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LEVIS Ion Source and Beam Characterization on PBFA-II*

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Abstract

We report on the continuing development of the LEVIS (Laser Evaporation Ion Source) lithium active ion source for the 15-cm radial focussing ion diode on PBFA-II. We found previously that DC-heating of the anode surface to 150°C maximum for 5 hours resulted in a pure lithium beam. This paper discusses the characterization of LEVIS source uniformity by Faraday cup arrays and multiple lines of sight for visible light spectroscopy. These diagnostics give some evidence of nonuniformity in both A-K gap electric fields and ion current density. Despite this, however, the measured focal spot size appears smaller than with a passive LiF source operated in the same magnetic field topology. Experiments using a curved anode for vertical beam focussing show reduced ion beam turn-on delay by 5 ns by altering the magnetic field topology as well as anode curvature. Another 3-5 ns reduction was achieved by switching from a passive LiF to the active LEVIS source.

Introduction

The Laser Evaporated Ion Source (LEVIS) has been developed as a lithium ion source for the 15-cm radial focussing ion diode on the PBFA-II accelerator at Sandia National Laboratories. LEVIS is an active source, i. e. it makes use of a two-stage laser irradiation of the anode surface to produce a plasma prior to the diode power pulse, from which ions can be accelerated. A Nd:YAG pulse (1.06 μm, 8 ns, ~ 0.2 J/cm^2) produces a thin vapor layer (~1 mm, 10^{16} cm^{-3}) by evaporation of lithium from a thin-film alloy. The vapor layer is then ionized by a dye laser (670.8 nm, 1 μs, ~ 50 mJ/cm^2) tuned to the first resonant transition of lithium. We have reported previously[1] on the preparation of the thin-film LiAg used as the lithium-bearing source, on the optimization of the laser fluence levels, the uniformity of the laser energy deposition, and the development of a DC-heating technique for cleaning the LiAg surface prior to a machine shot. Time- and space-resolved spectroscopic observations in the anode-cathode (A-K) gap of the LEVIS source[2] verified the existence of a preformed plasma with LEVIS, and the absence of this plasma when a passive LiF ion source[3] was fielded on PBFA-II instead of LEVIS. These observations also showed large reductions in relative impurity line intensities in the A-K gap (factor 3-5 for carbon lines, factor 40 for hydrogen) after 3 hours of DC-heating to a maximum 125 degrees C, implying that impurity concentrations in the anode plasma were greatly reduced. The resulting ion beam was almost entirely free of proton and carbon contaminants, measured at the beam focus. Spectroscopic meaurements also indicated control of the anode plasma thickness by varying the timing of the vaporization laser firing relative to the power pulse. Thus we have previously shown the validity of the LEVIS concept as a source for a pure Li beam on PBFA-II.

This discussion concentrates on the behavior of the ion beam produced by the LEVIS source, in particular as compared with the beam produced by the LiF source, which has been optimized by extensive testing on PBFA-II. One result produced by both sources is that the beam focal spot size on target is

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consistent with a 20-35 mrad divergence, despite the fact that the source divergence has been estimated from spectroscopic observations at considerably less. LEVIS source divergence has been estimated at 4-9 mR, about half the15 mR LiF source divergence. There are several possible causes of the increase in spot size: electromagnetic instabilities in the A-K gap; and nonuniformities in the anode source plasma. Theoretical studies[4] have predicted a correlation between nonuniform ion emission and beam divergence. The effect is maximized when the length scale of nonuniformities is comparable to the A-K gap. It was a goal of the measurements detailed here to assess the importance of these contributions to LEVIS focal spot size.

In addition, almost all prior LEVIS shots used a flat anode geometry in the vertical dimension, which aids in clarifying the spectroscopic observations, but limits the power density on target. We fielded a curved focussing anode to both raise signal levels on diagnostics located at the beam focus, and to better compare LEVIS performance directly with a LiF source operated with the same diode parameters (insulation field topology, etc.).

Configuration

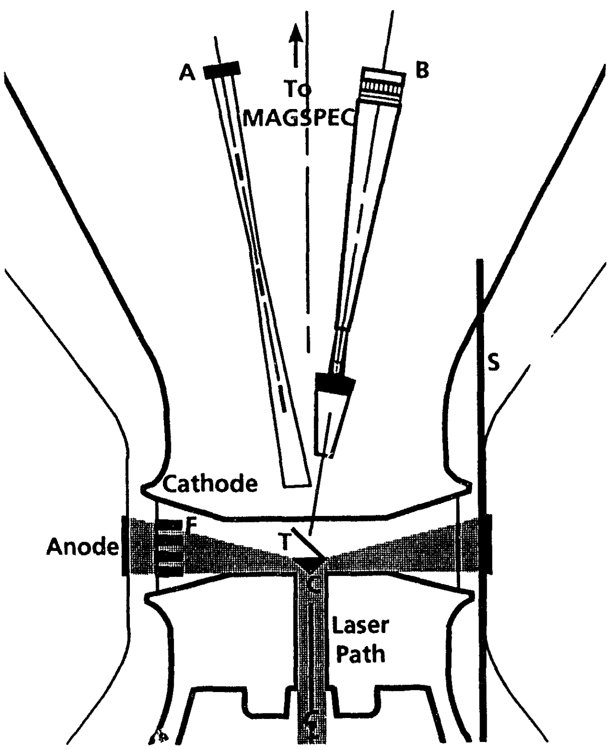

Figure 1

Figure 1 shows an overview of the diode region, the spectroscopy line-of-sight (S), and the various beam diagnostics discussed below. At each of two locations 180 degrees apart in azimuth, there were between 4 and 7 individual lines-of-sight (LoS) for spectroscopic observations on any given shot, each with a 2 mm resolution. Light from the two LEVIS lasers arrives from below, reflects off the laser distribution cone (C), and illuminates a 6-cm anode height coated with LiAg, creating a plasma from which the ion beam is drawn. The resultant beam propagates radially inward through a 1.5 μ mylar foil towards a gold scattering target (T) on axis. Scattered ions are measured by an array of diagnostics. A Magnetic Spectrometer (MAGSPEC) is located 1.1 meter above the target along the axis of symmetry. The MAGSPEC utilizes both 3 linear arrays of PIN diodes and CR-39 nuclear track-counting material to form a time- and energy-resolved image of the beam focus. Ions are also scattered slightly off axis towards a single frame camera (A), with another piece of CR-39 behind a 7.5 MeV Li range filter, giving a time-integrated focal image, from which total ion energy on axis can be estimated. The Ion Movie Camera (B), a 2-D array of PINs also located slightly off-axis, generates a time-resolved image of the beam focus.

A small fraction of the ion beam is collected by an array of Faraday cups (F) located at the radius of the mylar foil. A total of 12 cups were fielded in groups of 4 located 90 degrees apart. Several cups per shot were filtered with 36 μ Al, which transmitted only protons, thus allowing qualitative measurement of hydrogen impurities in the Li beam. Though it appears in the drawing that the Faraday cups interfered with the laser beams, through the use of reflecting mirrors this interference was kept to a minimum.

Results

Several different configurations were studied, and their results discussed here: flat anodes using both LEVIS and passive LiF ion sources, a focussing anode shot with each type of source, and a flat anode shot in which the LiF source was subject to the same DC heating cycle as the LEVIS source. The heated LiF shot differed only slightly in behavior from unheated LiF results.

The LEVIS source exhibited more azimuthal variation in Faraday cup magnitude than the LiF source. Typical variations in cup magnitudes for LiF were ± 20 to 30%, with as much as 15 ns temporal variation in attainment of peak magnitude. This variation increased slightly on the heated LiF shot. The variation on LEVIS shots ranged from ± 15% to as much as factors of 5 variation in peak magnitude. The LEVIS shots also exhibited little temporal variation in the signal peak. These combined observations suggest large local variations in current density being drawn from the LEVIS source. There was little correlation, however, between this Faraday cup variation and the size of the resulting beam focus, as will be discussed below.

The Faraday cups filtered to accept only protons generally followed the same behavior for either source, i.e. minimal amplitude before peak beam power, followed by increasing proton contamination.

Spectroscopic measurements of the electric field in the two LoS locations indicated the presence of large field asymmetries as a function of time, for both LEVIS and LiF sources. Fig. 2 shows average electric field for the two azimuthal locations at two different times in the diode power pulse. The 58 ns plot roughly corresponds to the time of peak beam power. Based on these and other observations, the degree of asymmetry is seen to increase and decrease several times during the power pulse.

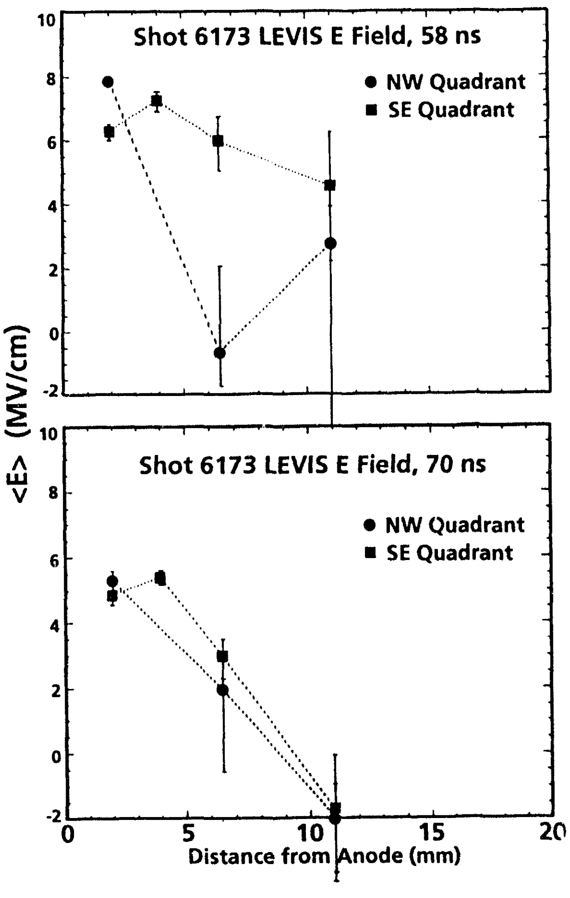

Figure 2

Both ion sources thus appear to suffer both electric field fluctuations of significant magnitude, and azimuthal variations in Faraday cup signals, with more temporal variation in the signals with the LiF source, and more peak magnitude variations with LEVIS.

The focal spot behavior is estimated from the time-dependent Ion Movie Camera image, and the time-integrated Single Frame Camera and Magnetic Spectrometer CR-39. It is difficult to estimate spot behavior with the Ion Movie Camera for flat anodes, due to small signal levels. The other diagnostics have consistently yielded a spot size FWHM of between 8 and 9 mm for a half-dozen LEVIS shots taken with a flat anode, with energies delivered to the center comparable with LiF shots with similar geometry (~ 75 kJ). The LiF shots taken in flat geometry in this test series yielded large (13 mm) spot sizes, with energy delivery comparable to the flat LEVIS shots. This is a larger spot size than the 10 mm that is typically attained with LiF shots in flat geometry. But even using the smaller 10 mm figure, the flat LEVIS focal spot size is consistently smaller than for an LiF source operated with the same diode parameters. This smaller LEVIS spot size occurs despite the more nonuniform beam behavior as indicated by the Faraday cup waveforms.

One shot each was taken with the LEVIS and LiF sources in the same focussing geometry. Use of a curved anode results in a different magnetic field topology in the A-K gap, and may help to explain the difference in operating behavior with both sources, relative to their flat counterparts. In both cases, the "turn-on" time of the diode, i.e. the time when significant signal appears on the Faraday cups, was earlier than with flat anodes. In flat geometry the turn-on time was similar for both sources, but with a curved anode, the LEVIS source turned on a full 10 ns earlier, while for LiF the figure was 5-7 ns earlier. Because of the focussing geometry, the signal levels on the Ion Movie Camera increased for both sources, enabling time-dependent focal images for both cases. These data are portrayed in the form of plots of maximum signal level, and are shown in Figs. 3 and 4 for a LEVIS shot (6173) and LiF (6176), respectively. The x-axis indicates position within a row of PIN diodes imaging the horizontal axis of the beam focus. The y-axis shows the maximum signal level at each PIN location at times ranging from 0 to 27.5 ns into the ion beam pulse. Except for the ion source, these were otherwise identical shots. In Fig. 4, the data have been time-shifted 4 ns to align the two power pulses. In Fig. 3, analysis of

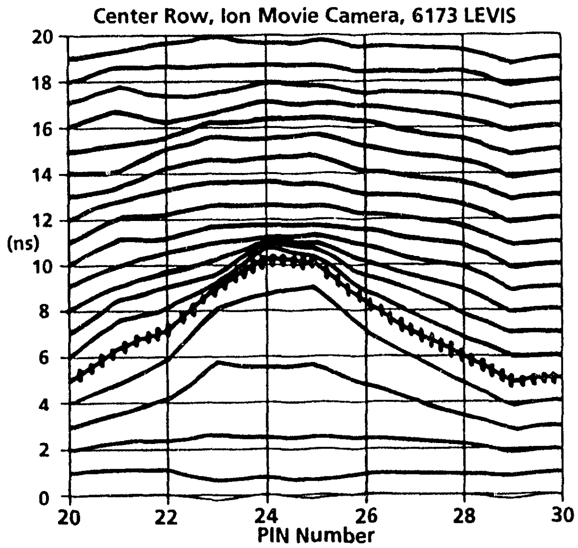

Figure 3

the plots show that the LEVIS beam attained an 8mm FWHM at about 4 ns into the beam pulse. This corresponds to a total beam divergence of 27 mR. The vertical-hatched contour at 5 ns indicates the time of approximately the maximum signal level attained during the pulse. By 8 ns, the focus has increased to 9-10 mm, and the intensity level has decreased significantly. In Fig. 4, by contrast, a 10 mm FWHM is attained at a similar 4 ns (the FWHM of the vertical-hatched contour), but the number of significant level contours exceeds the LEVIS shot. This indicates a beam of inferior focus but of longer duration with the LiF source. The energy delivered to the center was larger on the LiF shot, 80 kJ compared to about 40 kJ for the focussing LEVIS shot. Some of this may be explained by the larger Faraday cup signals on Shot 6176 (LiF), but the Ion Movie Camera clearly indicates that the beam focus disappears earlier with the LEVIS source.

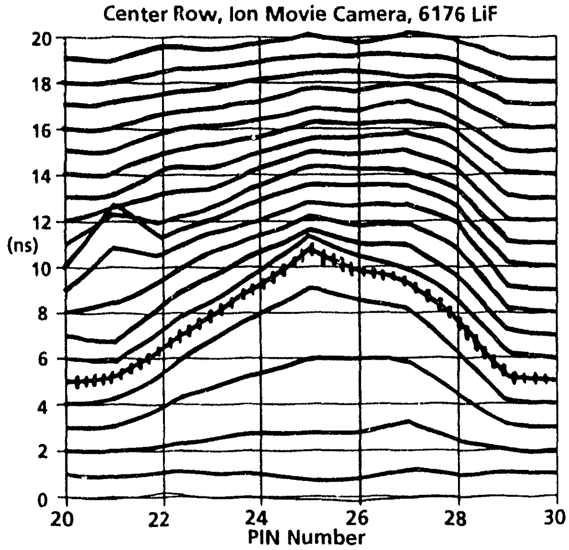

Figure 4

To gain further insight into the beam behavior with the two ion sources, the diode was modeled with the 3-D, fully electromagnetic QUICKSILVER[5] particle-in-cell (PIC) code. The diode geometry was accurately modeled, but the vacuum transmission lines above and below the diode were not. The LEVIS source was assumed to be a Child-Langmuir emission surface, while the LiF anode was modeled as a source of field-emitted ions with a threshold emission voltage of 9 MV.

A characteristic signatures of the PBFA-II ion diode seen in previous QUICKSILVER simulations was the presence of two electromagnetic instabilities. Early in time, a high frequency diocotron mode does not significantly affect ion orbits. This is followed by a transition to a lower frequency 'Ion Mode' when the beam current density reaches an enhancement between 6 and 10 over the two-species Child-Langmuir value, greatly increasing beam divergence. Since space-charge-limited sources operate at higher enhancement earlier in time, they make this transition earlier and more abruptly. The simulation of the curved anode LEVIS shot showed an earlier transition from the diocotron to the Ion Mode than with LiF, and the resulting beam divergence degradation similarly worsened. Beam divergence increased in the Ion Mode to 40 mR with the LiF source, and 70 mR with LEVIS. This latter figure is large enough to completely diffuse the beam focus, which is consistent with the Ion Movie Camera data from the LEVIS shot.

Another simulation of the curved LEVIS shot was performed with a 15% increase in the insulating magnetic field. In this simulation, the onset of the Ion Mode was delayed by 5 ns, and the beam divergence in the Ion Mode phase was reduced to a maximum of 50 mR. Thus, one approach to improvement of LEVIS focal behavior suggested by QUICKSILVER is diode operation with higher magnetic field, which has been seen to improve overall beam quality in experiments with other diodes.

It must be pointed out that in terms of power on target and energy delivered to the center, the LiF shot 6176 exceeded LEVIS 6173 by factors of two (80 to 40 kJ, 0.4 to 0.2 TW/cm^2). Other shots with the LiF source on PBFA-II have yielded power densities exceeding 1 TW/cm^2. However, the LiF source and geometry have been optimized over many shots, and we report here the result of only one focussing LEVIS experiment. A LEVIS optimization path would be different from that taken with LiF to capitalize on LEVIS advantages. For instance, the magnetic spectrometer on the focussing LEVIS shot clearly indicates ions emitted well before the diode voltage peaked, in contrast to the LiF source. This led to ion velocity (and beam power) bunching, which cannot occur where the beam voltage is monotonically decreasing during ion emission. This observed velocity bunching is a design requirement for future higher power ion driven inertial confinement fusion concepts.

Summary

A number of beam experiments were undertaken on PBFA-II in which both the LEVIS and LiF ion sources were operated. With each source, both flat and focussing anodes were fielded. The goal of these experiments was to investigate the possible contribution of anode plasma nonuniformities and electromagnetic instabilities to the increase in beam divergence from the 4-9 mR inferred at the anode surface, to the 20-30 mR seen at the target.

Measurements from a multiple Faraday cup array indicated considerable azimuthal variation in peak magnitude in the case of the LEVIS source, more than with a passive LiF source. Both sources exhibited considerable azimuthal variation in electric field in the A-K gap. Despite the Faraday cup behavior, the LEVIS source in flat geometry consistently produced smaller focal spot sizes than for a LiF source operated in similar geometry.

When the anode was switched from flat to curved, both sources "turned on" significantly sooner, 5-7 ns in the case of the LiF source, and 10 ns with the LEVIS source. On the one LEVIS shot using a curved anode, ion emission began well before the diode voltage peaked, leading to beam power bunching not seen with the LiF source. It should be pointed out that, because of the general delay in ion current iniation experienced in all Applied B diodes, a reduction in this delay of only 5 ns could potentially lead to a significant increase in beam power. The beam diagnostics showed that the LEVIS focussing beam focal spot size was smaller than for an otherwise identical shot taken with a LiF source, but the beam dwell time on target was reduced, leading to decreased peak beam power and energy deposited as compared to LiF. QUICKSILVER simulations of both sources indicate that a possible explanation for this behavior is that the LEVIS-generated beam is more susceptible to the Ion Mode instability. QUICKSILVER also suggests that a way to improve the LEVIS divergence is to operate the diode with a higher insulating magnetic field.

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