AN RFQ LINAC FOR HEAVY ION ACCELERATION

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Summary

An rf characteristic has been studied on an RFQ model cavity with two kinds of vanes, straight and modulated. The measured resonant frequency is 296.0 MHz for the TE210 mode and well agrees with the calculated value 296.5 MHz by SUPERFISH for the straight vane. The measured one is 293.5 MHz for the modulated vane which has the same cross section as the straight vane at its quadrupole symmetry plane. The measured electric field in the acceleration bore agrees with the calculated one within the statistical error. A sufficient mode separation and uniform field distribution have been obtained with a single loop coupler which matches the cavity to the feeder line.

On the basis of the modelling study, a lithium ion test linac 'LITL' has been designed and is in course of construction. It is designed to accelerate heavy ions of 5 keV/u with charge to mass ratio, q/M of $1\sim1/7$ to the final energy of 138 keV/u in the vane length of 1.22 m. The operating frequency is 100 MHz and the rf power is fed with a single loop coupler. The maximum intervane voltage is 62 kV, which corresponds to 1.8 times the Kilpatrick's limit.

Introduction

The NUMATRON is a high energy heavy ion accelerator proprosed at INS.[1] It consists of injector linacs and two synchrotrons which accelerate heavy ions including uranium to $1\sim2$ GeV/u. The injector linacs are required to accelerate heavy ions from several keV to 10 MeV/u. An RFQ linac is preferable at the lowest energy stage of the injector owing to its buncher function and applicability to high intensity beams in a low β region.[2,3] On application of an RFQ linac to heavy ions the following subjects remain to be studied on the structure and rf power feed.

In order to get sufficient focusing force for particles with low charge to mass ratio q/M, it should be operated at a low frequency, for example, 25 MHz for U^{5+}. This frequency results in a cavity diameter of 2.5 m. Then the first problem is how to mount the vanes to such a large tank with a close tolerance and good electric contact. The second is how to tune the cavity to get the required resonant frequency and field distribution. The required rf power is inversely proportional to $(q/M)^2$ and the beam loading much differs with ion species. The rf power in a wide dynamic range should be fed to the cavity with a variable input impedance. A loop coupling is desirable because it needs no outer chamber and is flexible to the change of the input impedance. It is the third problem how to make a uniform field and get a sufficient mode separation with a single loop coupler.

To study these subjects, a modelling study has been done on a low power model. In parallel with the modelling study, a beam dynamics study has been done. On the basis of these works, a test linac has been designed and is in course of construction. In this paper the results of the modelling study and the design of the test linac are described.

Modelling Study

Model Cavity

The cavity was manufactured with close tolerance in order to study the effect of the mechanical errors on the field distribution. The vanes are attached to the tank in the ways of setting and electric contact which are applicable to an actual acceleration cavity, though the cavity dimension is much smaller than an actual one. The tank is 258 mm in inner diameter and made of aluminum alloy. The vane is 35 mm thick, 960 mm long and has gaps of 20 mm to the end walls, and is made of copper. The straight vanes were attached to the tank and then replaced by the modulated vanes. The modulated vane has a constant cell length of 30 mm and a characteristic radius of 14.3 mm. The modulation factor m is 2. The minimum aperture radius is 10 mm. The cell length and aperture are exaggerated for the convenience of the filed measurement in the bore. The vane tip is approximated to a circular arc. The straight vane has the same geometry as the modulated vane at the quadrupole symmetry plane. The vane tips were machined with an NC milling machine. The vanes are contacted to the tank with copper braids which have elastic cords inside. The final error of the vane setting is within 0.1 mm. Opposed to the vane ends eight end tuners are mounted on the end walls. The side wall has 36 holes for the rf coupling and field measurement.

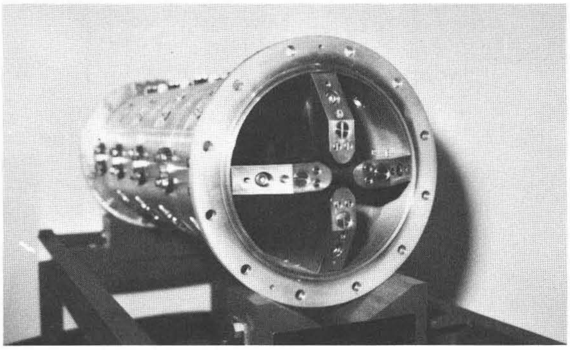

Fig.1. Model cavity with modulated vanes.

Field Distribution

The cavity has been tuned by means of the end tuners so that the magnetic field distribution might be uniform longitudinally and azimuthally in the four chambers. The field distribution has been measured by the perturbation method. Before the tuning the nonuniformity of the field amounted to ± 25 % in spite of the close tolerance. After the tuning nonuniformities within ± 2 % have been obtained for the both sets of the vanes.

The electric field distribution on the axis has been measured by using an aluminum perturbing ball 6 mm in diameter. The result agrees with the calculated one (Fig.2). The electric field distribution around the vane tips is similar to that of the magnetic field in the chambers. In the case of an acceleration cavity whose bore is so small as to make the field measurement difficult, the electric field in the bore will be estimated by means of the magnetic field measurement.

Mode Separation

Figure 3 shows the resonant frequencies for the various modes in the cavity with the straight vane, which is tuned so as to give a uniform field for the TE210 mode. The resonant frequency for the TE210 mode is 296.0 MHz and well agrees with the calculated value 296.5 MHz by SUPERFISH. The ones for the TE110 modes are 294.0 and 293.2 MHz, and considerably higher than the SUPERFISH value 285.7 MHz. For the modulated vane the resonant frequencies are 293.5 MHz for the TE210, 289.6 and 288.7 MHz for the TE110 modes. In the case of the TE110 modes, the magnetic flux is dominant in a pair of opposing chambers and faint in the other pair. TE110 mode has two resonant frequencies corresponding to the choice of the pair. When plates have been placed in the zero potential surfaces for the TE210 mode, the mode separation has been bigger two times with little effect on the field distribution around the vane ends.

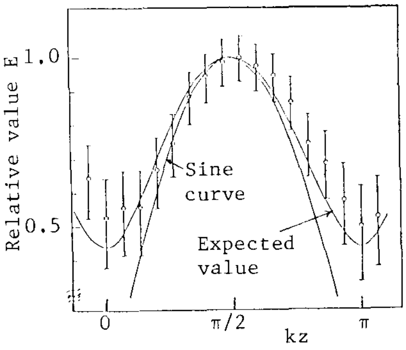

Fig.2. Electric field distribution on the axis.

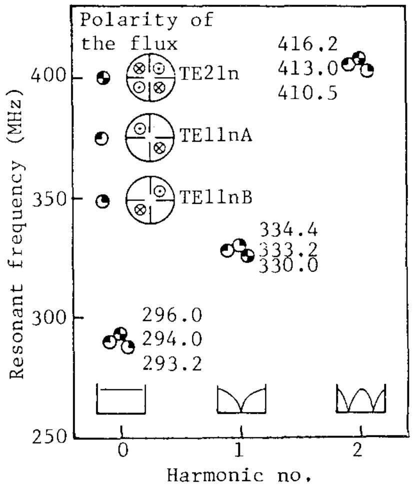

Fig.3. Resonant frequencies for various modes of the cavity with the straight vane.

The Q Value and rf Coupling

The loaded Q values have been obtained from the decay time constant of the stored energy in the cavity for various rotation angles of the input coupling loop. The pulsed rf power is fed to the cavity through a circulator and the reflected power from the cavity is dissipated in a 50 Ω resistor. The unloaded value Q_o has been obtained from the decay time constant with an infinitesimal coupling. For the straight vane, Q_o is 3400, which is 44 % of the calculated value. With an effective loop area of 23 cm^2 the loaded Q value is half of Q_o, and the cavity has been matched to the feeder line, which has been assured by the use of a network analyzer. This loop area agrees with a calculated value by an equivalent circuit analysis.4)

The magnetic field was stronger in the chamber with the loop and weaker in the opposing chamber, whereas a slight re-tuning has brought a uniform field with the strong coupling.

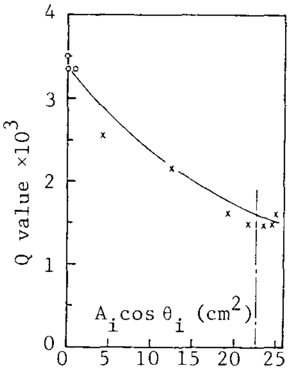

Fig.4. Loaded Q value vs. $A_i\cos\theta_i$.
A_i: Area of input coupling loop,
×; 25 cm^2,
○; 1 cm^2.
θ_i: Rotation angle.

An RFQ Lithium Ion Test Linac 'LITL'

Beam Dynamics Study

An RFQ test linac has been designed in order to study the following subjects: rf power feed to the cavity with beam loading, sparking limit, cavity cooling and comparison of the characteristics of the accelerated beam with the PARMTEQ results.

Considering the ion sources and related power supplies available at INS, the input beam parameters have been chosen as follows: $q/M = 1 \sim 1/7$ ($H^+ \sim N^{2+}$, Li^+), the injection voltage $V_i = 5$ keV/u, and the normalized emittance $\varepsilon_n = 0.5\,\pi$ mm·mrad. The maximum surface field strength of 20.5 kV/mm has been adopted, which corresponds to 1.8 times the Kilpatrick's criterion at the operating frequency of 100 MHz. Under these conditions the optimum vane parameters have been searched.

Details of the design procedure and the vane shape of the radial matching section are described in the separate papers.5,6) The PARMTEQ parameters and result of the beam dynamics simulation are shown in Figs.6,7. In 132 cells including 12 cells of the radial matching section, the particles are accelerated from 5 to 138 keV/u. The characteristic aperture radius has a constant value $r_o = 4.1$ mm except at the radial matching section. The modulation factor m is varied 1 to 2.2. The minimum aperture radius is 2.5 mm. The intervane voltage is 61.8 kV for $q/M = 1/7$. The transmission is 97 % for the injected dc beam with a normalized emittance $\varepsilon_n = 0.6\,\pi$ mm·mrad when the space charge effect is negligible. This value becomes 85 % for a 5 mA beam of q/M = 1/7.

Acceleration Cavity

The cavity cross section at the quadrupole symmetry plane has been determined with SUPERFISH so that the resonant frequency is 100 MHz for the TE210 mode. The geometry has a calculated resonant frequency of 97.6 MHz for the TE110 mode. The tank is 560 mm in inner diameter, 1.4 m long and made of copper plated mild steel. The vane has a length of 1223 mm and gaps of 5 mm to the end walls, and is made of OFHC. Each end space for the magnetic return path has an area nearly equal to one eighth of the cavity cross section. The central part of the both end walls are protruded to the vane ends to keep the narrow gaps. The tank and vane are electrically contacted with silver coated stainless steel tubes. The vane tip is approximated to a circular arc which has a radius equal to the radius of curvature of the theoretical shape at the vane top. With the vane shape, higher vane voltage is applicable due to the wider intervane distance and a practically quadrupole field is obtained in the acceleration bore. The cavity is evacuated with turbomolecular pumps, operated at a vacuum pressure below $1\cdot10^{-7}$ Torr. The tank and vanes have cooling passes which suppress the elongation of the vane length by temperature rise below 100 µm on cw operation at full power.

The rf power is supplied with a master oscillator and power amplifier system. A tetrode tube Eimac 4CW25000 supplies a cw rf power of 25 kW. The intervane voltage of 62 kV requires 14 kW with the calculated Q value of 18000. At that time the peak current on the cavity wall is 15.2 A/cm.

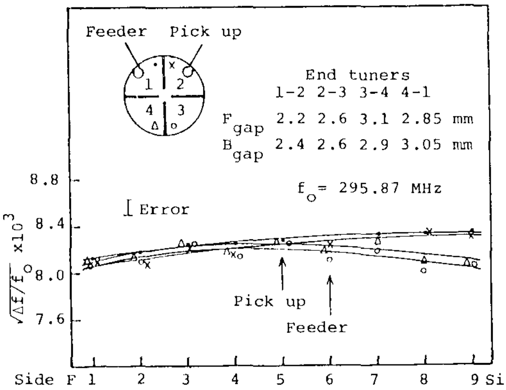

Fig.5. Magnetic field distribution in the cavity matched to the feeder line.

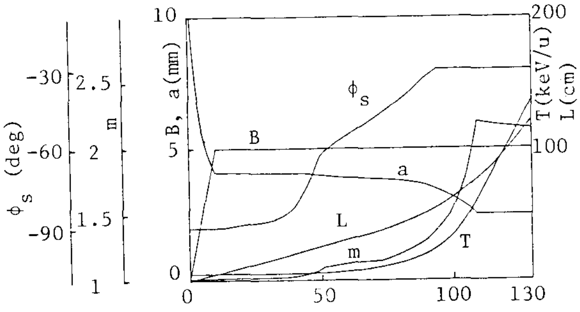

Fig.6. The PARMTEQ parameters for LITL.

Conclusion

The modelling study has shown that a sufficient mode separation and uniform field can be obtained with a single loop coupler. The beam dynamics study has given a vane design which has a satisfactory acceptance and an average acceleration rate of 0.8 MV/m over the full length. On the basis of these works, a test linac 'LITL' and an rf power system are now in course of construction. Measurements on the following subjects will be made and compared with the PARMTEQ results:(1) Dependences of the transmission on the vane voltage, the intensity, emittance and input energy of the input beam:(2) Emittance, energy spread and time structure of the output beam.

Acknowledgement

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6) S. Yamada, contributed to the Conference.

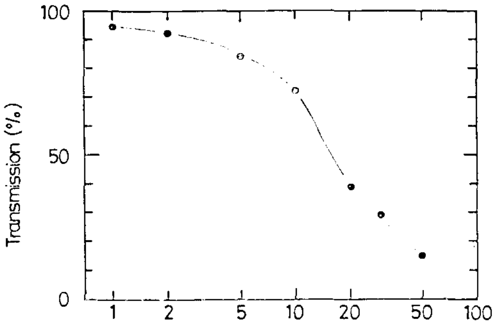

Fig.7. Transmission vs. input beam intensity(q/M=1/7).

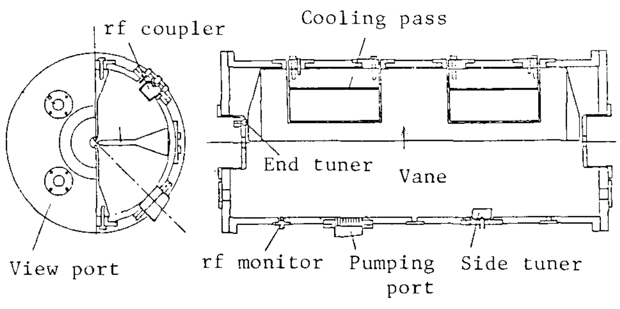

Fig.8. Cavity structure of LITL.