Particle Accelerators, 1990, Vol. 32, pp. 21–26
Reprints available directly from the publisher
Photocopying permitted by license only
© 1990 Gordon and Breach, Science Publishers, Inc.
Printed in the United States of America

EXTENSIONS TO THE RFQ DOMAIN

DONALD A. SWENSON
Science Applications International Corporation, Division 212,
Albuquerque, New Mexico, USA.

Abstract Conventional four-vane or four-bar RFQ linacs have met with enormous success. They have set new performance standards for our accelerators and, in so doing, earned a role in most future proton and other ion accelerator systems. Now, certain changes to the conventional RFQ structure and parameter space promise to extend the RFQ domain to an even larger role in more applications. One of these, the RFQ lens, represents the strongest "symmetrical" lens for low-energy beam transport (LEBT) applications. Another, the Four-Finger RFQ Linac Structure, offers efficient ion acceleration to higher velocities with higher space-charge limits than conventional RFQ structures. Another, the Dust Particle Accelerator, explores new regions of the RFQ parameter space with lengths as long as 100 m and frequencies approaching the audio range. These extensions to the RFQ domain will further increase the performance that we expect from our accelerators.

INTRODUCTION

RFQ linacs, a Russian invention, have revolutionized linac technology. They represent the best transformation between the cw beams that come from ion sources and the bunched beams required by linac accelerators. Their forces, being electric, are independent of velocity, allowing them to focus and bunch beams at much lower energies than their magnetically focused counterparts. Their capture efficiency can approach 100% with minimal emittance growth. They have made a major impact on the design and performance of proton, deuteron, light-ion, and heavy-ion accelerator facilities.

Three extensions to the normal domain are reported here, namely:

* as a lens for matching beams into an RFQ linac,
* a new geometrical configuration to extend their velocity range, and
* a submegahertz version for acceleration of charged dust particles.

Each of these extensions requires some variation on the normal RFQ configuration for success.

In the lens application, where the size of the beam is considerably larger than it is in the linac, there is a serious limitation on achievable lens strength in the normal configuration. It is important to note that certain configurations produce net focusing that is independent of phase. In these configurations, it is possible to operate the RFQ lens at frequencies that are lower than that of the linac, thereby gaining in effective strength of the lens.

In the other two extensions, a four-finger geometry has been invoked that introduces a new degree of freedom into the system that allows the operating frequency to be raised at higher velocities to improve the accelerator's efficiency without losing traverse focusing strength. By so doing, it is possible to double or quadrupole the acceptable particle velocities, which, of course, extends the energy range by factors of 4 to 16.

In the dust particle accelerator, the frequencies are so low as to present a host of new problems and solutions. Micron-diameter dust particles can be charged to a mass-to-charge (M/Q) ratio that is two million times that of a proton. Hence, the RFQ frequency should be something like the square root of two million time less than that for a conventional proton RFQ. This puts the rf frequency in the few-hundred kilohertz range -- almost audio frequency!

THE RFQ LENS FOR LEBT APPLICATIONS

The success of RFQ linacs presents us with lower energy beams in the LEBTs and the need for more strongly convergent beams at the entrance to the linacs. Achieving the required focusing with quadrupoles or solenoid lenses has become a problem. The lower beam energies give added impetus to the use of electric, as opposed to magnetic lenses in these regions.

The RFQ lens is an electric quadrupole lens with the added advantages that no insulators are required to support the resonant electric fields in the structure and the required "alternating gradient" feature is provided by the temporal alternation in the polarity of the fields.

The focusing strength for conventional RFQ devices is proportional to $E\lambda^2/(r(M/Q))$, where E is the surface electric field on the tip of the electrode, λ is the rf wavelength, and r is the radial aperture to the electrode.

The optimization of RFQ linacs for focusing and acceleration of small diameter particle beams essentially precluded the use of RFQ lenses, operating at the linac frequency, on the larger diameter beams in LEBTs, because of inadequate lens strength. The key observation, presented here, is that there are some configurations of RFQ lenses that do not have to be at the linac frequency in order to effect a useful transformation on the beam and, in particular, may operate at a lower frequency where their strengths can be substantially higher.

An RFQ lens, having a radial matching section on both ends to "ramp" the lens effect on and off over some distance can have an action on the beam that is independent of the phase of the beam with respect to the rf lens excitation. It is this independence of phase that removes the normal linac constraint on phase, and hence frequency, correlation with the linac fields.

Consider a beam in an LEBT that is ten times the diameter of the beam in a 425-MHz RFQ linac. The achievable RFQ lens strength in the LEBT at that frequency is down an order of magnitude from that in the RFQ linac. The possibility of using a 100-MHz lens, instead of a 425-MHz lens, regains that order of magnitude in strength.

The beam profiles through an RFQ lens and into an RFQ linac, as evaluated by the computer program TRACE, are shown in Fig. 1. The horizontal beam profiles are shown above the center line and the vertical beam profiles are shown below. The four different trajectories, visible in each profile near the center of the lens, correspond to four different phasings of the beam relative to the lens excitation. The fact that these trajectories coalesce at the end of the lens demonstrates that the lens action is independent of phase.

The RFQ lens exhibits a net focusing in each transverse plane, maintains a near circular beam throughout the lens, may be exceptionally low in aberrations, has no frequency or phase constraint to subsequent linac

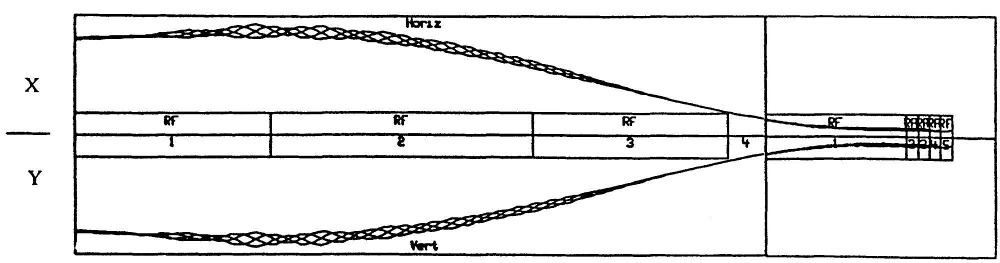

Figure 1. Beam profiles through RFQ lens and into RFQ linac.

structures, has acceptable surface field strengths, and is tunable, simultaneously in both transverse planes, by rf amplitude. The RFQ lens, as described here, may represent an important new element for low-energy beam transport systems.

THE FOUR-FINGER RFQ LINAC STRUCTURE

In the four-vane and four-bar configurations of the radio frequency quadrupole (RFQ) linac structure, the quadrupole focusing action alternates in sign from cell to cell going through one complete period in one particle wavelength ($\beta\lambda$). In the four-finger RFQ structure described here, the orientation of the fingers about the axis determines the sign of the quadrupole focusing action, thus yielding an additional degree of freedom in the design of RFQ linacs. In particular, with this structure, it is possible to have focal periods that are longer than the particle wavelength.

In the four-finger RFQ linac structure, the beam passes through a series of electrodes that alternate in polarity and are spaced at one-half the particle wavelength. A cell of the structure is defined as the region between the centers of adjacent electrodes. Each electrode has two fingers extending into the cell creating a strong transverse quadrupole component to the electric field in the cell.

At higher frequencies, where resonant cavity sizes permit, the four-finger RFQ takes the form of a cross-bar cavity resonator. This structure consists of a cylindrical cavity, loaded with transverse bars, alternating in orientation by 90 degrees and spaced at one-half the particle wavelength.

In each of these structures, the principal advantage of the four-finger structure over the four-vane or four-bar structure is that the periodicity of the focal structure is independent of the periodicity of the accelerating structure. For synchronous acceleration, the length of one period of the accelerating structure must be equal to the particle wavelength, $\beta\lambda$. Let $N\beta\lambda$ be the length of one period of the focusing structure. In the four-vane and four-bar structures, N is constrained to unity. In the four-finger structure, N can have any positive value, although integer values lead to more regular structures. The four-finger structures for $N = 1$, 2, and 3 are shown in Fig. 2. Note the similarity between the $N = 1$ four-finger and more conventional structures; $N > 1$ structures are unique to the four-finger configuration.

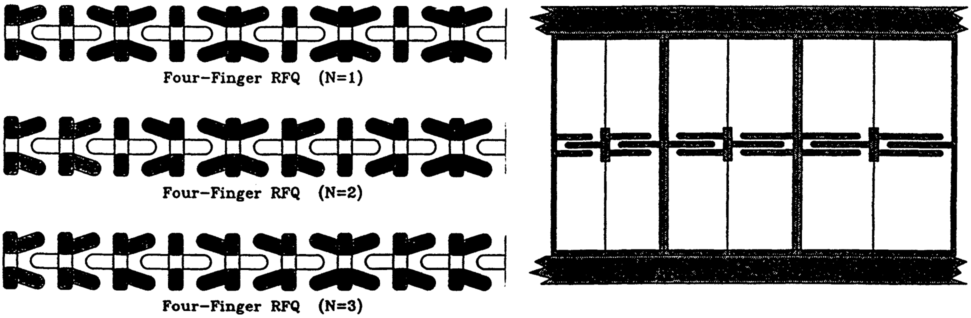

Figure 2. Four-finger sequences for N = 1, 2, and 3.

The acceleration rate is proportional to $Er/\beta\lambda$, and the focusing strength is proportional to $EN^2\lambda^2/(r(M/Q))$. As the particle accelerates, β increases and the acceleration rate drops. At some point, the performance of the RFQ linac structure drops to the point where some change is desired. Under the constraint that N = 1 and the assumption that E is already at the surface field limit, there are no changes to r and λ that will increase the acceleration rate without decreasing the focusing strength. The normal solution for proton structures has been to change to the magnetically focused drift tube linac at a proton energy of about 2 MeV.

With the four-finger structure, it is possible to double the frequency and the N value simultaneously in order to double the acceleration rate while holding the focusing strength constant. This would allow the RFQ structures to be extended by a factor of 2 in velocity or a factor of 4 in energy. In some cases, it might be possible to double the frequency and N value a second time, leading to an extension of the RFQ energy by a factor of 16.

This new structure does not replace or compete with the conventional RFQ structures, but rather extends their useful range by major proportions.

THE "DUST PARTICLE" RFQ LINAC

There are scientific, industrial, and military interests in the collision of micron-diameter particles with material surfaces of velocities in the range of 70-200 km/s. A particle traveling that fast carries enough kinetic energy to vaporize many times its own mass in target atoms. The net result is that the momentum imparted to the target surface is greater than the momentum of the impacting particle. The ejecta cloud from the target will contain highly ionized gas and will emit radiation in various energy ranges. The phase composition of the ejecta as a function of time after impact is of interest.

The best particle-charging schemes can produce M/Q ratios for micron-diameter particles as low as two million times that of a proton. Van de Graaff accelerators have been used to accelerate such particles to energies of a few MeV/proton-charge, corresponding to velocities of a few tens of kilometers per second. Energies in the range of 100-MeV/proton-charge are required to accelerate these particles to velocities in the range of 100 km/s.

The RFQ linac can be adapted to accommodate these unusual particles. Because of the exceptionally large M/Q value, the resonant frequency must be in the range of hundreds of kilohertz. At the lowest velocities, the four-bar structure with an external, multiturn inductor is appropriate. As the velocity increases, it is advantageous to switch to the four-finger structure to increase the acceleration rate and shorten the structure.

The five-section RFQ linac, presented in Table I, starts with a four-bar section at 220 kHz followed by 4 four-finger sections at successively higher frequencies and accelerates microparticles from 200-keV/proton-charge to 100-MeV/proton-charge, corresponding to a velocity of 100 km/s, in 100 m.

TABLE I Five-Section, Dust Particle RFQ Linac (M/Q = 2 million)

Section	N	Frequency (MHz)	Energy (MeV)	Velocity (km/s)	Accumulated Length (m)
1	1	0.220	16.3	40.0	20
2	2	0.440	36.7	60.0	40
3	3	0.660	59.4	76.0	60
4	4	0.880	84.0	90.0	80
5	5	1.100	110.6	103.0	100

CONCLUSIONS

The extensions to the RFQ domain presented in this report offer some exciting new dimensions in radial aperture, particle velocity, and particle mass for both the conventional accelerator fare (protons and ions) and unconventional projectiles (charged dust particles). These extensions result from variations in the structure geometry and operating parameters described here. They will lead to new levels of performance from our accelerators.