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Complete 6D tracking of a single electron in the IOTA ring

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Motivation for the single electron studies

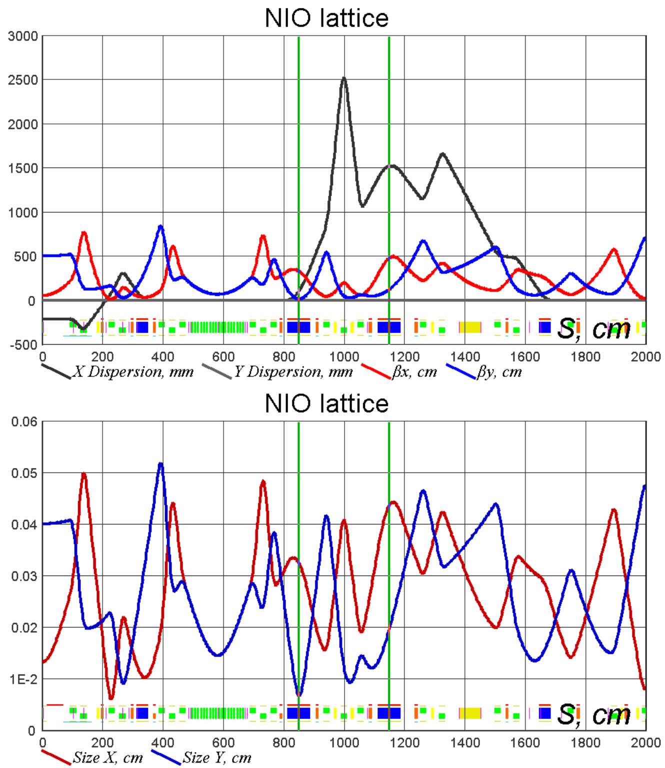
- Observation of a truly point-like object in a storage ring allows deep understanding of a single-particle dynamics
  - Mandatory basis for a successful implementation of advanced beam control concepts
    - Halo and losses suppression
    - Instabilities suppression
    - Higher beam power
  - Valuable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

More motivation

- Previous single electron studies at IOTA:
  - Longitudinal dynamics
  - Slowly changing mode amplitudes
  - Proof of principle measurement of betatron phases
- Experimental tracking of an electron in a real accelerator opens a new class of accelerator diagnostics with wide range of capabilities. Some are available with conventional tools but with less accuracy. Some are unique, relying on the point-like nature of an electron:
  - Long term tracking of dynamic variables, such as invariants of motion
  - High-precision and high-rep-rate measurements of betatron and synchrotron tunes
  - Chromaticities
  - Dependance of tunes on mode amplitudes

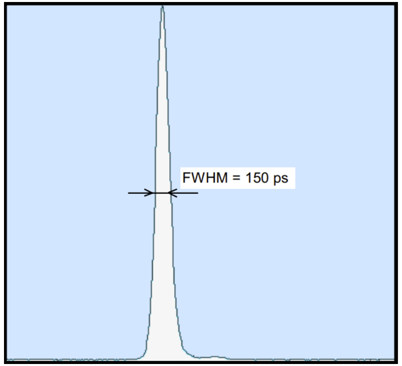
NIO lattice

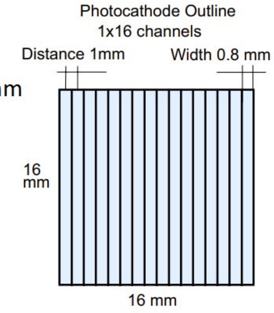
Parameter	Value
Perimeter	39.96 m
Momentum	150 MeV/c
Bunch intensity	1 e^-
RF frequency	30 MHz
RF voltage	350 V
Betatron tunes, (ν_x, ν_y)	(5.2965, 5.3)
Synchrotron tune, ν_s	3.5×10^{-4}
Damping times, (τ_x, τ_y, τ_s)	(2.08, 0.65, 0.24) s
Horizontal emittance, ϵ_x	127 nm
Momentum spread, $\Delta p/p$,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

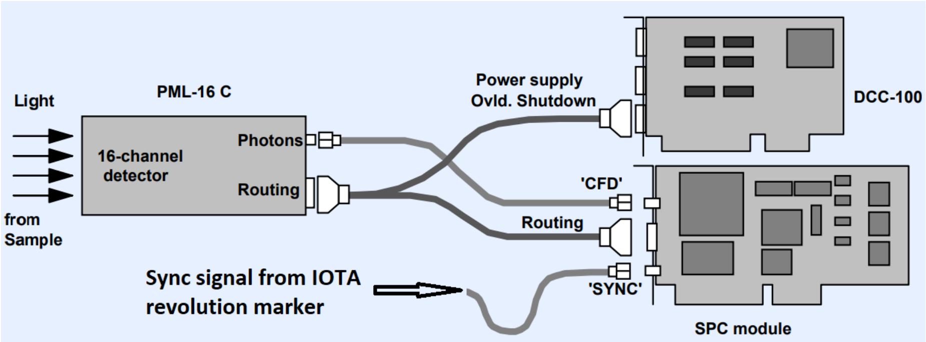


Electron tracking tools

- Two multianode PMTs (PML-16) from the Becker-Hickl were bought for the experiment.
- Dark noise rate from all channels is about 600 Hz
- Time resolution ~0.15 ns
- Two PML-16 must be connected to a Windows PC with ~3 m long cables







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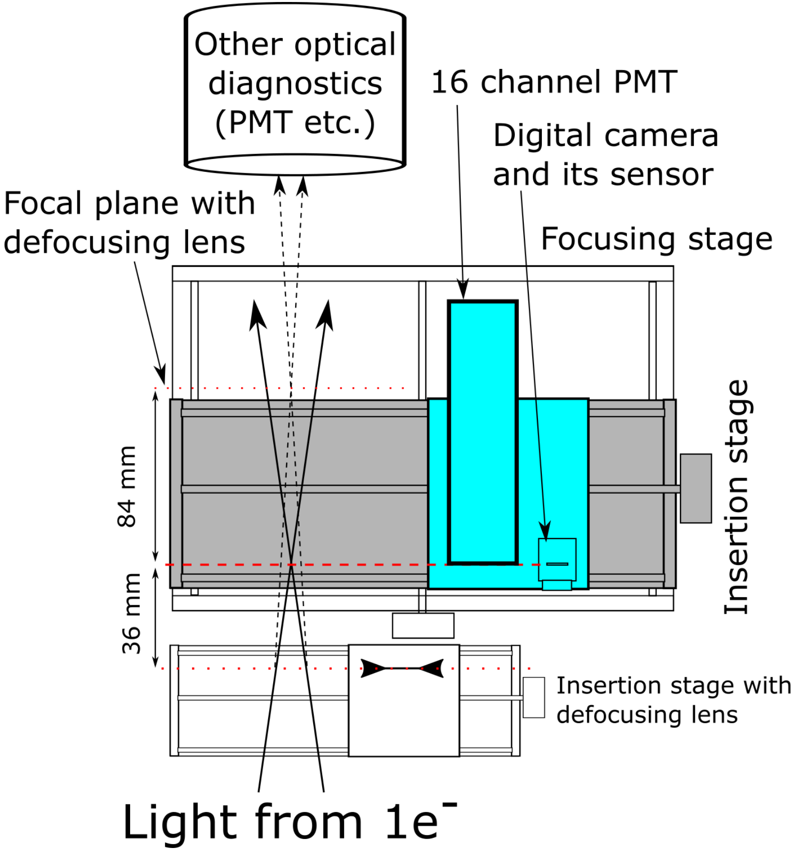
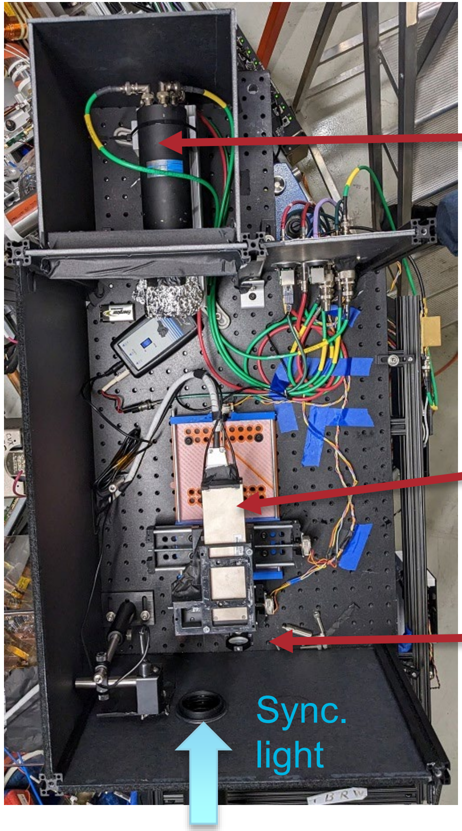
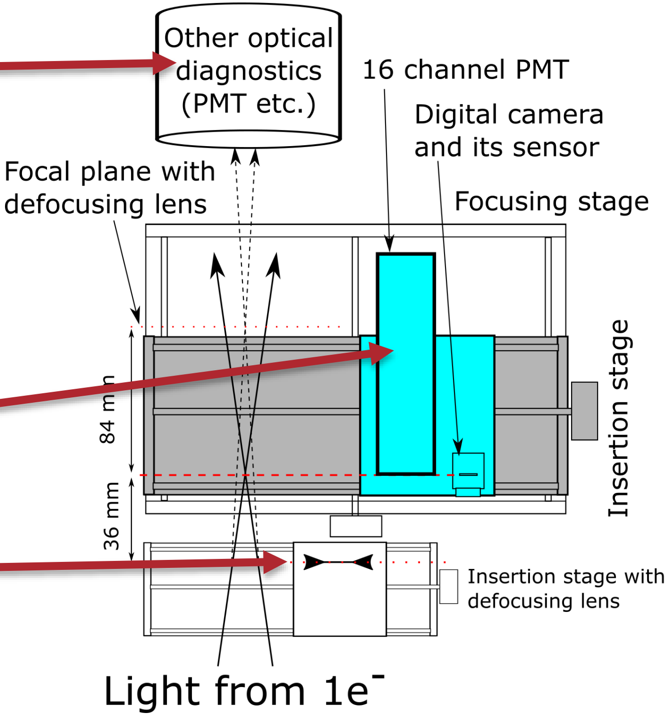
Experimental setup M3L

Both 16ch PMT and a digital camera (blue shaded) are located on a stack of movable stages. Focusing stage can move insertion stage (grey shaded) to position sensors in the focal planes. The insertion stage can position either one of the sensors on axis of the light beam or let the light pass through to other detectors. Additional insertion stage can move a defocusing lens in and out of the photons path changing magnification factor from 88% to 400% which matches beam size to the size of 16ch PMT

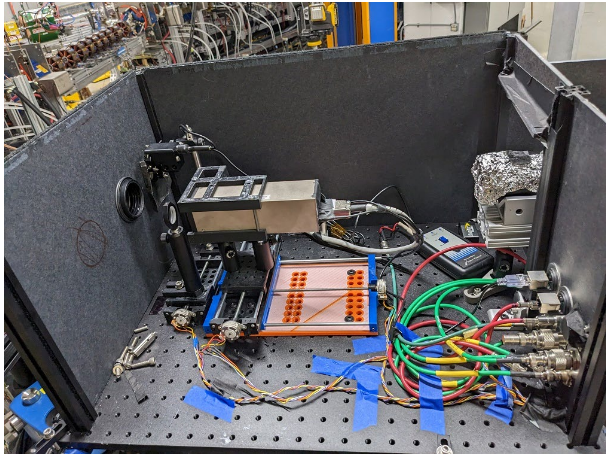


Experimental setup M3L





Side view



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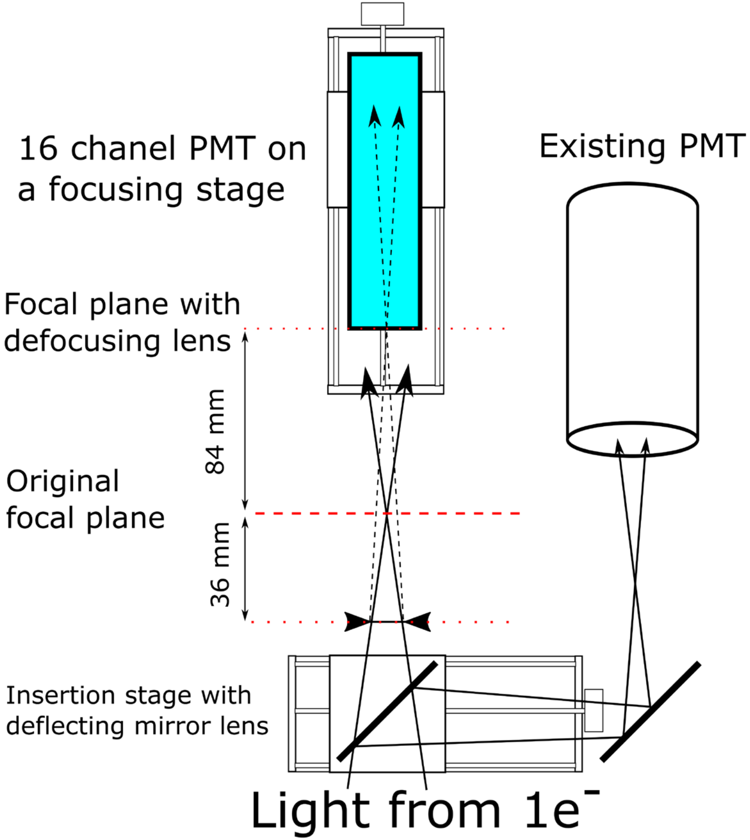
Experimental setup M2L

PML-16 replaces digital camera which also used to verify proper focusing after installation of the fixed magnification lens.

Magnification factor is approximately the same as for M3L station



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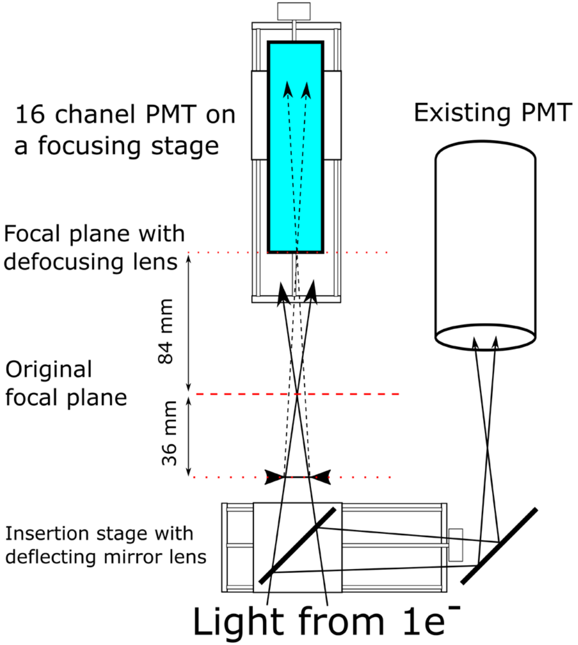
Experimental setup M2L

Setup with camera to focus

Setup with PML-16



Experimental data

- PML-16 record continuous series of data entries for individual photons. Each entry consists of the following:
  - Absolute turn number
  - Detection time within the turn
  - Number of a segment that detected the photon
  - Service information
- Two detectors are synchronized, and each produce a record of its own data series
- Duration of the data recording and fine tuning of signal processing can be controlled with graphical user interface

- On average per one photon:
  - 765 turns for X
  - 677 tuns for Y

Data fit method

- A maximized Fourier amplitude with variable phase advance rate is used to find the phase and tune. A dense brut-force scan over a range of tunes is done to find the best match.

$$x_{real}(n) = 0 + A_{real}\sin[2\pi(\psi_{real}(n) + \psi_{0,real})]$$

$$\psi_{mod}(n) = \sum_{i=1}^{n}\nu(i) \simeq \int_0^n \nu(i)\,di$$

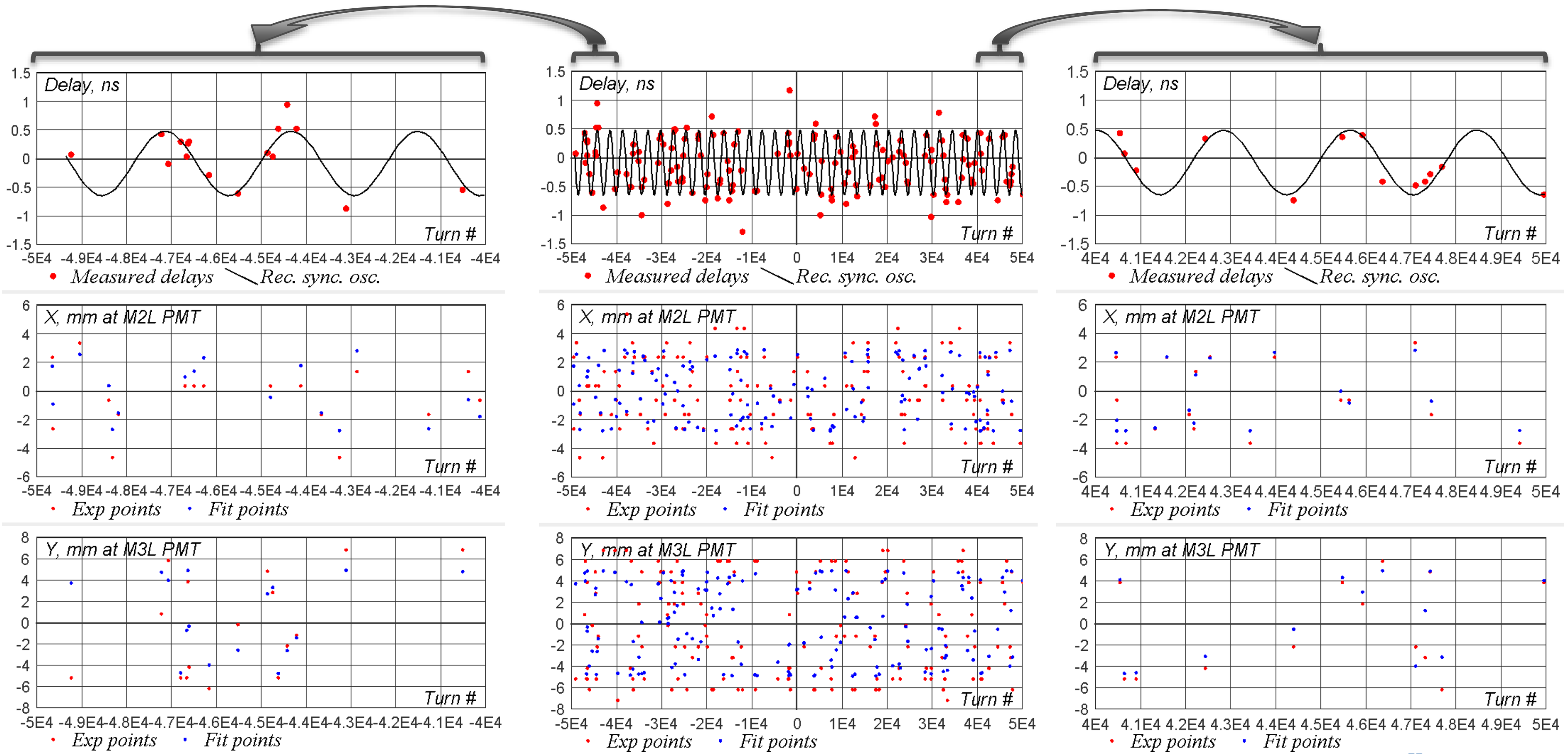
$$\nu(n) = \nu_0 + \nu' n + \sum_k M_k \sin[2\pi(\nu_k n + \psi_k)]$$

$$\psi_{mod}(n) = \nu_0 n + \frac{1}{2}\nu' n^2 + \sum_k \frac{M_k}{2\pi\nu_k}(\cos[2\pi\psi_k] - \cos[2\pi(\nu_k n + \psi_k)])$$

$$S_s = \sum_{n_\gamma} x_{real}(n_\gamma)\sin[2\pi\psi_{mod}(n_\gamma)];\quad S_c = \sum_{n_\gamma} x_{real}(n_\gamma)\cos[2\pi\psi_{mod}(n_\gamma)]$$

$$A_{mod} = \frac{2}{N}\sqrt{S_s^2 + S_c^2};\quad \psi_{0,mod} = \frac{\mathrm{ArcTan}[S_c/S_s]}{2\pi}$$

6D tracking of a single electron (100 000 turns)



Reconstruction accuracy

- The bootstrap method is used to estimate uncertainties:

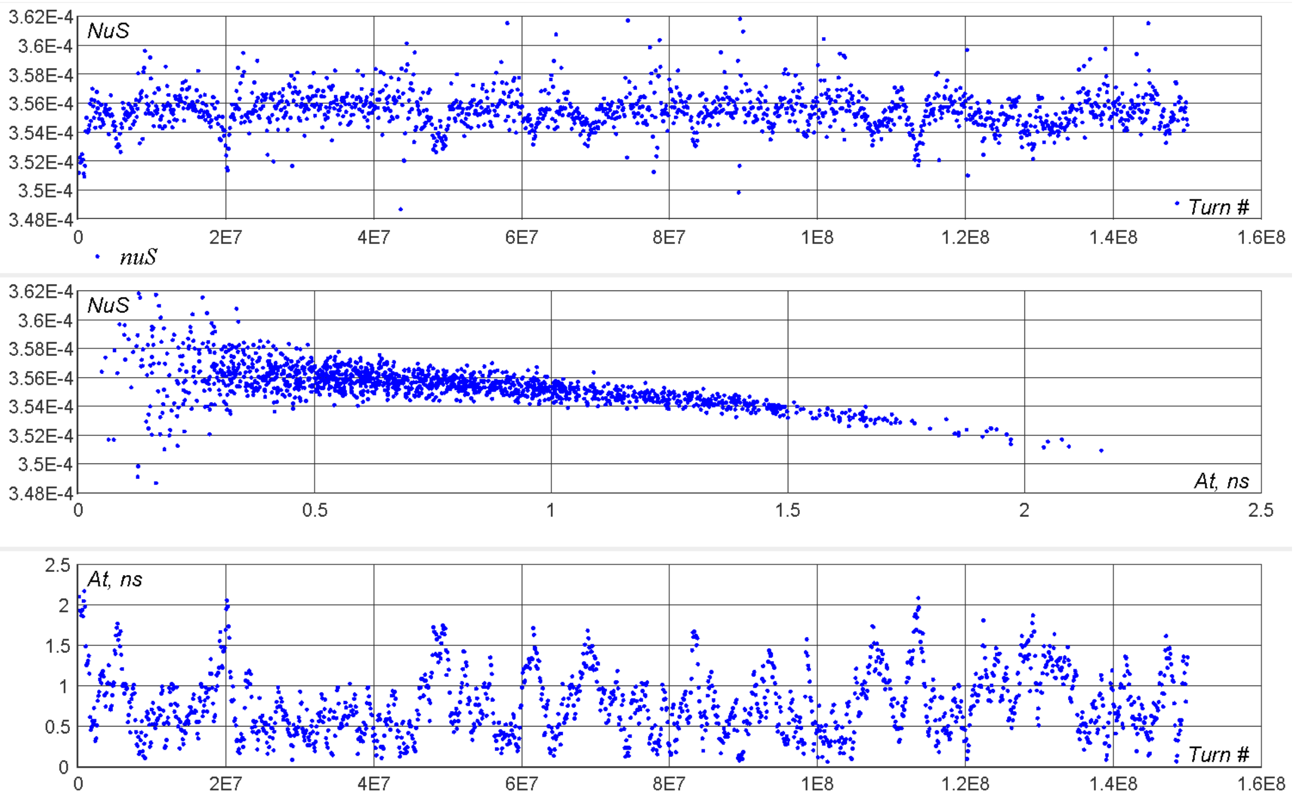
  (For the data streak from the previous slide)

$$x=2.8(2)\ \mathrm{Sin}[2\pi(5.2954305(3)+0.19(1))]$$

$$y=4.9(5)\ \mathrm{Sin}[2\pi(5.3015235(5)-0.351(15))]$$

10^{-7} !

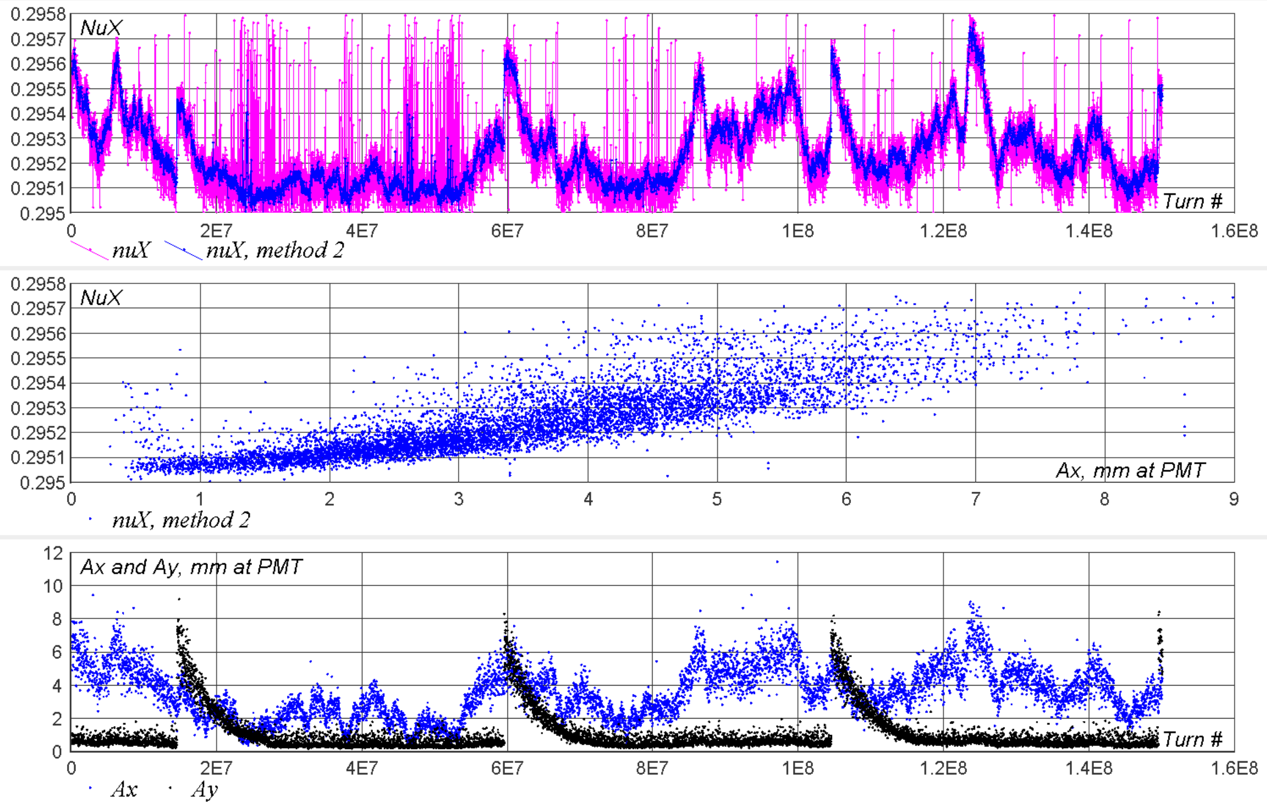
Synchrotron oscillations over 20 seconds



100k turns per point

Sync period 2800 turns

Horizontal oscillations over 20 seconds



15k turns per point

50k turns per point with grid interference removed

Vertical kick every 6 seconds

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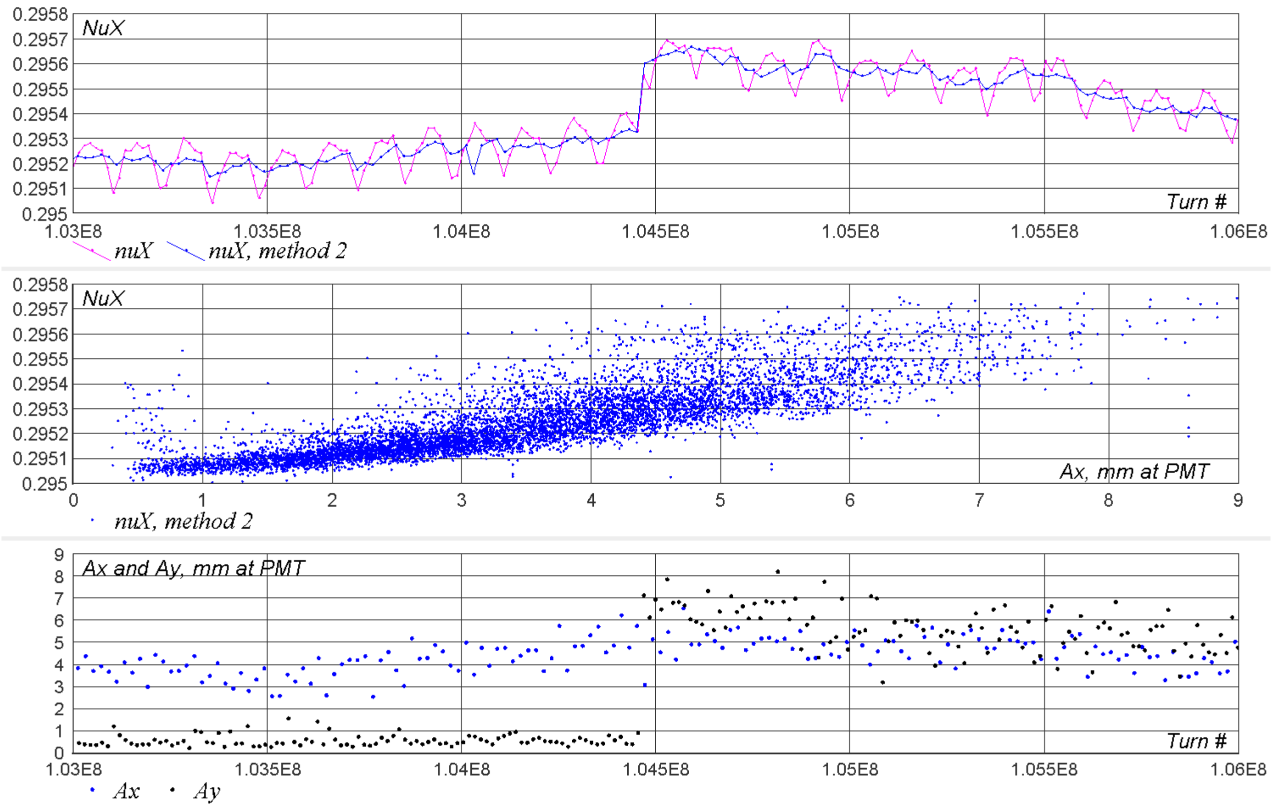
Horizontal oscillations over 20 seconds



NuX dependson Ay

Clear grid ripple on 60, 120 and 180 Hz

Amplitudes are quite noisy, way more than pixel width:
poor focusing?

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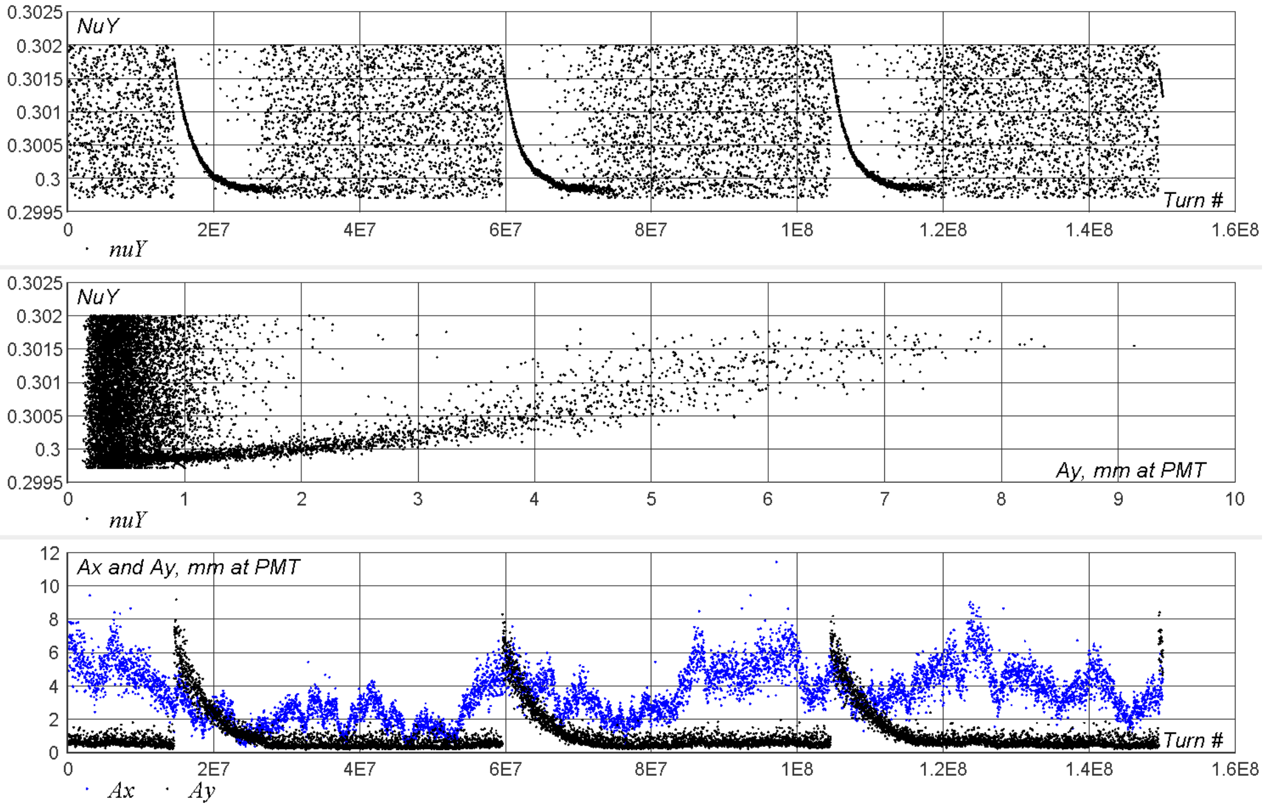
Horizontal oscillations over 20 seconds



15k turns per point

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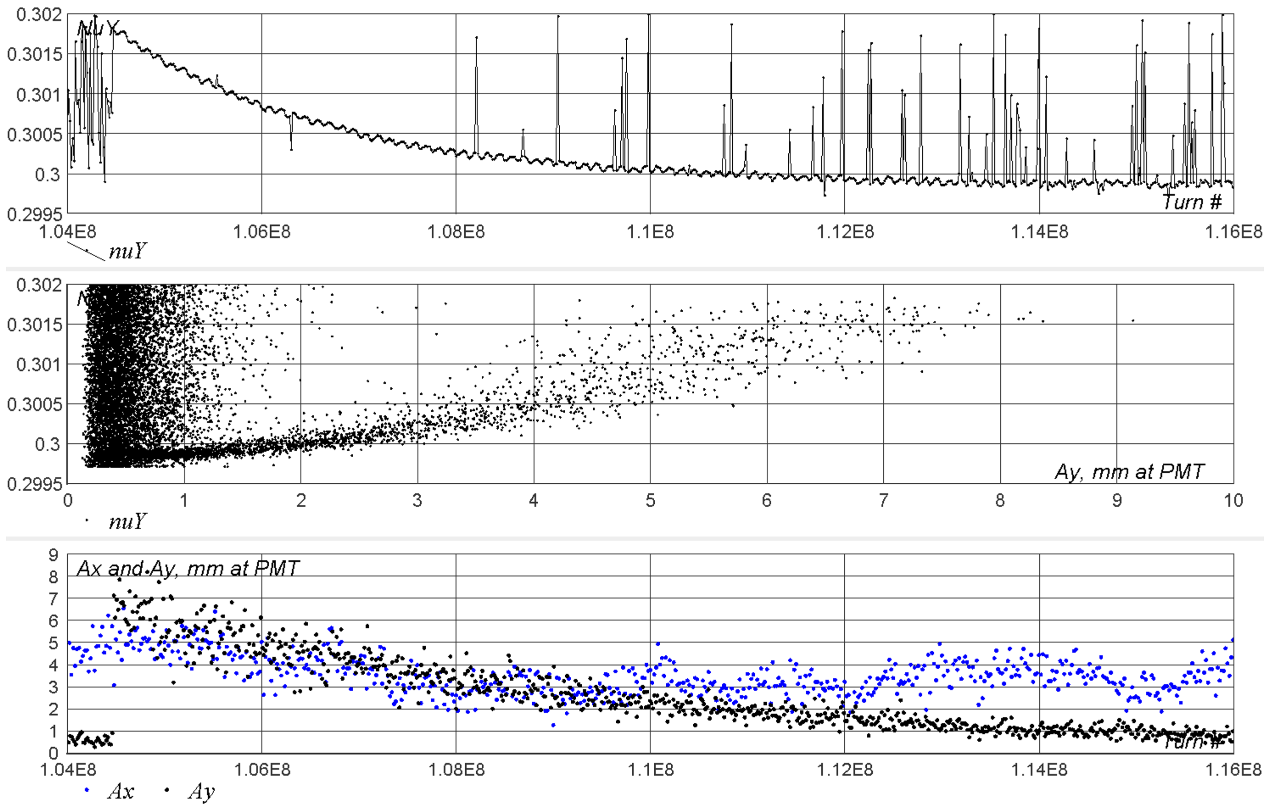
Horizontal oscillations over 20 seconds



Smaller grid ripple

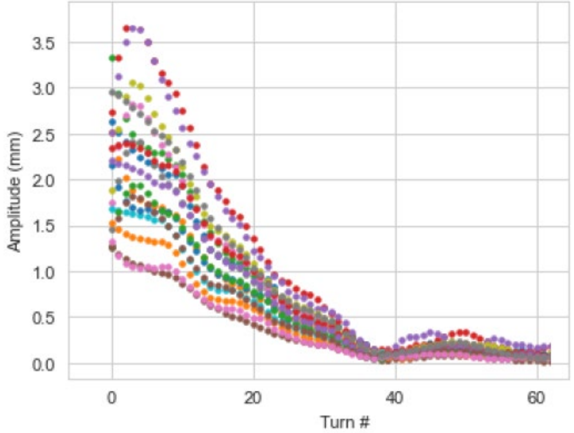
Grid ripple is ~45 degrees off phase with that in X plane:
more than 1 source shifted in phase.

A 6D tracking for non-linear lattices

The ultimate 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
  - – Sparce 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

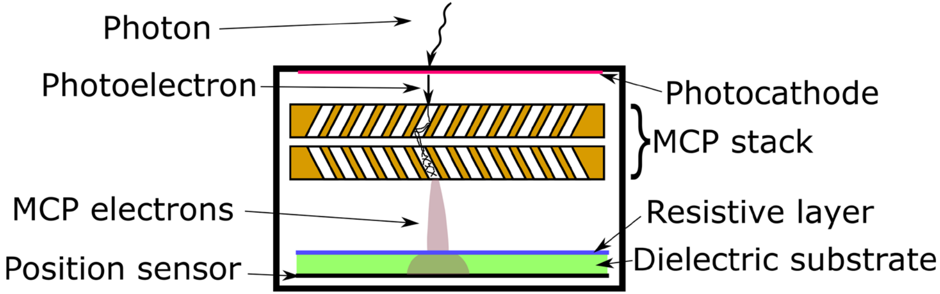
Turn-by-turn beam coordinates in the IOTA ring with a non-linear lattice, each color correspond to a specific BPM.



Future of the 6D 1e- tracking

LDRD grant was approved to demonstrate full 6D tracking of a single electron at IOTA, which was achieved as presented here.

- The first stage studies of 6D tracking conducted during run-4 at IOTA
  - Two 16-channel PMTs were used to track electron with limited resolution
- The second stage studies will rely on MCP based detectors
  - Single photon sensitivity with quantum efficiency of 15-20%@500nm
  - Spatial resolution of 30-50 um
  - Temporal resolution of 200-300 ps
  - True 2D resolution with sensitivity to coupling



Available data from Run-4

- 8 shifts with data acquisition (some opportunistic when macroscopic injections were not possible or with leftover beam).
- 3 dedicated accesses for installation and several opportunistic accesses for quick fixes and checks.

- Scan of DN insert from t=0 to t=0.5 (integer resonance)
- Several longer data sets with 120 seconds of data
- Electron on the coupling resonance
- Data files with 2 and 3 electrons, in some cases stored in different separatrices

Summary

- SETI experiment demonstrated complete 6D single electron tracking
- When fully automated, the developed instruments will be very useful for lattice tuning
- Analysis is ongoing with the ultimate goal of tracking a single electron in a strongly nonlinear system
- 2D area detectors with good spatiotemporal resolution will farther boost capabilities of the lattice diagnostics with a single electron tracking