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Overview of laser systematics

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Abstract. This paper discusses systematic effects in parity experiments that originate from the laser and optics system that are used in a polarized electron source. Covered are both the sources of systematics, as well as strategies for their minimization.

PACS. 29.25.Bx Electron sources – 29.27.Hj Polarized beams – 42.25.Ja Polarization – 42.25.Lc Birefringence – 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries

1 Introduction

In general, experiments that study parity violation in electron scattering utilize a polarized electron source that is based on photo-emission from various types of gallium arsenide (GaAs) crystals. The photo-emission is induced using circularly polarized light from a laser. Because the helicity of the electron beam is determined by the polarization state of the laser light, the electron polarization can be reversed or "flipped" quickly and in a quasi-random manner by using an electro-optical device such as a Pockels cell to circularly polarize the light. Parity experiments typically measure tiny helicity-dependent asymmetries in the scattering of polarized electrons off unpolarized targets. The asymmetries themselves might range from 0.1 parts per million (ppm) to 100 ppm, and it is sometimes necessary to control helicity-correlated systematic effects at the level of parts per billion. In experiments where electronic crosstalk is sufficiently under control, the helicity-correlated changes in the parameters of the electron beam generally originate in helicity-correlated changes in the light used to induce photo-emission. Laser systematics are thus critical to achieving increasingly accurate measurements of parity violation in electron scattering.

Ever since the first pioneering experiment that observed parity violation in electron scattering [1], the understanding of laser-based systematics has grown. It is now possible to catalog some of the dominant effects, including how they can be diagnosed, and in some cases corrected. Indeed, the improvement of our understanding of laser systematics has played a critical role in making increasingly sensitive parity experiments possible.

This paper will examine some of the laser systematics that were dominant during several experiments with which the author was involved [2–5], as well as discussing strategies for their minimization.

2 The various types of systematics

In the absence of any effort to control them, the largest systematic in a parity experiment will generally be helicity-correlated asymmetries in the charge delivered to the target. While it is certainly important to measure and correct for "charge asymmetries" this can only be done up to a point. Beam current measuring devices will always have nonlinearities at some level. Even if one had a perfect device for measuring beam current, there is still the possibility that through interaction with the accelerator, such as beam loading, charge asymmetries could be translated into other helicity-correlated effects. Fortunately, it is reasonably straightforward to "balance" the charge delivered to the target over the course of an experiment at the level of a few hundred parts per billion (ppb) resulting in systematic uncertainties in the parity violating asymmetry of a few ppb.

If charge asymmetries are the "zeroth-order" effects, the first-order effects are then helicity-correlated differences in the beam position. Since charge asymmetries are reasonably straightforward to control, these "position differences" end up being a more troublesome problem. Many recent parity experiments have had significant contributions to their systematic errors from helicity-correlated position differences [4,5].

Even if charge and position differences are reduced to negligible levels it is still possible to be troubled by higher-order effects. For instance the spot size of the laser can systematically change while position and charge are held fairly constant. One issue that needs to be considered is whether the elimination of lower-order effects simply results in the increase of higher-order effects. This makes it desirable to have diagnostics for higher-order effects even if there is no obvious way to control them.

3 The sources of systematics

3.1 Charge asymmetries

Charge asymmetries result when the average current associated with one helicity state is different from the average current associated with the other helicity state. The dominant mechanisms associated with this effect are well understood, and have been described in some detail for both simple [6] and more complex [7] optics setups. The asymmetries stem from the fact that when making circularly polarized light, there are always small admixtures of linear polarization which cause a small degree of ellipticity. When the helicity of the light is flipped, it is often the case that the major axis of the polarization ellipse will rotate by 90°. Since most optics systems have many elements (for instance mirrors) that transport one linear polarization better than another (a property we will refer to as a transport asymmetry), flipping the helicity can cause a change in the efficiency with which the light delivered to the cathode. Historically, this type of effect has sometimes been referred to as the "PITA" effect, where PITA is an acronym standing for "polarization induced transport asymmetry" [6]. The PITA effect thus results from the fact that the optics system has an "analyzing power" with an accompanying analyzing-power axis.

In polarized electron sources, the optics transport system is not the only component with an analyzing power. Bulk GaAs has a theoretical maximum polarization of 50%, and values of 35-45% are typical. Recently it has become common to use modified GaAs crystals such as strained GaAs or super-lattice GaAs because in such crystals a degeneracy associated with the valence band is broken raising the theoretical maximum polarization to nearly 100%, with values of 70-82% being typical. The improved polarization of these photocathodes comes at a price. When irradiated with linearly polarized light, these photocathodes have a quantum efficiency (QE) that depends on the orientation of the light's polarization axis with respect to an axis that lies in the plane of the crystal's surface. The crystal itself thus has an analyzing power. Figure 1a illustrates the direction of the analyzing-power axis. The QE anisotropy associated with the analyzing-power axis can be as much as 15%.

The analyzing power of the crystal has essentially the same effect on beam current as does a transport asymmetry. When the crystal is illuminated with elliptically polarized light, the photo-emitted current depends critically on the position of the major axis with respect to the analyzing-power axis. If the polarization ellipses associated with the two helicity states are as indicated in Fig. 1b, a maximal charge asymmetry will result. If the polarization ellipses are oriented as indicated in Fig. 1c, a minimal charge asymmetry will result.

Whether a charge asymmetry results from a laser-beam transport asymmetry, or from an anisotropy in the photocathode's QE, it is straightforward, and useful, to characterize the effect quantitatively. For definiteness, we will assume that the device used to produce circular polarization is a Pockels cell, oriented so that its fast axis is at ±45° with respect to horizontal. We will further assume that prior to traveling through the Pockels cell, the light is linearly polarized in the horizontal direction. It is convenient to parameterize the phases introduced by the Pockels cell as

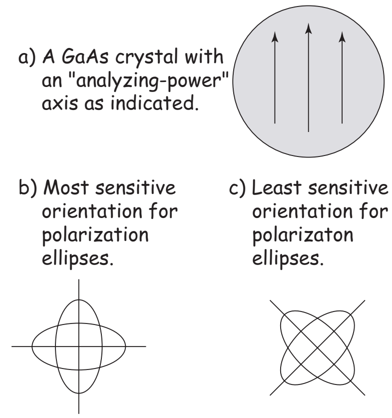

Fig. 1. a Illustrated is a GaAs crystal with a quantum efficiency that is sensitive to the orientation of linear polarization with respect to the indicated analyzing-power axis. **b** Polarization ellipses for nominally positive and negative helicity light resulting in maximum charge asymmetry. **c** Polarization ellipses for nominally positive and negative helicity light resulting in minimum charge asymmetry

$$\delta^R = -\left(\frac{\pi}{2} + \alpha_1\right) - \Delta_1 \qquad (1)$$

$$\delta^L = +\left(\frac{\pi}{2} + \alpha_1\right) - \Delta_1 \quad . \qquad (2)$$

If $\Delta_1 = \alpha_1 = 0$, the phases introduced by the Pockels cell are $\pm\frac{\pi}{2}$, and in principle, the light will have perfect circular polarization. If either Δ_1 or α_1 are nonzero, however, elliptical polarization will result. I note in passing that we are using the subscript 1 for α and Δ to be consistent with the notation of [7]. Let us now assume that the light, after passing through the Pockels cell, passes through an asymmetric transport system, characterized by two orthogonal axes x' and y', where the x' axis makes an angle θ with respect to the horizontal. We will assume that light linearly polarized along the $x'(y')$ axis will be transported with a transmission coefficient $T_{x'}(T_{y'})$, and define the quantities $T = (T_{x'} + T_{y'})/2$, and $\varepsilon = T_{x'} - T_{y'}$. With these definitions, the charge or equivalently current asymmetry A_I can be written to first order as

$$A_I = \frac{I^R - I^L}{I^R - I^L} = \frac{\varepsilon}{T}\Delta_1 \cos 2\theta \qquad (3)$$

where $I^R(I^L)$ are the electron beam intensities associated with the Pockels cell phases $\delta^R(\delta^L)$. The reason we chose to write the phases as we did in 1 and 2 is immediately apparent. The equation for A_I depends linearly on Δ_1, but not at all on α_1. The reason is as follows. If $\Delta_1 \neq 0$, polarization ellipses result whose major axes will rotate by 90° when the helicity is flipped. That is, if $\Delta_1 \neq 0$ we have a situation such as is illustrated in Fig. 1b. If $\alpha_1 \neq 0$, the polarization ellipses for the two helicity states will be

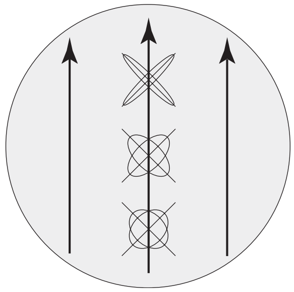

Fig. 2. Illustrated is a GaAs crystal being irradiated by light in which the residual linear polarization is varying from a maximum toward the top of the crystal to a minimum toward the bottom of the crystal

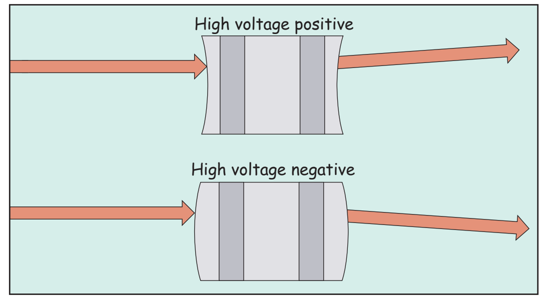

Fig. 3. Illustrated is steering due to a Pockels cell having lens-like properties when it is pulsed at high voltages

coincident with one another. Only the *direction* that the electric vector travels around the ellipse will change. We will discuss later how 3 can give us guidance in suppressing charge asymmetries.

One final comment regarding the phase Δ_1. It should be noticed that the *sign* of Δ_1 does not change when the phase on the Pockels cell is flipped. Thus, any object in the optics system, a vacuum window, a mirror, or even residual birefringence in the Pockels cell, can cause a non-zero value of Δ.

3.2 Position differences from phase gradients

In the previous section we discussed how a charge asymmetry can result from a non-zero value of the phase Δ_1. If we consider a laser beam spot illuminating a GaAs crystal, it can also be the case that the phase Δ_1, and hence the associated charge asymmetry, varies in some manner across the laser spot. Such a situation is illustrated in Fig. 2. If the charge asymmetry for the emitted electrons changes as we move from the top of the crystal to the bottom, the beam profiles for the two helicity states will have centroids that are shifted vertically with respect to one another. From the perspective of our beam position monitors, these shifts will be seen as helicity-correlated position differences. To first order, the position differences will be *proportional* to the gradient of the phase Δ_1, and *independent* of the average value of Δ_1.

3.3 Position differences from steering effects

Another source of helicity-correlated position differences is steering caused by the Pockels cell. The Pockels cell is alternately pulsed to positive and negative high voltage in order to introduce the phases given by 1 and 2. Empirically, it appears that this results in the Pockels cell behaving alternately as a diverging and converging lens. If a laser beam is sufficiently small in diameter and goes through the very center of the Pockels cell, the steering effects can be kept quite small. As one goes off center, however, some steering occurs as would also be the case with any lens. This effect, which is illustrated in Fig. 3 can be quite significant.

3.4 Position differences from gradients in the analyzing power of the cathode

The last class of effects we will mention arises from changes in the QE anisotropy as we move across the cathode. For instance, assume that the *direction* of the analyzing-power axis is constant, but that the *magnitude* of the anisotropy changes from 5% at the top of the cathode to 10% at the bottom. If the incident light is perfectly circularly polarized, there is no component of linear polarization and hence no charge asymmetry. If there is residual linear polarization, however, there could be a charge asymmetry whose size varies across the crystal, resulting in changes in the centroid of the electron beam's position much as was discussed in Sect. 3.1. The reader should note that this type of position difference should be proportional to the degree of ellipticity of the light, and hence Δ_1. This is in contrast to the position differences from phase gradients (Sect. 3.1) where to first order we would expect no dependence on Δ_1. This difference in response to Δ_1 is a useful diagnostic tool for distinguishing between phase gradients in the optics system and analyzing-power gradients on the cathode.

4 Controlling systematics

4.1 Charge asymmetries

There are at least three strategies for controlling charge asymmetries and 3 is useful for understanding two of them.

4.1.1 Phase adjustments

The phase Δ_1 can be controlled using the Pockels cell. The nominal voltage at which the Pockels cell is pulsed is $\pm 2.7\,\mathrm{kV}$. If a fixed voltage is added to the voltage associated with each polarity, one can introduce an arbitrary Δ_1. For instance one could run at $+2,900$V and $-2,500$V. Notice that it is not the magnitude of each voltage that is changed, but rather its actual value. If instead we changed the magnitude of each voltage by a few hundred volts, we would be adjusting α_1 and not Δ_1, and no change to the charge asymmetry would occur.

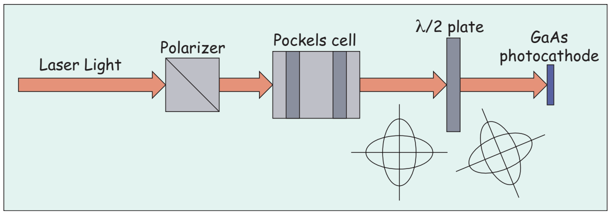

Fig. 4. Illustrated is the basic setup for using a rotating half-wave plate (RHWP) to rotate the polarization ellipses associated with the laser light

4.1.2 Rotating half-wave plate

Another way of controlling charge asymmetries is through θ (the angle that appears in 3). When the light emerges from the Pockels cell, the major axes of the ellipses are typically either vertical or horizontal. This is determined by the orientation of the fast axis of the Pockels cell, which is usually at $\pm 45°$. By introducing a half-wave plate, however, we can rotate the orientation of the ellipses. The basic setup is illustrated in Fig. 4. The goal is to rotate the ellipses toward the orientation illustrated by Fig. 1c, where the major axes are at $\pm 45°$ with respect to the analyzing-power axis. This is equivalent to adjusting θ to 45°. In a practical situation it is actually desirable to retain a small amount of sensitivity to the analyzing power of the cathode. In this way the charge asymmetry induced by adjustments of Δ_1 can be used as a diagnostic for maximizing the circular polarization of the light that actually strikes the cathode. This helps with, among other things, the position differences due to analyzing-power gradients on the cathode.

The effect of the rotating half-wave plate is illustrated dramatically by the data shown in Fig. 5. The charge asymmetry is shown as a function of the rotation angle θ of a half-wave plate using a setup similar to that shown in Fig. 4 (this θ is distinct from the θ appearing in 3). From the discussion presented here, we should expect the charge asymmetry to vary sinusoidally with 4θ. This is because a 90° rotation of the half-wave plate will rotate the polarization ellipses by 180°, at which point the pattern should repeat. This is close to what we see in Fig. 5, but not exactly. An analysis of the data (shown on the figure) reveals both 4θ and 2θ components. This is because the half-wave plate itself will have imperfections and introduce a "Δ-like" phase, and the fast and slow axes associated with that phase rotates with the half-wave plate.

For parity experiments at JLab, a rotating half-wave plate is an essential part of controlling charge asymmetries. I note in passing that at SLAC, we accomplished essentially the same thing (rotating the ellipses to an arbitrary angle) using two Pockels cell. For the sake of brevity, however, I will not discuss that approach here.

4.1.3 IA cell

The final technique for controlling charge asymmetries is to use what has come to be called an "Intensity Asymmetry" or IA cell. The IA cell is a Pockels cell that is set up between two polarizers so that it can be used as part of an electro-optical shutter. The charge asymmetry can be carefully measured, and the IA cell pulsed to a slightly different voltage for each helicity to achieve balance. This is sort of a brute-force technique, in that it does not address the underlying problems that are causing the asymmetry. It is well suited for use in a feed-back mechanism, however, and it can be done very quickly. For this reason, the use of an IA cell has become standard at SLAC, JLab, and other labs. During HAPPEX II (an IA cell was not used during HAPPEX I) and during E158, however, great care was taken to reduce charge asymmetries to something on the order of 100 ppm independent of the function of the IA cell. At SLAC this was accomplished using a "double-feedback" method. The IA cell was used in a relatively fast feed-back loop to minimize charge asymmetries, and the size of the correction being applied by the IA cell became the error signal for a second feedback loop which corrected the value of Δ_1. For HAPPEX II Δ_1 was adjusted manually before turning on the IA-cell feedback loop, and the size of the IA cell correction was monitored "by hand" to determine when further adjustments to Δ_1 were necessary. Keeping charge asymmetries small before turning on the IA cell is a good way to help ensure that higher-order effects do not become a problem.

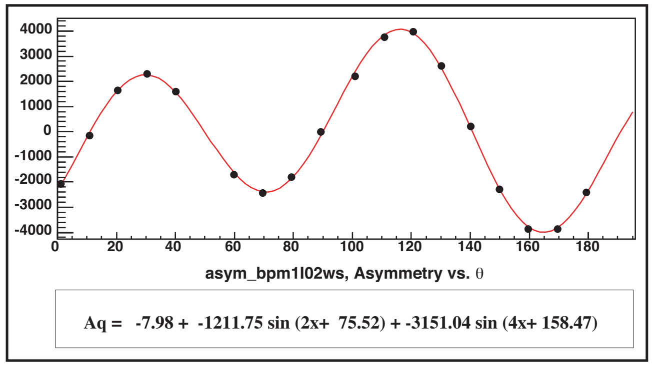

Fig. 5. Charge asymmetry (in ppm) is plotted as a function of the angle of the RHWP. Also shown are the results of a fit including a constant, a 2θ, and a 4θ component

4.2 Controlling position asymmetries

As it turns out, it is relatively easy to control charge asymmetries. Position asymmetries, however, can present a real challenge to parity experiments. There are several techniques, however, that are useful.

4.2.1 Minimizing steering

To the extent that a Pockels cell behaves like a lens, the minimization of steering can be accomplished by centering the laser beam on the Pockels cell. The Pockels cell is translated in two dimensions while monitoring the position differences. The one difficulty comes from the fact that there is no obvious way to separate position differences due to steering from position differences due to other sources. Thus, the experimenter can fool themselves that they are centering the Pockels cell when actually they are compensating for several problems at once.

In addition to precise centering of the Pockels cell, another technique for reducing the effects of steering is imaging. By using lenses to create an image of the Pockels cell at the location of the photocathode, steering effects can hypothetically be eliminated. In this configuration, rays of light emanating from the same point on the Pockels cell will all be imaged to the same spot on the cathode, regardless of their exit angle leaving the Pockels cell. Between centering and imaging, steering effects can be greatly suppressed.

4.2.2 Minimizing the effects of phase gradients

One important source of phase gradients is the Pockels cell itself. A Pockels cell will often have a residual birefringence that varies across the aperture of the cell. It is straightforward, however, to construct a small setup on an optics table to characterize such gradients. We have found that if we communicate to the vendor that this is a specification about which we are concerned, they are capable of controlling it at some level. If we subsequently characterize the phase gradients of each Pockels cell and select the best one, the effects from the Pockels cell can be substantially reduced.

Another source of phase gradients is the vacuum window through which the laser beam enters the polarized electron source. This window is generally under stress, which causes induced birefringence. It is useful to explore ways of minimizing these effects, even if this means nothing more than carefully selecting the window that is used.

Once the best Pockels cell and vacuum window have been chosen, it may still be possible to reduce the effects of phase gradients further. The position differences due to phase gradients are independent of the average value of Δ_1, but they do depend on the orientation of the fast axis associated with the gradients to the analyzing-power axis of the system. If the phase gradients are dominated by the Pockels cell, the rotating half-wave plate can in principle be used to "dial away" the effect. If the phase gradients are dominated by the vacuum window, the rotating half-wave plate will have little or no effect.

4.2.3 Minimizing the effects of QE anisotropy gradients

One obvious way of minimizing the effects of QE anisotropy gradients is to choose a photocathode in which the anisotropies are small. Assuming this has been done, it is still possible to reduce the effects to a negligible size by ensuring that the light falling on the cathode is perfectly circularly polarized. It must be remembered, however, that even if light of arbitrary polarization state can be produced outside of the vacuum system, the vacuum window will have an effect, the exact nature of which is generally unknown. In general it is not trivial to completely eliminate the effect.

If a single Pockels cell and a rotating half-wave plate are being used, there is a way to eliminate the effect of QE anisotropy gradients in the limit where the vacuum window has no birefringence. As mentioned earlier, QE anisotropy gradients are proportional to Δ_1. With a large Pockels cell voltage offset (large Δ_1), the effect will be large, and the rotating half-wave plate can be used for zeroing. In a practical situation where the vacuum window does matter, this orientation may or may not be optimal to minimize all the sources of position differences.

4.2.4 Active feedback

It is always possible to employ a piezo-electric driven mirror to actively steer the laser beam in a helicity-correlated fashion to suppress position differences. Such techniques can be quite effective, but it should be remembered that higher order moments of the laser spot will still be varying in a fully helicity-correlated manner. It is thus prudent to minimize the sources of position differences as much as possible before using brute-force feedback for suppression.

4.2.5 Adiabatic damping

If the accelerator is appropriately tuned and free of XY coupling, helicity-correlated position differences are damped as $\sqrt{A/P}$, where A is a constant and P is the momentum. This is due to the adiabatic damping of phase space that takes place as the beam is accelerated. In practice, adiabatic damping has resulted in factors of 3-10 in suppression of position differences. Factors of 50 do not appear unrealistic, but have not yet been achieved.

5 Reversals

Once everything has been done to minimize laser and optics related systematics, the experimenter can still reduce the size of systematic errors by employing a range of "reversals" in which some action is taken that changes the sign of the physics asymmetry without changing the sign of certain helicity-correlated systematics. In this manner the effect of the systematic cancels out when computing the final physics asymmetry. In certain cases reversals can play a large role in taking a very troublesome systematic and suppressing it to a negligible level.

One such reversal utilizes an "insertable half-wave plate", not to be confused with the rotating half-wave plate discussed earlier. Inserting such a half-wave plate will flip the helicity of the light striking the cathode, ultimately resulting in a flip of the sign of the physics asymmetry. Certain systematics, however, will not flip sign, including steering effects and electronic cross talk. Helicity-correlated steering is one of the important sources of beam-position differences, making the the insertable half-wave plate an important part of the full setup.

Another reversal that was used during SLAC E158 was an "asymmetry inverter" [7], which is essentially a pair of two beam expanders which, together with the other optical elements, provides either a positive or negative magnification of equal magnitude between the the object point near the Pockels cell and the image point at the cathode. Both position and angle differences should in theory be eliminated by using an asymmetry inverter.

The final reversal we will mention involves the use of $g-2$ precession, the fact that when an electron beam at high energies traverses an angle θ the spins will precess by an amount $(g-2)\,\gamma\,\theta/2$, where γ is the Lorentz factor. If it is possible to run at two different energies such that the electron will arrive at the target with two different helicity states while other energy-dependent quantities are sufficiently well understood, one has a way of flipping the physics asymmetry that truly has nothing to do with the polarized electron source, and would thus leave source-related helicity-correlated systematics unchanged. Perhaps the largest drawback of this approach is that changing energy is time consuming, and hence cannot be done as frequently as one might want from the perspective of controlling systematics. It is very reassuring, however, to see a physics asymmetry flip sign during such an energy change.

6 Summary

There has been significant progress in the understanding of laser systematics since the early studies of parity nonconservation in electron scattering in the late 1970's. The control of such effects has made it possible to study progressively smaller asymmetries with increasing accuracy.

Certainly an area of notable progress has been an improved understanding of the origins of position differences. Whereas steering effects have been identified for some time [2], the identification of phase gradients and QE anisotropy gradients as a source of position differences has brought an important new perspective to the field. I try to summarize some of what we have discussed in Table 1. In the first row of this 2×2 matrix are a few of the things to which the effects of phase gradients are sensitive. The first column represents the sensitivities of the effects of phase gradients in the Pockels cell and the second column represents the sensitivities of the effects of phase gradients in the vacuum window. It is noted that in both cases, the position differences are independent of Δ_1. In the case of phase gradients from the Pockels cell, however, the rotating half-wave plate (RHWP) can be used to zero out the effect. In the second row of this 2×2 matrix are a few of the things to which the effects of QE anisotropy gradients are sensitive. The first column represents the interaction of QE anisotropy gradients with the residual birefringence of the Pockels cell. The second column represents the the interaction of QE anisotropy gradients with the birefringence of the vacuum window. The table indicates that both Δ_1 and the RHWP can be used to control the effects of the Pockels cell residual birefringence with the QE anisotropy gradients. The table entry under vacuum window in the second column is indicating that these effects are zeroed in the limit of perfect circular polarization, but no specifics are given regarding how to achieve that limit.

Table 1. The sensitivities of position differences

	Pockels Cell	Vacuum window
Phase gradients	ind. of Δ_1 sens. to RHWP	ind. of Δ_1 insens. to RHWP
QE anisotropy gradients	prop. to Δ_1 sens. to RHWP	sens. to degree of circ. pol.

Table 1 is useful for formulating strategies to minimize position differences. One possibility is to magnify the effects of QE anisotropy gradients due to the Pockels cell by using a large offset voltage (Δ_1). The RHWP can then be scanned, and should show four zero-crossings for the position differences. Δ_1 can then be set to a nominal zero, and the RHWP scan repeated. The experimenter can then set the RHWP to a position close to the zero from the first scan for which the position differences are minimal during the second scan. The effects of column one are then minimal, and the effects of "column two row two" are probably also fairly small. What is left is presumably mostly due to phase gradients in the vacuum window.

The discussion given here certainly does not represent a definitive analysis of all forms of laser systematics. I hope, however, that this paper provides a useful perspective as we advance forward in our understanding of these often subtle effects. Future parity experiments will make increasingly stringent demands on the control of laser systematics. There is every reason to remain optimistic that these challenges can be met.

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