Repetitive petawatt-class laser with near-diffraction-limited focal spot and transform-limited pulse duration

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ABSTRACT

A repetitive petawatt-class Ti:sapphire laser system operating with high spatial and temporal beam quality is demonstrated. Maximum pulse energy of 30 J is obtained via five multi-pass amplification stages. Closed-loop feedback control systems in the temporal and spatial domains are used to yield Fourier-transform-limited pulse duration (33.7 fs), and diffraction-limited focal spot sizes (with several different tight focusing optics). The laser parameters have been fully characterized at high-power, and are monitored in real-time, to ensure that they meet the experimental requirements for laser-wakefield electron acceleration and x-ray generation.

Keywords: petawatt, diffraction limited, transform limited, spatial and temporal closed loop, vacuum measurement

1. INTRODUCTION

The application of the techniques of chirped-pulse amplification (CPA)[1] and Kerr-lens modelocking[2] to solid-state lasers has led to compact and robust systems capable of >1-petawatt peak power, and focused intensity of $>10^{21}$ W/cm^2.[3-5] This has created new research opportunities over a wide range of scientific disciplines. For instance, such high power lasers can now be used to accelerate electrons to near GeV energy over just a centimeter-scale distance, via the mechanism of laser-wakefield acceleration (LWFA).[6, 7] In order to optimize the focused intensity, which is critical for numerous applications, including LWFA, the quality of laser beam—both spatially as well as temporally—should be as high as possible. For high peak-power laser beams, the preservation of high beam quality requires, among other measures, avoidance of deleterious nonlinear effects, which can arise from propagation through atmospheric pressure air. For this reason, grating pulse compressors are generally operated only under vacuum conditions, as are high-field interaction experiments that make use of the compressed beam. However, optical systems necessary for measurement and assurance of beam quality at the interaction point are not designed to be compatible with operation under vacuum conditions.

The spatial quality of the amplified beam comprises both the near- and far-field spatial distributions. The former is a concern for the safety of the optics, especially for the compressor gratings, which have a relatively low damage threshold. A homogenizer to smooth the spatial distribution of the laser pump beam is often implemented in order to obtain a flattop spatial distribution of the amplified beam. A flat and uniform wavefront is also required in order to obtain a diffraction-limited focal spot.[8] Optical aberration in the amplification chain and thermally induced distortion are the main sources for wavefront deterioration. An adaptive optical system can both measure and correct the wavefront distortion. Chromatic aberrations can also be minimized by implementation of all-reflective optics or an achromatic lens in the final beam expander.

Because the temporal quality of the amplified beam is strongly affected by chromatic dispersion in CPA laser systems, it needs to be precisely controlled and minimized. Flat spectral phase over the entire spectral range is requisite for Fourier-transform-limited pulses. In a CPA laser system, the dispersion mismatch among the stretcher, any transmissive

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materials, and the compressor prevents the ideal compression of the laser pulses. In a mJ-level CPA laser system, the dispersion can be managed to match, up to fourth order, by designing the system to have the grating line density in the stretcher be different from that in the compressor.[9] However, it is difficult to completely eliminate high-order dispersion, which deteriorates the temporal intensity contrast. An adaptive spectral phase closed-loop system in the temporal domain can measure and compensate all the residual dispersion.

Laser parameters are typically measured using a low-power beam obtained by sampling the high-power laser output. However, the parameters measured under these conditions do not generally represent well the beam parameters at high power and under vacuum conditions. Moreover, it is important for experiments to establish the point at which the pulse has zero-frequency chirp. We report a closed-loop-spectral control system to obtain transform-limited pulses at the 100-TW peak power level, on target, and in vacuum. This allows the optimal pulse duration and focal spot to be obtained, which enables the highest intensity to be achieved, as well as the effects of optical phase to be investigated, in various high-field experiments.

The organization of the paper is as follows. In Section 2, we describe the petawatt-class laser (Diocles) at the University of Nebraska, Lincoln. In Sections 3 and 4, we discuss our achievement of both a diffraction-limited focal spot, and transform-limited pulse duration, by making use of two closed loops, one in the spatial domain, and another in the temporal domain. The summary follows in Section 5.

Table 1: Specifications of the 100-TW and petawatt beamlines.

Parameter	100 TW	PW
Energy	3.5J (compressed)	30 J (compressed)
Peak power	>100TW	1 petawatt
Repetition rate	10Hz	0.1 Hz
Pulse duration (FWHM)	~30fs (transform limit)	~30 fs
Beam diameter	75mm	175 mm
Pointing stability	3.5μrad	< 10 μrad
Temporal contrast	10^{-8} (ns); 10^{-7} (ps)	10^{-8} (ns); 10^{-7} (ps)
Spatial profile	Flat-top (near field) Diffraction-limited (far field)	Flat-top (near field) 9.9×8μm (FWHM) by f/6 OAP
Long-term energy stability	1% RMS (1 hours)	< 10 % (8 hours)

2. OVERVIEW of PETAWATT-CLASS LASER SYSTEM

The Diocles laser system consists of two beam lines (100-TW and petawatt) with different energy scales. The 100-TW system was built in collaboration with THALES LASERS. It is a CPA laser system, seeded by an ultra-short broadband nano-joule oscillator (*SYNERGY*, FEMTOLASERS, Inc.) at 76 MHz with pulse duration of 12 fs. An acoustic-optical programmable dispersion filter (AOPDF) (*DAZZLER*, FASTLITE, Inc.) is installed before the stretcher. The AOPDF is used to modify the spectrum of the seed pulse into the amplifier in order to minimize the gain narrowing effect, as well as compensate residual chromatic dispersion. The repetition rate of the pulses is stepped down to 1 kHz by the AOPDF. An Offner-type stretcher expands the femtosecond pulse to 500 ps in order to avoid the nonlinear effect and damage especially in the final amplification stages for petawatt beamline. The stretched pulse is then amplified to 1.3 mJ in a 1 kHz nine-pass amplifier (*FEMTOPOWER*, FEMTOLASERS, Inc.) pumped by a 9 mJ intra-cavity frequency doubled Nd:YLF laser (*JADE*, THALES LASERS). An electro-optic pulse cleaner in this amplifier stage filters the amplified spontaneous emission (ASE) and pre-pulses to enhance the temporal contrast to 10^{-8} within time scale of nanoseconds. The 10-Hz pulse after the pulse cleaner is amplified in a pre-amplifier stage and then two power amplifier that boost the energy to 50 mJ, 2 J and 5 J respectively. The beam from the 5-J amplifier is expanded to 3 in diameter and compressed to ~30 fs by a four-pass, two-grating compressor. The compressed pulse energy is 3.5 J, which corresponds to >100 TW peak power at 10 Hz repetition rate.

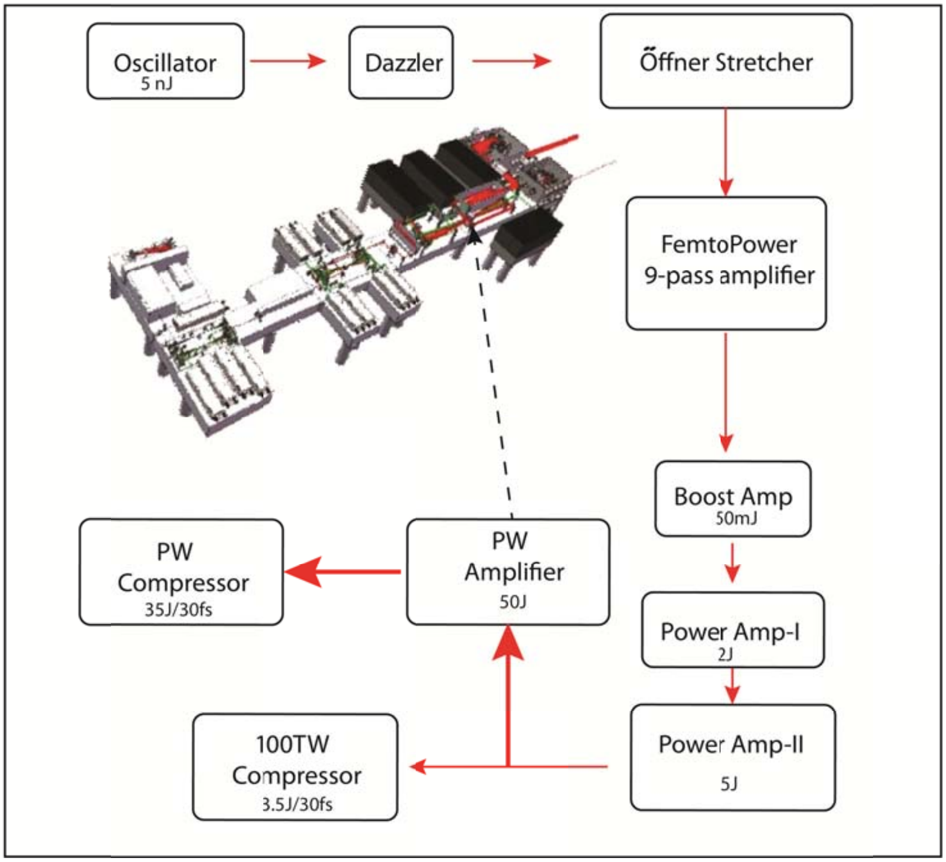

Figure 1: Block diagram, sketch, and 3-D layout of the Diocles petawatt laser. The pulse was amplified in two separate beamlines, to >5 J (100 TW) or to >40 J (petawatt).

The layout of the laser system is depicted in Fig.1. A turning mirror is inserted to switch from the 100-TW beamline to the PW beam line. The pulse from 5-J amplifier is boosted to ~42 J by another power amplifier which is pumped by four 25-J Nd:glass lasers (*ATLAS+*, THALES LASERS). The beam profiles of all the 25-J pump lasers are smoothed to perfect flattop with beam homogenizers. Figure 2 shows the beam profiles of the pump beam (after homogenization) as well as the profile of the amplified IR beam. The gain medium for the PW stage is a 115-mm diameter Ti:sapphire crystal, with a cladding of index-matching liquid, and absorption dye, used to avoid the transverse spontaneous emission or parasitic lasing due to the high-energy pumping. The beam is expanded to 7 in by an all-reflective parabolic telescope before sending to a larger scale compressor. The optical aberration is minimized by using parabolic telescope. The pulse energy after this compressor can reach ~30 J, corresponding to a peak power of >1 PW. The beam is focused using off-axis parabolic reflectors with different f/# in order to obtain a range of spot sizes on target. Section 3 will give detailed description on diffraction limited focal spot by closed loop in spatial domain. All the laser parameters for both 100-TW and petawatt are shown in Table 1.

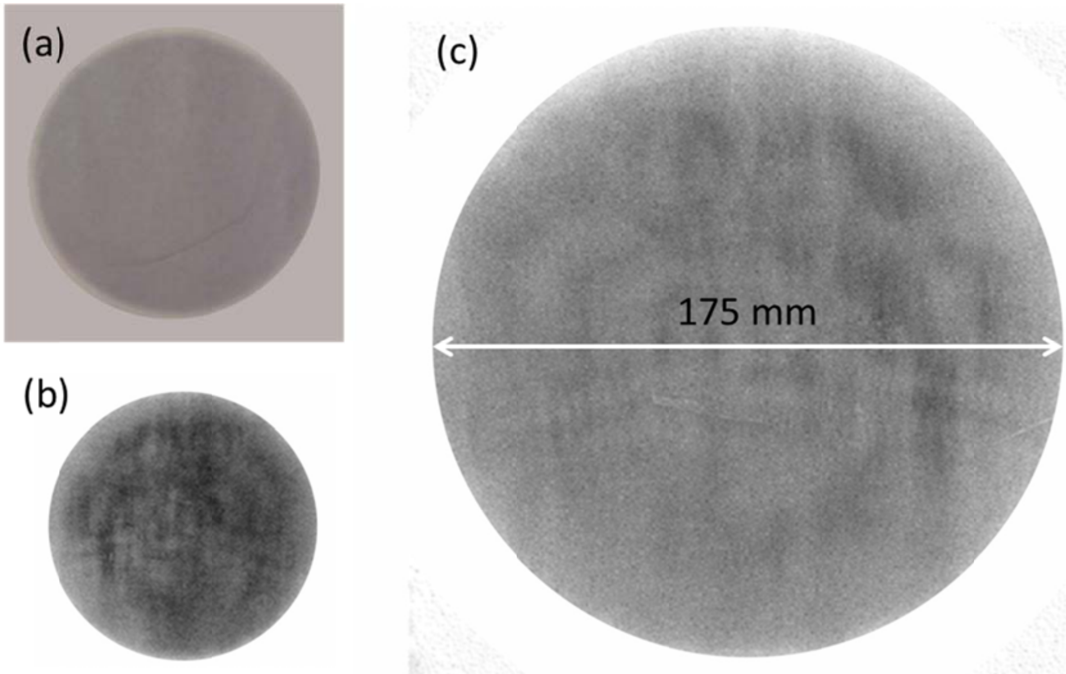

Figure 2: Beam profiles recorded on burn paper for the PW system (a) pump beam profile after homogenizer on the face of the crystal (70-mm diameter). (b) Amplified beam profile (67-mm diameter). (c) Beam profile at entrance to compressor.

3. DEFORMABLE MIRROR AND WAVEFRONT SENSOR CLOSED LOOP IN SPATIAL DOMAIN

As mentioned in Section 1, in a high power CPA system, wavefront distortion occurs because of the thermal effect in the high-energy amplification stages, especially with a repetition rate as high as 10 Hz. The large aperture optics for expanding the beam also introduces optical aberrations that contribute to the wavefront distortion. In both 100 TW and 1-PW beamlines, we employ aberration-free reflective parabolic telescopes to expand the beam before sending to the compressor. Compared to a lens-based telescope, reflective expanders spherical aberration and eliminate chromatic aberration. The residual wavefront distortion can then be corrected by an adaptive optics system consisting of a deformable mirror and a wavefront sensor (*SID4*, PHASICS Inc.). Instead of using equivalent plane imaging, we used a direct measurement to correct for the wavefront distortion. This was made possible by the ability of the wavefront sensor to measure a diverging beam. We could obtain an optimal focal spot by correcting for almost all the aberrations produced in the laser system. The deformable mirror (DM) (NIGHTN Ltd) was placed just after the compressor, and communicates with the wavefront sensor in a real-time close-loop feedback configuration. An off-axis parabolic mirror focuses the beam onto the target. A reflection off the front surface of a 45º uncoated wedge is used to sample the beam. Therefore, the measured values were exactly the same as those on target. The wedge can be moved in for measurements, and out for high-power experiments. Microscope objectives (10x, 20x and 40x) and a 12-bit camera (Q-Imaging Inc) were used in vacuum to characterize the focal spot. The "ON" time of the cameras was kept as short as possible (less than 10 minutes) to avoid the undesirable thermal effects. The wave-front sensor was place directly after the OAP. A band-pass filter (10 nm) was used just before the wave-front sensor to eliminate chromatic aberration. Moreover, the DM could also compensate the distortion from the misalignment of the OAP. The curved mirror and M2 were moved out before the wave front was being measured. A closed-loop feedback system was implemented between the DM and wave-front sensor to correct all the distortions in the laser system. The beam can be focused to 16× 16 m, 9.9× 8 µm, and 3.5× 3.9 µm by f/13.3, f/6, and f/2 off -axis parabolic mirrors, respectively. The measured focal spot sizes are shown in Figure 3.

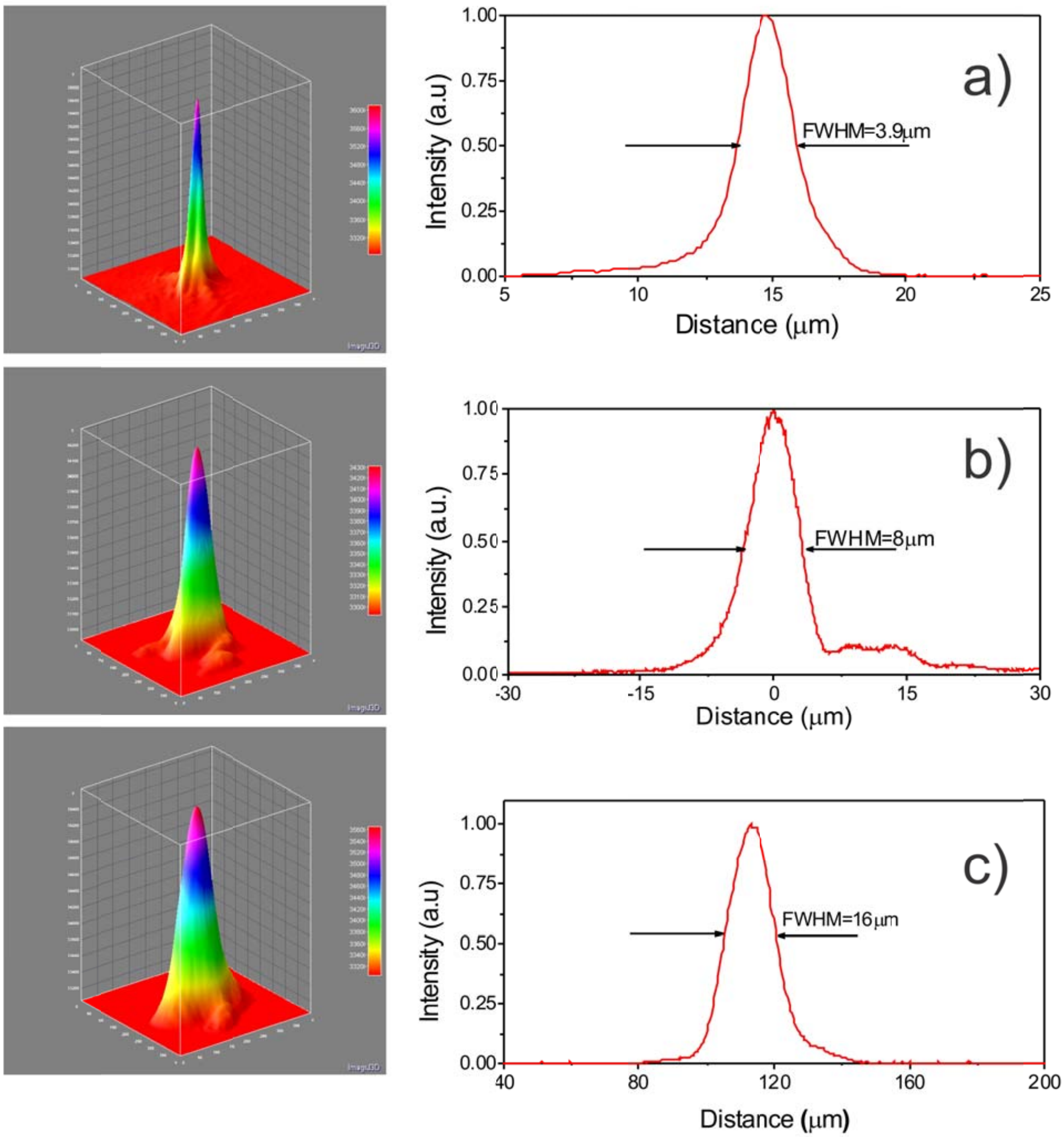

Figure 3: Focusability of the 3-in. diameter high-power laser pulse with wavefront correction for paraboloids with three different focal lengths (a) 6 in, (b) 18 in, and (c) 40 in.

4. SPECTRAL PHASE CLOSED LOOP FOR TRANSFORM LIMITED PULSE

In the temporal domain, both the pulse duration and temporal contrast are critical for experimental applications. The pulse duration in vacuum was found to be different from that measured in air. A flat spectral phase is required to obtain the shortest pulse duration and cleanest contrast on the time scale of several hundreds of femtoseconds. In our experiment, a high-dynamic-range single-shot self-referenced spectral interference device (SRSI) (*WIZZLER*, FASTLITE Inc.) measures the spectral phase and provides feedback to the AOPDF in temporal domain. The phase was measured both in vacuum and air, which has a ~3000 fs^2 difference in second order dispersion. This difference can also be indicated by the noticeable change of SHG signal when placing a BBO crystal just at the target point in air and in vacuum. The spectral phase difference between air and vacuum is probably due to the misalignment of compressor. The incident angle could change because the bending of the optical window at the entrance of the compressor chamber. The effective index of refractive for the boundary of gratings in the compressor will also be different. The change in pulse duration when the system is pumped down demonstrates that it is critical to optimize the temporal characteristics of the pulse on target and in vacuum.

In our measurements, the SRSI was placed just after the optical window of the target chamber. The measured pulse duration is not exactly equivalent to that on the target because of the optical window, which is 5-mm thick and made from fused silica. However, the additional dispersion created by the presence of the optical window in the beam path, can be pre-compensated by the SRSI itself. A closed loop between SRSI and AOPDF was implemented to compensate for the residual dispersion in the laser system. As a result of this process, Fourier-transform-limited pulses were achieved. The pulse duration was measured to be 33.7 fs, and the temporal contrast ratio, 10^{-5}, on the time scale of 400 fs. The pulse duration was independently measured by a frequency-resolved optical gating (FROG) (*GRENOUILLE*, SWAMP OPTICS Inc.) device, and both measurements were found to be in agreement. Figure 4 shows the measured spectral phase as well as the pulse duration in vacuum. This demonstrates the capability of our system to produce and measure in vacuum a transform-limited pulse duration at >100-TW power from a CPA laser system.

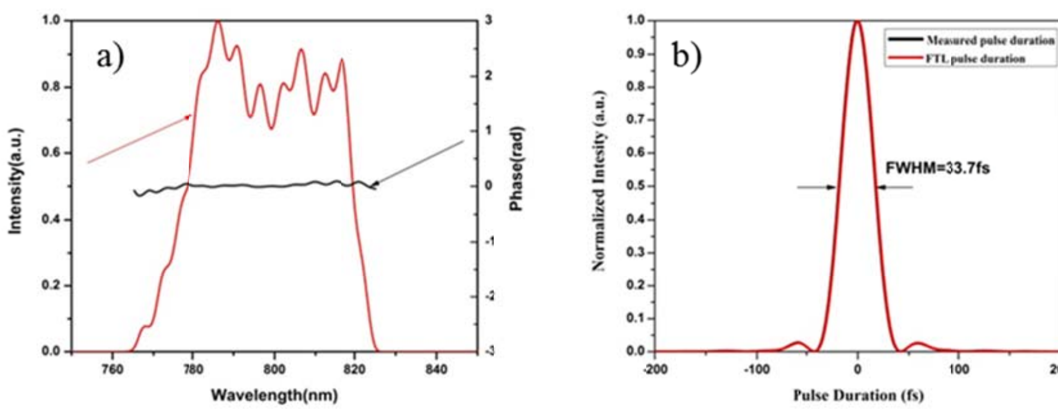

Figure 4: Spectral phase (a) and pulse duration (b) with spectral feedback closed loop.

5. SUMMARY

In this paper, we describe the complete characterization of both the spatial and temporal properties of a high power laser beam that was focused in vacuum. A near diffraction-limited focal spot was obtained using a deformable mirror and wave-front sensor in a closed-loop feedback system for spatial phase (wavefront) correction. Another closed loop between an AOPDF pulse shaper and an SRSI measurement device for spectral-phase correction was also implemented to obtain Fourier-transform-limited temporal pulse duration, with a 10^{-5} intensity contrast (on the 400-fs time scale). This advance makes it possible to precisely control the spatio-temporal characteristics of high power pulses for use in high-field physics research.

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