An Rf Focused Interdigital Ion Accelerating Structure*

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Abstract. An Rf Focused Interdigital (RFI) ion accelerating structure will be described. It represents an effective combination of the Wideröe (or interdigital) linac structure, used for many low frequency, heavy ion applications, and the rf electric quadrupole focusing used in the RFQ and RFD linac structures. As in the RFD linac structure, rf focusing is introduced into the RFI linac structure by configuring the drift tubes as two independent pieces operating at different electrical potentials as determined by the rf fields of the linac structure. Each piece (or electrode) of the RFI drift tube supports two fingers pointed inwards towards the opposite end of the drift tube forming a four-finger geometry that produces an rf quadrupole field along the axis of the linac for focusing the beam. However, because of the differences in the rf field configuration along the axis, the scheme for introducing rf focusing into the interdigital linac structure is quite different from that adopted for the RFD linac structure. The RFI linac structure promises to have significant size, efficiency, performance, and cost advantages over existing linac structures for the acceleration of low energy ion beams of all masses (light to heavy). These advantages will be reviewed. A “cold model” of this new linac structure has been fabricated and the results of rf cavity measurements on this cold model will be presented.

INTRODUCTION

Whereas the Alvarez drift tube linac structure, operating in the TM_{010} mode, has been the standard linac structure for acceleration of low energy protons, the interdigital drift tube linac structure, operating in the H_{110} mode, has been used for heavy ion acceleration for many years. One reason for this is that heavy ion acceleration generally favors the use of lower rf frequencies, where the diameter of the Alvarez linac structure is too large. The interdigital linac structure has a much smaller diameter at these low frequencies. Another significant advantage of the interdigital linac structure is its remarkable rf efficiency.

Rf electric focusing is particularly effective for focusing low energy proton beams during rf acceleration as evidenced by the tremendous popularity of the RFQ linac structure. It is even more important for focusing low energy heavy ion beams during rf acceleration where, because of the lower velocities for similar energies, the focusing forces of the magnetic option are weaker. The Rf Focused Drift tube (RFD) linac structure was developed\(^1\) to extend the remarkable rf focusing properties of the RFQ linac to higher energies and higher efficiencies. The RFD linac structure, however, is based on the TM_{010} cavity mode and, because of its large size at low frequencies, is not attractive for heavy ion applications. In this paper, we introduce the Rf Focused Interdigital (RFI) linac structure\(^5\), which promises to be an attractive alternative for both proton and heavy ion applications.

![FIGURE 1. The radii of the RFI and DTL linac structures in centimeters at 200 MHz.](image)

The size advantage of the RFI linac structure over the conventional drift tube linac is shown in Fig. 1. The interdigital structure is approximately one third the diameter of the Alvarez structure for the same...
frequency. The efficiency advantage of the RFI linac structure over the competition is shown in Fig. 2. The interdigital structure is 4 to 5 times more efficient than the Alvarez structure and 10 to 20 times more efficient than the RFQ in the energy range from 1 to 5 MeV. The rf electric focusing in the RFI linac structure results in better low energy performance and smaller diameter beams throughout the structure, which further enhances the efficiency over magnetically focused structures.

![Graph showing rf efficiencies (MΩ/m) of the RFI, DTL, and RFQ linac structures at 200 MHz.](image)

**FIGURE 2.** The rf efficiencies (MΩ/m) of the RFI, DTL, and RFQ linac structures at 200 MHz.

The drift tubes of an interdigital linac structure alternate in potential along the axis of the linac. Consequently, the electric fields between the drift tubes alternate in direction along the axis of the linac. The longitudinal dimensions of the structure are such that the particles travel from the center of one gap to the center of the next gap in one half rf cycle. Hence, particles that are accelerated in one gap will be accelerated in the next gap because, by the time the particles arrive there, the fields have changed from decelerating fields into accelerating fields.

In most drift tube linac structures, the drift tubes are supported on, and cooled through, drift tube stems extending from the wall of the cavity. In the interdigital linac structure, it is common to support the drift tubes alternately from the top and bottom (or left and right side) of the cavity to achieve the desired alternation of their polarity. These same practices have been adopted for the RFI structure. One possible configuration for the RFI structure is shown in Fig. 3.

![One possible configuration for the RFI Linac.](image)

**FIGURE 3.** One possible configuration for the RFI Linac.

![RFI drift tube, exploded and assembled.](image)

**FIGURE 4.** RFI drift tube, exploded and assembled.

The longitudinal distribution of the acceleration, focusing, and drift actions are quite different between the RFI and RFD linac structures. For example, when the accelerated particles are half way between the accelerating actions of the RFI structure (i.e. within the drift tube), the electric fields are near maximum strength in the opposite direction and are suitable for focusing the beam. When the accelerated particles are two thirds of the way between the accelerating actions of the RFI structure (i.e. in the latter portion of the drift tube), the electric fields are passing through zero operating at different electrical potentials as determined by the rf fields in the linac structure. Each piece (or electrode) supports two fingers pointed inwards towards the opposite end of the drift tube forming a four-finger geometry, as shown in Fig. 4, which produces an rf quadrupole field along the axis of the linac for focusing the beam.
strength and are not suitable for focusing the beam. As a result, the focusing action must be pushed forward (upstream) to lie as close to the accelerating gap as possible, leaving the latter portion of the drift tube solely as a drift action (no focusing, no acceleration). Hence, the drift tubes of the RFI linac structure are asymmetrical, consisting of a minor piece and a major piece as shown in Fig. 4.

The acceleration gaps (between the drift tubes) and the focusing gaps (inside the drift tubes) form capacitive dividers that place a portion of the rf acceleration voltage on each rf focusing lens. In order not to short out this focusing potential, the two-piece drift tubes are supported on two stems emanating from a single base, with each stem supporting one electrode of the two-piece drift tube. The major piece of each drift tube is supported on a major stem, while the minor piece is supported on a minor stem located upstream of the major stem. The two stems form an inductive divider, coupled to the magnetic fields surrounding the stem that yields the same potential difference to the rf lens that the capacitive divider does. This prevents the drift tube supports from shorting out the rf focusing lenses.

ACCELERATING AND FOCUSING FIELDS

The beam bunches arrive at the centers of the gaps between the drift tubes at times when the electric fields are optimum for acceleration. At this phase, the electric fields in the gaps are in the proper direction for acceleration of beam and are approaching their maximum magnitude. Typically, the acceleration phase is designed to be $30^\circ$ in advance of the peak magnitude in order to provide a longitudinal focusing action on the beam to keep it bunched. Associated with this choice of acceleration phase is a weak transverse defocusing action that must be overcome by additional transverse focusing incorporated into the linac structure.

The beam bunches arrive at the centers of the rf quadrupole focusing region one sixth of an rf cycle later when the electric fields have passed through their peak magnitude and are beginning to decrease. At this phase, the rf quadrupole fields within the drift tubes will provide a focusing action on the beam in one transverse plane and a defocusing action on the beam in the other transverse plane. As the azimuthal orientation of the four-finger geometry alternates from one drift tube to the next, the orientation of the transverse focusing fields alternates, resulting in a net transverse focusing in both transverse planes.

BEAM DYNAMICS

The beam dynamics performance of the RFI linac structure was investigated with the aid of TRACE-3D, a well-known, linear beam dynamics computer program. The effects of the rf acceleration and focusing fields in the RFI linac structure on low intensity beams of charged particles passing through the structure have been analyzed. These calculations establish the capabilities of the RFI linac structure for acceleration of low intensity beams of protons, deuterons, and heavier ions.

At higher intensities, the repulsive electric forces between the charged particle of the beam have a defocusing effect on the beam, tending to reduce the net focusing action provided by the RFI acceleration and focusing fields. The beam current at which this effect jeopardizes the useful performance of the linac structure is referred to as the “space charge limit”. The most restrictive space charge limit occurs at the very beginning of the linac where the beam energy is the lowest. The space charge limit of the RFI linac structure was investigated, using the TRACE-3D program, for all combinations of two operating frequencies (100 and 200 MHz) and three injection energies (0.5, 1.0, and 2.0 MeV). In all of these cases, the space charge limits were in excess of 60 mA. At 200 MHz, the space charge limits were in excess of 100 mA. These calculations establish the capabilities of the RFI linac structure for acceleration of high intensity beams of protons, deuterons, and heavier ions.

A PARMILA-like beam dynamics code, PARMIR (Phase And Radial Motion In RFDs), was written to facilitate the study of the beam dynamics in the RFD linac structure. Some modifications were made to this program to support beam dynamics studies of the RFI linac structure. PARMIR now simulates multi-particle beam dynamics in drift tube and interdigital linacs that employ rf focusing inside the drift tubes.

RF EFFICIENCY

Figure 2 shows the rf efficiency of the RFI linac structure to be 4 to 5 times that of the conventional DTL linac structure. It’s hard to understand how this can be!
For energies where the drift tubes are relatively short, the rf losses in the DTL structure come primarily from the longitudinal currents on the outer wall of the structure. There are no net currents on the drift tube support stems, and the rf losses on the drift tubes are negligible.

In the same energy region, the rf losses in the RFI structure come from significant radial currents on each drift tube support stem and similar transverse currents on the outer wall of the structure. Again, the rf losses on the drift tubes are negligible.

A simple analysis of the rf circuits for equivalent lengths of the two structures at 3 MeV suggests that the resistance of the rf circuit in the RFI structure is 137 times that of the DTL structure. On the other hand, for equivalent excitations, the total stored energy in the DTL structure is 28 times that of the RFI structure and the total rf current in the DTL structure is 22 times that of the RFI structure. Hence, the $I^2R$ losses for the RFI structure is only 28% of that for the DTL structure.

Relative to the magnetically focused DTL structure, the distributed rf focusing of the RFI linac structure results in smaller diameter beams, allowing smaller diameter bore holes, which result in better transit time factors. This, coupled with the lower power losses, supports the rf efficiency advantage shown in Fig. 2 for the RFI linac structure.

The rf efficiency of the RFI linac structure is so high that CW operation should be quite practical. The tendency to think of rf linacs as pulsed devices may be a thing of the past.

**COLD MODEL**

Whereas, much can be learned from cavity field calculations, much can also be learned from the measurement of rf field distributions and cavity modes in a cold model. Here, the term “cold model” refers to a relatively simple mechanical model of the structure, without the complications of vacuum seals and/or cooling channels.

A cold model of the RFI linac structure, shown in Fig. 5, is in fabrication. Initially, this model will be used to study the proposed interdigital linac structure, without the complication of the two-piece drift tubes supported on two stems. The “bead perturbation” technique will be used to measure the axial field distribution as a function of stem diameters and end wall tuning. Next, a few RFI-type drift tubes and stems will be fabricated and tested in this model.

![RFI cold model in fabrication.](image)

The 0.5-m-long cold model is designed to resonate at 200 MHz and will have 12 drift tubes spanning the proton energy range from 0.5 to 2 MeV. Rf calculations suggest that the inner diameter of the tank must vary from 240 to 300 mm over that energy range.

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**REFERENCES**


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