Journal of Physics: Conference Series **599** (2015) 012033 doi:10.1088/1742-6596/599/1/012033

TRIGA-SPEC: the prototype of MATS and LaSpec

S. Kaufmann[1,2], T. Beyer[3], K. Blaum[3], M. Block[4,5], Ch. E. Düllmann[4,5,6], K. Eberhardt[1,5], M. Eibach[1,3], C. Geppert[1], C. Gorges[1,2], J. Grund[6], M. Hammen[1], J. Krämer[1,2], Sz. Nagy[3,4], W. Nörtershäuser[1,2], D. Renisch[1], F. Schneider[1,7], K. Wendt[7]

[1]Institut für Kernchemie, Johannes Gutenberg-Universität, 55128 Mainz; [2]Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt; [3]Max-Planck-Institut für Kernphysik, 69117 Heidelberg; [4]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt; [5]Helmholtz-Institut Mainz, 55099 Mainz; [6]PRISMA Cluster of Excellence and Institut für Kernchemie, JGU Mainz, 55128 Mainz; [7]Institut für Physik, Johannes Gutenberg-Universität, 55128 Mainz

E-mail: s.kaufmann@uni-mainz.de

Abstract. Investigation of short-lived nuclei is a challenging task that MATS and LaSpec will handle at the low energy branch of Super-FRS at FAIR. The groundwork for those experiments is laid-out already today at the TRIGA-SPEC facility as a powerful development platform located at the research reactor TRIGA Mainz. The latest status, new developments and first results of commissioning runs are presented here.

1. Introduction

LaSpec (**La**ser **Spec**troscopy of short-lived nuclei at FAIR) [1] and **MATS** (Precision **M**easurement of very short-lived nuclei using an **A**dvanced **T**rapping **S**ystem) [2] are both experiments for investigating exotic short-lived nuclei which will be produced at the low energy branch at FAIR using atomic physics techniques of laser spectroscopy and mass spectrometry. LaSpec will use collinear laser spectroscopy (CLS) to obtain charge radii from isotope shifts, nuclear moments and spins from hyperfine structure measurements in ions and atoms. MATS will perform precise mass measurements and in-trap decay spectroscopy. While FAIR just started construction, the development platforms already now provide the opportunity to optimize the experiments for their future application.

2. TRIGA-SPEC

Situated at the research reactor TRIGA Mainz the TRIGA-SPEC experiment benefits from the possibility to create short-lived nuclides by neutron-induced fission of a heavy actinide target, e.g. ^{249}Cf. A gas chamber containing the target is placed close to the core of the reactor. Fission fragments are stopped inside the chamber and transported through the biological shield of the reactor by an aerosol gas-jet and guided into the surface ion source. The source is operated on a high voltage platform and the ions are accelerated into the beamline towards a 90° mass separator on ground potential. The mass separation is followed by an RFQ cooler and buncher used to reduce the emittance and transform it into short ion bunches, which is critical for both experiments [3]. The cooling leads to a higher transport efficiency and a reduced


Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

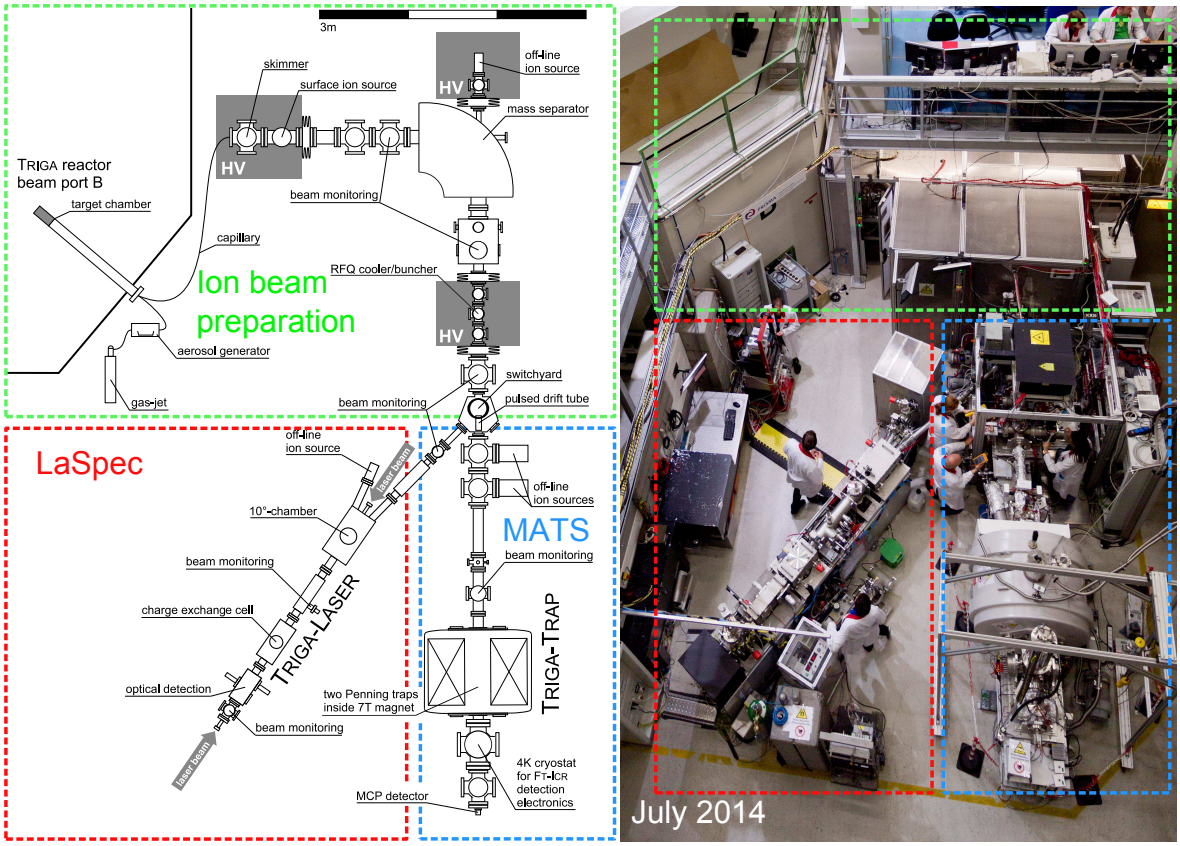


Figure 1: left: Floorplan of the TRIGA-SPEC experiment, detailed description in the text. right: picture inside the TRIGA hall with the TRIGA-SPEC experiment connected to beamport B.

broadening of spectral lines thanks to the reduced emittance. The CLS experiment benefits from the pulsed beam structure since the deterministic passing time of the ion bunch through the optical detection region (ODR) allows restricting the photon detection to the temporal length of the ion bunch (typically a few μs). This leads to a tremendous (up to 10^4) suppression of the constant background by the continuous laser light. Thus CLS on ions at rates down to 100 ions/s is feasible [4]. The Penning trap experiment benefits from the bunch structure by an increased injection efficiency into the trap. Both branches can be supplied with ion bunches in turns by use of fast switching electrodes in the switchyard.

2.1. TRIGA-TRAP

The Penning-trap mass spectrometer TRIGA-TRAP is used routinely to determine the masses of various nuclides with a relative precision $\Delta m/m$ of down to $5{\cdot}10^{-9}$ [5, 6, 7]. These measurements are performed so far with the well-established time-of-flight ion-cyclotron-resonance detection technique (TOF-ICR) [8]. The implementation of advanced measurement techniques such as Fourier-transform ICR [9] and phase-imaging ICR [10] is currently being prepared. The Penning trap is a superposition of a strong homogeneous magnetic field and a weak electric quadrupole field, which confines charged particles in three dimensions. Ion motion inside the trap is a superposition of an axial motion and two radial motions: a slow magnetron and a rapid modified cyclotron motion. The mass m of a charged particle orbiting around the field lines of a magnetic field B is linked to its cyclotron frequency $\nu_c = qB/(2\pi m)$, where q denotes the charge of

the particle. The magnetic field B is calibrated by frequency measurements of a reference ion. TRIGA-TRAP exclusively uses carbon clusters $^{12}C_x$ as reference ions because the mass of carbon defines the current mass standard ($m(^{12}C)$=12 u).
TRIGA-TRAP was constructed as a test bench for the MATS experiment. However, its location at the TRIGA reactor in Mainz offers access to neutron-rich fission products with mass numbers from 80 to 140. Mass measurements will reveal information about the evolution of shell structure, collectivity and shell closures [11] as well as second-order differentials such as odd-even staggering of nuclear masses [12]. TRIGA-TRAP also features a powerful off-line laser ablation ion source [13] for the measurement of stable nuclides all over the nuclear chart. Recent highlights include mass measurements around the deformed $N = 152$ neutron shell closure, which were performed on very small sample sizes of 10^{15} atoms by coupling the ion source to a miniature RFQ [6], and Q-value measurements for neutrino physics applications [14].

2.1.1. Electrostatic deceleration stage
As the TRIGA-SPEC ion source and RFQ cooler and buncher are biased on 30 kV potential, the produced ion bunch must be decelerated prior to the injection into the Penning-trap mass spectrometer. Therefore, at TRIGA-TRAP, an electrostatic deceleration stage has been built as described in, e.g. [15], to slow down incoming ion bunches prior to injection. As the deceleration of an ion bunch from the kinetic energy E_{high} to E_{low} increases its emittance by a factor of $\sqrt{E_{\mathrm{high}}/E_{\mathrm{low}}}$, the reduction of the ions' motional amplitudes inside the RFQ is critical. The ion bunch is then transported at a low energy (1 keV) to the Penning-trap setup.

2.1.2. The double Penning-trap setup
TRIGA-TRAP consists of two Penning traps. In the first one, the purification trap, the mass-selective buffer-gas cooling technique [16] is applied. The typical mass resolving power $m/\Delta m$ is around 10^4 and sufficient to separate isobaric contaminants from the wanted ion species. The purified ion ensemble is then transported through a small aperture, which also acts as a differential pumping barrier, to the second Penning trap, the so-called precision trap. The precision trap features an ultra-high vacuum and a hyperbolic shape to minimize electric-field inhomogeneities. In the TOF-ICR procedure, the eigenfrequency of the ion ensemble is probed by the application of a quadrupolar RF field with frequency ν_{q} around ν_{c}. Then, the ion ensemble is ejected towards an MCP detector outside the magnetic field and the time of flight is recorded. A resonant quadrupole excitation results in a minimum time of flight, and the corresponding frequency is used to extract the mass. The control and data acquisition system at TRIGA-TRAP is based on the CS framework developed at GSI [17].
In order to demonstrate the successful transport of ions from the on-line ion source into the Penning traps, a TOF-ICR of $^{85}Rb^+$ has been recorded (see Fig. 2).

2.2. TRIGA-LASER
The ions reach this branch by a right turn in the switchyard followed by a transfer tube. In the following 10°-chamber the ions are deflected by a pair of electrodes to overlap with the laser light that is coupled into the beamline through a window either in collinear or in anticollinear geometry with respect to the ion motion. The ions will then pass the charge exchange cell (CEC), where they can be neutralized if an optical excitation scheme in the atom is favored. This is followed by the ODR, where two photomultiplier tubes supported by a two stage mirror system detect the fluorescence light. Resonance spectra are recorded by changing the ion/atom velocity by applying a voltage of up to 10 keV to the ODR. The change of the ion velocity leads to a corresponding change of the laser frequency in the ion's restframe according to $\partial\nu/\partial U = \nu_{\mathrm{Laser}} e/\sqrt{2eUmc^2}$. This is an advantage since the laser frequency can be kept fixed in the laboratory frame.

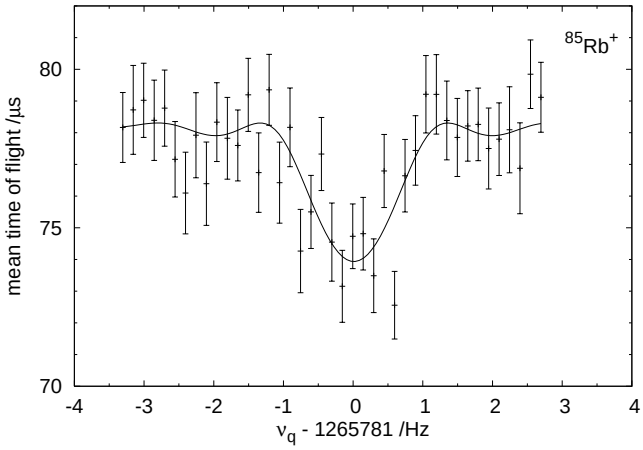


Figure 2: First TOF-ICR spectrum at TRIGA-TRAP of an ion species produced in the online surface ionization ion source, in this case $^{85}Rb^+$. The black line is the fit of the theoretical curve to the data points.

2.2.1. TRIGA pyThon cONtrol system - TRITON
In order to efficiently operate and control the setup, we have developed a control system which is custom-built for the slow controls of our experiment. Python was chosen as the programming language. TRITON is based on a modular distributed structure and the communication between different computers is realized using network sockets. This offers the opportunity to control all devices which are needed to prepare and monitor the experiment from any PC inside the network. The modularity of TRITON thereby makes it as simple as possible for the user to add a new device and reuse as much code as possible while programming a new device.

2.2.2. TRIGA Laser Data Acquisition - TILDA
TILDA is the completion to TRITON and will be responsible for the fast experiment control and the data acquisition (DAQ). CLS on bunched beams requires a separation between the photons detected during the bunch passing time and the background photons. This can be realized by recording each photon with a time stamp and therefore recording the complete timing information for off-line analysis. We developed a prototype for this DAQ with a small (Virtex-II) field programmable gate array (FPGA) and tested it successfully while commissioning the RFQ (see 2.2.4). TILDA is the follow up of this prototype and will use two independent FPGAs (Virtex 5) located in one PXI rack. One is foreseen for the fast control, e.g. loading and extracting the RFQ, the other one is acquiring data in parallel. Synchronisation is realized through the back plane of the PXI.

2.3. Commissioning of the RFQ cooler and buncher using CLS
The commissioning of bunched beam CLS with the RFQ had the goal to optimize the RFQ settings in order to create bunches with a small longitudinal emittance and hence a low energy spread and a short bunch length to achieve high background suppression and high resolution. With the time resolved DAQ, both parameters could be monitored online while optimizing the RFQ settings. The well-known D1 transition in stable Ca^+ ions was chosen for CLS with the highest abundance in $^{40}Ca^+$. The bunch length after optimization for CLS is about 0.5 μs with an energy spread of approximately 9 eV at full width at half maximum. The corresponding linewidth is about 150 MHz which is compared to a natural linewidth of $\approx$ 20 MHz still subject for further improvement. The typical TRIGA-SPEC RFQ operating parameters obtained during

commissioning are listed in Tab. 1. With these parameters we measured the D1 line of the isotopes $^{42,43,44,48}Ca^+$. The least abundant one of these is $^{43}Ca^+$ with a natural abundance of 0.135% and the resonance spectra splits up into four peaks due to hyperfine splitting. The density plot of the photon signal is shown in Fig. 3 (top) with the Doppler tuning voltage on the x-axis and the time relative to the RFQ extraction pulse on the y-axis. The fluorescence rate is color-coded. Besides the resonance positions it is also observable that the photon rate is increasing while the bunch is passing by, i.e. in the time period between 21 and 21.6 μs. This is due to inelastic residual gas collisions that lead to the excitation of the residual-gas and subsequent photon emission. In the lower part of Fig. 3, the projection on the x-axis is shown with a multiple Voigt profile fitted to the data.

Parameter	Symbol	Value
radio frequency	ν_{RF}	1.0 MHz
RF amplitude	V_{RF}	100 V
axial well depth	U_{DC}	6–10 V
capture voltage	U_{15hi}	25 V
buffer-gas pressure	p_{RFQ}	$\sim 4.6 \cdot 10^{-3}$ mbar
accumulation time	t_{acc}	0.1–100 ms
cooling time	t_{cool}	10–20 ms
ejection frequency	f_{eject}	40 Hz
ejection voltage	U_{15lo}	40 V
kicking voltage	U_{13hi}	40 V

Table 1: Standard parameters for operation of the TRIGA-SPEC RFQ in bunching mode.

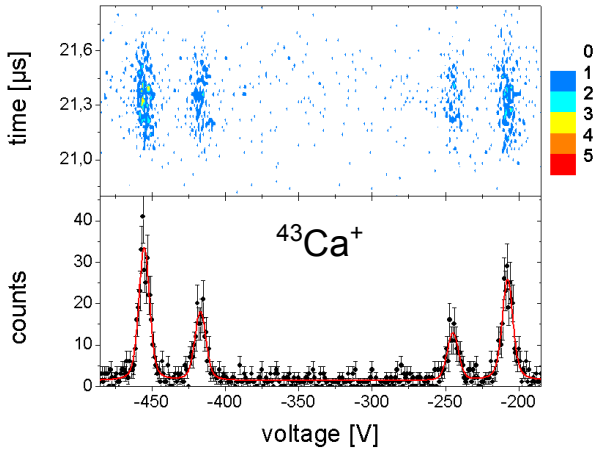


Figure 3: CLS spectra of $^{43}Ca^+$ bunches, obtained during commissioning. For details, see text.

Acknowledgments

The TRIGA-SPEC collaboration would like to thank the Bundesministerium für Bildung und Forschung (BMBF), the Max-Planck society, the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRE), the Precision Physics, Fundamental Interactions and Structure of Matter (PRISMA) cluster of excellence and the Helmholtz-Institut Mainz (HIM) for financial support.

References

[1] Nörtershäuser W, Campbell P and the LaSpec collaboration 2006 *Hyperfine Interact.* **171** 149-56
[2] Rodriguez D, Blaum K, Nörtershäuser W et al. 2010 *Eur. Phys. J. Spec. Top.* **183** 1-123
[3] Beyer T et al. 2014 *Appl. Phys* B **114** 129–36
[4] Nieminen A, Campbell P et al. 2002 *Phys. Rev. Lett.* **88** 094801
[5] Ketelaer J, Krämer J et al. 2008 *Nucl. Instr. Meth.* A **594** 162–77
[6] Eibach M et al. 2014 *Phys. Rev.* C **89** 064318
[7] Smorra C et al. 2012 *Phys. Rev.* C **86** 044064
[8] König M, Bollen G, Kluge H J, Otto T and Szerypo J 1995 *Int. J. Mass Spectrom. Ion Process.* **142** 95
[9] Ketelaer J et al. 2009 *Eur. Phys. J.* A **42** 311–17
[10] Eliseev S et al. 2014 *Appl. Phys.* B **114** 107–28
[11] Lunney D, Pearson J M and Thibault C 2003 *Rev. Mod. Phys.* **75** 1021–82
[12] Satula W, Dobaczewski J and Nazarewicz W 1998 *Phys. Rev. Lett.* **81** 3599–602
[13] Smorra C et al. 2009 *J. Phys.* B **42** 154028
[14] Smorra C et al. 2012 *Phys. Rev.* C **85** 027601
[15] Herfurth F et al. 2001 *Nucl. Instr. Meth.* A **469** 254–75
[16] Savard G et al. 1991 *Phys. Lett.* A **158** 247–52
[17] Beck D et al. 2004 *Nucl. Instr. Meth.* A **527** 567–79