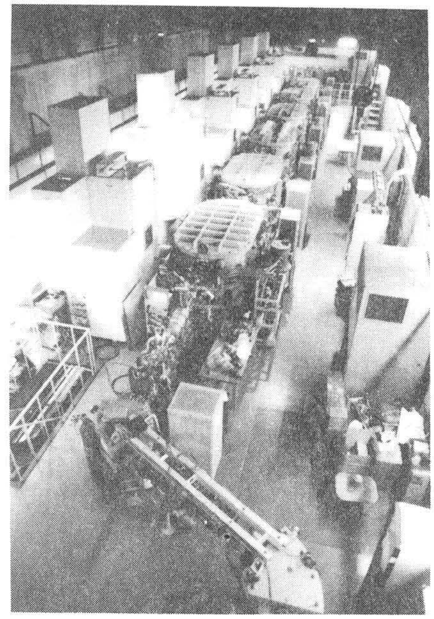

Fig. 3 Photograph of the RILAC seen down stream from the injector side.

Table 1. Specifications of RILAC

Charge to Mass Ratio(q/m)	: 1/27 minimum
Maximum Energy	: 4 MeV/n for q/m=1/4 0.8MeV/n for q/m=1/20
Acceleration Frequency	: 17～45MHz
Acceleration Mode	: π/3π for the first cavity π/π for the others
Total Effective Acceleration Voltage	: 16MV for high freq. 20MV for low freq.
Injector Voltage	: 500kV maximum
Maximum total RF Power Dissipation (CW)	: 400kW for the lowest freq. 1200kW for the highest.
Cavities	: 6 cavities of a-quarter-wave co-axial type
Length of Each Cavities	: 3m
Drift Tube Apertures	: 20～30mm
Quadrupole Magnets	: Set in the drift tubes at the ground potential
Field gradient of Quadrupoles in the Drift Tubes	: 6.0kG/cm maximum
Radial Phase Acceptance	: 400mm·mrad maximum
Vacuum System of cavities	: Turbomolecular pumps of 5000 and 2400 l/s for each cavity.
Final pressure in Cavities	: 2×10^{-7} Torr without RF and 5×10^{-7} Torr after 3days of pumping from atomospheric pressure.
Control	: Distributed microcomputers and a central computer
Stripper	: At the exit of 6th cavity
Completion	: 1980

3. Status of operation

In table 2, the species and intensities of ions obtained at entrance of the acceleration column of the injector terminal are shown. About 5 - 20 % of the beam current indicated in the table is available for the experiments depending on the beam qualities required. Typical value of the life time of the source is about 20 hours and higher currents are possible at the cost of the lifetime.

Table 2 Beam intencities and lives of ion source.

ION	CHARGE STATE	INTENSITY (μA)	LIFE (hr)
He	1+	100	
C	1+ 2+	7.5 1.1	
N	1+ 2+	20 20	>50
O	1+ 2+	6.8 1.1	
Ne	1+ 2+	4.2 6.5	
Al	2+ 3+	4.0 2.8	∿20

ION	CHARGE STATE	INTENSITY (μA)	LIFE (hr)
Ar	3+ 4+ 5+ 6+	40 60 3.5 2.0	∿30
Cu	4+ 5+ 6+	16 1.2 0.31	∿20
Kr	5+ 6+ 7+	4.0 0.56 0.03	
Xe	6+ 7+ 8+	3.5 1.2 0.3	∿16

Figure 4 shows the distribution of accelerated ions plotted against the frequency and the voltage gain. The ions are distributed over the planned frequency range. At frequencies lower than 30 MHz, the total voltage gain reaches about 16MV which is our first goal. There remains some problems in stability of amplifiers at high power operation at frequencies higher than 35 MHz. It is possible that, in the low frequency region, the upper limit of voltage gain would be pushed up to 20 MV by making improvement on the RF system and increasing the maximum voltage of injector from 500 to 600 kV. In the region of frequency higher than 30 MHz, where the RF power of the later resonators limits the total voltage gain, a charge-stripper is required between the 4th and 5th resonators in order to lower the RF powers of the last two resonators.

Energy resolution of accelerated ions is 0.6 % in fwhm and width of beam bunch is 1.2 ns in fwhm at the exit of sixth cavity. Improvement of the energy resolution and the shorter bunch width are expected by use of a beam chopper which will be available in summer 1984.

The frequency tunable linac has a special feature that beam energy can be continuously adjusted by adjusting the frequency. However, it takes long time to change the frequency since almost all the accelerator parameters must be readjusted. We have found that the acceleration energy can be changed easily by tuning the RF voltage and phase of the last resonator in use. When this method is combined with simple method of switching off of a few cavities in the later portion of the linac, energy can be continuously set down to about 30 % of the maximum energy which is obtained by excitation of the whole resonators within a relatively short time without degrading the beam qualities so much.

In spite of numerous combinations of parameters for every ions and energies, setting of the corresponding instruments becomes possible by a few stroke at key board on the operation console. Starting up from the cold state takes one to three hours depending on ion species and frequencies to be used. Those for which good number of operation has been realized in the past needs least time to send beam onto targets.

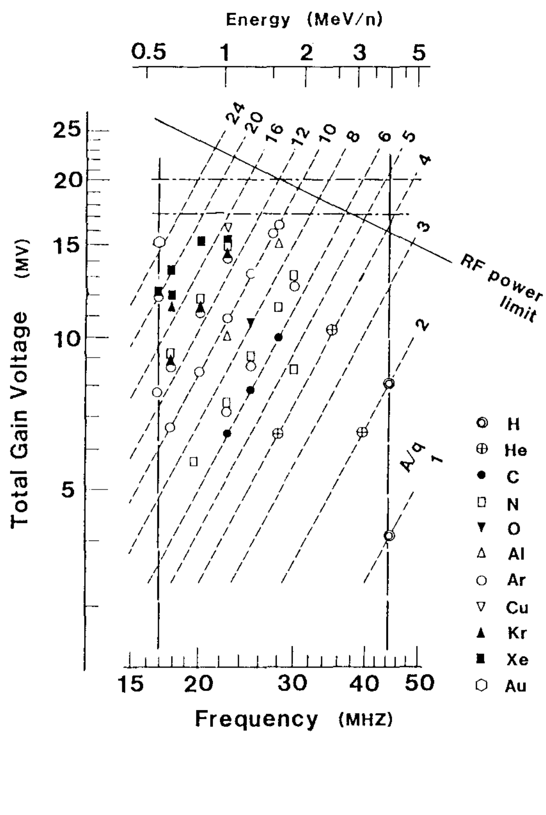

Fig. 4 The distribution of ions accelerated till spring in 1984. The vertical axis is the total effective value of total gain voltage. The horizontal one is the acceleration frequency which corresponds to the energy-per-nucleon as shown in the upper end of the figure. The mass-to-charge ratio A/q has a constant value along the inclined broken lines.

4. Conclusion

All the frequency range planned has been covered already. Unless high power operation is desired at frequencies higher than 35 MHz, machine is quite stable and current on the target remain constant for long time.

5. Acknowledgement

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Reference

1) M. Odera and T. Tonuma; Proc. Sixth Interna. Cyclotron Conf. 1972, Vancouver, AIP Conf. Proc. No.9 p283 (1972).

2) H. Kamitsubo; in this proceedings.