Ion acceleration in the ‘dragging field’ of a light-pressure-driven piston

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Abstract
We propose a new acceleration scheme by employing the enormous electric potential behind a light-pressure-driven piston, namely ‘dragging field acceleration’. When a thin foil driven by light pressure of an ultra-intense laser pulse propagates in underdense background plasma, it serves as a shock-like piston, trapping and reflecting background protons to ultra-high energies. Unlike in shock wave acceleration, the piston velocity is not limited by the Mach number and can be highly relativistic. Background protons can be trapped and reflected forward by the ‘dragging field’ potential attached to a piston, which is not employed in light-pressure acceleration. Our one-dimensional particle-in-cell simulations and analytical model both show that proton energies of several tens to hundreds of GeV can be obtained. The injection conditions are investigated. Generation of mono-energetic tens-of-GeV proton bunch in two-dimensional geometry are discussed. Finally, the scheme is demonstrated with a three-dimensional simulation, where the effect of radiation reaction is included.

Keywords: ion acceleration, light pressure, dragging field, particle-in-cell
1. Introduction

Laser-driven ion acceleration attracts more and more attention nowadays because of its potential to realize table-top sized ion accelerators, which would greatly reduce the expense and occupying area compared to conventional accelerators. In most proposals, intense/ultra-intense laser pulses are employed to stimulate strong electrostatic fields with amplitude several magnitudes higher than that of conventional methods. Because these fields move at high velocities, ions can be continually accelerated to large energy levels in a short distance. In target normal sheath acceleration (TNSA) [1–8], the sheath field, formed at the target back by laser-heated super-thermal electrons, moves at several to tens of the ion acoustic speed. Ions co-move with the field and are accelerated to tens of MeV, while energy above a hundred MeV is quite a challenge because of the weak scaling law versus laser intensity. In light-pressure acceleration (LPA) [9–16], electrons in the thin plasma foil are pushed inward by the laser pressure and build up an intense charge-separation field, by which protons are accelerated. As the foil is driven as a whole, protons move along with the electrostatic field and are successively accelerated to energies that theoretically may reach GeV. Nevertheless, even in simulations it is difficult to overcome the 10 GeV barrier for protons with LPA, since the accelerating gradient drops quickly due to the relativistic Doppler effect. As soon as the protons become relativistic, their energy grows very slowly with time ($\sim t^{1/3}$). One may improve the increasing law to about ($\sim t^{3/5}$) by considering the transverse expansion of the foil, which decreases the number of accelerated ions in the irradiated region [17].

Recently, a breakthrough in collisionless shock wave acceleration [18–23] has been reported [20]. It suggests that a multi-pulsed picosecond (ps) laser pulse can efficiently excite a collisionless shock and maintain its velocity in a density-decaying plasma target. The produced protons have a much larger energy and lower energy spread than predicted by the hole-boring shock [21]. When the shock propagates, some protons are trapped and reflected to a speed twice of the shock velocity, which is determined by the energy density jump across the shock front. The exponentially decaying density profile of the target is important for keeping the shock velocity high and constant [20]. However, plasma itself also expands at the ion acoustic speed simultaneously. It seems the pressure gradient will be weakened at a later stage. This would put a limit on the final energy gain. From other side, the shock wave velocity is limited by the Mach number, which cannot be very high [22].

Generally, the shock front may be considered as a fast-moving piston carrying a strong electrostatic field. Imagine, one could free the limitation on its velocity, e.g. the shock becomes relativistic [24]. Then, the trapped and reflected protons would reach a relativistic $\gamma$ factor of about $\gamma = 2\gamma_s^2$, where $\gamma_s$ is the relativistic factor of the shock wave. This is way beyond simple thermal shock wave acceleration. A strong electrostatic field moving at relativistic velocity is required. One possibility might be the plasma wakefield. It works very well for electron acceleration, but it may be not strong enough to trap protons. There are some proposals to trap pre-accelerated protons and accelerate them further by the wakefield to very high energies [25].

We propose here that the electrostatic field of LPA can serve as the perfect relativistic piston. Its velocity is close to the light speed and the charge-separation field is sufficiently high to trap background protons. In this paper, we develop an analytical model and use particle-in-cell (PIC) simulations to show that when a thin foil driven by ultra-intense circularly polarized (CP) laser pulses, with peak amplitude $a_0 = eE_\perp/m_ec\omega_0$ from 50 to 200, passes through an
underdense plasma region, reflected protons can achieve energies up to hundreds of GeV. Here $e$ and $m_e$ are fundamental charge and electron mass, $E_L$ and $\omega_0$ are electric field amplitude and angular frequency of the laser pulse, $c$ is the light speed, respectively.

The expression of the accelerating field amplitude as a function of time is derived, which, together with the foil momentum equation, clearly describes the movement of the background protons and the trapping condition. The scaling laws indicate that the peak energy increases with $t^{2/3}$ and $\omega_0^2$. The scheme was verified in two-dimensional (2D) geometry, where we further discussed the possibility of producing mono-energetic proton beams. In the end, to show the validity of our proposal, a three-dimensional (3D) simulation is also performed, where the effects of photon emission and radiation reaction (RR) are included by a QED model.

2. One-dimensional (1D) model on ‘dragging field’ acceleration (DFA)

The mechanism is sketched in figure 1. As known in LPA, the laser-driven foil is accompanied by an intense charge-separation field. When it propagates through the low-density plasma, background protons can be continuously trapped under certain conditions. The foil plays the role of a relativistic piston. In the frame of the relativistic piston, background protons clash towards the electrostatic field at the foil velocity, then are slowed down by the field in and behind the foil, and finally reflected.

In figure 2, we show a typical profile of the charge separation field and the proton distribution in the phase space (longitudinal momentum versus position). Two regions are identified. In the highly compressed electron layer, the acceleration field decreases with distance, hence protons are focused in the phase space, showing a spiral structure. On the contrary, the field behind the electron layer increases versus distance. Protons left behind in this region are defocused in phase space (protons with higher energy experience a high accelerating field). In such a way, as the interaction goes on, the distance between the electron layer and the mostly left-behind protons grows. It leads to a charge-separation field that stretches up to several tens of laser wavelengths, namely, the dragging field (DF).

In LPA, protons are accelerated by the field localized in the ultra-thin skin layer only, leaving the enormous DF unused. In our scheme, the background protons pass through the skin layer and are greatly accelerated by the DF, which contains much higher electrostatic potential.
than the field inside the layer. As a result, the reflected protons can obtain an order of magnitude higher energy than foil protons in the simple LPA regime.

To demonstrate the mechanism, a 1D PIC simulation is performed by the VLPL code [26]. A dense thin foil, with density of \( n_f = 80n_e \) and thickness of \( d_f = 0.57\lambda_0 \), is driven by a CP laser pulse with peak amplitude \( a_\omega = 150 \), where \( n_e = m_e\omega_\omega^2/4\pi e^2 \) is the critical density and \( \lambda_0 = 0.8\mu m \) is the laser wavelength. For simplicity, we used a trapezoidal laser pulse. Its amplitude increases linearly to the maximum in \( 2T_0 \) (\( T_0 \) is the laser period) and then stays constant for \( 80T_0 \). We chose a relatively long pulse to keep the simulation ongoing for a sufficiently long distance and time. Hence, one can see how the acceleration evolves with time and the potential of this mechanism. Here the foil thickness is optimized for LPA [27]. A background plasma with density of \( n_b = 0.001n_e \) is located in front of the foil. Figure 3(a) shows distributions of the electrostatic field and momentum of background protons. The field decays quickly at first and much more slowly later. It is so intense, well beyond \( E_\omega = m_e\omega_\omega c/e \) even at the end of the interaction, that background protons are gradually trapped and reflected to about 70 GeV in 3 mm, while protons in the front foil have a peak energy below 10 GeV.

The trapping and acceleration of charged particles are determined by the velocity, amplitude and length scale of the DF structure. Since the DF co-moves with the foil, its dynamics can be derived by the momentum equation of the piston [11]

\[
\frac{d (\gamma_f\beta_f)}{dt} = \frac{m_e}{m_i} \frac{2a_{i\gamma_f}^2}{N_f D_f} \frac{1 - \beta_f^2}{1 + \beta_f^2}.
\]

Here \( \beta_f \) is the foil velocity normalized by \( c \), \( \gamma_f = (1 - \beta_f^2)^{-1/2} \), and \( m_i \) is the ion mass. \( N_f \) and \( D_f \) are initial density and thickness of the foil normalized by the critical density \( n_e \) and laser wavelength \( \lambda_0 \). All lengths and the time are normalized by \( \lambda_0 \) and \( T_0 \), respectively. The velocity of the DF structure is thus \( \beta_s = \beta_f \), and can be obtained by solving equation (1). The evolution of the foil protons without background plasma is shown in figure 5(b), where good agreement can be seen between 1D simulations and equation (1).

More critical is the evolution of field amplitude. Former researches have suggested that considering the balance of the electron thin layer between the light pressure and electrostatic
force, the peak amplitude of the DF should be proportional to the Doppler factor \((1 - \beta_f)/(1 + \beta_f)\) [28]. This means that it would drop by \(1/4\gamma_f^2\) in the relativistic regime. In the above simulation \(\gamma_f \approx 5\) at \(t = 500T_0\), the DF amplitude should decrease by some factor 100. However, as seen in figure 3(a) The DF at \(t = 500T_0\) is still above \(E/E_0 > 15\), roughly one tenth of initial maximum field. A new scaling should then be deduced. In figure 3(b) the distributions of laser field and electrons at \(t = 500T_0\) are presented. The laser ponderomotive force acts on only a small portion of the electrons at the surface and not on the whole electron layer. This is because the light pressure is severely weakened when the foil becomes relativistic so that it cannot confine all foil electrons. The situation is then similar to the electrostatic shock or the hole-boring process [9], except the whole system is moving fast.

Since the foil velocity varies slowly with time, it is reasonable to assume the piston frame as an inertial reference system, where relationships in Reference [9] can be applied after Lorentz transforming all quantities. Considering the balance of the electron skin layer instead of the

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**Figure 3.** (a) Distributions of electrostatic field (black solid) and momentum of background protons (red solid) at different stages with \(a_i = 150\), \(n_i = 80n_e\), \(d_i = 0.57\lambda_0\) and \(n_e = 0.001n_e\). (b) Distributions of the dimensionless laser field \(a = \sqrt{a_i^2 + a_e^2}\) (black solid), electron density (red solid) and proton density (blue solid) at \(t = 500T_0\). (c) Evolution of the peak electrostatic fields of \(a_0 = 50\), 100 and 150, from analytical model (blue solid) and 1D simulations. (d) Evolution of the maximum energy of background protons with \(a_0 = 50\), 100 and 150, from analytical model (blue solid) and simulations. Here the dashed lines show that the peak energy increases with \(\sim t^{2/3}\).
whole electron layer, the peak DF is \( E'_{x0} \sim \sqrt{P_{rad}} \), where \( P_{rad} \) is the light pressure in the moving frame \( K' \). The longitudinal electric field and light pressure turn out to be Lorentz invariants, thus the peak amplitude in laboratory frame is conveniently obtained by \( E_{x0} \sim \sqrt{P_{rad}} \sim \sqrt{\left( 1 - \beta_j \right) / \left( 1 + \beta_j \right)} \). On the other hand, the ponderomotive force acting on electrons is approximately \( |e\beta_e \times B_L| \approx E_L, \) therefore \( E_{x0} \sim E_L \), giving the normalized peak amplitude (normalized by \( E_0 \)) of

\[
E_{x0}(t) \approx a \sqrt{\frac{1 - \beta_j}{1 + \beta_j}}.
\]

Both estimations above show that the field scales are proportional to the square root of the Doppler factor, i.e., about \( 1/2\gamma_j \). This is a much weaker decay than formerly assumed. We compare the results from equations (1) and (2) with 1D PIC simulation results in figure 3. One can see that for \( a = 50, 100 \) and \( 150 \), equation (2) describes the simulation results properly. This new scaling is very important to guarantee the DF structure can be maintained for a long distance and does not vanish in a relativistic regime.

The dynamics of background plasma protons encountered in the field of the piston are then derived by

\[
\frac{d(\gamma_p \beta_p)}{dt} = \frac{2\pi n_x E_x(t, x_p)}{m_p}.
\]
As seen from figure 4(a), the DF drops almost linearly with the distance shortly behind the foil. The long weak tail far behind the foil is neglected since protons located there are no longer trapped. We simplify the description by assuming the charge-separation field behind the skin layer decays to zero in a length scale of $d_E$

$$E_x(t, x_b) = E_{x0}(t) \left( 1 - \frac{x_f - x_b}{d_E} \right), \quad \text{for } x_f - d_E \leq x_b \leq x_f$$  \hspace{1cm} (4)

and 0 for elsewhere. Here the $x_b$, $\beta_b$, $\gamma_b$ are the position, normalized velocity and $\gamma$-factor of the background protons. The scale length of the electrostatic field localized inside the skin layer is so small that we ignore it. Simulations suggest that the DF scale is about $d_E \approx 60\lambda_0$. Protons initially located at different positions of $x_b|_{t=0}$, which are also the injected positions, obtain final energy when $x_b = x_f$. So the maximum energy of all reflected protons as a function of time can be analytically derived by changing the $x_b|_{t=0}$ in equations (3) and (4).

Equations (1)–(4) offer a complete description of the mechanism. Peak momenta of the trapped protons at different simulation times and from the analytical model are shown in figure 3(d), for $a = 50$, 100 and 150, respectively. Again, the analytical results and the simulations are in a good agreement. As already mentioned, the foil momentum in LPA is approximately $p_b \propto t^{1/3}$, leading to $P_{rad} \propto t^{-2/3}$. For background protons $dp_b/dt \sim E_x(t, x_b) \sim \sqrt{P_{rad}}$, yielding $p_b \propto t^{2/3}$ naturally. This is clearly seen in the fitting lines of figure 3(d), which perfectly predicts the evolution of the peak momentum. This fast-increasing law stems from the slower decaying of the DF. Within a few millimeters the protons are accelerated close to 100 GeV in 1D. Since DF contains much more electrostatic potential than the field in the layer, BG protons are able to catch up with the foil protons and finally surpass the flying piston with a larger energy.

It should be mentioned that though the initial pulse duration is large, only a portion of laser energy is consumed at each moment. For example, according to figure 3(a), at $t = 500T_0, 900T_0, 1300T_0, 1700T_0$, about 15, 22.5, 28 and 32 laser cycles have been depleted, respectively. Hence, the duration of the consumed laser is smaller than 100fs in our simulations.

For DFA, the piston is continuously accelerated. Thus, the later local protons are injected, the higher energy they obtain. However, the DF amplitude also decays simultaneously, so that after a certain point it loses the intensity needed to trap stationary protons. The trapping condition is obtained by balancing the kinetic energy of the incoming protons against the DF electrostatic potential in the relativistic piston frame

$$\frac{1}{2}eE'_{x0}(t)d_E' = (\gamma_f - 1)m_p c^2,$$  \hspace{1cm} (5)

where $E'_{x0}(t) = E_{x0}(t)$ and $d'_E = \gamma_f d_E$ is the peak amplitude and length scale of the DF in the moving frame. The critical foil $\gamma$-factor beyond which background protons are no longer trapped is then
\[ \gamma_{fc} \approx 1 + \frac{\pi m_e a_0 D_E}{m_p} \cdot (6) \]

For \( a_0 = 150 \) and \( D_E = d_E/\lambda_0 = 60 \), the critical value is about \( \gamma_{fc} \approx 8.7 \). According to figure 4(b), the estimated critical injecting position is around \( \lambda \approx 1600\lambda_0 \).

Protons injected at different positions obtain different final energies. In figure 5(a), we show the relationship between the final energies and the initial proton positions, together with the analyzing results. The analytical model describes the simulation results very well. The final energy increases almost linearly with the injecting position up to about 1000\( \lambda_0 \). The threshold of injecting position is about \( \lambda_1500 \) in analysis, while in simulations it is between \( 1700\lambda_0 \) and \( 1800\lambda_0 \). The rough estimation from equation (6) (see in figure 4(b), the numerical results of the analytical model in figure 5 and the simulation results seem to agree with each other quite well. The small difference comes from the simplified DF model we employed, which may underestimate the threshold a bit. Figure 5(b) also reveals that the acceleration time can rise dramatically for generating over 200 GeV protons.

As the \( \gamma \)-factor of the foil reaches the critical value, protons passing through the DF structure thereafter will not be trapped any more. This defines the maximum energy obtainable by this mechanism. The scaling law between the maximum obtainable energy and \( a_0 \) from simulations is compared with the model in figure 6. The simulation results are shown for \( a_0 = 50 \) and 100. It indicates that the maximum energy is proportional to the square of the laser amplitude \( \sim a_0^2 \). This mechanism allows to accelerate protons to hundreds of GeV.

Quasi-monoenergetic spectrum can be achieved by reducing the plasma length and selecting appropriate injection window. For example, we chose four different injecting positions 50\( \lambda_0 \), 100\( \lambda_0 \), 200\( \lambda_0 \), and 400\( \lambda_0 \) each with a plasma length of 10\( \lambda_0 \). The mono-energetic proton energy spectra are listed in figure 7.
3. 2D simulations

We chose low background densities in 1D simulations to ensure the DF is not affected. In multi-dimensional geometry, the situation becomes more complicated. First, instabilities may destroy the thin foil during the interaction [3, 19, 29]. This could be restrained by using a highly relativistic laser pulse, e.g., \(a_0 > 100\) in our case. Second, the focused laser intensity profile will cause foil deformation. Diffracted parts of the laser fields would interfere with each other behind the moving piston. The DF structure may break down when the perturbations arrive at the axis. To address this, we increase the background plasma density. A main effect is that the relativistic piston is slowed down, so that the trapping of local protons becomes much easier. In addition, the DF might be enhanced by the additional charge-separating field in background plasma.

The energy gain might be smaller than in 1D, but still several times higher than in LPA. The 2D simulation results are shown in figure 8. The laser pulse has the same temporal profile

\[ P_{\text{max}} / m_p c \]

\[ a_0 \]

\[ \sim a_0^2 \]

Figure 6. Scaling law of the maximum achievable momentum versus peak laser amplitude from analytical model (black square) and simulations (blue pentacle). The fitted red line indicates the power-law of \(~a_0^2\).

Figure 7. Energy spectra with different injecting positions from simulations. The plasma length is reduced to \(10\lambda_0\) other parameters are the same as in figure 5.
as in 1D and the super-Gaussian distribution transversely $\sim e^{-\left(w_y/\mu\right)^4}$, where $w_y = 35\mu$m. Here a relatively large laser focal spot is also used to further reduce the foil deformation. To restrain multi-dimensional instabilities, the laser peak amplitude is increased to $a_0 = 200$. The diffraction and reflection of the incident pulse are minimized by using a density matched foil, i.e., the foil is with density distribution of $n_f(y) = n_0 e^{-\left(y/\mu\right)^4}$ [16]. The foil density and thickness are $n_0 = 80n_t$ and $d_f = 0.62\lambda_0$ while the background plasma density is increased to $n_b = 0.1n_t$. The resolution is 50 cells per wavelength in $x$ direction (laser propagating direction) and 10 cells per wavelength in $y$ direction (transverse direction).

Figure 8(a) shows the distributions of DF, electrons in the foil and background protons at $t = 60T_0$. It is seen that the DF is well formed behind the thin layer. Before the diffracted laser field perturbs the accelerating field, some of the background protons are trapped and accelerated. As seen in figure 8(b), the maximum energy of reflected protons at $t = 500T_0$ is about 25 GeV, approximately four times as the peak energy in LPA. Though the initial pulse duration is $80T_0$, only a duration of $16T_0$ of the pulse has been depleted. It should be mentioned that some foil protons left behind the layer are also trapped and accelerated to high energy.

The 1D simulations have proven they can generate mono-energetic proton bunches by selecting appropriate interaction windows. The scenario can be extended to 2D geometry. The difference is that in 2D, a background plasma made of heavy ions and electrons is required. Hence, we use helium gas as the background to slow down the piston, while He-ions will not be trapped due to the smaller charge-mass ratio. The witness protons supposed to be accelerated are placed at a certain injection position. After several test simulations, we discovered that the optimized injecting position is $x_c \approx 50\lambda_0$ with the simulating time of $500T_0$.

In the simulation set-up, the collecting length is reduced to $2\lambda_0$, i.e., the hydrogen layer occupies an area of $70 - 72\lambda_0$ (the foil is at $x_f = 20\lambda_0$) longitudinally with a full width transversely. The rest of the plasma is made of helium. The proton spectrum is shown in
figure 9, together with the momentum and spatial distributions. It is shown that protons in the layer are well trapped and accelerated, forming a quite compact bunch along the axis. The bunch peaks at about 22 GeV with an energy spread of only $\sim 10\%$. The spectrum also stretches to 10 GeV, exhibiting another peak at $\sim 12$ GeV. In figure 9(a) we denote the transverse edge of the background plasma. One notices that the low-energy peak comes from protons located around the plasma edge, while the mono-energetic bunch at 22 GeV originates from the propagating central. Hence, the relatively low energy peak can be eliminated by placing a gate in the propagation path, which allows the passage of only the central part, while shielding the off-axis protons.

4. 3D simulation including QED effects

When it comes to such a high laser intensity, the photon emission by ultra-relativistic electrons and the induced radiation reaction (RR) effect emerge. Hence, in the following 3D simulation, we introduced a QED model in the VLPL code to fully count them in. The simulation box is $80\lambda_0 \times 50\lambda_0 \times 50\lambda_0$ in $x \times y \times z$ directions, with a cell size of $0.1\lambda_0 \times 0.4\lambda_0 \times 0.4\lambda_0$. The time step is $\Delta t = 0.02$. We put in eight particles per cell for all species, i.e., electrons, protons and photons. Periodic and absorbing boundary conditions are employed for laser fields and particles, respectively.
The results are shown in figure 10. The laser pulse has the same trapezoidal profile as in 1D and 2D simulations in time domain, with a pulse duration of $\tau = 10T_0$ and a super-Gaussian distribution transversely $\sim e^{-r/r_0^2}$, where $r = \sqrt{y^2 + z^2}$ and $r_0 = 15\lambda_0$. To restrain instabilities, the laser peak amplitude is $a_0 = 200$, corresponding to a total laser pulse energy of around 10 kJ. The diffraction and reflection of the incident pulse is minimized by using density matching foil, i.e., the foil has the density profile of $n_f(r) = n_0 e^{-r/r_0^2}$. The foil density and thickness are $n_f = 80n_i$ and $d_f = 0.62\lambda_0$ while the background plasma density is $n_b = 0.1n_i$.

From figure 10(a), one clearly sees that when the foil is driven by the CP laser pulse, some of the background protons are dragged by the DF and catch up with the flying piston. The corresponding DF at $z = 0$ is displayed in figure 4(b), together with the phase spaces of foil and background protons, simultaneously. It is shown that the DF is well formed behind the thin layer. A considerable portion of local protons are gradually accelerated and trapped, undergoing a long-distance acceleration. After $300T_0$ simulation, the maximum energy of reflected protons exceeds 12 GeV, while the peak energy of foil protons is a mere $\sim 2.5$ GeV, as presented in

![Figure 10](image-url)
figure 10(c). Some foil protons left behind the layer are also trapped and accelerated to high energy. The total energy of reflected background protons is about 3% of all foil protons, which is quite considerable considering the low background density. One would expect higher energy efficiency by using denser background plasma. Due to the emission of electrons, the amount of energy comparable to that of foil protons goes to the high-energy photons. In our case, the emitted photons took about 15% of the laser energy. In such an intensity region, photon emission and RR effect can no longer be ignored [30].

5. Conclusion

In conclusion, a method to accelerate protons beyond tens of GeV is proposed. It takes advantage of the electrostatic field dragging behind the flying foil in LPA to trap background protons. The dragging field keeps trapping and accelerating protons to energies greatly higher than that obtained in LPA. The analytical model shows that the electrostatic field decays more slowly than formerly assumed, resulting in larger energy increasing rate (∼t⁻²³). The final maximum energy scales as ∼a₀⁻³. 3D simulations proved the proposal, generating protons with peak energy beyond 10 GeV.

We should mention that the new breakthrough laser technology with an unforeseen potential-ICAN [31] allows for exact pointing and shaping of the laser focus arbitrarily, including super-Gaussian profiles. Recent developments in plasma-based compression of laser pulses [32] may help generating relativistic laser pulses with sharp rising edges. These advances give us great confidence to realize the proposal experimentally in the near future. It should be stressed that this mechanism may also serve to explain the existence of high-energy cosmos rays, where the ultra-violent light pressure could be provided by the explosion of supernovas.

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