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Laser ion source for Columbia University's microbeam

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Abstract

A laser ion source that will be installed on the new High Voltage Engineering (HVE) 5 MV Singletron accelerator at the Columbia University Radiological Research Accelerator Facility (RARAF) will expand the linear energy transfer (LET) range available for irradiation experiments with mammalian cells. Through laser ablation the laser ion source can produce heavy ions with high charge states from a solid target; after acceleration, these ions will have sufficient energy to irradiate cells on a thin surface at atmospheric pressure. A high-power 100 Hz pulsed Nd:YAG laser used with the laser ion source has produced aluminum ions with charge states greater than nine. Proper power management issues are important in obtaining the high charge states while protecting sensitive laser optics. We expect that the laser ion source will enable us to use ions from hydrogen to iron, providing an LET range of about 10–4500 keV/μm for cell targets.

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Keywords: Laser ion source; Spherical electrostatic analyzer; Microbeam irradiation

1. Introduction

The centerpiece at the Columbia University Radiological Research Accelerator Facility (RARAF) is a focused ion microbeam dedicated for single-particle single-cell irradiation studies on mammalian cells. This irradiator uses an electrostatic quadrupole lens system for focusing the ion beam [1] and is tunable to a specific linear energy transfer (LET) for radiation dose delivery to predetermined, sub-cellular components. This technique can induce deliberate DNA damage to facilitate studies on DNA repair mechanisms, for example. The present facility contains a 4.2 MV Van de Graaff particle accelerator equipped with a duoplasmatron ion source. With the interest to increase the range of available LET values, a laser

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ion source (LIS) has been designed and built as an ion source option for a new 5 MV High Voltage Engineering (HVE) Singletron particle accelerator that will replace the Van de Graaff particle accelerator and will be installed at RARAF during summer 2005. This LIS is expected to provide ions from hydrogen to iron that, after acceleration, will have sufficient energy to irradiate mammalian cells on a thin membrane at atmospheric pressure with an LET range of about 10–4500 keV/μm. Laser ion sources [2], in which a high-power, pulsed light beam is focused to micron dimensions resulting in power densities on the order of 10^{12} W/cm^2, produce high initial charge states of heavy ions in sufficient fluxes for microbeam experiments.

2. Apparatus

The LIS scheme at Columbia University is based on laser ablation. High-power Nd:YAG laser pulses will penetrate the accelerator tank through a window, pass through the SF_6 insulating gas and enter a vacuum region through an optical port to deliver a focused, high-power-density pulse onto a solid target, impinging at 8.5°. Ions created during the energy transfer of an ablation event are ejected in the form of a plasma plume in a direction that is preferentially normal to the solid target surface. These ions are emitted with a distribution in charge state, kinetic energy, and angle. Following a drift distance for plasma expansion, a spherical electrostatic analyzer (ESA) selects ions with a particular energy per charge and focuses them to a point coinciding with the 3.18-mm entrance aperture of the accelerator tube. The LIS is pictured in a table-top configuration in Fig. 1.

2.1. Laser

To maximize the ion flux, a Quanta-Ray LAB-190-100 Nd:YAG pulsed laser system from Spectra Physics was chosen for its high repetition rate (100 Hz) and high power (325 mJ/pulse, 10 ns Q-switch pulse duration). The laser pulses enter the vacuum system through a special vacuum entrance port with anti-reflection (AR) coating for the Nd:YAG fundamental wavelength, 1064 nm; this port is also built to withstand the eventual environment for the LIS, up to 10 atm of accelerator

Fig. 1. Picture of the Columbia University LIS on the work bench. The optical path of the Nd:YAG laser has been drawn with white arrows to show where it enters the vacuum system. Except for the pump manifold, the vacuum components on the right, up to the ion image point, are the essential LIS parts to be installed in the accelerator terminal.

tank insulating gas. The focusing lens for the laser is mounted on a holder inside the vacuum system. With a lens focal length of 12.2 cm and a laser divergence of 0.5 mrad, the focal spot diameter (the product of the focal length and the beam divergence) is 61 μm. This spot size ideally provides a focused power density of 2.2×10^{12} W/cm^2.

2.2. Optics

There is significant spatter (particulates emitted from the target surface during ablation at high power density) that coats the internal vacuum chamber walls and components. To contend with this issue, a 2 mm thick piece of AR-coated, BK7 glass is used as a lens protector to inhibit spatter accumulation on the focusing lens. Sequential laser pulses keep a clean path through the lens protector by an evaporative auto-cleaning process. It is important to maintain a good balance between energy to evaporate the deposited spatter and keeping the heat in the lens protector low enough to not induce optics damage.

2.3. Ablation target

The assembly drawing for the Columbia University LIS is shown in Fig. 2. The ablation target is a cylindrical solid attached to a differential drive manipulator. The manipulator was designed and built in-house with an optimized choice of gears that allow the target to nominally rotate (69 μm/step) and advance (100 μm/revolution) at rates that maximize the target's usable lifetime. The target stage rotates by a vacuum-compatible stepper motor (in microstepping-drive mode) triggered by the laser pulse. The differential drive was designed so that target increment distances were on the order of the laser focus spot size. However, a torque-ripple effect associated with the microstepping drive and stepper motor combination has introduced an oscillation in the step size. The impact here is that some step increments are smaller or larger than the laser spot size. Larger steps tend to waste target surface area, and the impact of smaller steps is that craters from sequential ablation events will overlap. Previous studies have shown that the yield of high charge states is diminished in plasma generated from an area of a previous ablation event [3].

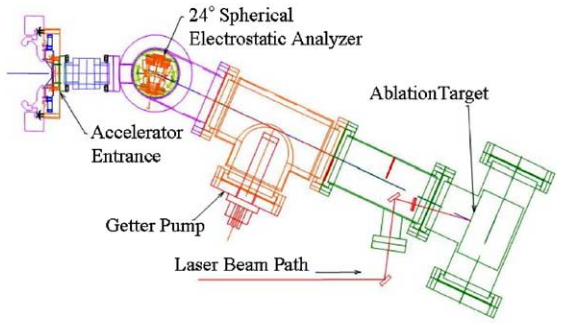

Fig. 2. Assembly drawing of the Columbia University LIS. The plasma plume (induced by the laser ablation event) travels along the center line of the vacuum housing components towards the 24° ESA; plasma expansion occurs along the initial 70 cm drift distance.

2.4. Electrostatic analyzer

Ions generated from the laser ablation process have a wide distribution in charge state and energy. To select a particular ion charge state and energy, the plasma first expands through a drift distance of 70 cm [4] and then enters a 24° spherical ESA that was designed and built in-house. This ESA is a double-focusing element and is documented in a previous journal article [5]. The design for the improved ESA incorporated Hermann Wollnik's recommendations for treating fringe fields [6] and it has interchangeable apertures leading in and out of the ESA to limit the energy resolution of the transmitted ions. A photograph of our spherical ESA is shown in Fig. 3. The ESA is a self-contained module mounted on a 6-in. flange. Special attention was also given to the type of electrical feed-throughs for a vacuum system residing inside a pressurized container. An electrostatic field within the ESA selects ions by energy/charge. So for each pulsed, laser-ablation event, the ions that pass through the ESA can be characterized by a time-of-flight (TOF) spectrum. The highest charge-state ions have the highest energy and arrive at the accelerator entrance aperture first, while the lowest charge-state ions arrive last.

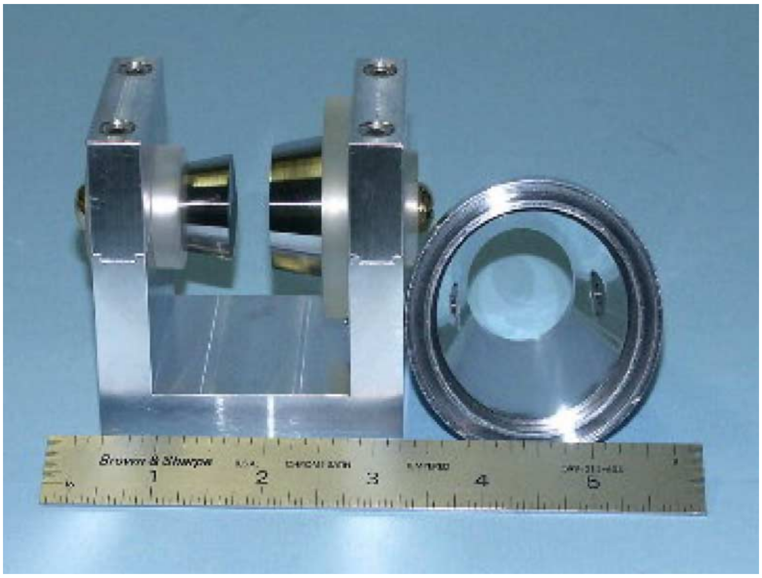

Fig. 3. This photograph of our spherical ESA shows two electrodes and their insulating stand-offs mounted in a U-frame. On the right is a conical sheath that is placed around the electrodes. The sheath is an electrically grounded surface that is used to shape the effective electric field boundary.

3. Results and discussion

3.1. Vacuum

High charge state yields increase with improved vacuum of the laser ion source. Since the component of the laser ion source that requires vacuum conditions will reside at the terminal end of the accelerator column, it will also experience an external environment of high pressure, the insulating gas within the accelerator tank. This situation is inconvenient for vacuum pumps that require an exhaust to atmospheric (or higher) pressure. Tests with a titanium sublimation pump (TSP) have shown that a gettering pump is a viable option for maintaining proper vacuum conditions in the LIS. For this trial, the inlet to a turbo pump on the laser ion source was constricted with a small aperture to emulate the pumping action on the laser ion source from the turbo pump located at the exit end of the accelerator. The addition of the TSP brought the operating pressure down by an order of magnitude in the LIS. Operating the LIS with an aluminum target demonstrated that the improved vacuum condition extended the high charge state range from Al^{7+} to Al^{11+} and possibly higher. The enhanced ion yield is evident in the spectra comparisons in Fig. 4. These spectra were obtained with the ESA tuned for 400 eV/Z and

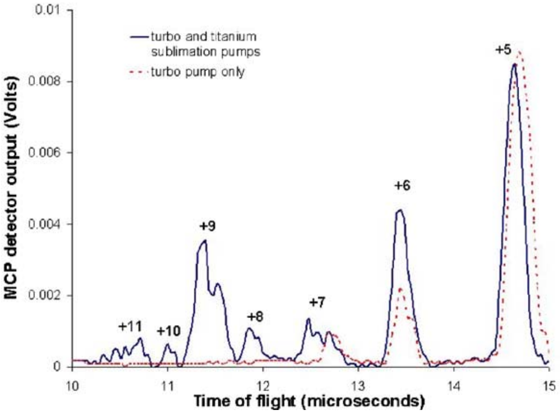

Fig. 4. TOF spectra comparison that depicts the tendency of the high charge-state yield from the LIS when vacuum is improved with a getter pump. These spectra are averages from 256 laser ablation events on aluminum.

from a prototype LIS system that employed a cylindrical ESA [3].

3.2. Coupling to the Singletron

Several considerations were made to tailor-fit the LIS footprint into the forthcoming Singletron machine. Initially, a TSP was chosen as an appropriate gettering pump in a design that would suit installation onto the present Van de Graaff particle accelerator. In that design, the TSP would be built from a tee section with an external cooling jacket, the ion ablation plume would pass through the run of the tee and the titanium filament source would be housed in the leg side of the tee. Auxiliary power available at the Singletron terminal, however, presented a limitation to using a TSP, so an alternate plan was to use a non-evaporable getterer (NEG) pump. Fortunately, an NEG pump has less power requirements, and the mount and length of an appropriate NEG cartridge was nearly identical to that for a TSP filament. Hence, this pertinent change was incorporated into the final LIS, with negligible redesign cost.

Additionally, it is crucial to have a match between the ion source emittance [5] and acceptance of the Singletron accelerator tube. In collaboration with HVE, appropriate modifications were made to the primary accelerator tube sections to optimize the transmission of the LIS-produced ions and also conserve the function of the duoplasmatron, the primary ion source incorporated on the Singletron.

3.3. Preliminary laser ion source data

First data from the Columbia University LIS includes a voltage study of the ESA. Fig. 5 implies that the ion yield does vary with the voltage across the ESA, verifying the spherical ESA's capability to select a particular ion energy/charge from a distribution. The data show that by varying the ESA voltage, it is possible to obtain a highest yield for a particular charge state which translates into an increased ion beam flux for irradiation experiments.

The ion peaks in these TOF spectra are not well resolved. At this junction, it is difficult to conclusively identify and label the charge states for the spectral peaks. Conveniently, resolution improvements will be made by reducing the size of the ESA apertures. With resolved peaks and accurate charge-state identification, a thorough evaluation of the ESA will be possible.

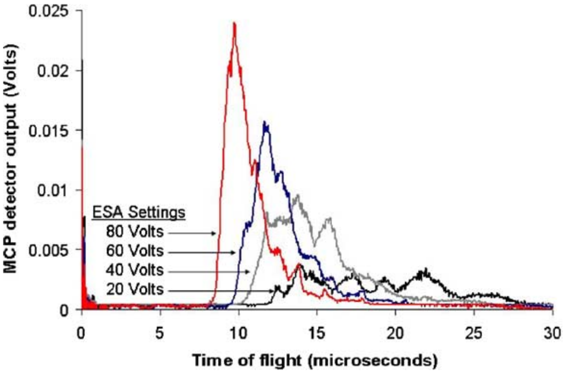

Fig. 5. Time of flight spectra from the LIS as a function of ESA voltage. Note that as the ESA voltage increases, the spectra arrive earlier in time, implying that the ESA is selecting ions with greater energy/charge. Each spectrum is an average of 1024 ablation events.

4. Conclusion

The Columbia University LIS has been built and tested on a bench top. This ion source has the capacity to extend the laboratory's LET range for radiobiological experiments by dramatically increasing the choice of available ions. An increased resolution from the ESA will enable a full characterization the ion charge states available through ESA selection.

Acknowledgement

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