Digital holographic interferometry for particle detector diagnostic

A. Arena*, G. Cantatore†, M. Karuza‡
* University of Rijeka, Rijeka, Croatia / INFN Sezione di Trieste, Trieste, Italy
aldo.arena@ts.infn.it
† University of Trieste/INFN Sezione di Trieste, Trieste, Italy
giovanni.cantatore@ts.infn.it
‡ University of Rijeka, Rijeka, Croatia / INFN Sezione di Trieste, Trieste, Italy
mkaruza@phy.uniri.hr

***Abstract*—In high precision scattering experiments particle tracks must often be reconstructed from a series of hits in successive detector planes. The relative distance between these planes is a critical parameter that must be monitored during operation. To address this problem we have developed a digital holographic interferometer dubbed Holographic Alignment Monitor (HAM) to be used in the MUonE project at CERN. MUonE aims at a precision measurement of the scattering angle between particles after an elastic muon-electron scattering. The HAM is designed to monitor the relative distance between position-sensitive sensor planes inside a MUonE tracking station with a resolution better than the required 10 μm. The system uses a 532 nm fiber-coupled laser source both to illuminate a portion of the detector plane (object), and to provide the reference beam. A CMOS image sensor acquires the raw data, and the reconstructed holographic image of the silicon sensor being observed is computed using an algorithm containing a Fourier transform. The relative distance between silicon planes is monitored by superposing successive raw images of the same object on an initial reference one and observing the interference fringes appearing on the reconstructed holographic image. Preliminary tests have yielded a distance resolution of less than 1 μm.**

Keywords*—digital holography, interferometry, detector diagnostic, particle tracking, calibration, muon scattering

I. INTRODUCTION

Scattering experiments in particle physics often require following with high precision particle tracks through the detectors. In many cases, this is accomplished by several position-sensitive detector planes recording particle hits, which are then used to reconstruct the tracks. The precision with which the relative positions of the tracking planes is known is a critical parameter determining the overall precision of the measurement. The MUonE project at CERN aims at a direct determination of the hadronic contribution to the muon gyromagnetic anomaly [1]. This contribution, which cannot be calculated in a perturbative approximation, enters the theoretical computation of the muon anomaly and affects its accuracy. Given the recent measurements of the muon anomaly by the "Muon G-2" collaboration, confirming a discrepancy between the experimental result and the number predicted by Standard Model theory [2], a new determination of the hadronic contribution has become of fundamental interest. In the MUonE scheme, this quantity is extracted directly from an accurate measurement of the muon-electron differential scattering cross-section. The MUonE beamline basically consists of a 160 MeV muon beam traversing a series of 1 m-long "stations", up to 40 in the final configuration, each one having a thin, low Z target, and three pairs of silicon tracking detector planes to reconstruct the tracks of the outgoing particles and obtain the scattering angle. The multiplicity of stations is needed to bring the statistical error on the scattering angle within the required uncertainty. In addition, to reduce systematic uncertainties it is critical to monitor, during operation, the relative distance between tracking planes inside a station at the 10 μm level. To solve this problem we have developed a system, called Holographic Alignment Monitor (HAM), which uses digital holographic interferometry to monitor relative displacements between silicon detector planes, within a MUonE tracking station, at the sub-μm level.

II. HOLOGRAPHIC ALIGNMENT MONITOR

The basic idea of the Holographic Alignment Monitor is to use off-axis digital Fresnel holography [3] to image a sufficiently large circular portion (diameter of $\approx$ 3 cm) of the surface of a silicon tracking plane. The two beams necessary for holography are obtained by passing the output of a 532 nm fiber-coupled laser through a fiber splitter. The "object" beam source is fixed on one of the detectors planes and illuminates, at a distance of $\approx$ 30 cm, the adjacent plane to be monitored: its back-scattered diffused light impinges on a CMOS digital image sensor fixed to the same plane as the "object" source. The "reference" beam, again fixed to the "source" plane, illuminates directly the CMOS sensor, which produces the raw image data. After taking an initial image, successive images are then superimposed on the first one to generate interference fringes giving the relative displacement, as a function of time, between the "source" detector plane and the adjacent illuminated plane. The splitting ratio between "object" and "reference" beams is chosen to maximize fringe contrast.

A. *Off-axis Fresnel holographic imaging*

The basic principle of holographic imaging is to illuminate an object of interest with a monochromatic coherent beam of wavelength λ. The scattered, or "object", wave is recorded by an image sensor together with a "reference"

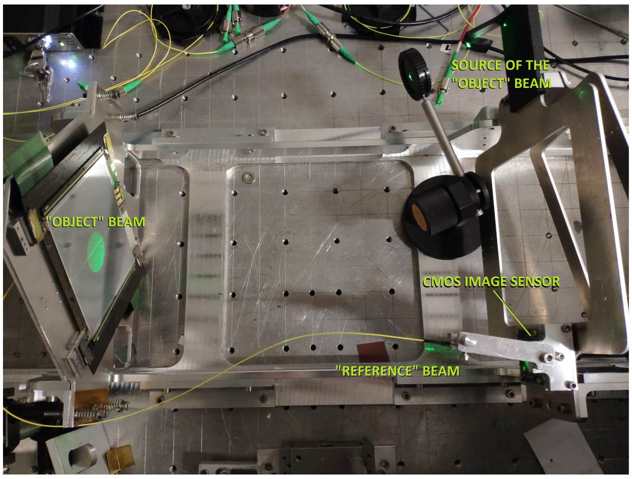

Fig. 1: View of the HAM test setup from above the optical bench. The silicon sensor surface to be monitored is visible at left illuminated by the "object" beam. The source of the "object" beam is mounted on an Al frame rigidly connected to a support structure designed for the MUonE tracking station. The "reference" beam is carried by an optical fiber to a mounting bracket fixed to the same frame as the source of the "object" beam and illuminates a CMOS digital image sensor located under the beam mounting bracket. The distance between the silicon sensor surface and the frame is $\approx$ 30 cm. The x-y plane (see text) coincides with the silicon sensor surface and the z-axis runs horizontally from this surface to the Al frame.

beam coming from the same source. The superposition of these two beams generates the holographic image.

There are many methods and many variations of the basic principle for creating an hologram described above. For our purposes, given the mechanical and dimensional constraints of the MUonE tracking station, we decided to use digital, lens-less, off-axis Fresnel holography [4]. This method, where the object O and the sensor S are placed at a distance d_0 along the z-axis and shifted in the x-y plane by a value of x_0 and y_0 (see Fig. 1 and the caption therein), proved to be the best match for the geometry of our experimental setup. We use a scheme without lenses in order to keep the experimental configuration as simple as possible.

The data recorded by the CMOS sensor must be processed in order to reconstruct the digital hologram of the object. To obtain an interferometric hologram, two raw images, one taken at arbitrary initial time t_0 and a second one, taken at a later time t_1, are superimposed. The resulting data, in array form, are processed using a discrete solution of the Fresnel integral (eq. 2-7 in [4]). The data are multiplied by a complex phase containing the information about pixel size, wavelength of the source beam, spatial coordinates and reconstruction distance d_R. This complex array is then processed by a Fourier transform and spatially filtered. This procedure leads to a final complex-valued result from which amplitude image data are extracted and stored.

This method leaves some degree of freedom in image processing since it does not use explicit formulations that strictly constrains parameters such as the distance O-S or the size of the recorded object. Of course, the choice of wavelength, the position and distance of the reference beam (since the beam is gaussian and collimating lens is not used) and all other parameters affect the final result of the imaging process. In particular, the image resolution and its sharpness are changed [3].

B. Experimental setup

The experimental setup is presented in Fig. 1. The silicon sensor is a dummy module produced as test device for the outer tracking detectors used by the CMS experiment at CERN (2S modules [5]). The laser is a fiber coupled CW laser (Oxxius LCX-532S) emitting $\approx$ 85 mW at 532 nm. The power output of the laser is meant to cover more than one setup, so for our experiment we used only about 25% of the total power. The laser output is fed into a 90:10 fiber optic splitter delivering 90% of the power to the "object" beam and the remainder to the "reference" beam, which is further attenuated by a voltage-controlled fiber attenuator. All fibers are single mode. The CMOS image sensor (IDS UI-3581LE) has a 4.92 megapixel resolution and a pixel size of 2.2 μm. The raw image data acquired by the CMOS sensor are readout and processed by a computer running a custom LabVIEW code.

The relatively high reflectivity of the silicon surface introduces noise and high intensity artifacts in the holographic image recorded by the CMOS sensor. We therefore reduce the size of the observed object by inserting an aperture in front of the source of the "object" beam, covering a $\approx$ 3 cm diameter circular portion of the silicon sensor surface, and align the "object" beam to avoid direct illumination of the sensor by light reflected from the surface. The measured light powers finally hitting the surface of the sensor are $P_{obj} = 30$ nW and $P_{ref} = 180$ nW.

C. Method and results

To monitor the relative displacements of the silicon sensor plane with respect to the frame holding the "object" beam source and the CMOS sensor, we record an initial raw image at at arbitrary time t_0, then we record raw images at later instants in time t and superimpose them on the initial one. The data, at time t_0 and at t, are recorded using an exposure time on the sensor of 0.07 s. The reconstructed holographic image of such superpositions shows interference fringes evidencing displacements of the illuminated portion of the surface in the time interval between t_0 and a later instant t_1.

Fig. 2 shows the holographic reconstructed image of the object taken at the initial time t_0. The diagonal band visible in the image is a feature of the silicon sensor surface. To test the system, the object is slightly moved and a new image is recorded at a later time t_1. The software

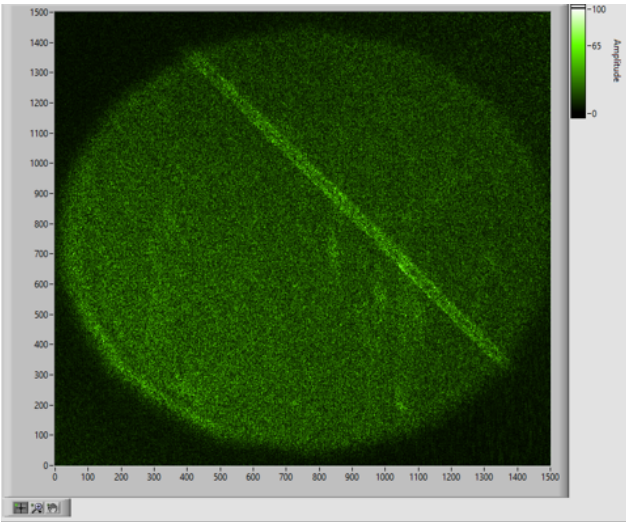

Fig. 2: Reconstructed holographic image of the illuminated portion of the silicon sensor surface at time t_0 (see text).

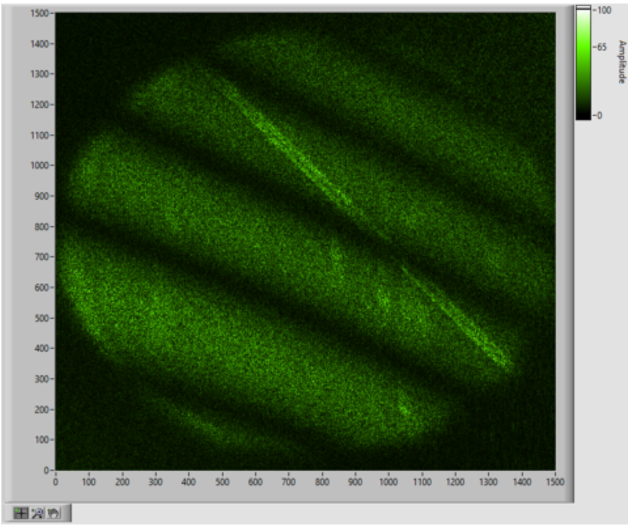

Fig. 3: Reconstructed holographic image of the superposition of the raw images of the "object" taken at time t_0 and at a later time t_1 (see text). Note the interference fringes showing that the "object" has moved in the $t_0 - t_1$ time interval.

then superimposes the t_0 and t_1 raw images generating the reconstructed holographic image shown in Fig. 3, where interference fringes appear. Since each fringe corresponds to a $\lambda/2$ displacement, the observed $n = 5$ dark fringes show that the object has moved by ≈ 1.3 μm in the time interval $t_0 - t_1$. This resolution is well below the 10 μm required by MUonE.

III. Conclusions

We have developed an Holography Alignment Monitor to monitor the relative displacements of two of the silicon sensor planes present in a tracking detector station designed for the MUonE experiment at CERN. To comply with the mechanical and dimensional requirements of the MUonE apparatus, beam transport is carried out completely through optical fibers, save for the final legs of the optical paths from the "object" scattered beam, and from the "reference" beam, to the image sensor. Displacement monitoring is accomplished by time-domain holographic interferometry based on an adaptation of the off-axis Fresnel holography imaging method. During preliminary tests, we have obtained reconstructed holographic images with interference fringes showing a displacement of the monitored object, over time, of the order of ≈ 1 μm. This experimentally demonstrated resolution is already sufficient to satisfy the 10 μm resolution mandated by MUonE.

Acknowledgements

A. A. thanks his supervisors, G. C. and M. K., for giving him the opportunity to be a part to this project.

References

[1] G. Abbiendi, “Status of the muone experiment,” *arXiv:2201.13177*, 2022.

[2] T. Albahri, A. Anastasi, A. Anisenkov, K. Badgley, S. Baeßler *et al.*, “Measurement of the anomalous precession frequency of the muon in the fermilab muon $g-2$ experiment,” *Phys. Rev. D*, vol. 103, p. 072002, Apr 2021. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevD.103.072002

[3] P. Picart and J. Leval, “General theoretical formulation of image formation in digital fresnel holography,” *J. Opt. Soc. Am. A*, vol. 25, no. 7, pp. 1744–1761, Jul 2008. [Online]. Available: http://opg.optica.org/josaa/abstract.cfm?URI=josaa-25-7-1744

[4] M. Karray, P. Slangen, and P. Picart, “Comparison between Digital Fresnel Holography and Digital Image-Plane Holography: The Role of the Imaging Aperture,” *Experimental Mechanics*, vol. 52, no. 9, pp. 1275–1286, 2012. [Online]. Available: https://hal.archives-ouvertes.fr/hal-02012133

[5] “The Phase-2 Upgrade of the CMS Tracker,” CERN, Geneva, Tech. Rep., Jun 2017. [Online]. Available: https://cds.cern.ch/record/2272264