CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF NUCLEAR SCIENCES AND PHYSICAL ENGINEERING

BŘEHOVÁ 7, 115 19, PRAHA 1

Ph.D. thesis review

Semiconductor pixel detectors for nuclear physics and quantum astrometry

Supervisor: Ing. Michal Marčišovský, Ph.D.

Author: Ing. Sergei Kulkov

The Ph.D. thesis titled *"Semiconductor Pixel Detectors for Nuclear Physics and Quantum Astrometry"* by Sergei Kulkov presents the results achieved during his doctoral research, spanning two distinct projects. The first project builds upon work initiated during his Master's studies, focusing on the detection of secondary radiation produced by runaway electrons in tokamaks using semiconductor detectors based on the Timepix3 readout chip.

Runaway electrons generated during tokamak operation can reach high energies, and their loss, followed by contact with plasma-facing components, can cause significant damage to the vacuum vessel, jeopardizing the functionality of the entire tokamak system. To ensure the safe operation of tokamaks—especially future thermonuclear fusion reactors—comprehensive diagnostics are needed for the timely detection and analysis of runaway electron characteristics.

Kulkov worked with a 200-μm thick silicon sensor coupled with the Timepix3 readout chip. This advanced diagnostic tool, with its excellent 1.5 ns timing resolution and a matrix of 256 × 256 pixels (each with a 55 μm pixel pitch), offers valuable insights into runaway electron physics. The detector setup developed by Sergei was successfully used to detected bremsstrahlung x-ray and gamma radiation generated by runaway electrons during their interactions with the bulk plasma and the vacuum vessel wall. Furthermore, Sergei calibrated the detector to determine the energy of the detected radiation.

The results were obtained during the final two experimental campaigns at the COMPASS tokamak before its shutdown for an upgrade. These findings were published in the *Journal of Instrumentation*, with Sergei Kulkov as the first and corresponding author.

The second project focuses on testing new detectors for applications in stellar interferometry, specifically in intensity interferometry and quantum-assisted amplitude interferometry. This work is a collaboration between the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague (FNSPE CTU), the AQUA Lab at the Swiss Federal

Institute of Technology (EPFL) in Switzerland, and Brookhaven National Laboratory (BNL) in the United States.

Sergei Kulkov joined the project in spring of 2022, leveraging his expertise with semiconductor detectors from his previous work with Timepix3 to explore the LinoSPAD2 detector. This detector, based on single-photon avalanche diodes (SPAD) and developed by Professor Edoardo Charbon's group at AQUA Lab, plays a crucial role in this research. For intensity interferometry and quantum-assisted methods, nearly simultaneous detection of two stellar photons (e.g., from different points on a star) is essential for measuring the Hanbury Brown-Twiss (HBT) effect, which reveals enhanced photon coincidences due to the super-Poissonian statistics of thermal light sources such as stars.

LinoSPAD2, with its 40 ps timing resolution and a linear array of 512 SPADs (each with a 26.2 μm pitch), represents a significant advancement in semiconductor detector technology. It opens up new possibilities not only in stellar interferometry but also in quantum optics and associated quantum networking.

Sergei has developed a robust and comprehensive data analysis tool for the LinoSPAD2 detector, including real-time imaging software, which was published on GitHub and made freely available to the scientific community. Additionally, he created an original experimental setup at CTU, enabling several novel types of measurements. His involvement in the project included participation in numerous experiments both at BNL and in the established laboratory in Prague.

The key results of the project include the development of a fast spectrometer capable of measurements exceeding the Heisenberg uncertainty principle by a factor of 10, the first simultaneous measurement of the HBT effect across multiple photon wavelengths, and a detailed comparison of cross-talk effects with the HBT phenomenon. These results were submitted as three separate articles to *Applied Optics*, *APL Photonics*, and the *Journal of Instrumentation*, with Sergei contributing as both corresponding author and co-author.

The thesis is structured as a collection of four topical publications, preceded by a comprehensive introduction consisting of four chapters.

The first chapter provides an in-depth description of the Timepix3 and LinoSPAD2 detectors, including alternative technologies and potential future iterations. In the second chapter, the student presents the theoretical background on runaway electron physics in tokamaks, explaining the mechanisms of their generation. This chapter also covers the HBT effect, its significance in intensity interferometry, and quantum-assisted astrometry, along with a brief review of modern stellar intensity interferometry observatories and two quantum-assisted schemes.

The third chapter details the experimental setups used at the COMPASS tokamak, along with various setups involving the LinoSPAD2 detector, including the spectrometer, which the student helped develop during his stay at the Brookhaven National Laboratory. This chapter also explains the calibration procedures for the LinoSPAD2 detector and describes the data analysis software developed by the student.

The final chapter introduces the four publications that summarize the research outcomes from the student's Ph.D. studies. These publications are included in the Appendix of the thesis. Additionally, Chapter 4 includes a detailed discussion of supplementary measurements related to improvements in the spectrometer setup, which were not included in the publications.

During his doctoral studies, Sergei Kulkov demonstrated the ability to work independently and conduct high-quality original research. This is evidenced by two manuscripts where he is the first and corresponding author—one of which has been published, while the other is currently under review in various journals. In addition to his experimental research, Sergei developed advanced data analysis skills, culminating in the creation of comprehensive software for processing LinoSPAD2 data, which has been made publicly available on GitHub and is now widely used by collaborators at BNL.

As part of the project, he also co-supervised several bachelor students working on LinoSPAD2-related topics. Sergei actively engaged with the broader scientific community, participating as a speaker at several international conferences where he presented his research.

In light of these achievements, I strongly recommend Sergei Kulkov for the award of a Ph.D. degree, pending a successful oral defense.

In Prague, September 30, 2024

………………………………………..
Michal Marcisovsky