Precise, real-time, every-single-shot, carrier-envelope phase measurement of ultrashort laser pulses

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In this Letter we demonstrate a method for real-time determination of the carrier-envelope phase of each and every single ultrashort laser pulse at kilohertz repetition rates. The technique expands upon the recent work of Wittmann and incorporates a stereographic above-threshold laser-induced ionization measurement and electronics optimized to produce a signal corresponding to the carrier-envelope phase within microseconds of the laser interaction, thereby facilitating data-tagging and feedback applications. We achieve a precision of 113 mrad (6.5°) over the entire 2π range.

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For few-cycle laser pulses, the carrier-envelope phase (CEP) plays an increasingly important role as the pulse duration decreases and the possible electric field asymmetry increases. The pioneering work on CEP was done with its equivalent frequency-domain representation and enabled a revolution in frequency metrology as well as CEP stabilization [1,2]. Moreover, CEP plays a critical role in strong-field laser-matter interactions, e.g., the production of extreme-UV pulses [3,4], which serve as the basis for much of the burgeoning field of attosecond science [5].

At present, the CEP effects on a given process are typically measured by locking and scanning the CEP while recording data, e.g., see [3,6]. For ultrashort pulses, this is complex and typically achieved via often temperamental feedback loops. Thus, stabilization of the laser operating parameters, e.g., temperature and power [7,8], is required if phase lock over a period of hours is to be achieved. Therefore, for many applications, it may be simpler and more effective to forgo the CEP locking mechanisms if a precise CEP measurement can be made for each laser pulse.

Ideally, one would like to have a precise, robust, real-time, every-single-shot CEP measurement. This way, the information could be used to tag data recorded in a parallel event-mode measurement or as an alternative measurement method in a feedback loop. Additionally, in situations when CEP locking is desired, such a technique could serve as a powerful diagnostic or an alternative method of feedback [9]. Although multiple techniques have been developed that are capable of retrieving the CEP [2,10–13], determining the CEP of each and every laser shot individually and continually in real-time for an intense, ultrashort, kilohertz laser system has, until now, been out of reach.

In this Letter we go beyond the method recently reported by Wittmann *et al.* [14] and demonstrate a real-time, every-single-shot, carrier-envelope phase measurement of ultrashort laser pulses precise over the full 2π range. Ultrashort laser pulses (~6 fs, 790 nm, 30 μJ) from a Ti:sapphire Femtopower Compact Pro HP/HR CEP are used to ionize xenon (Xe). Then the above-threshold ionization (ATI) spectra are examined using the apparatus depicted in Fig. 1(a), i.e., the carrier-envelope phase meter (CEPM) [15]. This versatile configuration allows for a stereographic measurement of the ATI electron spectra, emitted within ~2° (half-angle) of the laser polarization, on two detectors, i.e., left and right. This arrangement is particularly well suited to detecting the energy-dependent asymmetry in ATI yield associated with changes in the CEP of few-cycle laser pulses.

In conjunction with the CEPM, we have developed and employ electronics [see Fig. 1(b)], which allow for the

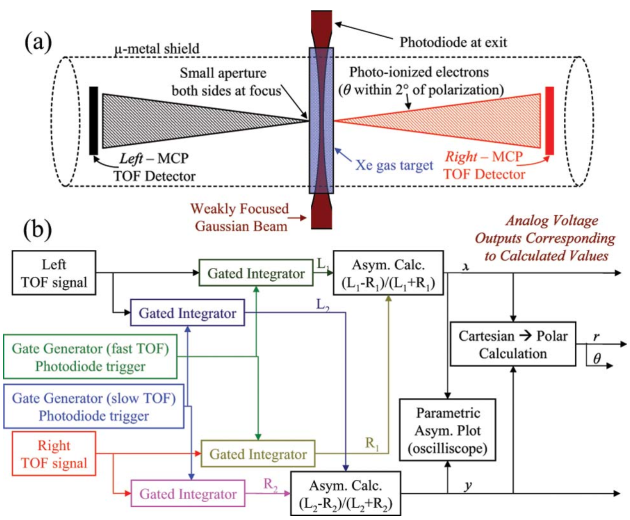

Fig. 1. (Color online) Schematics of (a) the stereographic apparatus used to measure ATI [15] and (b) the electronics used to determine the CEP from this measurement [16]. These electronics take the current signals from the microchannel plates of the ATI measurement, i.e., L and R, shown in panel (a), and then perform the calculations outlined in the text. The results, i.e., x, y, r, and θ, are output as analog voltage levels.

calculation of the CEP within $\sim 20\,\mu s$ of the laser interaction [16]. This combination represents a significant step forward in CEP measurement as it enables the real-time determination of the CEP for each laser pulse in a kilohertz pulse train. That is to say, (i) the CEP is determined for each laser shot completely independent of adjacent pulses, i.e., there is no averaging; and (ii) there is no dead time between laser shots or groups of laser shots. Moreover, these are the ideal properties for data tagging, as the CEP can easily be recorded alongside the information for another measurement. For example, while collecting data in event mode, one only needs to add analog-to-digital converter (ADC) channels for the CEP output of this apparatus to facilitate determination of CEP effects. Additionally, these properties are optimum for diagnostics and feedback loops.

To facilitate the CEP determination, we utilize the facts that the energy-dependent Xe ATI yield along the polarization direction varies with the CEP in a roughly sinelike manner in the plateau region and that the phase of this dependence varies with energy (see [17]). Furthermore, the visibility of this CEP dependence is enhanced by looking at the asymmetry in the number of electrons detected on the left (L) and right (R) detectors in a particular energy region, $A = (L - R)/(L + R)$. Thus, by choosing two energy regions, which will be referred to as high and low, with a large asymmetry and a sinelike dependence on the CEP that varies by roughly a phase of 90°, one can produce a parametric plot (A_{high} versus A_{low}) revealing the CEP. The benefits of this representation are the following: (i) the selected energy regions are more sensitive to variations in the CEP than an integration over the entire ATI spectrum; (ii) the asymmetry parameters are more responsive to changes in the CEP than the yield in either direction is alone; (iii) the CEP (ϕ) varies roughly linearly with the polar angle in the parametric asymmetry plot (PAP), i.e., the measured quantity θ.

Although a linear relationship between θ and ϕ is ideal, as shown in Figs. 2(a) and 2(c) and the previous work of Wittmann *et al.* [14], for most choices of energy regions, and in the general case, the PAP has neither a constant radius (r) nor a uniform distribution in θ. Therefore, one must determine how to retrieve the CEP from the measured values, i.e., $\phi(\theta, r)$, if a phase measurement over the full 2π range is desired. This is done by taking a measurement with a random CEP variation and high statistics. In this case, the CEP distribution is uniform over the full 2π range, thus,

$$d\phi = \frac{\rho(\theta)}{\langle\rho\rangle} d\theta = \lambda(\theta) d\theta \rightarrow \phi(\theta) = \phi_0 + \int_0^{\theta} \lambda(\theta') d\theta', \quad (1)$$

where $\rho(\theta)$ is the density of laser shots as a function of θ, $\langle\rho\rangle$ is the average density of laser shots as a function of θ, and $\lambda(\theta) \equiv \rho(\theta)/\langle\rho\rangle$. (See Fig. 2 for typical values of the relevant quantities). This means that the PAP need not be perfectly uniform for one to determine the CEP. Moreover, one can determine the absolute CEP, i.e., determine ϕ_0 in Eq. (1), using theoretical calculations of the ATI spectra [18].

Although the PAP is not *a priori* uniform in θ, one can typically generate, at least roughly, such a distribution by carefully controlling the experimental conditions. First, one must ensure that the left (L) and right (R) measurements are identical. Second, one must optimize the bounds of the high and low energy regions used to calculate A_{high} and A_{low}. In this case, r, the deviation in r (Δr), and λ are independent of θ, $\phi(\theta) = \phi_0 + \theta$, and the PAP is a uniform circle. As shown in Fig. 2, these conditions can be closely met, providing a nearly linear relationship between ϕ and θ. In addition to minimizing or eliminating the need for the θ-to-ϕ mapping shown in

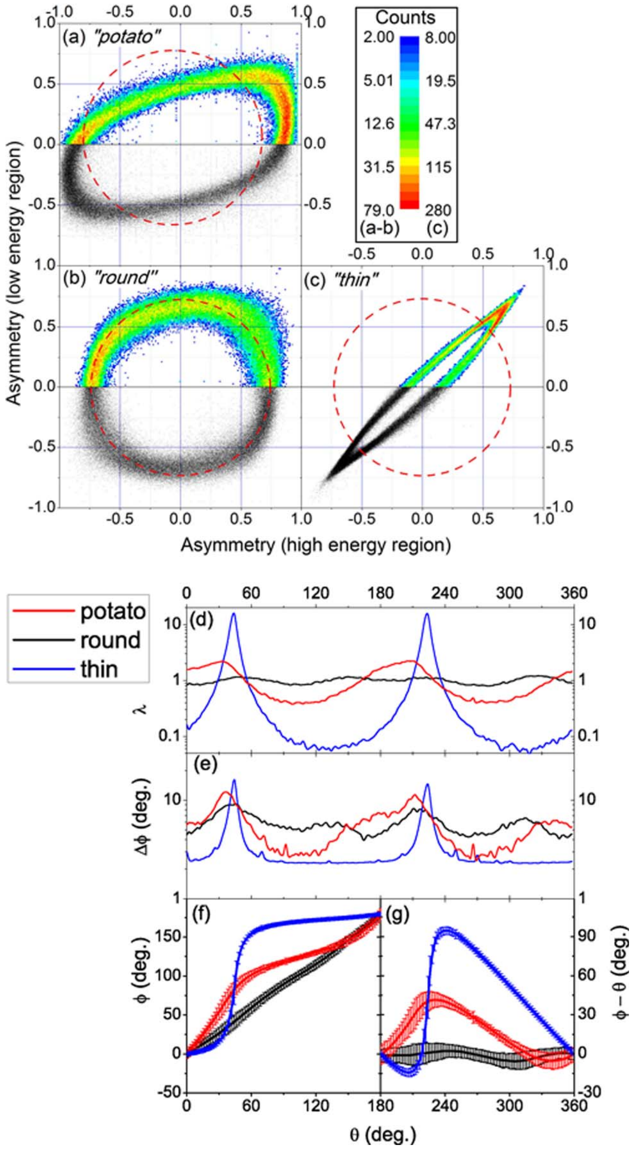

Fig. 2. (Color online) (a)–(c) PAPs, A_{high} versus A_{low}, for the same 200,000 non-CEP-locked individual laser shots, i.e., data points, with different gate position. The top halves of the figures are logarithmic two-dimensional (2D) histograms, and each bottom half shows a point for each laser shot. The dashed line at $r = 0.75$ is simply to guide the eye. Note that this is experimentally collected data and not from a numerical simulation. (d)–(g) θ-dependence of the data shown in Fig. 2 binned in 2° increments, where "potato," "round," and "thin" refer to panels (a), (b), and (c), respectively. (d) θ-dependent density of laser shots $\lambda(\theta)$. (e) θ-dependent error in CEP, $\Delta\phi(\theta)$. (f) CEP dependence on θ, $\phi(\theta)$. (g) Same as (f) plotted as $\{\phi(\theta) - \theta\}$ to enhance the nonlinearities. See text for details.

Eq. (1), this also facilitates easy implementation of the CEPM into a feedback loop.

Unlike the relationship between θ and ϕ, the precision of the CEP measurement, $\Delta\phi(\theta)$, is not easily determined from the distribution of points in the PAP. The error in the CEP measurement is dominated by statistical error, due to discrete electron counting, and by intensity fluctuations. We use the measured ATI spectra themselves to determine $\Delta\phi$. By averaging the ATI spectra over a small CEP range, one can create a reference spectrum to which jitter associated with statistical noise and/or intensity fluctuations can be added via a Monte Carlo algorithm. Using this technique to simulate the statistical noise, we find the θ-dependent error distributions shown in Fig. 2(e). Moreover, for a circular distribution, e.g., that shown in Fig. 2(b), we find that the statistical error is $\Delta\phi \simeq \Delta\theta \simeq \Delta r/r$. Although intensity fluctuations have little effect on r, they create an additional spread in ϕ. We find that for the circular case, the uncertainty due purely to intensity fluctuations is 35 mrad per 1% intensity uncertainty, which is around a factor of 3 better than that achieved in f-$2f$ measurements [19,20].

In conclusion, we have demonstrated an every-single-shot absolute carrier-envelope phase measurement of ultrashort laser pulses precise over the full 2π range in real time with a precision of 113 mrad (6.5° or 48 as) and are consistently able to sustain continuous measurements for more than 10 hours. These properties make it ideally suited for determining the CEP dependence of any process under study via data tagging. Moreover, since this technique has no dead time and removes the need for typically complicated and often erratic CEP locking, its robust nature will allow access to and accuracy in measurements previously unobtainable due to statistical limitations. Additionally, this technique presents an excellent alternative feedback mechanism when CEP locking is desired and serves as an invaluable diagnostic, as it allows for simple real-time examination of ultrashort pulse characteristics, i.e., CEP, intensity, and pulse duration, with only an oscilloscope [18].

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