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CONSTRUCTION, FIELD TUNING AND BEAM TEST OF THE RFQ LINAC 'TALL'

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Summary

An RFQ linac 'TALL' is designed to accelerate heavy ions with charge to mass ratio of 1 ~ 1/7. The acceleration cavity is of four vane structure driven with a loop coupler. The cavity is 58 cm in diameter and 730 cm in length. The rf electric field was tuned to have a uniformity within an error of ± 1.5% azimuthally and ± 5% longitudinally by using two dozen side inductive tuners. The TE210 mode was tuned at 101.5 MHz, 0.9 MHz lower than that of the closest mode TE111. Beam test was done by using proton beam. Transmission was 80% at the normal vane voltage and exceeded 90% at 1.1 times the voltage. When the injection energy had errors of + and - 5%, the transmission decreased to 70% and 50%, respectively, at the normal voltage, but it exceeded 90% at 1.5 times the voltage. When the focusing field had an excitation error of ± 7%, the transmission decreased to 65%, but it also exceeded 90% at 1.5 times the volatge. Energy and its spread of the output beam were measured to be T = 824 keV and $\Delta T/T$ = 1.6% in FWHM.

Introduction

The RFQ linac TALL was constructed as the first stage of an injector linac system for a heavy ion synchrotron 'TARN II' which is under construction at INS.[1] An RFQ linac is best for the stage because it can accept low velocity beam and has bunching function. The machine is designed on the basis of the experience of the test RFQ linac LITL.[2] The parameters of the TALL are given in Table 1. The machine can accept ions with charge to mass ratio of 1 ~ 1/7. By using an ECR ion source it can accelerate heavy ions up to Xe and W.[3] Injected ions at 8 keV/u are accelerated up to 800 keV/u. For 100 MHz, the $\beta\lambda$ at the output energy is 12.4 cm and long enough to be accepted by the following drift tube linac.

Acceleration Cavity

Structure

The acceleration cavity is of four vane structure driven with a loop coupler. The cavity is 58 cm in diameter and 730 cm in length. The cavity is longitudinally separated into four sections, each of which is 1.8 m long.

Each section is assembled and aligned independently. The vane is mounted in a cavity cylinder with three base plugs. The cylinder is made of mild steel, copper plated to a thickness of 100 μm. Each section has 16 holes of 10 cm in diameter for side tuners, pumping ports and rf power feed. It also has one monitor loop in each quadrant.

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The four cylinders are jointed with rf contactors of silver coated metal O-rings. The vanes have narrow gaps of 0.2 mm to tolerate machining errors and unequal thermal elongation at the longitudinal joints. They are contacted with copper rods at the joints. The surface field around the joints will not be stronger than other places, because the edges are rounded and the vanes are separated at the modulation tops or bottoms where the surface field is weakest.

Vanes

Two sets of vanes were prepared for the TALL. One is for low power operation. It is made of aluminum and has no cooling channel. The other is made of oxygen free copper and has cooling channels for high power operation. The field tuning and beam test with the aluminum vanes were already presented.[4] On the basis of experience with the aluminum vanes, the end shape of the vanes was improved and the copper contacting rods at the longitudinal joints were added. The vanes and cylinders are electrically contacted with stainless steel tubes, silver coated to a thickness of 50 μm.

The transverse geometry of the vane tip is approximated by a circular arc similar to the LITL. The modulation was machined with a numerically controlled milling machine by using a ball end mill of 30 mm dia. in most of the vane length. Mills of 12 and 20 mm dia. were used on the first section where the cell length is short and the modulation factor increases steeply. The modulation machining was checked to be within a tolerance of ± 30 μm by an inspection machine.

Alignment

The cylinder has square flanges on both the ends. The vertical and horizontal rims of the flanges are the fiducial planes for the alignment. Both the vane ends have fiducial holes near the vane tip. They were used to measure the radial positions of the vane tips. The side flats of the vanes near the tip and base were used as the azimuthal fiducial planes. The accuracy of the vane positioning was checked with an inspection machine.

Table 1. Parameters of the TALL.

Ions (q/A)	1 ~ 1/7
Operating frequency (MHz)	101.5
Input energy (keV/u)	8.24
Output energy (keV/u)	824
Total number of cells	300
Vane length (cm)	725
Cavity diameter (cm)	58
Characteristic bore radius, r_o (cm)	0.54
Minimum bore radius, a_{min} (cm)	0.29
Maximum modulation, m_{max}	2.5
Focusing strength, B_o	3.8
Maximum defocusing strength, Δ_{rf}	- 0.075
Synchronous phase, ϕ_s(deg)	- 30
Intervane voltage for q/A = 1/7 (kV)	81
Maximum field (kV/cm)	205 (1.8 Kilpat.)
Rf power wall loss for q/A = 1 (kW)	4.5

The vanes were assembled first with no rf contactor and no vacuum seal. After the vanes were aligned within an error of ± 50 μm , the positions of the vanes, base plugs and cylinders were fixed with locator pins. Then the cavity was disassembled and cleaned up. Guided with the locator pins, the vanes were assembled with rf contactors and vacuum seals. Again the vane position was measured with the inspection machine and re-aligned. The final error of the vane alignment was within ± 30 μm.

The four section was jointed on a bed. The bed has five support flats. They were leveled within an error of ± 20 μm. The square flanges were jointed so that there remained no clearance between the horizontal fiducial planes and the flats, and so that the vertical fiducial planes were in a plane.

The beam axis was aligned within an error of 200 μm over the length of 7.3 m. The steps between the longitudinally adjacent vanes are within 100 μm at the joints. A computer simulation shows that alignment errors of the beam axis of 100 μm at the three joints do not decrease the transmission significantly.[5]

Field Tuning

Resonant frequencies of various modes were measured with the vane ends shorted to the both end plates. From the dispersion relations the cutoff frequencies were determined to be 97.6 and 101.1 MHz for the dipole and quadrupole modes, respectively. The calculated ones by SUPERFISH for the cross sectional geometry at the quadrupole symmetrical plane are 98.3 and 100.6 MHz, respectively.

The field distribution was tuned roughly by varying the shape of the end inductive tuners which are mounted on each vane end. Then fine tuning was done by using side inductive tuners, that is, aluminum cylindrical blocks of 10 cm in diameter and various thicknesses inserted through the side holes. The electric field distribution between the vane tips was measured with the perturbation method by using a table tennis ball. A field uniformity within a deviation of ± 1.5% azimuthally and ± 5% longitudinally was obtained, by using two dozen side tuners of fixed length(Fig.1A). No end capacitive tuners was used. The separation between the TE210 and the closest mode, TE111 is 0.93 MHz.

Each quadrant has 4, one for each section, movable side tuners. They are water cooled copper cylinder 10 cm in diameter driven with stepping motors by a stroke of 5 cm. They will compensate the resonant frequency shift due to thermal elongation. By inserting eight side tuners of a pair of the opposing quadrants by 3.8 cm the resonant frequency is increased by 145 kHz without destroying the field uniformity.

By driving the side tuners unsymmetrically, the distribution is deformed. Figure 1B shows the electric field distribution when four side tuners of the quadrant 1 are inserted by 3.8 cm from the normal position. The excitation error is ± 7% azimuthally.

Beam Test

Beam line

Ions extracted from a microwave ion source at 8.24 keV are transported to a magnet through two einzel lenses. Protons are separated from other ions with the magnet. They are focused into the RFQ entrance with a triplet of electric quadrupole lenses and an einzel lens.

The emittance and intensity of the input beam are measured at 21 cm upstream of the RFQ entrance, that is, in the drift space downstream of the final einzel lens. The accelerated ions are focused with a triplet of quadrupole magnets on an object point of an analyzer magnet. The intensity of the beam was measured at the object point. Ions transported by the rf focusing field without acceleration cannot reach the point, because the focusing force of the Q magnets is too strong for the ions. The emittance is measured at 16 cm downstream of the RFQ exit by turning off the Q magnets.

The dispersion of the analyzer magnet is 160 cm. Slits of variable width are placed at the object and image points of the magnet. The momentum is measured with a resolution of 0.1%.

Transmission

Transmission efficiency was measured for input proton beam of 10 μA and an emittance of about 130π mm.mrad (100% emittance). The space charge effect is negligible for the beam intensity. The beam dynamic design was made for particles in an emittance area of 145π mm.mrad.

Transmission was measured when the injection energy had the normal energy of 8.24 keV and errors of ± 5%. With the normal injection energy the transmission was 80% and a little smaller than the design value, 94% (Fig.3). This may be due to the unstability of the vane voltage and to a slight mismatch of the input beam emittance with the design one. It exceeded 90% when 1.1 times voltage was applied. With + 5% and - 5% error of the injection energy, the transmission was 70% and 50% respectively. In both cases it exceeded 90% with 1.5 times the normal voltage.

Transmission was measured for the field with excitation errors which was introduced by inserting the side tuners unsymmetrically. With the excitation error of ± 7%, the transmission was 65% but exceeded 90% when 1.5 times the design voltage was applied (Fig.4).

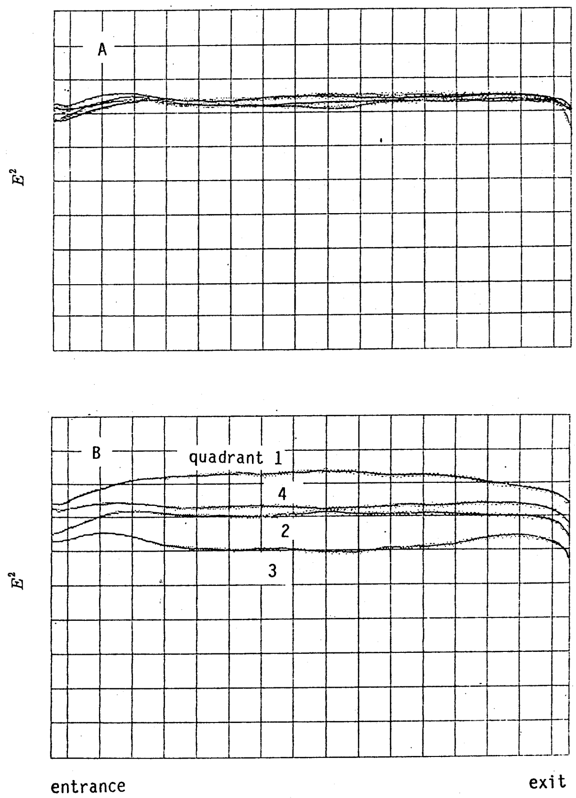

Fig.1. Electric field distribution between the vane tips. Ordinate: Square of the electric field strength (arbitrary scale). Abscissa: Position of a dielectric perturbator. A: Best tuned field distribuiton. B: Distribution deformed by inserting the four side tuners of the quadrant 1 by 3.8 cm from the normal position.

Quality of the output beam

The energy was measured to be 824 keV. Considering that the frequency is tuned at 101.5 MHz, the measured energy dose not cotradict with the design value 800 keV at 100 MHz. The energy spread was measured to be $\Delta T/T = 1.6\%$ in FWHM. It agrees with a computer simulation by PARMTEQ.

The measured emittance of the output beam was about 15π mm.mrad (100% emittance). It did not varied significantly when the vane voltage was varied and the field was deformed.

Rf characteristics

The beam test was done in pulse operation. The duty factor was 25% (2.5 ms duration/ 10 ms repetition period). The proton acceleration required rf power of 4.5 kW (peak). The unloaded quality factor Q_o was measured to be 10200. It is about 60% of a caluculated value for the copper vanes. With the loop coupler the cavity was stably operated up to the full power of 32 kW of a power supply now available. Multipactoring was observed in three zones below the proton acceleration rf level. On the first power test they were easily surmounted after a few hour outgassing.

The cavity is pumped with two turbo-molecular pumps of 500 l/s. The vacuum pressure was $6\cdot10^{-6}$ Torr with no rf power at the farthest point from the pumps. It increased to $2\cdot10^{-5}$ Torr when an average rf power of 8 kw was fed into the cavity.

Conclusion

The field distribution was tuned to have a uniformity within an error of ± 1.5% azimuthally and ± 5% longitudinally. The TE210 mode was tuned at 101.5 MHz with a sufficient separation of 0.9 MHz to the closest mode TE111. The cavity was driven stably with the single loop coupler. Transmission exceeding 90% was obtained. The output beam quality is satisfactory.

High power test will be made to know the sparking limit in the next spring.

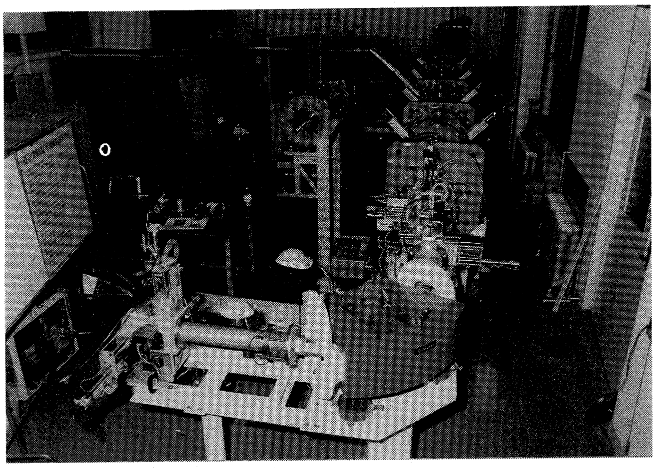

Fig.2. View of the TALL and output beam line.

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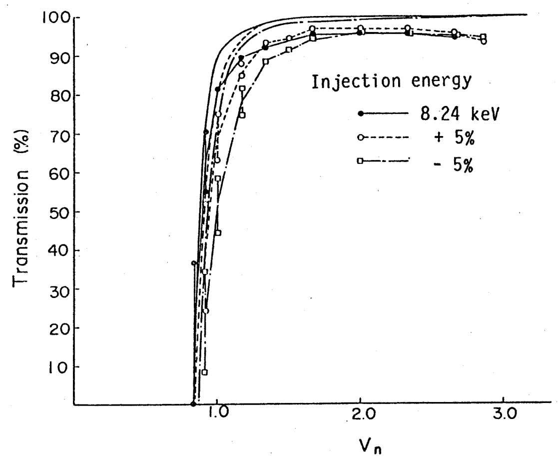

Fig.3. Transmission for beams injected with the normal energy of 8.24 keV and errors of +5% and -5% energies. The curves are simulated ones with PARMTEQ. Vn is the vane voltage normalized by the design voltage for protons.

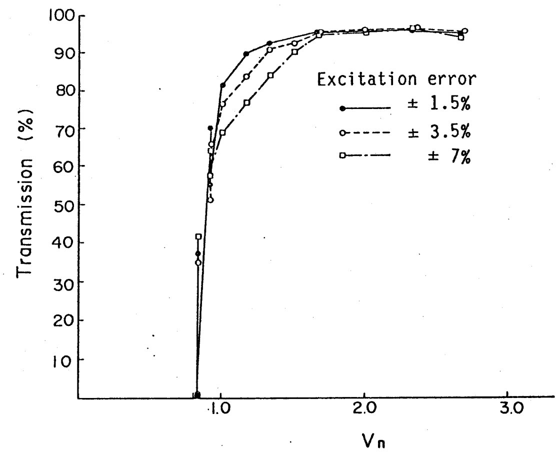

Fig.4. Transmission for the deformed field.