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Proposed laser ion source for the Columbia University microbeam

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Abstract

A laser ion source is scheduled as an upgrade for the 4 MV Van de Graaff accelerator at the Columbia University's Radiological Research Accelerator Facility (RARAF). The source has been designed for use with the RARAF single-particle single-cell microbeam, though it will be used also for broad-beam irradiations. The operating principle, laser ablation, can produce heavy-ions with high charge states so that their energies will be high enough to provide sufficient range – at least 20 μm – for irradiating cells on a thin surface at atmospheric pressure. The laser ion source being implemented at RARAF consists of three main components: a high-power 100 Hz Nd:YAG laser, a source vacuum chamber and a 24° spherical electrostatic analyzer and a double focusing element with point-to-point focusing in both the horizontal and vertical planes. We expect that the laser ion source will enable us to use ions of sufficient range from hydrogen to iron, providing a range of linear energy transfer from about 10 to 4500 keV/μm.

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1. Introduction

At Columbia University's Radiological Research Accelerator Facility (RARAF), fundamental investigations into the radiobiological effects on mammalian cells are conducted through a broad beam and through controlled single-particle single-cell microbeam irradiation [1]. Recent upgrades to our horizontal, single-ended 4.2 MV Van de Graaff particle accelerator include implementation of a laser ion source. The laser-ablation based ion source will produce highly charged heavy ions that will extend the linear energy transfer (LET) range of our experiments. This type of heavy ion source is favored over a conventional heavy ion source because its weight and power requirements can be supported at the high-voltage terminal end of our accelerator. The laser will reside outside the accelerator tank and the laser pulses will be guided to the source vacuum housing mounted at the accelerator terminal.

Presently, our duoplasmatron ion source can ionize atoms from the gaseous phase, namely from hydrogen and helium. These ions are suitable for particle irradiation experiments with an LET range of 9.5–210 keV/μm. Expectations are that

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the laser ion source will enable us to obtain ions from hydrogen to iron with an approximate LET range of 10–4500 keV/μm. To that end, examples of minimum charge state requirements are: Al^{8+}, Ti^{14+} and Fe^{15+}.

In the field of laser ion sources, two common modes of ion production are laser ablation and resonance ionization spectroscopy, a species-selective technique that requires tunable lasers [2]. The operational mechanism of our laser ion source is plasma generation through laser ablation of a solid target. Focused Nd:YAG laser pulses supply the power density required to create a plasma plume [3]. The plasma ions have distributions over charge state, energy and angle. To then reduce the beam load on the accelerator vacuum system, an electrostatic analyzer (ESA) selects ions with a particular energy per charge.

Our laser ion source design originated with a prototype based on the laser operated ion source acquired from Hughes at the University of Arkansas [4]. Ion trajectories in this source experienced in turn, 70 cm of plasma expansion drift, a 180° cylindrical ESA, two Einzel lenses, and a final drift distance to a detector whose position would effectively be the location of the 3.18 mm diameter entrance aperture of the particle accelerator. For a particular charge state, maximum current magnitude observations from the prototype source were 10^3 ions/laser pulse. This is adequate for single-particle single-cell microbeam experiments, but not ideal for broad beam experiments. Dimension details of the original laser operated ion source have been provided elsewhere [5]. Furthermore, the following simulation results complement a previous document of our laser ion source development [6].

2. Prototype simulation

Ion trajectories through the prototype laser ion source were simulated with the ion optics package, SIMION [7]. In SIMION, the potential at points outside electrodes and poles is determined by solving the Laplace equation by finite difference methods [8]. Virtual ion optical components are constructed and arranged on an ion optics workbench. Ions flown through such an optical system retain characteristic information useful for generating phase space patterns for simulated ion source emittance measurements.

In the ion optics workbench setup for the prototype laser ion source, it was required to construct virtual ion optical elements that paralleled as much as possible the physical configuration. The optical elements were constructed with a grid resolution of 1 mm/grid unit. To project an optical element into three-dimensional space, SIMION supports both planar and cylindrical symmetries. Planar geometry was used for the cylindrical ESA, and cylindrical geometry was used for the Einzel lenses. Initial characteristics of the ions flown through the simulation were mass, charge state, position, energy and angle. A random function within certain bounds was applied to offsets about the energy and the angle. Typical ion parameters were: aluminum, singly charged positive, origin about a circular area representing the ablation crater (0.25 mm diameter), 400 eV mean energy and normal emission with a random divergence within a 0.2° cone angle. Voltage settings on the optical elements during the simulation were 69.35 V across the analyzer, −200 V on the first Einzel lens and 100 V on the second Einzel lens.

Emittance results emerged from analysis of the ion flight data. In a typical case, the vertical extent of the ion beam was acceptable for input to the accelerator aperture. However, the horizontal ion beam component extended beyond the aperture boundary, suggesting reduced ion transmission. For other voltage settings on the Einzel lenses, a variety of spot patterns were produced, but none could match the aperture size constraints in the vertical and in the horizontal direction simultaneously. This limitation to the prototype laser ion source was an artifact of the ion optical geometry.

3. Spherical ESA

A double focusing, spherical ESA with point-to-point focusing in both the horizontal and vertical planes suited the design requirements for our laser ion source. With this one ion optical element, laser plasma plume ions are both E/Z analyzed and focused to the accelerator entrance aperture. The footprint of this option fit well within the accelerator terminal. Einzel and quadrupole lens options were also considered, but their linear arrangements would require structural modifications of the accelerator terminal frame.

Guided by spatial limitations in the particle accelerator and by a desired plasma expansion drift distance of 70 cm[3], the ESA dimensions were narrowed to a 24° bend with a 68.58 mm radius. This geometrical solution was found by applying Barber's rule; the object point, the center of curvature and the image point lie on a straight line [9].

Spherical ESA theory and fringing field effects are well documented in Wollnick's treatment of electrostatic prisms [10]. Wollnick's guidelines for fringing field termination provided additional dimension details to the ESA. Electrode spacing and field-terminating diaphragm dimensions were set similar to those in the prototype's ESA. For a 10 mm space between electrodes, a 5 mm arc length from the ESA electrodes to the diaphragm, and a 5 mm diameter diaphragm aperture, the 24° ESA would have a 21.32° arc for the physical electrodes and a 29.68° arc for the diaphragm. The ideal field boundary would, in theory, have a 24° arc. A top view cross-section diagram of the 24° ESA is shown in Fig. 1.

For the simulation of the 24° ESA, the ion optics workbench setup in SIMION was similar to the one presented in the prototype simulation section. However, an increased resolution (0.2 mm/grid unit) was used for the 24° analyzer. Again, the component dimensions in the simulation paralleled as much as possible the intended "real world" case. To insure that the electric field lines were fully terminated in the ESA element, an ideal grounded mesh was wrapped about the ESA diaphragm material at a 5 mm offset distance from the inside of the diaphragm.

For the proposed laser ion source, the simulated spot size is shown in Fig. 2. Horizontal and vertical histograms across this ion spot are shown in Fig. 3. Simulated emittance measurements for the proposed laser ion source are shown in Figs. 4 and 5. For comparison, these plots have a 20 mm x-axis span; this was the approximate horizontal ion beam width from the prototype simulation mentioned earlier. The improvements are clear; the spot size is smaller and the ions tend to focus in both the horizontal and the vertical directions. The structure in the emittance patterns is due to aberrations that arose from the use of a spherical optical element. However, upright ellipse envelopes about the emittance patterns do still imply a focus at the entrance aperture to the particle accelerator. One more note is that the simulation results suggest an energy resolution compatible with input requirements of a six-element electrostatic quadrupole lens with Russian symmetry that is under

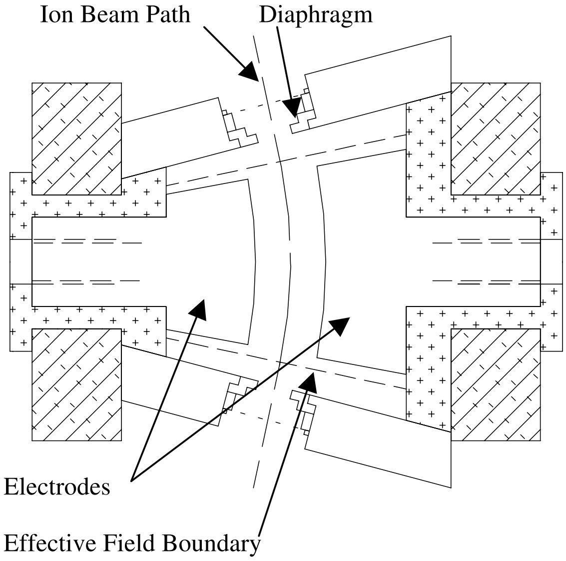

Fig. 1. Top view cross-section diagram of the 24° ESA.

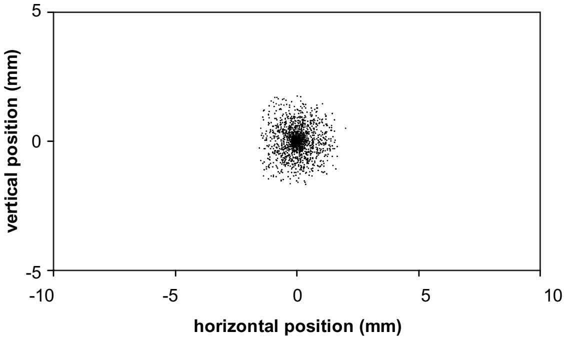

Fig. 2. Spot pattern of proposed laser ion source. Focus is acceptable.

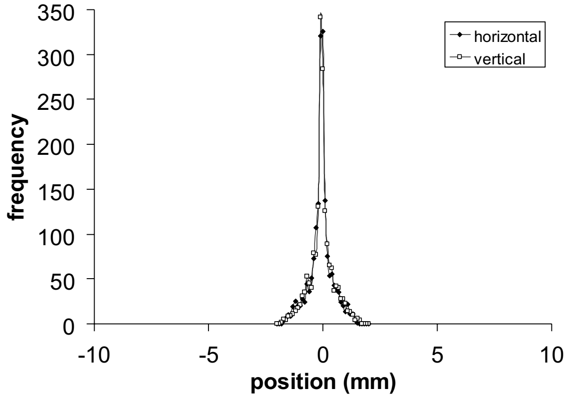

Fig. 3. Intensity histograms across the ion spot pattern shown in Fig. 2.

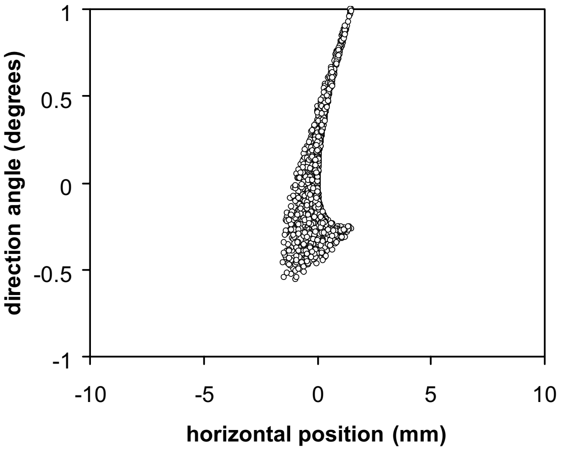

Fig. 4. Horizontal emittance simulation from the proposed laser ion source.

development. To tune the resolution, interchangeable diaphragms are available for the ESA.

4. Construction notes

An interest in the fabrication of the ESA is to match the simulation geometry as best as possible. The physical dimensions used in the simulation will be retained except for one feature. The spherical ESA design in SIMION utilized a slot diaphragm. During the simulation, a virtual round diaphragm was realized by limiting the cone angle of the incident ions. The construction will incorporate circular diaphragms.

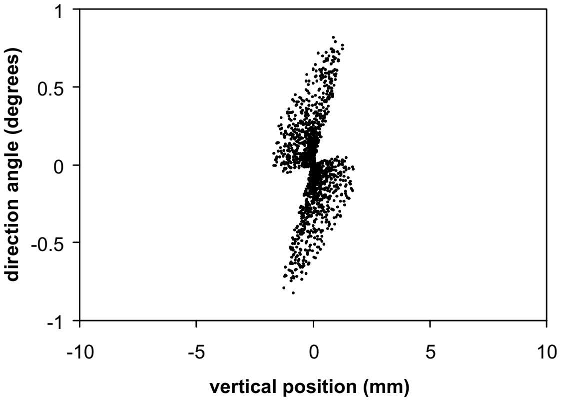

Fig. 5. Vertical emittance simulation from the proposed laser ion source.

In constructing the laser ion source, alignment issues are crucial. In particular, the ESA must be placed in its designated position and the electrode orientation should be optimized. The construction will utilize a self-aligning technique to insure proper placement. During the electrode machining process, flat surfaces and alignment holes for indexing pins incorporated into the outsides of the electrodes will allow them to accurately rest in a frame mount.

Electrode surface treatment will also be an issue. A thin layer of carbon will be deposited on the electrodes in order to reduce patch potentials. This should lead to a smoother electric field within the ESA.

Acknowledgements

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