MERITS OF THE RFD LINAC STRUCTURE FOR PROTON AND LIGHT-ION ACCELERATION SYSTEMS*

D.A. Swenson, F.W. Guy, Linac Systems, 2167 N Highway 77, Waxahachie, TX 75165
K.R. Crandall, Consult Crandall, 26 South Mountain Rd, Sandia Park, NM 87047

Abstract

The Rf-Focused Drift-tube (RFD) linac structure, under development at Linac Systems, has the high acceleration efficiency of the DTL linac and the strong rf-electric focusing of the RFQ linac. Because of the rf electric focusing, the RFD linac structure operates well at much lower energies than the conventional magnetically focused DTL. Consequently, the transition energy between the RFQ linac, required to capture the unbunched beam from the injector, and the RFD linac can be much lower than for conventional RFQ/DTL combinations. The acceleration efficiency of the RFQ is relatively high, and similar to that of the RFD, at these lower energies. Because of the rf electric focusing in the RFD, the transverse focusing (and beam size) in the RFD is similar to that in the RFQ. Consequently, no complex matching section is required between the two linacs. The consequences of these merits on the cost and complexity of small proton and light-ion linac systems for scientific, medical and industrial applications will be addressed.

1 THE RFD LINAC STRUCTURE

The RFD Linac Structure[1-4] resembles a drift tube linac (DTL) with radio frequency quadrupole (RFQ) focusing incorporated into each "drift tube". As in conventional DTLs, these drift tubes are supported on single stems along the axis of cylindrical cavities excited in the TM_{010} rf cavity mode. The RFD 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 produces an rf quadrupole field distribution along the axis. The fundamental periodicity of this structure is equal to the "particle wavelength", $\beta\lambda$. 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 uses both phases of the rf fields to affect 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 focusing and defocusing action on the beam in each transverse plane.

A very important advantage that the RFD structure has over the RFQ structure is acceleration efficiency. A comparison of the rf efficiencies for the RFD and RFQ linac structures is shown in Fig. 1. In the range of 1-to-5 MeV, the RFD structure has approximately 4 times the shunt impedance of the RFQ structure.

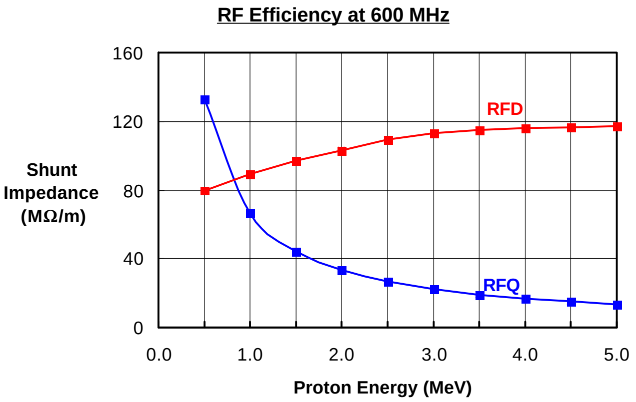

Fig. 1. RFQ and RFD Acceleration Efficiencies.

2 PRACTICAL LINAC SYSTEMS

Most proton and light-ion linac systems start with an RFQ linac section to capture the beam from the ion source and to bunch it for acceleration in more efficient linac structures. As shown in Fig. 1, the rf efficiency of the RFQ linac structure drops rapidly with energy. In proton linac systems, the RFQs have been called upon to accelerate the beam to an energy of 2.0 MeV or so where the magnetically focused DTL can handle it. At this point, however, there is a serious mismatch in the acceleration and focal properties of the two structures, necessitating some provision for “matching” the two.

The RFD linac structure provides a graceful way to accelerate the small diameter, tightly bunched beams that come from RFQ linacs to higher energies. Because of the rf electric focusing, the RFD linac structure operates well at much lower energies than the conventional magnetically focused DTL. Consequently, the transition energy between the RFQ linac, required to

---

* Work supported by the National Institute of Mental Health (NIMH).

capture the unbunched beam from the injector, and the RFD linac can be significantly lower than for conventional RFQ/DTL combinations, perhaps in the 0.5 to 1 MeV range. In this energy range, the RFQ has a very respectable shunt impedance and the acceleration and focal properties of the RFQ are very close to that of the RFD. Consequently, little or no matching is required between the structures. The RFQ structure can be bolted directly to the RFD structure and resonantly coupled to it. We believe that this new structure will become the structure of choice to follow RFQ linacs in many applications.

A "matching scheme" between two linac structures that works well for all beam currents requires that there be no discontinuity in the phase advances per unit length of the transverse and longitudinal oscillations of the two structures at the point of transition. The two sections below elaborate on this situation for the RFQ/DTL and RFQ/RFD transitions.

2.1 RFQ/DTL Transition

At the relatively high transition energy (2.0 MeV) of a 425-MHz RFQ/DTL combination, the RFQ has stronger transverse and weaker longitudinal focusing than the DTL. This situation, where no effort has been made to match the two structures, is shown in Fig. 2.

The transverse focusing of an RFQ can be decreased by flaring out the vanes and increasing the transverse radius of the vane tip, which complicates the machining. The longitudinal focusing of the RFQ can be increased by making its synchronous phase more negative, and the longitudinal focusing of the DTL can be decreased by "ramping" the accelerating gradient from a lower value at the beginning of the structure to the desired value somewhere downstream (RGDTL). The "match" that can be achieved by these means is shown in Fig. 3. Both of these solutions make the linac longer and more complicated. The alternative is to have a complicated "matching section" between the RFQ and DTL, which would add significantly to the cost and complexity of linac systems for commercial applications.

2.2 RFQ/RFD Transition

The drift tubes of the RFD linac structure lend themselves to miniaturization more readily than do those of the magnetically focused DTL. Hence, the RFD linac structure can be pushed to higher frequencies (and acceleration gradients) than can the conventional DTL.

At the relatively low transition energy (0.8 MeV) of a 600-MHz RFQ/RFD combination, the transverse and longitudinal focusing of the RFQ and RFD are very similar, thereby making the "matching" exercise almost unnecessary. This situation, where no effort has been made to match the two structures, is shown in Fig. 4.

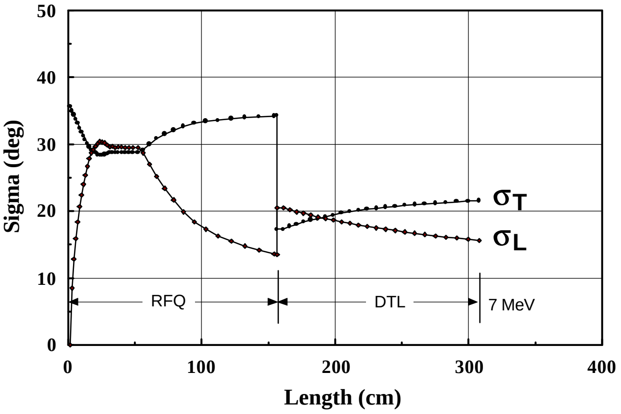

Fig. 2. Phase Advances (σ) for Unmatched RFQ/DTL.

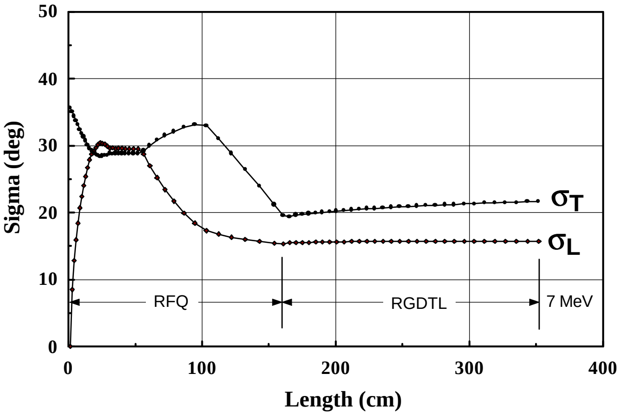

Fig. 3. Phase Advances (σ) for Matched RFQ/DTL.

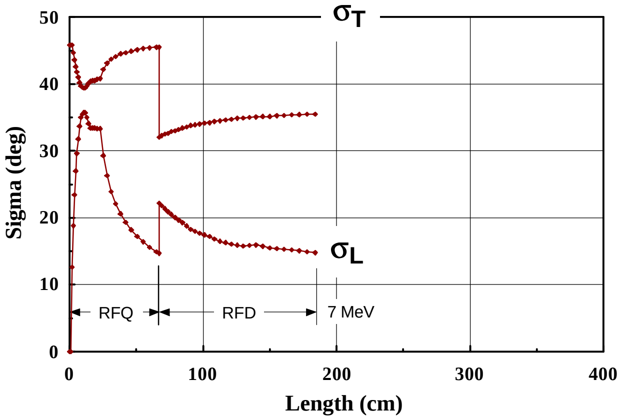

Fig. 4. Phase Advances (σ) for Unmatched RFQ/RFD.

The TRACE-3D program has been used to study this interface. The small "mismatch" between the two structures can be removed by making relatively small adjustment to the electrical properties of the first few cells in the RFD linac structure. The resulting solution is shown in Fig. 5. The ellipses on the left represent the phase space of the matched beam in the RFQ and the ellipses on the right represent the phase space of the matched beam in the RFD. The two waviest lines at the

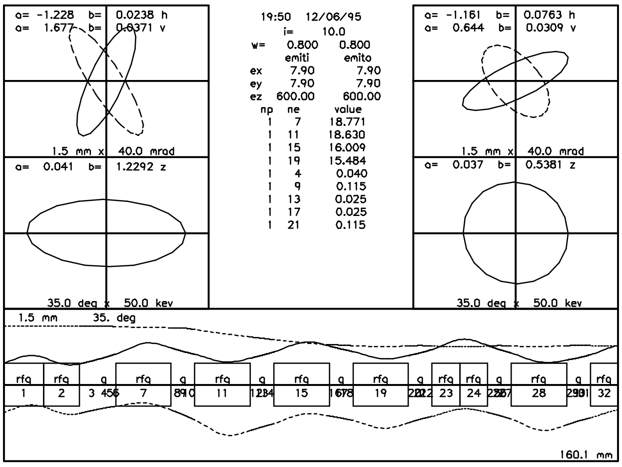

Fig. 5. TRACE-3D Solution for Matched RFQ/RFD.

bottom of the figure are the horizontal and vertical profiles of the beam through this region. The transverse match is accomplished by making minor adjustments to the strengths of the first four RFD lenses. The less wavy line is the longitudinal profile of the beam through this region. The longitudinal match is accomplished by making some changes to the “transit time factors” of first, third, and fourth RFD gaps.

The RFQ can be bolted directly to the RFD and the two can coupled with a resonant coupler. The resonant coupler serves to couple the excitation of the two linac structures by locking the relationship of the phase and amplitude of their fields to the desired values. In effect, it will extract the amount of rf power from the RFD structure required to excite the RFQ structure.

The stronger transverse focusing of the RFD linac structure results in smaller diameter beams, which allow higher frequency operation and imply better coupling (transit time factor) to the beam. The higher frequency and gradient operation will result in shorter and less expensive linacs for scientific, medical and industrial applications. Fig. 6 show the length of the RFQ/DTL and RFD/RFD linac combinations cited above for energies up to 7 MeV.

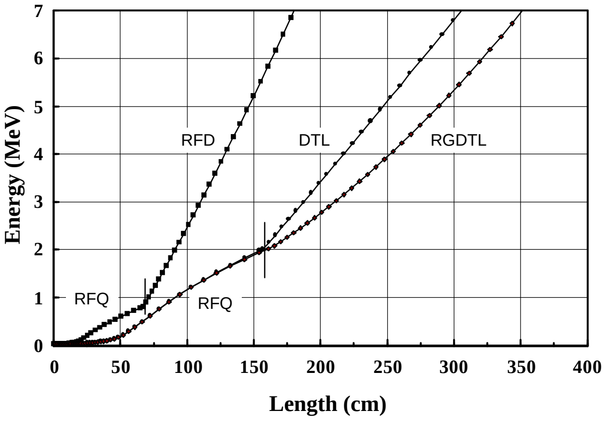

Fig. 6. Length vs. Energy for Three Linac Systems.

3 RFD HIGH-DUTY CAPABILITY

Three features of the RFD linac structure combine to suggest that it will have a much higher-duty factor capability than the equivalent RFQ linac structure: 1) In the energy range from 1 to 7 MeV, the shunt impedance of the RFD is 4 times that of the RFQ. Hence the rf power for the RFD is 1/4 of that for the equivalent RFQ. 2) The internal surface area of the RFD is twice that of the RFQ. Hence, the power density in the RFD is only 1/8 of that for the equivalent RFQ. 3) In this energy range, 90% of the power is dissipated on the cylindrical outer wall of the structure. The task of providing controlled cooling to a simple cylindrical structure is significantly easier than that of cooling a vane loaded RFQ structure.

We conclude that CW operation is eminently practical with the RFD linac structure. This, of course, remains to be proven.

4 POTENTIAL RFD APPLICATIONS

We expect the RFD linac structure to form the basis of a new family of compact, economical, and reliable linac systems serving a whole host of scientific, medical, and industrial applications. The principal medical applications include the production of short-lived radio-isotopes for the positron-based diagnostic procedures (PET and SPECT), the production of epithermal neutron beams for BNCT, and accelerated proton beams for injection into proton synchrotrons to produce the energies required for proton therapy. S-Band versions of the structure might prove economical enough to serve as 70-MeV injectors to 250-MeV coupled cavity linacs (CCL) for the proton therapy application.

The principal industrial and military applications include the production of intense thermal neutron beams for Thermal Neutron Analysis (TNA), Thermal Neutron Radiography (TNR), and Nondestructive Testing (NDT). High duty factor RFD linac systems could produce nanosecond bursts of fast neutrons to support Pulsed Fast Neutron Analysis (PFNA).

REFERENCES

[1] D.A. Swenson, “Rf-Focused Drift-Tube Linac Structure”, 1994 Int. Linac Conf., Tsukuba, Japan.

[2] D.A. Swenson, “A New Linac Structure for the BNCT Application”, 1994 Workshop - Accelerator-Based Neutron Sources for BNCT, Jackson,

[3] D.A. Swenson, K.R. Crandall, F.W. Guy, J.W. Lenz, A.D. Ringwall, L.S. Walling, “Development of the RFD Linac Structure”, 1995 PAC Conf., Dallas, TX.

[4] Linac Systems’ Web Pages: http://steps.atsi.edu/users/swenson/linac.html