LOW-BETA LINAC STRUCTURES*

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Summary

The magnetically focused, post-coupled, drift-tube linac is the standard linac structure. It offers efficient acceleration and adequate focusing over a remarkably large range of beta from $\beta = 0.04$ to $\beta = 0.50$. The term "low-beta linac structure" has come to mean those linac structures that out-perform the standard Alvarez structure in the region below $\beta = 0.04$, and the term "high-beta linac structure" has come to mean those linac structures that out-perform the standard Alvarez structure in the region above $\beta = 0.50$. A companion to this paper will be presented in this conference on the subject of high-beta linac structures.[1]

Low-beta linac structures are the bane of the existence of linac specialists. It is here that one must work hardest and achieve the least in the way of acceleration and focusing. The structures in this region are characterized by inadequate focusing, limited apertures, and poor transit-time factors. It is here that the beams are the most poorly bunched, have the largest angular divergence, are the most susceptible to space-charge effects, and are thought to be the most vulnerable to "emittance growth" driving terms. Everything that is bad in linacs is worse at the low-beta end. Nevertheless, every linac has one, and work is continuing to develop and improve these structures.

Introduction

The principal linac structures that are considered for this duty, in addition to the standard Alvarez linac, are: (1) the $2\beta\lambda$ Alvarez linac structure; (2) the π,π Wideroe linac structure; (3) the $\pi,3\pi$ Wideroe linac structure; (4) the Interdigital H-Mode structure; (5) the Parallel-Plate Transmission Line structure; (6) a variety of heavily loaded, low-frequency cavity structures with independent phasing and intercavity focusing; (7) the Alternating Phase Focused (APF) linac structure; and (8) the Radio-Frequency Quadrupole (RFQ) linac structure. The relative geometry of a number of these structures is shown in Fig. 1 from the particle's point of view.

The most serious problem at low beta is to keep the beam small compared to $\beta\lambda$. As always, focusing elements are needed to control the size of the beam. The vast majority of the efforts have been expended on magnetically-focused structures in spite of the fact that magnetic focusing is particularly ineffective at low beta because of the velocity term in the force equation. Electric focusing, on the other hand, has no such velocity term in the force equation and should be a prime candidate for the focusing role in low-beta linac structures.

Linac designers have, for a variety of practical reasons, chosen not to develop the electrostatically-focused linac structure in spite of its potential advantage at low beta. Perhaps in the renewed quest for low-beta linac structures for the heavy-ion fusion program, a fresh look will be taken at the practical problems of electrostatic focusing,[2] and some solutions will be found.

Two types of rf electric focusing are being studied at LASL. One is the APF linac structure[3], which was developed for the low-beta chore in PIGMI (Pion Generator for Medical Irradiations)[4] under the support of the National Cancer Institute. The other is the RFQ linac structure[5] which is being developed for the low-beta chore in the Fusion Materials Irradiation Test (FMIT) facility[6] under the support of the Department of Energy. An operating model of the APF structure exists, and progress is well underway towards a working model of the RFQ structure.

APF Linac Structure

The APF linac structure[7] is being developed for the acceleration and focusing role in the low-beta portion of PIGMI. In this structure, the transverse, as well as the longitudinal focusing forces are produced by the rf

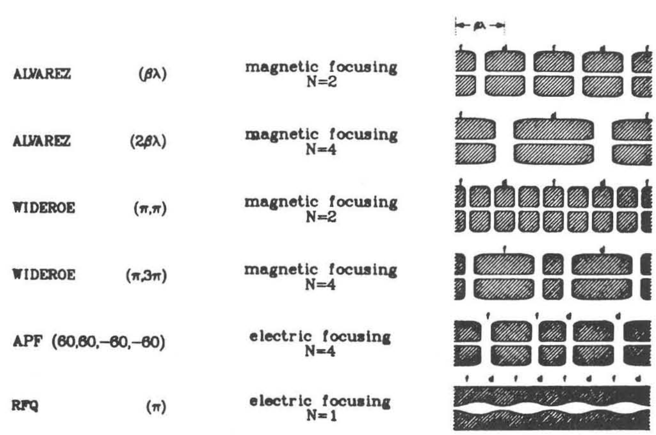

Fig. 1. Low-beta linac structures from the particles point of view.

*Work performed under the auspices of the U. S. Department of Energy and the National Cancer Institute.

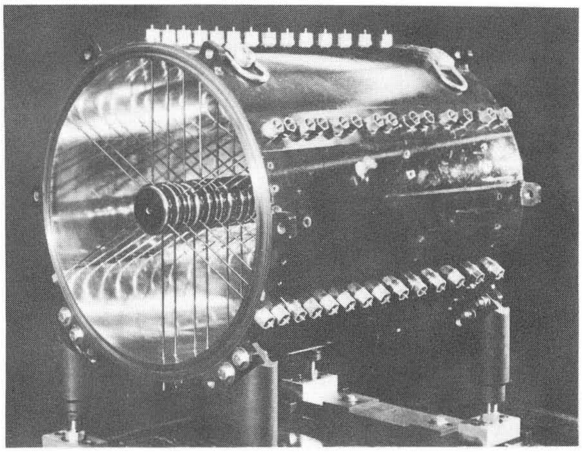

Fig. 2. The PIGMI prototype.

electric fields. By arranging the drift-tube lengths, and hence gap positions, in an appropriate way, in an essentially conventional standing-wave drift-tube linac, the particles can be made to experience acceleration and a succession of focusing and defocusing forces which result in satisfactory containment of the beam in six-dimensional phase space without dependence on additional focusing fields.

The APF portion of the PIGMI prototype[8] is shown Fig. 2. It is 63 cm long, 46 cm in diameter, and contains 28 drift tubes, none of which contain quadrupole lenses. The drift-tube bodies vary in length from a minimum of 0.690 cm to a maximum of 3.003 cm, and are 8 cm in diameter. The bore-hole radius increases from 0.402 cm in the first drift tube to 0.487 cm in the 28th drift tube. It is designed to operate at 450 MHz and to accelerate a proton beam from 250 keV to 1.011 MeV.

Preliminary tests of the performance of the APF linac structure were made in the following way. The APF section, which has no provisions for rf excitation, was bolted to another short linac section that does have such provisions. A special drift tube, containing an energy-discrimination foil (600 keV) followed by a Faraday cup, was installed between the structures to adjust the resonant frequency of the combination and to provide a minimal beam-diagnostics capability. The combined structure requires a total rf power of about 700 kW to reach the design excitation.

The combined structure was driven to a peak power of about 850 kW, corresponding to an average axial electric field approximately 10 per cent higher than the design value of 6 MV/m. The maximum surface fields were in the vicinity of 28 MV/m.

The 250-keV proton beam from the PIGMI injector[9] was used for the preliminary beam tests. The net current signals from a Faraday cup at the entrance to the linac, the energy-discrimination foil in the special drift tube,

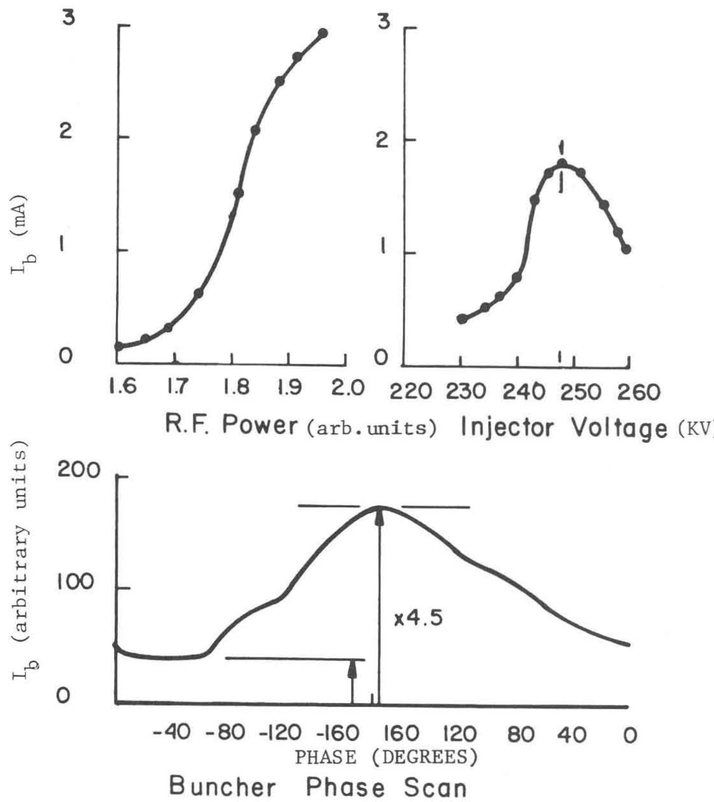

Fig. 3. The APF performance data.

and the Faraday cup in the special drift tube were monitored as a function of rf power, injector voltage, solenoid current, steering current, buncher excitation, buncher phase, and ion source parameters. Some of these data are presented in Fig. 3.

Protons entering the special drift tube with an energy less than 600 keV are absorbed in the foil and contribute to the signal from that element. Protons entering the special drift tube with an energy greater than 600 keV pass through the absorber and contribute to the signal from the Faraday cup within the drift tube. Stray electrons from the foil and Faraday cup are returned to their original element by a 1-kG magnetic field produced by a pair of permanent magnets. The signal from the Faraday cup is taken as a measure of the accelerated beam current.

The dependence of accelerated current, I_b, on rf power is shown in Fig. 3. The threshold for acceleration (1.75 in the arbitrary units given here) corresponds to an rf power of 750 kW, and the peak acceptance corresponds to an rf power of 850 kW. These data are in fair agreement with our expectations.

At the optimum excitation, the percentage capture of a well-collimated beam is 15.7% or ± 28 degrees of phase. This is in good agreement with the expected performance.

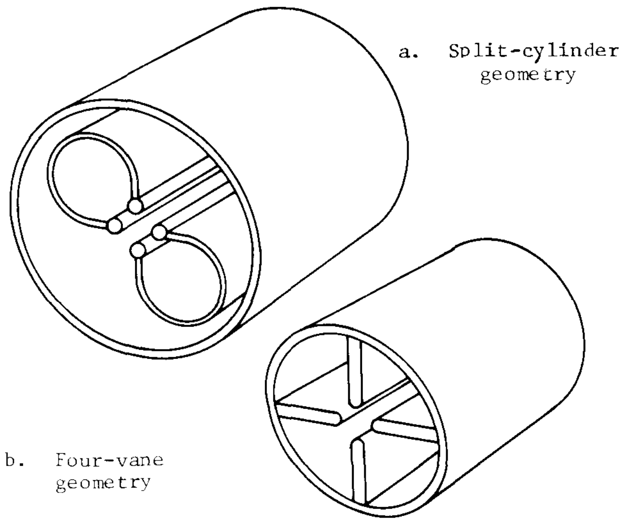

Fig. 4. Two basic configurations of the RFQ.

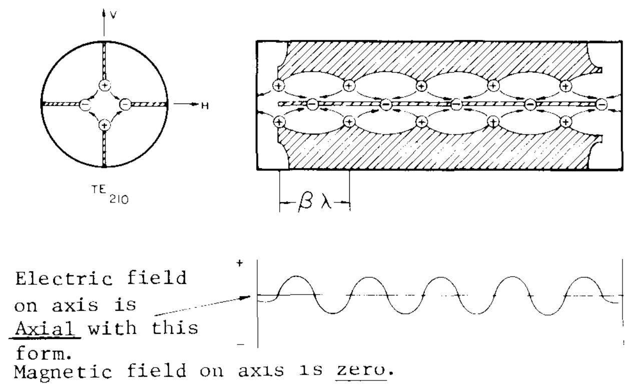

Fig. 5. Four-vane linac structure.

The dependence of accelerated beam on injector voltage is shown in Fig. 3, revealing a rather sharp peak at 248 kV. The width of the peak is in good agreement with the design calculations. The apparent deviation of the peak position from the design value of 250 kV may be real or may be due to an error in the calibration of the voltage measurement.

The dependence of accelerated beam on buncher phase is shown in Fig. 3 for the buncher excitation that produces the maximum accelerated beam at the optimum phase. The general features of this phase scan look correct, but the detailed shape has not been analyzed.

The maximum current accelerated to date is 3 mA. There are a number of hardware problems and it is hoped that this limit can be raised in the near future.

RFQ Linac Structure

A variety of schemes for producing a quadrupole focusing component in the rf accelerating fields of linac structures have been described in the literature of the last decade. Some of the most recent and promising work is that of I. M. Kapchinskii and V. A. Teplyakov[10] and of N. V. Lazarev[11] based on a four-wire configuration excited so as to produce an electric quadrupole field in the plane perpendicular to the wires.

In the case of uniform wires with no longitudinal variations, the electric fields are strictly transverse, and have no accelerating component. As such, the structure is primarily a focusing structure and not an accelerating structure. Kapchinskii and Teplyakov have introduced an accelerating component by modulating the wire geometry in a periodic way. In this form it represents a very exciting accelerating and focusing structure for low-velocity protons, deuterons, and heavy ions.

There are a variety of ways to connect the four wires into an rf circuit. The Russians have chosen to use the "split-cylinder" geometry shown in Fig. 4a. Our interest is based primarily on the "four-vane" geometry shown in Fig. 4b. At LASL, preference is for the four-vane configurations, based on its four-pole symmetry, and its apparent mechanical simplicity. Nevertheless, in preliminary investigations, both configurations were studied.

Figure 5 shows the four-vane configuration with a "ball and scallop" modulation on the vane geometry. The structure is excited so that the top and bottom vane tips are of one polarity, while the side vane tips are of the other polarity. The quadrupole electric field is readily apparent in the end view. These same vectors, when viewed from the side, have a longitudinal component that is due to the interlaced nature of the horizontal and vertical vane modulations. From the symmetry, it can be established that the electric fields on the axis are strictly axial, and that there are no transverse electric fields or magnetic fields on the axis. The axial electric field alternates in direction as shown in the figure.

The structure shown in Fig. 5 should be capable of both accelerating and focusing a beam of charged particles. Because the focusing forces are electric, the focal properties are velocity-independent, and the structure should be superb for low-beta applications.

In actual practice, the vanes would not be built with the "ball and scallop" geometry, but rather with a smooth scalloped geometry as shown in Fig. 6, where the modulation factor "m" is seen to be the ratio of the maximum radial dimension to the minimum radial dimension over the scallop. The longitudinal components of the electric field are zero at the two points of symmetry in the scalloped geometry, and non-zero elsewhere. The transverse components of the elctric field are spatially uniform, and independent of the longitudinal position within the scalloped geometry.

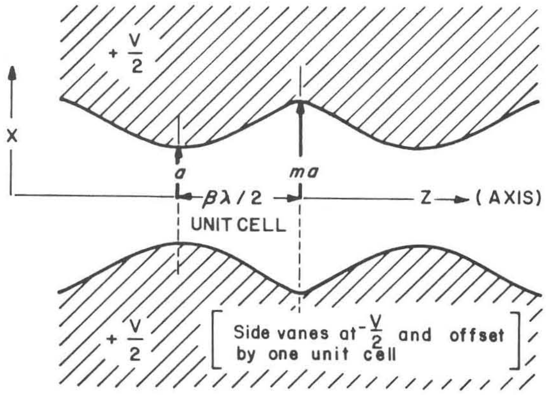

Fig. 6. The RFQ pole-tip geometry.

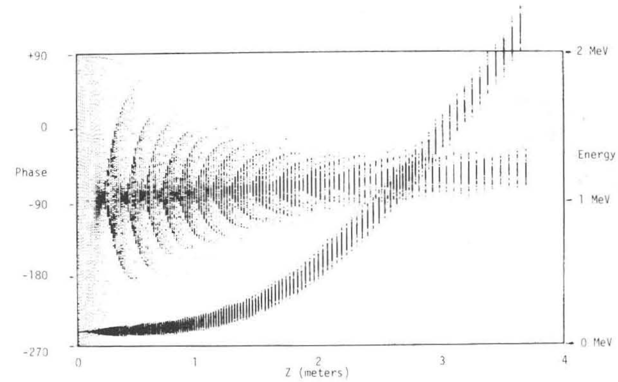

Fig. 8. Phase and energy profiles through the structure.

The structure is simple, consisting of a vane-loaded cylinder excited with rf power. In fact, the structure is so simple that, for the first time, one might consider configuring the linac for adiabatic capture of a continuous beam at low energy. This could be done by introducing the scallops gradually so that the structure acts primarily as a buncher at the beginning, transforming gradually to an accelerator at the end. A computer-generated picture of such a vane tip is shown in Fig. 7.

Simulation of the longitudinal beam dynamics without space charge in such structures demonstrates that capture efficiencies approaching 100% are feasible in reasonable lengths.[12] Figure 8 shows the phase and energy profiles of a beam in one such structure that bunches a 100-keV deuteron beam and accelerates 100% of it to 2 MeV in a total length of about 3.6 meters. Figure 9 shows the longitudinal phase space at 12 points throughout the structure. Subsequent calculations, including the transverse motion and space-charge effects, suggest capture efficiencies in excess of 90% and emittance growths of less than 50% for a 100-mA deuteron beam injected at 100 keV.[13]

The rf cavity mode employed in these structures is a TE_{210}-like mode,[14] which is a "cut-off" mode, and cannot be excited in a finite-length closed cylinder. With special terminations, however, it is possible to excite the mode in all but the immediate vicinity of the end walls. The vanes must not touch the end wall of the termination, as this would short-out the desired mode. The vanes may be cut away near the cylinder wall to provide a cross-over for the magnetic flux, and extended toward the terminating plane near the axis to provide additional capacitive loading between the vanes and to the terminating plane. These features tend to support the wanted TE_{21} modes and destroy the unwanted TE_{11} modes.

A coaxial manifold has been developed that provides a symmetrical, multi-slot driving arrangement for the RFQ cavity.[15] A coaxial cavity surrounding the RFQ cavity is excited in a coaxial TEM mode. The magnetic fields in the TEM mode are orthogonal to the magnetic fields in the RFQ mode. These fields can be coupled by diagonal slots, where the slot angle is

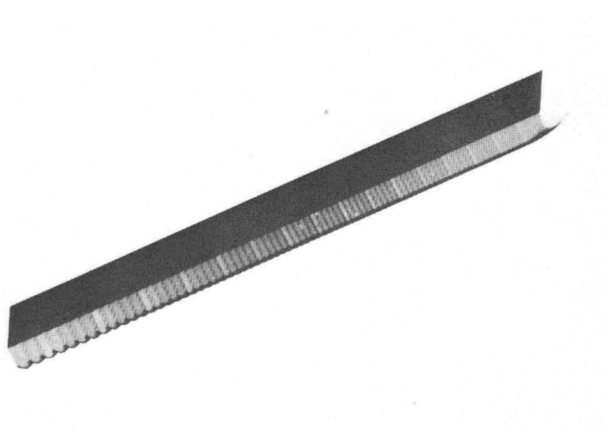

Fig. 7. An RFQ vane tip.

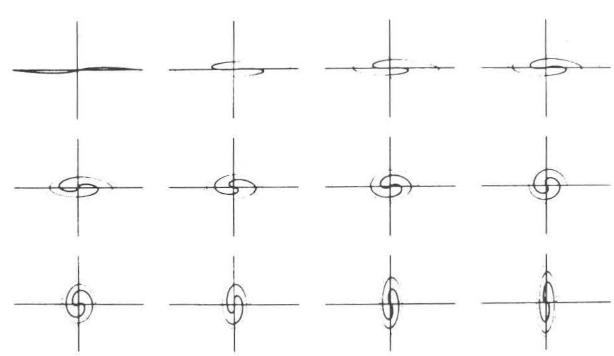

Fig. 9. Longitudinal phase space at every 10th scallop.

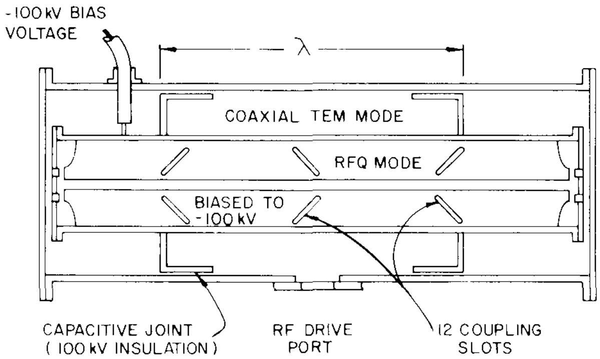

Fig. 10. Biased, manifold-driven RFQ linac structure.

determined by the magnitude and direction of the magnetic fields in the vicinity of the slot.

The first operational model of the RFQ linac structure to be tested at LASL is shown in Fig. 10. Fabrication is well underway. The structure will accelerate 100-keV protons to an energy of 640 keV in a length of 1.2 meters. It will be manifold-driven through a total of 12 symmetrically located coupling slots. For the first test, the structure will be electrically grounded, rather than biased as shown in the figure. For subsequent tests, the structure can be biased to -100 kV, making it possible for the ion source and its control and instrumentation to be at ground potential.

Comparison of Linac Focusing Properties

It is natural to extend the magnetically-focused linac structures downward in energy (and beta) to the limits of the technology. In so doing, it is necessary to pack as much magnetic focusing in the limited confines of the drift tubes as possible. The standard 200-MHz Alvarez linac has been pushed to a beta of 0.04 by this technique. To go lower in beta with these structures, it is necessary to increase the space available for focusing, or increase the field intensities that can be packed into the available space.

One way to get more room for focusing is to lower the frequency, making everything larger. At the lower frequencies, the larger size of the Alvarez structure is a distinct disadvantage, and the smaller size of the Wideroe structure becomes a significant advantage.

Another way to get more room for focusing is to eliminate some of the accelerating gaps in exchange for longer, larger drift tubes. In the Alvarez structure this is referred to as the $2\beta\lambda$ configuration, and in the Wideroe structure it is referred to as the $\pi,3\pi$ configuration.

Recent developments in permanent magnet technology by K. Halbach[16] of Lawrence Berkeley Laboratory, R. Holsinger[17] of New England Nuclear, and J. Farrell of LASL, and independently by N. V. Lazarev and V. S. Skachkov[18] of the Institute of Theoretical and Experimental Physics, Moscow, offer significant increases in the magnetic-field gradients which can be packed into small volumes. Furthermore, these quadrupoles require no power supplies, need no cooling, exhibit no ripple, and offer no control. These "superquads" should find their way into low-beta linac structures.

All of these linac structures employ a periodic alternating-gradient focusing system of either the magnetostatic, electrostatic, or rf electric type. In the static versions, the alternations occur in space, whereas in the rf version, the alternation occurs in time with a spatial uniformity in the instantaneous fields.

In either case, the general differential equation describing the particle motion is

$$\ddot{x} + [(g + h\cos(\omega t)x] = 0 \qquad (1)$$

where g accounts for constant linear forces and $h\cos(\omega t)$ accounts for the alternating gradient force. By changing to the independent variable n, where $n = \omega t/2\pi = ft$, the equation can be written as a function of two parameters, namely $A = g/f^2$ and $B = h/f^2$:

$$\frac{d^2x}{dn^2} + [A + B(\cos 2\pi n)]x = 0 \quad . \qquad (2)$$

The quantity n advances by unity during each period of the focusing structure. The x, dx/dn phase space is identical to the $x,\dot{x}/f$ phase space of Smith and Gluckstern.[19]

This is Mathieu's equation,[20] the general properties of which are well known. It is stable for some combinations of A and B, and unstable for others. It is standard practice to map the A-B space, designating the stable and unstable regions, and giving some properties of the stable motion in the stable regions.

Figure 11 represents the stability chart for the first and most useful stability region of this equation. The properties of the stable motion are described in terms of the μ, α, β, and γ quantitites of Courant and Snyder,[21] where μ is the phase advance of the solution per period, and β is related to the size of the beam of a given emittance at a given moment. The quantity β_+ corresponds to the beta for the maximum beam size, and occurs at the moment of maximum focusing. The quantity β_- corresponds to the beta for the minimum beam size, and occurs at the moment of maximum defocusing. At these two moments, $\alpha = 0$ and $\gamma = -1/\beta$. The flutter factor, F, is defined equal to β_+/β_-. Contours of μ, β_+, and F are included on the stability chart.

For A = 0, the equation has a range of stability from B = 0 to B = 17.92, where $B = (dF/dx)/m(f/N)^2$, dF/dx is the electromagnetic force gradient, m is the particle mass, F is the frequency of the rf, and N is the length of focal period divided by $\beta\lambda$. For magnetic focusing, $dF/dx = q\beta c(dBy/dx)$, and for electric focusing $dF/dx = q(dEx/dx)$, where q is the particle charge and βc is the particle

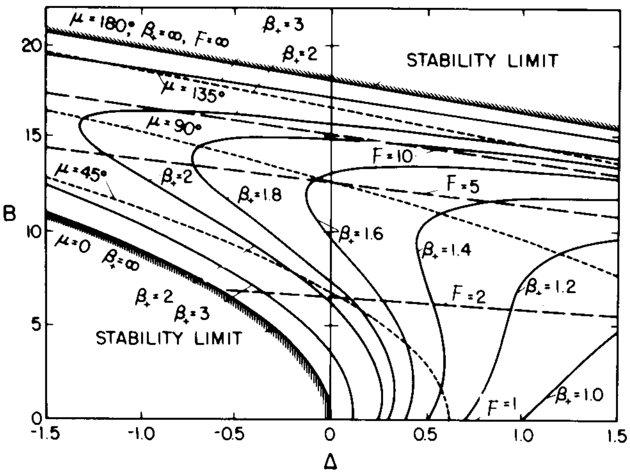

Fig. 11. The RFQ stability chart.

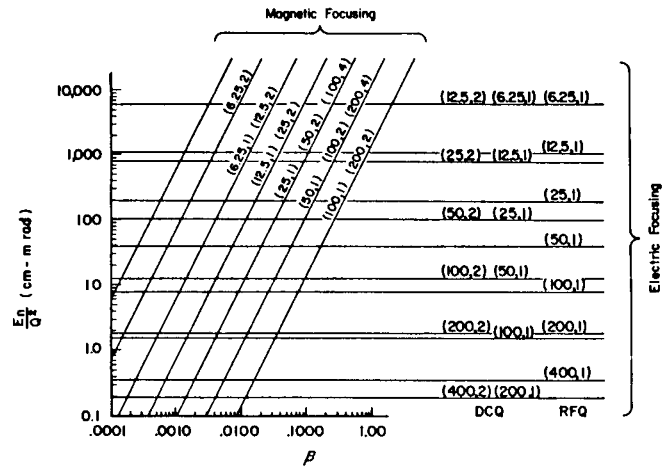

Fig. 12. Admittance of low-beta linac structures.

velocity. The maximum acceptance for A = 0 occurs at B = 11.39 where β_+ has its minimum value of 1.554.

The area in the x, dx/dn phase space that is admitted by a structure with a radial aperture of "a" is $\pi a^2/\beta_+$. Because $n = z/(N\beta\lambda)$, the admittance of the structure in the x,x' phase space is $\pi a^2/(\beta_+ N\beta\lambda)$, and the normalized admittance (area in xx' over π times $\beta\gamma$) is $a^2\gamma f/(\beta_+ Nc)$.

A convenient comparison of the relative focal properties of different linac structures can be made if one imposes a couple of reasonable constraints, namely that (1) the structures be compared at the same operating point in the stability chart (A,B); (2) the bore radius, a, be increased until the pole-tip fields reach some prescribed limit (B_s in the magnetic case, and E_s in the electric case); and (3) the average of the focusing fields over a half period is approximately consistent with the average of the sine wave over a half period. Under these constraints, the normalized admittance of the magnetically-focused structure is

$$E_n = \frac{c^3}{\beta_+ B^2}\left(\frac{ecB_s}{m_o c^2}\right)^2 \frac{\beta^2 Q^2}{\gamma}\left(\frac{N}{f}\right)^3 , \qquad (3)$$

and the normalized admittance of the electrically-focused structure is

$$E_n = \frac{c^3}{\beta_+ B^2}\left(\frac{eE_s}{m_o c^2}\right)^2 \frac{Q^2}{\gamma}\left(\frac{N}{f}\right)^3 , \qquad (4)$$

where Q is the charge-to-mass ratio of the particle as compared to a proton.

Figure 12 facilitates this comparison for the operating point A = 0 and B = 11.39, where $\beta_+ = 1.554$, a pole-tip magnetic field limit of 1 Tesla, and a pole-tip electric field limit of 10 MV/m for the static case, and 1.5 times the Kilpatrick limit[22] for the rf case. The numbers in brackets on the lines are the frequency in MHz and the N value of the focusing period. For example, the (200,2) slanted line corresponds to our standard 200 MHz, magnetically-focused, drift-tube linac structure in the + − + − configuration.

The lines representing the magnetically-focused structures have a slope of 2 on this log-log plot as a result of the β^2 dependence of the admittance. The admittance of the electrically-focused structures is independent of β, and hence represented by the horizontal lines. The admittance of the RFQ structure is higher than the admittance of the corresponding electrostatically-focused structure (DCQ), because of the higher surface field limits at rf frequencies.

Given the normalized emittance, E_n, of the ion beam, the charge-to-mass ratio, Q, and the N value of the first magnetically-focused structure, the following quantities are immediately obvious from Fig. 12: (1) the maximum frequency of the RFQ that will accept the beam, (2) the beta value at which the admittance of this RFQ intercepts the admittance of the magnetically-focused structure with the same frequency and given N value. The aperture, a, of the RFQ can readily be determined from the equations given above, from which the minimum suitable beta for the RFQ can be determined ($\beta_{min} \sim 2a/\lambda$).

A Uranium +11 RFQ Example

Let us consider an RFQ/Wideroe marriage for U^{+11}. This choice allows convenient comparison with the first Wideroe tank (π,3π) of the UNILAC,[23] which spans a range of beta from 0.005 to 0.0216 in a length of 5.58 meters.

TABLE I

URANIUM +11 RFQ LINAC STRUCTURE

Frequency	25 MHz
Cavity length	4 m
Number of cells	88
Radial aperture	1.3 - 0.9 cm
Injection voltage	100 kV
Beta initial	0.00315
W/q initial	0.1 MeV
Beta final	0.01580
W/q final	2.5 MeV
Normalized admittance	0.28 cm mrad
Capture efficiency	92%

Tom Wangler of LASL did a preliminary design of such a machine. The admittance of a 25-MHz RFQ is approximately equal to the admittance of a 25-MHz (π,3π) Wideroe linac at β = 0.005 corresponding to the UNILAC injection voltage of 250 kV for U^{+11}. However, this initial beta does not realize the maximum benefits from the RFQ, which for the best bunching action, prefers a lower starting value.

The design presented in Table I is based on an initial beta of 0.00315 corresponding to an injection voltage of 100 kV for U^{+11}. This RFQ intercepts the (π,π) Wideroe linac acceptance at a beta of 0.0158, corresponding to an energy of 2.5 MeV per unit charge.

General Role of RFQ

The general properties of the RFQ and some speculation on its role in the general scheme of things are:

1. It is the strongest focusing device now known for low beta.
2. Consequently, the beam sizes are shockingly small.
3. Furthermore, the aperture for a given normalized emittance is independent of β, and hence constant throughout an accelerating structure.
4. The minimum β would seem to be limited only by the relationship of $\beta\lambda$ to the beam aperture. Perhaps, for some applications, $\beta\lambda$ could be as small as twice the radial aperture.
5. The maximum β is also limited by the relationship of $\beta\lambda$ to the beam aperture. As this ratio gets too large, the acceleration efficiency drops. It appears to be a prime candidate up to the point where the Wideroes can take over.
6. It offers some of the same size advantages that the Wideroe offers in comparison to the Alvarez structure. In the four-vane configuration, it is considerably smaller than an Alvarez structure of the same frequency but somewhat larger than a Wideroe.
7. The rf efficiency is a strong function of frequency and aperture, and in general is comparable or superior to the other low-beta structures.
8. It is mechanically sound and simple, particularly in the four-vane configuration.
9. It is the best buncher ever observed, offering capture efficiencies in excess of 90%.
10. It offers the lowest injection voltages of any known structure.
11. It offers higher frequencies than other very low-beta structures.
12. In the realm of emittance growth, it seems to be no worse than, and perhaps even better than, other known structures.

In addition to this impressive list of properties, the biased version of the RFQ offers: (1) a grounded ion source with its associated equipment and control; (2) a grounded rf manifold and drive port; (3) no exposed high voltage; and (4) no beam loading on the high-voltage power supply.

Acknowledgments

We are all indebted to I. M. Kapchinskii of ITEP and V. A. Teplyakov of IHEP and their associates in the USSR for their invention of the RFQ linac structure, and their pioneering work in the design, analysis, fabrication and operation of the first prototypes.

The author credits J. J. Manca of Varian, Pierre Grand of BNL, and R. A. Jameson of LASL for triggering our current interest in the RFQ in this country. The RFQ developments reported here are the work of a strong team pulled together at LASL for this purpose consisting of R. Stokes (theoretical program coordinator), K. Crandall (beam dynamics), T. Wangler, S. Schriber (CRNL), S. Inagaki (KEK), J. Potter (rf structures), F. Humphry, A. Thomas, S. Williams (HEDL), G. Rodenz, and C. Fuller (engineering).

The APF linac structure whose initial operation is reported here was designed, fabricated, and put into operation by J. Stovall (principal responsibility for the PIGMI laboratory), L. Hansborough (chief mechanical engineer), E. Bush, V. Hart, R. Hamm (ion source), R. Sturgess, T. Boyd, P. Tallerico, D. Keffeler, J. Johnson, R. DePaula, S. Klosterbuer (control and diagnostics), and V. Martinez.

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Discussion

Ohnuma, Fermi Lab: You mentioned so many good things about RFQ that the natural reaction I have is that it can't all be true. I admit that I'm an old-fashioned man so that's kind of natural. Just one or two questions - As I understand it, one of the peculiar features of this focusing system is that it is spatially uniform, as you mentioned, and it is changing as a function of time. When the unbunched beam comes in, the matching requirement would be changing as a function of time, so that for some particles, it would be matched, but for some other particles, it will be unmatched. I would expect, depending on the aspect ratio of x and y in the throbbing matched shape, you would get some kind of dilution. I didn't quite understand the function of the tapered initial section.

Swenson: If you start out essentially with the rf quadrupole turned off, that is, with a very large aperture where you have no focusing, and then at some distance (we originally said some 20 cm later), turn it on by tapering these poles down, the beam that enters will be influenced by the gradual introduction of this rf quadrupole, such that it adjusts itself and is essentially matched.

Ohnuma: You said the beam size is shockingly small; does that require something very special in your low energy beam transport?

Swenson: Yes, I think if it's magnetically focused transport, the beam does not have to be shockingly small, it just has to be converging into the entrance of the RFQ.

Teng, Fermi Lab: Why did you choose that particular shape for the scallop of the pole? Is it because you want a spatially uniform transverse focusing?

Swenson: Yes, Dick Stokes tells me that this shape produces a perfect quadrupole field in the transverse space and a sinusoidally varying field in the longitudinal dimension which, we have approximated by some circular arcs truncated on the side, as shown.

Miller, SLAC: I have difficulty believing that the quadrupole fields are spatially uniform because the relationship between longitudinal fields and transverse fields involves the derivates of the longitudinal fields. Is that really true? It must depend on the shape, surely of the vanes. There must be space harmonics, depending on the shape you choose.

Stokes: The shape of the poles which we have chosen is really based on a lowest order of potential function given by Kapchinskii and Teplyakov, and this potential function does give the properties that have been described. The strength of the quadrupole field, in fact, is spatially constant through a unit cell and can be made constant through the whole accelerator if you wish. In addition, it produces a simple sinusoidal shape for the longitudinal field. Connected with this potential function, is a pole shape which is somewhat complex but can be realized mechanically.

Miller: I have a related question. Doesn't the longitudinal variation in the pole shape introduce some transverse magnetic field and, consequently, isn't there some component of magnetic focusing?

Stokes: We have estimated the strength of the magnetic fields and they are very low. Typically, the forces are something like 10^{-5} times the electric forces, and 0 on axis.