BNL-112228-2016-CP

RF synchronized short pulse laser ion source

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Presented at the 16th International Conference on Ion Sources
New York Marriott Marquis Hotel, New York, NY
August 23 – 28, 2015

May 2016

Collider-Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy
Office of Science, Office of Nuclear Physics

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RF Synchronized Short Pulse Laser Ion Source[a)]

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(Dated: 3 November 2015)

A laser ion source that produces shortly bunched ion beam is proposed. In this ion source, ions are extracted immediately after the generation of laser plasma by an ultra-short pulse laser before its diffusion. The ions can be injected into RF accelerating bucket of a subsequent accelerator. As a proof-of-principle experiment of the ion source, an RF resonator is prepared and H_2 gas was ionized by a short pulse laser in the RF electric field in the resonator. As a result, bunched ions with 1.2 mA peak current and 5 ns pulse length were observed at the exit of RF resonator by a probe.

I. INTRODUCTION

In typical ion sources, the pulse length of the extracted ion beams is longer than a micro second. For practical uses, the ion beams are required to be accelerated by RF (Radio Frequency) accelerators. However, the operation frequency of the RF accelerators is between a few tenth of MHz and several hundred MHz, and the ion beams must be bunched in the front end of the accelerator such as an RFQ (Radio Frequency Quadrupole) linear accelerator[1]. If the beam is already bunched at the exit area of an ion source, the bunched beam can be injected directly into the accelerating RF phase of the RFQ linac and the bunching section of the RFQ is no longer needed. Then, the accelerating efficiency of RFQ can be improved.

For production of such a bunched beam, laser plasma induced by an ultra-short pulse laser with femto-second pulse duration has a promising potential. While ion sources using laser have already developed such as laser ion source with Direct Plasma Injection Scheme[3], nano-second laser is used in the scheme and the ions are extracted from the plasma after its expansion. With the focused ultra-short pulse laser, the volume of the interaction region is small enough to produce bunched ions, and the generated plasma should be confined in the micro volume. If the plasma with the micro volume is generated in an RF electric field, the ions can be extracted by the RF bucket with the shortly bunched structure. Hence, the production of the short pulse ion bunch can be achieved and direct injection of the bunched ion beam into the 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 [4, 5], while the electrons are replaced with the ions.

In this paper, a proof-of-principle experiment to demonstrate the production of short pulse ion beam is described.

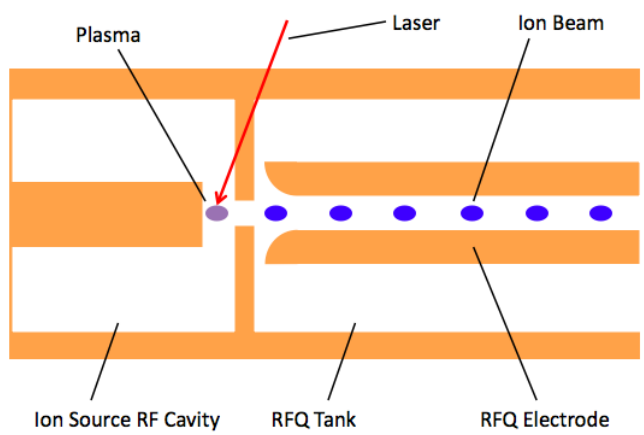

FIG. 1. Schematic image of RFQ with initially-bunched ion beams.

II. EXPERIMENT

To demonstrate the production of the short pulse ion beam with a short pulse laser and an RF electric field, H_2 gas was irradiated by a laser with femto-second pulse duration in an accelerating gap of an RF resonator and the accelerated charged particles were detected by a probe electrode. The experiment was performed in a vacuum chamber with a pressure of 0.02 Pa. The layout of experimental equipments is shown in Fig.2. In this section, the component used in this experiment is described.

A. 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 (OAP)

[a)] Contributed paper published as part of the Proceedings of the 16th International Conference on Ion Sources, New York City, NY, August 2015.

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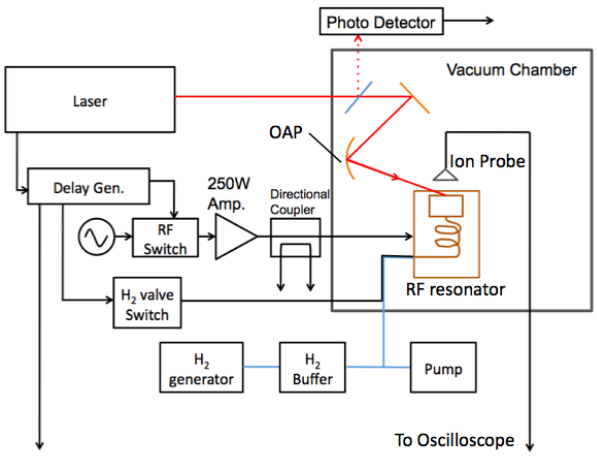

FIG. 2. The layout of experimental equipments.

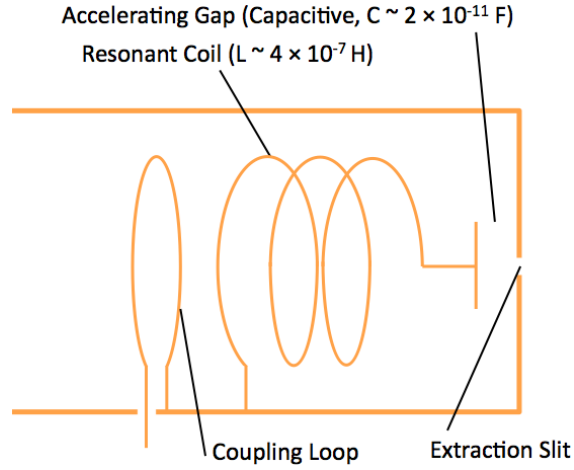

FIG. 3. A schematic image of the resonator.

mirror. The laser power density at the interacting point was estimated as $10^{14} \sim 10^{15}$ W/cm^2. The Rayleigh length of the laser at the interacting point is nearly 1 mm.

B. RF Resonator

To generate the longitudinal RF electric field at the plasma production area, an RF resonator was prepared. The frequency of the resonator and the accelerating gap length are chosen as 53.3MHz and 1 mm respectively, so that the ions with heavier masses compared with electrons can pass the acceleration gap in a period at a moderate excitation power. To install the resonator with an existing vacuum chamber, the dimension of RF resonator should be about 10 cm large. We selected to use the RF resonator with a spiral coil. The schematic design of RF resonator is shown in Fig. 3. The RF resonator is designed with OPERA/SOPRANO[2]. The designed RF resonator is shown in Fig. 4 and 5. The coil in the resonator is made of 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 the resonator. A PTFE gas tube runs 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 1 mm accelerating gap is located between them. Based on this design, a test model of the resonator was fabricated (Fig. 6). The peak-to-peak voltage applied between the gap was estimated 2.5 kV at 250 W RF power by a transmission measurement with a capacitive probe. The measured Q value of the resonator was 190. The beam extraction aperture on the bottom plate has a slit shape of 10 mm × 2 mm. One edge of the slit has a drilled conical hole with 3 mm diameter for a laser injection aperture. From this aperture, laser is injected into the interaction point with 22.5° grazing angle.

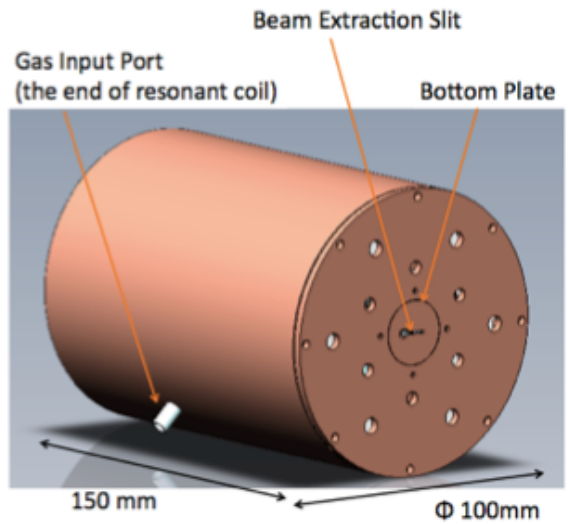

FIG. 4. An entire view of the designed resonator.

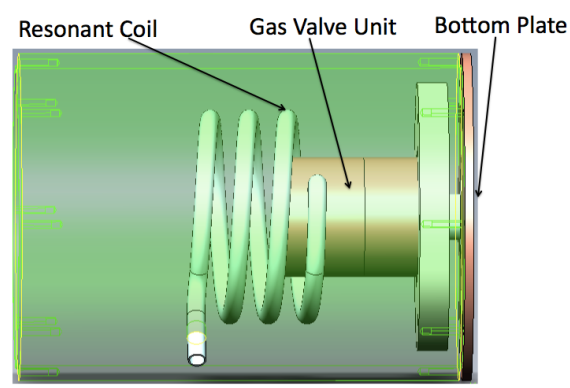

FIG. 5. An internal view of the designed resonator.

C. Gas System

Hydrogen gas was produced by a hydrogen generator and is reserved in a hydrogen gas buffer, whose pressure can be controlled up to 1000 hPa. The hydrogen gas comes to the gas valve unit through the PTFE tube in

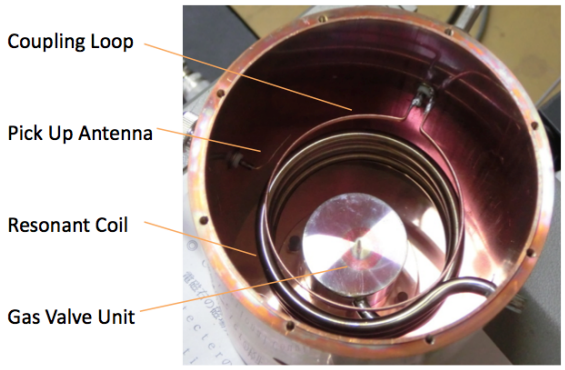

FIG. 6. A photograph of the fabricated resonator (taken from upstream of the beam direction).

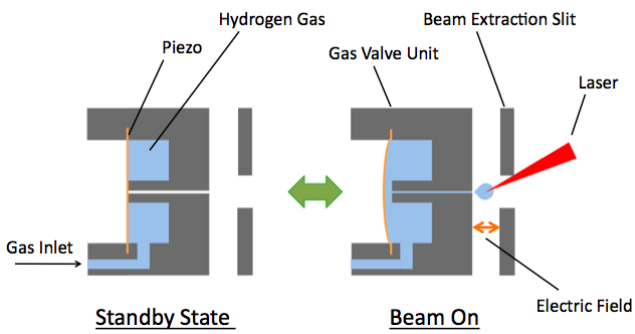

FIG. 7. An schematic image of the gas valve operation. The gas is supplied into the RF gap between the gas valve unit and the beam extraction slit. The extraction slit side can be assumed to have the ground potential.

the RF resonator coil pipe. In this experiment, the gas pressure was set approximately 400 hPa. The gas flow was controlled at a valve hole covered by a piezoelectric disk element that bended with applied voltage of ± 100 V. The piezo valve opened from 1 ms before a laser shot. The ejected gas was irradiated by a laser in the accelerating gap. Then the valve closed shortly after the laser irradiation. The cross sectional view of the gas valve unit is shown in Fig. 7.

D. 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 area of detecting surface is approximately 1 mm × 3 mm. The size of the ion beam at the detector position would be larger than the detection area.

III. 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 8 shows a typical current signal detected by the ion probe. The 1.2 mA ion current with pulse length less than 5 ns appears in this figure. For this signal, relative RF phase are estimated as 240°. Fig. 9 shows a 2D-map of ion probe signals as a function of time and RF phase, where 1000 signals were measured and sorted by relative RF phase. The horizontal axis is the time of flight, and the vertical axis is initial RF phases, whose origin was adjusted so that the phase span of the electron signal at $t = 0$ located between 0° and 180°, because the electrons are much lighter than ions and can be easily accelerated to pass through the gap quickly with the electric field. The area colored by red/blue is the time when positive/negative current signals were detected. In this figure, bunched ions were detected for about 90° phase span.

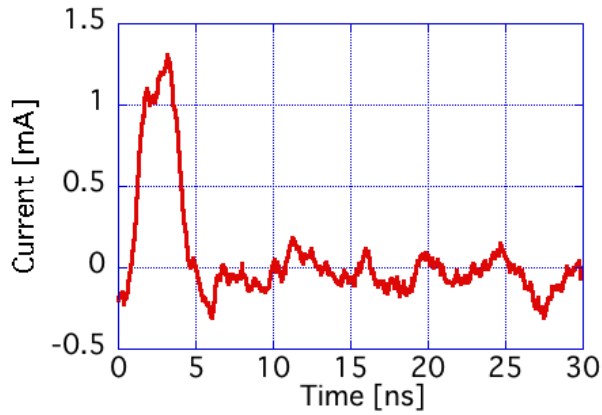

FIG. 8. Typical current signal detected by the ion probe (RF phase = 240°).

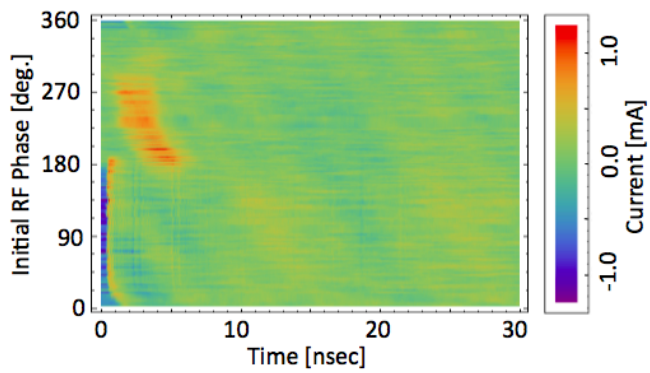

FIG. 9. The contour plot of current signals for various RF phases. Positive current was detected in the red area, negative current in the blue, while green indicates no signals.

IV. DISCUSSION

The bunched ion beams were detected by the experiment. To simulate this result, 1D particle tracking without space charge was performed. In this simulation, homogeneous RF electric field is applied at the gap between z = 0 mm and z = 1 mm, and detector was set at the point z = 3 mm. The amplitude of the voltage between the gap