The Liquid Metal Ion Source – A Hot Ion Source

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Introduction

- The main purpose of this talk is to describe the most widely used ion source technology for high resolution focused ion beam work – the LMIS. Implicitly, I describe the bar that must be exceeded by any new ion source technology:
- The LMIS is simple and cheap (even if FIBs are not), has high performance and is very reliable.

Introduction

- The liquid metal ion source (LMIS) is a field ionization type source that uses a liquid metal (usually Ga) as the material to be ionized.
- The LMIS when coupled with appropriate optics becomes a FIB (focused ion beam) system.

Introduction

- A Ga metal LMIS can produce an angular intensity $dI/d\Omega \approx 20\ \mu A/sr$ of Ga^+ ions and has a virtual source size of $d_s \approx 50$ nm (FWHM).
- A LMIS can be used to focus $I_{beam} \sim 1 - 5$ pA ion current into a beam spot $d \sim 5$ nm ($J \sim 10\ A\ cm^{-2}$); at larger beam sizes currents of ~ 50 - 80 nA can be obtained.
- Although the most-used metal for the source is Ga, many other metals have been used (e.g., Bi, In, Al, Au) as well as compounds (e.g. As+B+Pd, Si+Au, Au+Si+Be) in what are called Liquid Alloy Ion Sources (LAISs).

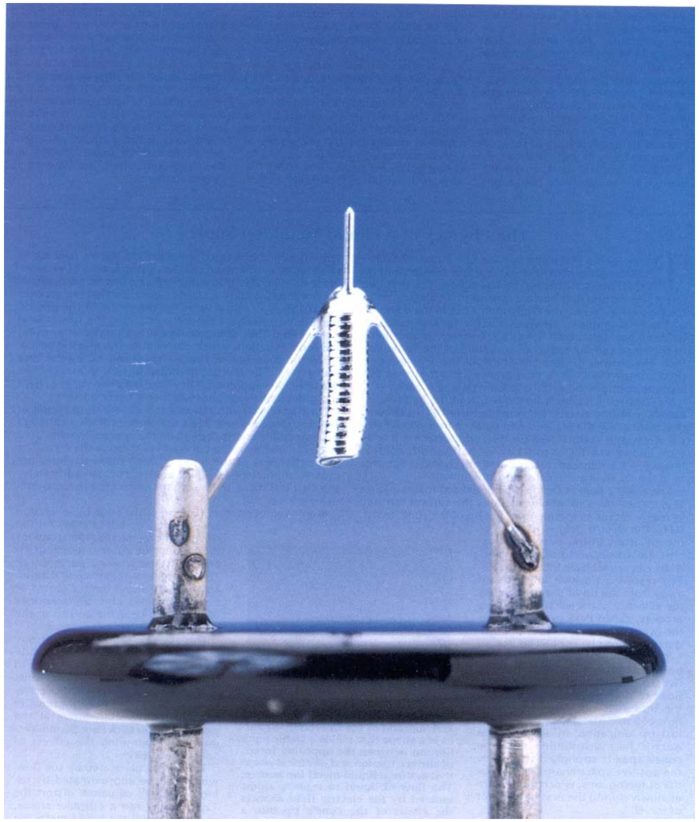
Complementary Ion Sources

- The LMIS is currently the ion source of choice in the range $d \approx 5$ nm – 5 μm ↔ $I_{beam} \approx 1$ pA – 50 nA.
- The gas field ionization source (GFIS), with a much smaller source size and smaller energy spread provides superior performance for $d < 5$ nm.
- The plasma ion source provides superior current density for beam spot sizes greater than ~ 0.1 μm.
- We are waiting to see what the cold atom source does.

LMIS Description

- The LMIS consists of a substrate that is essentially a blunt field emitter with an end radius ≈ 5 μm, coated with a liquid metal.
- When a high field (F ~10^{10} V/m) is applied the liquid metal is drawn into a conical shape (“Taylor Cone”) and ion emission occurs at the liquid cone apex. The end radius of the liquid is ~ 5 nm.

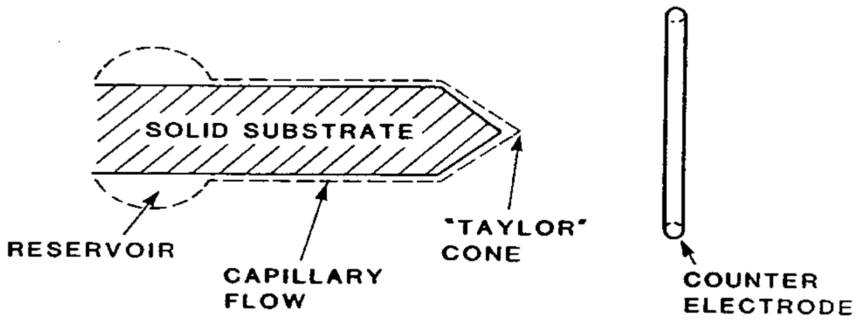
A Typical Ga LMIS



The spiral Ga reservoir holds a supply of metal good for ~1500 µA-hrs. The diameter of the base is ~ 1 cm.

LMIS Source Configuration

SUMMARY OF LMIS MECHANISMS



BASIC MECHANISM

1. CONE STABILIZATION
2. LIQUID FLOW FROM RESERVOIR
3. ION FORMATION
4. EXTERNAL BEAM INTERACTIONS

LMIS Properties

- The apparent source size of the emitter d_s is ~ 50 nm, which is ~ 10X the physical source size (due to space charge effects).
- The total ion current drawn from a LMIS is generally kept to 1 - 2 μA to avoid increased energy spread. Current is emitted into a solid angle $\Delta \Omega \approx 0.1$ sr, corresponding to an angular intensity $dI/d\Omega \approx 10 – 20$ μA/sr.

LMIS Properties

- The energy spread ΔE of the LMIS emitter depends on the total current. For Ga at 1-2 μA total current ΔE ≈ 5 eV (FWHM).

- The brightness

$$\beta = \frac{dI\,/\,d\Omega}{\frac{\pi}{4} \times d_s^2 \times V}$$

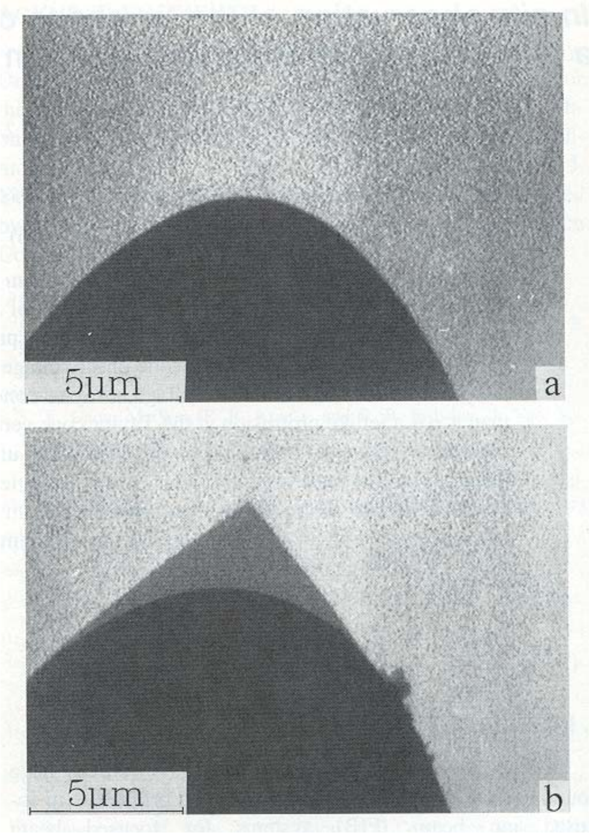
is approximately 10^6 A sr^{-1} M^{-2} V^{-1} , corresponding to an emittance

$$\varepsilon_x = \sqrt{\frac{2I}{\pi^2 \beta}} \approx 4 \times 10^{-7}\ \text{M rad V}^{1/2}$$

Physical Operation of the LMIS

- The LMIS consists of a thin film of liquid metal supported by a needle-like substrate.
- An applied electric field F stresses the liquid which, under the opposite stress due to surface tension, takes on a conical shape (“Taylor Cone” or “Gilbert Cone”).
- Field evaporation and ionization of the atoms takes place at the cone apex.

The Taylor Cone Shape



Micrograph of a Au LMIS (off, upper micrograph) and at low current (lower micrograph). (Niedrig).

Physical Operation of the LMIS

The static Taylor Cone is described by an equation expressing the balance between surface tension and electrostatic stress forces:

$$1/2\ \varepsilon_o F^2 = 2\gamma/r$$

F = field
r = radius of the cone
ε_o = permittivity of vacuum
γ = surface tension of the liquid.

Physical Operation of the LMIS

- Atoms ionized from the cone apex are replaced by a flow of liquid metal through the cone. The flow (v ~ 1 M/s near the apex) results in a negative pressure $\Delta P = 1/2\ \rho v^2$ (Bernoulli effect) causing the cone to deform into a jet-like shape:

$$1/2\ \varepsilon_o F^2 = 2\gamma/r \rightarrow 1/2\ \varepsilon_o F^2 = 2\gamma/r + \Delta P$$

The Taylor Cone Shape

TEM micrograph of a Au LMIS operated at high current (~ 40 μA) showing the negative curvature which is apparent at this high current. Apex of the cone is not resolved. (Niedrig)

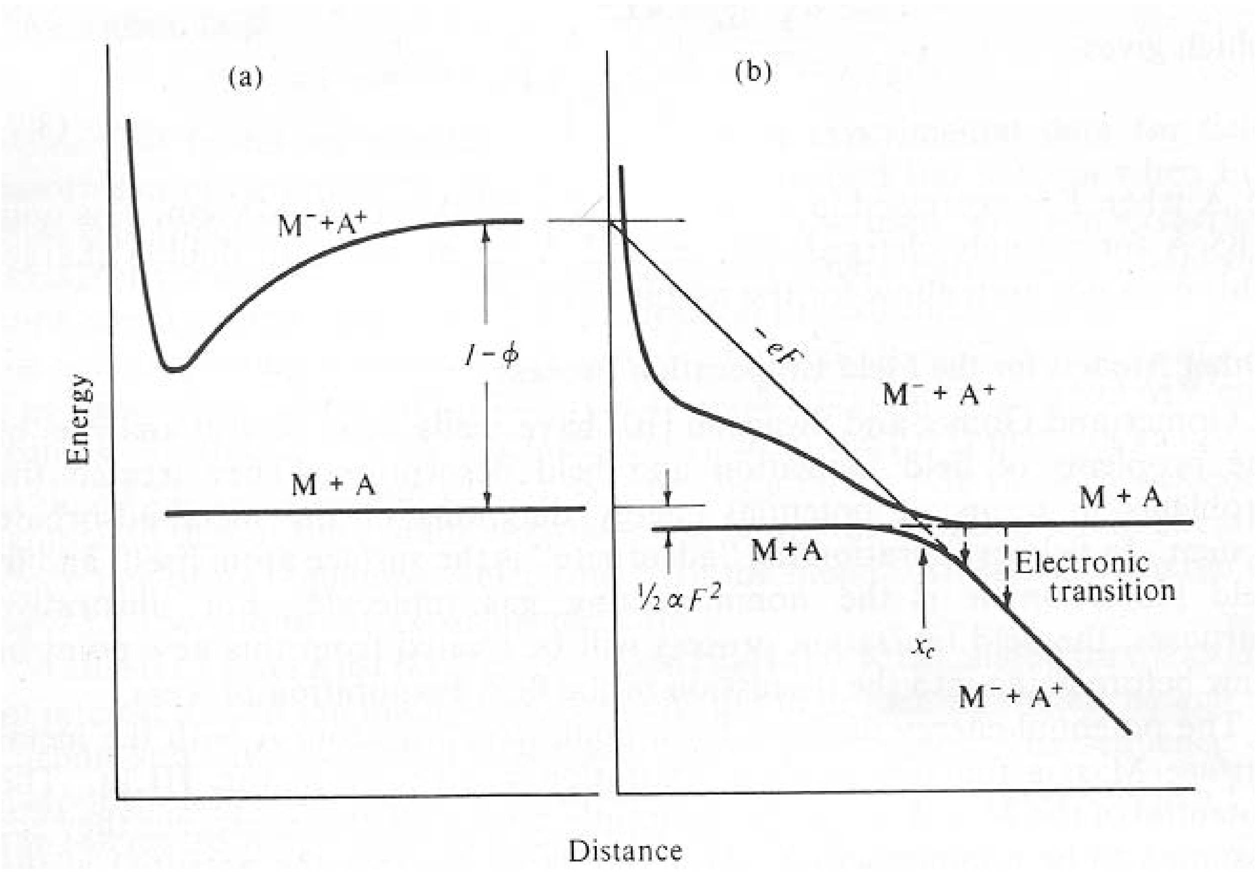
Physical Operation of the LMIS

- The ion emitting area is ~ 5 nm in diameter. As a result space charge near the cone apex due to the ion current is extremely large ($J \sim 10^{10}$ A M^{-2}) and causes trajectory perturbations of the ions, resulting in an optical source size (virtual source size) d_s of 30 - 50 nm diameter.

Ion Production

- Ions are produced by field evaporation of atoms followed by ionization in the high electric field $F \sim 10^{10}$ V/M.
- The LMIS system can be described in terms of the energy of the initial neutral metal [M] and neutral atom [A] → the final metal plus electron [M^-] and the ionized atom [A^+] in a strong electric field F. This is shown schematically as

Field Evaporation/Ionization Energy Diagram



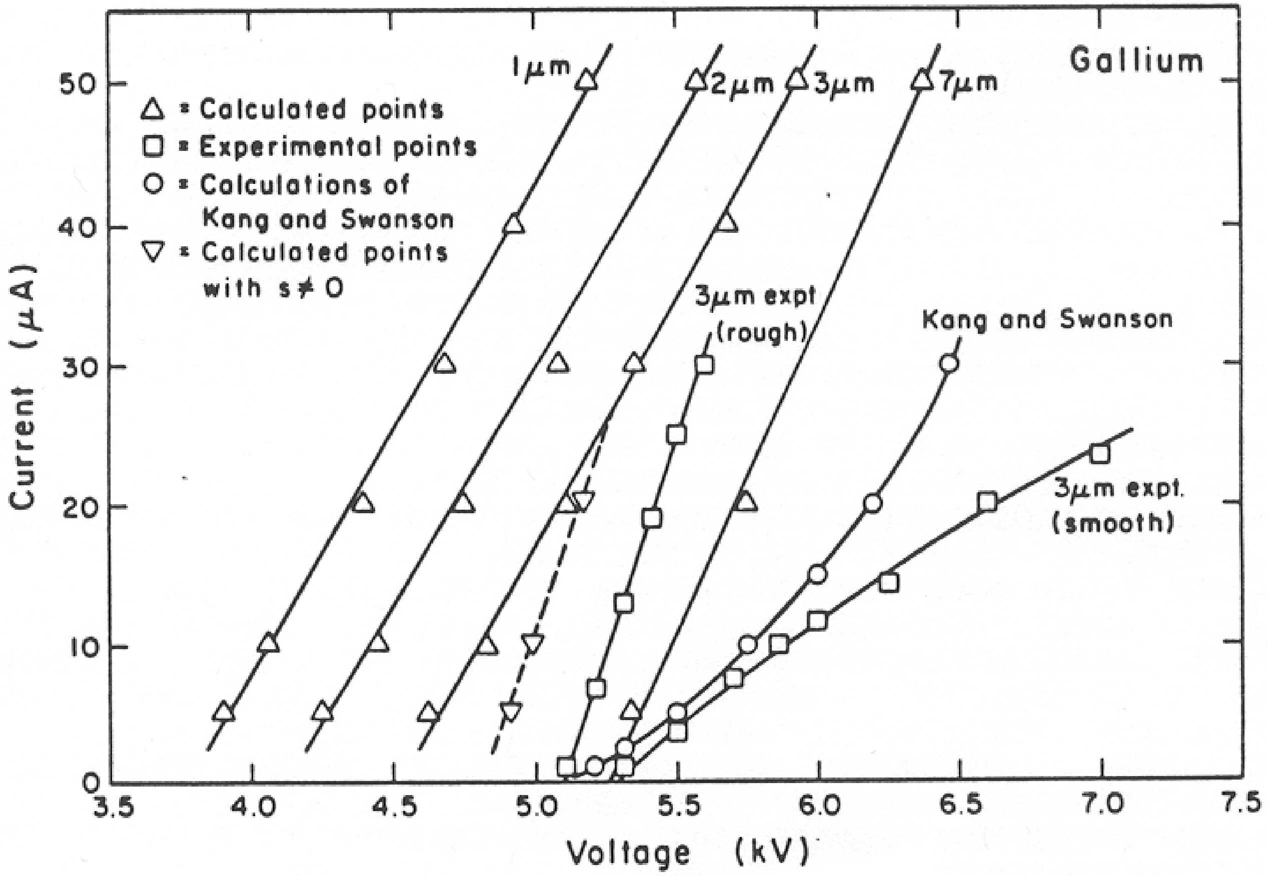
Field Evaporation

- A quantum mechanical calculation for a two state system shows that the curves representing the two energies don’t cross and that a transition between the M + A and the M^- + A^+ states is possible.
- The majority of ions are created at the position x_c where the energies would cross classically (the neutral M + A curve is slightly displaced because of the atom polarization energy 1/2 αF^2).

Physical Operation of the LMIS

- The physical description of the operation of the LMIS is complicated because of all the elements at play:
  - Liquid flow
  - Field evaporation
  - Space charge due to the ion current
  - Liquid shape-dependent surface tension
- A model by Kingham and Swanson taking these into account successfully predicts the current-voltage behavior of the LMIS, as shown.

The Kingham-Swanson Model: I-V Characteristics



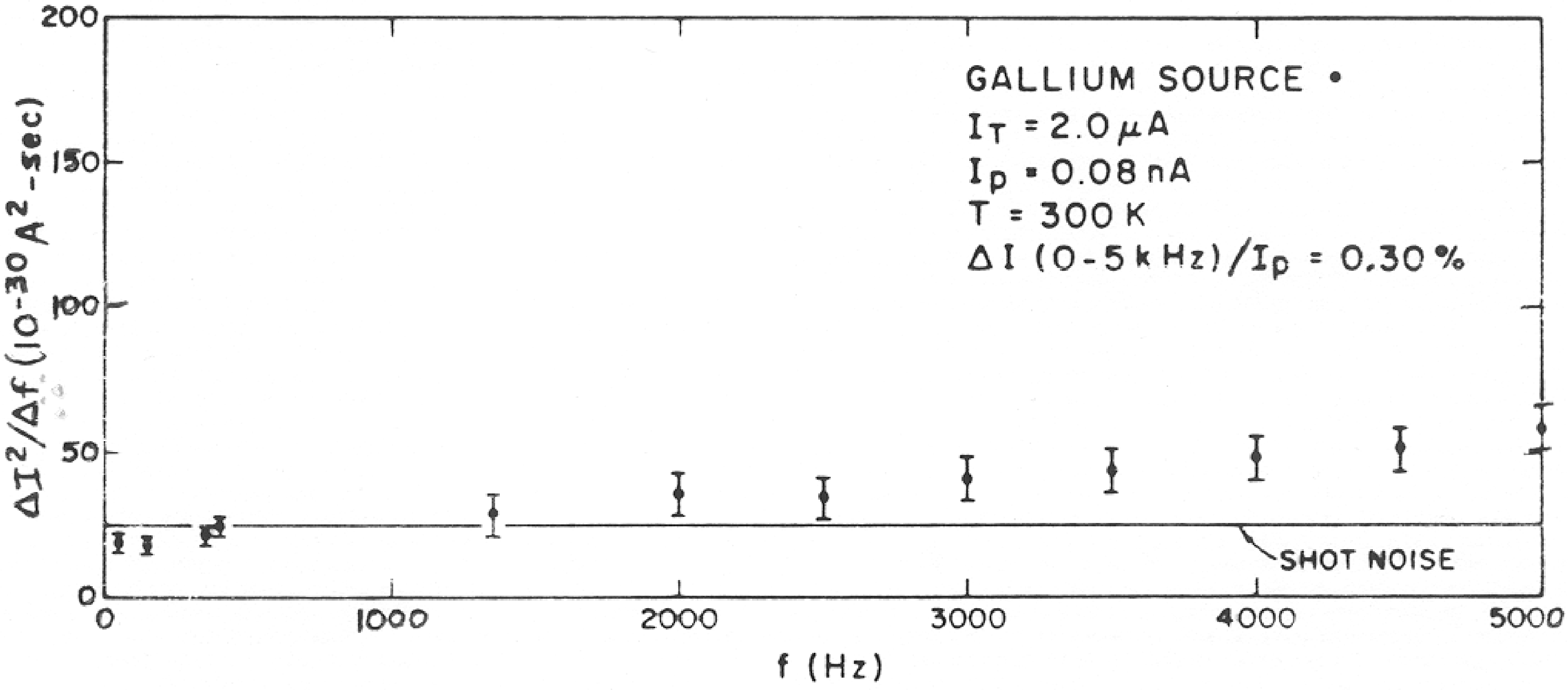
The Kingham-Swanson Model: I-V Characteristics

- The agreement with experiment gives us reason to believe the proposed mechanism for the operation of the source is reasonably accurate

LMIS Noise

- Noise in the LMIS current has a flat spectrum (“white noise”) to at least 400 kHz ,with fluctuations about twice that of shot noise; the noise seems to be governed by the Neyman rather than the Poisson distribution (Ward et al). Noise is suppressed by space charge:
  - Local fluctuations in current result in fluctuations in the current density immediately above the local emitting area.
  - An increase/decrease in current density results in a local change of the electric field and a consequent variation of the emission current: the effect is a negative feedback that suppresses current fluctuations.

LMIS Beam Noise

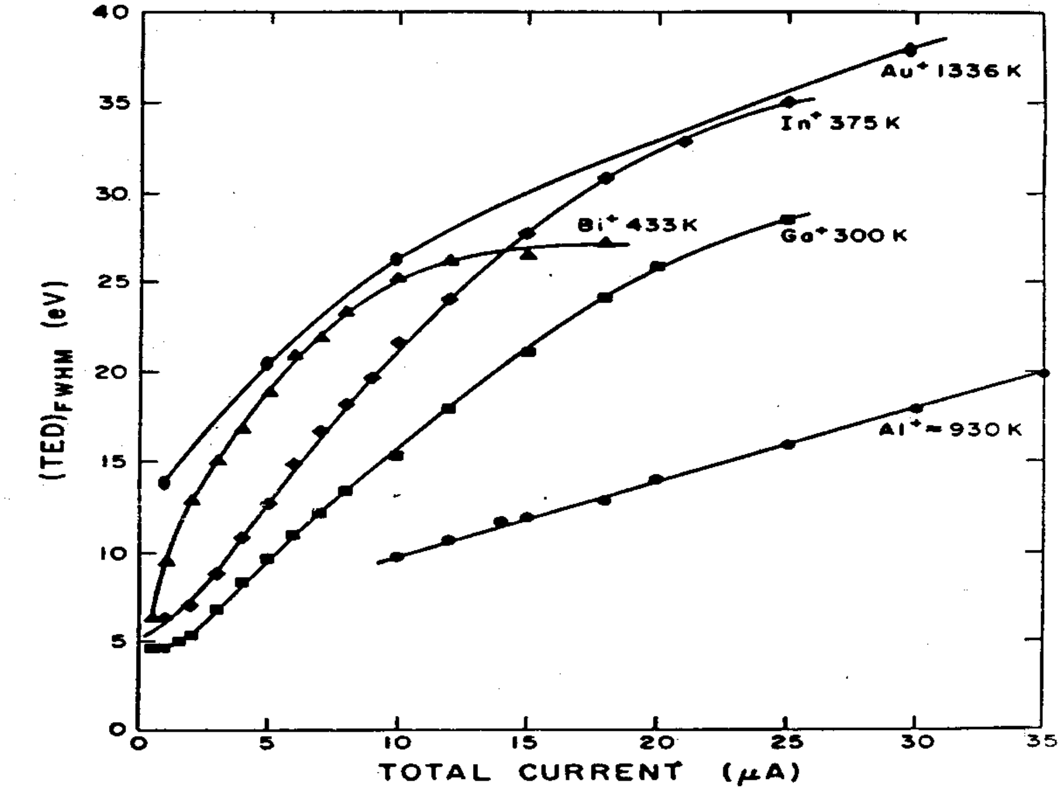


Noise Spectrum of a Ga LMIS (Bell).

LMIS Energy Distribution

- The FWHM of the energy distribution of ions emitted from a LMIS is $\geq$ 5 eV typically, and depends strongly on the ion current, ion mass and ionic charge through random particle interactions.
- This has important implications for the optical design of a FIB.

LMIS Energy Distribution



Total Energy Distributions (TED) of LMISs of varying materials (Swanson et al). It can be seen why the current is kept to ~ 1 µA.

LMIS Energy Distribution

- Experimentally there is a lower limit to the energy spread of ~ 5 eV (depending on ion species).
- The behavior for currents greater than ≈ 1 µA is mainly due to space charge effects in the beam. The largest effects mostly occur in the first few micrometers of travel, but coulomb effects occur throughout the beam path.

Summary

- The LMIS has complicated physics of operation but has favorable properties which are easily exploited:
  - High angular intensity
  - High brightness
  - Low noise
  - Moderate energy spread
  - Limited angular distribution
  - Small source size

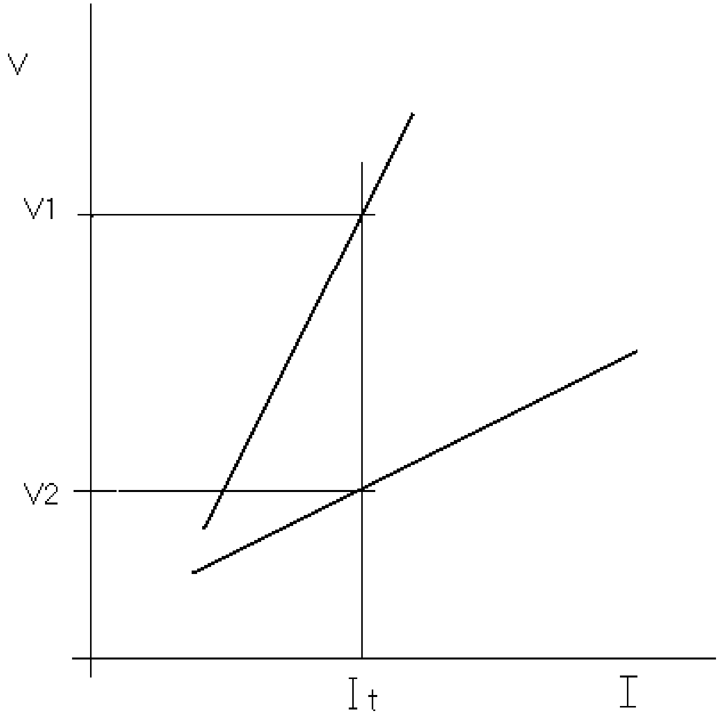
Summary

- As a consequence the LMIS is ideally suited for high resolution ion probes since the optical system necessary to produce a high quality focused beam needs few lenses and can be made simple and compact.
- By keeping in mind the salient features of LMIS physics it is possible to optimize the behavior of the source for FIB work.

Some References for LMIS Operation and Applications

- The physics of LMIS operation is complicated and is only outlined here. For more detail on the subject and on the optics and applications of FIB, refer to: “Handbook of Charged Particle Optics” 2nd Ed., J. Orloff, editor, CRC Press (2009) and “High Resolution Focused Ion Beams: FIB and it Applications,” J. Orloff, M. Utlaut and L. W. Swanson, Springer Verlag (2002).
- For information about the optical properties of the GFIS and how they relate to the source physics, see X. Liu and J. Orloff, “A Study of Optical Properties of Gas Phase Field Ionization Sources,“ in Advances in Imaging and Electron Physics **138,** Elsevier Press (2005)
- For further information on applications of LMIS based FIB, see “Introduction to Focused Ion Beams: Instrumentation Theory, Techniques and Practice,” L. Gianuzzi and F. Stevie, Springer Verlag (2005)

I-V Characteristics



V-I curves for an emitter before (lower curve) and after (upper curve) extensive re-deposition of aperture material. Note higher voltage necessary to maintain a constant operating current I_t (V1 > V2). The lower curve can be regained by heating the emitter.

I-V Characteristics

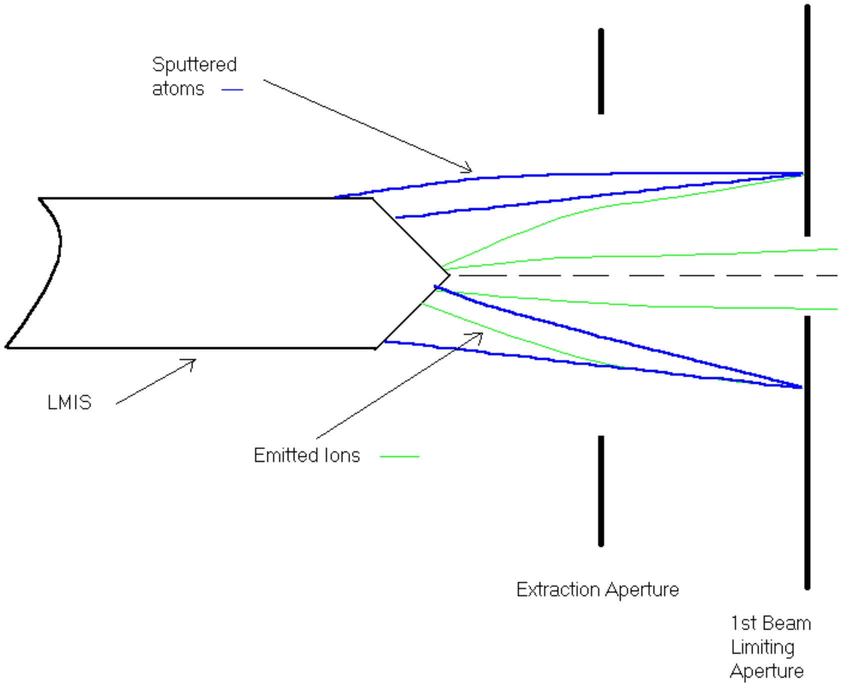
- In operation the slope of the I-V curve of an ion gun is found to decrease with time
  - this was explained theoretically by Mair and also by Wagner, who postulated that the current depended on the liquid film thickness T, the emitter radius R, the emitter length L, the liquid metal viscosity η, the pressure across the length of the emitter ΔP due to the field F and the liquid density ρ as

$$I \sim (\rho/\eta)\ (T^3/L)\ R\ \Delta P(F)$$

I-V Characteristics

- The change in current with time is due to material sputtered from the ion gun electrodes onto the liquid metal which constricts the flow and effectively decreases the metal thickness T.

I-V Characteristics



Paths of ions hitting first limiting aperture (green) and paths of sputtered atoms hitting the LMIS (blue).