Development of a detector for inertial sensing of positronium at AEḡIS (CERN)

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Abstract. The primary goal of the AEgIS collaboration at CERN is to measure the gravitational acceleration on neutral antimatter. Positronium (Ps), the bound state of an electron and a positron, is a suitable candidate for a force-sensitive inertial measurement by means of deflectometry/interferometry. In order to conduct such an experiment, the impact position and time of arrival of Ps atoms at the detector must be detected simultaneously. The detection of a low-velocity Ps beam with a spatial resolution of (88 ± 5) µm was previously demonstrated [1]. Based on the methodology employed in [1] and [2], a hybrid imaging/timing detector with increased spatial resolution of about 10 µm was developed. The performance of a prototype was tested with a positron beam. The concept of the detector and first results are presented.

1. Introduction

Positronium is a hydrogen-like matter-antimatter bound state of an electron and a positron. In the ground state, it exists in two different spin configurations:

- Singlet 1^1S (para-Ps) with a lifetime of 0.125 ns
- Triplet 1^3S (ortho-Ps) with a lifetime of 142 ns

The long-lived 2^3S state of Ps has a lifetime of 1.14 μs and excitation of Ps to Rydberg states (Ps*) increases its lifetime up to several tens of microseconds. With their increased lifetimes, Rydberg positronium and 2^3S Ps are of interest for inertial measurements, where the effects of an external force exerted on the matter/antimatter atoms are studied. Rydberg Ps and 2^3S Ps both have previously been produced at AEgIS (CERN) [3][4][5].

Inertial measurements can be performed with inertial sensitive devices such as a classical moiré deflectometer or a Mach–Zehnder interferometer. These devices can be composed of two gratings and a detector. Particles not being stopped or deflected from either of the gratings generate a periodic pattern on the detector plane. An external force, like a magnetic force or gravity, acting on the particles will shift the position of this pattern. Information about this force can be extracted from the magnitude of the shift [6].

2. Time- and position-sensitive detector for neutral low-energy matter/antimatter atoms

To measure the displacement of the atoms induced by an external force, an atom detector with a spatial resolution in the order of 10 μm and a temporal resolution better than 100 ns would be of great benefit. We report on a prototype fulfilling these requirements, combined with a high detection efficiency. It consists of three main elements: an ionization stage, a drift region for the ionized particles and a detection module. The spatial resolution and efficiency of the detection module were tested with a low-energy positron beam.

2.1. Detection principle

The detection principle is illustrated in Fig. 1. It is based on the methodologies described in [1] and [2]. The incoming Ps atoms are ionized by means of a combination of field- and photoionization. The positrons freed in this process are transported towards a spatial- and time-sensitive detection module. In the drift region, a uniform magnetic field perpendicular to the surface of the detection module traps the positrons on their cyclotron orbit. Therefore, the spatial position of the Ps atoms in the plan transverse to the magnetic field is conserved in the spatial position of the positrons.
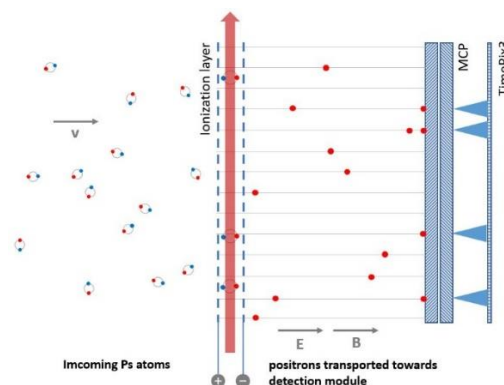

Figure 1: Schematic of experimental setup and detection principle: Incoming positronium atoms are ionized, followed by the detection of the ionization products.

The positrons are imaged by a detection module, which consists of a microchannel plate (MCP) chevron stack read out by a TimePix3 ASIC (TPX3) [7]. An image of the detection module is shown in Fig 2a. The two plates have a channel diameter of 10 μm and a channel pitch of 12 μm. TPX3 is a 256 x 256 matrix of pixels with a size of 55 x 55 μm^2.

Positrons impinging with a few hundred eV on the MCP release secondary electrons which get amplified in the channels. In the gap between MCP and chip the resulting electron clouds expand and cover multiple pixels at the level of the chip. The charge amplification and the acceleration of the electron cloud in the gap between the MCP and TPX3 can be controlled by the voltages applied to the MCP front face and MCP back face, as illustrated in Fig. 2b. For the tests presented here, the MCP gain voltage was varied in a range of 1150 V and 1400 V and the acceleration voltage was between 100 V and 600 V.

Sub-pixel resolution is achieved by reconstructing the impact position of the positrons on the surface of the MCP with an event centroiding algorithm.
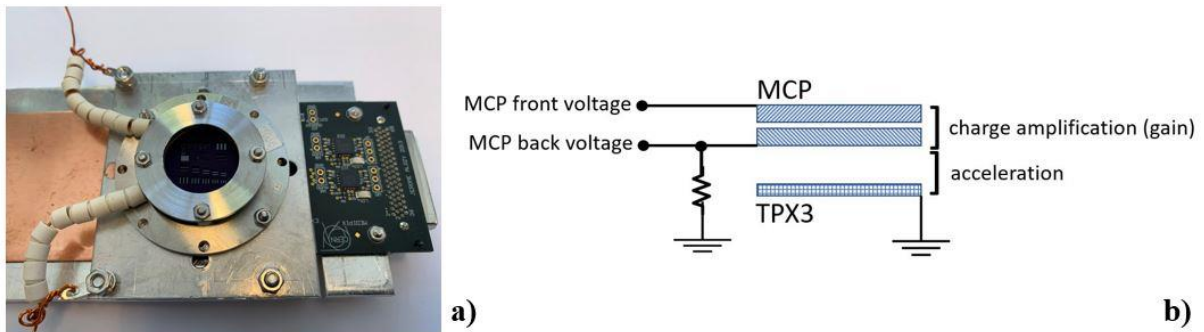

Figure 2: a) MCP chevron stack mounted on a TimePix3 chip, b) Electronic schematic of the detection module

2.2. Spatial resolution of the detection module

The spatial resolution of the detection module was determined with the edge spread function method. An image of a sharp edge was obtained by imaging a positron beam of 0.5 keV. The image intensity is integrated along the edge and fitted with an error function:

$$y = \frac{a}{2}\left[erf\left(\frac{x_0-x}{\sigma\sqrt{2}}\right) + 1\right],$$

where a is the amplitude, x_0 the mean and σ the standard deviation of the corresponding gaussian distribution function. The resolution is extracted from the fit by multiplying the standard deviation σ with the pixel size.

The results show a strong tendency towards better resolutions with an increased electric field in the gap between MCP and chip, where the electron cloud emitted by the MCP is concentrated on a smaller number of pixels and the centre-of-mass of the cluster can be reconstructed more accurately. The best resolution of (10.5 ± 1.1) μm in this configuration was obtained with a MCP gain voltage (MCP front voltage) of 1250 V and an acceleration voltage (MCP back voltage) of 500 V.

2.3. Temporal resolution of the detection module

TPX3 has a temporal resolution of 1.56 ns. The temporal resolution of the detection module however is limited by the time spread of the electron clouds arriving at the chip. The time spread depends on the cluster size which is a function of the MCP gain voltage and the acceleration voltage. Depending

on these parameters, the temporal resolution is in the order of 30 ns for low MCP gain- and acceleration voltages (small clusters) and 170 ns for high MCP gain- and acceleration voltages (large clusters).

2.4. Efficiency of the detection module

The efficiency of the detection module was measured as the ratio of positrons impinging on the surface of the MCP and the number of clusters registered by the device. The number of positrons was measured with a calibrated NaI scintillator coupled to a photomultiplier tube.
The efficiency of the detection module is dependent on the MCP gain voltage and the acceleration voltage. Maximising those parameters in the given range yields a positron detection efficiency of (41.1 ± 2.1) %.

3. Conclusion

A hybrid imaging/timing detector with simultaneous high spatial and temporal resolution for low-intensity and low-energy beams of neutral matter/antimatter atoms, similar to that demonstrated in [8] yet allowing event-by-event identification, was developed. Enabling inertial measurements and counting experiments, it is a versatile device suitable for a broad range of applications in positronium research. Such detector could also find application in measurements involving other antimatter systems like antihydrogen or protonium.

Acknowledgements

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