BNL - 68272

Practical Approach to Monochromatic LWFA

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July 1998

National Synchrotron Light Source

Brookhaven National Laboratory
Operated by
Brookhaven Science Associates
Upton, NY 11973

Under Contract with the United States Department of Energy
Contract Number DE-AC02-98CH10886

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Practical Approach to Monochromatic LWFA

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Abstract. Dependence of the LWFA performance upon the laser wavelength is applied to optimization of the plasma-channeled standard LWFA operating in a linear regime. Electron beam energy spread, emittance and luminosity depend upon the proportion of the electron bunch size to the plasma wavelength. This proportion tends to improve with the laser wavelength increase. We propose the two-stage ~1 GeV LWFA with the controlled energy spread and emittance based on realistic capabilities of the BNL ATF that features: picosecond terawatt CO_2 laser and a high-brightness electron gun.

1. INTRODUCTION

After the successful experimental demonstration of the ultra-high gradient (up to 100 GeV/m) laser electron acceleration [1-3], the next goal in the laser accelerator development is to produce extended quasi-monoenergetic acceleration for appreciably bulk electron charges (~0.1 nC). Similar to conventional RF linacs, injection of electron bunches small to compare with a period of the oscillatory driver field is a condition for producing highly monochromatic, low emittance electron beams in laser accelerators.

In the case of RF linacs, with their ~100 MHz driving fields, the required electron bunches are generated using photocathode RF guns driven by picosecond lasers. Orders of magnitude higher frequencies of the drive field in laser accelerators require proportionally short electron bunches. Proposals to generate such bunches for plasma-based laser accelerators look as intricate as the laser accelerators themselves. One of such accelerator schemes, called LILAC [4], is based on using focused femtosecond laser pulses that inject plasma electrons precisely into the maximum of the accelerating wake field. According to another scheme, the quasi-relativistic electron bunches are formed due to frequency beating of two laser beams counter-propagating in plasma [5].

Practicalities of the mentioned above electron microbunch injection methods are subject to further analysis which we do not attempt here. In the present paper, we approach monochromatic laser acceleration from a different position. Our concept is based on a combination of the emerging ps-TW CO_2 lasers with a high-brightness conventional electron injectors.

The first ps-TW CO_2 laser is being commissioned at the BNL ATF [6-8]. Because the 10 times longer wavelength, λ, than the conventional T^3 solid state lasers, CO_2 laser may open new opportunities for the advance laser accelerator development. For processes based on electron quiver motion, like in the LWFA, the advantage of CO_2 lasers is primarily due to a gain of two orders of magnitude in the energy acquired

CP472, Advanced Accelerator Concepts: Eighth Workshop,
edited by W. Lawson, C. Bellamy, and D. Brosius

by the electron oscillating in EM laser field. The enhancement of the plasma wake formation with the CO_2 laser driver allows to reduce the plasma density in the LWFA without jeopardizing the net acceleration. Then, a conventional photocathode electron gun may be considered as a suitable injector for the LWFA with the controlled beam properties. The BNL/ATF, with its high-brightness RF gun and the world first ps-TW CO_2 laser, is equipped for the proof-of principle experimental test of such laser accelerator approach.

The ATF's electron linac delivers up to 3 nC, 10-0.3 ps, 50 MeV electron bunches with a peak current of 100-300 A, energy spread of 0.2%, and a normalized emittance ε_n=0.5 mm.mrad. Note, that with the present 10-ps UV photocathode laser driver, the electron bunch compression to 370 fs is achieved by the proper electron phasing to the RF field in the gun [9]. A shorter, down to 100 fs, electron bunch duration may be attained with the faster, ~1 ps, laser driver.

In Section 2, we discuss the dependence of the LWFA performance upon the laser wavelength and apply our findings to improving the energy spread of the plasma-channel LWFA operating in a linear regime.

In Section 3, we describe the 2D PIC simulations of the single-stage LWFA driven by the prospective 50 TW, 1-ps CO_2 laser and 50 MeV linac used as an injector. As is shown in Section 4, the performance of the GeV LWFA may be improved and as small as 1% energy spread obtained when the LWFA buncher is used between the conventional 5-MeV electron injector and the LWFA acceleration stage.

2. DEPENDENCE OF THE LWFA PERFORMANCE UPON THE LASER WAVELENGTH

The LWFA [10] operating in the linear regime is generally considered as the preferable scheme for the advanced high-gradient electron laser accelerators. The interest to this regime is due to a relatively high stability and regularity of the plasma wake. This offers an opportunity to achieve a reasonably good quality (emittance, monochromaticity) of the accelerated beam while maintaining the acceleration gradient ~100 times higher than with conventional RF accelerators.

In the standard LWFA scheme, plasma wave is initiated by a short laser pulse equal in duration to the half-period of the plasma wave, $\tau_L \approx \lambda_p/2c$, that depends upon the plasma density, n_e,

$$\lambda_p[\mu m] = 3\times10^{10} n_e^{-1/2}\left[cm^{-3}\right], \tag{1}$$

An important parameter that characterizes how strong is the laser effect on the plasma electrons is a normalized laser vector-potential,

$$a = eE_L / mc\omega = 0.3\, E_L\, [TV/m]\, l\, [mm], \tag{2}$$

where $$E_L[TV/m] = 15 P_L^{1/2}[TW] / r_L[\mu m], \tag{3}$$

P_L is the laser power, and r_L is the radius of the laser focus spot.

The amplitude of the accelerating field, E_a, due to the charge separation in a plasma wave is [11,12]

$$E_a[V/cm] = 0.37a^2\sqrt{n_e}\left[cm^{-3}\right], \tag{4}$$

or using Eq.(1),

$$E_a^{\max}[GV/m] = 10^3 a^2/\lambda_p[\mu m]. \tag{5}$$

Thus, increase of plasma density favors attaining ultra-high acceleration fields much above the conventional RF linacs. However, energy is not the only parameter important for a practical particle accelerator, which shall provide also a reasonable monochromaticity ($\Delta E/E \le 1\%$) and an appreciably high charge ($N_e \geq 10^9$ electrons/bunch).

The maximum number of the electrons per bunch is defined by the condition that the self-field of the bunch does not alter the plasma wakefield structure,

$$N_e \le n_e\left(c/\omega_p\right)^3 = 4\times 10^6\lambda_p[\mu m]. \tag{6}$$

The condition for a small energy spread requires the electron bunch to be much shorter than the plasma wake period, $\tau_b << \lambda_p/c$. This again favors bigger l_p. Thus, a certain trade-off needs to be resolved during the design of the high-gradient laser accelerator capable to deliver a good quality electron beam.

It is shown [13,14] that due to the enhanced ponderomotive action of the long wavelength radiation, CO_2 laser may help in designing the GeV compact electron accelerator with the appreciably high, ~0.1 nC, bunch charge. Below, we discuss how to do it with a low energy spread and a controlled emittance.

3. LIMITATIONS OF THE SINGLE STAGE LWFA DUE TO THE ELECTRON BUNCH DURATION

The approach to the mono-energetic LWFA is based on using the seed electron bunches small to compare with l_p. The initial bunches with the required quality and charge may be produced with the conventional technique using a photo-cathode RF gun.

2-D PIC simulations [15,16] for electron acceleration by plasma wake excited in the matched parabolic plasma channel help to verify the conditions for practically achievable monochromatic LWFA. The following input parameters have been used in simulations: CO_2 laser with t_L=1 ps, P_L=50 TW, a^2=0.5; plasma parameters $k_p r_L$=3.8, $k_p R_{ch}$=14.3, l_p=800 μm. Note that l_p and k_p are defined at the axis of the plasma channel that has the profile $n_e(r) = n_e^0\left(1+\left(\frac{r}{R_{ch}}\right)^2\right)$.

In the preliminary simulations discussed in this section, we considered the 50 MeV injected electron bunch with the energy spread 0.2%, geometric emittance of 3 mm.mrad, and the 30 μm (100 fs) length. These experimental conditions can be practically realized at the BNL ATF using a combination of the prospective ps-TW CO_2 laser, a compact high-brightness linac, and a plasma channel produced by the high-current capillary discharge in vacuum [17].

As is demonstrated in Fig.1, the above plasma and laser parameters lead to excitation of fairly regular wakefield. For the electron bunch injection, we choose the moment of the maximum accelerating field at the beginning of the focusing phase.

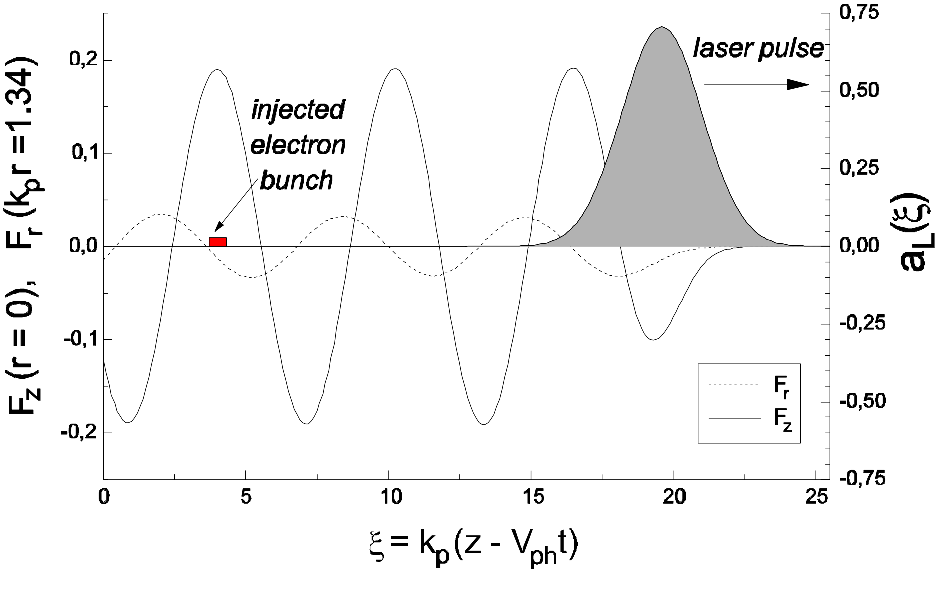

FIGURE 1. Accelerating F_z and focusing F_r wakefield forces in a matched parabolic plasma channel; CO_2 laser t_L=1 ps, P_L=50 TW, a^2=0.5; plasma parameters $k_p r_L$=3.8, $k_p R_{ch}$=14.3, l_p=800 μm.

Simulations of the electron bunch acceleration in the plasma wake illustrated by Fig.2 demonstrate a significant, up to 20%, energy spread to the end of the acceleration cycle when up to 1.7 GeV net energy gain is expected. More detailed dependencies of the electron beam quality upon the initial emittance and the bunch size are shown in Fig.3. The simulations demonstrate the importance of using possibly small (longitudinally and transversely) electron bunches in order to control the beam quality in the course of acceleration. Strong bunch focusing in the wakefield allows to maintain a low emittance. However, the selected initial bunch duration and a highly relativistic initial energy do not permit to achieve a low energy spread.

4. MONO-ENERGETIC LWFA WITH ps-TW CO_2 LASER DRIVER

Subsequently, the LWFA scheme evolved into the two-stage design where the first stage serves for bunch compression and second for monochromatic acceleration. In this section, we consider the 5 MeV injected electron bunch with the energy spread 1.5%, geometric emittance between 0.3-0.6 mm.mrad, the 30 μm (100 fs) length, and 50-100 μm radius at the entrance to the plasma channel. Laser and plasma parameters are taken similar for both stages and the same as in the simulations discussed in Section 3.

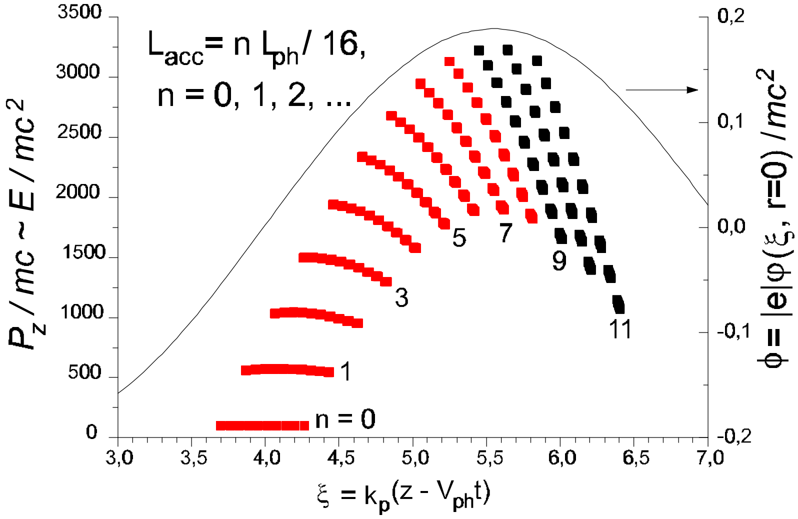

FIGURE 2. Wakefield acceleration of electron bunch by channel guided CO_2 laser pulse; a=0.71, k_pr_L=3.8, k_pR_{ch}=14.3, L_{ph}=512 cm, γ_0=100, L_b=r_b=0.1 λ_p.

Simulations of bunch dynamics through the bunching stage are illustrated in Fig.4 and 5. We see that by choosing the proper injection phase, at the negative slope of the wake, significant compression of the bunch (up to 6 times) may be attained over the short acceleration distance. Simulations show again the importance of maintaining a small radius of the electron bunch at the entrance to the bunching stage for both, bunch compression and a low emittance.

Extracted from the bunching stage at the 40 MeV energy, the compressed to 20 fs electron bunch is injected into the accelerating stage at the moment of the maximum accelerating field at the beginning of the focusing phase. The quasi-monochromatic energy gain up to 1.5 GeV with the energy spread of <2% is observed over the rest of the accelerating phase (see Fig.6). An important result is the preservation of the normalized emittance in the course of the acceleration (see Fig.7).

The presented simulations shall be considered as preliminary, and further optimization is under way. For example, the parameters of the bunching stage are assumed similar to the acceleration stage. Just the injection phase and the channel length are different. The bunching stage may probably be optimized to consume less of the laser energy. We can also extend the acceleration stage over the entire L_{ph} distance that may double the net acceleration.

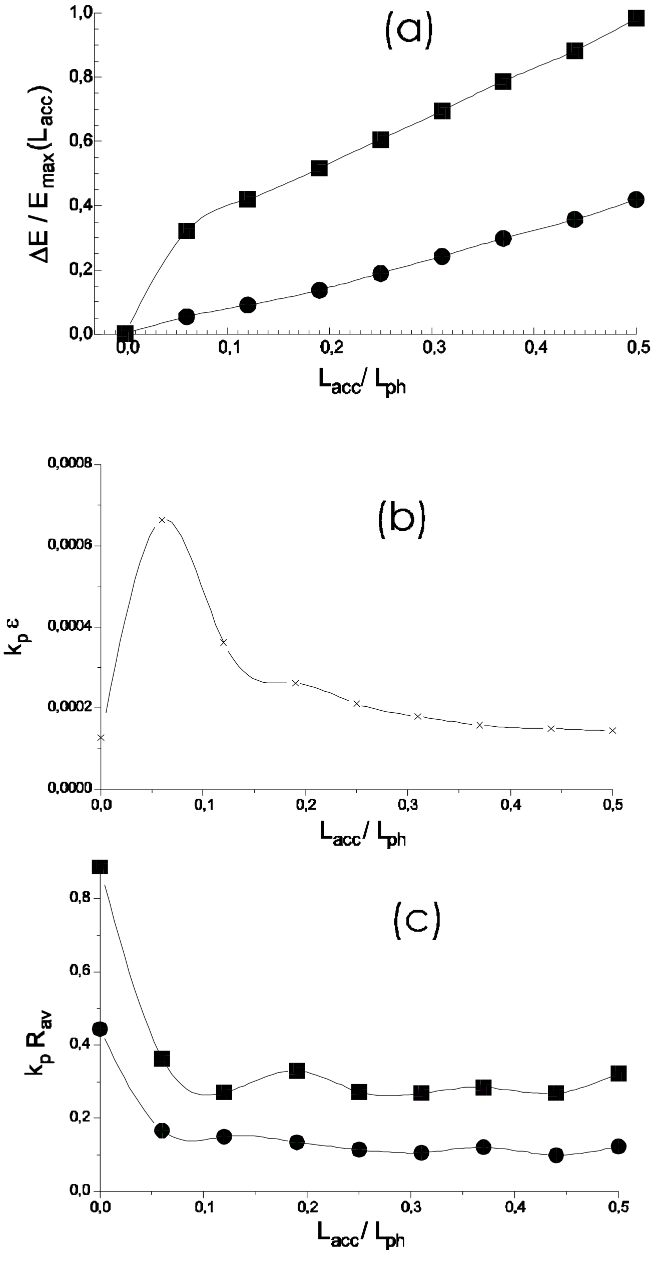

FIGURE 3. Quality of accelerated electron bunch in channel guided LWFA; a=0.71, $k_p r_L$=3.8, $k_p R_{ch}$=14.3, γ_0=100, L_{ph}=512 cm, (a), energy spread; (b) dynamics of emittance with the initial bunch sizes L_b=r_b=0.1 λ_p.; (c) average e-beam radius; circles- L_b=r_b=0.1 λ_p , boxes-L_b=r_b=0.2 λ_p

Summarizing, we see that a small proportion of the electron bunch dimensions to the plasma wavelength is a prerequisite for the reasonably monochromatic acceleration. As far as the used initial electron bunch parameters represent state of the art in the conventional photocathode RF gun technology, then the chosen plasma wavelength may also be considered being close to the minimum allowed for the proposed monochromatic LWFA scheme. Under these conditions, replacement of the CO_2 laser with the solid state laser of the equivalent peak power results, according to Eqs.(2) and (4), in approximately two orders of magnitude reduction in the acceleration gradient. Thus the proposed monochromatic GeV LWFA can be realized only with the CO_2 laser driver.

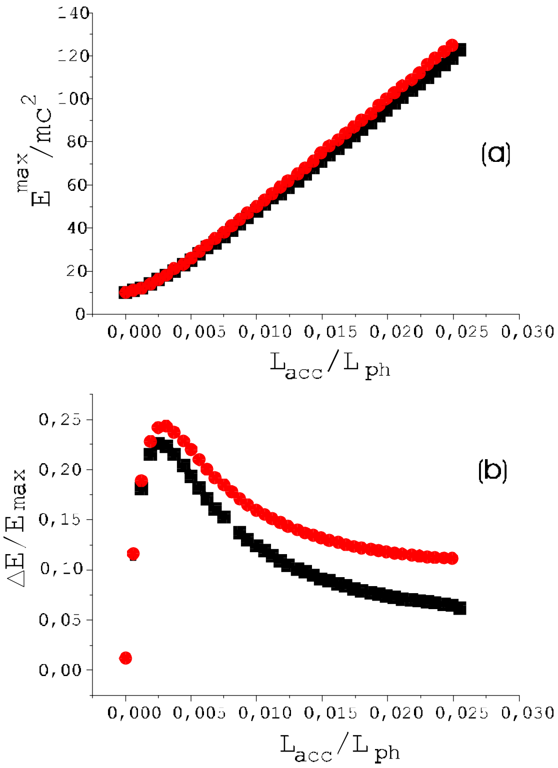

FIGURE 4. Energy modulation in bunching stage; initial bunch length, τ_{b0}=100 fs, γ_0=10; squares - r_b=50 μm, ε_0=0.6 mm.mrad; circles - r_{b0}=100 μm, ε_0=0.3 mm.mrad

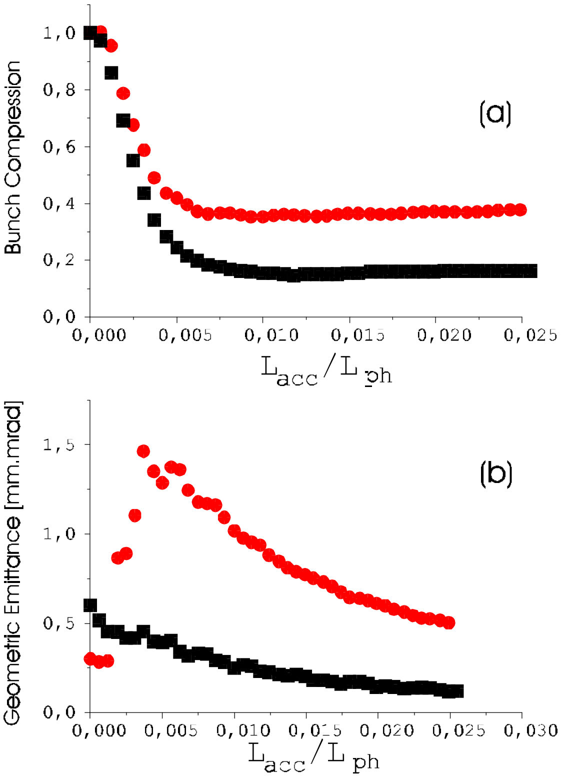

FIGURE 5. Bunch compression, and geometric emittance in bunching stage; initial bunch length, τ_{b0}=100 fs, γ_0=10; squares - r_{b0}=50 μm, ε_0=0.6 mm.mrad; circles - r_{b0}=100 μm, ε_0=0.3 mm.mrad

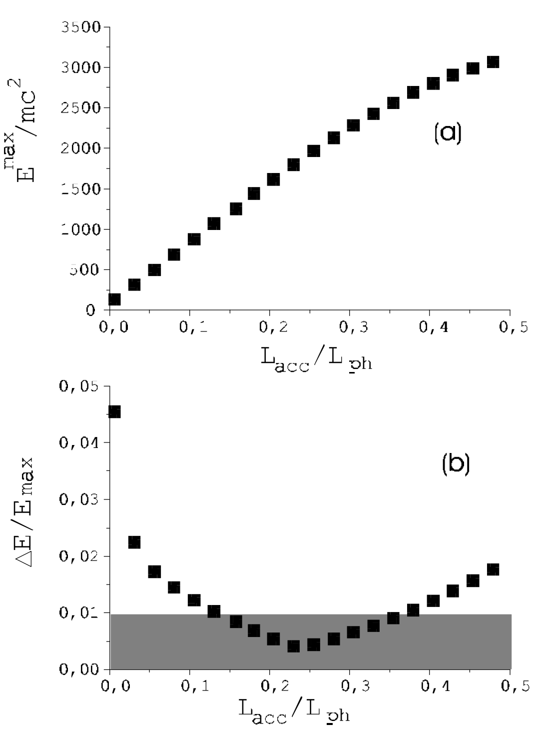

FIGURE 6. Energy modulation in the first acceleration stage; initial electron bunch parameters (before bunching stage): τ_{b0}=100 fs; r_{b0}=50 μm, ε_0=0.6 mm.mrad

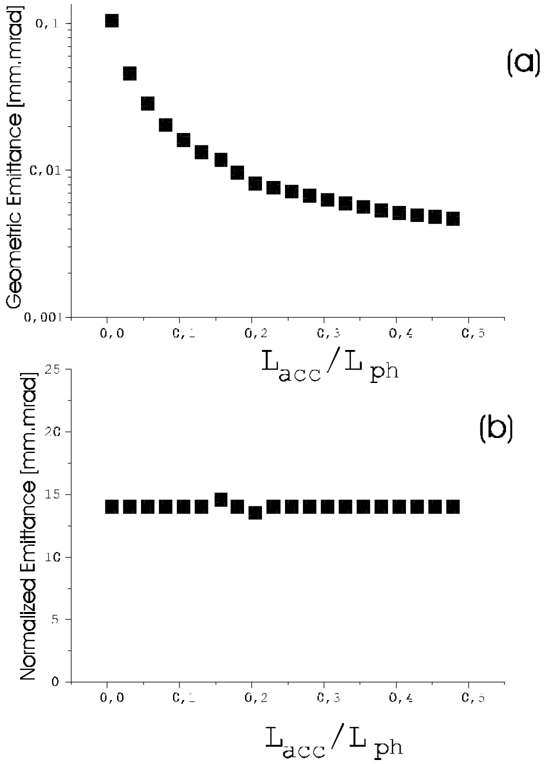

FIGURE 7. Electron emittance in the first acceleration stage; initial electron bunch parameters (before bunching stage): τ_{b0}=100 fs; r_{b0}=50 μm, ε_0=0.6 mm.mrad

5. ACKNOWLEDGMENTS

The authors wish to thank I. Ben-Zvi and X.J. Wang for valuable input and discussions.

This work was supported by the U.S. Dept. Of Energy under the Contract DE-AC02-76CH00016 and by Russian Foundation for Basic Research under the Grant 98-02-16263.

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