Li^+ alumino-silicate Ion Source development for NDCX-II

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HIFS-VNL collaboration
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Outline

- Source requirements and design
- Challenges for the production of a high current & high-quality Li^+ beam
- Fabrication of the alumino-silicate ion source and beam extraction
- Li^+ beam current density
- Emission life span

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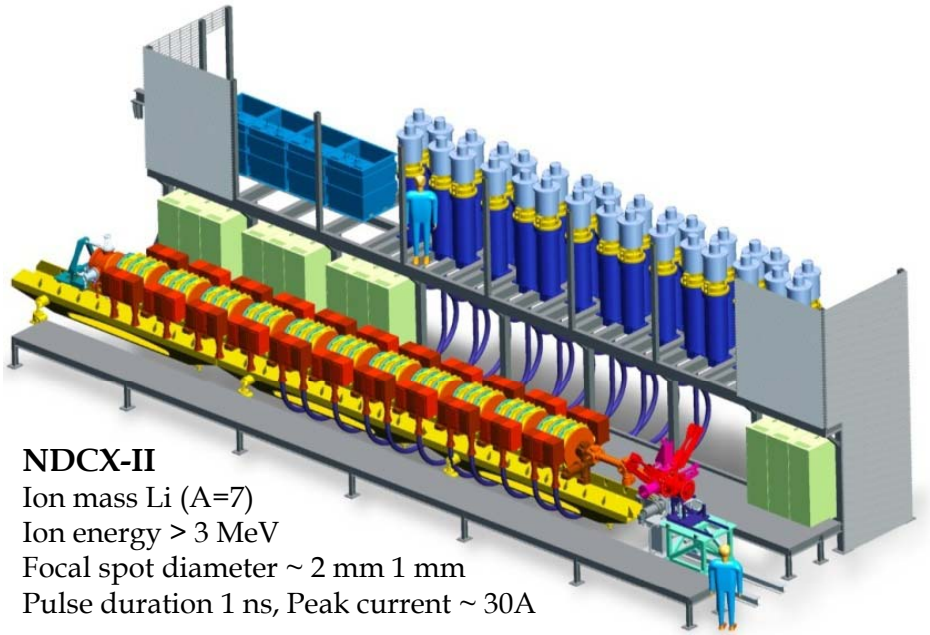
Li^+ alumino-silicate ion source is for NDCX-II towards warm dense matter experiments



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

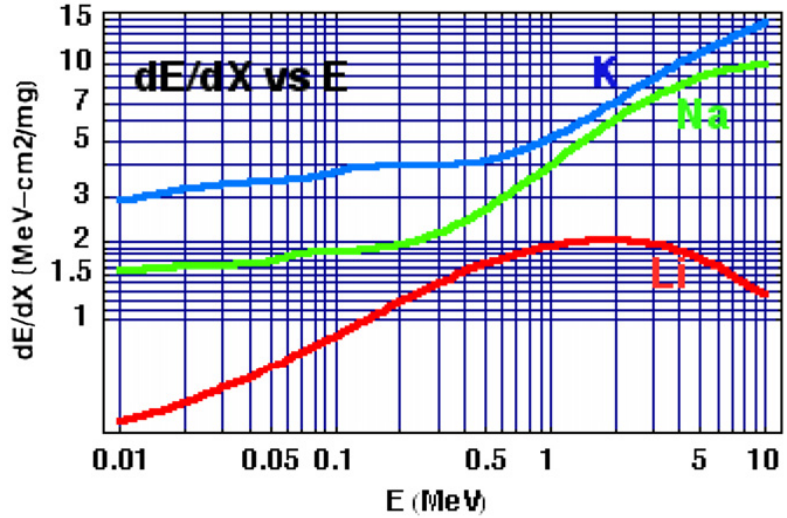


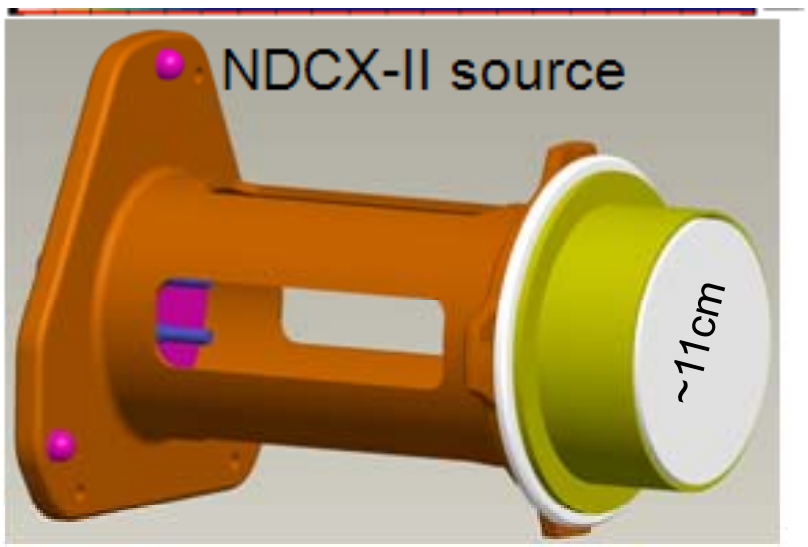
Fig. Energy loss rate (dE/dX) as a function of ion energy in solid Al (data from the SRIM code, J.J. Barnard et al, NIMA A 577 (2007) 275).

- NDCX-II goals is to uniformly heat targets to electron-volt temperatures for the study of warm dense matter.
- 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 on a thin target.
- Lower mass ions, such as lithium, have a peak dE/dx at a lower kinetic energy.

See Frank Bieniosek, Joe Kwan, John Barnard, W.M. Sharp, Alex Friedman , D. P. Grote's talks in this conference

NDCX -II source requirements and design

- Li^+ beam, final K.E. 2 MeV, charge 50 nC
- Pulse length 500 ns.
- Beam current ~100 mA



Based on our observations to date, we have found that

- At T≈1275° C,
- Space charge limited Li^+ $J \geq 1$ mA/cm^2, lifetime ≈50 hours, enabling approximately one week of running on NDCX-II.
- In order to obtain 100 mA at the same current density, the required source diameter 11 cm, and heater power ≈3kW.

Space-charge limited emission

The space charge limit effectively smoothes out spatial variations in emission.

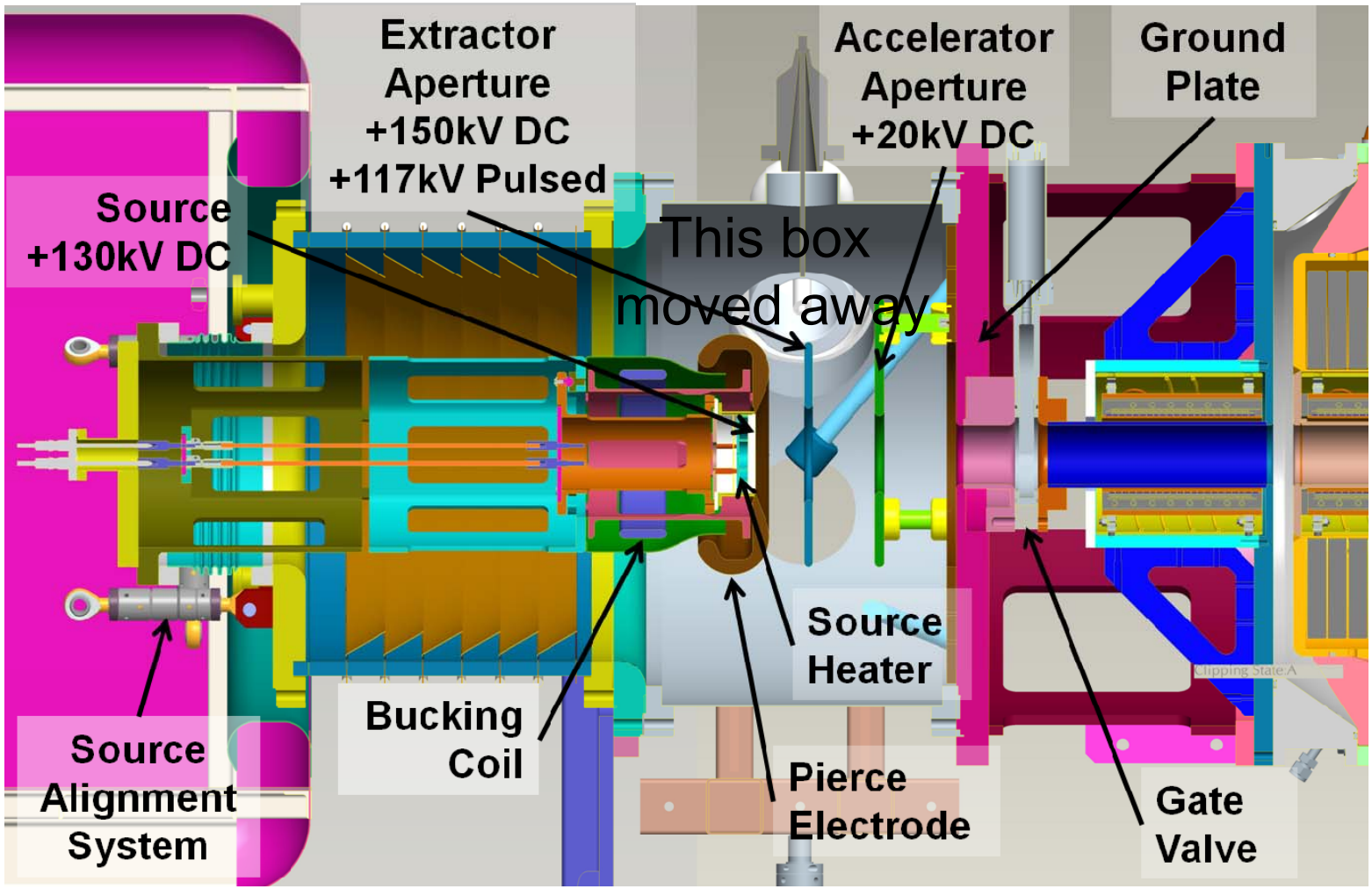
- Low field region, space charge limited current density is defined by Childs-Langmuir law as:

$$J(\chi, V, d) = \chi \frac{V^{3/2}}{d^2}, \qquad \chi(q,m) = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m}}$$

- In general, low field region space-charge limited Child Langmuir current is:

$$I_E = PV^{3/2}, \qquad P = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m}}\frac{(\pi r^2)}{d^2}$$

Sketch of NDCX-II Injector Components



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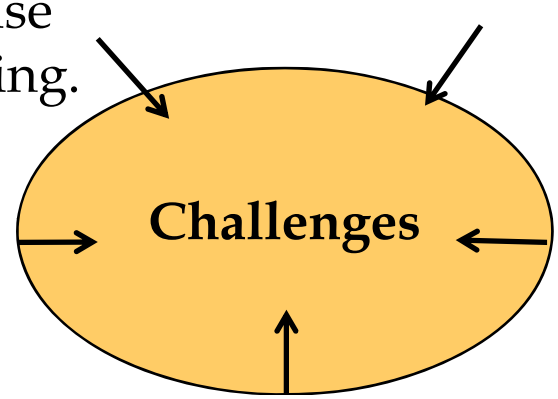
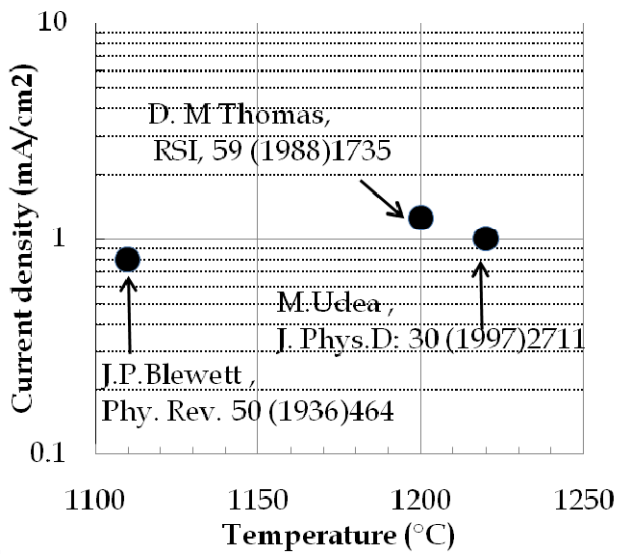
Challenges for the production of a high current & high-quality Li^+ beam

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

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

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





- Extreme anisotropy in thermal expansion coefficients. (a direction: $+8.2\times10^{-6}$ per °C. c-direction: -17.6×10^{-6} per °C)

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

- Sufficient references on Li^+ SCL current density, and charge accumulation data are not available.

$$Q = J(\pi r^2)\tau_{pulse}$$

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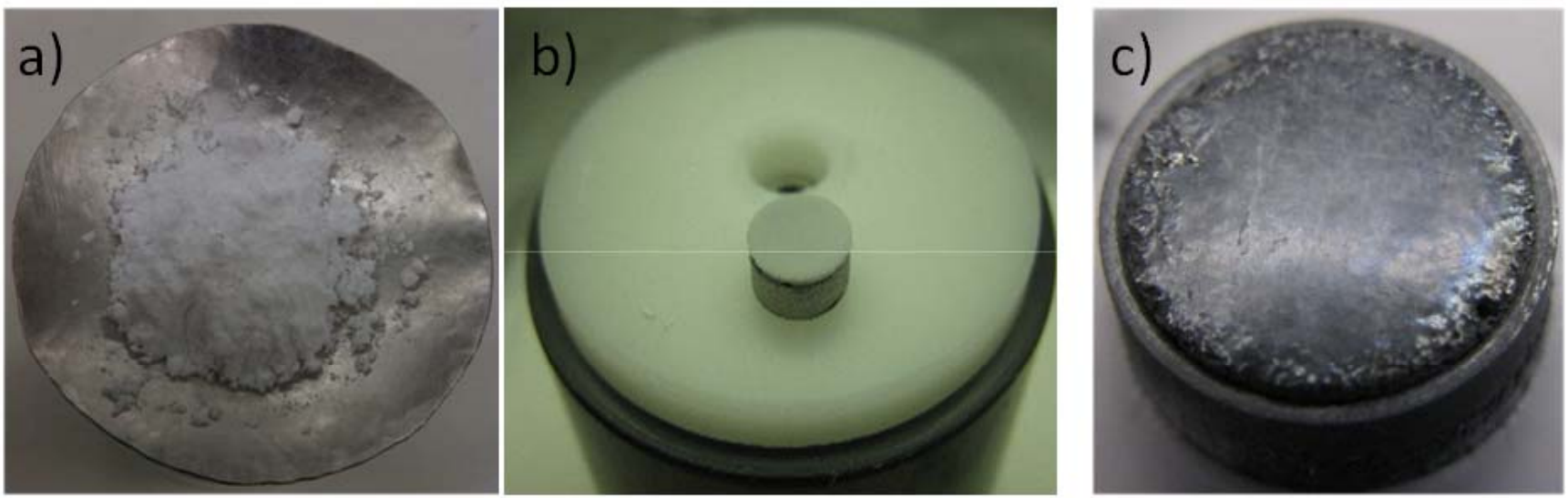
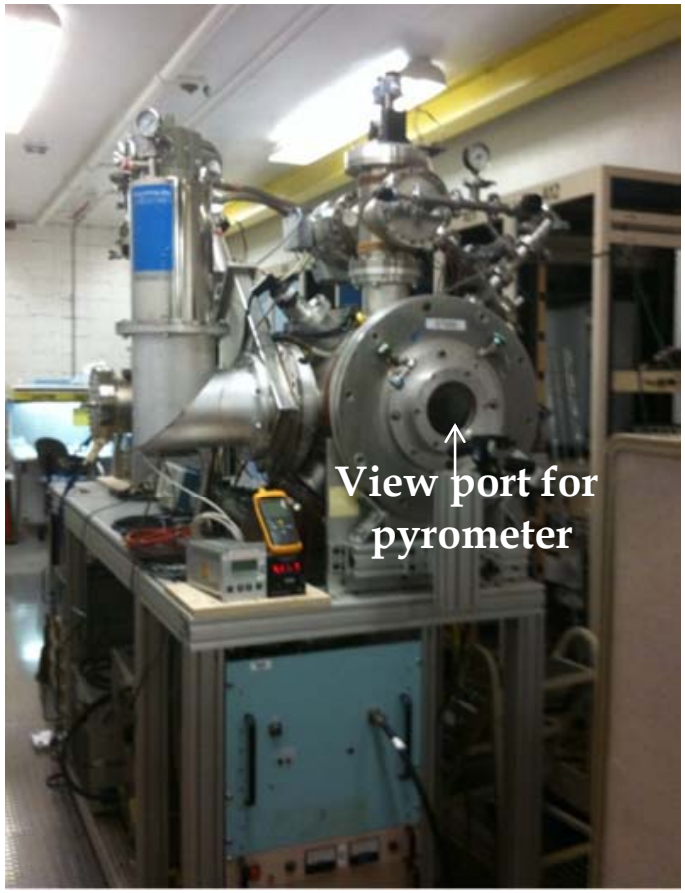
Fabrication of alumino-silicate ion source (0.64 cm diameter in this case)

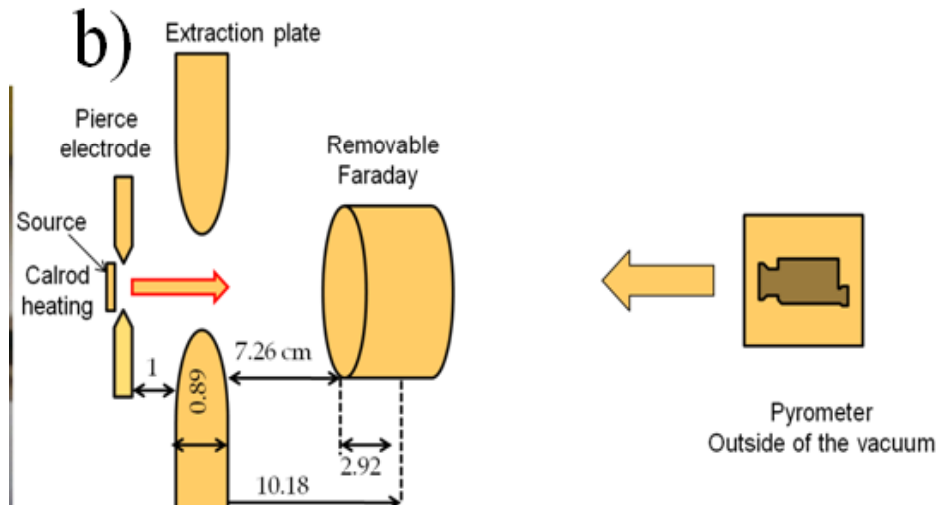
$$Li_2CO_3 + Al_2O_3 + 2(SiO_2) \Rightarrow Li_2O\text{-}Al_2O_3 - (SiO_2)_2 + CO_2 \Uparrow$$

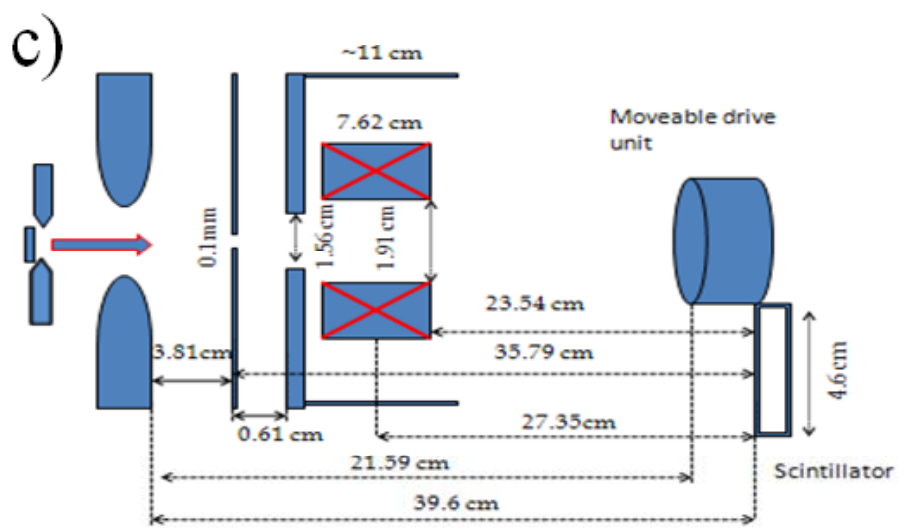


(a): A sample of reacted Li β-eucryptite (Li_2O-Al_2O_3-$2SiO_2$); (b) a coated tungsten button, and (c) a sintered Li β-eucryptite (Li_2O-Al_2O_3-$2SiO_2$) source is ready to use for beam current extraction.

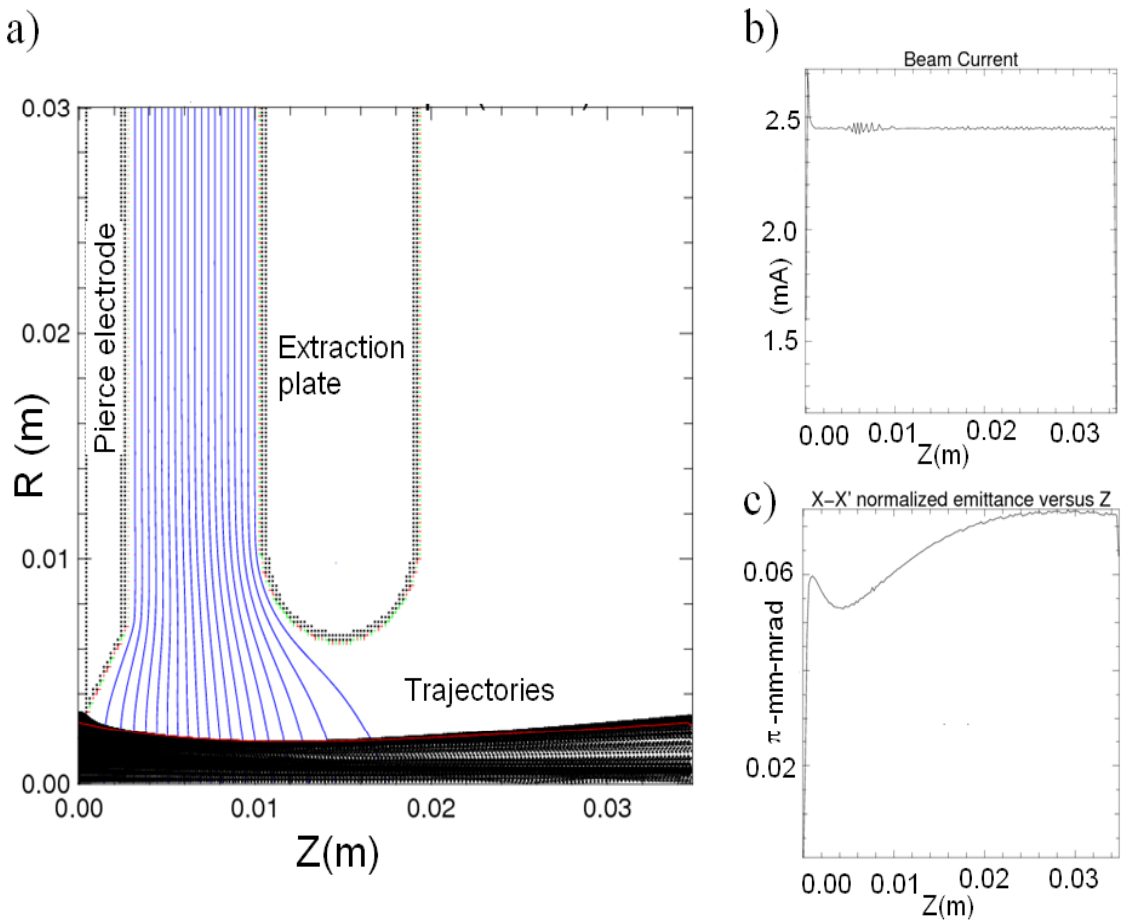
Setup of (a) small source test stand; (b) beam current and temperature measurements; and (c) ExB filter.





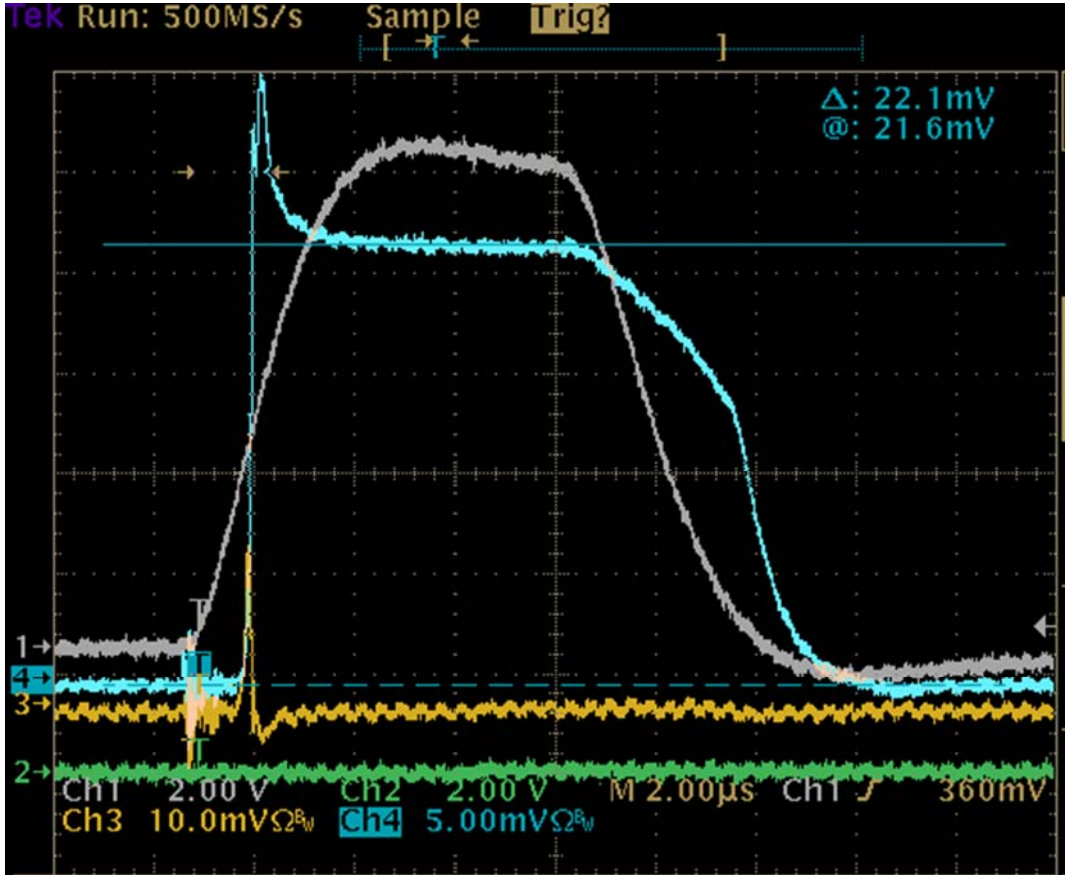


Simulation of a 0.64 cm diameter Lithium source emission using WARP code



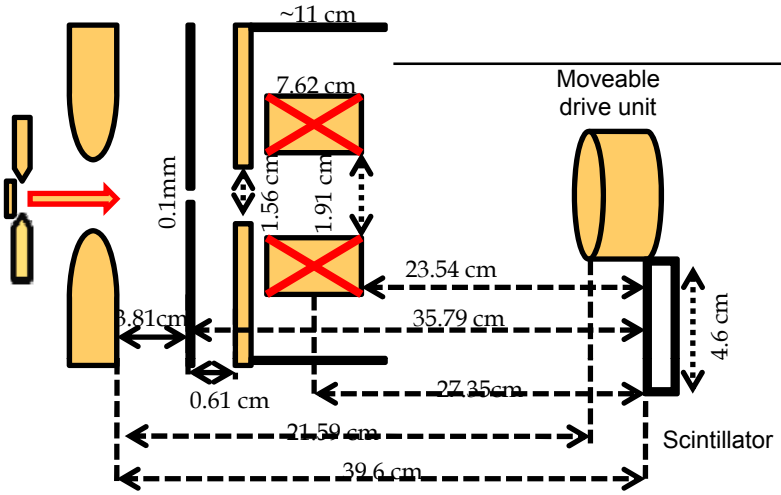
- Source diameter: 0.64 cm
- Pierce angle: 60° angle
- Distance between the Pierce electrode and the emitter surface: 0.4mm
  (a source of some nonlinear aberrations.)
- The extraction electrode aperture plate diameter: 1-cm
- Distance between the source surface and the mid-plane of the extraction electrode: 1.48 cm.
- A 10 kV extraction voltage (V) predicts a beam current, and current density of ~2.5 mA or ~7.9 mA/cm^2, respectively.
- Single particle transit time, $\tau=3d/\sqrt{(2qV/m)}$, inside the injector for Li of mass (m) 7 amu is 85 ns,

Typical beam extraction voltage and current waveforms

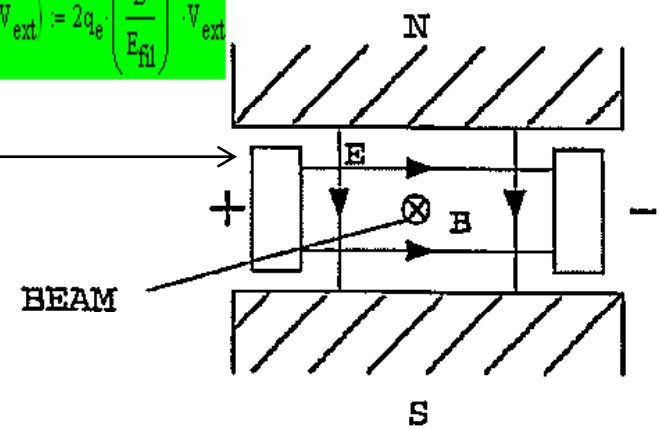


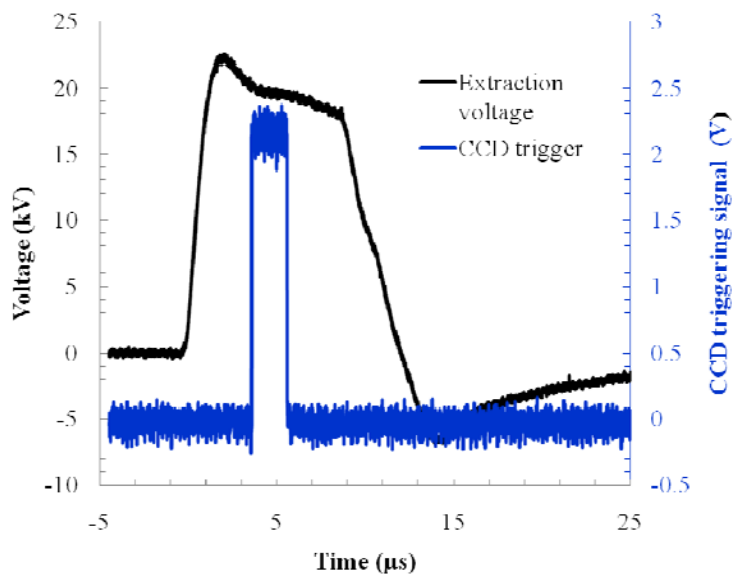
A 5-6µs beam extraction voltage waveform (channel 1) and beam current waveform (channel 4) on an oscilloscope when the source surface temperature was 1260ºC-1275°C. Beam current was registered by the Faraday cup collector (+300V) with a 50Ω resistor in series to ground. The signal corresponded to a current density of 1.5 mA/cm^2.

Beam emission element was identified using an EXB filter

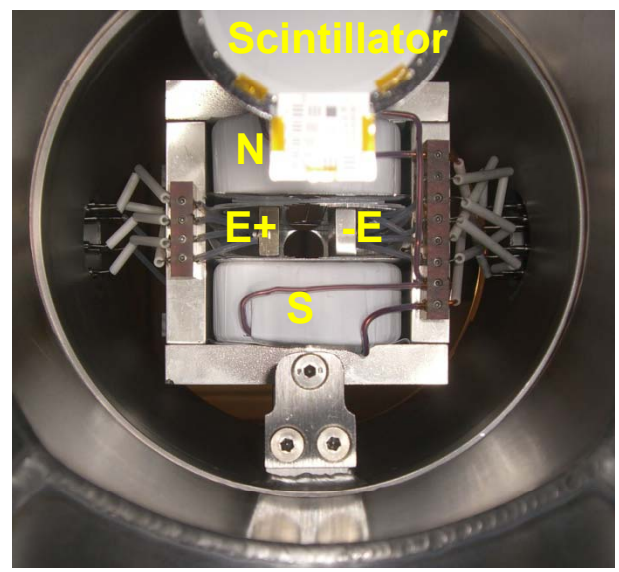


$$M_{uknown}(B, E_{fil}, V_{ext}) := 2q_e \cdot \left(\frac{B}{E_{fil}}\right)^2 \cdot V_{ext}$$

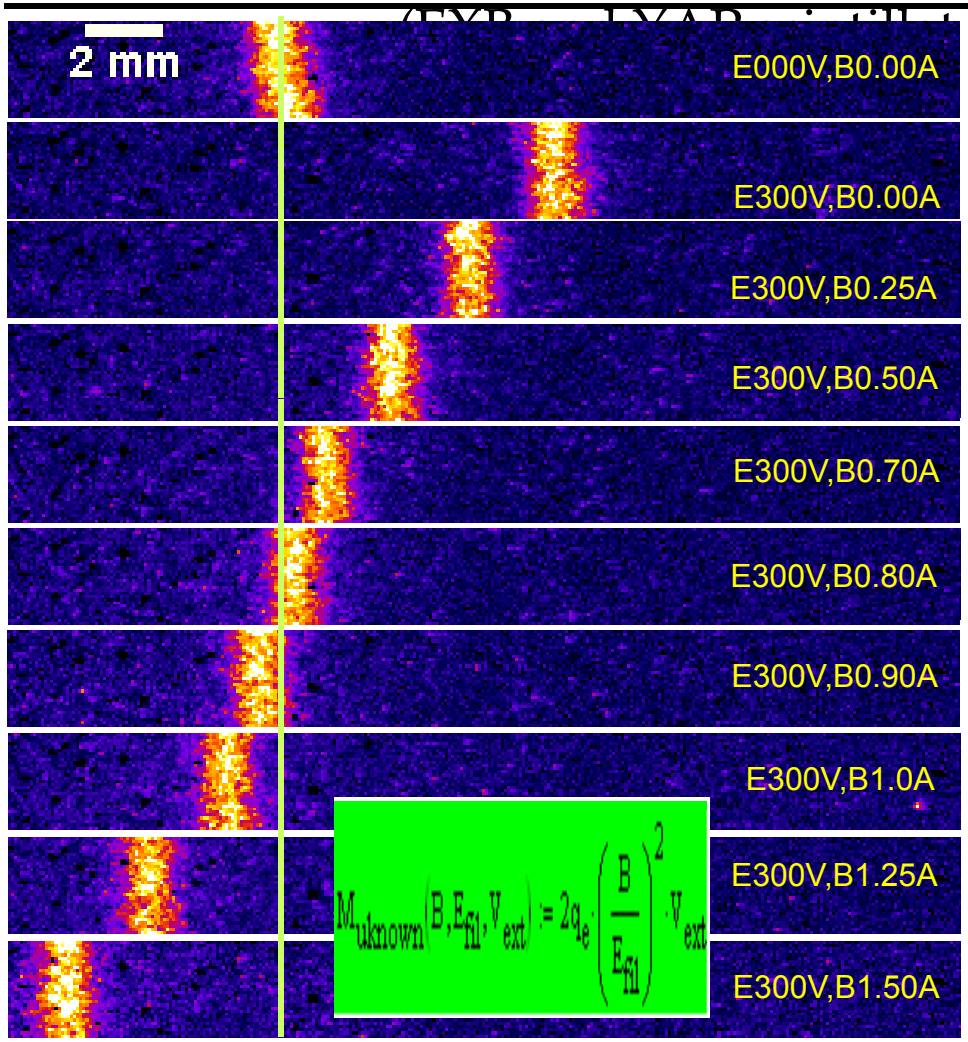




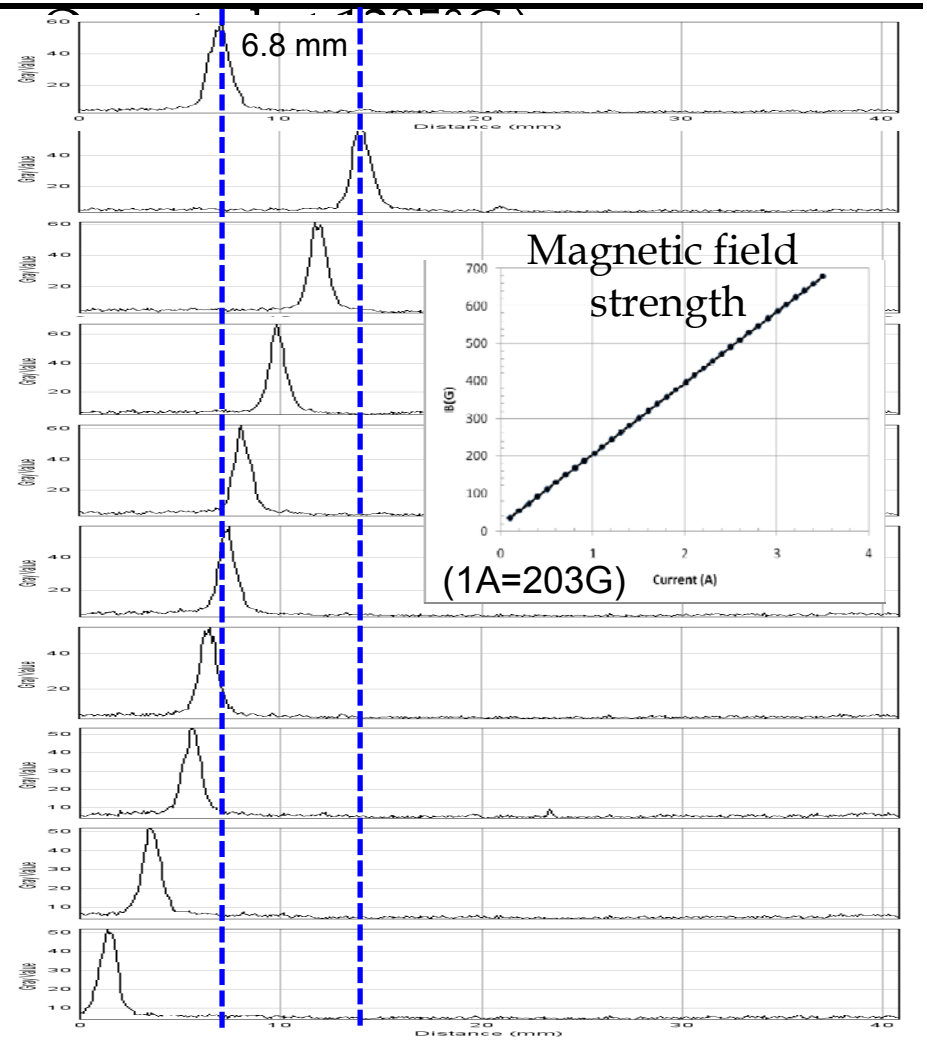
EXB filter



Lithium of mass 7 amu was identified (E field constant)



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



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

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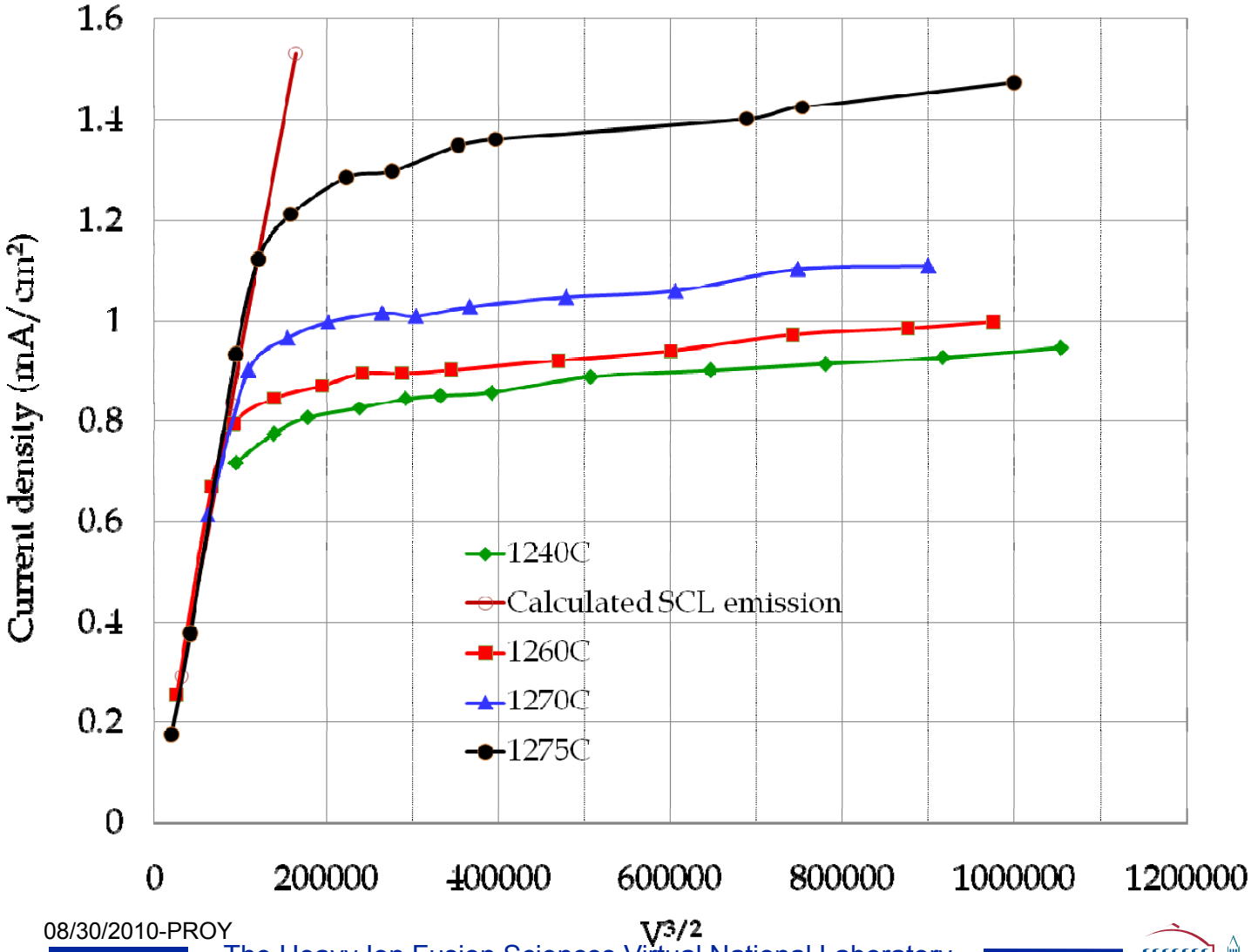
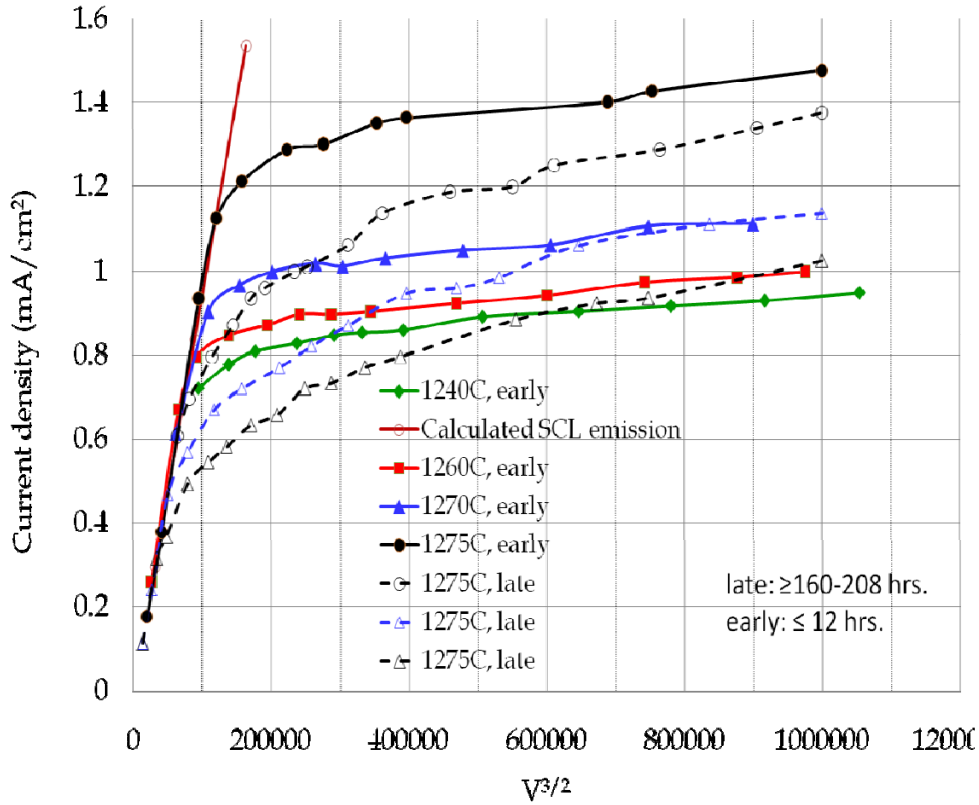
- **Li^+ beam current density**
- Emission life span

1275°C is a adequate temperature to have Li^+ current density of ≥1 mA/cm² in the space-charge limited mode

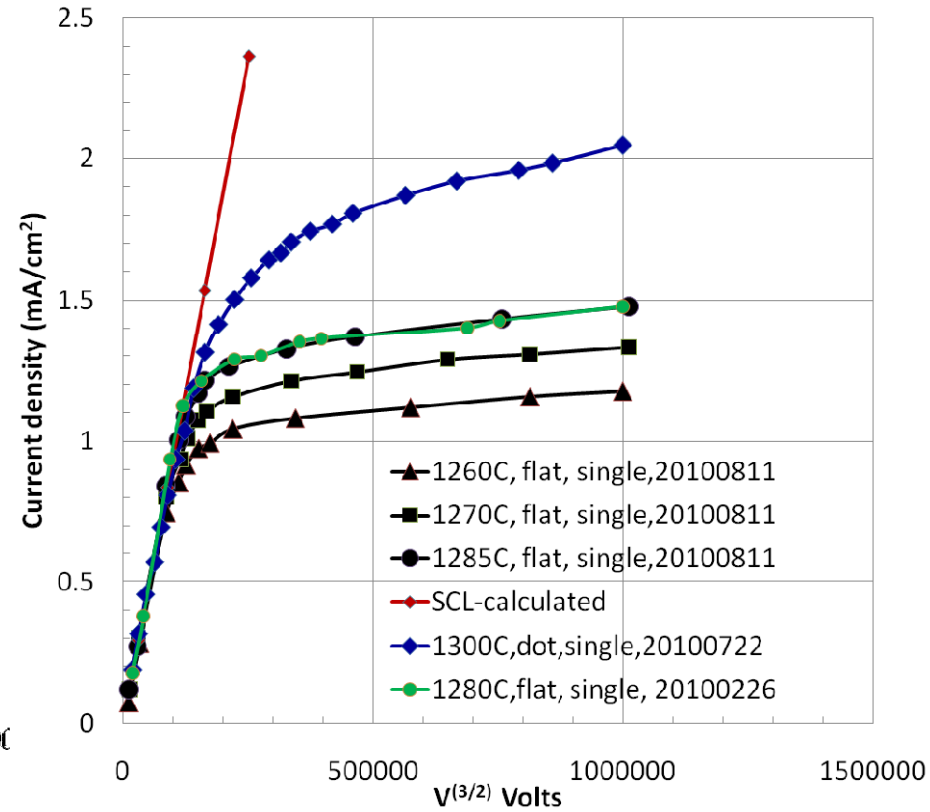


- Source sintered in a partial pressure of Ar+ 4% H_2 furnace.
- Beam duration:4- 5μs.

Performance of beam emission from a Li^+ β-eucryptite alumino-silicate source



Beam current is reduced gradually after certain hours of operation at a high temperature.



Reproducibility of emission from fabricated Li^+ alumino-silicate sources is reliable.

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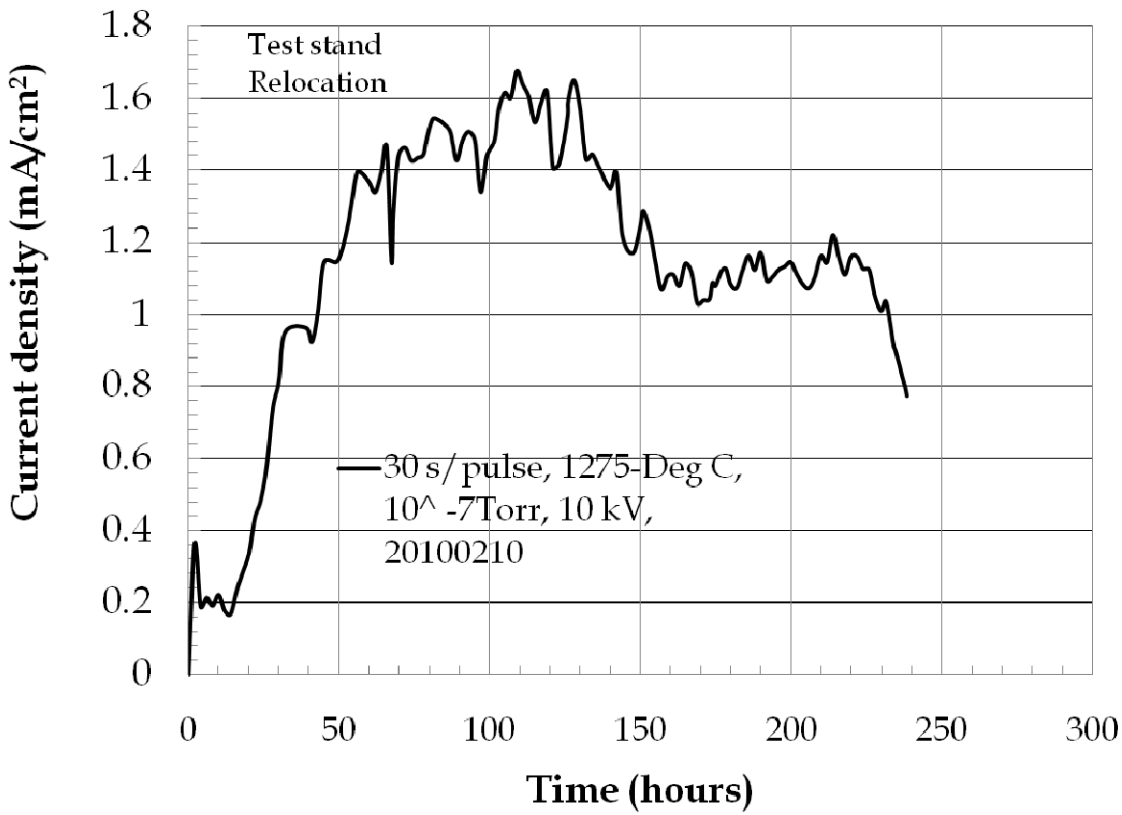
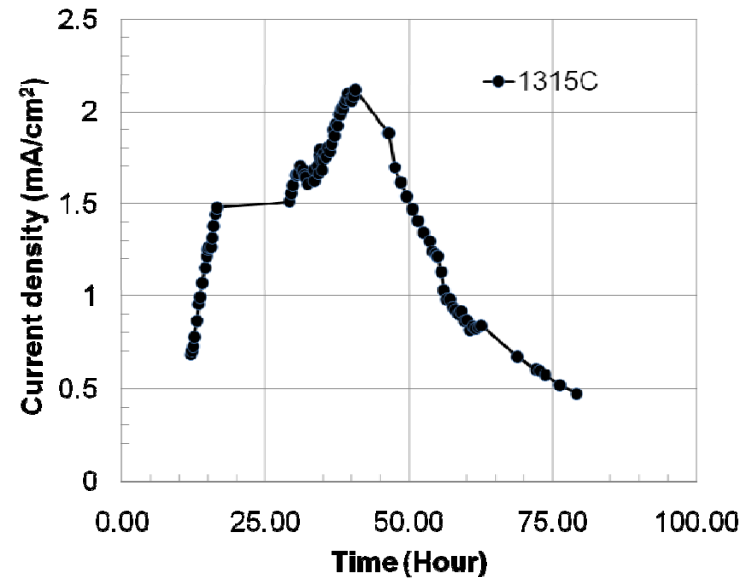
- **Emission life span**

Life time is >50 hours for ≥ 1 mA/cm^2 at temperature 1275°C (30s/shot, 4 μs pulse)



High temperature radiation to a source surface reduces emission life span



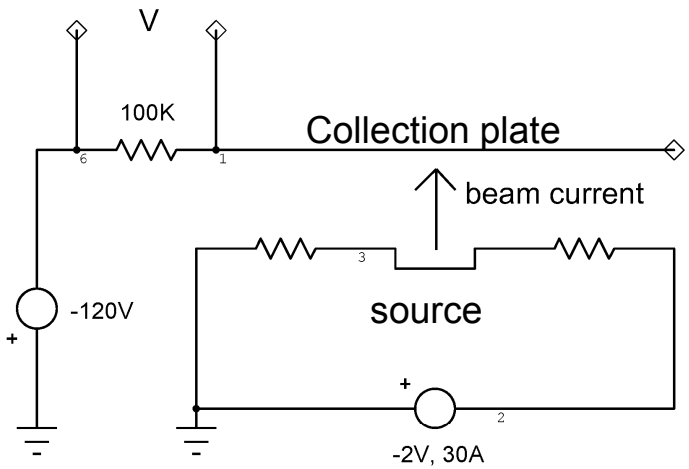
In general, source preparation and a life time test in a pulse mode beam extraction is a time constrained process. Basically it takes two weeks per source test.

An additional experiment was performed in a in-situ DC extraction test facility

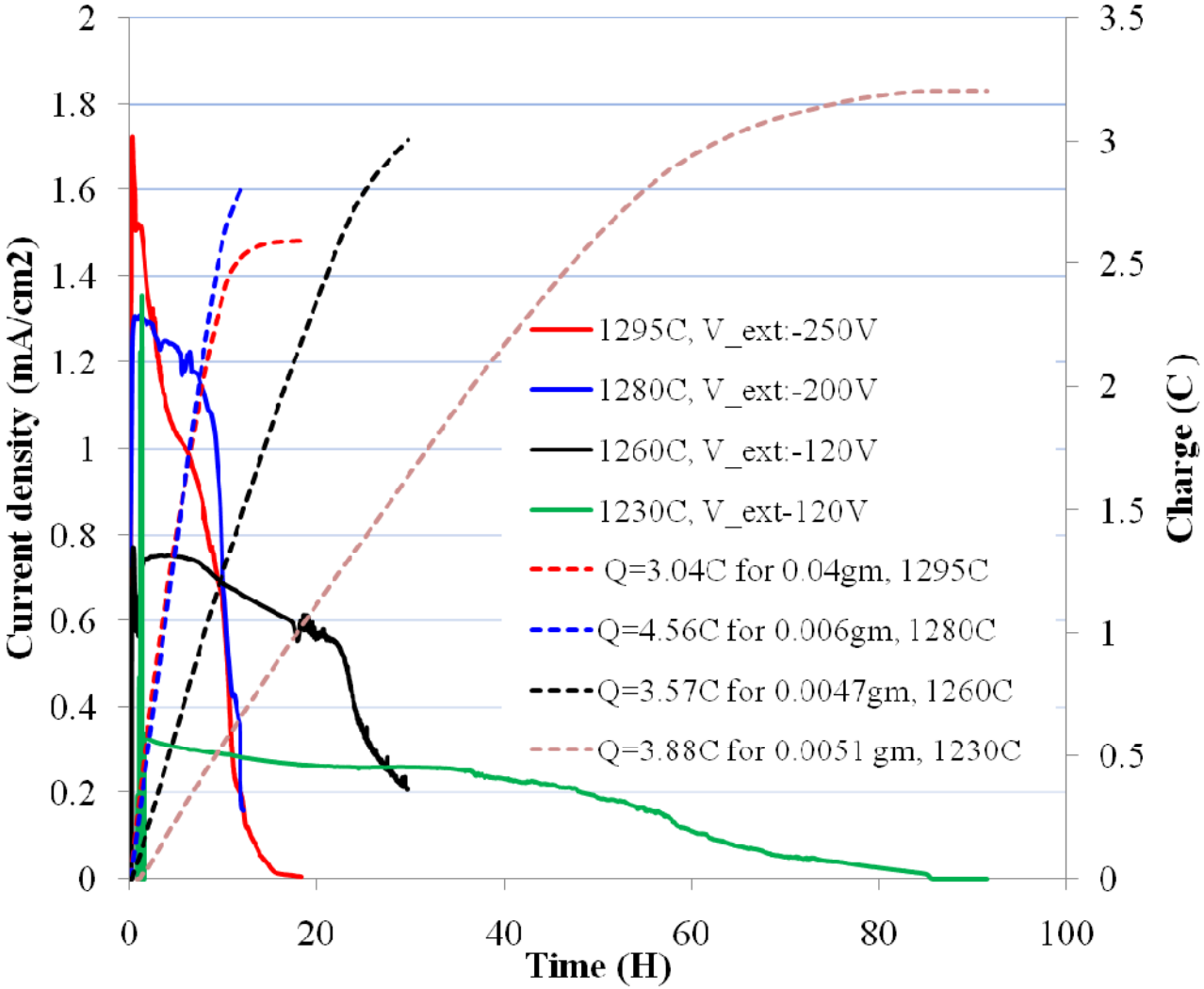
- A defined quantity of Li-alumino-silicate material is placed on to a ~1.8mm diameter dimple of a 0.5 cm width molybdenum filament.

- Source material was melted at 1400°C, and then cool down to source operating temperature.

- Extracted beam on a negative bias plate, located at 4 mm far from the emitting surface.



Time span with variation of temperature and integrated beam emission



It was observed that accumulation of charge is of ~75% for a dC mode extraction

Sample of charge calculation

Mass of Li alumino silicate $m1 := 0.0044 \cdot gm$

Weight of the Lithium $W_L := 5.56\%$

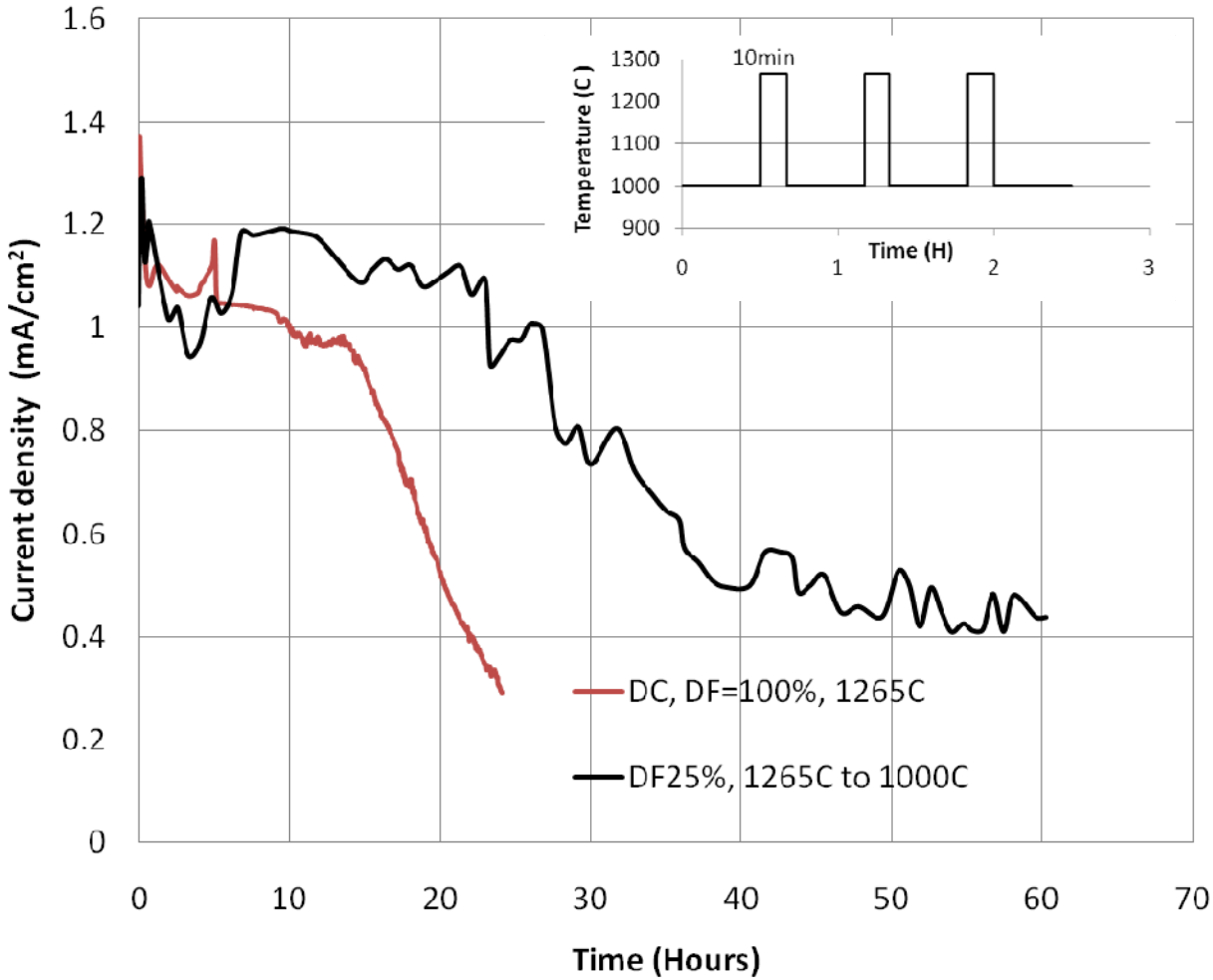
Mass of Lithium $m_7 := 7 \cdot \left(1.6726 \cdot 10^{-24}\right) \cdot gm$

1 Charge $q_e := 1.6 \cdot 10^{-19} \cdot coul$

Total charged contained $C_{Li} := \frac{m1 \cdot W_L}{m_7} \cdot q_e$

$C_{Li} = 3.343\,C$

Life span can be extended further by reducing temperature when beam is not extracted



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

Summary

- ≥1 mA/cm^2 space charge limited emission has been measured, repetitively. A temperature of ≥ 1275°C is required to obtain the required current density.

- Source Life time is ≥50 hours in a pulse mode, is satisfactory for project requirements, possible to improve by further R &D.

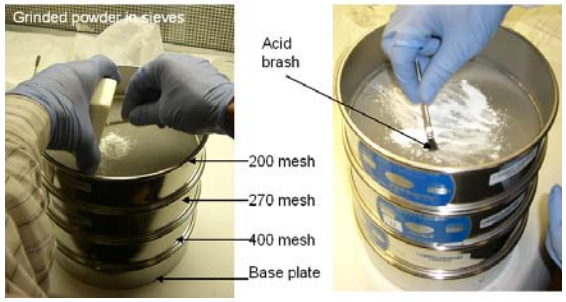
- We are in a stage to fabricate a larger diameter source, and in parallel we will be continuing R & D to lengthen the life time of a source.

BACK UP

Tighter tolerance in sintering the Li alumino-silicate to the substrate

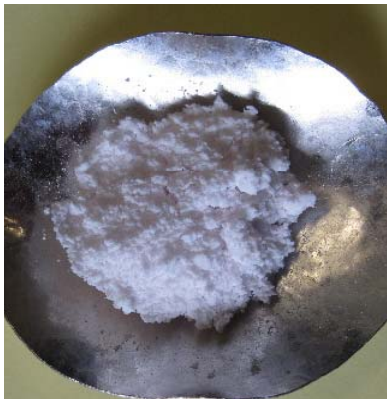
$$Li_2CO_3 + Al_2O_3 + 2(SiO_2) \Rightarrow Li_2O\text{-}Al_2O_3 - (SiO_2)_2 + CO_2 \Uparrow$$

Chemical preparation

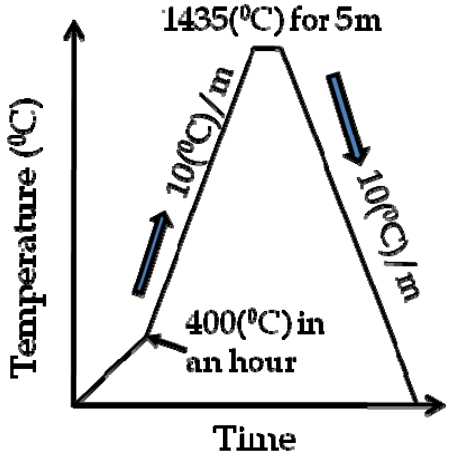


Coated and dried in a humidity control chamber

A prepared source sample.
Crystal structure somewhat similar to quartz at high temperature, with half the silicon atoms replaced by aluminum. (reflection of light shows brighter spots.)



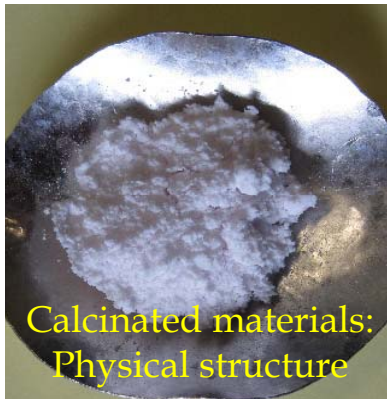
After calcination (800+1175)°C

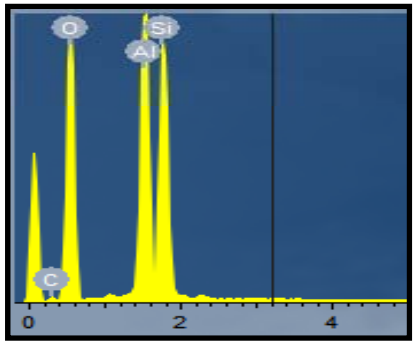


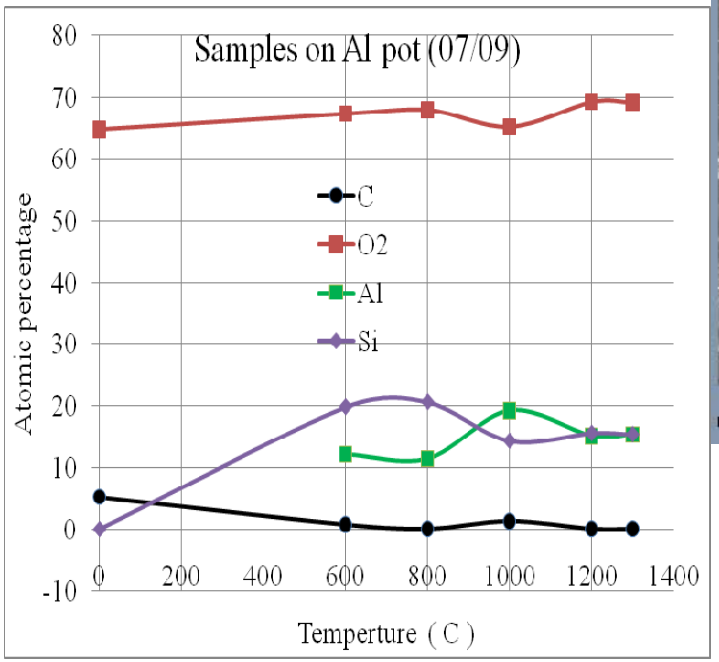
Li-β-eucryptite calcination temperature is critical to preparing carbon-free material

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

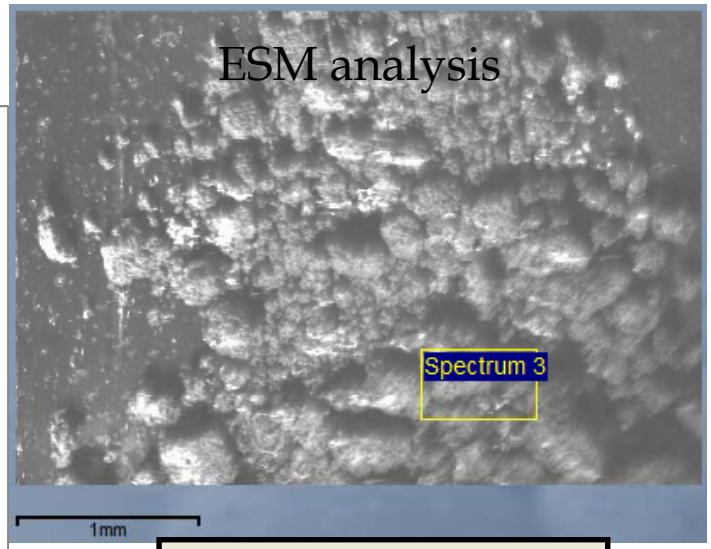
For purity, made in the laboratory using the isotopically pure ^{7}Li carbonate







Temperature study to have carbon free source materials



Summary results :

Element	Weight%	Atomic%
C	9.79 +/- 0.48	14.57
O	57.41 +/- 0.36	64.15
Al	15.60 +/- 0.14	10.34
Si	17.20 +/- 0.15	10.95
Totals	100.00	100.00

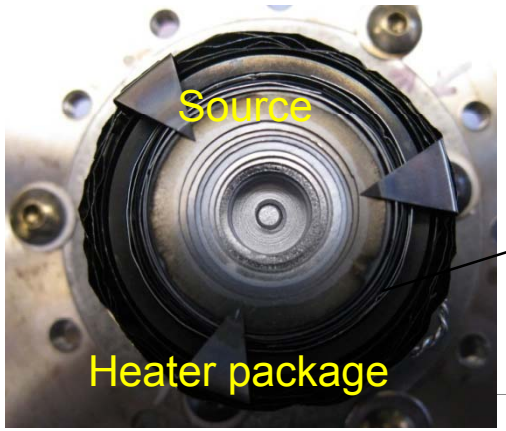
In space charge limited mode, the zero-field emission is typically characterized by the Richardson-Dushman equation

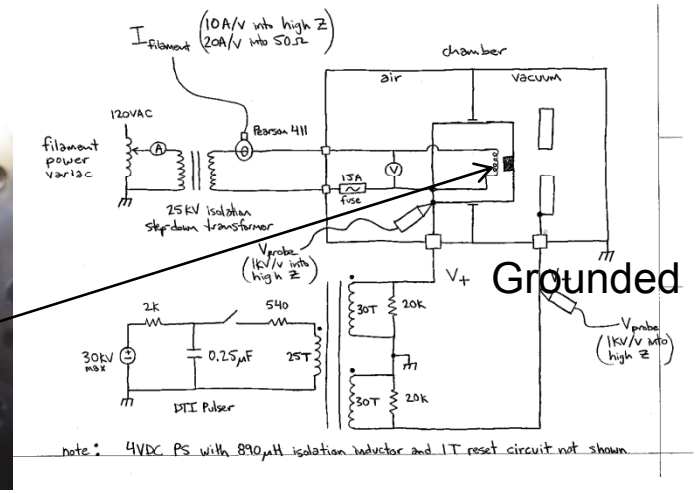
$$J_0 = AT^2 e^{-\frac{\phi_w}{k_B T}}$$

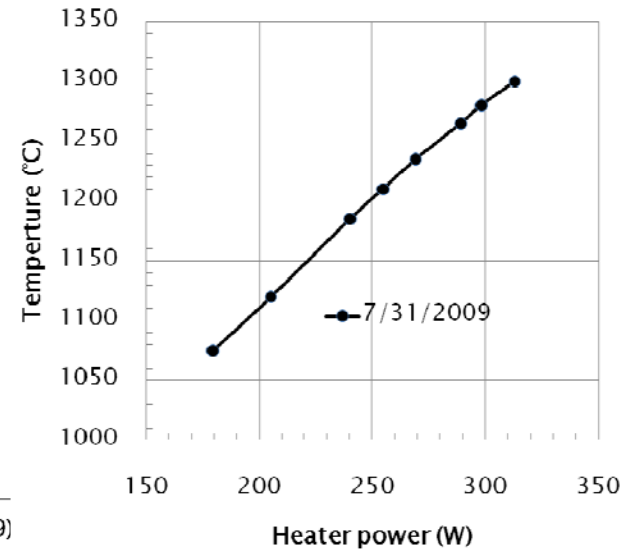
Although the alumino-silicate material is known as an ion conductor, it is not an electron conductor and therefore the work function of alumino-silicate surface is not a well-defined number.

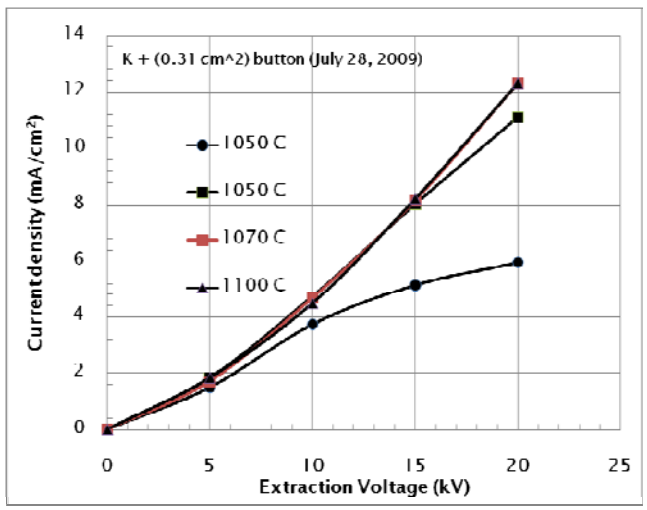
The Richardson-Dushman law can only be used in an empirical way to describe emission of an alumino-silicate ion sources for work function variation.

Ion gun tester is verified by measuring beam current of a K^+ alumino-silicate

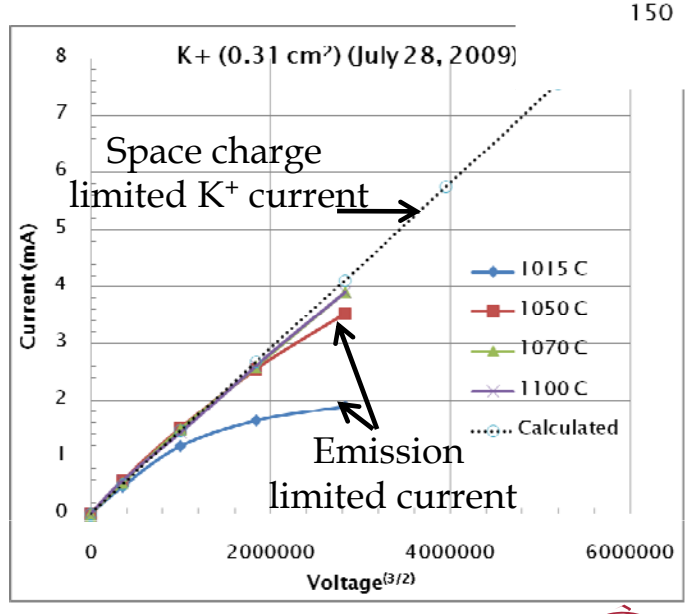








K^+ current density



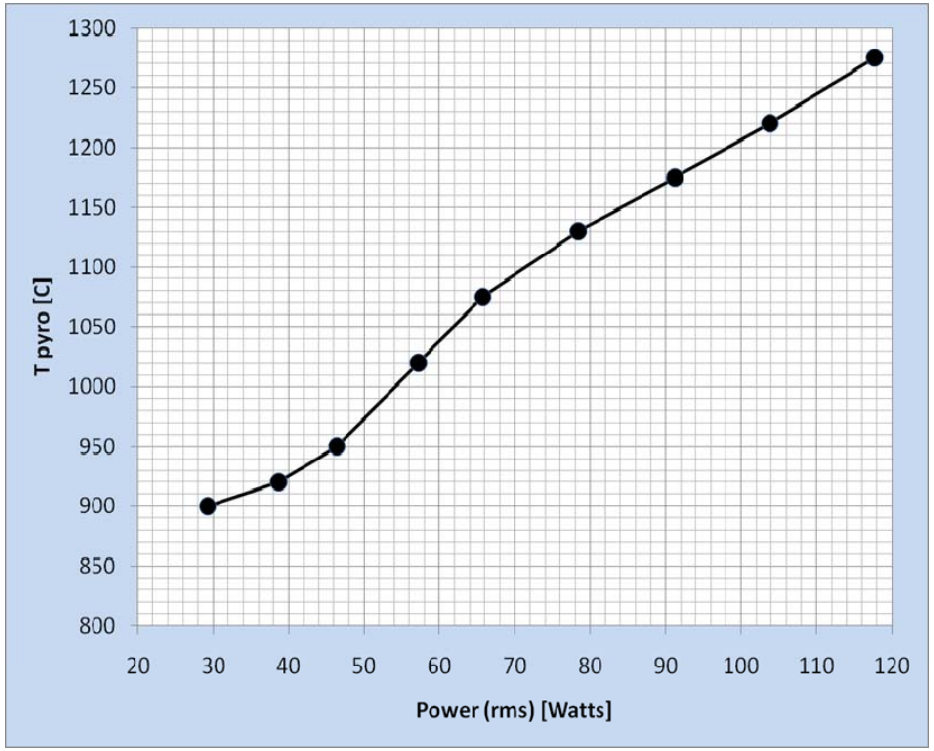
$$I(\chi, V, r, d) := \pi \cdot \chi \cdot V^{\frac{3}{2}} \cdot \left(\frac{r}{d}\right)^2$$

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

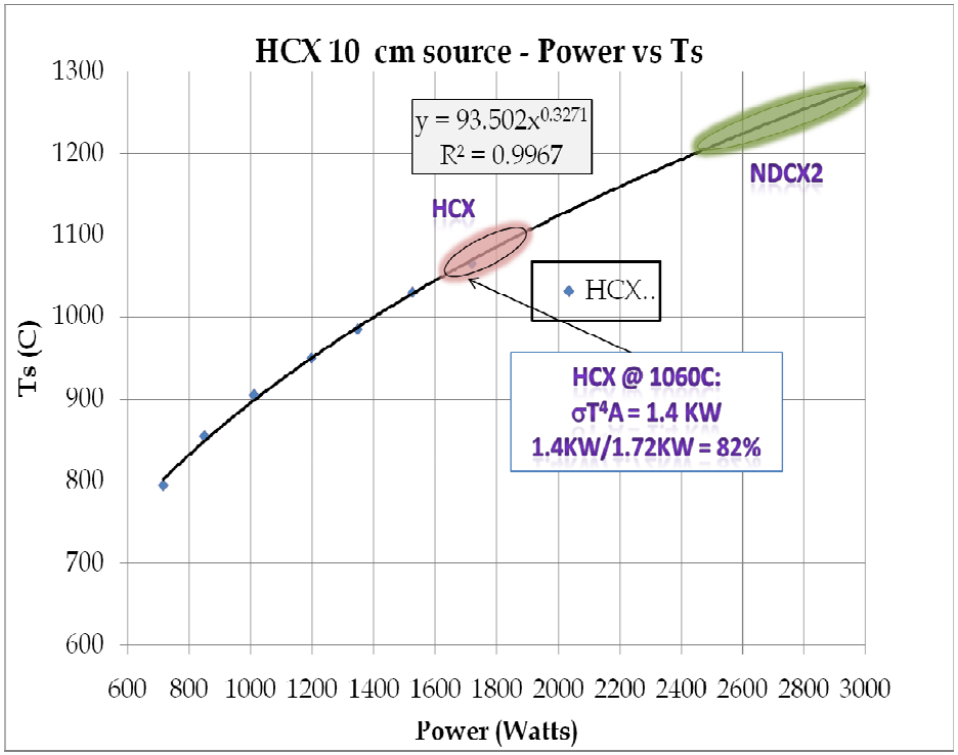
d=1.38 cm,
r source radius

Source heater power vs. source surface temperature for STS50 and NDCX II.

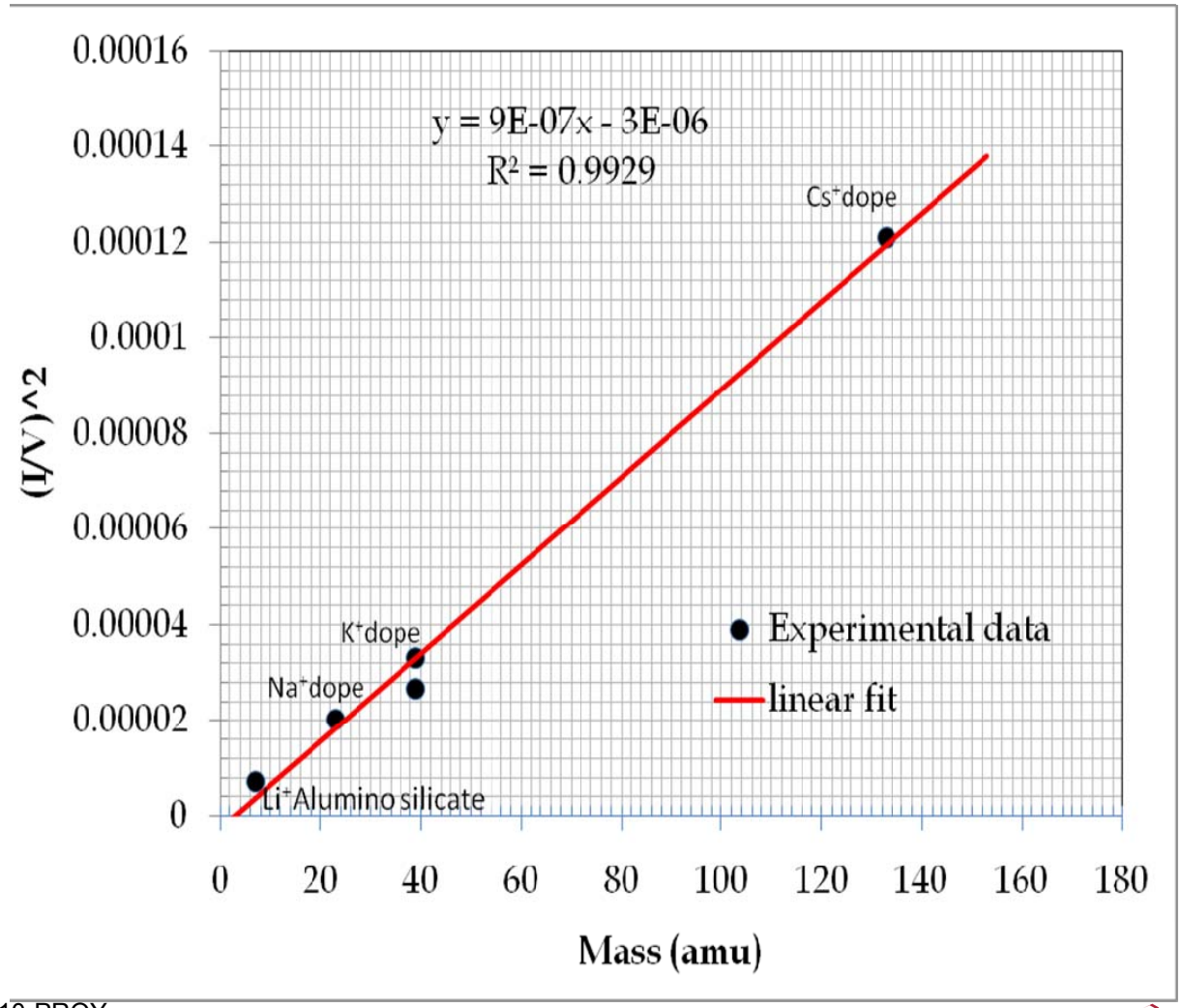
STS-50



NDCX-II

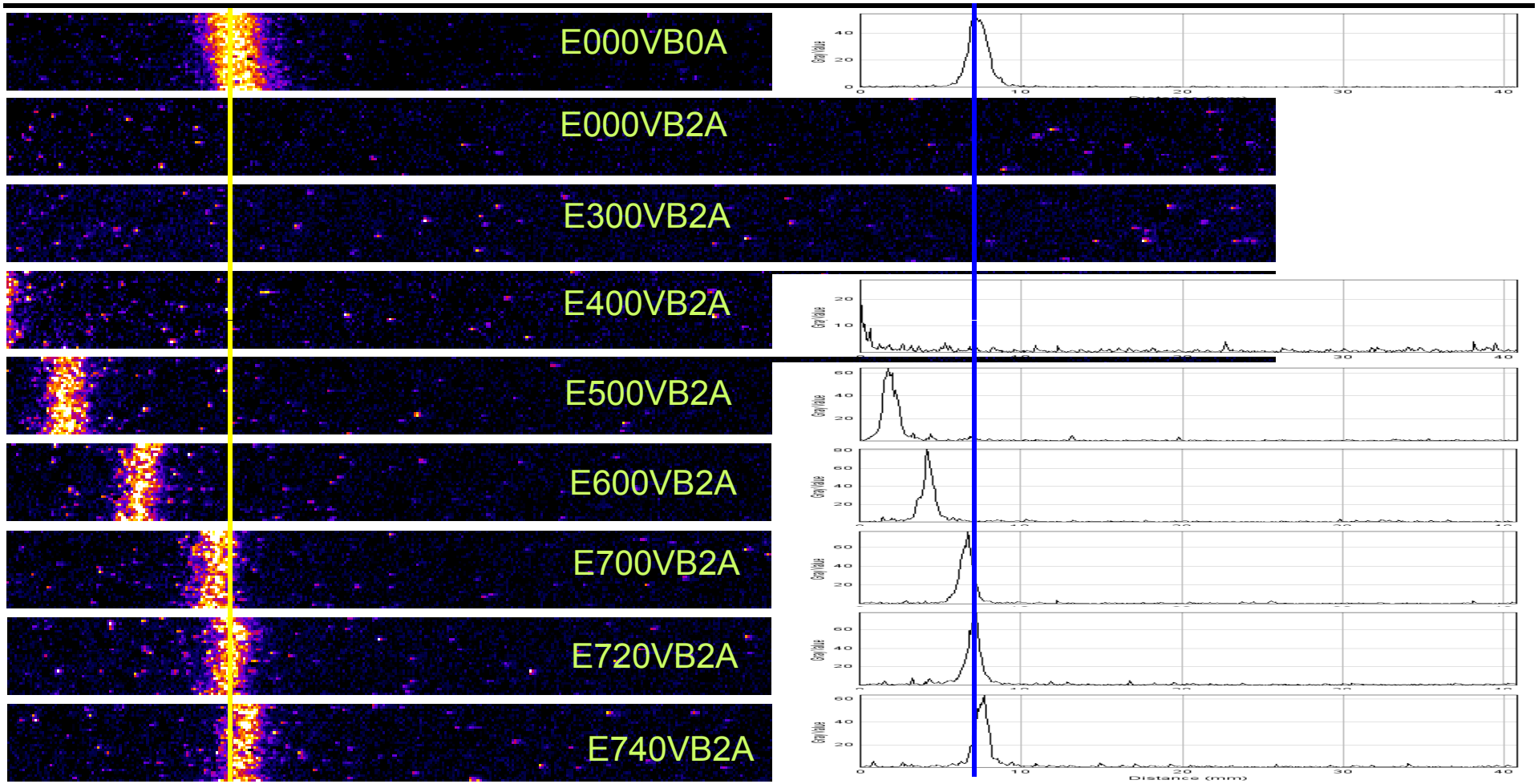


Li-7 element was identified using ExB filter



Lithium identified, B constant

(EXB & YAP scintillator(800+1100+1425)° C)



720V , B=2A ((406 G) identified Li-7, 1mm=12.5 pixel

Lithium Alumino-silicate source performance

- >1.8 mA/cm^2 (80%W-substrate) 09/25/09 at 1225 °C with 20 kV extraction
- >1.4 mA/cm^2 (80%W-substrate) 09/25/09 at 1225 °C with 10 kV extraction.
- >1 mA/cm^2 (80% W-substrate) 08/06/09 (not full coverage)

- 0.52 mA/cm^2 (70% W-sub.) 06/18/09
- 0.3 mA/cm^2 (50% W-sub.) 06/22/09

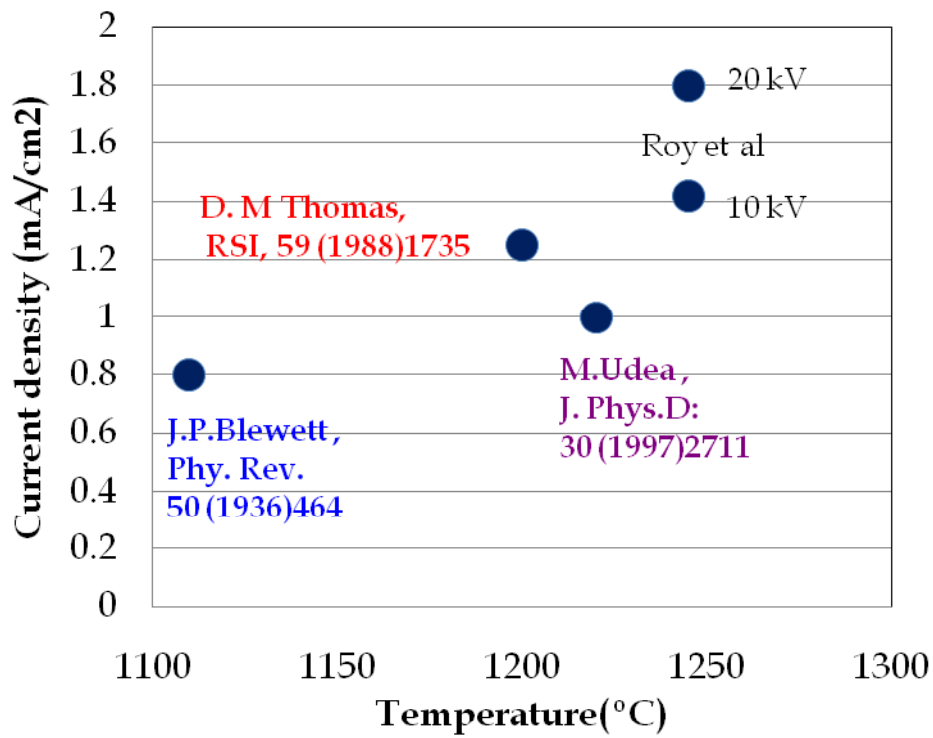
Historic measurements:

- 0.5 mA/cm^2 (1120°C) J.P.Blewett et al., Phy. Rev. 50 (1936)464

- 0.01 mA/cm^2 (1180°C) R.K. Feeney et al., RSI. 47 (1976) 964

- 1 mA/cm^2 M Ueda et al.,J. Phy. D: Appl. Phys. 30 (1997) 2711

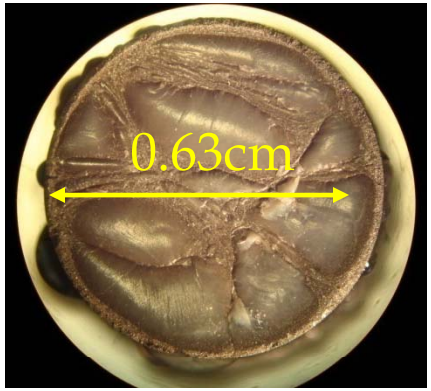
- <0.3 mA/cm^2 (during β-eucryptite melting) M Ueda et al., J. Phy. D: Appl. Phys. 30 (1997) 2711.

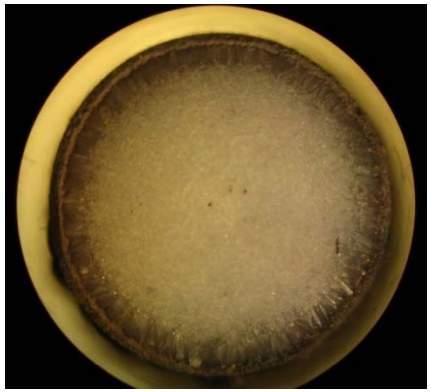


Alumino-silicates sources of K^+ & Cs^+ used extensively due to their low ion temperature-low emittance beam.

•However, it's difficult to make Li^+ Alumino – silicate source compared to K^+ and Cs^+ sources.

Samples of bad sources



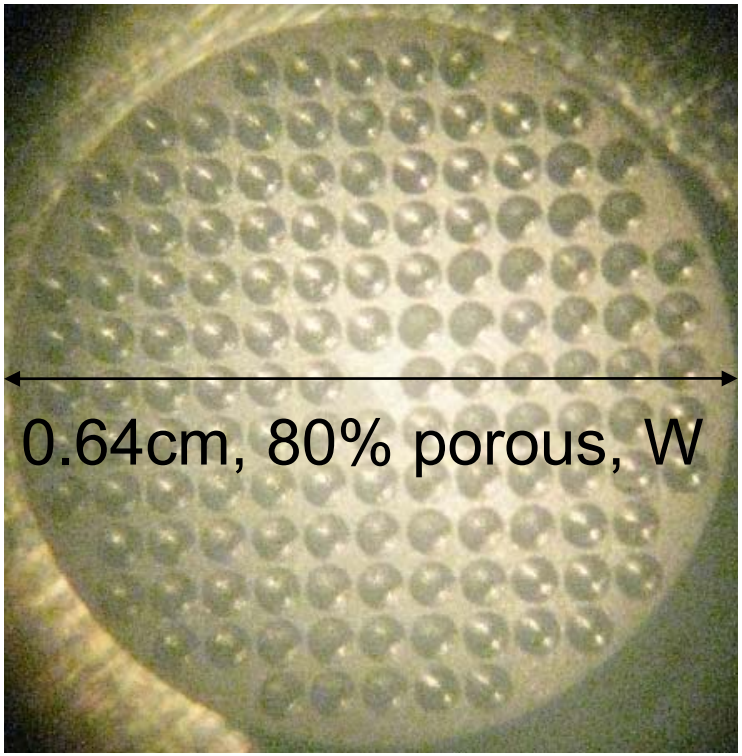


A sample of good source

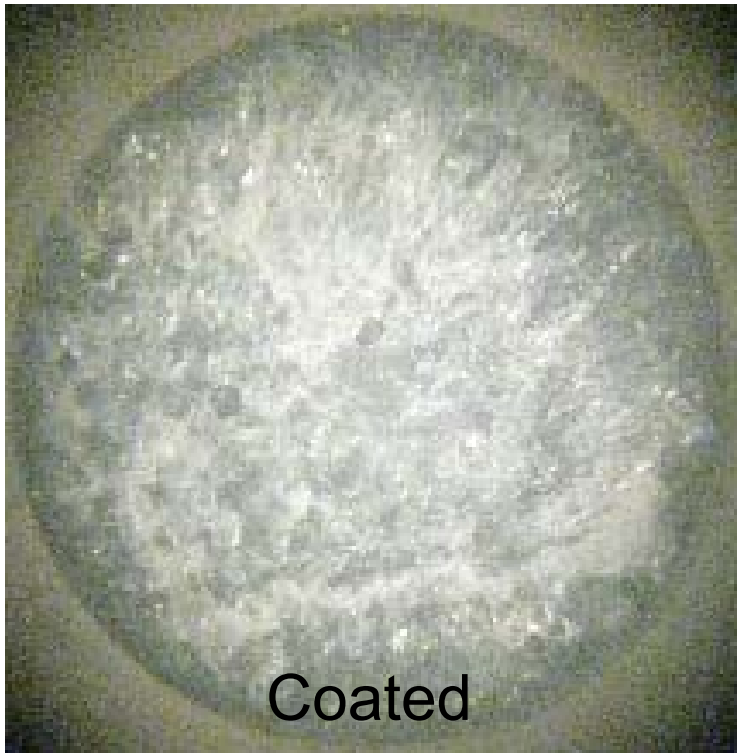
•Li alumino silicate source material is extreme anisotropic in thermal expansion coefficients. This anisotropy is a reason for the difficulty of forming good coatings.

First dot-matrix substrate and source

0.015" diameter holes, 0.015" deep in 0.25" W emitter. New cutter for this one.



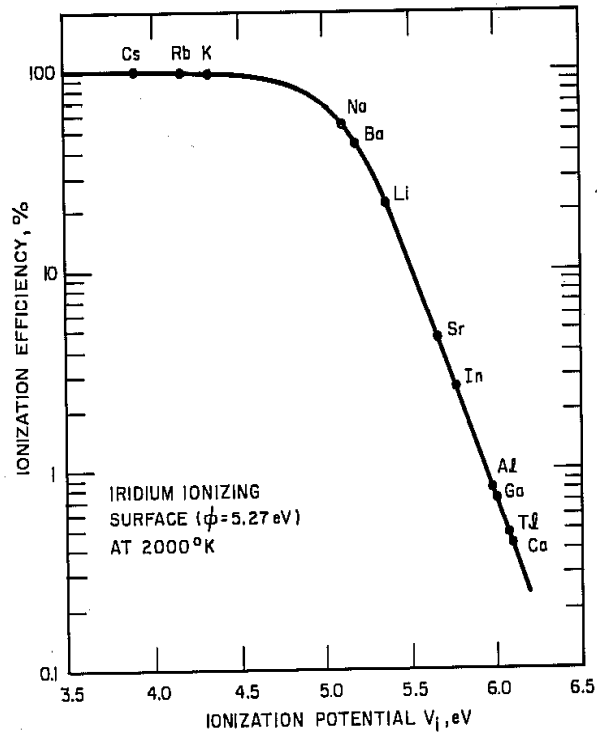
New hole array source with Li coating. Coating was 0.02" thick before melt. Good first results.



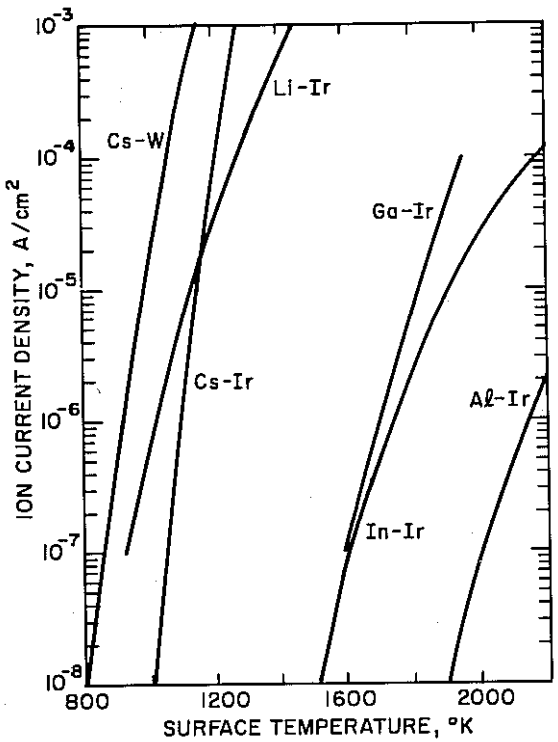
Ionization efficiency is ~100% for Potassium, and this efficiency is ~20% for Lithium (dope source?)

(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	%



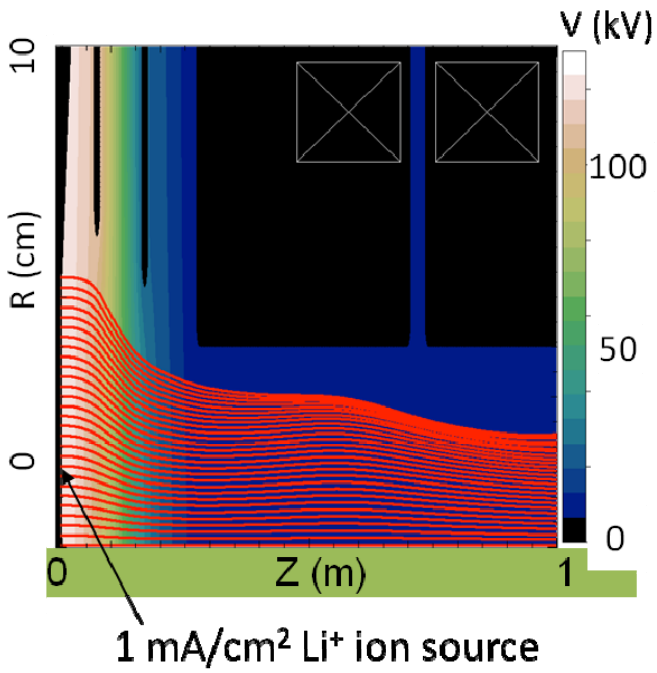
Surface-ionization efficiency for various elements on iridium (calculated)



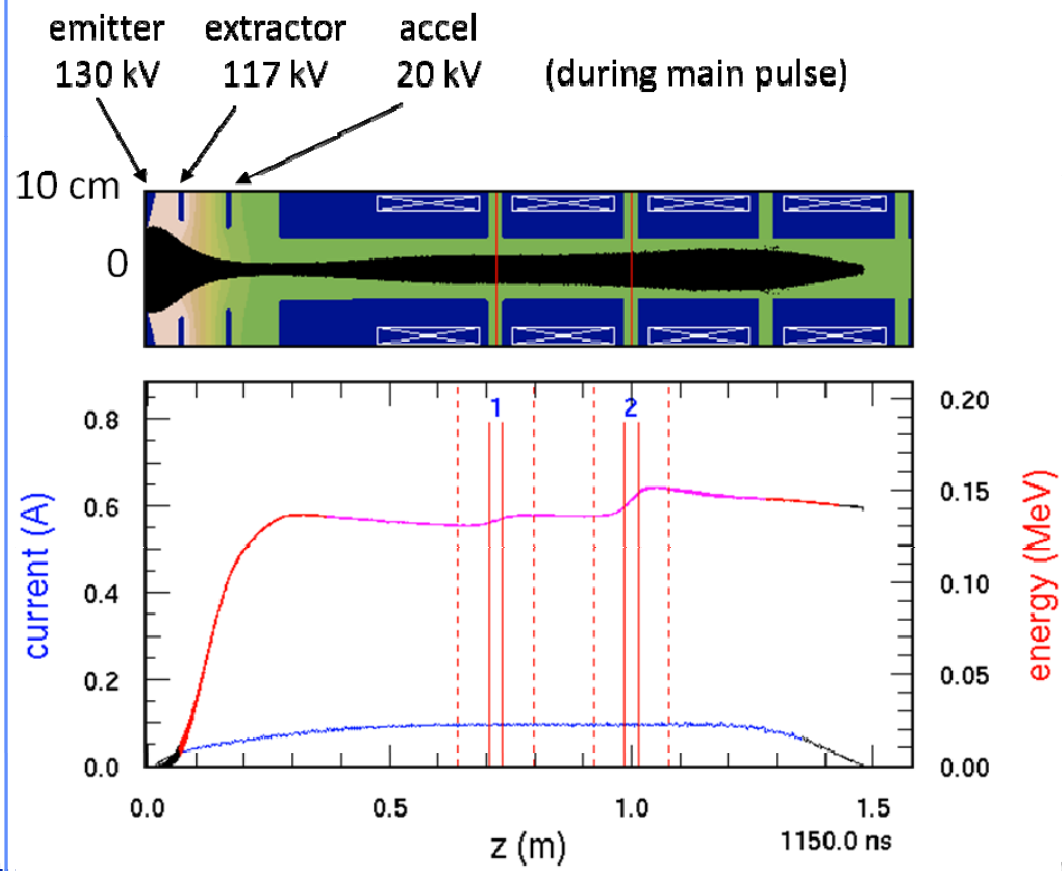
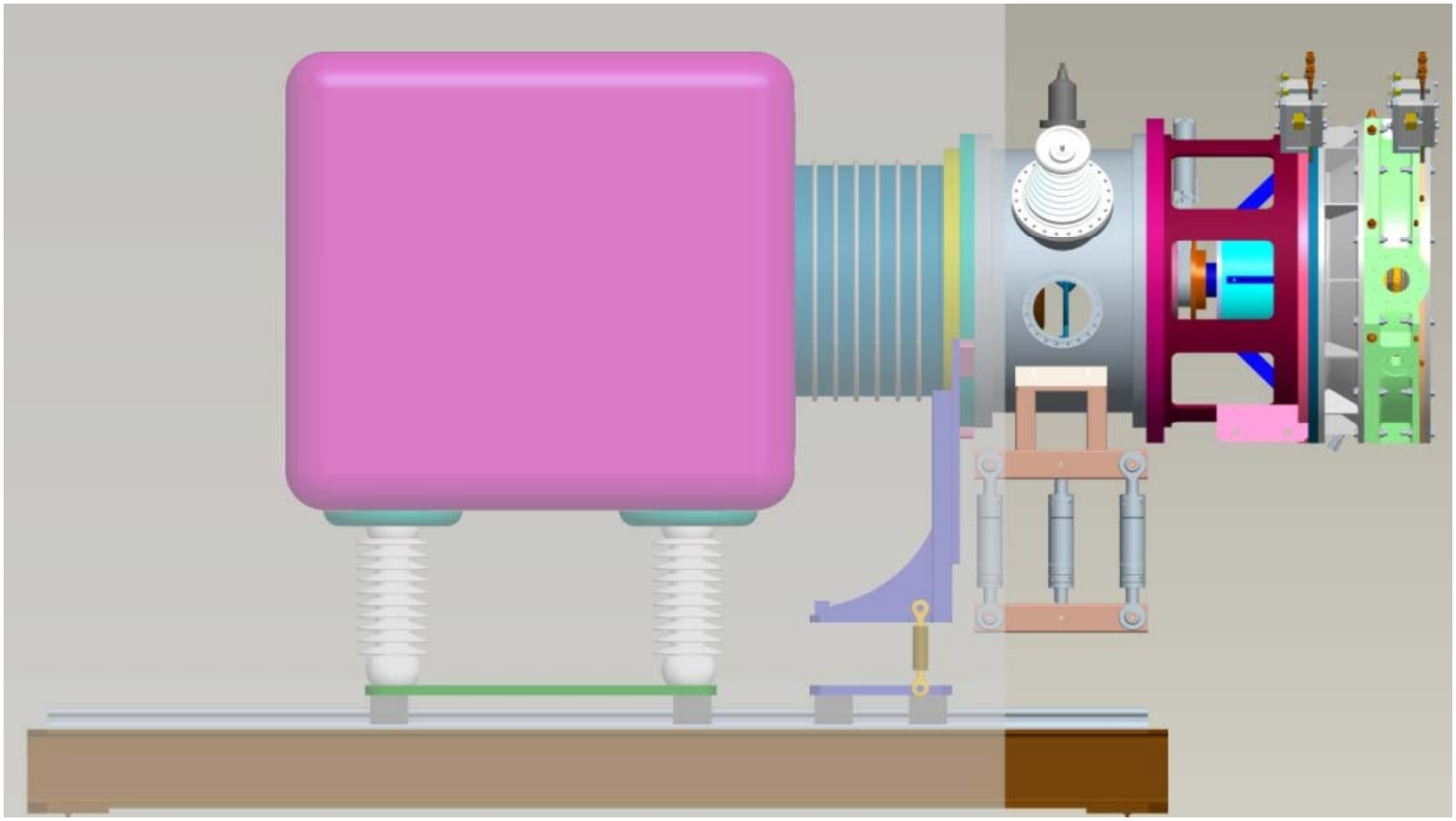
Ion current density versus ionizer temperature for surface ionization of several ion-substrate system (from experimental data)

Injector design was developed using Warp in (r,z) geometry /by Dave Grote

First, used steady-flow "gun" mode to design for a nearly laminar flow:



Second, carried out fully time dependent simulation:



A sketch of INDCX II injector