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Efficient cooling and pre-acceleration of positron beams via a surface-plasmon wakefield

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Phase-space cooling of positron beams in plasma remains a central challenge for realizing compact, high-brightness positron sources. Here we propose and numerically demonstrate a surface-plasmon-driven wakefield scheme that simultaneously provides longitudinal and transverse phase-space cooling as well as pre-acceleration of a positron beam in a dense plasma micro-tube. Coupled Geant4 and particle-in-cell (PIC) simulations show that a single-stage configuration can integrate positron generation, phase-space cooling, and pre-acceleration within a self-induced surface-plasmon wakefield that sustains an average accelerating gradient of ~ 0.5 TV/m. In this scheme, the positron beam is accelerated to 5.68 GeV within 33.4 ps, while its relative energy spread is compressed to 10.3%, its transverse emittance and divergence are strongly reduced, and the longitudinal capture efficiency exceeds 95%. This surface-plasmon wakefield cooling stage provides a compact pathway toward

next-generation high-brightness positron injectors based on plasma micro-structures.

1 Introduction

Conventional radio-frequency accelerators are limited to accelerating gradients of a few hundred MV/m by material ionization and breakdown thresholds [1, 2]. To overcome this barrier, advanced acceleration schemes have emerged in the past years, including laser-plasma wakefield acceleration, which achieves unprecedented gradients exceeding 100 GV/m [3, 4, 5, 6, 7], dielectric laser acceleration, which enables programmable gradients in the range of 1-10 GV/m [8, 9, 10], and THz-based acceleration, which provides 100 MV/m-scale gradients through pulse compression [11, 12, 13]. These developments have enabled significant advances in particle beam generation. For electrons, laser wakefield acceleration has seen rapid progress, with experiments demonstrating high-energy acceleration over short distances, precise control of the acceleration dynamics, and a substantial reduction of energy spread toward high-quality, quasi-monoenergetic beams [14, 15]. By contrast, positron acceleration remains more challenging, characterized by short effective acceleration phases, transverse defocusing, low generation efficiency, and beam-quality degradation induced by plasma instabilities [6, 17, 18, 19, 20].

Radiation-based schemes show particular promise, with coherent transition radiation enabling efficient positron generation via the Bethe–Heitler (BH) process [21, 22], and hollow-channel configurations achieving up to 30% energy extraction efficiency with 1% energy spread [23, 24]. Additionally, few-period radiation fields provide ultra-high acceleration gradients [26, 27]. Surface plasmons, recognized for their ability to confine strongly enhanced electromagnetic fields at material interfaces [28], have already enabled compact MeV-scale electron acceleration [29, 30], indicating that surface-plasmon-driven

wakefields offer a promising route toward efficient positron acceleration and the extension of radiation-based schemes to higher electron energies.

This work extends this promising approach to positron acceleration in a dense plasma micro-tube structure. As illustrated in Fig. 1(A), when a relativistic electron beam propagates through the micro-tube, the synergistic interaction between the beam self-field (E_{yp}) and the charge-separation field (E_{cs}) drives coherent surface electron oscillations. This mechanism generates a high-gradient longitudinal wakefield and establishes accelerating phases that are stable in both the transverse and longitudinal directions. The resulting configuration enables simultaneous positron generation, longitudinal and transverse phase-space cooling, and pre-acceleration of the positron beam, achieving an exceptional longitudinal capture efficiency exceeding 95%. At the optimal acceleration phase, the positron beam reaches 5.68 GeV with a 10.3% energy spread, while the transverse geometric emittance is reduced from ~ 0.06 to $0.007 \text{ mm} \cdot \text{mrad}$ and the rms divergence is compressed to nearly sub-mrad, with the corresponding normalized emittance remaining in the range of 60–90 $\text{mm} \cdot \text{mrad}$ at multi-GeV energies.

The paper is organized as follows. Section 2 analyzes positron acceleration driven by surface-plasmon wakefields and demonstrates effective longitudinal and transverse phase-space cooling within a stable region spanning $20 \text{ } \mu\text{m}$ longitudinally and $100 \text{ } \mu\text{m}$ transversely, including the evolution of emittance and divergence. Section 3 investigates the wakefield excitation mechanisms, revealing high accelerating gradients generated by surface-plasmon-driven oscillations. Section 4 discusses implementation aspects, showing robust acceleration under transverse injection misalignments up to $10 \text{ } \mu\text{m}$ and a factor of 2–3 enhancement in energy-transfer efficiency in multi-bunch operation. Section 5 summarizes the main conclusions and outlines the implications for future compact high-brightness positron source development.

2 Analysis of surface-plasmon-driven e^+ acceleration in a dense plasma tube

2.1 Integrated simulation model and initial beam properties

Our proposed scheme offers three key advantages: (i) robust excitation of transverse oscillations through synergistic field coupling; (ii) generation of longitudinally stable wakefields with TV/m-scale accelerating gradients; and (iii) a fully integrated architecture that combines positron generation, injection, cooling, and acceleration in a compact configuration. We employ a two-stage simulation framework (Fig. 1(A)). In the first stage, Geant4-based Monte Carlo simulations [31, 32, 33] model positron generation via the BH process from a 5.5 GeV electron beam. With 2×10^8 initial particles, the simulation yields 5.1×10^7 electrons and 9.4×10^5 positrons, corresponding to a positron-to-electron ratio of 0.019. These results provide critical input parameters for the subsequent wakefield simulations. In the second stage, we perform SMILEI particle-in-cell (PIC) simulations [34] of the wakefield dynamics, in which a 20 nC drive beam corresponds, via the above ratio, to a positron bunch charge of approximately 0.38 nC. As shown in Fig. 1(B), the Geant4 simulations confirm that positrons are predominantly generated at low energies, whereas electrons exhibit both a low-energy component and a high-energy (5.5 GeV) peak. For the PIC initialization, we prescribe the total bunch charges and interpret the 2D Cartesian geometry as representing a three-dimensional slab of effective thickness $L_z = c/\omega_0$ in the ignorable direction. A uniform macro-particle weight W is assigned such that $Q_{\text{bunch}} = \pm en_c W \Delta x \Delta y L_z N_{\text{macro}}$, where the sign corresponds to electrons or positrons, Δx and Δy are the cell sizes, and N_{macro} is the number of macro-particles in the bunch imported from the Geant4 Monte Carlo simulation. Here the macro-particle weights are normalized to the critical density $n_c = \varepsilon_0 m_e \omega_0^2 / e^2$.

The accelerating-field profiles in Fig. 1(C) (panels C3 and C4) reveal a stable half-wave accelerating phase that extends over $\sim 20 \mu\text{m}$ transversely and $\sim 100 \mu\text{m}$ longitudinally, which is essential for efficient positron capture and pre-acceleration. The initial PIC distributions (Fig. 1(C)) show beam envelopes of $\sigma_x = 4.53/4.61 \mu\text{m}$ and $\sigma_y = 15.82/15.61 \mu\text{m}$ within $\Delta X \approx 40 \mu\text{m}$ ($4\sigma_x$) and $\Delta Y \approx 60 \mu\text{m}$ ($2\sigma_y$) at a plasma density of $n_c = 2.82 \times 10^{25} \text{ m}^{-3}$. As the high-charge drive beam traverses the dense target, it also generates transition radiation whose field amplitude scales with the bunch charge [21]. In the present parameter regime, the transition-radiation fields are comparable in magnitude to the surface-plasmon-driven wakefields and overlap with the surface-plasmon tail that accelerates the positrons. In this work, however, we primarily focus on elucidating the surface-plasmon excitation and its role in shaping the wakefield structure and positron dynamics. This integrated simulation framework therefore establishes a viable pathway toward compact GeV-scale positron sources with superior beam properties, featuring high-gradient acceleration, strong phase-space cooling, and reduced energy spread.

2.2 Evolution of densities, accelerating fields, and energy spectra

Stable phase regions in wakefields are essential for efficient charged-particle acceleration. In this subsection, we analyze the positron acceleration dynamics from PIC simulations, focusing on the evolution of particle densities, accelerating fields, and energy spectra. The simulations use a spatial resolution of $0.1 \mu\text{m}$ in both longitudinal and transverse directions, with a time step of 0.05 for field integration. The computational domain contains 4736×1600 grid points and employs perfectly matched layer (PML) boundaries for field absorption, together with current and field filtering to suppress numerical artifacts. The high-density plasma tube has an electron density of 10^{28} m^{-3} , a radius of $50 \mu\text{m}$, and a wall thickness of $30 \mu\text{m}$. Initial particle phase-space distributions from preceding Monte

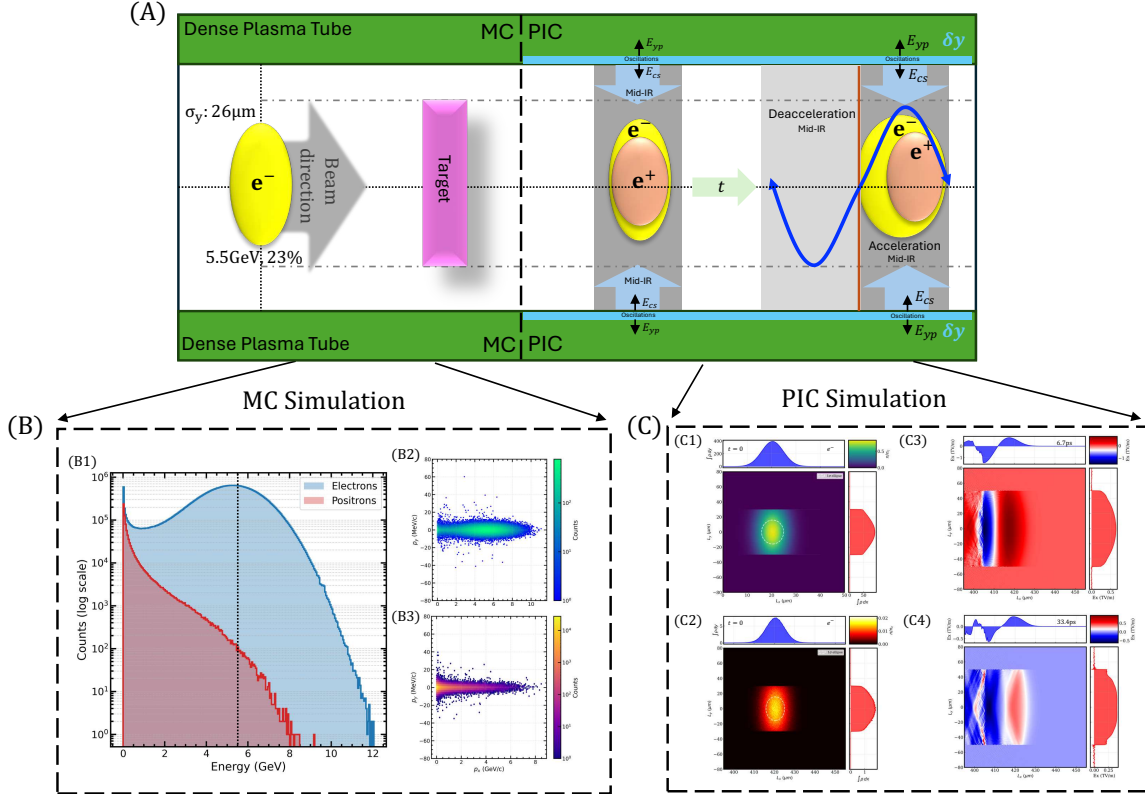


Figure 1: Mechanism of positron generation, cooling, and pre-acceleration in a high-density micro-tube. (A) Integrated MC-PIC simulation framework: the electron-beam self-field excites surface plasmons in the nanoscale layer (δ_y), generating a stable radiation wakefield via synergistic E_{yp} - E_{cs} coupling that enables phase-locked acceleration. (B) Geant4 energy spectra showing low-energy positrons and electrons, while the electron distribution retains a 5.5 GeV peak. (C) Initial densities of (C1) electrons and (C2) positrons, and accelerating field E_x at 6.7 ps and 33.4 ps, demonstrating a stable $\sim 20 \times 100 \mu\text{m}$ accelerating region.

114 Carlo simulations are used as input conditions.

115 Figure 2 summarizes the key beam dynamics over the 86.7 ps acceleration process.
116 Figure 2(A) shows the longitudinal electron density evolution at $L_y = 0$, where pro-
117 nounced deformation occurs after $t \gtrsim 30$ ps due to radiation losses: the main density
118 peak shifts from $420 \mu\text{m}$ to $410 \mu\text{m}$, accompanied by the formation of multiple sub-peaks.
119 Figure 2(B) illustrates the excitation of a strong accelerating wakefield ($\sim 0.5 \text{ TV/m}$)
120 mediated by surface-plasmon oscillations in the micro-tube wall. Beyond 30 ps, distor-
121 tion of the electron beam leads to phase shifts of the accelerating structure, which in turn
122 influence the positron energy spread. The positron density distribution in Fig. 2(C) re-
123 mains confined within $410\text{--}430 \mu\text{m}$ longitudinally, corresponding to a locked accelerating
124 region that maintains continuous acceleration and achieves a longitudinal phase capture
125 efficiency exceeding 95%.

126 The dynamics of energy transfer are shown in Figs. 2(D)–2(F). The electron spectrum
127 in Fig. 2(D) exhibits progressive energy loss, confirming efficient energy transfer from the
128 drive beam to the wakefield. In contrast, the positron beam in Fig. 2(E) undergoes strong
129 acceleration up to a maximum peak energy of 8.68 GeV; the optimal acceleration phase,
130 indicated by the two vertical dashed lines, corresponds to a peak energy of 5.68 GeV. To
131 enable quantitative comparison of spectra in the presence of substantial particle depletion,
132 all energy distributions are normalized to the initial maximum density at $t = 0$ ($9.4 \times$
133 $10^{21} \text{ GeV}^{-1}\text{m}^{-3}$). Figure 2(F) shows the corresponding scaling factors, which increase up
134 to 22 at maximum depletion; at the optimal phase ($t = 33.4 \text{ ps}$), the factor is 10 relative
135 to the initial condition.

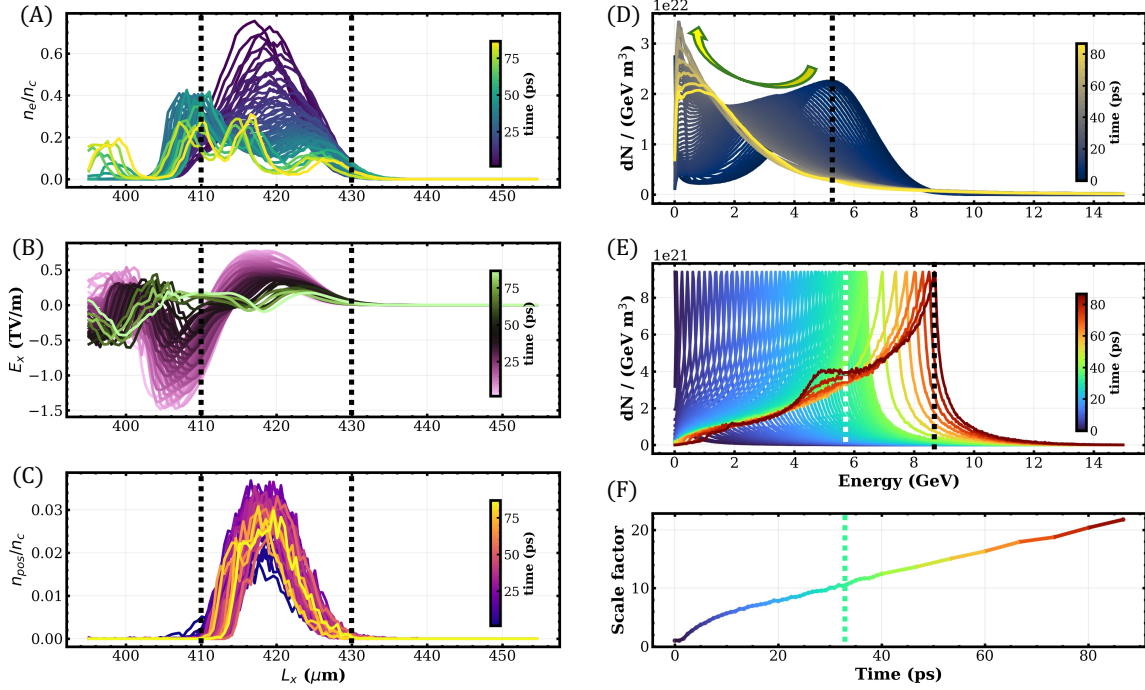


Figure 2: Particle dynamics from PIC simulations. (A) Electron density evolution at $L_y = 0$ over 86.7 ps, showing peak shift ($420 \rightarrow 410 \mu\text{m}$) and structural deformation due to radiation losses. (B) Surface-plasmon-driven wakefield ($\sim 0.5 \text{ TV/m}$) with phase shifts induced by beam spreading. (C) Positron confinement within $410\text{--}430 \mu\text{m}$, achieving $> 95\%$ longitudinal phase capture. (D) Electron spectrum showing progressive energy transfer to the wakefield. (E) Positron acceleration up to 8.68 GeV ; dashed lines mark the optimal (5.68 GeV) and maximum energies. (F) Scaling factors used for spectral normalization to the initial peak density of $9.4 \times 10^{21} \text{ GeV}^{-1} \text{ m}^{-3}$.

2.3 Phase-space cooling and pre-acceleration in longitudinal and transverse directions

We show that the surface-plasmon-driven wakefield sustained in the high-density micro-tube simultaneously provides longitudinal and transverse phase-space cooling of the positron beam while pre-accelerating it to multi-GeV energies. Figure 3 quantifies the positron acceleration dynamics in the micro-tube by showing the evolution of the peak energy, relative energy spread, and peak number density. The peak positron energy increases monotonically from its initial value to 8.68 GeV, while the peak density gradually decreases due to particle depletion, reaching $\sim 1/20$ of its initial value by $t = 86.7$ ps. The relative energy spread initially decreases to a minimum of 10.3% at $t = 33.4$ ps (corresponding to a peak energy of 5.68 GeV), and then broadens to 21.1% at the maximum recorded energy as the electron driver is distorted and the accelerating phase shifts. These trends identify $t \approx 33.4$ ps as an optimal acceleration window, where the positron bunch exhibits pronounced longitudinal phase-space cooling with minimized energy spread and high capture efficiency.

The longitudinal phase space at $t = 3.34$ ps and $t = 33.4$ ps, shown in Figs. 3(B) and 3(C), reveals the interplay between the electron density, radiative wakefield, and positron distribution. At $t = 3.34$ ps, acceleration takes place in a stable locked region (Lock region) extending from 411 to 430 μm (length $\sim 19 \mu\text{m}$), where about 97% of the positrons remain phase-locked and experience longitudinal phase-space cooling, with only a small fraction entering the decelerating Loss region. By $t = 33.4$ ps, the electron driver has elongated due to deceleration, shifting the peak of the accelerating phase while maintaining a nearly constant accelerating-phase length of $\sim 18 \mu\text{m}$ (413–431 μm). Throughout this evolution, more than 95% of the positrons stay in the accelerating phase, keeping the longitudinal phase-loss rate below 5% and demonstrating robust longitudinal phase-space

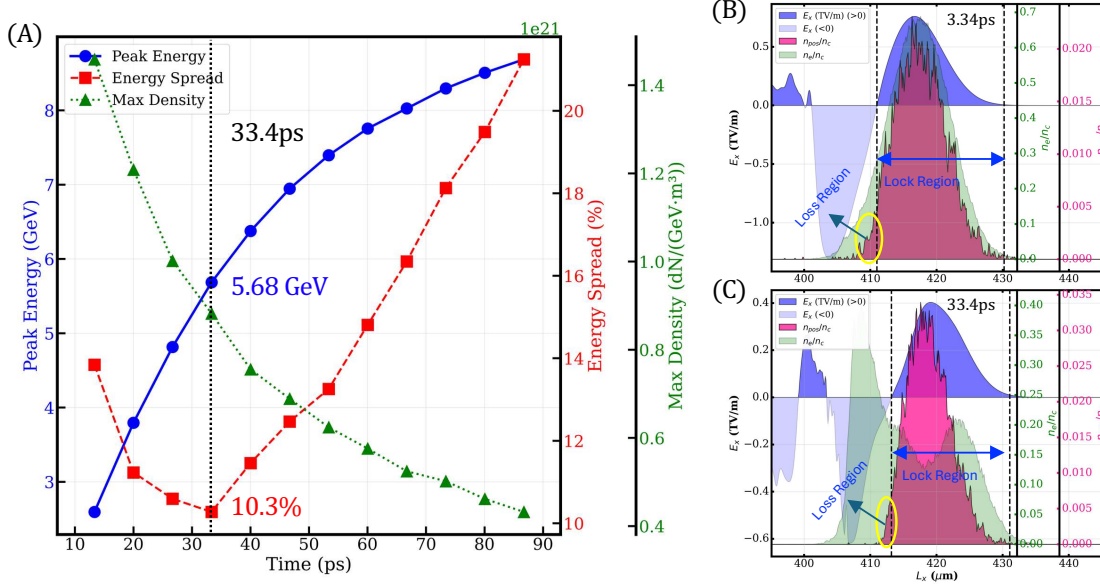


Figure 3: Phase-space cooling and locked acceleration dynamics. (A) Temporal evolution of the positron peak energy, relative energy spread, and maximum number density. At $t = 33.4$ ps, the energy spread reaches a minimum of 10.3% at a peak energy of 5.68 GeV. (B,C) Electron density, accelerating field E_x , and positron phase distribution at $t = 3.34$ ps and $t = 33.4$ ps. The Lock region (accelerating and cooling) and Loss region (decelerating) are highlighted, with the longitudinal phase loss kept below 5%.

cooling in the locked accelerating window.

In the transverse direction, Figure 4 summarizes the evolution of the positron beam and the associated cooling. Panels (A1)–(A4) of Fig. 4 show y – p_y phase-space slices at $t = 6.7, 20, 33.4$, and 86.7 ps. At early times, the distribution forms a left-tilted ellipse with $y > 0, p_y < 0$ and $y < 0, p_y > 0$, indicating a net focusing force toward the axis. As the interaction proceeds, the ellipse straightens and contracts toward $(y, p_y) \approx (0, 0)$: the core becomes compact and nearly circular, while the large-angle halo is progressively removed. At later times, a small quasi-stationary ellipse remains, corresponding to a phase-space-cooled positron core confined by a quasi-static focusing channel.

170 The geometric emittance is defined as $\varepsilon_y = \sqrt{\langle y^2 \rangle \langle \theta_y^2 \rangle - \langle y \theta_y \rangle^2}$, $\theta_y \simeq \frac{p_y}{\sqrt{\langle \gamma \rangle^2 - 1}}$, and for
 171 a highly relativistic beam the corresponding normalized emittance satisfies $\varepsilon_{n,y} \simeq \langle \gamma \rangle \varepsilon_y$.
 172 Figure 4(B) shows the temporal evolution of ε_y for the electron driver and positron
 173 witness. The driver emittance increases from $\lesssim 0.01$ to $\gtrsim 0.13$ mm · mrad, indicating
 174 transverse heating, whereas the positron geometric emittance decreases from ~ 0.06 to
 175 0.007 mm · mrad, nearly an order-of-magnitude reduction that signifies transverse geo-
 176 metric cooling. Over the same interval, the normalized emittance $\varepsilon_{n,y}$ of the positron
 177 beam increases only moderately, from about 60 to 92 mm · mrad as the mean energy rises
 178 from ~ 0.5 to ~ 6.6 GeV, reflecting the rapid growth of $\langle \gamma \rangle$ in the strong accelerating field
 179 rather than an increase of the underlying geometric phase-space area. The rms divergence
 180 σ_{θ_y} in Fig. 4(C) follows the same trend as the geometric emittance: the drive beam is
 181 blown up by energy deposition and the plasma response, while the positrons evolve from
 182 a wide angular spread to an almost sub-mrad, highly collimated beam.

183 Figure 4(D) plots $1/\langle \gamma \rangle$ for electrons and positrons, showing driver deceleration and
 184 sustained positron acceleration. The positron divergence can be approximated as $\sigma_{\theta_y} \simeq$
 185 $\frac{\sigma_{p_y}}{\sqrt{\langle \gamma \rangle^2 - 1}}$, where σ_{p_y} varies only slowly while $\langle \gamma \rangle$ increases rapidly, so that $\sigma_{\theta_y} \propto 1/\gamma$ is
 186 strongly reduced by relativistic angular compression. Together with the decrease of ε_y ,
 187 this shows that both the angular spread and the correlations $\langle y \theta_y \rangle$ and $\langle y^2 \rangle$ are optimized,
 188 indicating genuine transverse phase-space cooling rather than merely a narrower beam
 189 profile.

190 Only positrons that enter the stable accelerating and focusing phase are trapped and
 191 continuously accelerated; large-angle or phase-mismatched particles are scattered and
 192 peeled off, effectively realizing a phase-space filter. This leads to a pronounced reduction
 193 in geometric emittance and rms divergence, demonstrating efficient cooling of the positron
 194 beam in the surface-plasmon-driven wakefield. Longitudinal acceleration remains stable

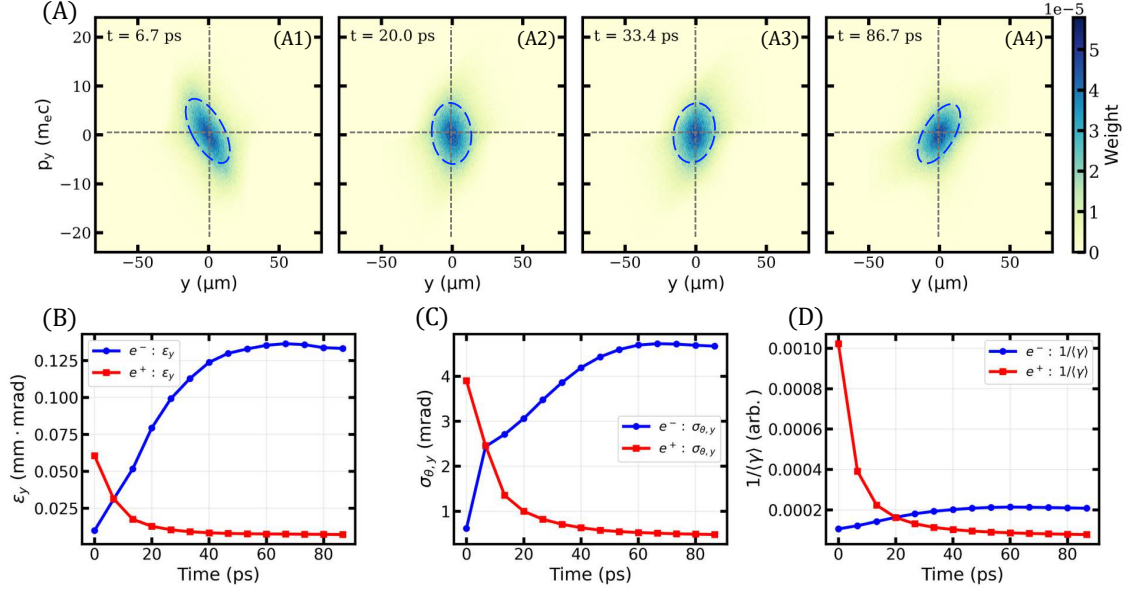


Figure 4: Transverse evolution of the positron beam and cooling mechanism during acceleration. (A) Snapshots of the positron y - p_y phase space at different times. As the beam propagates [panels (A1)–(A4)], the ellipse contracts, the large-angle halo is removed, and the centroid remains near $(y, p_y) \approx (0, 0)$, showing that a cooled positron core is trapped in a stable focusing channel. (B)–(D) Time evolution of (B) the geometric emittance ε_y , (C) the rms divergence $\sigma_{\theta,y}$, and (D) the inverse mean Lorentz factor $1/\langle\gamma\rangle$ for the electron driver and positron witness. The positron beam exhibits strong emittance reduction and divergence shrinking that closely correlate with the increase of $\langle\gamma\rangle$ (decrease of $1/\langle\gamma\rangle$), evidencing relativistic angular compression combined with transverse phase-space cooling.

and continuous, and the focusing field is transversely uniform over $\sim 100 \mu\text{m}$, consistent with Fig. 1(C). Although some particles are lost due to finite focusing strength, the high-density micro-tube provides effective transverse guiding and supports stable acceleration in both longitudinal and transverse directions, realizing simultaneous longitudinal and transverse phase-space cooling in a single compact stage.

3 Stable radiation-wakefield excitation via surface plasmons

3.1 Self-field dynamics of a relativistic e^- beam in a dense plasma micro-tube

Consider a relativistic electron beam propagating along the x -axis in free space, characterized by normalized velocity $\beta_0 = v_x/c$ and density distribution ρ_b . The initial beam current is $J(x, t = 0) = \beta_0 \rho_b$. In the laboratory frame, the electrostatic potential Φ satisfies the relativistic Poisson equation [35]:

$$\left[\frac{1}{\gamma_0^2} \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right] \Phi = -\rho_b, \quad (1)$$

where $\gamma_0 = 1/\sqrt{1 - \beta_0^2}$ is the beam Lorentz factor. The electrostatic potential Φ is computed numerically using a fast Fourier transform (FFT)–based cosine transform, and the electric-field components are then obtained as

$$E_x = -\frac{1}{\gamma_0^2} \frac{\partial \Phi}{\partial x}, E_y = -\frac{\partial \Phi}{\partial y}. \quad (2)$$

Because of the $1/\gamma_0^2$ prefactor, the longitudinal field E_x is much weaker than the transverse field E_y , reflecting the strong relativistic anisotropy of the beam self-fields in free space. The initial electric-field distribution used in our analysis was obtained from PIC simulations performed in cylindrical coordinates with 2D spatial resolution and 3D particle tracking. The Gaussian electron bunch carries a charge of 3.4 nC with Lorentz factor $\gamma_0 \approx 1957$, corresponding to a beam energy of 1 GeV, and has a longitudinal rms length of $\sigma_{xe} = 3.3 \mu\text{m}$ and a transverse rms size of $\sigma_{re} = 26 \mu\text{m}$. Figures 5(A) and 5(B) display the resulting electrostatic field components E_x and E_y , respectively. Within the $50 \mu\text{m}$ -radius plasma micro-tube, the transverse field E_y —reaching approximately 200 GV/m, significantly stronger than that of a static electron bunch—interacts with the inner tube walls. As it penetrates the dense plasma layer, this field decays exponentially (denoted

221 E_{yp}) according to

$$E_{yp} = E_0 \exp \left[-\sqrt{k_x^2 - 1 + \omega_{pe}^2} \delta y \right], \quad (3)$$

222 where $\delta y = y' - r$ is the charge-separation distance, $r = \sqrt{y^2 + z^2}$ is the tube radius, and y'
 223 is the field penetration depth. The plasma frequency $\omega_{pe} = \sqrt{4\pi e^2 \rho / m}$ is approximately
 224 5.6×10^{15} Hz for the given micro-tube density ρ . With the electron-beam length fixed
 225 at $\lambda \sim 7 \mu\text{m}$ and the normalization parameter chosen as $L = (c/\omega_L) \times 10^6 \mu\text{m}$ with
 226 $\omega_L = 2\pi c/\lambda$, a strong charge-separation field E_{cs} emerges, proportional to δy :

$$E_{cs} = \frac{e}{\varepsilon_0} \rho \delta y. \quad (4)$$

227 Figure 5(C) illustrates the interplay between the plasmonic field E_{yp} and the charge-
 228 separation field E_{cs} in the micro-tube. Force equilibrium ($F = 0$) is achieved in the
 229 surface electron layer (at $\delta y = 1.1 \text{ nm}$) when $E_{yp} = E_{cs}$, maximizing momentum transfer
 230 to plasma electrons via surface plasmons. As shown in Fig. 5(D), this balance sustains
 231 collective surface-plasmon oscillations in the inner-wall electron layer. The net force
 232 $F = -e(E_{yp} - E_{cs})$ drives periodic electron motion, in which the nanometer-scale electron
 233 film undergoes push-pull dynamics—alternating between outward ($F > 0$) and inward
 234 ($F < 0$) motion for $y > 0$. This process maintains coherent surface-plasmon waves along
 235 the tube wall, enabling efficient energy transfer and stable radiation-wakefield excitation.

236 3.2 High-gradient wakefield driving via surface-plasmon excitation

237 The net force $F = -e(E_{yp} - E_{cs})$ drives surface-plasmon-mediated oscillations of the
 238 nanometer-scale electron layer ($\delta y = 1.1 \text{ nm}$), where E_{yp} denotes the plasmonic field and
 239 E_{cs} the charge-separation field. Maximum electron energy gain is achieved under force
 240 equilibrium ($F = 0$), corresponding to optimal momentum transfer. The energy acquired

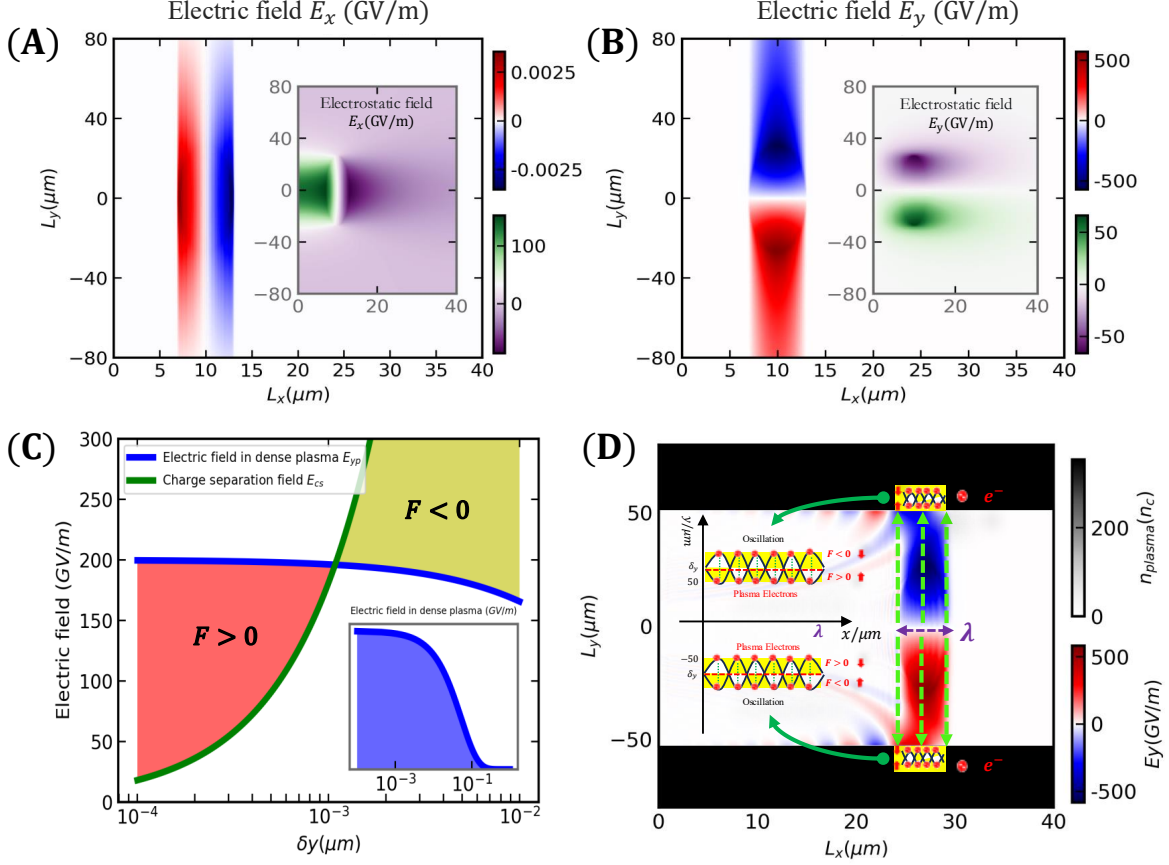


Figure 5: Self-consistent field dynamics in the dense plasma micro-tube. (A) Initial longitudinal electric field E_x of the relativistic electron beam. Subplot shows the corresponding electrostatic field from a static electron beam. (B) Initial transverse electric field E_y . Subplot displays the electrostatic field of a static electron beam for comparison. (C) Field interaction between plasmonic field E_{yp} and charge-separation field E_{cs} . Force equilibrium ($F = 0$) occurs at $\delta y = 1.1$ nm, enabling optimized momentum transfer. (D) Surface-plasmon-driven collective oscillations in the nanometer-scale electron layer (δy) via net force $F = -e(E_{yp} - E_{cs})$, sustaining coherent wave propagation along the tube wall.

241 by plasma electrons is given by

$$\int_0^{\delta y} (eE_{yp} - eE_{cs}) dy = (\gamma_p - 1) m_e c^2, \quad (5)$$

242 where γ_p is the Lorentz factor of plasma electrons and m_e the electron mass. For
 243 $\delta y = 1.1$ nm, we obtain $\gamma_p \simeq 1.0002$ and a corresponding normalized electron velocity
 244 $\beta_p \approx 0.0206$. Figure 6(A) displays the momentum distribution of the oscillating plasma
 245 electrons from PIC simulations, showing a maximum momentum of $\sim 0.016 m_e c$ near
 246 the longitudinal position x_0 of the drive electron beam. As illustrated, only electrons
 247 on the inner surface of the micro-tube gain significant kinetic energy. These collective
 248 oscillations attenuate as the drive beam propagates, leading to a gradual decrease in the
 249 electron velocity.

250 The nanometer-scale electron layer ($\delta y = 1.1$ nm) thus undergoes surface-plasmon-
 251 mediated collective oscillations, emitting phase-coherent radiation through plasmon-electron
 252 energy exchange. The electric field radiated by a single oscillating electron is

$$E_{\text{rad}} = \frac{e}{4\pi\epsilon_0} \left[\frac{\vec{n} \times (\vec{n} \times \dot{\vec{\beta}}_p)}{Rc(1 - \beta_p \cos \theta)^3} \right], \quad (6)$$

253 where $\dot{\vec{\beta}}_p = e\vec{E}/(cm_e\gamma_p^3)$, θ denotes the angle between the observation direction $\vec{n}$ and the
 254 electron velocity vector $\vec{\beta}_p$, and R is the distance from the source to the observation point.
 255 For the collective interaction within the micro-tube, the total radiation field is obtained
 256 by integrating over the three-dimensional electron distribution:

$$E_{\text{rad}}^{\text{tot}} = \int E_{x,\text{rad}} \rho x d\varphi dx dy = \frac{e \dot{\beta}_p \rho \delta y p}{2\epsilon_0 c} \int_0^\theta \frac{\sqrt{1 - \cos^2 \theta} \sin^2 \theta}{(1 - \beta_p \cos \theta)^3 \cos^2 \theta} d\theta, \quad (7)$$

257 where $E_{x,\text{rad}} = E_{\text{rad}} \sin \theta$ is the longitudinal radiation-field component, $p = R \cos \theta$ is the
 258 distance from the reference point to the micro-tube wall, ρ is the electron density, and
 259 $L_y = 50$ μm is the transverse size of the system. Numerical evaluation of Eq. (7) yields

260 $E_{\text{rad}}^{\text{tot}} \approx 38 \text{ GV/m}$ for $p = 1 \text{ }\mu\text{m}$. Notably, increasing the drive-beam charge enhances the
 261 oscillation amplitude, leading to higher acceleration gradients—reaching up to 0.5 TV/m
 262 as shown in Fig. 1(C). Figure 6(B) presents the radiation-field distribution from PIC
 263 simulations at $t = 0.14 \text{ ps}$ and $t = 0.28 \text{ ps}$, illustrating the temporal evolution of the
 264 accelerating structure.

265 The surface-plasmon collective oscillations at the micro-tube interface generate a
 266 transverse-magnetic (TM) radiation mode with wavelength $\lambda \sim 24 \text{ }\mu\text{m}$. This field ex-
 267 hibits characteristic surface-plasmon propagation: longitudinal transmission along the
 268 wall interface combined with exponential decay in the transverse direction. The cylin-
 269 drical symmetry of the micro-tube causes constructive interference of these evanescent
 270 transverse fields on the central axis, producing a strongly enhanced accelerating field.
 271 Key characteristics of this radiation field, including its intensity, wavelength, and depen-
 272 dence on the micro-tube radius, are discussed in detail in Ref. [27].

273 4 Discussions

274 4.1 Transverse off-axis e^+ bunch injection

275 The accelerating wakefield shown in Fig. 1(C) exhibits a nearly uniform transverse dis-
 276 tribution within the micro-channel, forming a stable accelerating phase extending over
 277 $\sim 100 \text{ }\mu\text{m}$. This inherent field uniformity enables substantial tolerance to injection
 278 misalignment, as demonstrated by our systematic study of externally injected positron
 279 bunches. To quantify acceptable misalignment thresholds, we performed two-dimensional
 280 PIC simulations with controlled transverse offsets from the central axis. The simulations
 281 employed a moving window of $204.8 \text{ }\mu\text{m} (L_x) \times 160 \text{ }\mu\text{m} (L_y)$, discretized into 2048×640
 282 cells, with positron bunches injected at $y_0 = 0, 5 \text{ }\mu\text{m}$, and $10 \text{ }\mu\text{m}$ while keeping all other
 283 parameters consistent with the cylindrical-coordinate simulations.

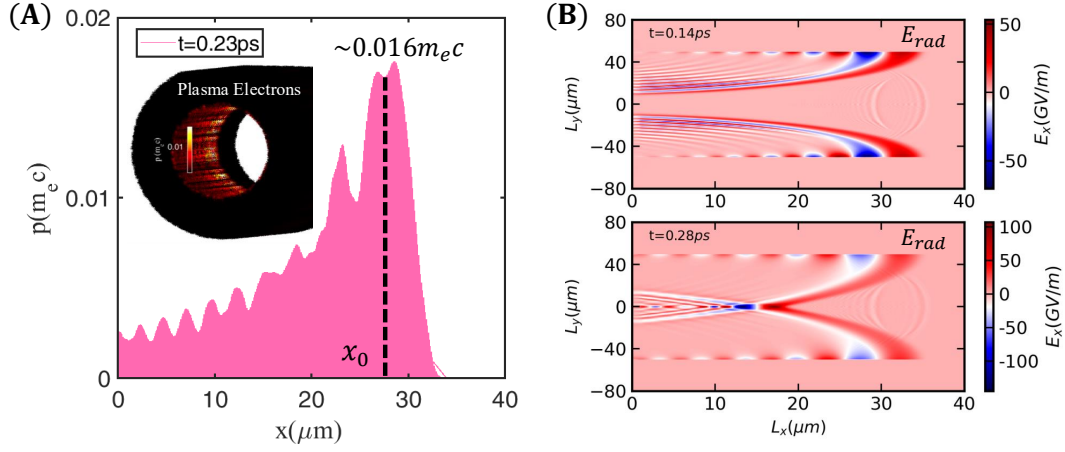


Figure 6: Surface-plasmon-driven radiation fields in the micro-tube. (A) Momentum distribution of plasma electrons showing surface-localized energy gain, with inner-wall electrons reaching $\sim 0.016 m_e c$ (inset: schematic of the excitation process). (B) Evolution of the accelerating field at $t = 0.14 ps$ and $t = 0.28 ps$, exhibiting characteristic surface-plasmon propagation with longitudinal transmission along the wall and transverse evanescent decay. Field superposition on the central axis enhances the amplitude to several tens of GV/m .

Figure 7(A) shows the asymmetric phase-space distribution of a positron bunch injected with a $10\ \mu\text{m}$ transverse offset, in comparison with the symmetric on-axis case. Figure 7(B) presents the corresponding density distributions in the x - y plane after prolonged acceleration. Although the initial injection offset induces a persistent asymmetry during propagation, both the central energy and the energy spread remain largely unchanged, owing to the uniformity of the longitudinal accelerating field. Figure 7(C) systematically compares the energy spectra for different injection offsets ($y_0 = 0, 5\ \mu\text{m}$, and $10\ \mu\text{m}$). While all cases achieve essentially identical final energies for a fixed acceleration duration, the main difference appears in the peak charge density at the central energy, which in turn affects the energy transfer efficiency η . In particular, a $10\ \mu\text{m}$ offset reduces η by approximately 10% relative to perfect on-axis injection. This remarkable tolerance to transverse misalignment significantly relaxes experimental alignment constraints for positron injection.

4.2 Series acceleration of multiple positron bunches

The periodic longitudinal structure of the accelerating wakefield enables simultaneous injection and acceleration of multiple positron bunches. Leveraging the stable surface-plasmon-driven field, we demonstrate a series-acceleration scheme using two-dimensional PIC simulations [Fig. 8(A)]. A single electron beam propagating through the micro-tube excites an accelerating field that concurrently drives three distinct positron bunches—labeled $x_{\text{positron}}^{(1)}$, $x_{\text{positron}}^{(2)}$, and $x_{\text{positron}}^{(3)}$ —initially positioned at $178\ \mu\text{m}$, $156\ \mu\text{m}$, and $126\ \mu\text{m}$, respectively. As shown in Fig. 8(B), all three bunches, starting from an initial energy of 5 GeV, experience substantial energy gain. The energy transfer efficiency in this multi-bunch configuration reaches approximately 2–3 times that of single-bunch acceleration, highlighting the potential of series acceleration in this scheme for significantly

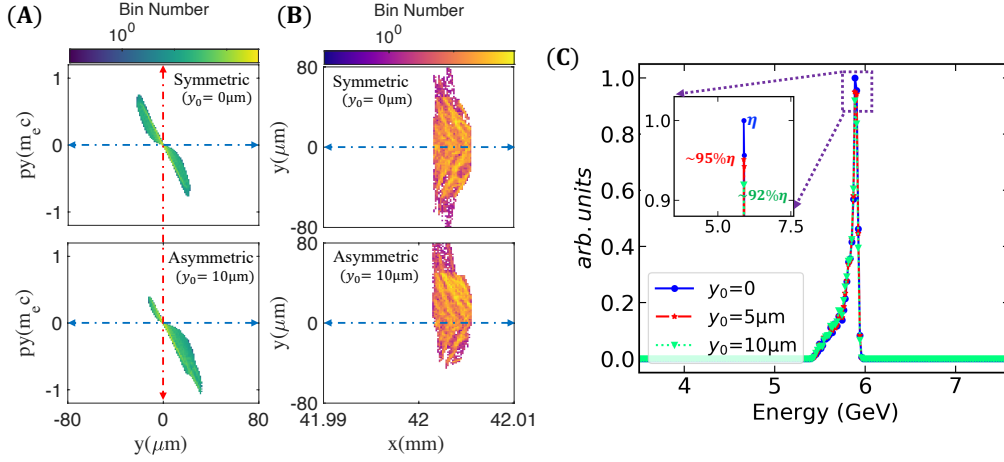


Figure 7: Effects of transverse injection misalignment. (A) Phase-space distributions for on-axis and off-axis ($10 \mu m$ offset) injections. (B) Transverse density profiles after prolonged acceleration. (C) Energy spectra and transfer efficiency η for $y_0 = 0, 5 \mu m$, and $10 \mu m$; a $10 \mu m$ offset reduces η by $\sim 10\%$.

enhancing the overall efficiency of positron beam production and acceleration.

5 Conclusion

In summary, we have proposed and numerically demonstrated an integrated positron acceleration scheme that achieves simultaneous longitudinal and transverse phase-space cooling together with stable pre-acceleration by means of surface-plasmon-driven wakefields in a dense plasma micro-tube. The configuration generates a quasi-uniform accelerating and focusing region spanning approximately $100 \mu m$ transversely and $20 \mu m$ longitudinally, enabling efficient positron capture with more than 95% longitudinal phase matching and less than 5% particle loss. By jointly optimizing positron generation and wakefield-acceleration dynamics, the scheme produces high-quality positron beams reaching a peak energy of 5.68 GeV with an energy spread compressed to 10.3% at the optimal

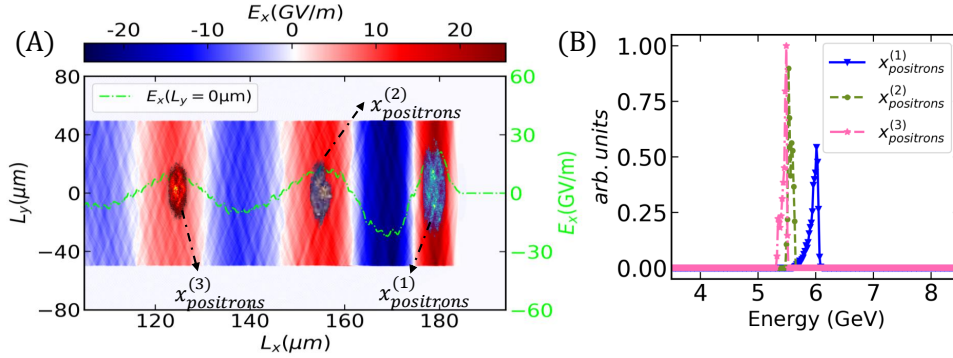


Figure 8: Series acceleration of multiple positron bunches. (A) Surface-plasmon-driven wakefield excited by a single electron beam simultaneously accelerates three positron bunches initially positioned at $178 \mu\text{m}$, $156 \mu\text{m}$, and $126 \mu\text{m}$. (B) Resulting energy spectrum after acceleration, showing significant energy gain for all three bunches and an overall enhancement in energy transfer efficiency.

acceleration window ($t = 33.4 \text{ ps}$), accompanied by a pronounced reduction in transverse emittance and divergence. The system exhibits strong robustness, maintaining stable acceleration under transverse injection misalignments up to $10 \mu\text{m}$ and achieving a factor-of-2–3 enhancement in energy-transfer efficiency in multi-bunch operation compared with the single-bunch case. This compact surface-plasmon wakefield cooling platform effectively addresses key limitations of conventional positron sources—such as bulky beamlines and insufficient beam brightness—and establishes a viable pathway toward next-generation high-brightness positron injectors for future colliders and advanced radiation sources.

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