Lithium Ion Sources

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with
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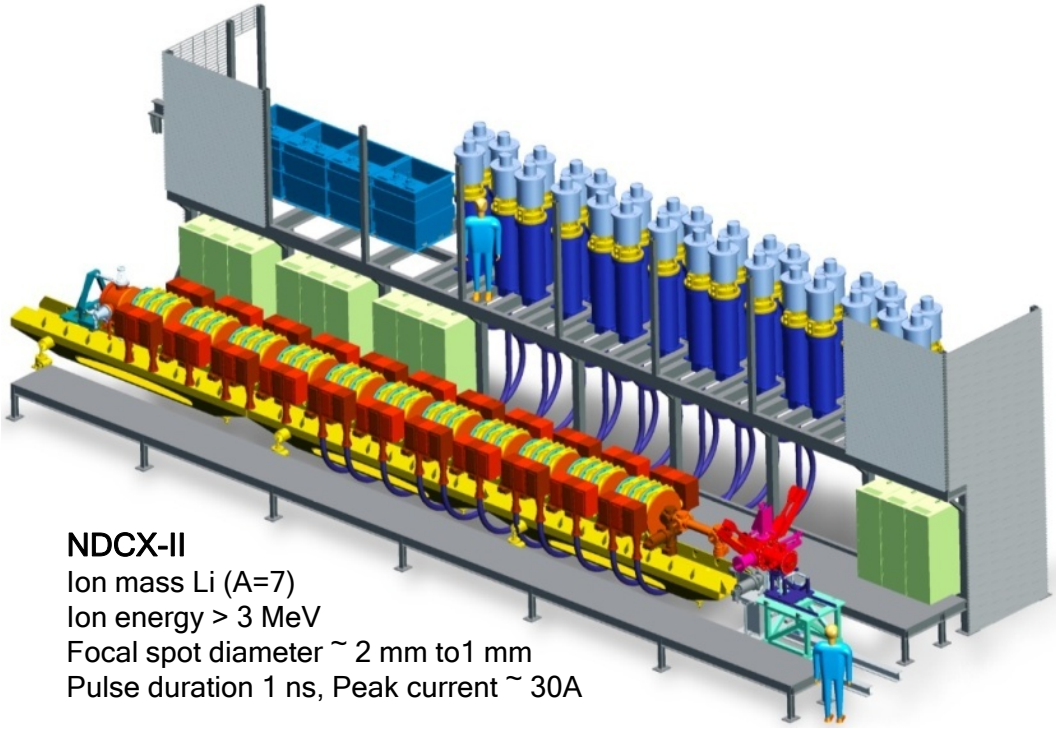
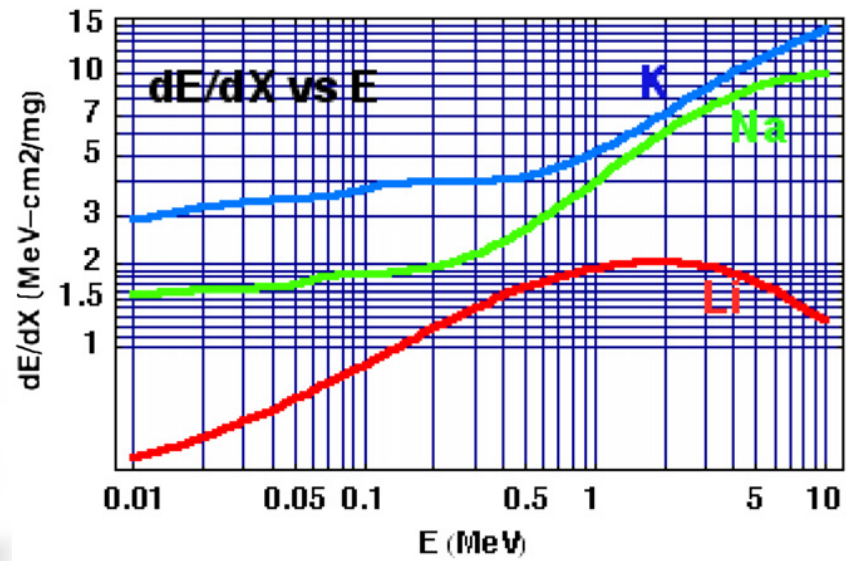
Outline

- Past history and uses of lithium sources
- Challenges for the production of a high-current & high-quality Li^+ beam
- Source performance (J, T, τ_{life}, m)

We choose Li^+ alumino-silicate ion sources for beams for warm dense matter experiments



NDCX-II
Ion mass Li (A=7)
Ion energy > 3 MeV
Focal spot diameter ~ 2 mm to1 mm
Pulse duration 1 ns, Peak current ~ 30A



Energy loss rate (dE/dX) as a function of ion energy in solid Al *(data from the SRIM code, J.J. Barnard et al, NIMA A 577 (2007) 275).*

- One strategy is to deposit most of the ion energy at the peak of energy loss (dE/dx) with a low (E < 5 MeV) kinetic energy compressed beam of ns pulse duration on a thin target.
- Lower mass ions, such as lithium, have a peak dE/dx at a lower kinetic energy.

Several methods to produce a lithium beam are known

- Lithium-vapor sources:

(a) Problem with beam reproducibility , and beam quality (emittance).

(b) Problem maintaining good vacuum, though provides high current.

- Surface ionization sources:

--Unfavorable due to the greater ionization energy of Li than other alkali ions (K^+, Cs^+), and W- substrate.

- The alumino-silicate source approach:

--Appears to be a better choice for : (a) beam reproducibility , (b) beam quality , and (c) easier to handle in a low vacuum pressure.

Li^+ alumino-silicate ion sources used for diagnostics, some examples:

Who they are	Purpose	Operating condition	Results
J. P. Blewett *et al.* Phys. Rev. 50, 464 (1936)/ Princeton Univ	Mass spectroscopy, beams of +ve ions	Filament type,	• J=0.5 mA/cm^2, 20% Li, •Emission limited •β-eucryptite •T=1115 °C , t=?
R. K. Feeney *et al.* RSI 47, 964 (1976)/ Georgia Inst. Technology	Charge particle-charge particle collision experiments	Filament -type, (Impurities Na+, K+)	•J=<0.2 mA/cm^2 •Emission limited (500V/cm) •β-spodumene •T=1115 °C, t=>10hours
D. M. Thomas *et al.* RSI 59, 1735 (1988)/ General Atomics	Plasma diagnostics	Source disk/ pulsed	•J=1 mA/cm^2 •Emission limited (4-6kV/cm) •β-eucryptite •T=1200 °C, t=>?
M. Ueda *e t al.* J. Phys. D: Applied Physics 30, 2711(1997)/ INPE, Brazil	Plasma diagnostics, Li+ emission properties of pasty, liquid and glassy	Crucible/CW	• J=1 mA/cm^2 • Emission limited (2.5kV/cm) •β-eucryptite •T=1150 °C, t=5hours

We overcame many challenges for the production of high brightness Li^+ beams

Extreme anisotropy in thermal expansion coefficients.
("a" direction: $+8.2 \times 10^{-6}$ / C.
"c" direction: -17.6×10^{-6} / C)

Insufficient references for Li alumino-silicate source fabrication & characterization

Tighter tolerances (temperature , duration) for calcination, leucite phase preparation & sintering.

Li^+ source emits lower charge density than other sources (K^+, Cs^+).

High temperature (>1200° C) for required beam emission (ionization 5.38 eV).

Life time is short.
(not years as with K^+)

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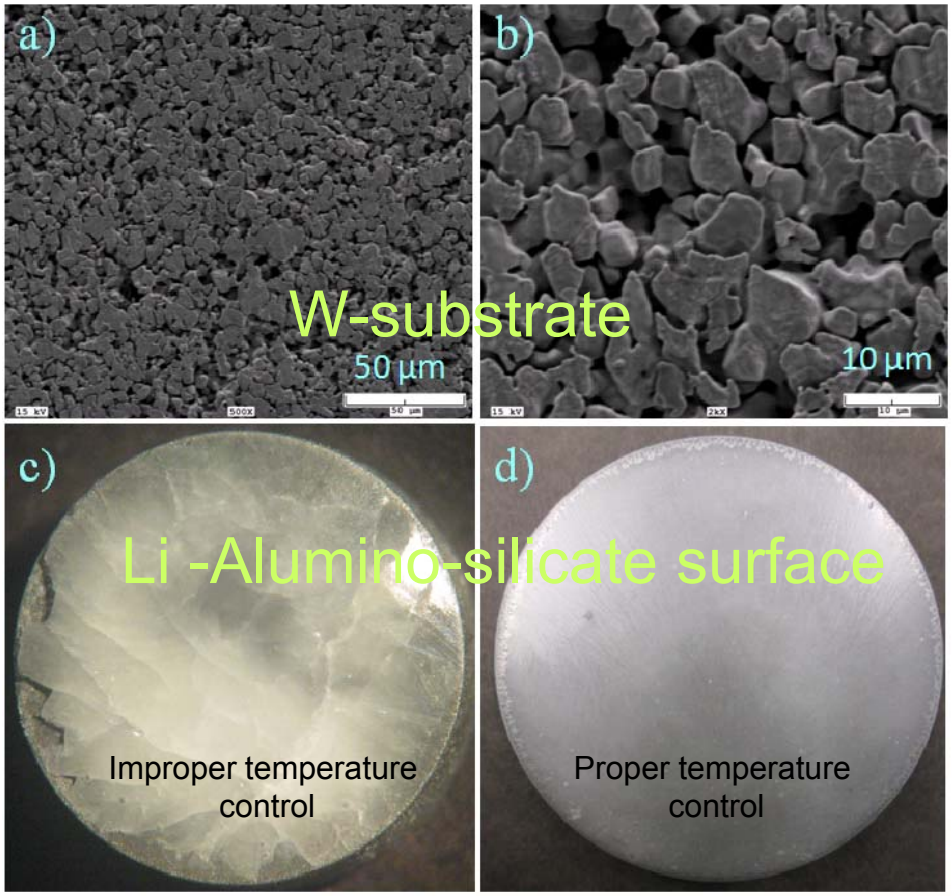
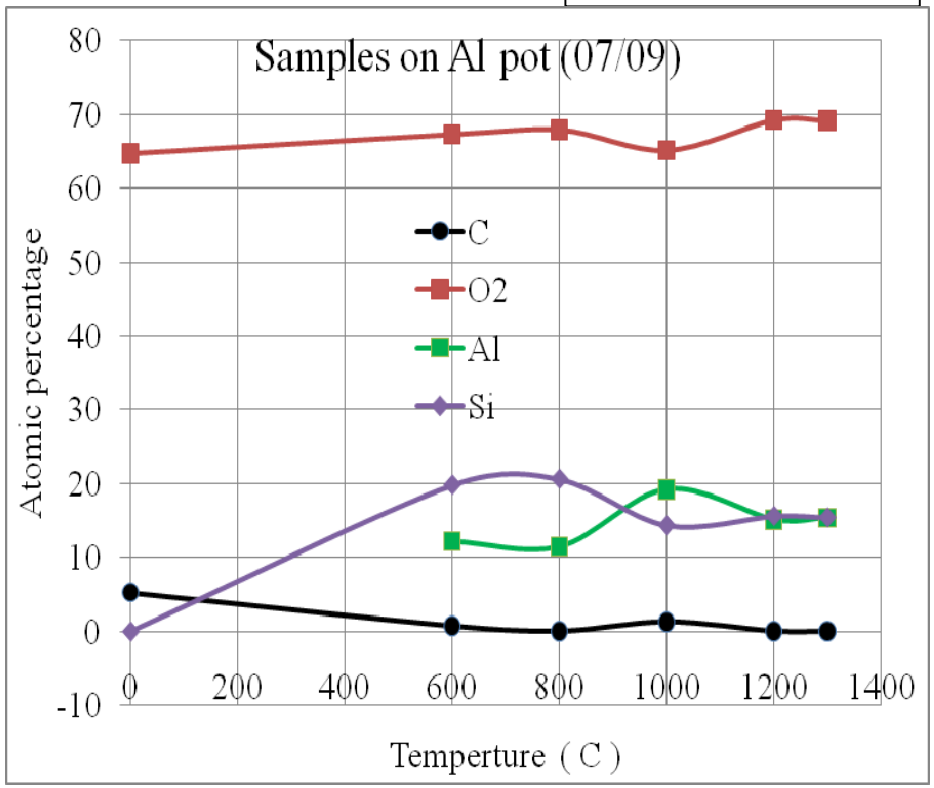
Sources were fabricated with 70 - 80% dense tungsten substrate, sintered using a heat cycle

$$Li_2CO_3 + Al_2O_3 + 2(SiO_2) \Rightarrow Li_2O\text{-}Al_2O_3 - (SiO_2)_2 + CO_2 \Uparrow$$

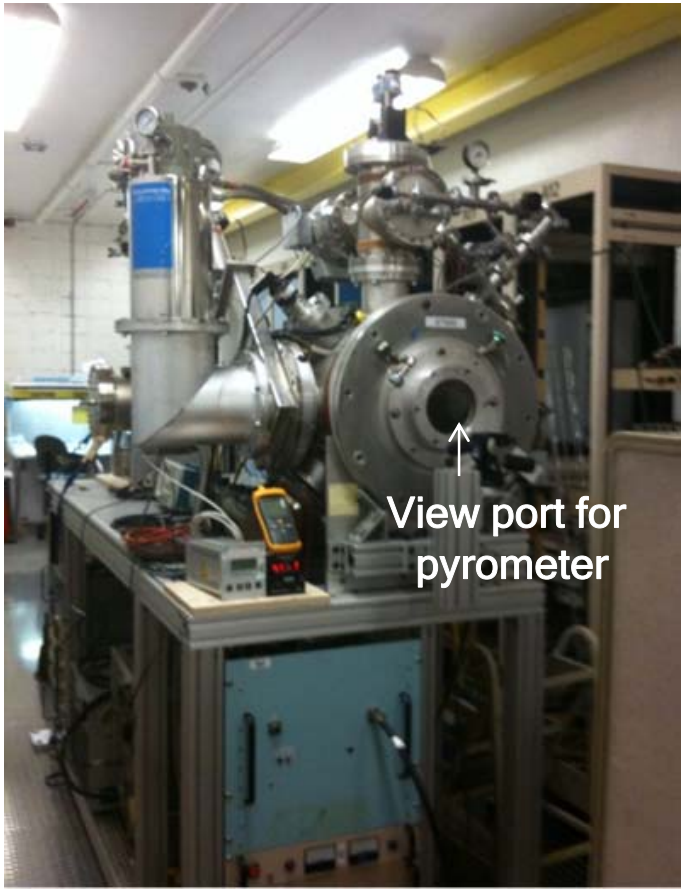
99.999% isotopically pure lithium carbonate is used



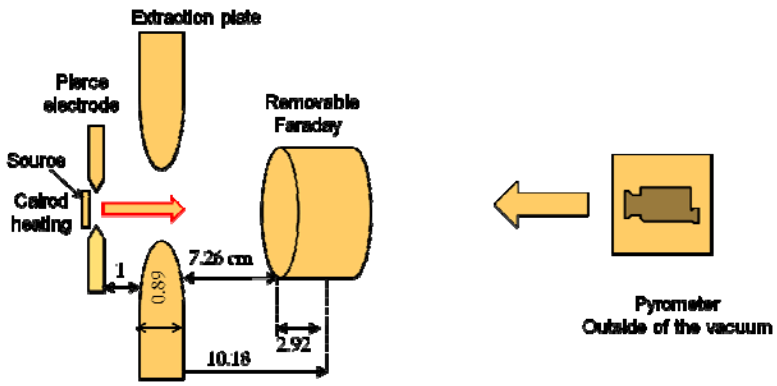


SEM was used to analyze Lucite phase

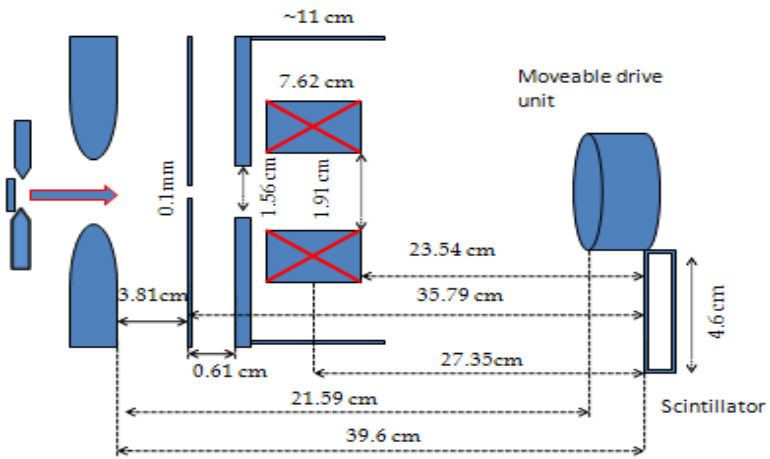
We fabricated and tested 0.64 cm diameter sources in pulsed mode



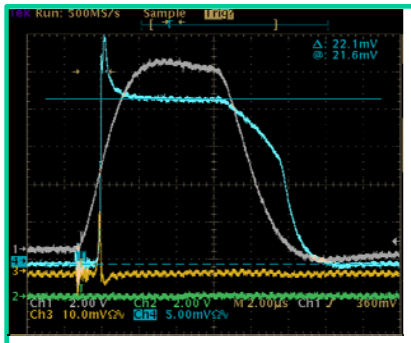
Test stand-STS 50



Current - temperature measurements

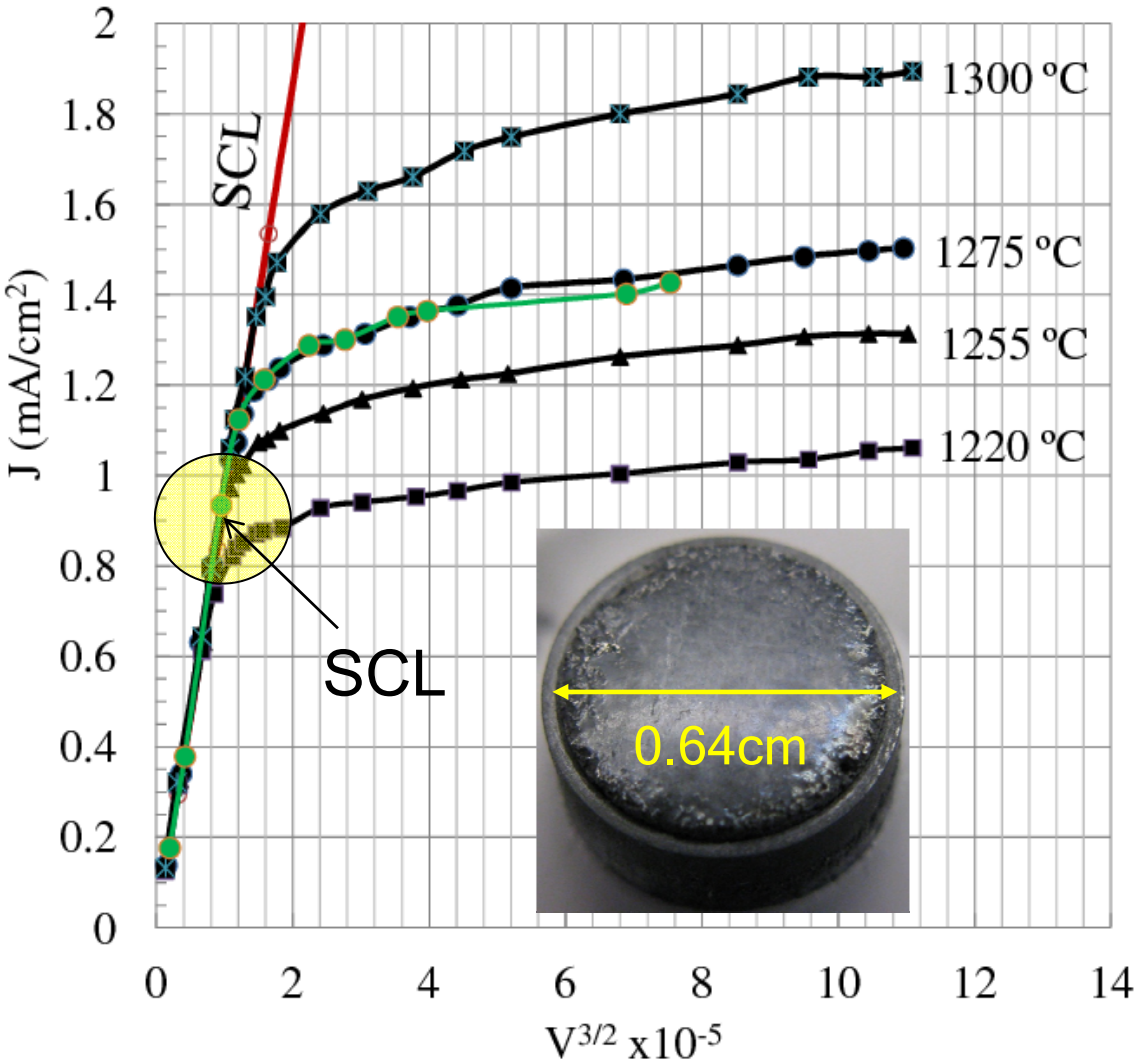


Element identification with ExB filter



- A 5-6μs beam extraction voltage waveform displayed on an oscilloscope.
- Beam current was registered by the Faraday cup collector (+300V) with 50Ω in series to ground. The signal corresponded to a current density of 1.5 mA/cm^2 with
- T= 1260ºC-1275°C and 10 kV

A well sintered Li β-eucryptite source provides J≈1mA/cm^2 with space-charge limited extraction



Low field region, space charge limited current density is defined by Child-Langmuir law as:

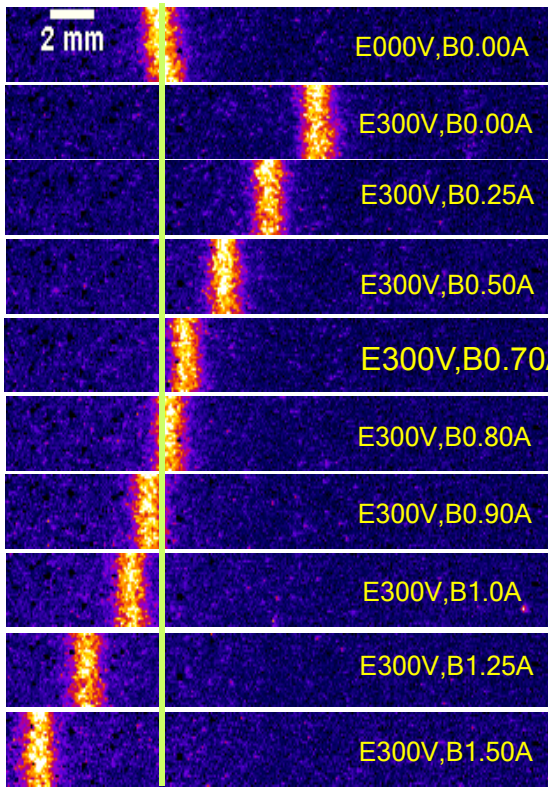
$$J(\chi, V, d) = \chi \frac{V^{3/2}}{d^2},$$

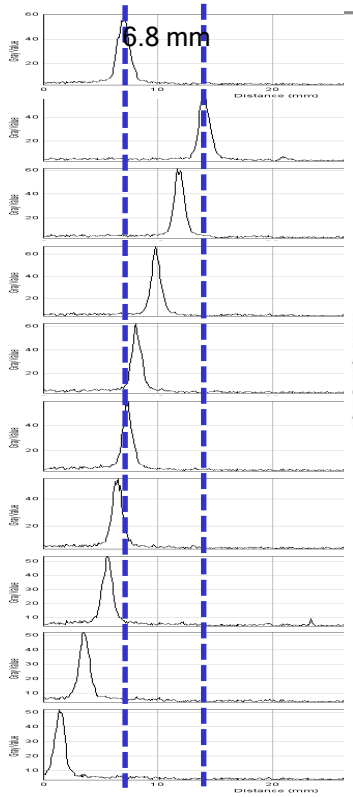
$$\chi(q, m) = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m}}$$

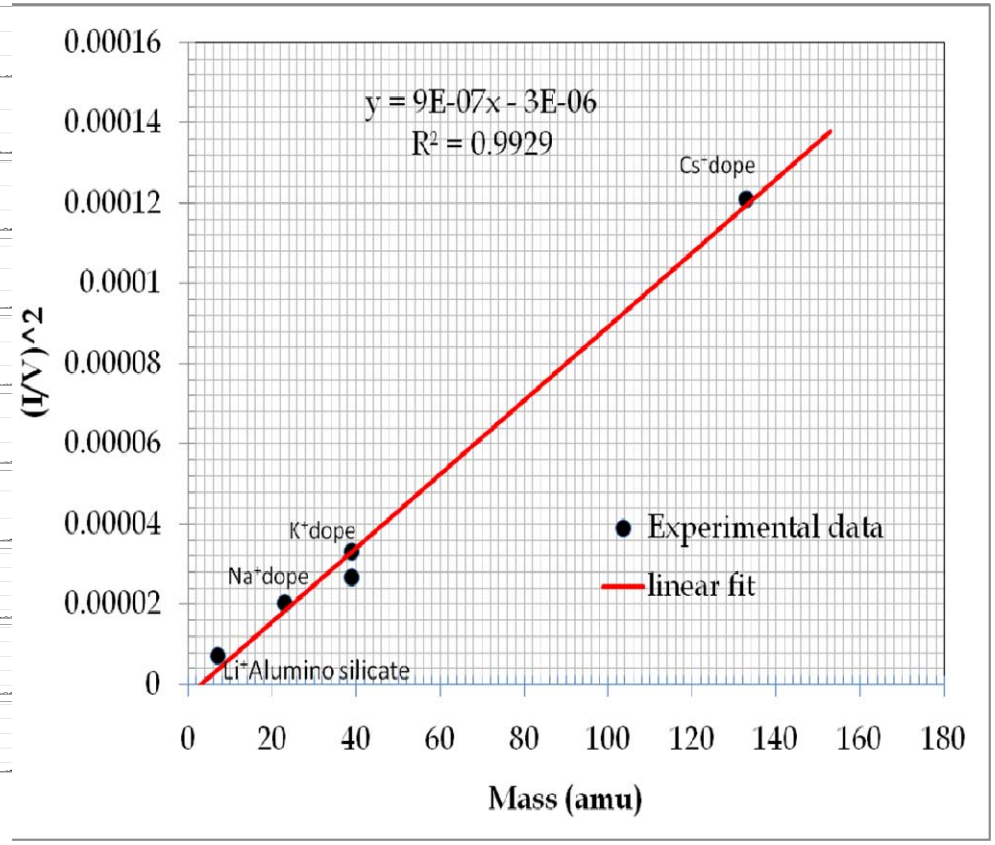
Roy *et al.*, RSI, 82, 013304 (2011)

7 amu Lithium was identified using ExB spectrometer and YAP scintillator

(E field constant, T=1285°C)







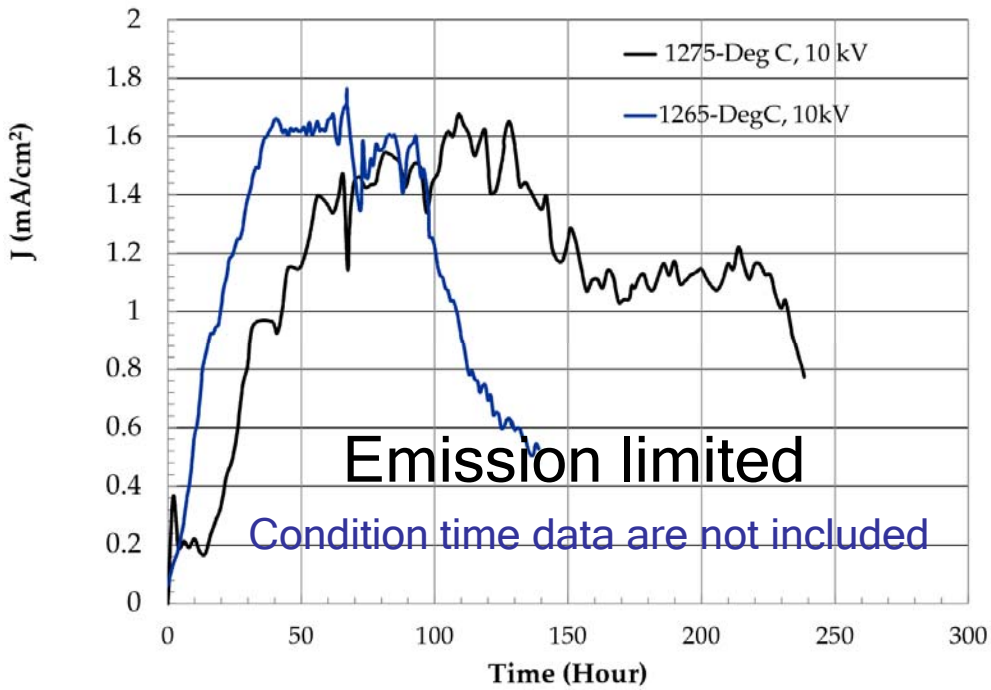
(1A=203G)

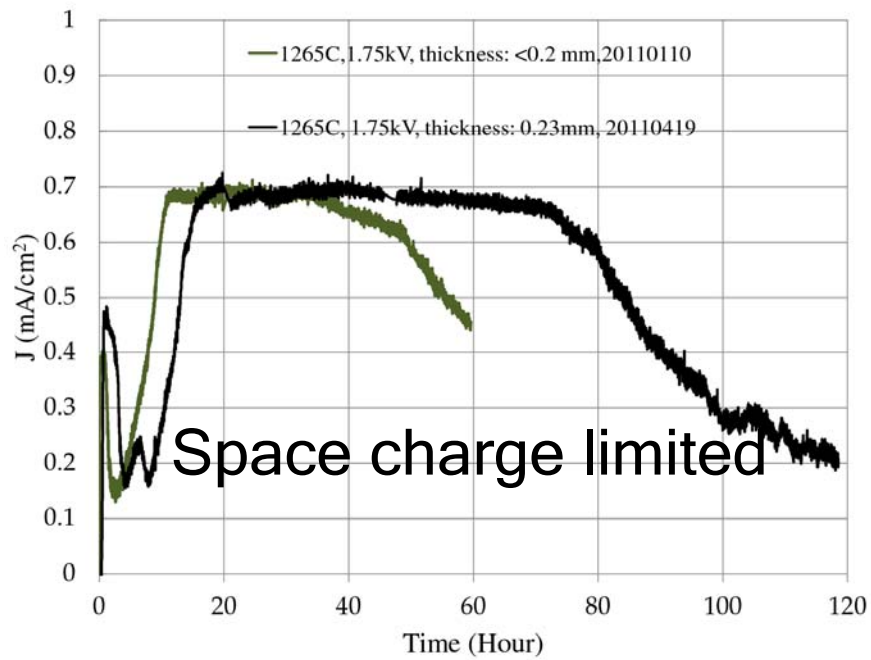
$$M_{uknown}(B, E_{fil}, V_{ext}) := 2q_e \cdot \left(\frac{B}{E_{fil}}\right)^2 \cdot V_{ext}$$

0.83 A=168.5G identified Li-7, 1mm=12.5 pixel

Typical lifetime of a 0.64 cm diameter source is ≥40 hrs when pulsed, source temperature=1275°C continuous

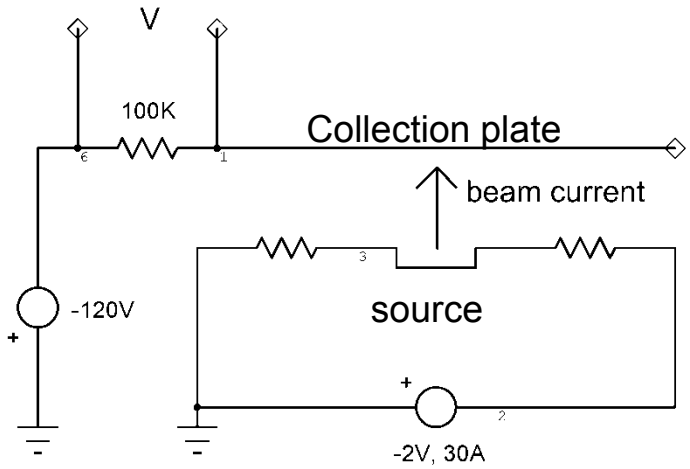
The duty factor is 10^{-7}

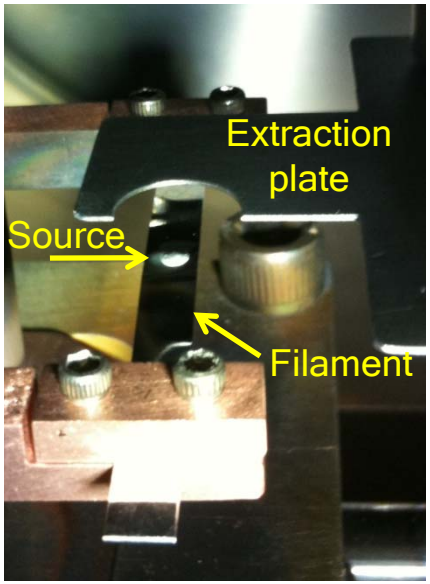




- The space charge limit effectively smoothes out spatial variations in emission.
- It is possible to increase lifetime by reducing operational temperature and improving mass deposition – as demonstrated by the next experiments.

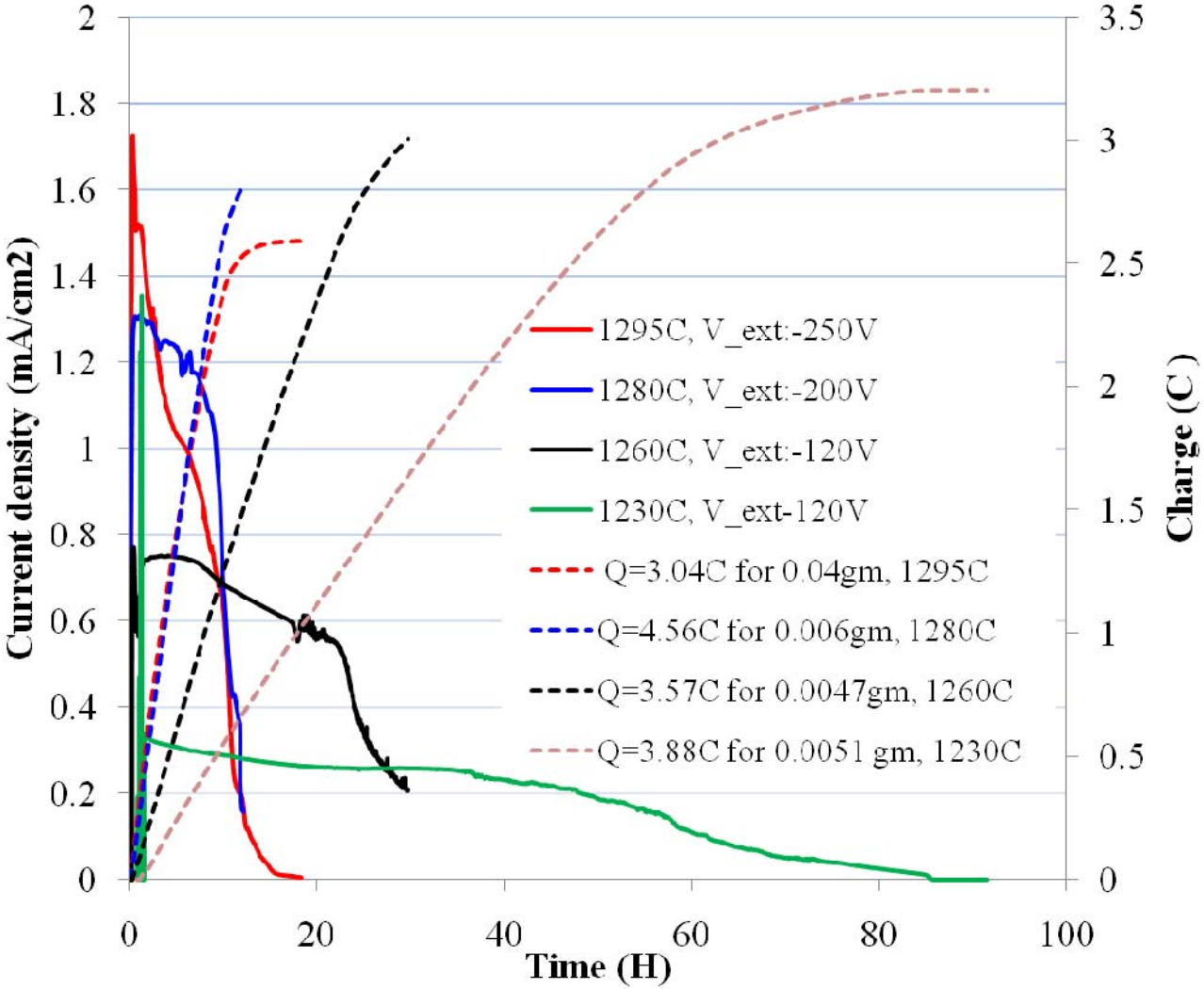
Additional experiments were performed in a DC extraction test facility to measure lifetime vs. temperature and mass deposition





- A defined quantity of Li-alumino-silicate material is placed in a ≈1.8 mm diameter dimple on a 0.5 cm width molybdenum filament.
- Extracted beam on a negative bias plate, located at 4 mm far from the emitting surface.

A reduced temperature increases lifetime of a source but reduces current emission



$$J_0 = AT^2 e^{-\frac{\phi_w}{k_B T}}$$

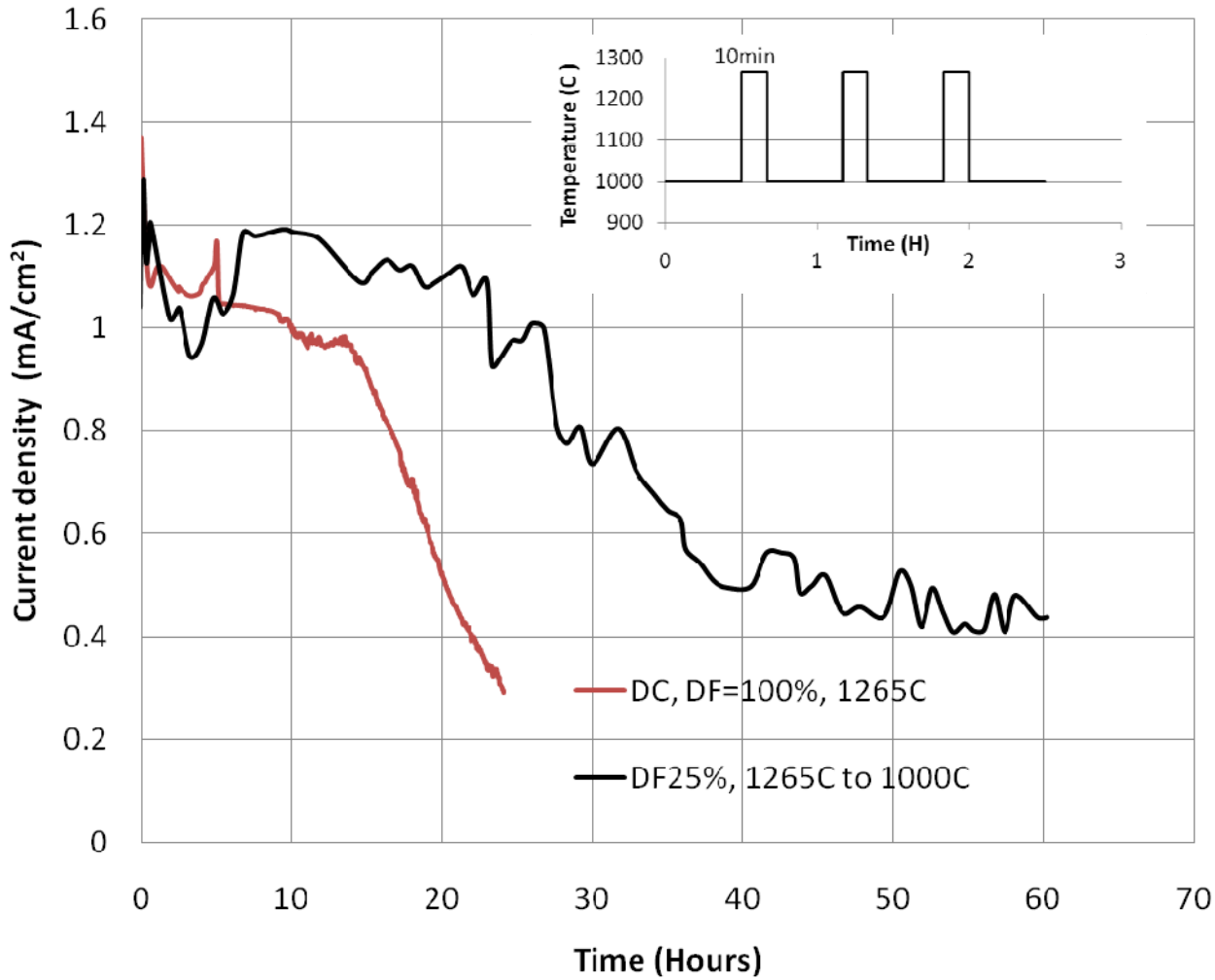
The Richardson-Dushman law can only be used in an empirical way to describe emission of an alumino-silicate ion sources for work function variation, since surface is non conducting.

≈85% charge is extracted for DC mode extraction

Mass of Li alumino silicate	$m1 := 0.0044 \cdot gm$
Weight of the Lithium	$W_L := 5.56\%$
Mass of Lithium	$m_7 := 7 \cdot (1.6726 \cdot 10^{-24}) \cdot gm$
1 Charge	$q_e := 1.6 \cdot 10^{-19} \cdot coul$
Total charged contained	$C_{Li} := \frac{m1 \cdot W_L}{m_7} \cdot q_e$

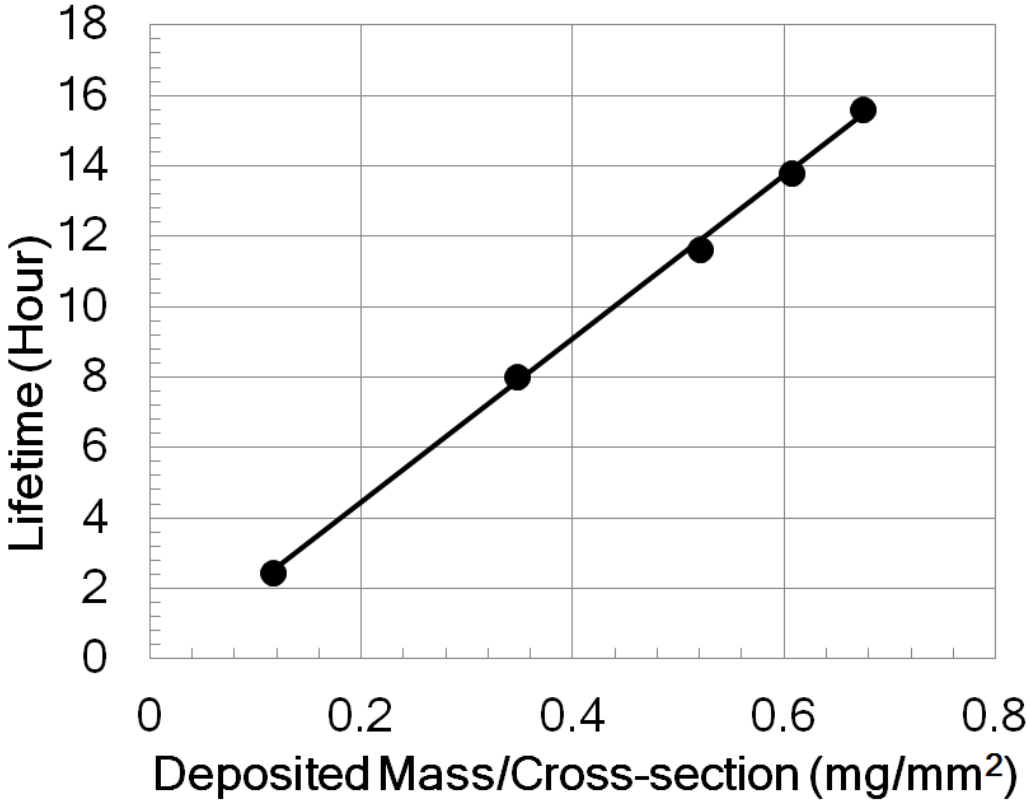
$C_{Li} = 3.343\,C$

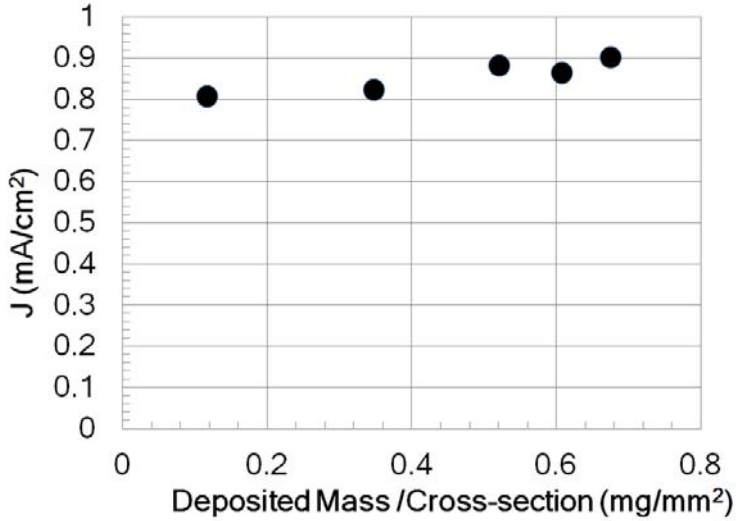
Lifetime is extended by cycling temperature

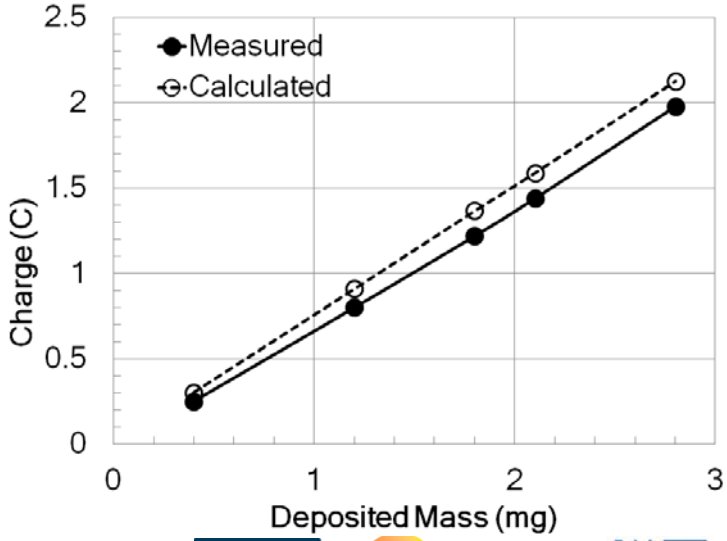


Beam current vs. lifetime for sources with duty factor (DF) 100% (lower line) and 25% (top line). Both sources were operated at a temperature of 1265°C during beam extraction. Temperature of the source with DF 25% was reduced to 1000°C during non extracting beam time.

Increasing deposited β-eycryptite mass is another method to increase lifetime

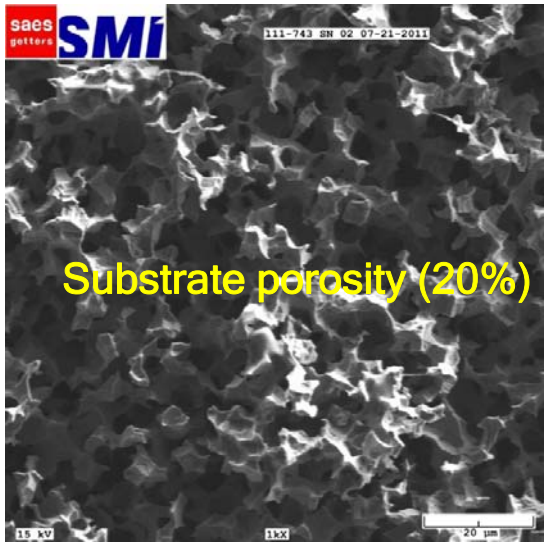


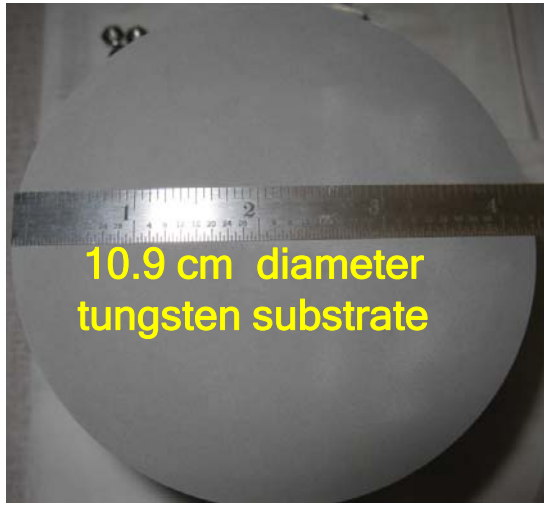


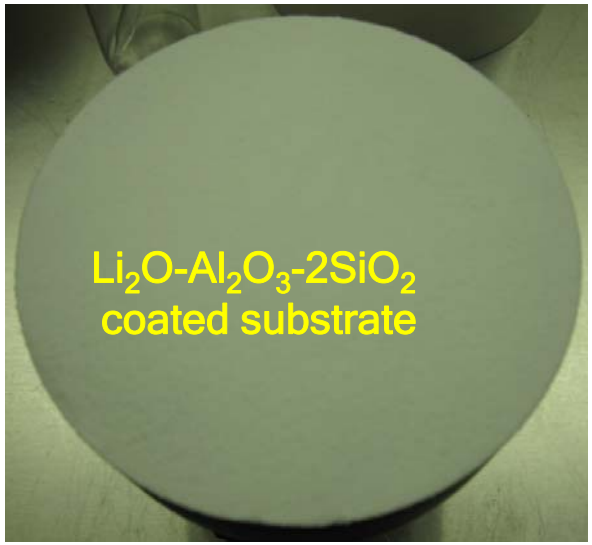


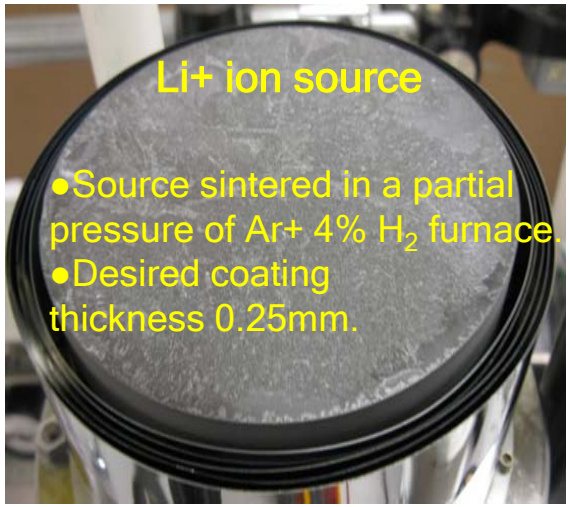
Roy *et al.*, RSI, 83, 043303 (2012)

Experience on small sources used to fabricate 10.9 cm diameter NDCX-II source





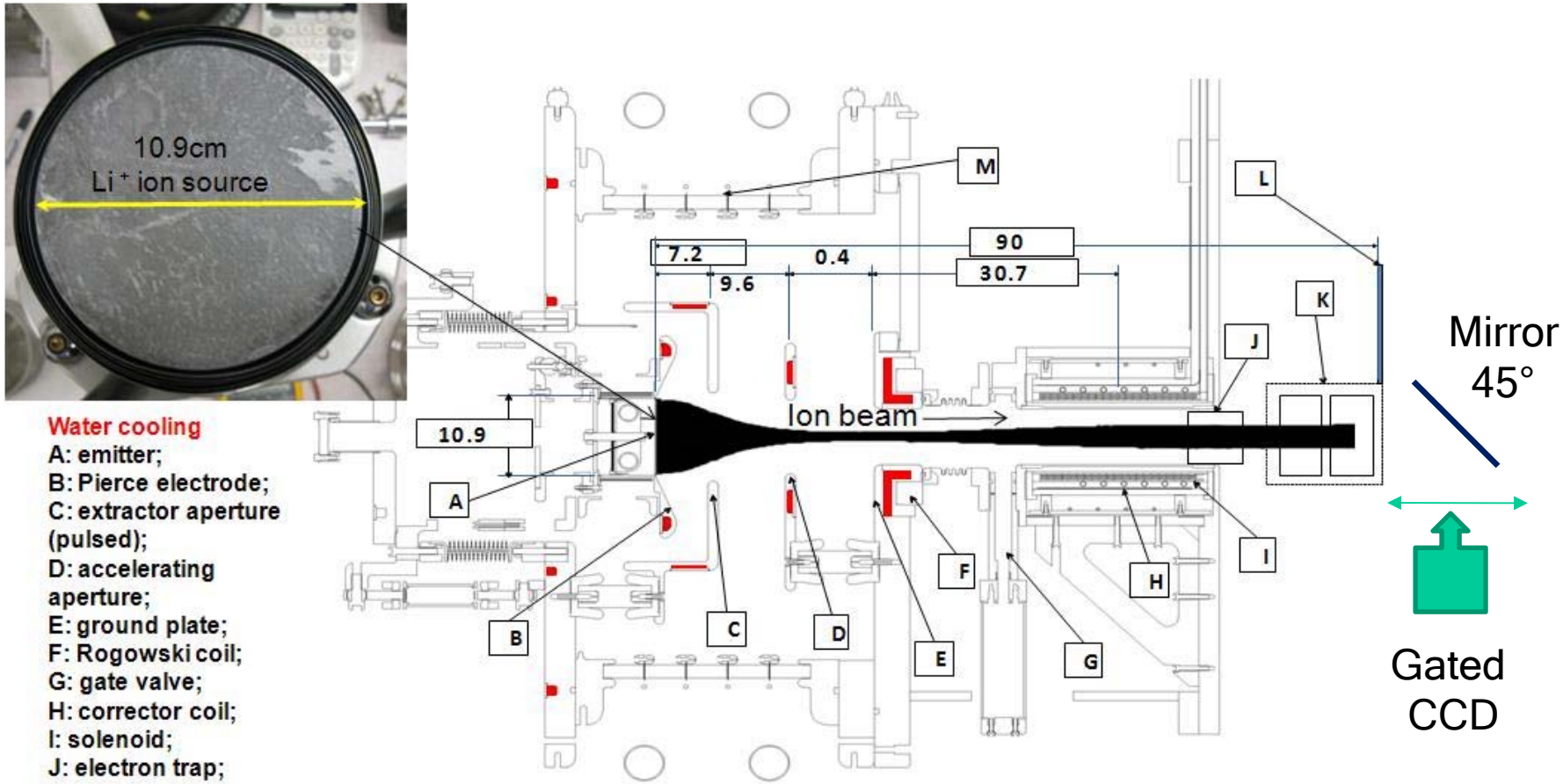




- Operating temperature 1250° to 1275° C with ≥3.6 kW ohmic heating.
- This is under modification for better performance.

Configuration of NDCX -II injector to have beam experiments with the large lithium source

- Li^+ beam, injector final energy 130 keV, ●charge 50 nC ● Pulse length 500 ns. ●Beam current ~100 mA



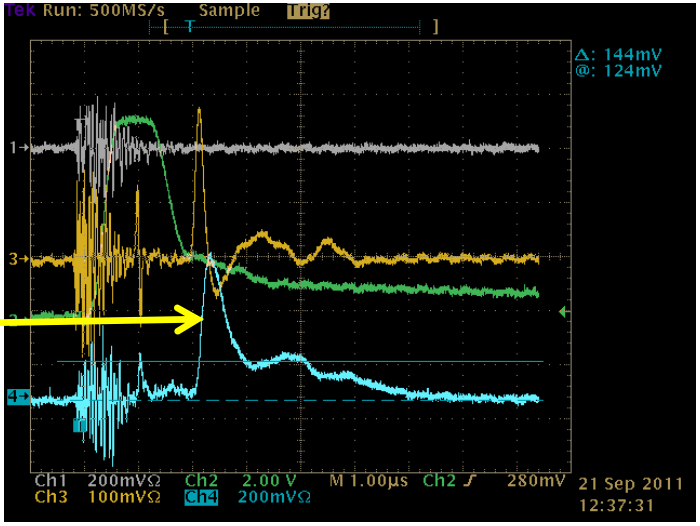
Water cooling
A: emitter;
B: Pierce electrode;
C: extractor aperture (pulsed);
D: accelerating aperture;
E: ground plate;
F: Rogowski coil;
G: gate valve;
H: corrector coil;
I: solenoid;
J: electron trap;
K: Faraday cup;
L: scintillator;
M: insulating column.

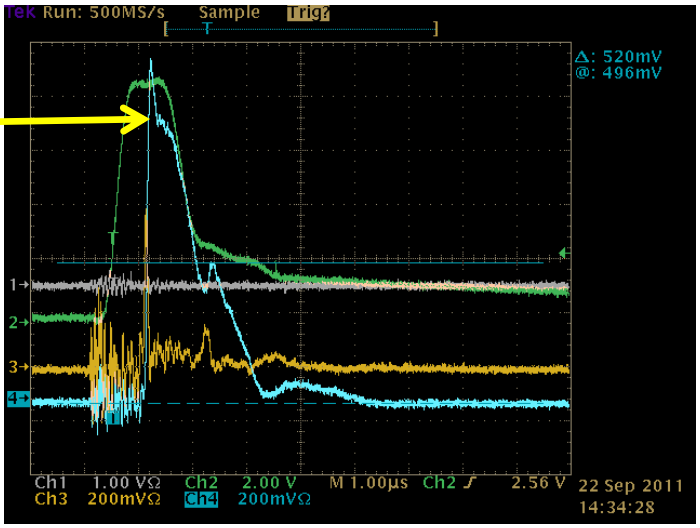
First NDCX-II beam waveform with 10.9 cm diameter Lithium alumino-silicate ion source

Started extracting ion beam on September 16, 2011.

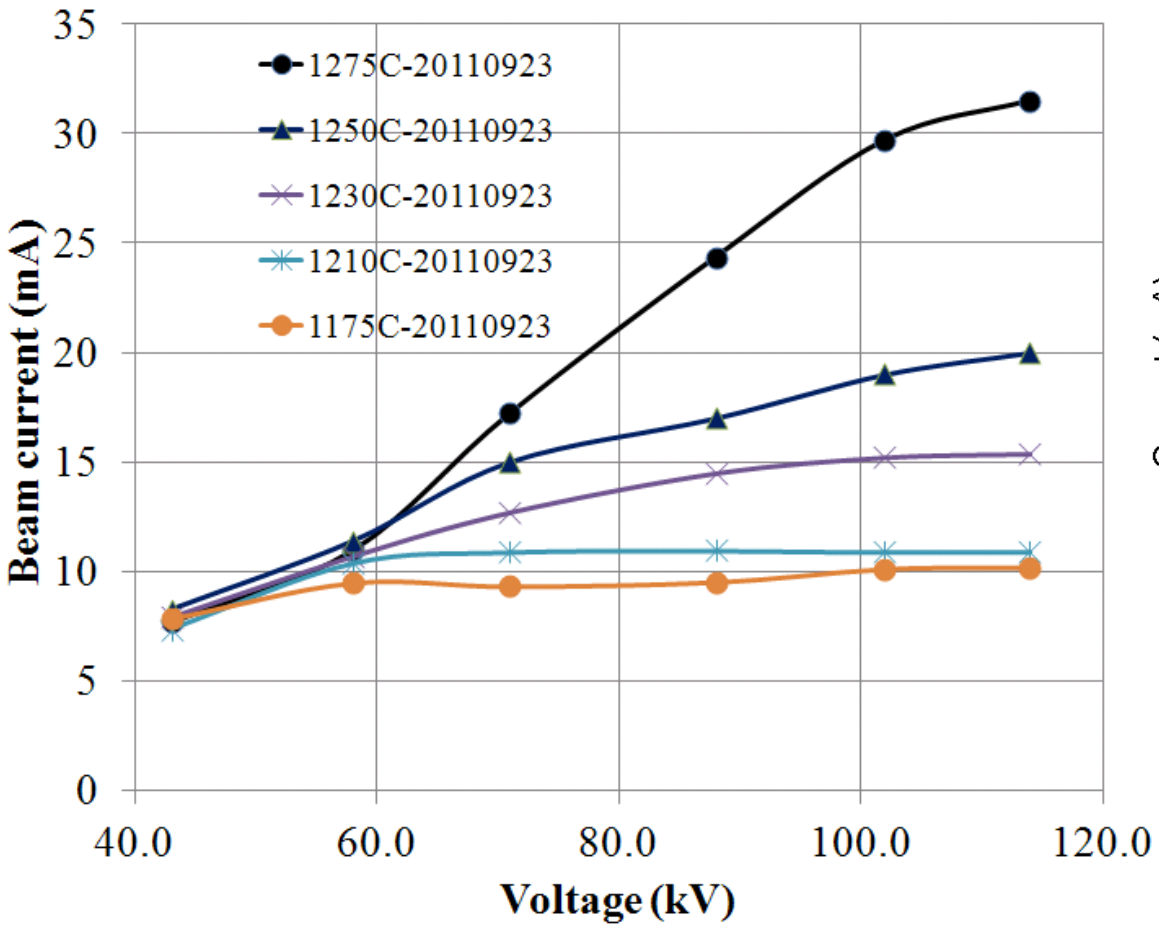
At first K^+ impurity was observed.

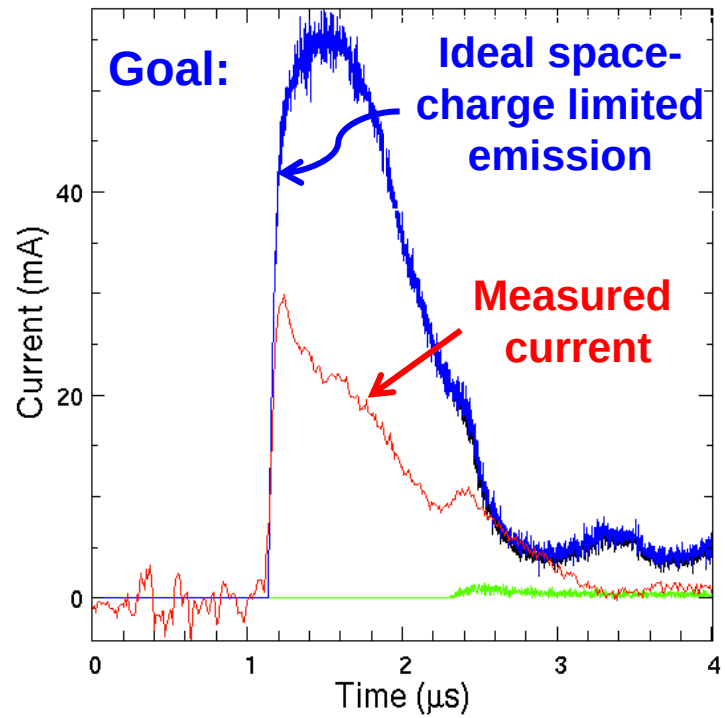
After ≈18 hours of conditioning (including ramp up temperature), Li^+ became dominant.



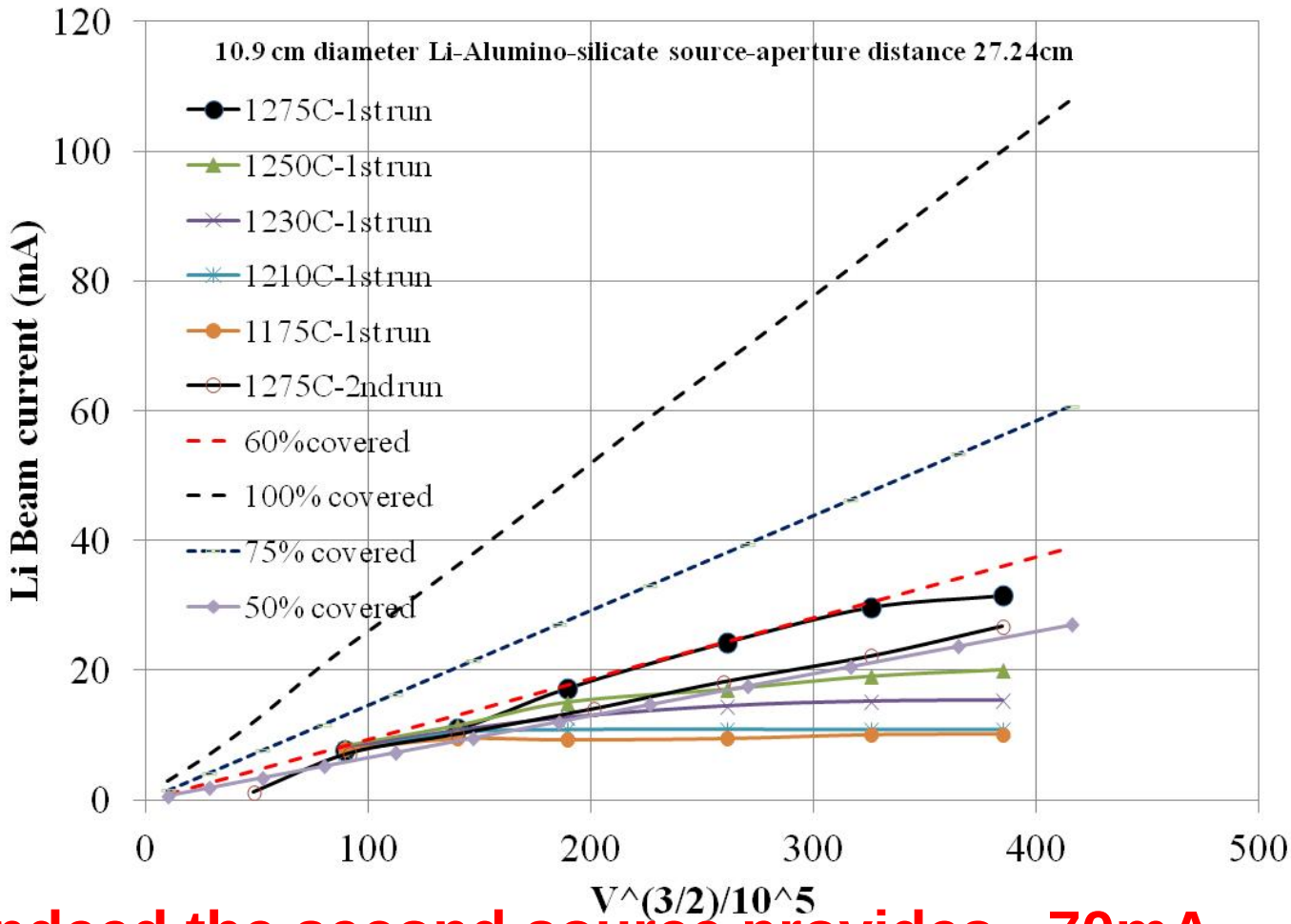


Beam current measured from a 10.9 cm source while varying temperature and voltage



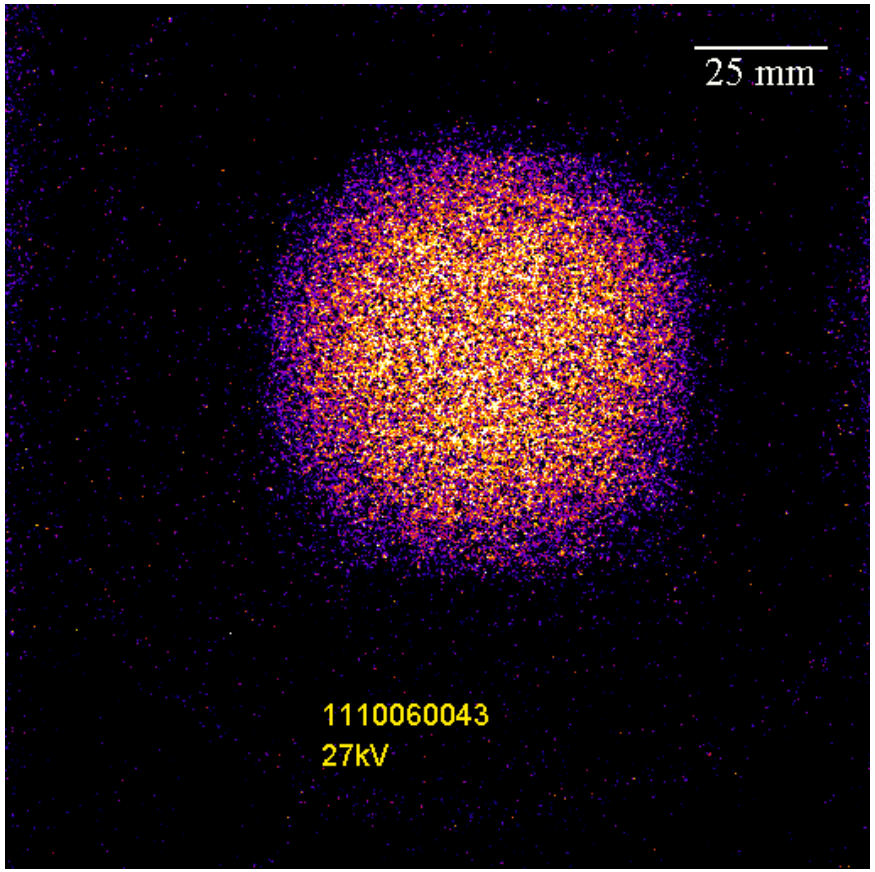


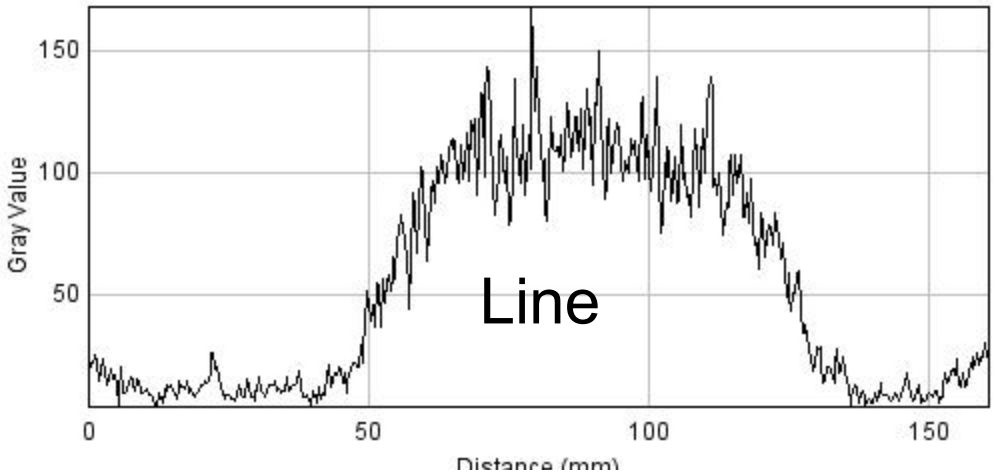
Performance of the first source corresponds to 60% surface coverage

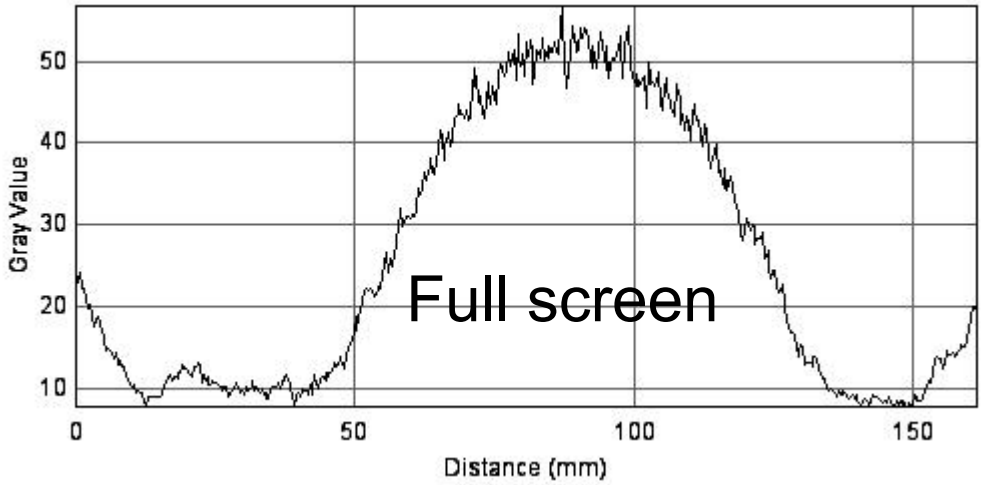


Indeed the second source provides ~70mA with better coverage of coating

A uniform beam profile when 10.9 cm source operated at 1250°C for V_{inj} =27 kV







Summary

- A typical 0.6 cm diameter lithium alumino-silicate source provides J >1mA/cm^2 in the space charged limited mode of operation. But, J is less for a 10.9 cm source at present, probably due to a surface covering issue. We hope to improve this in the coming days.

- 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.

- Beam emittance of the 10.9 cm diameter source is being measured as we progress NDCX-II commissioning. However, more ion source work is needed to improve the large source performance.

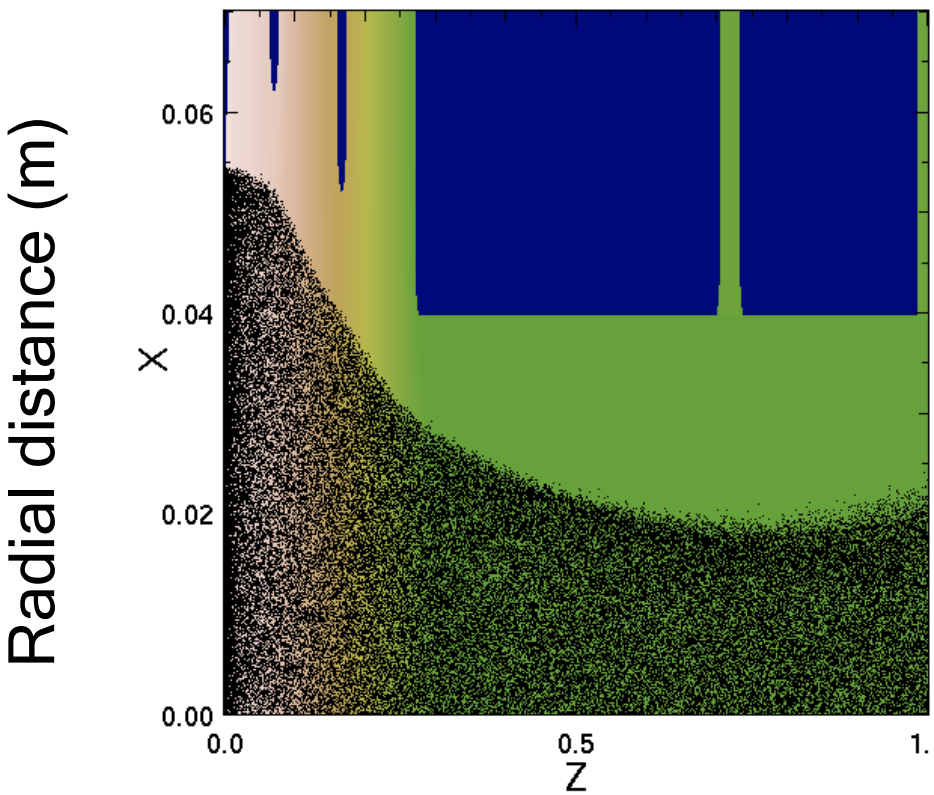
Backup

WARP simulation guided for beam profiles and geometrical parameters of diagnostics

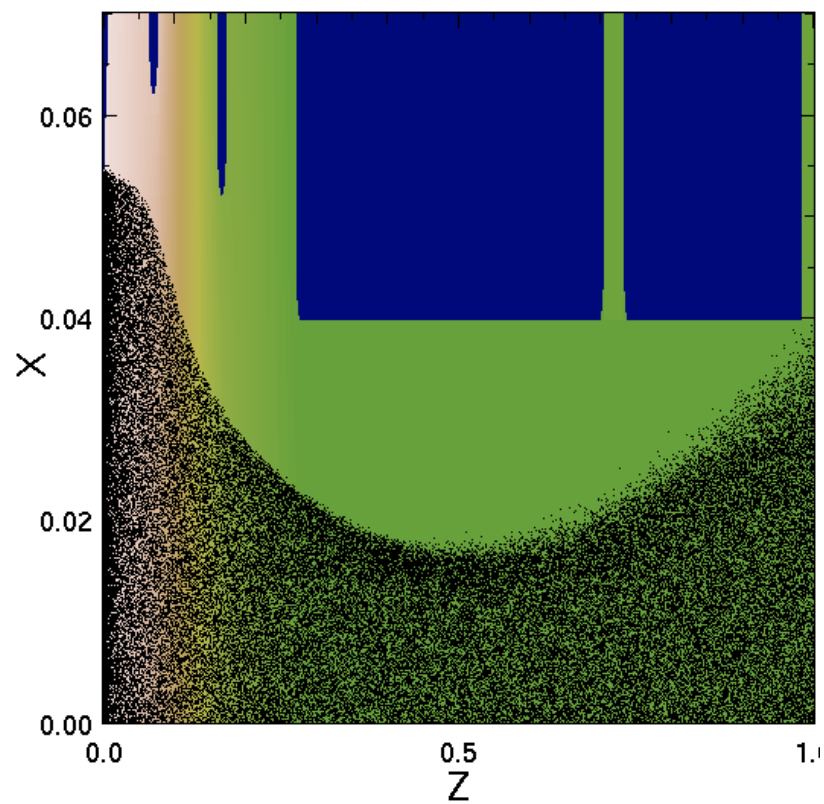
(solenoid off cases)

J= 0.5mA/cm^2
≈4.8 cm diameter at the end

J= 1mA/cm^2
≈7.36 cm diameter at the end

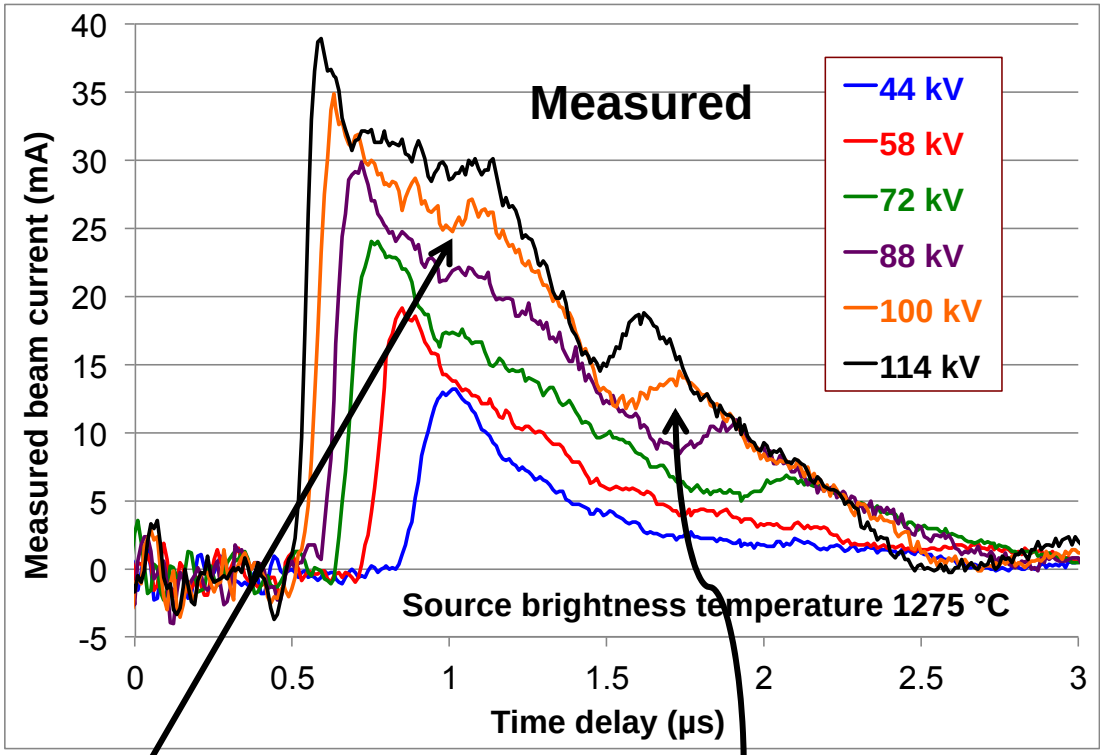


Z-Distance (m)



Z-Distance (m)

WARP modeling helps understanding of experimental waveforms

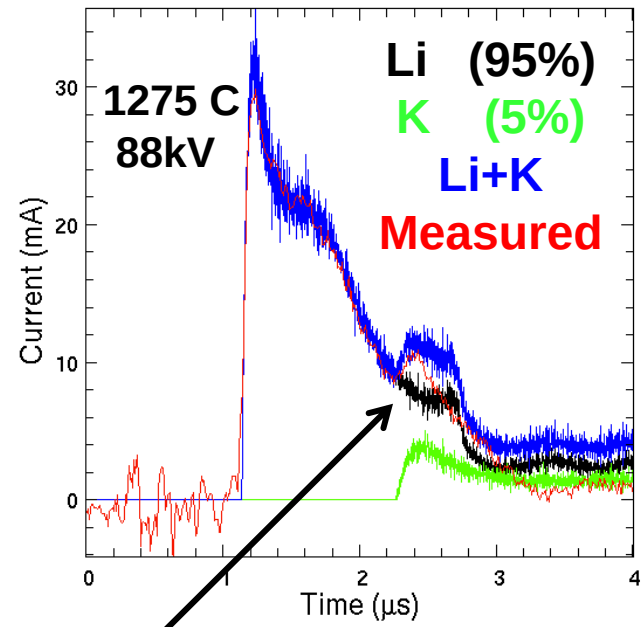


Li^+

Time-delayed impurity
(K^+ , deduced from time-of-flight)

WARP modeling of emission limited extraction including empirical mixture of Li+ and K+

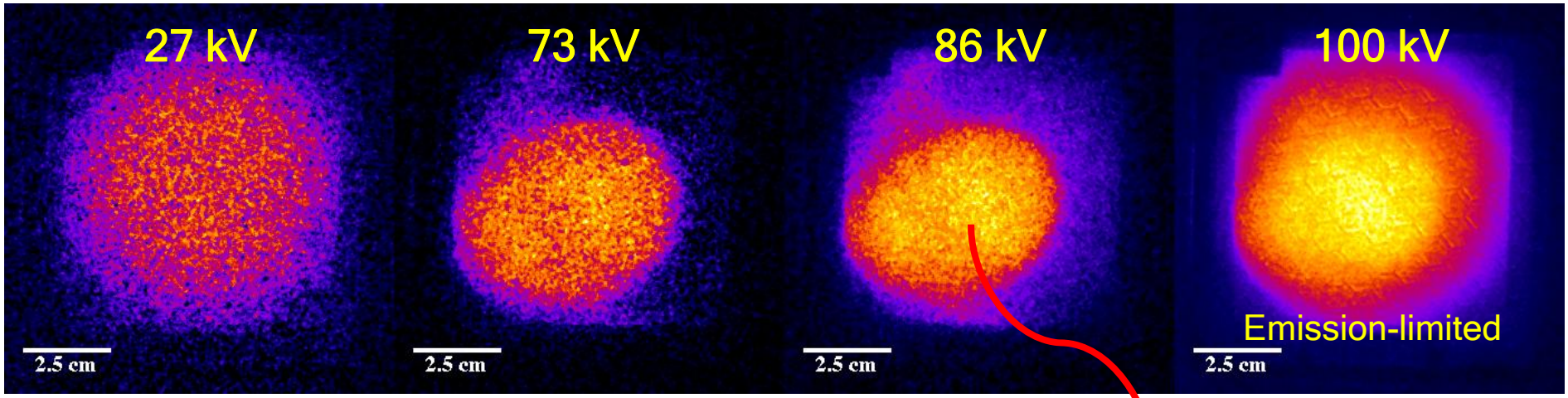
Measured + WARP



Experimentally, the impurity K+ emission is observed to decrease with conditioning time.

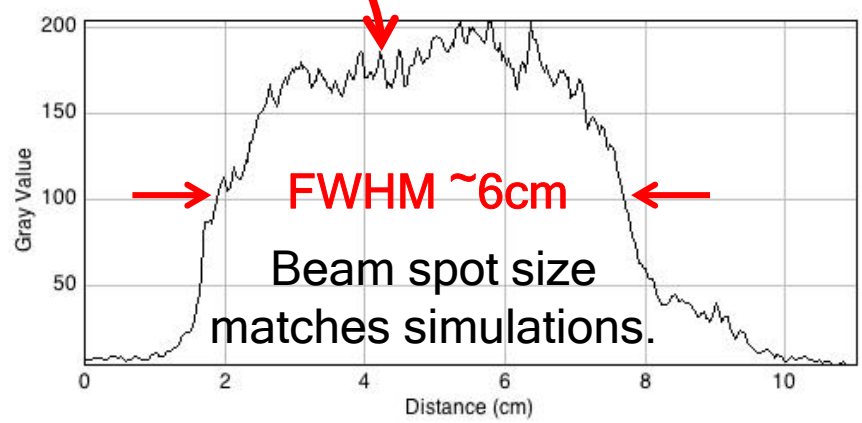
Beam images show evolution to emission-limited flow

Scintillator images obtained at downstream diagnostic station.
500ns camera gate captures most of the Li beam only.

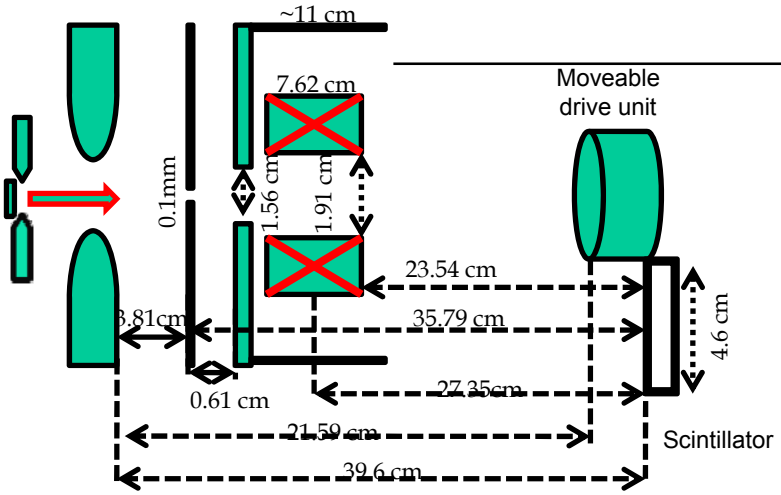


Ion source brightness temperature at 1250 °C

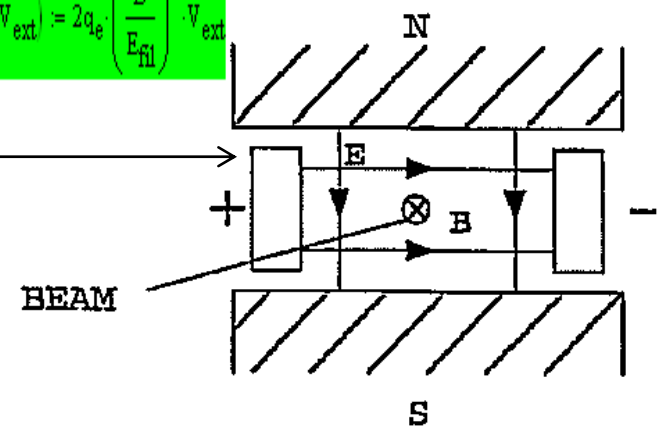
Beam spatial uniformity confirms uniform emission from source.

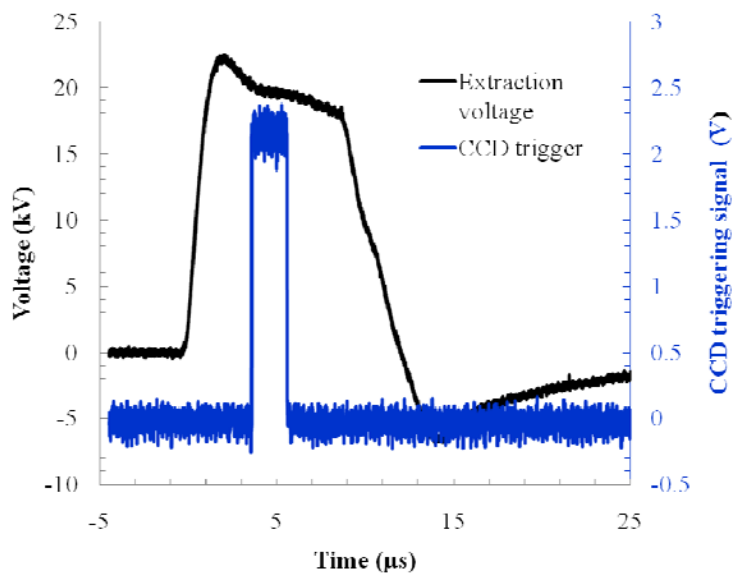


Beam emission element was identified using an EXB filter

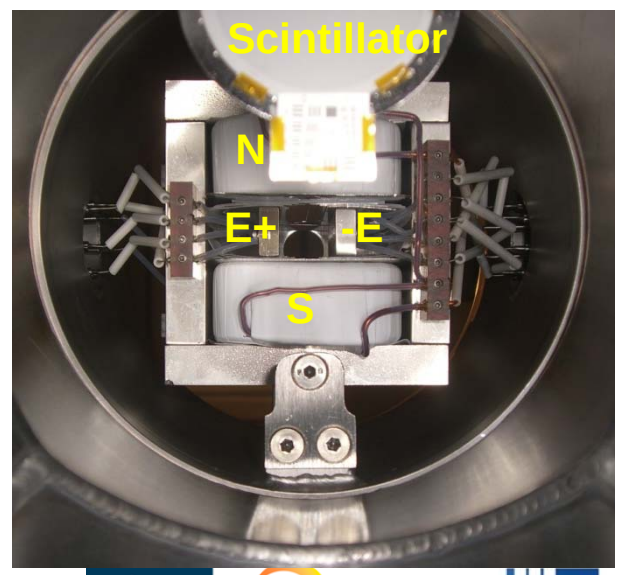


$$M_{uknown}(B, E_{fil}, V_{ext}) := 2q_e \cdot \left(\frac{B}{E_{fil}}\right)^2 \cdot V_{ext}$$





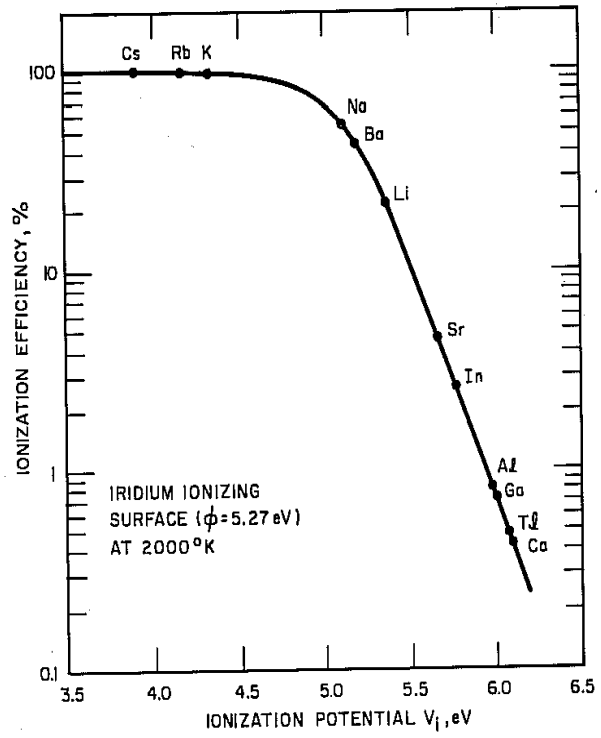
EXB filter



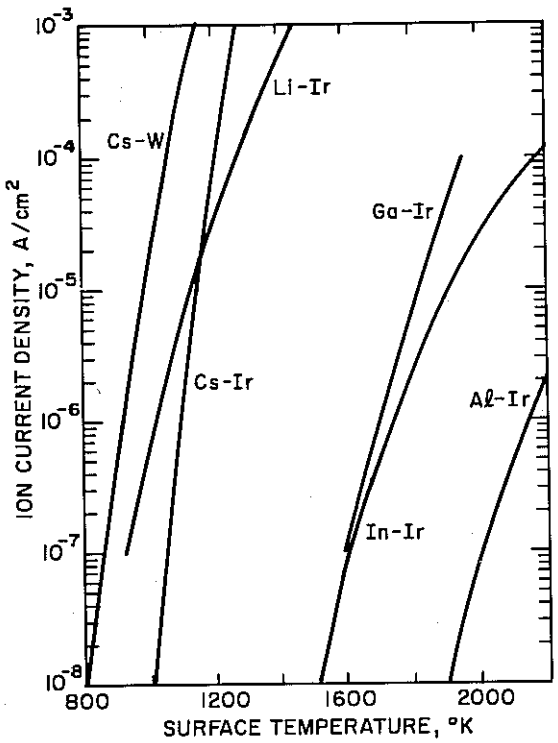
Ionization efficiency is ~100% for Potassium, and this efficiency is ~20% for Lithium (dope source?)

(R. G. Wilson, and G. R. Brewer, *Ion beams with application to ion implantation*, Willy, 1973)

Parameters	Values	Unit
Z (atomic number)	3	
M (mass)	6.9395	amu
Atomic or metalic radius	1.55	Å
Ion radius	1+0.70	Å
Covalent radius	1.22	Å
Ionization potential	5.38	eV
Work function or electron affinity	2.5, 2.8	eV
Atomic surface density	1.68×10^{15}	$1/cm^3$
Melting point temperture	180.5, 186	°C
Ionization Efficiency	20	%



Surface-ionization efficiency for various elements on iridium (calculated)



Ion current density versus ionizer temperature for surface ionization of several ion-substrate system (from experimental data)