DEVELOPMENT OF A VOLTAGE MONITORING SYSTEM FOR ION SOURCES*

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Abstract

At iThemba Laboratory for Accelerator Based Sciences (LABS), proton beams extracted from an internal Penning ion source, are pre-accelerated in a K8 injector cyclotron and further accelerated in a K200 Separated Sector Cyclotron. The accelerated beams are transported to various target stations used for radionuclide production. An important parameter of the Penning ion source is its lifetime. The multitude of factors which impacts this parameter remains not well-understood for the Penning ion source at iThemba LABS. From previous investigations it is known that this parameter is strongly influenced by the discharge voltage and current. The discharge current is however less sensitive to revealing the presence of high-frequency plasma phenomena. As a result of this empirical observation, voltage monitoring will be the focus of this investigation. To develop a deeper understanding of the impact of voltage monitoring on the source lifetime, a new diagnostic is currently being developed in collaboration with the ISIS Facility of the Rutherford Appleton Laboratory. The proposed work builds on pioneering development of a similar system on the pulsed Penning ion source at ISIS. This contribution presents a preliminary design of the voltage monitoring system as well as sputtering analysis of the cathode of the ion source after operation. The latter investigation was performed with X-ray fluorescence (XRF) to determine the elemental composition of the cathode material post-operation. This reveals more information on the "poisoning" of the cathode during operation which is thought to be one of the main factors limiting the lifetime of the Penning ion source at iThemba LABS.

INTRODUCTION

To produce the proton beam at iThemba LABS, a Penning ion source has been used since the mid-1980s. Figure 1 shows a photo of the Penning ion source at iThemba LABS with the molybdenum front plate removed. The photo shows the main plasma-facing components of the ion source. The biggest limitation with these proton sources is its limited lifetime. The most common modes of failure for Penning ion sources have been discussed in the literature [1]. From Ref. [1] it was concluded that erosion of the electrodes by physical sputtering is the main limitation on ion source lifetime. To assess the relative importance of this mode of failure on the lifetime of the Penning ion source at iThemba LABS, two novel diagnostic systems are currently being implemented. It is known from Ref. [2] that the rate of sputtering depends on factors such as the projectile atomic mass and energy, angle of incidence and target material properties. Based on empirical equations for sputter yields at normal incidence [3], the plasma-facing components of the Penning ion source at iThemba LABS is estimated to have a low sputtering yield under hydrogen ion bombardment at the operating conditions. The goal of this work is to understand how the discharge voltage influences the sputtering rate of plasma-facing components in arc discharge ion sources.

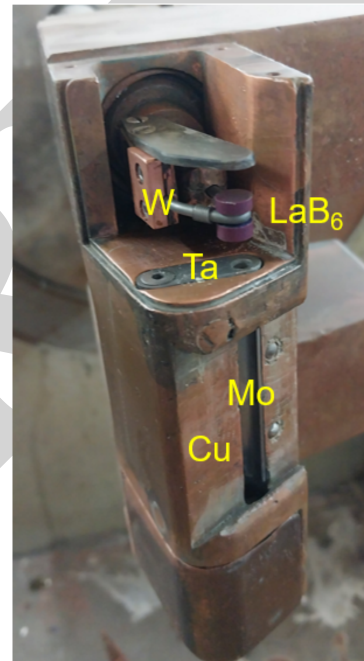

Figure 1: Penning ion source at iThemba LABS with the molybdenum plate removed.

VOLTAGE MONITORING ON THE ITHEMBA LABS PENNING ION SOURCE

Figure 2 shows the interconnections on the Penning ion source at iThemba LABS. The top part of the schematic is the connection to the tungsten filament which heats the lanthanum hexaboride cathode. As a result of this heating, thermal electrons are emitted in a process called thermionic emission. To increase the kinetic energy of the thermal electrons, a voltage is applied between the cathode and anode of the ion source. This connection is shown in the bottom part of the schematic. Floating on top of this voltage (cathode-

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to-anode) is the tungsten filament voltage. The ion source is operated in discharge current controlled mode. This implies that the current is set by the ion source operator while the discharge voltage is a dynamic parameter adjusting to a certain value depending on the demand-current and ionisation rate of the H_2 gas present in the discharge volume. Measuring the cathode-to-anode voltage, as is done in this work, reflects the changes in the plasma reservoir which in turn is indicative of the many processes occurring inside the discharge volume of the ion source leading to ion production.

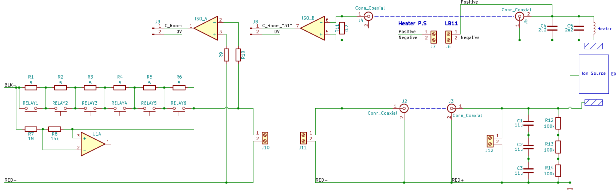

Figure 2: Schematic of the SPC1 Penning Ion Source connections.

Tarvainen *et al.* developed a sputtering model for pulsed arc discharge ion sources [4]. Though the Penning ion source considered in this work is operated in cw mode, the model gives an indication of the relative sputtering to be expected of plasma-facing components. Because the Penning ion source at iThemba LABS is mostly operated with hydrogen gas, the hydrogen sputtering on all the major plasma-facing components can be estimated using the sputtering model developed in Ref. [4]. From the sputtering model, the threshold energy for sputtering by the incoming projectile ion on the target atom can be determined. Using the equation developed in Ref. [4], the threshold energy for proton sputtering on different plasma-facing materials in a Penning ion source is calculated and given in Table 1 below. It is worth noting that in Ref. [4], the point is made that the sputtering yields is directly proportional to the arc current (flux of bombarding agents) but has a complex dependence on the arc voltage. Notably, the threshold energies for proton sputtering of the metals potentially found in direct contact with the ion source plasma (either structural or evaporated) are below the particle energies corresponding to the typical discharge voltage range of 200-100 V except for copper. On the other hand, the self-sputtering energy threshold of the metals listed in the table is on the order of a few tens of eV, easily attained by the discharge voltage.

Table 1: Threshold Energy (in eV) for Hydrogen Sputtering on Four Different Target Materials

Mo	Cu	W	Ta
280	90	600	590

X-RAY INDUCED FLUORESCENCE ANALYSIS

The typical lifetime of the Penning ion source at iThemba LABS is approximately two weeks. The predominant mode of failure is currently unknown, but it is postulated that the cathode is coated during operation with atoms from the plasma-facing components. The above sputtering considerations suggest that self-sputtering could be an important source of erosion. This coating impedes the electron emission from the cathode, a process commonly known as cathode poisoning. To verify this hypothesis, the cathode of the ion source was sent for XRF measurements to determine the contaminants on the surface of the high-purity lanthanum hexaboride cathode, post-operation. The Epsilon3 was used for energy-dispersive XRF analysis using six different modes. Each of the modes allows for the characteristic X-rays of the contaminants of the different heavy ion species to be measured. In Fig. 3 the spectrum for elements from phosphorus to silicon is presented. The most prominent peaks are from silicon, molybdenum and silver. The silicon peak originates from the silicon crystal in the detector used for the XRF measurements. The molybdenum originates from the molybdenum plate removed in Fig. 1. The silver peak in the background is due to the silver filter used by the Epsilon3.

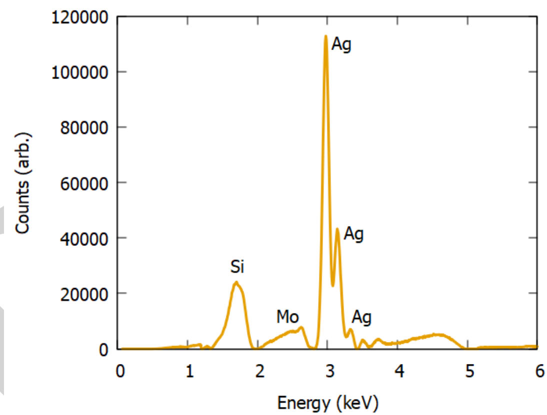

Figure 3: Spectrum of the post-operation lanthanum hexaboride cathode using conditions to measure F-Si.

In Fig. 4 the spectrum for elements from chromium to cobalt and praseodymium to thulium is presented. This spectrum is dominated by lanthanum peaks from the cathode.

CONCLUSION

In this paper we combine voltage monitoring and XRF measurements to gain some insight into the mechanisms that negatively impact the lifetime of the Penning ion source at iThemba LABS. One of the main causes of source failure is speculated to be due to cathode poisoning. According to this hypothesis, the plasma-facing components are sputtered by various ions and as a result of this process coat the surface of the lanthanum hexaboride cathode. From the results presented in Table 1 above, it seems clear that under normal operating conditions, the cathode-to-anode voltage is too low to cause a significant amount of sputtering by hydrogen bombardment.

From the XRF analysis and voltage monitoring a number of striking conclusions can be drawn. Firstly it should be noted that most of the spectra are dominated by lanthanum.

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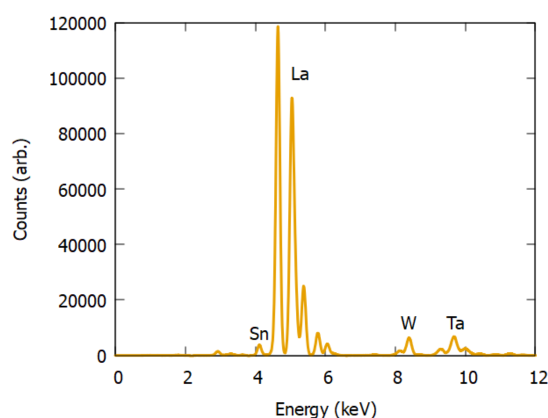

Figure 4: Spectrum of the post-operation lanthanum hexaboride cathode using conditions to measure Cr-Co and Pr-Tm.

As a light element boron is very difficult to measure by traditional XRF methods, hence it does not appear in any of the spectra. The other dominant peaks are tantalum and tungsten. The measurements also show some molybdenum peaks. The typical value of the cathode-to-anode voltage is approximately 130 V. From the values calculated in Table 1 it is clear that this voltage is not sufficient for hydrogen bombardment to cause the sputtering observed from the spectra. This leads to a number of conclusions that can be drawn about the sputtering. It is postulated that the sputtering is caused by impurities. The origin of these impurities are multiple. To kick-start the discharge, a current is passed through the tungsten filament. The value of this current is typically 200 A which heats the filament to a temperature of approximately 1326.85 °C. This can result in evaporation from the tungsten filament and is one possible source of impurities. Another source of impurities could be due to the oxidation process. Water can be absorbed on the various surfaces of the ion source especially when the source earlier developed a water leak. Similar to boron, oxygen is typically not detected by XRF and only characteristic X-rays as low as sodium can be detected by the Epsilon3. Another possible source of impurities is during the cutting of the lanthunum hexaboride cathode. The cathode is bought as a rod which is cut into smaller pieces using a cutting tool and a coolant. In previous years, the cathodes were baked in an oven to remove the contaminants on the surface of the cathode post-cutting. Because the cathode is in any case exposed to atmosphere post-baking, this practise was stopped. A third possible source of impurities could originate from the hydrogen gas used in the Penning source. In previous years we used grade 6 hydrogen but in latter times we have been using grade 5 due to challenges in securing grade 6 hydrogen. The additional impurities in the gas could be a source of concern though this possibility is thought to be quite low. Each of these sources of impurities could result in sputtering of the cathode which far exceeds the hydrogen bombardment. By accelerating each of these heavy ion impurities can lead to sputtering into the plasma-facing components. The tungsten peaks observed in the spectra is therefore in all likelihood sputtering of an impurity into the tungsten filament. Similarly the tantalum peaks are caused by sputtering of the anode. Additionally the collimator shown in fig. 1 is also made of tantalum. The source of the molybdenum in the spectra is caused by the molybdenum plate in the ion source head not shown in Fig. 1. The spectrum also includes a peak at 4.10 keV. The identity of this peak is not clear and while it could be some tin from the silver soldering, the absence of peaks from copper and zinc makes this option less likely. To enhance our diagnostic system, we are developing a voltage monitoring tool to pick-up fast variations of the discharge voltage caused by plasma instabilities. These instabilities could cause the voltage to momentarily exceed the sputtering threshold for protons. It is also worth mentioning that the lack of copper in the XRF further suggests direct sputtering of the ion source components is not causing the cathode poisoning. It seems that there's some filament evaporation as well as potential evaporation of the silver solder, both of thermal origin. We are also developing optical diagnostics to observe impurities, most importantly oxygen, which could drastically contribute to the cathode poisoning.

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REFERENCES

[1] D. Mitchard *et al.*, "Experiments towards operational improvements of the ISIS Penning H⁻ ion source", *J. Instrum.*, vol. 20, no. 05, p. C05023, 2025. doi:10.1088/1748-0221/20/05/C05023

[2] P. Sigmund, "Theory of sputtering. I. Sputtering yield of amorphous and polycrystalline targets", *Phys. Rev.*, vol. 184, no. 2, pp. 383–416, 1969. doi:10.1103/PhysRev.184.383

[3] Y. Yamamura and H. Tawara, "Energy dependence of ion-induced sputtering yields from monatomic solids at normal incidence", *At. Data Nucl. Data Tables*, vol. 62, no. 2, pp. 149–253, Mar. 1996. doi:10.1006/adnd.1996.0005

[4] A. Garcia Sosa *et al.*, "Impedance characteristics and sputtering behaviour of two pulsed DC arc discharge H⁻ sources", presented at ICIS'25, Oxford, UK, Sep. 2025, unpublished.

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