

# DEVELOPMENT OF A GAS-TARGET LASER ION SOURCE TEST SYSTEM FOR THE LAPRIS CONCEPT

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## Abstract

LaPRIS (Laser Plasma RF Ion Source) is a pulsed ion source concept for generating high-quality ion beams using a gas jet, an RF field, and an ultrashort-pulse laser. To investigate laser-induced ion extraction relevant to LaPRIS, we constructed a test system using DC high-voltage extraction and performed preliminary measurements of ions generated by strong-field ionization in a gas target. Time-of-flight measurements using an MCP detector showed laser-correlated ion signals and their dependence on the extraction voltage. These results provide a preliminary demonstration of laser-induced ion extraction relevant to future LaPRIS development.

## INTRODUCTION

In high-resolution nuclear physics experiments, the quality of the ion beam injected into the accelerator strongly affects the experimental performance. Experiments using the AVF cyclotron and the ring cyclotron at RCNP require particularly high energy resolution.

At RCNP, a continuous beam generated by an ECR ion source is injected into the accelerator and collimated by slits installed along the beam transport line to achieve high beam resolution. While the transverse emittance can be improved by beam slits, improvement of the longitudinal beam quality requires the phase slit of the cyclotron. To obtain high energy resolution, the injected beam must be confined within a narrow RF phase width. However, since the ECR ion source produces a continuous beam, a buncher is required to compress the beam in the longitudinal direction. Although the present buncher can increase the beam density, it cannot form a sufficiently short bunch. Therefore, phase slit collimation is still required, making it difficult to obtain a high-quality beam with high efficiency.

To address this limitation, we propose a new ion source called LaPRIS (Laser Plasma RF Ion Source) [1]. LaPRIS is a pulsed ion source that generates localized plasma in a gas jet using a focused ultrashort-pulse laser and extracts ions by an RF electric field. Since the laser pulse duration is on the sub-picosecond scale, the generated ion bunch is expected to have an intrinsically ultrashort bunch duration.

Therefore, LaPRIS may significantly improve the bunching efficiency compared with conventional methods. In addition, since ionization occurs only in a localized

region near the laser focus, the generation of a low-emittance beam is also expected.

H<sub>2</sub> is considered a future target gas for LaPRIS because it can be used as a source gas for proton beam generation in precision nuclear physics experiments. Fig. 1 shows the tunneling ionization yields of N<sub>2</sub> and H<sub>2</sub> calculated using the MO-ADK model [2,3]. At the peak intensity of  $1 \times 10^{14}$  W/cm<sup>2</sup> used in this experiment, the ionization yields are estimated to be about 50 ions/shot for N<sub>2</sub> and about 10 ions/shot for H<sub>2</sub>.

As a step toward the development of LaPRIS for practical application in precision nuclear physics experiments, we constructed a laser-induced ion extraction test system using DC high voltage instead of RF extraction and performed initial measurements of ion signals and their dependence on the extraction voltage.

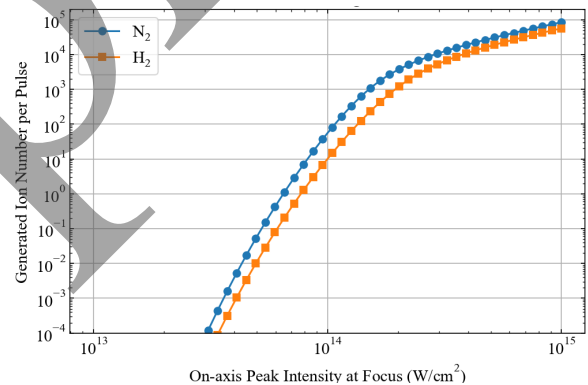


Figure 1: Estimated ionization yield calculated using the MO-ADK model.

## EXPERIMENTAL SETUP

Figure 2 shows a photograph of the DC laser-induced ion extraction test system used in this experiment. The system consists of a gas target, DC extraction electrodes, and an MCP detector installed in a vacuum chamber. The chamber pressure was  $5 \times 10^{-4}$  Pa without gas injection and  $1 \times 10^{-2}$  Pa during pulsed gas injection with an average flow rate of 1 sccm.

For gas injection, we used the same piezoelectric pulsed gas valve as in the previous LaPRIS study [1]. The valve was operated with a pulse width of 1 ms and a repetition rate of 10 Hz. For timing control, leakage light from the compressor was detected by a photodiode and used as the

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timing signal. This signal was frequency-divided by a DG645 delay generator and sent to the piezoelectric valve control system through an optical fiber. Air was used as the target gas in this experiment.

A Yb fiber femtosecond laser with a pulse duration of 340 fs, a repetition rate of 50 kHz, and a pulse energy of 22  $\mu\text{J}$  was used [4]. After being introduced into the vacuum chamber, the laser beam was focused at the gas jet position using an aspheric focusing lens with  $f = 100$  mm (Thorlabs: AL50100H-B). The estimated peak intensity was  $1 \times 10^{14}$   $\text{W}/\text{cm}^2$ . An achromatic lens with  $f = 80$  mm was also used as imaging optics for alignment and focal spot observation.

Ions generated near the laser focus were accelerated by a DC high voltage of 3–5 kV and detected by an MCP located about 6 cm downstream of the extraction electrodes.

For signal acquisition, the time of flight (TOF) from the laser focal region to the MCP detector was measured. The TOF time origin was defined as the rising edge of the photodiode signal detecting leakage light from the laser system on CH1. The MCP output waveform was recorded on CH2 using an oscilloscope. The measured cable propagation delays of the PD signal on CH1 and the MCP signal on CH2 were 11.43 ns and 10.60 ns, respectively, giving a systematic timing offset of 0.83 ns between the two channels.

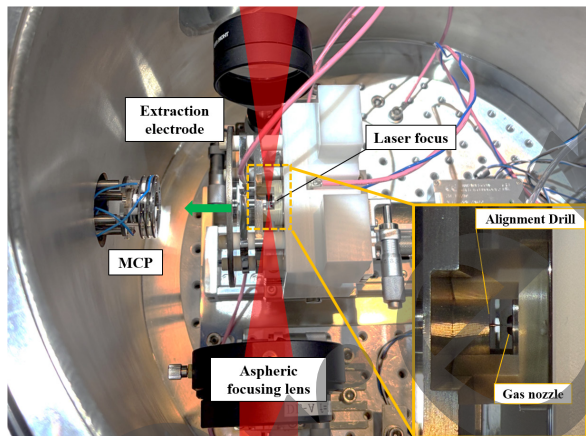


Figure 2: Experimental setup of the DC laser-induced ion extraction system.

## OPTICAL ALIGNMENT

Since the overlap between the laser focus and the gas jet position directly affects the ion generation efficiency, alignment was performed using a dedicated jig. Fig. 3 shows an observation image during the alignment procedure and the measured laser focal spot profile.

First, the optical axes of the focusing lens and the achromatic imaging lens were aligned. Then, a jig equipped with a drill bit with a tip diameter of 40  $\mu\text{m}$  was inserted through the extraction aperture and positioned so that the tip coincided with the designed focal position on the gas nozzle axis. The electrodes and the drill-bit jig were translated using a motorized one-axis stage, and their positions were finely adjusted so that the image of the drill tip could be observed on the CCD camera.

The image of the drill tip was observed using the achromatic imaging lens with  $f = 80$  mm, and the lens position

was adjusted to obtain the sharpest image on the CCD camera. Using the known drill tip diameter of 40  $\mu\text{m}$  as a reference, the magnification of the imaging optics was estimated to be about 11. Under this condition, the depth of field was about 30  $\mu\text{m}$ , as shown in the left panel of Fig. 3. After removing the drill-bit jig, the focusing lens was inserted into the beam path and finely adjusted along the optical axis to minimize the laser spot size on the CCD camera. The  $1/e^2$  full widths of the laser focal spot, evaluated by Gaussian fitting, were 11  $\mu\text{m}$  in the X direction and 10  $\mu\text{m}$  in the Y direction, as shown in the right panel of Fig. 3.

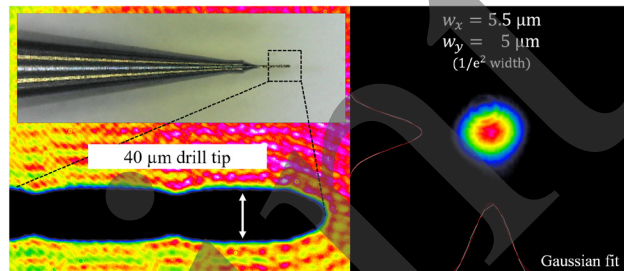


Figure 3: Laser alignment and measured focal spot profile.

## PRELIMINARY MEASUREMENTS

Figure 4 shows the TOF distributions of the MCP signals measured at extraction electrode voltages of 3 kV, 4 kV, and 5 kV. The TOF histograms were constructed with a bin width of 20 ns. For each voltage condition, 100 MCP-triggered waveforms were accumulated. The numbers of peak candidates were 48, 47, and 55 at 3 kV, 4 kV, and 5 kV, respectively. The dashed lines in the figure indicate reference arrival times calculated assuming ion acceleration by the applied extraction voltage and are not used for ion-species identification. The systematic timing offset between the two channels was measured to be 0.83 ns, which is much smaller than the bin width.

As the extraction voltage increased, the arrival times of the MCP signals tended to shift toward shorter TOF values. This tendency is consistent with the presence of ion signals accelerated by the extraction field. The pre-trigger region, where laser-induced ions cannot physically arrive, was used to estimate the background level. The total number of MCP peak candidates observed after the laser timing was significantly higher than that expected from the pre-trigger background, indicating laser-correlated ion signals.

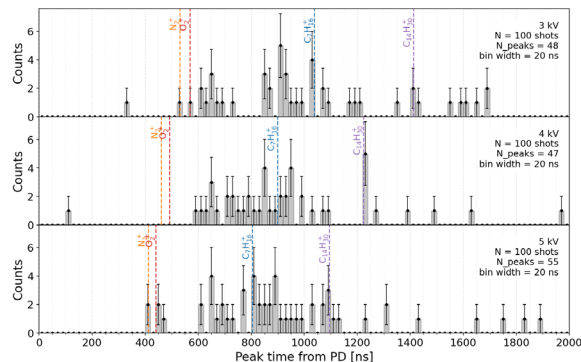


Figure 4: MCP timing distributions measured under different extraction voltages.

## DISCUSSION

As shown in the Introduction and Fig. 1, the MO-ADK-based estimates gave ionization yields of about 50 ions/shot for N<sub>2</sub> and about 10 ions/shot for H<sub>2</sub> under the present experimental conditions at a peak intensity of  $1 \times 10^{14}$  W/cm<sup>2</sup>. These values represent the estimated number of ions generated near the laser focus and do not directly correspond to the number of MCP counts, because the observed signal intensity is affected by the gas density at the laser focus, ion transport to the detector, and the MCP response. For H<sub>2</sub>, the calculated ionization yield was about 10 ions/shot. Therefore, improved experimental conditions, including a higher laser peak intensity and a denser gas target, are required for future studies using H<sub>2</sub>.

As an order-of-magnitude estimate, the pressure-scaled stopping power of protons from the PSTAR database gives an estimated distance of about 3 m for a 1% energy loss of 1 keV protons at a chamber pressure of  $1 \times 10^{-2}$  Pa [5]. This distance is much longer than the flight length in this experiment, about 6 cm, indicating that the effect of energy loss due to stopping power is negligible. Hydrocarbon molecules originating from pump oil and outgassing components from PEEK materials may also have been ionized by the laser and contributed to the background signals in the later TOF region. The broad TOF distribution may reflect the presence of multiple ion species, including molecular and possible cluster ions.

## CONCLUSION

In this study, as a preliminary experiment toward the realization of LaPRIS, we constructed a laser-induced ion extraction test system using a DC extraction field and performed an initial operation test based on TOF measurements. MO-ADK-based estimates gave ionization yields of about 50 ions/shot for N<sub>2</sub> and about 10 ions/shot for H<sub>2</sub> under the present experimental conditions. Air was used as the target gas in this preliminary experiment. The tendency of the arrival time to decrease with increasing extraction voltage suggests that the observed MCP signals included ions accelerated by the extraction field. The total number of MCP peak candidates observed after the laser timing was significantly higher than that expected from the pre-trigger background, indicating laser-correlated ion signals. The MCP peak candidates were distributed over several hundred nanoseconds. In future work, a laser with a higher peak intensity and a purified gas target with higher density will be introduced to advance the demonstration of LaPRIS using gases such as H<sub>2</sub>.

## ACKNOWLEDGEMENTS

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