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4-Rod RFQ Proton Acceleration Tests

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A 4-Rod RFQ was constructed to accelerate protons from 30 keV to 100 KeV. The PARMTEQ code was used to determine the RFQ parameters at the operating frequency of 100 MHz and 10 kV inter-electrode voltage. The RFQ structure was installed in the copper tank of 190 mm diameter. The resonant frequency was tuned to within 1% of the design value by adjusting the electrode support inductance. We constructed a test stand for proton acceleration. A proton beam was extracted from the cusp-field ion source and beam was focused by an Eintzel lens. The output beam was analyzed with a magnet and an E × B velocity filter. At RF power of approximately 1 kW, protons were successfully accelerated to the final energy.

KEY WORDS: Proton linac/ 4-Rod RFQ/

INTRODUCTION

A compact MeV implanter has been a much sought machine in the micro-device manufacturers for the application of high-energy implantation in semiconductors[1, 2, 3]. A conventional electrostatic accelerator provides a stable beam up to a few MeV but the beam current and the size of the machine is not acceptable in modern IC production environment. We believe that RFQ is a very promising candidate of the technical break through for a MeV implanter design of the next generation. Invented in 1970 by two Russian physicists, I. M. Kapchinskii and V. A. Teplyakov[4] and later developed to technical sophystication in Los Alamos Scientific Laboratory[5], RFQ has been a subject of intense technical and theoretical investigation in contemporary accelerator developments. Though no one has yet to our knowledge succeeded to make RFQ work in the application of silicon dopant implantation, its features and engineering challenge draw a great deal of attention form accelerator designers. We chose the 4-Rod structure rather than the vane structure for its compactness and easy maintenability. The 4-Rod RFQ was originally developed by such people as A. Schempp[6] and R. W. Müller[7] in West Germany. We have studied the RF characteristics of our 4-Rod RFQ[8] and recently constructed a proton accelerator to test the RFQ principle. A brief account of the experimental setup and the results were summarized in this paper.

ELECTRODES

The pole-tip parameters were determined with PARMTEQ. A list of those parameters are summarized in Table 1 and the synchronous phase, ϕ_s, the moduration, M, and the focusing strength, B are plotted as a function of electrode length in Fig. 1.

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Table 1 A list of the RFQ parameters for the 4-Rod RFQ.

Frequency	100 MHz
Input Energy	30 keV
Output Energy	100 keV
Bore Radius, ro	4 mm
Inter-electrode Voltage	10 kV
Electrode Length	75 cm
Number of cells	48
Maximum Modulation	1.92
Focusing Strength, Bo	5.14
Transmission (2 mA)	54%

Because we wanted to make the electrode to be short enough to allow for easy machining, ϕ_s had to be varied somewhat unfamilially to get to the final energy. When ϕ_s is brought to a smaller value, the protons are allowed to accelerate as they get bunched in the early stage of so called "gentle buncher" section. This violates adiabatic bunching process and results in lower transmission efficiency.

The electrode rods were made of copper and two-dimensionally machined with a 40 mm diameter concave cutter. The rods were bored with a 4 mm holesaw along the axis. Both ends of the holes were weld-capped and in/outlet fitting were soldered at near the end to allow water flows inside the electrodes. A cooling path was formed by connecting the tube fittings of each electrode in series so that only a pair of in/out pipes were needed to be made vacuum tight. Cooling pipes were made of 6 mm diameter copper tube, and they were kept inside the groove at the bottom of the base plate above which the RFQ structure was fixed. Each pair of electrodes were securely supported by "U"-shaped post structure. They, too, are made of copper and built sufficiently rigid.

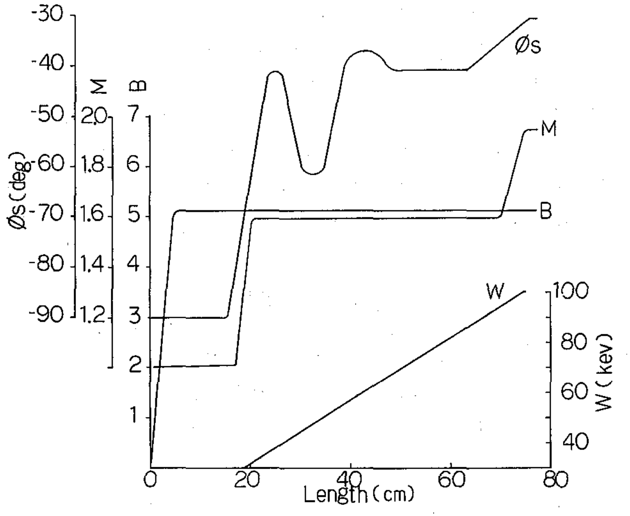

Fig. 1. A plot of the RFQ parameters.

Those supports are then firmly bolted to the 13 mm thick copper plate. One of good things about the Rod-RFQ is that the whole structure can be assembled and aligned on a bench outside the vacuum tank. This makes a maintenance of the RFQ structure particularly easier than for that of a vane RFQ. A cross-shaped alignment jig was inserted along the electrodes at the ends. Also the back to back separation of a pair of electrodes were measured at several points and were coordinated to within 0.1 mm accuracy.

TUNING

The resonant frequency of the RFQ structure must be tuned as closely as possible to the design value. A PARMTEQ simulation shows that if the resonant frequency is off by more than 10%, the transmission becomes nearly zero. The resonant frequency of the 4-Rod RFQ is roughly restricted by its inter-electrode capacitance and the support inductance but it can be altered for instance by the surrounding condition. At the bore radius of 4 mm, our RFQ's resonant frequency was 94.0 MHz outside the vacuum tank but it increased to 100.4 and 109.0 MHz inside a 190 mm and a 150 mm inner diameter copper tank, respectively. Fine tuning of the resonant frequency was done by fixing a copper bar at the bottom of the base plate. When the cross section of the bar is large, it reduces the inductance thereby raising the resonant frequency. The procedure was a trial and error however, with a few attempts it was brought to 100.9 MHz, which is within 1% of the design value. The unloaded Q-value was about 1600 at that frequency.

THE TEST-STAND AND THE PRE-EXPERIMENT OBSERVATION

A schematic drawing of the test-stand is shown in Fig. 2. The output of the cusp ion source was matched at the RFQ by an eintzel lens, though this lens has been replaced with an electrostatic Q-doublet in the course of the experiment. We designed the Q-

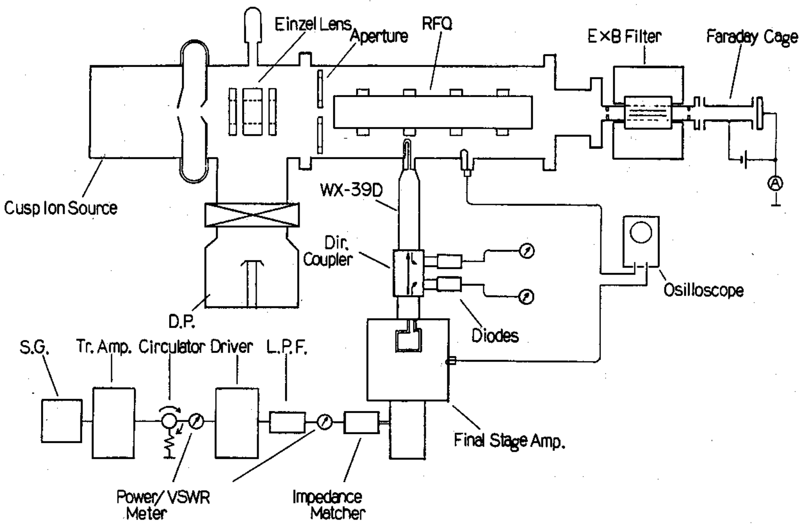

Fig. 2. A schematic drawing of the test-stand for proton acceleration.

doublet using thick-lens approximation[9] as well as simple envelope calculations. The length of the Q-electrode is 4 cm, with the aperture radius of 0.8 cm. The first quadrupole is separated by 5 cm from the second one and it was positioned 5 cm upstream of the radial matching section of the RFQ. The strength of the Q-lens was adjusted by varying the potential of each pair of the quadrupoles. We used 4 units of regulated HV supplies and potentiometers to provide a stable and fine adjustment of the Q strength. The Q doublet gave much satisfactory results increasing the beam current of the RFQ by an factor of 10. The beam was then analyzed with a 60 degree sector magnet and with an E × B velocity filter. The results of those independent analysis were needed to remove the uncertainty of particle identification. In either case, the beam current was measured with a Faraday cage which consisted of a beam catch and a secondary-electron suppression tube. The later electrode has a large length to aperture ratio and it was negatively biased with respect to the beam catch with a 40 V battery.

The RF power system consisted of three-stage tuned amplifiers. For the final stage, we constructed a square-coaxial quater-wave resonant cavity which houses an Eimac 4CW-10000A. Such a resonant circuit can be thought as a shorted-coaxial with a capacitive-load connected at the end[10]. The line length of the cavity was calculated given the inter-electrode capacitance of the vacuum tube, the resonant frequency, and the characteristic impedance of the coaxial line. The results agreed very well with the measured value, 34 cm and 13 cm for the output and input cavity, respectively. Operated in cathode-driven and grounded-grid configuration, the final stage amplifier's power gain was about 13 dB. The output of the final stage amplifier was extracted by a one-turn loop coupler and again inductively coupled to the RFQ. The coupling strength was optimized by adjusting the orientation and the position of the loop using a network analyzer. This simple procedure sufficed to attain the maximum power transfer into the RFQ tank without any appreciable reflection. At the input of the final stage amplifier, however, an impedance matcher—a kind of one stub tuner made with a variable capacitor—had to be inserted to reduce the VSWR below 1.1. A small pickup loop was attached at the RFQ tank and at the output cavity of the final stage amplifier in order to monitor the resonant condition with an osilloscope. Power transmission between the final stage amplifier and the RFQ was monitored with a directional coupler. RF diodes were connected to the output of the directional coupler to get DC level signal, square of which are roughly proportional to the RF power. That power monitor system was calibrated to a through line power meter terminated with a 50 ohm dummy load. The RFQ tank was cooled by running water through the copper pipe soldered to the tank. This as well as cooling of the electrodes were necessary to suppress the detuning effect caused by the thermal expansion of the RFQ structure. Our observation is that the resonant frequency tends to go down slightly as RF power is delivered to the RFQ. The frequency shift was less than 0.04% at the RF power of 1.8 kW with the coolant flowing at a few liters per min. Though frequency compensation circuitry was not included in the RF system, we had no difficulty in setting up the RF power system at the proper condition with manual operation.

The alignment of the beam line was done with a laser beam by careful coordination of the position and the angle of the components. This had to be done with extreme care and precision for proper matching and better transmission. A single 500 l/s oil-diffusion pump sufficed to bring the base pressure of the vacuum tank as low as 7×10^{-6} torr. At beam production, the pressure level went up slightly and it was about 1.5×10^{-5} torr.

EXPERIMENTS AND THE RESULTS

At first, we observed a discharge at RF power as low as 30 W and the degassing from the RFQ structure raised the pressure considerably. It was a beautiful(?) purple-color glow occuring alternately either at the front or back portion of the RFQ. If a discharge takes place, the most of the power is reflected back so that very little power enters the RFQ tank. It took four to five hours before the input RF power reached an order of kW and the pressure went down to below 1×10^{-5} torr.

After the RF conditioning, the momentum and velocity spectra were taken. Fig. 3 shows a typical momentum spectrum for different input RF power. Careful analysis shows that the first peak right to the 30 keV H_3^+ peak is indeed that of H^+ 100 keV. The velocity spectra were shown in Fig. 4 for the same situation and again a H^+ 100 keV peak was identified. Notice that because the injection beam is not analyzed, those peaks of un-accelerated components such as H_2^+ and H_3^+ could appear in the spectra. Fig. 5 is a plot of the measured output beam as a function of the input power. The computed results of the beam transmission from PARMTEQ simulation is shown

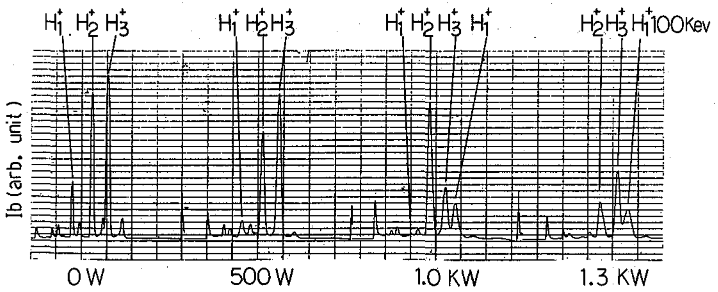

Fig. 3. Typical momentum spectra for different input RF power. The abscissa is the magnet current and the ordinate is the beam current in arbitrary units.

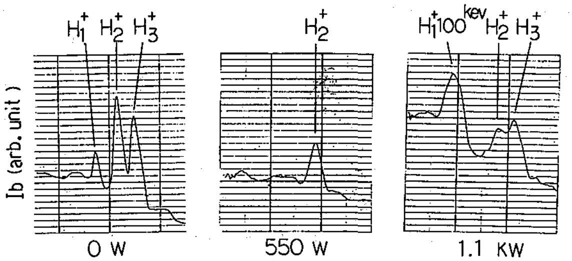

Fig. 4. Typical velocity spectra for different input RF power. The abscissas are the magnet current and the ordinates are the beam current in arbitrary units.

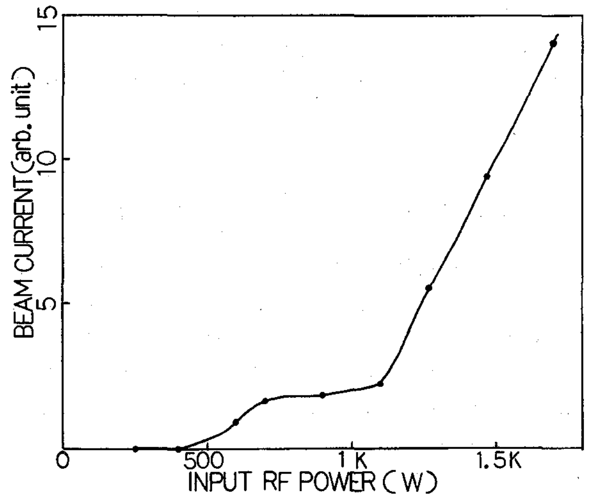

Fig. 5. The measured output beam current as a function of input RF power.

in Fig. 6. The results indicate that more power is required to further investigate the transmission efficiency. The tuning of the Q-lens strength had a prominent effect on the beam transmission. A typical Q-doublet voltage was ±930 V for the first—the one close to the ion source—quadrapole and ±700 V for the second quadrupole. A simple thick-lens calculation gives the focal length of our Q-doublet to be −5.8 cm in the DF plane and −3.9 cm in the FD plane of the Q-lens at the above condition.

Fig. 7 is the velocity spectra obtained at different injection energies. There are two things to note. One is that protons cannot be accelerated at 25 keV injection, which is 5 keV below the designed value. At higher injection energies, on the other

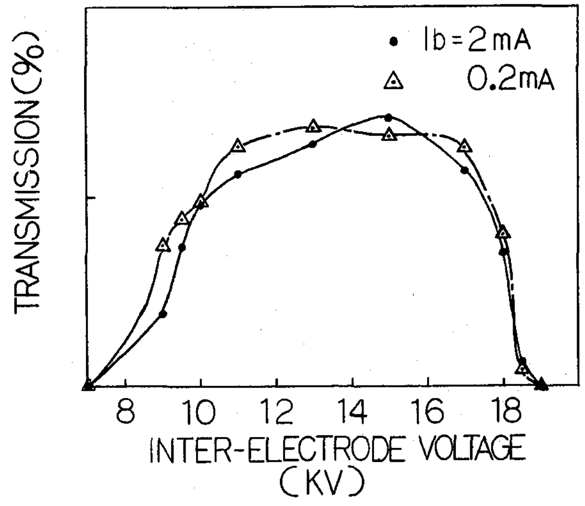

Fig. 6. The beam transmission from PARMTEQ simulation.

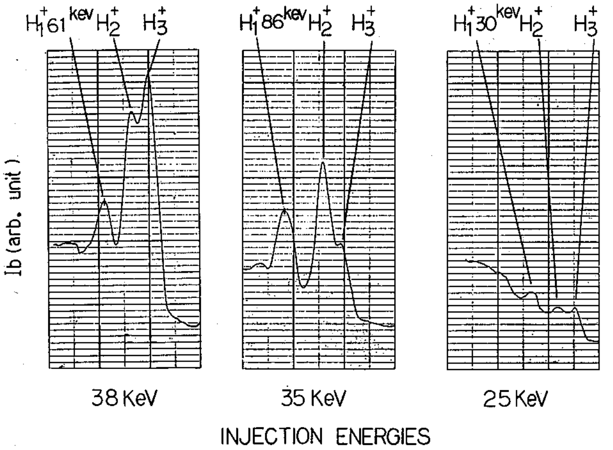

Fig. 7. The velocity spectra at different injection energies. The abscissas are the magnet current and the ordinates are the beam current in arbitrary units.

hand, the particles are accelerated but to lower energies than what we expect. As the input energy goes up further beyond 30 keV, the output energies become lower. This is an interesting phenomenon and may provide a use of it for say varing the beam energies of the RFQ.

CONCLUDING REMARKS

It was shown with our 4-Rod RFQ model that protons were accelerated as predicted by PARMTEQ calculations. Although we are left with several measurements to be done for deeper understanding of the RFQ principles, the results are satisfactory and they provided us with a firm foot-ground for the future plan. This was our first step for the development of the RFQ accelerator for the application of high energy ion implantation. The authors with to thank Hiromi Okamoto and Masaru Sawamura for their cooperation and helpful discussion.

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