Stability analysis of linearly chirped Gaussian pulse stacking in laser plasma reaction

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We analyze the stability of linearly chirped Gaussian pulse stacking (LCGPS) in the laser plasma reaction (LPR) in the inertial confinement fusion (ICF) system. The LPR can be treated as the process that the stacked pulse is first intensity filtered and then induces the plasma due to the thermalization time of the plasma. We also examine the stability of LCGPS over the change of the thermalization time of the plasma, the timing delay, and the intensity attenuation of the stacked pulse in the LPR, and compare the results with those of none chirped Gaussian pulse stacking (NCGPS). Our results show that LCGPS is more stable than NCGPS.

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Pulse shaping in nanosecond level is of urgent need in the front-end lasing system of inertial confinement fusion (ICF)[1−4]. Nowadays, there are several techniques of pulse shaping including spectral shaping, amplitude modulation, and pulse stacking methods[5−13]. Spectral shaping method was proposed by Weiner to generate ultrafast pulses[5−7,11], but was restrained for pulses in femtosecond and picosecond level due to the spectral resolution[14]. Amplitude modulation was also introduced to generate nanosecond pulses[8,12], but the modulators and optical sources limited the rising edge and shaping quality[2].

In the pulse stacking method, the shaped pulse was formed by superimposing a series of sub-pulses, which were power attenuated and timing delayed individually[15,16]. The advantage of this technique is the ability of arbitrary shaping of long pulses and avoiding problems of optoelectronic conversion (such as the slow rising edge and the bandwidth of the modulator)[14]. By the coherence of the sub-pulses, this method can be classified into two types: incoherent pulse stacking (IPS) and coherent pulse stacking (CPS). Because IPS uses incoherent pulses as sub-pulses, there is no coherent noise in the stacked pulse of IPS, so the pulse generated by IPS is stable. But the incoherent sub-pulses in IPS are difficult to obtain, and the stacked pulse may suffer a low nonlinear efficiency in the frequency-doubling process of the ICF system[3], IPS is not applied in the ICF shaping systems.

The technique of CPS uses coherent pulses as sub-pulses. There are also two types of methods divided by the chirp properties of the sub-pulses: linearly chirped Gaussian pulse stacking (LCGPS) which uses linearly chirped Gaussian pulses as sub-pulses[17] and none chirped Gaussian pulse stacking (NCGPS) which uses Fourier-transform-limited Gaussian pulses as sub-pulses. Because the technique of smoothing by spectral dispersion (SSD) in ICF systems could benefit from the chirp characteristics of the stacked pulses[18,19], the LCGPS has been widely adopted in the ICF front-end systems, including Gekko-XII and SG-III[3,15,20]. However, coherence-induced instability was observed in some experiments[15,19]. The instability of the stacked pulse by environmental perturbation may seriously deteriorate the shaping quality of the ICF front-end system and affect the experimental results of laser plasma reaction (LPR) process and ICF systems. Although LCGPS was studied theoretically in recent years[9,10,14,21,22], stability of the stacked pulse in the case of both LCGPS and NCGPS in the LPR has not been analyzed. Moreover, the laser-induced plasma has a thermalization time in LPR[23,24], so when we study the stability of LCGPS, we should also consider the behavior of LPR response.

In this letter, we study the LPR in the ICF system by applying Fourier optics firstly, and then analyze and compare the stabilities of both LCGPS and NCGPS in the LPR. At last, we discuss the stabilities of LCGPS in the LPR over the change of the thermalization time of the plasma, the timing delay, and the intensity attenuation of the stacked pulse in detail.

During the LPR process in the ICF system, the laser transfers its energy to the electrons, and by electron-ion collisions, the energy is redistributed between the ions and the electrons. This process continues until the ions and the electrons in the plasma reach the same temperature, so there is a thermalization time for electron-ion collisions in the laser-induced plasma[23,24].

In LCGPS and NCGPS methods, the plasma is induced by the stacked pulse, and there are fluctuation structures along the waveform of the stacked pulse. The fluctuation periods (frequencies) could be obtained by Fourier-transforming the intensity of the stacked pulse. If the fluctuation periods are smaller than the thermalization time of plasma, these fluctuation structures would not affect the electron-ion collisions and the results of the LPR[25]. Suppose that the intensity of the stacked pulse and the plasma's response function are $I_0(t)$ and $h(t)$, respectively, and the received intensity after the LPR is

$$I(t) = \int_{-\infty}^{+\infty} I_0(t-\tau)h(\tau)\mathrm{d}\tau$$
$$= I_0(t) * h(t). \quad (1)$$

If $I(\omega)$, $I_0(\omega)$, $H(\omega)$ are the Fourier transform of $I(t)$, $I_0(t)$, and $h(t)$, respectively, then

$$I(\omega) = I_0(\omega)H(\omega). \quad (2)$$

From Eq. (2), because the high frequency of the temporal fluctuations (the fluctuation periods smaller than the thermalization time of the plasma) of the stacked pulse would not affect the LPR process, the LPR can be treated as the process that the stacked pulse is first intensity filtered by an intensity filter $H(\omega)$ (in order to remove the unnecessary high frequency intensity fluctuations of the stacked pulse) and then induces the plasma. Typically, the thermalization time of plasma in the LPR is about 10 ps, so the bandwidth of $H(\omega)$ is about 1/10 ps=0.1 THz[25].

Because the pulse shaping system could be perturbed by the environment in the case of both LCGPS and NCGPS, the generated pulse could also be unstable. And the instability of the stacked pulse may affect the LPR. In order to study the stability of the LPR, we need to analyze the stability of the stacked pulse after the intensity filter $H(\omega)$ in both LCPGS and NCGPS.

Now we consider the intensity of the stacked pulse in the cases of both LCGPS and NCGPS. In our theoretical analysis, the initial pulse is supposed to be linearly chirped and Gaussian shaped with a chirp factor of C, a timing delay of τ, and a pulse width of T as follows[26]:

$$E(t) = A_0 \exp\left[-\frac{t^2}{2T^2}(1+\mathrm{i}C)\right]\exp(-\mathrm{i}\omega_0 t)$$
$$= A(t)\exp\left[-\mathrm{i}\omega'(t)t\right], \quad (3)$$

where $A(t)$ and $\omega'(t)$ stand for the real amplitude and the instant frequency, respectively, which are

$$A(t) = A_0 \exp\left(-\frac{t^2}{2T^2}\right), \quad (4)$$

$$\omega'(t) = \omega_0 + \frac{Ct}{2T^2}. \quad (5)$$

In LCGPS, the intensity of the stacked pulse with an amplitude attenuation of α_j and a timing delay of τ_j (j=1, 2,$\cdots$, n) is given by

$$I_{10}(t) = \left|\sum_{j=1}^{n} E(t-\tau_j)\right|^2 = \left|\sum_{j=1}^{n}\alpha_j A(t-\tau_j)\right|^2$$
$$= \sum_{j=1}^{n}\alpha_j A(t-\tau_j)^2$$
$$+ 2\sum_{\substack{j,k \\ j<k}}\alpha_j\alpha_k A(t-\tau_j)A(t-\tau_k)\cos\phi_{jk}(t), \quad (6)$$

where $\phi_{jk}(t)$ is

$$\phi_{jk}(t) = \omega_0(\tau_k-\tau_j) + \frac{C(\tau_k-\tau_j)t}{T^2}$$
$$- \frac{C(\tau_k-\tau_j)(\tau_k+\tau_j)}{2T^2}. \quad (7)$$

Suppose $I_{10}(\omega)$ and $I_{20}(\omega)$ are the Fourier transform of $I_{10}(t)$ and $I_{20}(t)$, respectively. From Eq. (6), $I_{10}(t)$, the stacked pulse with a chirp, can be divided into two parts: the IPS and the coherent item. As the result, the intensity spectrum $I_{10}(\omega)$ is the sum of corresponding Fourier transform of both the IPS and the coherent item. The corresponding spectrum of the IPS is within 0.44/100 ps = 4.4 GHz, because for nanosecond applications, the initial Gaussian pulse is about 100 ps. The spectrum of the coherent item is mainly affected by the fast varying sinusoidal item ($\cos\phi_{jk}(t)$). From Eq. (7), the corresponding spectrum of $\cos\phi_{jk}(t)$ is a set of separated parts[21]

$$\nu_{jk} = \frac{1}{2\pi}\frac{\partial\phi_{jk}}{\partial t} = \frac{C(\tau_k-\tau_j)}{2\pi T^2}. \quad (8)$$

Generally for nanosecond applications, the chirp factor C, the timing delay difference $(\tau_k-\tau_j)$, and the pulse width T are 200, 70 ps, and 100 ps, respectively, and ν_{jk} is about 0.22 THz. So in the intensity spectrum, there are several frequency sidebands, and the IPS part is within the basebands while the coherent item part is within high frequency sidebands. The sidebands with frequencies higher than 0.1 THz would not affect the electron-ion collisions in the laser-induced plasma because the corresponding fluctuation periods are smaller than the thermalization time. After an equivalent intensity filter of 0.1 THz, most of the high frequency coherent items are removed, and the resulting pulse is contributed mainly by the IPS part. So the LCGPS after the intensity filter is equivalent to the case of IPS, where there is no coherent problem. Figure 1 shows the case with the parameters chosen in Table 1, and the intensity filter are chosen to be a Gaussian shape with the bandwidth of 0.1 THz. There are fluctuation structures in the waveform of the stacked pulse of LCGPS in Fig. 1(a), and the intensity spectrum of the stacked pulse consists of several sidebands. But after the intensity filter of 0.1 THz, only the baseband remains

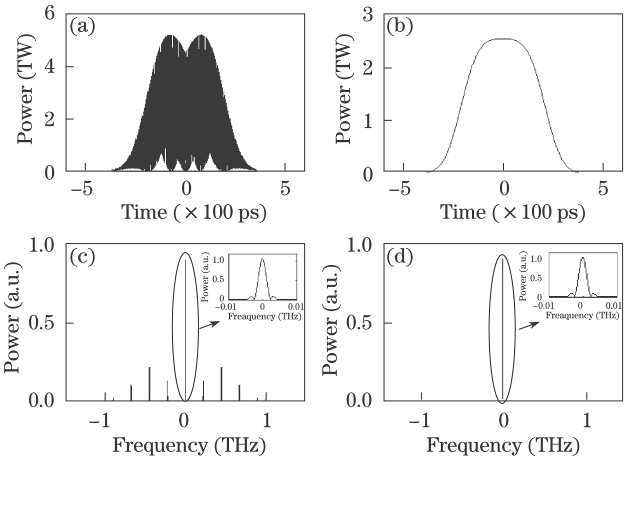

Fig. 1. (a) The stacked pulse of 6 LCGPSs with an initial pulse of 100 ps, an equal attenuation, and a timing delay of 70 ps. (b) The received signal after the intensity filter with the bandwidth of 0.1 THz. There are fluctuation structures in the waveform of the stacked pulse of 0.1 THz. (c) The corresponding Fourier transform of (a). (d) The corresponding Fourier transform of (b).

Table 1. Parameters of Initial Gaussian Pulse in the Simulation

Parameters	Explanation	Value
C	Chirp Factor	200
T(ps)	Pulse Width	100
P_0 (TW)	Peak Power	1
$\Delta\omega$ (THz)	Bandwidth of Intensity Filter	0.1

in the intensity spectrum, and the strongly fluctuating structures are removed in Fig. 1(b), which means the coherent-induced noises would not affect the laser-induced plasma, showing a stability of the system.

Figure 2 shows the stability of the LCGPS in the LPR. If the timing delay of the stacked pulse with a chirp is perturbed by the environment, in the spectrum, the IPS part is hardly affected while the coherent parts change. As a result, the waveform of the stacked pulse changes as shown in Fig. 2(a). But after the intensity filter of 0.1 THz, most of the coherent parts are filtered. So in the spectrum, only the IPS part remains as shown in Fig. 2(d). As a result, the signal remains the same as that in Fig. 1(b) after the intensity filter, as shown in Fig. 2(b). So in the case of LCGPS, because the timing delay perturbation mainly affects the high frequency sidebands, the perturbation would not strongly affect the LPR, and the stacked pulse of LCGPS is stable in the LPR with the timing delay perturbation.

In NCGPS, there is no chirp (C= 0), and the intensity of NCGPS with amplitude attenuation α_j and timing delay τ_j(j=1, 2, ..., n) is given by

$$\begin{aligned} I_{20}(t) &= \left|\sum_{j=1}^{n} E(t-\tau_j)\right|^2 = \left|\sum_{j=1}^{n} \alpha_j A(t-\tau_j)\right|^2 \\ &= \sum_{j=1}^{n} \alpha_j A(t-\tau_j)^2 \\ &+ 2\sum_{\substack{j,k \\ j<k}} \alpha_j \alpha_k A(t-\tau_j) A(t-\tau_k) \cos[\omega_0(\tau_k-\tau_j)] . \end{aligned} \quad (9)$$

In this case, although the intensity can also be divided into the IPS part and the coherent items part, there is no fast varying item in the coherent part of $I_{20}(t)$ because the coherent items part at this time is time-independent, and the spectrum of the coherent part is within the range of that of the IPS. After the intensity filter of 0.1 THz, the stacked pulse remains the same. When there is a perturbation towards NCGPS, the stacked pulse varies and the unstable stacked pulse will affect the LPR, as shown in Fig. 3. The parameters are chosen as Table 1 except C=0. Because the coherent items are in the range of the IPS part, when there is a timing delay perturbation in the case of NCGPS, the intensity spectrum varies, as shown in Figs. 3(c) and (d). As a result, the stacked pulse in NCGPS is unstable in the LPR with a timing delay perturbation.

In the cases of both LCGPS and NCGPS, the thermalization time of the plasma may be altered by the density and the temperature of the plasma[23], and the timing delay and the power attenuation may be altered by the environmental perturbations, which may cause the instability of the stacked pulse in the LPR. In order to measure the stability of the stacked pulse in the LPR, we introduce degree of stability (DOS) as follows:

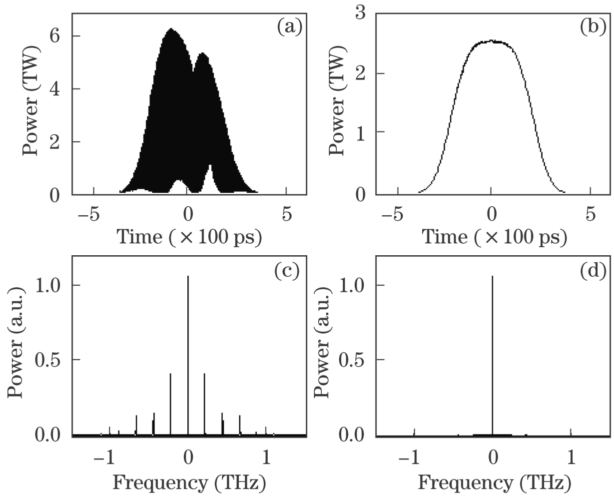

Fig. 2. (a) The stacked pulse of 6 LCGPSs with an initial pulse of 100 ps, an equal attenuation, and a timing delay of 70 ps, with a timing delay perturbation $\delta\tau_3$ at the third pulse, where $\omega_0\delta\tau_3 = \pi$. (b) The received signal after the intensity filter of 0.1 THz. (c) The corresponding Fourier transform of (a). (d) The corresponding Fourier transform of (b).

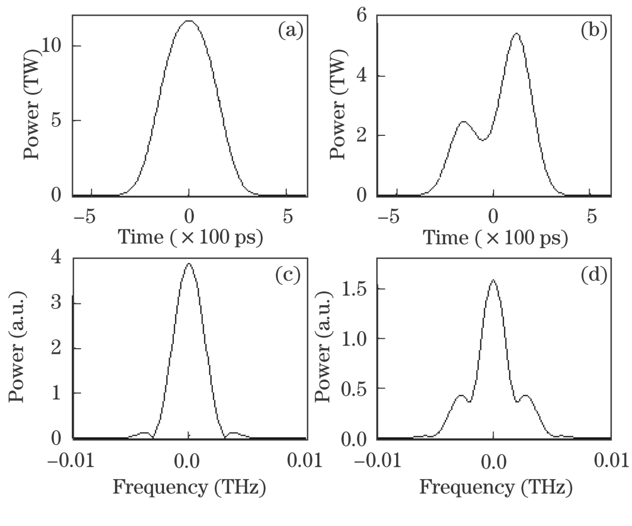

Fig. 3. (a) The stacked pulse of 6 NCGPSs with an initial pulse of 100 ps, an equal attenuation, and a timing delay of 70 ps. (b) The stacked pulse of 6 NCGPSs with an initial pulse of 100 ps, an equal attenuation, and a timing delay of 70 ps, with a timing delay perturbation $\delta\tau_3$ at the third pulse, where $\omega_0\delta\tau_3 = \pi$. (c) The corresponding Fourier transform of (a). (d) The corresponding Fourier transform of (b).

$$\mathrm{DOS} = \left| \frac{I_1(t) - I_2(t)}{I_1(t) + I_2(t)} \right|_{\max}, \tag{10}$$

where $I_1(t)$ and $I_2(t)$ are the intensity of the signals before and after a perturbation, respectively.

It is easy to find that the pulse stacking system is stable in the LPR with a perturbation if DOS is small. For a requirement of ICF system, the fluctuation should be no more than 10%[3], and DOS should be

$$\mathrm{DOS} \leq 0.05. \tag{11}$$

Equation (11) gives a criterion for the stability of the system and also suggests a perturbation range. One should carefully control the change of the environment in order to maintain the stability of the pulse stacking system.

When the thermalization time of the plasma in the LPR increases, the bandwidth of equivalent intensity filter $H(\omega)$ decreases. In this case, more high frequency sidebands in the intensity spectrum of the stacked pulse will be removed, so the LCGPS system would be more stable with the increase of the thermalization time of the plasma in the LPR, as shown in Fig. 4. Here we use 6 linearly chirped Gaussian pulses for pulse stacking and add a timing delay perturbation $\delta\tau_3$ at the third pulse with $\omega_0\delta\tau_3 = \pi$. The parameters are chosen as Table 1. In order to satisfy Eq. (11), the thermalization time of the plasma in the LPR for this case should be at least 5.5 ps.

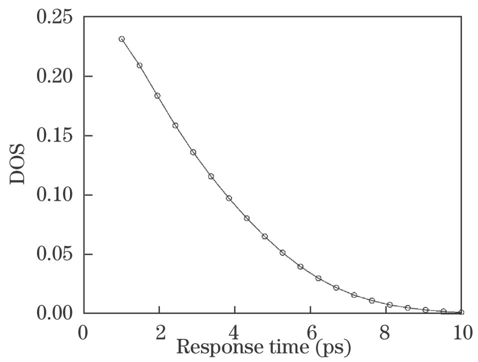

Fig. 4. DOS of 6 LCGPSs with an equal attenuation and a timing delay of 70 ps versus the response time (thermalization time) of the plasma. There is a timing delay perturbation $\delta\tau_3$ at the third pulse, where $\omega_0\delta\tau_3 = \pi$.

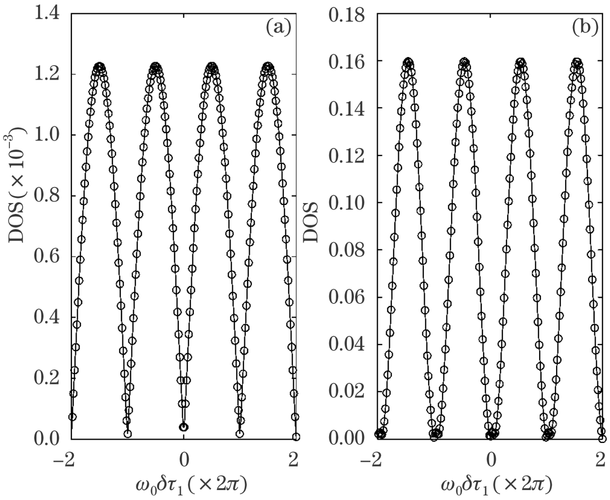

Fig. 5. DOS of both (a) 6 LCGPSs and (b) 6 NCGPSs versus the timing delay perturbation $\delta\tau_1$ which is added on the first pulse.

Figure 5 shows the stability of both LCGPSS and NCGPS in the LPR with a timing delay perturbation $\delta\tau_1$on the first pulse. The parameters are chosen as Table 1, and the perturbation $\omega_0\delta\tau_1$varies from -4π to 4π. From Fig. 5, one can clearly find that the technique of LCGPS is far more stable than that of NCGPS in the LPR. When the perturbation is added to an individual timing delay in the LCGPS system, the IPS part is hardly affected while the coherent part varies, indicating a variation in the side-bands of the intensity spectrum of the stacked pulse. But during the LPR process, the high frequency sidebands of the intensity spectrum of the stacked pulse will not affect the reaction result in the LCGPS system, and most IPS parts take part in the LPR. As a result, the stacked pulse of LCGPS in the LPR becomes stable with an individual timing delay perturbation, and DOS is within 0.0014 as shown in Fig. 5(a). While for the NCGPS, the individual timing delay perturbation would be in the baseband of the intensity spectrum of the stacked pulse, so the perturbation will affect the LPR, and DOS for this case could be larger than 0.05. We notice that there are sinusoidal oscillations in DOS from Fig. 5 and contribute this to the fact that the intensity filter are chosen to be Gaussian shape with a bandwidth of 0.1 THz, and the sinusoidal oscillations in the coherent items of the stacked pulse cannot be fully removed by a Gaussian filter.

The stabilities of LCGPS and NCGPS in the LPR with a timing delay perturbation on every pulse are shown in Fig. 6. The parameters are also chosen as Table 1. There is a symmetric structure in Fig. 6. The timing delay variance should be no more than 35 ps for 6 LCGPS and

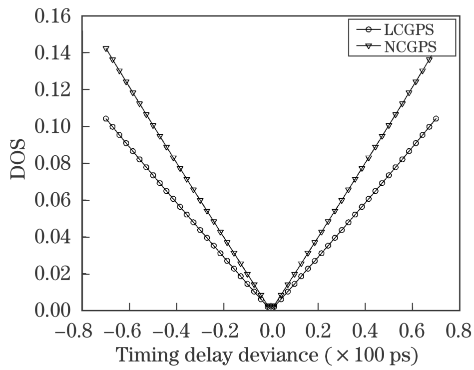

Fig. 6. DOS of both 6 LCGPSs and 6 NCGPSs versus the timing delay perturbation which is added on every pulse equally.

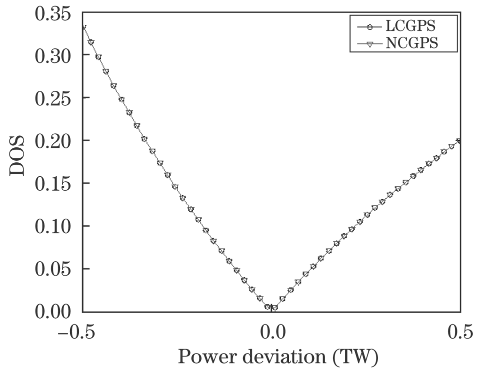

Fig. 7. DOS of both 6 LCGPSs and 6 NCGPSs versus the power perturbation which is added on every pulse equally.

26 ps for 6 LCGPS for the requirement of Eq. (11).

Figure 6 also shows a difference of DOSs between LCGPS and NCGPS. For the same level of perturbation, the system with a larger DOS is more unstable. According to Fig. 6, LCGPS is more stable than NCGPS for the total timing delay perturbation.

Figure 7 shows the stabilities of LCGPS and NCGPS in the LPR with a power attenuation perturbation on every pulse. From Fig. 7, we can find that the stabilities of both LCGPS and NCGPS are nearly the same with a power attenuation perturbation on each pulse. We can also find that the DOS distribution is not symmetric. DOS is 0.33 when the power deviation is −0.5 TW and is 0.2 when the power deviation is 0.5 TW, which is due to the definition of DOS. When the power is changed from 1 to 0.5 TW, DOS is 0.33, and when the power is changed from 1 to 1.5 TW, DOS is 0.2. For the requirement of Eq. (12), the power perturbation should be within 0.1 TW.

In conclusion, we study the LPR in the ICF system and analyze the stabilities of both LCGPS and NCGPS in the LPR. The LPR can be treated as the process that the stacked pulse is the first intensity filtered and then induces the plasma due to the thermalization time of the plasma. We also discuss and compare the stabilities of both LCGPS and NCGPS over the change of the thermalization time of the plasma, the timing delay, and the intensity attenuation of the stacked pulse in the LPR. Our results show that LCGPS is more stable than NCGPS in the LPR with the change of the environment in the ICF system. We believe this would be helpful for experiments of the ICF front-end systems.

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