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Data analysis scheme for correcting general misalignments of an optics configuration for a voltage measurement system based on the Pockels electro-optic effect

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ABSTRACT

Having a sub-ns response time and not requiring physical contacts to the measurement points, a voltage measurement system based on the Pockels electro-optic effect, referred to as a PE (Pockels effect)-based voltmeter, is widely used for pulsed high voltage devices such as accelerators and X-pinch systems. To correct for the misalignment of a Pockels cell and the transmittance ratio of a beam splitter, a polar-coordinate-based data analysis scheme has been proposed. This scheme also overcomes a limitation on the measurable range of a PE-based voltmeter without ambiguity and can measure the half-wave voltage of a Pockels cell. We present an improved polar-coordinate-based data analysis scheme using an ellipse fitting method, which can correct for misalignments of *all the optics components* of a PE-based voltmeter while keeping the advantages of the previous scheme. We show the results of the improved data analysis scheme for measuring a slowly modulated voltage up to approximately 5 kV in about 30 s and a pulsed high voltage up to 7 kV with a rise time of less than 20 ns.

I. INTRODUCTION

A voltage (or electric fields) measurement system with a Pockels cell, exhibiting the Pockels linear electro-optic effect, is widely used for systems where direct electrical connections to the measurement points are not desirable,[1–3] in addition to its classical usage as a voltage-controlled wave plate. Since the Pockels effect (PE) typically has a sub-ns response time,[4] such measurement systems have provided rich information on how pulsed electric fields temporally evolve within accelerators,[5–7] high energy density plasmas of X-pinch,[8] laser–plasma interaction,[9] and a pulsed power system.[10]

The basic optics arrangement of a voltage measurement system based on the Pockels effect, referred to as a PE (Pockels effect)-based voltmeter hereafter, is shown in the dashed square box in Fig. 1, which is known as the Sénarmont arrangement. In this exemplary arrangement, we have used a DKDP (KD_2PO_4, deuterated potassium dihydrogen phosphate) crystal as a Pockels cell in a longitudinal configuration, i.e., externally applied electric fields are parallel to the direction of the injected laser beam. If the voltage across the crystal is controlled, then the crystal acts as a wave plate, and while the voltage is not known, then one can use a detected signal to infer the voltage.

Due to the external voltage (V) felt by the DKDP crystal, the injected laser beam changes its polarization. With the Sénarmont arrangement shown in Fig. 1, the transmission of the system measured using Detector S (D_s) denoted as T_s is given by

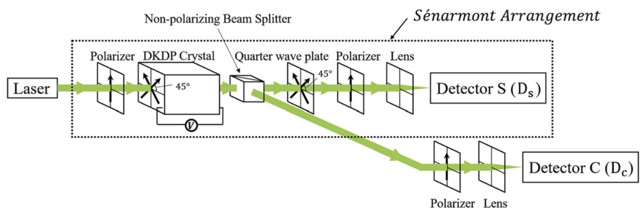

FIG. 1. Basic optics arrangement of a PE-based voltmeter in the dashed square box known as the Sénarmont arrangement. By adding Detector C with the non-polarizing beam splitter, a limitation on the range of measurable voltages without ambiguity for the Sénarmont arrangement can be overcome.

$$T_s = \frac{1}{2}(1 + \sin\Gamma), \tag{1}$$

where $\Gamma = \pi\frac{V}{V_\pi}$. V_π, known as the half-wave voltage, is a constant set by the properties of a Pockels cell and the wavelength of the laser beam. Since the properties of the crystal are sensitive to the temperature,[11,12] a separate measurement of V_π must be carried out before using a PE-based voltmeter. The V_π value of the crystal used in this work is 3.10 kV based on the manufacturer's specification at room temperature with a 532 nm laser beam.

The Sénarmont arrangement, owing to a periodic nature of T_s as in Eq. (1), has a limitation on the range of measurable voltages without ambiguity. To overcome such a limitation, another optics setup is proposed,[13,14] where the laser beam after the crystal is split into Detector C (D_c) without passing through the quarter-wave plate as shown in Fig. 1. The transmission of the system measured using Detector C (T_c) is, then,

$$T_c = \frac{1}{2}(1 + \cos\Gamma). \tag{2}$$

We note that using two wavelength laser beams can also overcome the limitation on the range of measurable voltages.[3]

Equations (1) and (2) are both valid only when all the optics components shown in Fig. 1 are precisely aligned, i.e., relative angles among the polarizers, the axis of the crystal, and the quarter-wave plate, with the transmittance ratio of the horizontal component to the vertical component of the polarized laser beam at the non-polarizing beam splitter being unity. If the value of V_π is known in advance, then we can create reference values of T_s and T_c by applying known voltages to the system so that we do not have to concern about the precise optics alignments. However, as mentioned above, V_π itself is a quantity to be measured, which requires a good alignment of all the optics components. Moreover, even if we know the value of V_π, alignments of the optics components may change over time, which means that we have to create the reference values every now and then (if not every time).

To correct for the misalignment of the crystal and the transmittance ratio of the non-polarizing beam splitter, a polar-coordinate-based data analysis scheme has been proposed recently,[15] where the authors have provided the corresponding analytical formulas for T_s and T_c. This scheme is useful in that it provides not only a (partially) corrected value of the applied voltage across the crystal in addition to the value of V_π but also a degree of the misalignment and the transmittance ratio, which can be used to improve the optics system.

In addition to the corrections proposed by the previous work,[15] misalignments of all the polarizers and the quarter-wave plate and the unexpected absorption of the incoming laser beam within the non-polarizing beam splitter and slightly different efficiencies of the two detectors need to be taken into account for a better measurement of the voltage. Some of these effects can be theoretically described by the well-known Jones calculus and generate the formula accordingly.[16] However, such a formula becomes quite complicated if one considers physical fitting parameters, hindering practical usage of it.[16,17]

Therefore, in this work, we present a simple data analysis scheme using an ellipse fitting method on how one can obtain a corrected value of the applied voltage across the crystal from a PE-based voltmeter with all the undesirable effects mentioned above. We note that a similar method has been developed and applied to a Faraday rotation measurement[16] and a velocity interferometer system.[18] In Sec. II, we describe the developed data analysis scheme using an ellipse fitting method. Then, we show how much improvements we can obtain with our analysis scheme in terms of bias errors and how we can directly measure the half-wave voltage (V_π) of a Pockels cell in Sec. III. In this section, we also show the result of the pulsed high voltage measurement (up to 7 kV with a rise time of less than 20 ns) with the aim of applying the data analysis scheme to X-pinch systems. Then, we provide our conclusions in Sec. IV.

II. POLAR-COORDINATE-BASED DATA ANALYSIS SCHEME WITH ELLIPSE FITTING

If we plot $2T_s - 1 (= \sin\Gamma)$ and $2T_c - 1 (= \cos\Gamma)$ in a polar coordinate using the measured intensities of T_s and T_c from a PE-based voltmeter, they ideally track a unit circle where an angle on the circle corresponds to $\Gamma = \pi\frac{V}{V_\pi}$, which provides us information on the applied voltage across the crystal as shown in Fig. 2(b). Due to misalignments and even not-precise-enough manufacturer's specifications of the optics components, the circle, what one would ideally expect, is distorted to an ellipse in general as shown in Fig. 2(a) with blue crosses and a red ellipse. We have included only six data

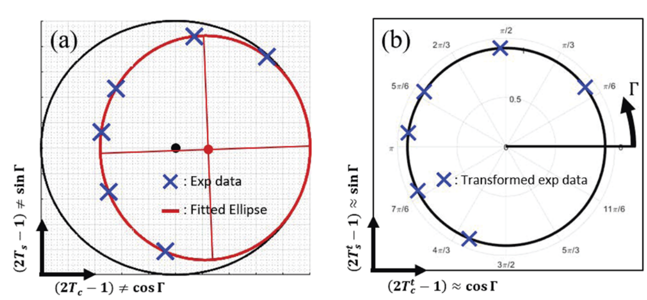

FIG. 2. An example of the polar-coordinate-based data analysis scheme. (a) Sample data $2T_s - 1$ and $2T_c - 1$ (blue crosses) track an ellipse (red) rather than an ideally expected unit circle (black). Centers of the ellipse and the circle are indicated by the red and black dots, respectively. Red lines inside the ellipse indicate major and minor axes. (b) With necessary factors of translation, normalization, and rotation, transformed data $2T_s^t - 1$ and $2T_c^t - 1$ track the unit circle where an angle Γ provides a value of the applied voltage across the crystal.

points in Fig. 2 so that one can easily identify how the data points are transformed from an ellipse to a circle.

Once we obtain the ellipse fit, then we perform the following three procedures to transform the ellipse into the unit circle [from the red ellipse in Fig. 2(a) to the black circle in Fig. 2(b)]: (1) translate the center of the ellipse [red dot in (a)] to the origin $(0, 0)$ in a polar coordinate, which is the center of the circle [black dot in (a)], (2) normalize the major and minor axes of the ellipse [red lines in (a)] to unity, and then (3) rotate the circle [with step (2), the ellipse is now a circle] such that the $V = 0$ point is located at (1, 0) corresponding to the $\Gamma = 0$ case. We use the values of T_s and T_c at $V = 0$ ($\Gamma = 0$) as the reference values.

These transformation procedures from an ellipse to a circle provide us necessary factors of translation (step 1), normalization (step 2), and rotation (step 3), which can be used to obtain the transformed values of T_s and T_c denoted as T_s^t and T_c^t, respectively. Figure 2 shows an example of the transformation from (a) the measured values T_s and T_c to (b) the transformed values T_s^t and T_c^t. The accuracy (or the limiting factor) of the method is basically determined by how good an ellipse fitting can be performed on measured raw data.[16,19] The noise level of the data points, how many data points are available, and how much an elliptical arc length is covered by the data points affect the accuracy.

III. EXPERIMENTAL RESULTS

We have set up our PE-based voltmeter as shown in Fig. 1 with two identical photodetectors, namely, Detector S and Detector C (DET025AL/M from Thorlabs). We use a PC12SR-532 from Eksma Optics as the DKDP crystal and a fiber coupled 532 nm cw diode pumped laser (Cobolt 04-03 Samba™ from Hübner Photonics) capable of generating up to 150 mW of the laser beam. A collimator is used to couple the laser beam from the fiber to the free space optics components.

Since our PE-based voltmeter is designed to diagnose an X-pinch system, we examine the functionality of the voltmeter (before applying to an X-pinch system) by using a pulsed high voltage generator[20] producing about 7 kV with a rise time of less than 20 ns. The applied voltage to the DKDP crystal is also measured using a separate high voltage probe (Tektronix P6015A) simultaneously to confirm the validity of the proposed data analysis scheme.

A. Calibration: From the ellipse to the circle

As mentioned above, we need to obtain the value of V_π for the DKDP crystal before applying the PE-based voltmeter to any other experiments. For this purpose, we apply a slowly modulated voltage up to approximately 5 kV in about 30 s to the DKDP crystal and obtain the values of T_s and T_c from the two photodetectors, while the applied voltage is also measured using the high voltage probe. The raw data and the applied voltage are shown in Fig. 3(a).

We plot measured $2T_s - 1$ and $2T_c - 1$ as shown in Fig. 4. Blue dots are the measured values, and the blue line is an ellipse fitting to them. As described in Sec. II, measurement points trace an ellipse well; thus, we can obtain the factors of translation, normalization, and rotation to transform the data points on the ellipse to the ideal unit circle, which is shown in Fig. 5 (blue dots). Using estimated $\Gamma (= \pi \frac{V}{V_\pi})$ from the transformed data on the polar coordinate in Fig. 5

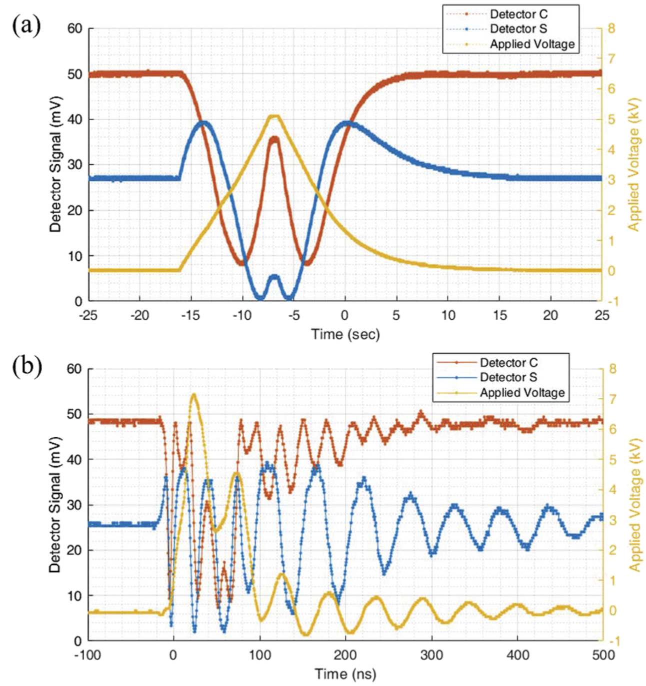

FIG. 3. Raw data from Detector S (D_s) in red and Detector C (D_c) in blue with (a) slowly modulated voltage up to 5 kV for calibration (Sec. III A) and (b) pulsed high voltage up to 7 kV (Sec. III B) after removal of noise patterns. Yellow lines are the applied voltages separately measured using the high voltage probe.

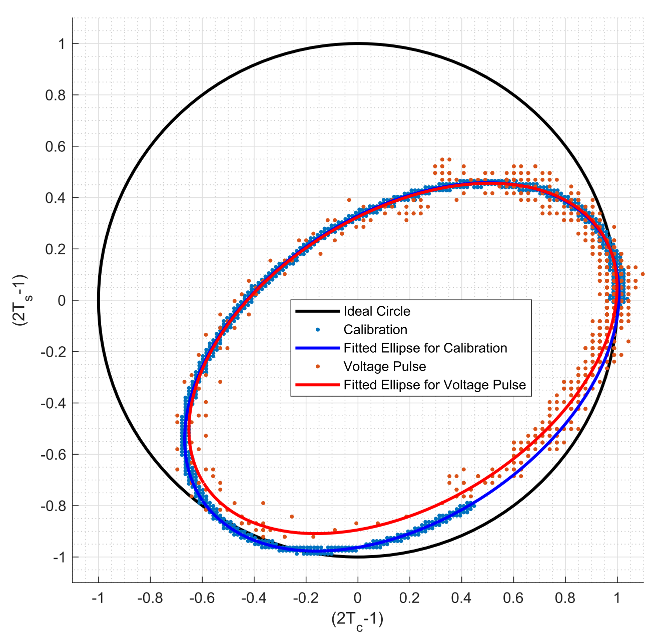

FIG. 4. Experimental data (dots) and an ellipse fitting (lines) for calibration (blue) based on Fig. 3(a) and a pulsed voltage (red) based on Fig. 3(b). As a reference, we also draw the ideal unit circle (black).

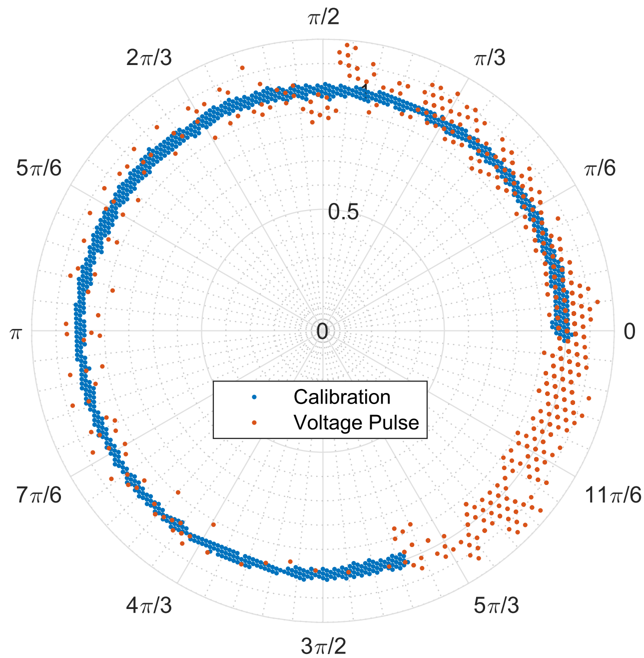

FIG. 5. Transformed experimental data to a unit circle on a polar coordinate for calibration (blue) and a pulsed voltage (red) based on the corresponding ellipses in Fig. 4. The polar angle Γ provides the voltage level felt by the DKDP crystal.

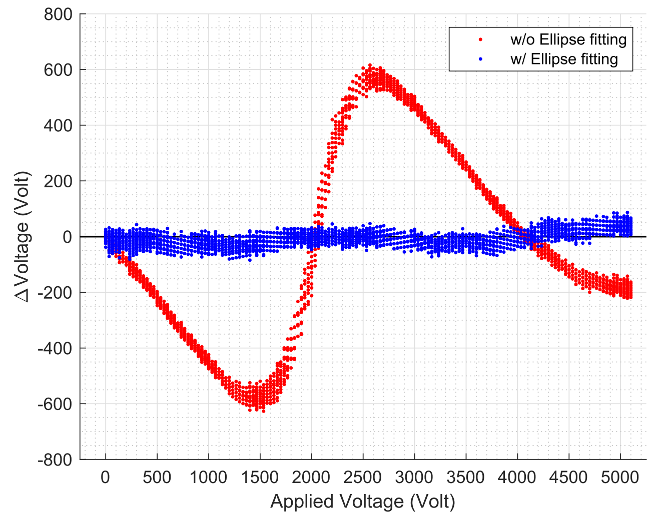

FIG. 6. Experimental data verifying that the proposed data analysis scheme using an ellipse fitting works well. The difference (bias error) between the applied voltage and the measured voltage denoted as ΔV (ordinate) has decreased dramatically from the maximum difference of 600 V (without the ellipse fitting method, red dots) to 100 V (with the ellipse fitting method, blue dots). Abscissa is the applied voltage to the DKDP crystal.

and voltages from the high voltage probe, we can easily infer V_π. For our system, we determine that V_π is 3.20 ± 0.01 kV. Note that the manufacturer specifies its value to be 3.10 kV.

With the determined value of V_π, Fig. 6 shows the goodness of our proposed data analysis scheme using an ellipse fitting method. The abscissa is an applied voltage to the DKDP crystal measured using the high voltage probe, and the ordinate is a difference between the measured voltage from the PE-based voltmeter and the applied voltage for the cases of using the proposed scheme (blue) and not using it (red). Maximum differences (bias errors) are dramatically decreased from 600 to 100 V. We emphasize that the optics components for the PE-based voltmeter have been carefully aligned as much as we can, yet we have up to a 600 V measurement error if the proposed scheme is not used.

B. Measurement of a pulsed high voltage

Unlike slowly varying voltages, a PE-based voltmeter to measure pulsed voltages requires a good temporal synchronization between the two photodetectors; thus, we use two 1 m-long (same length) BNC cables for the detectors. Furthermore, as a pulsed power system typically generates electromagnetic noises that may be picked up by any electronic components, we have to suppress such noises. Temporal patterns of the noise for our pulse generator[20] (7 kV with a rise time of less than 20 ns) used to examine the PE-based voltmeter are very similar among the pulses, allowing us to remove the noise patterns from the measured signals.

Figure 3(b) shows the raw data after removal of the noise patterns, and the red dots in Fig. 4 show the measured $2T_s - 1$ and $2T_c - 1$ values when a pulsed high voltage is applied to the DKDP crystal with the noise patterns removed. The fitted ellipse (red) is slightly different from the blue ellipse, which may be caused by unintentional changes of the optics alignments as we prepare the pulse generator. We are not worried about the difference since we can obtain the factors of translation, normalization, and rotation again for the (red) ellipse to be the unit circle as shown in Fig. 5 (red dots). Here, we do not have to re-determine the value of V_π, which is a function of temperature, because the temperature of the crystal has not been changed.

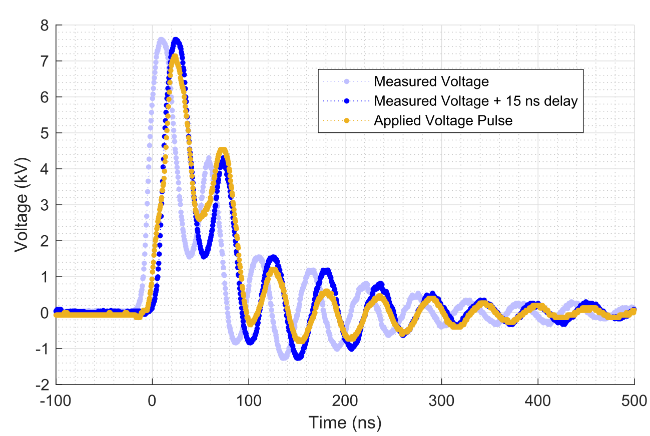

FIG. 7. Measurement of a pulsed high voltage applied to the DKDP crystal using the PE-based voltmeter (light blue). By applying 15 ns delay to the measurement, we obtain a very good agreement between the measured (blue) and applied (yellow) voltages.

The inferred voltage applied to the crystal is obtained using the proposed data analysis scheme and shown in Fig. 7 with light blue dots. The applied voltage (yellow dots) is measured using the high voltage probe. Because of different time responses of two measurement systems, we see different time delays. The PE-based voltmeter has 10 ns time delay, while the high voltage probe has 25 ns time delay from the pulse generator. Thus, by adding 15 ns delay on the PE-based voltmeter, we observe that the agreement between the time delayed inferred voltage (blue dots) and the applied voltage (yellow dots) is very good. The applied voltage does not evolve as sharp as the inferred ones, which is caused by a narrower bandwidth (75 MHz) of the high voltage probe than that (2 GHz) of the photodetectors.

IV. CONCLUSION

In this work, we have presented an improved data analysis scheme for a voltage measurement system based on the Pockels effect (PE-based voltmeter), where the previous scheme[15] is limited to correct for a misalignment of the Pockels cell (the DKDP crystal in this work) and a transmittance ratio of the non-polarizing beam splitter. The improved scheme based on a general ellipse fitting corrects for misalignments of *all the optics components* and allows one to easily measure the half-wave voltage of a Pockels cell, which is a critical constant for a PE-based voltmeter. Furthermore, we do not have to worry about unintentional changes (as many experiments are performed over time) of the optics alignments that we are not aware of because the proposed data analysis scheme allows one to correct for the effects of misalignments solely based on the current measurement.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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