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EXPERIMENTAL 4D TRACKING OF A SINGLE ELECTRON IN IOTA*

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Abstract

We present the results of the first experiments on 4-dimensional phase-space tracking of a single electron in a storage ring, using a linear multi-anode photomultiplier tube for simultaneously measuring transverse coordinates and arrival times of synchrotron-radiation pulses. During the next few months, full 6D tracking will be implemented. This technology makes it possible to characterize the motion of a single particle, i.e. simultaneously tracking of amplitudes and phases for slow synchrotron oscillations and fast betatron oscillations. Complete tracking of a single particle enables the first direct measurements of dynamical properties, including invariants, amplitude-dependent tunes, and chaotic behavior.

INTRODUCTION

Complete tracking of a charged particle in a circular accelerator enables a new class of diagnostics capabilities for investigating linear and nonlinear dynamics: dynamical invariants, amplitude-dependent oscillation frequencies, chaotic behavior, etc. True single-particle measurements can also be employed for benchmarking long-term tracking simulations, for training machine-learning algorithms, and for precise predictions of the performance of present and future accelerators.

Observation of a single electron in storage rings has a long history that goes back to experiments at AdA, the first electron-positron collider [1, 2]. Several experiments using various instruments were done in the past to track single electron dynamics in storage rings, with the goal to track relatively slow synchrotron oscillations [3–5]. In IOTA, we initiated a research program to fully track the motion of a single electron. The first results were presented in Refs. [6–8]. The goal of the present study is to demonstrate for the first time a complete 6-dimensional tracking of a single electron in a storage ring. The first phase, presented in this paper, is based on a single position-sensitive photodetector with fine temporal resolution, covering the horizontal and longitudinal planes. In the next few months, a second detector will be installed, adding vertical measurement capabilities.

EXPERIMENTAL SETUP

The 8 main dipoles in IOTA [9] are equipped with synchrotron-light stations installed on top of the magnets

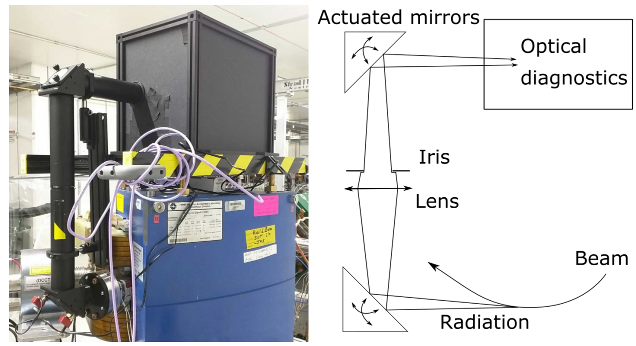

Figure 1: Photograph (left) and schematic diagram (right) of the optical diagnostics setup at one of IOTA's main dipoles.

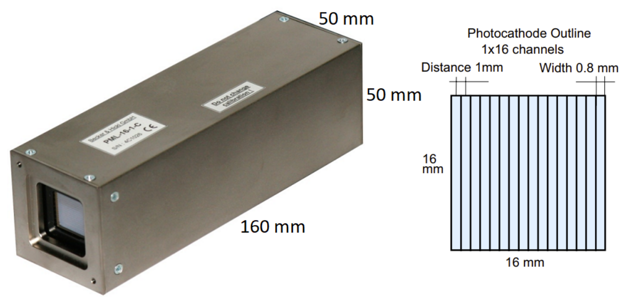

Figure 2: The PML-16 multi-anode PMT (left) and the geometry of its sensitive area (right).

themselves. The light emitted in the dipoles is deflected upwards and back to the horizontal plane with two 90-degree mirrors. After the second mirror, the light enters the dark box, which is instrumented with customizable diagnostics, as shown in Figure 1. A focusing achromatic lens with a 40 cm focal length and an iris are installed in the vertical optical transport tube that connects to the mirror holders. This experiment used one of such diagnostics stages located at the M3L dipole.

We used the PML-16 detector from the Becker & Hickl company [10], based on a Hamamatsu multi-anode photomultiplier tube (PMT). Figure 2 shows a general view of the detector and its dimensions, including the geometry of the sensitive area. The PML-16 detectors have an active area of 16×16 mm with 16 individual cathodes arranged in a linear array. To fully utilize this relatively large area, a defocusing lens was added to the optical system, so that the horizontal or vertical rms size of the light beam was around 2 mm at the sensitive area of the PMT.

The PML-16 detector has a pre-amp and channel-encoding electronics attached to the PMT, forming a single unit, in order to minimize noise and time jitter. Control of the detector high voltage is done by the DCC-100 card. The SPC-130 card measures the time of arrival and position of

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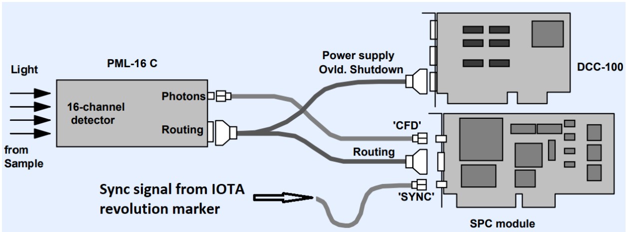

Figure 3: Connection scheme of the PML-16 detector. DCC-100 is a voltage-control and overload-protection unit that can handle two detectors. The SPC modules are used to record intra-cycle time, consecutive cycle number, and position of the segment that detected a photocount. Each detector requires one SPC module.

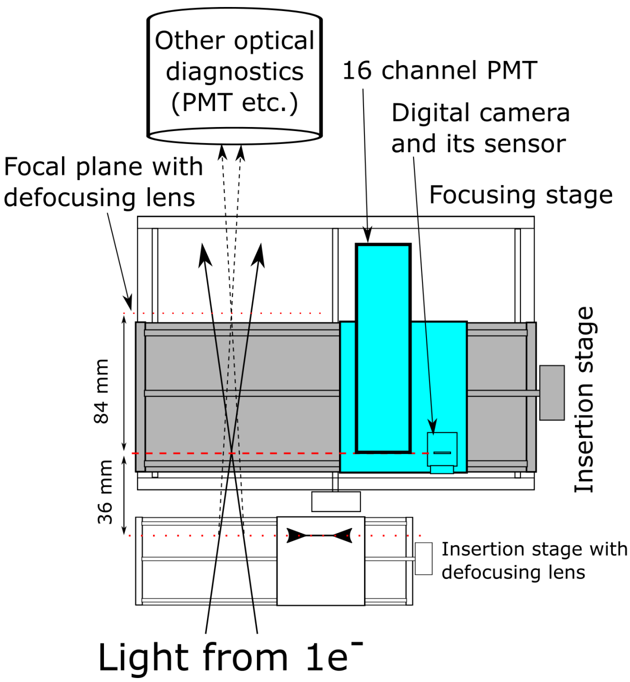

Figure 4: Schematic diagram of the optomechanical setup for electron tracking.

the segment that detected a photocount. Figure 3 shows the connection layout.

A modification to the existing IOTA optical and mechanical systems was done to match the beam and the detector sizes and to preserve the existing functionality. Figure 4 shows the layout of the instruments. Both the 16-channel PMT and a digital camera (blue) are located on a stack of movable stages. The focusing stage can move the insertion stage (grey) to position sensors in the focal plane. The insertion stage can position either one of the sensors on the axis of the light beam or let the light pass through to an existing large-area photomultiplier. An additional insertion stage is used to move a defocusing lens in and out of the light path and to change the magnification factor: (a) the nominal 88% and (b) 400%, to effectively use the large active area of the PML-16 detector.

Table 1: IOTA Parameters During the Experiment

Parameter	Value
Perimeter	39.96 m
Momentum	150 MeV/c
Bunch intensity	1 e^-
RF frequency	30 MHz
RF voltage	350 V
Betatron tunes, (ν_x, ν_y)	(5.2965, 5.3)
Synchrotron tune, ν_s	3.5×10^{-4}
Damping times, (τ_x, τ_y, τ_s)	(2.08, 0.65, 0.24) s
Horizontal emittance, ϵ_x	127 nm
Momentum spread, $\Delta p/p$, RMS	1.3×10^{-4}
Momentum compaction, α_p	0.083
Natural chromaticity C_x, C_y	-10.9, -9.4

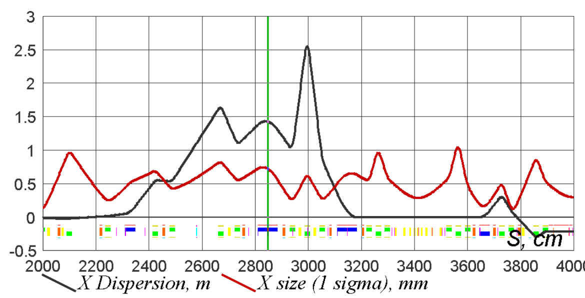

Figure 5: Horizontal beam size and horizontal dispersion of the IOTA lattice. The second half of the ring is shown, ending at the injection straight section. The vertical green line shows the location of the detector (M3L dipole).

Measurements were done concurrently with other ongoing experiments in IOTA, without any special modifications to the lattice parameters. The only difference was a small change of the horizontal betatron tune to move the working point away from the coupling resonance and have a flat beam. The resulting IOTA parameters are listed in Table 1. The lattice was characterized using the LOCO method. The following tolerances are expected for the points of observation of the optical instruments: (a) beta function accuracy of 5%; (b) dispersion function error smaller than 1 cm; (c) betatron tunes within 0.001. Figure 5 shows the horizontal beam size and dispersion for this IOTA configuration.

RESULTS

The core data consists of a list of 3 numbers for each photocount: the turn number, the arrival time with respect to the latest revolution marker, and the number of the PMT segment that detected the photon. We show the results based on a data set of 102,767 photocounts detected over 10 s.

Figure 6 shows an example of tracking an electron in 4D phase space over about 60,000 turns, using 80 photocounts detected over that time. Table 2 contains the corresponding trajectory parameters, assuming harmonic oscillations in the longitudinal and horizontal planes. Uncertainties on the parameters were calculated using the bootstrap method.

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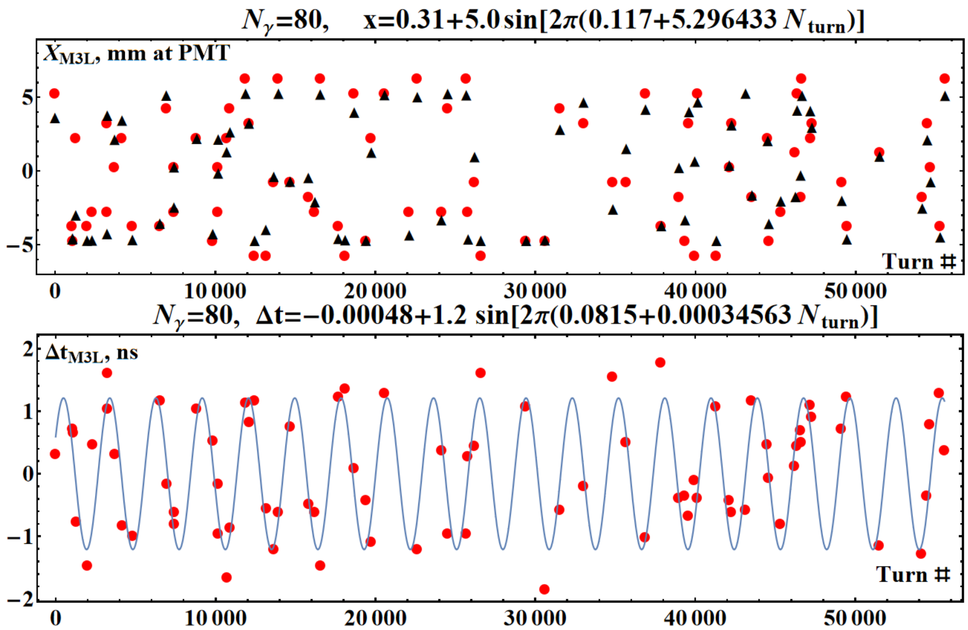

Figure 6: (Top) Horizontal positions of an electron measured (red circles) and reconstructed on the same turns (black triangles) assuming harmonic oscillations. (Bottom) Reconstruction of the synchrotron oscillations (solid line) compared to the measured delays of the arrival time (red circles). the same photon detection events were used for both plots.

Table 2: Example of parameters extracted by 4D tracking of a single-electron trajectory, measured using 80 photocounts over 60,000 turns.

Parameter	Value
Horizontal betatron tune	5.2964325(5)
Horizontal betatron phase	$2\pi \cdot 0.12(2)$
Horizontal betatron amplitude	5.0(2) mm
Synchrotron tune	0.0003456(7)
Synchrotron phase	$2\pi \cdot 0.09(2)$
Synchrotron amplitude	1.20(8) ns

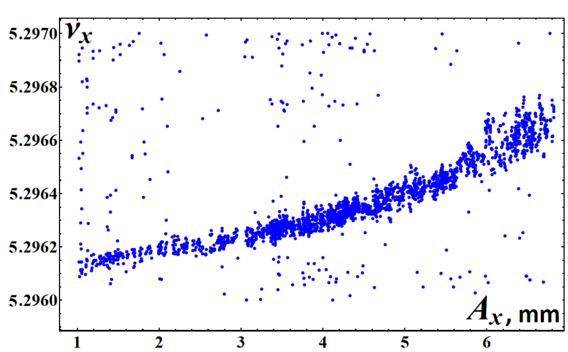

Figure 7: Dependence of the horizontal betatron tune on the amplitude of the horizontal oscillations at the image plane.

Because of random recoils from radiation emission and residual-gas scattering, oscillation amplitudes change randomly in time. This allows one to naturally scan phase space without external excitations. Figure 7 shows the dependence of the horizontal betatron tune on the horizontal betatron amplitude from the sample data set. For this preliminary analysis, we used a simplified algorithm, which is fast but also introduces some noise. The Fourier transform of the arrival times of 20 photocounts was used to extract the spectrum with fine peak detection in the range between 5.296 and 5.297 in betatron tunes.

As a by-product of this analysis, we were able to detect tune oscillations at 60 Hz at the 2×10^{-4} level due to power-supply ripple. This type of diagnostics will be used to improve the performance and stability of the ring. (These oscillations were filtered out in the plot of Figure 7.)

SUMMARY

We presented the first simultaneous experimental tracking of betatron and synchrotron oscillations of a single electron in a storage ring, using synchrotron radiation detected by position-sensitive photodetectors with high temporal resolution. This 4D phase-space tracking is a proof-of-principle demonstration of our upcoming experiments with an additional vertical detector, to fully track a single electron in 6D phase space.

As an example of practical use, the horizontal betatron tune was measured with the exceptional precision of 5×10^{-7}. In addition, the dependence of the tune on oscillation amplitude was determined without external excitations.

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