# Study of Fluctuations in Undulator Radiation in the IOTA Ring at Fermilab

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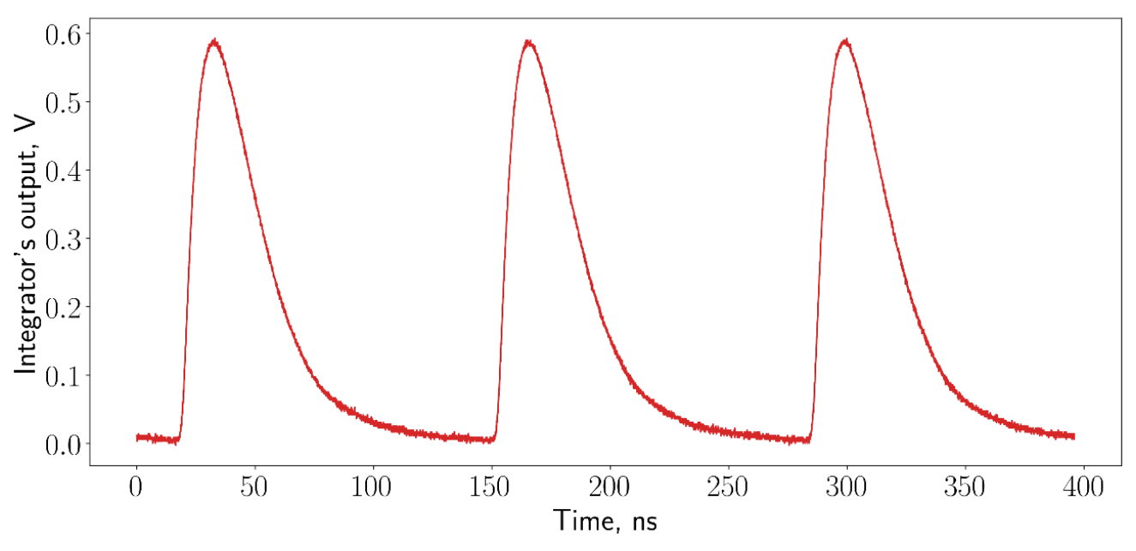
## Abstract:

We study turn-by-turn fluctuations in the number of emitted photons in an undulator, installed in the IOTA electron storage ring at Fermilab, with an InGaAs PIN photodiode and an integrating circuit. In this paper, we present a theoretical model for the experimental data from previous similar experiments and in our present experiment, we attempt to verify the model in an independent and a more systematic way. Moreover, in our experiment we consider the regime of very small fluctuation when the contribution from the photon shot noise is significant, whereas we believe it was negligible in the previous experiments. Accordingly, we present certain critical improvements in the experimental setup that let us measure such a small fluctuation.

## #1 Experiment idea

- We installed an undulator in the IOTA ring (late Feb).

- And built an integrating circuit for the photodiode's current. The amplitude of the output voltage was proportional to the number of photoelectrons generated in the photodiode.

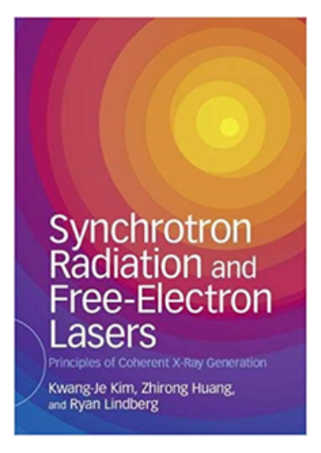


- In the experiment (late Mar), we studied the fluctuation in the number of photoelectrons, namely, the variance:

$$\mathrm{var}(\mathcal{N})=\langle\mathcal{N}^2\rangle-\langle\mathcal{N}\rangle^2$$

### Theoretical prediction

[2] Page 28:



$$\mathrm{var}(\mathcal{N}_{\mathrm{ph}})=\langle\mathcal{N}_{\mathrm{ph}}\rangle+\frac{1}{M}\langle\mathcal{N}_{\mathrm{ph}}\rangle^2$$

Discrete quantum nature of light

Chaotic light. Incoherent sum over randomly phased electrons

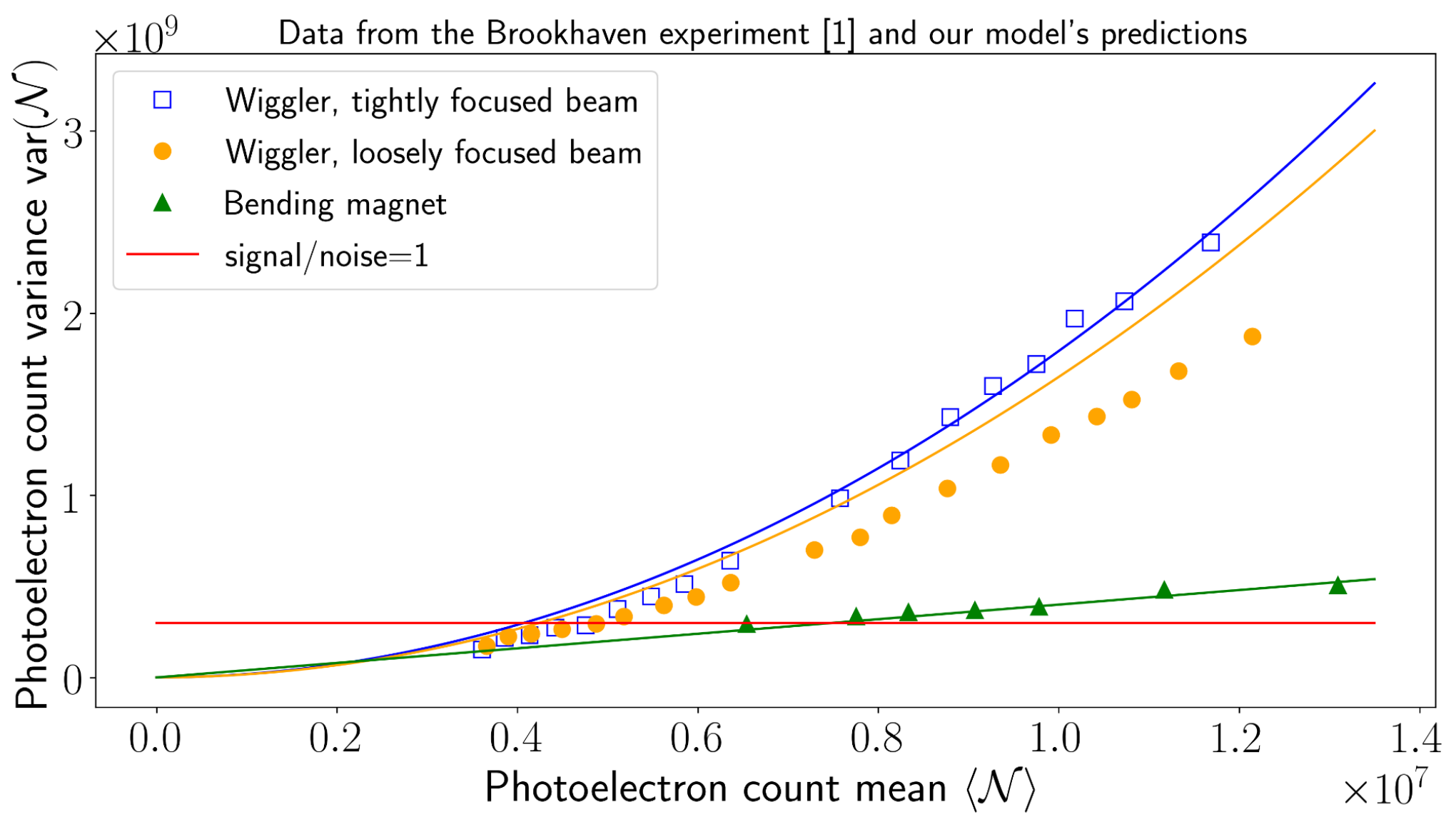
In our experiment:

- #1 Wide band, large solid angle, high QE=80%
- #2 The two terms are comparable
- #3 RMS fluctuation ~ $10^{-4}-10^{-3}$

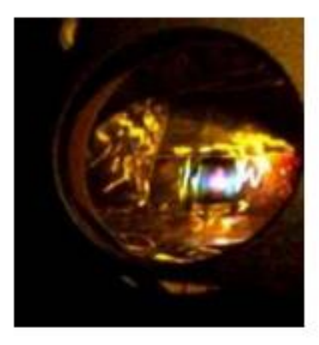
$$\frac{d\mathcal{N}^{(1)}_{\mathrm{q.c.}}}{d\boldsymbol{k}}=\eta_{\boldsymbol{k}}I^{(1)}_{\boldsymbol{k}}$$

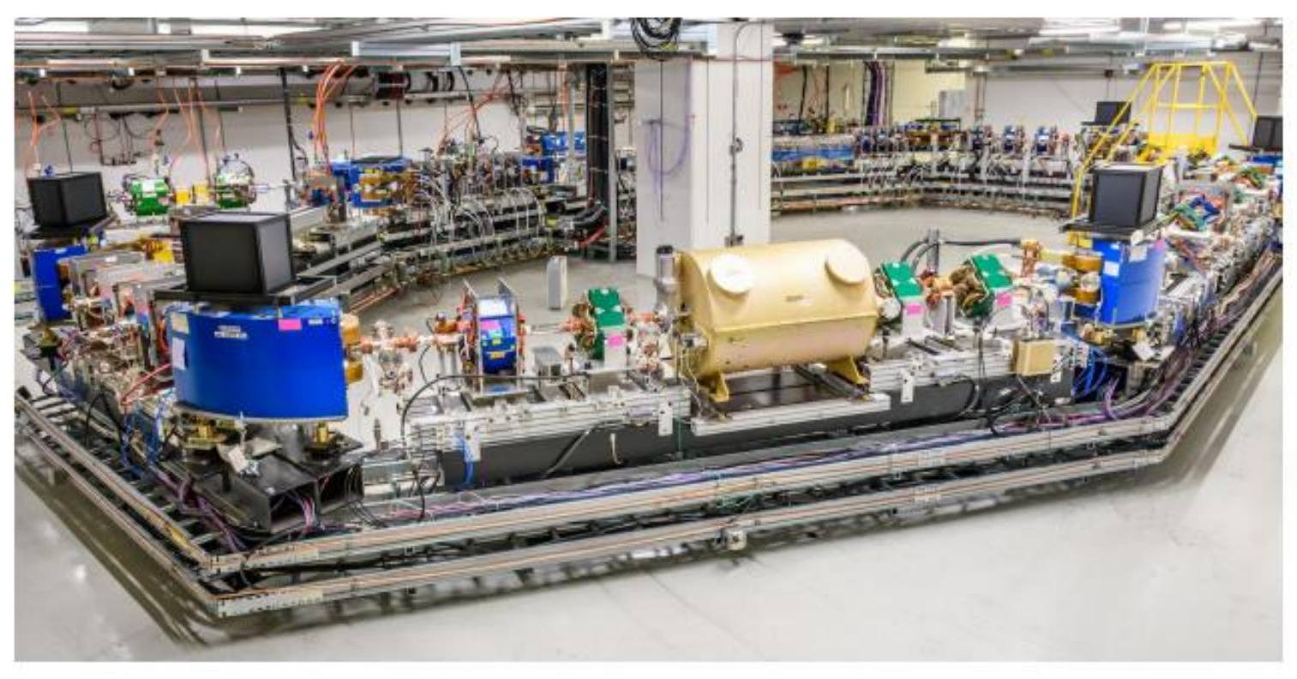
[3]

$$\frac{1}{M}\equiv\frac{\mathrm{var}(\mathcal{N}_{\mathrm{q.c.}})}{\langle\mathcal{N}_{\mathrm{q.c.}}\rangle^2}=\frac{\frac{\sqrt{\pi}}{\sigma_z}\int dkd\Omega_1d\Omega_2k^4\eta_{k\boldsymbol{n}_1}I^{(1)}_{k\boldsymbol{n}_1}\eta_{k\boldsymbol{n}_2}I^{(1)}_{k\boldsymbol{n}_2}e^{-k^2\sigma_x^2(\theta_{1x}-\theta_{2x})^2-k^2\sigma_y^2(\theta_{1y}-\theta_{2y})^2}}{\left(\int d\boldsymbol{k}\eta_{\boldsymbol{k}}I^{(1)}_{\boldsymbol{k}}\right)^2}$$



## #2 Experiment layout. Main parameters





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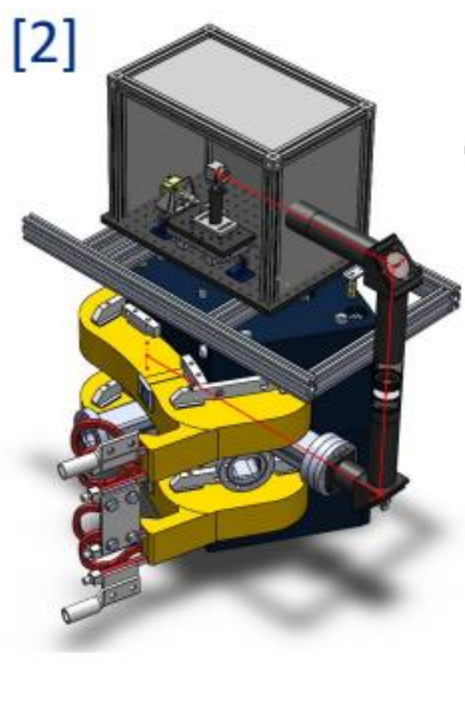
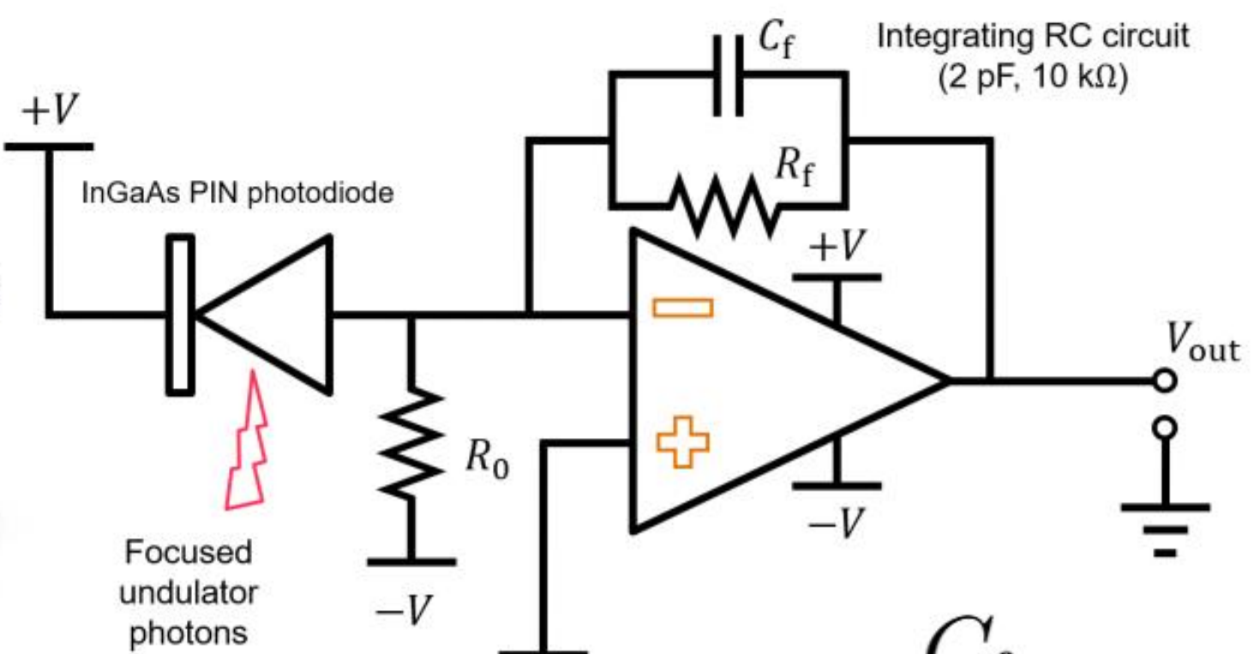
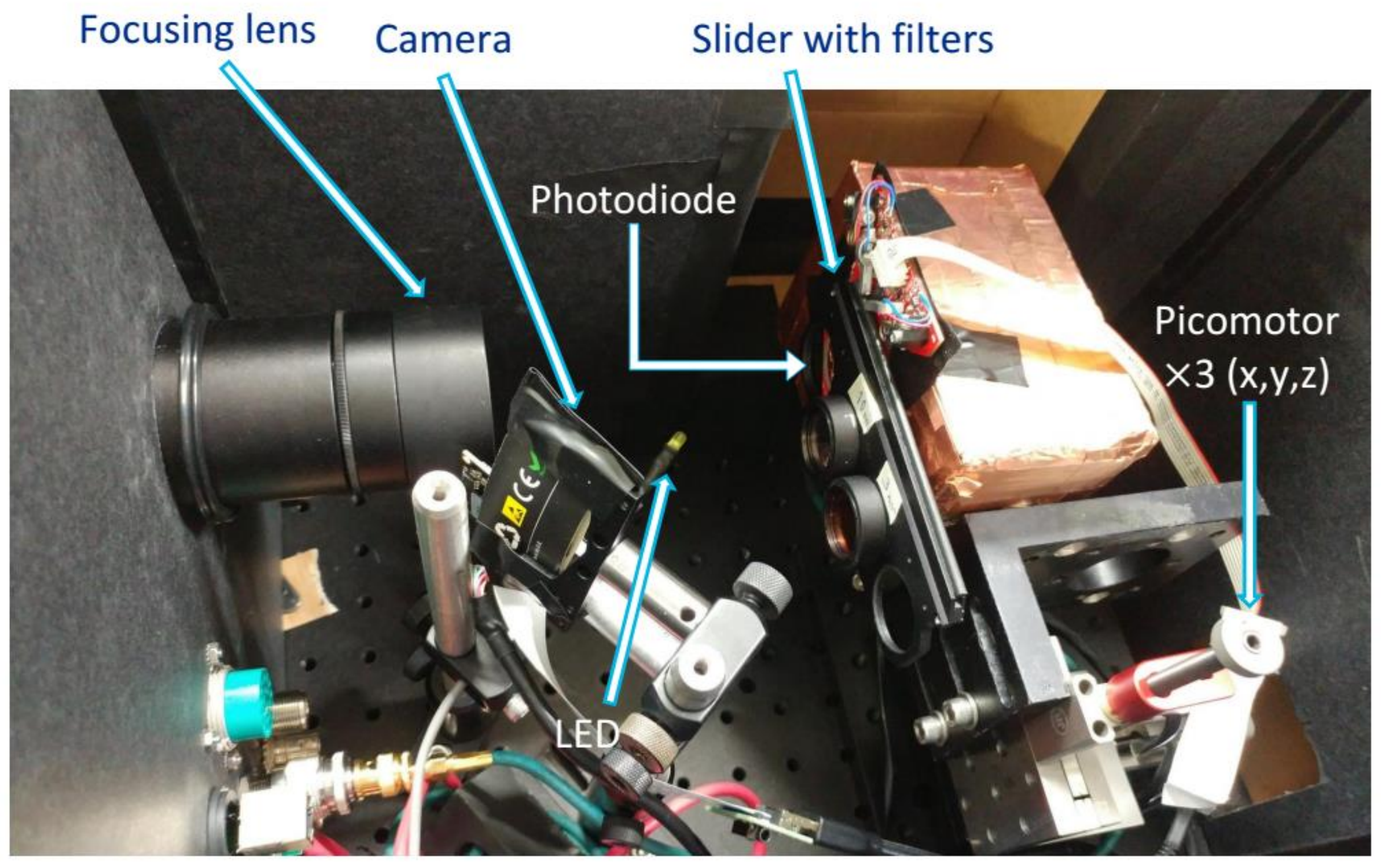


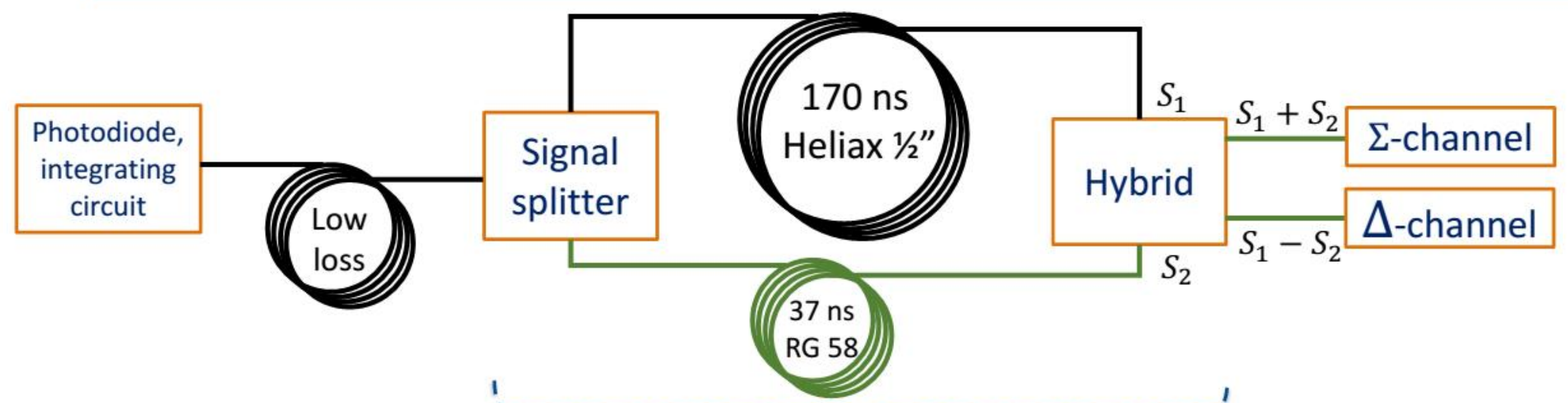


$$\mathcal{N}=\frac{C_\mathrm{f}}{e}A$$



| | |
|---|---|
| IOTA circumference | 40 m (133 ns) |
| Beam energy | 100 MeV |
| Max average current | 4.0 mA |
| $\epsilon_x$, $\epsilon_y$ | 0.32 μm, 31 nm |
| $\sigma_p$ | $3.1\times10^{-4}$ |
| $\beta_x$, $\beta_y$ | 1.82 m, 1.75 m |
| $D_x$, $D_y$ | 0.87 m, 0 m |
| $\sigma_x$, $\sigma_y$ | 815 μm, 75 μm |
| $\sigma_z$ | 38 cm |
| Rad. damping rates $1/\tau_x$, $1/\tau_y$ | $0.336\,\mathrm{s}^{-1}$, $0.852\,\mathrm{s}^{-1}$ |
| $1/\tau_p$ | $2.22\,\mathrm{s}^{-1}$ |
| Undulator parameter $K_\mathrm{u}$ | 1.0 |
| Undulator period | 55 mm |
| Number of undulator periods | 10 |
| Fundamental harmonic wavelength | 1077 nm |
| Photodiode diameter | 1 mm |
| Quantum efficiency @1077 nm | 80 % |
| Beam lifetime | > 10 min |

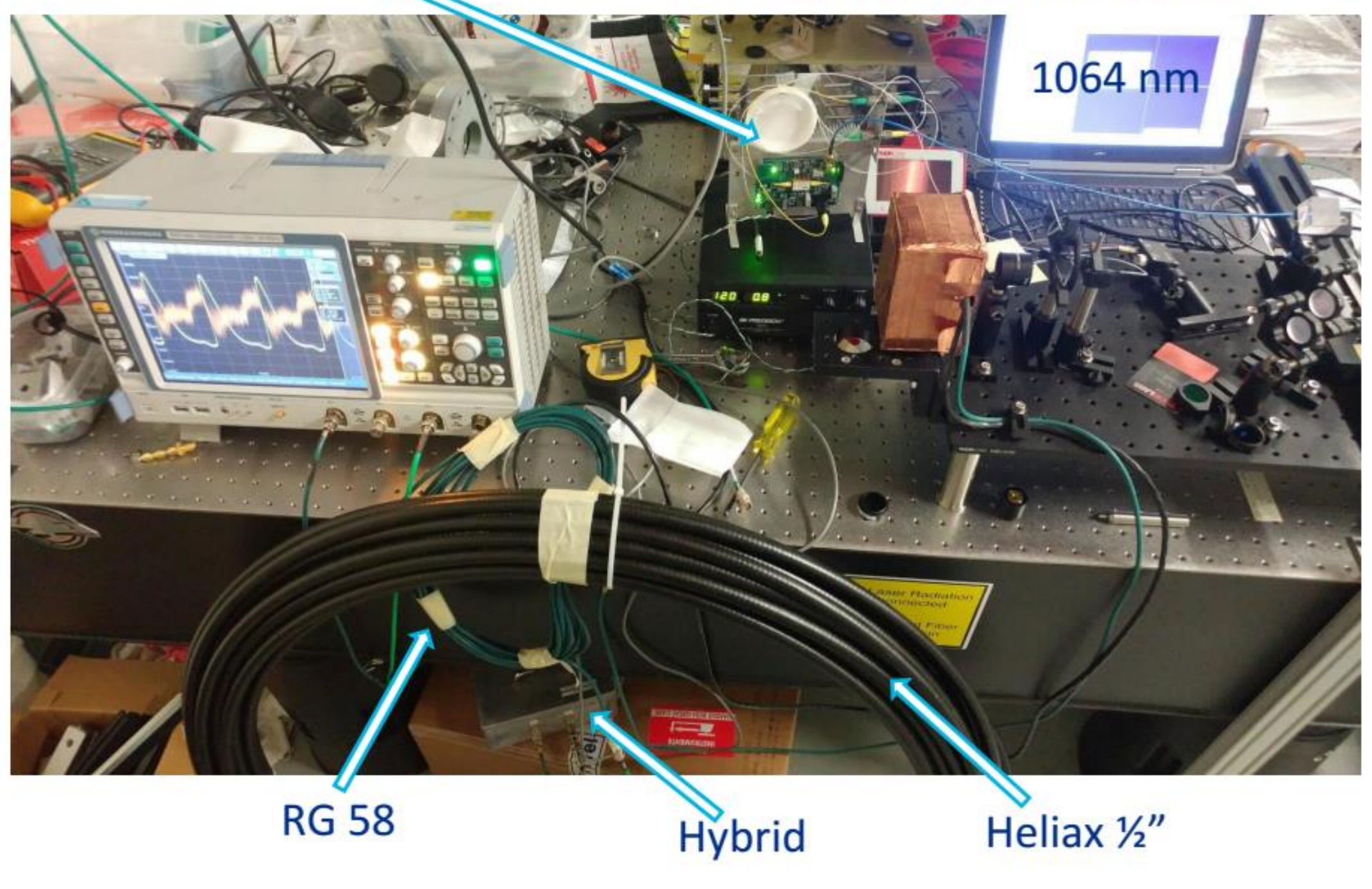
## #3 Comb filter. Testing the setup



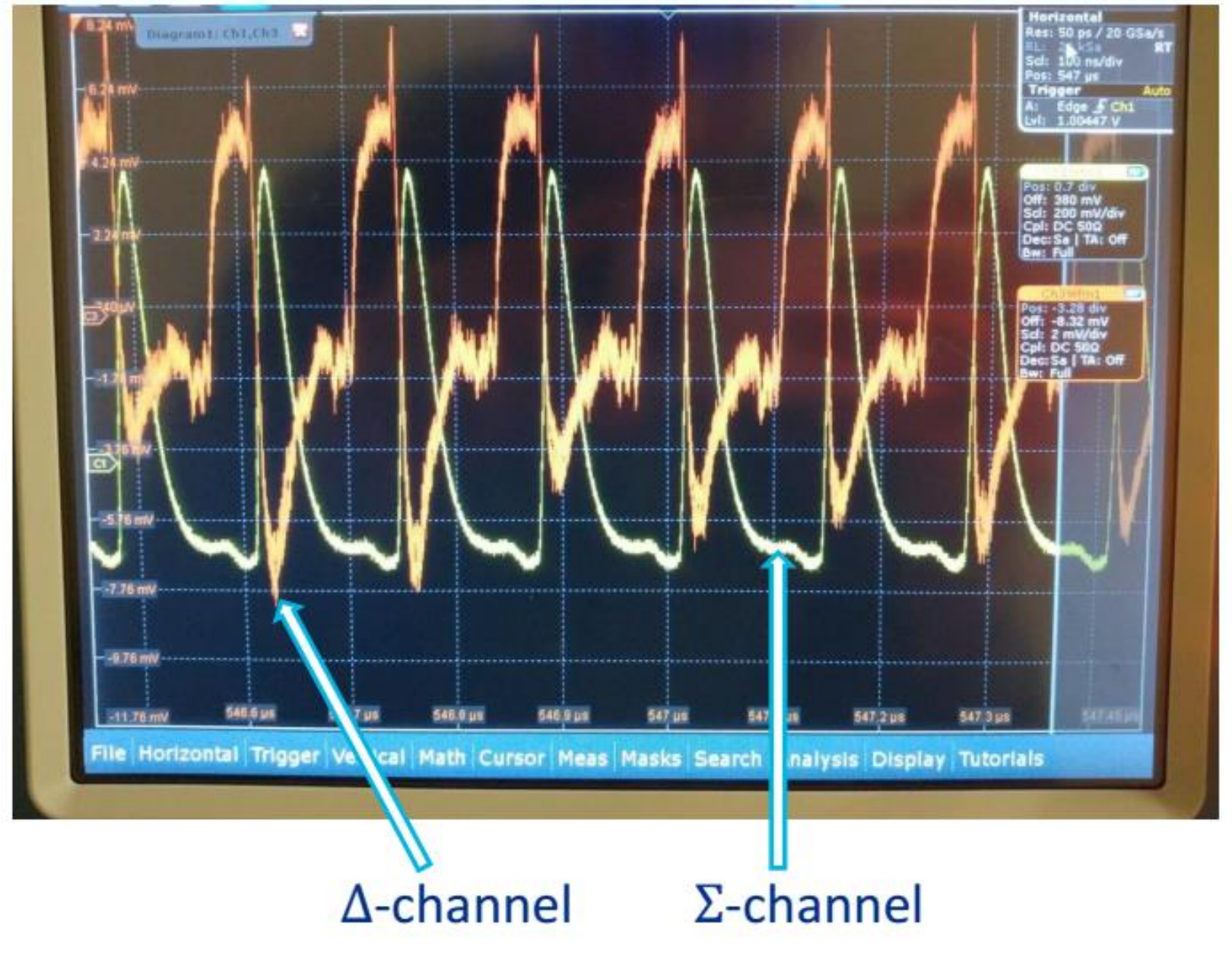
Test light source (modulated laser diode)

Exactly one IOTA revolution (133 ns) delay between the two cables:

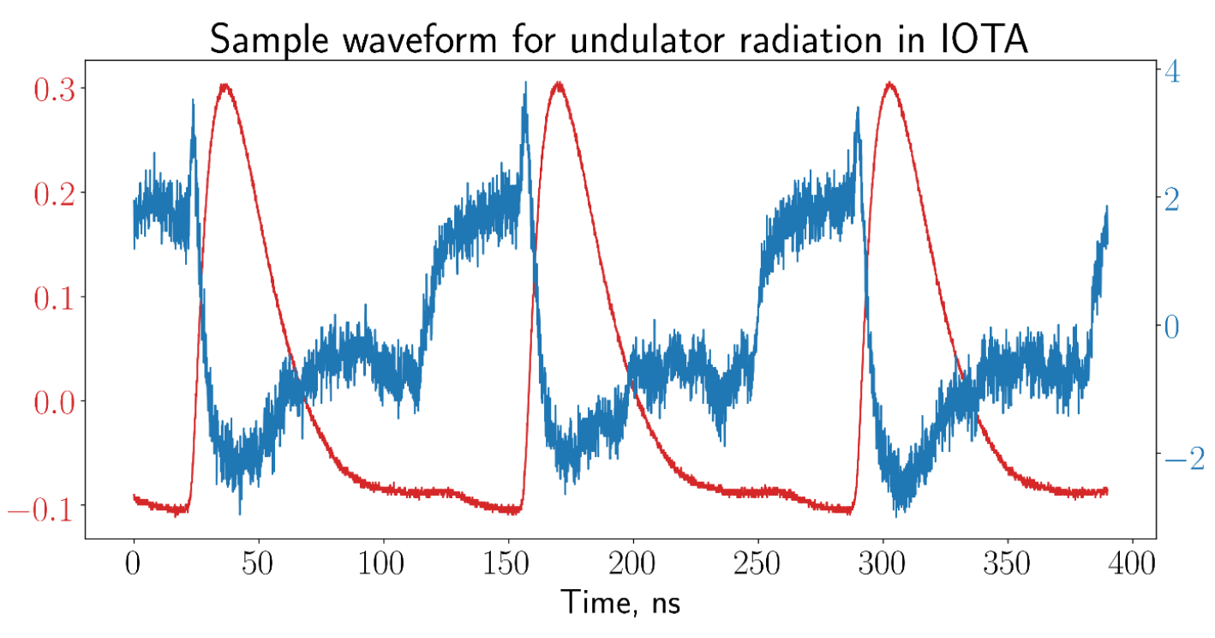
$$S_1=(1+\delta_1)S(t)$$
$$S_2=(1+\delta_2)S(t)$$
$$\Sigma=S_1+S_2\approx2S(t)$$
$$\Delta=S_1-S_2=(\delta_1-\delta_2)S(t)$$
$$A=(1+\delta)S(t_{\max})$$
$$\mathrm{var}(\delta_1-\delta_2)=2\mathrm{var}(\delta)$$
$$\mathrm{var}(A)=\mathrm{var}(\Delta(t_{\max}))/2$$



One dataset is 1.5 ms (~11000 turns)



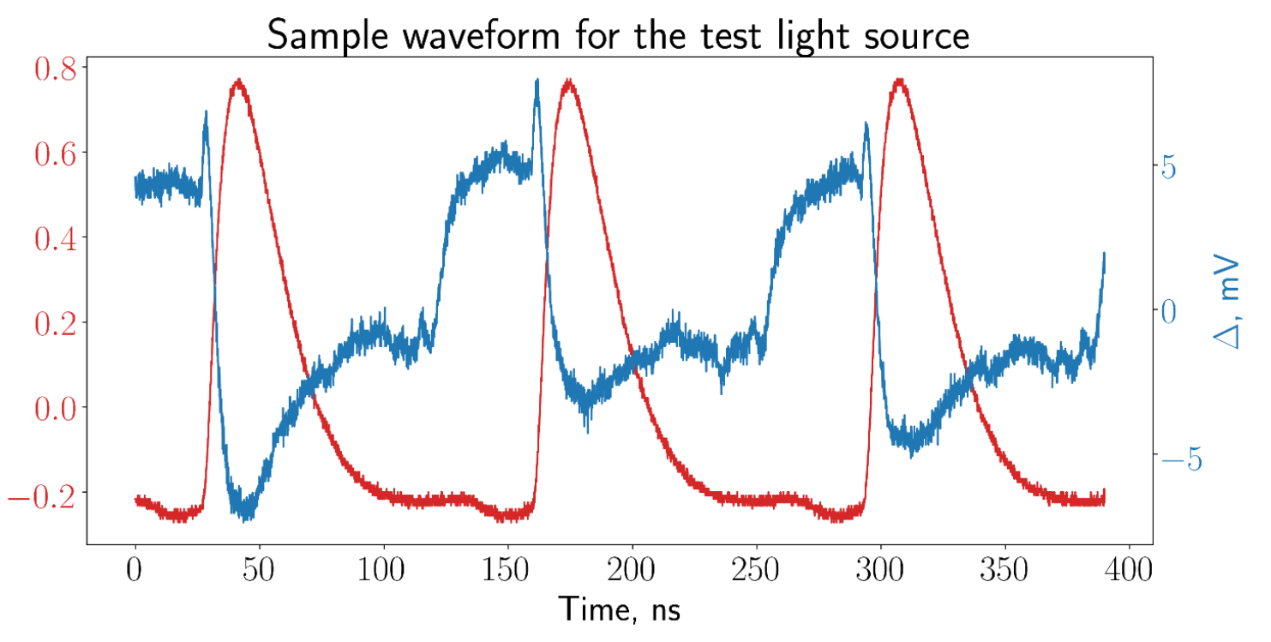
## #4 Testing the setup. Finding the setup's precision



Main sources of noise:

- The oscilloscope 1mV peak-to-peak
- The integrator's op-amp 1.5mV peak-to-peak (together with the scope)

Total RMS noise: ≈ 0.3mV



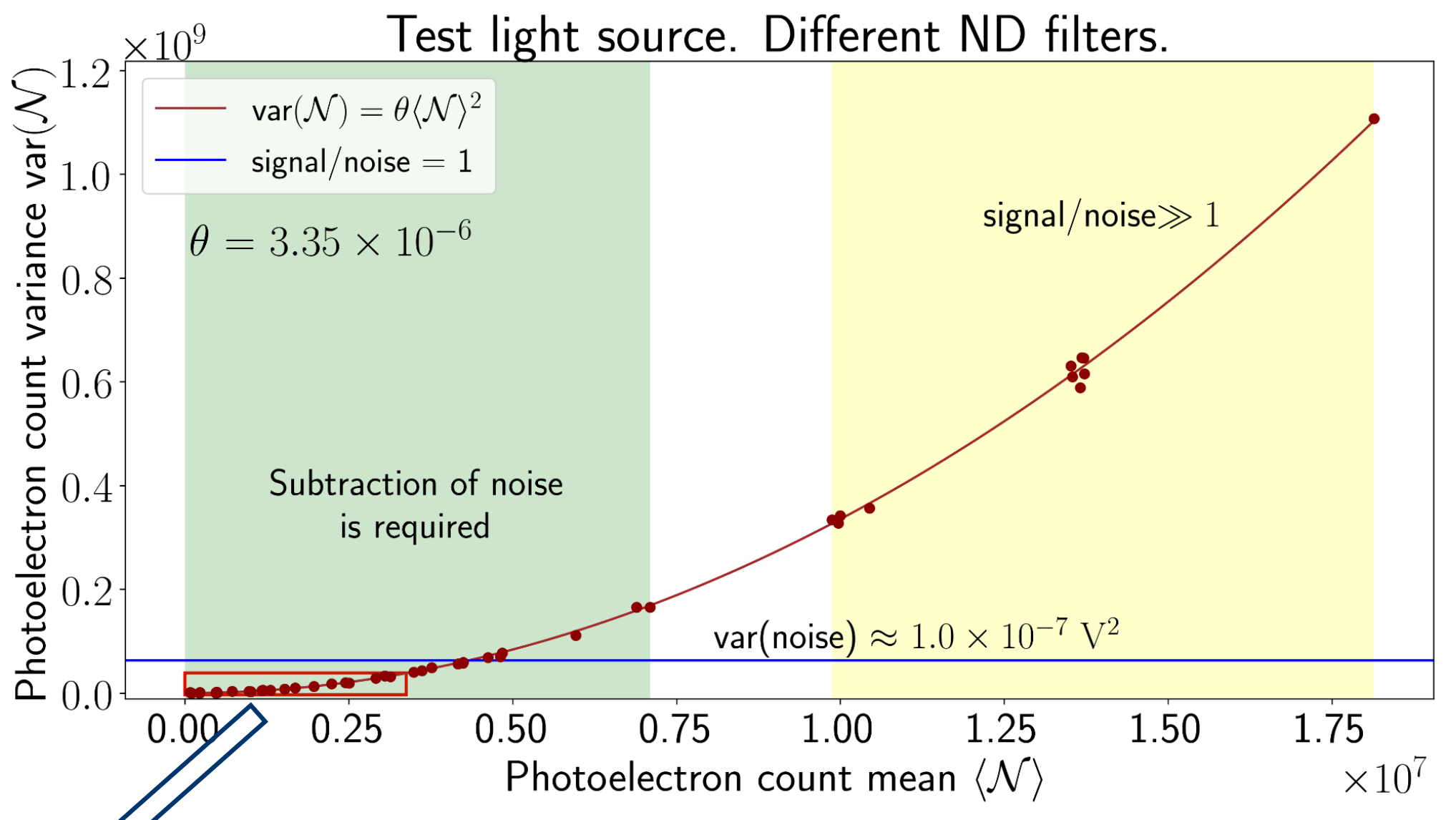
Noise subtraction algorithm:

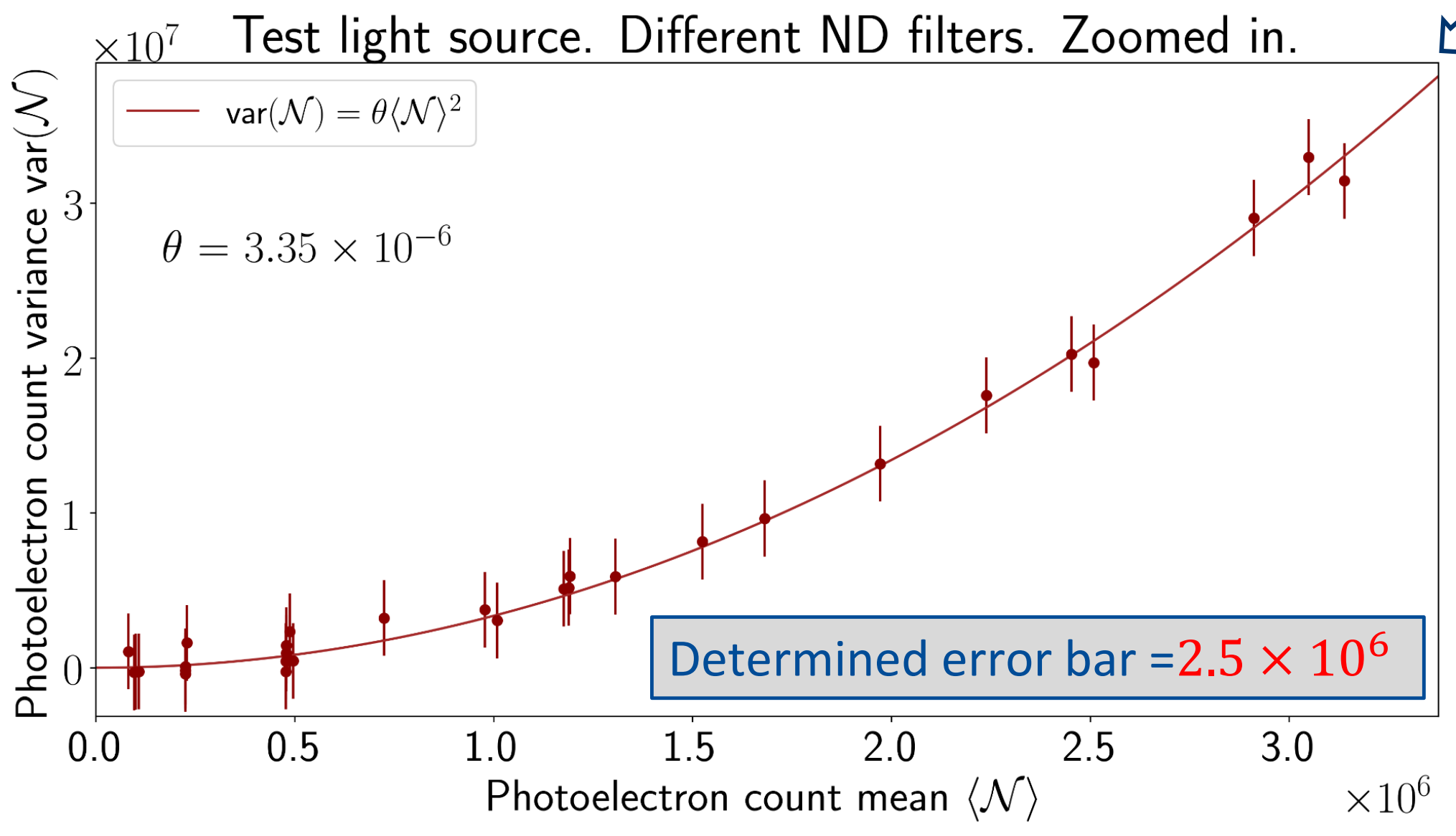
- #1 Find the period with high accuracy (>7 figures)
- #2 Map all Δ-channel data to one period
- #3 Bin the data along the time axis
- #4 Take variance of Δ-channel in each bin:

$$\Delta(t)=(\delta_1-\delta_2)S(t)+\mathrm{noise}$$

@ fixed t

$$\boxed{\mathrm{var}(\Delta(t))=2\mathrm{var}(\delta)S^2(t)+\underbrace{\mathrm{var}(\mathrm{noise})}_{\text{const}}}$$





Determined error bar =$2.5\times10^6$

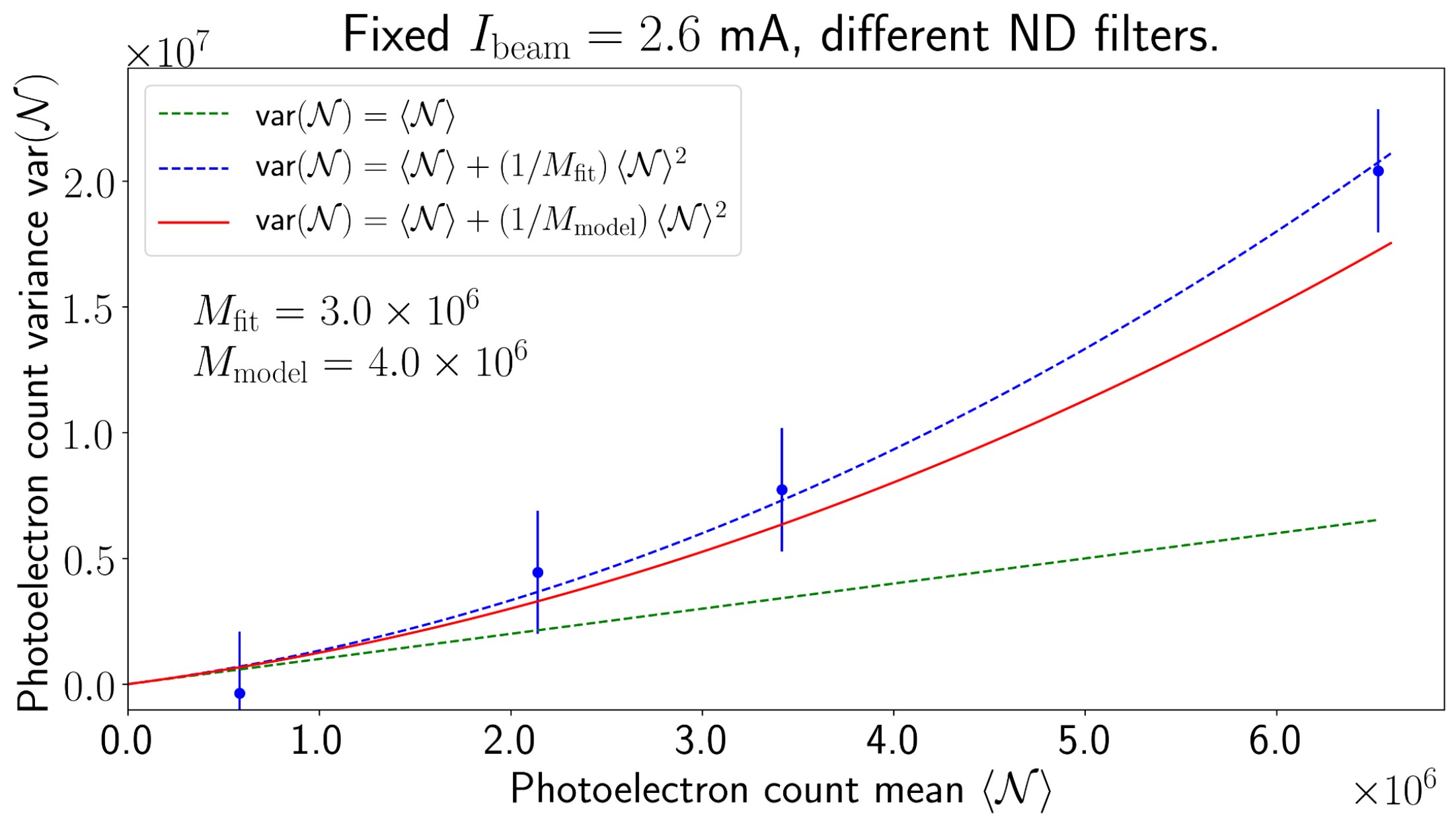
Detector test idea:

Keep the test light source in the same regime and use different ND filters. Then, relative classical fluctuation (due to pulse generator errors) must stay the same:

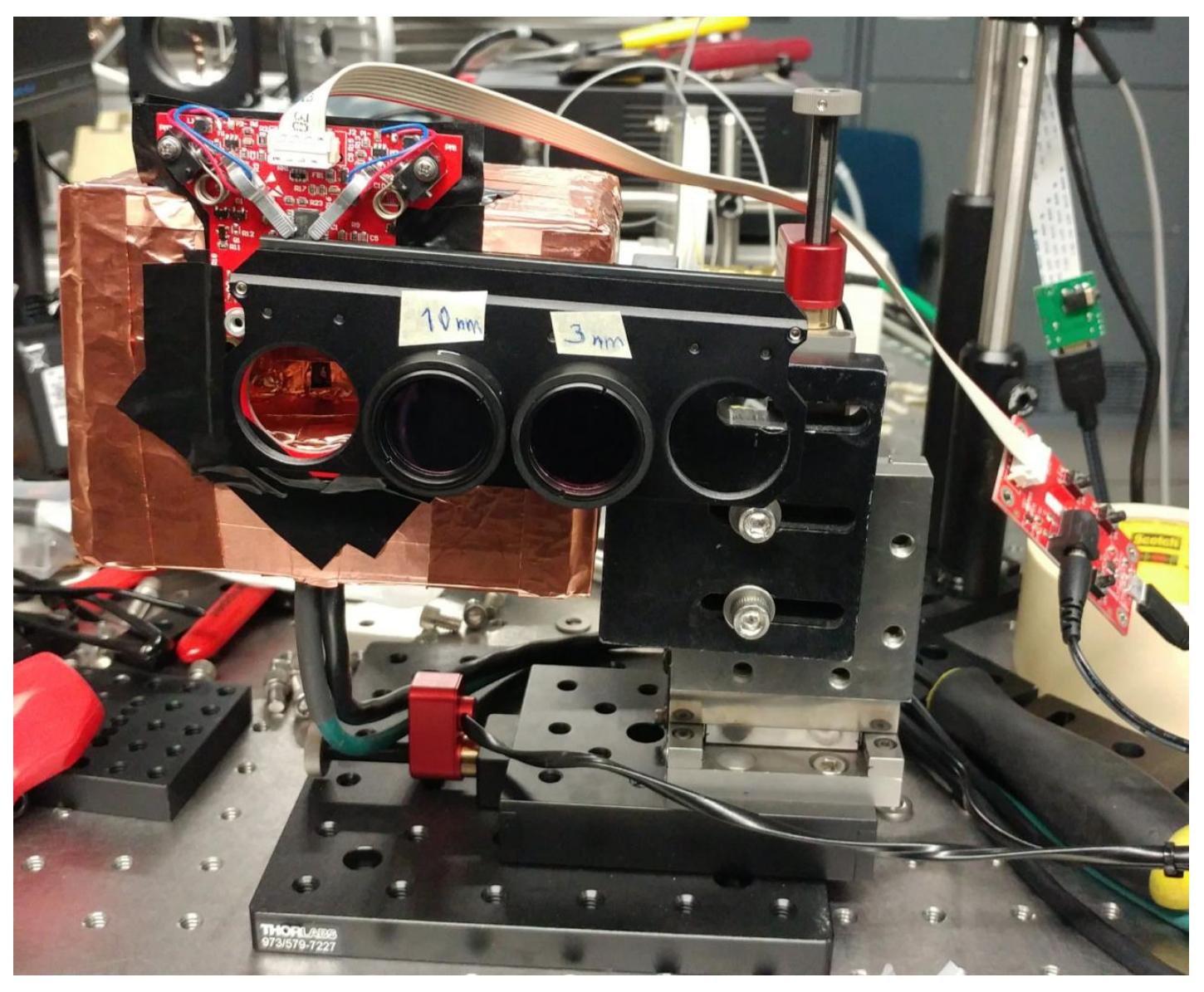
$$\frac{\mathrm{var}(A)}{\langle A\rangle^2}=\frac{\mathrm{var}(\mathcal{N})}{\langle\mathcal{N}\rangle^2}=\theta=const$$

- $\theta$ is determined at large $\langle A\rangle$, when signal/noise≫ 1.
- Poisson contribution was negligible.

## #5 Measurement results for undulator radiation in IOTA



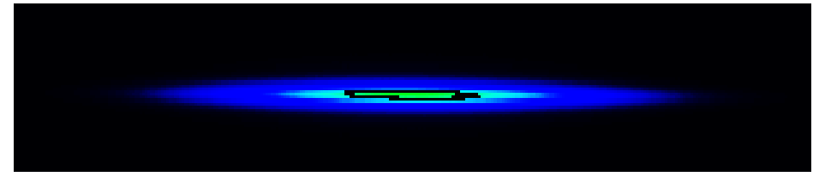
Decreasing optical density of the filters

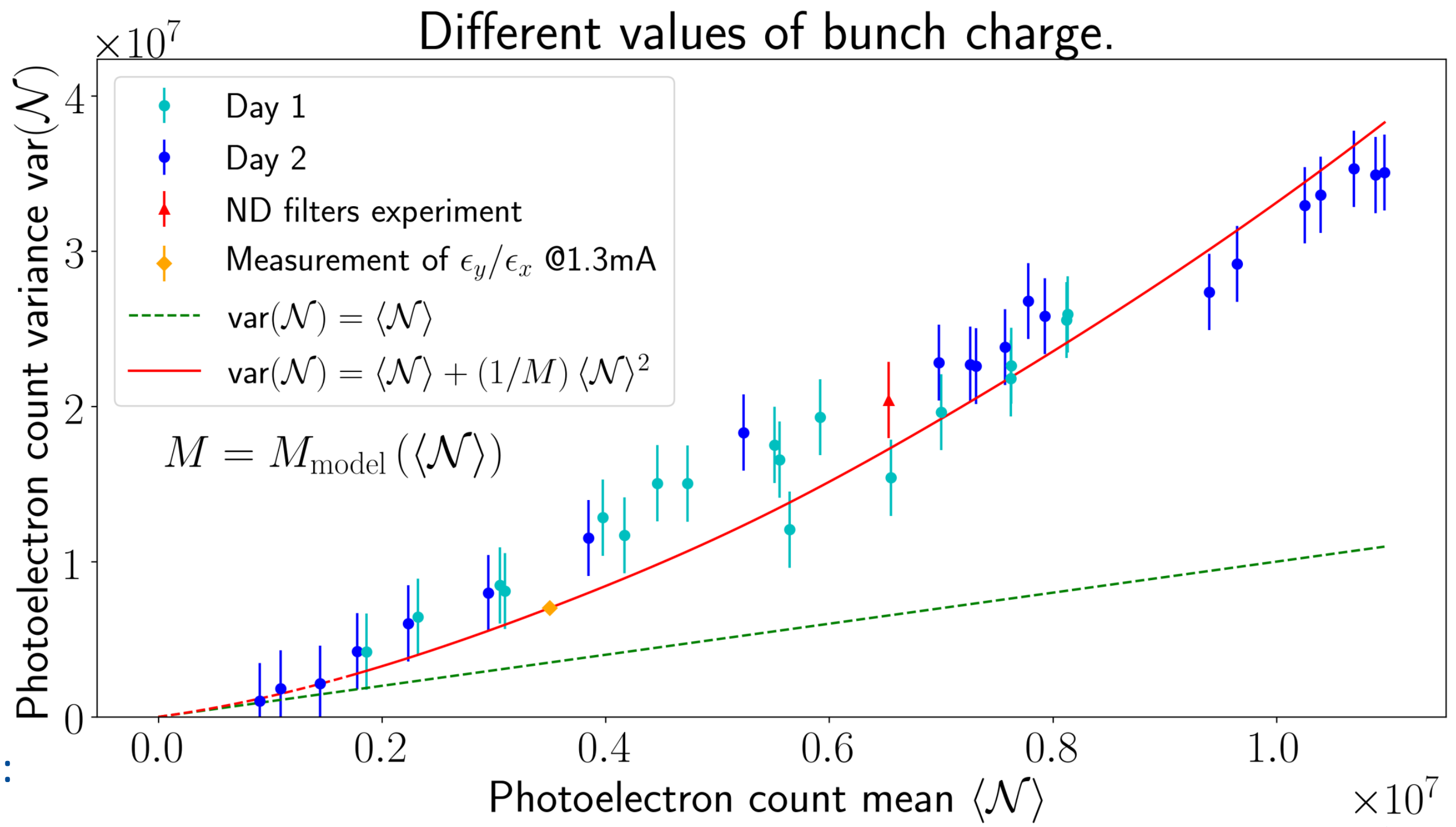


Model for bunch dimensions:

- Longitudinal size is constant, measured with a wall-current monitor
- Vertical size is constant and determined by multiple scattering on the background gas
- Horizontal size and momentum spread are determined by **intrabeam scattering** [4]

Measurement of $\epsilon_y/\epsilon_x$ @1.3mA:





Increasing charge of the electron bunch

## #6 Conclusions

- Quantitative theoretical model for the experiment from [1] was developed and verified in an independent experiment in IOTA [3].
- It helped corroborate a model of intrabeam scattering in IOTA [4]. The agreement is expected to improve in the future.
- Along with measurements of longitudinal bunch size [5-8] the fluctuations can be used to measure transverse bunch size.

Improvements as compared to the similar experiment from [1]:

- Better precision due to using the comb filter with one-turn delay and the special noise subtraction algorithm.
- Fluctuations data collected for different values of bunch charge.
- The transition from Poisson statistics to Super-Poisson statistics was observed in undulator radiation for the first time.

[1] M. C. Teich, T. Tanabe, T. C. Marshall, and J. Galayda, Statistical properties of wiggler and bending-magnet radiation from the Brookhaven Vacuum-Ultraviolet electron storage ring, Phys. Rev. Lett. **65**, 3393 (1990).

[2] K.-J. Kim, Z. Huang, and R. Lindberg, *Synchrotron radiation and free-electron lasers* (Cambridge University Press, 2017).

[3] I. Lobach, V. Lebedev, S. Nagaitsev, A. Romanov, G. Stancari, A. Halavanau, Z. Huang, and K.-J. Kim, Intensity fluctuations in undulator radiation, will be submitted to PRAB.

[4] S. Nagaitsev, Intrabeam scattering formulas for fast numerical evaluation, Phys. Rev. ST Accel. Beams **8**, 064403 (2005).

[5] F. Sannibale, G. Stupakov, M. Zolotorev, D. Filippetto, and L. Jägerhofer, Absolute bunch length measurements by incoherent radiation fluctuation analysis, Phys. Rev. ST Accel. Beams **12**, 032801 (2009).

[6] P. Catravas, W. Leemans, J. Wurtele, M. Zolotorev, M. Babzien, I. Ben-Zvi, Z. Segalov, X.-J. Wang, and V. Yakimenko, Measurement of electron-beam bunch length and emittance using shot-noise-driven fluctuations in incoherent radiation, Phys. Rev. Lett. **82**, 5261 (1999).

[7] V. Sajaev, Measurement of bunch length using spectral analysis of incoherent radiation fluctuations, in *AIP Conf. Proc.*, Vol. 732 (AIP, 2004) pp. 73–87.

[8] V. Sajaev, *Determination of longitudinal bunch profile using spectral fluctuations of incoherent radiation*, Report No ANL/ASD/CP-100935 (Argonne National Laboratory, 2000).