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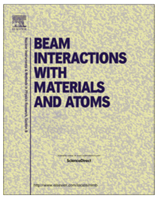

Advances in surface ion suppression from RILIS: Towards the Time-of-Flight Laser Ion Source (ToF-LIS)

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ABSTRACT

We present results from the development towards the Time-of-Flight Laser Ion Source (ToF-LIS) aiming for the suppression of isobaric contaminants through fast beam gating. The capability to characterize high resistance ion sources has been successfully demonstrated. A ninefold selectivity gain has been achieved through suppression of surface ionized potassium, while maintaining >90% transmission for laser-ionized gallium using a thin wall graphite ionizer cavity combined with a fast beam gate. Initial results from the investigation of glassy carbon as a potential hot cavity ion source are presented. Power-cycle tests of a newly designed mount for fragile ion source cavities indicates its capability to survive the thermal stress expected during operation in an ISOLDE target unit. Finally, we introduce fast ion beam switching at a rate of 10 kHz using the ISOLDE ion beam switchyard as a new concept for ion beam distribution and conclude by highlighting the potential applications of this ion beam multiplexing technique.

1. Introduction

The Resonance Ionization Laser Ion Source (RILIS) [1] is the primary ion source at the ISOLDE radioactive ion beam facility [2] at CERN. While laser ionization is both efficient and highly element-selective as compared to other ionization mechanisms, its application to certain experiments is limited by the presence of isobaric contaminants due to the surface ionization of neighboring elements. Different approaches have demonstrated varying degrees of efficacy in addressing this problem: suppressing the production of surface ions by selecting low work function cavity materials [3], the use of a surface ion repeller in the Laser Ion Source and Trap (LIST) [4], and the use of a pulsed electrostatic ion deflector to deviate the DC beam of surface ions away from the pulsed beam of laser-ions [5–7]. The latter μ-gating technique exploits the bunched structure of the RILIS ionized beam. The time structure of the ion beam is a consequence of the 10 kHz (100 µs period) pulse repetition rate of the RILIS laser system. By pulsing an electrostatic ion deflector synchronously with the RILIS lasers, one can select the time window of the beam containing the majority of the laser ions to be transmitted to the experiment. The unwanted surface ionized contaminants, produced continuously, would be suppressed by a factor defined by the ratio of the period to the beam gate duration. The laser ion bunch length is determined by the applied voltage along the hot cavity where the polarity of the heating current is chosen such that the laser-generated ions are guided towards the extraction electrode. Laser-ions will have a different velocity when leaving the cavity depending on the local electric potential at which they were created; i.e. ions generated at the back will leave the cavity with a higher velocity. With a typical longitudinal field of 0.2 V/cm an ion bunch of the order of 30 µs (FWHM) is formed [5]. Using thin wall cavities it has been possible to obtain shorter bunches, due to the higher cavity resistance and a corresponding increase in voltage: ≈ 14 µs for a 0.5 mm thick Nb cavity [5] and 4 µs for 0.03 mm thick Ta/W foil combination [6]. Adding a field-free drift region between the cavity and the extraction electrode, with an equal length to the cavity, enables extraction at the time focus of the ions leaving the hot cavity which would reduce the bunch length even further [8]. The three building blocks of this Time-of-Flight Laser Ion Source (ToF-LIS) are therefore: (i) a hot cavity with an increased electric

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field gradient, (ii) an operational fast ion beam gate and (iii) an RFQ ion guide structure (e.g. a modified version of the LIST) to provide transverse ion confinement along a longitudinally field-free region.

Here we present an overview of the ongoing development towards the implementation of the ToF-LIS technique. We describe the setup established at the ISOLDE off-line facility and the first results confirming the operation of the components. We then present a possible candidate for a new hot cavity material – glassy carbon. Finally, we propose a new concept for ion beam distribution at ISOLDE, based on kHz beam switching and highlight some of the potential applications.

2. Setup at the ISOLDE off-line separator facility

The ISOLDE off-line facility includes a mass separator and a replica of an ISOLDE frontend [2]. Ions can be accelerated to 32 kV and are mass separated by a dipole magnet. The ion beam can be detected using a Faraday cup or an MCP detector. We have chosen gallium (Ga) as the reference element for our studies for practical reasons: it is easy to evaporate from a sample, and the laser ionization scheme {287.42 nm|532 nm} with just one resonant transition is relatively easy to set up and provides a good efficiency of 21% [9]. The laser system comprised a frequency-tripled titanium:sapphire (Ti:Sa) laser [10] and a commercial frequency-doubled Nd:YAG laser (*Edgewave GmbH*), generating the UV light for the resonant excitation step and the 532 nm for the non-resonant ionization step, respectively.

A thin-walled graphite ionizer cavity tube (l = 34 mm, od = 5.0 mm, id = 4.4 mm) was machined from 2114PT graphite and mounted in a standard ISOLDE target unit with no transfer line or target container attached. An independently resistively-heated tantalum capillary (mass marker) containing a sample of Ga was connected to the back of the ionizer cavity, enabling independent control of the supply of Ga atoms to the hot cavity. The graphite cavity was heated resistively with a current of up to 80 A. Single gallium laser-ions were detected with an MCP detector installed near the focal plane of the mass separator. The ion arrival times with respect to the laser pulse were recorded as a histogram using an oscilloscope (*LeCroy Waverunner 104 Xi*). The resulting acceleration potential of $U_{\text{gr.}}$ = 9.3 V (acquisition from ionizer cavity heating power supply) along the thin graphite cavity resulted in a laser-ion bunch length of $\tau_{\text{gr.}} = 3.8$ μs (FWHM). This bunch width is in good agreement with the expected behavior of $\tau \sim l/\sqrt{U}$ when comparing it to an ion bunch length of $\tau_{\text{Ta}} = 13$ μs (FWHM) obtained for a standard ISOLDE tantalum (Ta) cavity (l = 34 mm, od = 5.0 mm, id = 3 mm) connected to a transfer line (l = ≈34 mm) with a potential of U_{Ta} = 2.2 V (acquisition from ionizer cavity and transfer line heating power supply). The recorded time-of-flight spectra are shown in Fig. 1(a). Similar results were obtained previously using an externally heated sapphire cavity and a thin-walled niobium cavity [11]. A one dimensional model for RILIS time structures has been discussed by Liu et al. [12].

A fast high voltage pulser (*BEHLKE GHTS60*) was then connected to an electrostatic vertical deflector plate, located in the beam line before the dipole magnet. A deflection voltage of U_{def} = 500 V was sufficient to fully suppress the ion beam. The mass scan shown in Fig. 1(b) demonstrates a reduction of potassium and calcium surface ions and only a small change for the two gallium isotopes at masses 69 and 71 amu using a 10 μs wide beam gate. The mass separator was then optimized for ^{39}K and ^{69}Ga to determine the suppression factor $\sigma_{\text{K}} = 10$ for potassium and the transmission of $\eta_{\text{Ga}} = 91\%$ for gallium, respectively. The gain in selectivity serves as a figure of merit and can be calculated as $\gamma = \sigma_{\text{K}}\eta_{\text{Ga}} = 9.1$. The reduction in transmission for the Ga can be attributed to the removal of the pre-peak seen in 1(a) at around 12 μs, the tails of the 3.8 μs FWHM laser ion bunch and the 90% suppression of the surface-ionized Ga.

3. Glassy carbon as potential hot cavity material

Glassy carbon (vitreous carbon, available as SIGRADUR® G, referred to as Sigradur in the following) exhibits favorable properties in terms of service temperature (up to 3000 °C), vanishing porosity, high hardness and crucially a high specific electrical resistance. A tube (l = 34 mm, od = 5 mm, id = 3 mm) from Sigradur G was purchased from *HTW GmbH*. A graphite (2114PT) tube with identical dimensions was manufactured for reference measurements. To allow for future coupling to an ISOLDE target, an expansion compensating ion source mount as shown in Fig. 2 was constructed. The design was inspired by the slotted ohmic heater of the sapphire cavity described in [5]. The design goal was to allow for slight longitudinal expansion of the holder whilst ensuring that most of the heating power is deposited in the carbon tube held in the center.

Electro-thermal simulations (*Comsol 5.1*) were carried out during the design phase; representative results are shown in Fig. 3. The simulations were used to estimate the longitudinal voltage drop across the hot cavity tube. For Sigradur, mounted in this construction, a temperature of ≈1900 °C was measured at an estimated potential difference of 9 V across the tube, based on the simulation results for the whole assembly and the power supply readout.

Both the graphite and Sigradur cavities were stress tested using the following procedure: the cold source was heated stepwise over

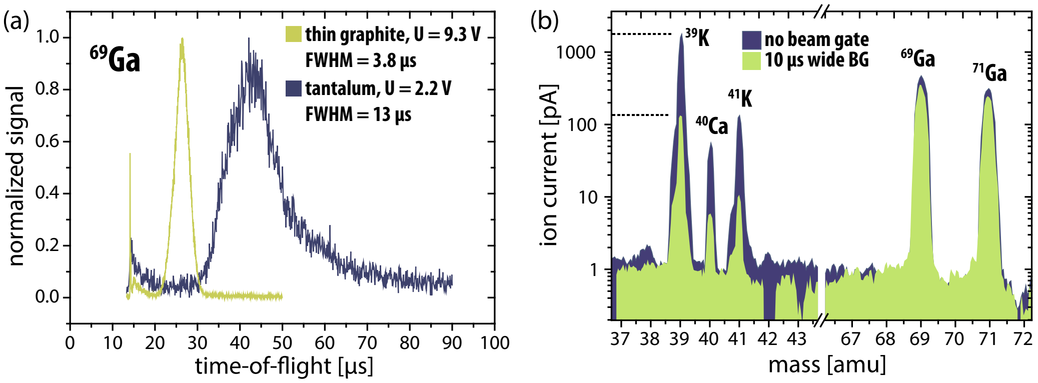

Fig. 1. Results from the thin-walled graphite and μ-gating. (a) Time-of-flight spectrum for thin-walled graphite and tantalum ionizer cavity. (b) Mass spectrum with and without 10 μs beam gate, synchronized with the 10 kHz laser pulse, obtained with the thin-walled graphite cavity.

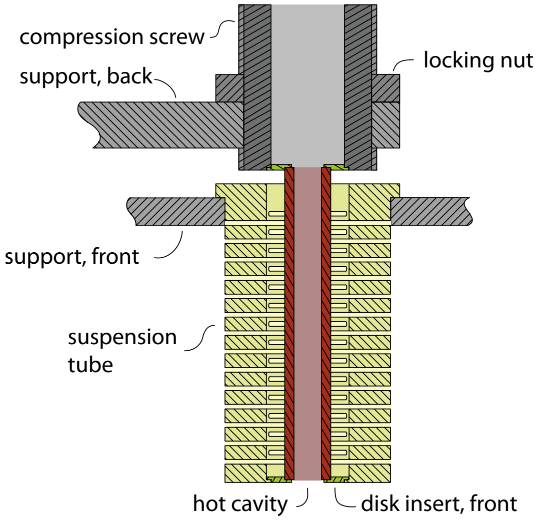

Fig. 2. Drawing of the suspension mount for fragile carbon cavities. All parts other than the hot cavity tube are made from graphite. A cylindrical connector for the mass-marker capillary (not shown) can be inserted into the compression screw.

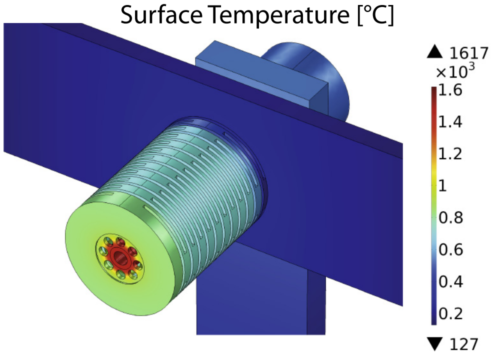

Fig. 3. Result of the electro-thermal simulation of the ion source mount for carbon cavities using *Comsol 5.1*.

the course of ≈60 min, allowing for thermalization and subsequent temperature measurements. The final temperatures of 2200 °C for graphite and 1900 °C for Sigradur were recorded using a pyrometer. After each ramp, the resistive heating current was cut off and the source was allowed to cool down. Then the cycle was repeated.

Fig. 4 shows the trend of the resistance of the construction over the heating cycle number. We observed a relatively constant resistance for the graphite source. For the Sigradur however, following power cycle number 6, an increase of resistance over time was observed, which was attributed later to corrosion at the connection of the Sigradur tube and the front disk inside the holder. Since the same disk was used earlier for the 9 heating cycles with the graphite tube, it remains inconclusive at this point if this is a feature of Sigradur.

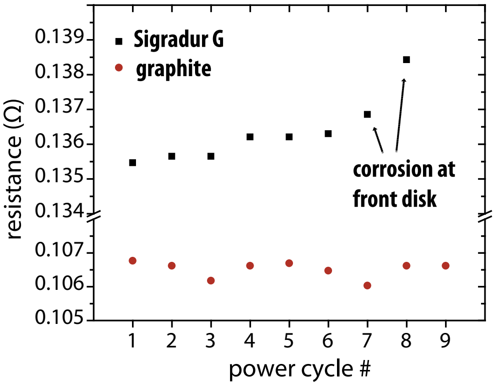

Fig. 4. Results from the stress-test for graphite and Sigradur cavities.

Fig. 5 shows images obtained with a *Zeiss* *Σigma* scanning electron microscope (SEM) of the cavity surfaces taken before and after the heating cycles which illustrate the fundamental difference between the two carbon types: The irregular structure of the 2114PT graphite (which was already thermally treated by the manufacturer) remains unchanged after applying the heating cycles. The Sigradur however exhibits a completely closed surface before heating (the structures in the SEM image are dust particles used to correctly focus the microscope). This underlines the manufacturer's claim of Sigradur as a non-porous material in contrast to 2114PT graphite which exhibits 9% of open porosity.

After the heating cycles, clusters of spherical structures with a diameter of ≈150 nm formed on the Sigradur surface. The deposit may be attributed to soot generated by the degradation of the front disk insert. It remains to be verified what the origin is and if the surface below is still closed. The effects of these nano-structures on surface ionization, electron emission and sticking times of atoms need to be studied. The claimed non-porosity of Sigradur and therefore its suitability as a hot cavity material has to be verified e.g. with an ionization efficiency measurement using laser ionized gallium or surface ionized lithium. In the next stage of testing the Sigradur cavity will be coupled to the target container and transfer line and the time structure measurements will be repeated.

4. Pulse-width modulated heating

Decoupling the voltage drop across the cavity from the cavity temperature (determined by the dissipated electrical power) would enable a direct study of the dependence of the laser ion bunch length on the cavity voltage. The application of a pulsed ohmic heating of the cavity has been described in [8], where an acceleration voltage of 15.2 V was achieved for a graphite cavity by pulsing a 24 V DC power supply. A continuous variation of the applied voltage while maintaining the average dissipated electrical power would be possible by adjusting the duty factor in a pulse-width modulated (PWM) heating scheme. The duty factor D can be determined from the relation $D = PR/U^2$, where P is the dissipated power, R is the cavity resistance and U is the chosen acceleration voltage.

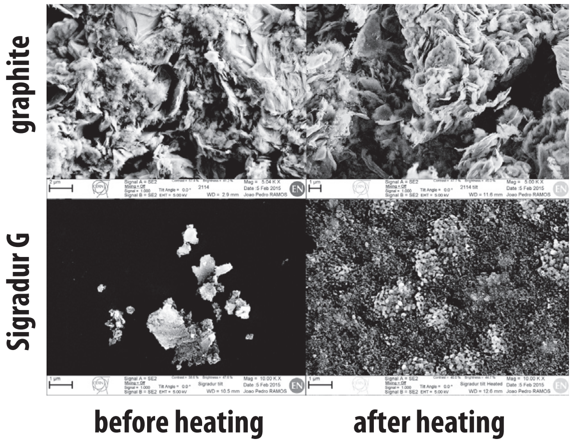

Fig. 5. SEM images of the two cavity materials before and after heating cycles.

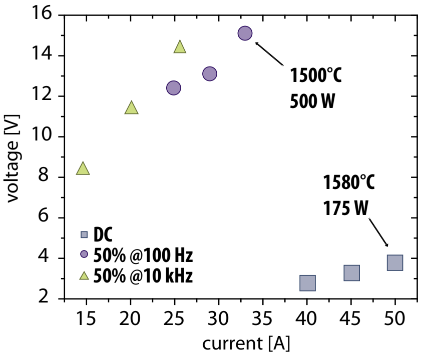

Fig. 6. U/I plot of the mass-marker heating in DC and 50% PWM.

The PWM heating technique was validated using a tantalum mass-marker capillary as an ohmic load, mounted at a pump stand. Comparable results are expected for an ionizer cavity. A high current solid-state Insulated-Gate Bipolar Transistor (IGBT) switch (*IXYS MID145-12A3*), operated at 10 Hz and 10 kHz with a 50% duty cycle was used to pulse the DC power supply. The U/I plot in Fig. 6 shows a reduced current and an increase in voltage when using PWM, as expected. However, the factor ≈3 reduced heating efficiency indicates induction losses in the assembly that need to be accounted for in future tests. The present setup may not be suitable to be applied to on-line operation coupled to RILIS, it remains however a powerful tool for the characterization of the high resistance cavities which can be carried out at a fraction of the laser repetition rate.

5. A new ion beam distribution concept: μ-switching

Whilst a 10 kHz microsecond beam gate is a pre-requisite for the ToF-LIS, using the same technology, a new quasi-cw beam-sharing concept, realized by pulsing the kicker voltage of an ion beam switchyard at a repetition rate of 10 kHz and with different duty factors has been suggested [13]. Ion beams from the General Purpose Separator (GPS) and the High Resolution Separator (HRS) are merged before being distributed using electrostatic switchyards [2]. The existing static DC voltage sources of this beam distribution system restricts the delivery of ions through the central beam line (CA0) to only one experimental setup at a time. Here we demonstrate multiplexing of ion beams to different setups by applying our fast high-voltage switching method to the kicker plates of the ISOLDE switchyard. The operating principle is sketched in Fig. 7. The feasibility of this technique has been demonstrated by connecting fast high voltage switches (*BEHLKE GHTS60*) to the two deflector plates of the ion beam kicker of the 3-way switchyard serving for beam distribution between ion beam lines LA0 (deflecting to left side), CB0 (no deflection) and RA0 (deflection to the right).

This enabled control of the polarity of the deflector plates independently using TTL signals. Depending on the polarity combination, the kicker plates apply an offset (≈20 mm) to the ion beam to either side or leave the beam unaffected. The guiding fields generated by the bending plates inside the switchyard remain unchanged. The DC voltages connected to the HV switches were provided locally by HV power supplies (*Stanford PS350*) and TTL signals to control the switches were generated by a pulse delay generator (*Quantum Composers Series 9520*). An argon ion beam from the HRS separator was detected with Faraday cups located in the LA0 and the CB0 beam lines. Fig. 8 shows the relative transmission ratio of an ion beam switched between the ISOLDE LA0 and CB0 beam lines.

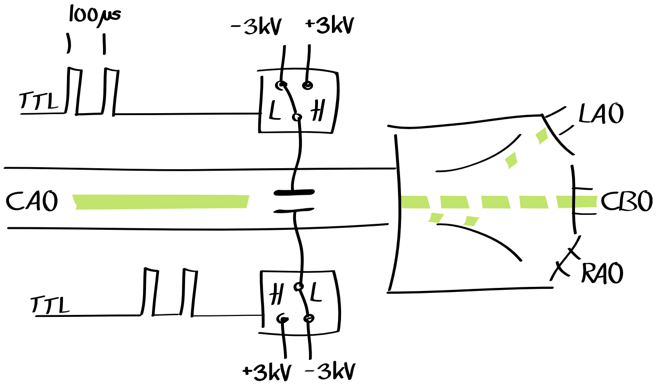

Fig. 7. Two fast high voltage switches control the voltage of the kicker plates of a switch-yard. Depending on the on-time the beam is fed into the three possible beam lines.

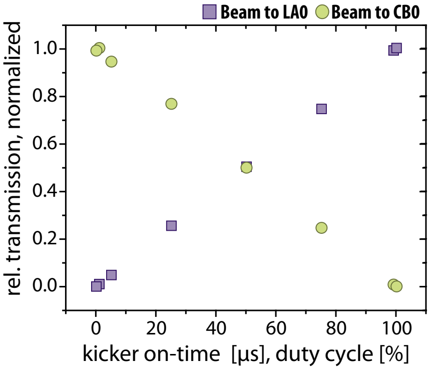

Fig. 8. Demonstration of beam line multiplexing or μ-switching at 10 kHz for the ISOLDE LA0 and CB0 beam lines.

The ratio can be selected by the duty cycle of the TTL pulses sent to the HV switches. An important feature of the μ-switching technique with respect to the μ-gating is that the unwanted fraction is sent to a designated well defined location (and not dumped inside of the vacuum chamber) and is therefore still available for other purposes, e.g. for normalization of ion beam intensities.

Besides its application as a fast beam gate, the μ-switching functionality can be used for other applications at ISOLDE. The high frequency switching that has been demonstrated implies that the technique could be used for variable ion beam sharing between ISOLDE users. Switching with lower rates allows for minimally-invasive on-line ion beam monitoring. This can become a powerful tool for RILIS optimization and for long-term user-friendly target performance monitoring, when the beam composition can be periodically monitored e.g. using the ISOLDE tape station, or detectors available at the ISOLDE experimental stations.

This technique can potentially be used to overcome the bottleneck of the HRS/GPS merging switchyard [14,2]. The HRS/GPS merging switchyard is an inverted version of the CB0 switchyard (see Fig. 7), which is used to direct ion beams from the HRS or the GPS target to the shared central beam line CA0, thus currently limiting the simultaneous operation of GPS and HRS target stations. When the HRS/GPS merging switchyard and the downstream CB0 switchyard are controlled in a concerted manner it could be possible to allow e.g. the transmission from HRS to one setup after LA0 for a short fraction of time after the proton impact on that target, and then transmitting the GPS beam to another experiment, e.g. at CB0. The availability of the autotune ion beam optimization software facilitates the matching of the tune of each separator to the acceptance of the concerted switchyards. This technique could be used to extract isotopes from HRS and GPS and send them to one experiment e.g. for reference measurements using different isotopes or to increase the intensity by extracting the same isotope from both separators.

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