Silver Ion Generation, Deflection and Deposition in Vacuum

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Abstract The potential problems arising during the operation of a pebble bed modular type reactor has stimulated a number of research avenues in different fields. This study presents results of a first approach method of deflecting a silver ion beam, in vacuum. These results serve as a building block for the future research that needs to be conducted in helium. An experimental apparatus was constructed and it was found that theoretically predicted deflections corresponded to within about 20% of the experimental results. The test apparatus could also be used as a practical supplementing a Physic course.

Keywords: Ions, Electric field, Deflection, Silver

Notation

a_y	transverse acceleration, m/s
D	deflector plate length, m
e	elementary charge, C
E	Electric field strength, V/m
E_{kin}	kinetic energy, J
L	drift length, m
L'	distance from the middle of the deflector plate to the target, m
m	mass of the ion, kg
t	time, s
v_x	longitudinal velocity, m/s
V_e	extraction (accelerating) voltage, V

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V_e extraction (accelerating) voltage, V

V_x deflection voltage, V

v_y transverse velocity, m/s

y transverse deflection, m

y' total transverse deflection, m/s

Subscripts

kin kinetic

x x-axis

y y-axis

Superscripts

$'$ maximum deflection

1 Introduction

The genesis of the PBMR (pebble bed modular reactor) design began with the German high-temperature reactor (HTR) development programme. This programme included two operational prototypes, the 15 MWe AVR (Arbeitsgemeinschaft Versuchsreaktor) and the 300 MWe thorium high temperature reactor (THTR) (Ion et al., 2004). The concept of the PBMR was introduced to South Africa in 1993 due to the anticipated increase in the demand for electrical power.

The PBMR reactor is a small (400 MW-thermal), modular reactor that is helium cooled and graphite moderated. It makes use of spherical fuel elements (or *pebbles*) which are approximately the size of tennis balls and can be recycled through the reactor without shutting down the reactor, thereby significantly increasing the fuel utilisation efficiency. The pebbles consist essentially of a 5 mm thick graphite shell containing a 50 mm spherical graphite matrix in which 15 000 small fuel kernels of 0.9 mm diameter are distributed. Each particle in turn consists of a 0.5 mm diameter uranium dioxide kernel with a graphite buffer layer to compensate for deformation and contained by a pyrolytic graphite layer, then a silicon carbide layer and again with a pyrolytic layer, the so-called TRISO fuel.

Although the fission products are successfully contained within the fuel under normal operating conditions it was reported that small quantities of silver are released at temperatures greater than 1250 ^{o}C (Cogliati and Ougouag, 2008). The silver, and in particular the radioactive silver-110m isotope with a half-life of 245 days, may find its way into the power conversion unit and potentially significantly increase waiting times before normal maintenance procedures can be initiated (Harding, 2005).

PBMR (Pty) Ltd, the company developing the reactor, has collaborated with a number of research institutions and universities in order to better understand how the silver is released from the fuel and how it may be removed from the hot helium coolant stream as it leaves the reactor. The work reported in this paper is a small part of this relatively large collaborative effort but focuses on two main specific objectives. The first objective is to investigate how silver ions may be produced, how they may be directed to move towards a target and how they may be deflected from there original flight path, in a vacuum. It was decided to first use a vacuum in order to assess what can be more-easily done before using the helium. The second objective was to construct an experimental set-up so that it could be incorporated into the physics course as a student practical. The work that was done in meeting these objectives, was done as part of a Masters Thesis project in the Mechanical Engineering Department, Stellenbosch University, South Africa.

In meeting these objectives, a brief literature review and basic theory is presented in section 2 of this article. In section 3 the experimental set-up is described, in section 4 the theoretical and experimental results are given, and in section 5 conclusions are drawn. Being a student practical, a safety and operational procedure is also given as appendix A.

2 Literature and theory

As the idea is to construct a vacuum chamber containing a silver-ion source, a means of extracting and accelerating ions, a collimator deflection plates and target plate onto which the ions may deposit, literature relating to these aspects was reviewed. Based on this review a formula for the deflection of ions passing through an electric field is then derived.

2.1 Literature

A vacuum arc is a high current, low voltage electrical discharge (Boxman, 1995) between two electrodes situated in a vacuum (Grisson and McClure, 1971). Vacuum on its own cannot support a high current discharge at low voltage and so a conducting medium is required. Arcing creates its own medium in the form of a highly ionized plasma of vaporized electrode material, produced by an intensive interaction of a plasma (ionized gas) with the electrodes (Siemroth et al., 1995). A vacuum arc is characterised by arc spots on the cathode (Takeda and Tekeuchi, 2002). Cathode spots are a source of plasma between the electrodes and have a degree of the number of atoms being ionised of between 50 and 100% (Fuchs et al., 1998).

Application of ion beams in research laboratories; industry and medical therapy have stimulated great interest in accelerated ion beams. Extraction and focusing of the beam is influenced by the geometry of the electrode system. The amount of the extracted ion current depend on the shape of the plasma surface in the extraction hole of the collimator, and depends on the ion source construction, size of the extraction hole and the extraction voltage (Hassan et al., 2008).

2.2 Deflection Theory

Referring to figure 1, the ions are extracted from the plasma formed during the arcing process by the extraction voltage V_e applied on the collimator; the collimator itself consisting simply of a 2.4 mm diameter hole in a 0.5 mm thick plate. The ions passing through the collimator hole enter the region between the two deflector plates of length D and which are spaced symmetrically along the x-axis a distance d apart. A relatively uniform electric field can be generated in this region by applying a potential difference V_d between the two deflector plates. In the electric field the ions experience a transverse deflection in the y-direction and are ultimately intercepted and deposited onto a target plate.

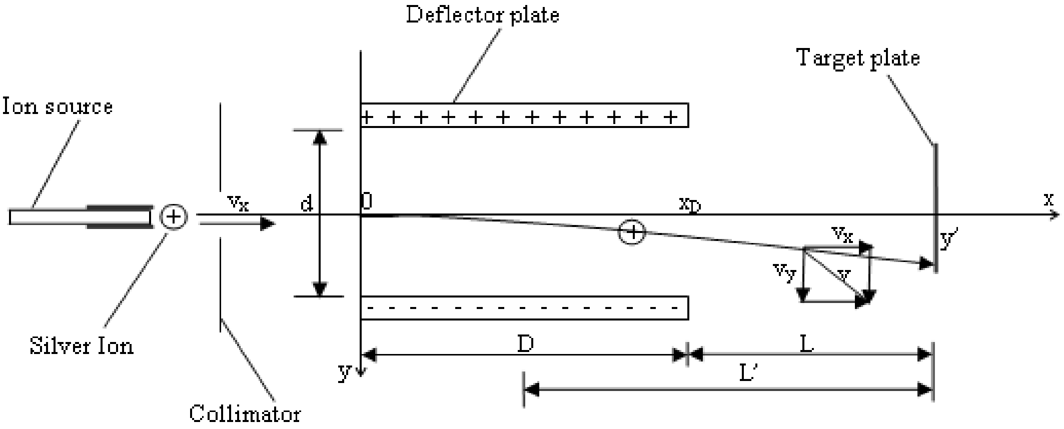

Figure 1 Deflection of silver ions in a uniform electric field (Young and Freeman, 1996)

Ions emerge from the arc with a kinetic energy determined by the extraction voltage (accelerating voltage) *V*. The kinetic energy E_{kin} is given by

$$E_{kin} = \frac{mv_x^2}{2} = eV_e \quad 1$$

Where *e* is the elementary charge of the silver ion

By rearranging equation 1, the longitudinal velocity v_x is expressed as

$$v_x = \sqrt{\frac{2eV_e}{m}} \quad 2$$

Considering ions with velocity v_x which enter a region of uniform transverse field *E*, the transverse force on the ion is *eE*. This force produces a transverse acceleration a_y whose magnitude is given by Newton's law of motion

$$ma_y = F_y = eE \quad 3$$

and hence the transverse acceleration is given by

$$a_y = \frac{eE}{m} \quad 4$$

Acceleration lasts for a time t_D, equal to the time spent in the field of

$$t_D = \frac{D}{v_x} \quad 5$$

where D is the length of the deflection region. The transverse deflection at x_D (where the deflector plates end) is given by

$$y_D = \frac{a_y t_D^2}{2} \qquad 6$$

The acquired transverse velocity is therefore

$$v_y = a_y t_D \qquad 7$$

Substituting a_y from equation 4 and t_D from equation 5 into equation 7 gives

$$v_y = \frac{eED}{mv_x} \qquad 8$$

The ion travels with uniform velocity and takes an additional time

$$t_L = \frac{L}{v_x} \qquad 9$$

to reach the target where L is the longitudinal distance between the deflector plates and the target. The ion undergoes a displacement y (after it has passed the electric field region) given by

$$y = \frac{Lv_y}{v_x} \qquad 10$$

Substituting for v_y from equation 8 into equation 10 gives

$$y = \frac{LeED}{v_x m v_x} \qquad 11$$

Substituting for v_x from equation 2 into equation 11 gives

$$y = \frac{LDE}{2V} \qquad 12$$

Electric field strength is determined by the potential difference V_x between the plates and the plate separation distance d and is given by

$$E = \frac{V_x}{d} \qquad 13$$

Substituting E as given by equation 13 into equation 12 gives

$$y = \frac{LDV_X}{2dV} \qquad 14$$

This is the transverse deflection which occurs after the ion leaves the deflection region. The total transverse deflection is obtained by adding equation 6 and 14

$$y' = \frac{V_X D}{2dV_e}\left(\frac{D}{2} + L\right) \qquad 15$$

where $\left(\frac{D}{2} + L\right) = L'$ is the distance from the middle of the deflector plates to the target plate.

3 Experimental construction details and set-up

Four different silver ion source electrode geometries were built and tested using different arc voltages, in the kV range, to generate the silver ions. In the first design the two silver electrodes were separated by a 1 mm glass slide which acts as an insulator, as shown in figure 2(a). One electrode is earthed and the other electrode has a positive potential. This design for an ion source was very delicate and the glass insulator would crack due to high voltage while the experiment was running. This caused arcing to take place through the crack and made it necessary to continuously make new ion sources, a second improved design was thus considered.

The second design of the ion source, shown in figure 2(b) consisted of a 3 mm diameter grounded silver electrode and a concentric outer sheet of silver electrode covering the glass insulator. The outer electrode had a positive potential and this connection led to the silver particles being generated on this electrode. During the experiment the glass insulator expanded and cracked due to the high voltage. Constructing more of these ion sources was hindered by the 3.1 mm diameter glass tube, which broke easily during the assembly of the ion source. Both of these ion sources used a dc power supply and arc voltages between 1.0 and 10.0 kV. The ion sources stopped working because they were sensitive to high voltages and deposition of silver was not observed on the target plate.

The third ion source design considered consisted of two silver electrodes with flat surfaces at the end of the electrodes, as shown in figure 2(c). Figure 2(c) shows the ion source and the target during testing of the ion source whilst figure 3 shows the complete experimental set-up used to conduct the experiment. For this ion source design, plasma could not form using the same power supply used for the first and second design of the ion sources. A higher voltage Heinzinger HNCs 40 kV/-15 mA was used to initiate arcing. When running the experiment an arc would form between the electrodes with one electrode at ground potential and the other electrode at -20 kV. The pulses of the power supply were however inconsistent and the time difference between the pulses varied which caused the experiment to run for too long a time. However, running the experiment for a long time interfered with the electronic circuitry of the turbo pump.

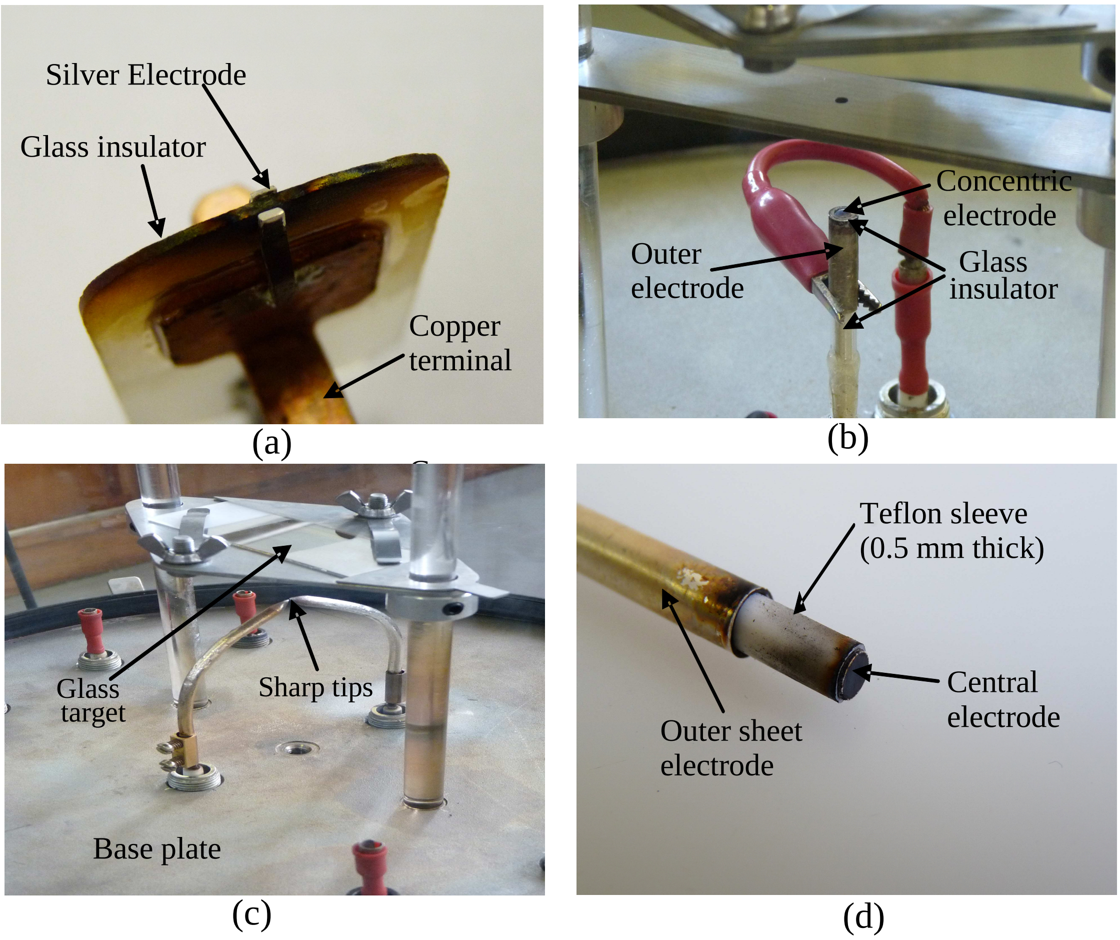

Figure 2 First design of the ion source (a), Second design of the ion source (b), Third design of the ion source (c), Fourth and final design of the ion source (d)

Several measures were undertaken to prevent this interference, but none were successful. The methods investigated included placing the power supply of the turbo pump far away from the experiment so that electromagnetic waves produced during arcing would not interfere with the power supply of the turbo pump as shown in figure 4. Covering the glass cylinder of the experimental set-up with aluminium foil to stop the electromagnetic waves and the cable of the power supply that runs from the power supply to the turbo pump with aluminium foil did not help. The use of this ion source was therefore discontinued because it required very high voltage and caused the safety interlock in the electronic controller to switch intermittently off the power to the turbo pump.

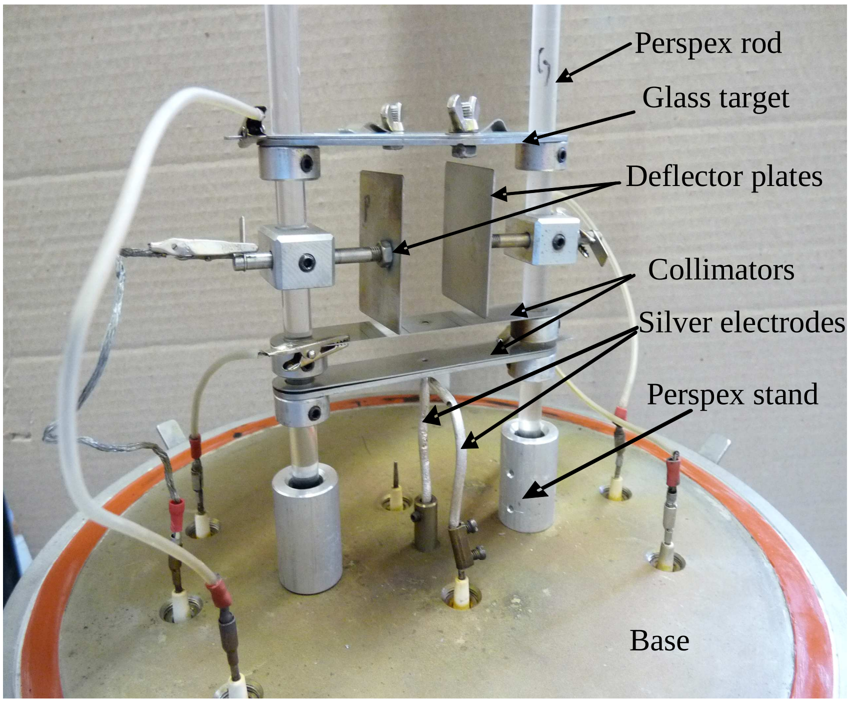

Figure 3 Close-up of the experimental set-up

The fourth and final design for the ion source is similar to the second design, but with a different insulator material. The two electrodes are separated by a Teflon sleeve as shown in figure 2(d) and in operation, in figure 5. The final design of the ion source showed that changing the insulating material from glass to Teflon instead of glass significantly improved the performance of the ion source. The voltage connection was also different for this ion source. The central electrode had a positive potential (2 kV) and the outer sheet (electrode) was grounded. Ions were formed from the central electrode and accelerated upwards due to the positive charge on the positive electrode and the extraction voltage (-3 kV) of the collimator, shown in figure 3. A dc power supply was also used for this ion source with a maximum output voltage of 3 kV and 15 mA. The arcing voltage was 2 kV, the extraction and acceleration voltages (voltage on the target) were both -3 kV and the deflection voltage was 1 kV. The power supply could not produce voltage and current pulses at a uniform rate, triggering of the power supply by hand was thus done to reduce the time difference between the pulses. In this way it was possible to increase the rate of deposition of silver ions on the target plate.

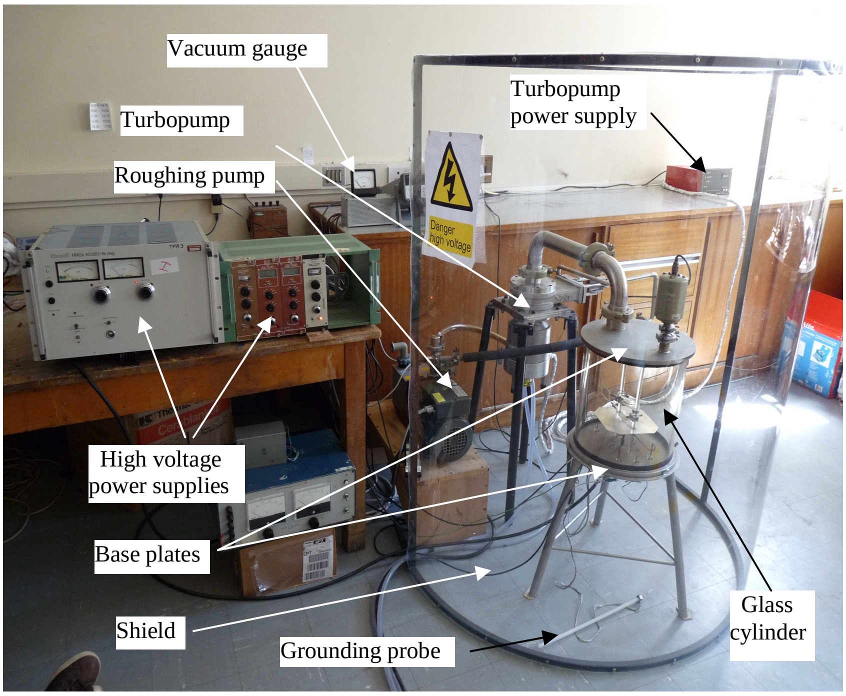

Figure 4 Experimental set-up

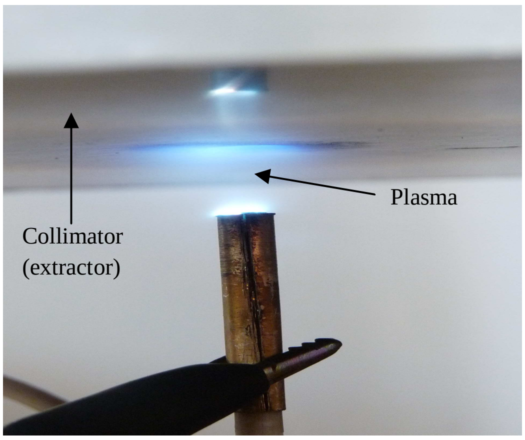

Figure 5 Plasma formation from the ion source

4 Results

Figure 6(a) shows all the results obtained after running the experiments. The top slide in figure 6(a) is the reference target slide with the silver deposited on it. The beam of silver was collected on the left hand side of the target so that the silver deposit can be seen to have moved to the right hand side of the target as the particles experience deflection. For the reference target indicated as 0 V the deflection voltage was not switched on. The deflection voltages used for the second, third and fourth target were 1.0, 1.5 and 2.0 kV respectively. As the deflection voltages were increased the deposit spots were observed to move to the right hand side, which confirmed deflection of silver ions by the uniform electric field.

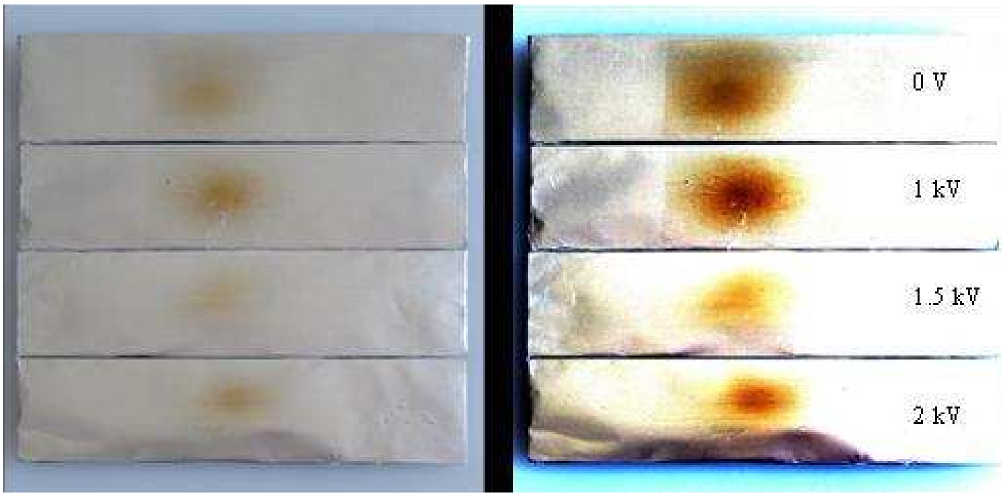

Figure 6 Final results (a), and enhanced photographs of the final results (b)

Table 1 shows the experimental deflection results measured independently by different people. This was done because the exact deflection is not clearly defined and its precise position is subject to personal interpretation and hence a number of people were asked to do the measurements. The samples measured are shown in figure 6(a). The measured values on the second, third and fourth target were subtracted from the reference value to obtain the experimental deflection results shown in table 1. Each row in the table represents a set of results measured by each individual. The columns categorise the deflection results according to their deflection voltages.

Table 1 Experimental results of deflection measured independently by different people

Deflection (mm) at 1 kV	Deflection (mm) at 1.5 kV	Deflection (mm) at 2 kV
3.0	2.6	5.3
1.7	2.1	4.9
1.5	2.4	4.0
1.9	2.3	4.8
2.2	1.0	4.4
2.7	2.3	4.5
1.9	1.2	4.2
2.2	2.5	4.6

Table 2 shows the average deflection results given in each column of table 1, whilst table 3 shows the average theoretical deflection results obtained using different deflection voltages. The theoretical and experimental deflection results obtained when deflection voltages of 1 and 2 kV were used are in agreement to within 11.6 and 5.9 % (as shown in table 2 and table 3 respectively. However the deflection results for theory and experiment when a deflection voltage of 1.5 kV was used are not in agreement. The experimental result differs by 43 % from the theoretical. This was due to an erratic voltage switching device in the electronic circuit of the power supplies.

Table 2 Average experimental deflection results

Extraction voltage (kV)	Deflection voltage (kV)	Average experimental Deflection (mm)
3.0	1.0	2.14
3.0	1.5	2.05
3.0	2.0	4.59

Table 3 Average theoretical deflection results

Extraction voltage (kV)	Deflection voltage (kV)	Average theoretical Deflection (mm)
3.0	1.0	2.42
3.0	1.5	3.62
3.0	2.0	4.88

The average theoretical and average experimental deflection results are shown in figure 7 as a function of the deflection voltage. Both the theoretical and experimental results show a linear relationship as the deflection increases. The 1.0 and 2.0 kV results are seen to compare well with each other; the experimentally determined deflection at 1.5 kV was not that close; this was attributed to equipment limitations, as discussed in section 3.

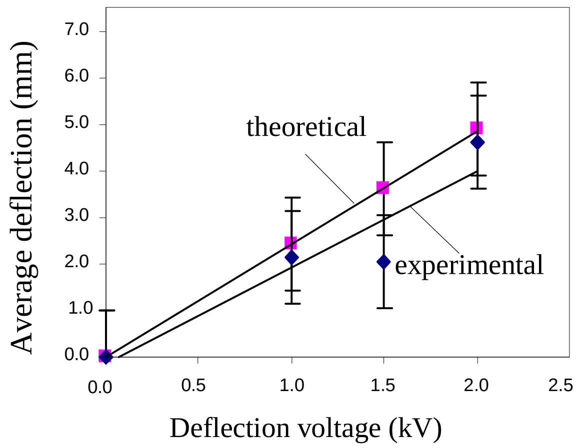

Figure 7 Theoretical and experimental results

5 Conclusions

The stated objectives of this study were met, ions were generated, extracted, deflected and deposited in vacuum. The first and second designs of the ion sources did not generate silver ions due to their unreliability. The third design of the ion source was discontinued because it required very high arcing voltage (20 kV). [The electromagnetic radiation produced when high voltages were used activated a cut-out protection switch in the electronic circuitry that caused the turbo pump to stop working.] With the first three designs of the ion sources no silver ions were successfully generated. The fourth and final design of the ion source did however not only produce silver ions but operated for a longer time at relatively low arc voltages (2 kV). The performance of this ion source was improved by the use of Teflon as an insulator between the electrodes.

The silver ions were observed to move away from the ion source due to the positive charge on the central electrode and the high negative charge on the collimator. Figure 6(a) shows that the deflection of silver ions was achieved and the deposition of silver ions was observed to move to the right hand side of the target plate. The theoretically determined deflection compared favourably well with the experimental results. The secondary objective was also met in as much that the experimental apparatus and set-up was shown to be useful as a student practical to supplement a physics course.

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Appendix A

Safety and experimental procedures

Safety measures

- Personnel must wear a lab coat, safety goggles and closed shoes at all times.
- During experimental operation personnel must be separated from the experimental setup by the safety glass shield.
- No unauthorised person may operate or change the experimental set-up.
- High voltage power supply must be handled with care.
- Before switching on the vacuum pumps ensure that all the valves are sealed.

Possible Hazards

- Electric shock
- Explosion of the glass cylinder in high vacuum
- Water leak

Preventatives Measures:

- Electric shock
  - Switch off the power supplies before changing the deflector plates and collimators.
  - No unauthorised person may change/adjust the deflector plates and collimators.

- Explosion of the glass cylinder
  - Ensure the safety glass shield is in place between the personnel and the experiment.

- Water leak
  - Switch off the power mains and then dry the area.

Operating Procedure

- Ensure all safety gear is worn (safety goggles, lab coat and closed shoes).
- Before assembling the apparatus make sure that all the power supplies are on safe mode/switched off and use the ground stick to check whether it is safe to assemble the apparatus.
- The glass cylinder must be safely stored on an allocated cushion in the laboratory cupboard before and after operation.
- Assemble the apparatus. Recheck for any errors in the assembly.

- Vacuum: switch on the rotary vacuum pump first until the pressure of 10^{-3} Torr is reached, then switch on the turbo molecular pump. Test for leaks while the rotary pump is drawing vacuum, before the turbo pump is switched on.
- Before switching on the arcing power supply make sure that deflector plates, collimators and target plate are at the correct potential and that there is no arcing between them.
- Switch on the arcing power supply.
- Open the tap water to run water for cooling and ensure that there is no water leak.

Safety procedure during operation

- Stand behind the safety glass during operation.
- Do not step on water or touch the experimental apparatus if there is a water (leak to prevent electric shock).

Safety procedure after running the experiment

- Switch off the turbo molecular pump first. Wait for 8 minutes and then switch off the rotary vacuum pump.
- Switch off all power supplies and arcing power supply before dissembling the apparatus and use the ground stick to check for voltages.
- Dissemble the apparatus and ensure that the glass cylinder safely stored.