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THE INCHWORM* AS A PRECISION TRANSLATOR IN A HIGH MAGNETIC FIELD AND UHV ENVIRONMENT

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The Inchworm* as a precision translator
in a high magnetic field and UHV environment

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ABSTRACT

A new set-up has been designed and tested for on-line, high-precision mass measurements of short-lived radioactive isotopes via a determination of the ion cyclotron resonance. Ions delivered by the on-line isotope separator ISOLDE at CERN/Geneva are stored in a Penning trap installed in a superconducting solenoid. Due to severe space limitations in the bore of the solenoid, it is impossible to use conventional mechanical feedthroughs for the necessary manipulations inside the UHV chamber. Instead, a number of Inchworms, a high-precision positioning device based on the piezo-electric effect are employed. This publication reports on the first application of this device in an UHV environment at a magnetic field of nearly 6 Tesla.

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I. INTRODUCTION

Until now, precise mass measurements were restricted to the valley of β -stability in the chart of nuclei or its direct neighbourhood.¹ The extension of systematic high-precision measurements to nuclei far away from this valley is demanded for by nuclear physics and astrophysics.

The mass of an isotope can be determined directly by measuring its cyclotron frequency ω_c

$$\omega_c = (e/m) \cdot B \quad (1)$$

in a known magnetic field B . By storing the ions in a so-called Penning trap, an accuracy of better than 10^{-6} can be achieved in on-line operation.²

The set-up used up to now had one important handicap: Time-consuming and uncomfortable adjustment procedures were necessary in order to align the incoming ion beam parallel to the axis of the magnetic field. This is a stringent requirement for injection with high efficiency but low radial energy. The proper alignment was especially cumbersome because movable monitors were missing for the position and the spatial profile of the injected ions. Thus, the new design had to include variable diaphragms as beam monitors and, in addition, a movable Penning trap for optimum injection.

II. REQUIREMENTS

Severe boundary conditions exist for such a precision measurement:

(i) Space: The diameter of the inner bore of the superconducting magnet is only $d = 89$ mm. The number of necessary manipulations for beam analysis and optimum trap performance add up to six to be mounted inside the bore of the magnet in a vacuum tube. In addition to the beam monitors, a number of space-consuming elements are mounted inside the tube like the Penning trap, ion optical lenses, a retardation system and a long drift tube for the detection of the cyclotron resonance.

(ii) Vacuum: Collisions of the ions investigated with the residual gas destroy the coherence between the cyclotron motion of the stored ions and the exciting radio frequency (RF) field. This results in a broadening of the cyclotron resonance and hence in a loss of resolving power. An accuracy of better than 1 ppm of the mass determination corresponds to a vacuum of $< 10^{-8}$ mbar. Hence ultra-high vacuum is required in the region where the Penning trap is mounted. Since vacuum pumps can only be installed at the entrance and exit of the vacuum tube in the bore of the superconducting magnet, about 50 cm away from the Penning trap, material with low outgassing rate is required.

(iii) Magnetism: The material inside the superconducting solenoid (nearly 6 Tesla) should have a low susceptibility, so that the homogeneity of the magnetic field is not affected. Any inhomogeneity of the magnetic field within the storage volume of some mm^3 of $\Delta B/B > 10^{-6}$ results in a line broadening and a line shift of the cyclotron resonance at the cost of accuracy.

(iv) Precision: The diameter of the ion beam is less than 0.3 mm inside the region of the high magnetic field. Any angle between the direction of the injected ion beam and the direction of the magnetic field lines results in an increase of the radial energy of the trapped ions. This gives rise to poorer cyclotron-resonance signals. Hence, the precision of the beam monitors should be better than 100 μm .

III. SOLUTION

Besides the problem of (i), squeezing six conventional mechanical linear or rotation feedthroughs to a flange of the vacuum tube inside the $d = 89$ mm bore of the magnet and (ii), still leaving space for the ions injected into or ejected out of the trap, the movements have to be transmitted reliably over distances of the order of 50 cm to the elements to be manipulated. Hence, it was quite doubtful, that the required precision could be met. Therefore, a new concept had to be developed combining compactness with precision at no expense of vacuum performance and homogeneity of the magnetic field.

The basic idea is to install a small electric device near the element to be manipulated. Since electromagnetic motors do not easily work in high magnetic fields and/or influence the homogeneity of the magnetic field, a piezo-driven linear device is the most suitable solution. Such a device is the Inchworm consisting of three independently operated piezo-electric elements: Two cylindrical piezo crystals which grip or release a movable shaft and a third one, able to be extended or contracted and mounted between the two clamping piezos. The direction of movement is changed by reversing the sequence. A maximum translation speed of 1 mm/s can be obtained.

The Inchworm is a compact device (diameter $d = 19$ mm, length $l = 60$ mm for a translation length of $L = \pm 7$ mm which can be as long as $L = \pm 100$ mm). In a special version it is designed for UHV applications. The precision of positioning is $1 \mu\text{m}$. It is constructed from alumina, PZT ceramic, beryllium-copper and silver. In the UHV-series Inchworms applied in the described set-up, a small amount of UHV epoxy is used in order to seal the PZT ceramic to the alumina housing. Hence the construction material of the Inchworm is non-magnetic and has a low susceptibility. The motor is backable at temperatures of 150°C and can withstand an axial load of maximum 1 kg.

IV. EXPERIMENTAL SET-UP

The essential part of the experimental set-up for the mass measurements is shown in Fig. 1. The apparatus is connected to the on-line isotope separator ISOLDE/CERN.³ A Penning trap (trap 1), not shown in Fig. 1, is placed in the pole gap of an electro magnet for bunching the continuous ion beam of the ISOLDE on-line isotope separator. The ion pulse is guided by a transfer line with a number of lenses, deflectors and diaphragms into another Penning trap (trap 2), placed in the stable and homogeneous field of the superconducting magnet where the ions are captured with high efficiency.⁴ A blow-up of this region and a photography are shown in Fig. 2 and 3. In this trap, the

ions are stored and excited by RF. Afterwards, the ions are ejected and drift through a drift tube to a channel plate detector mounted above the drift tube D_4 where their time of flight and thus the frequency of the cyclotron resonance are measured. In the whole set-up, eleven Inchworms are employed, six of those within the superconducting magnet as shown in Fig. 1. Table 1 compiles the different tasks of the eleven motors which are mounted between the inner wall of the vacuum tube inside the bore of the solenoid and the tubes for guiding the ion beam.

The principle of the beam monitors is shown in Fig. 4. The ion beam is sent through a hallow cube, the aperture of which can be opened or closed by rotating the cube around an axis. This rotation is activated by the linear motion of the Inchworm via a lever as shown in the figure. For optimum precision the full travel length of the Inchworm is used. Since each cube represents a slit aperture, two such devices in x- and y-direction set up a diaphragm with the additional advantage of being able to analyse the beam profile in the x- and y-direction separately. In a similar way, the Penning trap can be rotated around a shaft centered by two Ruby balls in order to inject the ion beam a little bit off center of the trap as required for ω_c -excitation.⁵

With exception of the Inchworms, the Ruby balls and the stainless steel vacuum tube, all parts inside the vacuum tube are made of MACOR or oxygen-free copper. At places where the ion beam comes very near to electrodes as, e.g., the end caps of the Penning trap, these parts are covered by electrolytically deposited gold. Thus the building up of surface charges is drastically reduced.

The piezos of the Inchworms are activated by pulses (1000 V, $\leq$ 100 mA) fed through polyimide-insulated wires ($d = 0.3$ mm). Each Inchworm requires seven connections, four for the activation of the movement and three for the signals of limit switches. Multi-pin UHV feed-throughs are used to connect the Inchworms to the electronic motor controller. In order to reduce the costs, only one controller channel is used. Its signal is multiplexed by a self-made unit to the eleven Inchworms.

V. PERFORMANCE

The set-up described above has been installed recently at the ISOLDE facility at CERN. Without backing, a pressure well below 10^{-8} mbar is obtained by a combination of a cryopump (1500 l/s) and a turbo molecular pump (50 l/s) below and a turbo molecular pump (170 l/s) above the magnet. The Inchworms are found to work reliably at magnetic fields as high as 5.7 Tesla. No degradation of the homogeneity of the magnet field was found up to the detection limit of $\Delta B/B = 10^{-6}$ within the storage volume of some mm^3 . The precision and reproducibility of the Inchworms was tested and found to meet the requirements as stated above.

VI. CONCLUSION

The Inchworm has proved to be a reliable device for positioning purposes in an UHV environment at high magnetic field. Its high accuracy in combination with low susceptibility make it suitable for precision measurements. Due to its compactness it can be installed near the device to be manipulated and is easily remote controlled. The price is comparable with that of mechanical rotation feedthroughs if a larger number of Inchworms is employed and the signals of the electronic motor controller are multiplexed.

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Table 1: Compilation of Inchworms installed in the set-up for mass measurements. Except for Inchworm I_5 ($L = \pm 100$ mm), all Inchworms have a travel length of $L = \pm 7$ mm. The location of $I_6 - I_{11}$ is shown in Fig. 1.

Inchworm Location	Purpose
I_1, I_2 in the transfer tube between the bunching trap (trap 1) and the precision trap (trap 2)	x-, y-beam profile and position monitor, opening from 0 to 10 mm
I_3, I_4 as Inchworm I_1 and I_2	x-, y-beam profile and position monitor, opening from 0 to 6 mm
I_5 as Inchworm $I_1 - I_4$	to bring in a channel plate detector for measurements of the transfer efficiency and an electron gun for alignment
$I_6 - I_9$ at the entrance of the superconducting magnet	x-, y-beam profile and position monitor, opening from 0 to 2.1 mm, also used as cut-off diaphragms for the radial energy of the injected ions
I_{10} below the Penning trap	rotation of the Penning trap from 0 to 2.5 mm off axis and activation of a shutter
I_{11} above the Penning trap	monitor for the radial distribution of the ions in the trap opening from 0 to 5 mm

Figure Captions

- Fig. 1: Experimental set-up for mass measurements of short-lived isotopes. A vacuum tube is mounted inside the bore of a superconducting magnet. The ions enter the transfer tube from the bottom of the drawing, are retarded by a retardation system (R), and injected in a Penning trap (trap 2). After excitation by radio frequency the ions are ejected out of the trap and drift through drift tubes (D_i) to a channel plate detector installed above the magnet. Beam profile monitors for the x-direction (X_i) and y-direction (Y_i) are mounted at the entrance of the magnet and above the trap. A shutter (S) is installed for current measurements and for blocking the path of the ions and nuclear-decay particles. In addition, the trap can be rotated in a plane perpendicular to the direction of the magnetic field. The manipulations are activated by Inchworms (I_i).
- Fig. 2: Blow-up of the Penning trap section. Below the trap, the retardation lens (R) is shown in addition to the Inchworm ($I_{1,0}$) for the rotation of the trap around the shaft and for activation of a shutter. The linear motion of the Inchworm is transformed to a rotation by a special gear (G). The Penning trap consists of two end caps (EC), a ring electrode (RE) and four correction electrodes (CE) kept at the proper spacing by precision insulators made of MACOR and distance holders (DH). Above the Penning trap, the drift tube (D_1) is shown and an x-profile monitor activated by another Inchworm ($I_{1,1}$).
- Fig. 3: Photography of the Penning trap section showing roughly the same part as Fig. 2 but rotated by about 90° .
- Fig. 4: Scheme of the beam profile and position monitor in open (left) and closed (right) position. The Inchworm opens or closes a slit by rotating a hallow cube around an axis (A).

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Fig. 1

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Fig 2.

Fig. 2

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