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MEMS BASED MULTI-BEAM ION LINAC*

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Abstract

We report on the development of multi-beam RF linear ion accelerators that are formed from stacks of low cost wafers. Wafers are prepared using MEMS techniques. We have demonstrated acceleration of ions in a 3×3 beamlet array with ion currents in the 0.1 mA range and acceleration of 10 keV in a lattice of RF (13 MHz) acceleration units and electrostatic quadrupoles. We will describe the status and plans for scaling to 10×10 beams, ion currents >1 mA and ion energies >100 keV in a compact, low cost setup for applications in materials processing.

INTRODUCTION

Beams of energetic ions are widely used in manufacturing and for the development of nuclear materials where the energetic ions mimic damage induced by neutrons. Today, energetic ions are delivered to targets from accelerators in single beams with ion currents in the range of microampere to a few milliampere. The achievable ion current density is limited by space charge forces and the total ion current is limited by the size of the extraction aperture from which ions can be extracted to form a beam with low enough emittance for efficient transport in the beam line [1]. The concept of multi-beam ion accelerators was developed in the late 1970s by Maschke et al. with the concept of a Multiple Electrostatic Quadrupole Linear Accelerator (MEQALAC) [2]. MEQALACs are RF-driven linear accelerators where the total ion current can be scaled by adding more beams and the ion kinetic energy can be increased by adding accelerator modules. In the first implementations, MEQALACs used RF cavities to achieve ion acceleration with high voltages driven at frequencies in the 25 MHz range [3]. We have recently reported on the development of multi-beam RF accelerators that we assemble from stacks of low cost wafers [4, 5]. We form RF-acceleration structures and electrostatic quadrupole (ESQ) focusing elements on printed circuit board and silicon wafers with 10 cm diameter using standard microfabrication techniques [6]. In our prior work, we have extracted 0.1 mA Ar^+ ions through an array of 3×3 beamlets and demonstrated beam acceleration at an energy gain of 2.6 keV/gap [7]. In the article, we will describe the status and plans for scaling to 10×10 beams, ion currents >1 mA and ion energies >100 keV in a compact, low cost setup for applications in materials processing.

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STATUS OF POWER SCALING

The approach we have taken to scale the ion current to 1 mA is to use more beamlets. With an aperture of 0.5 mm in diameter, we expect to extract 10 µA of Ar^+ from each aperture and reach a total current of 1 mA, a factor of ten increase compared to our prior experimental results. This uses our existing ion source, where we have not invested into pushing the current density. Ion sources with improved current densities can be adapted to our beamlet arrays in the future, further boosting the total ion current.

We have fabricated a new ion extraction column, that consists of total 120 beamlets, as shown in Fig. 1. The size of each extraction aperture is 0.5 mm in diameter, and the center-to-center distance is 3 mm. The region that covers all the 120 apertures is about 3.5 cm in diameter. This design is denser than the original 3×3 arrays (center to center distance was 5 mm). Further optimization of beamlet density might be possible and we will learn about this from the performance of our new arrays.

Figure 1: Extraction column with total of 120 beamlets (each of which is 0.5 mm in diameter, and 3 mm center-to-center spacing).

With the new extraction column, we were able to achieve a current of ~0.5 mA of Ar^+ ions, as shown in Fig. 2. We are still investigating the reason why the total current we measured is a factor of 2 lower than expected. One cause may be that the region of uniform plasma in our ion source is estimated to be about 2 cm in diameter, only covering about 33% of the total 120 beamlets. We are in the process of improving the ion source uniformity.

To realize higher current, we have started fabrication of RF (radio-frequency) and ESQ (electrostatic quadrupole) wafers with 120 beamlets. Compared with the 3×3 wafers developed previously, we decrease the center-to-center distance of adjacent unit cell from 5 mm to 3 mm.

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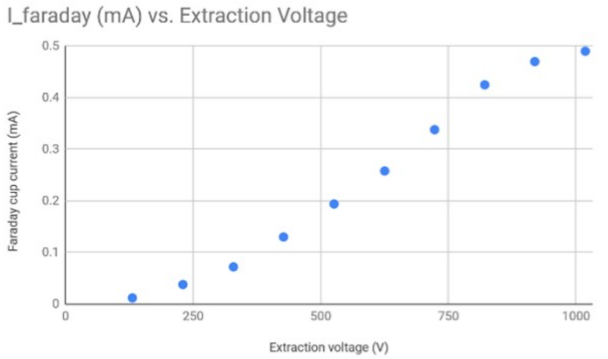

Figure 2: The measured total Ar^+ current in the Faraday cup reached 0.5 mA from an array of 120 extraction apertures as shown in Figure 1.

For RF wafers, we used laser micromachining (LPKF ProtoLaser U4) to pattern the top and bottom metal layers, and to drill holes through the PCB (printed circuit board). Alignment between the top and bottom is achieved by using an integrated vision system and prefabricated alignment fiducials. Steps of the process to fabricate RF wafers are given in Fig. 3. In this process, we start with a FR-4 based board that has copper on both sides as seen in the cross section (Fig. 3(A)). The circular holes are created using a laser tool. Then laser cutting is used to define the top and bottom metal routing. The layout of the fabricated RF wafer are shown in Fig. 3(B). Figure 3(C) shows one unit cell of the design. The copper trace is reduced from 700 µm to 200 µm to fit more beamlets on one wafer. The decrease of metal area also decrease the capacitance of the wafers, which benefits in driving the RF wafers with the power amplifiers.

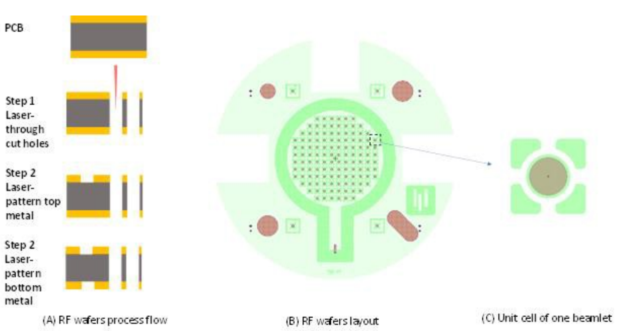

Figure 3: (A) PCB fabrication procedure of RF wafers (B) Layout of RF wafers. The red holes are the laser cut through part and the dark green is places where metal is removed. (C) Design of a unit cell.

We have assembled our first RF stack with 120 total beamlets. The photo of the assembly is shown in Fig. 4. The measured capacitive load of this unit is approximately 23 pF.

The layout of the ESQ wafers and the details of one unit cell of the design are shown in Fig. 5. The microfabrication of ESQ PCB wafers is in progress.

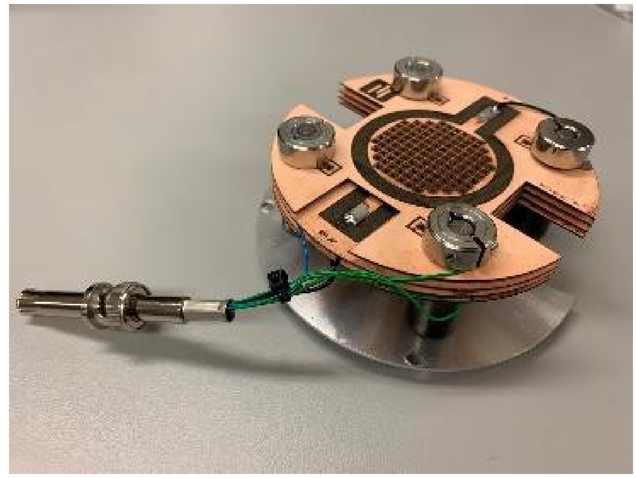

Figure 4: First RF stack made out four PCB wafers with 120 beamlet apertures were manufactured by laser-cutting and have been successfully assembled.

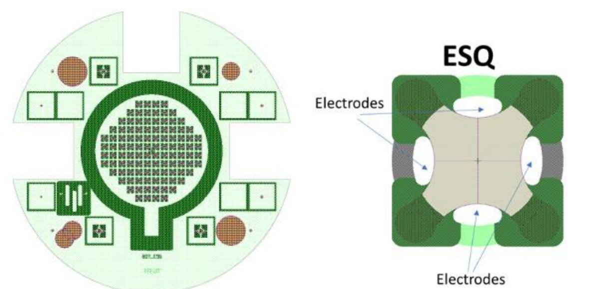

Figure 5: (Left) Layout of ESQ wafers. The red holes are the laser cut through part and the dark green is places where metal is removed. (Right) Design of a unit ESQ cell.

We have made a lot of progress in design and board-level implementation of both the 13.56 MHz and 27.12 MHz RF power amplifiers. The topology of the high-frequency power amplifier is shown in Fig. 6. A full-bridge inverter converts

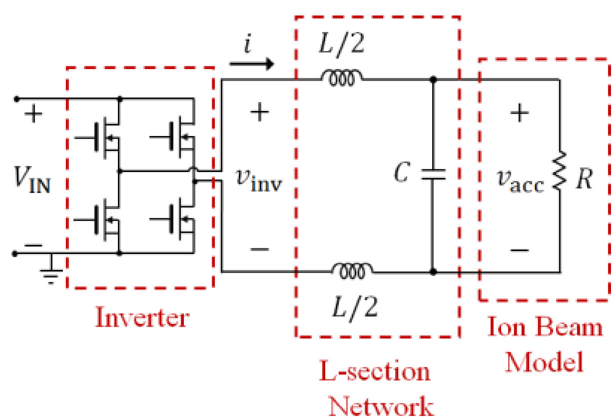

Figure 6: Schematic of the 27.12MHz RF power amplifier.

the dc input voltage (VIN) into a high-frequency ac voltage (vinv), which is stepped up by an L-section matching network to produce the large ac voltage required to accelerate

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the ion beams. In Fig. 6, the load presented by the energy transferred to the ion beam is modeled by a resistive load. When the amplifier is operated at the multi-MHz level frequency, it is desirable to maintain zero-voltage switching (ZVS) of the inverter transistors so as to minimize switching losses and ensure that the inverter is thermally stable. The power amplifier of Fig. 6 is designed to provide a desired voltage gain while ensuring ZVS of the inverter transistors.

Two high-frequency prototype power amplifiers are designed to produce up to 10 kV output voltage, and are built and tested. Bench tests indicated that the peak output voltage of the 13.56 MHz prototype is 10 kV, and for the 27.12 MHz prototype, the peak output voltage is 8.3 kV.

WARP particle-in-cell simulations were set up to optimize ESQ parameters and help further understanding of beam acceleration and transport. This will also help us improve the design to optimize the performance of the compact accelerator. The calculations of fringe fields, space charge effects, exit lens effects, transit time effects, and image charge effects are non-trivial for particle bunches in our RF linac structure. Examples of a Warp output file for an ion bunch going through several consecutive RF gaps are shown in Figs. 7 and 8. The simulation are still a work in progress.

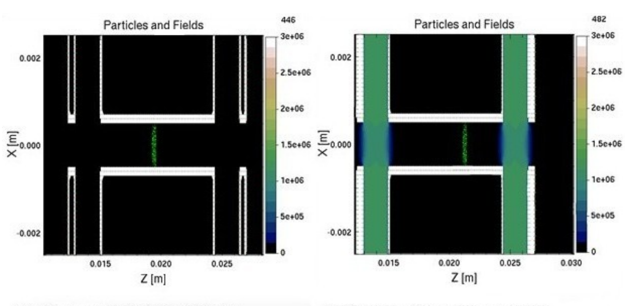

Figure 7: An example of a Warp output file of a 1ns-long particle bunch going through RF gaps. Z is the axial direction of ion travel and coincides with the accelerator main axis. X and Y are the transverse directions normal to the Z axis. On the left the particles are travelling in a drift gap in between an RF unit when the voltages on the RF wafers are zero. On the right the particles are approaching the right acceleration gap with the RF voltage increasing in value.

SUMMARY

We have fabricated a new ion extraction column and assembled the first RF stachs with 120 beamlets that will enable us to achieve 1 mA of total current. We have also demonstrated that the RF power amplifier circuits at both 13.56 MHz and 27.12 MHz can achieve voltage output higher than 8 kV, which is an important step to scale the ion energies to >100 keV.

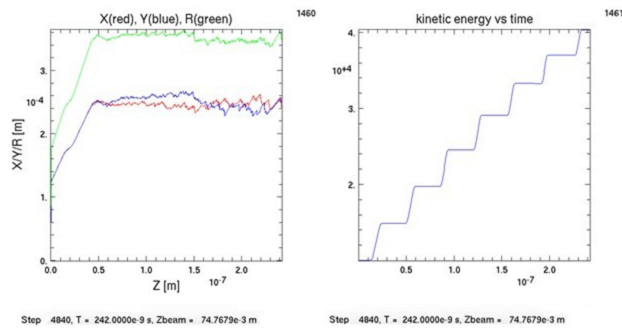

Figure 8: On the left, the average of the tracked particles movements in the x, y and radial direction are plotted against distance traveled. On the right, the average kinetic energy is plotted versus time, showing energy gain in steps. It also shows a gradual decrease in the amount of kinetic energy gained in consecutive acceleration gaps, indicating that the RF phase or acceleration gap placement is not yet optimized in phases in this simulation.

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