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RFQ LINAC FOR THE NUMATRON PROJECT

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Summary

An radio-frequency quadrupole (RFQ) linac is under development at INS, aiming at a preaccelerator in the NUMATRON. The research is performed with model cavities for experimental study, as well as computer codes for calculation of field generated in a cavity and beam dynamics. This paper describes the present status of the research.

Introduction

The most serious problem in extending a performance of low velocity is to keep the compatibility bewteen longitudinal and transversal stability, that is to obtain a sufficiently strong focusing force. In a standard drift-tube linac a beam is focused magnetically and the force depends on velocity. Kapchinskii and Teplyakov proposed an RFQ linac, of which the principle is acceleration and focusing of a beam with electric field generated by four modulated vanes installed in an rf cavity.[1] A proto-type RFQ, the Proof-of-Principle (POP) structure, was constructed at the Los Alamos Scientific Laboratory (LASL), and operational feasibility was successfully demonstrated. The POP operates at 425 MHz and accelerates a proton beam from 100 to 640 keV through 165 cells, or a 111 cm vane length.

An RFQ has several advantages for a low velocity beam: (1) As the focusing of a beam is performed in an rf electric field, it is possible to produce a strong focusing force in a low-beta region where a conventional drift-tube linac with quadrupole magnets cannot work. Furthermore a high current beam is acceptable, because the strong focusing force overcomes a repulsive space charge force. (2) A dc beam is captured and bunched with high efficiency by increasing the acceleration phase adiabatically from -90°. With an optimum design a capture efficiency nearly 100 % could be attained. (3) The structure of the linac itself as well as the overall operation system are more simple and compact than an ordinary linac.

Owing to these merits an RFQ is promising in various science fields. A Cockcroft-Walton generator as a preaccelerator for a high energy proton synchroton should be replaced by an RFQ, because of its capability of a dc beam and compactness. In a heavy ion accelerator it will accelerate an ion beam of a small charge to mass ratio to velocity high enough for a standard linac. Also in scientific fields other than particle and nuclear physics, an RFQ will be employed due to its compactness and operational feasibility. For the study of fusion engineering an intense beam is indispensable. For instance, in the design of fusion reactor it is necessary to investigate the neutron radiation damage of the first wall in the reactor, which can be performed with an intense deuteron beam. Furthermore in inertial fusion with a heavy ion beam, e.g. Xe^{1+} or U^{1+}, it is impossible, at the present stage of accelerator technology, to design a driver system without a preaccelerator of an RFQ.

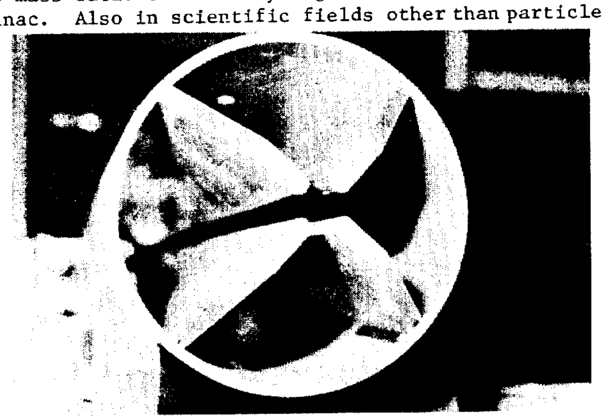

Fig. 1 Cold model I.

On the other hand, at INS we have a project to construct an accelerator complex named NUMATRON, which provides ion beams from α to uranium of up to 1 GeV/u, and designed a linac system consisting of three Wideröe linacs and two Alvarez ones.[2] We have already performed experimental study with a scaled model cavity of a Wideröe linac,[3] and are investigating other linac for low-beta region, e.g. an RFQ and an interdigital H structure.[4] We consider that a linac complex with an RFQ located between a Cockcroft-Walton generator and a drift-tube linac, Wideröe or IH, is promising.

The development of an RFQ is now in progress with following subject:

(1) Experimental Study with Model Cavities. Characteristics of an four-vane cavity, i.e. field distribution, resonance frequency, excitation mode, and feed of rf power, are investigated.

(2) Calculation of the Field with SUPERFISH. The computer code is modified to apply to an RFQ cavity.

(3) Design Study of Beam Dynamics. A computer program is coded to grasp the behaviors of the beam and to search an optimum set of parameters of the linac.

(4) Construction of an Acceleration Model. An ion beam of a charge to mass ratio not less than 1/7 is to be accelerated. The construction will be completed in 1981, and technical problems on the RFQ of the NUMATRON will be solved.

Cold Model I

A four-vane cavity has been manufactured to grasp basic characteristics of the cavity. It is made of alminum, 1 m long and 19 cm in inner diameter. The vanes without modulation are installed in the cavity as shown in Fig. 1. The radii of the pole tip and the aperture are 5

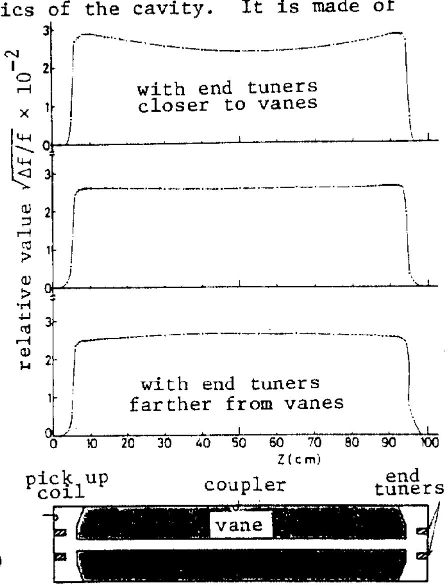

Fig. 2. Longitudinal field distribution. It collapses with end tuners closer to vanes (top), and swells with those farther from them (bottom)

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mm and 10 mm, respectively.

Four end tuners are mounted to each of the end walls. To excite the TE201 mode the phase must advance by $\pi/2$ between the side wall and the vane tip. The end tuners regulate the phase advance by changing the capacitance between the end of vane and the end wall. According to an equivalent circuit analysis of the cavity, the longitudinal field distribution swells with a phase advance smaller than $\pi/2$, and collapses with that larger than $\pi/2$. Figure 2 shows the longitudinal field distributions along the central axis measured by a perturbing ball method. The effect of end tuners agrees with the equivalent circuit analysis. The relative magnetic field in the four chambers were also measured by comparing the frequency perturbation by a brass rod through holes on the side of the cylindrical cavity.

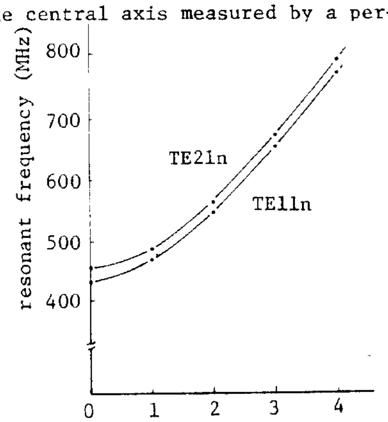

Fig. 3. Mode spectra of TE21n and TE11n modes.

Mode spectra of the Te11n (dipole) and the TE21n (quadrupole) families are measured for the structure. The dispersion curves are shown in Fig. 3. The measured resonant frequency for the TE210 mode is 452.8 MHz, while a predicted one by SUPERFISH is 453.9 MHz.

Cold Model II and Hot Model

Another model with modulated vanes, cold model II (Fig. 4) is under construction to study the feasibility of rf power feeding with loop coupling and the effect of the machining and alignment errors on the field distribution. Loop coupling is preferable to iris coupling, because the outer chamber for iris coupling will be bery big for a 25 MHz cavity planned on the NUMATRON injector. The tank is an aluminum cylinder of 258 mm in inner diameter and 1000 mm in length. The vane, of constant modulation and cell length, is an exaggerated one for convenience of field distribution measurement. Its minimum uperture is 20 mm in diameter, the unit cell length is 30 mm and the modulation parameter is 2. The operating frequency is 300 MHz according to SUPERFISH.


Fig. 4. Cold Model II nearing completion. Vanes with exaggerated modulation are attached.

A hot model is designed to solve practical problems on construction of an actual accelerator; such as rf power feeding, installation and rf contact of the vane to the tank, frequency and field distribution tuning, cooling, vacuum and so on. A 100 MHz and 25 kW rf system is under preparation for this model. It is also planned to investigate the limit of hich voltage applicable to the vanes.

Application of SUPERFISH to an RFQ

The computer code SUPERFISH, for an axisymmetric field, is modified for an RFQ cavity.

Figure 5 shows the field distribution at the cross section having quadrupole symmetry. An ideal quadrupole electric field is obtained in the useful aperture by approximating the vane top to a circle, and higher rf voltage is applicable than a hyperbolic vane.

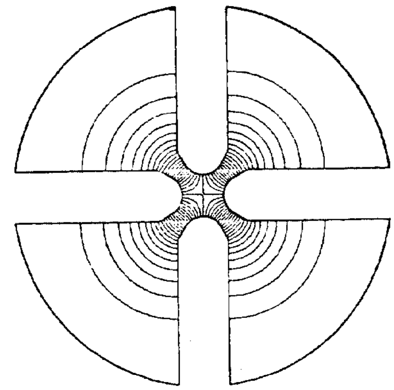
Fig. 5. Field distribution at the cross section of quadrupole symmetry.

Figure 6 shows that the resonant frequency is inversely proportional to the cavity radius. This means that the capacitance is concentrated near the vane tips and the inductance si proportional to the cross section area. Assuming $L = \mu_0 A/\ell$, we can calculate a capacitance from a resonant frequency using a relation $2\pi f = 1/\sqrt{LC}$, where A and ℓ is the cross section area and the length of the cavity, respectively, and μ_0 is the permiability of vacuum.

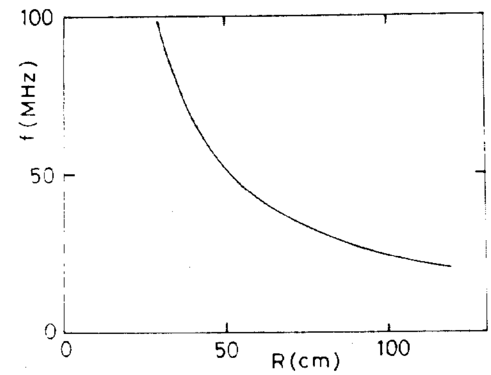

Fig. 6 Dependence of resonant frequency on the radius of the cavity.

Resonance frequencies have been computed for various values of r_0 with a fixed cavity radius, where r_0 is the radius of the inscribed circle to the vane tips at a quadrupole symmetric cross section. Figure 7 shows the result, where calculated capacitance from the resonant frequency is also shown.

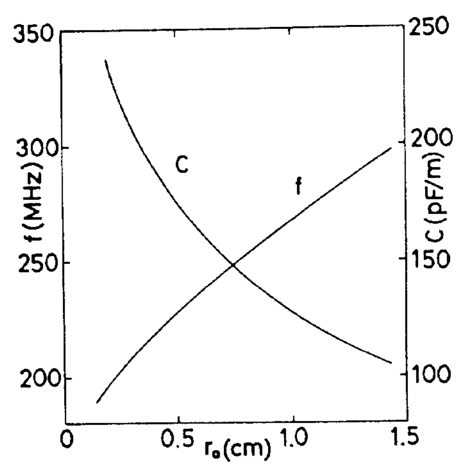

Fig. 7 Dependence of resonant frequency on r_0. The curve of capacitance is derived from the frequency.

Figure 8 shows the capacitances for non-symmetric vane tip curvatures corresponding to various sections along the axis. The capacitance is maximum at the symmetric cross section and decreases as going awam from the quadrupole symmetry point

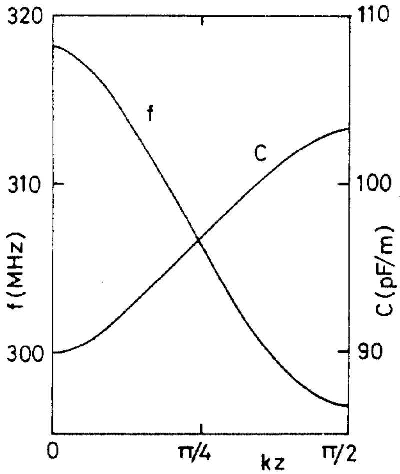

Fig. 8. Variation of resonant frequency on the radius of the cavity.

Design Study of Beam Dynamics

A computer program for design study of beam dynamics is coded based on the formalism given by the LASL group.[5]

The Acceleration Model

We have searched parameters of the model toaccelerate an ion beam of a charge to mass ratio of 1/7, for instance N^+. The injection voltage is 35 kV, and the input energy is 5 keV/u. The rf frequency is chosen at 100 MHz. The intervane voltage is 45 kV, and the maximum surface gradient of the electric field is 204 kV/cm, 1.8 times larger than the Kilpatrick's limit.[6] Variations of the synchronous phase and the vane modulation through cells are shown in Fig. 9. An output

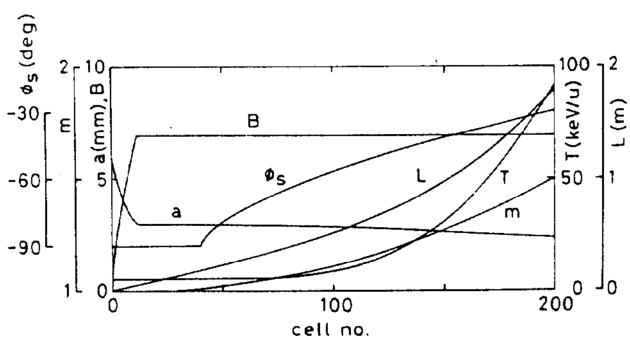

Fig. 9. Parameters of the acceleration model, acceptable of a N^+ beam.

energy of 91 keV/u is attained after 200 cells, or an overall length of 179 cm. The capture efficiency is 94 % for a dc beam with an emittance shown in Fig. 10. According to this emittance the normalized acceptance is 0.3 mm mrad. Without the radial matching section at the entrance of the linac, is reduces to 0.12 mm mrad with a capture efficiency of 80 %. Figure 11 shows profile of phase oscillation.

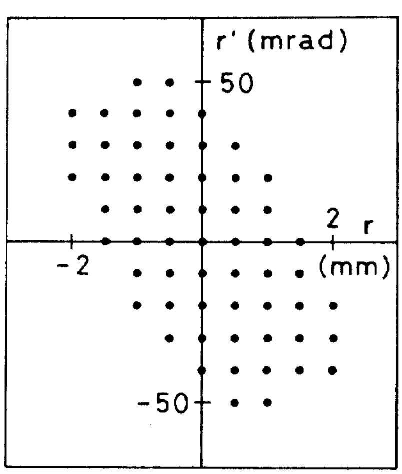

Fig. 10. Acceptance of the acceleration model.

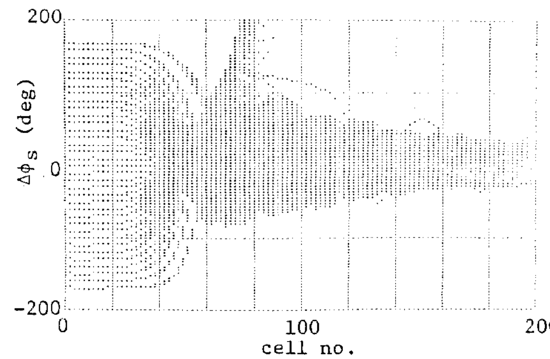

Fig. 11. Profile of phase oscillation.

The RFQ for the NUMATRON

The RFQ must be designed so that it accept a uranium beam, of which the acceleration is more difficult than that of any other ion. In the previous design of the NUMATRON[2] a U^{7+} beam extracted from a 500 kV Cockcroft-Walton generator is fed to a Wideröe linac. The present design is performed for a U^{5+} beam, because a higher intensity than a U^{7+} beam is expected. In addition a high capture efficiency is attained with an RFQ and the beam intensity will be enhanced by several times or more. The capability of the RFQ for a low velocity beam makes it possible to decrease the terminal voltage of the Cockcroft-Walton generator to 250 kV, which lighten technical difficulties on the generator.

The RFQ is designed preliminarily under above conditions. The rf frequency is 25 MHz, and intervane voltage of 68 kV is applied to vanes, twice higher than the Kilpatrick's limit.[5] Parameters are shown in Fig. 12. The beam of 5.3 keV/u at injection is accelerated to 31.4 keV/u after 516 cm long vanes. The normalized acceptance is 0.17 π mm·mrad to attain a capture efficiency of 76 %.

A better set of parameters are now searched to increase the acceptance and the capture efficiency.

Conclusive Remarks

According to the computer simulations, an ion of a charge to mass ratio around 1/7, is accelerated from several keV/u to about 100 keV/u through a compact RFQ of 2 m long. For a heavy ion beam, such as uranium, the advantage is that the RFQ can accelerate a beam of a low charge number, which is extracted from a ion source with a high intensity. In the extreme case, the linac is designed to accept a U^{1+} beam for heavy ion fusion.

To confirm the results of computational study, construction of a test RFQ linac acceptable of a N^{2+} beam is now in preparation.

Acknowledgement

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