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Laser-plasma-based linear collider using hollow plasma channels☆

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Abstract

A linear electron-positron collider based on laser-plasma accelerators using hollow plasma channels is considered. Laser propagation and energy depletion in the hollow channel is discussed, as well as the overall efficiency of the laser-plasma accelerator. Example parameters are presented for a 1-TeV and 3-TeV center-of-mass collider based on laser-plasma accelerators.

Keywords: laser-plasma accelerator, linear collider

1. Introduction

Plasma-based accelerating structures have attracted significant interest as an accelerator technology because of their ability to sustain extremely large acceleration gradients, orders of magnitude larger than those achievable using conventional metallic RF structures, which are limited in gradient by material breakdown. Excitation of high gradients in the plasma requires high peak power drivers, and intense lasers can be used as drivers for plasma structures [1]. The electric field of the electron plasma wave (or wakefield) excited by an intense laser can be on the order of $E_0 = cm_e\omega_p/e$, or $E_0[\mathrm{V/m}] \simeq 96\sqrt{n_0[\mathrm{cm}^{-3}]}$, where $\omega_p = k_p c = (4\pi n_0 e^2/m_e)^{1/2}$ is the electron plasma frequency, n_0 is the ambient electron number density, m_e and e are the electron rest mass and charge, respectively, and c is the speed of light in vacuum. These high accelerating gradients, E_0~1–100 GV/m, have been experimentally demonstrated in laser-plasma accelerator (LPA) experiments. For example, 4.2 GeV electron beams have been produced in a 9 cm plasma channel, using a 40 fs laser pulse containing 15 J of laser energy [2]. The rapid experimental progress in LPAs over the last decade has resulted in interest in the development of laser-plasma-based acceleration as a basis for future linear electron-positron colliders [3–6].

Future colliders based on LPAs will require both high average (or geometric) accelerating gradient to reduce the size of the facility (i.e., reduced construction costs) and low power consumption (i.e., reduced operating costs). Low power consumption requires efficient energy transfer from wall to the laser driver and from the driver to the accelerated beam. Development of high-efficiency laser drivers is a topic of active research, and combining fiber-based laser systems offer the possibly of operating with very high efficiency [7]. In addition to high gradient and efficiency, the LPAs must maintain high beam quality to achieve the required luminosity. This implies ultra-low emittance preservation throughout the accelerator without significant energy spread growth to allow the beams to be focused at the collision point.

Typically, in a plasma accelerator the focusing forces acting on the low emittance beams originate from the transverse plasma wakefields. These transverse wakefields can be on the order of the longitudinal accelerating fields, and the low emittances and strong focusing forces result in high beam densities. For beam densities much larger than the background plasma density, $n_b \gg n_0$, the beam will expel the surrounding electrons. In this regime, the focusing of the electron beam will be determined by the background plasma ions [1] with betatron wavenumber $k_\beta = k_p/\sqrt{2\gamma}$, where $\gamma m_e c^2$ is the particle energy. The (matched) electron beam transverse size will decrease as the beam accelerates $\sigma_x = [\epsilon_n/(\gamma k_\beta)]^{1/2}$, where ϵ_n is the normal-

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ized transverse emittance, and the beam density will increase. For sufficiently high beam density in a uniform plasma $n_b/n_0 \gg Z_i M_i/m_e$, where M_i is the ion mass and Z_i is the charge state, the background plasma ions will move on the plasma period time-scale ($< \omega_p^{-1}$), leading to emittance growth [8]. Maintaining $n_b \sim n_0$ typically requires weak focusing $k_\beta = \epsilon_n/(\gamma\sigma_x^2) \ll k_p/\sqrt{2\gamma}$. However, this weak focusing can lead to emittance growth via Coulomb scattering with background ions in the plasma [9].

Independent control of the transverse focusing and longitudinal accelerating forces is highly desirable for control of the beam radius, matching the beam to the focusing fields, enabling positron focusing, and avoiding deleterious effects of ion motion. For laser-driven plasma waves in the quasi-linear regime, one method for controlling the focusing forces is to use shaped transverse laser intensity profiles [10]. Control over the focusing forces can also be achieved by shaping the transverse plasma density profile. Near-hollow plasma channels have been proposed to provide control over the focusing and accelerating fields for electron beams [9]. A near-hollow plasma channel has an initial plasma density of the form $n(r) = n_c$ for $r < r_c$ and $n(r) = n_w$ for $r \geq r_c$, where n_w is the electron plasma density in the wall, n_c is the electron plasma density in the channel, with $k_c^2 = 4\pi n_c e^2/m_e c^2 \ll k_w^2 = 4\pi n_w e^2/m_e c^2$, and r_c is the channel radius. Plasma wakefields excited in near-hollow ($n_c \ll n_w$) [9], or hollow ($n_c = 0$) [11, 12], plasma channels have excellent acceleration properties. In addition, by providing control over the focusing forces, this plasma structure enables acceleration and focusing of positron beams and mitigates emittance growth from scattering and ion motion [9].

In this paper we outline a possible design of a TeV electron-positron collider based on laser-plasma accelerators using hollow plasma channels. All the plasma density and laser wavelength scalings derived in Refs. [4, 6] are valid for a hollow plasma channel. In Refs. [4, 6] it was shown that operating at a plasma density of $n_w \sim 10^{17}$ cm^{-3} reduces the power costs ($\propto n_w^{1/2}$) while providing for a high accelerating gradient ($\propto n_w^{1/2}$), and acceptable beamstrahlung background ($\propto n_w^{-1/2}$).

2. Plasma wakefield excitation

The accelerating wakefield excited inside a hollow channel will consist of an electromagnetic wakefield owing to surface currents driven in the channel walls. A near-hollow plasma channel may be employed for accelerating electron beams where the fields owing to the background ions in the channel n_c provide focusing. Positron beam acceleration would operate in a hollow channel with focusing provided by external magnets. For a sufficiently sharp channel-wall interface $[n(r)/\partial_r n(r) \ll k_w^{-1}]$, electrostatic wakefields excited outside the channel will not couple to channel modes [13, 14]. A derivation of the linear wakefields, valid for $|E_z(z, r, t)| < E_w = m_e c^2 k_w/e$, driven by the ponderomotive force of a laser and/or the space-charge force of a particle beam is presented in the Ref. [15]. In the limit $k_c^2 \ll k_w^2$, the longitudinal field inside the channel is dominated by the currents in the wall,

$$\frac{E_z}{E_w} \simeq W_0\Omega^2 \int_\infty^\xi k_w d\xi' \cos[\Omega k_w(\xi - \xi')] I(\xi')/I_A - \Omega^2 \int_\infty^\zeta k_w d\zeta' \cos[\Omega k_w(\zeta - \zeta')] a^2(r_c, \zeta')/4, \quad (1)$$

where $\zeta = z - \beta_p ct$, $\xi = z - \beta_b ct$, $\beta_p c$ is the laser driver velocity with $\gamma_p = (1 - \beta_p^2)^{-1/2} \gg 1$, $\beta_b \simeq 1$ is the beam velocity, $a(r, \zeta) = eA/m_e c^2$ is the normalized transverse vector potential profile of a laser driver (the quasi-linear regime $|a(r_c)|^2/2 < 1$ is assumed), $I(\xi)$ is the particle beam current, and $I_A = m_e c^3/e$ is the Alfvén current. For a laser driver, $\gamma_p \sim k_0/k_w = 2\pi/(k_w\lambda_0)$, where λ_0 is the laser wavelength. The electromagnetic channel mode wavenumber is $k = k_w\Omega$, with [11, 12]

$$\Omega = \left[1 + \frac{k_w r_c K_0(k_w r_c)}{2K_1(k_w r_c)}\right]^{-1/2}, \quad (2)$$

and the beam-driven wake amplitude [12] is

$$W_0 = \frac{2K_0(k_w r_c)}{k_w r_c K_1(k_w r_c)}. \quad (3)$$

For example, $\Omega \simeq 0.8$ and $W_0 \simeq 1.03$ for $k_w r_c = 1.5$.

For a laser profile with envelope $a^2 = a_0^2 \cos^2(\pi\zeta/L) \exp(-2r^2/w_0^2)$ with $|\zeta| < L/2$, where $L/2$ is the FWHM intensity pulse length and w_0 the laser spot size, the wake amplitude behind the laser is

$$\hat{E}_L = \frac{a_0^2\Omega}{4} \left[\frac{\sin(\Omega L/2)}{1 - (\Omega L/2\pi)^2}\right] e^{-2r_c^2/w_0^2}, \quad (4)$$

with $\hat{E}_L = E_{\text{peak}}/E_w$. A witness charged particle beam will be accelerated by the total wakefield generated by the laser driver and the witness particle beam.

3. Laser propagation and depletion in a hollow plasma channel

The most severe limitation to energy gain in an LPA is typically reduction of the effective laser-plasma interaction length by diffraction of the laser pulse. This can be overcome by using a plasma channel to guide the laser pulse, and a hollow plasma channel can act as a guiding structure for the laser. The condition for quasi-matched propagation (i.e., without evolution in the transverse second moment of the laser intensity) in the channel for relativistic intensities $a_0 \sim 1$ can be calculated following Ref. [16]. The condition for guiding in a hollow plasma channel (neglecting guiding contributions from the wakefield and laser self-focusing) is [15]

$$w_0 = r_c/[\ln(k_w r_c)]^{1/2}. \tag{5}$$

Equation (5) is an excellent approximation to the guiding condition in the regime of quasi-linear laser wakefield excitation $a_0 \lesssim 1$ [15]. For the matched spot size Eq. (5), the wake amplitude scales as $\hat{E}_L \propto a_0^2 \exp(-2r_c^2/w_0^2) = a_0^2/(k_w r_c)^2$.

The velocity of the laser in the channel β_L approximately determines the phase velocity of the wakefield $\beta_p \approx \beta_L$. Assuming $(a_0/k_w r_c)^2 \ll 1$ and a Gaussian laser profile, the velocity of the laser intensity centroid propagating in the hollow plasma channel may be calculated following Ref. [17]:

$$\beta_L = 1 - \frac{1}{(k_0 w_0)^2} - e^{-2r_c^2/w_0^2}\frac{k_w^2}{2k_0^2}. \tag{6}$$

For matched laser propagation, Eq. (5), the Lorentz factor of the laser velocity is

$$\gamma_L = \frac{k_0}{k_w}\frac{k_w r_c}{\sqrt{1 + 2\ln(k_w r_c)}}. \tag{7}$$

As the laser propagates in the plasma channel, a wakefield is excited and the laser loses energy. The rate of energy depletion of the laser in the hollow channel is $dU_L/dz \simeq -U_L/L_{pd}$, where L_{pd} is the laser pump depletion length. For $L_c < L_{pd}$, where L_c is the hollow plasma channel length, the fraction of laser energy deposited in the plasma channel is $\eta_{pd} \simeq L_c/L_{pd}$. The laser-driven wakefield excites an electromagnetic mode, driven by surface currents in the channel wall and an electrostatic mode in

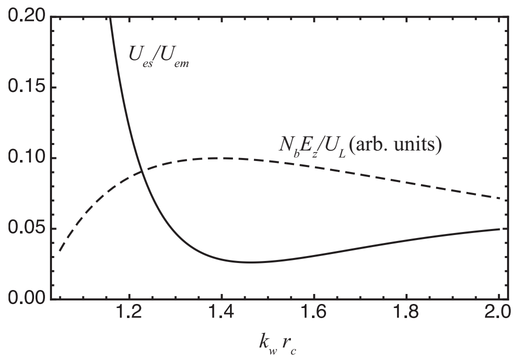

Figure 1: The ratio of energy in the electrostatic wakefield to electromagnetic wakefield U_{es}/U_{em} (solid curve) and the ratio of beam energy gain to laser energy $\propto N_b \hat{E}_L/U_L$ (dashed curve) versus the normalized channel radius. Note that matched guiding requires $w_0 = r_c/[\ln(k_w r_c)]^{1/2}$.

bulk plasma $r > r_c$. The energy deposited in the wakefields by the laser-driver is $U_i = U_{\rm em} + U_{\rm es}$, where $U_{\rm em}$ and $U_{\rm es}$ is the total energy in the electromagnetic and electrostatic modes, respectively. The transverse laser mode may be chosen to excite only the electromagnetic mode, however, for typical parameters the fraction of energy deposited in the electrostatic mode by a Gaussian laser is a few percent [15]. The solid curve in Fig. 1 shows the ratio of laser energy deposited in the electrostatic mode to electromagnetic mode. For $k_w r_c = 1.46$, $U_{\rm es}/U_{\rm em} \simeq 2.6\%$.

For a laser propagating in a hollow plasma channel, the laser pump depletion length is

$$L_{pd} = \frac{4\Omega^2 K_0(k_w r_c)}{k_w r_c K_1(k_w r_c)}\frac{U_L/\hat{E}_L^2}{(1 + U_{\rm es}/U_{\rm em})}\left(\frac{r_e}{m_e c^2}\right), \tag{8}$$

where $\hat{E}_L$ is given by Eq. (4) and U_L is the initial laser energy. Note that operating at modest laser pump depletion is acceptable since the remaining fraction of laser energy at the end of the plasma channel $(1 - \eta_{pd})$ can be recovered using a photovoltaic device, as discussed below.

4. Beam loading

Shaping of the current distribution of the witness beam may be used such that the total longitudinal wakefield experienced by the beam is constant throughout the beam, thereby eliminating energy spread growth in a plasma accelerator [18–20]. For a properly shaped beam, the induced energy spread will be zero, and there will be a trade-off between accelerating gradient and efficiency. In the following we will neglect slippage effects. Small slippage effects may be compensated by a plasma taper.

Consider a linearly ramped current distribution in a hollow channel: $I = (1 + \xi/L_b)I_b$ for $-L_b \leq \xi \leq 0$, with length L_b and the bunch head at $\xi = 0$. Solving Eq. (1) yields

$$\frac{E_{zb}}{E_w} = \left\{ \frac{[1 - \cos(\Omega k_w \xi)]}{k_w L_b} + \Omega \sin(\Omega k_w \xi) \right\} W_0 \frac{I_b}{I_A}, \tag{9}$$

within the region of the beam $-L_b \leq \xi \leq 0$. If we consider a laser-driven wakefield accelerating the particle beam, the total longitudinal field experienced by the beam is $E_z = \hat{E}_L \cos(\Omega k_w \xi + \varphi) + E_{zb}$. This ramped current distribution can be used to generate a constant accelerating gradient throughout a bunch, which, consequently, implies zero induced energy spread. A constant gradient throughout a beam of $E_z/E_w = \hat{E}_L \cos(\varphi)$ can be achieved with a beam of length $k_w L_b = \tan(\varphi)/\Omega$ using a peak beam current $I_b/I_A = \hat{E}_L \sin(\varphi)/(W_0\Omega)$, where the φ is the phase position of the head of the beam with respect to peak of the unloaded accelerating field. The beam charge that can be accelerated is [15]

$$N_b = \hat{E}_L \frac{\tan(\varphi)\sin(\varphi)}{2W_0\Omega^2 k_w r_e}, \tag{10}$$

where $r_e = e^2/m_e c^2$ is the classical electron radius. Note that, for fixed normalized accelerating field amplitude $\hat{E}_L$, the number of particles that can be accelerated in the plasma wakefield increases for decreasing plasma density in the wall, $N_b \propto k_w^{-1} \propto n_w^{-1/2}$.

Shorter beams $k_w L_b < \tan(\varphi)/\Omega$ may be of interest for beamstrahlung mitigation [6]. Ultra-short beams may also be accelerated with zero induced energy spread in a hollow plasma channel by bunch shaping. Bunch trains may be employed to achieve high efficiency using ultra-short beams [15].

5. Efficiency

For an optimally shaped bunch to eliminate the energy spread, the peak field following the bunch is reduced by $\cos(\varphi)$. Since the relativistic witness beam only excites an electromagnetic mode, the final energy in the plasma channel after the beam-plasma interaction is $U_f = U_{\text{em}} \cos^2(\varphi) + U_{\text{es}}$. The efficiency of energy transfer from the laser-driven electromagnetic wakefield to the witness particle beam is

$$\eta_b = 1 - \frac{U_f}{U_i} = \frac{\sin^2(\varphi)}{1 + U_{\text{es}}/U_{\text{em}}}. \tag{11}$$

In general, with no wake-induced energy spread, there is a trade-off between efficiency η_b and accelerating gradient $\hat{E}_L \cos(\varphi)$. The energy in the electrostatic mode does not couple to the witness particle beam and reduces the overall efficiency, however, for a matched Gaussian laser in a hollow channel with $k_w r_c > 1.3$ the energy in the electrostatic mode is only a few percent of the total wake energy. (cf. Fig. 1).

The overall efficiency of the LPA is determined by the efficiency of laser generation (wall-to-laser efficiency) η_{laser}, the fraction of laser energy deposited in the plasma $\eta_{pd} \simeq L_c/L_{pd}$, and the efficiency of transfer from the wake to the beam η_b. The fraction of the remaining laser energy after the laser-plasma interaction $(1-\eta_{pd})$ may be recovered by transporting the laser to a photovoltaic device, with some conversion efficiency η_{recovery}. The total efficiency of the LPA is then,

$$\eta_{\text{total}} = \frac{\eta_b \eta_{pd}}{[1/\eta_{\text{laser}} - (1 - \eta_{pd})\eta_{\text{recovery}}]}. \tag{12}$$

A second, trailing, laser pulse, properly delayed following the witness beam, may be considered to absorb the remaining energy in the wakefield leaving no remaining energy in the coherent plasma oscillations [21]. This technique for wake energy extraction may be used for heat management of the plasma target, however, power savings are only realized for sufficiently high wall-to-laser efficiency η_{laser}.

6. Collider example

A laser-plasma-accelerator linac may be envisioned based on staging multiple LPA stages. Consider a design of a single LPA stage using a hollow channel operating at a wall density of $n_w = 10^{17}$ cm^{-3} and laser wavelength $\lambda = 1$ μm. (The LPA density and laser wavelength scalings can be found in Ref. [4].) The FWHM laser duration $\tau_L = L/(2c)$ may be chosen to maximize the beam energy gain per laser energy $\propto N_b \hat{E}_L/U_L \propto \hat{E}_L^2/U_L$, i.e., using Eq. (4), $k_w \Omega L \simeq 3.816$. The laser spot,

Table 1: LPA stage laser-plasma parameters.

Plasma density (wall), $n_0[\mathrm{cm}^{-3}]$	10^{17}
Plasma wavelength, $\lambda_p[\mathrm{mm}]$	0.1
Channel radius, $r_c[\mu\mathrm{m}]$	24.5
Laser wavelength, $\lambda[\mu\mathrm{m}]$	1
Normalized laser strength, a_0	1
Laser spot size, $w_0[\mu\mathrm{m}]$	39.8
Peak laser power, $P_L[\mathrm{TW}]$	34
Laser pulse duration (FWHM), $\tau_L[\mathrm{fs}]$	133
Laser energy, $U_L[\mathrm{J}]$	4.5
Normalized accelerating field, E_L/E_0	0.14
Peak accelerating field, $E_L[\mathrm{GV/m}]$	4.2
Laser depletion length, $L_{pd}[\mathrm{m}]$	10.4
Plasma channel length, $L_c[\mathrm{m}]$	2.36
Laser depletion, η_{pd}	23%

Table 2: Shaped electron/positron beam parameters.

Bunch phase (relative to peak field), φ	$\pi/3$
Loaded gradient, $E_z[\mathrm{GV/m}]$	2.1
Beam beam current, $I[\mathrm{kA}]$	2.5
Charge/bunch, $eN_b = Q[\mathrm{nC}]$	0.15
Length (triangular shape), $L_b[\mu\mathrm{m}]$	36
RMS beam length, $\sigma_z[\mu\mathrm{m}]$	15
Efficiency (wake-to-beam), η_b	73%
$\mathrm{e}^-/\mathrm{e}^+$ energy gain per stage	5 GeV
Beam energy gain per stage	0.75 J

and the corresponding channel radius for guiding given by Eq. (5), can be chosen by optimizing beam loading efficiency, i.e., minimizing the ratio of energy into the electrostatic to electromagnetic modes $U_{\mathrm{es}}/U_{\mathrm{em}}$, i.e., $k_w r_c \simeq 1.46$ (with a guided laser spot $k_w w_0 \simeq 2.4$) and $U_{\mathrm{es}}/U_{\mathrm{em}} \simeq 0.026$ (cf. Fig. 1). Table 1 shows the corresponding laser-plasma parameters for a single LPA stage. Table 2 shows the electron and positron beam parameters using an optimally shaped beam injected at a wake phase $\varphi = \pi/3$.

To reach a sufficiently high luminosity, high laser repetition rates ($\sim$100 kHz) are required, with hundreds of kW average laser powers. There continues to be rapid progress in the development of high average power, short pulse laser systems. Such laser systems will also require high efficiency and will most likely rely on combining many diode-pumped fiber lasers [7]. (Incoherent combination of multiple lasers is also possible for the LPA application [22].) The potential overall wall-to-laser efficiency may be estimated by considering that the electrical-to-optical efficiency of the diode-pumped lasers can be $\sim$70%, the optical-to-optical efficiency of the fibers can be $\sim$90% (owing to the low quantum defect), and the efficiency of combining/stacking fibers can be $\sim$95%, yielding a potential overall wall-to-laser efficiency of $\eta_{\mathrm{laser}} \sim$60%. Although technically possible, achieving these efficiencies is challenging.

Table 3: Example parameter sets for a 1 and 3 TeV center-of-mass, laser-plasma linear collider operating at plasma density $n_0 = 10^{17}$ cm^{-3}.

Energy, center-of-mass, $U_{\mathrm{cm}}[\mathrm{TeV}]$	1	3
Beam energy, $\gamma mc^2 = U_b[\mathrm{TeV}]$	0.5	1.5
Beam power, $P_b[\mathrm{MW}]$	5.5	29
Luminosity, $\mathcal{L}[10^{34}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}]$	1	10
Laser repetition rate, $f_L[\mathrm{kHz}]$	73	131
Horiz. beam size at IP, $\sigma_x^*[\mathrm{nm}]$	50	18
Vert. beam size at IP, $\sigma_y^*[\mathrm{nm}]$	1	0.5
Beamstrahlung parameter, Υ	1.1	9
Beamstrahlung photons, n_γ	0.5	0.9
Beamstrahlung energy spread, δ_γ	0.07	0.2
Number of stages (1 linac), N_{stage}	100	300
Distance between stages [m]	0.5	0.5
Linac length (1 beam), $L_{\mathrm{total}}[\mathrm{km}]$	0.29	0.86
Average laser power, $P_{\mathrm{avg}}[\mathrm{MW}]$	0.33	0.59
Efficiency (wall-to-beam)[%]	9.2	13
Wall power (linacs), $P_{\mathrm{wall}}[\mathrm{MW}]$	120	450

Table 3 shows an example of parameters for a 1 TeV and 3-TeV center-of-mass laser-plasma linear collider operating at plasma density $n_0 = 10^{17}$ cm^{-3}. Here we consider operation with flat beams at the interaction point (IP) for reduced beamstrahlung. The distance between stages was chosen to allow coupling of the drive lasers (cf. Table 1) in/out of each plasma stage using plasma mirrors. The total wall-to-beam efficiency is given by Eq. (12), assuming $\eta_{\mathrm{laser}} = 0.4$ and $\eta_{\mathrm{recovery}} = 0.9$ for the 1-TeV collider example and $\eta_{\mathrm{laser}} = 0.5$ and $\eta_{\mathrm{recovery}} = 0.95$ for the 3-TeV collider example.

7. Summary

In this work we have considered a linear electron-positron collider using laser-plasma-accelerators with hollow plasma channels. Hollow plasma channels operating in the linear wakefield regime enable independent control of the focusing and accelerating fields, allow positron acceleration, and mitigate emittance growth from ion motion and Coulomb scattering. We have considered LPA operation at a particular plasma density (10^{17} cm^{-3}) and laser wavelength (1 μm). The LPA and collider parameters scale with plasma density and laser wavelength as described in Refs. [4, 6]. We expect that this plasma density choice, as well as other parameter choices, will be dictated by the available laser technology that develops for efficient, high-peak and average power lasers.

Here we have outlined only the LPA-based linacs. Significant technology developments are required, as well as LPA maturity, before a detailed LPA-based collider design (e.g., integrated injector, cooling, LPA-based linac, and final focus) is possible. We anticipate that the LPA-collider parameters presented here will evolve as the laser-plasma-based accelerator technology advances.

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