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High brightness sources for MeV microprobe applications⁺

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State of the art MeV ion microprobe facilities are now approaching current density limitations on targets imposed by the fundamental nature of conventional gaseous ion sources. With a view to addressing this problem efforts are under way which have the ultimate objective of developing high brightness Li liquid metal ion sources suitable for MeV ion microprobe applications. Prototype Li⁺ and Ga⁺ liquid metal ion sources have been designed, fabricated and are undergoing preliminary testing. This paper describes the first total emittance and brightness measurements of a Ga liquid metal ion source. The effect of the geometry of the ion extraction system is investigated and the brightness data are compared to those of a radio frequency ion source.

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The Harwell microprobe [1] uses a magnetic quadrupole lens system to produce a demagnified image of a set of adjustable and positionable slits illuminated with MeV protons. The ion beam is generated in a radio frequency (rf) ion source and accelerated electrostatically. The microprobe facility was initially located on a 3MV Van de Graaff accelerator which produced a beam spot size of $3 \times 3 \mu\text{m}^2$ on target. More recently the microprobe has been relocated on a 5 MV Laddertron and now provides a beam spot of about $2 \times 2 \mu\text{m}^2$ with a current of 150 pA [2]. Other laboratories have constructed microprobes with the same basic features as the Harwell system and some, with improved quality lenses and slits, have achieved reductions in spot size to about $1 \times 1 \mu\text{m}^2$ at a current of 100 pA [3,4]. However, further significant improvements are proving difficult to realize because of limitations of the ion beam quality from the accelerator. This can be illustrated by reference to table 1 which shows the calculated contributions to a $1 \mu\text{m}^2$ spot for a lens of the Harwell geometry operated in either doublet, triplet or quadruplet modes. Similar magnitude contributions arise from chromatic aberration, spherical aberration and finite object size. These contributions may be reduced if brightness is sufficient to allow increased collimation whilst still transmitting an ion current that is at a practical level for scanning.

A potential route to increased brightness ion beams is through the use of proton field ionization (FI) sources [5] or liquid metal ion sources (LMIS) [6]. These sources have reported brightnesses [7,8] of up to 10^5 times greater than conventional gaseous sources. Their use on microprobe facilities has been discussed elsewhere [2]. In the present paper, we describe the first measurements of the total emittances and brightnesses of ion beams generated in a Ga LMIS. The results of these measurements allow direct comparisons of the emittances and brightnesses with those determined from rf sources and thereby establish the relative merits of the two sources for such applications. The present studies are being performed with Ga because of the ease of operation with this metal. A Li LMIS is being developed and will ultimately be used for microprobe applications.

2 Emittance and brightness measurements

2.1 Ion source descriptions

The LMIS consists of a tungsten needle with a tip radius of about 10 μm wetted with gallium and supported in a reservoir tube [9]. Ions are extracted from the tip by making it 5 to 6 kV positive relative to the extraction electrode. The ion current may be adjusted from a few μA to several tens of μA by making small adjustments to this voltage. After extraction the ions are accelerated by a further 20 to 25 kV and passed through a molybdenum aperture plate to limit the divergence. A 50 mm diameter gridded einzel lens is located downstream of the aperture. Two extraction geometries, shown in figs 1 and 2, have been investigated. The planar geometry system is expected to have lower aberration coefficients due to reductions of field curvature in the extraction and gridded post acceleration stages.

The rf source which is currently in use on the Harwell microprobe facility was used to provide a comparison with the LMIS brightness. It is a HVEC design with a canal length and diameter of 19 mm and 1.5 mm respectively. Ions are extracted at about 2.5 kV and accelerated to 20 kV prior to focusing.

2.2 Definitions

Liouville's theorem postulates that the motion of a group of particles under the action of conservative force fields is such that the local number density in the six dimensional phase space x, y, z, p_x, p_y, p_z everywhere remains constant. If the transverse components are mutually independent the motion of the particles in orthogonal planes (x, p_x) , (y, p_y) and (z, p_z) will be uncoupled and can be treated separately. For a beam moving in the z direction under the action of a conservative force the four dimensional phase space (x, p_x, y, p_y) is a conserved quantity. If p_z is constant p_x and p_y can be replaced by angular components x' and y' . The respective transverse phase space areas are then proportional to the areas xx' and yy' .

To account for changes in the axial momentum p_z we define the normalized emittance as

$$\epsilon_{nx} = \pi x x' E^{\frac{1}{2}} \quad 1)$$

and

$$\epsilon_{ny} = \pi y y' E^{\frac{1}{2}} \quad 2)$$

where E is energy. The units of emittance are usually given as π mm mrad $\text{MeV}^{\frac{1}{2}}$.

A related measure of the quality of an ion beam is the brightness which is defined in terms of the ion current I per unit area per unit solid angle [10];

$$B = \frac{2I}{\epsilon_{nx} \epsilon_{ny}} \quad 3)$$

2.3 Total emittance estimates

An estimate of the total source emittance and brightness was made using two sets of adjustable x , y slits separated by a distance l . The ion beam was focused through the two sets of slits and into a suppressed Faraday cup. With the slits set at $2a_1$ by $2a_1$ and $2a_2$ by $2a_2$ the beam was focused to give small and equal ion current readings on the eight independently isolated slit edges. The acceptance phase space areas are given by,

$$A_x = A_y = \frac{4a_1 a_2 E^{\frac{1}{2}}}{l} \quad 4)$$

and the beam emittance by the largest ellipses that can be fitted into these areas. Including π in the units gives normalized emittances of

$$\epsilon_{nx} = \epsilon_{ny} = \frac{a_1 a_2}{l} E^{\frac{1}{2}} \quad 5)$$

Beam brightness may be obtained by substitution into Eq 3

2.4 Emittance contours

Emittance contour measurements were performed on the $^{69}\text{Ca}^+$ beam from the LMIS. Mass analysis was performed with a $\rho = 610$ mm double focusing magnet. The source einzel lens focused the beam at the object slits of the magnet and the magnet formed a waist at the image slits. Further downstream was the emittance measurement device [11] which consists of two identical stepping motor driven detector units for determining the emittance of an ion beam in either x or y direction. Each detector unit (Fig 3) consists of an

electrically isolated slit aperture, positioned 0.4 m in front of a detector unit which is made up of 32 electrically isolated plates. The current striking each of the detectors is used to determine the differential angular divergence of the ion beamlet which is allowed to pass through the slit aperture at a given x or y position.

An emittance measurement consists of automatically stepping the slit-detector system through an ion beam in a chosen direction while monitoring the total ion current striking the slit unit and the differential ion currents striking each of the 32 detectors during a fixed integration time (~ 20 ms). The locations of the 50 positions at which data are accumulated are determined using a precision linear potentiometer. All signals are digitized and stored on hard disc. Angular and positional resolutions are 1 mrad and 0.9 mm respectively. Each complete (x,x') or (y,y') measurement takes about 10 minutes.

After accumulation the data are subjected to a point by point background subtraction by use of a background file taken immediately after the beam measurement. This procedure is necessary because of the difficulty in electronically reducing the background to zero in all of the 32 detector channels. In order to compensate for small variations in beam intensity during a particular measurement, the data set is normalized by multiplying each of the 32 detector channel readings by the ratio of maximum slit current reading to the slit current at each of the 50 positions. Emittance contours are then determined by performing a Simpson's rule volume integration over the xx' and yy' versus intensity data. Contour levels which contain 10-80% of the total beam are calculated in increments of 10% to an accuracy of 0.1%.

3 Results and discussions

The total emittance and brightness of the conical geometry LMIS were measured using the method described in section 2.3. The source drain was 60 μA and the beam divergence half angle was limited to 9° . Measurements were repeated with various values of a_1 and a_2 and the focus conditions modified accordingly to achieve approximately 100% beam transmission. The average total ion current and total brightness were 11.7 μA and 0.09 μA ($\pi^2\text{mm}^2\text{mrad}^2\text{MeV}$) $^{-1}$ respectively. If only the $^{69}\text{Ga}^+$ ion is considered this value is modified to 0.06 μA ($\pi^2\text{mm}^2\text{mrad}^2\text{MeV}$) $^{-1}$. Similar measurements were

performed on the rf ion source for total ion currents of 25, 50, 75 and 100 μA . The average brightness was $19.4 \mu\text{A} (\pi^2\text{mm}^2\text{mrad}^2\text{MeV})^{-1}$.

Emittance contour measurements were made by the use of equipment and procedures described in section 2.4 on the conical and planar geometry LMIS at a total source drain of 60 μA . The beam divergence was limited to a half angle of 9° and 11.4° for the respective geometries. This difference was reflected in the slightly lower analysed beam current of 5.7 μA for the conical geometry source compared to 6.93 μA for the planar geometry source. Ion currents prior to analysis were consistent with a source beam consisting of the two isotopes of Ga with 100% transmission through the beam transport system. Examples of the x and y direction emittance contours are shown in fig 4 and 5. The phase space is not a perfect ellipse due to distortions introduced either by the LMIS needle or the ion transport system. Measurements were repeated five times to obtain an average 2 dimensional emittance versus percentage of total analysed ion beam. These data (fig 6) indicate that the planar geometry source has a lower emittance than the conical geometry in accordance with the lower predicted aberrations in this source. Brightness data are given in fig 7 which show an increased brightness of the planar geometry over the conical geometry due to a combination of lower emittance and higher transmitted beam current. Extrapolation of the conical geometry data to the 100% contour gives a brightness of $0.09 \mu\text{A} (\pi^2\text{mm}^2\text{mrad}^2\text{MeV})^{-1}$.

In contrast to this rather low total beam brightness for the LMIS the central 10% beam contour (0.7 μA) of the planar geometry source has a brightness of $135 \mu\text{A} (\pi^2\text{mm}^2\text{mrad}^2\text{MeV})^{-1}$. Furthermore, extrapolation of the data presented in fig 7 suggests a rapid increase in brightness for smaller beam fractions. This is particularly significant for microprobe applications where the 0.01% contour ($\sim 100\text{s}$ of pA) is important. The data also shows that the low aberration planar geometry has an increasingly significant benefit for the more central portions of the beam.

Previous data [2] for the brightness of the central beam contours of the rf ion source do not show such a dramatic increase as that indicated in fig 7 for the LMIS. The brightness of the 10% beam contour (0.5 μA) for the rf ion source was determined to be $100 \mu\text{A} (\pi^2\text{mm}^2\text{mrad}^2\text{MeV})^{-1}$ (as defined by eqs 3 and 4) i.e. only a factor of five increase over the total beam brightness. The above value is essentially that required to illuminate the

Harwell microprobe with the acceptances given in table 1 in order to provide the state of the art 100 pA into a $1 \mu\text{m}^2$ spot. This suggests that there are only limited further increases in the rf ion source brightness below the 10% beam contour.

4 Summary

The first measurements of the total emittance and brightness of a Ga LMIS have been presented and compared to estimates of the brightness of a rf ion source of the type widely used on MeV ion microprobe facilities. The data indicate that whilst the total beam brightness of the LMIS is poor, it increases rapidly in the central portion of the beam and exceeds that of the rf ion source at the 10% total beam contour. Extrapolation of the data to beam currents required for microprobe applications suggests brightnesses considerably exceeding those of the rf ion source. This conclusion supports previous estimates [7] of the brightness of the central portion of the LMIS ion beam. The data also indicate the requirement for a low aberration ion source extraction and acceleration system. A Li LMIS presently under development will shortly be installed on the Harwell microprobe facility to investigate whether the high brightness beam from the LMIS can be transmitted through the accelerator without degradation.

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Figure captions

- 1 Schematic drawing of the conical geometry LMIS and focusing lens. A reservoir heater is incorporated for subsequent work with Li and was not used with Ga. The aperture diameter, a , is 11.2 mm.
- 2 Schematic drawing of the planar geometry LMIS and focusing lens. This geometry is expected to have lower aberration coefficients than the conical geometry due to the larger diameter extraction electrode and gridded acceleration stage. The aperture diameter, a , is 10.5 mm.
- 3 Schematic drawing of the emittance measurement detector unit.
- 4 x-direction contour for the planar geometry LMIS. Ion species: $^{69}\text{Ga}^+$; beam current: 6.93 μA ; ion energy: 31 keV.
- 5 y-direction contour for the planar geometry LMIS. Ion species: $^{69}\text{Ga}^+$; beam current: 6.93 μA ; ion energy: 31 keV.
- 6 Emittance versus percentage of total ion beam from the conical and planar geometry LMIS. The planar geometry source exhibits a lower emittance.
- 7 Ion beam brightness versus percentage of total ion beam from the conical and planar geometry LMIS. The planar geometry has a higher brightness. Ion beam brightness for both geometries rapidly increases in the central portion of the beam.

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	Quadruplet	Triplet	Doublet
Vertical object aperture y	6.25 μm	12.6 μm	27.7 μm
Horizontal object aperture x	6.25 μm	44.8 μm	3.95 μm
Vertical divergence ϕ	± 0.24 mrad	± 0.028 mrad	± 0.18 mrad
Horizontal divergence θ	± 0.14 mrad	± 0.08 mrad	± 0.15 mrad
First order image Δx	0.64 μm	0.64 μm	0.64 μm
Δy	0.64 μm	0.64 μm	0.64 μm
Chromatic aberrations $2\Delta x_{\text{ch}}$	0.59 μm	0.67 μm	0.55 μm
$2\Delta y_{\text{ch}}$	0.54 μm	0.68 μm	0.57 μm
Spherical aberrations $2\Delta x_{\text{sph}}$	0.52 μm	0.24 μm	0.67 μm
$2\Delta y_{\text{sph}}$	0.67 μm	0.52 μm	0.43 μm
Acceptance	5.3 $\mu\text{m}^2 \text{ mrad}^2$	5.1 $\mu\text{m}^2 \text{ mrad}^2$	11.8 $\mu\text{m}^2 \text{ mrad}^2$

Table 1 Calculated contributions to a 1 μm beam spot for the Harwell microprobe lens operated in doublet, triplet and quadruplet modes [2]. The main contributions the image size are object size, chromatic aberrations and spherical aberrations. The ion beam brightness required to illuminate the object slits and provide a 1 μm^2 beam with a current of 100 pA in the doublet mode is 150 $\mu\text{A} (\pi^2 \text{mm}^2 \text{mrad}^2 \text{MeV})^{-1}$.

<u>Percentage of total beam intensity</u>	<u>Ermittance (π.mm.mrad)</u>
10	.68
20	5
30	6.83
40	9.91
50	16.96
60	19.46
70	22.75
80	25.47

Ga⁺ LIQUID METAL ION SOURCE

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