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Trajectory bending and energy spreading of charged ions in time-of-flight telescopes used for ion beam analysis

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ABSTRACT

Carbon foil time pick-up detectors are widely used in pairs in ion beam applications as time-of-flight detectors. These detectors are suitable for a wide energy range and for all ions but at the lowest energies the tandem effect limits the achievable time of flight and therefore the energy resolution. Tandem effect occurs when an ion passes the first carbon foil of the timing detector and its charge state is changed. As the carbon foil of the first timing detector has often a non-zero voltage the ion can accelerate or decelerate before and after the timing detector. The combination of different charge state properties before and after the carbon foil now induces spread to the measured times of flight. We have simulated different time pick-up detector orientations, voltages, ions and ion energies to examine the tandem effect in detail and found out that the individual timing detector orientation and the average ion charge state have a very small influence to the magnitude of the tandem effect. On the other hand, the width of the charge state distribution for particular ion and energy in the first carbon foil, and the carbon foil voltage contributes linearly to the magnitude of the tandem effect. In the simulations low energy light ion trajectories were observed to bend in the electric fields of the first timing gate, and the magnitude of this bending was studied. It was found out that 50–150 keV proton trajectories can even bend outside the second timing gate.

1. Introduction

Time-of-flight (ToF) telescope comprising two carbon foil time pick-up detectors (for short: timing gates) is one of the most versatile and useful detectors in the field of ion beam analysis. It can be used for all ions and usable energy regime extends down to few tens of keVs [1]. The energy resolution of the ToF-system for monoenergetic ions depends from the individual timing accuracy of the detectors, the distance of the flight path, the energy straggling and the thickness variation of the first carbon foil and also from the tandem effect [2], to list a few. The performance of the MCP, anode [3,4] and the isochronous electron transportation [5,6] in the timing gates contribute also to the energy resolution. Another additional factor is the timing gate orientation [7] in which, for example, the forward emitted electrons have increased probability for higher energies in wider emission angles [8] which will lead to non-isochronous electron transportation from the foil to the MCP. The better known limitations of the ToF-detectors are the detection efficiency for hydrogen and low energy heavy ion scattering in the carbon foil [9] of the first timing gate (T1). One additional limitation which comes in question with the tandem effect is the use of high or low voltages: when using the MCP for electron amplification, either the carbon foil or anode needs to be at elevated voltage. If the carbon foil is in high voltage and enhances the tandem effect, then the anode can be grounded. The grounded foil-situation requires an anode in high voltage while it also increases the background events because of the free electrons are then more easily accelerated towards the MCP.

When high depth resolution for thin film sample analyzes is aimed for elastic recoil detection telescopes equipped with ToF it is beneficiary to use lower energies [10]. In lower energies, however, one has to also consider the tandem effect [2] and the bending of the ion trajectories in the electric fields of the first timing gate. The tandem effect can generally be described as a time-of-flight (and energy) spread due to the charge state exchange of the passing ion in the carbon foil of the first timing gate. This phenomenon is often listed as one of the most important factors limiting the resolution of ToF detectors for ion beam analysis using the lowest beam energies [2,10–12]. The additional energy spread of the passing ion caused by the tandem effect has often been written in a form: $\sigma_{\text{tandem}} = \Delta \bar{q} \cdot V_{\text{T1 foil}}$, where $\Delta \bar{q}$ is the average change of the charge of the ions upon their passage through the

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T1 foil having voltage of $V_{\mathrm{T1\ foil}}$. However, further quantification of the Δq has generally not been explained.

For low energy charged ions also notable bending of ion trajectories takes place in the time pick-up detectors due to electric fields and can even lead to a situation that no ions reach the second timing gate at all if both gates have strictly limited solid angles.

We have simulated with SimION software [13] different timing gate configurations and measured experimentally results with the time-of-flight elastic recoil detection (ToF-ERD) spectrometer in Jyväskylä to test and to gain better knowledge of the ion trajectory bending and the tandem effect. The aim was to find the optimal timing gate design, if not the one used at the moment in the view of bending of ion trajectories and the tandem effect.

2. Simulation and experimental setups

Simulation software used was SimION [13] which is a 3D capable electron and ion transport simulation program. The time-of-flight telescope dimensions were replicated to the simulation program from the real ToF-ERD system existing in our laboratory. The wire grids in the timing gates were modeled as transparent potential barriers. Similar simplification was applied also to the carbon foils.

Most important assumption made in this study is that the charge exchange equilibrium is always reached for energetic (>50 keV) ions in both T1 carbon foil ($\sim$3 μg/cm^2) and in the sample from which the ions, scattered or recoiled, emerge towards the ToF-E telescope. There are numerous publications detailing with the charge exchange processes for different targets, incident ions and energies but for the essentials, a general illustration of the field is summed well in [14] and a more specific case for lower energies is presented in [15]. In these references it is shown that about 1 μg/cm^2 of material is already enough for MeV ions to reach the charge state equilibrium. If this statement is expected to be valid then the charge states of the ions incoming to the first time pick-up detector and leaving from the T1 foil are independent of each other but follow the same energy dependent charge state distribution. This means that for the He ions, for example, there are total 3×3 different charge state combinations for the ions that have emerged from the sample and passed the T1 foil and thus 9 different ToFs can exist after the T1 foil for the He ions.

During the simulations, the timing gate orientations (see Fig. 1) and voltages were changed to examine how the transmitted ions behave in different configurations. In simulations, when non-zero voltage was applied to the T1 carbon foil, it was assumed that the incoming ions had scattered/recoiled from a sample in ground potential and reached the charge state equilibrium characteristic for that particular energy. The charge state distributions for different energies were taken from the tables of comprehensive database [16] where different ion-target combinations are summed up from numerous publications from the past decades. For this study, only carbon foil as a target (=T1 foil) material was considered.

Experimental setup consists of a sample located at the distance of 32 cm from the first timing gate, particle suppressors, two carbon foil time pick-up detectors similar to the design of Busch et al. [6] and with the time-of-flight distance of 62 cm. After the second timing gate there is a silicon energy detector allowing coincident ToF-E measurements and thereafter mass identification of

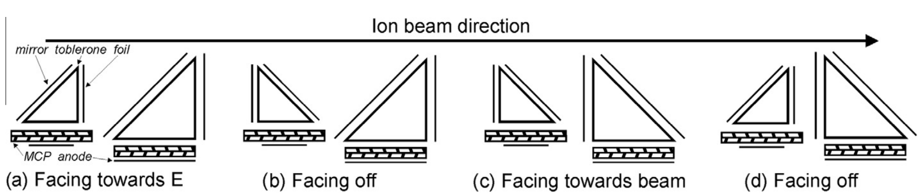

Fig. 1. Different timing gate orientations. In all simulations the distance from foil-to-foil was kept the same. The both timing gate carbon foils in (a) face towards the E detector, in (b) face off from each other, in (c) face towards the beam and in (d) face towards each other.

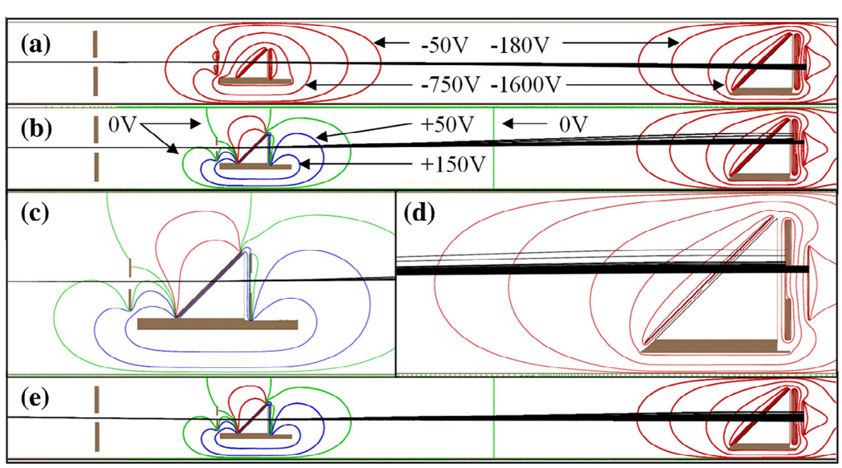

Fig. 2. Bending of hydrogen ion trajectories in timing gates. Low energy hydrogen ion paths (initial energy 100 ± 50 keV) were simulated with SimION through the ToF-ERD spectrometer with E-detector being further right after the T2 timing gate. Red color: negative potential, green color: 0 V potential and blue color: positive potential. In (a) both T1 and T2 have foil and mirror voltage at −2800 V and virtually field free toblerone part at −1800 V. In the rest of the figures the T1 foil is at the ground potential, the mirror at −500 V (to repel free electrons as in experimental setup) and the toblerone part for the T1 at +1000 V. One can see that in (b) and in the close-ups of (c) and (d) the hydrogen paths for lowest energies will not end up to the E-detector when the foil opening at T2 is 18 mm diameter. In (e) 1% downward declination is used for incoming hydrogen ions with respect to the straight line of sight. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)