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11 fs, 1.5 PW laser with nonlinear pulse compression

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Abstract: The PEARL laser output pulse with a duration of 60-70 fs was compressed to 11 fs after passing through a 5-mm thick silica plate and reflecting from two chirping mirrors with a total dispersion of -250 fs^2. The experiments were carried out for the B-integral values up to 19 without damage of the optical elements, which indicates that small-scale self-focusing was suppressed. The results obtained show the possibility of further nonlinear compression scaling to multipetawatt power in pulses with duration commensurate with the field period.

1. Introduction

Numerous applications of high-power femtosecond lasers make the enhancement of their peak power one of the main tasks in quantum electronics [1]. At present, the power and, hence, the focal intensity of laser radiation, are limited by the size and laser damage threshold of the compressor diffraction gratings. A multiple increase in power is possible using mosaic gratings in the compressor or *N* parallel CPA channels, each of which ends with its own conventional compressor. In these cases, the power and energy of the pulse increase by *N* times, while its duration is maintained. An increase in the pulse energy entails a multiple increase in complexity, size, and price of the laser. The recently developing approach, according to which power is enhanced due to a decrease in the pulse duration after the compressor rather than due to an increase in energy, is free from this drawback. So diffraction gratings of the compressor are no longer a bottleneck. This approach has different names/acronyms: TFC (Thin Film Compression) [2], CafCA (Compression after Compressor Approach) [3], or post-compression [4]. The underlying idea is to stretch the pulse spectrum due to self-phase modulation (SPM) during propagation in a medium with Kerr nonlinearity and then to compress the pulse on reflection from the chirping mirrors (CM) with negative dispersion.

The idea of using cubic nonlinearity for SPM was proposed as early as in 1969 [5]. In the same year, a several fold compression of a 20-ps pulse at SPM in a cuvette with CS_2 was demonstrated in [6]. Later, nonlinear compression was implemented in a fiber in a femtosecond range [7], in hollow waveguides [8], and in a bulk material with a limited transverse direction [9]. Despite a large number of studies (see, for example, the references in the review paper [3]), pulse compression with energy only on the order of mJ was attained, as in all these experiments the beam diameter was less than 1 mm. For scaling, it was necessary to use the SPM at a free propagation of a collimated beam having a diameter of 1 cm and more. However, small-scale self-focusing (SSSF) induced by the Bespalov-Talanov instability plays a significant role at such propagation [10]. The instability increment is determined by the B-integral

$$B = kLn_2I, \tag{1}$$

where n_2 and L are, respectively, the nonlinear index of refraction and the thickness of the nonlinear medium, k=2π/λ, λ is the wavelength in vacuum, and I is the peak intensity. Usually,

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at B=3, the beam breaks up into multiple filaments. Consequently, until recently it was believed that CafCA is possible only in a narrow 2<B<3 range [11–13]. At the same time, a large value of B-integral is required for effective compression. A detailed investigation, including the impact of medium dispersion, was presented in [3]. For estimates, one can also make use of the expression obtained in [14] for the intensity increase factor $F_i = I_{out}/I_{in}$ within dispersionless approximation:

$$F_i \cong 1 + B/2 \tag{2}$$

Thus, from (1, 2) it follows that for B<3 the maximum intensity increase factor is 2.5. A more significant increase in power using CafCA seems impossible at first sight: one and the same effect (Kerr nonlinearity) and, moreover, the same parameter (B-integral) are both, useful and parasitic. The solution proposed in [15] is based on the idea of self-filtering of the beam freely propagating in vacuum. In [16,17] it was demonstrated that self-filtering mitigates the once inviolable limitation B<3. This served as an impetus for both theoretical and experimental research in recent years. The theoretical works were aimed at detailed numerical modeling [14,2,18], as well as at expanding the capabilities of the technique. For example, the application of the method for a pulse after wide-angle non-collinear optical parametric chirped-pulse amplification (WNOPCPA) [19], the enhancement of the pulse time contrast simultaneously with its compression [20–23], and the use of a nonlinear medium with a large n_2 [24]. Pulse compression of the lasers of moderately low power (below 50 TW) [25–32], as well as of the lasers with a power of 100 TW and higher [33–37] was experimentally demonstrated at free beam propagation in a nonlinear medium. Note also the demonstration of the two-stage CafCA in both these ranges [32,38].

The maximal B-integral value in the performed experiments was 7.8 [36], which is much higher than the above limitation of B<3. At the same time, the results reported in [16] show that, under definite conditions, SSSF may be avoided for the B-integral values up to 25. In this work we experimentally studied the compression of the PEARL (PEtawatt pARametric Laser [39]) laser output pulse at the values of the B-integral from 9 to 19 and obtained record parameters of the compressed pulse: a duration of 11 fs and a power of 1.5 PW.

2. Experimental setup

The schematic diagram of the experiment is shown in Fig. 1. After reflection from the last diffraction grating of the compressor, the PEARL beam (central wavelength 910 nm) with a pulse energy of up to 18 J, a duration of 54-74 fs, and a diameter of 18 cm propagated 2.5 meters in free space for self-filtering [15]. After that, the beam was propagated in a 5-mm thick silica. We believe that 5mm thickness is optimal for our experiments, but we have only a 4mm-thick silica plate (SP) and a 1mm-thick SP. So, we use two SPs with a total thickness of 5 mm. The reflection from the first (reflective) SP surface was used to measure the spectrum and the autocorrelation function (ACF) of the input pulse. The measurements were made for a small part of the beam with a diameter of 1 cm. After free propagation over a distance of 6 m, the beam was reflected from two CMs with a diameter of 20 cm manufactured by UltraFast Innovations GmbH (reflection coefficient >99%, bandwidth >200nm). To measure the parameters of the output (compressed) pulse, a glass wedge (GW) with an aperture of 1×2 cm and a mat back surface was placed in the beam path. The beam reflected from the first surface of the wedge was directed to the spectrometer and the autocorrelator. The position of the wedge within the beam aperture corresponded to the place where the ACF and the spectrum of the input beam were measured, which made it possible to measure the characteristics of the input and output pulses in a single shot.

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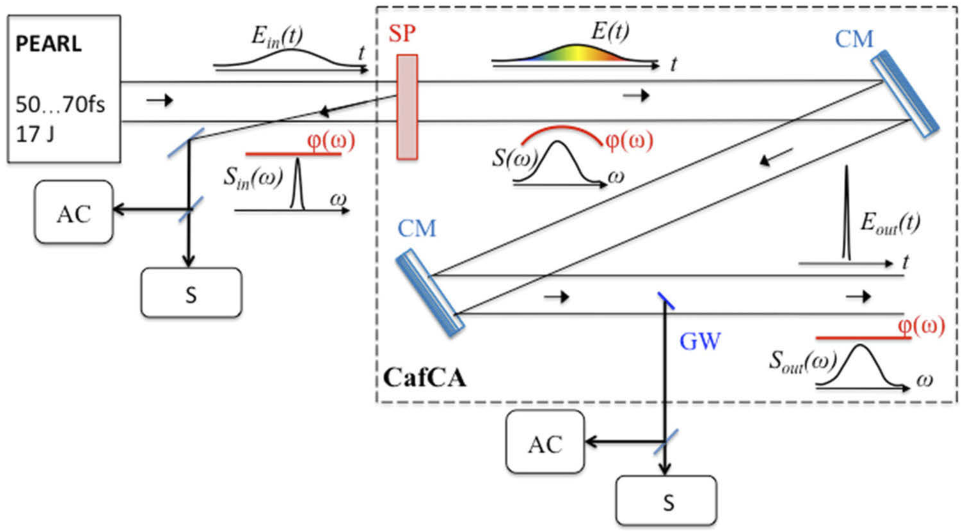

Fig. 1. Schematic of the experiment. SP – silica plate, CM – chirping mirrors, GW – small-aperture glass wedge, AC – autocorrelators, S – spectrometers. The figure is not to scale: the distance between the SP and the first CM is 6m, between two CMs 2m, and before the second CM and GW 1.5m.

3. Experimental results

We measured three pairs of CMs with a total dispersion of −325 fs^2 (−175 fs^2 and −150 fs^2), −250 fs^2 (−100 fs^2 and −150 fs^2), and −200 fs^2 (−100 fs^2 and −100 fs^2). For high values of the B-integral (B>10), the best results were obtained for the total dispersion of −250 fs^2. Note that the optimal value obtained in [36] was −400 fs^2 for B=3. . . 6 and −300 fs^2 for B=6. . . 8. Thus, the value −250 fs^2 obtained in this work corresponds to the theoretical predictions of the reduction of CM dispersion with increasing B-integral [3].

The measured spectra and ACF are shown by solid curves in Fig. 2 for the input pulse with peak intensity I_{in}=1.4 TW/cm^2, B=13. For the measured spectrum of the input pulse we selected a spectral phase that gives the closest match to the measured ACF. The shape of this pulse and its ACF are plotted by dotted curves in Fig. 2. For the selected input pulse shape, we calculated the output pulse parameters presented in Fig. 2 by the dotted curve. The calculations took into account the wave nonstationarity (nonlinear dispersion). We assumed the silica dispersion to be 28 fs^2/mm and n_2=2.45 × 10^{-16}cm^2/W.

Table 1. Comparison of experimental and theoretical parameters

	Experiment			Numerical study for zero (optimal) TOD of CMs			
B	τ_{in}, fs	τ_{out}, fs	$F_\tau=\tau_{\text{in}}/\tau_{\text{out}}$	τ_{in}, fs	τ_{out}, fs	$F_\tau=\tau_{\text{in}}/\tau_{\text{out}}$	$F_{\text{i}}=I_{\text{out}}/I_{\text{in}}$
9.6	54 ± 5	10.9 ± 1.5	5.0	58	12.3 (9.0)	4.7 (6.5)	4.2 (5.8)
9.9	58 ± 6	11.3 ± 1.5	5.1	58	12.2 (8.9)	4.8 (6.5)	4.0 (5.7)
13	60 ± 6	11.5 ± 1.5	5.2	64	11 (7.9)	5.8 (8.1)	5.0 (7.2)
19.2	72 ± 7	10.3 ± 1.5	7.0	75	10.2 (6.5)	7.4 (10.5)	5.7 (11.3)

As can be seen from Fig. 2, the experimental results are in a good agreement with the theoretical data. The ACFs are consistent quantitatively, and the output pulse spectra are consistent qualitatively, including typical narrow peaks. These peaks arise because the input pulses are not Fourier-transform-limited (FTL), see [14] for details. Note that the measured

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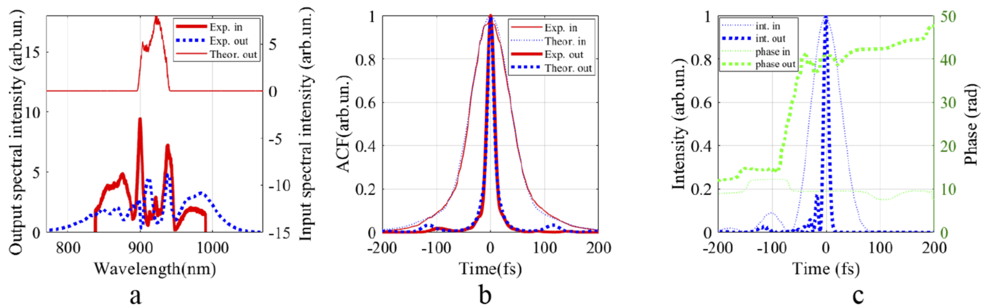

Fig. 2. (a) Spectra, (b) ACFs, and (c) pulse shapes at the input (thin curves) and output (bold curves) of the CafCA system: experimental (solid red curves) and theoretical (dotted blue and green curves). Parameters of the pulses are shown in Table 1 (B=13). The spectrum of the input pulse has sharp tails due to strong nonlinearity of parametric amplification in the laser PEARL. The spectrum of the output pulse, on the contrary, is limited by the bandwidth of the used spectrometer (840. . . 990 nm).

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The measured and calculated parameters of the input (in) and compressed (out) pulses for the shot depicted in Fig. 2 (B=13) and some other shots are given in Table 1. The experimental pulse duration was calculated as an ACF duration divided by 1.42, like for a Gaussian pulse. In experiments the pulses and ACFs are not Gaussian at the tails but the main peak is very close to Gaussian, so for FWHM pulse duration the value of 1.42 looks reasonable. Also, the results of our numerous theoretical modelings of SPM and post-compression showed that the ratio of ACF's FWHM and pulse' FWHM is very close to 1.42.

The data without parentheses in the right-hand part of Table 1 are the results of modeling assuming that CMs induce only quadratic dispersion. CMs usually introduce higher-order dispersions as well, but we do not have exact data on them for the mirrors used in our experiment. We performed numerical modeling by varying the TODs of the CMs. The results demonstrated that a negative TOD of the CMs increases the duration of the compressed pulse, with the increase being less than 10%, if the TOD absolute value of the CMs is less than 400fs^3 for B=9 and less than 250fs^3 for B=19. If the TOD of the CMs is positive, there exists an optimal value at which the sum TOD of the pulse is equal to zero and its duration is minimal. The results of the calculations for the optimal value of TOD of the CMs are presented in the parentheses in Table 1. The values of F_τ and F_i increase significantly, with F_i approaching F_τ at a high B-integral. This is explained by the fact that the zero value of the pulse TOD reduces the fraction of the energy concentrated in its tails.

The obtained values of the pulse compression factor $F_\tau=\tau_{in}/\tau_{out}$ and the compressed pulse duration τ_{out} as a function of the B-integral are shown by the blue squares in Fig. 3. We included in these graphs results of all known to us experimental studies in which SPM occurred at free beam propagation. Note that the experimental B-dependences of F_τ and τ_{out} plotted in Fig. 3 are quite smooth, which was also confirmed by calculations. It should be taken into consideration that the spread of τ_{out} in Fig. 3(b) is caused, among others, by the different durations of the input pulse. Consequently, F_τ and τ_{out} change little over the cross section for beams close to flat-top ones. This enables us to claim that the pulse duration integrated over the beam is close to τ_{out}, and the power increase factor $F_p=P_{out}/P_{in}$ is close to F_i. This was studied in ample detail for supergaussian beams in [3].

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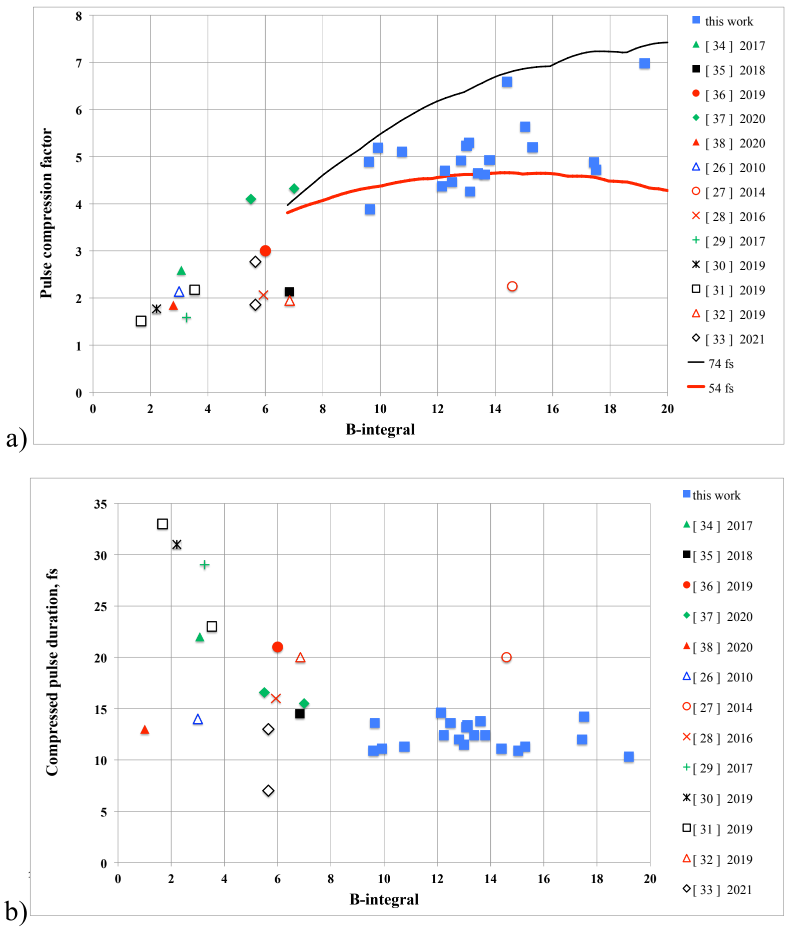

Fig. 3. Pulse compression factor $F_\tau=\tau_{in}/\tau_{out}$ (a) and compressed pulse duration τ_{out} (b) vs B-integral. The colored symbols correspond to the experiments with an input pulse power of 100 TW and more [33–37], all the rest – less than 50 TW [25–32]. The curves in Fig. 3(a) were calculated for a Gaussian input FTL-pulse with an FWHM duration of 54 fs and 74 fs.

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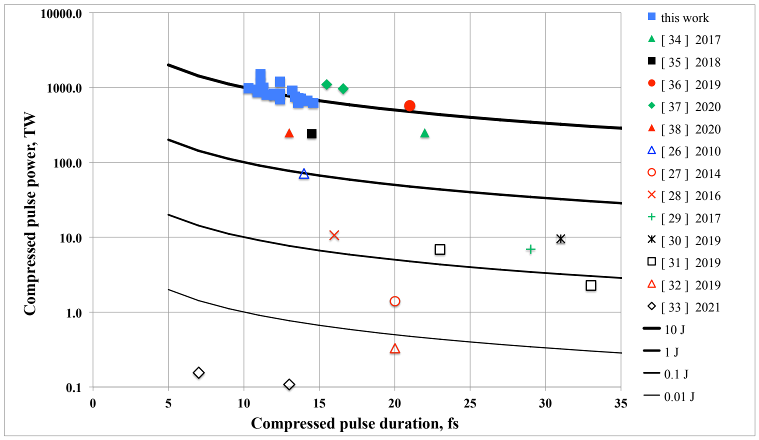

Fig. 4. Experimentally obtained parameters (duration and power) of pulses after nonlinear compression. Solid lines correspond to pulse energies of 0.01, 0.1, 1, and 10 J.

4. Discussion of the results

The calculated curves of pulse compression $F_\tau(B)$ in Fig. 3(a) were plotted for the Gaussian input FTL-pulse with an FWHM-duration of 54 fs and 74 fs, that were the shortest and the longest pulses used in the experiment. The good agreement between the theoretical curves and the experimental values suggests that CafCA for real (non-Gaussian, not FTL) pulses is as effective as for the ideal pulse. The growth saturation and even the decline of the $F_\tau(B)$ curves at large values of B are associated with the fact that the -250 fs^2 dispersion of CMs becomes higher than needed for the compression of the positively chirped pulse after the SPM. Excess dispersion leads to a negatively chirped pulse and, hence, to its longer duration.

Note that even optimal CMs dispersion provides the zero value only of the second-order spectral phase. At the same time, the higher order spectral phase of the input pulse is not zero, further it grows during SPM and, finally, CMs contribute to it too. As a result, the input pulse in the experiment was much longer than the FTL-pulse. For example, the FTL-pulse with the spectrum shown in Fig. 2(a) by dotted curves has an FWHM duration of 7.5fs. This value is much smaller than the results of measurements (11.5fs) and calculation with a pure parabolic spectral phase of CMs (11.0 fs), as shown in the penultimate line in Table 1. This indicates a possibility of a still more efficient compression with the appropriate control of the higher order spectral phase: selecting an optimal phase of the input pulse, using nonlinear media other than silica, and optimizing CMs.

From Fig. 3(a,b) it is seen that we have greatly advanced both in terms of compression F_τ>6 and minimal pulse duration τ_{out}=11 fs. (The pulse duration of 7 fs shown in Fig. 3(b) [32] was obtained at an extremely lower power of 0.1 TW.) The maximal power of the compressed pulse P_{out} of 1.5 PW was also a record value for lasers with CafCA. This is clearly demonstrated in Fig. 4, where the results of all the experimental works, in which the SPM took place at free beam propagation, are presented in the plane of parameters of a compressed pulse (P_{out}, τ_{out}). It is worthy of notice that, for the petawatt lasers, a duration of 11 fs is currently a record one, to the best of our knowledge.

Despite the huge values of the B-integral, there were no signs of damage either on the SP or on the CMs. It is important to note that, according to our previous experiments, the CMs damage threshold is no more than twice the fluence used in the experiment. Consequently, the absence of damage indicates that the SSSF was suppressed. The maximum admissible value of B

typical for nanosecond lasers is approximately 3. Since the Kerr nonlinearity is inertia-free even for femtosecond lasers, this limitation on the B-integral is frequently "mechanically" (see, e.g., [11–13]) extended to femtosecond lasers, which is wrong for three reasons.

First, a fundamental feature of SSSF in ultra-high-power (intensity after compressor of about 1 TW/cm^2) lasers is a very large (tens of mrad) value of the angle θ_{max} of propagation of spatial noise with the largest instability increment. Such large values of θ_{max} allow using self-filtering (proposed in [15]) of the beam freely propagating in vacuum for SSSF suppression – the most dangerous noise components come out of the beam aperture. In other words, free space is a filter of spatial frequencies, the transmission coefficient of which was derived in [40]. In [16,17], self-filtering was demonstrated in direct experiments.

Second, the spectral density of noise decreases at high spatial frequencies. The main source of spatial noise is the non-ideal surface profile of the optical elements, which leads to a non-uniform cross-section phase. High spatial frequencies correspond to small spatial scales of inhomogeneities, for which the modulation depth is much lower. These two reasons were analysed in detail in [3,40].

Third, the SSSF for laser pulses with a small number of field oscillations was investigated in [41,42]. It was shown analytically that the type of instability changes to the convective one. As a result, for laser pulses with a duration of less than 10 field periods, the SSSF must be suppressed, which was confirmed numerically. Experimental confirmation of this effect has not been demonstrated yet. However, making use of the results reported in [3,40] and of the experimental parameters it can be shown that the first two reasons are insufficient for suppressing SSSF at B=19. This indirectly confirms the suppression of SSSF due to convective instability, although the pulse duration in a nonlinear medium in our experiments exceeded 10 field periods. A detailed study of this effect will be presented elsewhere.

The possibility to use large values of the B-integral in addition to the large pulse compression factor has two more important advantages: smaller values of the CM dispersion [3] and sufficiently thick (up to several mm) nonlinear plates. Reduced requirements for CM dispersion allow producing them with a larger bandwidth, as well as reducing their number. This can be especially important for lasers with pulse durations of hundreds of femtoseconds, for which the required CM dispersion is thousands of fs^2. Thick plates can be made from a wider range of materials, which expands the possibilities for optimizing CafCA. In particular, the KDP crystal has attractive properties, as its dispersion (ordinary wave) at a wavelength of 910 nm is only 11 fs^2, which is 2.5 times less than that of fused silica, while n_2, on the contrary, is greater than that of fused silica. Moreover, in KDP, n_2 depends on the angle φ. Therefore, by rotating a z-cut crystal (θ=0) around the z axis it is possible to smoothly change the B-integral by almost one and a half times: $n_2(\theta=0, \varphi=0) = 4.6\times10^{-16}$cm^2/W, and $n_2(\theta=0, \varphi=\pi/4) = 3.3\times10^{-16}$cm^2/W [43]. It should be noted that large B-integral values also have a drawback: the focusability degrades for non-flat-top beams.

During propagation in SP the laser beam acquires a nonlinear phase. If the beam is non-flat-top, this phase is spatially inhomogeneous, i.e. temporally nonstationary nonlinear aberrations arise in the beam. These aberrations deteriorate beam focusing. A qualitative analysis of the nonlinear beam aberrations was made in [44]. For qualitative description of aberrations researchers most frequently use the parameter M^2 [45] and the Strehl ratio S [46]. To a first approximation, the nonlinear phase is equal to the B-integral (1), i.e. it is proportional to the input intensity. This case was considered in [3], where it was shown that, for supergaussian beams with the parameter m, there is no need to aim for large values of m. The value m=2-3 is quite sufficient, and for B<6, the Strehl ratio S>0.8, which means that the aberrations will reduce the focal intensity by no more than 20%. The focusing efficiency was experimentally demonstrated in [30,32] for small B. At large B, an adaptive mirror should be used. As the amplitude of phase distortions is approximately equal to B, even for B=19 it is only three wavelengths, which can well be attained by the present day adaptive mirrors [47,48]. The numerical 3D modeling performed in [36] demonstrated that, even for a non-supergaussian beam with 50% intensity modulation, a set of Zernicke polynomials with radial indexes no more than seven is sufficient for the Strehl ratio to reach 0.85. At the same time, it is worthy of notice that, due to the nonstationarity of nonlinear aberrations, standard algorithms of adaptive mirror operation will require modification and experimental verification.

5. Conclusions

In our studies of the nonlinear compression of high-power laser pulses (TFC, CafCA, post-compression), we obtained record values of the pulse compression factor $\tau_{in}/\tau_{out}>6$, the duration of the compressed pulse $\tau_{out}=11\pm1.5$ fs, and its peak power 1.5 ± 0.3 PW. To the best of our knowledge, the duration of 11 fs is the shortest for all petawatt lasers worldwide.

The experiments were carried out at values of the B-integral from 9 to 19, with no damage of the optical elements, which indicates the suppression of small-scale self-focusing. One of the reasons for this is a significant shift of the maximum increment of the self-focusing instability to the region of high spatial frequencies and the resulting decrease in the noise power in the region of the maximum increment due to the decay of the noise spectral density and self-filtering of the beam during free propagation. Another possible cause, namely, the convective nature of the self-focusing instability at a short pulse duration requires further investigation.

Taking into account the obtained results and undoubted merits of nonlinear compression (simplicity, low cost, negligible pulse energy losses, and applicability to any high-power laser), we predict further development of this approach toward multi-PW power and single cycle pulse duration simultaneously.

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Data availability. No data were generated or analyzed in the presented research.

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