

HIFAN 1866

Lithium ion sources

by

Prabir K. Roy, Wayne G. Greenway, Dave P. Grote, Joe W. Kwan, Steven M. Lidia,
Peter A. Seidl, William L. Waldron

Lawrence Berkeley National Laboratory (on behalf of U.S. HIFS-VNL)
1 Cyclotron Road, Berkeley, CA 94720
Accelerator Fusion Research Division

and

Lawrence Livermore National Laboratory

August 2012

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or

This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California.

This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Lithium ion sources

Prabir K. Roy^{a,*}, Wayne G. Greenway^a, Dave P. Grote^b, Joe W. Kwan^a, Steven M. Lidia^a, Peter A. Seidl^a, William L. Waldron^a

^aLawrence Berkeley National Laboratory (LBNL), One Cyclotron Road, Berkeley, California, CA-94720, USA

^bLawrence Livermore National Laboratory LLC, CA-94550, USA

Abstract

A 10.9 cm diameter lithium alumino-silicate ion source has been chosen as a source of ~ 100 mA lithium ion current for the Neutralized Drift Compression Experiment (NDCX-II) at LBNL. Research and development was carried out on lithium alumino-silicate ion sources prior to NDCX-II source fabrication. Space-charge-limited emission with the current density exceeding 1 mA/cm^2 was measured with 0.64 cm diameter lithium alumino-silicate ion sources at 1275^0 C . The beam current density is less for the first 10.9 cm diameter NDCX-II source, and it may be due to an issue of surface coverage. The lifetime of a thin coated (on a tungsten substrate) source is varied, roughly 40-50 hours, when pulsed at 0.05 Hz and with pulse length of $6 \mu\text{s}$ each, i.e., a duty factor of 3×10^{-7} , at an operating temperature of 1250 to 1275^0 C . The 10.9 cm diameter source lifetime is likely the same as of a 0.64 cm source, but the lifetime of a source with a 2 mm diameter (without a tungsten substrate) is 10-15 hours with a duty factor of one (DC extraction). The lifetime variation is dependent on the amount of deposition of β -eucryptite mass, and the surface temperature. The amount of mass deposition does not significantly alter the current density. More ion source work is needed to improve the large source performance.

Keywords: Ion source, Ion beam, Induction accelerator, Lithium ion sources

1. Introduction

Within the scope of Heavy Ion Fusion Energy Sciences, the unique penetrating ability of intense beams of heavy ions to heat targets is useful, in the near term for basic high energy density physics studies, and ultimately for inertial fusion energy. An emerging research area is the behavior of a variety of targets as they absorb a larger amount of power per unit volume from the beam. Such experiments promise to reveal novel material properties in the “warm dense matter” (WDM) regime [1], temperature usually 0.1 to 10 eV, and 0.01 to 1 x solid density. In order to carry out WDM experiments, a new facility with a linear array of induction cells, namely the Neutralized Drift Compression Experiment (NDCX-II) facility [2, 3, 4, 5] is under going commissioning [6, 7] at present, and is utilizing a 10.9 cm diameter lithium alumino-silicate ion

source. The beams are the tools for generating homogeneous warm dense matter. The ion beam deposits energy uniformly near the flat portion of the energy dE/dx curve, i.e. Bragg peak. Other favorable characteristics of the ion beam include: precise control of energy deposition, benign environment for diagnostics, immune to blow off plasma, high rep rate and reproducibility. For warm dense matter studies on NDCX-II [4, 5] using a Li^+ beam with $\sim 50 \text{ nC}$ of charge, and 500 ns of pulse length, a beam current of 100 mA is desired.

There are several ways to prepare ion sources. A lithium vapor source provides higher current, but beam reproducibility, beam emittance, uniformity, and vacuum conditions do not meet our requirements. Surface ionization [8, 9] is another method to produce ions, however this method is unfavorable due to the greater ionization energy (5.36 eV) and the higher neutral atom loss rate of lithium than Cs^+ , K^+ etc. The alumino-silicate source approach [10] appears to be a better choice for many applications, such as mass spec-

*Corresponding author

Email address: pkroy@lbl.gov (Prabir K. Roy)

41 troscopy [10], charge particle collisions [11], beam-
 42 plasma interaction experiment[12], plasma diagnos-
 43 tics [13, 14, 15, 16, 17], and material phase studies
 44 [18]. But there appears to be no description of a
 45 bright, high current, space-charge limited lithium
 46 beam in the literature which meets the needs of
 47 our WDM experiments. Beam density data for
 48 high current and high-quality Li⁺ sources, includ-
 49 ing variation of source lifetime, surface tempera-
 50 ture, heating and beam repetition rate are the main
 51 subjects of this article.

52 2. Review of the ion-gun

53 2.1. Ion gun

54 Since an alumino-silicate surface is not con-
 55 ductive, the Richardson-Dushman law can only be
 56 used in an empirical way to describe emission of an
 57 alumino-silicate ion sources [19]. The temperature
 58 of a thermionic source may be increased by Ohmic
 59 heating [20, 21], laser radiation [22, 23], induction
 60 heating or other methods [24]. The source surface
 61 temperature (T) places a lower bound on the re-
 62 quired input power, $P = A\sigma\varepsilon T^4$; where A is the
 63 cross sectional area (πr^2) of the emission surface,
 64 σ is the Stefan-Boltzmann constant, and ε is the
 65 emissivity of the material. This is less than the re-
 66 quired input power due to conductive and radiative
 67 heat loss from the sides and back of the source as-
 68 sembly. Once an operating temperature is achieved,
 69 ions are extracted by applying an electric field.

70 The field between the source surface and the ex-
 71 traction electrode defines the extracted current den-
 72 sity. According to the Child-Langmuir law, the
 73 space-charge limited current density of an ion gun
 74 is given by :

$$J(\chi, V, d) = \chi \frac{V^{3/2}}{d^2}, \quad (1)$$

75 where, $\chi = \frac{4\varepsilon_0}{9} \sqrt{\frac{2e}{m_i}}$, d is the distance between the
 76 source and extraction electrode, V is the beam ex-
 77 traction voltage, m_i is the mass of the ion, (for Li⁺,
 78 $m_i=1.16 \times 10^{-23}$ g), e is the ion charge, and ε_0 is the
 79 permittivity of vacuum. If the intrinsic emission
 80 limit exceeds the space-charge limit everywhere on
 81 the surface, then the extracted beam is insensitive
 82 to variations in the intrinsic emission properties of
 83 the emitter, and we refer to this as space-charge
 84 limited extraction.

85 2.2. Charge and lifetime

86 The total ion charge (Q) produced by a source
 87 depends on the beam pulse duration (τ) and ex-
 88 traction voltage (V), and on the ratio of the emit-
 89 ted alkali ions to neutral atoms. In general, for a
 90 pulsed ion source, the total beam charge per pulse
 91 is

$$Q = J_b A \tau, \quad (2)$$

92 where J_b is the beam current density (assumed uni-
 93 form), and A is the emission area. The theoretical
 94 lifetime of a source for complete extraction (neglect-
 95 ing emission of neutrals) is related to the compound
 96 mass by

$$T_{\text{life}} = \left(\frac{M_s \eta}{m_i} \right) \left(\frac{e}{I_b} \right), \quad (3)$$

97 where $I_b = J_b A$ is the beam current for the source
 98 surface area A . M_s is the mass of source compound
 99 (in g) that is used to fabricate the source, and
 100 η is the concentration of element atom by weight
 101 within the total compound. For example, using a
 102 5.8 mg lithium alumino-silicate compound that has
 103 a 5.56% concentration of lithium atom can provide
 104 a beam current (I_b) of 65 μA with a lifetime of
 105 19 hours. As will be seen later, this is in fair agree-
 106 ment with DC extraction measurements.

107 2.3. Ion species identification

108 Admixtures of contaminant ions in the extracted
 109 beam are due to contaminants in the source mate-
 110 rials and vacuum system. Common contaminants
 111 are the other common alkalis: K⁺, Na⁺, Cs⁺, which
 112 will be easily extracted due to their lower ionization
 113 potential. Since the emitter surface also contains
 114 Al, O, and Si, these are also possible contaminants.
 115 An ExB filter was used as a spectrometer to analyze
 116 the ion species in the beam. The unknown mass of
 117 an element is determined by balancing the electric
 118 force against the magnetic force as

$$m = 2qV \left(\frac{B}{E} \right)^2, \quad (4)$$

where, qV is the ion kinetic energy with potential
 V across the electrostatic deflector plates, E is an
 electric field perpendicular to the magnetic field B .
 The measurements confirmed lithium as the princi-
 pal ion emitted [25]. The upper limit of mass sen-
 sitivity was limited to 198 amu due to the available
 electric and magnetic field of the filter, the extrac-
 tion voltage across the anode-cathode gap of the

127 source, and the geometry of the YAP scintillator.
 128 The lower limit, or sensitivity to contamination was
 129 about 5-10% of the peak detected lithium signal. At
 130 this sensitivity, no contaminating ion species were
 131 detected.

132 3. Measured beam density and emission life- 133 time of 0.64 cm diameter sources when 134 pulsed

135 A mixture of isotopically pure Li_2CO_3 , Al_2O_3 ,
 136 and SiO_2 was prepared following the stoichiomet-
 137 ric ratio for β -eucryptite type sources, $\text{Li}_2\text{O-Al}_2\text{O}_3$ -
 138 2SiO_2 . There are several steps to prepare a lithium
 139 alumino-silicate source: (1) produce the chemical
 140 compound, (2) grind the compound into powder,
 141 (3) apply a “green coating”, (4) melt the material
 142 to form a hard surface layer. These processes have
 143 been discussed recently elsewhere [26].

144 Once a sintered source is placed in an injector
 145 under low pressure, the required energy with heat
 146 and extraction voltage is applied, and emission is
 147 detected. The emission level was variable at the
 148 beginning until the surface ‘cleaned’ under condi-
 149 tions of sustained heat and extraction voltage. As
 150 time passed, emission reached a steady level for a
 151 given condition.

152 Several 0.63 cm diameter sources were used suc-
 153 cessively for testing of beam current density. The
 154 pulse rate was 0.05 Hz and with pulse length of 6 μs
 155 each. Figure 1(a) shows the measured beam current 177
 156 density as a function of the extraction voltage rang- 178
 157 ing from 0.5 kV to 10 kV for source temperatures 179
 158 set from 1220° C to 1300±7° C. The source tempera- 180
 159 ture was measured using a disappearing filament- 181
 160 type brightness pyrometer [27] calibrated with the 182
 161 emissivity of tungsten. A disappearing filament 183
 162 type brightness pyrometer is an optical pyrometer, 184
 163 in which a tungsten filament is used as a radiator. 185

164 Two of the approximately 0.25 mm thick sources 186
 165 were operated at a temperature of 1265 °C to ex- 187
 166 tract 6 μs beam pulses with $V=1.75$ kV. The pulses 188
 167 were repeated at a rate of 0.05 Hz until emission of 189
 168 the sources was significantly reduced. Figure 1(b) 190
 169 shows lifetime data from the sources when the beam 191
 170 was extracted in the space-charge limited regime. A 192
 171 uniform current density profile was observed for a 193
 172 duration of 40 to 50 hours after 10 to 15 hours 194
 173 of initial operation. It is speculated that the initial 195
 174 approximately 15 hours was affected by contami- 196
 175 nation while the heat and pulsed extraction volt- 197
 176 age gradually removed the contamination. We note 198

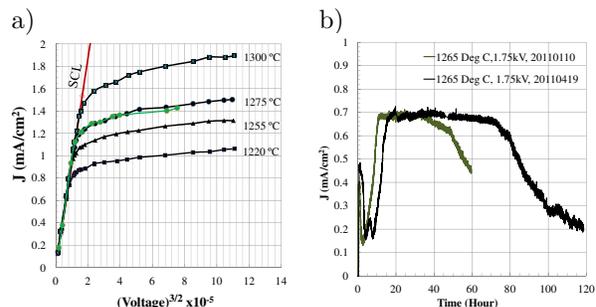


Figure 1: a) Measured Li^+ beam current density (J) plotted versus $V^{3/2}$, with voltage (V) in volts. A space-charge limited current density of 1 mA/cm^2 was achieved under (SCL) space-charge limited conditions when the sources were operated at or above 1275° C with a 1.5 kV extraction bias. At higher extraction voltages, the source appears to become emission limited with $J \geq 1.75$ mA/cm^2 , and J varies weakly on the applied voltage. Data in the dotted line at 1275° C (green) demonstrates reproducibility of beam emission from a different source prepared under similar conditions. The line shows the space-charge limited (SCL) current density according to the Child-Langmuir law. (b) Measured Li^+ beam current density (J) of pulsed source versus time. The thickness of sintered alumino-silicate was about 0.25 mm, but not kept constant. The source surface temperature of $\approx 1265^\circ$ C and extraction voltage of $V=1.75$ kV were unchanged during the data collection.

that for the duty cycle here (3×10^{-7}), the lifetime of the emitter is dominated by neutral emission. This is evident because the 40-50 hours lifetime is only ~ 2 x greater than the DC-extraction lifetime in Fig. 2, while the mass of the coating greatly exceeds the DC extraction samples and the extracted current density is similar. It was observed that the lifetime varied from source to source even when the operating temperature, pulsed voltage and pressure of the chamber were not significantly altered. One possibility for the variation of source lifetime is due to the variation in the mass of alumino-silicate deposited on the surfaces. Therefore a separate experiment was set up to measure the lifetime as a function of temperature and mass of Li alumino-silicate used. In this experiment, a non-porous thin tungsten substrate of 5 mm wide was used to facilitate a precise determination of amount of deposited mass on a source surface. Moreover, it was set for constant emission using a DC extraction in order to obtain rapid results. Results of the DC extraction test facility are presented in the following section.

4. Lifetime of 0.2 cm diameter sources with DC extraction

In this setup, a narrow molybdenum foil with an embossed spherical depression at the center is used as the source substrate and simultaneously as a heater ribbon. A small amount of alumino-silicate material is deposited in the depression of pocket to form an emitting surface. A biased conducting plate, located at a distance of 4 ± 0.2 mm from the source surface, was used as a collector to measure current. With the source at ground potential, the bias of the collector was set at negative 120 V to ensure space-charge limited emission. In this simple diode set up, secondary electrons coming off the collector plate are not suppressed and therefore the measured collector current will include secondary electron current. Fortunately, the secondary electron coefficient is very low [28] at 120 eV ion energy such that the collector current can be expected to be not more than a few percent ($\sim 2\%$) higher than the actual beam current.

4.1. Lifetime varies with duty factor

The lifetimes of three ribbon sources were measured by varying their duty factors. The pressure in the chamber was 2×10^{-6} Torr. There were 3 cases: (A) continuously on for beam extraction, (B) pulsed on for 5 minutes followed by off for 10 minutes, (C) on for 5 minutes followed by off for 20 minutes. Thus the corresponding duty factors are 1, 0.33 and 0.2. The amount of alumino-silicate used was 6.9 ± 0.03 mg in case A, and 5.8 mg in both case B and C. The surface area of each of the sources was 3.14 mm^2 . For all sources, during on time the temperature was held at 1265° C and the applied extraction voltage was 120 V, whereas during off time the temperature was reduced to 800° C with the extraction voltage turned off. The experiment continued until the sources were nearly depleted. As shown in Fig. 2(a), after a short initial period the beam current in all 3 cases reached the same level (over $60 \mu\text{A}$) which persisted for many hours depending on the duty factor. The elapsed time to depletion of case A was approximately 16 hours (from the time the current has approached maximum to the time when the current decreased to roughly 50%). For cases B and C, the corresponding elapsed time to depletion was 29 hrs and 49 hrs. Note that if the lifetime is defined as the useful beam time, which is the product of elapsed time and the duty factor, then the measured lifetime

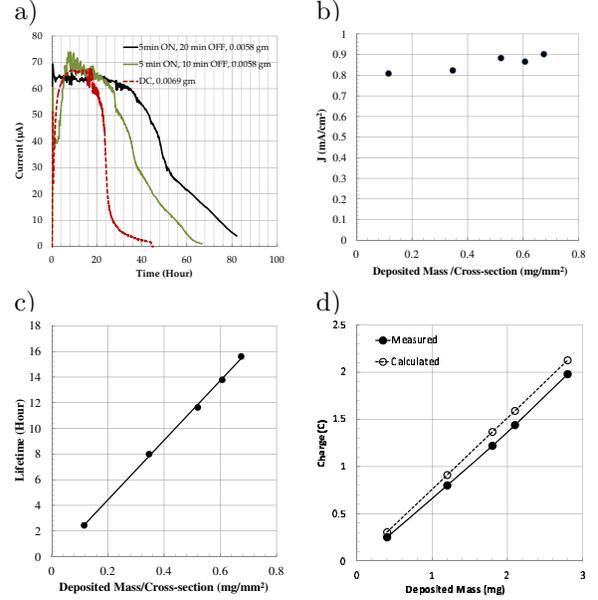


Figure 2: a) The beam current versus lifetime of three sources with different duty factors. During on time, the temperature was at 1265° C and an extraction voltage of 120 V, and during off time, the temperature was at 800° C and zero extraction voltage. The surface area of each source was 3.14 mm^2 ; b) Current density versus mass variation. The sources were operated at 1265° C . The surface area of the sources varied between 3.14 mm^2 and 4.15 mm^2 ; c) The source lifetime as a function of alumino-silicate mass deposited; d) Calculated and measured total extracted charge of sources with 0.4 mg, 1.2 mg, 1.8 mg, 2.1 mg, and 2.8 mg of alumino-silicate material deposited.

for these cases A, B, and C are 16 hrs, 9.6 hrs, and 9 hrs, respectively. Since case A has a higher alumino-silicate mass than cases B and C, the lifetime comparison should be further normalized by their weights (see next section). The corresponding normalized ratio is $1 : 0.71 : 0.67$, not the $1 : 1 : 1$. Therefore, even for fairly high duty factors (such as 0.2, 0.33) neutral loss is already accounting for approximately 30% of the lifetime.

4.2. Lifetime varies with the mass deposited

Five sources with different deposited amounts of lithium alumino-silicate were measured to compare their lifetimes. The other parameters of the experiment such as the distance between the source to collector plate (4 mm gap), the operating temperature, the beam extraction voltage, and the vacuum pressure (10^{-6} Torr) were all unchanged. The emitting surface area of the sources varied between 3.14 mm^2 to 4.15 mm^2 due to an error during the source fabrication process. All of the sources were operated

269 at 1265° C and the beams were extracted, contin-
 270 uously, with 120 V, until the beam current signal
 271 was reduced to a minimum detectable level relative
 272 to the peak current. The beam current density was
 273 expected to have little variation with mass because
 274 the space-charge limited current density should de-
 275 pend only on the surface area and be independent
 276 of the source mass deposited insofar as there remain
 277 sufficient ions to be emitted. This is consistent with
 278 results shown in Fig. 2(b) where the measured beam
 279 current density (J) is plotted against the deposited
 280 source mass for a given area and operating temper-
 281 ature. Figure 2(c) shows the lifetime variation
 282 with the mass density of lithium alumino-silicate
 283 deposited. The lifetime of the alumino-silicate is
 284 measured from the time beam current has transi-
 285 tioned from the cleaning phase to the operational
 286 mode to the time where the beam current has de-
 287 creased to 50% of its current at the transition level.
 288 As expected, the lifetime increases almost linearly
 289 with the lithium alumino-silicate mass deposited in
 290 the source.

291 The theoretically available charge can be calcu-
 292 lated from the known mass of lithium in the β -
 293 eucryptite mixture. Figure 2(d) shows compari-
 294 son of the calculated and measured time-integrated
 295 charge extracted from the sources. The extracted
 296 charge of the sources was proportional to the mass
 297 of the deposited alumino-silicate material. The dif-
 298 ference between the measured charge and the theo-
 299 retical limit is within approximately 10%. Which
 300 shows that the ion extraction rate is significantly
 301 greater than the neutral rate. However, for very
 302 low ion beam duty factor operation, neutral emis-
 303 sion dominates the emitter lifetime (Sec. 3).

304 5. Performance of a 10.9 cm source

305 Figure 3 shows a sketch of NDCX-II injector with
 306 the 10.9 cm diameter Li^+ ion source. The com-
 307 puter code simulation (WARP)[29] has been used
 308 to address the geometrical parameters of diagnos-
 309 tics used to capture ions. The diagnostics are a
 310 Faraday cup to measure beam current signal, and
 311 a gated camera with scintillator to determine beam
 312 images. Figure 4 shows a simulated beam profile
 313 for current densities of (a) $J=0.5 \text{ mA/cm}^2$, and (b)
 314 $J=1 \text{ mA/cm}^2$.

315 5.1. Source temperature and lithium beam current

316 The Faraday cup is temporarily removed from
 317 the beam axis (without breaking vacuum) when do-

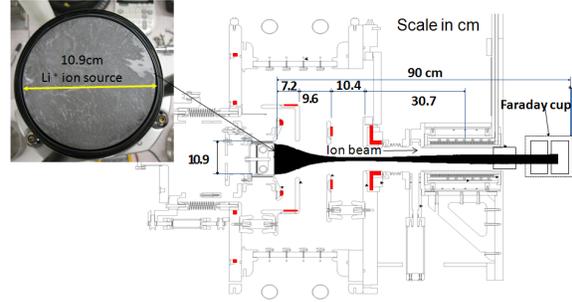


Figure 3: A sketch of the NDCX-II injector with a 10.9 cm diameter lithium alumino-silicate ion source.

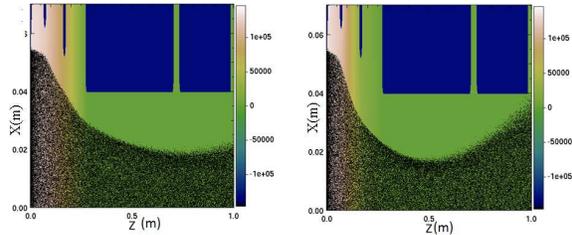


Figure 4: Results of WARP simulation for $J=0.5 \text{ mA/cm}^2$ (left), and $J=1.0 \text{ mA/cm}^2$ (right).

318 ing the temperature measurement with the pyrom-
 319 eter. A source surface temperature of 1250 °C was
 320 measured when 3.5 kW electrical heating power was
 321 applied. Figure 5 shows measured heating power vs.
 measured surface temperature.

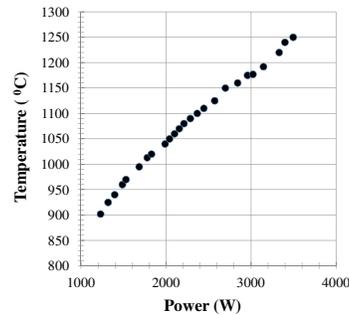


Figure 5: NDCX-II 10.9 cm diameter source heating power versus surface brightness temperature.

322 At a temperature of 1250 °C, the Faraday cup
 323 was placed on the beam axis and the beam current
 324 was measured as a function of extraction voltage.
 325 This is shown in Fig. 6(a). A series of measure-
 326 ments were performed by varying the source sur-
 327 face temperature from 1100 to 1250 °C. The beam
 328 current increased with the source surface tempera-
 329 ture and extraction voltage. Figure 6(b) shows mea-

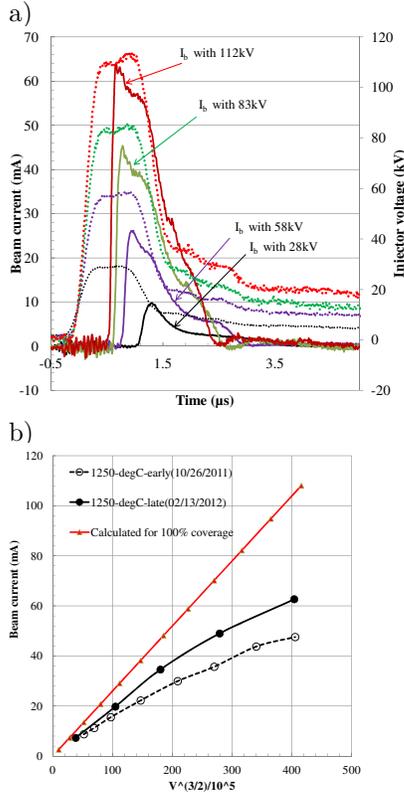


Figure 6: a) NDCX-II beam extraction voltage and beam current waveforms. The waveforms with solid lines represent beam current (primary vertical axis) with variation of voltage (secondary vertical axis with dotted lines); b) Beam current varies with $V^{3/2}$ of injector voltage. The line at the left represents calculated current using the Child-Langmuir law with the distance of $d=27.24$ cm, and mass of the element is of 7 amu.

331 measured beam current with variation of applied voltage. A maximum charge of 50 nC was measured for
 332 115 kV with the source surface temperature of 1250
 333 - 1275 °C. The beam optical image was captured
 334 using a Roper Scientific gated CCD camera. Figure
 335 7 shows the evolution to emission-limited flow.
 336 These are scintillator images obtained at a down-
 337 stream diagnostic station. A 500 ns camera gate
 338 captures most of the lithium beam only. Earlier
 339 measurements and comparisons to particle-in-cell
 340 simulations [7] showed a 10% contamination from
 341 K^+ , in contrast with the contamination studies on
 342 very small emitters discussed in the section 2.3. For
 343 the large emitters, this contamination is transient,
 344 and is most abundant at the beginning of the life
 345 cycle of an emitter. The contamination level ap-
 346 pears lower in these new results, and the measured
 347 beam current is closer to (but still significantly be-
 348

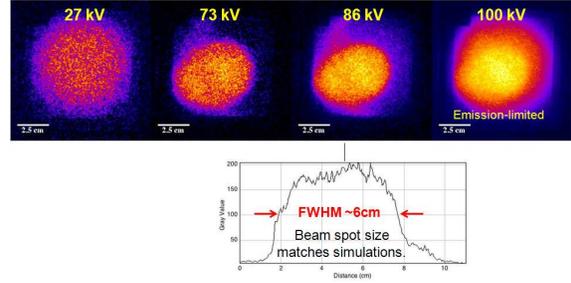


Figure 7: Lithium ion beam optical profile.

349 low) the space charge limit. A typical 0.6 cm di-
 350 ameter lithium alumino-silicate source provides $J=$
 351 1-1.4 mA/cm² in the space-charged limited mode
 352 of operation. But, J is less (0.7 mA/cm²) for a
 353 10.9 cm source at present, probably due to a sur-
 354 face covering issue; i.e., source material was not dis-
 355 tributed uniformly or equally throughout the sub-
 356 strate surface, when the source was prepared. This
 357 is an area of ongoing development. The beam emit-
 358 tance of the 10.9 cm diameter source is being mea-
 359 sured as NDCX-II commissioning progresses. How-
 360 ever, more ion source work is needed to improve the
 361 large diameter source performance.

362 6. Conclusion

363 Space-charge-limited emission with current den-
 364 sities exceeding 1 mA/cm² was obtained from
 365 0.64 cm diameter lithium alumino-silicate ion
 366 sources when operating at 1275° C. The measured
 367 current density level is 0.7 mA, below the space
 368 charge limit for the injector geometry and operat-
 369 ing voltage, for the first 10.9 cm diameter NDCX-II
 370 source, and it may due to a surface coverage issue.
 371 The lifetime of a thin coated (on a 80% dense tung-
 372 sten substrate) lithium alumino-silicate source was
 373 40-50 hours when pulsed at 0.05 Hz and with pulse
 374 length of 6 μs each, a duty factor of 3×10^{-7} , and at
 375 an operating temperature of 1275° C. This lifetime
 376 is dominated by a relatively low neutral emission
 377 rate compared to the ion emission rate. A longer
 378 lifetime, nearly 100 hours was reported recently [25]
 379 for similar sources. But, the amount of mass den-
 380 sity deposition on the 0.64 cm diameter sources,
 381 which were sintered on the porous tungsten sub-
 382 strate, were not identified. The total beam charge
 383 extracted during the lifetime with such low duty
 384 factor pulsed mode was very small. In comparison,
 385 the beam charge that was extracted in 16 hrs life-

time when operated in DC mode was near the theoretical limit of the amount of lithium ions contained in the mass of alumino-silicate. This discrepancy suggested that the loss of lithium as neutral atoms was at a similar rate to the ion current extraction when the ion source temperature was 1265° C. Thus the lifetime of a lithium ion source depends mostly on the total elapsed time that the source is kept at high temperature. Consequently, one way to extend the useful lifetime is to momentarily reduce the operating temperature during the idle time between pulses. This could be a practical method if the pulse rate is very slow, such as once or twice per minute; but even approximately 800 °C was not low enough to reduce the neutral emission to a negligible level. Increasing the amount of deposited mass to increase the lifetime is possible, but it is also difficult to fabricate a thick source due to anisotropic nature of lithium alumino-silicate material. Overall, a typical pulsed beam source life is around 40 hours; however this could be further improved by increasing mass deposition, reducing operational temperature, reducing surface cleaning time. Cleaning time of a hot source could be reduced by low voltage DC extraction for a short time at the beginning of source operation period. More ion source work is needed to improve the large source performance including re-arrangement of source heating to overcome filament failure.

7. Acknowledgments

The authors wish to thank A. Friedman, S. M. Lund, B. G. Logan, and W. M. Sharp for useful discussions. T. M. Lipton, M. R. Dickinson, and T. E. Katayanagi provided valuable technical assistance. One of the authors (P. K. Roy) is grateful to Super-conducting Magnet Program at LBNL for allowing sufficient time to complete the manuscript. This work was performed under the auspices of the U.S. Department of Energy by LBNL under Contract DE-AC02-05CH11231.

References

[1] F. M. Bieniosek, J. J. Barnard, A. Friedman, E. Henestroza, J. Y. Jung, M. A. Leitner, S. Lidia, B. G. Logan, R. M. More, P. A. Ni, P. K. Roy, P. A. Seidl, and W. L. Waldron, 'Ion-Beam-Driven Warm Dense Matter Experiments,' IFSA 2009, J. Phys. Conf. Ser. **A 244**, 032028. (2010).

[2] B. G. Logan, F. M. Bieniosek, C. M. Celata, J. Coleman, W. Greenway, E. Henestroza, J. W. Kwan, E. P. Lee, M. Leitner, P. K. Roy, P. A. Seidl, J.-L. Vay, W. L. Waldron, S. S. Yu, J. J. Barnard, R. H. Cohen, A. Friedman, D. P. Grote, M. Kireeff Covo, A. W. Molvik, S. M. Lund, W. R. Meier, W. Sharp, R. C. Davidson, P. C. Efthimion, E. P. Gilson, L. Grisham, I. D. Kaganovich, H. Qin, A. B. Sefkow, E. A. Startsev, D. Welch, and C. Olson, Nucl. Instrum. Methods Phys. Res., **A 577**, 1 (2007).

[3] J. W. Kwan, A. Faltens, J. Y. Jung, E. P. Lee, M. Leitner, B. G. Logan, W. L. Waldron, A. Friedman, Bulletin of the American Physical Society, **54(15)**, 192 (2009).

[4] W. M. Sharp, A. Friedman, D. P. Grote, R. H. Cohen, S. M. Lund, M. Leitner, J.-L. Vay, W. L. Waldron, Bulletin of the American Physical Society, **54(15)**, 211 (2009).

[5] A. Friedman, J. J. Barnard, R. H. Cohen, D. P. Grote, S. M. Lund, W. M. Sharp, A. Faltens, E. Henestroza, J.-Y. Jung, J. W. Kwan, E. P. Lee, M. A. Leitner, B. G. Logan, J.-L. Vay, W. L. Waldron, R. C. Davidson, M. Dorf, E. P. Gilson, and I. D. Kaganovich, Phys. of Plasma, **17**, 056704 (2010).

[6] S. M. Lidia, Proceeding of IPAC 2012.

[7] P. A. Seidl, W.W. Greenway, D. P. Grote, J.-Y. Jung, J.W. Kwan, S. M. Lidia, P. K. Roy, J. Takakuwa, J.-L. Vay, and W. L. Waldron, Phys. Rev. STAccel. Beams, **15**, 040101 (2012).

[8] S. A. MacLaren, Ph.D. diss., University of California, Berkeley, 2000. <http://escholarship.org/uc/item/9qs631sm#page-1>.

[9] F. M. Bieniosek, C. M. Celata, E. Henestroza, J.W. Kwan, L. Prost, P. A. Seidl, A. Friedman, D. P. Grote, S. M. Lund, and I. Haber, Phys. Rev. ST Accel. Beams, **8**, 010101 (2005).

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

[11] R. K. Feeney, W. E. Sayle II, and J. W. Hooper, Rev. Sci. Instrum., **47**, 964 (1976).

[12] Y. Zhang, H. Boehmer, W. W. Heidbrink, and R. McWilliams, D. Leneman and S. Vincena, Rev. Sci. Instrum., **78**, 013302 (2007).

[13] D. M. Thomas, W. P. West, and K. McCormicks, Rev. Sci. Instrum., **59(8)**, 1735 (1988).

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

[15] K. McCormick, S. Fiedler, G. Kocsis, and J. Zoletnik, Fusion Eng. and Design, **34-35**, 125 (1997).

[16] J. Vukanic and I. Terzic, Nucl. Instrum. Methods, **111**, 117 (1973).

[17] G. Anda, G. Petravich, S. Zoletnik, and S. Bato, Fusion Eng. Des. **74**, 715 (2005).

[18] M. Ueda, R. R. Silva, R. M. Oliveira, H. Iguchi, J. Fujita and K. Kadota, J. Phys. D: Appl. Phys., **30**, 2711 (1997).

[19] J. W. Kwan, IEEE Trans. Plasma Sci., **33(6)** , 1901 (2005).

[20] M. E. Herniter, and W. D. Getty, IEEE Trans. Plasma Sci., **15** , 351 (1987).

[21] P. Loschialpo, and C. A. Kapetanakos, J. Appl. Phys., **63** , 2552 (1988).

[22] P. K. Roy, A. Moon, K. Mima, S. Nakai, M. Fujita, K. Imasaki, C. Yamanaka, E. Yasuda, T. Watanabe, N. Ohigashi, Y. Okuda, and Y. Tsunawaki, Rev. of Sci. Instrum., **67(12)** , 4098 (1996).

[23] P. A. Ni, J. W. Kwan, P. K. Roy, and W. L. Waldron,

498 Rev. of Sci. Instrum., **682** , 023304 (2011).
499 [24] G. Kuznetsov, Nucl. Instrum. Methods., **A 340** , 204
500 (1996).
501 [25] P. K. Roy, W. G. Greenway, J. W. Kwan, P. A. Seidl, W.
502 L. Waldron, and J. K. Wu, Rev. Sci. Instrum., **82**(2011)
503 013304.
504 [26] P. K. Roy, W. G. Greenway, and J. W. Kwan, *et al.*,
505 Rev. Sci. Instrum., **83**(2012) 043303.
506 [27] Optical Pyrometer made by Leeds and Northrup, UK.
507 [28] P. M. Waters, Phy. Review, **111** (4), 1053 (1958).
508 [29] D. P. Grote, A. Friedman, I. Haber, J-L. Vay, 'The
509 WARP Code: Modeling High Intensity Ion Beams,'
510 Proc. of the 2004 ECRIS Workshop, AIP Conf. Proc.,
511 March 15, 2005, **749**, 55.