The Poisson Alignment Reference System
Implementation at the Advanced Photon Source[*]

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1. INTRODUCTION

1.1 Background

Lee Griffith of Lawrence Livermore National Laboratory has proposed an alignment system for accelerators and free-electron lasers (FEL) utilizing the Poisson spot [1]. The Poisson spot (aka the Spot of Arago [2]) is a diffraction effect that occurs when an opaque sphere is illuminated with a plane wave from a laser beam. First, a line of light, the Poisson line, is generated in the shadow of the sphere that extends from the center of the sphere normal to the initial plane wave. Second, as distance from the sphere increases, the intensity increases asymptotically reaching no more than the incident intensity. Third, the diameter of the line is inversely related to the diameter of the sphere. A larger sphere results in a thinner line and vice versa. Finally, the diameter of the line increases with distance, yet it can always be kept smaller than a Gaussian beam. As a result, the location of the beam can always be resolved with higher accuracy [1].

To be defined as a straight line reference (SLR), the location of a minimum of two points on this line must be known. The center of the sphere is the first point while the center of a quadrant detector may be the second point. A quadrant detector uses four photovoltaic or photoresistive elements to provide an indication of the displacement of the mean energy of a light spot relative to the center of the detector. Due to vibrations, laser drift, thermal expansion, and related phenomena, the Poisson line may not intersect the center of the detector; therefore, active steering of the line is necessary to insure this alignment. The result: a SLR.

Griffith describes the setup for generating an SLR (shown in Figure 1) as follows. A laser provides the necessary coherent light that is filtered by a pinhole. Next, the light is reflected from a piezoelectrically steered mirror. This mirror allows the Poisson line to be steered so that it always coincides with the center of the detector. Then the light is collimated, projected on a sphere, propagated through a vacuum pipe, and finally observed at the detector. A feedback system insures that the Poisson spot generated by the line is always centered on the detector. Once generated, the SLR can be used as a reference by inserting more spheres and detectors in the collimated laser beam. These spheres would be attached to beamline components that need alignment. The position of the Poisson spots on the additional detectors would be indicative of the alignment state of the accelerator.

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The Poisson alignment system (PAS) has several advantages. First, it would ultimately provide accuracy to 25 µm over a distance of 300 m; a factor of four improvement over previous methods [1]. Second, the system would offer the ability to monitor accelerator alignment in real time. Also, conceptually the system is fairly simple and able to be constructed without highly specialized parts.

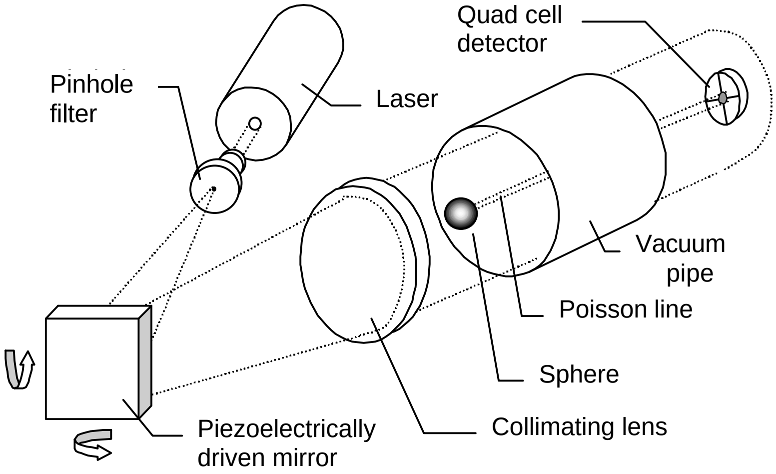

Figure 1: Poisson straight line reference (SLR) system proposed by Griffith.

These are promising advantages. An experimental setup of the PAS has been started at the Advanced Photon Source (APS), located at Argonne National Laboratory, so that its practical functionality can be evaluated. Success of the project could lead to a new alignment system for the low-energy undulator test line (LEUTL) currently under construction at the APS.

1.2 Project steps

The project was divided into several phases:

- Phase One goals: To establish a visible Poisson spot.
  To monitor spot drift using a quad cell.
- Phase Two goal: To establish an SLR using a feedback loop.
- Phase Three goal: To actively monitor the alignment status of a second sphere.

The rest of this paper focuses on describing the advancements and stumbling blocks met in phases one and two. Recommendations are also provided for future work needed to complete phase two and begin phase three.

2. METHODS AND MATERIALS

2.1 Data acquisition/processing equipment

A National Instruments E series 16-bit I/O (model AT-MIO-16XE-10) coupled to a rack-mounted BNC adapter and an IBM-compatible 166-MHz Pentium computer were used for data acquisition and analysis. This data acquisition card provides up to eight differential inputs and two analog outputs. The National Instruments VirtualBench Suite was also used as a real-time oscilloscope and data logger. The differential data acquisition mode was used exclusively.

2.2 Optical equipment

Laser: A Class IIIa, 3 mW, 635 nm, continuous diode laser, manufactured by Applied Laser Systems, was used. In terms of power, this is comparable to a standard laser pointer commonly used for presentations. A Newport focusing lens was placed in front in order to pass the beam through the pinhole.

Pinhole: A 10-micron platinum-iridium pinhole was used.

Kinematic mirror mount and driver: The kinematic mirror mount was a Thor Labs Inc. KC1-PZ three-axis model coupled to a Thor Labs model MDT690 three-channel piezo driver. The driver had inputs for each channel enabling easy connection to the output of the DAQ card. A first surface mirror was mounted on the stand. The manufacturer claims a 5%-10% positional hysteresis value at room temperature. However, this is not important since only the spot displacement on the detector and not actual mirror position is of importance.

Collimating lens: A 7.5-cm-diameter collimating lens was chosen.

Poisson spheres: Three spheres of differing diameters were investigated: 0.09375”, 0.15625”, and 0.1875”. They were opaque black spheres that were glued to a glass plate and placed in the collimated laser beam.

Detector/amplifer: The quadrant detector was a model 1240 manufactured by Graseby Optronics. It is a silicon photovoltaic detector. Two Model 301-DIV (one for each axis) signal conditioning amplifiers were used to amplify the signal from the detector. These have multiple amplification settings ranging from 3 k to 1 M. The bandwidth is DC to 5 kHz. The position output of each is equal to the difference between the currents of the two cells of an axis divided by the sum of the currents, times 10 volts. Thus the range is –10 V to +10 V with 0 V corresponding to perfect alignment. One amplifier is used for each axis. The detector was mounted on an X-Y translation stage.

Lock-in amplifier system (LIAS): A model MC100 optical chopper, model PC100 phase controller, and model LIA100 lock-in amplifier, all from Thor Labs, were used. These were borrowed for 30 days in order to investigate their feasibility to improve the signal-to-noise ratio. Any improvements that were found did not justify the additional cost of this equipment. They were returned to the vendor.

Optical table: A Newport 5’ × 3’ stainless steel/composite sandwich breadboard (model SG-32-2) was used. Standard ¼-20 holes were spaced equally 1” apart. The stand was a simple steel support with no damping mechanisms (Newport model VH-3660).

Camera: A single-lens reflex camera with standard 35-mm color film was used to photograph the diffraction patterns from the Poisson spheres.

2.3 Experimental setup and calibration

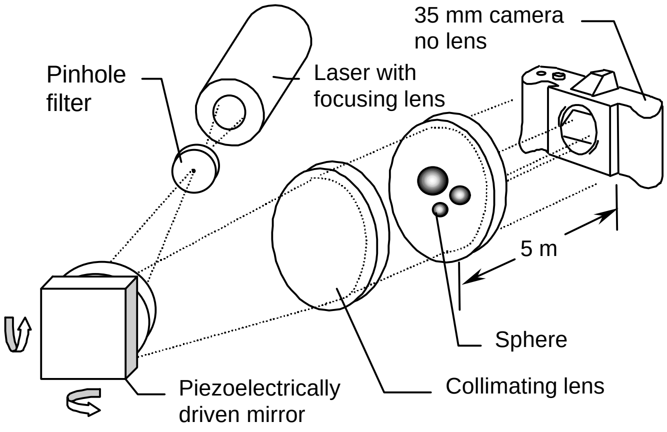

Figure 2: Experimental setup for photographing Poisson spots. Note that the diffraction pattern is exposed directly on the 35-mm film.

Photographing the Poisson spots: The experimental setup was similar to Griffith's. To photograph the Poisson spots, a single lens reflex camera without any lenses was used as shown in Figure 2. In this way the resulting diffraction pattern was exposed directly on the film.

Feedback investigation: Figure 3 shows the experimental setup used in phase two to establish an SLR. The output from the quad cell is amplified by two amplifiers, one for each axis. The result is a voltage output that is proportional to spot displacement from the detector center. Next, the signals are processed by a 166-MHz Pentium PC with a 16-bit I/O card. The feedback processing was done using LabView, a graphical programming language. Then, using the output channels of the card, the signals were sent to the piezo driver. Finally, the driver amplifed the signal to the 0-150 V working range of the piezo stacks in the kinematic mirror. Note that although both the mirror and the driver allow up to three axes of rotation, only two were used.

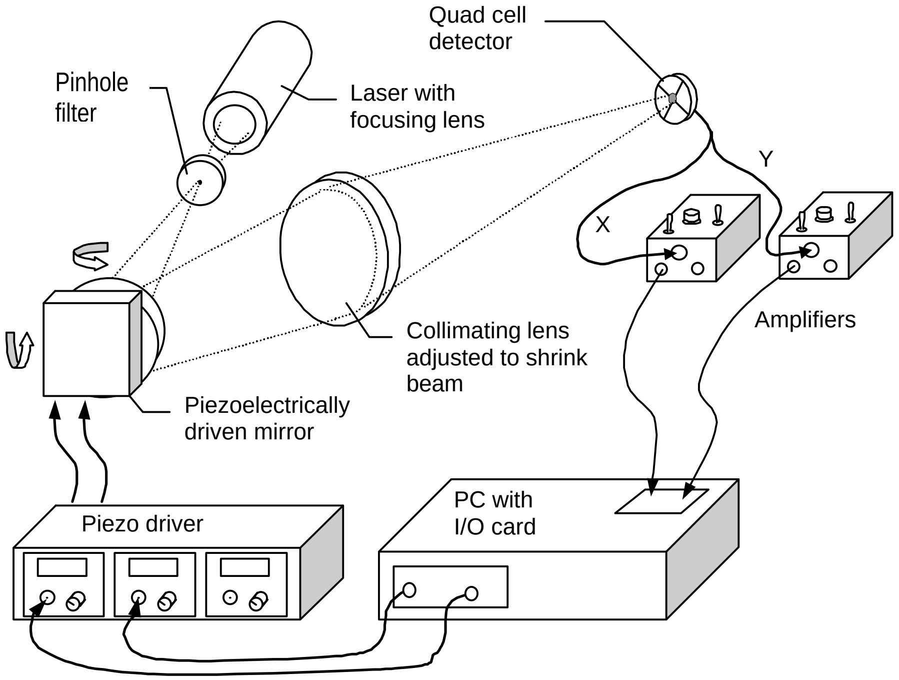

Figure 3: Experimental setup for investigating digital feedback system.

Calibrating the detector: The detector was mounted in a V clamp on a translation stage so that it moved in the plane perpendicular to the beam. A 3-mm spot was obtained by moving the collimating lens and by adjusting an iris placed between the mirror and the lens. Although the iris caused a circular diffraction pattern in the spot, it was still used. The amplification on both 301 DIVs was set at 300 k. In order to limit the effects of transient air currents and vibrations, each micrometer was moved by 0.01 mm and then 1000 samples were taken from both X and Y position outputs at a sample rate of 10 kS/s. The average of the samples was used for each calibration data point. The direction of translation was then switched, resulting in two lines for each axis. The Virtual Bench Oscilloscope module was used to acquire the data. The rotation of the detector was visually adjusted so that its X and Y axes were coincident with the X and Y axes of the translation stage. One overhead neon bulb remained on with the side toward the detector covered by black masking tape. The collimator lens was about 5 m away from the detector. In total, 70 separate data sets were taken; however, the first 13 were discarded because of initial errors in the setting of the micrometers.

3. RESULTS

Much time was invested in securing the equipment necessary for this project in order to collect data.

3.1 Phase One results

The interference patterns generated by the three spheres are shown in Figure 4. Note that the largest sphere created the smallest spot while the smallest sphere created the largest spot. Qualitatively, the diffraction patterns are readily visible and the Poisson spots are easy to distinguish. However, the downward sloping waves covering the whole photograph indicate some spurious interference caused by the optical components. The effects are negligible as compared to overall intensity.

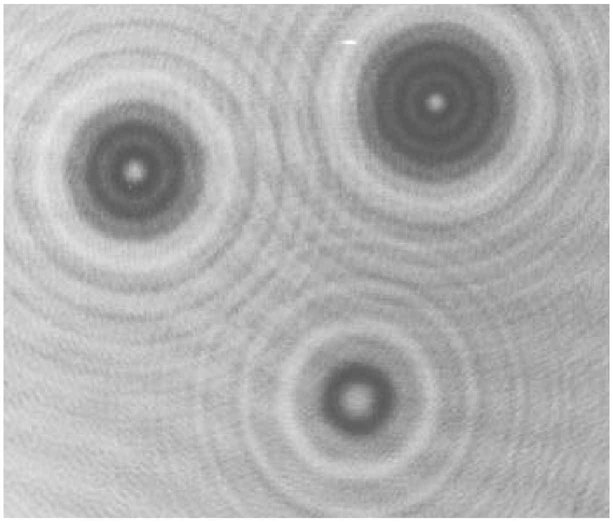

Figure 4: Poisson spots at 5 m from 0.09375", 0.15625", and 0.1875" diameter spheres.

The largest spot was chosen and monitored using the oscilloscope software. An iris coinciding with the first dark ring was placed immediately in front of the detector to prevent the detector from ‘seeing’ anything but the spot. As expected, the signal strength was quite low even with a maximum amplification of 1 M. After all, the beam was expanded to 7.5 cm from only a 3-mW laser. Even so, vibrations and moving air were readily apparent. Even placing a hand under the beam shifted the spot noticeably since the heat caused a rising air current with a different refractive index than the surrounding air.

3.2 Phase Two results

Since neither a more powerful laser nor a more sensitive detector were immediately available, the collimating lens was adjusted to contract the beam to a spot that we hope is comparable in intensity to one that would be possible with a stronger laser. This is the ‘simulated’ spot. See Figure 3.

Detector calibration: As Figure 5 shows, the calibration curve for both axes is highly linear with one volt being equal to 75 microns of displacement.

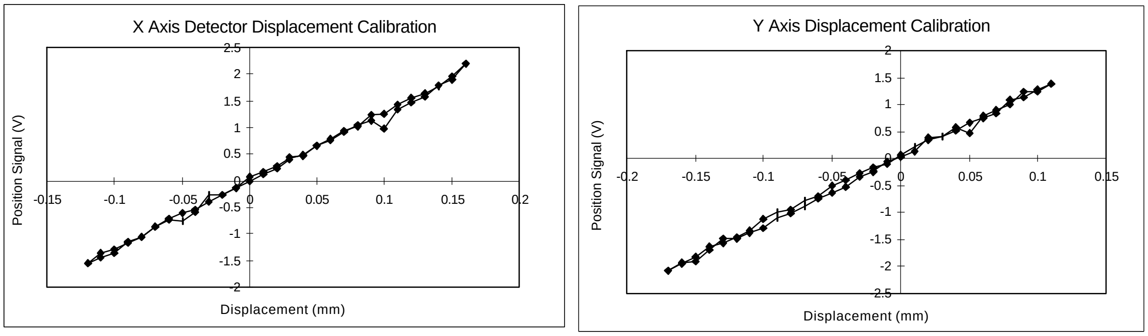

Figure 5: X and Y axis detector calibrations for 3-mm ‘simulated’ spot at a distance of 5 m.

Single axis controller: A LabView proportional-integral-derivative (PID) controller was chosen to correct for the drift in the X axis. Using educated guesses, the PID loop was tuned to the correct parameters. Based on the screen refresh rate, the bandwidth of the LabView program was estimated to be 47 ± 9 Hz. The system succeeded in reducing longer-term variations from zero; however, it was not fast enough to reduce oscillations exceeding 5 Hz. An audible clicking was constantly heard during operation. Based on the calibration data, we estimate that the system kept the spot centered on the X axis to within 8 ± 2 microns.

Biaxial controller: The single-axis controller program from above was modified in order to control both axes. Due to software conflicts within LabView, this program proved to be useless.

Effect of spot size on amplifier signal output: During experimentation we noted that, for a given displacement, the sensitivity of the system depends on spot size. The smaller the spot size, the higher the sensitivity. A simple theoretical analysis enforced this empirical data [3]. A constant intensity spot of radius *r* was projected on two hypothetical, adjacent photovoltaic cells separated by an infinitesimal line. Then, for a given spot displacement, a value representative of amplifier output was derived in terms of the radius *r* and the displacement y_d [3]. The resulting equation is

$$S(r, y_d) = \frac{\pi r^2 - 4\int_0^{r-y_d} \left(r^2 - (y - y_d)^2\right)^{\frac{1}{2}} dy}{\pi r^2} \quad . \qquad (1)$$

A plot for y_d=0.5 units may be found in Figure 6; it verifies the experimental observation.

4. RECOMMENDATIONS

4.1 Recommended equipment

For continuation of the project, the following equipment is recommended:

- *Oscilloscope:* to monitor analog signals while freeing up the computer for dedicated DAQ
- *Sealed vacuum pipe:* at least 15 cm in diameter with a length of at least 5 meters; should have a vacuum of at least 10^{-3} Torr but the higher the vacuum the better
- *Detectors and amplifiers:* several more quad cell detectors and biaxial amplifiers; preferably quad cells with smaller detector areas in order to enhance the signal-to-noise ratio
- *Analog PID controller:* for higher feedback bandwidths, [3] contains a sample schematic
- *Laser and power supply:* a more powerful laser (see below)

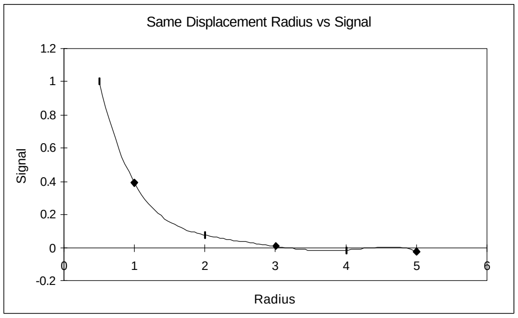

Figure 6: Theoretical radius vs. signal for a single-axis detector with y_d=0.5 units.

4.2 Laser power necessary for best detector signal

The most effective way to improve the signal is to increase the power density of the light incident as the Poisson spot. The maximum power density for the 1240 series quad detectors is 10 mW/cm^2. A simple estimate of the amount of laser power needed may be found by multiplying this maximum power density by the area of the collimated beam. For a 7.5-cm beam, this corresponds to about 500 mW, much greater than the 3-mW laser that was used. Of course, this is a conservative calculation since some power is lost by reflection from optical surfaces and stray illumination (as in light hitting apertures). A better estimate would be closer to 1W. Both estimates indicate that a Class IIIb laser is needed. Too much power should not be a severe concern because the power can be easily adjusted in diode lasers by regulating the current. Other lasers may be modulated optically.

4.3 Novel Poisson sphere positioning system

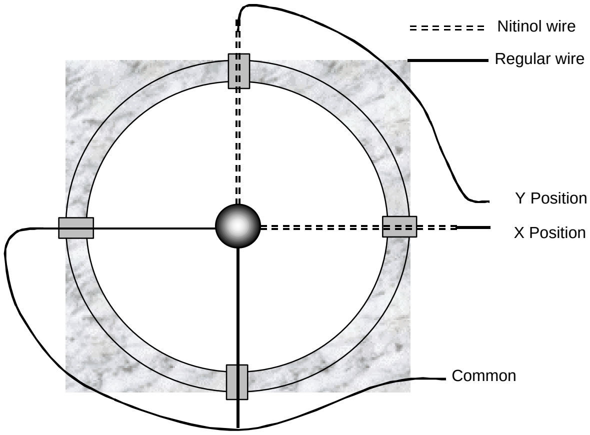

Figure 7: Novel sphere positioning system.

At times it may be necessary to reposition a Poisson sphere by moving it very slightly without costly mechanical methods such as translation stages. Presented in Figure 7 is an idea for positioning a sphere in a plane. The basic mechanism consists of four radial wires stretching outward from a common electrically conductive connection at the center. Two adjacent wires are made out of regular material such as copper, aluminum, or steel. The other two are 'muscle wires' (nitinol) that have the unusual property of being able to contract when an electric current flows through them because of the locally generated heat. By varying the current through each of these two wires they can be made to contract with a very fine resolution. The regular wires will lengthen slightly because of their elasticity, and the sphere can be positioned with great finesse. Because the precision of this device depends upon the temperature of the wires, it will not work when exposed to intense radiation fluxes, air currents, etc. However, it may be ideal for use in a shielded vacuum pipe where only relatively low-power laser light will be present.

5. SUMMARY & CONCLUSION

The Poisson spot was established using a collimated laser beam from a 3-mW diode laser. It was monitored on a quadrant detector and found to be very sensitive to vibration and air disturbances. Therefore, for future work we strongly recommend a sealed vacuum tube in which the Poisson line may be propagated.

A digital single-axis feedback system was employed to generate an SLR on the X axis. Pointing accuracy was better than 8 ± 2 microns at a distance of 5 m. The digital system was found to be quite slow with a maximum bandwidth of 47 ± 9 Hz. Slow drifts were easily corrected but any vibration over 5 Hz was not. We recommend an analog PID controller for high bandwidth and smooth operation of the kinematic mirror.

Although the PAS at the Advanced Photon Source is still in its infancy, it already shows great promise as a possible alignment system for the low-energy undulator test line (LEUTL). Since components such as wigglers and quadrupoles will initially be aligned with respect to each other using conventional means and mounted on some kind of rigid rail, the goal would be to align six to ten such rails over a distance of about 30 m.

The PAS could be used to align these rails by mounting a sphere at the joint between two rails. These spheres would need to be in a vacuum pipe to eliminate the refractive effects of air. Each sphere would not be attached to either rail but instead to a flange connecting the vacuum pipes of each rail. Thus the whole line would be made up of straight, rigid segments that could be aligned by moving the joints. Each sphere would have its own detector, allowing the operators to actively monitor the position of each joint and therefore the overall alignment of the system.

6. ACKNOWLEDGEMENTS

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8. REFERENCES

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[3] I. Feier, Argonne National Laboratory, private communication.