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An ultra-stable voltage source for precision Penning-trap experiments

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ABSTRACT

An ultra-stable and low-noise 25-channel voltage source providing 0 to -100 V has been developed. It will supply stable bias potentials for Penning-trap electrodes used in high-precision experiments. The voltage source generates all its supply voltages via a specially designed transformer. Each channel can be operated either in a precision mode or can be dynamically ramped. A reference module provides reference voltages for all the channels, each of which includes a low-noise amplifier to gain a factor of 10 in the output stage. A relative voltage stability of $\delta V/V \approx 2 \times 10^{-8}$ has been demonstrated at -89 V within about 10 min.

1. Introduction

Penning traps are ideal tools to perform precision experiments with stored ions in many fields of research, among others high-precision atomic and nuclear mass measurements [1,2], stringent tests of fundamental symmetries using highly charged ions or antimatter [3–7], and the determination of fundamental constants [8–10]. These measurements require ultra-stable magnetostatic and electrostatic fields as both determine the ion's oscillation frequencies, the quantities to be measured [1]. Penning traps combine a strong homogeneous magnetic field and a weak electrostatic quadrupolar potential (see Fig. 1(a)) to achieve a confinement of charged particles in the radial and the axial direction, respectively [11]. The mass determination of the stored ion is carried out by measuring the ion's cyclotron frequency

$$\nu_c = \frac{1}{2\pi}\frac{qB}{m_{\text{ion}}}, \tag{1}$$

where q/m_{ion} is its charge-to-mass ratio and B is the magnetic field strength.

As shown in Fig. 1(b) the trajectory of an ion stored in a Penning trap is a superposition of three independent harmonic oscillator modes, which are characterized by the modified cyclotron frequency ν_+, the axial frequency ν_z, and the magnetron frequency ν_-. The three eigenfrequencies are measured by means of the non-destructive image-current detection technique [12]. Thus, the cyclotron frequency ν_c can be obtained via the eigenfrequencies employing the invariance theorem [1]

$$\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2. \tag{2}$$

Thus, the relative stability of ν_c is given as:

$$\frac{\delta\nu_c}{\nu_c} = \left(\frac{\nu_+}{\nu_c}\right)^2\frac{\delta\nu_+}{\nu_+} + \left(\frac{\nu_z}{\nu_c}\right)^2\frac{\delta\nu_z}{\nu_z} + \left(\frac{\nu_-}{\nu_c}\right)^2\frac{\delta\nu_-}{\nu_-}. \tag{3}$$

The correlation coefficients were neglected as the measurement of the three eigenfrequencies is not performed simultaneously.

1.1. Voltage-source requirements for PENTATRAP

The voltage source presented here, called StaReP (Stable Reference for Penning-trap experiments) was developed for the

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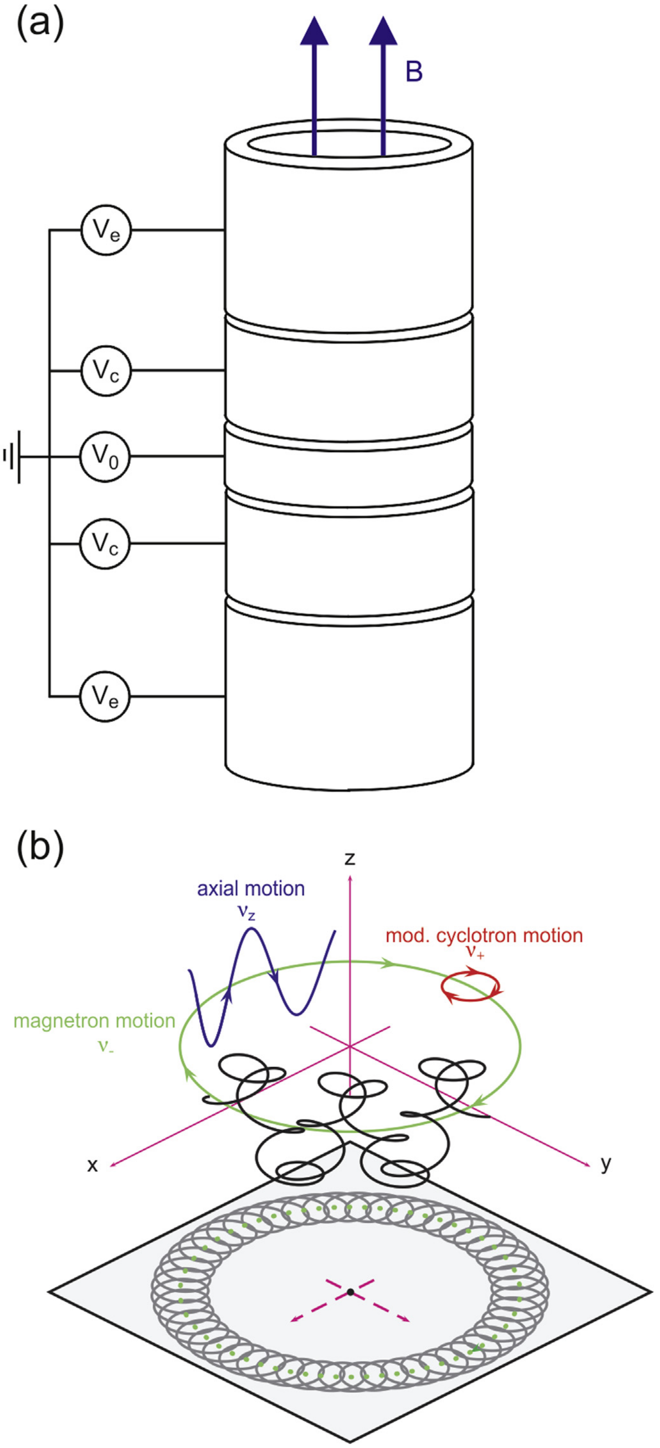

Fig. 1. (a) Cylindrical five-electrode Penning trap with ring voltage V_0, correction electrode voltages V_c and end cap voltages V_e in a magnetic field B. (b) Ion trajectory (black) in a Penning trap consisting of three eigenmotions: modified cyclotron motion (red), axial motion (blue) and magnetron motion (green). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

PENTATRAP mass spectrometer [13] in collaboration with the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig. It is suitable for many high-precision Penning-trap experiments including the PENTATRAP experiment [13], THe-Trap [14] or ALPHATRAP [10] at the Max-Planck-Institut für Kernphysik (MPIK) in Heidelberg. PENTATRAP and THe-Trap are dedicated to mass measurements, whereas ALPHATRAP is designed to determine the g-factor of the bound-electron in heavy ions. The PENTATRAP experiment is aiming for ultra-high-precision mass determinations, i.e., relative uncertainties in the cyclotron frequency measurement of 10^{-11} and below. As the uncertainty contribution of the axial frequency to the cyclotron frequency is, according to Eq. (3), suppressed with $(\frac{\nu_z}{\nu_c})^2$, the axial frequency has to be measured on a level of at least $\frac{\delta\nu_z}{\nu_z} = 2 \times 10^{-8}$. Typical frequencies of highly charged ions used in the three Penning-trap experiments at MPIK are listed in Table 1. Although voltage fluctuations affect the modified cyclotron frequency as well, a larger influence on ν_+ results from magnetic-field fluctuations.

Due to the dependence of the axial frequency on the trapping voltage V_0:

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{qV_0}{m_{\text{ion}}d^2}}, \tag{4}$$

where d is a geometrical parameter characterizing the size of the trap [15], the relative voltage stability should be better than

$$\frac{\delta V_0}{V_0} = 2\frac{\delta\nu_z}{\nu_z} = 4 \times 10^{-8}. \tag{5}$$

This stability should be achieved in an interval of 10 min, which is the typical duration of a measurement cycle of the cyclotron frequency. In total, PENTATRAP contains five traps consisting of five electrodes each (see Fig. 3 in [16]). Therefore, a voltage source with 25 channels is required to supply the trap tower. PENTATRAP is equipped with a narrow-band detection system [13,16]. Thus, the axial frequency is fixed and different voltages are required for different ion species and/or charge states to tune the ion's axial oscillation frequency accordingly. The required voltage source should provide a voltage range from 0 to −100 V, which allows one to trap various positively charged ion species as listed in Table 1. Apart from the fact that higher voltages are favorable since the relative effect of patch potentials [17] is reduced, it allows one also to trap and identify ions in lower charge states for optimization purposes.

At PENTATRAP mass measurements are performed using two ions, i.e., an ion of interest and a reference ion. These ions are stored in two adjacent Penning traps. As described in [13], ions are swapped between the two traps which is part of the measurement procedure. Since the disturbance of the measurement due to magnetic-field fluctuations generally increases with time, the ion exchange between the two traps has to be done fast, i.e. in the order of a second time scale. Therefore, the voltage source has to provide a ramping option which allows one to shuffle ions between the traps.

Many Penning-trap experiments employ either commercial voltage sources like the UM1-14 [18] or sources which were specifically designed for the needs of the respective experiments [19,20]. Before StaReP has been available, PENTATRAP was equipped with the commercial voltage source UM1-14, which limits the experiment according to Table 1 to few ion species due to the restricted voltage range of 0 to −14 V. Furthermore, the UM1-14 contains only 3 independent precision channels, which is insufficient for the PENTATRAP setup.

The main part of StaReP consists of a reference module, which has an output of $V_{\text{ref}} = +10\,\text{V}$ and provides the input for the 25 channels. The channels include the precision and ramping section to set the desired voltage value. At the output stage of each voltage channel there is a low-noise operational amplifier, which inverts the voltage and provides an amplification by a factor of 10. In the following, the StaReP design is described and characterizing measurements of the source are presented.