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The MR-TOF-MS isobar separator for the TITAN facility at TRIUMF

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Abstract At TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) a multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) will extend TITAN's capabilities and facilitate mass measurements and in-trap decay spectroscopy of exotic nuclei that so far have not been possible due to strong isobaric contaminations. This MR-TOF-MS will also enable mass measurements of very short-lived nuclides (half-life > 1 ms) that are produced in very low quantities (a few detected ions overall). In order to allow the installation of an MR-TOF-MS in the restricted space on the platform, on which the TITAN facility is located, novel mass spectrometric methods have been developed. Transport, cooling and distribution of the ions inside the device is done using a buffer gas-filled RFQ-based ion beam switchyard. Mass selection is achieved using a dynamic retrapping technique after time-of-flight analysis in an electrostatic isochronous reflector system. Only due to the combination of these novel methods the realization of an MR-TOF-MS based isobar separator at TITAN has become possible. The device has been built, commissioned off-line and is currently under installation at TITAN.

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1 Introduction

The TRIUMF rare ion beam facility ISAC [1] currently serves 18 state of the art experiments. One of the experimental facilities at ISAC is TITAN [2, 3], a multi-ion trap system for precision experiments, such as mass measurements and in-trap decay spectroscopy. The main research fields are nuclear structure, nuclear astrophysics and fundamental symmetries and interactions. The latest upgrade to the TITAN facility is a multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS). MR-TOF-MS have been installed recently at many rare ion beam facilities around the world [4–7]. It has been demonstrated that these systems can achieve outstanding performance, such as transmission efficiency up to 50 %, mass resolving power up to $m/\Delta m_{\mathrm{FWHM}} = 600{,}000$, mass accuracies down to ∼0.1 ppm, repetition rates up to 400 Hz, ion capacity in excess of $> 10^6$ ions per second and high sensitivity [8]. They can be used as highly accurate, fast and sensitive mass spectrometers or as isobar separators. At ISOL facilities like ISAC, mass measurements with an MR-TOF-MS enable access to shorter-lived nuclides and nuclides produced at lower rates than currently accessible with the standard Penning trap techniques. When the MR-TOF-MS is used as a mass separator, it facilitates measurements that are otherwise impossible due to isobaric contaminations. It has been shown that an MR-TOF-MS can be even used to provide isomerically clean beams [9]. In addition, the high mass resolution and capability to measure all isobars of one mass unit simultaneously enable a very efficient investigation and optimization of the target and ion source operation. Because of their versatility and compact and robust design they also find applications in other research fields such as in life sciences and in-situ analytical measurements [10].

2 Mass resolving power for mass separation at ISOL facilities

At ISOL facilities, the production yields of less exotic contaminants are often many orders of magnitude higher than the yields of the ions of interest, resulting in demanding requirements on the performance of the mass separator. This is especially true for ISAC, which has the highest power on target of all ISOL facilities world-wide.

The MR-TOF-MS offers an unparalleled combination of high ion capacity and mass resolving power [5] and is thereby the ideal solution for TITAN. In order to determine the necessary mass resolving power of the separator at an ISOL facility, the number of accessible nuclides were calculated for different mass resolving powers of the separator. The ISOLDE yield database was used for this investigation, because it has more entries than any other ISOL yield database. A nuclide was defined as accessible in this investigation if more than 50 % of the beam current after the separator corresponds to the nuclide of interest. The peak shape of the transmission spectrum of the separator was assumed to be Gaussian. The investigation was performed separately for the different ion sources, because each ion source provides a different composition of the beam. Only the four major ion sources surface ionization, plasma ionization, resonant laser ionization (RILIS) and forced electron beam induced arc discharge (FEBIAD) have been considered. To simplify matters the different energies, beam currents and targets have not been considered. The yields from surface ionization are added to the yields of the other three ion sources, because surface ionization

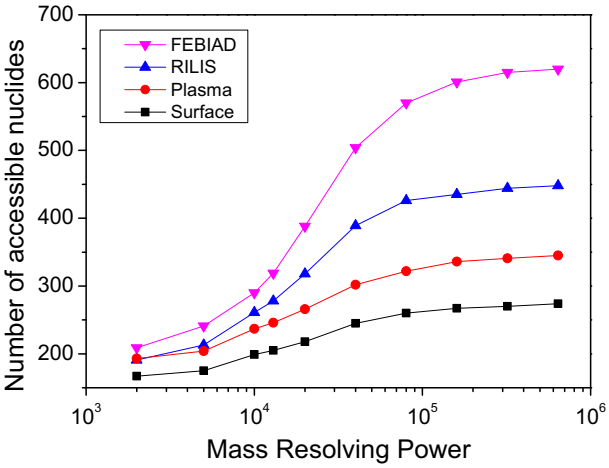

Fig. 1 The number of accessible nuclides for different ion sources in dependence of the mass resolving power (FWHM) of the separator at ISOL facilities, for details see text

always occurs and the production of the other ionization methods come in addition. After the yield database was divided into these four subgroups it was checked if more than one entry per isotope exists; if so, only the one with the highest yield was used.

In Fig. 1 one can see that a resolving power of 10,000 is necessary to significantly increase the number of accessible nuclides compared to the standard dipole magnet of ISAC, which has a mass resolving power of 2,000 [11]. For a mass resolving power of 20,000 about 70 % of the nuclides are accessible. To have more than 90 % accessible, a mass resolving power of about 50,000 is required.

3 Experimental setup

In Fig. 2, the layout of the TITAN facility is shown. The ISAC beam is captured, cooled and bunched in the radio-frequency quadrupole (RFQ) buncher [12]. There are numerous options for the experiment to proceed further: (i) transport of the bunched ions back downwards to other experiments, e.g. laser spectroscopy [13], (ii) direct transport to the measurement Penning trap (MPET) for mass measurements if no additional isobar separation is necessary, (iii) trapping in the electron-beam ion trap (EBIT) for in-trap decay spectroscopy or charge breading and (iv) further transport of the charged-bred ions to the MPET for mass measurements. In the future the highly charged ions can also be cooled in the cooler Penning trap (CPET) before the mass measurement is done in the MPET. The MR-TOF-MS will enhance all operation modes (i-iv) by providing isobarically clean beams, and (v) it can be used as a mass spectrometer on its own to measure the most short-lived and rare nuclides.

The TITAN beamline is very compact and does not include any longer drift sections suitable for installation of the MR-TOF-MS. Thus the installation of the device ”outside” the existing beamline as shown in Fig. 2 is the only option. This solution has the additional advantage that the system can be installed without major changes to the existing ion optics and beamline of TITAN, which is important since TITAN is a running facility.

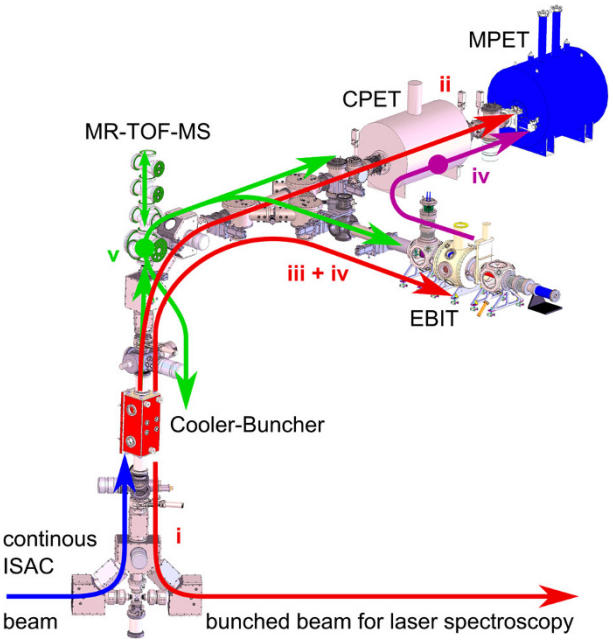

Fig. 2 Layout of the TITAN facility including upgrades (MR-TOF-MS and CPET) and the different operation modes, for details see text. The continuous beam from ISAC is shown in blue, singly charged ions bunched ions from the TITAN buncher are shown in red, singly charged ions processed by the MR-TOF-MS are shown in green and highly charged ions are shown in purple

Furthermore, the available space on the TITAN platform is very limited. A very compact device is necessary, because only a space of 0.8x0.8x1.5 m^3 is available on top of the first 45° bender.

In conventional MR-TOF-MS isobar separators, the temporal separation is converted to spatial separation by a Bradbury-Nielson-Gate (BNG) behind the MR-TOF-MS [4]. The ions are then retrapped in an additional trap or they are transported electrostatically to the next experimental stage. This additional electrostatic beamline behind the MR-TOF-MS is not possible at TITAN due to the space restrictions discussed above. Two novel mass spectrometric methods had to be developed to allow for such a compact device: (i) Ion transport into and out of the device is performed using a buffer gas-filled RFQ-based ion beam switchyard [14]. The switchyard enables in- and ejection in all directions and merging of the exotic nuclides with ions from several off-line ion sources for calibration and optimization. The buffer gas-filled RFQ-based switchyard provides ion cooling and distribution without the need for additional differential pumping, thereby allowing a very efficient, compact, simple and reliable beam distribution. (ii) Mass selection is performed using dynamic mass-selective retrapping in the injection trap of the MR-TOF-MS after time-of-flight analysis in the isochronous reflector system. By closing the injection trap at a proper point in time, the spatial separation of ions is achieved, removing undesired ions and only storing the ions of choice. A detailed description and study of the mass-selective retrapping is given in [15, 16]. The system is based on the same analyzer as in [8, 17]. The combination of mass-selective retrapping and the RFQ-based switchyard allows to use the same trap and beamline for transport in and out of the system. An additional beamline can be omitted and

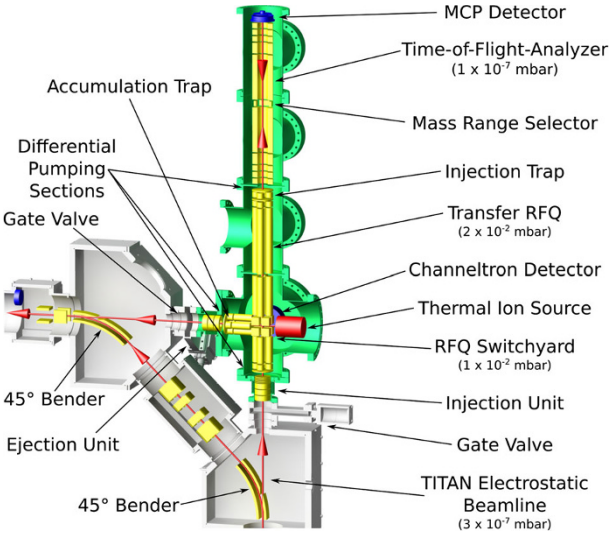

Fig. 3 Schematic Layout of the MR-TOF-MS at TITAN

a very compact system becomes possible. Thus, the combination of these novel methods allows the realization of an MR-TOF-MS based isobar separator at TITAN.

In Fig. 3 the schematic layout of the MR-TOF-MS at TITAN with its most important components can be seen. After the ions are ejected from the TITAN RFQ buncher at a potential of 30 kV, their kinetic energy is adjusted in a pulsed drift tube to about 1350 eV at ground potential, and they are transported to the electrostatic injection unit of the MR-TOF-MS. In the injection unit, the ions are steered, slowed-down and focused onto a set of vacuum separating apertures. In a gas-filled RFQ, the ions are cooled and can be stored. The RFQs of the MR-TOF-MS have a potential of about 1330 V. The ions travel through the RFQ switchyard, a transfer RFQ, and they are then cooled and bunched in the injection trap system. From the trap system, they are injected through two differential pumping stages into the time-of-flight analyzer [17], in which they travel with a kinetic energy of 1300 eV. A mass range selector (MRS) in the analyzer can be used to deflect ions that fall outside the desired mass range to ensure that the mass spectrum is unambiguous, i.e. all ions stored in the analyzer have undergone the same number of turns [8]. From the analyzer, the ions can be ejected either onto an MCP detector for measurement of their time-of-flight (e.g. for identification or mass measurement) or back into the injection trap system. After retrapping, the ions are cooled and sent through the transfer RFQ and the RFQ switchyard into the accumulation trap. Here the ions from several separation cycles are accumulated, thereby decoupling the operation frequency of the MR-TOF-MS (100 Hz) from that of the other TITAN components downstream of the MR-TOF-MS. The ions are ejected from the accumulation trap (potential of about 1280 V) into the EBIT or Penning traps. A channeltron detector and a thermal ion source are connected to the RFQ-based switchyard and provide diagnostic capabilities. At a later stage, a calibration ion source can be added as well. Ion transport from the accumulation trap back into the injection system and the re-injection into the analyzer for another consecutive separation cycle is possible allowing higher contaminant rejection if required. Ejection back into the TITAN RFQ buncher is possible as well in order to perform laser spectroscopy with isobarically separated ions. The MR-TOF-MS is connected to the

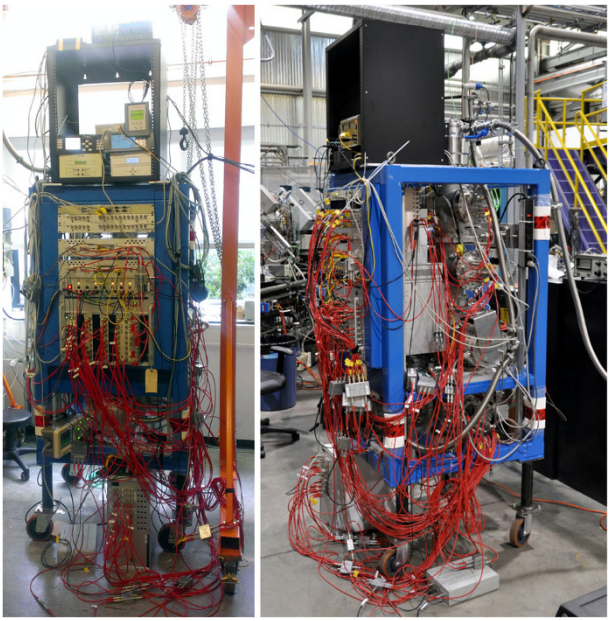

Fig. 4 The MR-TOF-MS in the laboratory in Gießen (*left*) and at TRIUMF (*right*)

existing TITAN vacuum system via gate valves, allowing independent operation of the TITAN facility as well as independent operation of the MR-TOF-MS. All ion optical elements, vacuum components and electronics are mounted in a single support frame to enable an easy transport, off-line tests and integration in the TITAN system.

The vacuum vessel of the MR-TOF-MS consists of DN160/250CF vacuum crosses. Three turbomolecular pumps (500 l/s) are used to evacuate the system. Encapsulated RFQs are employed in order to avoid additional differential pumping sections and pumps and thus to reduce cost and space requirements. Vacuum measurement of the pressures in the RFQs is performed using vacuum-compatible pressure gauges mounted directly on the RFQs in vacuum. The MR-TOF-MS uses highly stable power supplies (W-IE-NE-R Plain & Baus GmbH, Germany, Cologne and iseg Spezialelektronik GmbH, Germany, Radeberg). Custom-built circuits are used for HV stabilization, for generation of the RF voltages of the RFQs and traps and for HV pulsing. A digital storage oscilloscope is used for data acquisition.

For the commissioning before the installation on the TITAN platform the system has been equipped with an additional ion source (thermal Cs ion source, Heatwave Labs, USA, Watsonville) in front of the injection unit and an additional detector (MagneTOF, ETP Electron Multipliers, Australia, Clyde) behind the ejection unit. This allows the investigation of the beam transport through all components of the system.

4 Results

The system has been built, assembled and commissioned at the Justus-Liebig-University in Gießen, Germany. The MR-TOF-MS was shipped as an assembled system to Vancouver in September 2014 and re-commissioning starting in October 2014 at TRIUMF [18]. In Fig. 4

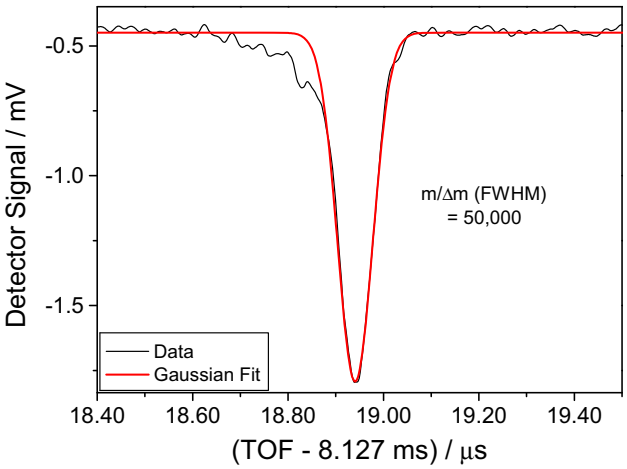

Fig. 5 Mass spectrum of $^{133}Cs^{+}$ after 253 turns in the time-of-flight analyzer. The peak shape is almost Gaussian-like

photographs of the device in the laboratory in Gießen and at TRIUMF can be seen. Because the electronic circuits for floating the potential of the RFQs were not ready at the start of the commissioning, the ion kinetic energy had to be reduced to 650 eV for all measurements shown here.

As a first commissioning step, the ion transport from the external ion source to the MCP detector behind the time-of-flight analyzer and MagneTOF detector behind the accumulation trap was optimized. On the MCP detector, peak widths as short as 16 ns have been measured after 2 turns of the ions in the time-of-flight analyzer. The mass resolving power for large turn numbers has been investigated for $^{133}Cs^{+}$ ions. A maximum resolving power of about 50,000 (FWHM) was measured in a mass spectrum after 253 turns in the time-of-flight analyzer. In the separator mode this mass resolving power would be sufficient to access more than 90 % of the nuclides produced (see Section 2). The peaks are in good agreement with Gaussian peak shapes (Fig. 5); they only show a weak tail on the left hand side. The tail is due to the particular tuning of the voltages of the MR-TOF-MS and the reduced kinetic energy, which leads to a larger beam diameter in the analyzer. In a next step, the mass-selective retrapping was tested. Resolving powers as large as 13,000 have been achieved (Fig. 6). The peak shape in separator mode shows less pronounced tails than the Gaussian peak shape. This is highly beneficial for the separation of ions with strongly different intensities. Because the MR-TOF-MS was operated at only half the design energy during the commissioning and since the time for the commissioning and optimization was limited, further performance improvements are expected in the future. However, already now the MR-TOF-MS provides a factor 6 higher resolving power than the dipole magnet currently used at ISAC and thereby almost 300 exotic nuclides for the different ion sources become now accessible.

5 Envisaged applications

The TITAN facility at TRIUMF offers superb possibilities for the research with exotic nuclides, particularly in the fields of nuclear structure, nuclear astrophysics and

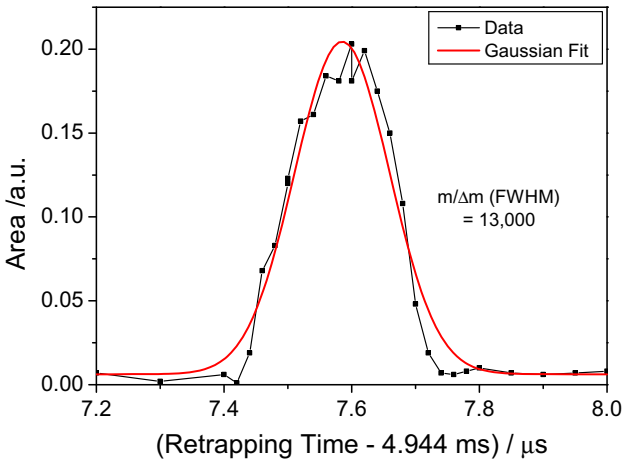

Fig. 6 Mass-selective retrapping of $^{133}Cs^{+}$ after 155.5 turns in the time-of-flight analyzer. The mass resolving power in separator mode demonstrated here is a factor 6 higher than currently available by the ISAC dipole magnet separator

fundamental symmetries and interactions. Many experiments have so far been hindered by strong isobaric contaminations. In the following, two examples will be given where the use of the MR-TOF-MS as isobar separator would be highly beneficial.

Exotic decay modes in the vicinity of proton-drip line for Z<30 [19] Of particular interest is β-delayed two-proton emission which was first predicted by Goldanskii [20] and was first experimentally observed for ^{22}Al [21]. Direct two-proton (2p) decay is another exotic decay mode. The direct 2p-decay process was first proposed theoretically by Goldansky [22]. Nuclides with a proton separation energy $S_p > 0$ and a two-proton separation energy $S_{2p} < 0$ are possible candidates for the two-proton radioactivity. The 2p-decay rate is extremely sensitive to S_{2p} and hence an accurate determination of this quantity is required [23]. Direct precise mass measurements will pin down the sign of S_{2p} and help to confirm experimentally the possibility of 2p-radioactivity. The measurements can be done by using the MR-TOF-MS as a separator and the Penning trap for the mass measurement or, in case of the most short-lived and weakly produced nuclides, the MR-TOF-MS will be used for the mass measurement.

In-trap decay spectroscopy For in-trap decay spectroscopy performed in the EBIT, isobaric contaminations result in increased background and complicated spectra [24, 25]. Thus these experiments will strongly benefit from isobarically clean beams provided by the MR-TOF-MS, which will result in an increase in sensitivity and accuracy.

6 Conclusions

The MR-TOF-MS at TITAN is based on novel mass spectrometric methods, the buffer gas-filled RFQ-based ion beam switchyard and the mass-selective retrapping. Only due to these,

the installation on the TITAN platform becomes possible. The system has been commissioned at the Justus-Liebig-University in Gießen and installation at the TITAN facility is underway. The device can be used to optimize and monitor the production of the exotic nuclides, as an isobar separator and for mass measurements of the most short-lived nuclides. The system will facilitate many new opportunities by increasing the number of accessible nuclides at TITAN. A mass separation power of 50,000, which is sufficient to access more than 90 % of the nuclides produced at ISOL facilities, is within reach.

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