DEVELOPMENT OF THE BOLVAPS-LIBORS LITHIUM ION SOURCE FOR THE PBFA-II ACCELERATOR

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Abstract

A large area surface source of Lithium plasma for use as an ion source in the PBFA-II ion beam diode is described. BOLVAPS produces a 1-2 mm thick layer of Li vapor with a density approaching 1×10^{17} cm^{-3} by rapid ohmic heating of a thin film laminate, one layer of which contains Li. The principal design issues of the vapor source being built for use on the PBFA-II accelerator are described. LIBORS uses 670.8 nm laser light to efficiently ionize the Li vapor. The results of small-scale Physics tests and full-scale component development are summarized.

Introduction

The Particle Beam Fusion Accelerator II (PBFA-II) is being developed to produce a ~4 MA, 30 MeV Li$^+$ beam.[1] PBFA-II is a 36 module, pulsed power generator driving an Applied-B ion diode.[2] The diode's ion emission area is 500-1000 cm^2. The requirements on the Li$^+$ ion source [3] are (1) to supply a 5 kA/cm^2 beam for 50 ns, (2) to conform to the anode surface and be < 2 mm thick, (3) the beam purity be >80%, (4) be capable of providing ions within 1-2 ns after the arrival of the accelerating voltage pulse, and (5) be compatible with the PBFA-II environment. A 1-2 mm thick 10^{16-17} cm^{-3} density Li$^+$ plasma on the anode would be a suitable ion source. We are pursuing the BOLVAPS-LIBORS [4,5] technique to make this plasma. BOLVAPS (Boil-Off Lithium VAPor Source) makes a thin layer of Li vapor by rapid ohmic heating of a thin film laminate on the anode surface, one layer of which contains Li. LIBORS (Laser Ionization Based On Resonance Saturation) uses 670.8 nm laser light to ionize Li gas.

BOLVAPS films consist of a 3 μm thick Mo layer, a 1 μm LiAg layer, and a 0.3 μm Ag overcoat sputter-deposited [6] on a rigid substrate. The films are preheated to 700 °C for ~10 ms to melt the LiAg and outgas volatile contaminants, and then heated to 1100-1200 °C in ~400 ns to evaporate high density Li. The anode is then illuminated with 1 μs long, 10-100 mJ/cm^2 pulses of 670.8 nm light. Small scale tests using films on polished alumina ceramic made Li plasmas with electron densities of 5×10^{16} cm^{-3} and an estimated thickness of 2 mm.

This paper describes BOLVAPS system being built for PBFA-II. Major design issues are addressed as a part of the component descriptions. We summarize important results from small scale BOLVAPS-LIBORS experiments.

BOLVAPS Components

BOLVAPS' components are shown schematically in Fig. 1. One design constraint was to fit BOLVAPS-LIBORS into an Applied-B ion diode with a 15 cm anode radius and a 2 to 7 cm half-height. Fig. 2 is a simplified drawing of the BOLVAPS-LIBORS diode. The anode is split into symmetric top and bottom halves for the disk transmission lines that feed heating current to the BOLVAPS films.

FIGURE 1. The major components of BOLVAPS. A schematic cross-section of an "unfolded" anode is shown. The Li reservoir is a layer of LiAg alloy covered with a thinner layer of Ag.
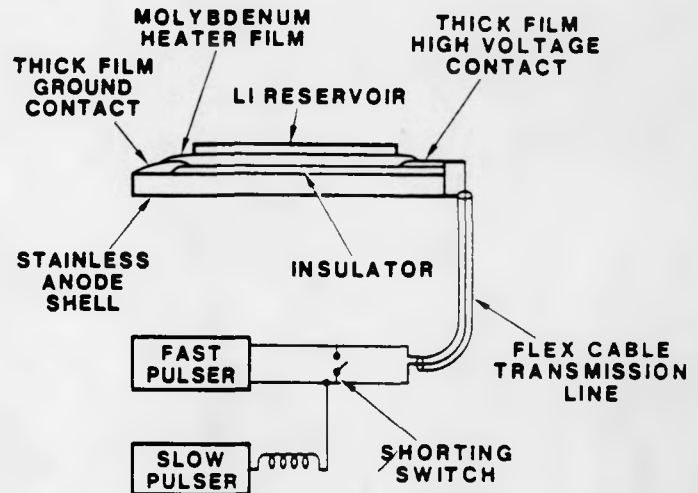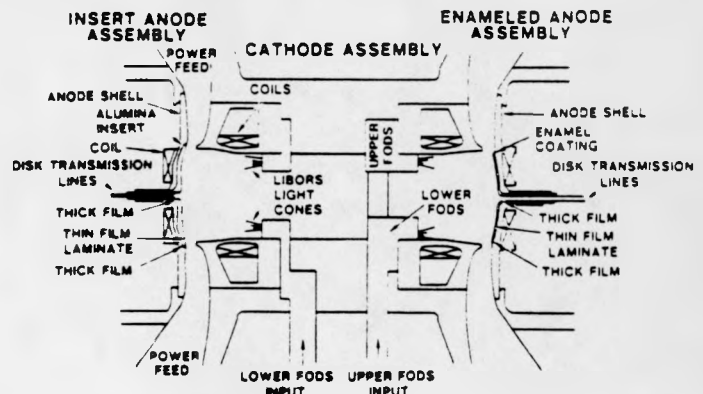

FIGURE 2. The major components of an Applied-B diode with a BOLVAPS-LIBORS ion source. The anode is 30 cm in diameter. FODS is an acronym for FiberOptic Distribution System for LIBORS light. The alumina insert anode design option is on the left and the enameled anode option on the right.

BOLVAPS anodes are built up on a stainless steel anode shell. The shell is a structural member and also a part of the heating current return path. The BOLVAPS films are insulated from the shell by a refractory insulator, as shown in Fig. 1. The insulator may be either (1) an alumina ceramic "insert" attached to the shell, or (2) porcelain enamel fused to the shell. These two design options are shown in the left and right sides of Fig. 2. The insert option provides a robust insulator that need not be thermal expansion matched to the steel.

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In early experiments we had good success with adhesion of Mo heaters to alumina substrates through these stressful heating cycles. Consequently, we have emphasized the insert option with machined alumina ceramic inserts. However, the enamel option offers substantial cost and performance advantages. We have recently developed an enameling process and an acid-etching procedure that yields "good" substrates. Adhesion of Mo heaters to these substrates is good, and they heat with high uniformity. Results presented here were obtained using alumina substrates.

A 10 μm "thick-film" gold coating is fused to the ceramic to continue the thin films around a corner and connect to the transmission lines. The gold is applied by airbrushing, which gives a smoothly tapered edge under the thin films. Transmission lines are Pb-In soldered to the gold. Gold is used because anodes are subjected to heavily oxidizing cleaning steps in preparation for thin film deposition. The leads' approximate location on the anodes is indicated in Fig. 2. The high voltage lead goes around the corner from the equatorial flange to the active region of the anode. A second lead makes the ground connection at the top (or bottom) of each half-anode.

The thin film laminate has three layers, which are sputter deposited using a post-cathode magnetron sputtering system.[6] We chose to use the three separate layers to serve the functions of (1) adhesion and heater layer, (2) a Li reservoir, and (3) a corrosion barrier. The heater layer is 3 μm thick Mo. The Li reservoir is a 1 μm thick layer of LiAg alloy. The corrosion barrier is 0.3 μm of Ag. The reasons for choosing the particular thicknesses are described below. The heating function is of course mixed between all three layers, since all three are electrical conductors. The Li reservoir is not entirely separated from the Ag corrosion barrier because Li diffuses into the Ag.

Mo was chosen as the heater layer for several reasons, including: (1) a low thermal expansion coefficient, (2) good adhesion to oxides, (3) it is inert to Li, (4) it is refractory, and (5) has low resistivity compared with LiAg. Large thermal stresses are developed in the Mo and at the Mo-substrate interface during the 700 °C preheat pulse. Low thermal expansion and good adhesion are important for the interface to survive the thermal cycle. Obtaining adequate Mo-substrate adhesion has been the most difficult problem to solve in developing the BOLVAPS anodes. Molten Li will chemically reduce oxide substrates, so the heater layer also serves as a barrier to the Li. Items 4 and 5 have to do with the thermo-resistive stability of the ohmic heating process. Resistivities of metals increase with temperature, and have step increases when the metals melt. Mo has a low thermal coefficient of resistivity, and melts at 2500 °C, well above our operating temperature. Experimentally, the sputtered Mo films have a resistivity about 10 times the bulk value at 25 °C, but they have a resistivity change of <10% from 25-1000 °C. This is very important for uniform and reproducible heating, because heating is nearly thermo-resistively stable. Experimentally, we find that Mo films can be heated uniformly, but that LiAg films alone heat very non-uniformly.

The 50 atomic % LiAg alloy was chosen as a Li reservoir because it is relatively corrosion resistant compared with Li, and has high vapor pressure compared with other alloys. Free or alloyed Li combines with atmospheric water to form refractory LiOH. LiAg films retain sufficient vapor pressure for about two hours in 50% relative humidity (R.H.) air, compared with about two minutes for Li.

The top layer of 0.3 μm Ag slows LiAg corrosion, extending its useful life in 50% R.H. air to four hours. This extra two hours is important for the day-long experiment setup on PBFA. The LiAg-Ag

combination melts at about 600 °C.

Using ion-sputtering and Auger analysis of the laminate we found that Li diffuses into the Ag layer; we were unable to distinguish a boundary between the two layers by this technique. We also found that several thousand angstroms of the laminate was corroded after the four hour exposure to air. X-ray Photoelectron Spectroscopy indicates that the corrosion product is largely LiOH.

The corrosion layer thickness roughly sets minimum thicknesses for the different layers in the laminate. The 0.3 μm Ag layer is a minimum to provide corrosion protection. The 1 μm LiAg is a minimum to have sufficient metallic Li remaining in the film after air-exposure. The 3 μm thick Mo is a rough minimum to retain the benefits of its electrical properties. The thickness and heat capacity of the laminate must be minimized to keep the fast heating pulse requirements within reason.

The pulsed power system that provides the heating pulses consists of a "slow" (or "preheat") pulser, a fast pulser, and a transmission line system for each anode half. The pulsers are located on top of the accelerator, about 12 m from the anode. The preheat pulsers are 38 mF, 2.25 kV capacitor banks which charge 200 μH inductors in series with the anode films. They have an LC risetime of 4 ms to a peak current of 22 kA and are crowbarred with free-wheeling diodes to give an L/R fall time of 30 ms. To minimize stray resistance, a bundle of four size 0000 welding cables carries current to the anode. This waveshape will heat the films to 700 °C in 8 ms and roughly maintain temperature for about 10 ms. This pulse length was chosen to allow volatile contaminants to diffuse through the entire PBFA vacuum system before the accelerator is fired.

The fast heating pulse length is limited by two factors. First, Li gas at 1200 °C has a thermal velocity of 1 mm/μs. Calculations of collisionless expansion of the gas show that the density-gradient-scale-length lengthens for heating pulses longer than 1 μs. Second, the voltage due to the heating current causes the evolving Li gas to break down, shorting out the heating pulse. Small-scale tests showed that heating is maximized by arranging for the breakdown to occur in 400 ns. Conduction of heat from the film into the substrate is negligible on a sub-μs time scale. A simple calculation shows that an action ($\int I^2 dt$) of 1.25×10^5 Amp^2-s will heat a 5 μm thick, 100 cm circumference Mo film, from 700 to 1200 °C, assuming bulk Mo properties for the film.

The fast pulsers are composed of four parallel 15 μF capacitors with individual gas switches. The risetime is set by an inductance originally chosen to give a 1 μs rise to a peak current of 500 kA. To avoid pre-ionizing the Li, and preheating the plasma, the pulse is ended by a fuse driven shorting switch that decouples the capacitors from the transmission line. The fast pulse is then damped in about 200 ns by a resistor. Transmission lines consisting of two parallel, 12 m long, 60 milli-ohm tri-plates connect each fast pulser to the anode. The tri-plates are hot-press laminated copper sheet and Kapton.

At this writing, we have developed techniques for assembling the alumina-insert anodes.[7] A number of prototype anodes, with heater films only, have been tested using the preheat bank. The principal diagnostics are pyrometers and open-shutter photographs of self-luminescence. Based on micro-densitometry, we infer heating uniformity as good as ±40 °C at an average temperature of about 800 °C.

The pulsed power heating system has been installed in PBFA-II. However, ion source tests have been delayed by transmission line breakdowns.

A dye laser with a 100 J, 1.5 μs output at 670.8 nm has been installed in PBFA-II.[9] A conventional optical beamline transports the light to a FiberOptic

Distribution System (FODS) in the ion diode. About 40 J strikes the anode.

Small-Scale Experiments

We have performed experiments to study ohmic heating, film heating uniformity, Li evaporation, and combined Li evaporation and ionization using the apparatus sketched in Fig. 3. Our standard sample, on either alumina or enameled stainless steel, is a "coupon" 3.5 cm wide by 7.6 cm long. Thick film gold contact pads 1.8 cm wide with a 3.8 cm separation are screen printed and fused to the insulator. A 1.5 cm wide thin film laminate is sputter-deposited over and between the contact pads, using the same system used to coat PBFA-II anodes. The films are heated by small preheat and fast banks. Temperature during the preheat pulse is inferred from near infra-red radiance in a 5 mm diameter focal spot measured using an Ircon Model 1100 pyrometer. Uniformity is examined qualitatively by open shutter photography of self-luminous films at 800-900 °C, and quantitatively using two or three pyrometers. Heating uniformity of a few % on 0.2-20 mm scale lengths appears to have been achieved on both alumina and enameled coupons.

Li vapor density in the range of 1×10^{13} to 1×10^{16} cm^{-3} is measured during the preheat pulse using a laser pumped fluorescence technique shown in Fig. 3. A dye laser beam is split into a reference beam and a probe beam. The reference beam passes through a heat pipe that maintains Li vapor at a known density. The probe beam passes through BOLVAPS vapor. The 319.6 nm light pumps the forbidden transition in Li and decay light at 610.4 nm is detected with photomultipliers PMT's). The BOLVAPS vapor density is obtained by comparing the two PMT signals, taking into account known geometrical factors.

FIGURE 3. A schematic diagram of the experimental setup used for testing coupons, and a level diagram showing the laser fluorescence density diagnostic.

LASER PUMPED FLUORESCENCE
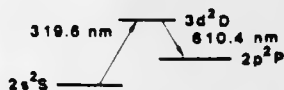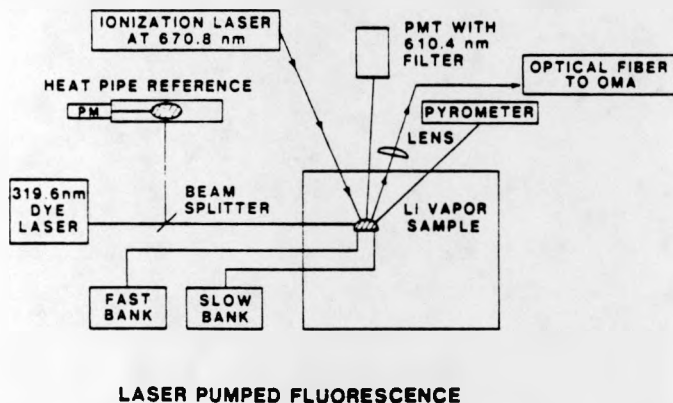
Li density vs. temperature is shown in Fig. 4 for two different experiments. Both experiments used free-standing 25 μm thick Ta foil heaters. In the first experiment, Li films 1 or 2 μm thick were vapor deposited in situ, and in the second, 1 or 2 μm thick LiAg films were used. The foils were heated with 3 ms duration pulses, and the measurements were made 0.1 ms after they ended. The density measured using pure Li is in reasonable agreement with a literature value[7], with departures that we attribute to depletion of Li during the heating pulse. The Li density from LiAg is reduced from pure Li by two orders of magnitude. Li

density from the Mo-LiAg-Ag laminate on alumina coupons falls within the dashed lines on the graph.

FIGURE 4. Lithium vapor density from Li- and LiAg-coated Ta foils heated with 3 ms pulses.
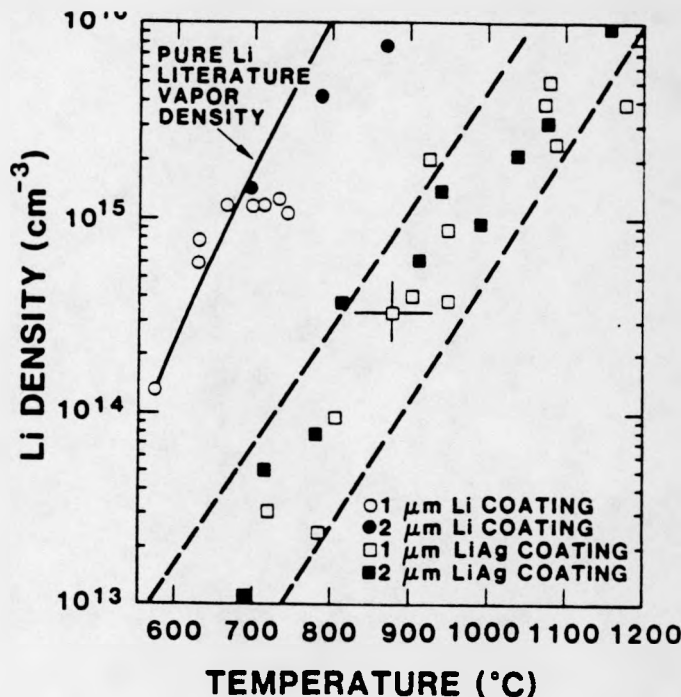
We also examined outgassing during the preheating pulse. Using a Beam Dynamics [10] fast ionization gauge we found a large gas release when the LiAg is heated to about 600 °C, approximately its melting temperature. The gas release is reduced by a factor of 10-20 on a second shot. We also measured a ~10 mTorr pressure rise after a heating pulse with the vacuum chamber sealed. This corresponds to a contaminant release of 3×10^{17} molecules/cm^2, compared with the initial lithium inventory of 2×10^{18} Li atoms/cm^2 in the LiAg, and the few $\times 10^{15}$ ions/cm^2 required for the ion beam. Preheating is evidently a very effective technique for removing contaminants from the LiAg.

We also performed combined BOLVAPS-LIBORS experiments. The BOLVAPS films were preheated for 18 ms to about 700 °C. At this time we measured Li densities of about 1×10^{14} cm^{-3} by laser induced fluorescence. After another 600 ns a fast heating pulse was applied to increase the temperature to 1150-1250 °C. The temperature at the end of the fast-heating pulse was inferred from the ohmic power dissipation. At these temperatures, we expect Li densities of 0.5-5 $\times 10^{16}$ cm^{-3} based on the data in Fig. 4. The fast heating pulse current was sinusoidal with a 600 ns quarter-cycle risetime. The 3 kV resistive voltage drop caused an arc breakdown in the evolving Li gas, ending the heating after about 400 ns. A spark gap partially diverts the fast pulse away from the test film, starting at about 600 ns.

The Li vapor was then ionized by the LIBORS laser 2.0 μs after the fast heating pulse ended. Laser energy densities were varied from 0-240 mJ/cm^2, corresponding to intensities of up to 4.8×10^5 W/cm^2. (The PBFA-II LIBORS laser delivers > 3×10^4 W/cm^2 to the anode surface.) The line shape of the Li 460.3 nm transition was recorded using an optical multichannel analyzer (OMA) which was gated on for 3 μs at the beginning of the laser pulse. The plasma's electron density was inferred from Stark broadening of this line[11]. The Li$^+$ density is assumed to be equal to

the electron density. The results of several measurements on coupons from the same coating run and where the final film temperatures were nearly equal are summarized in Table I. Preheat Temp is the temperature measured at the end of the preheating pulse and n_0 is the Li density measured at this temperature. Peak Temp is the temperature inferred after the fast heating pulse, and n^e is the electron density inferred from the broadening of the 460.3 nm. _line?_ There is an uncertainty of 15% in the interpretation of this measurement due to uncertainty in the electron temperature. For this series of shots, the typical time- and depth-averaged density is about 1.5×10^{16} cm^{-3}. Because the plasma density is independent of the incident laser energy, we conclude that the Li can be fully ionized with the smallest laser energy that we used, 14 mJ/cm^2. This energy density is in general agreement with expectations based on modeling of the LIBORS process [12]. Approximately 40 mJ/cm^2 is available on PBFA-II. On shots without the LIBORS laser, the plasma density (from the fast-bank-driven arc) was lower than on shots with the laser, $< 0.5 \times 10^{16}$ cm^{-3}, and the plasma light was less than one-tenth as bright.

FIGURE 5. The broadening of the 460.3 nm lithium transition is shown for three plasma densities. The absorption at the highest density shown in (a) is due to neutral excited lithium in the observation path.
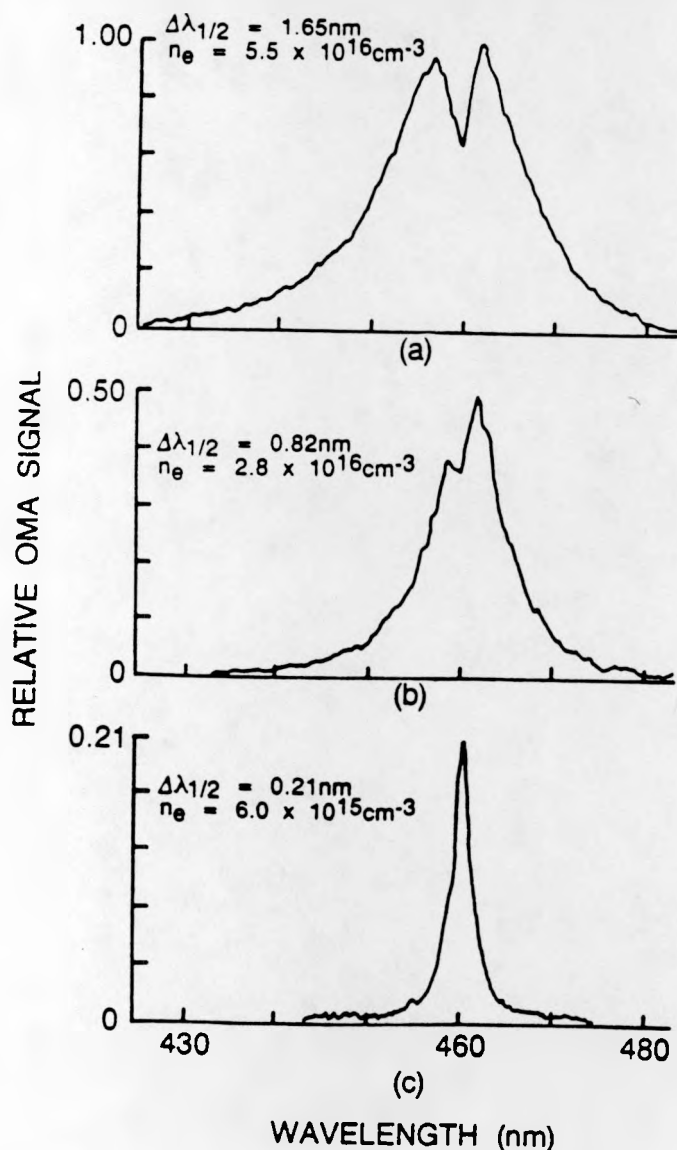
Table I. Measured Lithium and Electron Densities

Laser Energy mJ/cm^2	Preheat Temp $^\circ$C	n^0 10^{14} cm^{-3}	Peak Temp $^\circ$C	n^e 10^{16} cm^{-3}
0				
14	690	1.3	1220	2.1
14	690	1.1	1220	1.3
14	670	0.8	1220	1.8
31	670	0.9	1200	1.5
31	700	1.3	1210	1.6
149	730	0.9	1210	1.7
158	690	2.0	1220	1.2

Larger, irreproducible, plasma densities were observed in other tests. The line shapes from three different tests are shown in Fig. 5. The absorption line near the peak of the spectra is due to low density neutral Li vapor between the coupon and the detector.

In order to determine what impurities might be present, several shots were taken where the emission spectra were recorded with low resolution over a ~80 nm range, as shown in Fig. 6. Many of the lines can be attributed to Li ns^2S or nd^2D to $2p^2P$ transitions. Two silver lines and one Li$^+$ line were identified. The intensities do not yield quantitative information on the densities for silver or Li$^+$.

FIGURE 6. Spectra of the ionized lithium for three wavelength regions.

RELATIVE OMA SIGNAL

WAVELENGTH (nm)
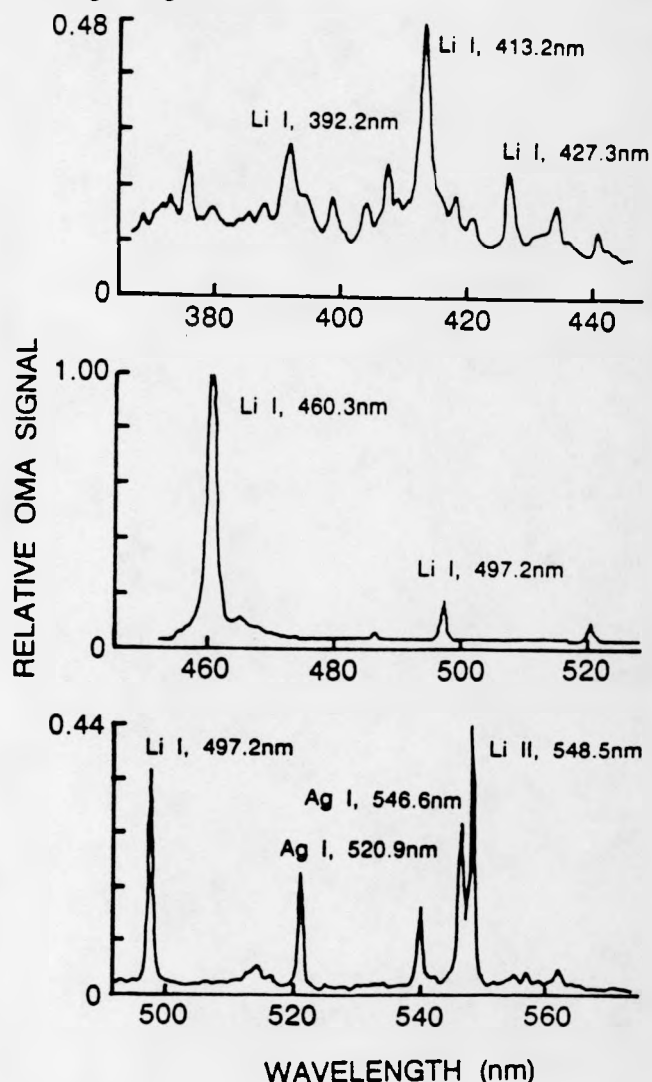
A complementary test was performed using the Refractive INdex Gradient (RING) diagnostic. This diagnostic passes a 15 mW CW HeNe laser beam over the surface of the test coupon. Time dependent gradients in Li gas or plasma density produce index of refraction gradients that deflect the laser beam. The laser beam deflection is detected, and from it we infer a path-averaged gradient in the index of refraction. BOLVAPS films were heated with preheat and fast banks as described above, but we did not deliberately ionize the gas with LIBORS. We inferred plasma gradients of 10^{18} cm^{-4}, but did not observe any neutral gradients. This indicates plasma density >1 x 10^{17} cm^{-3}. The high density plasma was expanding at 1-2 mm/µs. There was no indication of fast material moving at high speed (cm/µs or more). These results are inconsistent with the BOLVAPS-LIBORS observations described above, and we are unable to explain why.

Summary

A BOLVAPS Li vapor source is being built for use in an ion source on the PBFA-II accelerator. It is composed of a thin film laminate sputter-deposited on the anode surface and a pulsed power system for ohmically heating it. The laminate has a Mo heater layer, an LiAg layer that is a Li reservoir, and an Ag layer to inhibit corrosion. The anode assembly has top and bottom halves consisting of a stainless steel shell with an alumina ceramic insert attached to it. The insert serves as the substrate for the thin films, and electrically insulates them from the shell. Prototype anodes are being tested. The pulsed power system has been built and installed in PBFA. Small scale experiments have produced Li plasmas with electron densities of up to 5 x 10^{16} cm^{-3}, and an estimated thickness of 2 mm.

Acknowledgements

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