DEVELOPMENT OF RFQ LINACS FOR HEAVY IONS

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Summary

The RFQ test linac LITL accelerated successfully ions such as H^+, $^3He^+$ and $^7Li^+$ from 5 up to 138 keV/u. The machine is of four vane structure driven with a loop coupler at 99.6 MHz. The detailed acceleration characteristics are studied by using protons and helium ions. Transmission exceeding 90 percent was obtained for H^+ beam of 0.1 mA. Measured momentum, its spread and emittance of the output beam agree well with the PARMTEQ simulation.

A new long RFQ is being constructed. The machine is designed to accelerate ions with charge to mass ratio, q/A, of 1/7 from 8 up to 800 keV/u. The operating frequency is 100 MHz. The cavity is 7.3 m in length and 58 cm in diameter. It is made by connecting four sections, each of which has dimensions similar to the LITL's. The first beam test will be made early in 1985.

Introduction

After the successful acceleration of light particles of high intensity at low energy region, various types of RFQ linacs have been investigated for heavy ion acceleration in several laboratories.[1,2,3,4] In the INS, the RFQ test linac LITL of four vane structure was constructed and its performance is being studied by using ion beams such as H^+, $^3He^+$ and $^7Li^+$. Detailed description of the structure and beam test is given in another paper.[5] On the basis of the study, a new long RFQ 'TALL' was designed and now is under construction. In this paper the peformance study of the LITL is summarized and the design of the TALL is presented.

Performance Study of the LITL

Design Features

High accelerating rate. The design parameters of the LITL is given in table 1. The accelerating rate per charge is 760 kV/m. This is considerably higher than those of the Los Alamos machines. On the LITL design rapid bunching is accomplished in a section named prebuncher, where separatrix area is kept constant and the synchronous phase is increased to 60 degrees within a half period of the small longitudinal phase oscilation. This method is very effective for low intensity beams.[6]

Low injection voltage. A low injection voltage gives easy accessibility to the ion sources, low cost of the focusing elements and a short length of the buncher section of the RFQ. It gives, however, difficulties of extraction from ion sources and transportation of high intensity ion beam. On the LITL design it was chosen at 5 keV/u.

Radial matching section. A new formulation of the radial matching section was introduced.[7] It leads to a focusing strength increasing sinusoidally along the beam axis as $B(z)=B_0\sin(kz)$, where $k=\pi/2\ell$ and ℓ is the length of the section. With this formalism, the overlap between the input beam phase ellipse and the time dependent RFQ acceptance was calculated at higher than 90 percent. The length is set at $6\beta\lambda$, or 12 cells.

On the output side the vanes are truncated with no matching section at the plane where no axial component of the electric field exists.

Single loop driving. The cavity is driven with a loop coupler. On the model study it was found that satisfactory field uniformity and mode separation can be obtained with a single loop coupler in four vane cavities.[8] The loop coupling brings a much simpler cavity structure than that with manifold coupling. It will make much easy tuning of frequency and field distribution, cavity cooling and construction.

Beam Test

Test stand. A surface ionization type ion source was used for Li^+. A duoplasmatron type ion source was used to produce ion beams of gaseous elements. The duoplasmatron was replaced by a microwave ion source which is expected to produce an intense beam with a good emittance.[9] By using this source space charge effects on the low energy beam transport and acceleration in the RFQ will be studied.

With a bending magnet the extracted ions are mass analyzed and matched to the acceptance phase space of the RFQ by using einzel lenses and a triplet of electric Q lenses. The beam intensity and emittance are measured at 7 cm upstream and 26 cm downstream of the RFQ.

Transmission efficiency. The transmission exceeding 90 percent was obtained for proton beam of 0.1 mA. The measured dependence of transmission on vane voltage agrees well with the computer simulation. This shows the formulation of the radial matching section is good.

Momentum measurement. The momenta of the accelerated ions were measured with an analyzer magnet for various vane voltages. The average momenta and spreads agree well with the computer simulation. The spread is about 2 percent in full width for the normal vane voltage.

Output beam emittance. In Fig.1 are shown the measured and computer simulated emittance profiles of the output beam. The measured emittance agrees well with the computer simulation. This shows that the truncation of the vane ends at the output side with no matching section gives no significant effect.

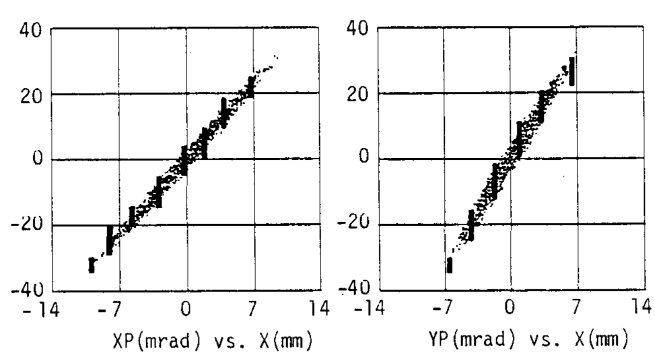

Fig.1. Output beam emittance for protons of 0.1 mA at 26 cm downstream of the RFQ. The dots are for computer simulated (ε_n = 0.6 π mm.mrad for x, y with 99 percent beam), and the bars are for the measured.

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Rf chracteristics study

Cold test. By using eight capacitive tuners on the end flanges, the field uniformity within ± 2 percent azimuthally and ± 3 percent longitudinally was obtained. The resonant frequency was measured at 99.6 MHz for the TE210 mode, though the frequency for the cross section at the quadrupole symmetry plane was calculated at 100.0 MHz with SUPERFISH. The nearest mode was a TE110 with a resonant frequency 1.3 MHz higher. TE211 mode was found at 153.5 MHz.

High power test. In cw operation. a vane voltage of 62 kV which corresponds to 205 kV/cm. or 1.8 times of the Kilpatrick's criterion at 100 MHz was applied. The observed frequency shift due to temperature rising was. however. much bigger than estimated. This may be due to the closing of the gaps between the end flanges and vane ends. Cooling method and compensation system for the frequency shift should be improved.

The results of rf characteristics study and beam test show that a satisfactory field distribution was obtained with the single loop coupler.

Construction of the Long RFQ Linac

General. The long RFQ linac 'TALL' will be worked at a lowest energy part of an injector for a heavy ion synchrotron proposed at INS. In table I the design parameters are given. The operating frequency is 100 MHz. The minimum q/A is chosen at 1/7. With appropriate ion sources it can accelerate heavy ions with medium mass number such as $^{40}Ar^{6+}$ and $^{84}Kr^{12+}$ up to 800 keV/u. At this energy the $\beta\lambda$ is 12 cm at 100 MHz and it gives an enough drift tube length for a following linac.

It was suggested that the beam loss in the LITL injection line is not negligible on a certain assumption of the charge distribution and aberration of the einzel lenses.[10] The injection energy of the TALL is chosen at 8 keV/u. The space charge limited current in the injection line will be increased by two times compared to the LITL.

The radial matching section has 40 cells instead of 12 cells on the LITL. The envelope angle of the input beam is decreased to 43 mrad against 80 mrad on the LITL. The higher injection voltage and smaller envelope angle of the input beam at the entrance of the RFQ will make easy the low energy beam transport. On the output side no matching section is placed.

Cavity structure. The cavity has a diameter of 58 cm and a length of 7.3 m. The cavity is made by connecting four sections. each of which is 1.83 m long and has a cross sectional geometry similar to the LITL's. because it is difficult to manufacture vanes of this length in a piece (Fig. 4).

Each section has 16 (4x4) holes of 10 cm diameter on the side wall for evacuation, rf power feed and side tuning. The cavity is made of mild steel plated with 100 μm copper. The vane top is made of oxygen free copper and it is welded to the vane basement made of copper plated mild steel. The cavity is driven by loop coupling.

Field stabilization. With a cavity cross section of the quadrupole symmetry, the resonant frequencies of the TE210 and TE110 modes are calculated at 100.6 and 98.3 MHz, respectively. On our experience of four vane cavities, the dipole modes are expected to have sufficiently lower resonant frequencies than the quadrupole one with the cavity length of 2.4 times the wave length. The cavity has no 'vane coupling ring'. Each quadrant has 12 side tuners which are used field stabilization and frequency tuning against thermal elongation. On the end walls eight capacitve tuners are attached.

Vane alignment. By a computer simulation the beam loss due to the errors of alignment of the beam axis at the joints is estimated. With the errors of 0.1 mm each at the three joints, significant decrease was not found (Fig. 2). The design tolerance of the alignment of the beam axis at the joints is chosen at 0.1 mm.

Longitudinal joint of four vane cavities. Some spacing at the longitudinal vane joints is desirable to tolerate machining errors of the vanes and unequal thermal elongation. The sections are connected with spacings of 0.2 mm and no rf contactor between the vanes. Effects of the spacing on the field distribution and Q value were studied on a four vane model cavity that was made by separating the cold model II.[6] With zero spacing the end tuners were set to give a uniform field distribution, azimuthally and longitudinally. Then with the end tuning fixed and rf contact between the outer conductors kept, the spacing between tha vanes was varied. As for TE210 like mode, spacings of 0.2 to 2 mm gave no significant effect on the distribution and Q value.

Rf contact. The vanes are mounted to the tank in the same way as the LITL. The rf contact between vanes and tank is made with stainless steel tubes of 3.2 mm diameter and 0.35 mm thick which is silver plated in a thickness of 50 μm. With a test resonator of coaxial structure, Q values were measured versus contact force at 100 MHz for several contactor materials.[11] The tube made for vacuum seal gave a satisfactory Q value with a contact force 20 percent of that required for vacuum seal (Fig.3). The contactor is designed to be used in a strain range between 0.1 and 0.5 mm.

TABLE I. Design parameters of the LITL and TALL

	LITL	TALL
Ions (q/A)	1 - 1/7	
Operating frequency (MHz)	100	
Input energy (keV/u)	5	8
Output energy (keV/u)	138	800
Total number of cells	132	300
Cell number of radial matching section	12	40
Vane length (cm)	122	725
Characteristic bore radius. r_0 (cm)	0.41	0.54
Minimum bore radius, a (cm)	0.25	0.29
Margin of bore radius. a/a_{beam}	1.10	1.15
Maximum modulation. m_{max}	2.1	2.5
Focusing strength, B_0	5.0	3.8
Maximum defocusing strength, Δ_b	-0.110	-0.075
Synchronous phase, ϕ_s (deg)	-30	
Intervane voltage for q/A = 1/7 (kV)	62	81
Maximum field (kV/cm)	205 (1.8 Kilpat.)	
Rf power wall loss for q/A = 1/7 (kW)	22 (exp.)	180
Transmission for input beam with 0 mA	0.94	0.94
a normalized emittance of 2 mA	0.92	0.91
0.6π mm.mrad for q/A = 1/7 10 mA	0.64	0.63

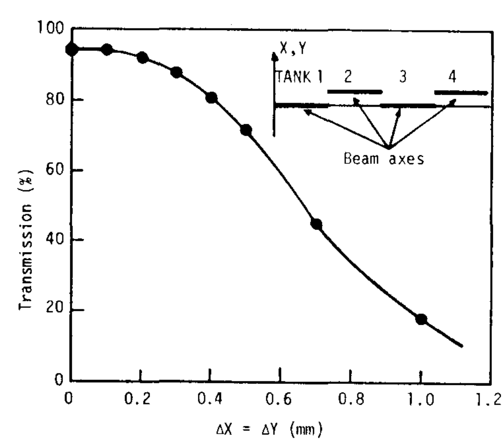

Fig.2. Computer simulated transmission vs. errors of the beam axes at the vane joints.

Cooling. High duty operation is required by some nuclear chemists and physicists who plan to use low energy beams, though TALL is constructed as a part of an injector for the heavy ion synchrotron. The cavity cooling is designed for rf power dissipation of duty ratio higher than 25 percent at full vane volatge. In Fig. 4 is shown a calculated temperature distribution for a homogeneous wall loss of 1 W/cm^2, 100 percent duty. The power dissipation corresponds to 1.3 times of continuous operation at the vane volatge for q/A = 1/7.

The first beam test of the TALL will be done early in 1985.

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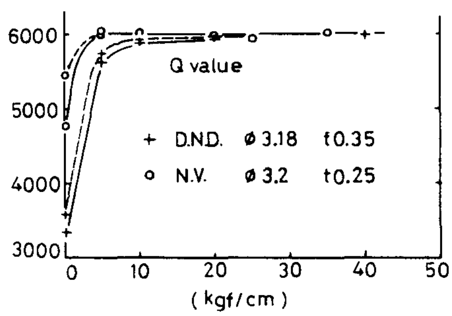
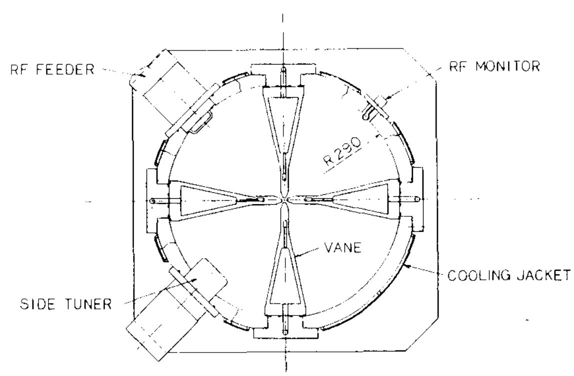


Fig.3. Q value vs. contact force with metal O-rings made of silver plated stainless tube. The ideal Q value was calculated at 6800 with SUPERFISH. D.N.D. and N.V. are abbreviated names of the makers. The recomended contact forces for vacuum seal are 110 and 55 kgf/cm for 0.35 (D.N.D.) and 0.25 (N.V.) mm thick, respectively. The dashed curves show one on the second run with the same contactors.



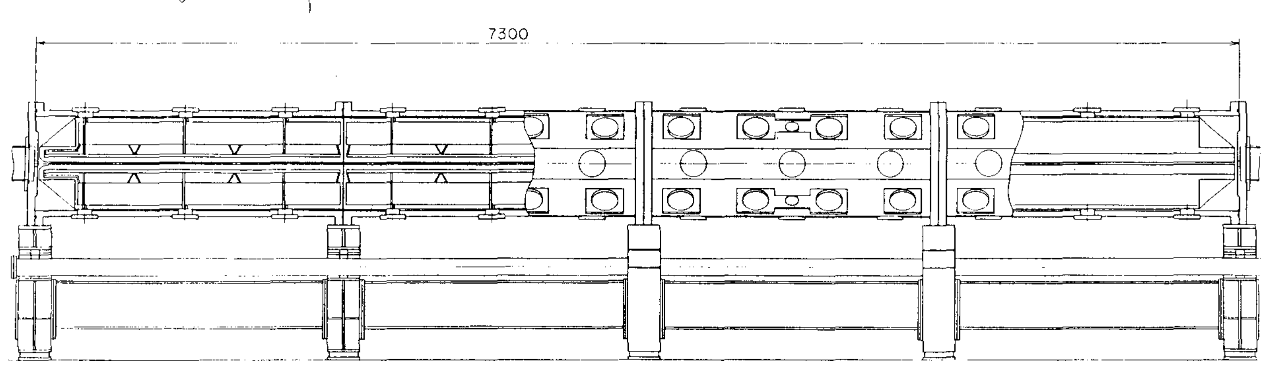


Fig.5. Schematic drawing of the TALL.

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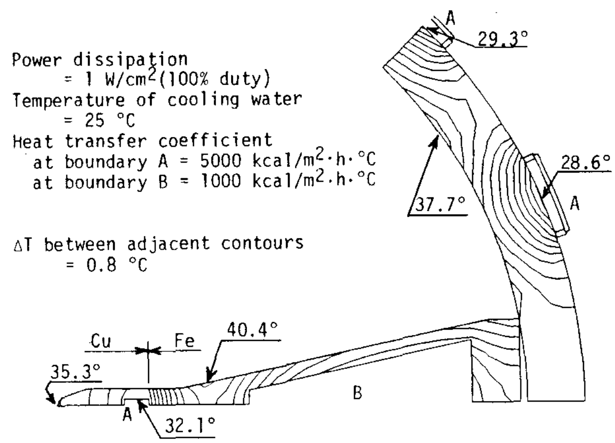

Fig.4. Calculated temperature distribution of the TALL.