MOPA170

Two-Photon Undulator Radiation

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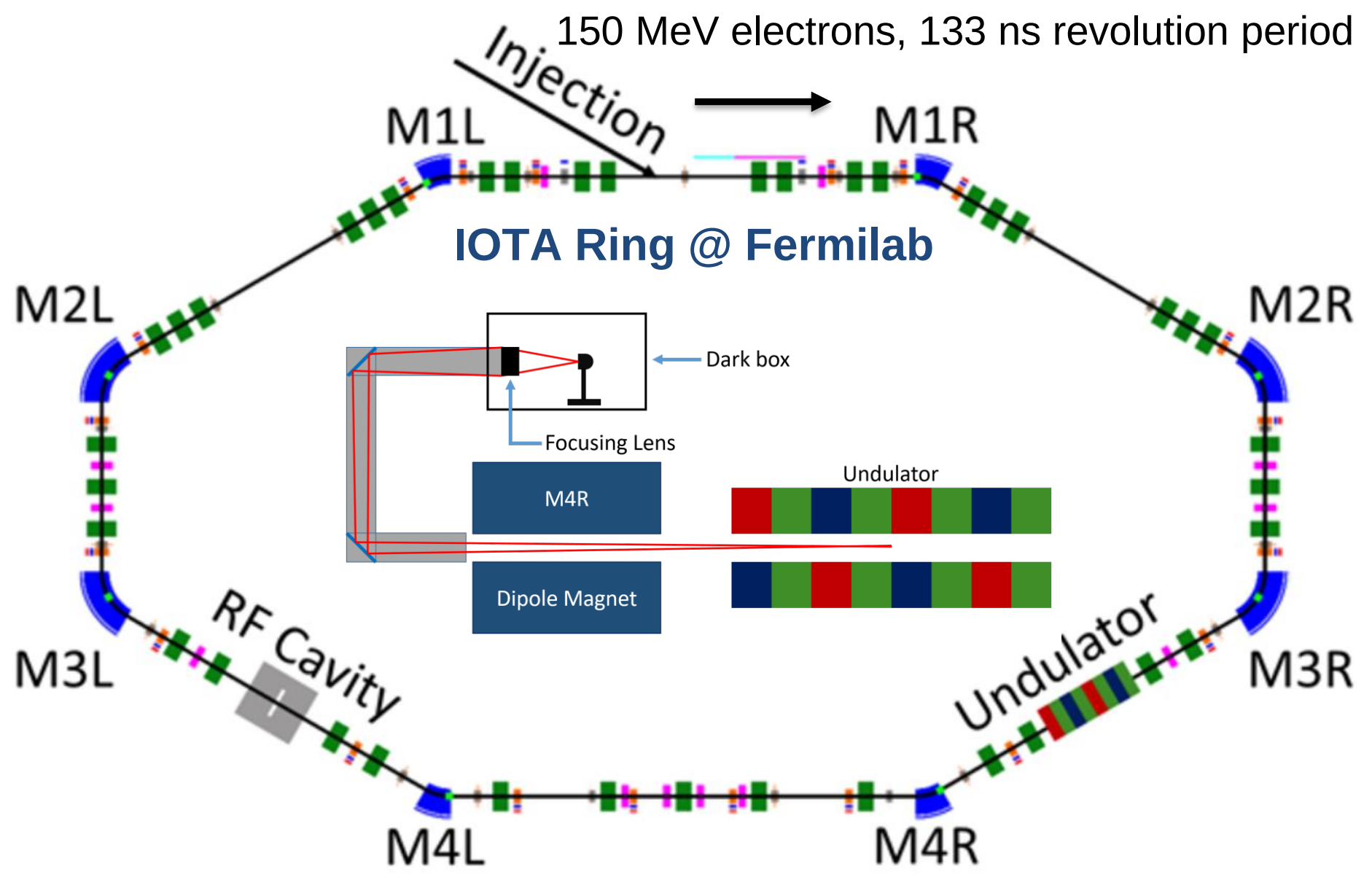
ABSTRACT

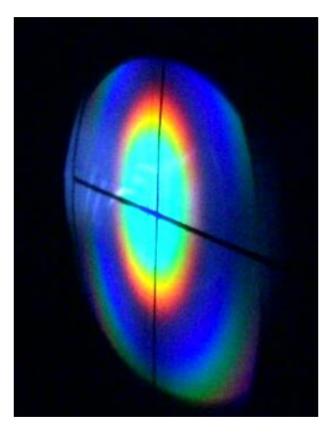
We report on experimental investigations of a single electron, circulating in the Fermilab IOTA storage ring, focusing on two-photon undulator emissions. We employ a Mach-Zehnder interferometer (MZI) for the undulator radiation to determine the photon coherence length as well as to measure its statistical properties. In this experiment, the pulse of radiation in one arm of the interferometer is delayed by a certain optical delay. The optical delay can be adjusted with a step as small as 10 nm. We show that when the optical delay is varied, we observe oscillations of photon count rates in the two outputs of the interferometer. This interference pattern contains information about the temporal shape of the undulator radiation pulse, also known as the radiation coherence length. It may also contain information on non-classical two-photon statistics. In this paper, we present and discuss our measurements of this coherence length and statistical properties in both multi-electron and single-electron regimes..

INTRODUCTION

Previous experiments [1] have demonstrated that a single electron in a storage ring behaves like a classical object, although its synchrotron radiation is quantized. Recently, an experiment, which employed an MZI with many electrons in a ring, has obtained an autocorrelation trace for a tandem undulator and confirming the classical behavior of spontaneous undulator radiation [2]. In our experiment we also employed MZ interferometry of the undulator radiation in IOTA. In these experiments, a pulse of radiation in one arm of the interferometer is delayed by a certain optical delay, before passing through the second beam splitter and on to the detectors. The optical delay can be adjusted with a step as small as 10 nm. It can be shown that when the optical delay is adjusted, we will observe oscillations of intensity in the two outputs of the interferometer. This interference pattern contains information about the temporal shape of the undulator radiation pulse, also known as the radiation coherence length.

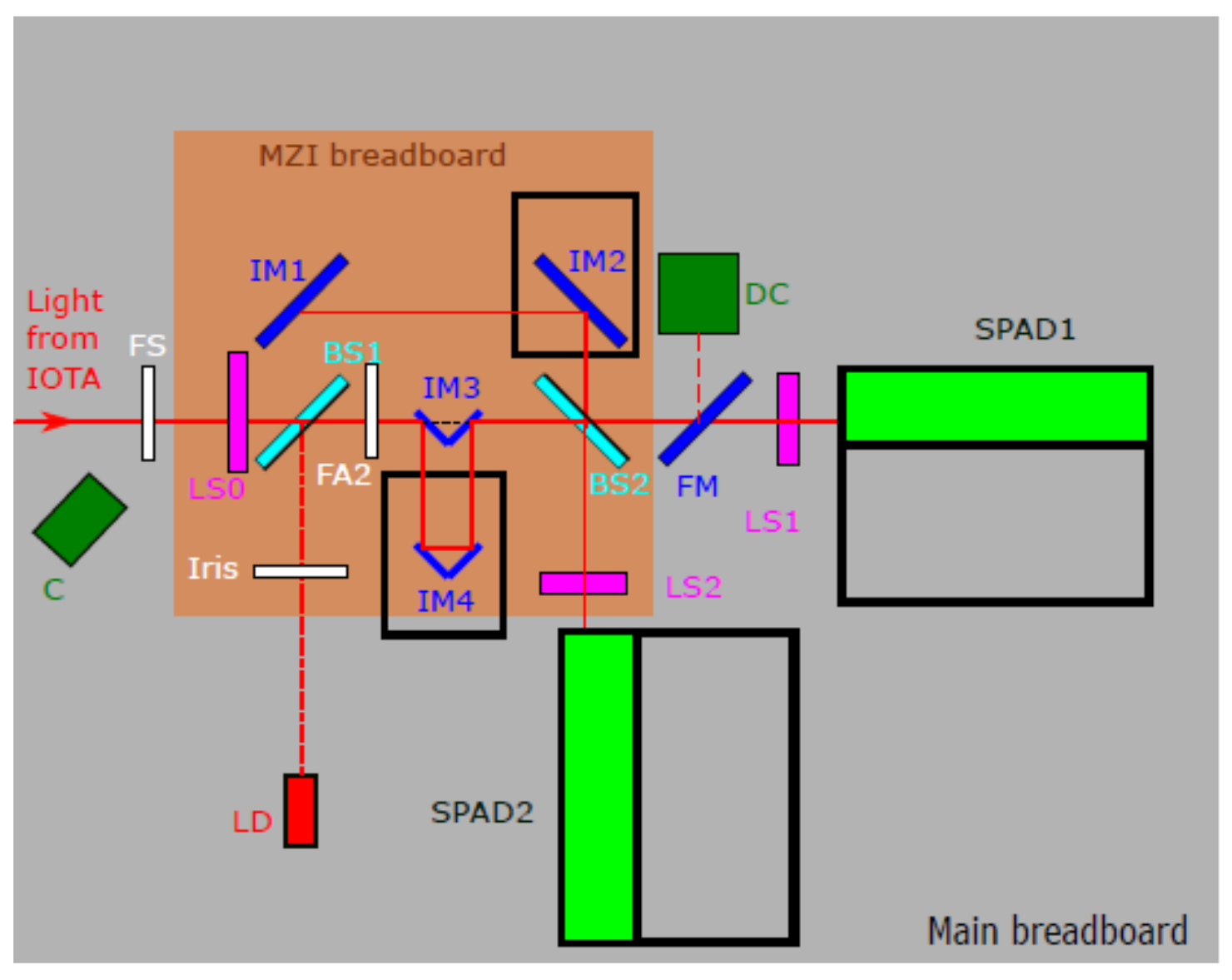
150 MeV electrons, 133 ns revolution period

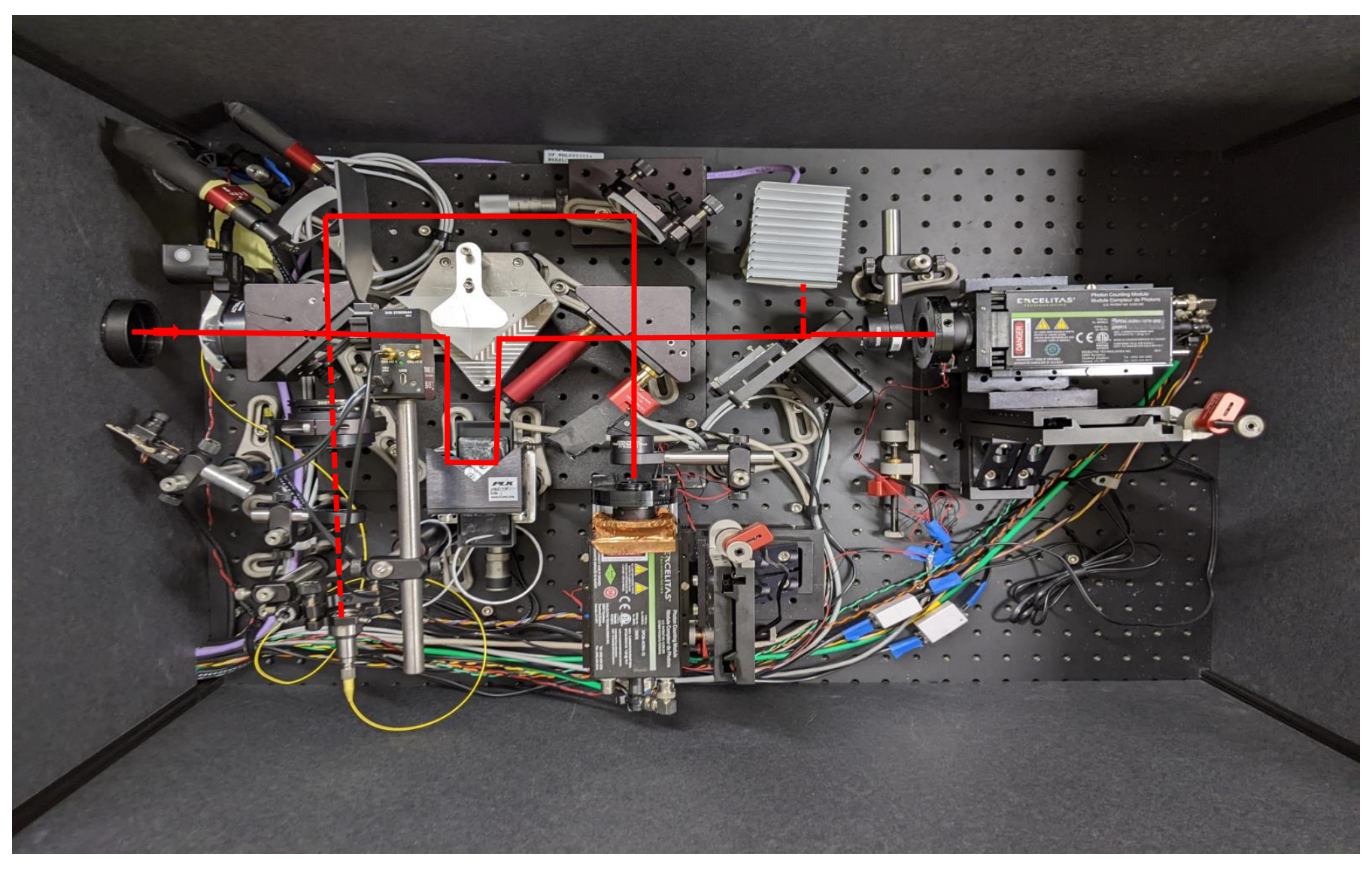




Number of periods: $N_u = 10.5$
Undulator period length: $\lambda_u = 55$ mm
Undulator parameter (peak): $K_u \sim 1$

APPARATUS



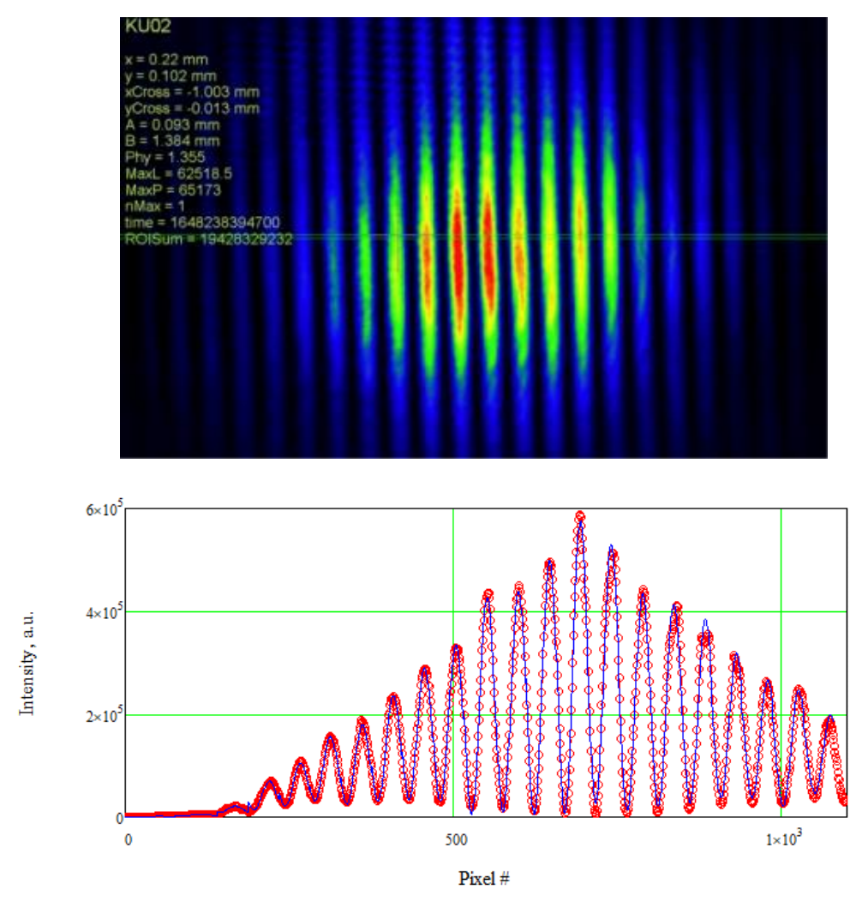


Detector: Single Photon Avalanche Diode (SPAD)

Excelitas SPCM-AQRH-10

Active area (diameter)	180 μm
Photon detection efficiency at 650 nm	65%
Dark count	~100 cps
Dead time	22 ns
Pulse height	2 V
Pulse length	10 ns

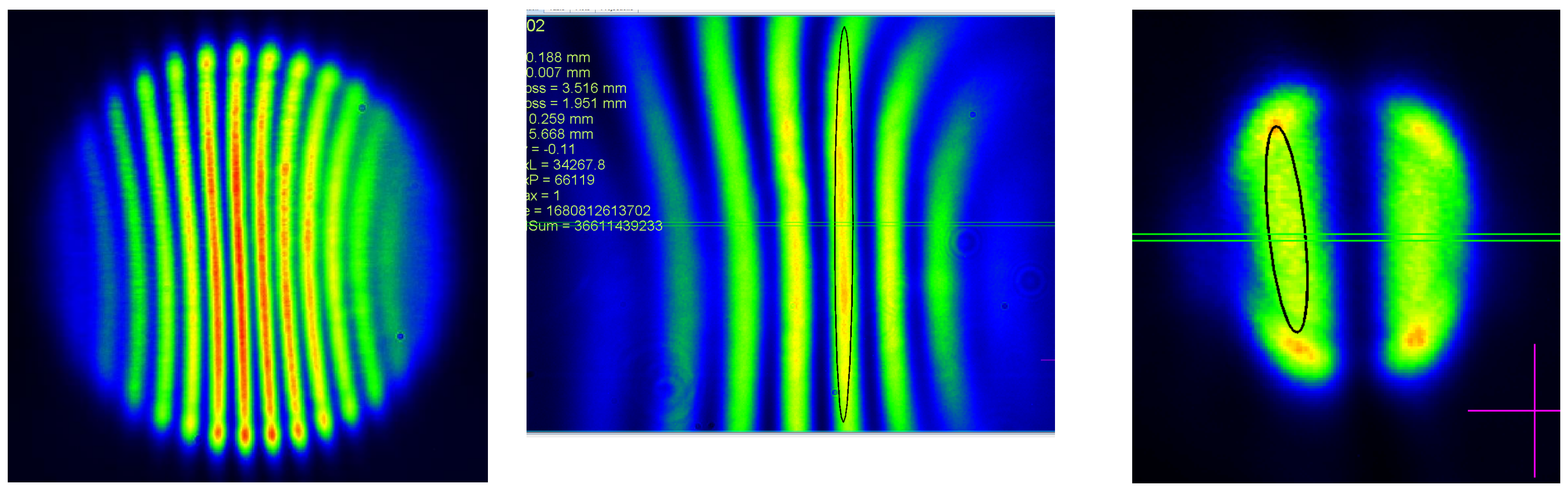
Digital Camera (LED test example)



Intensity of the camera image across its central horizontal line. The angle between light fronts coming out of two MZI arms is 2.3 mrad. Red circles – data, blue line – cosine fit of individual fringes.

For laser diode, the coherence length defined as sigma of a Gaussian fit is 8.6 wavelength. Maximum visibility ~100%. LD operates far below the lasing threshold.

MANY ELECTRONS



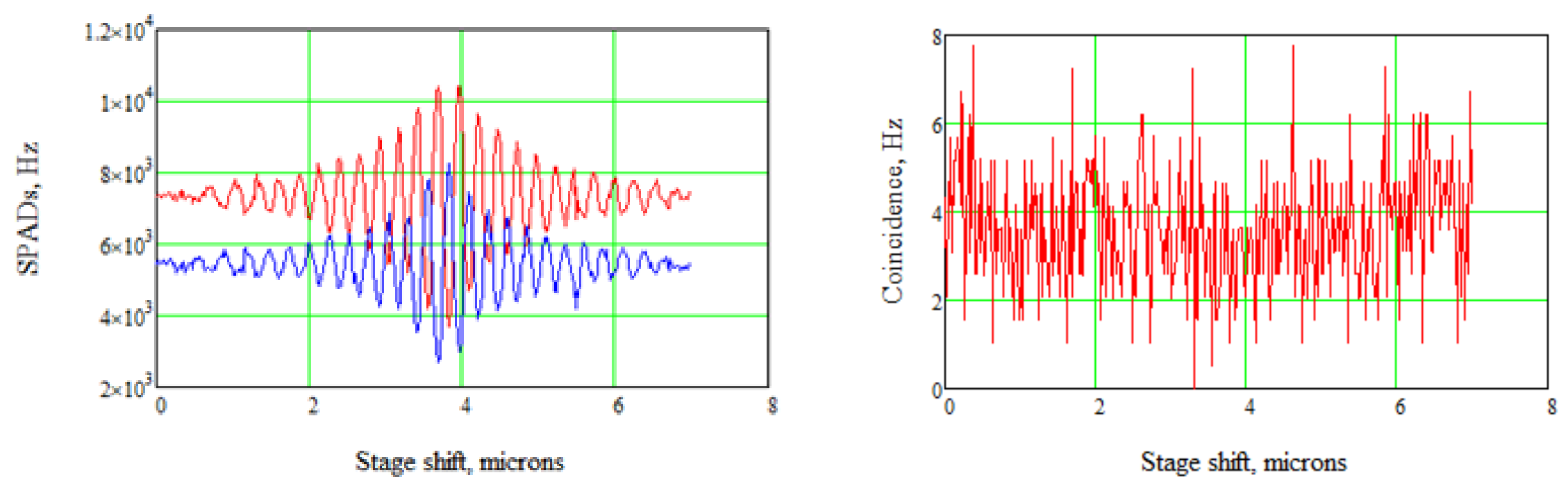
Uncollimated undulator light at the digital camera for different MZI angles. False colors.

SINGLE ELECTRON

SPAD signals are recording continuously. The coincidence rate is within 20 ns window

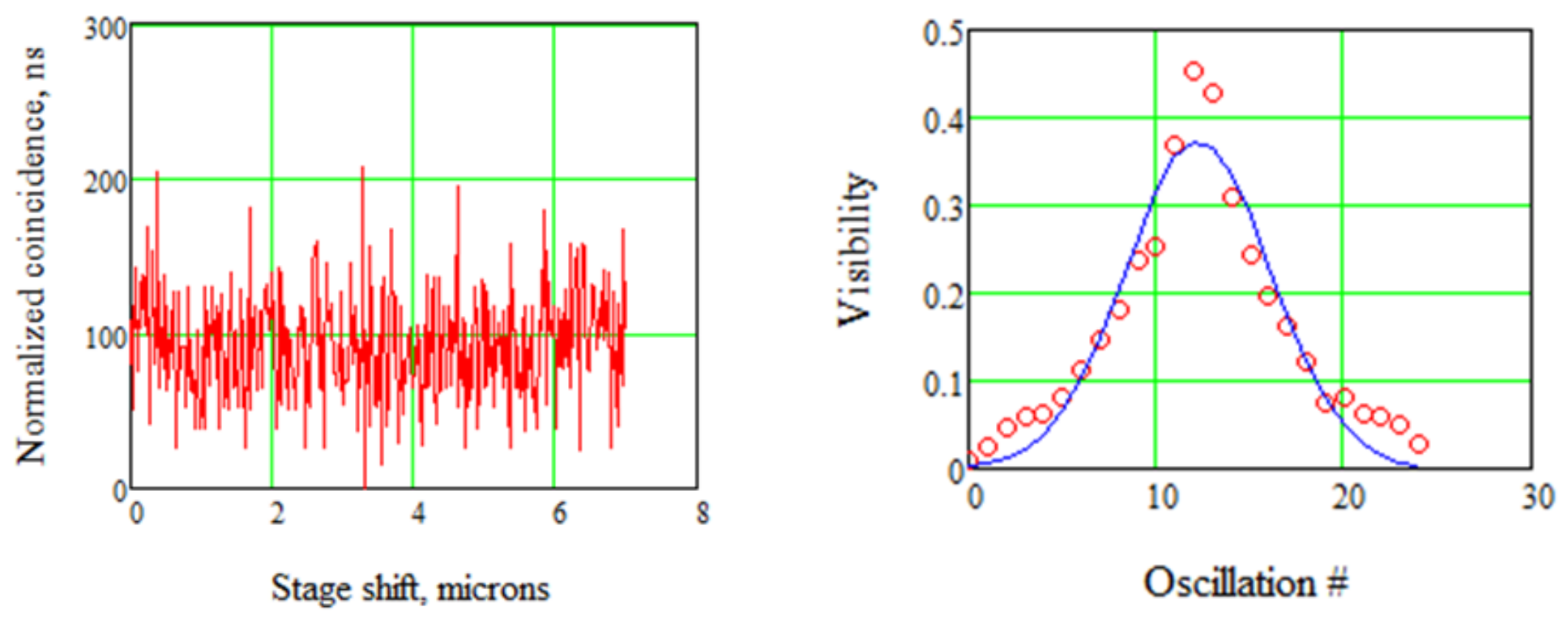
Normalized coincidence rate:

$$f_{ncr} = \frac{f_{coin}}{f_1 f_2}$$



Scan is symmetrical. Low visibility.
-- λ=538 nm
-- Coherence length from a global fit 2.8λ.

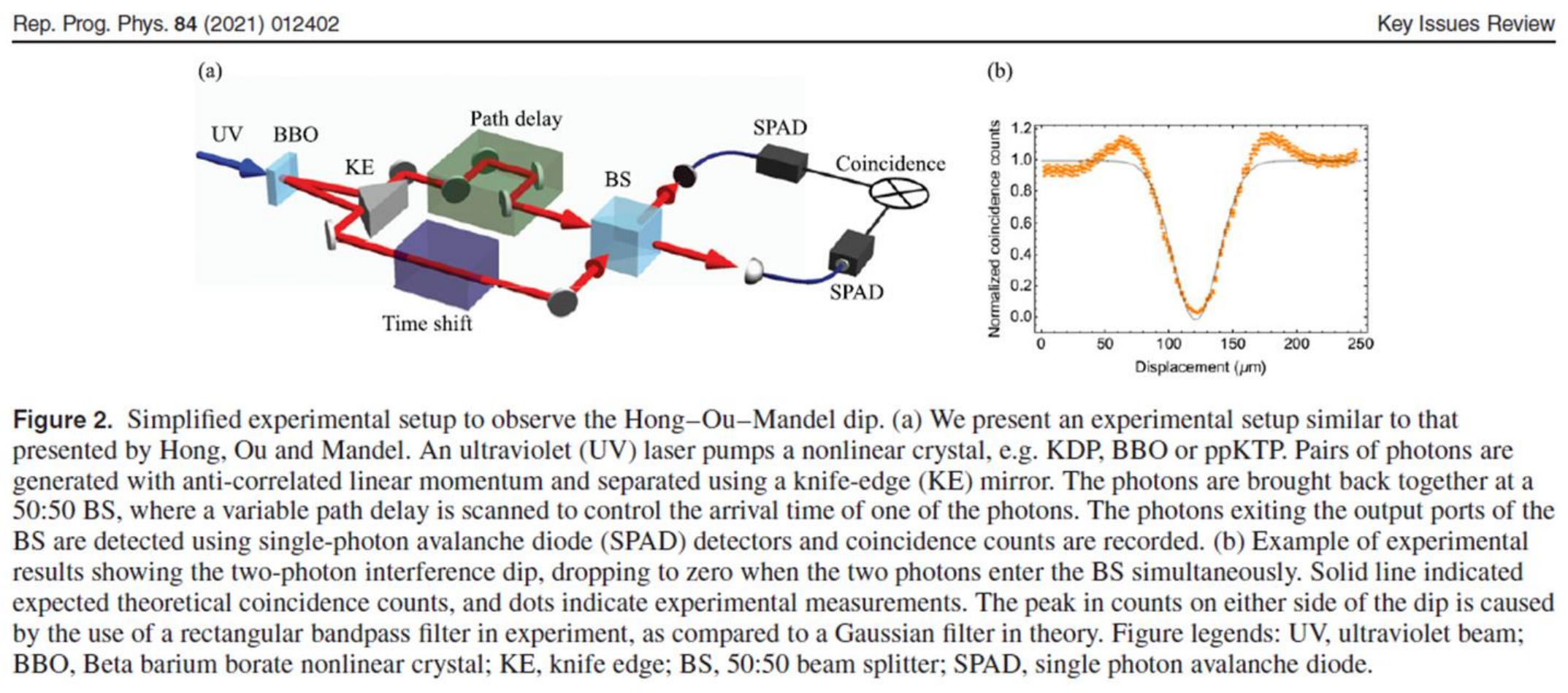
1e, small iris opening



Visibility curve from fitting individual fringes and its Gaussian fit.

DISCUSSION: Fock State vs Coherent State

F. Bouchard *et al* , *Two-photon interference: the Hong–Ou–Mandel effect,* 2021 *Rep. Prog. Phys.* **84** 012402



Rep. Prog. Phys. **84** (2021) 012402 Key Issues Review

Figure 2. Simplified experimental setup to observe the Hong–Ou–Mandel dip. (a) We present an experimental setup similar to that presented by Hong, Ou and Mandel. An ultraviolet (UV) laser pumps a nonlinear crystal, e.g. KDP, BBO or ppKTP. Pairs of photons are generated with anti-correlated linear momentum and separated using a knife-edge (KE) mirror. The photons are brought back together at a 50:50 BS, where a variable path delay is scanned to control the arrival time of one of the photons. The photons exiting the output ports of the BS are detected using single-photon avalanche diode (SPAD) detectors and coincidence counts are recorded. (b) Example of experimental results showing the two-photon interference dip, dropping to zero when the two photons enter the BS simultaneously. Solid line indicated expected theoretical coincidence counts, and dots indicate experimental measurements. The peak in counts on either side of the dip is caused by the use of a rectangular bandpass filter in experiment, as compared to a Gaussian filter in theory. Figure legends: UV, ultraviolet beam; BBO, Beta barium borate nonlinear crystal; KE, knife edge; BS, 50:50 beam splitter; SPAD, single photon avalanche diode.

Kim, H., Kwon, O. & Moon, H.S.
Two-photon interferences of weak
coherent lights. *Sci Rep* **11**, 20555 (2021)

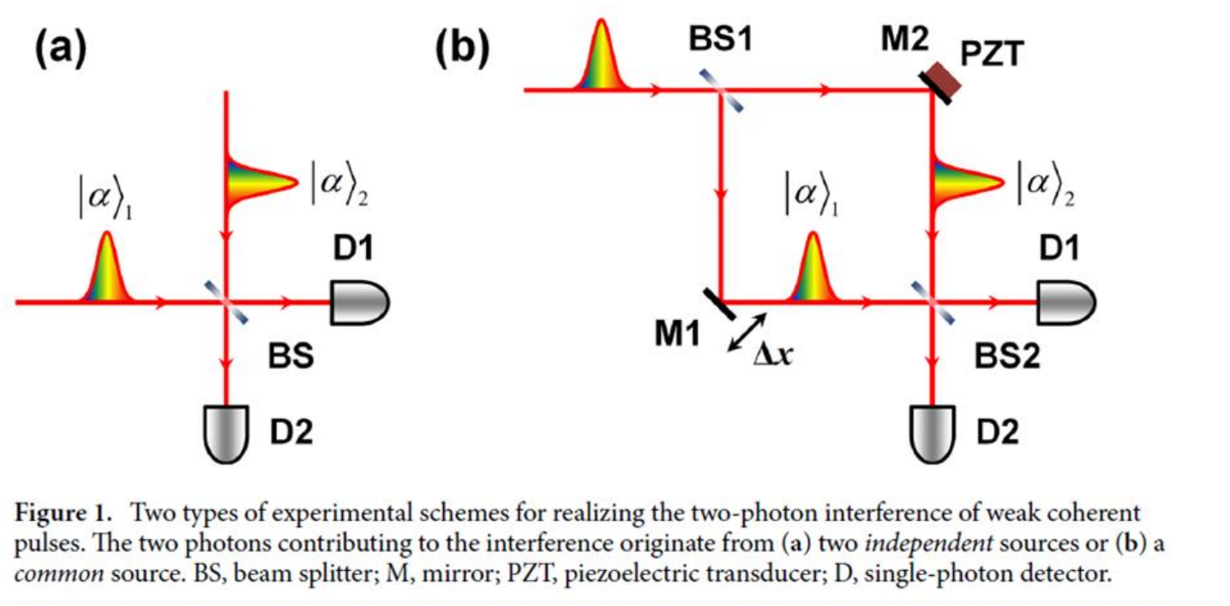


Figure 1. Two types of experimental schemes for realizing the two-photon interference of weak coherent pulses. The two photons contributing to the interference originate from (a) two *independent* sources or (b) a *common* source. BS, beam splitter; M, mirror; PZT, piezoelectric transducer; D, single-photon detector.

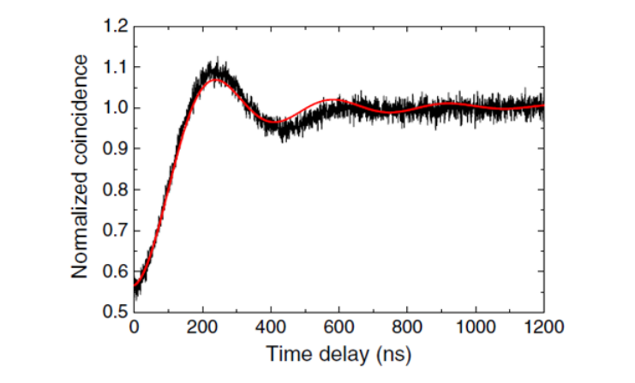


Fig. 3. Hong–Ou–Mandel interference fringe with two independent continuous-wave coherent photons. Experimental result and theoretical curve fitting under the conditions of a bandwidth of 3.3 MHz and $\Delta\omega = 0$.

SUMMARY

So far, we have not observed any deviation from the classical behavior for undulator photon pairs and a single electron in a storage ring. Future work should allow for setting a limit on quantum/classical nature of undulator radiation.

REFERENCES

[1] I. Lobach et al., Single electron in a storage ring: a probe into the fundamental properties of synchrotron radiation and a powerful diagnostic tool, 2022 JINST 17 P02014

[2] T. Kaneyasu et al., Nature Scientific Reports vol. 12, Art. 9682 (June 2022)

ACKNOWLEDGMENTS

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