FERMILAB-PUB-24-0403-STUDENT
2024 URA-Fermilab Undergraduate Women in STEM
July 29, 2024

Research Report

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EXPLORING INTERFEROMETRY DIAGNOSTICS FOR OPTICAL STOCHASTIC COOLING AT FAST/IOTA

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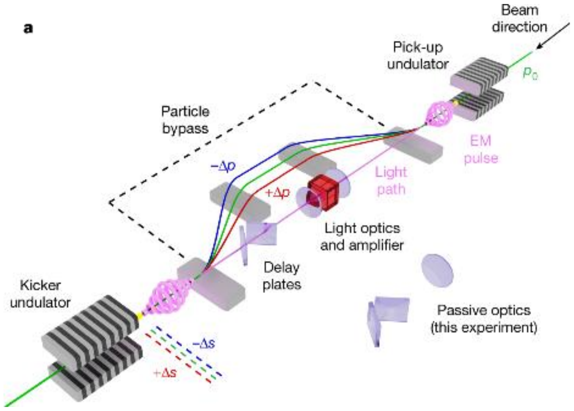
ABSTRACT

Optical Stochastic Cooling (OSC) is an advanced beam-cooling technique that will advance the traditional stochastic cooling. This method leverages optical radiation and high-precision feedback to cool the particles more efficiently than traditional stochastic methods by more than three orders of magnitude. As such, it is an enabler for the development of next generation discovery science machines at the frontiers of energy and intensity. This paper focuses on the development of the second phase of OSC and improving extreme beam cooling techniques in accelerators. The goal was to build and characterize a Mach-Zehnder Interferometer (MZI) in the FAST laser lab using known glass plates thickness which will allow future measurements of unknown phase change due to nonlinear amplification processes.

INTRODUCTION

In particle accelerators, beam cooling is essential to reduce the energy spread and increase the density of particle beams. Traditional methods such as electron cooling and stochastic cooling use interactions with electrons and electromagnetic radiation. In Electron cooling by co-propagating a cooler electron beam with a particle beam, energy is transferred using coulombs interactions from the hotter particles to the cooler electrons resulting in a more focused and denser particle beam. However, the scaling of Electron cooling with beam energy becomes unfavorable for relativistic beams. In Stochastic cooling, by measuring deviations with a pickup, processing the signals, and applying corrections with a kicker this process cools the beam. Traditionally, this has only been done in a microwave regime. The extension of stochastic cooling to optical frequencies could increase the cooling rates by more than three magnitudes. OSC uses free-space electromagnetic waves as the signaling medium, magnetic undulators to couple the radiation to the circulating particle beam, and optical amplifiers for signal amplification.

Figure 1. Optical Stochastic Cooling System



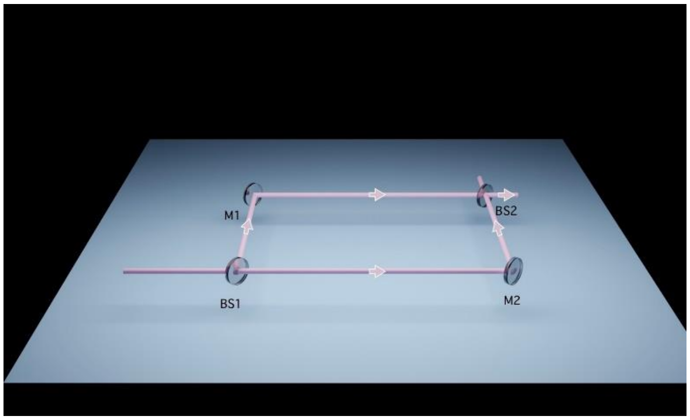
The transit-time method of OSC is displayed in fig. 1. At the beginning of the cooling system, each particle passes through a pick-up undulator where it generates a short pulse of electromagnetic radiation (light) containing information about the particle. The light and beam are then separated using a magnetic chicane which allows for the temporal allowance for in-line optics, and a correlation between the particle's momentum deviations at the pickup undulator and their respective arrival times at the bypass exit. At the end, the kicker undulator mediates an energy exchange between the particles and their light pulses. This results in corrective energy kicks and a corresponding reduction of each particle's synchrotron and betatron oscillation amplitudes. Phase 2 of OSC involves amplifying the light. The problem, however, is that if this is not done correctly, it can corrupt the information in the generated electromagnetic radiation. A method must then be developed to measure if it is corrupted and how. It must also be determined whether the procedure is being carried out correctly. One technique is the use of an interferometer which can yield the best results.

INTERFEROMETRY

The principle of interference is based on the interaction of two or more waves. As the waves carrying energy overlap, the energy merges and creates a third wave whose shape and size depend on the heights and depths of the merging waves at each point where they intersect. Upon shining two coherent waves onto a screen, a characteristic pattern, called fringes can be observed. These fringes consist of light and dark areas which is examined using an interferometer. This instrument is used in many fields to measure and analyze interference patterns between light waves. The patterns generated provide highly precise information about the properties of the light waves and the objects or phenomenon they interact with. Despite the different applications and different designs, all interferometers superimpose beams of light to generate an interference pattern.

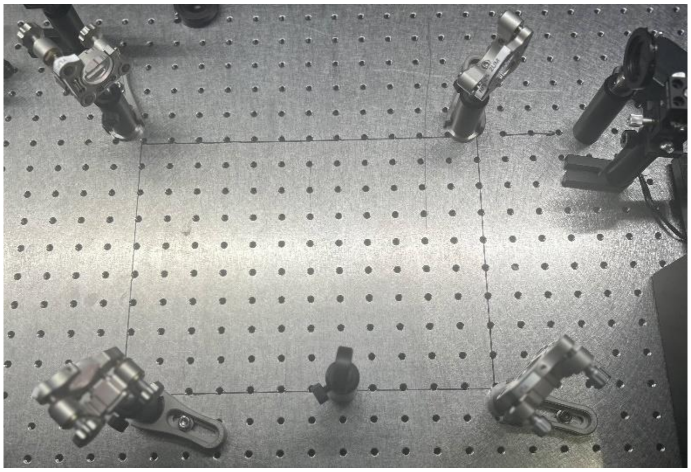
The Mach-Zehnder interferometer (MZI) is the design built in this experiment and is an amplitude splitting interferometer which divides the incoming beam into two paths. The experiment takes place on an optical breadboard and starts by turning on the laser and aligning the beam. The laser used is a five-picosecond pulse laser with 5 Hz repetition rate at a wavelength of 1053nm (near infrared spectrum). To align the beam, two adjustable mirrors are placed such that the laser hits the center point of the mirrors and is reflected 90 degrees by each of the mirrors. Two irises are used further on the path of the beam after being reflected from the second mirror. Then the first iris is left open, the second iris closed, and the beam is adjusted to fall on the center of the second iris by adjusting the first mirror. After this is completed the first iris is then closed, and the second mirror is adjusted so that the beam will fall on the center of the first iris. These adjustments will cause deviations from the center of each iris, so this process is repeated until the beam passes through the center of both irises. This allows for the laser to be aligned and the interferometer to then be constructed.

Figure 2. Schematic of the Mach-Zehnder Interferometer



The components of the interferometer must now be aligned to stay in the path of the beam spanned by the two irises. These components include two 50% beam splitters, BS_1 and BS_2, which are devices that divide the laser beam into two paths, and two mirrors, M_1 and M_2, which reflect the split beams. These were placed on stages and mounts that allow for the precise control for fine adjustment and alignment of the mirrors. The layout for the interferometer is included in fig. 2. which details the rough setup of the interferometer in the laser room. The beam must fall on the center of all the optical components. By placing a laser viewing card in the path of the beam, two dots coming from the two paths in the interferometer can be observed. The mirrors are then adjusted until there is one unified dot showing the overlapping of each path. A detector camera is then placed at the location where the recombined beam exits the BS_2 allowing for the interference pattern to be observed on the screen.

Figure 3. Instrumental setup of the Mach Zehnder Interferometer



The main goal of this project is to build and calibrate the interferometer. Introducing a glass slide to one path creates a time delay because of a change in optical path length due to the refractive index the beam is now passing through. This slide is introduced in the path traveling between BS_1 and M_2. There were up to three slides inserted with a 1mm glass thickness and between each change an image was saved using a camera for displaying the interference pattern. Another method used to observe change in pattern was rotating the stand the glass slide was on to increase the distance the laser travels through the glass. There were 4 slides used and the stands position started at 280 degrees as a reference. The angle was then decreased by 10 degrees until the pattern was no longer visible. Using these two methods can result in significant effects on the fringe pattern observed in interference experiments.

INTERFERENCE RESULTS & DISCUSSION

Fig 4.Pattern without glass slide

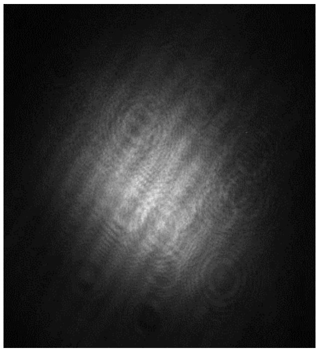


Fig 5. pattern with one glass slide

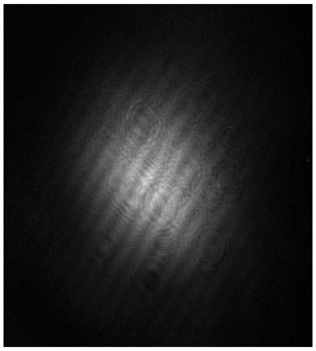


Fig 5.pattern with two glass slides

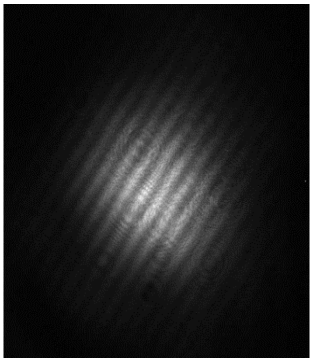


Fig 7. Pattern with three glass slides

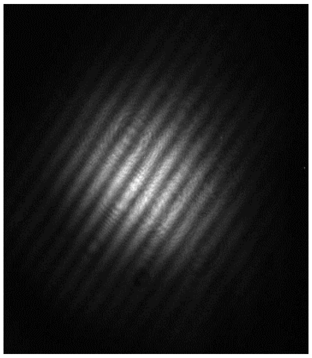


Figure 6. pattern at 280°

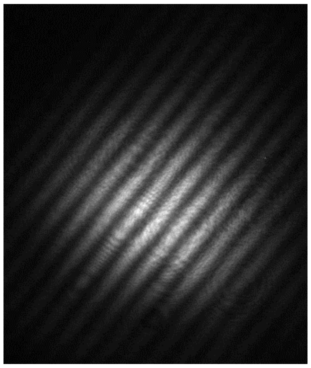


Figure 9. pattern at 270°

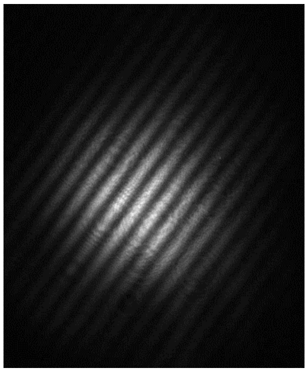


Figure 10. pattern at 260°

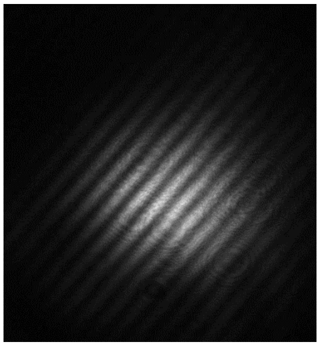


Figure 11. pattern at 250°

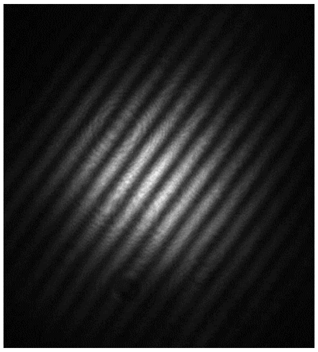


Figure 12. pattern at 240°

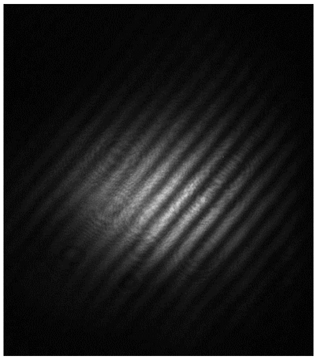


Figure 13. pattern at 230°

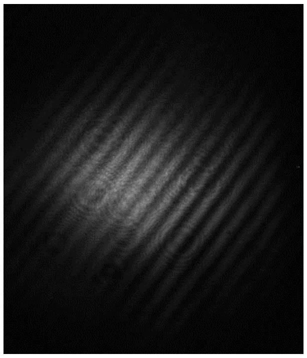


Figure 14. pattern at 220°

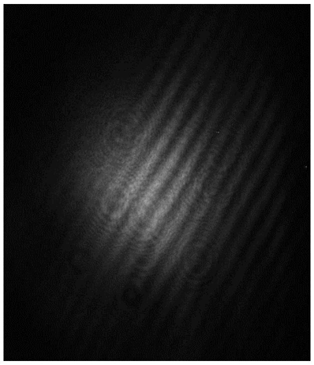


Figure 15. pattern at 210°

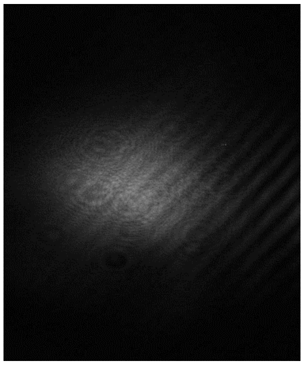


Figure 16. Plot for pattern with 2 glass slides

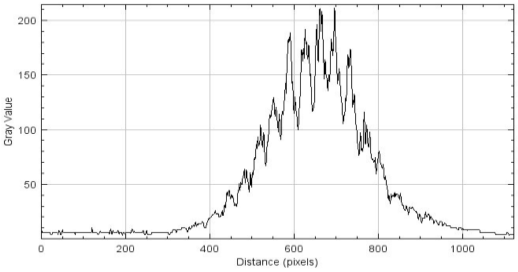


Figure 7. Plot for pattern with 3 glass slides

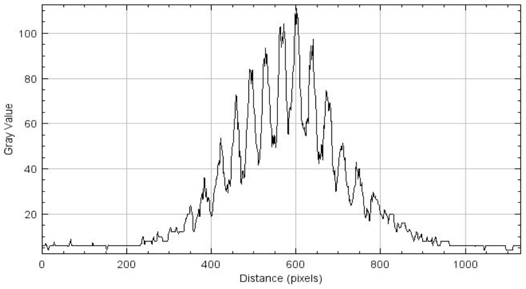


Figure 18. Plot for pattern at 280°

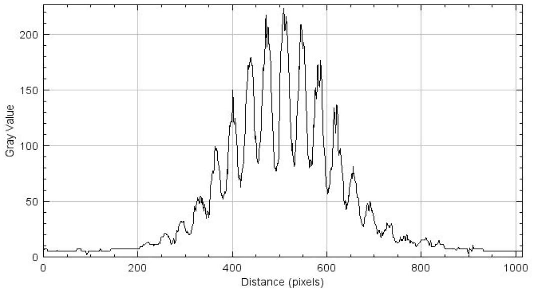
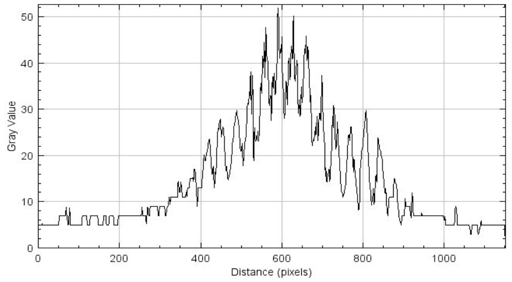


Figure 19. Plot for pattern at 230°



The MZI built in the FAST laser lab successfully showed interference patterns during this experiment. The fringe pattern is a result of the two different beam paths falling on the screen at different angles creating two virtual coherent sources. For different positions of the screen at which the beam falls upon, the interacting beams acquire different phases. If the phase of one path is changed, the position of the dark and bright fringes will shift. The introduction of glass slides within one arm creates this change in phase. This is due to the increased optical path length of one arm. Consequently, a large phase discrepancy results in a prominent shift of the constructive and destructive interference patterns. The glass slides can also be rotated to increase or decrease the amount of glass traversed by the light as shown in Figure 8-15. As the optical path length increases due to the rotation of the glass at a greater angle, the fringe width becomes narrower. The increase in the number of fringes as the angle with which the glass plates are rotated can be seen from figure 18 to figure 19.

The addition of glass slides or the rotation of glass slides in one arm of the interferometer both have the same effect on the interference pattern of the beam. Opting for the addition of glass slides remains the most effective approach as it ensures the beam's trajectory remains unchanged. Due to refraction a change in the angle will also change the path. By simply increasing the quantity of slides along the path, the beam will strike the surface of the slide perpendicularly, thus maintaining its trajectory unaffected due to the refraction angle being zero. Conversely, rotating the slides and increasing the angle at which the beam strikes the glass slide will result in a parallel path to the beam, indicating a slight shift as it deviates from its original trajectory. For the recombination of the beam, alignment of both paths is imperative to achieve the optimal interference pattern; thus, deviating the path would not be advisable in general.

When the images are observed, the diminished fringe contrast can be attributed to inadequate longitudinal overlap of pulses in the two arms. This problem may also arise from dust particles that have been captured either on the slide or the camera, thereby causing interference with the resulting images. Enhanced data quality and a more methodical approach to measurements would be necessary to facilitate a quantitative analysis. Nevertheless, the fundamental principle of Interference is effectively illustrated, indicating the potential utility of this technique in the context of the forthcoming phase 2 of the OSC experiment. The characterization of the interferometer using the glass slides allows us to study the change in phase which causes a change in fringe pattern. By extracting this data adjustments and alignments can be made. After which we can use one arm of the interferometer for the nonlinear amplification process and measure the unknown phase changes due to the nonlinear conversions.

CONCLUSIONS AND SUMMARY

In preparing for the upcoming phase 2 of the Optical Stochastic Cooling experiment, a Mach-Zehnder interferometer will be employed to measure phase distortions of the amplified light as a function of amplifier gain. A basic Mach-Zehnder Interferometer system was prototyped to gain familiarity with the instrumentation and procedures for the required phase measurements. Interference was observed using a 1053-nm pulsed laser, and glass slides were then used to modify the relative phase (delay) of the interferometer's two arms. For the upcoming 2-mm OSC measurements, automation of the fringe measurements using diode detectors and closed-loop piezoelectric stages is needed.

ACKNOWLEDGMENTS

I express my gratitude to my primary supervisor, Travante Thompson, for his invaluable guidance during the process of acquiring knowledge and carrying out my project. I am also thankful to my secondary supervisor, James Santucci, for his assistance in documenting the project and for serving as an exceptional advisor and mentor throughout the entirety of the project. Furthermore, I extend my appreciation to Abhishek Mondal, who played a crucial role as the principal physicist in the laser facility, enabling me to conduct my project effectively, and to Johnathan Jarvis for his efforts in educating and reviewing various aspects for me. Lastly, I wish to acknowledge the URA for affording me the privilege of this prestigious internship at such an early stage of my professional journey, and for offering opportunities for young female undergraduates like me to enhance their knowledge and advance in their respective careers.

SCIENCE POLICY STATEMENT

The mission of the Fermilab Accelerator Science and Technology facility is to develop a fully equipped R&D accelerator chain to facilitate the advancement of accelerator science and technology for upcoming generations of particle accelerators. The primary focus is the Integrable Optics Test Accelerator (IOTA) ring, which is the center of the advanced beam cooling project. Moving stochastic cooling from the microwave regime to optical frequencies and bandwidths can increase achievable cooling rates by three to four orders of magnitude and provide a powerful tool for future accelerators. This directly aligns with the mission of the laboratory to build and operate world-leading accelerator and detector facilities. Using OSC, there is a chance to cool much denser beams allowing for more efficient accelerators. The role of National science policy in securing funding for this project is crucial to make this a possibility. By securing adequate funding for long term research plans and ensuring the labs and facilities are well-equipped the advancement of OSC research can be achieved and can create a profound impact on the development of new technologies.

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This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.