

ANODE SPUTTERING CHARACTERISTICS OF THE BERKELEY 2.5 MV SOURCE*

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Abstract

This paper reports an investigation of a number of parameters affecting the performance of the SuperHILAC 2.5 MV Adam injector source. The description will emphasize anode sputtered materials, and will discuss in some detail calcium and gold ion production. Parameters varied include electrode geometry, support gas type and electrode bias, to optimize beam intensity and electrode consumption. A factor of three improvement with high n^+ gold ions appears evident with a new displaced electrode geometry.

The source is operated in cold mode, is pulsed and operates usually at less than 0.6 amperes average current. Under these conditions source life has been measured to be six hundred hours at 25% duty factor, when generating calcium ions, with neon support gas.

Introduction

The SuperHILAC ion source generates ions with charge to mass from 0.05 to 0.075 for acceleration from a pressurized 2.5 MV injector system.¹ The charge states of materials within this charge to mass range are selected for study. Arc currents range from 1.5 to 3.5 amperes peak, at potentials about 1100 v. Only the most relevant parameters affecting sputtering are examined. The minimization of the calcium consumption rate is of primary importance whereas the heavier elements are optimized for peak intensity. In instances measured results are puzzling. Explanations are suggested.

Description of Source Sputtering Parameters

The anode sputtering electrode of the SuperHILAC Adam source is placed in a fixed position, and embraces the center plane region of the plasma column. As sputtering occurs, so does the electrode surface wear away and retract from the main plasma sheath. Current to the electrode will gradually drop as this surface recedes deeper into a pocket of the anode. The life of the electrode is set by its thickness and the current drain from the plasma is proportional to electrode surface area. Current to the electrode quickly reaches saturation at bias voltages above ten volts. Currents vary from 0.2 to 1.2 amperes, and also are altered by electrode material and support gas. A large surface area is desirable since a greater atomization rate per unit thickness is gained. The useable thickness of the electrode is matched to the life of the arc cathodes.

Ions accelerated across the anode plasma sheath, sputter electrode material into the plasma in proportion to the sputtering yield of the electrode. This yield is strongly affected by the mass and energy of the incident ion. Since the velocity of the sputtered atoms is probably only a weak function of the incident ion energy, the density of metallic materials in the discharge is considered proportional to the sputtering yield. The sputtering electrode is conveniently placed opposite the exit window. Since this slit is best not sputtered away, the electrode cannot be coaxial with the plasma column in center position (Figure 1a).

An unfavorable perturbation to the plasma was thought possible given the electrode's eccentric configuration. Possibly a substantial fraction of metallic ions extracted could well have made but a single traverse in the discharge. (The anode is not sufficiently hot to return metallic vapor to the discharge, therefore the anode will pump ions lost through the anode sheath.) Additional, it has been noted that a favorable CSD exists for metallic ions fed from the axial arc cathodes albeit their total yield be lower due to radial loss.¹ Therefore two ring sputtering electrodes moved as far away from the exit window as this

geometry allows (anode length ≈ 2.5 cm), will be compared to the centrally located electrode (Figure 1b).

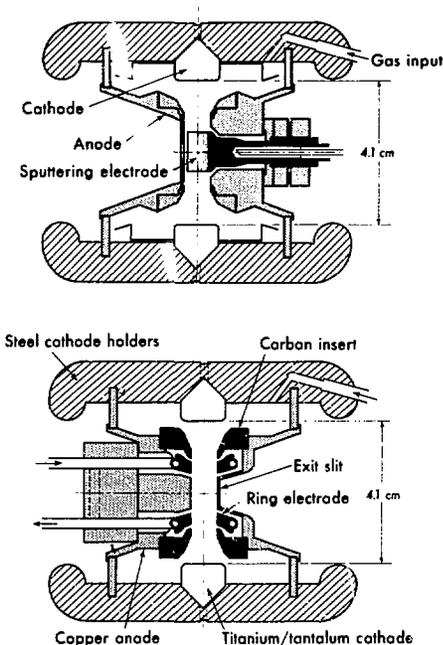


Figure 1. Section view of ion source. Standard center electrode geometry (a), ring electrode geometry (b). Electrode surface area: (a) -0.93 cm^2 , (b) -1.73 cm^2 .

Other parameters affecting the production of metallic ions are the following: First, support gas selection, of which more will be said later. Second and of vital influence, is the main discharge current. Space will limit a detailed discussion. In general the higher the extracted charge state tuned for, the steeper the increase with current. This is true for metallic ion production as well as for gas fed operation. Figure 2 displays typical curves for xenon, iron and gold. If the arc current is increased by a factor of two, the support gas may be reduced about 18%. The data points of Figure 2 are taken at minimum gas.

Operation with peak arc currents of 3.2A (60% 20%) cannot usually be exceeded with titanium or vanadium cold cathodes now in use. Lifetime and power supply considerations favor the selection of these cathode materials. High melting point thermally emitting cathodes allow for greater currents and therefore improved performance. However the life of such cathodes, given this source geometry, will be one

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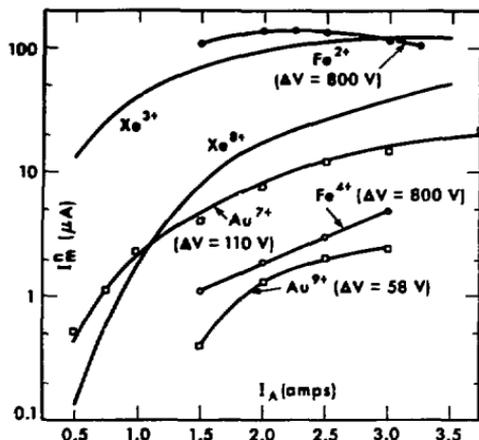


Figure 2. Extracted ion current vs. arc current. Sputtering support gas argon, flow minimized. Electrode bias recorded.

half that of titanium at near equal current and performance, with heavy ions, as xenon. Therefore higher current operation will require greater room in the cathode area, and also larger size cathodes for a satisfactory lifetime.

Thirdly, and a deterrent to orderly data collection is the adjustment of the lateral position of the extractor as well as extractor gap spacing, a critical tuning parameter, particularly when optimizing high n^+ metallic ion beams. At this time it is not possible to record the extractor position in predictable fashion. Optimization likely does effect emittance shape, area and brightness. Attention should be given to one or both of these parameters during a scan of source performance.

Critical measurements are repeated three or more times. Each run will differ from another for no other reason than the age of the source. I have smoothed data points to simplify display. All beams reported, are measured in a magnetically shielded cup. For increased resolution, the beams pass through two collimators 5.9 and 13 mm wide close to the radial focal point, 70 cm from the analyzing magnet. Peak ion currents are in measured units and appear in proportion to an integration of these peaks. A typical data spectrum is illustrated in Figure 9 of the Appendix.

Results

Calcium:

The calcium to be atomized and accelerated will be ^{48}Ca . Since this isotope is available in metal form, and will be recycled to a metal state, a simple holding and cooling procedure is desirable. A rectangular strip of calcium rolled to ~3 mm thickness and bonded to copper may be made without machining waste. A 2.2×0.72 cm strip rolled to a 4 mm radius is attached to copper with a silver epoxy conductive adhesive. $\sim 40 \text{ w/cm}^2$ may be transferred across the thin adhesive boundary. The centrally located electrode (Figure 1a), is most suitable for this costly isotope. A cross section of this electrode is shown in Figure 10a.

It has been observed that when tuning the source for a constant $70 \mu\text{A}$ of $^{49}\text{Ca}^{3+}$, the bias voltage must be increased over a six hour period from 500 to 1400 volts, given a krypton support gas discharge. This increase in ΔV compensates for electrode wear and bore constriction. (If the bias is not increased, the beam intensity would decrease with time). On the other hand when ^{22}Ne was used for support, the bias voltage requirement, dropped to from 100 to 600 volts over a sixteen hour period. Calcium consumption rates were measured with the requirement that a constant $70 \mu\text{A}$ current of Ca^{3+} be maintained, (2 amp arc @ 15%), as suitable for accelerator use. They were found

to vary from 0.6 to 3.1 microns/hr/ $\mu\text{A Ca}^{3+}$ (~7%) for neon and krypton respectively. This is equivalent to weight losses of 125 and 680 $\mu\text{g/hr}/\mu\text{A Ca}^{3+}$ respectively. Xenon required even higher consumption than krypton, atom somewhat less. The consumption rate then, for equivalent beams is increased a factor of 5 to 21 when operating with neon rather than krypton, (or xenon). The column flow rate measured under these conditions appears to be about 50% a typical argon rate. The yield of two calcium ion species vs. support gas is shown in Figure 3.

Whether sputtering or not, the total particle ion current will closely resemble the shape of curve 4a of Figure 4. Several source types are indicated at minimum gas condition: a) ADAMI source at a fixed ΔV of 250 v and associated gas flow (b); c) ADAMI source with thermally emitting cathodes; d) GSI cold Penning source.² A comparison of input flow rates with total ion output indicates an increase in ionization efficiency at starvation. When support gas flow rates are increased, the CSD of both metallic and gaseous ions decrease. Under this condition, total gaseous ion currents rise but metallic ion currents will drop about 20% for a 2X increase in flow rate.

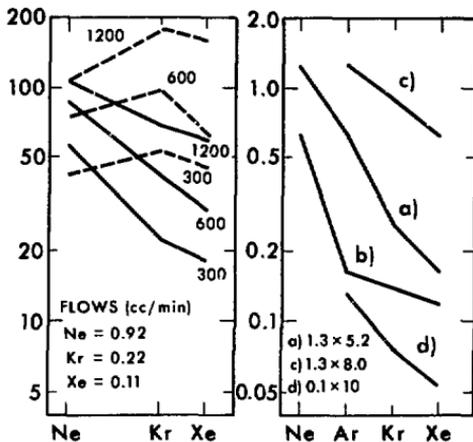


Figure 3. Beam current (μA) Ca^{3+} , and Ca^{2+} (dashed) vs. support gas. Bias (ΔV) recorded. 5.9 mm. collimation. $I_{\text{ARC}} = 1.9\text{A}$. 18%; Extr. 18KV.

Figure 4. Total beam current (mA) vs. gas type (a, c, d). Gas flow (cc/min) vs. gas type (b). Anode slit size noted (mm), 1.27 mm. collimation.

Curves a and b of Figure 5, while closely similar, illustrate seemingly unrelated parameters, i.e., the total fraction of calcium leaving the source magnet, and that bias voltage sufficient to produce a constant $70 \mu\text{A Ca}^{3+}$ outside the magnet over a range of four different support gases. As the bias voltage is increased (5b), the fractional contribution of the support gas to the total ion yield is decreased; first because of a measured increase in calcium atomization and second, because the optimum flow rates and ion yields of heavier gases will always be considerably lower. Thus with xenon support, over 70% of the source output is found to be helium. Additionally, the support gas yield is depressed as the total calcium ion output is increased, as shown in 5c, d, e.

Of interest, no dependable decrease in support gas flow may be taken when sputtering with a center electrode.

It suggests itself that a higher density discharge could be associated with neon, benefiting the production of calcium ions, particularly charge state three. A greater probability of ionization of a neutral

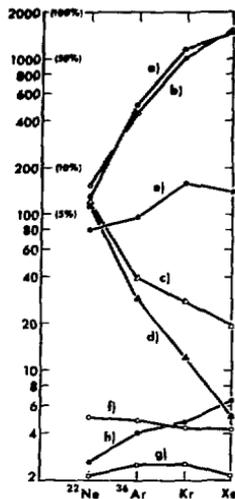


Figure 5. Various parameters vs. support gas type.

- a) Percent calcium of total source ion output (%)
 b) Bias voltage (ΔV). Ca^{2+} fixed at $70\mu\text{A}$
 c) Total extracted particle ion beam (μA , scale $\times 10$)
 d) Total extracted particle support gas beam (μA , $\times 10$)
 e) Total extracted particle calcium ion beam (μA)
 f) Average charge Ca (± 2)
 g) Electrode current (mA, $\times 10$)
 h) Average charge support gas (± 2)
 i) 1.9A. arc (15%; $72\mu\text{A}$ Ca^{2+} ; 5.9 mm. collimation, extraction 18 kV
 j) 5.9 mm. collimation, extraction 18 kV

in traversing the neon discharge would be a reasonable assumption, in view of the measured, lower consumption, or, feed rate of the calcium. This improved environment, however, leads only to a minor change in the CSD of calcium (see 5f).

If the density of the neon discharge is aiding Ca^{2+} production, the near uniform sputter currents (see 5g) need explanation. The sputter current is the product of the number of ions and the average charge of the bombarding ions. Therefore if calcium is the major bombarding particle, then the ion radial loss, as distinct from neutral loss, would have to be similar given a near equal CSD. And if instead the support gas be dominant, the higher average charge of that gas (see 5h) would allow for the near equal sputter currents. Apparently then, a larger fraction of atoms are lost in the xenon arc, therefore calling for greater bombarding energy. If this greater energy tended to sputter clusters of atoms, not as readily ionized to a 3^+ state, the feeding rate would of course rise. G. Carter has pointed out that the sputtering yield from multiply charged ions has been shown to exceed that value derived from a simple momentum consideration.²⁰ Experimental results appear to be sparse.

Measurements made in estimating calcium recovery rates are complicated by a high titanium contamination rate, at the center of the discharge.* Cathode to cathode spacing is about 41 mm. As a consequence, a tuning of the electrode bias voltage will increase extracted ion currents of the cathode material. Initially an insert tube was placed in the discharge column in hopes of recycling the calcium which would normally be pumped to anode walls. Several runs indicated a $30\% \pm 10\%$ reduction in wear rate. However the insert tube was found, naturally, to have moved the calcium collection surfaces to areas where collection is more awkward. Therefore the insert tube was abandoned for ^{40}Ca ionization, since emphasis here is with efficient collection. The cooled anode window plane (Figure 1a, 10a) will collect about 32% of the sputtered calcium. A modification of this plane to embrace the calcium electrode allows $80\% \pm 10\%$ recovery of calcium, but is useable only with neon since the collected calcium deposit with heavier gases, appears to limit the life of the main discharge, by altering bore size. A compromise between these two collection surfaces remains to be accomplished. A measurement of the calcium atom flux

*Titanium contamination must be accounted for. $25\% \pm 10\%$ of the deposit on the window plane is titanium, and has been estimated from x-ray fluorescence testing and from observation of the rate of titanium deposit on calcium.

to the slit in conjunction with total calcium beam measurements indicate that 1 out of 6 (± 3) calcium atoms are ionized for a xenon supported run. This measurement has not been conducted with other gases. See Appendix for a description of an unsuccessful experiment to extend the life of a calcium electrode.

The two ring electrode configuration (Figure 1b) showed a small improvement in the yields of Ca^{2+} and Ca^{3+} when tuned for equal Ca^{2+} production. Ca^{2+} dropped with the ring electrodes indicating a more favorable CSD with these electrodes. However the bias voltage, ΔV , was increased about 30%, probably due to calcium ion radial loss between electrodes and exit window. This increase accompanies nearly a two fold increase in surface area. Thus the total max flow from the electrode was more than doubled but the ring wear rate is 10% lower for equal performance in spite of the increase in ΔV .²¹ This no doubt may be explained by a greater fraction of calcium return to the electrodes. The longer path lengths between point of entry to point of departure appears to raise the probability of multiple ionization. Were a higher charge state of calcium required ($\sim 3^+$) and the conservation of calcium not critical, these rings would be considered a superior geometry.

Gold:

Other materials examined are titanium, iron, germanium, niobium, rhodium, tantalum, gold, and several fluoride compounds. Data collected with gold will be presented here.

The heavier support gases are found to be as effective as neon for the production of these heavier, high n^+ ions. As true for calcium, the heavier gases require greater bias voltages, or larger feed rates at near constant sputter currents. Argon has been selected for support, duly considering lifetime and the high peak arc current operation required for high charge state production. In all cases it is observed that the higher the charge state tuned for, the lower will the bias voltage be set and also the more critical the tuning. A high charge state yield is strongly attenuated by an excessive metallic feed rate, just as gaseous ion yields behave to excessive gas flow. Unlike gaseous atomic feed, the metallic feed rate may be tuned independently from the requirement of a greater than minimum flow, and can be decreased to zero. Figure 6 displays the gold CSD as a function of feed rate (ΔV). The

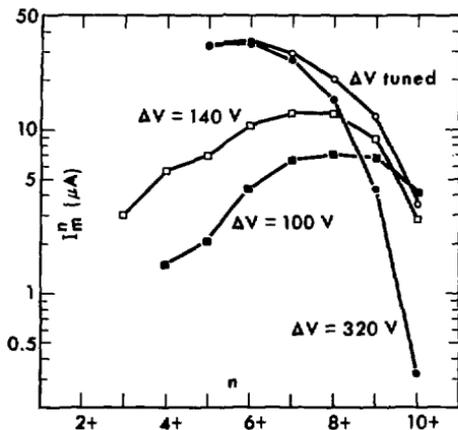


Figure 6. Gold ring electrode data, ion current vs. charge state. n. Support gas ^{36}Ar , 2.6 A. arc (18%), 5.9 and 12.7 mm. collimation. Extraction gap 2.8 mm, $U = 18\text{KV}$.

*Ring weight loss rates ($\mu\text{g}/\text{min.}/\text{cm}^2$) are $5\% (\pm 10\%)$ lower, as are the ring wear rates (microns/min.) lower by $10\% \pm 3\%$. Ring wear rate: 0.63 microns/minute (for $70\mu\text{A}$ Ca^{2+} , 5.9 mm coll., 0.3 A avg. arc I).

correct tuning for gold 10^+ , i.e., the $\Delta V = 100v$. curve, gives an extracted ion current average charge of six or more. (The lower charge states of gold are estimated.) The ionization potential of Au^{10+} compares closely to that of Ar^{10+} . However argon has an average charge of rarely any greater than two with this source.

The ' ΔV tuned' data indicates that ΔV is tuned for each specie, and will be used to compare the two electrode geometries reported in this paper.

The two ring electrode geometry shown in Figure 1b has been found to yield a more favorable CSD than the standard center geometry (Fig. 1a) used hitherto. These initial tests now in process indicate a factor of three improvement for the higher heavy-ion charge states. The ' ΔV tuned' data for center and ring electrode is compared in Figure 7b under identical operating conditions. Associated with this improved performance is a substantial increase in the tuned bias voltage of the sputtering electrode(s), as shown in Figure 7a. Careful weight measurements under controlled conditions have yet to be made with gold; presumably the ring electrode loss rate/cm² will not have increased in proportion to ΔV (as noted with calcium). Note that a greater gold concentration appears to be allowable before excessive gold feed rates attenuate the higher charge states.

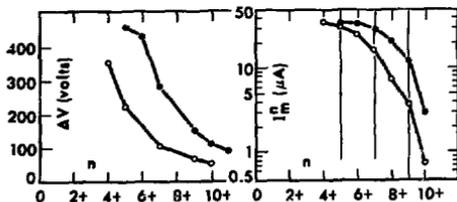


Figure 7. Center vs. ring electrode data; center (○), ring (●), 2:6 A. arc. Optimum ΔV vs. charge state gold (a), CSD gold, center vs. ring electrode at optimum bias, (b).

The ring electrode geometry was selected to insure a longer path length for those metallic ions extracted from the exit window. While this might well have been realized, another consideration bears attention.

A peaking of gold 9^+ and 10^+ as a function of gold feed rate (or sputter geometry, are shown in Figure 8.

The cathode material, titanium (or tantalum) is readily added to ion output due to the short length of this source. Indeed, the yield of titanium is readily optimized by sputtering away the continually generated thin coating of titanium depositing on the sputtering electrode. In Figure 8 one observes that the titanium concentration may be increased under those conditions selected for optimum gold production. Ti^{2+} and Ti^{3+} are increased from 3 to 6x respectively, when introducing a near equal fraction of gold atoms into the discharge. It is reasonable to conjecture that a gold (10^+) yield is attenuated by this high background of lower charge state titanium. The yield of titanium 2^+ for center and ring electrode geometry is shown in Figure 8. Of relevance is the more gradual increase of titanium with ring electrode geometry. The rapid increase in Ti^{3+} with center electrode, at those feed rates suitable for the higher charge states of gold, indicates that the gold yield is attenuated by the immediate reintroduction of titanium into the arc. Possibly the absence of a sputtering surface in the immediate vicinity of the slit allows the radial titanium ion flux to be collected to the anode wall and not reintroduced in the vicinity of the exit window.

It is puzzling that the Ti^{2+} yield appears to decrease only with massive localized gold feed rates from center electrode.

Finally, it should be noted that when sputtering is activated, a slight decrease in support gas flow appears possible with the ring elec-

trodes, and at low bias voltages ($< 100v$). Massive sputtering feed rates do not further reduce this gas flow rate.*

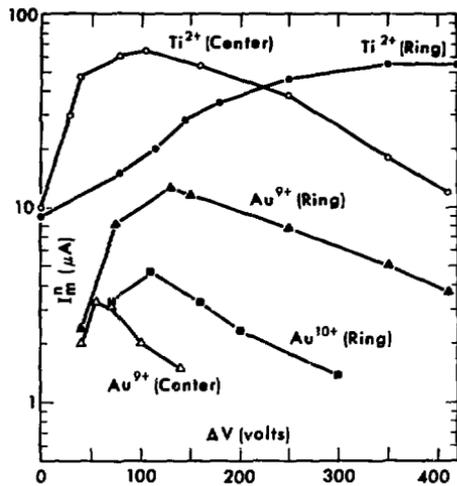


Figure 8. Center vs. ring electrode data; yield Ti^{2+} , Au^{9+} , Au^{10+} , vs. ΔV (volts). 2.6A, 900v arc (15%); ^{36}Ar support. 5.9 and 12.7 mm. collimation.

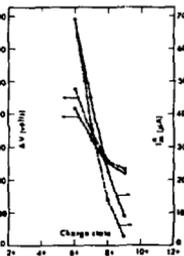
Summary

The placement of anode sputtering electrodes have traditionally been located in the immediate vicinity of the exit window. A different geometry has been studied. Two ring shaped electrodes have been placed midway between the exit window and the cathodes, i.e., about 7 mm above and below the center plane of the source. This geometry appears superior for high n^+ production for possibly two reasons. First, longer ion residence time, second, a reduction in the contamination of the arc column with cathode material at those bias voltages selected for optimum n^+ production. A factor of three improvement has been made with gold.

The consumption rate of material so introduced will exceed that of the customary center electrode, but the wear rate (microns/minute) is expected to be equivalent. Further measurements are called for. A low density of metallic material in the discharge, is inherent to best heavy ion production. High densities of atomized material do not

*It is noteworthy that when the support gas is raised, an increase in the solid feed rate is demanded for beam optimization. This effect is displayed in adjoining figure. The solid and dashed lines are at 0.11 cc/min. and 0.16 cc/min. (STP) argon support gas flow rates, respectively. The metallic flow does not appear to substitute for a gaseous flow.

ΔV vs. chg. state (n).
Iron current vs. n, gold



materially substitute for support gas. The attenuation of high n^+ metallic ions probably comes from a reduction in the electron temperature of the arc. Measurements of this temperature distribution are being considered.

The CSD of heavy metallic ions appears to be critically dependent upon the density of the metallic material in the discharge. The sputtering process allows the possibility for minute feed rates of metallic material. The average charge of this ionized material varies inversely with density. The peak value of average charge remains to be measured and will be substantially higher than with gaseous atomic feed.

Calcium consumption is a critical parameter for ionization of enriched ^{48}Ca . Neon support gas has been found to significantly extend the life of a calcium electrode, about a factor of 5 ± 2 when compared with a krypton supported discharge.

Approximately $1 \mu\text{A}$ peak current of Au^{1+} and $8 \mu\text{A}$ of Au^{10+} have been identified, with beam line attenuation. The source lifetime under this too performance condition is not yet determined.

Acknowledgement for excellent support is given to W. Stockton, and to Dr. D. Clark for his interest and support.

References

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Appendix

A typical data spectrum is illustrated below.

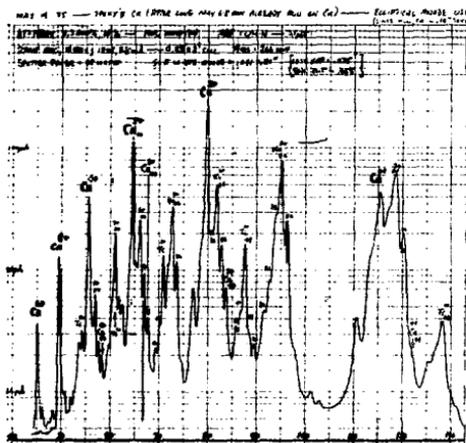


Figure 9. Ion yield (μA , peak) vs. magnet current (amps).

An experiment was run to ascertain whether the presence of the sputtering surface directly in line with the exit window was a factor in source performance. Figure 10b shows two calcium targets at right angles to the exit window. It was thought feasible that a favorable solid angle distribution from the sputtered targets would allow for self-recycling of calcium. However the rate of consumption (microns/ $\text{hr}\mu\text{A}$) was essentially unchanged from the standard geometry (10a) with neon support. Weight loss could not be measured due to the sputtering of the copper support between the two calcium targets.

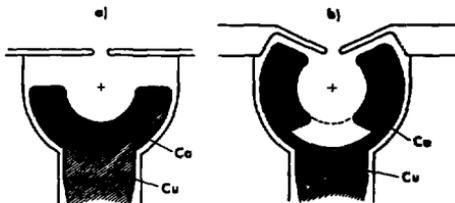


Figure 10. Cross section anode with standard Ca electrode; b) winged electrode at central position.