Appl. Phys. B 79, 817–821 (2004)
DOI: 10.1007/s00340-004-1621-4

Applied Physics B
Lasers and Optics

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Active optical storage ring for high-power laser pulses

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Received: 11 June 2004
Published online: 8 September 2004 **• © Springer-Verlag 2004**

ABSTRACT In an optical storage ring, a dye laser amplifier synchronously pumped by external laser pulses has been implemented and experimentally tested. The test was done at $\lambda = 580$ nm, but the optical system can be used without limitations in a broad band of 400–700 nm. It is shown that a selected turn of the stored laser pulse can be amplified by typically a factor of 200. Power consideration gives an increase of the efficiency of the optical storage ring with a dye amplifying cell, as compared to a single passage of the laser pulse through the experimental section, by 23 times and it is shown that it can reach a factor of more than 100.

PACS 42.60.Da; 42.60.Lh

1 Introduction

High peak power laser systems are of fundamental importance for applications in high-intensity physics such as multiphoton processes [1], laser-produced plasma and plasma diagnostics, and photon enhancement of collision cross sections. On the other hand, when using pulsed laser systems for reaching intense laser fields, one suffers quite often from a low duty factor, i.e. the product of repetition rate and pulse length. Recently, a laser-pulse trapper for Compton-backscattering applications [2], a ring resonator with a low-gain amplifier for generation of intense hard X-rays [3], and an optical storage ring for laser pulses [4] were developed to improve the pulsed laser duty factor in the case when the experimental section is optically thin. Typical examples where these laser pulse storage devices can be applied are: (i) Compton backscattering of high-power laser photons from high-energy electrons for a source of X-rays, high-energy gamma rays, and positrons; (ii) diagnostics of laser-produced plasma, e.g. by Thomson scattering ([5] and references therein), (iii) multiphoton ionization where the repetition rate of the laser limits the collection of electron counts produced from ionizing atoms by the intense laser field [6], and (iv) laser-induced radiative recombination (LIR) [7–9] and laser-induced dielectronic recombination (LIDR), where the interaction between electrons and ions takes place in the presence of a laser field. LIDR has not been observed so far due to the low duty cycle of the pulsed lasers. LIR was proposed for enhancing antihydrogen ($\bar{\mathrm{H}}$) production [10]. With the recent success of producing it in a Penning trap [11], this scheme of enhancing recombination into a well-defined quantum state with help of pulsed lasers gets renewed actuality.

In many applications, such as for instance LIR, one faces a saturation effect with the laser intensity and the gain is minimal above a certain laser pulse intensity. In these cases it is much more effective to increase the time of interaction between laser photons and ions or electrons. This interaction time is directly connected to the duty factor of the laser system, which in our case is increased by using the optical trap.

For the purpose of increasing the Compton-backscattering rate (example (i)) in a laser synchrotron source [3, 12] a recycler or low-gain amplifier has been introduced. This amplifier located inside the laser ring resonator replaces the energy lost through scattering and diffraction at the mirrors and upon impact with the electron beam. This system, based on solid-state lasers, works in the near infrared ($\lambda \approx 1\ \mu$m). Another system was developed by DULY Research, Inc. [2], where a laser pulse is trapped in an optical ring, called there a delay line, for multiple collisions of the laser pulse with electron multibunches. That also includes an amplifier based on solid-state technology and working in the near infrared. We present here a laser storage ring with an implemented amplifier capable of working in a broad optical wavelength range, from violet to infrared (IR), with only limitations in the broadband antireflecting coatings. Solid-state laser systems are so far not tested and seem difficult to realize for a broad range of wavelengths in the visible range. In our case, the injecting optical element, the Wollaston prism, works over a broad band of wavelengths without limitations and low losses. Most of the known systems based on solid-state amplifiers (Ti–sapphire), that can be used for intracavity experiments, like regenerative amplifiers for instance, work in the near infrared at one wavelength or at a very narrow bandwidth.

Our ring-shaped optical storage device [4] recirculates the laser pulse and in such a way increases the repetition rate of the laser system used. It can reach repetition rates of the order of 10–100 MHz determined by the optical path length in the ring and limited by the length of the laser pulse itself. The length

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of the pulse train is, of course, limited by optical losses. In [4] we reported a lifetime of the laser pulse inside the ring of about 5 µs. That device would improve the integrated laser power in the interaction region by a factor of four. Due to the losses by the optical elements in the laser ring ($\sim 17\%$), it becomes difficult to store the laser pulse for more than 5 µs with useful power.

The presented scheme increases the duty factor by an additional factor of six through an amplifying medium. For that a dye cell is inserted into the optical ring and pumped by an external synchronized laser source. In the tests, we have amplified the injected and stored laser pulse from the excimer dye laser system (so-called signal laser beam) [4] by about 100 times. That increases the duty factor of the pulsed laser system by a factor of 25. The gain of the system is limited by the saturation of the amplifying medium and the optical aperture of the elements used. This optical ring system can be used in any scheme where the experimental section can be located inside the laser ring and has a high transparency ($\geq 90\%$), otherwise the efficiency of the system will decay rapidly.

2 Experimental setup

The optical storage ring is described in detail in [4]. We therefore give here only a brief account. It consists of an electro-optical switch, four high-reflecting mirrors, and a focusing system. A Wollaston prism and a Pockels cell, driven by a high-voltage pulser, form the electro-optical switch. In the new setup we introduce an amplifying cell into the optical storage ring (see Fig. 1). It consists of a quartz cuvette (with a length of $l = 4$ cm), slightly tilted in order to use the reflection from the front wall for monitoring and time synchronization, and to avoid direct reflection and undesirable effects in the parallel walls.

For monitoring and synchronization, the reflection of the primary incoming signal laser pulse is sent to a high-speed photodiode PD1 (Si PIN Lavin photodiode, S5973-01, Hamamatsu). The signal from PD1 is monitored in a high-speed oscilloscope (LeCroy 9362, 1.5-GHz bandwidth), where it is compared with the monitoring signal from the high-voltage pulser driving the Pockels cell. From this comparison the delay of the gate/delay generator (GDG2) is chosen in order to get the laser pulse trapped.

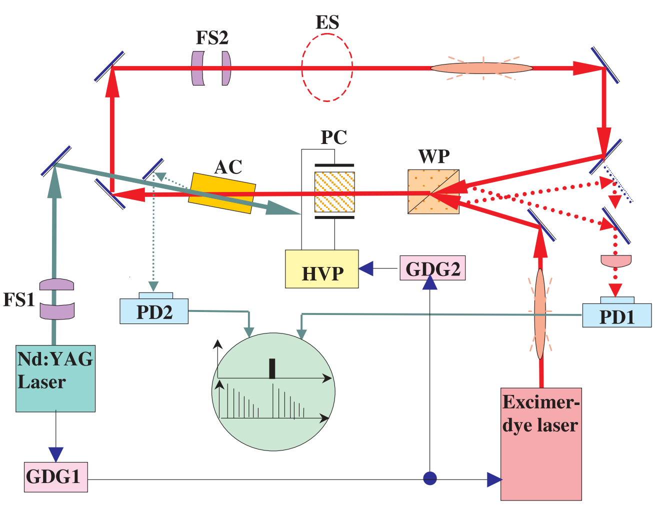

FIGURE 1 Schematic diagram of the optical ring with an implemented amplifying cell pumped by the synchronized external second harmonic of the Nd:YAG laser. FS, focusing system; PC, Pockels cell; WP, Wollaston prism; PD, photodiode; HPV, high-voltage pulser; AC, amplifying cell; GDG, gate/delay generator; ES, experimental section

We monitored the reflection from the front wall of the Wollaston prism of the trapped signal by PD1 and compared it in time with the reflected pump pulse from the front wall of the amplifying cell by a photodiode PD2. Both pulses were displayed with the help of the high-speed oscilloscope.

The triggering signal from the Q-switch of the Nd:YAG laser was used to trigger the excimer laser via a gate/delay generator (GDG1). This synchronization needs ns accuracy, which was achieved with the help of a digital delay/pulse generator DG535, with ps resolution (Stanford Research Systems, Inc.) and a very fast Si PIN Lavin photodiode.

A telescope focusing system, formed by a plane concave lens and a plane convex lens (FS1, see Fig. 1) was inserted in the pump beam for improving the alignment of the pump and signal beams.

The dye flow in the cuvette was vertical to the path of propagation of the signal laser beam. The configuration used for pumping the amplifier was chosen to be longitudinal single passage (called in the literature 'end-on-pumped configuration' [13, 14]).

3 Measurement and adjustments

We measured the intensity of the reflected light at the front wall of the Wollaston prism with the help of PD1; the signal was monitored by the oscilloscope.

The dye solution used was R6G in methanol. Different concentrations were tried for optimizing the gain in the system. For the available laser pump energy of the second harmonic of the Nd:YAG laser, $E_{2\mathrm{nd}}^{\mathrm{Nd:YAG}} \approx 50$ mJ at the entrance of the amplifying cell, the dye concentration of $c = 3.1 \times 10^{-5} \, \frac{\mathrm{mol}}{\mathrm{liter}}$ was optimal to get the pump laser beam filling all of the length of the cuvette, but not creating unnecessary laser generation in the walls of the cuvette or amplified superluminescence. The gain obtained from this concentration was lower than the one necessary to reach the threshold of laser generation of the dye solution in the ring cavity, and no laser generation in the ring cavity was observed. We measured just a very small part of the pump power after the amplifying cell. The measured absorbance for the dye R6G in methanol at the wavelength $\lambda = 532$ nm is $\sigma\,(\lambda = 532\,\mathrm{nm}) = 6.4 \times 10^4 \left[\frac{\mathrm{litre}}{\mathrm{mol\,cm}}\right]$, so that the remaining pump power at the end of the cell is as low as $E_{\mathrm{endofcell}} = E_{2\mathrm{nd}}^{\mathrm{Nd:YAG}} \, \mathrm{e}^{-\beta l} \approx 0.02$ mJ, with an attenuation of $\beta = \sigma\, c \approx 2\,\mathrm{cm}^{-1}$.

The efficiency of the pump for amplifying the signal beam was optimized experimentally by locating, with the help of the focusing system FS1, the waist of the focused pump beam at the center of the cuvette with only solvent in it. The Rayleigh length of the pump beam was about the length of the cuvette. This alignment was again adjusted with the dye solution in the cell because due to absorption in the dye the distribution of the pump power along the cuvette is not homogeneous. Both beams were made as collinear as possible, but this alignment was optimized considering maximum amplification of the trapped pulse; the intensity of the amplified pulse in Fig. 2 at the desired turn was chosen to be as high as possible.

At optimum, the diameter of the pump beam was a few mm bigger than that of the signal laser beam (8–10 mm at the entrance of the cuvette). This optimum is reached when the quantity of excited dye molecules on the passage through the cell is maximal; it means that we get the maximum gain in the system. The concentration used is optimal for this pump laser power and the used dimensions of the signal laser beam at the entrance of the amplifying cell. Almost all the pumping power is absorbed in the dye solution and used up in the amplifier.

We experimentally adjusted the time overlap between signal laser pulse and pump laser pulse to improve the performance of the laser storage ring. It is necessary to get both laser pulses at the 'same time' overlapping in the amplifying cell. This overlapping demands ns precision or better, because of the length of the pulses involved. The length of the excimer dye laser pulse is $\tau_{\mathrm{ExcDye}} \approx 7$–$9$ ns and the length of the second harmonic of the Nd:YAG laser is $\tau_{\mathrm{2nd\,h}}^{\mathrm{Nd:YAG}} \approx 8$–$10$ ns. The time window of the Pockels cell of $\tau_{\mathrm{PC}} \approx 30$ ns was sufficient for trapping the signal laser pulse in a ring with a length of $L = 15$ m (time for one turn of the signal pulse around the ring: $T = 50$ ns, which corresponds to the time separation between stored pulses). The available ns precision of the time synchronization for both laser pulses and Pockels cell was enough to optimize the amplification.

By adjusting the time delay for pumping the amplifier, it was possible to select the pulse from the train that should be amplified in the stored laser beam. This means at which turn the dye amplifier is activated in the optical storage ring. For one of our best alignments the measured amplification factor for the 13th turn was $\chi = I/I_0 \approx 194$, where I and I_0 are the intensities of the stored signal laser pulse at this turn with and without pumping of the amplifier.

For convenience, we have used a repetition rate of $f = 10$ Hz, for injecting into the ring throughout these measurements.

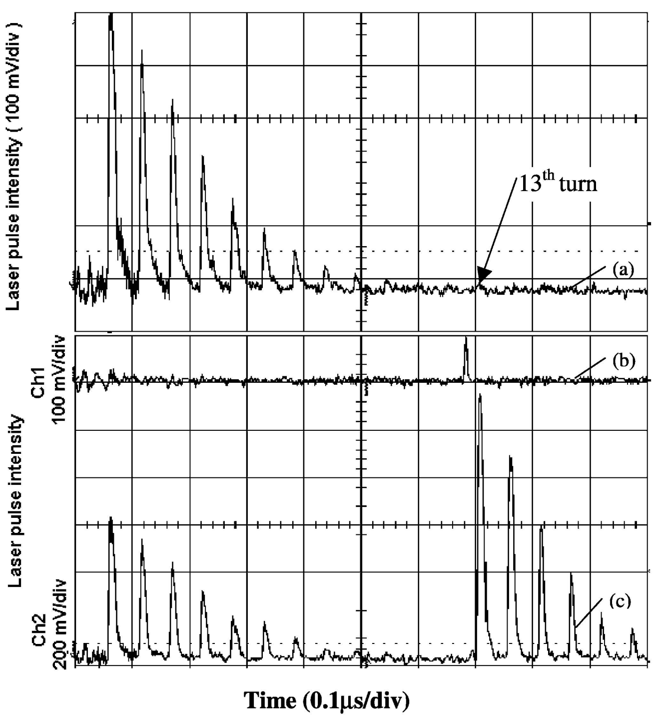

FIGURE 2 (a) The stored excimer dye laser pulse in the laser ring. (b) The timing pulse of the associated pump pulse from the Nd:YAG laser, indicated in Ch. 1. (c) Ch. 2 shows the amplification of the 13th turn of the stored laser pulse in the laser ring

4 Results and discussion

Figure 2a and c show the results of the measurements of the stored laser pulse without and with amplification, respectively. Figure 2b shows the pump laser pulse monitored by PD2. Here, a selected turn has been amplified when the pump is matched in time in the amplifier. As can be seen in Fig. 2, the already weak laser pulse (because of optical losses) after a number of turns in the trap grows when passing through the amplifier at the exact time when it is pumped.

No change in time and frequency profiles of the amplified selected turn was observed, with the available precision of about 1 ns. We tried anticollinear pumping of the amplifier and found that it gave almost the same results as the collinear pumping.

For the geometrical parameters used (cross section at the entrance of the cuvette) of the circulating signal beam, the intensity was much inferior to the saturation intensity of the dye amplifier. The saturation intensity for the dye R6G in methanol can be evaluated from [15]: $I_{\mathrm{Sat}} = \frac{\hbar\omega}{\sigma_{\mathrm{Emission}}\,\tau_{\mathrm{eff}}} \approx 0.34 \left[\frac{\mathrm{MW}}{\mathrm{cm}^2}\right]$, where $\hbar = h/2\pi$, h is the Planck constant, $\hbar\omega = 0.034 \times 10^{-17}$ J, $\lambda = 580$ nm, the emission cross section for R6G is $\sigma_{\mathrm{Emission}} \approx 2 \times 10^{-16}\,\mathrm{cm}^2$ [16], and $\tau_{\mathrm{eff}} \approx 5 \times 10^{-9}$ s is the spontaneous emission lifetime of the dye. In our tests we had the intensity of the injected pulse: $I_{\mathrm{inj}} = \frac{E_1}{A\,\tau_{\mathrm{ExcDye}}} \approx 0.1 \left[\frac{\mathrm{MW}}{\mathrm{cm}^2}\right]$, where the injected laser pulse energy was $E_1 \approx 0.5$ mJ and the area of the beam at the entrance of the cuvette was $A \approx 0.5$–$0.8\,\mathrm{cm}^2$. This value is slightly lower than the one for saturation of the dye.

Certainly, we can still increase the concentration of the dye and in such a way increase the gain of the amplifying cell, but for covering of all of the length of the cuvette used we have also to increase the pumping power to efficiently use all the volume of the dye in the cuvette. For concentrations below the one necessary for dimerization of the dye, the gain was directly proportional to the dye concentration. The other thing is that in order to be away from saturation of the dye used we have to increase the cross section of the amplifier. In our case we were limited by the aperture of the Pockels cell used.

When amplifying the first turn we could observe the effect of saturation because the amplification was low, about 1.5–2, but for a larger number of turns the amplification was larger (more than two times), because the signal to amplify was of lower intensity, and for the amplified 13th turn we could get a larger amplification and no saturation. For $n > 13$ the pulses were weaker and, even with the same amplification, the efficiency of the system was lower. It could be shown that the amplification did not vary with the turn selected as long as we: (i) could identify it clearly, (ii) the amplified turn was still below the value for saturation of the amplifier, and (iii) the amplified signal did not saturate the photodiode used.

Optimizing the optical trap at another turn (in the case of time-selective experiments) demands adjusting the gain of the amplifier and this can be done between pumping pulses by just steering the pump power. For a higher turn we have to increase the gain, i.e. the pump power, in order to get the same efficiency in the system. For a lower turn we have to decrease the gain in order to avoid saturation of the amplifier.

To compare the efficiency of different optical setups: single-pass configuration (no optical trap), optical storage ring with inactive amplifier, and optical storage ring with pumped amplifier, some helpful parameters have been introduced: the parameter of losses q and the accumulating factor $k_0^{\infty}(q)$. For the studied optical trap with an implemented amplifying cell, the total optical losses are $\alpha = 25\%$ (17% optical losses in the optical trap [9] and 8% optical losses in the quartz amplifying cell). The parameter of losses defined as $q = 1 - \frac{\alpha[\%]}{100} = 0.75$ depends on optical losses α and describes the decrease in energy of each turn seen at the experimental target. In Fig. 2, the factor $E_1\, q^n$ is proportional to the intensity at the nth turn for an injected pulse of energy E_1. The accumulating factor, $k_0^{\infty}(q) = \sum_{n=0}^{\infty} q^n = 3.99$, of the optical trap is defined as the sum of q^n, which is proportional to the energy of each turn that contributes to the total power accumulated in the trap, $E_{\Sigma} = \left(E_1\, q^0 + E_1\, q^1 + E_1\, q^2 + ... + E_1\, q^n + ...\right)$. Finally, the integrated power in the optical storage ring with inactive amplifier can be evaluated as $P_{\mathrm{NoAmp}} = E_1\, k_0^{\infty}(q)\, f = 20\,\mathrm{mW}$.

When the amplifier is pumped at some defined turn (in this particular case it was the 13th turn), we have to consider the gain of the dye amplifier in the expression for the integrated power, $P_{\mathrm{Amp}}^{13} = E_1\, k_0^{11}(q)\, f + E_{13}^{\mathrm{Amp}}\, k_0^{\infty}(q)\, f = 115\,\mathrm{mW}$. In this expression, the first term describes the accumulated power up to the turn when the amplifier is pumped. $k_0^{11}(q) = \sum_{n=0}^{11} q^n = 3.87$ is the accumulating factor up to the 12th turn (note that the '0' index in the sum means the first turn in the optical trap). The second term describes the contribution to the accumulated power originated by the amplified 13th turn when the pump is on. The energy of the trapped laser pulse at the 13th turn before amplification is $E_{13} = E_1\, q^{12} = 0.015\,\mathrm{mJ}$. Then, considering that at this turn E_{13} is amplified by $\chi = 194$ times, $E_{13}^{\mathrm{Amp}} = E_{13}\, \chi = 2.9\,\mathrm{mJ}$. Concerning saturation of the amplifier: before amplification of the chosen turn, E_{13} was far from saturation and when this turn was amplified (E_{13}^{Amp}) the intensity was nearly the saturation intensity for the dye (for an aperture of about 11 mm, $I_{13}^{\mathrm{Amp}} \approx 0.34 \left[\frac{\mathrm{MW}}{\mathrm{cm}^2}\right]$). In the measurements we did not observe saturation at this turn when the pulse was amplified.

Defining the efficiency of the optical trap $\xi\,(n)$ as the ratio between the integrated power in the trap with pumped amplifier at the nth turn and the power in one-pass configuration ($P_{\mathrm{OnePass}} = 5\,\mathrm{mW}$), $\xi(13) = \frac{P_{\mathrm{Amp}}^{13}}{P_{\mathrm{OnePass}}} \approx 23$, we can compare the efficiency of the optical storage ring pumped at different turns. In the case of pumping the turns 14 and 15, the efficiency of the system will decrease: $\xi(14) \approx 18$ and $\xi(15) \approx 14$. The pulse to amplify at these turns becomes weaker, the gain is not enough to compensate optical losses, and the efficiency of the optical trap is decreasing. In our case the optimum is reached at $n = 13$, but for every configuration a specific optimum can be found.

Using the optical storage ring and considering its enhancement factor, we gain a factor of almost four in comparison with the one-pass configuration. By implementing the dye amplifier into the optical ring with an amplification factor of about 200, we gain another factor of about six. That means that the optical storage ring with the implemented amplifier allows us to gain in total a factor of about 23 in comparison with a single passage of the pulse. The obtained efficiency ξ could still be increased up to a factor of more than 100, by means of optimizing the optical elements of the trap, for example decreasing optical losses to about 15%. This is possible if we replace the focusing system by curved high-reflecting mirrors and use broadband antireflecting coatings in the amplifying cell, which will reduce optical losses in the amplifying cell to one-half. The integrated power for this optimized case can be as high as $P_{\mathrm{Amp}}^{\mathrm{Opt}} \approx 900\,\mathrm{mW}$, where the parameter of losses is $q = 0.85$ and the accumulating factors are $k_0^{\infty}\,(0.85) = 6.7$ and $k_0^{11}\,(0.85) = 5.6$. The efficiency of the system will be $\xi\,(13) = \frac{P_{\mathrm{Amp}}}{P_{\mathrm{OnePass}}} \approx 180$ if pumped at the chosen 13th turn. For the results presented in Fig. 2, we got $\chi \approx 70$, $P_{\mathrm{Amp}} \approx 60\,\mathrm{mW}$, and $\xi\,(13) \approx 12$. These values are lower than those obtained with a higher gain, discussed before. Some time jitter between the pump laser and the signal laser from pulse to pulse affects the time overlap and thus the gain of the amplifier. This fluctuation in time overlap originates from the time jitter of about 1–2 ns in the triggering electronics of the available excimer laser. Improving the time jitter demands a better performance of the thyratron switch in the excimer laser discharge.

Increasing the energy of the injected laser pulse demands a larger aperture in optical elements and in the first place in the amplifying cell in order to avoid saturation of the dye solution. In our measurements, spatial inhomogeneities of the laser amplifier gain along the signal propagation path were not studied in detail, as they do not affect the performance of the amplifier in the optical trap. We just adjusted the focusing and optimized the alignment of the beams to get the maximum amplification in the system. In this way we could also keep the amplified superluminescence down to some per cent of the maximum, which is especially powerful in the direction of the parallel walls of the quartz cell where a regenerative feedback is present.

5 Conclusions

We have developed and studied the performance of a laser amplifier in an optical ring for trapping and storing ns laser pulses. The synchronously pumped dye cell amplifies a selected circulating pulse with a gain of about 70–200 dependent on the dye concentration. Increasing the concentration will give still more gain until reaching dimerization of the dye solution. For a good performance of the optical trap, the gain and alignment have to be optimized in order to keep the amplified spontaneous emission in the direction perpendicular to the cuvette walls low. For tests we injected a low-intensity laser pulse of moderate energy (0.5 mJ), but it is certainly possible to amplify this pulse first by complementary amplifiers (up to 100 mJ for instance) and then inject it into the optical trap with the proper optical aperture to avoid saturation and in this way gain in intensity and duty factor. By choosing different delays, we can amplify the stored laser pulse at different turns, which is an advantage in the case of time-resolved experiments. The pumped amplifier increases the integrated power in the optical storage ring by more than six times, and allows us to gain a total factor of about 23 in comparison to single passage of the laser pulse through an optically thin experimental section. This factor could be a very important issue in experiments where this optical system can be used. It is shown that by additional improvements of the proposed optical trap the efficiency of the system can reach a value of more than 100.

ACKNOWLEDGEMENTS Financial support for this research was received from the Swedish Natural Science Research Council (VR). T. Mohamed is grateful for support from the Egyptian Government.

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