Beam Quality of Variable-Frequency Linac, RILAC

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Summary

The variable frequency linac, RILAC, has some special features relating to the longitudinal phase motion. For a given frequency, energy can be varied finely by adjusting acceleration parameters of the final acceleration stage without degrading the beam quality so much. By combining the method with turning off the later portion of the linac, the continuous energy variation over the wide range is obtained. One of interesting questions in RILAC is how to keep a constant beam quality against the frequency adjustment (17 - 45 MHz). The effect of frequency-dependent change in the acceleration voltage distribution along the beam line in a resonator tank can be reduced by making the correction on the injection voltage and other parameters in the low energy region.

Introduction

RILAC is a heavy-ion linac which will be used as an injector of the separated sector cyclotron (the RIKEN SSC). In order to be a suitable injector to the cyclotron, RILAC was designed as new type linac, i.e. the variable frequency linac[1]. It has some features about beam dynamics as well as a number of advantages as the cyclotron injector. We will discuss in this report about the following two points relating to the longitudinal phase motion.

The first point is the capability of energy variation. As a multi-purpose machine like RILAC the energy variation in a wide range is desired to meet the request of many applications for different energies. The frequency tunable linac has a special feature that beam energy can be continuously changed by selecting the frequency. But since the operation with change of frequency requires the adjustment of almost all the acceleration parameters, it takes several hours to realize it. Moreover, when RILAC is used as an injector of separated-sector cyclotron, the fine energy tuning at a fixed frequency is sometimes required to change the harmonic number in the cyclotron. A simple method which is suitable for frequent and fine energy tuning is required.

The second point is the method how to resolve the beam dynamics problem arising from the frequency-dependent variation of acceleration voltage distribution along the beam line. It is desirable to get constant beam quality over the frequency range. But this voltage distribution affect the longitudinal phase motion and may produce the correlation between the frequency and the beam qualities such as phase acceptance, energy spread, bunch width. The compensation for the change of voltage profile is necessary.

Energy tuning

To meet the technological requirement of the variable frequency scheme, the length of each resonator tank of RILAC was selected to be relatively short (3 m) and the number of drift tubes in each resonator is limited. It makes the longitudinal phase oscillation in one resonator small especially in high velocity region and, therefore, the resonator in the later portion of RILAC does not work by itself sufficiently as a velocity filter like an ordinary linac.

Making use of this fact, the energy tuning with a fixed resonant frequency is available at RILAC. One can deviate the phase oscillation from the normal condition intentionally by adjusting the rf voltage and/or phase at the final acceleration stage for the purpose of the energy tuning.

Fig. 1 shows the energy variation by changing the injection phase of the last resonator in use. A wide energy range down to 30 % of the maximum energy can be covered by this method. We made a computer simulation for the phase motion in RILAC. The results of calculation for the longitudinal emittance (z-emittance) after the fifth resonator (tank #5) for several injection phases are shown in fig. 2. In the figure, one can see the tendency that, as the injection phase varies from -5 to -105 deg., the beam energy decreases and, at the same time, the energy spread becomes wider. The results for the energy spread are summarized in fig. 3 together with the experimental ones. The fairly good agreement between calculation and measurement

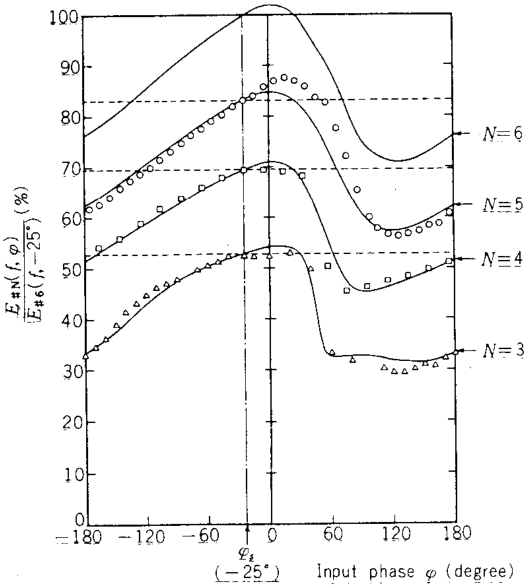

Fig.1 The beam energy vs. the injection phase angle. The energy is normalized to the designed value at the 6th cavity. The last cavity in use is denoted by N. Triangles, squares and circles are the experimental values obtained for N= 3,4 and 5. Solid lines are the calculations for N = 3,4,5 and 6.

can be seen. However, the minimum value of the measured energy spread is two times larger than that of calculation. The reason for this difference is not clear at present, but it may be due to the effect of the unstability of rf parameters (voltage and/or phase), the coupling of radial and phase motion in the low velocity region, and so on.

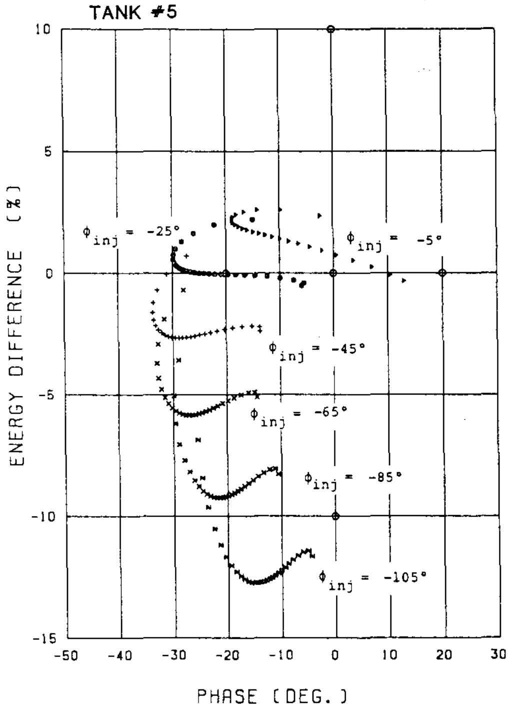

Fig. 2 The calculations of z-emittance at the exit of tank #5. The injection phase is varied from -105 to -5 deg.

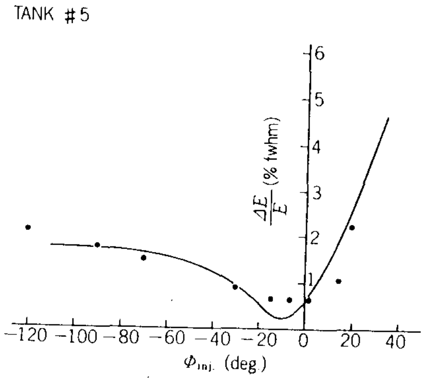

Fig. 3 The variation of energy resolution of beam of tank #5 against the injection phase to the tank. The solid line is the results of calculation in fig. 2, and the solid circles are the energy spreads measured with an SSD.

Fig. 4 also shows the results of calculation of the z-emittance. In this case, not only the injection phase but also RF voltage of tank #5 ($V_{\#5}$) are changed in such way that the energy spread will be minimized for each energy. As shown in fig. 5, the energy varies linearly and slowly with change of $V_{\#5}$ and goes down toward the normal energy of the previous tank (shown by a dot-dash line in the figure) as $V_{\#5}$ approaches to zero, and, on the other hand, the energy spreads are almost constant against the $V_{\#5}$ adjustment. By this method, the continuous energy tuning with nearly constant z-emittance can be obtained as far as RF voltage remains between the lower limit of RF system and the spark limit.

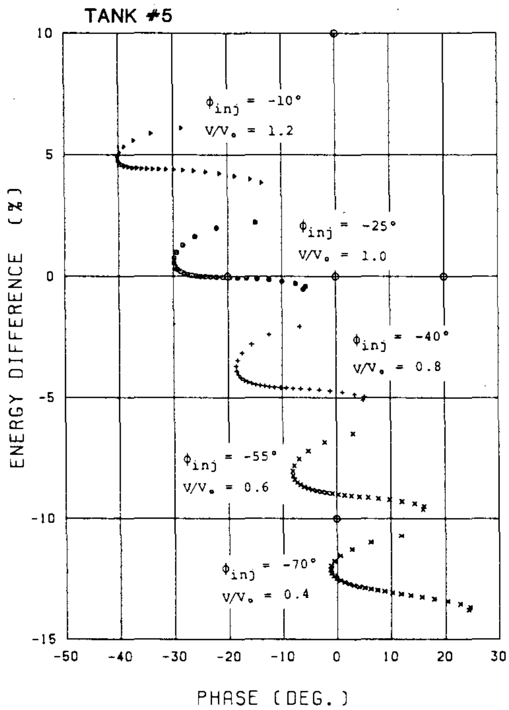

Fig. 4 The calculations of z-emittance at the exit of tank #5. The injection phase and $V_{\#5}$ are varied so that the z-emittance will have a constant shape.

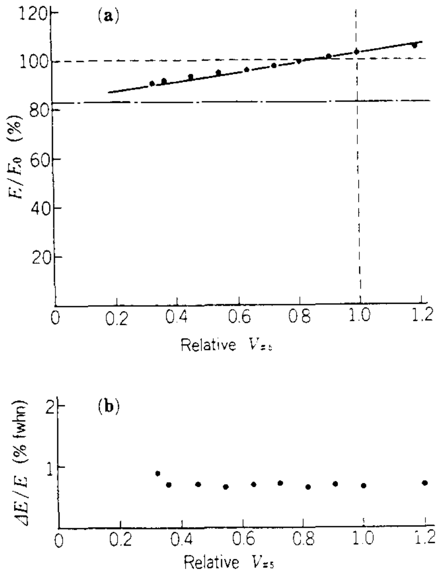

Fig. 5 The variations of energy (a) and energy resolution (b) for tank #5 with change of $V_{\#5}$ relative to normal value in the case of fig. 4. The solid circles in both figures are the experimental data and solid line is the calculations.

Effect of frequency change

As one of difficulties with use of variable frequency scheme for a drift-tube linac, we point out how to make a constant distribution of acceleration voltage along the beam line against the resonant frequency variation. Since the distribution depends on the frequency in general, it is serious problem for the variable-frequency linac.

After efforts were made to reduce the change of voltage profile against the frequency change in the model study, the non-uniformity in the distribution remains, as shown in fig. 6 for the case of the first cavity at f = 17 and 45 MHz. The accelerating voltage drops generally at both ends of resonator tank and this tendency becomes strong gradually as the frequency increases.

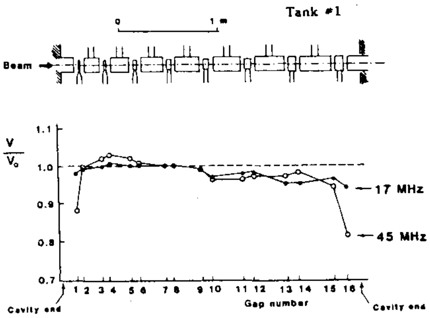

Fig. 6 The distribution of acceleration voltage in the first tank along the beam axis which was measured by parturbation method[2].

Since the cell length of drift tubes of RILAC was designed assuming the uniform voltage distribution over all the acceleration gaps in each resonator, the longitudinal phase motion of particles is affected especially at the higher frequencies and, as the result, the beam quality would be wrong at higher frequency. Especially in the first tank, where the phase oscillation is relatively large, these effects are important.

Fig. 7 shows the longitudinal acceptance of the first resonator tank calculated by using the voltage distribution at 45 MHz together with the design. The solid curves in the figure are contour lines of the relative energy difference of the ion at the exit of the first tank. The dashed curves are contour lines of corresponding phase when the ion reaches at the exit of first tank. The synchronism is not seen at the phase of -25 deg.. The small reductions of acceptable region for the normal injector level (0%) are seen.

When the corrections of injection level and acceleration voltage shown in fig. 8 are made, the z-emittance at the first tank can be nearly analogous to the design. The corresponding input and output phases of central particle in bunch are also shown in the figure.

Conclusion

We found that the shape of longitudinal emittance can be adjusted easily by tuning both voltage and phase of the final acceleration stage. So the energy tuning over a wide range is possible without degrading the beam quality. The compensation for the change of voltage profile against frequency is possible. Therefore the nearly constant beam quality could be obtained for any frequency in the variable frequency linac.

References
1) M. Odera et al.; in this proceedings.
2) Y. Chiba: IPCR Cyclo. Progr. Rep., 10 144 (1976).

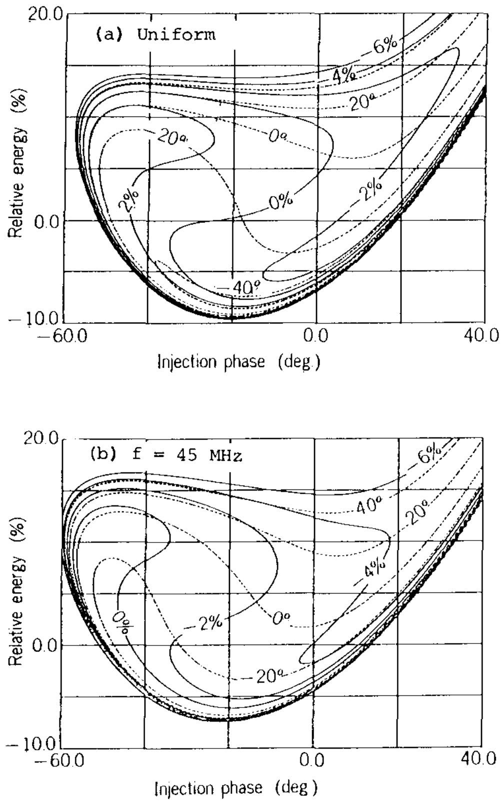

Fig. 7 Result of calculations of the energy and phase contour maps on the injection energy-phase space for the first tank. The acceleration-voltage distribution was assumed to be uniform in (a) and those at f = 45 MHz.

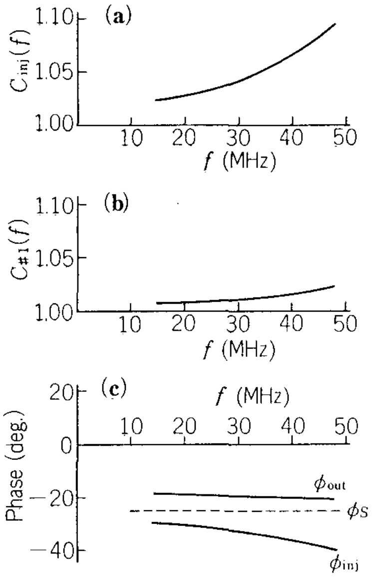

Fig. 8 Calculations of the correction factors for the injector voltage in (a), for the tank voltage in (b). They in themselves are proportional to f^2. The resultant injection and output phases of central ion in beam bunch are shown in (c).