A VARIABLE FREQUENCY HEAVY-ION LINAC

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Summary

A variable frequency linac, RILAC, was planned for acceleration of ions of elements throughout the periodic table. Total energies and rates of energy increase per unit length were chosen relatively small to make radiofrequency power loss modest, to realize a high duty factor operation. The accelerating frequency is variable to ease acceptance of ions having very different charge to mass ratios into an identical accelerator structure. The scheme is also effective to relax requirements of the large field gradients for the quadrupole focusing magnets in the drift tubes by use of the lower frequencies for the heavier projectiles. A quarter wave coaxial structure having an obround cross section was adopted as its resonator. Change of relative distribution of voltage amplitudes at the accelerating gaps with frequency was studied by the models and was found possible to be minimized in spite of a large frequency variation. The effective shunt impedance of the resonators is good and allows the large duty factor operation planned. The higher mode frequency spectrum is simple and presents no problem for discrimination of the unwanted modes.

Introduction

In the IPCR, many kinds of researches such as solid state and atomic physics, radio- and radiation chemistry, radiation biology as well as basic nuclear physics have been made using lighter heavy ion beams as boron, carbon, nitrogen and oxygen from its cyclotron for these eight years. A new accelerator was proposed to extend those research activities by acceleration of heavier particles.[1] Following requirements were made concerning what kind of accelerator should be built.

1. Elements throughout the periodic table can be used as projectiles.
2. Use of the multiply-charged heavy ion source.
3. Future extension to a larger accelerator complex must be feasible.
4. A large duty factor in operation is desirable at least for the prestripper part of the multistage facility.

Combination of a low energy linac and a cyclotron was chosen as the accelerator complex to satisfy the above requirements. The radiofrequencies of the two parts should be in the integer ratio in order to make beam transfer between them efficient. As the specific energy booster we have assumed a separated sector cyclotron. Revolution frequency of the heavy ions in the cyclotron is around 2.5 to 7 MHz, while the radiofrequency of dee system has to be 4 to 8 times of the ion frequency owing to its limited occupation width of azimuth of the circulating ion orbit. Thus, frequencies around 20 to 50 MHz may be used for the cyclotron. And the same range of frequencies is suited for Wideröe-type low velocity heavy ion linacs. Therefore, we decided to use the same frequency for the both accelerators.

It is evident that change of frequency according to charge to mass ratio of ions is desirable for a radiofrequency accelerator. Modern cyclotrons do so always. However, there are several problems to be solved before one can apply this condition to a linear accelerator. Firstly, distribution of the voltage amplitudes at accelerating gaps must not change drastically when frequency is changed. This requirement is most stringent for the upstream part of the linac where the velocity of ions is changing rapidly. Second problem is feasibility of a high power amplifier system which can work in the variable frequency mode in this region. There are also other difficulties such as increased complexity of operation. An attempt to solve first problem was made by use of a quarter wave coaxial structure with drift tubes attached at the open end as capacitive loads. A reasonable constancy of the distribution of accelerating voltage against frequency variation was obtained. The loss characteristics obtained by models were satisfactory and allow cw operation at least up to 36 MHz at the planned accelerating rates. The limit can be pushed up higher, probably to 40 MHz because much improvement of the shunt impedance was seen in the final model over the earlier model for which loss property was measured extensively. The possibility of cw operation helps to dispose the second problem by making design and operation of the radiofrequency circuit simpler than in the case of a low duty factor linac. The results of those studies by models and other characteristics of our linac are described below.

Structure of the resonator

Figure 1 shows structure of a model used to determine various parameters of the real resonator. The drift tubes hanging from the top have a large diameter to contain quadrupole magnets in them. Several upstream drift tubes have nearly three-fold length of the normal ones to keep field gradients of the quadrupole magnets in the drift tubes within a practical limit. Drift tubes supported on the center conductor have no magnets and have smaller diameter than those described above. Both types have short and thick stems. There is no problem of the stem resonance and supplying coolant or power feeding to the magnets is easy. Coarse frequency tuning is made by a movable shorting plane. There are two capacity compensators for fine tuning. The shape of the cross section of the resonator was determined to satisfy two requirements: a larger dimension along the beam direction to get as many accelerating gaps as possible and the structure strength of the vacuum vessel.

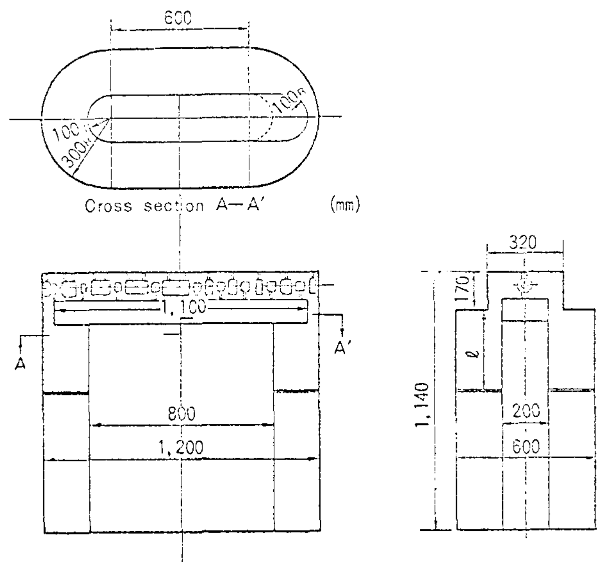

Fig. 1 : Obround-shaped model scaled by 1/2.5.

Voltage distribution

Distribution of voltage amplitudes in the drift tube gaps was investigated by the usual perturbation method along the acceleration axis of various mock-ups lined with copper plates. Local increase of capacity distribution is seen to result in gradual growth of the amplitudes towards the place where the deviation exists. The phenomenon is enhanced at high frequencies. Sensitivity to the unequality of capacity distribution can be decreased by forming outer conductor around the drift tubes as shown in Fig. 1. Such a change also occured by a large local deformation of the shorting plane. The amplitude enhancement always exists at or near the place where capacity and/or inductance are larger than other part. Following these observation we found a method to get a reasonably constant amplitude distribution against the frequency change. The method is to increase the diameter of the two drift tubes sitting on the center conductor at the entrance and exit ends. Figure 2 is an example of the distribution obtained for the model shown in Fig. 1. In this case, the diameter of the two tubes was increased to 150 mm, from the original 100 mm diameter.

The effects of the frequency dependence on the phase motion of ions were calculated.[2] An increase of the amplitude of motion in the phase and energy diagram naturally occurs; nevertheless, decrease of longitudinal acceptance and broadening of energy definition were found not inevitable by use of an appropriately designed chopper and buncher system. Other effect as on the transversal acceptance was investigated and was found harmless. It is true that voltage holding capacity of the drift tube array will be somewhat less for uneven amplitude distribution than for the perfectly uniform case. However, design fields at each gap were chosen conservatively and sparking will not be a problem even at the highest frequency where the largest inequality occurs. The largest field is less than 60 kV/cm in the first resonator and is even less for later cavities and for lower frequencies.

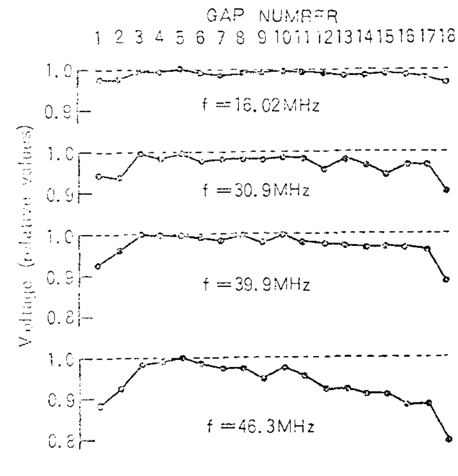

Fig. 2: Change of distribution with frequency of the voltage amplitudes at each gaps.

Higher modes

Resonant frequencies of various modes for the resonator of the Fig. 1 are indicated in Fig. 3 as a function of position of the shorting plane. Separation of the higher modes from the fundamental is large and the voltage distributions of the former ones have distinct pattern peculiar to each mode, viz., one node for f_1 and two for f_2. There seems no difficulty in discriminating the fundamental from the higher mode resonances. The power feeding point is chosen at the place where the nearest higher mode f_1 is difficult to be excited. The output stage of the exciter is designed to contain only small amount of harmonic components in its wave form.

Loss characteristics

The effective shunt impedance obtained for one of the models is shown in Fig. 4. The detailed structure of the model used is not the same with that of the Fig. 1 but can represent general tendency of high-frequency loss of the resonators of the present type. There is a point corresponding to a measurement on the model of the Fig. 1 which has a larger cicumference and more even current distribution for the inner conductor than other models. The shunt impedance of the point is excellent and we may expect similar improvement for other frequencies. Unfortunately, the model of the Fig. 1 was made for study of the voltage distribution at the gaps and the loss measurement was made only at one frequency. Therefore, necessary capacity of the radiofrequency power sources was estimated by the solid line of the figure.

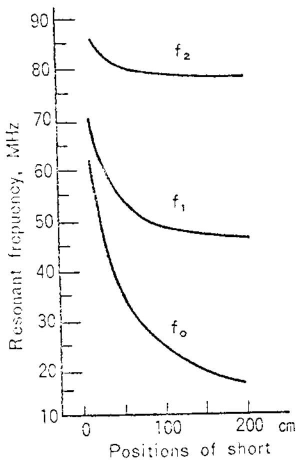

Fig. 3 : Resonant frequencies of the lower few modes.

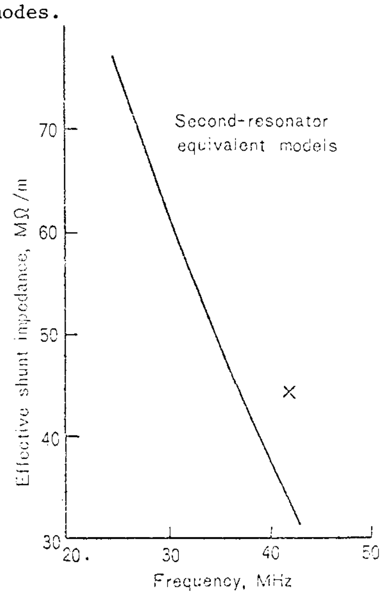

Fig. 4 : The effective shunt impedance obtained for models having a rectangular (solid line) and a obround (x) cross sections.

Radiofrequency system

Six sets of amplifiers excite six resonators separately. Tetrodes RCA 4648s will be used for the final stages. A prototype amplifer system including phase and amplitude feedback loops is being constructed in the laboratory. The set will be tested till the middle of 1977 and then the rest will be fabricated by a manufacturer. Automatic tuning of the resonator is done by a capacity compensator driven by difference signal of phases picked up from the resonator and the amplifier.

Quadrupole magnets in drift tubes

Focusing of the heavy ions of low velocity requires the large field gradients for the quadrupole magnets contained in the drift tubes. Though the gradients were somewhat relaxed in our case by use of 3π length for the upstream sections and lowering of frequency for acceleration of heavier elements, manufacturing of the compact sized quadrupoles is still not an easy task. For

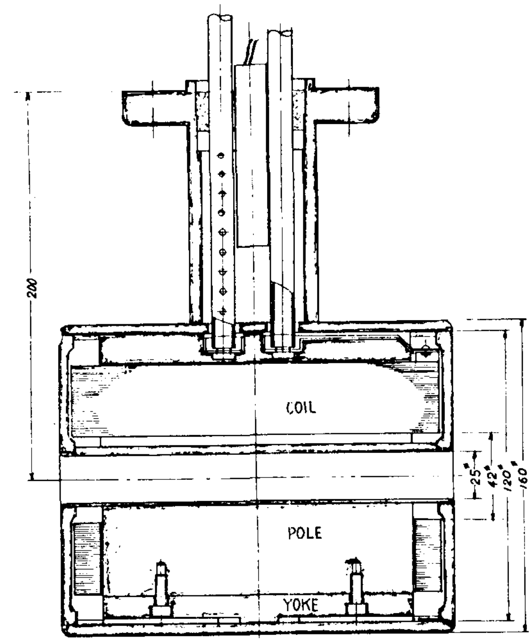

Fig. 5 : Cross section of a drift tube

a Wideröe-type resonator, small diameter of the drift tube is desirable to keep capacity small in order to obtain a good shunt impedance. The diameter was chosen as 160 mm. Yoke of the magnet has 150 mm outer diameter leaving 10 mm for the drift tube shell. Fig. 5 shows structure of a drift tube.

Cooling with Freon-113 of coils and the radiofrequency loss at the skin of tubes was judged best for continuous operation of both magnets and resonator. The tape-coil developed at the HILAC laboratory[3] and a quadrant-stacked plate-coil devised in our laboratory were tested. As shown in Fig. 6, the quadrant-stacked plate coil shows excellent cooling characteristics. However, it needs more hand-work to make it than the tape-coil. It will be used only for the part where use of the tape-coil is not safe. Fig. 7 is a photograph of the tape-coil in the magnet and the quadrant-stacked coil.

Location of the center axis of magnetic field was determined by a rotating Hall probe. Coincidence with the geometrical center of the magnet was found generally good. After insertion into the copper shell and vacuum seal by electron beam welding, deviation was discovered in some samples. The field center did not necessarily coincide with the axis of copper tube inserted between pole tips. When the deviation is too large the bore of the copper tube was reshaped to make the center of the new bore coincident with that of the magnetic field. The bore center is used for optical alignment of the drift tubes.

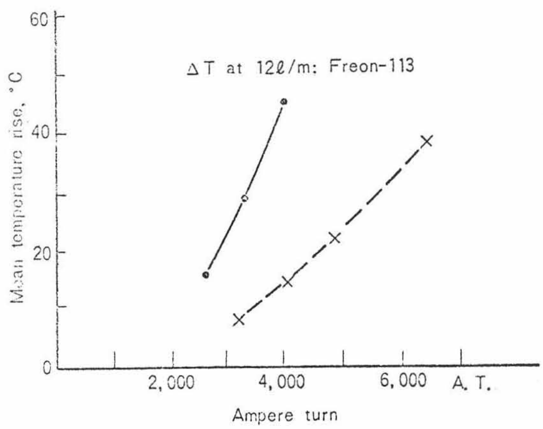

Fig. 6 : Mean temperature rise of coils. Solid line is for tape-coil and dotted is for quadrant plate coil.

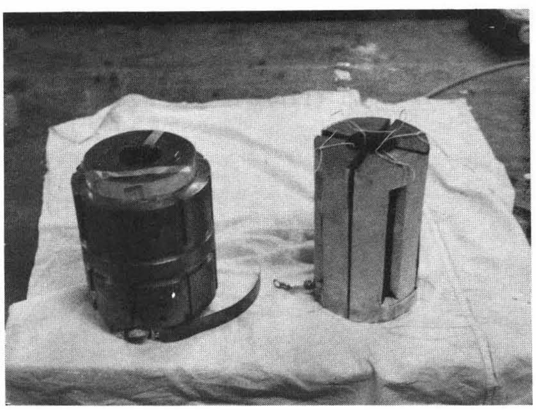

Fig. 7 : quadrant-stacked plate coil and the tape-coil in the magnet.

Arrangement of facility

The plan view of the RILAC facility is given in Fig. 8. The maximum potential of the injector is 500 kV. The high voltage platform has a 4m by 4m floor area and is provided with a 50 kVA generator driven by a motor on the ground via a fiber-reinforced epoxy -rod. The resonators are made of copper-clad steel and have volume of 13000 l each. A combination of a 5000 l/sec cryogenic pump and a 2000 l/sec turbo-molecular pump evacuates each volume to some 10^{-7} Torr. The radiofrequency amplifiers are placed closely on the side of each resonator and are coupled with short capacitive feeders. The strength of coupling is adjustable remotely by changing depth of insertion of the feeder. A switching magnet distributes beams to five directions.

Particle energies

The maximum energy of particles is variable depending on the voltage holding capacity of drift tube gaps. When the maximum mean field is 50 kV/cm, total energy obtainable is 16q MeV. Here, q is the charge number of the ion. If the voltage at each gap can be increased by a certain factor, say 1.2, particle energy will increase by the same ratio and the frequency of acceleration has to be higher by the root of the ratio, approximately 1.10. For the large mass elements for which the low frequencies are used and power loss is relatively small, this is quite possible. At present, particle energies are calculated as 16q MeV for light ions and 20q MeV for heavy elements. Table I shows an example of particles and energies. The charge states of ions in the upper part of the table are those obtainable with the conventional PIG ion sources. In view of the recent advance of ion source technology, much higher charge states may be expected for heavy elements. In that case, the particle energies can be increased by a large factor. The lower part of the table gives such cases.

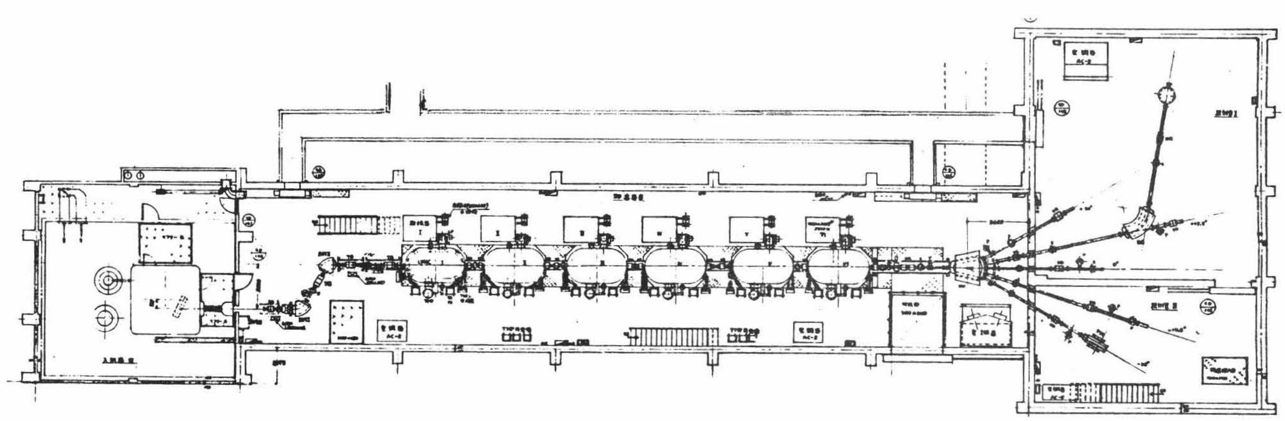

Fig. 8 : Plan view of the acclerator facility.

TABLE I

EXAMPLE OF PARTICLE ENERGIES

Element	Charge state	Energy MeV	Frequency MHz
Ne- 20	5+	80	44.7
Ar- 40	6+	120	38.7
Xe-132	8+	160	24.6
Xe-132	15+	300	33.7
U-238	30+	600	35.5

Conclusion

A variable frequency structure of a drift tube linac was investigated. Change of distribution of voltage amplitudes along the axis of acceleration has been studied by a number of models. It was found possible to keep change small by simply making the outer diameter of two drift tubes which are at the ends of the tube array on the center conductor of the resonator larger by a certain amount than others. Effective shunt impedance obtained by the models is good and a large duty factor (macroscopic) operation is possible. Higher mode spectrum is simple and discrimination of wanted from unwanted mode presents no problem. The large duty factor together with the frequency variable characteristics, this linac can be an attractive prestripper accelerator for a large heavy ion facility using a cyclotron as an energy booster.

The constructional work has started last year and the first resonator will be installed by the end of 1976. It will be coupled with a power amplifier which is also under construction and will be evaluated for next half year. The rest sets of resonators and amplifiers will be completed till the end of 1978. Acceleration will begin in the fall of 1979.

In view of the good high frequency characteristics, this quarter-wave structure may be used for a fixed frequency linac as well. If there is no need of frequency change, its structure can be much more simplified as shown in Fig. 9. It will be useful as a low β structure with its construction convenient for supply of power and coolant for the focusing elements. Uniform voltage distribution along the acceleration axis makes it simple to calculate velocity profile in the accelerator. Although partitions may be required to divide the accelerator volume into sections where different voltage amplitudes must be used, the cylindrical outer shell can be common and long. Tolerance of machining is not tight and tuning is not very critical since its higher mode is amply removed. Incidentaly, the resonator resembles a half Pottier's cavity based on the H-mode resonance of a cylindrical cavity.[4]

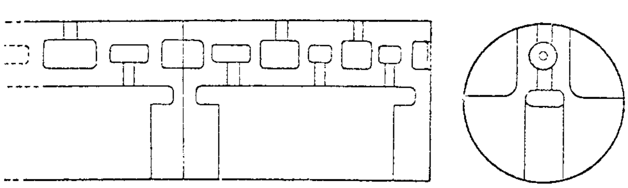

Fig. 9 : Cylindrical fixed frequency resonator

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