Simulation of the Lanzhou Penning Trap LPT*

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Abstract The LPT (Lanzhou Penning Trap) is under construction and its task is to perform direct mass measurement of fusion-evaporation residues and if possible for heavy isotopes. Detailed simulations have been done for a good understanding to the ion's movement and mechanics in the trap. The optimization of the LPT is also performed based on the simulation. With a scale of 0.5 mm per grid used in the simulation and many other limitations a highest mass resolution has been achieved to be 1.9×10^{-5}. An unexpected behaviour in the simulation related to magnetron motion has been found.

Key words Penning trap, super heavy, mass measurement, LPT

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1 Introduction

Mass is one of the most fundamental properties that can be obtained about an atomic nucleus. The atomic masses of the stable isotopes are very well known, but the accuracy of the known masses decrease rapidly for nuclei that are more and more unstable with respect to beta decay. Accurate masses of rare isotopes are important for a better understanding of nuclear structure, as an input for the modeling of element synthesis in nuclear astrophysics, and for fundamental tests of the weak interaction.

Many techniques have been developed for the mass measurement and there are two main approaches. The indirect approach is based on the determination of Q-values measured in nuclear reactions and radioactive decays. The direct method uses mass spectrometers for both stable and unstable nuclides. Penning trap mass spectrometry is one of the direct methods and maybe the most accurate tool for the mass measurement. With this technique mass measurement with a precision better than 1×10^{-10} is possible today.

Since more and more accurate and precise mass data are needed to understand the universe and the atomic masses measured by Penning traps can satisfy this request, many projects including Penning traps have been started. The running and R&D facilities around the world have been reviewed in Ref. [1]. The Lanzhou Penning Trap (LPT) is also under construction. Its main task is to perform direct mass measurement of fusion-evaporation residues and if possible for heavy isotopes. Fig. 1 shows the schematic setup of the LPT.

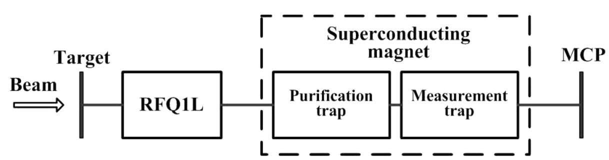

Fig. 1. Schematic setup of the LPT.

2 Basic knowledge of Penning trap

A Penning trap is an electro-magnetic trap. The combination of an electrostatic quadrupole field and a homogeneous magnetic field allows a charged particle to be stored in a well defined volume.

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If a charged particle with a mass of m and a charge of q moves in a pure magnetic field B, it will rotate in a pure cyclotron motion with a frequency of $\omega_c = qB/m$. Due to the existence of electric field, the pure cyclotron motion becomes a superposition of three independent harmonic motions. These motions are an axial oscillation with a frequency ω_z and two radial motions with frequencies of $\omega_\pm$. The most important thing is $\omega_c = \omega_+ + \omega_-$, thus direct determination of this sum frequency allows a mass determination via $m = qB/\omega_c$ which depends only on the magnetic field B. Practically, in order to reduce the influence of the instability of the magnetic field, the masses of the ion of interest and a reference are measured alternatively. For more details please refer to the Refs. [2, 3].

A real Penning trap is much more complicated than an ideal one. The precision of the mass measurement will be decreased by the defects of electric field, magnetic field, machining, assemble, the cross effect of ions in the trap and so on. The achievable highest precision of the mass measurement in a Penning trap will be determined by the control of these defects.

In order to detect the cyclotron frequency ω_c of the stored ions, to remove unwanted ions from the trap or to be able to use buffer gas cooling in a Penning trap it is necessary to drive the ion motion with oscillating electric fields. The effect of the driving field on the motion depends on the multipolarity of the field and its frequency.

With dipole fields the ion motions can be excited at their eigenfrequencies. The amplitudes of the eigenmotions increase assuming zero initial amplitude. A quadrupole field in general allows the excitation of two azimuthal ion motions at the sum or difference of the eigenfrequencies. Excitation by an azimuthal quadrupole field at a frequency of $\omega_+ + \omega_-$ is always used for the true cyclotron frequency ω_c.

3 Simulation

All simulations about the LPT is being done by using a commercial SIMION code[4] that is a good tool for calculation and visualization of trajectories of particles in electromagnetic systems. The model is created according to the real parameters of the LPT. The simulations have been done with the following parameters: The mass m and charge q of the ion are 100 amu and 1^+, respectively; the central magnetic field B of the superconducting magnet is assumed to be 6.95 T. Due to large number of parts and limitation of computer's capacity, a scale of 0.5 mm per grid is used for the simulation. Below are some typical results.

3.1 Axial cooling

The axial cooling, which the ions can be cooled to the potential minimum of the trap by collisions with the buffer gas, is performed in the first Penning trap of LPT. It is important in order to allow the ions to see the radio-frequency fields which are only applied in the center of the trap where the electric and magnetic field imperfections are minimized. Fig. 2 shows the ion's movement in LPT. The left panel shows the ion trajectory viewed along the axial direction and the right panel perpendicular to the axis. The ion rotates due to the existence of the magnetic field, and at the same time the amplitude of the ion's movement becomes smaller and smaller due to the drag force of the buffer gas.

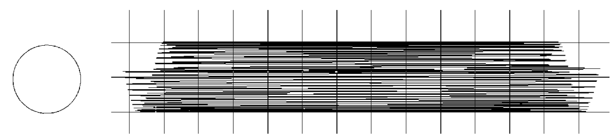

Fig. 2. Axial cooling of the ion in LPT. Left: Ion trajectory viewed along the axial direction; Right: Ion trajectory viewed perpendicular to the axial direction.

3.2 Magnetron excitation

In order to remove the unwanted ions magnetron excitation should be performed by an azimuthal dipole field. Theoretically, the amplitudes of the ion's eigenmotions will increase continuously if assuming a zero initial amplitude and finally the ion will be lost by striking on the wall[5]. The left panel of Fig. 3 shows the increase of the amplitude. It is very interesting that the amplitude of the ion's magnetron motion does not increase continuously. After reaching the maximum it decreases and then beating between the maximum and minimum. The right panel of Fig. 3 shows this unexpected behaviour. The reason is still unclear and it may be caused by the defects of the Penning trap.

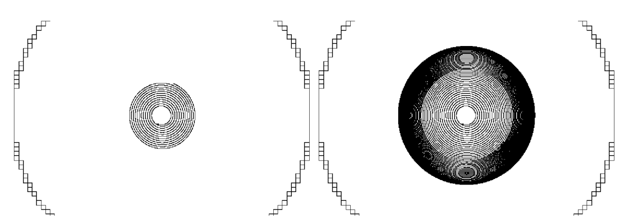

Fig. 3. Magnetron excitation of the ion. The initial place of the ion is near the center. See text.

3.3 Cyclotron excitation

After some time of magnetron excitation, all the ions have been driven to large orbits. An azimuthal quadrupole field with a specific frequency then excites the desired species and the magnetron motion converts into a cyclotron motion. If the two radial motions are excited at their sum frequency $\omega_c = \omega_+ + \omega_-$, they are continuously converted into each other. This is always used for determining the true cyclotron frequency. Fig. 4 shows the ion's trajectory. The left and middle panels demonstrate that the amplitude of cyclotron motion increases steadily and the right panel shows the detail of the cyclotron motion.

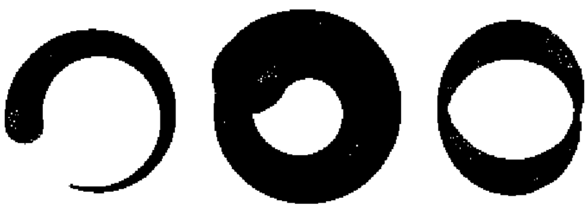

Fig. 4. Cyclotron excitation of the ion. Left and middle: The amplitude of cyclotron motion increases steadily; Right: Detail view of the cyclotron motion.

3.4 Time of flight

To determine the true cyclotron frequency ω_c of the ion of interest, one of the methods is releasing the stored ions and measuring the time of flight (TOF) to the detector. By tuning the frequency of the cyclotron excitation, the ions gain different energies. More energy means less TOF, so if the cyclotron frequency equals its ω_c the ion will gain the highest energy and the TOF is the smallest. Fig. 5 shows the TOF vs cyclotron frequency $f_{\rm rf}$ with different excitation times $T_{\rm rf}$ of 25 ms and 50 ms. It shows that a longer excitation time can improve mass resolution $\delta m/m$, which agrees the theory $\delta m/m \propto 1/T_{\rm rf}$ very well. The highest mass resolution in the simulations can only reach 1.9×10^{-5}.

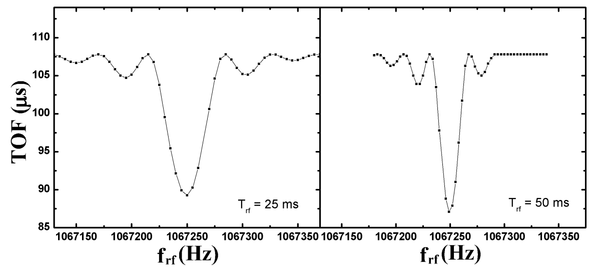

Fig. 5. Time of flight (TOF) vs cyclotron frequency $f_{\rm rf}$ with different excitation times $T_{\rm rf}$ of 25 ms (left) and 50 ms (right).

4 Summary

By a lot of big effort we can now simulate all the behaviours of the ions in Penning traps by using the SIMION code and based on the simulation the optimization is also performed. Due to the limitation of the capacities of the computer we have to use a scale of 0.5 mm per grid in the simulation. With this and many other limitations a highest mass resolution has been achieved to be 1.9×10^{-5}. If we would like to achieve a resolution of $\sim 10^{-7}$, the tolerances of the machining and the alignment of the central parts should be 5—10 μm. More simulation and optimization is still going on.

It should be noted that an unexpected behaviour in the simulation related to magnetron motion has been found. The amplitude of the ion's magnetron motion does not increase continuously and it beats between the maximum and minimum. The reason is still unclear and it may be caused by the defects of the Penning trap. It needs more investigation somehow.

The mechanic design is also on the way. As a necessary device for the LPT, the RFQ1L[6—11] is now under the test.

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