PRODUCTION OF POSITIVE ION BEAMS FROM SOLIDS

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Summary

We have recently reported a technique for making metal ions for cyclotrons.[1] Metal and non-metal ions from solids are produced in a Penning ion source by a process that involves ions that are unable to cross the first acceleration gap between the ion source and dee and are accelerated back into the ion source where they sputter charge material into the arc. This material is ionized and extracted from the ion source and accelerated. We have now used this technique for a large variety of ions, both metal and non-metal, including most recently aluminum from the metal and boron from boron nitride charge materials. We have also calculated the efficiency for making iron ions with different ion support gases and have experimentally checked these results.

We are presently designing a dual ion source for our dc Penning ion source test stand which we believe will make an excellent source for producing ions from solids for dc extracted Penning ion sources.

Introduction

Several methods of producing ion beams of solid materials for accelerators have been reported.[2,3,4] An additional method based on sputtering, discovered as a result of erosion of the ion source observed in the normal operation of the Oak Ridge Isochronous Cyclotron (ORIC), is described here. The erosion of the ORIC ion source plasma chamber had been observed and reported in 1971.[5] Figure 1 is a photograph of a new and a used ion source chamber. An eroded hole can be seen in the body of the used source when viewed through the ion source extraction slit. The significance of this erosion process was recognized when an exact analog (equal mass-to-charge ratios) copper beam was accelerated at the same time as a desired xenon beam. The detection of an accelerated beam having an intensity of ~1/2 microampere and its identification as copper led to experiments to determine its origin. Replacement of the back of the ion source chamber with different metals proved that the eroded region of the ion source chamber provided the charge material for the copper beam.

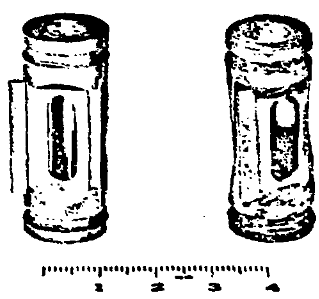

Fig. 1. New (left) and used ORIC ion source plasma chambers for gases. A hole has been eroded in the wall of the used chamber opposite the extraction slit. Typically, such a hole would appear after about two weeks of operation with argon.

*Operated by Union Carbide Corporation for the US ERDA.

ORIC Solid Material Penning Source

The ion source used on the ORIC for solids is shown in Fig. 2. It is a rotatable cold cathode[6] Penning ion source. The source plasma chamber is easily replaceable. The plasma chamber used for solid materials contains a pocket for a replaceable rectangular plate of the desired charge material (Fig. 3). The beams that have now been produced by this technique are given in Table 1.

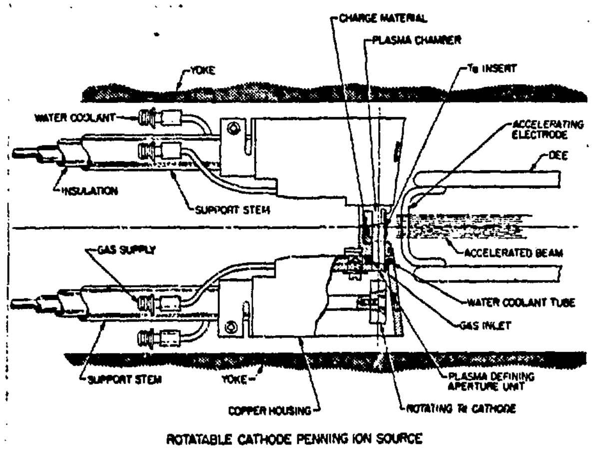

Fig. 2. A schematic view of the rotatable cold cathode ion source. The plasma chamber shown is designed to accept the solid plates which provide the material for sputtering.

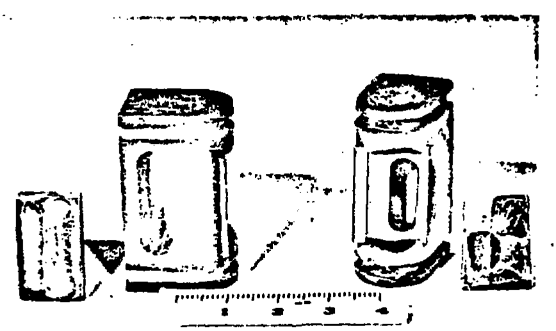

Fig. 3. Ion source plasma chambers for solids viewed from two different angles. The receptacle for the solid charge material can be seen on the left with a used aluminum source plate. The other source is viewed looking into the exit slit. Beside the chamber on the right is a used boron nitride plate.

Ion Production Calculations

Preliminary results of the performance of the source and calculations of the trajectories of the xenon ions that caused the erosion (sputtering) were reported earlier.[1] The calculations have now been extended to include an estimate of the quantity of beam returning to the source, and its effectiveness in producing sputtering, for xenon and other gases.

Table 1
Beams Produced from Solid Charge Material

Element	Charge State
Li	1,2,3
B	3
Mg	5,6
Al	4,5
Si	5,6
Ca	6,7,8
Ti	5,6,7,8
Fe	8,9,10,11
Ni	5,6,7,8
Cu	6,7,9
Zn	6,7
Nb	5,6,7,8,9

Ions return to the source because they are unable to cross the source-to-dee gap before the polarity of the dee voltage reverses. The ions that fail to cross the gap have a high mass-to-charge ratio resulting in a low velocity relative to the velocity of the desired ions. The rf phase at which they leave the ion source also determines whether they return to the source. A pictorial representation of the ion source with calculated orbits for late-phase, low-charge-state, xenon ions that return to the source is shown in Fig. 4. The xenon ions travel approximately halfway across the source-to-dee gap before the voltage changes polarity; the ions are then accelerated back into the ion source with energies in the 10's of keV range. The computed impact area for xenon ions is in agreement with the observed eroded area in the ion source. An approximate orbit of a successfully accelerated iron beam is also shown.

The quantity of beam that returns to the source to produce sputtering depends on three factors: the instantaneous voltage gradient, the mass-to-charge ratio, and the rf starting phase. The voltage gradient determines the quantity of ions leaving the source; the other two factors affect the quantity of ions returning to the source.

To determine the returning-ion "phase window" or span of the starting phase of the ions that return to the source and the ion impact energy, orbits at various rf phases have been computed. An impact energy of at least 5-10 keV is required to produce maximum sputtering. Essentially all of the ions that return to the source exceed this value (Fig. 5). The phase window for returning ions is dependent upon the m/q ratio. For example, $^{132}Xe^{1+}$ has a phase window of 180°, and $^{20}Ne^{2+}$ or $^{40}Ar^{4+}$ (m/q = 10) have a phase window of about 60°.

For each initial rf phase (θ), the relative intensity of returning ions for each charge state has been calculated assuming that the intensity is proportional to the dee voltage to the 3/2 power (Child's law), and by using the relative intensity of each charge state from dc ion source test stand data.

$$I(\theta)_i \;\alpha\; \frac{I_i}{q_i}\,[V\cos\theta]^{3/2},$$

where $I(\theta)_i$ is the relative intensity of charge i at phase θ, I_i is the relative intensity of charge state q_i obtained from dc ion source test stand data;[8] V is the peak rf voltage (80 kV). The result of this computation for xenon gas is shown in Fig. 6. This calculation shows charge state three to be the largest contributor to the sputtering process.

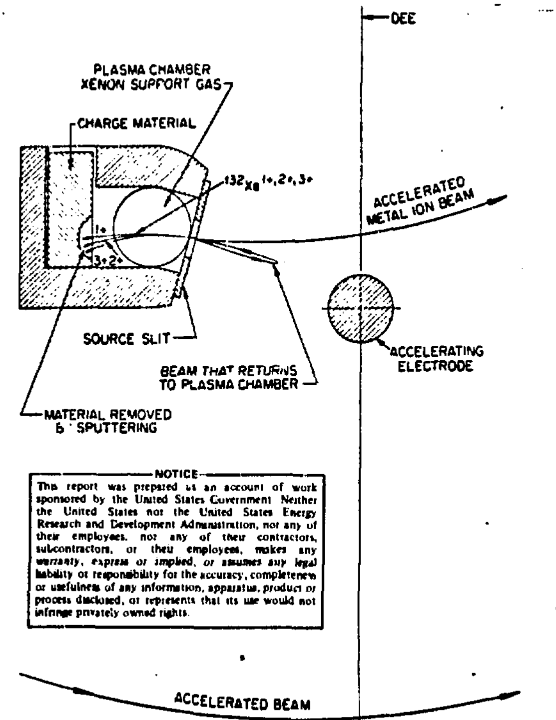

Fig. 4. Cross section of cyclotron central region with computed trajectories of $^{132}Xe^{1+,2+,3+}$ ions returning to the source. The accelerated beam is $^{56}Fe^{5+}$. Other assumed conditions were B = 1.8 Tesla; V_{max} = 80 kV; gap = 1 cm. The frequency is set for 3rd harmonic acceleration for the iron beam. This corresponds to about the 35th harmonic for $^{132}Xe^{1+}$.

In like manner the relative intensities of the beam available for sputtering when krypton, argon, and neon are used in the source have been calculated. Different gases produce different amounts of sputtering.[7] These relative yields are given in Table 2 and have been used in constructing the relative intensity curves of Fig. 7. The calculations indicate that krypton and xenon should produce beams of nearly equal intensity, with argon and neon considerably less effective. The observed intensities with different gases are consistent with the calculated values (Table 3). The cost of xenon is about four times that of krypton and hence the use of krypton would be favored.

Table 2
Sputtering Yield for Several Gases on Nickel Normalized to Xenon

Neon	0.27
Argon	0.55
Krypton	0.64
Xenon	1.0

Proposed DC Ion Source for Solids

The production of ion beams by the sputtering process as described above is only applicable to rf extracted sources (e.g., cyclotrons) since the reversed polarity electric field is required to cause a portion of the beam to return to the source. However, a dc beam of heavy ions from an adjacent ion source could be used to produce the required sputtering (Fig. 8) for a dc source. Such a source would have several advantages. By varying the output of the first arc the amount of material introduced into the second arc could be controlled. With a sufficiently intense beam from the first arc it is probable that no support gas would be required in the second arc, thereby giving more beam of the desired ions.

Table 3
Calculated intensity of returning ions, and extracted beam intensity of $^{58}Ni^{5+}$ for several gases (normalized to xenon)

	Calculated	Measured
Neon	0.24	0.13[a]
Argon	0.53	0.57
Krypton	1.14	1.1
Xenon	1.0	1.0

[a] Corrected for accelerator cryopumping efficiency.

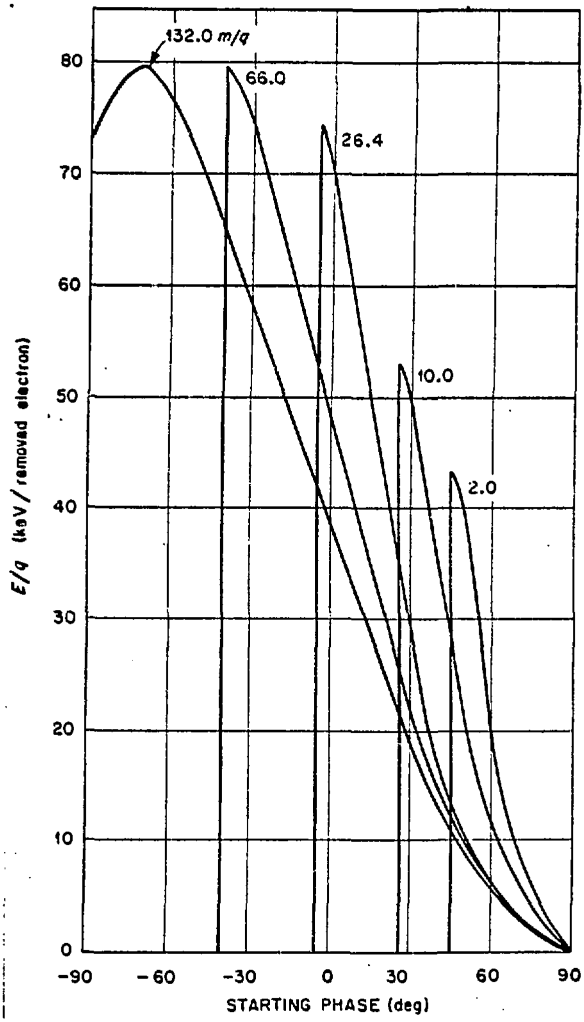

Fig. 5. Ion impact energy at the source versus starting rf phase for several values of mass-to-charge ratio. Ions that leave the source after the dee voltage has peaked (positive phase) constitute the bulk of the particles returning to the source for $m/q \geq 26$. For $m/q = 132$, all ions return to the source.

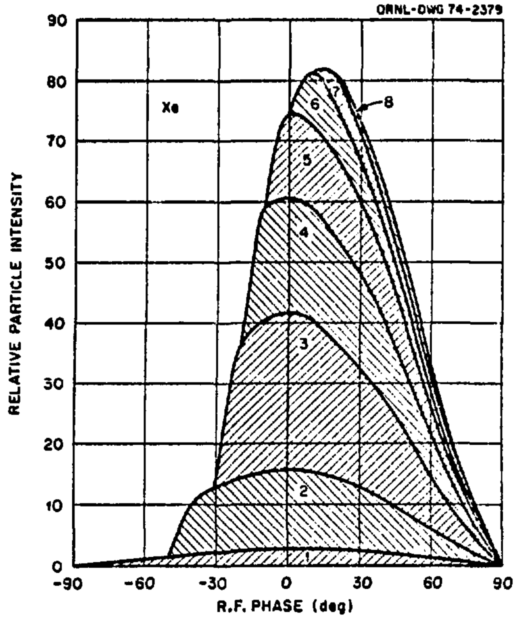

Fig. 6. Relative intensity of the ions returning to the source versus rf starting phase for the first eight charge states of xenon. The relative contribution of each charge state to the total beam is given by the area between adjacent curves.

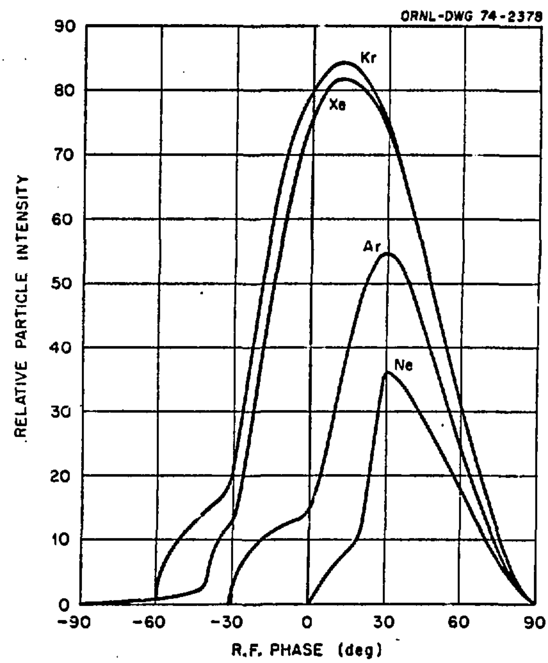

Fig. 7. The relative intensity of sputtered ions into the plasma for different source gases as a function of rf phase. The intensity for xenon and krypton are about equal.

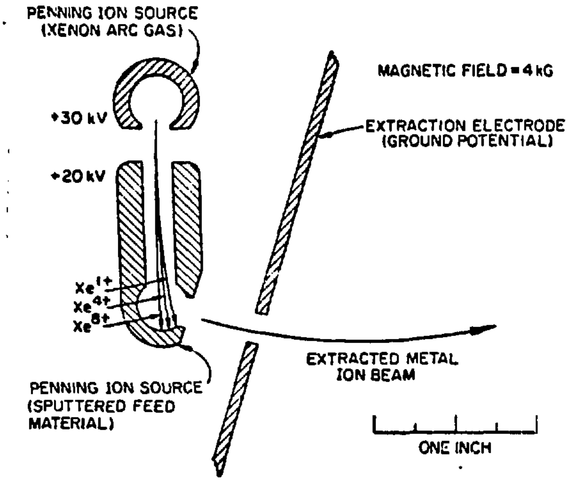

Fig. 8. Proposed dc metal ion source. A xenon arc is maintained in the source at +30 kV. Xenon ions are extracted and bombard the inside surface of a second arc plasma chamber at +20 kV and sputter solid material into the plasma. This material is then ionized and extracted from the second arc. This source could be used for continuous output (dc).

Ion Source Observations

The sputtering process can be used to explain several ion source phenomena in the ORIC. A niobium arc was found to be self-supporting when the xenon gas was turned off; however, when the dee voltage was turned off, eliminating the returning ion beam, the arc was extinguished. In another case, the $^{40}Ar^{9+}$ beam intensity increased after erosion of a hole in the ion source.[1] This effect is now believed to be due to the fact that the density of copper ions in the source is reduced when the hole is formed. When a hole of similar size was drilled into the arc chamber in a region not subject to sputtering from returning ions, no beneficial effect was observed.

Acknowledgements

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