High Efficiency and Low Cost LINAC System Design Suitable for High Energy Ion Implanters

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***Abstract*—A new radio frequency (rf) linear accelerator (LINAC) system with high efficiency has been developed by AIBT. The general designs of such a rf LINAC system are briefly discussed. This system includes a plurality of resonators each including an inductor circuit that is connected to at least two rf electrodes. Detailed designs of a system where two of the adjacent rf electrodes are connected to the same inductor circuit are presented. A prototype LINAC system of one resonator that has an inductor circuit connecting two rf electrodes was constructed and tested. The beam energy gains ($11B^+$ ions) of the prototype system were demonstrated to be 230 keV with input rf power of 2 kW. This result indicates that one can accelerate singly charged ions from 80 keV to 1 MeV with a four resonator LINAC system and 10 kW electric power.**

I. INTRODUCTION

Strong rf electromagnetic fields, bounded by resonant cavities, are commonly used in particle accelerator systems to accelerate charged particle beams. Gustav Ising proposed the first accelerator that used time-dependent fields in 1924[1]. The concept proposed by Ising was not tested until Rolf Wideroe conceived and experimentally demonstrated the first RF linear accelerator in 1927 [1]. The LINAC built by Wideroe was the forerunner of all modern RF accelerators. Wideroe's concept was to apply a time-alternating voltage to a sequence of drift tubes whose lengths were increased with increasing particle velocity so that the particles would arrive in every gap at the right time to be accelerated.

In Wideroe's experiment, an rf voltage of 25 kV from a 1-MHz oscillator was applied to a single drift tube between two grounded electrodes, and a beam of singly charged potassium ions gained the maximum energy in each gap. A final beam-energy of 50 keV was measured, which was twice that obtainable from a single application of the applied voltage. This was also the first accelerator to deliver a net energy gain to the beam with ground potential at both the entrance and the exit ends. The experiment established the principle that unlike an electrostatic accelerator, the voltage gain of an rf accelerator could exceed the maximum applied voltage.

Wideroe's experiment had great influence on modern LINACs. In 1931, Sloan and Lawrence built a Wideroe-type LINAC with 30 drift tubes and by applying 42 kV at a frequency of 10 MHz, they accelerated mercury ions to an energy of 1.26 MeV [2]. Kapchinskly and Tepliakov first presented the principles of operation of a radio-frequency quadrupole LINAC (RFQ) [1], which had four electrodes with modulated shapes to produce transverse and longitudinal electric fields to achieve both focusing and acceleration of charged particle beams.

LINAC technology has been used for accelerating ions up to MeV range for ion implantation application since 1980.[3] The recent development of LINAC focuses on improvement of LINAC power efficiency to reduce build cost and power consumption.[4]. Different from the RFQ LINACs, which have very small mass and energy operation ranges, a LINAC used in ion implantation is very similar to Wideroe's LINAC and consists of individual rf electrodes that can accelerate ion beams up to MeV energies (Fig. 1). Each rf electrode can be driven to a very high voltage (40 - 100 kV) by a resonant LC circuit. The resonant circuit including a coil, rf electrode(s), and enclosure wall, is referenced to as a resonator. The merit of the individual resonator configuration is that each resonator can be independently tuned and giving the LINAC more flexibility for accelerating ion species with different masses and charge states to achieve the desired ion energy.

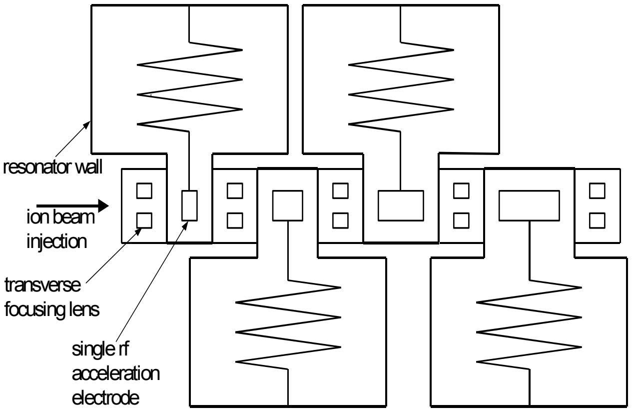

Figure 1 Functional block diagram of a conventional LINAC built with single electrode resonators.

However, each resonator assembly, including the resonator, rf amplifier, and tuning electronics, is very expensive. A resonator also consumes several kilowatts of electric power. Most of the power is dissipated as heat inside the resonator and less than 5% of the electric power can be used to accelerate the ion beams.

Increasing electrical efficiency of a LINAC system can reduce power consumption and the cost of rf accelerators to reach the same final ion energy. For the same power consumption per resonator, higher power efficiency also means higher output voltage on the rf electrodes, resulting in higher energy gain per resonator. This allows a reduction in number of resonators needed to obtain the same final ion energy. Glavish [5] claimed that his single electrode resonator could deliver 95 kV rf voltage on the rf electrode with 2.6 kW rf input power. Since there were two rf acceleration gaps in this single-electrode resonator system, the maximum energy gain per square root of input power (since rf voltage square is proportional to rf power) is 118 keV/(kW)$^{1/2}$ for a singly-charged ion. A single-electrode resonator that is used in an existing high energy implanter delivers 80 kV rf voltage with 3.0 kW input power. The maximum energy gain per input power would be 92 kV/(kW)$^{1/2}$.

Increasing the number of acceleration gaps is another way to increase energy gain per square root of input power. Fujisawa's triple-gap rf resonator could obtain an energy gain of 216 kV at input power of 5 kW [6]. The energy gain per input power was 97 kV/(kW)$^{1/2}$.

The above mentioned double-gap and triple-gap resonators have energy gain per input power around 100 kV/(kW)$^{1/2}$, proven by beam tests. This number is lower than desired and contributes high electric power consumptions and building costs of rf LINAC systems used in high energy ion implanters. Therefore, it is necessary to use a new approach to increase the acceleration efficiency. This paper presents a multiple-rf-electrode resonator that demonstrates a new concept for ion beam acceleration with the objective of providing much higher acceleration efficiency.

II. PRINCIPAL DESIGNS

The object of the design is to provide a new ion acceleration system for improving the ion acceleration efficiency by reducing the required number of resonators employed for an ion accelerator system. The new rf linear acceleration system is implemented with a new configuration by connecting at least two rf electrodes to an inductive circuit of the resonator. The number of inductive circuits (or resonators) required for generating high voltage rf resonating voltages are reduced and cost savings are achieved with this new configuration.

The geometry between the electrode and the focusing lenses are arranged to produce maximum acceleration by taking into account of the ion velocity, the frequency of the resonator and the mass/charge ratio of the ions. Improved acceleration efficiency is achieved so that required electric power input per rf electrode is reduced.

The new rf LINAC system includes a plurality of transverse focusing lenses, represented by lenses(j), where j=1,2,3, . . . n, and n is an integer, for guiding and focusing an ion beam. The rf LINAC further includes a plurality of resonators. Each resonator has an inductor circuit L(k), k=1,2,3, . . . , n' where n' is a second integer, wherein the inductor circuit is connected to at least two electrodes E(j'), j'=1,2,3, . . . (n-1), for applying an accelerating rf voltage thereto. Each of the electrodes E(j') is disposed between, and aligned with, two sets of the transverse focusing lenses (j') and lenses(j'+1), j'=1,2,3, . . . (n-1), as a linear array. There are at least two of the adjacent electrodes E(j') and E(j'+1) to be connected to a same inductor circuit L(k).

Fig. 2 shows the typical design of the rf LINAC system for accelerating an injected ion beam (110). The LINAC system includes a plurality of transverse focusing lenses (115) for guiding and focusing the injected ion beam (110) to project along a linear path. The LINAC further includes a plurality of resonators (120) enclosed in the resonator walls (125). Each resonator (120) includes inductor (L) circuit (130) with the resonator walls (125) serving as capacitor (C) to form an LC circuit. Each of the inductor circuits (130) are connected to two rf electrodes (135) in the resonators (120). The LC circuits drive the rf electrodes (135) to a very high voltage. As shown in the following discussions, when two rf electrodes are connected to a single resonator as shown in Fig. 2, the energy gain per input power is increased by a factor of two if power efficiency is the same. Therefore, the number of resonators in a LINAC can be reduced by a factor of two for the same final energy.

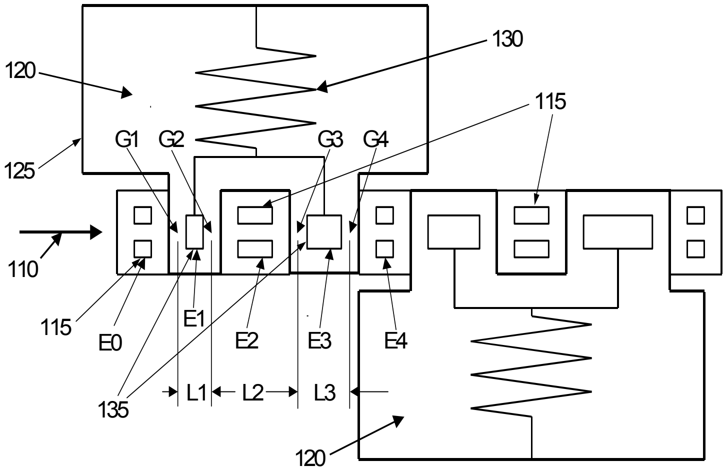

Figure 2. Functional block diagram of a rf LINAC built with double electrodes for each of the resonators.

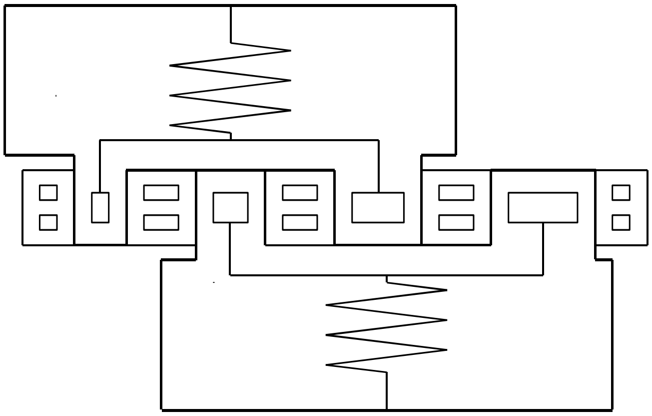

Figure 3. Functional block diagram of another rf LINAC built with double electrodes arranged with alternate neighboring configuration for each of the resonators.

There are several ways to connect a resonator with two electrodes in a LINAC as shown in Figs. 2 and 3. Fig. 2 shows a configuration with two neighboring rf electrodes connected to a single resonator and Fig. 3 shows a configuration with every other two neighboring rf electrodes connected to a resonator. In Fig. 2, since the two rf electrodes (135) are connected to each other and are also connected to the end of the inductive coil (130), the electrodes (135) have the same rf potential at any given time. A proper drift space is required between these two electrodes (135) in order to obtain optimal acceleration for ions.

Referring to Fig. 2 there are four acceleration gaps in this system labeled as G_1, G_2, G_3, and G_4. The distances between the midpoints of these gaps are L_1, L_2, and L_3. The intial energy of a singly charged ion of the ion beam (110) is E_0. (For simplicity, we will refer to all ions as singly-charged ions in the following discussion). Energies of the ion inside the first rf electrode, the drift space between G_2 and G_3, and the rf second electrode are represented by E_1, E_2, and E_3 respectively, and the final energy is E_4. The energy gain ΔE_i at each gap is approximately expressed as follows,

$$\Delta E_i = \Delta E_i - \Delta E_{i-1} = VT_i \cos(\Phi_i), \qquad (1)$$

where, V is the rf amplitude for all four gaps, . Φ_i is the rf phase at the ith gap when the ion is at the center of the gap, and T_i is the transit-time factor of the ion at the ith gap. In order to obtain maximum acceleration at each gap, the phase shift between the adjacent gaps should be ~ π, which can be realized by properly choosing L_i depending on rf frequency, mass and energies of an ion. Ideally, the final energy after the ion passing through the four gasps as shown in Fig. 2 is,

$$E_4 = E_0 + VT_1 + VT_2 + VT_3 + VT_4 = E_0 + 4V \quad (\text{if } T_i = 1). \qquad (2)$$

The energy gain of this double-electrode resonator is approximately 4V. Considering the energy gain of the single-electrode resonator is about 2V, the double-electrode resonator actually has twice of the energy gain per resonator if the amplitude V, or the power efficiency, is unchanged.

III. BEAM TESTS

Figure 4 shows a layout of the beamline to test ion energy gains in one resonator. The ion injection system comprises a Bernas ion source and 90° analyzer magnet. The system can select desired ion species and accelerate ions to 70 keV. There is a 90° final energy analyzer magnet at the end of the beamline. Two Faraday cups, one before the LINAC and another after the energy analyzer, measure beam currents. A 6 inch silicon wafer can be mounted at the end of the beamline and an implantation can be carried out. The LINAC was constructed based on the principles discussed previously in the last section, as shown in Fig. 2. A rf bunch circuit and two quadrupoles are build in the LINAC system to increase beam transmission for bunched beams and reduce peak widths in a energy spectrum and widths are functions of beam energy and angular spreading.

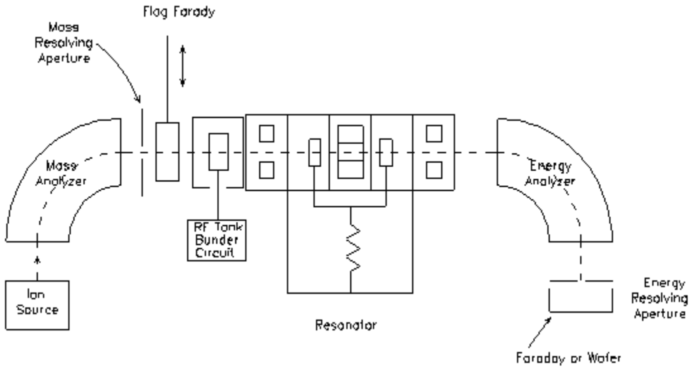

Figure 4. Beamline set up with double rf electrode LINAC

Boron beams were used to test the LINAC acceleration performance. Boron or other atom/molecular ions were generated in the ion source and accelerated to 70 keV (singly charged ions) with the dc acceleration. The boron ions (AMU ~ 11) were selected by the mass analyzing magnet. A Flag Faraday cup was used to set up the injection beam. The flag Faraday cup could be removed from the beam path and the 70 keV boron beams were injected to the LINAC. The two rf electrodes hung on the two ends of the resonator coil could drive a potential that is function of rf input power to the coil and a proper impedance match. 2 kW rf power was successfully delivered to the coil and the rf electrode potential was measured to be ~ 60 kV. The beam was accelerated to a final energy of 300 keV. An ion beam spectrum obtained by varying the magnetic fields of the final energy magnet is shown in Fig. 5. There are two peaks in the spectrum, smaller one (at ~ 70 keV) results from the injection beam and larger (at ~ 300keV) one is the accelerated beam. The net energy gain is 230 kV with a single resonator and 2 kW input power. The energy gain per square root of power is 160 $kV/(kW)^{1/2}$. This means only 4 resonators and 8 kW rf power are needed to accelerate singly charged ions from 80 keV to 1 MeV. This LINAC design can reduce the resonator number and rf power by a factor of 2. We expect that the double rf electrode LINAC system can be built and operated at half costs of a single electrode LINAC system. The parameters of the buncher and the quadrupoles were optimized to obtain the reasonable energy spectrum as shown in Fig. 5. The energy spreading can be further improved if a series of quadrupoles are installed along the acceleration path.

The $11B^+$ final energy was confirmed further by an implant. 6" wafers were placed at the end of the beamline as shown in Fig. 4. The 300 keV boron beams were set up and the wafers were implanted with the beams. Fig. 6 shows two SIMS depth profiles (curves A and B) of 300 keV boron ($11B^+$) implants at doses of ~ 1×10^{14} cm^{-2}. The SIMS results are very close to the results produced by Nagai et al. [7].

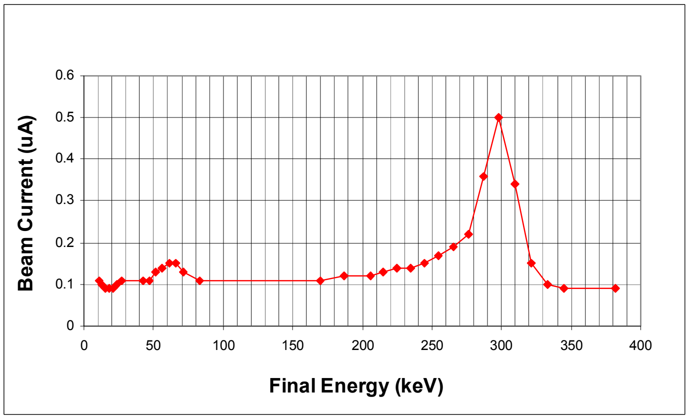

Figure 5. Boron beam energy spectrum, injection energy of 70 keV, and rf power of 2 kW.

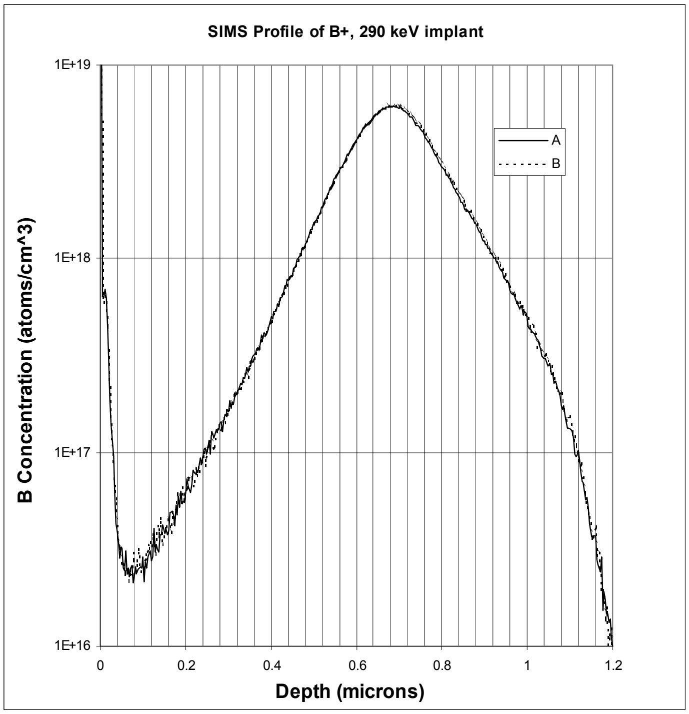

Figure 6. SIMS depth profiles of a 300 keV, 1×10^{14} cm^{-2} 11B^{+} implants.

IV. CONCLUSIONS

The LINAC system design discussed in this paper addresses the issue of improving the ion acceleration efficiency by reducing the required number of resonators. This will greatly reduce the manufacturing and operational costs of an accelerating system. The concept of more than two rf electrodes connecting to a resonator coil are proposed and discussed in this paper. A double rf electrode LINAC system was constructed. We have demonstrated, from this system, an energy gain of 230 kV per resonator assembly, which is twice the energy gain from a conventional resonator assembly used in a high energy ion implanter.

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