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RF ACCELERATION OF IONS PRODUCED BY SHORT PULSE LASER

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Abstract

An laser ion source which produces bunched ion beam is proposed to enhance an acceleration efficiency of ion accelerator front end with RFQ linac. To demonstrate a production of an initially bunched ion beam, H_2 gas was ionized by short pulse laser in an RF electric field. As a result, ions captured by the RF field were observed by an ion probe.

INTRODUCTION

RFQ (Radio Frequency Quadrupole) linac [1] has been the essential component of ion accelerator front ends for tens of years[2]. Since ordinary ion sources provide DC (unbunched) ion beam, the function of RFQ includes not only acceleration and radial focusing but also adiabatic bunching. Therefore, conventional RFQ consists of three or four sections; radial matching section, (shaper section), bunching section, and accelerating section[3]. At the bunching section, the beam is bunched adiabatically by longitudinal RF electric field. However, satisfying the adiabatic condition, the vane modulation and synchronous phase rise gradually to the values for accelerating section. Therefore, bunching section takes lengthy part of RFQ tank, where the longitudinal field contribute almost only for bunching and not for acceleration. Hence the accelerating efficiency along the entire RFQ tank decreases.

If the beam is already bunched at the entrance of RFQ, bunching section is not needed and beam can be accelerated along the whole part of RFQ tank. Then, the accelerating efficiency of RFQ can be improved. For production of such a bunched beam, laser plasma induced by short pulse laser has promising potential. The ions in the plasma produced by short pulse laser are supposed to have also short pulse structure. If the bunch of the short pulse ions can be captured by RF bucket at the laser interaction region before an expansion of plasma, the production of short pulse bunch can be achieved and direct injection of the bunched ion beam into RFQ can be realized. The schematic image of the front end with direct injection of bunched ions into RFQ is shown in Fig.1. This scheme is similar to the RF gun, while the electrons are replaced with the ions.

In this paper, an experiment to demonstrate the capturing of laser-induced ions in RF bucket is described.

EXPERIMENT

To demonstrate the capturing of ions produced with a short pulse laser by RF electric field, H_2 gas was irradiated

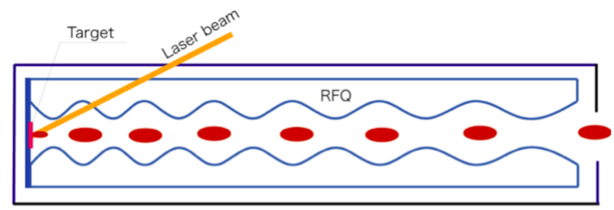

Figure 1: Schematic image of RFQ with initially-bunched ion beams.

by short pulse laser in an accelerating gap of an RF resonator and the accelerated charged particle was detected by a probe electrode. The layout of experimental equipments is shown in Fig.2. In this section, the component used in this experiment is described. The experiments were performed in a vacuum chamber with a pressure of 0.02 Pa.

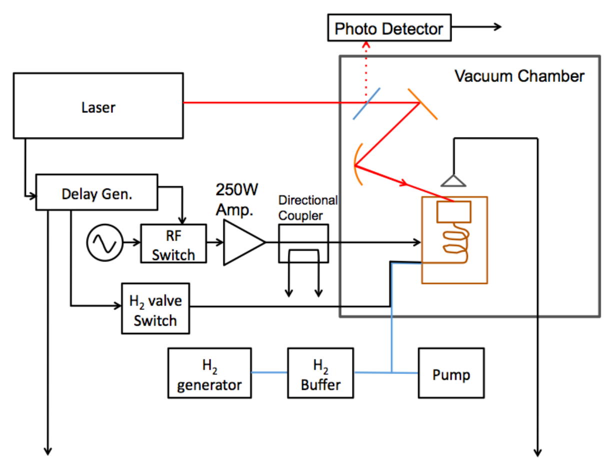

Figure 2: Image of Experimental Layout.

Laser

The experiment was performed with a terawatt 40-fs Ti:sapphire laser system in Institute for Chemical Research, Kyoto University. A laser pulse energy was tuned between 30 μJ and 100 μJ and a repetition rate of laser pulse was up to 5 Hz. The laser pulse was focused to a spot with 11 μm diameter by an off-axis parabolic mirror. The laser power density at the interacting point is $10^{14} \sim 10^{15}$ W/cm^2. The Rayleigh length of laser at interacting point is nearly 1 mm.

RF Resonator

To generate the longitudinal RF electric field, RF resonator was prepared. The frequency of the resonator is chosen as 53.3MHz, so that the ions with heavy masses com-

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pared with electrons can pass the acceleration gap in a period at a moderate excitation power. . To use the resonator with a existing vacuum chamber, the dimension of RF resonator should be about 10 cm large. We selected to use the RF resonator with spiral coil. The RF resonator is designed with OPERA/SOPRANO[4]. The designed RF resonator is shown in Fig. 3 and 4. The coil in resonator is made by bending 1 m length copper plated stainless steel pipe and a one end of the coil goes into a pulse gas valve unit and the other end penetrates the outer cylinder of resonator. A gas tube is installed in the pipe to supply H_2 gas from outside of the resonator to the gas valve unit. The downstream surface of gas valve unit is facing to a bottom plate of the resonator cylinder and the 2 mm accelerating gap is located between them. The beam extraction aperture on the bottom plate has a slit shape of 10 mm × 2 mm. One edge of the hole has a drilled conical hole with 3 mm diameter for a laser input port. From this port, laser is injected into the interaction point with 22.5° incident angle.

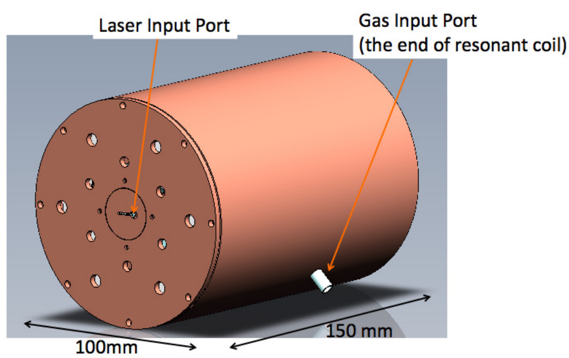

Figure 3: An entire view of the RF resonator.

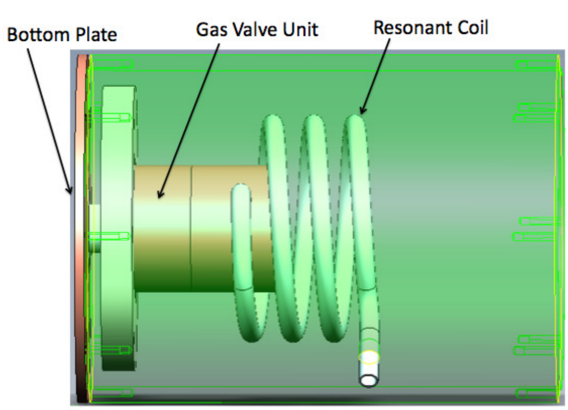

Figure 4: A internal view of the RF resonator.

Gas System

Hydrogen gas is produced by a hydrogen generator and is reserved in hydrogen gas buffer, whose pressure can be up to 1000 hPa. The hydrogen gas comes to the gas valve unit along the inside of the RF resonator coil pipe. In this experiment, the gas pressure was approximately 400 hPa. A piezo valve was opened from 1 ms before a laser shot. The ejected gas was irradiated by a laser in the accelerating gap. The cross sectional view of the gas valve unit is shown in Fig. 5.

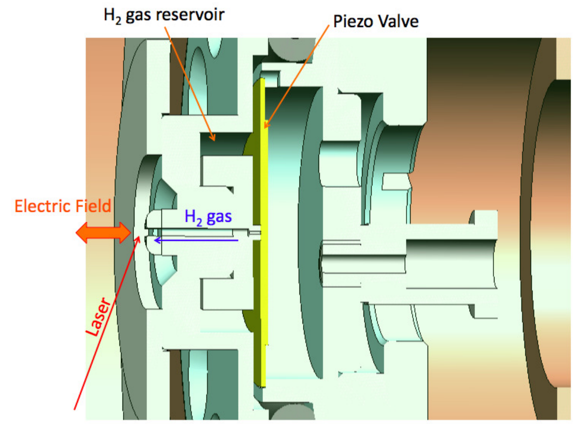

Figure 5: Cross sectional view of the gas valve unit in the resonator.

Ion Probe

An ion probe was made of semi-rigid coaxial cable. The ion Probe has to be set closed to the exit of accelerating gap. The cross section of detecting surface is approximately 1 mm × 3 mm.

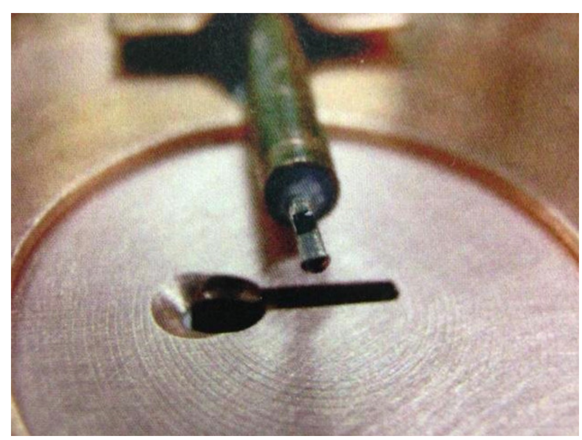

Figure 6: Ion probe made by cutting and stripping a semi-rigid coaxial cable. The probe was attached on the bottom plate of the resonator.

EXPERIMENTAL RESULT

In the experiment, laser was shot asynchronously with the RF phase. The relative phases of the laser shot against the RF cycle were derived from the monitored RF signal from the cavity and the laser timing signal. Figure 7 shows typical oscilloscope signal. In this picture, yellow and green signal show reflected RF power and pick up RF power, blue is laser signal detected by photo detector, and red curve is ion probe signal. The timings of these signals are relative because each signal was delayed in a cable with an indefinite lengths. Captured ions by RF fields were detected by

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the ion probe and their bunch lengths were about 2.5 ns. Fig. 7 shows ion probe signals for various RF phase. The horizontal axis is time of flight, and vertical axis shows initial RF phases. The area colored by red/blue is the time when positive/negative current signals were detected. In this figure, bunched ions are detected for about 90 ° phase range.

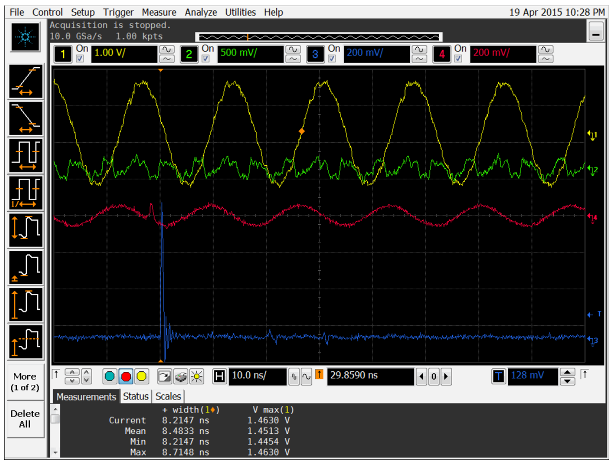

Figure 7: A typical detected signal on an oscilloscope.

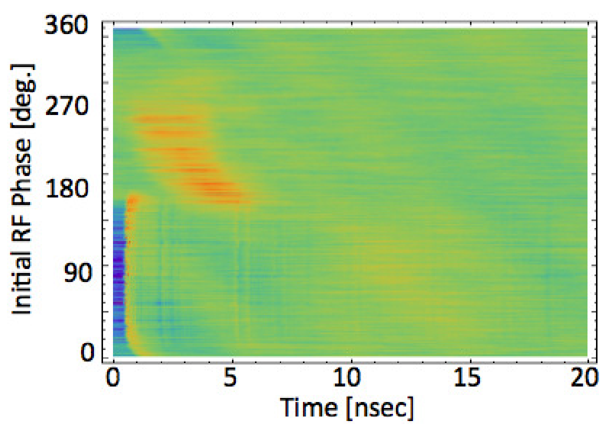

Figure 8: The contour plot of current signals for various RF phases. Positive current were detected in the red area, negative current in the blue, while green indicates no signal.

DISCUSSION

To simulate our result, 1D single particle tracking was performed. In this simulation, homogeneous RF electric field is applied at the gap between z = 0 mm and z = 2 mm, and detector was set at the point z = 4 mm. The amplitude of the voltage between the gap is V. The electron and H^+ion are located initially at z = 50 μm and the energy distribution was assumed to be the Maxwell distribution characterized by temperature T. As the result of simulation, the bunch length of ion beam without electric field was few tenth of ns, so this result suggets that the detected ion bunch in the experiment was formed by RF electric field. The required gap voltage to capture the bunch is about $V = 2$ kV. Figure 9 shows a simulation result with $V = 3$ kV, ion temperature is $T_{\text{ion}} = 100$ eV and electron temperature $T_{\text{electron}} = 10$ eV. In this figure, bunched ions and electrons exist similar region. However, time of flight of ions in the experiment are faster than the one of simulation result and ion bunch in the phase between 270° and 300° are different. These inconsistence are caused mainly by neglecting space charge interaction and that an initial condition of laser plasma is poorly understood. To investigate more closely, momentum/energy analysis is to be performed.

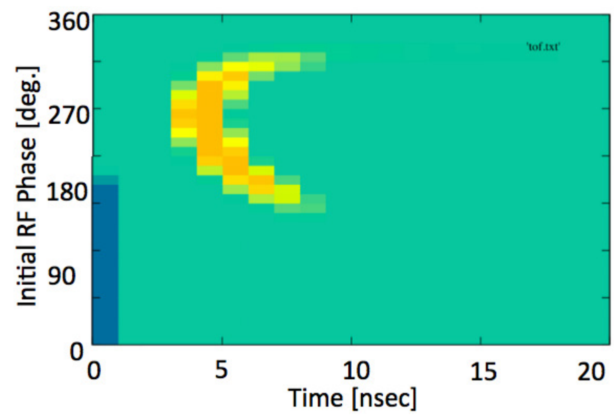

Figure 9: The simulation result of current signal for various RF phase. Positive/negative current is indicated as red/blue, and green indicates neutral.

CONCLUSION

An ion source which produces bunched ion beam with short pulse laser is proposed for enhancement of an acceleration efficiency of ion accelerator front end. To demonstrate a possibility of such types of ion source, H_2 gas was ionized by a laser with 40 fs pulse length in a RF electric field. As a result, initially bunched ions were observed.

ACKNOWLEDGMENT

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