Progress of the laser ion source upgrade (LION2) for RHIC and NSRL program at Brookhaven National Laboratory

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Abstract. At Brookhaven National Laboratory (BNL), the LION2 ion source is being constructed to replace an existing laser ion ablation ion source (LIS) at the EBIS facility, which provides heavy ion beams of multiple ion species for the operation of NASA Space Radiation Laboratory (NSRL) and Relativistic Heavy Ion Collider (RHIC). The LION1 ion source currently provides singly charged ions of Li, B, C, O, Al, Si, Ca, Ti, Fe, Cu, Zr, Nb, Ag, Tb, Ta, W, Au, Bi, and Th with a rapid-species-change capability. An electron beam ion source, Extended-EBIS captures, confines, and ionizes the ions to high charge state, suitable for injection and acceleration by an RFQ accelerator. Typically, single pulses of the LIS ion species for NSRL are changed sequentially during Galactic Cosmic Ray experiments, while multiple pulses of a given ion beam are provided quasi-simultaneously for RHIC. LION2 will have the same capability of the rapid-species-change with improved beam performance and reliability. LION2 is being constructed in a remote assembly location and is expected to finish in December 2023. The removal of LION1 and installation of LION2 is planned during the December 2023 or summer 2024 shutdown.

1. Introduction

At Brookhaven National Laboratory (BNL), a laser ablation ion source (LION1) provides single charge states of various species of heavy ion beams to an EBIS for further ionization. The resulting high charge state ion beams have been used by NASA Space Radiation Laboratory (NSRL) and the Relativistic Heavy Ion Collider (RHIC) since 2014. LION1 is a major contributor to successful operation of galactic cosmic ray study at NSRL in addition to heavy ion programs at RHIC. This is because a laser ion source can switch ion species in less than 1 second. Furthermore, the LIS can produce pulsed ion beams from any solid-state targets in high vacuum without a memory effect of a previous ion beam pulse. Full performance of the LIS beam is available from first pulse without a warmup period. Some of the operation experience of the LION1 can be found in ref. [1]. The importance of the LION1 was widely recognized and the LION2, an upgrade project of the LION1 was started in summer 2021. The LION2 design includes improvements of reliability and maintainability based on the operation experience of the LION1 in addition to improved beam performance. Figure 1 shows a schematic of the EBIS pre-injector to provide 2 MeV/u beams of heavy and highly-charged ions. Since the LION2 operation is similar to LION1, the operation of the LION1 is briefly summarized in the following: The LION1 provides singly charged heavy ions generated by laser ablation. Li, B, C, O, Al, Si, Ca, Ti, Fe, Cu, Zr, Nb, Ag, Tb, Ta, W, Au, Bi, and Th beams were provided from LION1 to RHIC-EBIS in the past. A new electron beam ion source called Extended-EBIS, has been in operation since 2023. Extended-EBIS captures and confines the LIS 1+ ions and

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ionizes them to high charge state. The high charge state ions are extracted from EBIS and accelerated to 2 MeV/u by a RFQ linear accelerator and an IH-type linear accelerator [2]. Typically, targets are installed in the LION1 during a summer shutdown, and don't need to be replaced during an entire run until the next summer shut down. Most of targets can be used for several years until target surface becomes degraded.

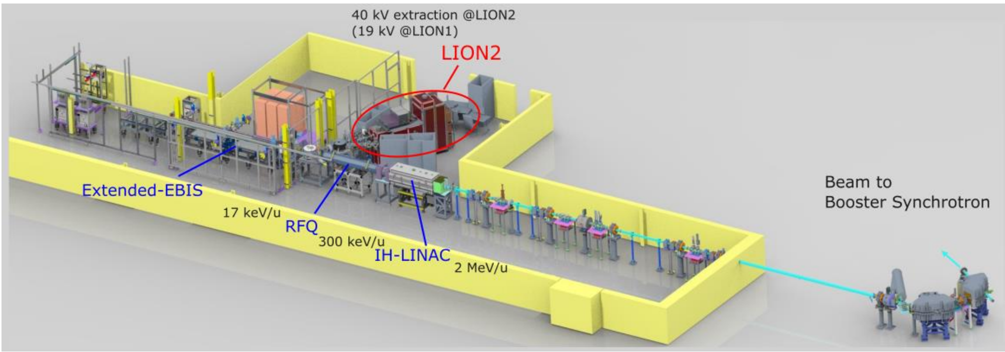

Figure 1. LION2 location at the RHIC-EBIS pre-injector.

2. LION2 design and progress of construction

In the future, LION2 will provide all heavy ions available from solid-state targets to the EBIS for use by NSRL and RHIC. Figure 2 shows the schematic of the LION2. The basic design is similar to LION1 which can be seen in ref [3]. One vacuum chamber contains two independent target systems: one is the xy target for NSRL species and the other is the rotary target for RHIC species. Laser produced plasma generated in the target chamber is transported by a long solenoid. Singly charged ions are extracted from the plasma at the end of solenoid and the ion beam is transported to an electron beam ion source for further ionization. LION2 was designed for higher beam currents: 500 μA of Au^{1+} compared to 100 μA used for the LION1 design. The LION2 extraction voltage is 40 kV compared to 20 kV for LION1. We used IGUN [4] for the ion extraction and beam transport simulation. LION2 has a shorter solenoid length and an extended beam transport at laboratory ground potential. The new beam transport is equipped with an Einzel lens and a scintillator beam monitor. The extended beam line allows better access to the vacuum system for easier maintenance.

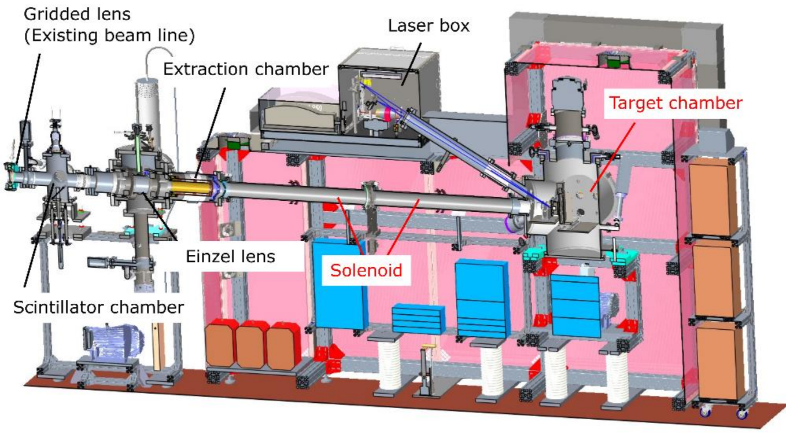

Figure 2. Schematic of LION2. High voltage is applied on the devices labeled in red color.

2.1. High voltage cage

A target chamber, solenoid magnets to transport laser produced plasma, and control racks reside on a high voltage platform at the extraction potential of 40 kV. A high voltage cage serves as a supporting frame for those devices and lasers on the ground potential are placed on top of the cage. Figure 3 shows the high voltage cage at assembly location. We will pre-assemble as many components as possible in a workshop based on the new high voltage cage. The assembled structure will then be moved to the EBIS facility installation site during shutdown.

2.2. Target chamber

In recent years, about 11 different species have been installed on the xy target holder for NSRL to accommodate beam requests at LION1; however, this is almost the limit for the existing holder. The height of the target holder at LION2 will be doubled to 114 mm, while preserving the target holder width of 254 mm. We will use the same rotary target system for RHIC operation. LION2 has a larger target chamber to accommodate the enlarged xy target. The fabrication of the LION2 target chamber has already completed.

2.3. Solenoid magnets to transport laser produced plasma

The length of the long solenoid magnet is shortened since our studies have shown that the beam width from LION1 (several hundred microseconds for Au^{1+}) is more than adequate for capture by the EBIS. The shorter solenoid magnet is expected to result in increased ion density at the ion extraction chamber. At LION2, a vacuum gate valve will be installed at the middle of the plasma transport line in between two solenoids. It has been observed that the valve does not affect the ion beam intensity at the LIS ion extraction [5]. LION2 will have a 990 mm coil, 99 mm gap for a vacuum valve and flanges, and then a 990 mm coil compared to a single 3008 mm coil length at LION1. Figure 4 shows the fabricated 2 coils on a test bench with a dummy pipe in between the solenoids.

2.4. Laser box

We will use the same laser model (Quantel laser Q-smart 850, 850 mJ, 6 ns, wavelength 1064 nm) at LION2. The laser energy and the laser spot size on a target is optimized to achieve a laser power density just above the plasma generation threshold to produce singly charged ions. At LION1, one laser for the NSRL targets and one laser for the RHIC target are placed in the same metal box for laser safety. Therefore, if one laser has an issue, it is necessary to stop both lasers and both NSRL and RHIC operations are stopped. At LION2, three lasers will be installed. Each laser line has a piezo actuated mirror holder, and each laser can switch laser line between all target systems remotely. One laser serves as a spare to resume operation with minimal down time. Each laser has an individual laser box and interlock system. Laser maintenance of a laser can be done without affecting operation of the other lasers. The laser box has been fabricated, and laser interlock system has been assembled and tested.

2.5. Extraction chamber

At the LION1, an ion extraction chamber was supported from the high voltage platform. A vacuum pumping system is also on the high voltage inside of the high voltage cage. Due to the cage and tight space around the extraction chamber, the vacuum system at the extraction chamber is very difficult to access and periodic maintenance of a roughing pump is time consuming. Instead, the extraction chamber of the LION2 is supported from the ground potential and is out of the high voltage cage. In addition, the new beam transport line between an ion extraction chamber to the existing transport line will be installed for better access to the vacuum systems. A new Einzel lens and a scintillator screen beam monitor will be installed in the extended transport line. At LION2, the ion extraction aperture is reduced to 10 mm in diameter compared to 15 mm at the LION1 since ion density is higher with shorter plasma drift distance. A new electron repeller electrode biased up to -5 kV will be added near a ground electrode to avoid possible breakdown at the extraction chamber. The extraction chamber has been assembled and a high voltage testing has been completed. Figure 5 shows the extraction chamber under the hi-pot test.

2.6. Einzel lens

To transport ion beams through the new extended transport line, an Einzel lens will be added. The aperture of this Einzel lens is 128 mm in diameter. Based on IGUN simulation, -56 kV will be applied to transport 500 µA of Au^{1+} beam at 40 keV. A center electrode is connected to a linear feedthrough and a three-dimensional linear stage. The position of the center electrode will be shifted in transverse direction if an extracted ion beam needs to be steered due to misalignment. The offset up to 1 mm is expected. 1 mm offset gives 8 mrad deflection. Figure 6 shows the inner structure of the Einzel lens. We completed a hi-pot test of the chamber.

2.7. Scintillator screen beam monitor

A scintillator screen will be installed in the new beam transport line. The scintillator screen is mounted with 45 degrees angle. A beam image on the screen will be captured by a camera mounted on top of the scintillator vacuum chamber through a vacuum window.

Figure 3. High voltage cage

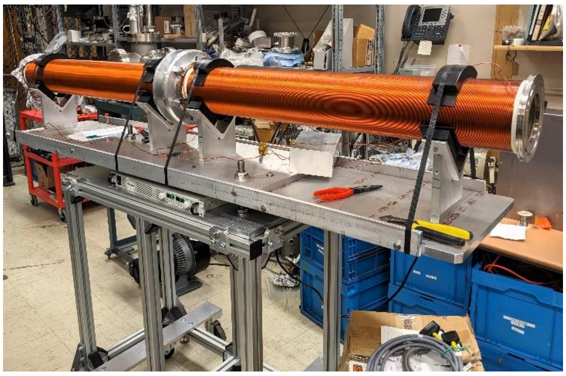

Figure 4. Long solenoid to transport laser produced plasma

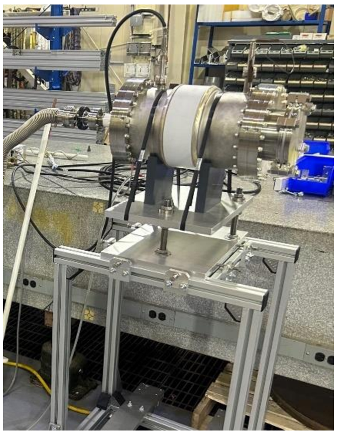

Figure 5. Extraction chamber under hi-pot test. 40 kV will be applied at ion source.

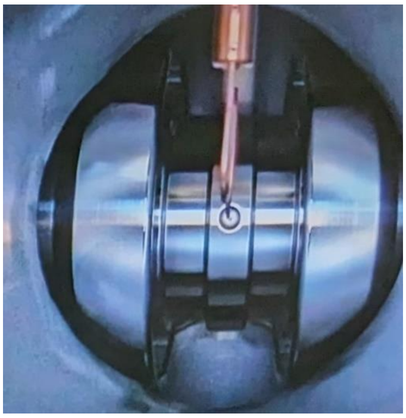

Figure 6. Inner structure of Einzel Lens. The center electrode can be shifted from air side to adjust beam angle caused by misalignment.

3. Development of a laser ion source with high repetition rate picosecond laser

The LION2 project includes the development of a low current quasi-continuous beam for slow ion injection into an electron beam ion source. This scheme is explained in detail in ref [6]. LION1 and LION2 provide 100 µA to 1 mA of singly charged ion beams with the pulse width of 100 ~ 300 µs depending on the ion species. These ions are captured by an EBIS using a “fast injection” scheme. The other ion injection scheme is a “slow injection”, in which a low current (~10 µA) and long pulse width (~10 ms) beam is slowly accumulated in the ion trap. The “fast injection” mode usually has a much higher trapping efficiency; however, the “slow injection” mode makes it possible to use an isotope separator between an external ion source and the EBIS, which can increase the resulting EBIS high charge state ion beam intensity of the isotope of interest [7]. We plan to develop a laser ion source design to provide quasi-continuous beam to realize the “slow injection” mode using a high repetition rate picosecond laser. Based on the feasibility study using a picosecond laser (400 Hz, 1.25 mJ per pulse) at Argonne National Laboratory [8], we purchased a 10 kHz picosecond laser from neoLASE. Table 1 shows parameters of the laser. Acceptance testing of the laser has been completed and we are preparing for the first experiments in our laboratory.

Table 1. Specification of the high repetition rate picosecond laser from neoLASE. This laser will be used for the development of low current quasi-continuous beam for slow injection into an electron beam ion source.

Wavelength	1030 nm
Repetition rage	10 kHz
Pulse energy	5 mJ
Pulse duration	4 ps
Beam diameter	4 mm

4. Conclusion

The fabrication of the LION2 is progressing well. The fabrication of most of major components has been finished. A high voltage testing of the extraction chamber and the Einzel lens were successfully concluded. After beam testing in our lab, the final assembly will be started. The fabrication at an assembly location is expected to be finished during December 2023. The removal of the existing LION1 and the installation of the LION2 will be conducted during a 2-month shutdown period. The installation at the accelerator is expected to take during the December 2023 or summer 2024 shutdown, depending on the NSRL and RHIC operations schedules.

5. References

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Acknowledgments

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