RF-FOCUSED DRIFT TUBE LINAC STRUCTURE

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Abstract

A new rf-focused drift tube linac structure is presented. It resembles a drift tube linac with rf focusing incorporated into each drift tube. As in conventional drift tube linacs, these drift tubes are supported by single stems along the axis of a cylindrical cavity that is excited in the TM_{010} rf cavity mode. These "drift tubes" comprise two separate electrodes, operating at different electrical potentials as determined by the rf fields in the cavity, supporting a total of four fingers that produce an rf quadrupole field distribution along the axis inside the drift tube. The fundamental periodicity of this structure is equal to the particle wavelength, $\beta\lambda$. Particles, traveling along the axis, traverse two distinct regions, namely the gaps between drift tubes, where the acceleration takes place, and the regions inside the drift tubes, where the rf quadrupole focusing takes place. This structure uses both "forward" and "reverse" phases of the rf fields to effect the beam. In this case, the "reverse phase" does not decelerate the beam as the fields inside the drift tubes are distorted into transverse focusing fields with little longitudinal component. The orientation of the fingers in the focusing regions alternate so as to create an alternating focusing and defocusing action on the beam in each transverse plane. This new linac structure does not replace or compete with the conventional RFQ, but rather provides a graceful way to accelerate the small diameter, tightly bunched beams that come from RFQ linacs to higher energies.

Introduction

An rf-focused linac, designed to accept a bunched beam from a conventional RFQ linac, need not have the spatially uniform focusing fields -- a valuable feature of conventional RFQs resulting from their continuous vane- or bar-like electrodes. By dropping this feature, several avenues open up for extending the useful energy range of rf-focused linac structures[1]. One format involves a combination of conventional acceleration gaps for acceleration and four-fingered-loaded gaps for the focusing.

The Russians have developed some structures like this to accelerate protons from 2 MeV to 30 MeV for injection into their major accelerator at Serpukov[2]. These structures employ a succession of drift tubes, supported on four or more stems per particle wavelength, immersed in an rf cavity mode with a longitudinal magnetic field (H-mode). This paper describes an rf-focused structure that, like the DTL, requires only one drift-tube stem per particle wavelength and utilizes the lowest frequency rf cavity mode with a transverse magnetic field (TM_{010}-mode). A suggested name for this structure is the "Rf-Focused Drift-tube" (or RFD) linac structure.

The RFD Linac Structure

The RFD linac structure, as shown in Fig. 1, resembles a DTL with RFQ focusing incorporated into each "drift tube". As in a conventional DTL, these drift tubes are supported by single stems along the axis of a cylindrical cavity excited in the TM_{010} rf cavity mode. These "drift tubes" comprise two separate electrodes operating at different electrical potentials, as determined by the rf fields in the cavity, each supporting two fingers pointing inwards towards the opposite end of the drift tube, forming a four-finger geometry that produce an rf quadrupole field distribution along its axis.

The fundamental periodicity of this structure is equal to the "particle wavelength", $\beta\lambda$, where β is the particle velocity in units of the velocity of light and λ is the free-space wavelength of the rf. The particles, traveling along the axis, traverse two distinct regions, namely gaps between drift tubes, where the acceleration takes place, and regions inside the drift tubes, where the rf quadrupole focusing takes place.

This structure used both phases of the rf fields to effect the beam; one for accelerating the beam and the other for focusing the beam. In this case, the "reverse phase" does not decelerate the beam because the fields inside the drift tubes are distorted into transverse focusing fields with little longitudinal component. The orientation of the fingers in the focusing regions alternate so as to create an alternating

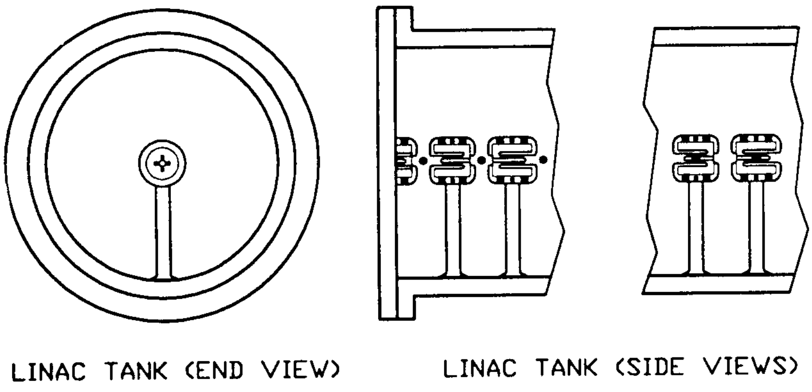

Fig. 1. RFD Linac showing particle locations during "Acceleration" and "Focusing".

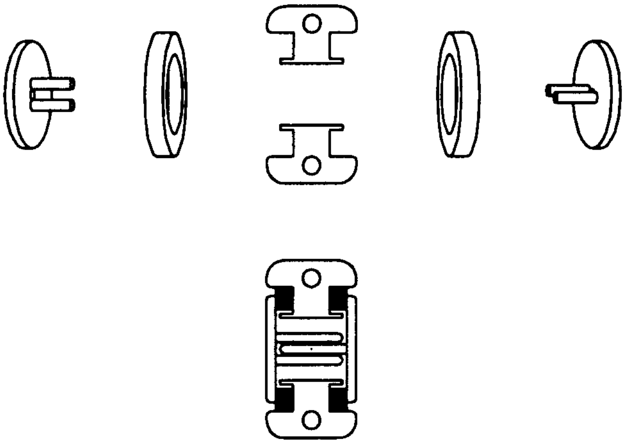

Fig. 2. Exploded and Assembled Views of a Possible RFD Linac Drift Tube Design.

focusing and defocusing action on the beam in each transverse plane.

The distribution of voltage between an accelerating gap and a neighboring focusing region is inversely proportional to the intra-electrode capacitance of each region. A most interesting feature of this structure is the ability to have a relatively high voltage on the relatively low capacitance accelerating gap while putting an adequate voltage on the focusing region.

The structure appears to have excellent properties with the changing geometry associated with the acceleration process. As the particle velocity increases, the cell length increases and the acceleration gap capacitance decreases. In a constant gradient configuration, typical of most drift tube linacs, an increase in cell length implies an increase in the acceleration voltage. If the intra-electrode capacitance of the drift tube body (and the focusing fingers) is approximately constant, regardless of drift tube length, the focusing voltage remains approximately constant while the acceleration voltage increases with particle velocity. This implies a constant beam diameter throughout the structure.

In a configuration, suitable for low duty applications, the drift tube electrodes can be supported through thin rings of ceramic from a water-cooled metallic ring to form a rigid drift tube unit, as shown in Fig. 2. The limited power dissipation on the drift tube electrodes and in the ceramic can be conducted through the ceramic to the cooled ring. For higher duty applications, the two electrodes of the drift tube can be joined into one rigid unit by an appropriately shaped conductor, which does not "short out" the lens excitation, or the two electrodes could each be supported directly from the wall of the tank.

The Beam Dynamics

The beam bunches arrive at the centers of the gaps at the times when the electric fields are optimum for acceleration, and the beam bunches arrive at the centers of the drift tubes one half cycle later when the electric fields have reversed their directions and are suitable for focusing the beam. Fig. 3a shows the RFD linac structure, with greatly exaggerated finger spacing, showing the distribution of electric fields (arrows) and electric charges (+ and - signs) within the structure at the "acceleration phase". Fig. 3b shows the same structure with the field directions and particle bunch locations as they would be at the"focusing phase". The directions, shown for the fields inside the drift tubes, pertain only to the component of the fields in the plane of the figure. The components of the fields normal to the paper are in the opposite direction relative to the axis. Particle traveling along the axis experience no focusing force, as the transverse fields vanish on the axis. Off-axis particles A and B will experience a"focusing" action on their motion, while particles C and D will experience a"defocusing" action on their motion.

The focusing parameter[3], B, for the RFD linac structure is approximately half that for an RFQ structure of the same frequency, vane-tip voltage and aperture, but with a focusing period corresponding to N = 2. This reflects the facts that only half of the space is dedicated to focusing the beam and that the focal period is twice as long as for the RFQ structure. The focusing parameter for the RFD structure (with N = 2) is:

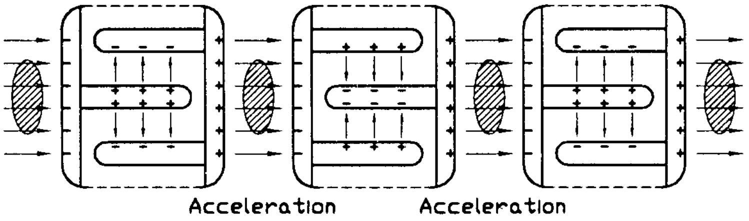

Fig. 3a. Electric Field, Charge and Particle Distributions at the "Acceleration Phase".

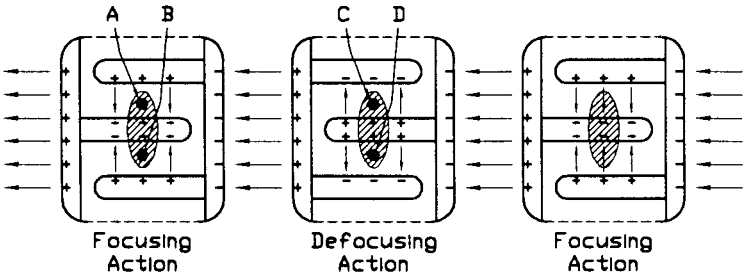

Fig. 3b. Electric Field, Charge and Particle Distributions at the "Focusing Phase".

$$B = \frac{2V\lambda^2}{(M/Q)a^2}$$

where V is the voltage between the fingers of the quadrupole lens (in Volts), λ is the free-space wavelength of the rf (in meters), M/Q is the mass to charge ratio of the beam particle (in electron Volts), and a is the average radial aperture of the quadrupole lens (in meters).

For example, consider an 800-MHz proton RFD linac with a radial aperture of 1 mm. This structure would require a total voltage on the focusing element of only 22 kV to produce a focusing parameter of 6.6, which lies well within the stable region of the beam dynamics.

The Kilpatrick limit for 800 MHz is about 28 MV/m. Modern vacuum and surface cleaning techniques make it acceptable to exceed Kilpatrick's limit by approximately a factor of 2. The maximum surface electric field on the fingers in this example is $1.4 \times V/a = 31$ MV/m, or a conservative rating of 1.1 Kilpatrick.

At an average axial electric field strength of 10 MV/m, the cell length for a 2-MeV proton would be about 24 mm long and the voltage across the acceleration gap would be about 240 kV. At a proton energy of 8 MeV, the cell length would be twice as long and the gap voltage would be twice as much, or 480 kV. For these two geometries, the focusing voltage is less than 10% of the gap voltages. Hence, only a small fraction of the linac excitation is used for focusing the beam, while a majority of the excitation is used for acceleration of the beam.

An example of a small RFD was simulated on a modified version of PARMILA. This compact, proton linac, with a total of 35 cells and a diameter of 0.25 meters, accelerates a 2 millimeter diameter proton beam from 1 to 10 MeV in a length of only 1.25 meters. It operates at 800 MHz and has an average axial electric field of 10 million volts/meter. The estimated rf power required to excite the structure is 1 MW.

The six similar graphs at the top and bottom of Fig. 4 show the two-dimensional "phase spaces" of the simulated beam at the entrance (top graphs) and exit (bottom graphs) of the linac. The total emittance of the simulated beam at the entrance to the structure is 1.3 cm-mrad in each of the transverse coordinates and 4.7 cm-mrad in the longitudinal coordinate. The vertical bands in the center of the figure show the profiles of the beam as it passes through the 35 cells of the structure.

Conclusions

This new linac structure does not replace or compete with the conventional RFQ structure, but rather provides a graceful way to accelerate the small diameter, tightly bunched beams that come from RFQ linacs to higher energies. It offers additional degrees of freedom to exploit in the pursuit of enhanced performance and lends itself to miniaturization more readily than its magnetically focused counterpart. Some notable features of this new structure are:

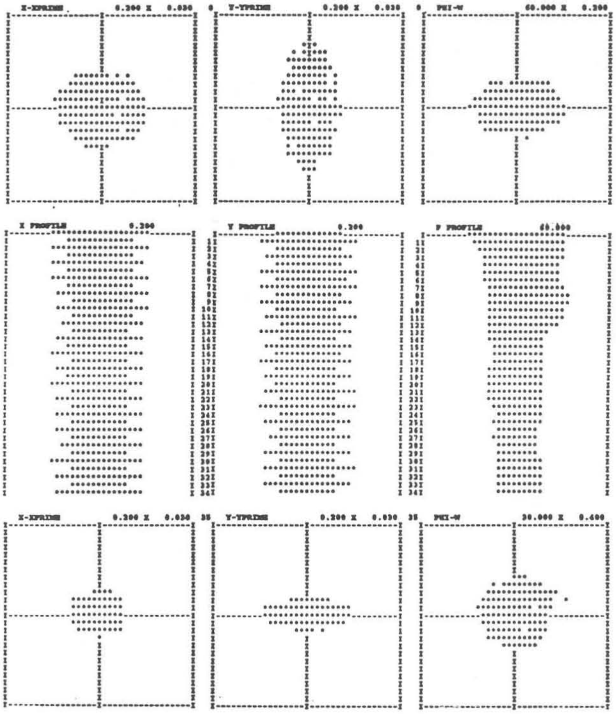

Fig. 4. Phase Spaces and Beam Profiles from a modified version of PARMILA.

- DTL-type acceleration using the familiar TM_{010} mode.
- Gap voltage increases as particle velocity increases.
- High acceleration rate per unit power consumption.
- RFQ-like focusing in an N = 2 configuration.
- Single support stem per drift tube (structure period).
- Drift tubes can be very small.
- Suitable for high frequency operation.
- Promises practical and economical fabrication.

These features represent significant extensions to the linac technology. They should lead to smaller and more economical ion linacs for medical and industrial purposes.

References

[1] D. A Swenson, "Extensions to the RFQ Domain", Particle Accelerators, 1990, Vol. 32, pp. 21-26.

[2] V. A. Tepliakov, "RFQ Focusing in Linacs", Proc. of 1992 Linac Conference, pp. 21-24.

[3] D. A. Swenson, "Low-Beta Linac Structures", Proc. of 1979 Linac Conference., pp. 129-136.