Operating a cesium sputter source in a pulsed mode

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A scheme is presented for pulsing of a cesium sputter negative ion source by periodically switching on and off the high voltage driving the sputtering process. We demonstrate how the pulsed ion beam can be used in combination with a pulsed laser to study the photodetachment process where a negative ion is neutralized due to the absorption of a photon. The experiments show that the lifetime of a cathode in the pulsed mode is increased by two orders of magnitude as compared with DC operation. We also investigate how the peak ion current compares with the ion current obtained when the source is run in a DC mode. We find that the peak current in the pulsed mode is strongly dependent on the ion species. In some cases we observed a strong enhancement, whereas others showed only a moderate, or even decrease, in peak current. We conclude that the pulsed mode operation can be of great value when the negative ion to be investigated requires cathodes that have short lifetimes, expensive materials or those with relatively small ion beam yields, in the latter case limited to elements with large enhancement factors.

I. INTRODUCTION

There are several important applications in various fields in which beams of negative ions are used. In many of these cases, one takes advantage of the fact that the outermost electron in negative ions is loosely bounded and hence easily removed. Accelerator Mass Spectrometry (AMS), which is a widely used method for detection of isotopes with very low abundances[1], is maybe the most well known example. AMS employs a tandem accelerator equipped with a negative ion source to produce and selectively analyze rare isotopes with high sensitivity.

The fundamental properties of negative ions are also of considerable interest due to the enhanced role played by electron correlation, making the structure of negative ions very different from that of isoelectronic atoms or positive ions. There has therefore been a great interest in studying the properties of negative ions, in which laser photodetachment spectroscopy using ion beams has been the method most often used[2,3].

The binding energies of negative ions, i.e. the Electron Affinity (EA) of the corresponding neutral atoms, have been determined for essentially all elements that form stable negative ions[3,4]. Also, many investigations of doubly excited states embedded in the photodetachment continuum have been conducted[5–7]. Further, facilities like DESIREE at Stockholm University[8,9] and CRS at the Max-Planck Institute in Heidelberg[10,11] allow for the investigation of negative ions that can be constrained for up to several hours in cryogenic storage rings due to the ultra high vacuum environment ($<10^{-13}$ mbar). Lifetime measurements of excited states of negative ions have been measured by probing the time dependent population of an excited state via a measurement of the photodetachment yield[12–14].

An example of an interesting application of negative ions is their potential for sympathetic cooling of anti-protons in a Penning trap[15]. Such a scheme would require an ion with an excited state that is connected to the ground state via an electric dipole allowed transition. Such cases are rare since typically negative ions only exist in the ground state. Only three such cases has been observed, namely the negative ion of lanthanum[16], cerium[17] and osmium[18], where lanthanum seems to be the most promising candidate.

All of the investigations of the properties of negative ions discussed above, have been performed with the ions in the form of a beam. The most versatile, and generally the most often used ion source for such studies, is the cesium sputter negative ion source, originally developed by Middleton for use in AMS in DC operation[19]. This ion source can be used to produce intense beams of most atomic and many molecular negative ions[20]. In such experiments pulsed lasers are normally used. The main advantage of a pulsed laser is the very wide range of output wavelengths, from the UV all the way to the far IR regions.

An important consideration is how efficiently the laser pulse temporally interacts with a DC ion beam. The pulsed lasers typically have repetition rates of 10 Hz. Such a temporal overlap would correspond to a duty cycle of the order of 10^{-7}. One outcome of this inefficient laser-ion beam interaction is the continuous erosion of the cathode material used in the DC-operated sputter ion source, since only a minute fraction of the ions that are produced actually interact with the laser light.

In this paper we present a method of pulsing a cesium sputter ion source. A similar technique has previously been applied by Steski *et al*[21], with the aim of increasing the peak current in a pulse of gold anions that were to be injected into the heavy ion collider, RHIC. We demonstrate how the pulsed ion source can be synchronized with a pulsed laser to improve the temporal overlap of the beams. The pulsing of the source increases the lifetime of the source cathodes by two orders of magnitudes. We also present results on how the peak current in the ion pulses compares with the typical currents obtained when the source is operating in a DC mode.

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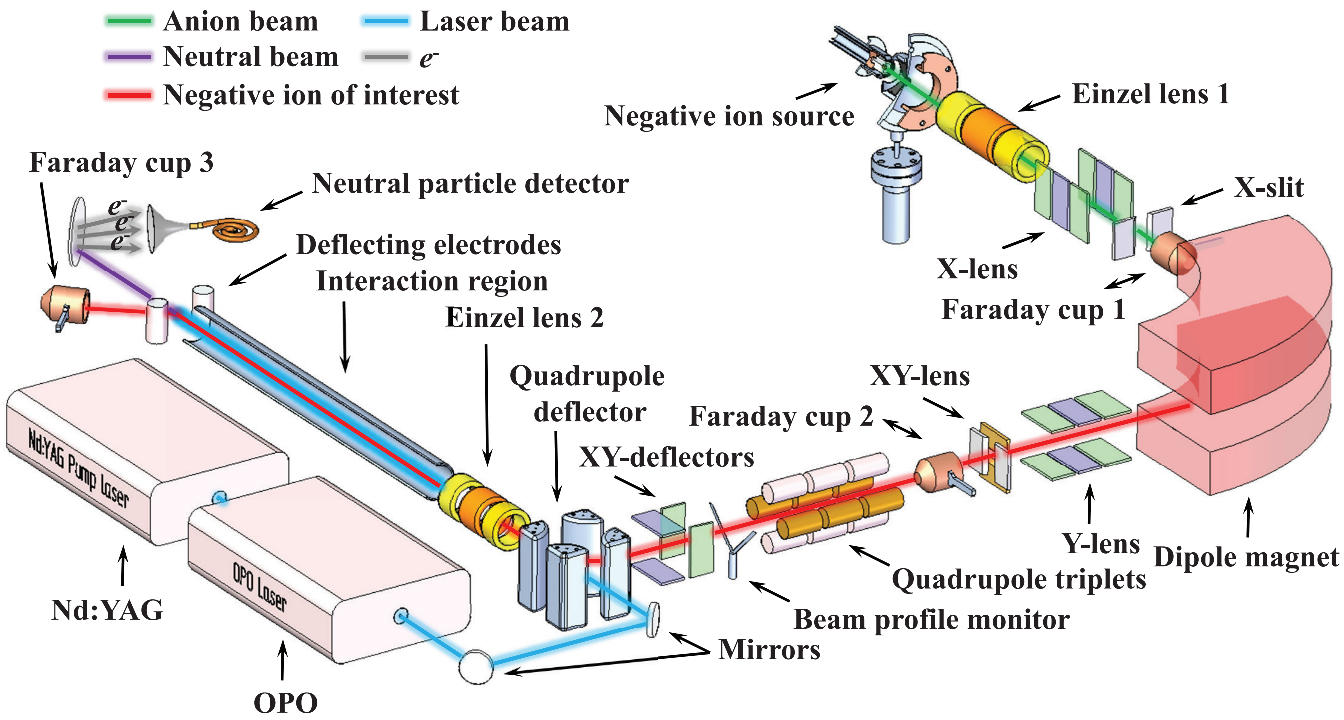

FIG. 1. A schematic drawing of the laser-ion beam apparatus GUNILLA.

II. METHOD

In this paragraph the experimental method is presented. First, the ion beam apparatus used in the experiment is briefly discussed and second the cesium sputter negative ion source is presented in some detail. Thereafter, the method used to pulse the ion source is discussed and finally the laser system that was used is presented.

A. Ion beam apparatus

The laser-ion beam apparatus GUNILLA (Gothenburg University Negative Ion Laser LAboratory) used in this work, is shown schematically in Fig. 1. The apparatus has been described in detail in the work by Diehl *et al*[22]. A beam of negative ions is produced in a cesium sputter source, described in more detail in section II B, and mass analyzed in a 90° bending magnet. With the help of a series of ion beam optics, the beam is transported to an interaction region that is defined by two 3.0 mm diameter apertures situated 610 mm apart. Here the ion beam is merged with a pulsed laser beam in a collinear geometry. After the interaction region the negative ions are bent into a Faraday cup, where the measured ion current is used for normalization purposes. Atoms or molecules produced by collisional- or photo-detachment in the interaction region travel forward into a neutral particle detector. An indium-tin oxide (ITO) coated glass plate is used to produce secondary electrons when neutral particles strike the plate. These electrons are detected using a Channel Electron Multiplier[23].

B. The cesium sputter ion source

In this work, a cesium sputter negative ion source (Model PS-120 from Peabody Scientific)[24], shown graphically in Fig. 2, is employed. A heated reservoir vaporizes cesium atoms that are directed towards a high temperature spherical tungsten ionizer. Here Cs^+ ions are generated in a surface ionization process. The ionizer is facing a cathode made of aluminum or copper into which a small crater has been machined. In the crater a powder of a selected material can be compressed. The selection of the powder depends on the element of interest for a particular experiment. A compilation of recommended target material for all elements or compounds is given in the standard work "The negative ion cookbook"[20]. A bias voltage is applied to the cathode, which in our case is -3 kV. The Cs^+ ions are accelerated towards the cathode, where upon impact, they sputter out atoms or small molecules from the selected cathode material chosen for the experiment. Simultaneously, a thin layer of Cs atoms accumulates on the surface of the cathode and acts as a charge exchange medium. Sputtered atoms or molecules, while passing through the Cs layer, pick up electrons and become negatively charged. The negative ions thus produced, are accelerated towards the ionizer-anode, where they pass through a central

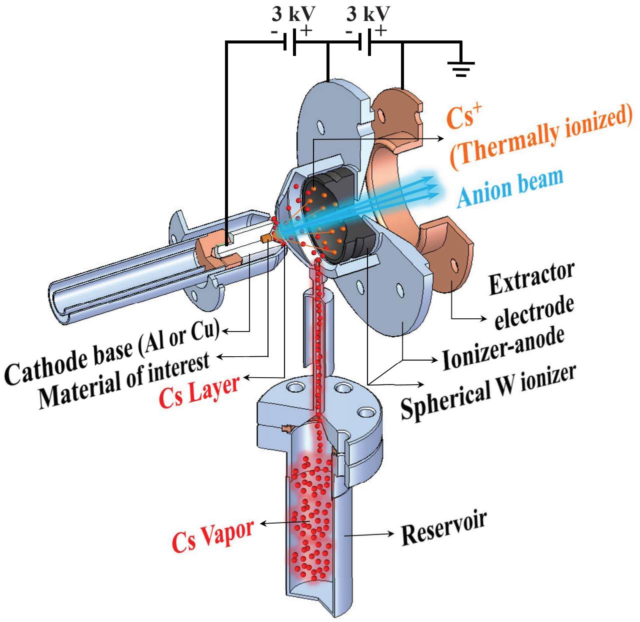

FIG. 2. A schematic drawing of the cesium sputter negative ion source used in this work.

hole. These ions are further accelerated by -3 kV towards an extraction electrode, where they exit through a central hole. By using electrostatic ion optics at the source exit, the negative ions are formed into a beam with a total kinetic energy of 6 keV.

C. Pulsing of ion source

In order to achieve pulsing of the ion source, we used a fast high voltage transistor switch, HTS 51 (5 kV DC / 30 Amps) from BEHLKE Power Electronics GmbH, for turning on/off the sputter voltage between the anode and cathode. This switching process is synchronized with the pulsed laser beam. A schematic diagram of the ion source high-voltage platform and the switching sequence is shown in Fig. 3. Within the time period of 0.1 s, determined by the 10 Hz repetition rate of our pulsed laser, the sputter voltage can be switched between -3.0 kV and -200 V. In the example shown in Fig. 3, the sputtering is turned on for a duration of 0.5 ms and then turned off for 99.5 ms. In this way, the sputtering process only occurs during 0.5 % of the time. This, in turn, reduces the erosion of the cathode material. The deposition of cesium atoms onto the cathode, on the other hand, is a continuous process.

D. Laser system

The laser system used in the experiment is an Optical Parametric Oscillator (OPO) pumped by the third harmonic of a Nd:YAG laser, thereby enabling the generation of tunable laser light in a wavelength range of 450 nm - 1800 nm. This laser-based system has a repetition rate of 10 Hz, a pulse width of 6 ns, a maximum pulse energy of about 1 mJ, and a bandwidth of 0.2 cm^{-1}. A pulse-delay generator is used to produce a signal that triggers the laser at a time selected such that the laser beam coincides with the peak current of the ion pulse. The photodetachment signal, in turn, is recorded using a time-gated acquisition system that monitors the number of detected neutral particles. The time window for collection is set to correspond to the time of flight for the residual atoms from the interaction region to the neutral particle detector.

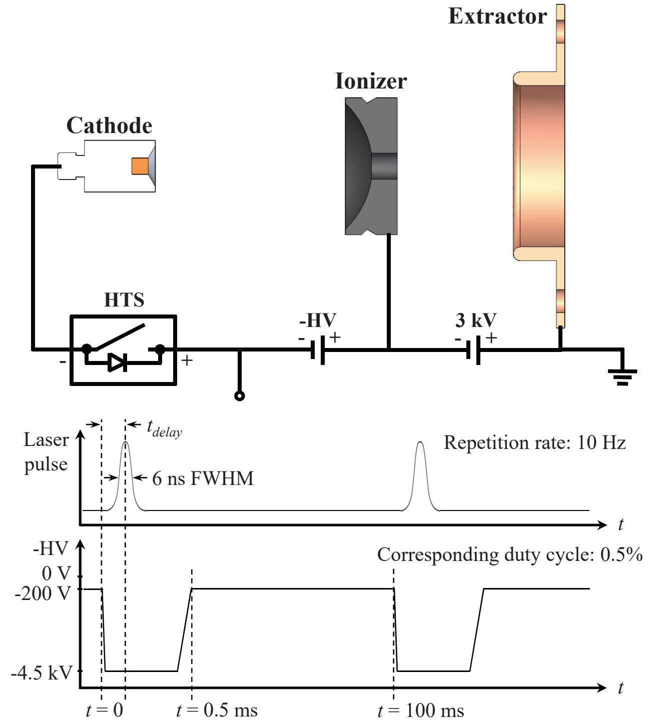

FIG. 3. Upper: A schematic diagram of the ion source high-voltage platform. Lower: The time diagram for pulsing the cesium sputter ion source.

III. RESULTS

A. Characteristic of a single ion pulse

For the purpose of determining how the ion current varies within a single ion pulse, we investigate the yield of neutral particles resulting from collisional detachment with the residual gas in the interaction chamber, which is proportional to the magnitude of the ion beam current. We use this procedure instead of simply measuring the ion current in a Faraday cup since an ampere-meter would not give the time resolution required to observe the temporal envelope of the ion pulse. Fig. 4. shows the time-resolved collisional detachment signal of a 500 µs pulse of OH^- ions. We observe the envelope of the collisional detachment signal corresponding to an ion pulse of 500 µs duration. The relative number of neutralized

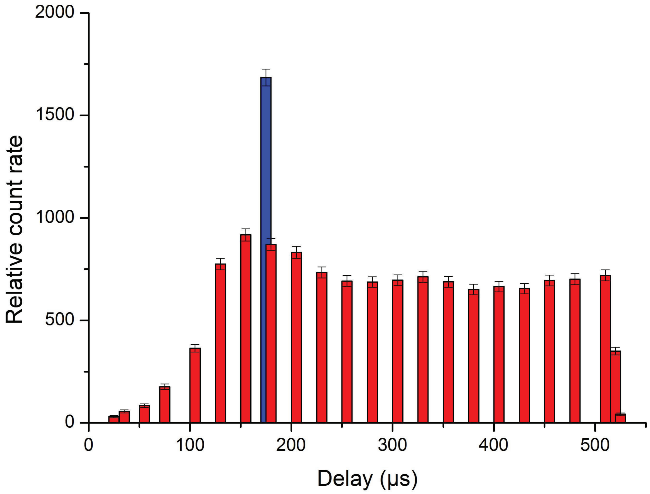

FIG. 4. The envelope of the pulsed ion current, as measured by the number of ions neutralized by collision with background gas, over a 500 µs duration (red). A photodetachment laser pulse was triggered 170 µs after the ion pulse, providing simultaneous temporal and spatial overlap of the laser and ion pulse (blue).

particles within a time window of 10 µs is shown as a function of the time delay relative to the switching of the sputter voltage. Each data point represents the number of counts integrated over 60 s. The slow rise in the ion current over the first 50 µs is determined by the rise time of the high voltage switch and the impedance of the output of the switch (i.e. the cathode with its cabling). Approximately 150 µs after the ion pulse is triggered, the ion current reaches its maximum, after which it plateaus for about 350 µs.

B. Photodetachment

We chose OH$^-$ as the ion to demonstrate how the pulsed laser can be synchronized with the pulsed ion source. The delay of the laser with respect to the high-voltage pulse was set to 170 µs in order to trigger the laser at the peak of the ion beam production. The blue bar in Fig. 4 represents the photodetachment signal. The signal was recorded over a 10 µs window which was set to cover the time of flight of the neutralized OH molecules from the interaction region to the neutral particle detector. The wavelength of the laser was set to 500 nm. The intensity of the laser power was reduced to yield a photodetachment signal of the same order as the collisional detachment signal.

C. Cathode erosion

The cathode gets eroded over time when it is operated in a DC mode. The shape of the cone crater changes and becomes deeper. Eventually the sputtering will take place so far into the crater that target particles cannot be extracted from the cathode. This requires a replacement of the cathode causing an interrupt in the ongoing experiment. The lifetime of a particular cathode differs a lot depending on the powder used to produce various ions. Fig. 5 shows three identical aluminum cathode bases that have experienced different operating conditions. In none of these cases the crater was filled with any powder. The left cathode base has not been used in the ion source. The cathode base in the center has been used in the ion source for 24 hours in a pulse mode of operation with a duty cycle of 1 %. The right cathode base, finally, has been operated for 24 hours in the ion source operated in a DC mode. In the latter case one observes that a very deep hole has been created by the sputtering process. In contrast, only small traces of erosion due to the sputtering can be seen in the middle cathode. The ionizer and cathode are not perfectly aligned in our source, giving trace of the sputtering slightly off center. The masses of the cathodes were measured both before and after the experiment. Before each mass measurement, the deposited Cs layer was cleaned off and the cathodes were dried out. The mass loss of the cathode shown on right one was 9.0±0.2 mg, while the mass loss in the middle cathode was only 0.2±0.2 mg. This means that the mass loss was about two orders of magnitude smaller in the case of pulsed sputtering than it was for sputtering using the DC mode of operation. This reduction in erosion produces a corresponding increase in the lifetime of the cathode. Thus, we have demonstrated that the cathode lifetime can be remarkably extended by pulsing of the ion source.

FIG. 5. Photograph of three aluminum cathode bases in which no powder has been pressed into the crater. Left: unused, Middle: pulse sputtered for 24 hours and Right: continuously sputtered for 24 hours.

D. Ion current vs. duty cycle

In our experiments, cesium atoms are continuously deposited on the cathode, whereas the sputtering process is pulsed. By varying the duty cycle one can therefore expect the thickness of the cesium layer to vary, which could affect the negative ion production rate. This has previously been demonstrated by Steski *et al*[21]. We here define an enhancement factor i.e., $\alpha = I_{puls}/I_{cc}$ as the ratio of the peak of the ion current in the pulsed mode and the ion current obtained in DC mode. This enhancement factor was measured as a function of the duty cycle of the pulsed beam. Fig. 6 shows the result for C_4^- ions. The graph shows that the ion current is about 8 times greater at a duty cycle of 5% compared to what it is with

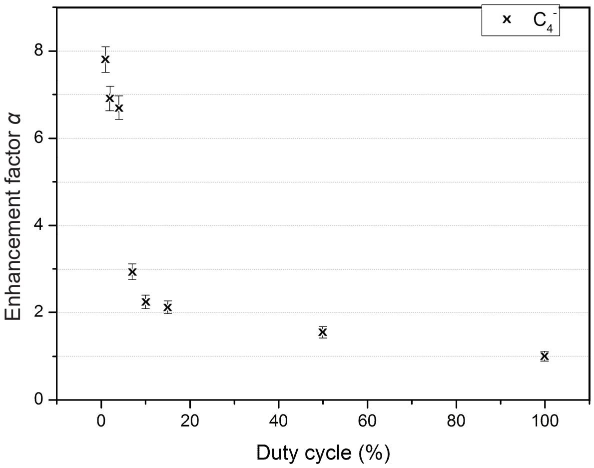

FIG. 6. Behavior of the ion current enhancement α in the pulse mode of operation for C_4^- ions as a function of the duty cycle. The error bars shown in the figure represent the statistical uncertainties.

DC mode operation (i.e. a 100 % duty cycle).

E. Ion currents vs. ions species

TABLE I. Enhancement factors α for twelve different negative ions and a common duty cycle of 10 % for the pulsed ion source. Only the statistical error is given.

Ion	α	Ion	α
C^-	3.7(1)	C_2^-	2.2(1)
C_4^-	2.2(2)	OH^-	26.4(7)
O^-	8.0(5)	O_2^-	3.6(9)
F^-	13.8(2)	Cl^-	0.7(1)
Ag^-	2.5(20)	Na^-	0.3(2)
Rb^-	0.5(1)	Cr^-	1.5(5)

The general behaviour of the enhancement factor α as a function of the duty cycle, when applied to different cathode materials, was in general the same as for the case of C_4^- shown in Fig. 6. Table I lists the measured enhancement factors for twelve different negative ions using a common duty cycle of 10 % for the pulsed ion source. As can be seen, the enhancement factor differs considerably for the different ions. In some cases, such as for Cr^-, the enhancement is relatively small, and in some cases it is even smaller than unity. However, for F^- and OH^-, enhancements of more than an order of magnitude are observed. We have not been able to see any pattern in the enhancement factors, although there seems to be a tendency that ions that are prolifically produced in the ion source have large values of the enhancement factor α.

IV. CONCLUSION

A scheme designed to operate a cesium sputter negative ion source in a pulse mode has been developed and implemented. The characteristic of a single ion pulse and the evolution of the pulsed ion current as a function of the duty cycle were investigated. Most importantly, we have demonstrated that pulsing of the ion source can significantly extend the lifetime of a cathode. This will be most valuable when the negative ion to be investigated necessitates cathodes with short lifetimes or expensive materials. We also show that the ion currents within the ion pulse are in many cases significantly higher than when the source is operated in DC mode. However, this doesn't seem to apply to all ion species and we have not observed any systematic trend. Hence, the possibility to enhance the ion yield needs to be investigated for each ion of interest.

The overall conclusion is that it is relatively easy to implement the scheme presented for pulsing the source, and it will be a valuable improvement in any facility where a sputter source is combined with pulsed lasers.

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