Summary of recent progress in the field of on-line laser spectroscopy and mass spectrometry relevant for MATS and LASPEC

At the 9th workshop on the "APPLICATION OF LASERS AND STORAGE DEVICES IN ATOMIC NUCLEI RESEARCH" in Poznan (Poland) from May 13th – 16th, members of the MATS and LASPEC collaborations presented results about recent developments and scientific research. In the following we shortly summarize some of the presented developments that are relevant for MATS and LASPEC and refer to the respective section in the Technical Design Report (TDR) for which these developments are important. This document is meant as a brief progress report on our approved TDR[1] to corroborate the fact that the collaborations are continually improving their devices and techniques. Recent progress is also summarized in the review article "Precision Atomic Physics Techniques for Nuclear Physics with Radioactive Beams" [2] based on three lectures presented at the 152nd Nobel Symposium entitled "Physics With Radioactive Beams". The fact that 3 speakers among a total of 31 have been chosen to present results from Penning-trap mass spectrometry and laser spectroscopy represents the growing importance of these fields in nuclear physics. Several members of the two collaborations have been awarded with ERC Grants, one Starting and two Advanced, demonstrating the strong efforts to raise third party funds in order to fully finance both installations.

General

The concept of a cryogenic gas-cell working at liquid nitrogen temperature has been developed[3], and in 2012 there was a commissioning experiment at the FRS at GSI. The results presented by Wolfgang Plass in the EMIS2012 conference are very promising. In his presentation[4] he gave an overall efficiency of 12(2) % and a mean extraction time of 24 ms. Thus, for very short-lived nuclei with 10 ms < $T_{1/2}$ < 100 ms, the cell efficiency ranges from 2.6% to 10.2%.

Tape Station (Common Beamline) [TDR Chapter 2.3.1]

Right now the work is centered on making a simpler layout for better access. Some standard electronics and vacuum parts have been bought and a final design and a large fraction of the system is expected to be by the end of the year. The main focus lies on the mechanics (band transport).

Multiple-reflection TOF-MS (Common Beamline) [TDR Chapter 2.5]

Multi-reflection time-of-flight mass spectrometers (MR-TOF-MS) have been built at several facilities for mass measurements on very short-lived nuclei. The determination of the mass of a radionuclide with a half-life of 19.5 ms obtained with a MR-TOF-MS system at GSI was presented during the XVI International Conference on Electromagnetic Isotope Separators and Techniques Related to their Applications (EMIS2012) held in December 2012 in Japan[4]. Also at ISOLTRAP, the masses of the very exotic isotopes ^{53,54}Ca ($T_{1/2}$~ 80−90 ms) were measured using such kind of device from the University of Greifswald and compared to two-neutron separation energy predictions based on 3N-forces[5].

3.2 Charge state breeder [TDR Chapter 3.2]

The application of Electron Beam Ion Traps (EBITS) to very short-lived nuclei was demonstrated very recently for the first time [6,7] with TITAN at TRIUMF measuring the mass of $^{74}Rb^{8+}$ ($T_{1/2}$= 64.9 ms) (*m/q* = 9.25) with a relative mass uncertainty of $\delta m/m = 8.7\times10^{-8}$. About 20 ms were needed to go from a charge state of 1+ to 8+. The system at TRIUMF was built by the experts at the Max-Planck Institute for Nuclear Physics (MPIK) in Heidelberg (Germany), who are the responsible for the MATS-EBIT.

The preparation Penning trap [TDR Chapter 3.4]

A Penning trap following the specifications of the TDR is under construction at the University of Granada within the ERC Starting Grant project TRAPSENSOR and it is part of a PhD thesis. The superconducting magnet similar to the TRIGA-TRAP magnet was installed and charged in October 2012.

The measurement Penning trap [TDR Chapter 3.5]

A Penning trap following the specifications of the TDR has been built at the TRIGA reactor in Mainz and it is fully operational together with a preparation Penning trap, and RFQ buncher and different types of ions sources, among them a carbon cluster source for absolute mass measurements[8]. This facility is a test bench for the implementation of the Fourier-Transform Ion-Cyclotron-Resonance (FT-ICR) technique on a single ion[9].

Instrumentation (mass spectrometry, in-trap / trap-assisted spectroscopy) [TDR Chapter 3.6]

In 2010 and 2012, the well-known Time-of-Flight Ion-Cyclotron-Resonance technique has yielded very important results pushing the limits of performance to ions delivered within GSI Radioactive Ion Beams with very low production yields, i.e., allowing for mass measurements on nobelium and lawrencium isotopes[10],[11]. The mass measurement of $^{256}Lr^{2+}$ ($T_{1/2}$ = 27 s), produced with a cross section of 1 ion per 10 s, was possible after 93 h, because of the development of a stability system for the superconducting magnet. A variant of this technique consisting of the application of an external octupole field has yielded results of importance in neutrino physics[12], and very recently, a new technique referred to as Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) has been developed within the ERC Advanced Grant project MEFUCO[13]. It has been successfully applied for mass measurements on stable isotopes, yielding an improvement of more than an order of magnitude in resolving power and close to a factor of 50 in measurement time, the potential use for MATS was demonstrated. This novel PI-ICR technique allows measurements at the relative mass uncertainty limit of 10^{-7} to 10^{-6} with only about ten registered ions.

A singular detector trap is under completion at the LMU in Garching (Germany) where tests of the detectors have been already carried out. The system can be tested in a similar configuration as described in the TDR using the MLLTRAP setup in Garching[14]. Trap-assisted spectroscopy experiments have flourished in the last years. Right now, these kinds of experiments are performed at different facilities. A remarkable example was the outcome from an experiment performed at the University of Jyväskylä[15].

2.4 Ion beam cooler and buncher (Common Beamline)

This is a device installed in all Penning traps at RIBs facilities, which allows changing from a continuous ion beam to a pulsed beam, with a full-width-half-maximum typically in the order of μs, to capture the ions in the Penning trap. The construction and commissioning of this device for MATS is under the responsibility of the JYFLTRAP group (University of Jyväskylä), who already started the work.

2.4.6 Optical manipulation within the ion beam cooler and buncher

The Radiofrequency Quadrupole cooler-buncher (RFQ) at the Jyväskylä IGISOL facility – the first device of this kind applied for laser spectroscopy – has been installed and re-commissioned at the new IGISOL-4 facility and first spectroscopic results have been obtained for neutron-rich molybdenum isotopes. While at the old IGISOL facility optical pumping of the ions took place in the RFQ[16], the new beamline is equipped with a ConeTrap in which ions are reflected back and forth between two electrodes and a laser beam can be superimposed for optical pumping. The main advantage compared to pumping in the RFQ is that the process is not hampered by buffer-gas collisions that might lead to quenching of the populated metastable states. It is further intended that the ConeTrap be explored as a possible beam delivery component for LaSpec. The device, sitting between the gas stopper and buncher, can act as an "ion beam elevator" and provide a mechanism for changing ion energy on a slow timescale (milliseconds) very suitable for precision laser spectroscopy.

The ISCOOL RFQ at ISOLDE now delivers bunched and cooled beams on a routine basis. Ion bunches have been first used for the spectroscopy of gallium and copper isotopes[17,18,19,20,21,22,23] and recently also for the spectroscopy of Cd isotopes[24]. Optical pumping using pulsed lasers from the RILIS cabin is also foreseen as soon as ISOLDE restarts operation. Furthermore, a new design of RFQ that is currently being commissioned at NSCL was presented. It provides buffer-gas cooling at cryogenic temperatures and a separate trapping zone at low pressure. This not only reduces possible losses due to molecular formation during the bunching process but will afford reduced energy spread and time focusing of the ion bunches.

In a new development, optical manipulation in an rf cooler-buncher is to be extended at the new IGISOL-4 facility to a method known as Ion Resonance Ionization Spectroscopy (IRIS). This will involve the transport of multiple pulsed laser beams via optical fibres to the cooler where they will be spatially overlapped and steered into the device. By selectively ionizing singly-charged ions to the doubly-charged state, the ions of interest or background contaminants will have a different time-of-flight during transport to the collinear laser interaction region. This should provide a powerful means of further suppressing ion beam scattered light caused by contaminants within an ion bunch leading to ultra-pure beams for collinear laser spectroscopy.

4.2.1 Atomic beamline deflection chamber & ion optics

The ion optics described in the TDR has been tested at TRIGA-SPEC, Mainz, and a beam created at the on-line ion source was cooled and bunched in the RFQ and afterwards transported through the TRIGA-LASER beamline with reasonable – yet improvable – efficiency.

4.2.2 Charge exchange cell

Two designs of charge exchange cells – a vertical one designed at TRIUMF and the horizontal COLLAPS design from Mainz - have been tested and compared at TRIGA-SPEC in collaboration with the BECOLA crew from NSCL[25]. Both designs worked well.

4.3 Beta-asymmetry-detected nuclear magnetic resonance

Optical pumping combined with β-asymmetry detection was recently employed at ISOLDE as a sensitive detection technique for isotope shift measurements for the first time. It was applied for determining the charge radius of ^{31}Mg after the feasibility was demonstrated with ^{29}Mg, an isotope that could be detected with β-asymmetry as well as with optical detection[26].

4.4 Diagnostics for the LaSpec experiment

The described beam diagnostics for LASPEC has been realized and tested during a Bachelor thesis project at the TRIGA-SPEC setup in Mainz.

4.5 Specifications of the LaSpec experiment

Continuous wave narrowband laser light down to 215 nm was generated by frequency quadrupling and has been applied for on-line measurements of Cd^+ ions at ISOLDE. This has opened a new window for laser spectroscopy. A remarkably linearity of quadrupole moments of the $11/2^-$ isomer from ^{111}Cd to ^{129}Cd was reported in a recent Letter[24].
Concerning the need for accurate high-voltage measurements[27], developments are going on at NSCL/MSU as well as at the Technical University of Darmstadt and at Mainz University. A high voltage divider which will provide an accuracy of 10^{-5} is currently under development at the Technical University of Darmstadt.

5 Timing, ion identification and controls

Here developments are going on for LASPEC at the TRIGA-SPEC facility at Mainz University. Ion bunches have recently been created with an RFQ (previous COLETTE) and are currently being investigated using MCP's as well as optical detection. Voltage scanning, ion bunch timing and photon detection have been implemented on a field programmable gate array (FPGA). Such a device has also been used online as a dead-time free digital delay for delayed-ion photon coincidence detection in the spectroscopy of ^{12}Be[28].

Apart from these developments, the CRIS collaboration at ISOLDE reported first results from collinear resonance ionization spectroscopy on francium isotopes and have successfully substantiated the high expectations in this method. The method has also been used to demonstrate the power of laser-assisted decay spectroscopy on the ground state and isomeric states in ^{204}Fr. Depending on further results, the LASPEC collaboration might want to adapt this technique as well in one of the two available beamlines.

Selected Publications of Members of the LASPEC / MATS Collaborations representing the recent developments (since 2010):

[1] D. Rodriguez *et al.*, European Physical Journal-Special Topics **183**, 1 (2010).
[2] K. Blaum, J. Dilling, and W. Nörtershäuser, Phys. Scripta **T152**, 014017 (2013).
[3] M. Ranjan *et al.,* Europhysics Letters **96**, 52001 (2011).
[4] W.R. Plass *et al.*, Nuclear Instruments and Methods inPhysics Research Section B, submitted.
[5] F. Wienholtz *et al.,* Nature **498**, 346 (2013).
[6] S. Ettenauer *et al.*, Physical Review Letters **107**, 272501 (2011).
[7] S. Ettenauer *et al.*, http://dx.doi.org/10.1016/j.ijms.2013.04.021.
[8] C. Smorra *et al.*, J. Phys. B **42**, 154028 (2009)
[9] J. Ketelaer *et al.,* Eur. Phys. J A **42**, 154028 (2009)
[10] M. Block *et al.,* Nature **463**, 785 (2010).
[11] E. Minaya Ramirez *et al.,* Science **337**, 1207 (2012).
[12] S. Eliseev *et al.,* Physical Review Letters **107**, 152501 (2011).
[13] S. Eliseev *et al.,* Physical Review Letters **110**, 082501 (2013).
[14] P. Thirolf, C. Weber, International Journal of Mass Spectrometry, submitted.
[15] A. Algora *et al.,* Physical Review Letters **105**, 20250 (2010).
[16] B. Cheal *et al.*, Phys. Rev. Lett. **102**, 222501 (2009).
[17] B. Cheal *et al.*, Phys. Rev. C **82** (2010) ;
[18] B. Cheal *et al.*, Phys. Rev. Lett. **104**, 252502 (2010
[19] K. T. Flanagan *et al.*, Phys. Rev. Lett. **103**, 142501 (2009);
[20] K. T. Flanagan *et al.*, Phys. Rev. C **82** (2010) ;
[21] T. J. Procter *et al.*, Phys. Rev. C **86**, 034329 (2012).
[22] P. Vingerhoets *et al.*, Phys. Rev. C **82**, 064311 (2010).
[23] P. Vingerhoets *et al.*, Phys. Lett. B **703**, 34 (2011).
[24] D. T. Yordanov *et al.*, Phys. Rev. Lett. **110**, 192501 (2013).
[25] A. Klose *et al.*, Nuclear Instruments and Methods in Physics Research Section A **678**, 114 (2012).
[26] D. T. Yordanov *et al.*, Phys. Rev. Lett. **108**, 042504 (2012).
[27] A. Krieger *et al.*, Nuclear Instruments and Methods in Physics Research A **632**, 23 (2011).
[28] A. Krieger *et al.*, Phys. Rev. Lett. **108**, 142501 (2012).