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Enhancing the extraction of laser-ionized beams from an arc discharge ion source volume

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ABSTRACT

The Versatile Arc Discharge and Laser Ion Source (VADLIS) is a recently established ion source for the CERN-ISOLDE radioactive ion beam facility. It offers either electron-impact ionization (VADIS-mode) or resonance laser ionization (RILIS-mode). The choice of operating mode depends on the element of interest or the required beam purity. Particle-in-cell simulations using the VSim software show that the ion extraction efficiency of the VADLIS in RILIS-mode can be improved if it is equipped with an insulated extractor plate, to which an optimal voltage can be applied. This enables optimization of the RILIS-mode ion extraction independently of the electron density. Experiments have been performed using a prototype VADLIS with an adjustable extractor plate voltage for the generation of gallium ion beams at the off-line separator as well as magnesium, molybdenum and mercury ion beams at ISOLDE. A factor > 2 increase of the VADLIS efficiency in RILIS-mode has been achieved.

1. Introduction

The Versatile Arc Discharge and Laser Ion Source [1] (VADLIS) combines the FEBIAD (Forced Electron Beam Induced Arc Discharge) ion source [2] and the RILIS (Resonance Ionization Laser Ion Source) [3], both employed at Isotope Separator On Line (ISOL) facilities for the production of radioactive ion beams. The ISOLDE variant of the FEBIAD is known as the VADIS (Versatile Arc Discharge Ion Source) [4] but they share the same design and operating principle based on electron impact ionization. At ISOLDE [5], reaction products (radioactive isotopes) produced in the high-temperature target effuse as atomic vapor towards the anode volume of the ion source, via a transfer line. The transfer line is connected to the cathode tube (see Fig. 1) through which the atoms effuse into the anode cavity, where they are ionized, primarily by electron bombardment. Electrons are emitted by thermionic emission from the flat surface of the cathode which is resistively heated to typically 2000 °C. A positive voltage is applied to the anode cavity (typically in the range of 100 V to 150 V). Electrons are therefore accelerated towards the grid. Those that pass into the anode do so as a mono-energetic electron beam with an energy corresponding to the anode voltage. An axial magnetic field, regulated by the current applied to the coils of a fixed solenoid installed around the ion source volume, increases the mean path length of the electron trajectory thus increasing the probability of an electron/atom interaction. The VADIS series of ion sources all use the anode geometry of the MK5 FEBIAD [6] though the material of the grid was replaced from graphite to molybdenum in an effort to reduce the CO^+ ion formation. The total ion load of the cavity decreases creating a low density plasma [4]. Previous experimental studies indicate a complex relationship between the anode voltage (electron energy) and the overall ion source performance [4]:

- The electron energy must exceed the ionization potential of the element of interest. The ionization cross section varies with electron energy and peaks at a value typically equal to 2–3 times the ionization potential.
- If the electron emission from the cathode is space-charge limited,

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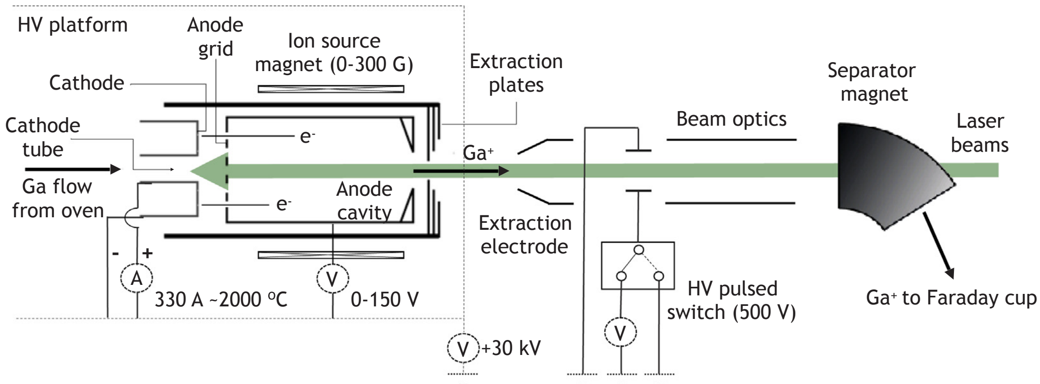

Fig. 1. Sketch of the VADLIS and general description of the experimental set-up. (not to scale).

then the electron flux is proportional to $V^{\frac{3}{2}}/d^2$, where V is the voltage difference and d the distance between the cathode and the anode [7].

- The anode body temperature is determined by its proximity to the hot cathode (~2000 °C). The anode is also heated by electron bombardment, which is determined by the electron current and the anode voltage. The anode temperature influences the surface ionization rate of the atoms and wall sticking times as well as electron emission from the walls. Theoretical estimations are given in [8].
- For the standard VADIS configuration, the extraction plates are held at the potential of the high voltage platform as indicated in Fig. 1 (locally grounded). The voltage difference between the anode and extraction plates is therefore equivalent to the anode voltage.

It is challenging to experimentally determine the relative importance of each of these aspects of the ion source in terms of the resulting ionization efficiency for a given species. For this reason, particle-in-cell (PIC) simulations of the ion source, for which individual physical effects can be switched on and off, can therefore provide a valuable insight. The CPO software [9] has been used in the past to demonstrate the impact of the so called 'active' volume in the overall efficiency of the ion source. A model describing the dependance between efficiency and the active volume was then inferred from experimental results over a wide range of operational parameters. More details can be found in [4,10].

Recently it was demonstrated that the VADIS cavity could be used as an effective laser-atom interaction region provided that the lasers can be transmitted through the 1.5 mm diameter exit aperture of the anode [1]. In this case the ion source is operated in so-called RILIS-mode, with the source magnet and the anode voltage optimized for laser-ion survival and extraction, whilst keeping the anode voltage below the required value for electron impact ionization to occur.

The development of this multi-purpose ion source (known as the VADLIS) has been crucial to the success of several experiments at ISOLDE since its first on-line use in 2015. For example, this approach enabled the first operation of RILIS with molten lead targets for the study of mercury isotopes by in-source laser spectroscopy [11] since a reliable means of coupling the standard hot cavity RILIS ion source with liquid targets does not currently exist. On-line experiments for the production of mercury, cadmium and magnesium beams have shown that RILIS-mode achieves a beam purity comparable to that of the standard hot-cavity RILIS ion source as well as an operating efficiency comparable to VADIS-mode for the laser-ionized species [1,11]. This additional degree of ion source flexibility proved vital to the success of the ISOLTRAP [12] experiment at ISOLDE described in Ref. [13,14] for which magnesium and neon beams were required in a single experiment and thus one target/ion source assembly should be used. Beams of neon isotopes need an electron impact ionization mechanism while magnesium can be ionized by both electron impact and laser ionization (RILIS). The RILIS-mode allowed the ^{23}Mg yield to be preserved with a much cleaner isobaric spectrum compared to the VADIS-mode (electron impact ionization).

In this work we characterize the performance of a modified VADLIS, equipped with an adjustable-voltage extractor plate, primarily intended to improve the performance of the RILIS-mode of operation in terms of selectivity and extraction efficiency. This is highly desirable at ISOL facilities: e.g users would benefit from a reduced number of shifts necessary to perform their experiments without any apparent drawback. Even though the VADIS operation mode can also benefit from these modifications, the enhancement in extraction efficiency was observed to be not as significant as for the RILIS-mode. We demonstrate that the source can perform as a standard VADIS with no loss of performance or drop in lifetime. The particle-in-cell software VSim [15,16] is used to study improved RILIS-mode extraction characteristics. VSim is also used to simulate the ion extraction time profile which shows good agreement with experimental results. In the outlook we discuss the prospects of this modified VADLIS as the new standard configuration, and suggest further modifications for improved ion source flexibility, diagnostics and performance.

2. Experimental set-up

The study performed in Ref. [1], which identified the different modes of operation of the VADLIS served as a starting point for a better understanding and optimization of the anode cavity as an efficient laser-atom interaction volume. The experimental studies were carried out at the ISOLDE off-line laboratory described in Ref. [8]. Gallium vapor was released from a $GaNO_3$ precipitate contained in a resistively-heated capillary oven, connected to the rear of the tubular cathode tube. Atomic Ga (ionization potential ~6.0 eV) effusing along the cathode tube is able to enter the anode cavity by passing through the anode grid, located 1 to 2 mm downstream of the cathode exit. The Ga atoms were ionized via a two-step, one-resonance ionization scheme (294.36 nm,532 nm) [17]. The first step involves a transition from the thermally-populated low-lying atomic energy level $3d^{10}4s^24p^2P^0_{3/2}$ to the $4s^24d^2D_{5/2}$ state. Up to 200 mW of 294.36 nm light was produced using a frequency-doubled Rhodamine 6G dye laser, pumped by 20W of 532 nm radiation from a frequency-doubled Nd:YAG laser (Edgewave IS series). The second step, non-resonant ionization to the continuum made use of up to 15W of residual 532 nm light from the dye pump laser. An optical delay line ensured coincidence of the ~8ns laser pulses in the ion source. The laser pulse repetition rate was fixed to 10 kHz for these studies.

The laser beams are transmitted to the ion source through a fused silica window in the separator vacuum chamber and enter the anode volume through the 1.5 mm diameter aperture of the anode extractor plate. A portion of the laser beams passes through both the anode cavity and the central hole of the anode grid, entering the cathode tube