Development of the RFD Linac Structure*

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The new Rf-Focused Drift-tube (RFD) linac structure resembles a drift tube linac (DTL) structure with rf quadrupole (RFQ) focusing incorporated into each "drift tube". As in the conventional DTL structure, these drift tubes are supported on single stems along the axis of a cylindrical cavity excited in the TM_{010} rf cavity mode. Four electrodes of each drift tube couple energy from the primary cavity mode to produce rf quadrupole focusing fields along the axis of the drift tube. The rf properties of this three-dimensional structure are being studied with the aid of HFSS (3D-rf code), CHARGE-3D (3D-electrostatic code), and SUPERFISH (2D-rf code). The beam dynamics of this structure is being analyzed with the aid of a new PARMILA-like beam dynamics code, PARMIR, and TRACE-3D. The results of these studies and descriptions of our target applications are presented.

I. Introduction

The RFD linac structure[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 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.

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.

II. Evolution of the Geometry

When first conceived, and as originally described, the rf focusing fields were completely contained within a drift-tube-like metallic shell. Indeed, there were some gaps in the shell allowing the fore- and aft-portions of the drift tubes to ride at different potentials, as determined by the axial electric field of the drift tube linac structure, thereby giving rise to a potential difference across the internal four-finger geometry that produced the rf quadrupole focusing field.

Even though a portion of the cell excitation is called upon for excitation of the rf quadrupole lens, the entire cell excitation is available for particle acceleration. The potential differences between the centers of drift tubes in the RFD structure is exactly the same as it is in the DTL structure for the same cell length and axial field.

In the DTL linac structure, the drift tubes concentrate the axial electric fields into the vicinity of the gaps resulting in a net acceleration from the rf fields, expressed quantitatively in terms of a transit time factor. In the RFD linac structure, the rf quadrupole electrodes extend the average potential of the drift tube along the axis towards the gaps, resulting in a concentration of electric fields in the gaps and acceleration from the rf fields, expressed in terms of a transit time factor.

For very short RFD cells, where a substantial portion of the cell voltage is required across the rf quadrupole lens, the original configuration tended to elongate the effective length of the gap fields, which resulted in a reduced transit time factor and acceleration rate. Our principal RFD geometry now involves rf quadrupole lens electrodes that are exposed to the rf gap accelerating fields. This results in transit time factors, for the RFD linac structure, that are similar to those of the more familiar DTL linac structure.

As originally conceived, the rf quadrupole lens electrodes were supported through thin rings of ceramic from a water cooled drift tube body, supported from the tank wall on a single stem as shown in Fig. 1. Recently, we have developed an understanding of the effects of inductive stems on the structure. Circuit-wise, these inductive-stem drift tubes appear as LC circuits in series with the drift tube linac gap capacitances. They offer better cooling for the two essential electrodes and elimination of the ceramic spacers. They still offer a complete drift tube package supported from the tank

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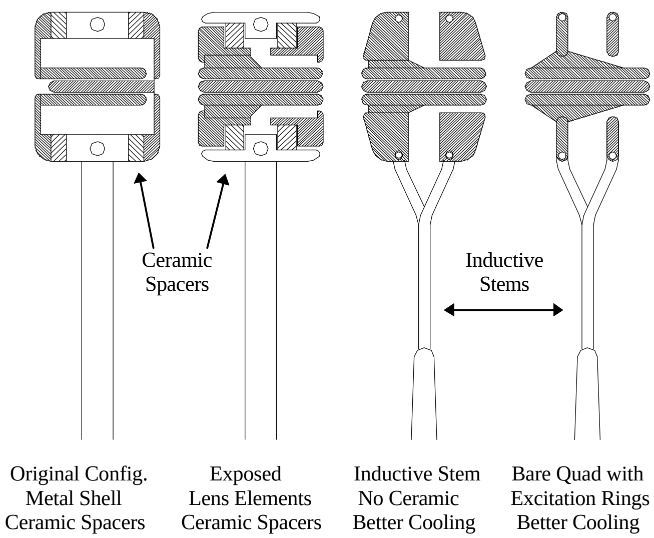
wall at a single point. The relative alignment of the four fingers can be inspected "on the bench" and adjusted if necessary. This preserves the simplicity of installation and alignment of our original configuration.

The latest step in the evolution of the RFD geometry involves the development of the "bare quad" configuration, which resembles four bare rods surrounded by two ring electrodes at different longitudinal stations, each of which are attached to an opposing pair of rods. The rods provide a good transit time factor for acceleration of the particles and a minimum capacitive loading to the drift tube linac circuit to insure the highest possible acceleration efficiency for a DTL-like structure. The rings provide a source of excitation for the rf quadrupole lens.

Fig. 1. Evolution of the RFD Geometry.



III. Merits of the Structure

The RFD Linac Structure opens the door to 850-MHz DTLs, just as permanent magnet quadrupoles opened the door to 425-MHz DTLs a decade ago. Each factor of two in frequency brings an order of magnitude reduction in the space available for focusing elements. The electrodes of the RFD are more readily scaleable to small dimensions than are permanent magnet quadrupoles.

Higher frequencies imply shorter cells and require smaller diameter beams for efficient acceleration. RFD linacs, which employ the same rf electric focusing as in RFQ linacs, will have the same small diameter beams that we have in RFQ linacs.

These higher frequencies offer higher efficiencies (shunt impedances), higher acceleration gradients (shorter structures), less rf power to generate, less thermal load on the cooling system, less weight, and less surface area to evacuate. These compact structures will be more transportable that their predecessors and, when required, will be easier to enclose in radiation shielding.

Fig. 2 compares the acceleration efficiencies for several linac structures that have been considered for 850-MHz operation, including the RFD, a permanent-magnet-focused DTL (PMQDTL), bridge-coupled DTL tanks (BCDTL)[2], and Coupled-Cavity DTL cells (CCDTL)[3]. The data are raw SUPERFISH results without any degradation for support stems, post couplers, coupling slots, bridge couplers, joints and/or surface finishes. The gap lengths in all cases were $\beta\lambda/4$. The RFD and PMQDTL, which include provisions for beam focusing within the basic structure, have bore diameters of 3 mm and are assumed to be long structures without significant end effects. The BCDTL and CCDTL structures, which do not provide focusing within the basic structure, have bore diameters of 6 mm and are broken at intervals of $5\beta\lambda$ for insertion of focusing elements with lengths of $1.5\beta\lambda$. The power and real-estate losses associated with these breaks are included in the net results. The drift tubes of all structures, except the PMQDTL, are 20 mm in diameter; the diameter of the drift tubes in the PMQDTL are 50 mm to accommodate the permanent magnet quadrupole lenses.

The RFD Linac Structure is also extendible to lower energies than possible for magnetically focused structures. At all proton energies above 0.5 MeV, the RFD structure, as shown in Fig. 2, is more than competitive with the RFQ structure. At 0.5 MeV, the RFD structure is approximately equal to the RFQ structure in acceleration efficiency; at 1 MeV, it is twice as efficient as the RFQ; at 2 MeV, it is 4 times more efficient; and at 5 MeV, it is 10 times more efficient. The RFD Linac Structure has significant advantages in acceleration efficiency over both RFQs and other DTL-like structures.

IV. Tools for the Development

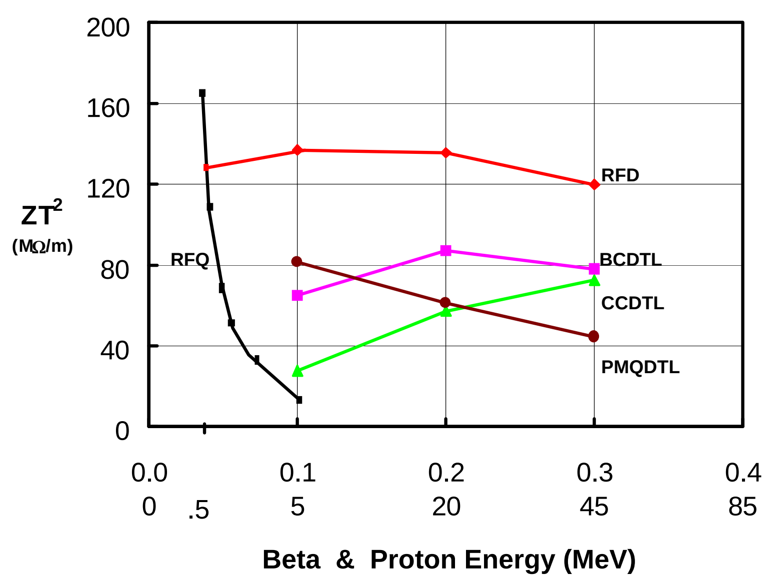


Fig. 2. Acceleration Efficiencies for Several Linac Structures.

The design and optimization of the drift tubes of the RFD Linac structure represents one of the most challenging technical tasks in the development of the structure. As the interior of the drift tubes are highly three dimensional, use of a 3D-RF code is required for precise information on resonant frequencies, field distributions, power dissipation, and other cavity parameters.

Calculations are currently in progress using Hewlett Packard's High Frequency Structure Simulator (HFSS) code, a 3D Finite Element RF and Microwave Modeling Code. It utilizes a solid modeling user interface, has a frequency domain solver, and requires at least one port to excite the structure. Output is in the form of s-parameters, fields, and field derived quantities. The elements of the geometry are tetrahedrons and structures can be developed as many different regions of differing element sizes. This allows accurate modeling, even for small irregular objects within larger structures, with a manageable problem size. The mesh is created and adapted automatically by the code. For complex geometries, the mesh generation process can be enhanced by "seeding" certain regions with user defined meshes. The code supports lossy materials and boundaries.

We have used the results from HFSS to verify that rf energy does indeed get inside the drift tubes, to reveal the field distribution along the axis of the drift tube, to establish the voltage division ratio between the drift tube gap and the rf lens, to get some indication of the strength and distribution of the rf fields inside the drift tube, to get some information on the distribution of the electric fields near the axis of the structure, to establish the frequency perturbation that the drift tube body capacitance imposes on the structure, and to get some idea of the ratio of the rf power losses inside the drift tube to the losses in the rest of the structure.

Once the effective properties of the interior of the drift tubes are determined by three dimensional calculations, effective use can be made of the two-dimensional rf codes, such as SUPERFISH, for further optimization of the structure. We have conceived of a SUPERFISH geometry that presents the correct capacitive loading to the cavity and has the correct effect on the axial field distribution. The resonant frequencies, voltage division ratios, and transit time factors agree quite well with those rendered by HFSS. HFSS has served to verify the utility of SUPERFISH for general RFD Linac design purposes.

The multipole content of the rf fields inside the fingers are essentially identical to what we find for electrostatic excitation of the fingers. Hence, useful approximations of these quantities are determined from the 3D electrostatics code, CHARGE-3D, written by one of the authors (KRC) in the early 1980's, and modified by him to support studies of the RFD linac structure.

The analysis and optimization of the beam dynamics in this structure represent another challenging technical task. A PARMILA-like beam dynamics code, PARMIR (Phase And Radial Motion In RFDs), was written to facilitate the study of the beam dynamics in this new linac structure. PARMIR simulates multiparticle beam dynamics in drift tube linacs that employ rf focusing inside the drift tubes. The formulation includes hard- and soft-edged quadrupole fringe fields and dodecapole effects. This code has been used extensively in our studies of the RFD structure. Recent modifications include a more precise soft-edged fringe field treatment, adjustability of bore size and lens voltage with beam energy, and incorporation of a variety of possible focusing options that may be advantageous for some applications.

Useful information of the performance of these structures can be obtained from the well known linear beam dynamics code, TRACE-3D. The RFD structure can be described to TRACE by using three types of elements; an RFQ with no acceleration, a drift, and an rf gap. Even though it cannot simulate non-linear fields or space charge forces, it can yield valuable information on the properties of the matched beam in the structures and a measure of their relative performance.

Thermal and mechanical analyses of the structures are being conducted with the aid of the finite element analysis code, COSMOS/M.

V. Applications for the Structure

At the present time, we are addressing the development of the RFD linac structure towards three distinctly different proton beam applications, namely;

1) Intermediate Energy (6-14 MeV), High Grad. (10 MV/m), Low Duty (0.5 - 2%), Proton Accelerator for the PET Isotope Production and/or Proton Synchrotron Injector Applications,

2) High Duty (100%), Low Energy (2.5 - 4 MeV), Low Grad. (1.5 MV/m) Proton Accelerator to produce Thermal and Epithermal Neutrons for the Neutron Radiography, Thermal Neutron Analysis (TNA), and Boron Neutron Capture Therapy (BNCT) Applications, and

3) Very High Frequency (3 GHz), High Energy (40-70 MeV), High Gradient (12 MV/m), Low Duty (0.1 %), Low Current (1-mA) Accelerator for the Proton Therapy Applications.

VI References

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