Precision control of carrier-envelope phase in grating based chirped pulse amplifiers

Chengquan Li, Eric Moon, Hiroki Mashiko, Christopher M. Nakamura, Predrag Ranitovic, Chakra M. Maharjan, C. Lewis Cocke, and Zenghu Chang

Chang@phys.ksu.edu

J. R. MacDonald Laboratory, Department of Physics, Kansas State University, Manhattan KS 66506

Gerhard G. Paulus

Department of Physics, Texas A&M University, College Station, TX 77843

Abstract: It is demonstrated that the carrier-envelope (CE) phase of pulses from a high power ultrafast laser system with a grating-based stretcher and compressor can be stabilized to a root mean square (rms) value of 180 mrad over almost 2 hours, excluding a brief re-locking period. The stabilization was accomplished via feedback control of the stretcher grating separation in the stretcher. It shows that the long term CE phase stability of a grating based chirped pulse amplification system can be as good as that of lasers using a glass-block stretcher and a prism pair compressor. Moreover, by adjusting the grating separation to preset values, the relative CE phase could be locked to an arbitrary value in the range of 2π. This method is better than using a pair of wedge plates to adjust the phase after a hollow-core fiber compressor. The CE phase stabilization after a hollow-core fiber compressor was confirmed by a CE-phase meter based on the measurement of the left-to-right asymmetry of electrons produced by above-threshold ionization.

OCIS codes: (320.7110) Ultrafast nonlinear optics; (140.7090) Ultrafast lasers; (120.5050) Phase measurement

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1. Introduction

The electric field of a laser pulse with a Gaussian temporal profile at a given observation point in space can be expressed as $E(t) = E_0 \exp[-2\ln(2)t^2/\tau_p^2]\cos(\omega_c t + \varphi_{\mathrm{CE}})$. Here E_0 is the peak amplitude of the field and ω_c is the carrier angular frequency. The carrier-envelope (CE) phase, φ_{CE}, specifies the offset of the electric field oscillation with respect to the pulse envelope. As the pulse duration, τ_p, approaches one optical cycle ($2\pi/\omega_c$), φ_{CE} becomes a critical parameter because when such intense few-cycle laser pulses interact with atoms or molecules, in many

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cases it is the electric field oscillation, instead of the envelope of the pulses, which determines the dynamics of the interaction.

CE phase stabilized pulses can be generated from chirped pulse amplification (CPA) lasers with a glass-block stretcher and a prism pair compressor [1]. The CE phase can be locked for tens of minutes by stabilizing the CE offset frequency of the oscillator providing the seed pulses and by subsequently correcting the slow drift which occurs during amplification. The stabilized CE phase can be changed by using a pair of glass wedge plates placed after the CPA system [2]. Such laser systems have been used in many researches where the processes to be studied are sensitive to CE phase [3–14].

Grating based CPA systems can produce much higher laser pulse energy than the prism based systems, which is important for generating attosecond pulses in gases [15]. It is also useful for increasing the photon flux and extending the spectral width of attosecond pulses generated in gases. Several investigations on the CE phase stability of such laser systems have been done by stabilizing the CE phase of the oscillators alone [16–18]. In our recent work [19], we studied the effect of varying the grating pair separation in the stretcher on CE phase and discovered that the slow CE phase drift of the CE phase in the amplifier could be compensated by feedback control of the effective grating pair separation. This gives another method for correcting the CE phase drift of the amplified pulses.

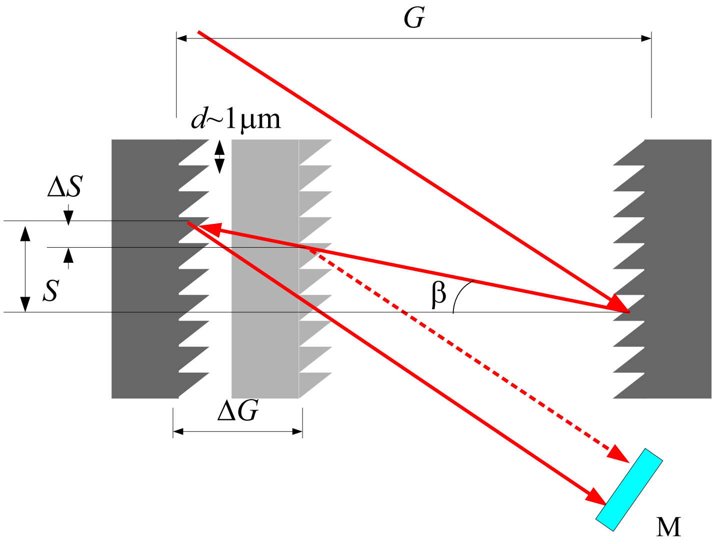

Fig. 1. Configuration of a double-pass grating compressor. G is the grating separation. d is the grating constant. β is the diffraction angle. M is a retro-reflection mirror.

The dependence of CE phase on the grating separation in stretchers and compressors has been analyzed in Ref. [20]. In a double-pass compressor shown in Fig. 1, the CE phase shift caused by the difference between the group delay and the phase delay is $\varphi_{\mathrm{CE}} = 2 \cdot 2\pi d G \tan[\beta(\omega_c)] = 2 \cdot 2\pi S/d$. The pre-factor 2 is due to the double pass. d is the grating constant, which is on the order of the laser wavelength. G is the grating separation. $\beta(\omega_c)$ is the diffraction angle at the carrier frequency. The meaning of $2\pi S/d$ is that the CE phase change for each pass is equal to the number of grooves covered by S multiplied by 2π. In other words, each groove introduces a 2π phase shift. From the above equation, it is obvious that when the grating separation changes by ΔG between two laser pulses, the CE phases of the two pulses will differ

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by $\Delta\varphi_{\mathrm{CE}} = 4\pi\Delta G\tan[\beta(\omega_c)]/d$. One only needs to change ΔG by an amount on the order of d to cause a significant change of the CE phase. The CE phase shift in grating stretchers can be described using the same equations as in compressors, except that for stretchers G is the effective grating separation that can also be changed by adjusting the separation of the telescope lenses or mirrors [20]. In practice, it is easier to translate a telescope mirror in the stretcher than a grating in the compressor because the weight of the mirror plus its mount is much less [19].

In this work, the effectiveness of this new feedback control approach on a time scale of hours is studied. For many experiments that involve the coincidence measurement of electrons and ions, the count rate could be sufficiently low that several hours of data acquisition necessary even when kilohertz lasers are used. We will show that the stabilized phase can be set to any value by controlling the grating separation, which make the wedge plates unnecessary.

2. Experiment

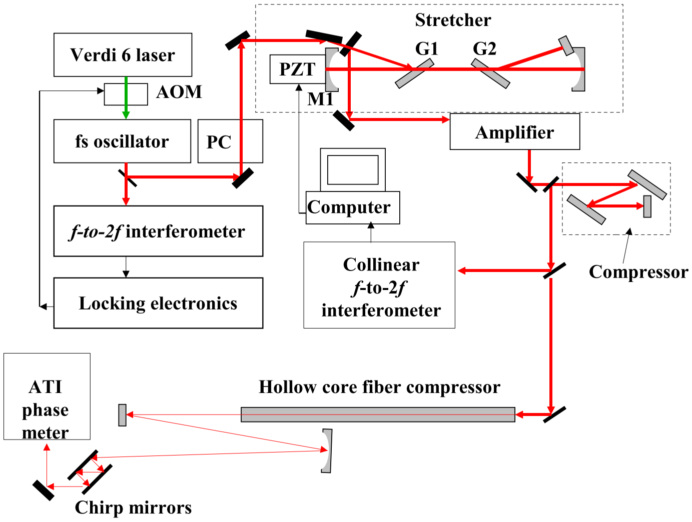

Fig. 2. The Kansas Light Source (KLS) CE phase controlled femtosecond laser system. The oscillator CE phase offset frequency f_0 is stabilized by feedback controlling the acousto-optic modulator (AOM). Pulses with the same CE phase are selected by the Pockels cell (PC) and sent to the CPA amplifier. The error signal from the collinear f-to-$2f$ interferometer is used to adjust the effective separation of two gratings G1 and G2 in the stretcher to stabilize the CE phase of the amplified pulses.

The CE phase stabilization was done by using the Kansas Light Source (KLS) laser system as shown in Fig. 2. Two phase locking loops are used to stabilize the CE phase rate of change in the oscillator and the CE phase drift in the CPA amplifier [19, 21]. The CE phase offset frequency, f_0, of the chirped mirror compensated Ti:sapphire femtosecond oscillator (Femtosource Pro) was locked to a quarter of the oscillator repetition rate f_{rep} (f_{rep}=80 MHz). Half of the oscillator output was spectrally broadened in a photonic crystal fiber and the offset frequency was obtained from a Mach-Zehnder-type f-to-$2f$ interferometer. The signal was sent to the locking electronics (Menlosystems GmbH, XPS 800) where the phase detector measured an error signal $\varepsilon = f_0 - f_{\mathrm{rep}}/4$ and converted it to a voltage for driving an acousto-optic modulator (AOM). The offset frequency was stabilized by modulating the power from the pump laser (Coherent Verdi 6) with the AOM [22].

To obtain higher output power, pulses with the same CE phase from the oscillator were then selected by a Pockels cell for amplification at a repetition rate of 1 kHz and sent to the stretcher. The seed pulses had ∼100 nm bandwidth and 3 nJ of energy and were stretched to ∼80 ps. These stretched pulses were amplified to 5 mJ via a 14-pass liquid nitrogen cooled Ti:sapphire amplifier. After amplification, the pulses were compressed by a pair of gratings to 25 fs. The pulse energy was reduced to 2.5 mJ due to the loss of the gratings. A fraction of the output beam ($<1\ \mu$J) was sent to a collinear f-to-2f interferometer, which measured the relative CE phase of the amplified pulses [1]. For a given pulse, its phase relative to a reference pulse was extracted from the measured interferogram by Fourier transform spectral interferometry [23, 24]. In our experiment, 30-50 laser shots were integrated to obtain the interferogram.

There are two sources of jitter in the CE phase of the amplified pulses: 1) fast jitter caused by noise in the CE phase stabilization of the seed pulses, and, 2) slow drift in the whole laser system caused by thermal effects and acoustic motion. The high frequency CE phase noise in the oscillator extends to the repetition rate, but the sampling by the Pockels cell aliases it to 0-1 kHz. Due to the bandwidth of the collinear f-to-2f interferometer, only the slow drift occurring at a frequency of 15Hz (30 laser shots integration) or lower may be compensated. In order to compensate the slow drift, we convert the relative phase to a voltage and control the effective distance of the grating pair in the stretcher instead of sending the control signal to the oscillator f_0 locking electronics [1, 2]. In our stretcher, one of the telescope mirrors, M1 in Fig. 2, was mounted to a piezoelectric transducer (PZT) driven stage. The feedback signal drives the PZT, thus controlling the effective distance between the two gratings [19]. This approach did not add additional modulation to the oscillator pump power, yielding a more stable f_0 locking than could be obtained with a second feedback loop to the AOM.

A hollow-core fiber compressor was used to generate few-cycle laser pulses [25]. Argon gas was used to obtain a broader spectrum via self-phase modulation and a set of chirped mirrors provided dispersion compensation. The post hollow-core fiber laser pulses have duration of 6-7 fs and energy of 0.6 mJ. The CE phase of these few-cycle laser pulses was measured with the stereo Above-Threshold-Ionization (ATI) phase meter [11].

3. Result and discussion

Figure 3 shows the temporal evolution of the relative CE phase φ_{CE}. Both the oscillator and amplifier were phase locked. The CE phase of the amplifier was locked over 110 minutes, except for 4 minutes during which the system was re-locked. There are three kinds of error spikes in Fig. 3(a). In the stable range, some isolated spikes (circle A in the figure, for example) due to an accidental disturbance, such as a slight vibration of the optical table, can be seen. The feedback control can relock the CE phase in two or three seconds on average. In the unstable range (circle B), the relative CE phase error made the PZT move hesitantly, which caused the relocking time to increase to about 30 to 60 seconds. The last region (circle C) is due to a loss of CE phase lock in the oscillator. If the offset frequency in the oscillator drifts outside the bandwidth of the servo loop, the seed pulses will not have identical CE phase. Such unlocked pulses when amplified will wash out the interference pattern in the interferometer. At 3000 s in Fig. 3(a), the oscillator became unlocked, but was relocked in 2 minutes. Once the oscillator CE phase was locked, the slow feedback control could stabilize the CE phase of the amplified pulses in a few seconds.

Figure 3(b) is extracted from Fig. 3(a). The displacement of the PZT is shown in the figure. Before the slow drift feedback stabilization was initialized, a DC offset was applied to the PZT to drive it to the center position. The displacement limit of the PZT is 5 μm. In the first 32 minutes, there was one isolated error spike due to a mechanical disturbance, of the kind discussed earlier. During the first 10 minutes, the PZT moved toward the positive direction to

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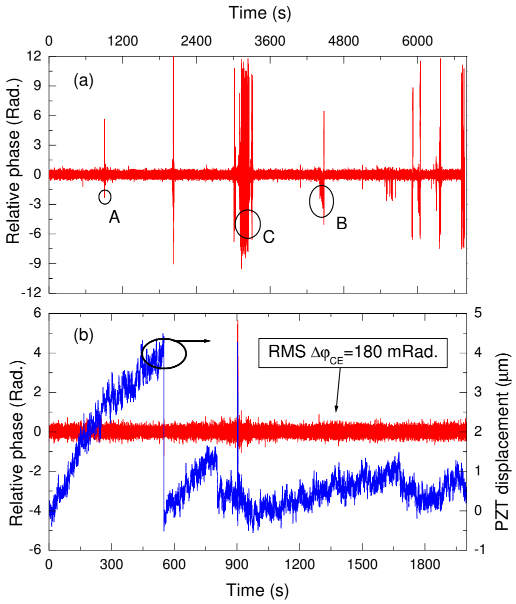

Fig. 3. (a), temproal evolution of relative CE phase $\Delta\phi_{\mathrm{CE}}$. A, B and C represent the three kinds of error spikes, repspectively. (b), the relative CE phase (red) and the displacement of PZT (blue) in the first 32 minutes in (a).

compensate the CE phase slow drift. When the PZT reached its maximum moving limit, it was reset to the center position again. The reset did not produce a measurable error in the CE phase. This was not expected since any large movement of the PZT should shift the phase. Including the big error spike at 900 second, the root mean square (rms) CE phase jitter was 180 mrad (or 70 as timing jitter) in this 32-minute period. The phase stability and lock time is comparable to the prism based CPA systems.

To check the CE phase variance of the few-cycle laser pulses, the CE phase stabilized 25 fs laser pulses were compressed to 6-7 fs through the hollow-core fiber compressor. The positive dispersion was compensated by a set of chirp mirrors (GSM010, Femtolaser). The stereo-ATI phase meter was used to monitor the CE phase of the few-cycle laser pulses. A pair of glass wedge plates were placed before the phase meter and used to change the CE phase of the short pulses. Figure 4(a) shows the diagram of the phase meter. A small portion (5%) of the short pulse beam was sent into Xe gas filled chamber. When the linearly polarized laser field ionized the atoms, the counts of photoionized electrons were recorded by two microchannel plates (MCP).

The ratio of electron yields detected by left and right MCPs was used to represent the measured CE phase. The phase meter result (time-of-flight spectrum) is shown in the intensity map in Fig. 4. Here, the ratio of electron yields detected by right (R) and left (L) MCP detectors $(L-R)/(L+R)$ was plotted. During the experiment, the relative CE phase from the CPA amplifier was stabilized with a jitter of 174 mrad in 10 minutes, as shown in Fig. 4(b). After that, both the oscillator and amplifier were phase unlocked. Every 60 seconds, the few-cycle laser pulse CE phase was abruptly changed by π by moving the wedge plates. Since the yield of high energy electrons is more sensitive than that of low energy electrons to the CE phase, the time-of-flight spectrum shows a higher contrast in the range of short time-of-flight (30-34 ns) than in the long range when the CE phase was changed by π. The data qualitatively confirms

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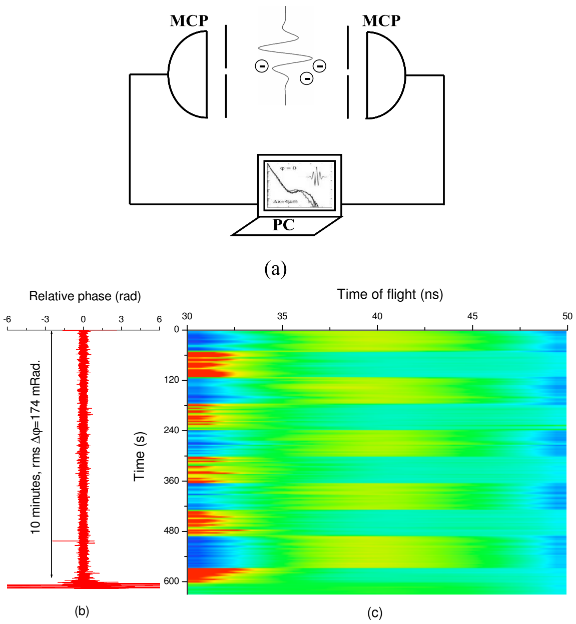

(a)

(b)

(c)

Fig. 4. (a) The diagram of ATI phase meter, MCP: microchannel plates. 10 minutes locked CE phase results measured by (b) collinear interferometer and (c) the stereo ATI phase meter. The CE phase was abruptly changed every 60 seconds by π by changing the thickness of the wedge plates. More electrons are detected by the one of the MCP (red) or the other (blue).

the stabilization of the CE phase in the amplifier and in the hollow-core fiber/chirped mirror compressor. To the best of our knowledge, this is the first demonstration of CE phase effects in strong field atomics physics experiments using grating based CPA systems.

Since the collinear f-to-2f interferometer gives a relative phase, the CE phase in the amplifier was locked to an arbitrary value and the relative CE phase $\Delta\varphi_{\mathrm{CE}}$ was a constant. Wedge plates were always used to change the CE phase, like in our CE phase meter measurements. The wedge pair introduces positive dispersion that must be compensated by chirped mirrors, however the compensation of high order dispersion is difficult. Nonlinear effects such as self-phase modulation and self-focusing also occur in the plates. Here we show another method for changing the CE phase. By changing the set-point for relative phase locking, the CE phase can be changed in the range of 2π, even 4π without using glass wedges. Figure 5 shows the results when the set point was varied from -1.1π to 0.9π in steps of 0.2π . The top intensity map shows the temporal evolution of the interference fringes taken by the f-to-2f interferometer. The bottom plot shows the dynamics of the relative CE phase. To start the scan at -1.1π, the locking point was changed continuously from 0 down to -1.1π in the first 30 seconds. At every set-point, the relative CE phase was locked for 1 min and shift to the next value with the 0.2π step in 1 second. As was expected, the interference lines shifted down almost 1 fringe when the locking point changed from -1.1π to +0.9π . Table 1 lists the set-point value, the averaged experimental CE phase (μ) and the standard deviation (σ) at each locking position. The results show that the CE phase was exactly locked at the set points with an averaged standard deviation of 161 mrad. It demonstrated that the CE phase can be stabilized and precisely controlled by feedback control of the grating separation.

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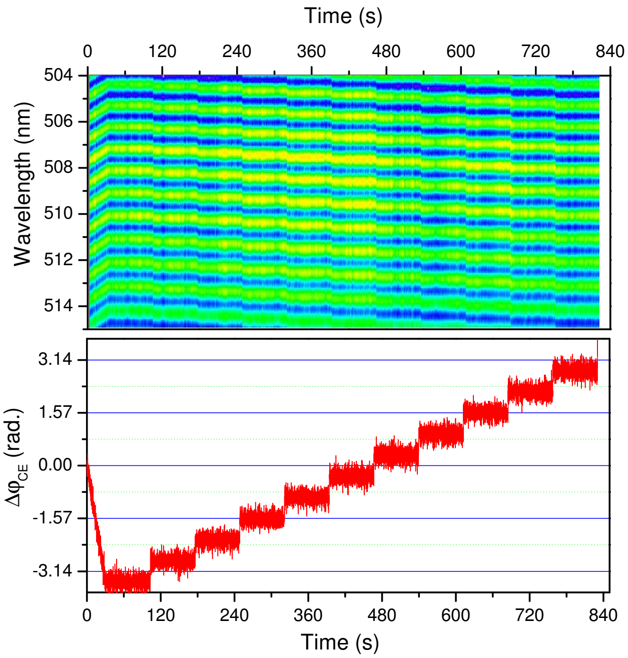

Fig. 5. Precisely controlling the CE phase in amplified pulse. Top, the temporal evolution of collinear f-to-2f interferometer. Bottom, the CE phase staircases

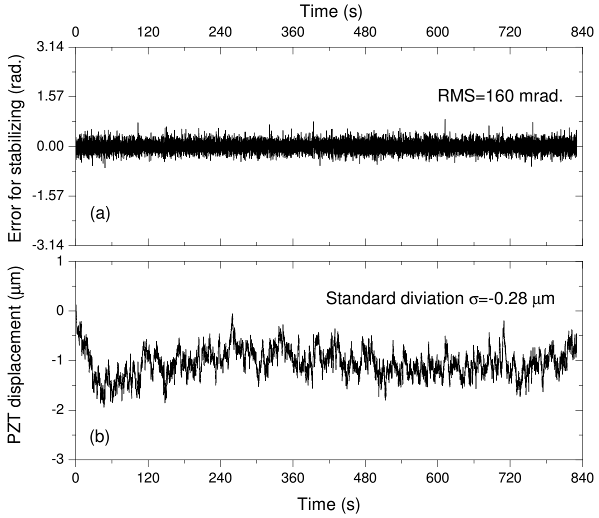

Fig. 6. (a) The error signal for the slow feedback stabilization, (b) the displacement of PZT when the set-point was shifted.

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Table 1. Comparison of set-point, averaged relative CE phase and corresponding standard deviation

Set-point (rad)	-3.454	-2.826	-2.198	-1.570	-0.942	-0.314
μ (rad)	-3.456	-2.828	-2.200	-1.571	-0.944	-0.314
σ(rad)	0.159	0.162	0.157	0.153	0.154	0.166

Set-point (rad)	0.314	0.942	1.570	2.198	2.826
μ (rad)	0.314	0.941	1.570	2.199	2.826
σ (rad)	0.170	0.164	0.156	0.163	0.171

The error signal for the feedback control of the grating separation and the corresponding PZT displacement are shown in Fig. 6. In Fig. 6(a), when the locking point was shifted linearly in first 30 seconds and in the subsequent staircase fashion, there were no disturbances capable of breaking the CE phase lock. The rms value of the errors is 160 mrad, very close to the averaged standard deviation. In Fig. 6(b), the PZT moved from the original position (0) by 1.5 μm to get to -1.1π. When the set-points changed from -1.1π to 0.9π , the PZT moved around an equilibrium position (-1.05 μm) with a standard deviation of 0.28 μm. This small value of PZT movement confirmed that the phase was very smoothly locked even we changed the locking point.

Thus, by controlling the effective grating separation, the CE phase of the amplified pulses can be precisely controlled as with using wedge plates. Unlike the wedge plate method, the control process in our method is implemented before the hollow-core fiber, thusly there is no need to compensate the material dispersion introduced by the wedge plates. Any nonlinear effects from the wedge plates are eliminated as well.

4. Conclusion

It is demonstrated that the long-term stability of the stabilized CE phase in grating based CPA systems can be as good as that in prism based system. When the CE phase of the seed laser pulses from the oscillator was stabilized, the CE phase of the amplified pulses could be stabilized with an rms variation of 180 mrad over 30 minutes by feedback control of the grating separation in the stretcher of the amplifier. The pulse energy from the laser system is 2.5 mJ, but can be scaled to much higher values, which is the main advantage of the grating compressor. The phase stability of the grating based laser is good enough for conducting phase sensitive strong field experiments, as the ATI phase meter measurements demonstrated. Finally, the CE phase could be changed by varying the locking set-point, obviating the glass wedge plates. This approach does not introduce additional dispersion into few cycle laser pulses. The natural combination of CE phase stabilization and precision control demonstrates that the grating separation in the stretcher and compressor is a powerful control parameter in CPA laser technology.

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