REPORT ON FREQUENCY TUNABLE LINAC

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Summary

A variable frequency linear accelerator for heavy ions, RILAC, was completed in 1981. It has been working stably without serious troubles for three years since. It consists of six quarter-wave resonators with drift tubes loaded at their open ends. Resonant frequency is tunable according to charge to mass ratio of ions between 17 and 45 MHz, by use of shorting devices and capacity compensators. The minimum charge to mass ratio of ions which can be accelerated is 1/28 at 17MHz and 1/4 at 45MHz. The maximum energy of ions is 0.6 MeV/amu at 17MHz and 4MeV/amu at 45MHz. Since the RF voltage for acceleration of the heaviest element is not very large, power consumption is relatively small, allowing continuous operation of the RF system. The CW mode has simplified the RF circuits and the control system of the accelerator

The linac has accelerated ions of element from hydrogen to gold. The beams are being used for experiments of nuclear chemistry, atomic physics, solid state physics and radiation biology. In future, the RILAC will serve also as an injector to a new post-stripper accelerator, a separated sector cyclotron. RF of the both machines is tuned to the same frequency. Energy will be multiplied by a factor of 17 and the range of application will be extended.

Introduction

RILAC is the first linac of which accelerating frequency is tunable in a wide range. It consists of an electrstatic injector up to 500 kV and six Wideroe type RF acceleration structures of which the resonant frequency is tunable between 17 and 45 MHz. RILAC was proposed in 1971 as a new type prestripper accelerator of a two-stage heavy-ion accelerator complex and its preliminary design was presented at the Sixth International Cyclotron Conference[1] in 1972.

Object of the frequency variable design was two-fold: 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. The first beam acceleration by the first resonator was achieved in 1979 and that by the whole six resonators in 1981. It has accelerated successfully ions of various elements ranging from hydrogen to gold at different accelerating frequency depending on the charge-to-mass ratio of ions. Acceleration of heavy ions is feasible by the frequency tuning as far as their charge to mass ratio is larger than 1/28. Power consumption is smaller for acceleration of the heavier ions by use of lower frequencies than for lighter ions for which higher frequencies are used. Since the RF voltage for acceleration of the heaviest element is not very large, power consumption is relatively small, allowing continuous operation of the RF system. The CW mode has simplified the RF circuits and the control system of the accelerator. A charge stripping technique can be applied to save the RF power if necessary.

The maximum energy of accelerated ions is 0.6 MeV/amu at the lowest and 4.0 MeV/amu at the highest frequency. RILAC by itself is being actively used for nuclear chemistry, atomic physics and material science. The energy of ions is multiplied by a factor of 17 by the next stage separated sector cyclotron which is under construction since 1980. In this report, design and performance of the RILAC are presented.

Design and Performance

The condition for the synchronous acceleration of ions in a drift tube linac is given by a simple relation between the accelerating frequency f, the velocity of ions v and the length L_n of the n-th cell. The velocity is further expressed in terms of mass A of the ion and its energy which is its charge multiplied by a sum of the effective accelerating voltages V_i. The sum is over the accelerating gaps which the ion has passed until it reaches the cell. When the effect of relativity is negligible, the resulting expression is

$$L_n = \frac{k}{f}\left(\frac{q}{A}\sum V_i\right)^{1/2} \qquad (1)$$

where k is a constant. The length L_n is fixed for each cell and the charge to mass ratio q/A is given by the ion source. When ions with different values of q/A are to be accelerated by the same accelerating structure, we have to adjust some other parameters in the expression to make the equality to hold.

In the present ion source technology, the ratio q/A is much different between light and heavy elements. According to Eq.(1), the voltage V_i must be proportional to A/q of ions if f is not adjustable. It means that much larger accelerating voltage is required for ions of heavy elements than for light ones. However, if we can change the frequency in proportion to the square root of q/A, there is no need to change the voltage for different ions. Extreme voltage holding capability is not required for drift tube gaps in acceleration of very heavy ions nor use of voltage unduly small for light ions. Therefore, the power consumption in the RF system is not so different between the acceleration of heavy and light ions.

Also the acceleration conditions of the linac should match with that of the post-stripper separated sector cyclotron. Synchronized operation of the two accelerators is easiest if the accelerating frequency of both is set to the same value.

For realization of the new scheme, the most important was the development of accelerating structure with its resonant frequency variable in a wide range. Other items were the high power variable frequency amplifiers, the control system and the beam diagnostic equipments necessary to facilitate operation of the accelerator in the variable frequency mode.

Resonator

In order to keep the synchronous accelerating condition under the variable frequency scheme, the change of the frequency should not affect the distribution of accelerating voltage at the gaps along the beam axis. The requirement as well as the conditions of the large frequency tunability and the minimum power consumption places certain restrictions on the type of resonators of the linac.

We decided to use a structure as simple as possible, with only one resonating element in the region of frequency concerned, so as to avoid complication of a coupled resonating system. As such a resonator, a co-axial quarter wave cavity having a race-track like cross section was proposed.[2] Figure 1 shows its conceptual drawing and Fig.2 an engineering design.

Frequency Tuning. A shorting device and two capacity compensators are used for the tuning of the resonant frequency. The frequency can be tuned between 17 and 60 MHz by changing the position of the shorting device by about 2000 mm, but the range of the frequency used for beam acceleration was chosen up to 45 MHz as a results of consideration of circulation frequency of ions in the cyclotron and limitations of the high power

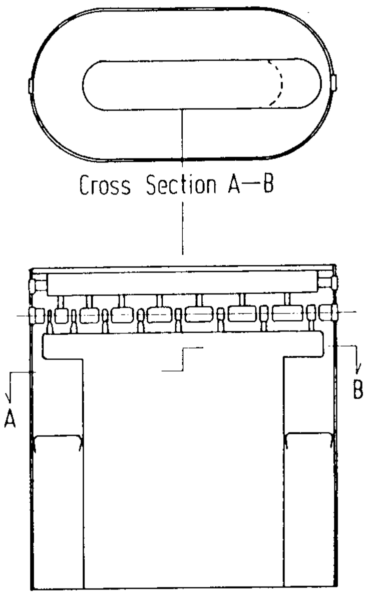

Fig. 1 Concept of a quarter wave coaxial resonator having a race track-type cross section with drift tubes loaded at its open end.

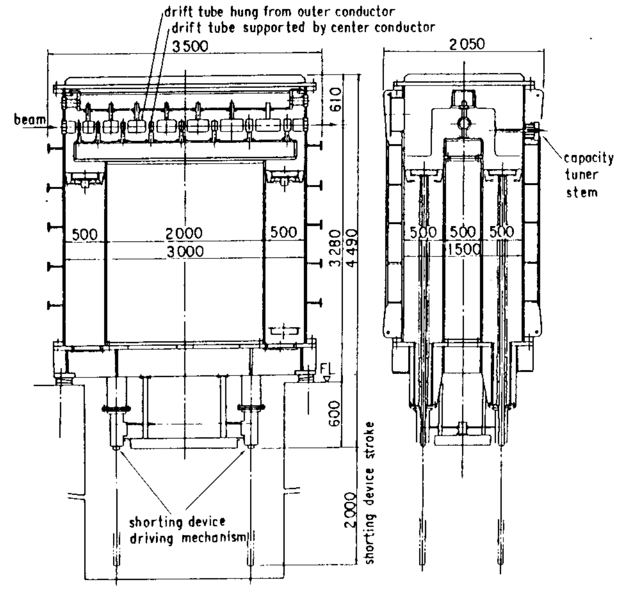

Fig. 2 Engineering design of accelerating structure. Coarse frequency change is made by the shorting device driven by four long stems vacuum sealed by long welded bellows. Fine frequency tuning is by capacitive tuner of which tuning range is 1 MHz at the highest frequency and 200 kHz at the lowest.

variable frequency amplifier technology. The profile of the voltage in the accelerating gaps along the beam axis could be made constant within 10 % in this frequency interval. Six resonators are necessary for the RILAC and each must be tuned with accuracy within 100 Hz of the given frequency. The capacity compensators are used for the fine frequency tuning required and also for automatic resonant frequency restoration during operation.

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. Though no failure of the contacts has been observed to date, use of a charge stripper after the fourth tank at the high frequency operation is being discussed to avoid overheating of the contacts in the fifth and sixth cavities and to save power.

Drift Tubes. The open end of the quarter wave resonator is enlarged in the direction of acceleration where drift tubes are aligned. The drift tubes are supported by the outer and inner conductors alternately and those supported by the outer conductor contain quadrupole magnets for beam focusing. The length of the drift tubes is made so that the phase of the RF field changes by π while ions transit through the drift tube section. However, in the first resonator where it is necessary to focus ions with low velocity and small q/A, the drift tubes which contain the magnets are made longer so that the phase of RF field changes 3- π during the transit of ions through the section.

Compact quadrupole magnet for drift tubes was developed. Its maximum field gradient is 7 kG/cm for pole gap of 23 mm. The maximum power dissipation is 1 kW. Two types of coils have been used to realize the high gradient and efficient cooling. One is an improved tape coil which originally was developed at LBL.[3] The other is a quadrant stacked coil devised and developed in our laboratory.[2] Both types enable to use a large ampere-turns in a narrow space and allow the size of the magnets and the drift tubes to be reduced.

Outer diameter of the drift tubes containing the magnets is 160 mm and that of the drift tubes without magnets is 100 mm. Figure 3 shows the drift tube array in the first tank. Center of the quadrupolar field was aligned with accuracy within 0.1 mm helped by a hot-wire technique. Note their short and thick stems to avoid local resonance. No position readjusting mechanism is provided.

Q-Values. Measured Q-value of the resonator is 18500 at 17 MHz and 12000 at 45MHz, which allows continuous excitation of the resonator by making accelerating gradient modest. The acceleration rate is 0.86

TABLE I RESONATOR CHARACTERISTICS

Numerals in parentheses correspond to the case when charge stripping is applied behind #4 resonator.

Resonator No.	Freq.	Unit	# 1	# 2	# 3	# 4	# 5	# 6
Max. peak RF voltage in acc. gaps		kV	180	200	230	250	280 (< 140)	300 (< 150)
No. of acc. gaps			16 (π/3π)	18	14	12	10	10
Effective energy gain/charge		MeV/q	2.2	3.1	2.8	2.6	2.4	2.6
Ratio of effective gain to sum of peaks		%	76	86	87	87	86	87
Effective shunt impedance	17 MHz 45 MHz	MΩ/m	61 15	150 36	90 22	65 16	45 11	45 11
Max. power loss	17 MHz 45 MHz	kW	26 108	33 133	43 176	51 208	64 261 (< 65)	74 300 (< 75)
Q-factors	17 MHz 45 MHz		18,500 12,000	18,500 12,000	Same to #2 " " "	Same to #2 " " "	Same to #2 " " "	Same to #2 " " "
Drift tube aperture		mm	25-30	20-30	25-30	30	30	30
Max. field grad.		kG/cm	3.3	6.0	3.8	3.2	2.7	2.7

MeV/m per charge at 45 MHz and around 1 MeV/m at low frequency.

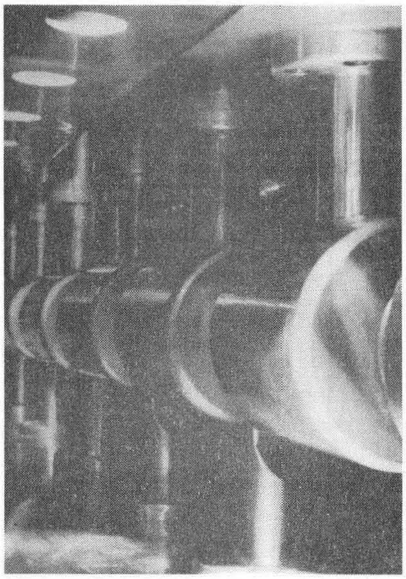

Fig. 3 Drift tubes of the first resonator.

Summary of Resonator Characteristics. Table I summarizes characteristics of the resonators. For the fifth and sixth resonators, values in parentheses correspond to the case where charge of ions is increased by stripping after the fourth resonator.

Amplifiers

Figure 4 shows a simplified circuit of the high power RF amplifier chain. A broad band amplifier with power level of 250 W excites the cathode of a grounded-grid triode, where no tuning procedures are necessary. The control grid and plate of the last stage power tube are tuned by coaxial stubs. Load impedance of the power tube is adjusted by a variable vacuum capacitor inserted between the plate and the power feeder. Matching between the resonator and the feeder is watched by measurement of the forward and reflected power by directional couplers attached to the side of the feeder. The matching is adjustable by varying the capacitance between the head of the feeder and the inner conductor of the resonator, manually or automatically.

There are four feed back loops for automatic stabilization or restoration of the accelerator parameters under operation. Those are loops for (1) resonant frequency, (2) amplitude of accelerating field, (3) phase and (4) restoration of cavity field after discharge. Drift of the resonant frequency of the resonators is watched either by phase difference between the cavity field and the feeder field or change of the reactive component of the resonator impedance seen by the feeder. The picked up signal is fed back to change position of the capacity compensators. The loops (2) and (3) interfere with (1). (1) is given priority.

Excitation of the resonators is automatically turned off as soon as loss of the high frequency field by some reason such as vacuum sparking is detected. Then excitation mode is switched from the continuous to pulse mode. It is essential to turn off the power immediately and to pause before resuming excitation for prevent growth of the multipactoring phenomenon. In the pulse mode, a fast rising over-voltage excitation is applied for an interval of a few ten milliseconds with repetition frequency of roughly 1.5 Hz. During the pulse, the field in the resonator is watched and once the field is restored the excitation mode is switched back to the continuous one and the excitation level is brought down to the normal level. The process is so fast that one seldom notice occurrence of the vacuum sparking.

There are other servo loops and auto-tuning loops for parameter presetting and optimization of the RF system. For instance, the position of the shorting device of the resonator and the length of the tuning stubs are set by the servo loops with reference signals sent from the central processor. Operation of the high power radiofrequency system with the feed back loops above described is very stable and reliable. It is not critical except at some frequencies higher than 35 MHz. For those frequencies, modification of the circuit has been found effective to remove instability. At present, due to the above problem, time to change frequency differs considerably according to the region of frequency to be used.

Summary of Radiofrequency System. To summarize, variable frequency operation of the radiofrequency system composed of the six high power amplifiers presents no serious problems which make routine operation difficult or too much laborious. The CW mode of operation has allowed use of the relatively simple circuitry for the high power amplifiers. When compared to the usual pulse operation, change of the accelerator parameters in time is very slow. Rapid response in the various feed-back loops is not required. Computer-assisted control with the relatively slow method of parameter reading by scanning can be used. Figure 5 shows the last stage tube with its tuning stubs installed in the amplifier box.

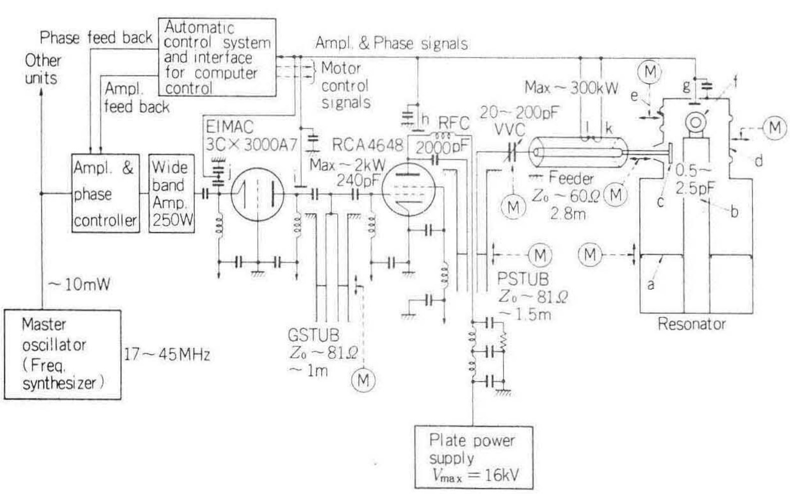

Fig. 4 Frequency tunable high power amplifier circuit.

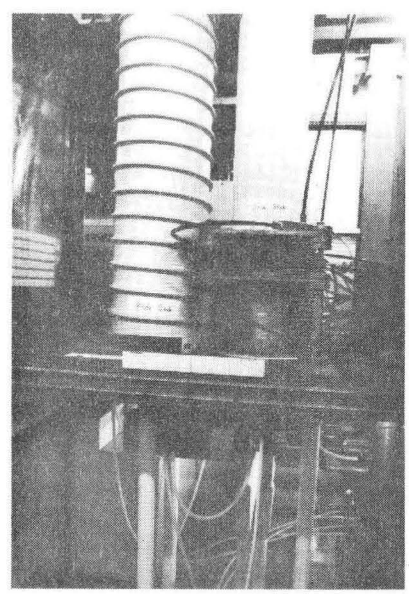

Fig. 5 Upper part of the amplifier box showing a power tube fitted with plate and grid tuning stubs.

Control System.

For operation of the multiparticle and frequency variable linac, many accelerator parameters must be set and tuned with possibility of numerous combinations. This procedure should not take too much time. Introduction of computers is inevitable. In our control system, microprocessors are distributed in the accelerator vault and measure parameter values or transform instructions from the central processor and control local instruments. Figure 6 is a block diagram of the control system. Use of the mass storage such as magnetic tapes and disks greatly helps operators in search and determination of the best operation conditions from the accumulated past operation records. Remarkable improvements in transmission efficiency of beam through resonators and reduction of starting time have been achieved by the computer assisted control system.

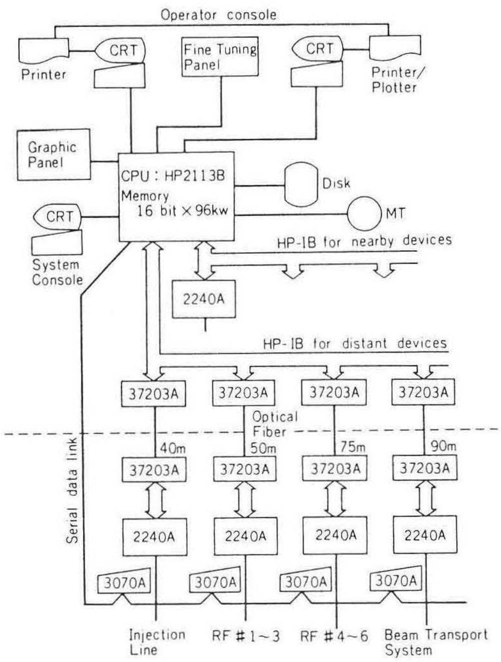

Fig. 6 Block diagram of the control system.

Layout

Layout of the RILAC facility is shown in Fig. 7. Horizontal distance between the exit of the RILAC and the post stripper cyclotron is 50 m. Levels of beam acceleration differs by 14 m. Fig. 8 is a photograph of the RILAC seen down stream from the injector side. Amplifiers are positioned as close as possible to each resonators.

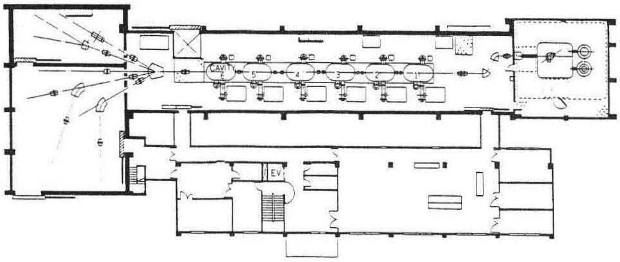

Fig. 7 Layout plan of the RILAC facility.

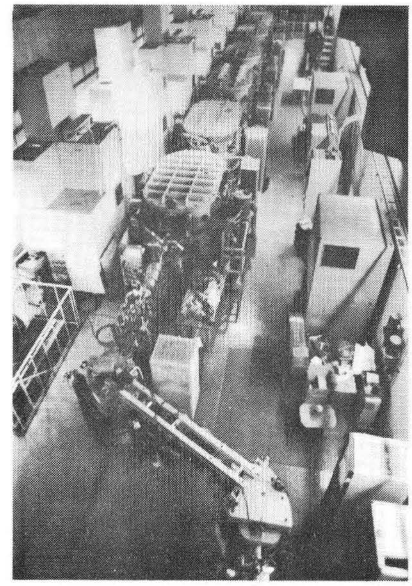

Fig. 8 Photograph of the main part of RILAC.

Status of Operation

Table II gives a rough specifications of the RILAC. Figure 9 shows the distribution of accelerated ions plotted against the frequency and the voltage gain. The ions are distributed over the planned frequency range. Energy resolution is 0.6 % in fwhm and width of beam bunch is 1.2 ns in fwhm at the exit of the sixth cavity. At present, 5 to 20 % of the beam current extracted from the ion source is obtained at targets depending on the beam qualities required.

The frequency tunable linac has a special feature that beam energy can be changed by selecting the acceleration frequency. But since the procedure to change the frequency requires the readjustment of almost all the acceleration parameters, it takes several hours. However, it has been found unexpectedly easy to change the acceleration energy 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, the energy can be set to any value down to as low as 30 % of the maximum energy within a relatively short time, without degrading the beam qualities so much.[4]

In spite of numerous combinations of parameters for every ions and energies, setting of the corresponding instruments is 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 frequency to be used. Those for which good number of operation has been experienced in the past needs least time to send beam onto targets.

TABLE II SPECIFICATIONS OF FREQUENCY TUNABLE LINAC RILAC

Special feature ;	Frequency variable
Frequency range;	17-45 MHz
Charge to mass ratio of ions;	>1/28
Number of cavities;	6
Energy per nucleon;	4 MeV/n for q/A=1/4
	0.8 MeV/n for q/A=1/20
Energy tuning;	Continuous

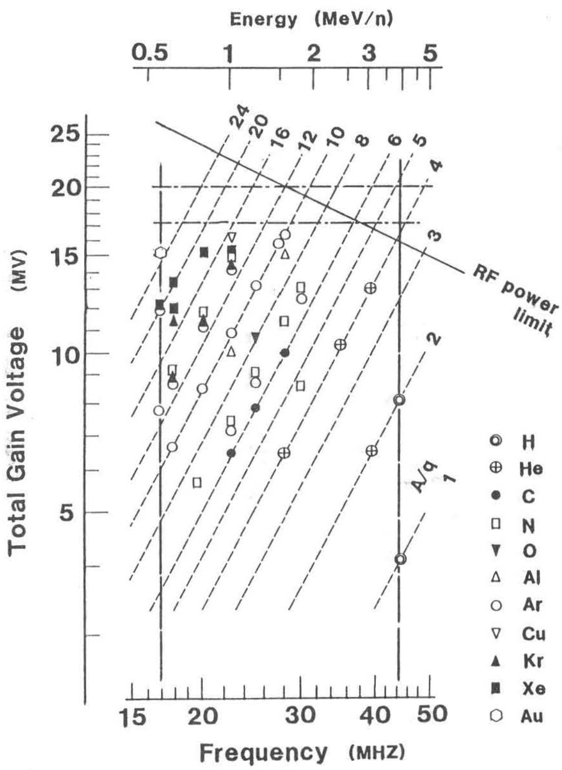

Fig. 9 Distribution of accelerated ions plotted against the frequency and the voltage gain.

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 remains constant for long time.

The variable frequency scheme of the RILAC seems proved to work. The success is helped partly by the recent remarkable development in the automatic feed back control technology and partly by simplification of control process made possible by continuous mode of operation of its radiofrequency system. The continuous mode in turn has been realized by use of the frequency tuning scheme, which has decreased necessary accelerating gradient for the ions of the heaviest elements. The availability of the beam for experiments is good.

Acknowledgements

The variable frequency linac project owes its completion and subsequent success in operation very much to cooperation of many persons in addition to effort of the members of the Linac Laboratory. To mention among them, members of the machine and electronics shops of the RIKEN gave us technical supports, especially in the stage of research and development. Also positive and sincere cooperation of members of the Sumitomo Heavy Industry with their precision machining technology in fabrication of the resonators, magnets and other parts are deeply acknowledged.

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