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PROGRESS OF THE MLLTRAP SYSTEM IN MUNICH*

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The MLLTRAP is a Penning trap system designed to perform high-accuracy nuclear mass measurements in its final stage aiming to use highly-charged ions. The goal is to reach an accuracy of 10^{-10}, which is required for high-precision fundamental physics studies like the determination of fundamental constants and measurements of electron binding energies for QED at strong fields. In the first development stage the setup will work with singly-charged ions. First results of systematic uncertainty investigations are presented.

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1. Introduction

The MLLTRAP ion-trap facility is presently being commissioned at the Maier-Leibnitz-Laboratory, Garching. The setup is designed to combine several novel techniques to decelerate, purify, charge breed and cool fusion-reaction products and perform high-accuracy nuclear mass measurements. The final aim is to reach a relative mass accuracy of about $\delta m/m \approx 10^{-10}$ needed for *e.g.* an improvement of the accuracy of fundamental constants, such as the molar Planck constant $N_A h$ or a unitarity test of the CKM-matrix. This accuracy can be achieved in Penning trap mass measurements with highly-charged ions (HCI) only.

In the first development stage, the facility operates with singly-charged ions, which allows to use a buffer-gas cooling technique [1]. In such a double Penning trap configuration an isobaric purification of low-energy ion beams (first trap) and high-precision ($\delta m/m \approx 10^{-8}$) nuclear mass measurements (second trap) are feasible.

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2. Experimental results

The basic tests of the trap system have been successful. The mass resolving power achieved with the first trap for $^{85}Rb^+$ ions amounts to $R = 139(2) \times 10^3$ [2], see Fig. 1, proving its functioning as an isobar separator.

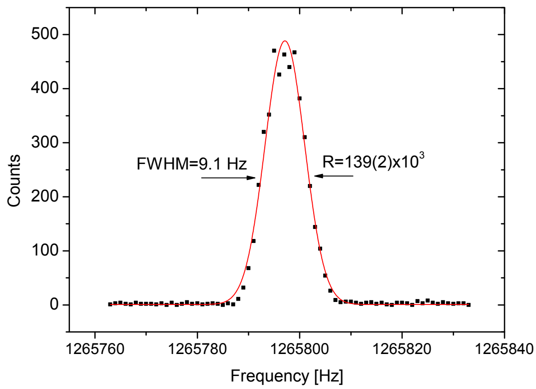

Fig. 1. Frequency scan in the purification trap for determining the cyclotron frequency of ^{85}Rb. The mass resolving power in the scan was $R = 139(2) \times 10^3$. Black dots are the measured points and the line is a Gaussian fit with a width of 9.10(15) Hz.

For the second, precision trap, time-of-flight dependence (TOF) *versus* the quadrupole excitation amplitude, at the relevant cyclotron frequency, for ^{85}Rb was investigated. Figure 2 shows an example of the so-called beating curve of ^{85}Rb ions at the frequency of $\nu_c = 1\ 266\ 324.3$ Hz us-

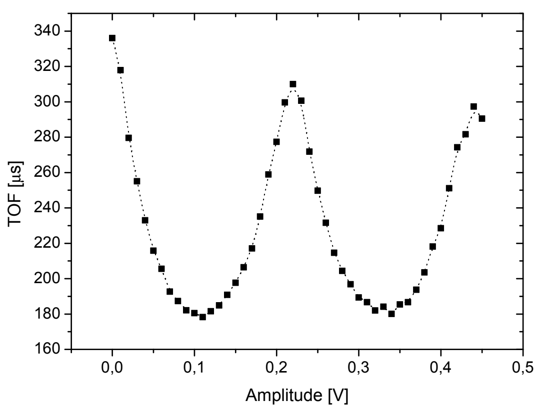

Fig. 2. Beating curve of $^{85}Rb^+$ ions, showing the periodic conversion between the magnetron and reduced cyclotron motion. The first minimum is located at 105 mV.

ing 100 ms excitation time. The best resonance conditions are reached in the first minimum. In this case, the conversion constant corresponds to $c = T_{\rm rf} \times A_{\rm rf} = 0.1$ s $\times$ 105 mV = 10.5 mVs.

In order to increase the magnetron radius of the ion motion a dipole excitation at the frequency of $\nu_- \approx 170$ Hz for $T_{\omega-} = 3$ ms with an amplitude of $A_{\omega-} = 91$ mV has been applied. Afterwards the quadrupole excitation was used for $T_{\omega_c} = 900$ ms with an amplitude of $A_{\omega_c} = 11.5$ mV while scanning the cyclotron frequency. Fig. 3 shows the result of two cyclotron resonances that were used to determine the achievable mass accuracy in the

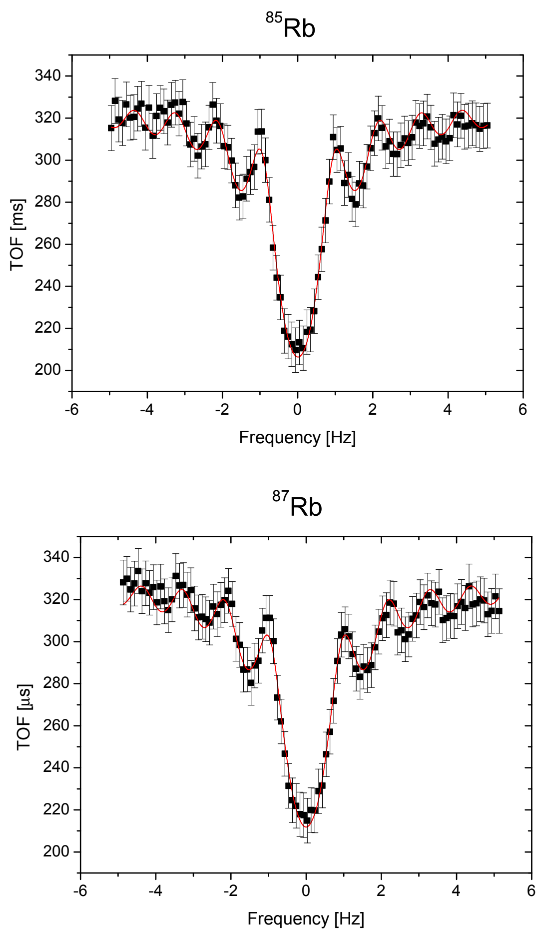

Fig. 3. Frequency scan for the $^{85}Rb^+$ and $^{87}Rb^+$ ions. Horizontal axes are centered at 1 266 324.354 Hz and 1 237 220.865 Hz corresponding to cyclotron frequencies of ^{85}Rb and ^{87}Rb, respectively. Black dots are experimental points and the line is a fit of the theoretical line shape.

measurement trap. The measured data were analysed by using a count-rate class analysis [3], where each measurement was divided into three classes according to the statistics. A relative mass uncertainty of $\delta m/m = 2.9\times10^{-8}$ was reached with the second trap (no analysis of systematic uncertainties included) when using ^{87}Rb as a reference ion for ^{85}Rb. The measured mass value of the ^{85}Rb, however, differs from the very accurate literature value by $(m_{\rm lit} - m_{\rm meas})/m_{\rm lit} = 3.6 \times 10^{-8}$ [4]. For a detailed description of the setup and experimental results, see Ref. [5].

3. Systematic error determination

Frequency measurements of the same ion species were performed over several days to obtain information on the short-term fluctuations in the magnetic field strength. During these runs the pressure in the helium exhaust line of the magnet was measured by using a capacitive (pressure) gauge, the bore temperature of the magnet and the room temperature in the experimental hall were measured by using PT-102 sensors. It was found that the changes in the cyclotron frequency correlate with the variations in the room temperature, see Fig. 4. The long-term decay constant of the magnetic field was determined as $-1.3(3) \times 10^{-9}$/h.

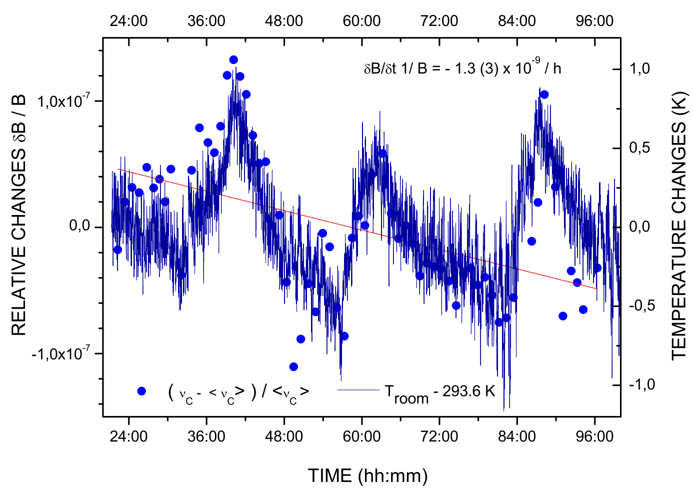

Fig. 4. Correlation between the cyclotron frequencies (circles, left ordinate), reflecting the magnetic field strength (proportional to the cyclotron frequency), and the temperature ((blue) histogram, right ordinate) measured next to the trap magnet. The changes in the measured cyclotron frequency relative to the mean value are clearly correlated with the room temperature. The stright (red) line depicts the long-term magnetic field decay with a time constant $\delta B/(\delta t \times B) = -1.3(3) \times 10^{-9}$/h.

To be able to estimate the systematic uncertainty arising from random B-field fluctuations a measurement series with ^{85}Rb and variable time intervals ΔT between the reference measurements has been made. The standard deviation of the differences between the magnetic field strength, derived from the measured cyclotron frequency, and the interpolated value was plotted as a function of time difference between the chosen reference measurements, see Fig. 5. A linear fit was applied to this data, resulting in a time-dependent fluctuation of the magnetic field (expressed in terms of the reference cyclotron frequency) $\delta_B(\nu_{\rm ref})/(\nu_{\rm ref} \times \Delta T) = 7.36(38) \times 10^{-9}$/h. This corresponds to a rather large correction compared to the equivalent quantity $1.3(3) \times 10^{-9}$/h [6] measured at SHIPTRAP, where a similar magnet in use, or the ISOLTRAP value $3.8(3) \times 10^{-9}$/h [3]. When one includes this correction to the statistical uncertainty one obtains $m(^{85}\text{Rb}) = 84.9117959(26)\ u$. This is just beyond the one sigma limit from the literature value 84.911 798 732 (14) u [4].

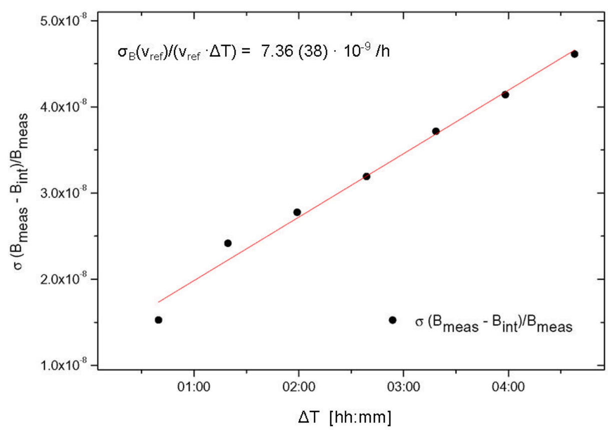

Fig. 5. Relative standard deviation $\sigma(B_{\rm meas} - B_{\rm int})/B_{\rm meas}$ as a function of the time duration ΔT between two consecutive reference measurements. The standard deviation was calculated from the cyclotron frequency values obtained in the long-term measurement. The time-dependent fluctuation of the magnetic field (expressed in terms of the reference cyclotron frequency $\nu_{\rm ref}$) amounts to $\delta_B(\nu_{\rm ref})/(\nu_{\rm ref} \times \Delta T) = 7.36(38) \times 10^{-9}$/h.

4. Project status

In order to obtain an improved estimate of the total systematic uncertainty one should investigate the systematic mass-dependent effect on frequency ratios and quantify the residual uncertainty of the result. This, however, would require a carbon cluster ion source, which is foreseen only in the later phase of MLLTRAP. Nevertheless, the relative accuracy of about 4×10^{-8} is a good start for the measurement program at MLLTRAP. As a first step of this program, it is planned to start the mass measurements of α decay daughter products from actinide nuclei (*e.g.* ^{244}Pu $\rightarrow$ ^{240}U).

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