
Faculty of Science

Faculty Publications

Commissioning of a multi-purpose offline ion source at the TITAN experiment

Jake A. D. Flowerdew, Ish Mukul, Anna A. Kwiatkowski, Michael E. Wieser, Robert I. Thompson, & Jens Dilling

July 2021

© 2021 Jake A. D. Flowerdew et al. This is an open access article distributed under the terms of the Creative Commons Attribution License. <https://creativecommons.org/licenses/by/4.0/>

This article was originally published at:

<https://doi.org/10.1016/j.nima.2021.165399>

Citation for this paper:

Flowerdew, J. A. D., Mukul, I., Kwiatkowski, A. A., Wieser, M. E., Thompson, R. I., & Dilling, J. (2021). Commissioning of a multi-purpose offline ion source at the TITAN experiment. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 1005, 1-8. <https://doi.org/10.1016/j.nima.2021.165399>.



Commissioning of a multi-purpose offline ion source at the TITAN experiment

Jake A.D. Flowerdew^{a,*}, Ish Mukul^b, Anna A. Kwiatkowski^{b,c}, Michael E. Wieser^{a,b},
Robert I. Thompson^{a,b}, Jens Dilling^{b,d}

^a Department of Physics and Astronomy, University of Calgary, Calgary, AB, Canada

^b TRIUMF, Vancouver, BC, Canada

^c Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

^d Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, Canada

ARTICLE INFO

Keywords:

Plasma Ion Source
SIMION
Time-of-Flight
Mass Spectrometry

ABSTRACT

The controlled focusing and transport of ion beams is of paramount importance in particle accelerators, high energy beamlines, and detector systems, as it determines the sensitivity and resolution of the instruments. Therefore, it is essential to model the beam dynamics before the commissioning of new instruments in order to optimise properties such as transmission and energy spread. In this paper, a commercial Plasma Ion Source (PIS), comprised of a heated filament and anode followed by its collimating optics, was modelled using Monte Carlo simulations run with the commercial software SIMION. The simulations were performed for the integration of the source within the existing ion transport optics of TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN). Optimising the voltage configurations using these simulations proved successful in the commissioning of the PIS operated in surface ionisation mode at the TITAN experiment. A Time-of-Flight (TOF) mass spectroscopy method was developed which allowed for the identification of species ionised by the source. The integration of a flexible ion source into the TITAN experiment will open up new opportunities to perform Isotopic Ratios Mass Spectrometry (IRMS) measurements at TITAN.

1. Introduction

TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) [1] is located at Canada's national particle accelerator centre, TRIUMF, and specialises in high precision mass measurements of short-lived isotopes [2]. The radioactive isotopes at TRIUMF are produced using the Isotope Separation On Line (ISOL) method at the ISAC facility. The isotopes are ionised and formed into a low-energy (60 keV) beam, mass separated, and delivered to the experimental hall where TITAN and typically 16 other experimental setups are located. Access to the Radioactive Ion Beams (RIBs) is therefore limited as the production of unstable atoms is shared with other experiments and only one experiment can receive beam at a time. As a result, RIBs are not available to TITAN for continuous use. The challenge of obtaining an uninterrupted supply of ions for investigation led TITAN to acquire an arc-discharge DCIS-100 Plasma Ion Source (PIS) [3] in order to provide an off-line stable-isotope ion beam that can be operated independently of the RIB. The PIS is a practical ion source for the TITAN set-up because the source produces continuous, high ion currents with low energy spreads, which are required by TITAN for ion-trap calibration. In addition, the PIS is a flexible source as it will allow for samples to be introduced as aerosols or for salts to be deposited onto a filament for surface ionisation. Combining a stable isotope source with

TITAN's Multiple-Reflection Time-of-Flight Mass Spectrometer (MR-TOF-MS) [4,5] will enable the system to be utilised for analytic mass spectrometry where intense isobaric backgrounds from molecules are a general challenge. An example of analytic mass spectrometry is Isotope Ratio Mass Spectrometry (IRMS), which provides information about the geographic, chemical and biological origins of substances [6]. So far, MR-TOF-MSs are relatively unexplored in this field and the addition of a multi-purpose ion source at TITAN will open up new opportunities for stable-beam physics.

When designing and commissioning an ion optical instrument, accurate predictions of ion trajectories are essential. The ability to predict how ions will interact with the system is crucial for the successful integration of the instrument into an existing experiment. Simulations provide a fast, effective and inexpensive way to understand the transport of ions, and allow for the accurate prediction of design parameters prior to the installation and testing of an instrument.

This paper will describe the modelling and commissioning of the PIS in a surface ionisation mode, where ions are produced by heating a filament coated with a sample. The basic design of the commercial source filament [3] was modified to enable the application of a more controlled sample deposition technique. An overview of the TITAN experiment is given in Section 2, followed by the details of

* Corresponding author.

E-mail address: jake.flowerdew@ucalgary.ca (J.A.D. Flowerdew).

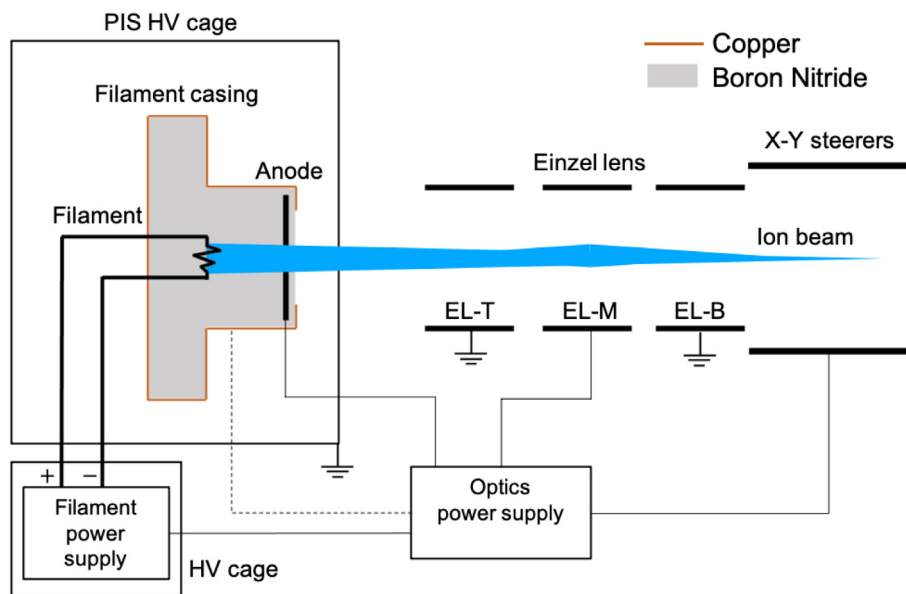


Fig. 1. Schematic of the Plasma Ion Source (PIS) operating in surface ionisation mode, proceeded by focusing and steering optics. The filament power supply was mounted in a separate High Voltage (HV) cage to the PIS. The dashed line shows the biasing of the filament casing, which was later added as a result of simulations (Section 3).

the design and installation of the PIS in Section 3. Section 4 describes how SIMION [7] was used for the Monte Carlo simulations of the ion source and the Nelder–Mead (downhill simplex) method [8] was used to optimise transmission of the electrode potentials for the efficient transmission of ions through the TITAN beamline. A Time-of-Flight experiment that was conducted to verify that the ions originated from the PIS is described in Section 5. These results demonstrate that this source could serve as the basis for a new and flexible supply of stable ions to the TITAN experiment.

2. Overview of the TITAN experiment

TITAN is a low energy (<60 keV) experiment that receives RIBs from the Isotope Separator and Accelerator (ISAC) facility [9]. ISAC uses the Isotope Separation On-Line (ISOL) technique to produce a RIB by bombarding a thick, metal, metal oxide or metal carbide (e.g. Pb, UO_2 , SiC) target with the proton beam from TRIUMF’s cyclotron. The ISOL technique produces a cocktail of different radioactive isotopes, which are then ionised and sent through an electromagnetic mass separator to select the desired isobar.

The RIB can be sent to the TITAN platform, where it is directed through a gas-filled Radio-Frequency Quadrupole (RFQ). The RFQ decelerates the DC 20 keV ions to a few 10’s of eV and ions are cooled as they collide with a helium buffer gas. The cooled ions are re-accelerated to around 2 keV and sent to one of three ion traps on the TITAN platform: the Multiple-Reflection Time-of-Flight Mass Spectrometer (MR-TOF-MS) [4], the Electron Beam Ion Trap (EBIT) [10] or the Measurement Penning Trap (MPET) [11].

The MR-TOF-MS is a highly sensitive Time-of-Flight (TOF) mass spectrometer that can work with extremely low ion yields (less than one particle per second) [5]. Through multiple reflections within the trap, the MR-TOF-MS can separate ions temporally with a mass resolution of up to $m/\Delta m_{FWHM} = 500,000$.

The integration of these three ion traps on one platform makes TITAN a powerful tool for probing nuclear physics. With the addition of a flexible stable ion source, TITAN’s capabilities would also be extended to analytic mass spectrometry.

3. Plasma Ion Source: Design & installation

The original PIS design was slightly modified to accommodate TITAN beamline requirements. This included modifying the original filament to allow for a sample to be deposited for surface ionisation. The PIS is composed of a boron nitride cylinder containing a tungsten filament and anode electrode. The main filament casing is covered by a copper enclosure that has the option of water cooling. The filament is floated at a voltage which controls the energy of exiting ions and a potential difference between the anode and filament of 50–150 V is supplied to aid extraction. The PIS and successive optics (Einzel lens and X–Y correction steerers) are shown in Fig. 1. The Einzel lens is an electrostatic focusing lens, which is segmented into three sections that are referred to as Einzel Lens Top (EL-T), Einzel Lens Middle (EL-M) and Einzel Lens Bottom (EL-B) in this paper. The X–Y steerers consist of four opposing plates. Two adjacent plates are independently powered and are referred to as Steerer North (ST-N) and Steerer West (ST-W). The remaining two plates, referred to as Steerer Common (ST-COM) are supplied with a common voltage and hence varying the voltage of ST-N and ST-W provides ion steering in the X–Y plane of the beam. The system was mounted at the end of the beamline and a high vacuum turbo pump ensured pressures of below 1×10^{-8} Torr.

The PIS is designed to generate a plasma with an arc discharge from the introduction of a gas into the filament casing. These ions are accelerated through a 0.5 mm diameter orifice in the anode. Due to the low potential difference between the filament and the anode (50–150 V), small energy spreads of less than 1 eV are expected for the ion beam [12]. In this experiment, the PIS was first commissioned in surface ionisation mode, in which a sample was deposited onto the filament that was then heated resistively with 5–12 A of current to produce ions. The implementation of the surface ionisation mode enabled the testing of the PIS under simplified and well controlled operating conditions, i.e. no connection of gas sources and lower current HV power supplies. Operation of the source in a surface ionisation mode allowed for the flexible and simple deposition of metal salts onto the filament that could be ionised at relatively low filament temperatures (<1000 °C) without requiring the formation of a plasma. A potential difference of between –50 to –150 V was applied between the filament and the anode in order to extract the positive ions.

The location of the PIS in the TITAN beamline along with the Photonics 1.25" Micro-Channel Plates (MCPs) are shown in a schematic in Fig. 2. This position of the source enabled the ion beam to be directed through the TITAN beamline to the three main ion traps independently.

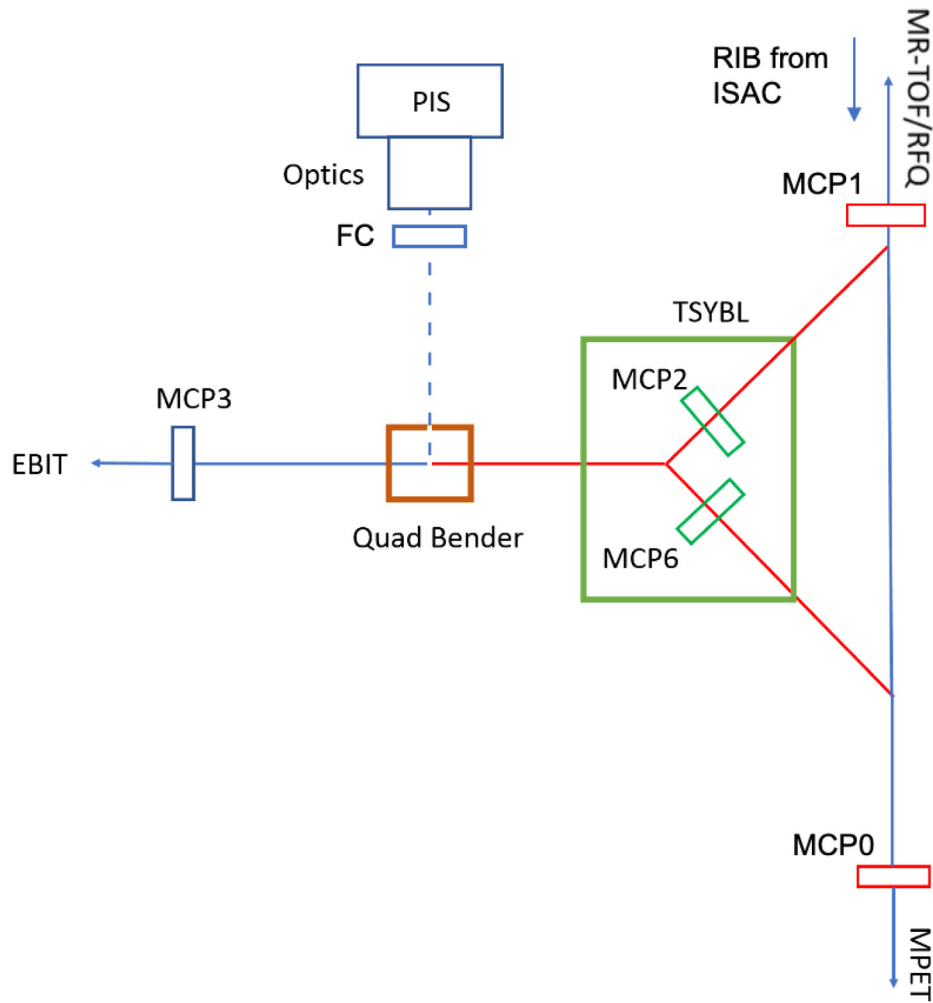


Fig. 2. Schematic of the TITAN beamline and Micro-Channel Plate (MCP) positions viewed from above. The PIS is positioned above the Quadrupole Bender and has been rotated 90° for this graphic to lie in the plane of the diagram, indicated by the dashed blue line. RIB from ISAC is transported through TITAN at the top of the figure after passing through the RFQ. The TITAN Switchyard Beamline (TSYBL) allows ion beam to be sent towards MR-TOF and MPET simultaneously.

4. Simulating ion transport in the Ion Source

The Monte Carlo simulation package, SIMION [7] was used to model the transmission of the ions in the PIS and preceding optics. The ion source geometry was generated with CAD files obtained from the manufacturer. Monte Carlo simulations were run with 20 groups of 3000 particles. Space charge forces were not included in order to reduce computation time. Ions of mass 40 u were randomly generated within a circle of radius 5 mm (radius of PIS filament) and were given an initial kinetic energy of 0.1 eV corresponding to a filament temperature of 1160 K. The initial voltage configuration, where the filament casing was grounded, gave a transmission efficiency in simulation from the filament to the Faraday Cup (FC) of 2.0 (1)%. The uncertainty in this value arises from the random fluctuation of particle initial conditions. Using the SimplexOptimizer function in SIMION [13], the potentials of the anode and EL-M were varied for a fixed filament bias (which defined the beam energy) and fixed voltages for EL-T and EL-B in order to maximise the simulated transmission through the source. However, this optimisation routine was unable to find a voltage configuration that improved upon the 2% transmission.

A close inspection of the simulated trajectories for this configuration of applied source potentials revealed that over 50% of the ions are accelerated towards the rear of the ion source in the direction of the grounded filament casing, as seen in Fig. 3a. If the filament casing is biased to the same potential as the filament, the simulations

demonstrated that all ions are accelerated towards the anode and the transmission improved by a factor of 10, resulting in a total simulated transmission of 20 (1)%, as shown in Fig. 3b. This transmission still seems relatively low, however, it should be noted that large losses are expected to occur at the anode due to its small aperture size. The PIS simulations proved crucial in demonstrating the need to bias the filament casing as well as predicting the voltages of the source lenses, especially as the source was not being operated as the manufacturer intended.

Based on the results from the ion trajectory simulations, the experimental set up was modified to bias the filament casing (Fig. 1 dashed line). The Nelder–Mead optimisation method was used to optimise the anode and EL-M voltages for ion transmission through the PIS. The remaining parameters were omitted from the optimisation and were tuned manually in order to steer the ions to MCP6 within the simulation (see Fig. 2). The simulation voltages were used as a starting point in tuning the beam to MCP6. The differences between simulated and experimental voltages are summarised in Table 1.

The experimental voltages are in good agreement with the values predicted by simulations. The largest difference between experimental and simulated voltages is 29.3%, i.e. in the case of the TITAN Switch Yard Beam Line: X-Correction Bender (TSYBL:XCB). This disagreement is most likely due to a discrepancy between the experimental and simulated positioning of components. As there is currently no comprehensive CAD model of the PIS integrated into the TITAN beamline, the positioning of the optics had to be measured by hand.

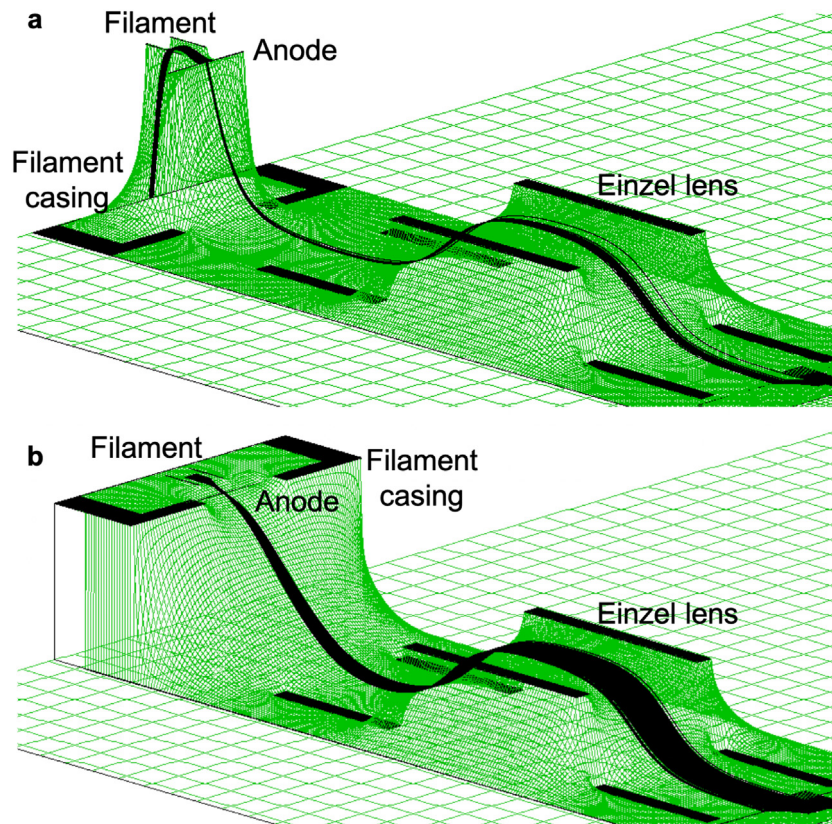


Fig. 3. Equipotential surface of the PIS, simulated in SIMION. (a) Initial voltage configuration where the filament is biased to 2000 V and the filament casing is grounded. (b) Biasing the filament casing to the same potential as the filament (2000 V).

Table 1
Optimised voltages predicted by SIMION simulations compared to the experimental tune to MCP6 at a beam energy of 2 keV.

| Component | Simulation voltages (V) | Experimental voltages (V) | Difference (%) |
|-------------------------|-------------------------|---------------------------|----------------|
| Filament bias | 2000 | 2000 | 0.00 |
| Filament casing | 2000 | 2000 | 0.00 |
| Anode | 1898 | 1900 | 0.11 |
| EL-T and -B | 0 | 0 | 0.00 |
| EL-M | 1320 | 1310 | 0.76 |
| ST-N | 200 | 180 | 11.1 |
| ST-W | 200 | 231 | 13.4 |
| ST-COM | 200 | 200 | 0.00 |
| Quadrupole Bender (+/-) | 2000 | 1980 | 1.01 |
| TSYBL:XCB | 220 | 311 | 29.3 |
| TSYBL:YCB | 160 | 160 | 0.00 |
| TSYBL:Bender8:POS | 250 | 270 | 7.41 |
| TSYBL:Bender8:NEG | -292 | -315 | 7.30 |

Modifying the experimental configuration by floating the filament casing to the same potential as the filament results in an experimental beam current increase above the background noise. A beam current of 1 nA was achieved on the Faraday plate and this allowed for a detectable ion beam which was directed to MCP6 in the TITAN beamline.

5. Identification of ions by Time-of-Flight mass spectrometry

In order to characterise the ions produced by the PIS, a method was devised to measure low-resolution TOF spectra on the MCPs positioned in the TITAN beamline. Despite the low mass resolving power of the TOF technique, it proved to be a simple but powerful diagnostic tool for the commissioning of the PIS.

A continuous beam of ions is produced by the PIS, and this beam is chopped using the X-Y steerers. The steerer electrodes are used as a low efficiency beam chopper by applying fast high voltage switches (Behlke HTS 61-01 GSM [14]) with a rise time of a few nanoseconds. Thus, by using the controlled timing signals from a pulse generator, a portion of DC beam is steered away, creating ion bunches on the order of 1 μs in duration. These bunches are steered 90° through the Quadrupole Bender before they are directed towards an MCP. The ions are all accelerated to the same energy, however heavier ions take longer to reach the MCP compared to lighter ions due to their lower velocities at equal kinetic energy. The temporal separation of ions enables the determination of ion mass m from

$$m = d(t - t_0)^2. \quad (1)$$

In this equation t is the time of flight from the X-Y steerers, t_0 is an offset that accounts for all electronic delays and d is a constant $d = 2E_k q/s^2$, where E_k is the kinetic energy of the ion, q the charge on the ion and s is the distance the ion travelled. The probability of the production of multiply charged ions is very low at the applied heating temperatures and hence q is assumed to be one.

A custom Data Acquisition software (DAQ) was written in Lab View for the FastComTec MCS4 DAQ module [15].

5.1. Time-of-Flight measurement and calibration

TOF spectra from a heated tungsten filament, detected on MCP0, MCP2 and MCP3 (refer to Fig. 2 for MCP locations) at beam energies of 1.3 keV and 2.2 keV, at a filament current of 4.5 A were obtained. The TOF spectrum recorded on MCP2 is shown in Fig. 4.

The two ion species seen in Fig. 4 were observed in all three TOF spectra. Using Eq. (1), assuming that $t_0 = 0$ and estimating the constant d using a path length $s = 1.74$ m, a mass range of 23–25 u was calculated for the low mass peak and 39–41 u for the high mass peak.

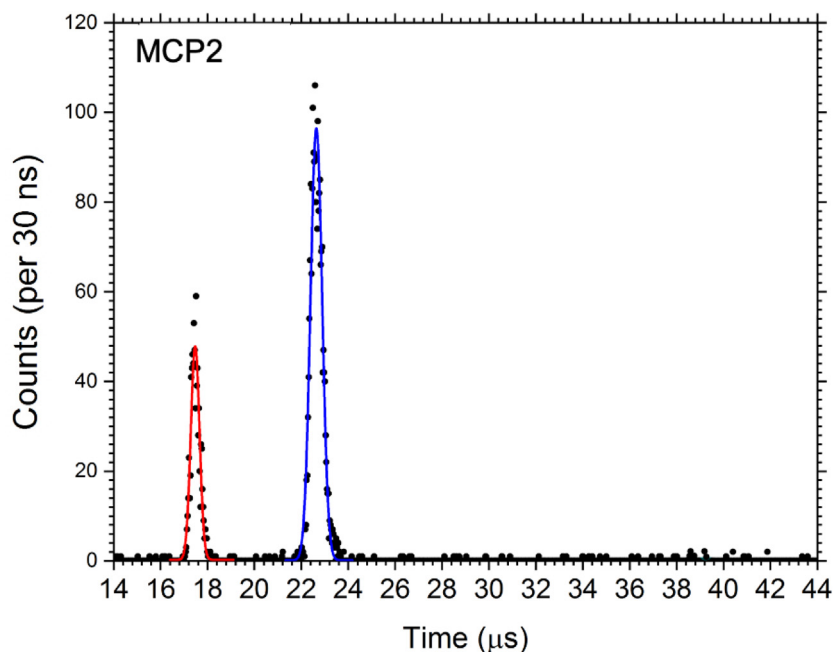


Fig. 4. TOF spectrum of species seen at filament current of 4.5 A. The spectrum was taking using MCP2 with ions at 1.3 keV in 0.8 μ s bunches.

The most significant contribution to the uncertainty in mass was due to the uncertainty in the path length measurement. For the given mass ranges, the most likely candidate for the lower mass ion was $^{23}\text{Na}^+$, with the higher mass peak containing unresolved $^{39}\text{K}^+$ and $^{41}\text{K}^+$ ions. The detection of these particular ions was due to the alkali metals' low ionisation energies and the fact that they are both also common contaminants of the tungsten filament material [16].

The filament was further heated to 6.15 A and a lower beam energy of 1.5 keV and shorter 1 μ s duration bunches were used. The lower energy increases the time it takes ions to reach the MCP, greater separating ion peaks temporally in a TOF spectrum, whereas the shorter bunch time reduces the Full Width Half Maximum (FWHM) of the peak, increasing resolving power. A TOF spectrum was recorded on MCP6, which can be seen in Fig. 5a, where the three species were identified as $^{23}\text{Na}^+$, $^{39}\text{K}^+$ and $^{41}\text{K}^+$. The mass of the ions are plotted against their TOF as recorded on MCP6 and a parabola is fitted with the equation $m = d(t - t_0)^2$, where m is the ions mass, t is the time of flight and d and t_0 are parameters to be determined (Fig. 5b).

Using the value of d obtained from the data in Fig. 5b, the path length travelled by the ions was calculated to be 1.78(4) m, which agrees with the minimum path length of 1.74 m that was inferred from CAD drawings. The isotope abundance of ^{41}K , calculated from the areas of the two peaks, is 5.94 (88)%, which is within 1σ agreement with IUPAC's tabulated relative isotopic abundance of 6.730% [17]. This supports the identification of the three species in this TOF spectra as $^{23}\text{Na}^+$, $^{39}\text{K}^+$ and $^{41}\text{K}^+$. Using the parameters obtained from Fig. 5b, Eq. (1) can then be used to convert the TOF spectrum (Fig. 5a) into a mass spectrum, as seen in Fig. 5c, allowing the identification of other masses. The filament current was limited to 6.15 A due to the high voltage float required and distance of the ion source from the power supplies. The electrodes were connected to the power supplies by long cables that increased resistance and in turn decreased current carrying capacity. In the future the filament power supply will be mounted in the HV PIS cage to reduce cable length and allow for an increase in filament current.

5.2. Rb deposition on the PIS cathode

Due to the limited power available from the power supply and hence the relatively low cathode temperatures that were achieved, Rb was deposited onto the filament because this element has a low ionisation energy and thus realises high ion yields. A conventional Thermal Ionisation Mass Spectrometry (TIMS) sample deposition method was chosen to deposit the Rb onto the PIS filament. To achieve this, the PIS filament was modified [18], as shown in Fig. 6 to increase the surface area for sample deposition. A Re ribbon was spot welded onto the top of the filament, in order to create a larger, flatter surface on which the sample was deposited on. A one microlitre aliquot solution of a RbCl salt dissolved in water (ICN Pharmaceuticals Lot 30255-A) was deposited on the Re ribbon and 1 A was run through the filament in order to evaporate the solvent, leaving 1 μ g of Rb on the ribbon.

5.3. Rb sample Time-of-Flight measurement

The filament was installed in the PIS and was heated to 3.2 A. A TOF spectrum was recorded on MCP6 with a beam energy of 1.8 keV and 2 μ s bunches. The spectrum was recorded for 30 min. MCP6 was chosen due to its higher performance (signal-to-noise ratio) it produced a spectrum with low background. Using the calibration method outlined in section 4.2, the mass spectrum in Fig. 7 was obtained. The low mass peak on the left at a mass of 39 u is identified as K^+ ions, as was previously seen, assumed to stem from impurities in the tungsten filament. At a bunch duration of 2 μ s and beam energy of 1.8 keV, $^{41}\text{K}^+$ could not be resolved from the $^{39}\text{K}^+$ peak as before. It was, however, necessary to use a bunch duration of 2 μ s, as this allowed the acquisition of more Rb+ ions in the spectrum due to a larger number of particles per bunch.

The high mass peak on the right of Fig. 6 was found to have a mass of 85 (1) u. The most abundant isotope of Rb, ^{85}Rb (72.17%), has a mass 84.912 u [17] which agrees within uncertainty with the TOF mass measurement made on MCP6. It can therefore be concluded that the high mass peak in the spectrum is indeed Rb, and that the PIS can successfully ionise alkali metals when operating in surface ionisation mode. It has also been demonstrated that the TOF method developed

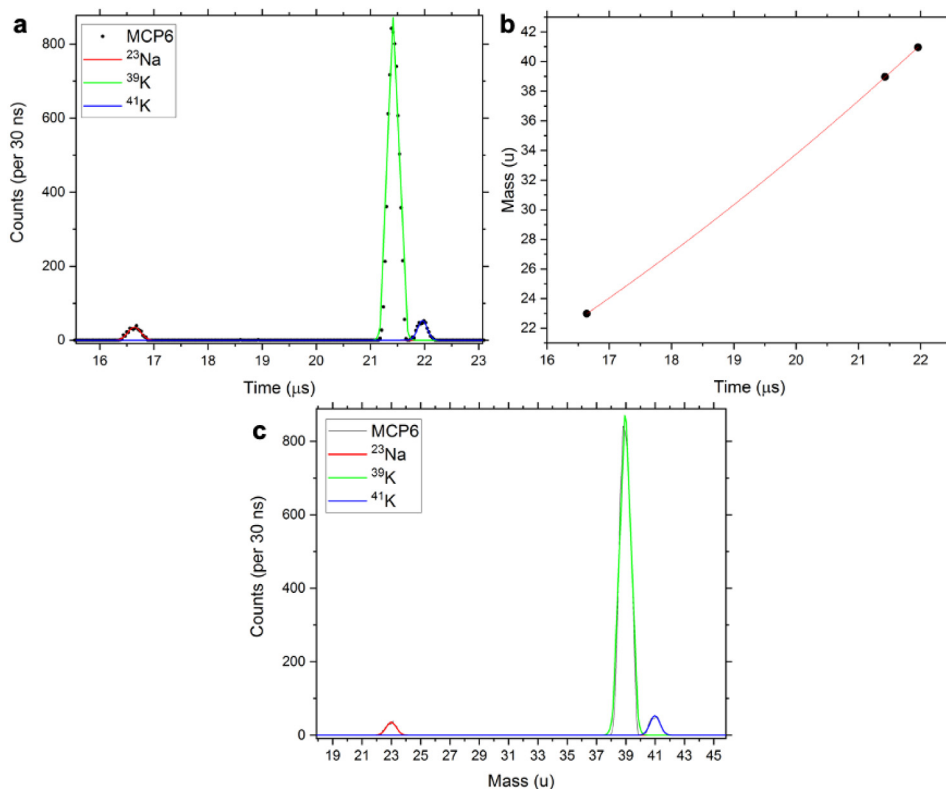


Fig. 5. (a) TOF spectrum of ions recorded on MCP6 with 1 μs ion bunches at 1.5 keV. Filament current was at 6.15 A. Three species were identified as ²³Na, ³⁹K and ⁴¹K for the analysis. (b) Plot of the assumed mass of the three species against their time of flight to obtain the parameters from the quadratic equation $m = d(t - t_0)^2$. (c) Mass spectrum calibrated using the parameters d and t_0 extracted from (b).

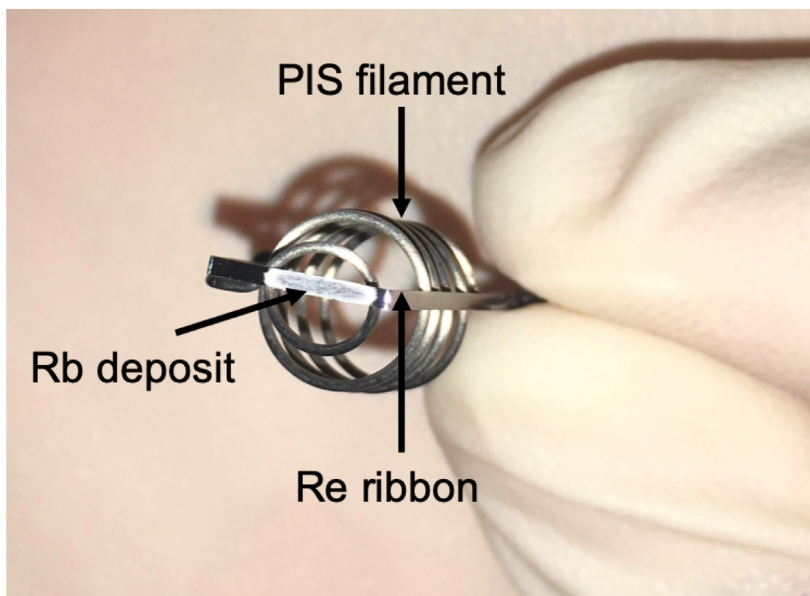


Fig. 6. Modified PIS filament with welded Re ribbon. Rb salt was deposited onto the Re ribbon.

in this experiment is able to identify ion species and has proven to be a useful diagnostic tool.

6. Conclusion

An arc-discharge PIS was installed on the TITAN platform as a means to provide a non-radioactive beam for instrument calibration. Monte Carlo simulations were used to assist in the optimisation of the

ion transmission through the source. The results of the simulations demonstrated that a significant improvement to ion transmission would be achieved by biasing the filament casing to the same potential as the filament bias, which increased the simulated transmission by a factor of ten. After adapting the experimental set-up to allow for the biasing of the filament casing, the experimental transmission was also greatly improved, allowing for a signal to rise above the background noise and to be detected on downstream MCPs. The simulations were

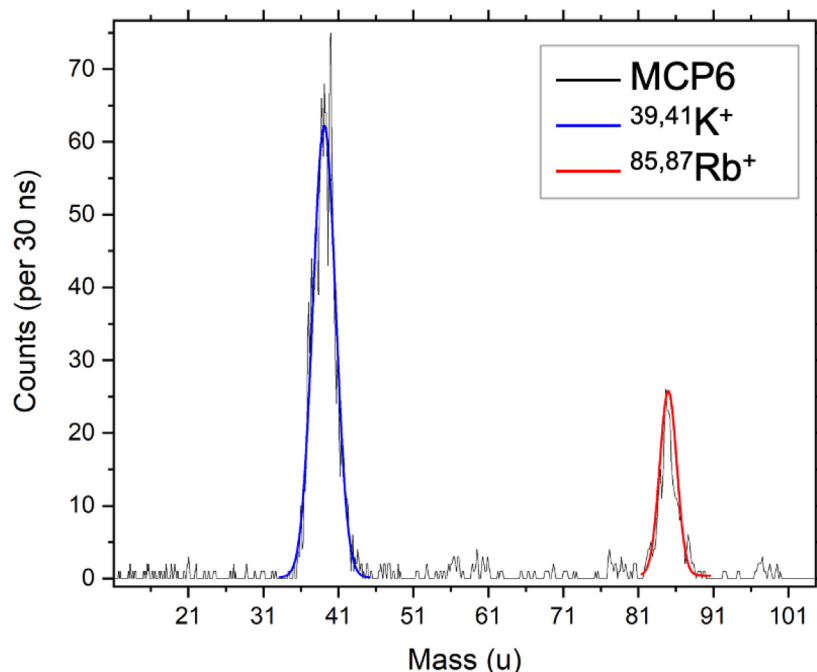


Fig. 7. Mass spectrum from Rb filament heated with 3.2 A and measured on MCP6. Beam energy of 1.8 keV and bunches of 2 μ s in duration.

also essential for tuning beams through the Quadrupole Bender and preceding optics.

Initial tests of the PIS source were performed using the source in a surface ionisation mode where ions were produced by heating salt-coated filaments. A rhenium ribbon was spot welded to the tungsten cathode of the PIS, which allowed for salts such as Rb to be deposited easily onto the filament. A TOF method was developed by bunching the PIS beam and timing the arrival of ions on an MCP in order to quickly and effectively identify the mass of the species. Rb was successfully ionised by the PIS and Na^+ and K^+ ions were also identified as impurities of the tungsten filament. The PIS was therefore successfully commissioned in surface ionisation mode and integrated into the TITAN beamline.

In the future, the introduction of a gas into the PIS filament casing will allow for the operation of the source in plasma ionisation mode, creating a multi-purpose ion source for stable isotope physics at TITAN. The combination of TITAN's multiple traps makes it an outstanding experiment for nuclear studies; in addition, the MR-TOF-MS will be used as a flexible instrument in Isotopic Ratios Mass Spectrometry (IRMS). The PIS will allow for a wide variety of stable ions to be easily ionised and transported to the MR-TOF-MS for IRMS in the future.

CRedit authorship contribution statement

Jake A.D. Flowerdew: Writing - original draft, Investigation, Formal analysis. **Ish Mukul:** Investigation, Formal analysis. **Anna A. Kwiatkowski:** Supervision, Conceptualization. **Michael E. Wieser:** Supervision, Conceptualization, Writing - review & editing. **Robert I. Thompson:** Supervision, Conceptualization. **Jens Dilling:** Project administration, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We want to thank the TITAN collaboration for their help with this project. This work was supported by National Science and Engineering Research Council of Canada (NSERC), federal funding through TRIUMF by the National Research Council of Canada (NRC).

References

- [1] J. Dilling, R. Baartman, P. Bricault, M. Brodeur, L. Blomeley, F. Buchinger, J. Crawford, J.R. Crespo López-Urrutia, P. Delheij, M. Froese, G.P. Gwinner, Z. Ke, J.K.P. Lee, R.B. Moore, V. Ryjkov, G. Sikler, M. Smith, J. Ullrich, J. Vaz, Mass measurements on highly charged radioactive ions, a new approach to high precision with TITAN, *Int. J. Mass Spectrom.* 251 (2) (2006) 198–203, <http://dx.doi.org/10.1016/j.ijms.2006.01.044>, <http://www.sciencedirect.com/science/article/pii/S1387380606000777>.
- [2] J. Dilling, K. Blaum, M. Brodeur, S. Eliseev, Penning-trap mass measurements in atomic and nuclear physics, *Ann. Rev. Nucl. Particle Sci.* 68 (1) (2018) 45–74, <http://dx.doi.org/10.1146/annurev-nucl-102711-094939>.
- [3] Beam imaging solutions, 2021, <http://beamimaging.com/product-category/ion-sources/>.
- [4] C. Jesch, T. Dickel, W.R. Plaf, D. Short, S. Ayet San Andres, J. Dilling, H. Geissel, F. Greiner, J. Lang, K.G. Leach, W. Lippert, C. Scheidenberger, M.I. Yavor, The MR-TOF-MS isobar separator for the TITAN facility at TRIUMF, *Hyperfine Interact.* 235 (1–3) (2015) 97–106, <http://dx.doi.org/10.1007/s10751-015-1184-2>.
- [5] T. Dickel, W.R. Plaf, W. Lippert, J. Lang, M.I. Yavor, H. Geissel, C. Scheidenberger, Isobar separation in a multiple-reflection time-of-flight mass spectrometer by mass-selective re-trapping, *J. Am. Soc. Mass Spectrom.* 28 (6) (2017) 1079–1090, <http://dx.doi.org/10.1007/s13361-017-1617-z>.
- [6] Z. Muccio, G.P. Jackson, Isotope ratio mass spectrometry, *Analyst* 134 (2009) 213–222, <http://dx.doi.org/10.1039/B808232D>.
- [7] D. Dahl, SIMION For the personal computer in reflection, *Int. J. Mass Spectrom.* 200 (1–3) (2000) 3–25, [http://dx.doi.org/10.1016/S1387-3806\(00\)00305-5](http://dx.doi.org/10.1016/S1387-3806(00)00305-5), <http://www.sciencedirect.com/science/article/pii/S1387380600003055>.
- [8] J.A. Nelder, R. Mead, A simplex method for function minimization, *Comput. J.* 7 (4) (1965) 308–313, <http://dx.doi.org/10.1093/comjnl/7.4.308>.
- [9] J. Dilling, R. Krücken, G. Ball, ISAC Overview, *Hyperfine Interact.* 225 (1) (2014) 1–8, <http://dx.doi.org/10.1007/s10751-013-0877-7>.
- [10] A. Lapiere, M. Brodeur, T. Brunner, S. Ettenauer, A.T. Gallant, V. Simon, M. Good, M.W. Froese, J.R. Crespo Lopez-Urrutia, P. Delheij, S. Epp, R. Ringle, S. Schwarz, J. Ullrich, J. Dilling, The TITAN EBIT charge breeder for mass measurements on highly charged short-lived isotopes - First online operation, *Nucl. Instrum. Methods Phys. Res. A* 624 (1) (2010) 54–64, <http://dx.doi.org/10.1016/j.nima.2010.09.030>.

- [11] A. Chaudhuri, C. Andreoiu, M. Brodeur, T. Brunner, U. Chowdhury, S. Ettenauer, A.T. Gallant, A. Grossheim, G. Gwinner, R. Klawitter, A.A. Kwiatkowski, K.G. Leach, A. Lennarz, D. Lunney, T.D. Macdonald, R. Ringle, B.E. Schultz, V.V. Simon, M.C. Simon, J. Dilling, TITAN: an ion trap for accurate mass measurements of ms-half-life nuclides, *Appl. Phys. B* 114 (1) (2014) 99–105, <http://dx.doi.org/10.1007/s00340-013-5618-8>, <https://doi.org/10.1007/s00340-013-5618-8>.
- [12] M. Menzinger, L. Wählin, High intensity, low energy spread ion source for chemical accelerators, *Rev. Sci. Instrum.* 40 (1) (1969) 102–105, <http://dx.doi.org/10.1063/1.1683697>.
- [13] SIMION SimplexOptimizer, 2021, https://simion.com/info/lua_simionx.SimplexOptimizer.html.
- [14] Behlke fast high voltage switches, 2021, <https://www.behlke.com/pdf/61-01-gsm.pdf>.
- [15] FastComTec MCS4, 2021, <https://www.fastcomtec.com/ufm/mcs4>.
- [16] M. Andrási, G. Forgács, A. Lőrinczy, The effect of potassium contamination of tungsten on filament-metallized devices, *Phys. Status Solidi (a)* 51 (2) (1979) 573–577, <http://dx.doi.org/10.1002/pssa.2210510232>.
- [17] J. Meija, T.B. Coplen, M. Berglund, W.A. Brand, P. De Bièvre, M. Gröning, N.E. Holden, J. Irrgeher, R.D. Loss, T. Walczyk, T. Prohaska, Atomic weights of the elements 2013 (IUPAC Technical Report), *Pure Appl. Chem.* 88 (3) (2016) 265–291, <http://dx.doi.org/10.1515/pac-2015-0305>.
- [18] J. Flowerdew, Optimising Ion Transport in a Thermal Ionisation Mass Spectrometer and Plasma Ion Source Using Monte Carlo Simulations (Master's thesis), University of Calgary, 2019, <http://hdl.handle.net/1880/111049>.