



Experimental Phase-Space Tracking of a Single Electron in a Storage Ring

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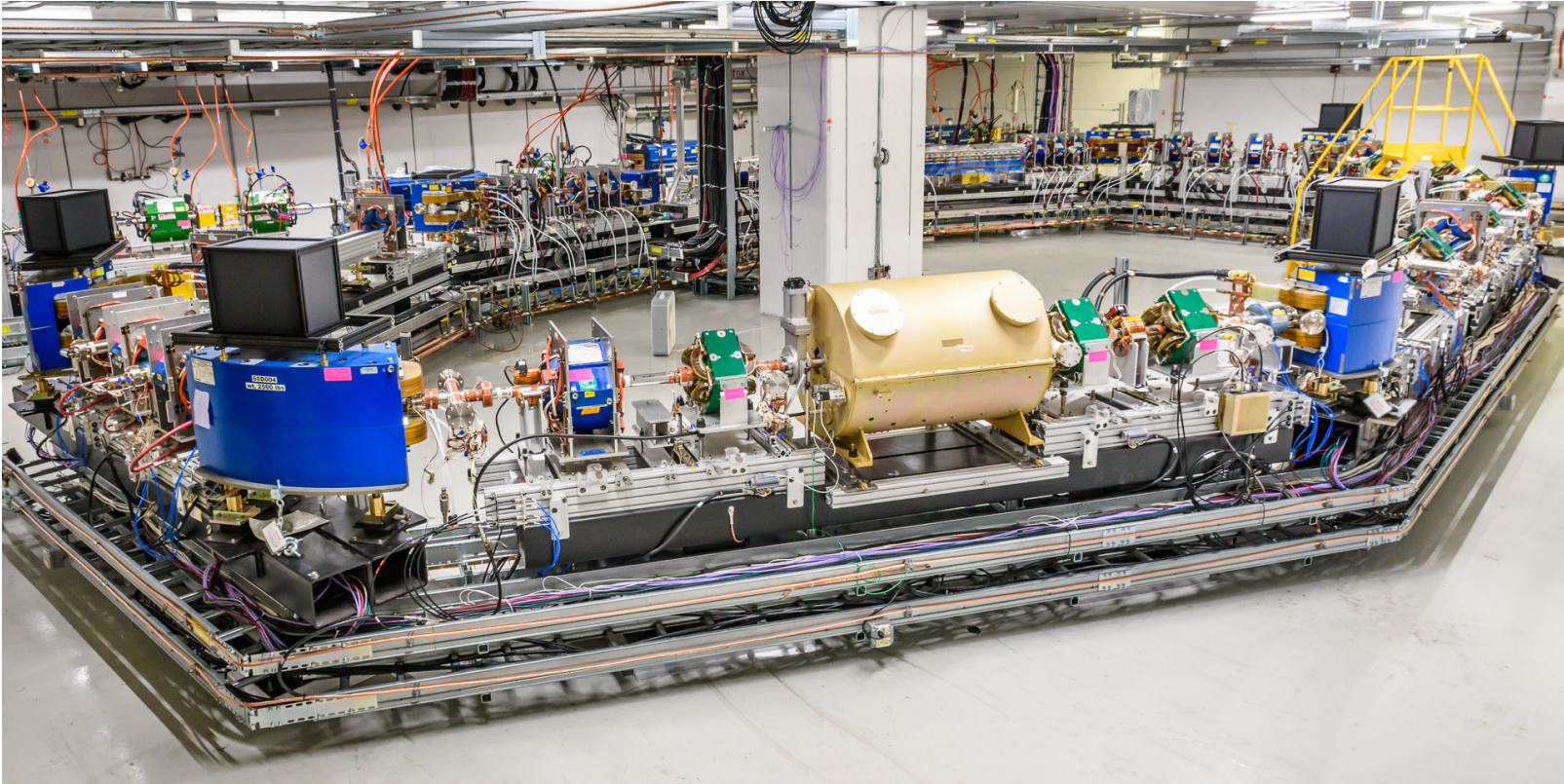
Motivation for the single electron studies

- Observation of a truly point-like object in a storage ring allows deep understanding of a single-particle dynamics
 - Mandatory basis for a successful implementation of advanced beam control concepts
 - Halo and losses suppression
 - Instabilities suppression
 - Higher beam power
 - Valuable machine diagnostics information
 - Betatron and synchrotron dynamics
 - Non-linear dynamics
 - Tune dependence on amplitudes
 - Residual gas properties
 - Validation of simulation tools

State of the art with a single electron tracking

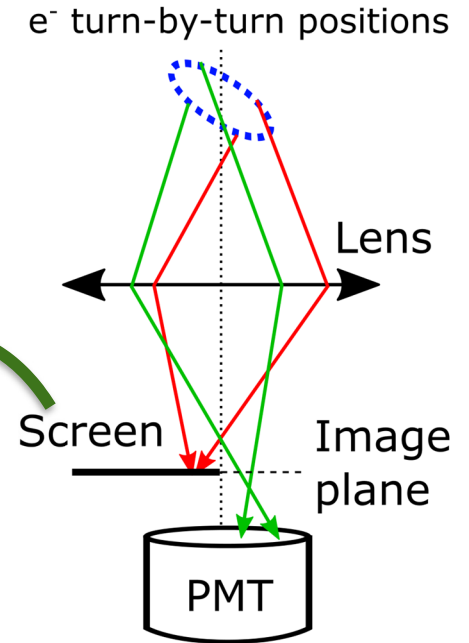
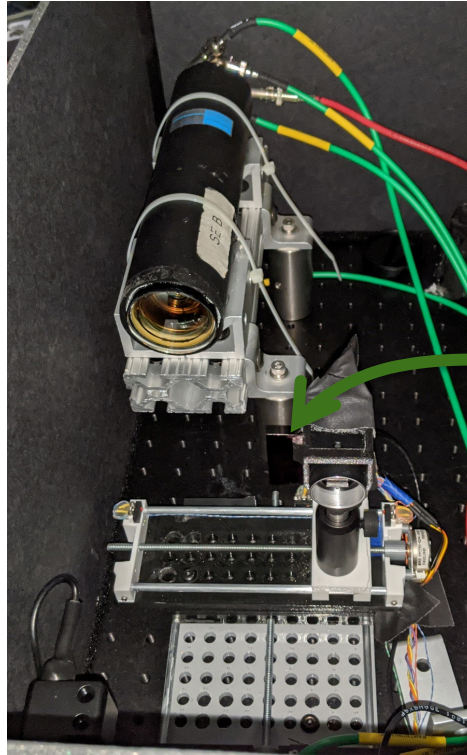
- Most studies of a single electron in storage rings were focused on a longitudinal dynamics.
 - Registration of arrival times of individual photons allows tracking of synchrotron oscillations of one or a few electrons.
- In previous experiments at IOTA we used digital cameras to track all 3 mode amplitudes (2 betatron and synchrotron) as well as PMTs and SPADs to track synchrotron oscillations
- Capability to track only 2 remaining dynamical variables – betatron phases - is necessary for a full 6-dimensional tracking!
- Therefore, we decided to demonstrate feasibility of a Betatron Oscillations Tracking of a Single Electron (BOPTSE)

IOTA overview



Experimental setup for BOPTSE experiment

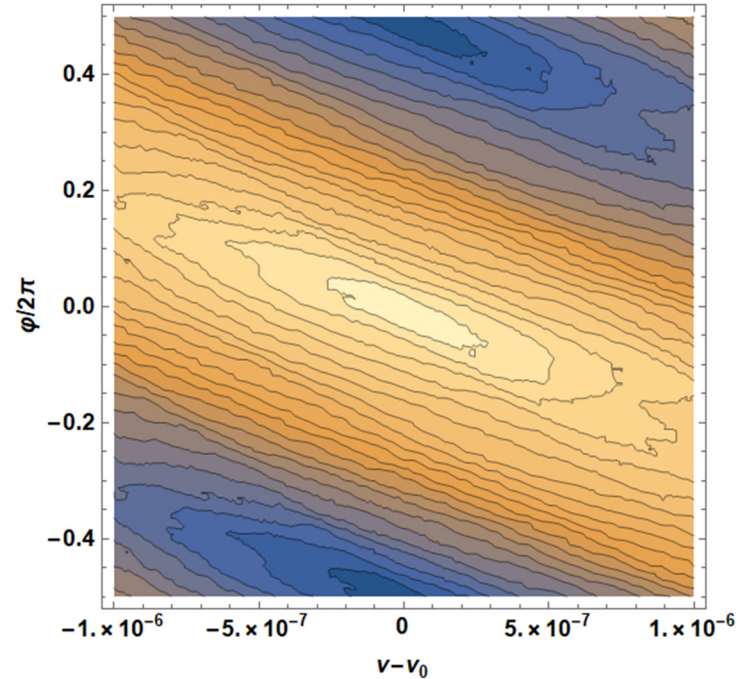
- Straight-edge screen is blocking one half of the image
- Screen is positioned in the same plane as camera sensor by the 3D-printed attachment
- Camera is installed on a stack of focusing and transverse stages
- Transverse position is selected such that the base counting rate of the PMT is reduced by 50%



Experimental data

- Described single-pixel detector collects photons from only one half of the phase space
- Even such a coarse “camera” can provide information if enough photons are collected
- Expected detection rate of photons is about 3750 counts per second, or about one per 2000 turns
- Data from $50\mu\text{s}$ (~ 180 photons), ideally, would give presented contour plot for the likelihood function:

$$F(\phi, \nu) = \sum_{i_\gamma} H [\sin(2\pi(i_\gamma \nu + \phi))]]$$



The root mean square spread of the reconstructed phases and tunes after 30 simulations were $0.02 \cdot 2\pi$ and $7 \cdot 10^{-8}$

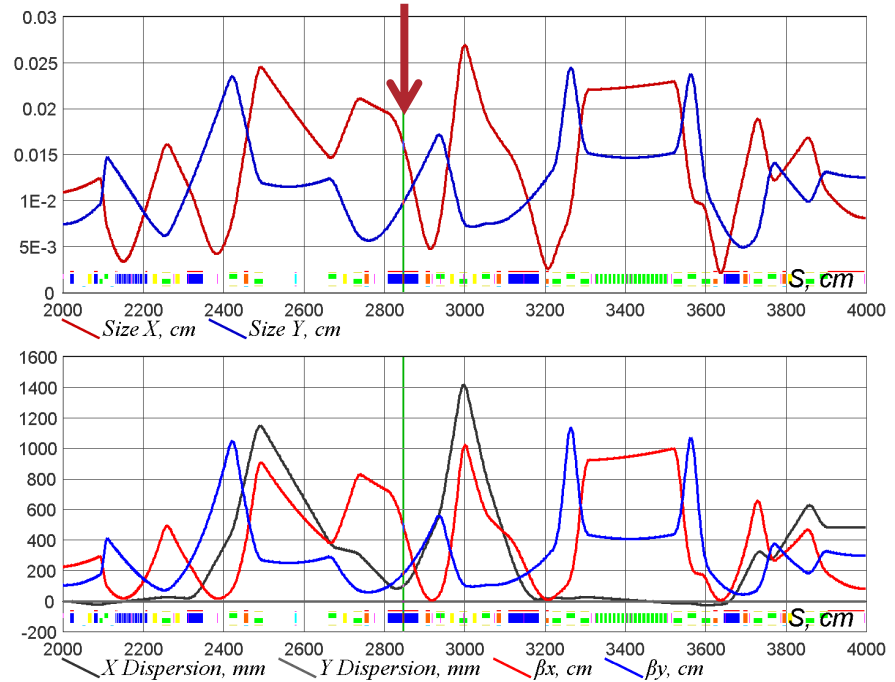
Lattice configuration

Special lattice was designed with favorable beam parameters:

- Big horizontal beam size at the M3L observation point
- Long damping times
- Zero dispersion in the regions with aperture restrictions

M3L

Parameter	Value
Perimeter	39.96 m
Momentum	101 MeV/c
Bunch intensity	1 – 1000 e^-
RF frequency	30 MHz
RF voltage	55 V
Betatron tunes, (ν_x, ν_y)	(5.41, 3.44)
Synchrotron tune, ν_s	7.18×10^{-5}
Damping times, (τ_x, τ_y, τ_s)	(2.34, 2.04, 0.96) s
Horizontal emittance, ϵ_x	11.3 nm
Momentum spread, $\Delta p/p$, RMS	9.7×10^{-5}
Momentum compaction, α_p	0.015
Natural chromaticity C_x, C_y	-13.4, -9.0



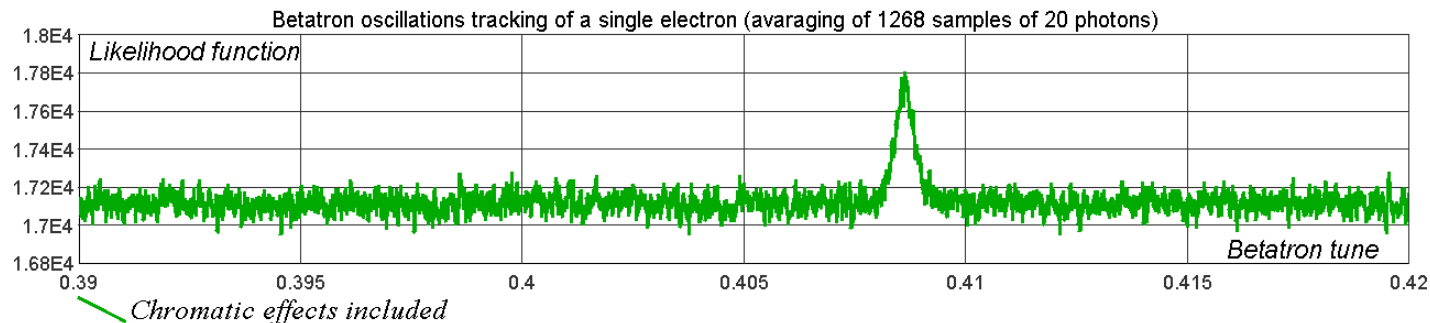
Studies timeline

- 2 hours of access were required to attach the straight-edge screen to the M3L camera and to verify light tightness of the M3L station.
- Initial commissioning of the data acquisition system were done in the nominal IOTA lattice, taking 2 half shifts.
- Commissioning of a special lattice with long damping times and larger horizontal size
 - Three 8-hour shifts and 4-hour shift (planned: three 8-hour shifts)
- Taking experimental data in various regimes
 - Two 8-hour shifts (planned: up to four 4-hour shifts)

The studies were completed within the requested time.

Main result: betatron tune of a single electron!

- Data analysis confirms groundbreaking potential of the ideas tested with the BOPTSE experiment:
 - **For the first time, betatron tune was measured using a single electron in a storage ring**
 - The last obstacle on the way towards full 6D tracking of a single particle is proven to be solvable



*Data taking duration:
3 minutes*

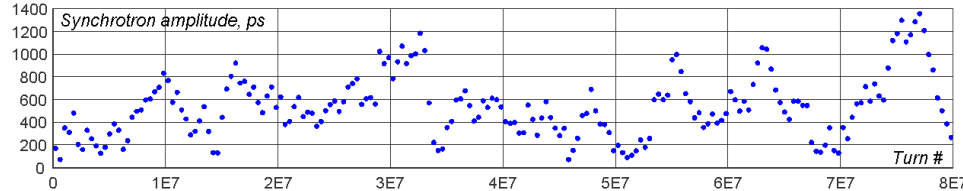
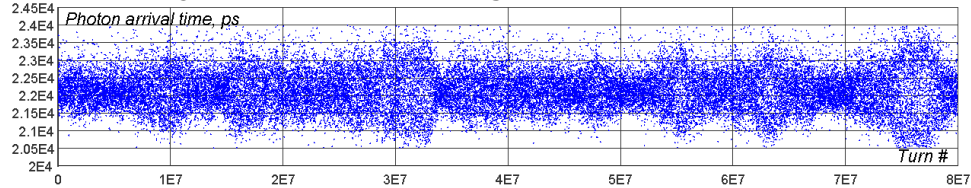
*Averaging of likelihood functions from 1268 streaks
of 20 photons arrived within 20000 turns*

Possible complications

- Tune dependence on the mode amplitudes
 - Chromatic effects from the synchrotron oscillations
 - Can be accounted for because data was taken with a PMT and time of arrival of each photon is available
 - Tune dependence on the betatron amplitudes
 - Images from 3 sensitive cameras were recorded in parallel with PMT measurements, this allows reconstruction of slowly changing betatron amplitudes
- Other non-linear dynamics from various imperfections and edge fields
 - Hard to account for, since there are too many variables, and the data is too coarse
- Power supplies ripple
 - Hard to account for, but closed orbit data analysis suggests that biggest ripples have frequency of 10 Hz, which should allow to work with a data streaks of 100-200 photons as if there is no ripple.

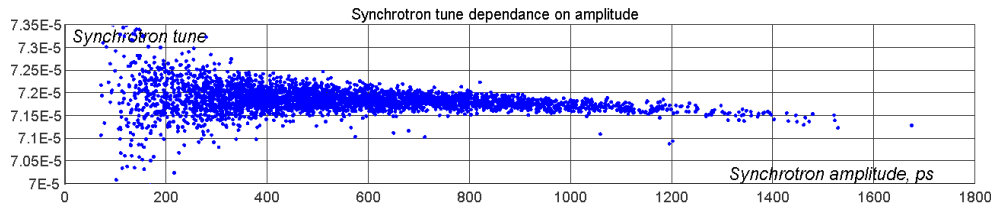
Synchrotron oscillations

- To account for chromatic effects, synchrotron oscillations were tracked through the entire data set.
- Chromaticity value was adjusted to maximize likelihood function



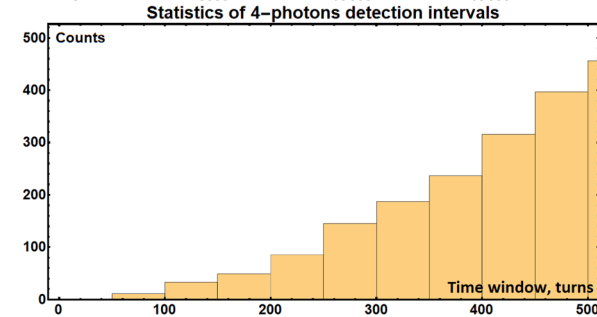
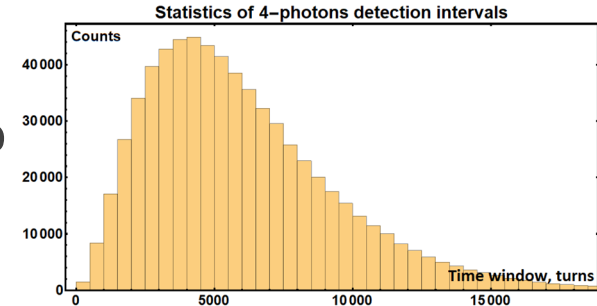
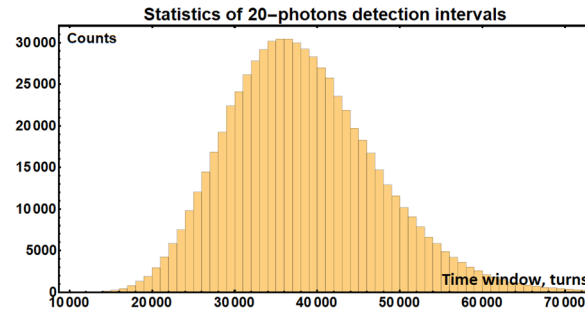
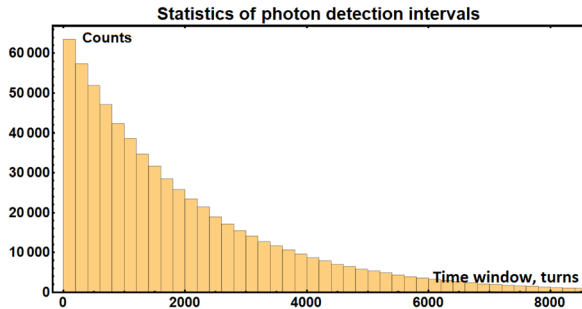
~10 s shown

180 s total



Time of arrival statistics

- On average, there is about 1 photon per 2000 turns, but since photon-to-photon intervals are random and follow exponential distribution, it is possible to hand-pick photon streaks that are denser than average.
 - With short enough streaks, it is even possible to avoid effects of synchrotron oscillations



Accounting for synchrotron oscillations

Slow synchrotron oscillations introduce perturbations that can change the betatron phase by more than π . To the first order, the dependence of the betatron tune on the relative momentum deviation of an electron can be presented as:

$$\nu_x = \nu_{x0} + C_x A_p \sin(2\pi\nu_s n + \varphi_{s0})$$

C_x - horizontal chromaticity, A_p - amplitude of synchrotron oscillations.

Assuming $\nu_s \ll 1$, this expression can be integrated to get a betatron phase:

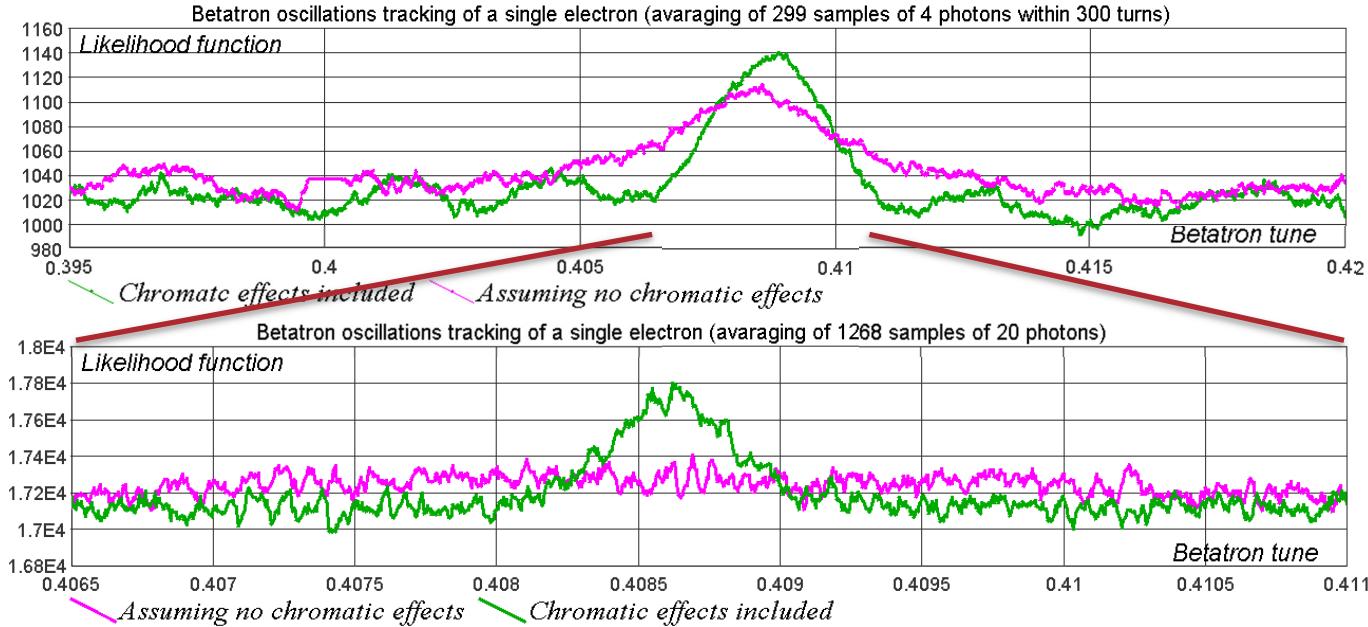
$$\frac{\varphi_x}{2\pi} = \nu_{x0} n + \frac{C_x A_t}{\alpha_p T_0} (\cos(\varphi_{s0}) - \cos(2\pi\nu_s n + \varphi_{s0})) + \frac{\varphi_{x0}}{2\pi}$$

The likelihood function for a set of photons with turn numbers n_γ :

$$F(\varphi_{x0}, \nu_x) = \sum_{n_\gamma} H[\sin(\varphi_x)]$$

Effect of synchrotron oscillations

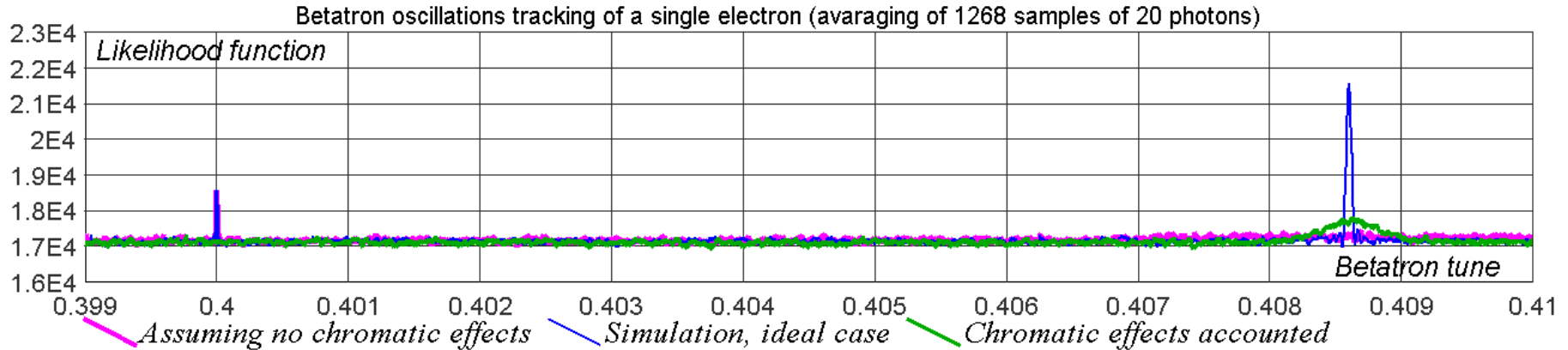
- Within a narrow window of 300 turns, even a simple sin-wave fit gives betatron tune



- Longer photons streaks require synchrotron oscillations to have visible signal

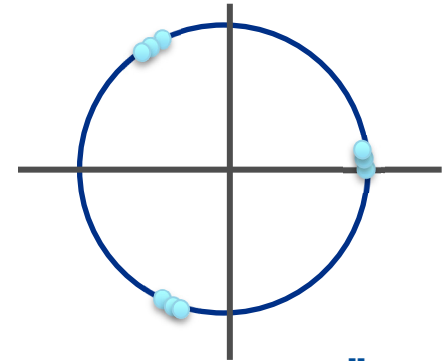
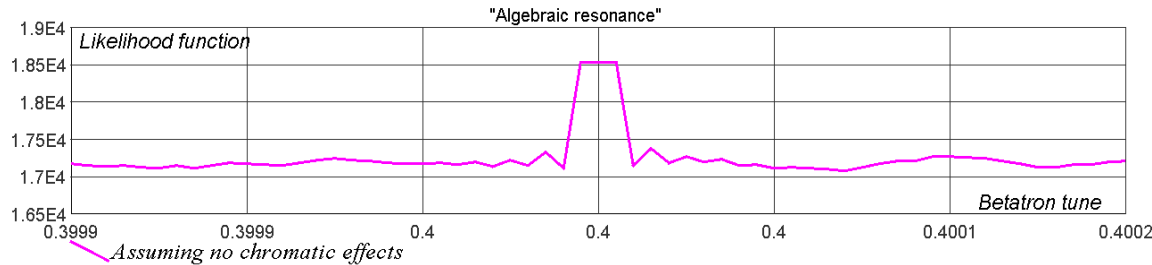
Unknown effects

- When compared to a simulation, it is clear that there are big systematic difference between the used model and the real electron dynamics in the IOTA storage ring



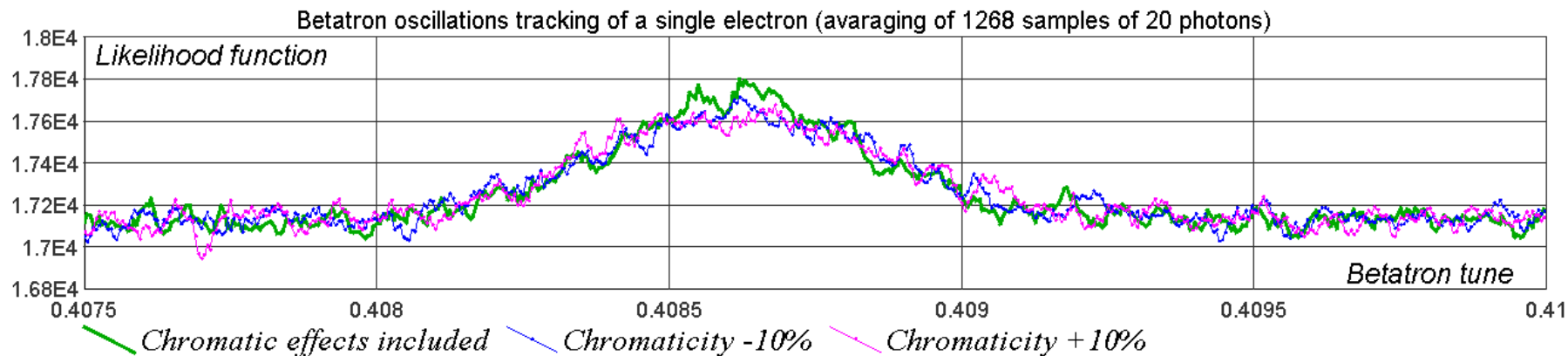
Instrumentation “resonances”

- Due to the fact that only one PMT was used there are “algebraic resonance lines” in the reconstructed betatron tune if chromatic effects are not included.
 - The most prominent lines are 1/3 and 1/5 and 2/5
- On average, for a wrong tune, likelihood function, should be slightly above $(N_\gamma/2 + \sqrt{N_\gamma/2})$
 - With tune on a “resonance”, all arrival phases cluster in 3 or 5 groups and it is possible to pick a phase that will match 2 or 3 biggest clusters.



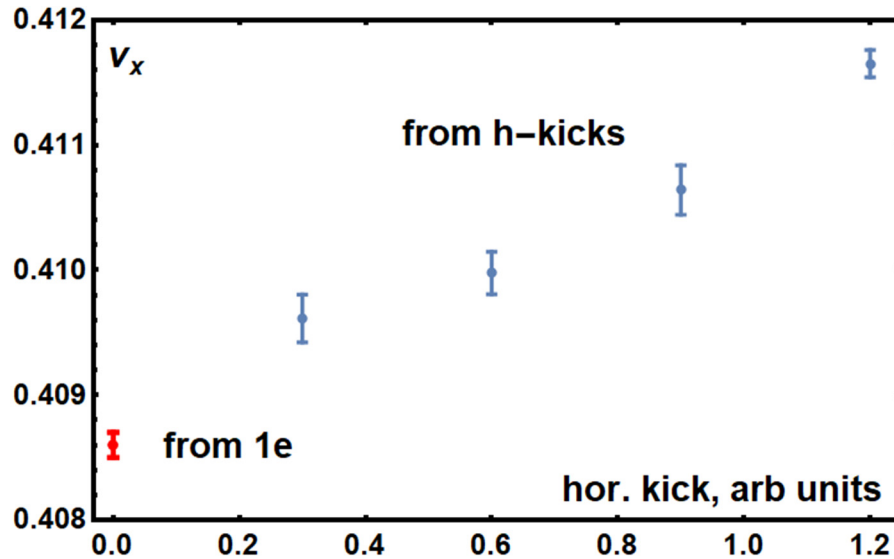
Chromaticity measurements

- The used simple tool allows precise measurements of the chromaticity
 - Single-parameter fits give $\sim 10\%$ accuracy



Amplitude tune dependance

- During the BOPTSE shift, a classic tune measurements were done for various kick amplitudes
 - BOPTSE data shows that even the smallest kick gives betatron tune that is different from near-zero amplitude tune normally experienced by particles

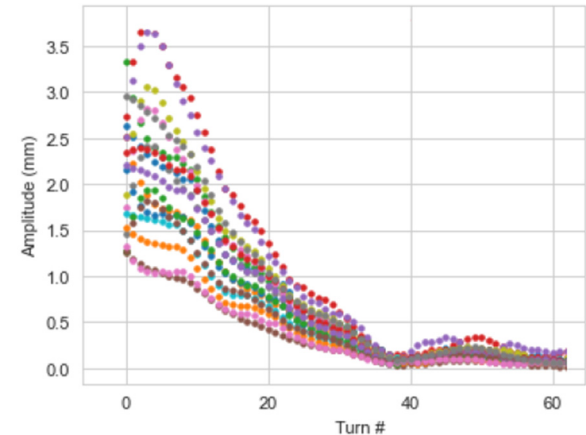


A 6D tracking for non-linear lattices

The goal: Direct observation of invariants and characterization of lattice parameters

- Pencil beam approach
 - Use of conventional diagnostics
 - Many points per turn
 - Limited resolution
 - Fast decoherence of the signal
 - Mixing of various decoherence sources
- Single electron tracking
 - Sparse data, about 1 point every 10-100 turns
 - Long coherence of the oscillations
 - True point-like test object
 - Natural scan of the phase space volume

Turn-by-turn beam coordinates in the IOTA ring with a non-linear lattice, each color correspond to a specific BPM.

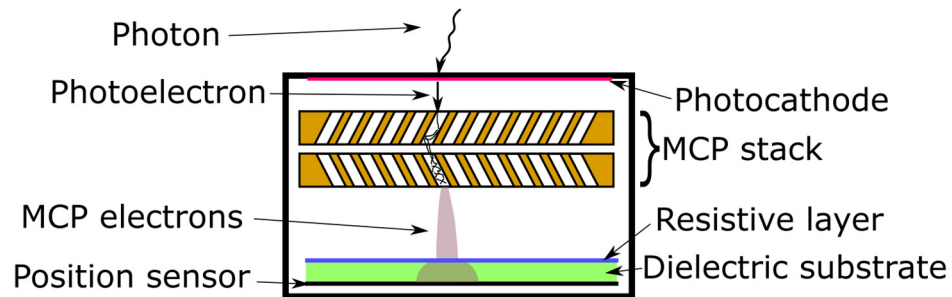
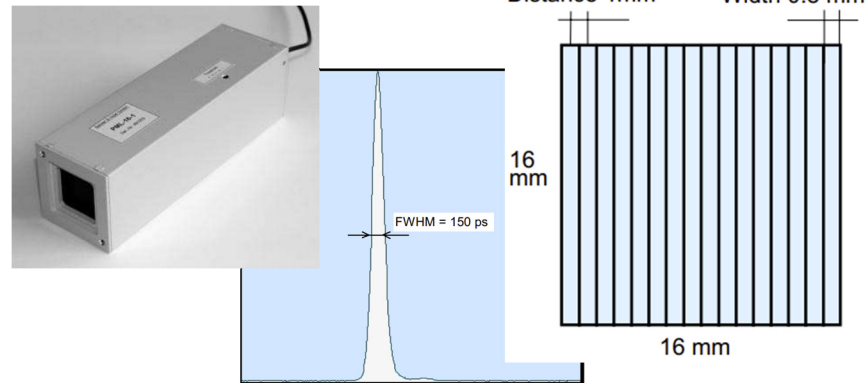


The path towards 6D tracking

LDRD grant was approved to demonstrate full 6D tracking of a single electron at IOTA

- The first stage studies are planned for the current IOTA's run-4
 - Two 16-channel PMTs will be used to track electron with limited resolution
- The second stage studies would rely on MCP based detectors
 - Single photon sensitivity with quantum efficiency of 15-20% @ 500nm
 - Spatial resolution of 30-50 μm
 - Temporal resolution of 200-300 ps
 - True 2D resolution with sensitivity to coupling

PML-16 from Becker & Hickl GmbH



Summary

- BOPTSE experiment demonstrated feasibility of a complete 6D single electron tracking
- Even a readily available instruments with small additions allow precision measurements of a true betatron tunes and chromaticities
- With addition of data from sensitive digital cameras, a precise information about amplitude dependance of betatron tunes can be measured
- Position sensitive photon detectors will enable an even deeper analysis and understanding of storage rings, which is crucial for successful design, commissioning and operation of future accelerators