A HIGH CURRENT DENSITY Li^+ ALUMINO-SILICATE ION SOURCE FOR TARGET HEATING EXPERIMENTS*

Prabir K. Roy†, Wayne G. Greenway, Joe W. Kwan, Peter A. Seidl, and William L. Waldron
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Abstract

The NDCX-II accelerator for target heating experiments has been designed to use a large diameter ($\simeq$ 10.9 cm) Li^+ doped alumino-silicate source with a pulse duration of 0.5 μs, and beam current of $\simeq$ 93 mA. Characterization of a small size lithium alumino-silicate sources is presented. Using 6.35 mm diameter emitters (coated on a $\simeq$ 75% porous tungsten substrate), at a temperature of $\simeq$ 1275° C, a space-charge limited Li^+ beam current density of $\simeq$ 1 mA/cm^2 was measured. At higher extraction voltage, the source is emission limited at around $\simeq$ 1.5 mA/cm^2, weakly dependent on the applied voltage. The lifetime of the ion source is $\simeq$ 50 hours while pulsing the extraction voltage at 2 to 3 times per minute with a pulse duration of several microseconds. Measurements show that the lifetime of the ion source does not depend only on beam current extraction, but also evaporation of lithium neutrals. The lifetime of a source is around 10 hours for DC extraction, and the extracted charge is $\simeq$ 75% of the available Li in the sample. For rep-rated operation, it is inferred that pulsed heating may increase the source lifetime.

INTRODUCTION

To heat targets to electron-volt temperatures for the study of warm dense matter [1] with intense ion beams, low mass ions, such as lithium, have an energy loss peak (dE/dx) at a suitable kinetic energy [2]. The Heavy Ion Fusion Sciences (HIFS) program at Lawrence Berkeley National Laboratory will carry out warm dense matter experiments using Li^+ ion beam with energy 1.2 - 4 MeV in order to achieve uniform heating up to 0.1 - 1 eV. The accelerator physics design of Neutralized Drift Compression Experiment (NDCX-II) has a pulse length at the ion source of about 0.5 μs [3]. Thus for producing 50 nC of beam charge, the required beam current is about 100 mA. Focus ability requires a normalized (edge) emittance $\leq$2 π-mm-mrad.

Li^+ ions have been produced by thermionic emission from the alumino-silicates compounds β-Spodumene and β-eucryptite [4, 5, 6], but it requires a higher operating temperature than for other heavier alkali ions, such as K^+, and Cs^+. Table 1 shows Li^+ current density data presented by several authors, but the dependence of the lifetime on temperature has not been extensively described. Krupnik et al. [9] demonstrated beam current density of 4 mA/cm^2 at 1400° C to 1500° C. The source was vertically oriented, so melting was less of an issue. If the source is placed horizontally, there is a concern about melting and or delamination of fragments from the substrate. Lifetime is an important attribute of these sources, which operate at high temperature. Progress on Li^+ ions source and beam study [10], towards target heating experiment, is presented in this proceeding.

Table 1: Li^+ Current Density Measured by Various Groups

Density (mA/cm^2)	Temp. (° C)	Ref.
≤ 1	≈ 1230	Blewett [4]
≈ 0.02 (Spodumene)	≈ 1200	Feeney [6]
≥ 1.5	≈ 1200	Thomas[7]
≤ 1	≈ 1300	McCormick [8]
≈ 1.9	≈ 1300	This proceeding
≈ 4	≈ 1500	Krupnik [9]

LITHIUM BEAM CURRENT DENSITY

Several small (0.64 cm diameter) lithium alumino-silicate ion sources, of β-eucryptite, have been operated in a pulsed mode, with similar repetition rate and pulse duration as needed for NDCX-II. The sources were installed horizontally. The source surface temperature was at 1270 $\pm$ 7° C. A 5-6 μs long beam pulsed was recorded by a Faraday cup (+300 V on the collector plate and -300 V on the suppressor ring).

Figure 1 shows measured beam current density (J) vs. $V^{3/2}$. A space-charge limited beam density of $\geq$1 mA/cm^2 was measured with extraction voltage of 2.5 kV at 1275° C temperature, after allowing a conditioning time of about $\geq$ 12 hours. At the same temperature, the current density was raised to 1.47 mA/cm^2 when the extraction voltage was increased to 10 kV. Beam emission stability with these current density levels was observed for more than 72 hours for a pulse repetition rate of 0.033 Hz. However, the beam current density decreased gradually after this period. The solid red line represents the space-charge limited current density, calculated using the Child-Langmuir law, $J\left(\chi, V, d\right) = \chi\frac{V^{3/2}}{d^2}$, where, $\chi = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m}}$, d=1.48 cm is the distance between source and extraction electrode, V is the beam extraction voltage, m=7 amu is the mass of an ion, and q is the ion charge.

Beam current density at lower extraction voltage follows the space-charge limited (SCL) Child-Langmuir law. At a higher extraction voltage, there are not enough ions on the source surface, at a given temperature, to extract and thus extracted current fall below the Child-Langmuir law and the extracted current is emission limited. It is preferable to

* This work was performed under the auspices of the U.S Department of Energy by LBNL under contract DE-AC02-05CH11231.
† PKRoy@lbl.gov

run an injector system in the space-charge limited extraction mode to ensure current uniformity.

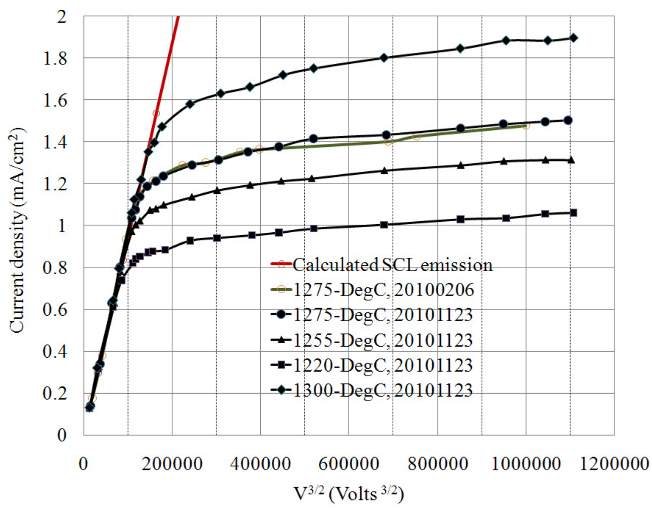

Figure 1: Measured Li^+ beam current density vs. $V^{3/2}$ for temperatures. The space-charge limited current density of $\simeq$ 1 mA/cm^2 was measured for $\geq$1275° C with $\leq$ 2.5 kV extraction.

LIFETIME

Lifetime in Pulsed Beam Extraction

Figure 2(a) shows emission lifetime for two thick ($\approx$ 0.25 mm) coating sources. At $\approx$1275° C and with a 10 kV extraction voltage, one of the sources was emitting a current density $\geq$1 mA/cm^2 for more than $\approx$100 hours at a repetition rate of 0.033 Hz. In another test, a current density of $\geq$1 mA/cm^2 was measured for $\approx$ 72 hours with the same beam pulse rate. Other measurements show that there is a wide variation in conditioning time (12 to 40 hours) to reach $J \geq$1 mA/cm^2, and in lifetime (40 to 200 hours) while $J \geq$1 mA/cm^2. Shortening the conditioning time will enhance the source's useful lifetime but further study is required to understand the process.

Figure 2(b) represents space-charge limited emission with a lower extraction voltage (1.75 kV), and demonstrates a constant, space-charge limited beam current for more than 30 hours. These two sources, Fig. 2(b), have a $\geq$ 0.1 mm coating.

Our measurements suggest that for the low duty factor ($\sim$10^{-8}) required for NDCX-II, the lifetime of a lithium ion source depends mostly on the duration that the emitter spends at elevated temperature, that is, at $\geq$1250° C. That is, lithium loss is due mostly to neutral loss (not charged ion extraction). The lifetime of a lithium source is determined by the loss of lithium from the alumino-silicate material either as ions or as neutral atoms. The neutral evaporation is what limits lifetime at high temperatures, as well as a low level emission reduces lifetime even when not extracted.

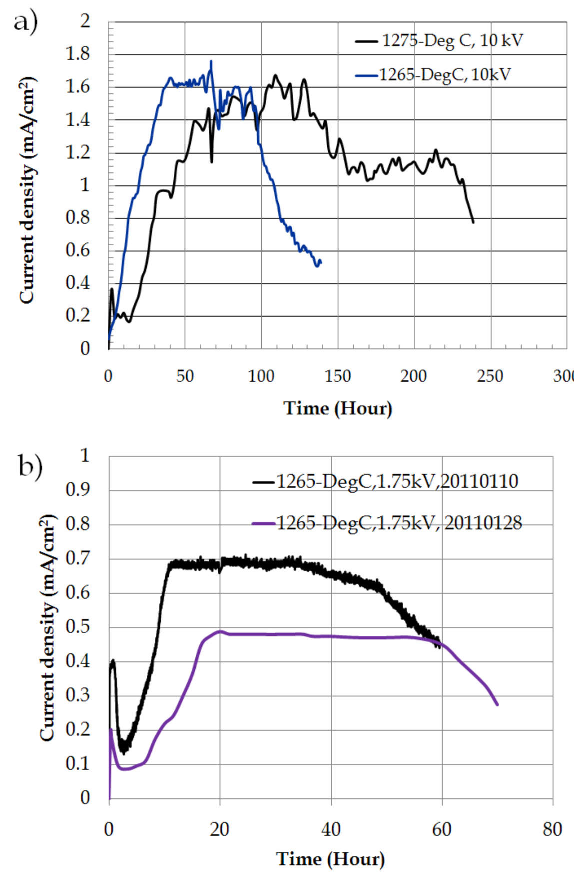

Figure 2: Litetime of Li^+ ion sources with (a) 10 kV extraction, and (b) 1.75 kV extraction.

Lifetime in DC Beam Extraction

In order to speed up a series of experiments, we built an in-situ sintering and beam extraction test stand. Beam was extracted to a negative bias plate, located $\simeq$ 4 mm from the emitting surface. Figure 3 shows the DC extraction beam current (primary vertical axis), and the extracted total beam charge (secondary vertical axis) vs. time of beam emission for several samples of different masses (2.4 mg, 3.1 mg, 6.9 mg, 7.9 mg). The diameter of the source samples varied between 2.5 to 3 mm. These data indicate that thickness of coating may contribute to the emission level, and a controlled experiment with a precisely surface area is necessary to verify this result further. It was observed that the lifetime of a source was around $\geq$10 hours in a DC mode extraction, and the extracted charge was $\sim$ 75% of the available Li^+ in the sample. This suggests that $\sim$ 25% was lost as neutral atoms, or remain trapped in the coating.

It was inferred that pulsed heating, synchronized with the beam pulse, might increase the lifetime of a source. Several source samples, mostly prepared in a furnace, were tested in the DC test stand. In this case, beam was extracted (120 V) for 5 minutes followed by reducing the filament

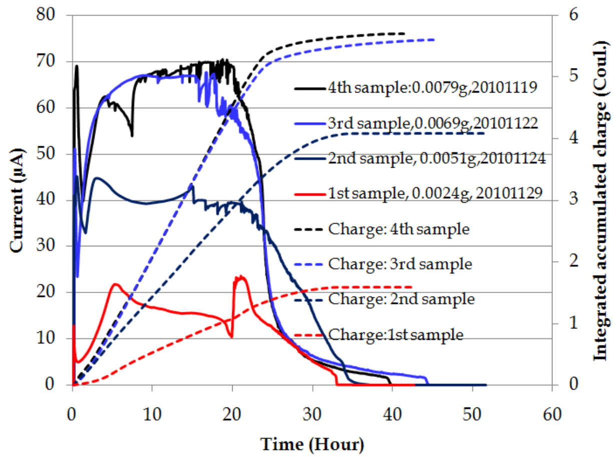

Figure 3: Beam emission and lifetime by varying mass of the samples. Diameter of the source samples was not the same, but was as ≤3 mm.

temperature to 800° C for a period of time, e.g., 5, 10, or 20 minutes. This cycle was maintained until depletion of emission was observed. Figure 4 shows that the lifetime of a Li alumino-silicate source is enhanced by reducing temperature in between pulses. A technique of pulse heating with a laser was recently investigated for a small size source [11] of this kind.

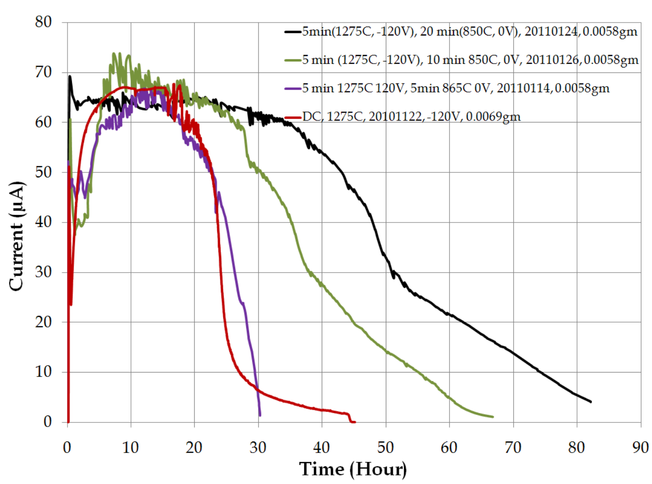

Figure 4: Litetime of several source samples for duty factors: DC, 0.5, 0.33, and 0.2, operated at ≈ 1265° C and ≤ 10^{-6} Torr pressure.

NDCX-II-INJECTOR

The NDCX-II design seeks to operate the ion source at the maximum current density without running into heat management and lifetime problems. In preparation to fabricate a large (10.9 cm in diameter) source for the NDCX-II experiment, recently a 7.6 cm diameter source was fabricated as shown in Fig. 5. The method of fabrication of this larger source was similar to that of fabrication of a 6.3 mm diameter source, except a longer furnace heating time was used due to mass differences. After many attempts, a uniformly coated (glassy) 7.6 cm source was produced. Figure 6 shows a computer code simulation (WARP) of a (a) J=0.5 mA/cm^2, and (b) J=1 mA/cm^2 Li$^+$ ion beam profiles for NDCX-II. NDCX-II injector construction is in progress [12].

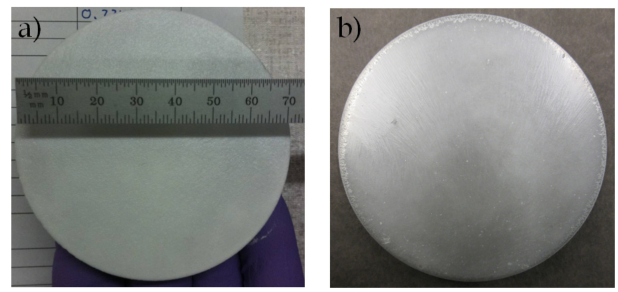

Figure 5: A 7.6 cm diameter source preparation (a) sample coated and dried , and (b) a glassy source surface, after sintering at 1400 ^{0}C.

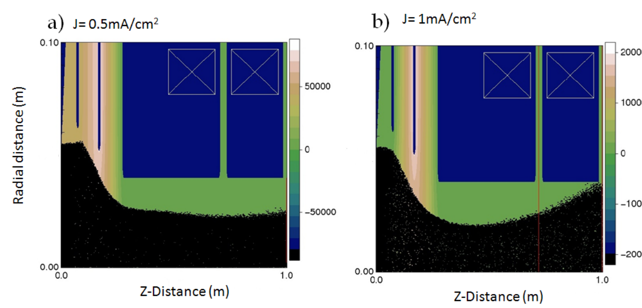

Figure 6: NDCX-II beam profile, using WARP code, for J (a) 0.5 mA/cm^2, and (b) 1 mA/cm^2 when the transport solenoid magnet is off. (Courtesy of D. P. Grote.)

REFERENCES

[1] F.M. Bieniosek et al., J. Phys. Conf. Ser.**244** (2010) 032028.

[2] J.J. Barnard et al., Nuclear Instrum. Method Phy. Res., **A 577** (2007) 275.

[3] W.M. Sharp, Bull. American Phy. Soc., **54(15)** 211 (2009).

[4] J.P. Blewett and E. J. Jones, Phy. Review, **50**(1936) 464.

[5] S.K. Allison et al., Rev. Sci. Instrum., **32** (1961) 1090.

[6] R.K. Feeney et al., Rev. Sci. Instrum., **47**(1976) 964.

[7] D.M. Thomas et. al., Rev. Sci. Instrum., **66(1)**(1995)806

[8] K. McCormick et al., Fusion Eng. Design, **34**(1997) 134.

[9] L.I. Krupnik et al., IEEE Trans Plasma Sci., **36**(2008) 1536.

[10] P.K. Roy et al., Rev. Sci. Instrum., **82**(2011) 013304.

[11] P. A. Ni et al., Rev. Sci. Instrum., **82**(2011) 023304.

[12] J. H. Takakuwa et al., 'Design and fabrication of the lithium beam ion injector for NDCX-II', these proceedings.