

Coherent attosecond x-ray pulses from beam-driven relativistic plasma mirrors

M. Lamač^{1,*}, P. Valenta¹, U. Chaulagain¹, J. Nejd^{1,2}, T. M. Jeong¹ and S. V. Bulanov^{1,3}¹*ELI Beamlines Facility, The Extreme Light Infrastructure ERIC, Za Radnicí 835, Dolní Břežany 25241, Czechia*²*Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 7, 11519 Prague 1, Czechia*³*Kansai Institute for Photon Science, National Institutes for Quantum Science and Technology, 8-1-7 Umemidai, Kizugawa, 619-0215 Kyoto, Japan*

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We propose a compact source of coherent attosecond x-ray pulses based on laser reflection from nonlinear plasma waves driven by relativistic charged particle beams. Analytical theory and particle-in-cell simulations show that such beams can excite strongly nonlinear plasma waves acting as relativistic mirrors. The reflection of millijoule-level laser pulses from such mirrors in micron-scale plasmas can produce coherent few-attosecond x-ray pulses with pulse duration, peak intensity, and spectral brightness potentially surpassing those of state-of-the-art coherent x-ray sources, all within a significantly reduced footprint. Laser intensification by up to 2 orders of magnitude is demonstrated. The resulting coherent attosecond pulses open avenues for probing ultrafast dynamics of atoms, molecules, and even electrons, enabling transformative applications across atomic physics, chemistry, materials science, and structural biology.

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Introduction. The reflection of light from a moving relativistic mirror was solved by Einstein in his seminal work on the theory of special relativity [1]. An electromagnetic pulse reflected from a mirror counterpropagating at velocity v will undergo a blueshift, pulse compression, and amplitude enhancement due to a double Doppler effect, which is shown schematically in Fig. 1(a). This can be written concisely as [1–4]

$$\frac{\omega_r}{\omega_0} = \frac{\tau_0}{\tau_r} = \frac{E_r}{rE_0} = \frac{1+\beta}{1-\beta} \approx 4\gamma^2, \quad (1)$$

where E_r , ω_r , τ_r and E_0 , ω_0 , τ_0 are, respectively, the electric field amplitude, angular frequency, and pulse duration of reflected and incident radiation, $\beta = v/c$ is the normalized mirror velocity, c is the speed of light in vacuum, $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor of the mirror, and r is the amplitude reflection coefficient of the mirror, with the asymptotic expansion on the right-hand side of Eq. (1) being valid for $\gamma^2 \gg 1$.

This concept offers a unique source of bright, coherent electromagnetic radiation. A relativistic mirror with tunable velocity could enable measurements with limitless spatiotemporal resolution. This is an ultimate prospect for many applications, including spectroscopy and imaging of atomic, molecular, and electronic dynamics with attosecond resolution [5–8], laboratory astrophysics experiments [9], or experimental study of nonlinear properties of quantum vacuum and

other topics of fundamental interest [10], such as investigating black hole information paradox with accelerating relativistic mirrors [11]. Such applications benefit from a coherent x-ray source with high brightness and ultrashort pulse duration, which is currently realized only with the kilometers-long and access-limited x-ray free electron lasers (XFELs) [7,8,12].

The study of relativistic mirrors has been a recurring topic, with reinvigorated interest today due to the availability of high-power infrared lasers that enable various implementations (see Refs. [3,13,14] for a review). Notable examples are the relativistic mirror formed by the plasma wake or bow wave of a laser pulse propagating in underdense plasma [2,15–21], the oscillating relativistic mirror driven by a laser on the surface of an overdense plasma target [14,22–27], or the relativistic mirror accelerated by the interaction of an intense laser with a thin target [28–30].

To realize Einstein's vision of a relativistic mirror moving at a constant velocity, nonlinear plasma waves driven in underdense plasma are especially attractive. If such a wave is driven close to the wave-breaking threshold, the plasma electrons composing the wave reach the velocity of the driver, and the reflectivity of the plasma wave is maximized. The amplitude reflection coefficient can then be calculated as (see the Supplemental Material [31])

$$r \approx 0.3 \left(\frac{n_0}{\gamma n_c} \right)^{2/3}, \quad (2)$$

where n_0 is the background plasma density, $n_c = m_e \epsilon_0 \omega_0^2 / e^2$ is the critical plasma density, m_e is the electron mass, ϵ_0 is the vacuum permittivity, and e is the elementary charge.

In the case when the driver is a laser pulse, the relativistic mirror velocity is coupled to plasma density through laser group velocity, as $\gamma \approx \sqrt{n_c/n_0}$. Equation (2) then predicts

*Contact author: marcel.lamac@eli-beams.eu

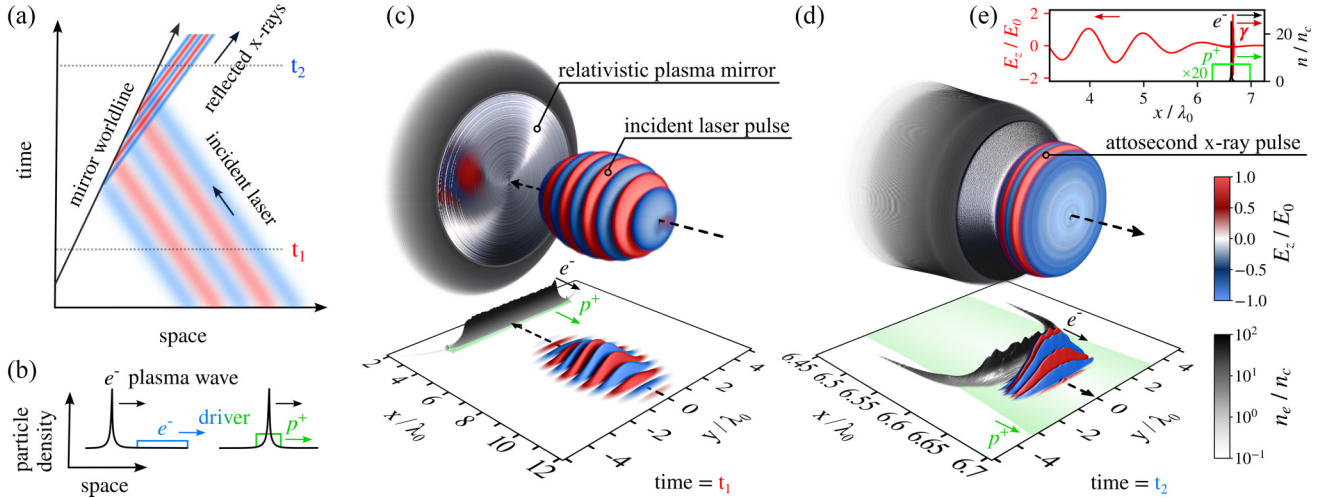


FIG. 1. Beam-driven relativistic plasma mirrors and 3D PIC simulation results. (a) Spacetime diagram showing a laser pulse reflecting from a relativistic mirror. (b) Schematic of plasma waves driven close to the breaking threshold by an electron (blue) or proton (green) particle beam. (c) Before the reflection, a nonlinear electron plasma wave, which acts as a relativistic mirror, is driven by a proton beam with Lorentz factor $\gamma = 5$ propagating in underdense plasma. The figure shows a 3D distribution of the electric field component E_z (colored, saturated) of the laser pulse and the plasma electron density n_e (gray scale). The overdense electron density ($n_e > n_c$) is indicated with a reflective surface. (d) After the reflection, the laser is compressed (note the change in x -axis scale) due to the double Doppler effect. The wavelength of the laser pulse is shifted from $\lambda_0 = 0.8 \mu\text{m}$ to $\lambda_r \approx 8 \text{ nm}$, the pulse is compressed from $\tau_0 \approx 4 \text{ fs}$ down to $\tau_r \approx 40 \text{ attoseconds}$, and the electric field amplitude is amplified, as $E_r/E_0 \approx 1.9$, which follows the predictions given by Eqs. (1) and (2). A slice through the plane $z = 0$ is shown at the bottom. The dashed arrows indicate the direction of radiation propagation. The dashed line corresponds to a lineout shown in panel (e), which also shows the transmitted pulse.

that the reflection coefficient decreases with mirror velocity as $r \propto 1/\gamma^2$. Unfortunately, such scaling exactly cancels with the $\propto \gamma^2$ amplitude enhancement due to the double Doppler effect (1), which makes the generation of bright x-rays using laser drivers challenging since $E_r \approx E_0$, and therefore no electric field amplification occurs upon reflection. Decoupling the mirror velocity from the background plasma density is therefore necessary to achieve not only laser pulse compression and frequency up-shift, but also field amplification. This could be achieved by using a charged particle beam to drive a plasma wave close to the wave-breaking threshold, instead of a laser pulse, as shown schematically in Fig. 1(b).

In this Letter, we use analytic theory, quasi-three-dimensional (q3D), and one-dimensional (1D) particle-in-cell (PIC) simulations to show that a relativistic proton or electron beam propagating in plasma can drive a nonlinear electron plasma wave, which acts as a relativistic plane mirror. We demonstrate that relativistic mirrors driven by charged particle beams can amplify the reflected laser field as $E_r \propto \gamma^{4/3} E_0$, unlocking the generation of bright coherent attosecond x-ray pulses.

To design such a mirror, we must first review the physics of plasma waves driven by a charged particle beam [32–34]. For a wide charged particle beam with a flat-top density profile, a key parameter characterizing the nonlinearity of the interaction with plasma is the normalized charge density $\rho = qn_b/n_0$, where n_b is the particle density of the driving beam and q is the charge number of the driver, e.g., $q = 1$ for protons and $q = -1$ for electrons. A nonlinear electron plasma wave can be driven in the wake as well as in the interior of a driving beam [34], depending on the charge number q , as shown in Fig. 1(b). In particular, for a high-reflectivity mirror, we

must precisely understand the wave-breaking thresholds. By adjusting ρ , the maximum velocity of plasma electrons v_e can be tuned to reach the velocity of the driving particle beam v , at which point the plasma electron density n_e forms a singularity and the mirror reflectivity is maximized.

For protons, wave breaking of the interior nonlinear plasma wave occurs when the beam has a normalized charge density of $\rho_+ \approx \gamma$, where γ is the Lorentz factor of the driver, and the driver has a length of $L_+ \geq \lambda_{\text{int}}$, where $\lambda_{\text{int}} \approx 2\sqrt{2/\rho_+}/k_{\text{pe}}$ is the wavelength of the nonlinear wave formed in the interior of the proton beam, $k_{\text{pe}} = \omega_{\text{pe}}/c$ is the linear plasma wave number, and $\omega_{\text{pe}} = \sqrt{e^2 n_0 / \epsilon_0 m_e}$ is the linear plasma frequency. For electron-driven wakefield, breaking occurs when $\rho_- \approx -0.5$ and $L_- \approx 2\gamma/k_{\text{pe}}$. In simple terms, proton beams must be dense, with respect to the background plasma electron density, while electron beams must be long and rarefied. Properties of nonlinear plasma waves driven by electron and proton beams, including the wave-breaking thresholds, are derived in a companion article [34].

To verify that the amplitude, frequency, and duration of laser pulses reflected from beam-driven relativistic mirrors follow Eqs. (1) and (2), we have employed the fully relativistic PIC code EPOCH [35] in 3D cylindrical geometry with azimuthal mode decomposition (q3D). The azimuthal decomposition uses two modes. We note that 2D Cartesian geometry is not a valid surrogate here, since it enforces out-of-plane invariance, which effectively corresponds to an infinitely wide driver [36]. Due to the high resolution required for reflected radiation, q3D with two azimuthal modes is the most direct computationally tractable approximation to 3D for initially axisymmetric drivers [37,38]. A Gaussian laser pulse, linearly polarized along the z axis, with normalized electric field

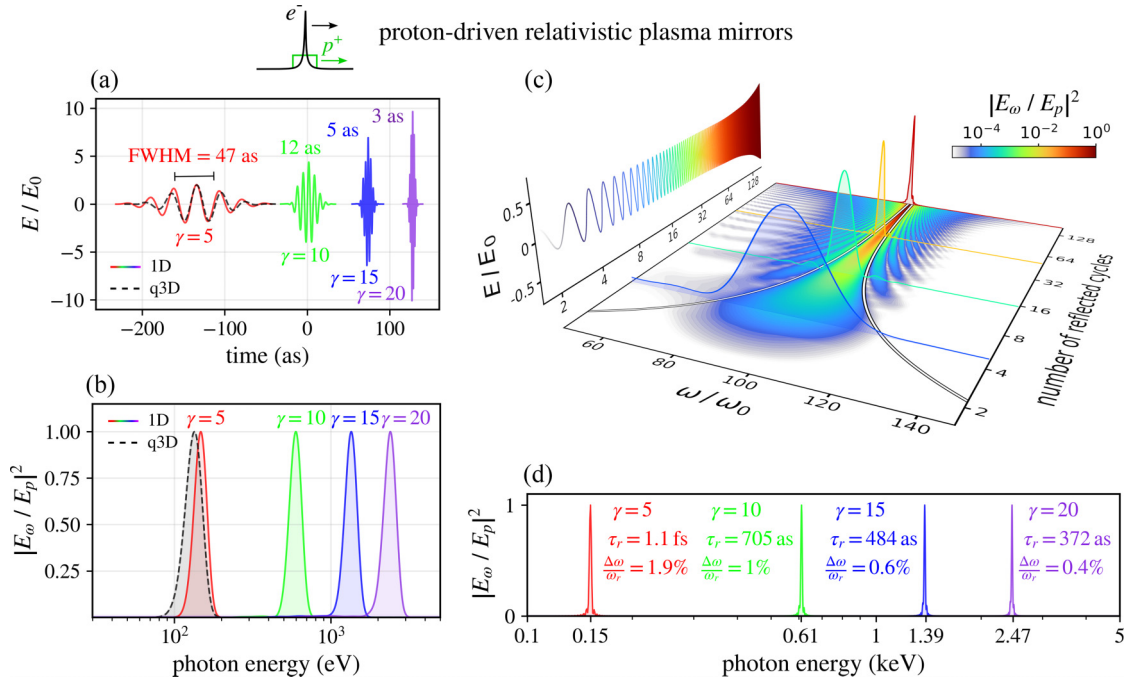


FIG. 2. 1D and q3D PIC simulations of proton-driven relativistic mirrors. (a) Temporal profile of attosecond pulses reflected from proton-driven relativistic mirrors with $\gamma = 5, 10, 15, 20$ and $n_0/n_c = 0.08$. (b) Normalized energy spectra of reflected laser pulses shown in panel (a), spanning from XUV to x-ray spectral range. q3D PIC result (dashed) corresponds to data shown in Figs. 1(d) and 1(e). (c) Normalized energy spectrum evolution of continuous wave radiation reflected for a relativistic mirror with $\gamma = 5$ propagating in underdense plasma with $n_0/n_c = 0.01$. The normalization constant is equal to $E_p^2 = E_r^2 \tau_r^2$ [31]. Theoretical relative spectral bandwidth (white lines, black outline) is given by $\Delta\omega/\omega_r = 1/N$, where N is the number of reflected laser periods (shown in logarithmic scale). The inset in panel (c) shows the corresponding temporal profile of the reflected continuous wave. Each spectrum is a Fourier transform of $E_z(t)$ over a window of N reflected cycles. (d) Final energy spectrum of a continuous wave reflected from proton-driven relativistic mirrors in a background plasma density of $n_0/n_c = 0.08$.

amplitude $a_0 = eE_0/m_e c \omega_0 = 0.05$, laser wavelength $\lambda_0 = 2\pi c/\omega_0 = 0.8 \mu\text{m}$, pulse duration $\tau_0 = 1.5\lambda_0/c$, and beam waist $w_0 = \lambda_0$, is focused into an underdense plasma target with background plasma density of $n_0 = 0.08n_c$.

Proton-driven mirrors. A counterpropagating flat-top proton beam is set up with Lorentz factor $\gamma = 5$. To prevent the mirror from breaking immediately, the charge density of the driver is set slightly below the wave-breaking threshold, as $\rho_+ = 0.96\gamma$. The driver length is $L_+ = \lambda_{\text{int}} \approx 0.8\lambda_0$. The proton driver has a beam radius of $r_+ = 3.5\lambda_0$. The total proton beam charge is therefore on the order of $Q_+ \approx \text{nC}$, corresponding to $N_+ \approx 10^9$ protons. We remark that these proton beam parameters are beyond the current state of the art. While the total charge is within the means of not only conventional accelerators, which provide up to 10^{11} protons [39–41], but also current laser-driven accelerators, which produce up to 10^9 protons [42,43], conventionally accelerated proton beams lack the high density, while laser-accelerated proton beams do not yet reach the considered velocity. With an increasing number of multipetawatt laser facilities available [44], we expect this could change in the foreseeable future [45,46]. The simulation box has a longitudinal size of $9\lambda_0$ and a radial size of $5\lambda_0$, with a resolution of 10^4 cells per λ_0 in longitudinal direction, which is approximately 10^2 cells per reflected wavelength λ_r , and 10^2 cells per λ_0 in transverse direction. The number of macroparticles per cell is 2 for all species.

The q3D PIC results are shown in Fig. 1. Figure 1(c) shows that as the proton beam enters the plasma, a nonlinear plasma wave is driven throughout its interior, forming a plane relativistic mirror. Upon reflection, shown in Figs. 1(d) and 1(e), the laser pulse undergoes a double Doppler effect, as seen from the compressed pulse duration and wavelength, in accordance with Eq. (1). The amplitude reflection coefficient from Eq. (2) can be calculated as $r \approx 0.02$ for the considered simulation parameters. Equation (1) then predicts the reflected amplitude as $E_r/E_0 \approx 4\gamma^2 r \approx 1.9$, which matches the q3D PIC result.

To verify the validity of Eqs. (1) and (2) in a broader parameter space, we have performed additional PIC simulations. Due to the significant computational cost of multidimensional PIC simulations at such high resolution, we have performed these scans in 1D geometry. This is a valid approximation for plane mirrors, as long as the mirror has a radius larger than the incident laser beam, as in the case of the q3D PIC result shown in Fig. 1(c). The Lorentz factor of the proton beam was varied from $\gamma = 5$ to $\gamma = 20$, with a constant background density of $n_0/n_c = 0.08$. For all simulations, the driver's normalized charge density is set at $\rho_b = 0.96\gamma$, and the longitudinal resolution is set at 10^2 cells per reflected wavelength $\lambda_r \approx \lambda_0/4\gamma^2$, e.g., for $\gamma = 20$, this corresponds to 1.6×10^5 cells per λ_0 . The laser pulse was set to have the same parameters as in the q3D simulation. The results are presented in Figs. 2 and 4, where they are also compared to the q3D result. The temporal

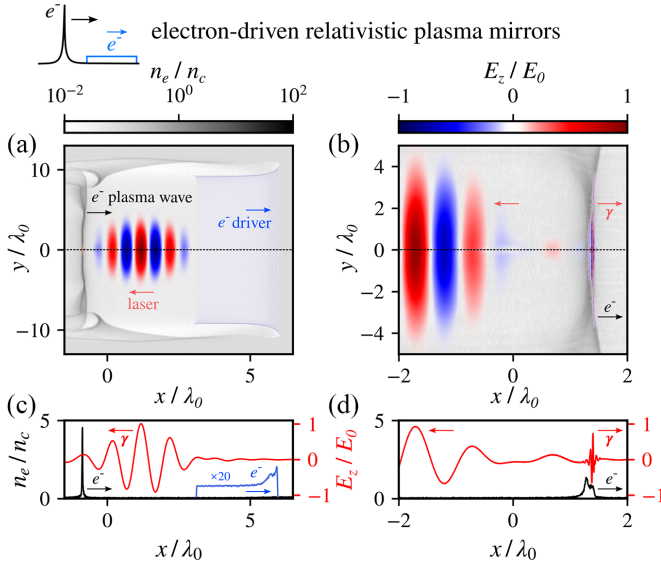


FIG. 3. q3D PIC simulation of an electron-driven relativistic mirror. (a) A nonlinear electron plasma wave is driven by an electron beam with Lorentz factor $\gamma = 2.5$. The normalized electron particle density n_e/n_c (gray scale) and transverse electric field normalized by the incident laser amplitude E_z/E_0 (colored) are shown before reflection. The dashed line corresponds to a lineout shown in panel (c). (b) Upon reflection, the laser splits into a transmitted and reflected pulse, which undergoes the double Doppler effect. The reflection coefficient given by Eq. (2) yields from Eq. (1) a reflected laser amplitude of $E_r/E_0 \approx 0.8$, which is in agreement with the q3D PIC result. The dashed line corresponds to a lineout shown in panel (d).

profile and energy spectrum of reflected pulses are shown in Figs. 2(a) and 2(b). By varying the proton beam velocity, the reflected attosecond pulse is tuned from XUV to the x-ray range, in accordance with Eqs. (1) and (2).

The fastest mirror with $\gamma = 20$ produces a 3 as pulse, with a photon energy of approximately 2.5 keV, which is less than the natural timescale of electron motion in atoms, the atomic unit of time $a_0/(\alpha c) \approx 24$ as, where a_0 is the Bohr radius and $\alpha \approx 1/137$ is the fine-structure constant. This is an order of magnitude shorter in comparison to the current experimental record of 53 as, produced using high-harmonic generation in gases [47]. The laser intensity is $100\times$ amplified, to a value of $I_r \approx 10^{18}$ W/cm², which is on the order of focused XFEL beam intensity [7] and corresponds to an electric field amplitude of $E_r \approx 2$ TV/m.

To test the temporal stability of the proton-driven mirror, we have set up a counterpropagating continuous wave, instead of a few-cycle laser pulse. Figure 2(c) shows the evolution of the energy spectrum of the reflected continuous wave for $\gamma = 5$ and $n_0/n_c = 0.01$. The mirror coherently reflects radiation up to approximately a hundred laser periods, after which it self-modulates, breaking the plasma wave. The results of the velocity scan for $n_0/n_c = 0.08$ are shown in Fig. 2(d). The final energy spectra of the reflected wave are shown to be quasimonochromatic, affirming high coherence due to the robustness of the proton-driven relativistic mirror, which can be attributed to the large mass of the protons. We find that the propagation distance of the mirror increases with the Lorentz

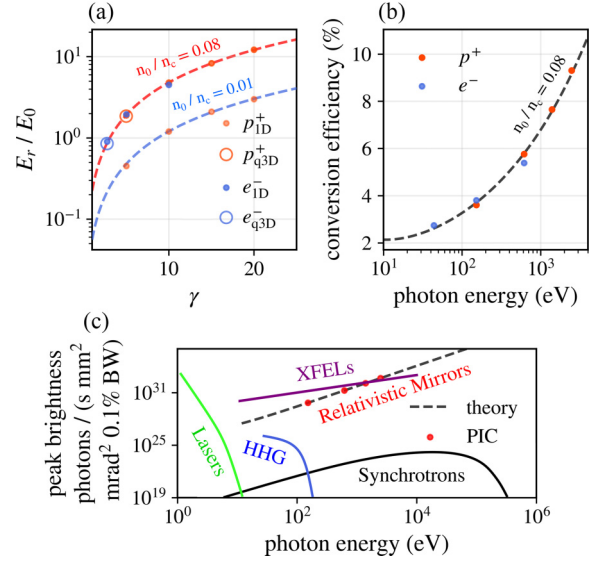


FIG. 4. (a) Comparison of theoretical scaling (dashed) of reflected amplitude E_r given by Eqs. (1) and (2), with respect to Lorentz factor of the driver γ and normalized background plasma density n_0/n_c , to 1D (dots) and q3D (circles) PIC simulation results for proton (orange) and electron-driven (blue) relativistic plasma mirrors. (b) Laser-to-x-ray energy conversion efficiency for proton- and electron-driven relativistic mirrors, with theoretical curve (dashed) described in text. (c) Peak spectral brightness obtained from 1D PIC simulations for background plasma density $n_0/n_c = 0.08$ and incident laser pulse energy $\mathcal{E}_0 = 10$ mJ, or $N_{\gamma,i} \approx 4 \times 10^{16}$ incident photons with 800 nm wavelength. The theoretical curve (dashed) is given by Eq. (3). Data for other light sources are taken from Ref. [8].

factor as $L_{\text{prop}} \propto \gamma$, since the relative spectral bandwidth of the reflected wave decreases linearly with γ . This is ascribed to a relativistic beam-plasma instability, a study of which we leave for future work. In the case of $\gamma = 20$, a coherent attosecond x-ray pulse is produced with a duration of 372 as and an XFEL-like [12] quasimonochromatic relative energy bandwidth of 0.4%, at a central photon energy of approximately 2.5 keV, showing a high degree of temporal coherence. A velocity scan was also performed for $n_0/n_c = 0.01$, with results shown in Fig. 4(a). The results confirm field amplification with increasing mirror velocity, as well as a decrease of mirror reflectivity due to reduced background plasma density, in agreement with Eqs. (1) and (2). Note that stable mirror propagation requires homogeneous background plasma density, as inhomogeneities could trigger wave breaking or reduction of reflection coefficient [18].

Electron-driven mirrors. A q3D PIC simulation was performed for the case of a relativistic mirror driven in the wake of an electron beam. A linearly polarized Gaussian laser pulse is considered with normalized amplitude $a_0 = 0.1$, laser wavelength $\lambda_0 = 0.8 \mu\text{m}$, pulse duration $\tau_0 = 1.5\lambda_0/c$, and beam waist $w_0 = 3\lambda_0$. The background plasma density was set as $n_0 = 0.08n_c$. A counterpropagating flat-top electron beam driving an electron plasma wave with $\gamma = 2.5$ is set up with normalized charge density of $\rho_- = -0.5$, driver length $L_- = 2\gamma/k_{pe} = 2.8\lambda_0$, and electron beam radius of $r_- = 7\lambda_0$. The electron beam energy is linearly chirped, from $\gamma = 2.5$ at the front to $\gamma = 43$ at its back. This chirp is introduced

to compensate driver deceleration in the wake and maintain mirror formation over the interaction length. These parameters correspond to a total beam charge of $Q_- \approx 2$ nC, or $N_- \approx 10^{10}$ electrons at a moderate average energy of 20 MeV, which has been demonstrated from laser wakefield accelerators [48]. The simulation box has the longitudinal and radial length equal to $13.5\lambda_0$, with 2.6×10^3 cells per λ_0 in longitudinal direction, which is approximately 10^2 cells per λ_r , and 10^2 cells per λ_0 in transverse direction. The number of macroparticles per cell is 2.

The results are shown in Fig. 3. A nonlinear plasma wakefield is driven behind the electron beam, with a counterpropagating laser pulse incident on the overcritical crest of the plasma wave, as shown in Figs. 3(a) and 3(c). As the driving beam propagates, it loses energy, which leads to self-modulation of the front side of the driver seen in Fig. 3(c). This eventually leads to wave breaking, at which point the incident laser reflects from the relativistic mirror. The reflected pulse is shown in Figs. 3(b) and 3(d), with amplitude, frequency, and pulse duration in accordance with Eqs. (1) and (2). To evaluate electron-driven relativistic mirrors at higher velocities, we conducted additional PIC simulations in 1D geometry, with results shown in Fig. 4(a). Since wave-breaking conditions for electron-driven mirrors require that the driving electron beam length increases with mirror velocity, as $L_- \approx 2\gamma/k_{pe}$, there are challenging computational requirements. Both the driving region and the wakefield region must be included, and resolved with high resolution, which we set at 100 cells per reflected wavelength $\lambda_r \approx \lambda_0/4\gamma^2$. Due to the quadratic scaling of resolution, as well as the enlarging simulation box, the scan was terminated at $\gamma = 10$. Within the simulated parameter space, 1D results show correspondence with the q3D result and theory, supporting the scalability of the scheme for even faster electron drivers.

Figure 4(a) summarizes the 1D and q3D PIC results obtained, comparing the reflected amplitude from electron and proton-driven mirrors to theory. Figure 4(b) compares the theoretical conversion efficiency, which can be obtained from Eqs. (1) and (2) as $\eta \approx 0.36 (n_0/n_c)^{4/3} \gamma^{2/3}$, to the PIC results. The numerical conversion efficiency follows the theoretical estimate and, counterintuitively, grows with mirror velocity (reflected photon energy). Following the theory, PIC results show $\eta \approx 9\%$ at 2.5 keV. The conversion efficiency increases with reflected photon energy, as long as the total reflected energy does not exceed the total energy of the electrons composing the relativistic mirror [20]. Due to this, beam-driven relativistic plasma mirrors have the potential to be one of the most efficient sources of coherent attosecond x-rays. Beam-driven mirrors could be even considered as exotic laser energy amplifiers, since the total energy of the reflected pulse becomes larger than that of the incident laser pulse ($\eta > 100\%$) when $\gamma > 4.63 (n_c/n_0)^2$.

The figure of merit for coherent light sources is the peak spectral brightness, $\mathcal{B}$ [7,8,49]. For beam-driven relativistic plasma mirrors, it can be derived as [31]

$$\mathcal{B} \left[\frac{\text{photons}}{\text{s mm}^2 \text{ mrad}^2 0.1\% \text{ BW}} \right] = \frac{32cN_{\gamma,i}|r|^2\gamma^6}{10^{15}\lambda_0^3}, \quad (3)$$

where $N_{\gamma,i} = \mathcal{E}_0/\hbar\omega_0$ is the number of incident photons and $\mathcal{E}_0$ is the energy of the incident laser pulse. Importantly,

Eq. (3) shows that peak spectral brightness of reflected radiation scales with mirror velocity as $\mathcal{B} \propto |r|^2\gamma^6 \propto \gamma^{14/3}$, which reveals the potential of beam-driven relativistic mirrors for ultrarelativistic drivers. Figure 4 compares Eq. (3) with 1D PIC simulation results, with the assumption of a homogeneous relativistic mirror, and the peak spectral brightness of other currently available coherent light sources [8]. The simulations correspond to background density $n_0/n_c = 0.08$, Lorentz factors ranging from $\gamma = 5$ to $\gamma = 20$, and an incident laser pulse with energy of 10 mJ. At photon energy of 2.5 keV, the peak brightness obtained is $\mathcal{B} \approx 10^{33}$ photons/(s mm² mrad² 0.1% BW), which could rival state-of-the-art XFELs.

Conclusion. In summary, we have proposed a concept for bright, coherent attosecond x-ray pulse generation based on laser reflection from relativistic plasma mirrors driven by electron or proton particle beams. We have shown that beam-driven relativistic plasma mirrors amplify reflected radiation, scaling with the Lorentz factor of the driver as $E_r/E_0 \propto \gamma^{4/3}$. An intensity amplification of 100× is demonstrated, via a beam-driven relativistic mirror moving with $\gamma = 20$. The laser-to-x-ray energy conversion efficiency is shown to grow with mirror velocity as $\eta \propto \gamma^{2/3}$, which is of significant interest for laser amplification. In excellent agreement with the presented theory, 1D and quasi-3D PIC simulations show coherent attosecond pulse generation, with tunable spectrum from extreme ultraviolet to x-rays, with pulse durations from a few to hundreds of attoseconds, and peak spectral brightness up to $\mathcal{B} \approx 10^{33}$ photons/(s mm² mrad² 0.1% BW) at x-ray photon energy of 2.5 keV, produced from the reflection of a 10 mJ infrared laser pulse.

Future work should study the effects of driving beam emittance and energy spread on the mirror formation, as well as benchmark the theoretical scaling at higher photon energies. Extrapolating beyond the results presented in this work, Eqs. (1) and (2) predict generation of zeptosecond pulses with peak spectral brightness scaling as $\mathcal{B} \propto \gamma^{14/3}$, highlighting the potential of beam-driven relativistic mirrors for both ultra-short pulse generation and laser amplification. The proposed concept presents a plasma-based alternative to free electron lasers, with coherent x-ray radiation generated over a distance of just a few micrometers, facilitating a potentially compact source for applications, where both high intensity and ultra-short pulse duration are desirable, such as nonlinear x-ray spectroscopy, coherent diffractive imaging, or exotic applications such as the laboratory study of nonlinear properties of quantum vacuum and black hole information loss.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

- [1] A. Einstein, Zur elektrodynamik bewegter körper, *Ann. Phys.* **4**, 891 (1905).
- [2] S. V. Bulanov, T. Esirkepov, and T. Tajima, Light intensification towards the Schwinger limit, *Phys. Rev. Lett.* **91**, 085001 (2003).
- [3] S. V. Bulanov, T. Z. Esirkepov, M. Kando, A. S. Pirozhkov, and N. N. Rosanov, Relativistic mirrors in plasmas—novel results and perspectives, *Phys. Usp.* **56**, 429 (2013).
- [4] T. Z. Esirkepov and S. V. Bulanov, Luminal mirror, *Phys. Rev. E* **109**, L023202 (2024).
- [5] F. Krausz and M. Ivanov, Attosecond physics, *Rev. Mod. Phys.* **81**, 163 (2009).
- [6] R. Neutze, R. Wouts, D. Van der Spoel, E. Weckert, and J. Hajdu, Potential for biomolecular imaging with femtosecond X-ray pulses, *Nature (London)* **406**, 752 (2000).
- [7] P. G. O'Shea and H. P. Freund, Free-electron lasers: Status and applications, *Science* **292**, 1853 (2001).
- [8] S. Boutet, P. Fromme, and M. S. Hunter, *X-ray Free Electron Lasers* (Springer, London, 2018).
- [9] S. Bulanov, T. Z. Esirkepov, M. Kando, J. Koga, K. Kondo, and G. Korn, On the problems of relativistic laboratory astrophysics and fundamental physics with super powerful lasers, *Plasma Phys. Rep.* **41**, 1 (2015).
- [10] G. A. Mourou, T. Tajima, and S. V. Bulanov, Optics in the relativistic regime, *Rev. Mod. Phys.* **78**, 309 (2006).
- [11] P. Chen and G. Mourou, Accelerating plasma mirrors to investigate the black hole information loss paradox, *Phys. Rev. Lett.* **118**, 045001 (2017).
- [12] C. Pellegrini, A. Marinelli, and S. Reiche, The physics of x-ray free-electron lasers, *Rev. Mod. Phys.* **88**, 015006 (2016).
- [13] M. Kando, T. Z. Esirkepov, J. K. Koga, A. S. Pirozhkov, and S. V. Bulanov, Coherent, short-pulse X-ray generation via relativistic flying mirrors, *Quantum Beam Sci.* **2**, 9 (2018).
- [14] U. Teubner and P. Gibbon, High-order harmonics from laser-irradiated plasma surfaces, *Rev. Mod. Phys.* **81**, 445 (2009).
- [15] M. Kando, Y. Fukuda, A. S. Pirozhkov, J. Ma, I. Daito, L. M. Chen, T. Z. Esirkepov, K. Ogura, T. Homma, Y. Hayashi, H. Kotaki, A. Sagisaka, M. Mori, J. K. Koga, H. Daido, S. V. Bulanov, T. Kimura, Y. Kato, and T. Tajima, Demonstration of laser-frequency upshift by electron-density modulations in a plasma wakefield, *Phys. Rev. Lett.* **99**, 135001 (2007).
- [16] A. Pirozhkov, J. Ma, M. Kando, T. Z. Esirkepov, Y. Fukuda, L.-M. Chen, I. Daito, K. Ogura, T. Homma, Y. Hayashi, *et al.*, Frequency multiplication of light back-reflected from a relativistic wake wave, *Phys. Plasmas* **14**, 123106 (2007).
- [17] M. Kando, A. S. Pirozhkov, K. Kawase, T. Z. Esirkepov, Y. Fukuda, H. Kiriya, H. Okada, I. Daito, T. Kameshima, Y. Hayashi, *et al.*, Enhancement of photon number reflected by the relativistic flying mirror, *Phys. Rev. Lett.* **103**, 235003 (2009).
- [18] M. Lobet, M. Kando, J. K. Koga, T. Z. Esirkepov, T. Nakamura, A. S. Pirozhkov, and S. V. Bulanov, Controlling the generation of high frequency electromagnetic pulses with relativistic flying mirrors using an inhomogeneous plasma, *Phys. Lett. A* **377**, 1114 (2013).
- [19] H. Moghadasin, A. R. Niknam, D. Komaizi, and M. Banjafar, Attosecond pulse generation by relativistic flying mirrors in laser-plasma interaction: Effect of plasma density and driver amplitude on the generated pulse, *Phys. Plasmas* **26**, 093105 (2019).
- [20] P. Valenta, T. Z. Esirkepov, J. Koga, A. Pirozhkov, M. Kando, T. Kawachi, Y.-K. Liu, P. Fang, P. Chen, J. Mu, *et al.*, Recoil effects on reflection from relativistic mirrors in laser plasmas, *Phys. Plasmas* **27**, 032109 (2020).
- [21] J. Mu, T. Z. Esirkepov, P. Valenta, Y. Gu, T. M. Jeong, A. S. Pirozhkov, J. K. Koga, M. Kando, G. Korn, and S. V. Bulanov, Relativistic flying forcibly oscillating reflective diffraction grating, *Phys. Rev. E* **102**, 053202 (2020).
- [22] S. V. Bulanov, N. Naumova, and F. Pegoraro, Interaction of an ultrashort, relativistically strong laser pulse with an overdense plasma, *Phys. Plasmas* **1**, 745 (1994).
- [23] R. Lichters, J. Meyer-ter Vehn, and A. Pukhov, Short-pulse laser harmonics from oscillating plasma surfaces driven at relativistic intensity, *Phys. Plasmas* **3**, 3425 (1996).
- [24] H. Vincenti, Achieving extreme light intensities using optically curved relativistic plasma mirrors, *Phys. Rev. Lett.* **123**, 105001 (2019).
- [25] F. Quéré and H. Vincenti, Reflecting petawatt lasers off relativistic plasma mirrors: A realistic path to the Schwinger limit, *High Power Laser Sci. Eng.* **9**, e6 (2021).
- [26] L. Chopineau, G. Blaclard, A. Denoeud, H. Vincenti, F. Quéré, and S. Haessler, Sub-laser-cycle control of relativistic plasma mirrors, *Phys. Rev. Res.* **4**, L012030 (2022).
- [27] M. Lamač, K. Mima, J. Nejd, U. Chaulagain, and S. V. Bulanov, Anomalous relativistic emission from self-modulated plasma mirrors, *Phys. Rev. Lett.* **131**, 205001 (2023).
- [28] V. V. Kulagin, V. A. Cherepenin, M. S. Hur, and H. Suk, Theoretical investigation of controlled generation of a dense attosecond relativistic electron bunch from the interaction of an ultrashort laser pulse with a nanofilm, *Phys. Rev. Lett.* **99**, 124801 (2007).
- [29] D. Kiefer, M. Yeung, T. Dzelzainis, P. Foster, S. Rykovanov, C. L. Lewis, R. Marjoribanks, H. Ruhl, D. Habs, J. Schreiber, *et al.*, Relativistic electron mirrors from nanoscale foils for coherent frequency upshift to the extreme ultraviolet, *Nat. Commun.* **4**, 1763 (2013).
- [30] W. J. Ma, J. H. Bin, H. Y. Wang, M. Yeung, C. Kreuzer, M. Streeter, P. S. Foster, S. Cousens, D. Kiefer, B. Dromey, X. Q. Yan, J. Meyer-ter-Vehn, M. Zepf, and J. Schreiber, Bright sub-cycle extreme ultraviolet bursts from a single dense relativistic electron sheet, *Phys. Rev. Lett.* **113**, 235002 (2014).
- [31] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/w9yj-4hh5> for derivation.
- [32] P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, Acceleration of electrons by the interaction of a bunched electron beam with a plasma, *Phys. Rev. Lett.* **54**, 693 (1985).
- [33] T. Katsouleas, Physical mechanisms in the plasma wake-field accelerator, *Phys. Rev. A* **33**, 2056 (1986).
- [34] M. Lamač, P. Valenta, U. Chaulagain, J. Nejd, D. Čáp, O. Morvai, and S. V. Bulanov, companion paper, Theory of beam-driven nonlinear plasma wake and interior waves, *Phys. Rev. E* **113**, 045209 (2026).
- [35] T. Arber, K. Bennett, C. Brady, A. Lawrence-Douglas, M. Ramsay, N. Sircombe, P. Gillies, R. Evans, H. Schmitz, A. Bell, *et al.*, Contemporary particle-in-cell approach to laser-plasma modelling, *Plasma Phys. Controlled Fusion* **57**, 113001 (2015).
- [36] A. Golovanov and I. Y. Kostyukov, Bubble regime of plasma wakefield in 2D and 3D geometries, *Phys. Plasmas* **25**, 103107 (2018).

- [37] A. F. Lifschitz, X. Davoine, E. Lefebvre, J. Faure, C. Rechatin, and V. Malka, Particle-in-cell modelling of laser-plasma interaction using Fourier decomposition, *J. Comput. Phys.* **228**, 1803 (2009).
- [38] A. Davidson, A. Tableman, W. An, F. S. Tsung, W. Lu, J. Vieira, R. A. Fonseca, L. O. Silva, and W. B. Mori, Implementation of a hybrid particle code with a PIC description in r - z and a gridless description in ϕ into OSIRIS, *J. Comput. Phys.* **281**, 1063 (2015).
- [39] A. Caldwell, K. Lotov, A. Pukhov, and F. Simon, Proton-driven plasma-wakefield acceleration, *Nat. Phys.* **5**, 363 (2009).
- [40] P. Muggli, E. Adli, R. Apsimon, F. Asmus, R. Baartman, A.-M. Bachmann, M. B. Marin, F. Batsch, J. Bauche, V. B. Olsen, *et al.*, AWAKE readiness for the study of the seeded self-modulation of a 400 GeV proton bunch, *Plasma Phys. Controlled Fusion* **60**, 014046 (2018).
- [41] L. Verra, G. Z. Della Porta, J. Pucek, T. Nechaeva, S. Wyler, M. Bergamaschi, E. Senes, E. Guran, J. Moody, M. Kedves, *et al.*, Controlled growth of the self-modulation of a relativistic proton bunch in plasma, *Phys. Rev. Lett.* **129**, 024802 (2022).
- [42] T. Ziegler, I. Göthel, S. Assenbaum, C. Bernert, F.-E. Brack, T. E. Cowan, N. P. Dover, L. Gaus, T. Kluge, S. Kraft, *et al.*, Laser-driven high-energy proton beams from cascaded acceleration regimes, *Nat. Phys.* **20**, 1211 (2024).
- [43] M. Streeter, G. Glenn, S. DiIorio, F. Treffert, B. Loughran, H. Ahmed, S. Astbury, M. Borghesi, N. Bourgeois, C. Curry, *et al.*, Stable laser-acceleration of high-flux proton beams with plasma collimation, *Nat. Commun.* **16**, 1004 (2025).
- [44] C. N. Danson, C. Haefner, J. Bromage, T. Butcher, J.-C. F. Chanteloup, E. A. Chowdhury, A. Galvanauskas, L. A. Gizzi, J. Hein, D. I. Hillier, *et al.*, Petawatt and exawatt class lasers worldwide, *High Power Laser Sci. Eng.* **7**, e54 (2019).
- [45] S. S. Bulanov, V. Y. Bychenkov, V. Chvykov, G. Kalinchenko, D. W. Litzenberg, T. Matsuoka, A. G. R. Thomas, L. Willingale, V. Yanovsky, K. Krushelnick, *et al.*, Generation of GeV protons from 1 PW laser interaction with near critical density targets, *Phys. Plasmas* **17**, 043105 (2010).
- [46] K. V. Lezhnin and S. V. Bulanov, Laser ion acceleration from tailored solid targets with micron-scale channels, *Phys. Rev. Res.* **4**, 033248 (2022).
- [47] J. Li, X. Ren, Y. Yin, K. Zhao, A. Chew, Y. Cheng, E. Cunningham, Y. Wang, S. Hu, Y. Wu, *et al.*, 53-attosecond X-ray pulses reach the carbon K-edge, *Nat. Commun.* **8**, 186 (2017).
- [48] C. Lazzarini, G. Grittani, P. Valenta, I. Zymak, R. Antipenkov, U. Chaulagain, L. Goncalves, A. Grenfell, M. Lamač, S. Lorenz, *et al.*, Ultrarelativistic electron beams accelerated by terawatt scalable kHz laser, *Phys. Plasmas* **31**, 030703 (2024).
- [49] D. Attwood and A. Sakdinawat, *X-Rays and Extreme Ultraviolet Radiation: Principles and Applications*, 2nd ed. (Cambridge University Press, NY, USA, 2017).