Review

Laser-driven electron beam and radiation sources for basic, medical and industrial sciences

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Abstract: To date active research on laser-driven plasma-based accelerators have achieved great progress on production of high-energy, high-quality electron and photon beams in a compact scale. Such laser plasma accelerators have been envisaged bringing a wide range of applications in basic, medical and industrial sciences. Here inheriting the groundbreaker’s review article on “Laser Acceleration and its future” [Toshiki Tajima, (2010)]1) we would like to review recent progress of producing such electron beams due to relativistic laser-plasma interactions followed by laser wakefield acceleration and lead to the scaling formulas that are useful to design laser plasma accelerators with controllability of beam energy and charge. Lastly specific examples of such laser-driven electron/photon beam sources are illustrated.

Keywords: laser plasma accelerators, relativistic laser plasma interaction, laser wakefield acceleration, electron and photon beams

1. Introduction

The exploration searching for the origin of matter and universe requires producing the highest energy state to investigate nature on the smallest scale, which is composed of the fundamental particles and forces. In this research direction, particle accelerators have played a main role of tools as microscopes to study the smallest world of nature, of which the size can be seen into nearly one-trillionth micron with the present high-energy frontier colliders producing the center-of-mass energy of 100 GeV. To date we are launching forth into a new energy regime of TeV-PeV. On the other hand, high energy electron accelerators with GeV beam energies have been utilized as synchrotron light sources generating short wavelength radiations in a wide range of sciences, such as material, chemical, biological, medical and industrial sciences. Intermediate energy hadron accelerators are indispensable in therapy of cancers as a successful medical application.

As mentioned by Tajima,1) taking the demise of the Superconducting Super Collider (SSC) as an example, we might have a long-standing feeling2) that the state-of-the-art high-energy accelerators become too large and costly, and possibly they approach the end of the road. To date high energy accelerators are based on high power RF technologies that accelerate charged particles with electric fields up to 100 MV/m at most, which is a limit stably produced in metallic, electromagnetic cavities due to electrical surface heating and breakdown. As illustrated with the Large Hadron Collider (LHC)3) and the future linear collider4) beyond the TeV energy range, the overall accelerator complex will range over several tens kilometer size and amount to enormous expenditure to be built. A remarkable scaling-down of high-energy accelerators may be simply brought through by using much higher accelerating fields than the present limits. In this context various novel concepts of charged particle accelerators that utilize super-high fields of lasers and plasmas have been proposed for the past years since the dawn of the laser evolution in the early 1960s.5)

The most prominent feature of laser acceleration is attributed to exploiting ultrahigh fields, which is characterized by the laser strength parameter \( a_0 \), where \( a_0 = eA_0/me^2 \) is the normalized peak ampli-
tude of vector potential $A_0$ with respect to the electron rest energy $m_e c^2$ with electron charge $e$ and vacuum speed of light $c$. For a linearly polarized laser pulse, the normalized vector potential is given by

$$a_0 = \left( \frac{2e^2 \lambda_L^2 I_L}{m_e c^5} \right)^{1/2} \approx 0.855 \times 10^{-9} I_L^{1/2} \lambda_L,$$

where $I_L$ is a peak intensity of the laser pulse in a unit of W/cm² and $\lambda_L = 2\pi c/\omega_L$ is the laser wavelength in a unit of μm with frequency $\omega_L$. The corresponding amplitude of the transverse electric field becomes $E_L[TV/m] \approx 3.2a_0/\lambda_L \approx 2.7 \times 10^{-9} I_L^{1/2}$. Considering the electron motion in a plane wave laser field, since the electron transverse momentum is given by $p_{\perp} = (m_e c^2) \gamma_e \beta_{\perp} = eA_0/(m_e c^2) = a_0$, where $\beta_{\perp} = v_{\perp}/c$ and $\gamma_e = E_z/(m_e c^2)$, the transverse motion of an electron becomes relativistic at $a_0 \sim 1$, correspondingly $E_z \sim 3 TV/m$ for $\lambda_L = 1 \mu m$ and $I_L \sim 1.4 \times 10^{18} W/cm^2$.

Particle acceleration in vacuum can eliminate the difficulties associated with gas and plasmas where the accelerating field is limited due to the gas breakdown and the plasma wave-breaking besides suffering from beam-gas and plasma collisions and laser-plasma instabilities. A major shortcoming of laser-vacuum acceleration is attributed to the phase velocity of the electric field in the accelerated direction of particles greater than the vacuum speed of light $c$ for a focused laser beam. Consider the electric field of the Hermite-Gaussian TEM$_{00}$ mode, assuming the propagation of a nearly plane wave. Since a Gaussian laser field propagating in the z direction is transversely bounded, the finite longitudinal component of the electric field is obtained as $E_z = -(1/ik_L) \nabla_\perp \cdot E_z$ that can accelerate electrons in the z direction, where $k_L$ is the laser wavenumber. The phase velocity of the electric field along the propagation axis is given by

$$v_{ph} = c \left[ 1 - \frac{l + m + 1}{k_L Z_R(1 + z^2/Z_R^2)} \right]^{-1} \gg c,$$

where $Z_R = \pi r_l^2/\lambda_L$ is the Rayleigh length, $r_L$ the minimum spot radius at focus, $\lambda_L = 2\pi/k_L$ the laser wavelength, $\omega_L = c k_L$ the frequency. Therefore relativistic electrons with the longitudinal velocity $v_z \simeq c$ will slip in phase with respect to the accelerating field $E_z$ and eventually decelerate. Acceleration only occurs over a slippage distance $Z_s \simeq \pi Z_R$. If a highly relativistic electron interacts over an infinite region ($z = -\infty$ to $\infty$), a net energy gain is zero resulting from deceleration canceling out acceleration. This is pointed out by the Lawson-Woodward theorem assuming that the region of interaction is infinite, no static electric or magnetic field is present, and nonlinear effects (e.g., ponderomotive, and radiation reaction forces) are neglected. In order to make a nonzero net energy gain, one or more of these assumptions must be violated.

A number of laser acceleration concepts in vacuum have been proposed by the use of a finite interaction geometry, the external fields, and the ponderomotive force to overcome the Lawson-Woodward theorem. As the relativistic strong laser field of $a_0 \gg 1$ increases, the longitudinal accelerating force exerted on an electron is proportional to $a_0^2$, whereas the transverse quivering force is just linearly proportional to $a_0$. This is the essence of the relativistic ponderomotive acceleration that dominantly produces energetic particles in the direct interaction of ultraintense laser fields with particle beams and plasma. The research on electron acceleration in vacuum by a relativistic laser ponderomotive force has made great progress in recent years both theoretically and experimentally. Masuda et al. find that the electron scattering can be suppressed by the longitudinal components of the TEM$_{00}$ mode when the laser pulse is tightly focused to a small spot size comparable to the laser wavelength, while if the longitudinal components are ignored, electrons are never focused even for higher order modes. The trapping effect by the higher order mode comes partially from the existence of the longitudinal field. As a result of optimizing a focusing spot size, the normalized energy gain of accelerated electrons with the initial normalized energy $\gamma_0$ can be given by $\Delta \gamma_f \approx 3\gamma_0 a_0^2/8$. The numerical simulations imply that the relativistic ponderomotive acceleration can produce high quality electron bunches characterized by an extremely short bunch duration of sub-femtosecond, the energy spread less than 1%, and the normalized transverse emittance less than 10 mm mrad. Although experimental tests on vacuum laser acceleration concepts are a proof-of-principle stage, recently some promising results have been obtained from the inverse free electron laser (IFEL) concept. Kimura et al. demonstrated mono energetic laser acceleration of trapped microbunch electrons for the first time by using a staged IFEL scheme consisting of two undulators, a phase control chicane and a 200 MW CO₂ laser of 10.6 μm wavelength at the BNL-ATF. In this experiment, the first IFEL is used to create microbunches, which are accelerated by a second IFEL using a tapered undulator. They successfully produced a high quality...
microbunch electron beam with the net energy gain of $>7\,\text{MeV}$, the r.m.s. energy width of $\sim 0.36\%$ and the microbunch length of $1\,\mu\text{m}$.

Laser-driven plasma-based electron accelerators have been evolving from a groundbreaking concept by Tajima and Dawson$^{17}$ into the reality of the next generation particle accelerator technologies. Relativistic electron beams from ultraintense laser plasma interactions can be conceived to be compact particle accelerators, inspiring a wide range of applications of unique particle beam and radiation sources as well as downsizing large-scale particle accelerators such as radiation sources of THz$^{18}$, betatron X-ray radiation$^{19}$, X-ray free electron lasers$^{20,21}$ and high-energy frontier colliders$^{22,23}$, some of which have been illustrated in the review article of this Journal.$^1$ In fact there has been significant experimental progress in laser wakefield acceleration of electron beams since the incipient experiments have successfully demonstrated ultrahigh gradient acceleration of the order of $100\,\text{GeV}/\mu\text{m}$, using chirped pulse amplification lasers with $10\,-\,\text{TW}$ class peak power and $1\,-\,\text{ps}$ pulse duration.$^{24,25}$ Such experiments are characterized in terms of the self-modulated wakefield regime,$^{26}$ where laser power should be higher than the critical power for relativistic self-focusing and the laser pulse duration is longer than the plasma period. In this regime, the laser pulse undergoes temporal intensity modulation and self-guiding through nonlinear interactions with plasma so that large-amplitude plasma waves are resonantly excited. Ultimately their wave-breaking occurs, generating relativistic electrons to be randomly trapped and accelerated by the wakefield throughout acceleration distances. Therefore, electron beams produced from single stage rude experiments showed the energy spectra with $100\%$ energy spread, as characterized by Maxwellian distribution with the highest energy tail reaching at most $100\,\text{MeV}$.$^{27}$ The energy gain of accelerated electrons may be determined by the acceleration distance that are restricted due to dephasing of electrons with respect to the correct acceleration phase of the wakefield and depletion of the laser pulse energy. For most experiments using a supersonic gas jet, the acceleration distance extends only to a few mm so that the energy gain has been limited to the order of $200\,\text{MeV}$.$^{28}$

For many practical applications of electron beams, the quality, stability and controllability in the beam performance such as energy, energy spread, emittance and charge are indispensable in addition to compact and robust features of accelerators. In this sense, breakthrough experiments$^{29-31}$ have been carried out for producing high-quality electron beams, so-called quasi-monoenergetic beams with ultra-short pulse, small energy spread and low emittance. Quasi-monoenergetic electron beams have been obtained from the use of ultrashort laser pulses with duration of the order of several tens femtoseconds and controlling plasma density precisely to make the dephasing length long enough to exceed the acceleration distance. Under these conditions, once plasma electrons expelled by the ponderomotive force (radiation pressure) of the laser pulse form a plasma cavity called as a “bubble”,$^{32}$ then some of them are self-injected into the wakefield by wavebreaking or restoring force exerted from an ion channel remaining unshielded behind the laser pulse. As a result of beam-loading trapped electrons the nonlinear wakefield amplitude inside the bubble is reduced below the trapping threshold. Consequently electrons trapped in the wakefield undergo the processes of acceleration and bunching to increase their energy and brightness unless the acceleration distance exceeds the dephasing length. This is a scenario of quasi-monoenergetic electron beam acceleration, based on the self-injection mechanism in the bubble regime that is visually shown by multi-dimensional particle-in-cell (PIC) simulations.$^{33,34}$ Since quasi-monoenergetic production of electron beams, experimental research on laser plasma acceleration has achieved high-energy, high-quality electron beams with energies beyond $1\,\text{GeV}$ in a cm-scale plasma$^{35-40}$ and qualities of a $1\%$-level energy spread,$^{41,42}$ a $1\,-\,\text{mm}$-rad-level transverse emittance,$^{43}$ and a $1\,-\,\text{fs}$-level bunch duration,$^{44}$ ensuring that the stability of reproduction is as high as that of present high-power ultra-short-pulse lasers.$^{45,46}$

In the preceding review article$^1$ on laser wakefield acceleration, a plain explanation for generation and particle acceleration by laser wakefields has been given, based on an analogical one-dimensional plasma wave model. Here Sec. II mentions recent progress in understanding the production of high-energy, high-quality electron beams through relativistic laser-plasma interactions. Sec. III illustrates various examples of laser-plasma accelerator-based applications. Sec. IV addresses discussions and conclusions as a summary.

2. Nonlinear laser wakefields in the bubble regime

Wakefield excitation by relativistic laser pulses in plasma. Laser wakefield accelerators are operated in underdense plasma of which the electron
plasma frequency is given by $\omega_p = (4\pi e^2 n_e/m_e)^{1/2}$ with electron density $n_e \ll n_i$, where $n_e = \pi/(r_e^2 \lambda_p^2)$ is the critical plasma density for laser wavelength $\lambda_p$ and $r_e = e^2/m_e c^2$ the classical electron radius. In this condition, laser pulses propagates through plasma at the linear group velocity given by $v_g = c(1 - \omega_p^2/\omega_L^2)^{1/2}$ for $\theta_0 \ll 1$.

Most of acceleration experiments that demonstrated the production of quasi-monoenergetic electron beams with narrow energy spread have been elucidated in terms of self-injection and acceleration of electrons in the bubble (or blowout) regime.\(^{33,34}\) In this regime, plasma electrons are expelled outward by the radiation pressure of the laser pulse forming a bubble, which is a cavitation of plasma electrons comprising a channel of unshielded ions surrounded with a narrow plasma electron sheath and the outer region of periodic plasma waves having the weak density perturbation. At the bubble boundary that is the trajectory of the innermost plasma electron, $r_B(\xi)$, where $\xi = ct - z$, the electron density rises from 0 to a large value in an infinitesimally short distance $\delta r_B \to 0$. Assuming azimuthal symmetry, the equation of motion for a plasma electron at the bubble boundary $r_B(\xi)$ can be written as\(^{37}\)

$$
\left( r_B + \frac{4}{k^2 r_B} \right) \frac{d^2 r_B}{d\xi^2} + \left( \frac{dr_B}{d\xi} \right)^2 + 2 \approx - \frac{a^2}{2} + \frac{1}{k^2 r_B^2} \frac{d|a|^2}{dr}, \tag{3}
$$

where $a(r, \xi)$ is the normalized laser field. Around $k r_B \sim 2$ and $\xi \gg c \tau_L$, where the driving term on the right-hand side is negligible, the equation of the boundary approximately meets the equation for a circle

$$
r_B \frac{d^2 r_B}{d\xi^2} + \left( \frac{dr_B}{d\xi} \right)^2 + 1 \approx 0. \tag{4}
$$

One can consider the fields inside a spherical electron cavity of radius $R_B$ moving in plasma with the relativistic velocity $v_B \approx c$ along $x$-axis, where $v_B$ is the bubble velocity, assuming that the ion dynamics is neglected, i.e., $R_B \ll c/\omega_{pi}$, where $\omega_{pi} = (4\pi e^2 n_i/m_i)^{1/2}$ is the ion plasma frequency with ion mass $m_i$ and ion density $n_i$. Inside the cavity with the electron density $n_e = 0$ and the normalized vector potential $a_x = eA_x/(m_e c^2) = 0$, the normalized wakefield potential $\Phi = a_x - e\phi/(m_e c^2)$ is given by the spherical symmetric solution of the equation $\Delta \Phi = -r^{-2}\partial_r \left( r^3 \partial_r \Phi \right) = 3k^2/2$ as $\Phi = 1 - k^2 p^2 (R_B - r^2)/4$ and $a_x = -e\phi/m_e c^2 = \Phi/2$ with $\Phi(R_B) = 1$, where $r^2 = \zeta^2 + y^2 + z^2$ and $\zeta = x - v_B t$.\(^{33}\) Accordingly, the electromagnetic fields inside the relativistic cavity are obtained from $E = -\nabla \phi - (1/c)\partial_t A$ and $B = \nabla \times A$ as $eE_x/(m_e \omega_p) = \partial_t \Phi = \zeta/2$; $eB_z/(m_e \omega_p) = 0$; $eE_z/(m_e \omega_p) = -eB_z/(m_e \omega_p) = \partial_z \Phi/2 = k_B y/4$; $eE_x/(m_e \omega_p) = eB_y/(m_e \omega_p) = \partial_z \Phi/2 = k_B z/4$. The Lorentz force acting of a relativistic electron with $v_e = c$ inside the cavity is given by

$$
\mathbf{F} = -e\mathbf{E} - (e/c)\mathbf{v} \times \mathbf{B}
$$

where $v_x = v_B = c$, while it is zero for the electron with $v_x = -c$, because of the relativistic compensation of the electrostatic force by the self-magnetic force.

At the beginning of the interaction, as there is no electron bunch inside, the cavity shape is determined by balancing the Lorentz force of the ion sphere exerted on the electron sheath containing a return current carried by weakly relativistic electrons with the ponderomotive force of the laser pulse, which causes a slow drift toward the low intensity region in the averaged motion of an electron. The transverse radius $R_y$ of the cavity at the center of the circularly polarized laser pulse is approximately estimated from the equation $k_B R_y/4 \approx -\partial_{R_B}[1 + c^2(\partial_R)/k_B]$. For $a_0^2 \gg 4$, the PIC simulations\(^{47}\) give $k_B R_y \sim k_p r_L \approx 2a_0$, as shown in Fig. 1(a). Thus, the maximum accelerating field $E_{max}$ can be estimated to be

$$
E_{max}/E_0 = (1/2)\alpha_c k_p R_B \approx \alpha_c \sqrt{a_0}, \tag{6}
$$

where $E_0 = m_e \omega_p/\epsilon \approx 96 \text{ [GV/m]} (n_e/10^{18} \text{ [cm}^{-3}])^{1/2}$ is the non-relativistic wave-breaking field and $\alpha_c$ represents a factor taking into account the accelerating field reduction due to beam loading.

**Injection of electrons into the plasma bubble.** An intense laser pulse propagating in plasma expels electrons due to its ponderomotive force and forms a narrow electron sheath surrounding a plasma cavity behind the pulse. Consider the injection of electrons into nonlinear wavefields in the bubble (the first period of the wake). The self-injection of electrons in a bubble wake can be analytically investigated by solving the equations of the electron motion inside the spherical bubble with radius $R_B$:\(^{48}\)
Fig. 1. (a) Electron density distribution obtained the 2-D PIC simulation for nonlinear laser wake in the bubble regime at plasma density $n_e = 2 \times 10^{19} \text{cm}^{-3}$ (plasma wavelength $\lambda_p = 23.6 \mu\text{m}$) when being driven by the laser pulse propagating from the left to the right at wavelength $\lambda_L = 0.8 \mu\text{m}$, normalized potential $\psi_0 = 4$, duration $\tau_L = 27 \text{fs}$ and spot radius $r_0 = 15 \mu\text{m}$, which is matched to a spherical cavity condition $k_pR_B \sim k_p r_0 \approx 2a_b^{1/2}$ as shown by a dotted circle. (b) Trajectories of the trapped (track 1) and untrapped (track 2 and 3) in the bubble moving to the right with the relativistic factor $\gamma_B = 4$, radius $R_B = 8$, electron sheath thickness $d = 0.3$. All trajectories have the initial momentum $p = 0$.

\[
dp_x/dt = -\zeta(1 + \gamma_B)f(r)/4 + yp_yf(r)/(4\gamma),
\]
\[
dp_y/dt = -(1 + p_x/\gamma)yf(r)/4,
\]
\[
d\zeta/dt = p_x/\gamma - v_B, \quad \text{and} \quad dp_y/dt = p_y/\gamma, \quad [7]
\]
where $\zeta = x - v_B t$, $v_B = v_B e_z \approx e_c$, is the bubble velocity, $\gamma^2 = 1 + p_x^2 + p_y^2$, and $\zeta^2 = \zeta^2 + y^2 + z^2$. The screen effect of an electron shear around the bubble is taken into account by $f(r) = \left(1/2\right)\left[1 + \tanh\left(R_B - vr \right)/d \right]$, where $d$ is the width of the electron sheath. Here all variables are denoted by dimensionless units, normalizing the time to $\omega_p^{-1}$, the length to $e/\omega_p = 1/k_p$, the velocity to $c$, the electromagnetic fields to $m_e\omega_p/e$, and the electron density $n$ to $n_e$, where $n_e$ is the background plasma density.

The trajectories of electrons can be shown by the numerical solution of the coupled equations Eq. [7] for the initially static ($p = 0$) electron, located at the bubble border ($y \approx R_B$) at $t = 0$, as shown in Fig. 1(b). The analysis for the electron capture in the bubble results in $R_B \geq 2^{1/2}\gamma_B$ with $\gamma_B = (1 - \gamma_B^2)^{-1/2}$, corresponding to the maximum accelerating field $E_{z,\text{max}}/E_0 \geq 2^{-1/2}\gamma_B$. Assuming the bubble radius $R_B \approx 2a_b^{1/2}$, the electron trapping threshold is obtained as $a_{th} \geq \gamma_B^2/2$. In the numerical solutions shown by Fig. 1(b), the trajectory 1 satisfies the trapping condition $R_B = 8 > 2^{1/2}\gamma_B \approx 5.7$ for the sheath thickness $d = 0.3$ and the initial position $y = 5$. However, the bubble model assuming a uniform sheath thickness may give an overestimate of the trapping threshold.

Although the self-injection is a robust method relying on self-focusing, self-compression of the laser pulse and expansion of the bubble\(^{49}\) that occur during the propagation of relativistic laser pulses, initially heated (accelerated) electrons with large transverse momentum are injected into nonlinear wakefields that excite betatron oscillation of accelerated electrons due to strong focusing field. Hence, in case the self-injection and the deterioration of beam qualities are suppressed, high-quality electron beams can be produced by various controlled injection schemes such as colliding optical injection\(^{50,51}\) density-transition injection\(^{52}\) or density down-ramp\(^{53}\) and ionization-induced injection.\(^{54-56}\)

**Acceleration of electrons in the plasma bubble.** Electron density in the sheath strongly peaks and spiky accelerating field emerges at the back of a plasma cavity so that electrons at that portion are accelerated by the strong longitudinal wakefield and get trapped into the plasma cavity when the electron velocity exceeds the bubble phase velocity $v_B$. Once an electron bunch is trapped in the bubble, loading of trapped electrons reduces the wakefield amplitude below the trapping threshold and stops further injection. Consequently the trapped electrons undergo acceleration and bunching process within a separatrix on the phase space of the wakefield. This is a simple scenario for producing quasi-monoenergetic electron beams in the bubble regime. The equations of longitudinal motion of a trapped electron are approximately written as\(^{57}\)

\[
dE_z/dx = (1/2) m_e c^2 \alpha_c k_p^2 (R_B - \xi), \quad \text{and}
\]
\[
d\xi/dx \approx 1 - v_B/c \approx 3\omega_p^2/(2\omega_L^2), \quad [8]
\]
where $\xi = x - vt_B$ ($0 \leq \xi \leq R_B$) is the longitudinal coordinate of the bubble frame moving at the velocity...
$v_B$ and $v_e = \text{d}x/\text{d}t$ is the longitudinal electron velocity. The bubble velocity is given by $v_B \approx v_g - v_{tech} \approx c[1 - (1/2 + 1)\omega_B^2/\omega_0^2]$, where $v_g$ is the group velocity of the laser pulse in uniform plasma and $v_{tech} \sim c\alpha_e^2/\omega_0^2$ is the velocity at which the laser front etches back due to the local pump depletion.\(^{34}\)

Integrating Eq. [8], the energy and phase of the electron can be calculated as

$$E_b(x) = E_i + (1/3)m_ec^2\alpha_e^2\gamma_g^2k_p^2R_B(1 - \xi/2R_B)$$

and

$$\xi = 3x/(2\gamma_g^2),$$

where $E_i$ is the injection energy and $\gamma_g = (1 - v_g^2/c^2)^{-1/2} = \omega_L/\omega_p = (n_e/n_c)^{1/2}$ is the relativistic factor for the group velocity. Hence, the maximum energy gain is obtained at $\xi = R_B$ as

$$\Delta E_b = E_f - E_i \approx (1/6)m_e c^2 \alpha_e^2 \gamma_g^2 p k_p^2 R_B$$

$$\approx (2/3)m_e c^2 \alpha_e^2 a_{01} (n_e/n_c).$$

Thus, the dephasing length $L_{dp}$ is given by

$$k_p L_{dp} \approx (2/3)k_p R_B \gamma_g^2 = (4/3)a_{01}^{1/2} (n_e/n_c).$$

In order to reach the maximum energy gain and high-quality beam with small energy spread, the dephasing length should be less than the pump depletion length due to pulse-front erosion, i.e., $L_{dp} \sim \sigma_T n_e/n_c \geq L_{dp}$. Therefore, the pulse length is set to be $\sigma_T \geq (2/3\pi)a_{01}^{1/2}\lambda_p$.

The abovementioned injection schemes provide us with high-quality electron beam injectors for a front end of multi-staged high-energy accelerators such as a multi-GeV laser plasma accelerator for compact X-ray FELs,\(^{20,21,58}\) a 100 GeV large-scale laser plasma acceleration experiment,\(^{57}\) TeV-range laser plasma colliders.\(^{21,23}\) As a simplest case, two laser-plasma acceleration has been successfully demonstrated in combination with ionization-induced injection.\(^{59,60}\)

**Beam loading of electrons.** In laser wakefield acceleration, an accelerated electron beam induces its own wakefield and cancels the laser-driven wakefield. Assuming the beam loading efficiency $\eta_b \equiv 1 - E_z^2/E_M^2$ defined by the fraction of the plasma wave energy absorbed by particles of the bunch with the rms radius $\sigma_b$, the beam-loaded field is given by $E_z = (1 - \eta_b)^{1/2}E_M = \alpha_c E_M$, where $E_M$ is the accelerating field without beam loading, given by $E_M \approx a_{01}^{1/2}E_0$ for the bubble regime $a_0 \geq 2$. Thus, a loaded charge is calculated as

$$Q_b \equiv (4k_L r_c/e)^{-1}\eta_b(1 - \eta_b)^{-1}k_p^2\sigma_b^2(E_z/E_0)(n_e/n_c)^{1/2}$$

$$\approx 76\ \text{[pC]}(1 - \alpha_c^2)\alpha_e^4 a_{01}^{1/2}k_p^2\sigma_b^2n_e^{1/2},$$

denoting $n_{18} \equiv n_e/10^{18} \ \text{[cm}^{-3}]$. The field reduction factor $\alpha_e$ for the accelerating charge $Q_b$ in the operating plasma density $n_e$ is obtained from solving the equation $\alpha_e^2 + B_0\alpha_e - 1 = 0$, where the coefficient $B$ is defined as $B = 0.013(a_{01}^{1/2}k_p^2\sigma_b^2)^{-1}Q_b[pC]n_{18}^{1/2}$. Thus, the field reduction factor is obtained by $\alpha_e = B[1 + 4B^{-2}]^{1/2} - 1)/2$. For $B \ll 1$, the field reduction factor becomes $\alpha_e \approx 1$ and contrarily for $B \gg 1$, $\alpha_e \approx 0$.

**Laser wakefield acceleration experiments.** To date most of experiments on laser plasma accelerators have been carried out by employing ultrashort pulse lasers with duration $\tau_0 = 30–80\text{fs}$, focused onto a short-scale plasma target such as a mm-scale gas jet and a cm-scale plasma channel at plasma densities in the range of $n_e = 10^{18}–10^{19}\text{cm}^{-3}$, where very large amplitude plasma waves of the order of 100 GV/m are excited and trap energetic electrons to be efficiently accelerated in a wake to high-energies of the order of 1 GeV. Here we overview the experiments on laser wakefield acceleration from methodological point of view in optical guiding, characterized as self-guiding and channel-guiding.

**Self-guided laser wakefield accelerators.** The self-guiding of relativistically intense ($a_0 \geq 1$) ultrashort (c$\tau_L \simeq \lambda_p$) laser pulses has been experimentally investigated in the blowout (bubble) regime. When such a laser pulse with power $P > P_c$ enters an under dense plasma ($\omega_p < \omega_L$), the plasma electrons at the head of the pulse are completely blown out radially during the rise time of the pulse in the first plasma period. Most of the laser pulse resides inside the electron density depression and thereby can be guided. However, due to the inertia of the electrons, the density or refractive index channel forms on a longitudinal scale length of the order of a plasma skin depth $c/\omega_p$. Hence, the very front of the laser pulse continuously erodes away due to diffraction so that the degree of guiding the remaining pulse is varying along the laser pulse.\(^{61}\) An estimate of the erosion rate is equated as $c/\omega_p$ per the Rayleigh length $Z_R$ which would limit the distance over which such an ultrashort pulse can be self-guided to a few Rayleigh lengths. However, when the spot radius is matched to the bubble radius $R_B$ so that $r_L \approx r_m \approx R_B \approx 2a_{01}^{1/2}/k_p$, in spite of diffractive erosion, self-guiding and wake excitation is possible over tens of $Z_R$ in the blowout regime.\(^{47}\) For $P/P_c > 1$ and $r_L > r_m$, the spot size will converge to (and remain at) a matched spot radius $r_m$.\(^{62}\) Where diffraction at the head of the laser pulse is minimized. As $r_L$ is reduced from the matched spot size, diffraction loss tends to increase.
As a matched laser pulse with $a_0 \geq 2$ propagate through the plasma, the front of the laser pulse locally pump depletes as the wake is excited, causing photons to shift to longer wavelength. These frequency downshifted photons slip back due to dispersion with a velocity $v_{\text{wake}} = c\omega_0^2/\omega_L^2$ into the wake where the transverse density depression is sufficient for guiding them. As a result, to the first order, the nonlinear pump depletion length is given by $L_{\text{rd}} = (c\tau_L)c/v_{\text{wake}} \approx (c\tau_L)\omega_0^2/\omega_L^2 = (c\tau_L) n_e/n_{e_c}$. Beyond the pump depletion limit, the pulse is so severely etched that it is no longer intense enough to excite a wake and thereby no longer guided.

**Channel-guided laser wakefield accelerators.** For guiding intense laser pulses over many Rayleigh lengths without diffraction that limits the accelerator distance to a few mm in a uniform plasma, a preformed plasma density channel with a parabolic radial distribution has been developed. Plasma waveguides for guiding ultraintense short laser pulses in plasmas are produced by a number of methods, including laser-induced hydrodynamic expansion,63–65 pulsed discharges of an ablative capillary,66–69 or a gas-filled capillary.70–72 The length of such a plasma channel has been limited to about 10 cm and the plasma density has been created for $n_e \geq 10^{17}$ cm$^{-3}$. Laser-induced plasma channels need a fast ignition by a few ns prior to propagating a main laser pulse, while a slow pulsed discharge capillary needs a jitter free trigger within a few ns. To guide ultraintense laser pulses, plasma channels must be produced in fully ionized gases with low atomic number $Z$ such as hydrogen or helium. Not fully ionized particles will be further ionized by the laser, disturbing the electron density profile.

Plasma density channels stabilize propagation of relativistically intense laser pulses under the matched condition, preventing laser-plasma nonlinear instabilities, such as filamentation and hosing that often occur in the self-guiding.73,74 Employing the centimeter-scale plasma waveguide, laser plasma accelerator experiments on GeV-level electron acceleration have been carried out with a gas-filled discharge capillary,35,40,43,75 or ablative discharge capillary,37,41 to demonstrate quasi monoenergetic electron beams with GeV-class energies.

**Scaling of laser wakefield accelerators.** For the last two decades, a number of laser-plasma accelerator experiments have been carried out under various conditions. Comparing these data with theoretical laser wakefield acceleration models, it may be useful to find a correct scaling law capable of predicting energy gain, accelerated electron charge and the required laser-plasma conditions. Table 1 summarizes parameters for experiments on laser wakefield acceleration driven by a self-guided laser pulse,36,38,39,59,60,76–79 and a channel-guided laser pulse,35,37,40,41,43,75 Since the maximum energy gain scales as $\Delta E_B \propto n_e \propto \lambda_L^2$ for a given $a_0$, most of previous experiments employ the chirped pulse amplification lasers with wavelength $\lambda_L = 800$ nm and pulse duration $\tau_L \leq 80$ fs, except for the case using a PW-class laser with wavelength $\lambda_L = 1057$ nm and $\tau_L \sim 150$ fs.38 The validity of the energy scaling formulas based on the present analysis, may be verified by comparison with these experimental results. Figure 2 shows the comparison of measured electron beam energies shown in Table 1 with the energy scaling formulas, which are given by Eq. [10] in terms of $a_0$ and $n_e$ for Fig. 2(a) and the following formula34 on the maximum energy gain $S$ in terms of focused laser power $P_L$ and $n_e$

$$S \approx 1.7 \text{[GeV]}(P_L/100\text{TW})^{1/3}(n_e/10^{18}\text{cm}^{-3})^{-2/3} \times (\lambda_L/0.8\mu\text{m})^{-4/3}.$$  

[13] assuming $a_0 = (8P_L/P_L)^{1/3}$ for Fig. 2(b), respectively.

3. **Applications of laser plasma accelerators**

**Design of laser plasma accelerators.** For applications of unique particle beam and radiation
the propagation direction, \( k_p \) constant spot size, under the condition for the beam propagating with a short pulse.

For a short pulse, \( c t_L \) with laser spot radius \( r_L \), propagating in uniform plasma, i.e., \( c t_L \ll k r_L^2 \) and \((c t_L)^2/r_L^2 \ll 1 + k_p^2 r_L^2 /4 \), the paraxial approximation leads to the reduced wave equation for the normalized vector potential \( a(r, \phi, z) \) describing the three-dimensional evolution of a laser pulse with duration \( \tau_L \) in a fully ionized plasma, written in cylindrical coordinates \( (r, \phi, z) \) as \(a^{00} = 0\):

\[
\left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} + 2ik \frac{\partial}{\partial z} \right] a(r, \phi, z) = \left[ k^2 \left( 1 - \frac{1}{\beta^2} \right) + \frac{k_p^2}{\gamma_L} + \frac{1}{\gamma_L} \nabla_\perp^2 \right] a(r, \phi, z),
\]

where \( k = \omega/c \) is the free-space wave-number along the propagation direction, \( k_p = \omega p/c \) is the plasma wave-number, and \( \gamma_L = (1 + \alpha_c^2/2)^{1/2} \) is the relativistic factor of the laser intensity for the linear polarization. In the square bracket on the right hand side, the first term represents free-space propagation, the second and third terms correspond to relativistic self-focusing and ponderomotive channeling, respectively.

The analyses of the wave equation with the standard paraxial form provide the matched spot radius \( r_m \) under the condition for the beam propagating with a constant spot size, i.e., \( R_m \equiv k_p r_L \), given by \(a^{57}\):

\[
R_m^2 = \ln(1 + a_0^2/2) \sqrt{1 + a_0^2/2 - 1 - 2 \ln \frac{1 + a_0^2/2 + 1}{2}}^{-1}.
\]

[15]

The corresponding matched power \( P_m \) is given by

\[
P_m = (k_p r_L a_0^2/32) P_c, \quad P_c = 17 n_e / n_c \text{ [GW]} \]

is the critical power for the relativistic self-focusing at the plasma density \( n_e \). For the matched condition that no phase shift of the laser pulse occurs, the group velocity is written as \( \beta_0^2 \approx 1 - k_p^2 / (\kappa_c k^2) \), where a correction factor of the group velocity is defined \(a^{57}\):

\[
\kappa_c = \frac{a_0^2}{8} \left( \sqrt{1 + a_0^2/2} - 1 - \ln \frac{1 + a_0^2/2 + 1}{2} \right)^{-1}.
\]

[16]

Self-guided LWFA in the bubble regime. For a given energy \( E_b \) GeV and charge \( Q_b \) pC, the parameters of self-guided laser wakefield accelerators can be designed as follows. First, using Eq. [12], the field reduction factor \( \alpha_c \) is obtained from solving the equation

\[
\alpha_c^2 + C \alpha_c^{3/2} - 1 = 0,
\]

where the coefficient \( C \) is given by \( C = (Q_b / 123) \kappa_c^{1/2} \lambda_L^{-1} E_b^{-1/2} (k_p \sigma_b)^{-2} \). Then, the operating plasma density is determined from Eq. [10], taking into account relativistic correction of the group velocity of the laser pulse at wavelength \( \lambda_L \) um, as

\[
n_e \text{ [cm}^{-3} \text{]} \approx 3.8 \times 10^{17} \kappa_c a_0 \lambda_L^{-2} (E_b / \alpha_c)^{-1}.
\]

[18]
The accelerator length equal to the dephasing length, i.e., \( L_{\text{acc}} = L_{\text{dp}} \), becomes

\[
L_{\text{acc}} [\text{cm}] \approx 3.6 a_0^{-1} \kappa_c^{-1/2} \lambda_L (E_b / \alpha_c)^{3/2},
\]

while the pump depletion length due to pulse-front erosion is given by \( L_{\text{pd}} \approx \eta_c n_e / n_e \). Since the dephasing length should be less than the pump depletion length, i.e., \( L_{\text{pd}} \geq L_{\text{dp}} \), the pulse length is set to be

\[
\tau_L [\text{fs}] \geq 38 a_0^{-1} \kappa_c^{-1/2} \lambda_L (E_b / \alpha_c)^{1/2}. \tag{20}
\]

For the matched propagation of the laser pulse, the spot radius is set to be

\[
r_L [\text{um}] \approx 8.7 R_m (a_0 \kappa_c)^{-1} \lambda_L (E_b / \alpha_c)^{1/2}. \tag{21}
\]

The matched peak power is calculated as

\[
P_L [\text{TW}] \approx 1.6 a_0 \kappa_c^{-1} R_m^2 (E_b / \alpha_c). \tag{22}
\]

Thus, the required pulse energy is

\[
U_L [\text{J}] = P_L \tau_L \geq 0.06 a_0 \kappa_c^{-1} R_m^2 \lambda_L (E_b / \alpha_c)^{3/2}. \tag{23}
\]

**Laser plasma accelerator-based EUV-FEL.**

Extreme Ultra-Violet ("EUV") with wavelengths below about 50 nm and more specifically around and below 13.5 nm can be used in microlithography processes to enhance the resolution of optical systems that are limited by the diffraction limit of light accompanying miniaturization of semiconductor integrated circuits. This technology called as extreme ultraviolet lithography (EUVL) is capable of providing resolution below 30 nm that had been impossible with conventional optical lithography utilizing deep ultraviolet (DUV) light sources with wavelengths of 248 nm or 193 nm.

The current technologies for generating high power EUV radiation at 13.5 nm, referred to as laser produced plasma (LPP), employs the deposition of laser energy into a source material such as molten tin (Sn) droplets, creating ionized gas microplasma at electron temperatures of several tens of electron volts. The current LPP radiation sources have a serious obstacle on the way to a high volume manufacturing (HVM) source such as small efficiency of the radiation source, a limited set of discrete wavelengths and the mitigation of the plasma debris required for the protection of the EUV optics. Free-Electron Laser (FEL) based radiation sources have evident advantages in wavelength tunability, high efficiency and high output power, compared to current LPP radiation sources. The problem of debris mitigation does not exist at all. There is no need to use a multilayer coated reflective collector, of which reflectivity is limited to about 70%. A proposed FEL\(^{81}\) producing a kW-level average output power of EUV radiation utilizes high-energy electron beams of the order of 1 GeV generated from a radio-frequency-based linear accelerator (RF linac) . The RF linac may consist of a high-brightness electron injector, a several-stage magnetic bunch compressor system to compress a bunch length and a main linac composed of a series of room-temperature or superconducting RF cavities with the accelerating gradient of the order of 10 MV/m as well as a beam transport system, lastly followed by undulators with a total length of 30 m. The alternating magnetic fields of the undulator force relativistic electrons in a bunch to emit EUV radiation coherently on a sinusoidal trajectory due to the microbunching process, called as self-amplified spontaneous emission (SASE) FEL.

The overall size of a RF linac-driven FEL-based EUV light source may require a 250 m long facility for a linac-based light source or a 120 m long, 60 m wide area for a recirculator-based light source. The costs for construction and operation of such facility may turn out incredibly so large as to hinder the FEL-based EUV light sources from industrial realization of the next generation lithography technology. Large costs of 200 M€, for facility construction including accelerator, cryogenic for super conducting RF (SRF), undulator, civil engineering etc. and operation costs of 20 M€/year for electricity, klystrons, optical components, detectors, general maintenance, repair and helium supply for SRF, etc.

A design of FEL based EUV light source can be made by the one-dimensional FEL theory\(^{82}\) as follows: The FEL amplification takes place in the undulator with the undulator period \( \lambda_u \) and the peak magnetic field \( B_u \) at the resonant wavelength \( \lambda_X \) given by

\[
\lambda_X = \frac{\lambda_u}{2 \gamma^2} \left( 1 + \frac{K_u^2}{2} \right),
\]

where \( \gamma = E_b / m_e c^2 \) is the relativistic factor of the electron beam energy \( E_b \), \( K_u = 0.934 B_u [T] \lambda_u [\text{cm}] = \gamma \theta_e \) is the undulator parameter, which is related to the maximum electron deflection angle \( \theta_e \). In the high-gain regime required for the operation of a SASE FEL, an important parameter is the Pierce parameter \( \rho_{\text{FEL}} \) given by

\[
\rho_{\text{FEL}} = \left[ \frac{1}{2 \gamma} \frac{I_b}{I_A} \left( \frac{\lambda_u K_u A_u}{2 \pi \sigma_b} \right)^2 \right]^{1/3},
\]

where \( I_b \) is the beam current, \( I_A = 17 \text{kA} \) is the Alfvén current, \( \sigma_b \) is the r.m.s. transverse size of the electron bunch, and the coupling factor is \( A_u = 1 \) for a helical
undulator and $A_u = J_0(\Xi) - J_1(\Xi)$ for a planar undulator, where $\Xi = K_u^2/[4(1 + K_u^2/2)]$ and $J_0$ and $J_1$ are the Bessel functions of the first kind. Another important dimensionless parameter is the longitudinal velocity spread $\Delta$ of the beam normalized by the Pierce parameter

$$
\Lambda^2 = \frac{1}{\rho_{\text{FEL}}} \left[ \left( \frac{\sigma_\gamma}{\gamma} \right)^2 + \left( \frac{\varepsilon \lambda_\mu}{4\lambda X \beta} \right)^2 \right] + \frac{1}{\rho_{\text{FEL}}} \left[ \left( \frac{\sigma_\gamma}{\gamma} \right)^2 + \left( \frac{\varepsilon^2}{\lambda_\mu^2 (1 + K_u^2/2)} \right)^2 \right],
$$

where $\sigma_\gamma/\gamma$ is the relativistic r.m.s. energy spread, $\varepsilon$ is the r.m.s. transverse emittance, $\beta = \sigma_b^2/\varepsilon$ is the beta function provided by the guiding field (undulator plus external focusing) and $\varepsilon_n$ is the normalized emittance defined as $\varepsilon_n \equiv \gamma \varepsilon$ assuming that a $\beta$-function is constant along the length of the undulator. A $\varepsilon$-folding gain length $L_{\text{gain}}$ over which the power grows with propagation distance $z$ exponentially according to $\exp(2z/L_{\text{gain}})$ is given by

$$
L_{\text{gain}} = \frac{\lambda_n}{4\pi \sqrt{3 \rho_{\text{FEL}}}} (1 + \Lambda^2).\tag{27}
$$

In order to minimize the gain length, one needs a large Pierce parameter $\rho_{\text{FEL}}$ and a normalized longitudinal velocity spread $\Delta$ sufficiently low compared to 1 that means a sufficiently small energy spread $\sigma_\gamma/\gamma$ and $\varepsilon$. This expression applies to moderately small beam size $\sigma_b$ such that the diffraction parameter $B \gg 1$ where $B$ is defined as

$$
B = \frac{16\varepsilon^2 A_u \sigma_b^2}{\lambda X \lambda_\mu} \left( \frac{K_u^2/2}{\gamma (1 + K_u^2/2)} \right)^{1/2} I_b.\tag{28}
$$

A saturation length $L_{\text{sat}}$ required to saturate the amplification can be expressed as

$$
L_{\text{sat}} = L_{\text{gain}} \ln \left[ \left( \Lambda^2 + 3/2 \right) \frac{P_{\text{sat}}}{P_{\text{in}}} \right],\tag{29}
$$

where $P_{\text{in}}$ and $P_{\text{sat}}$ are an input and a saturated power related. The input $P_{\text{in}}$ and saturated power $P_{\text{sat}}$ are related to an electron beam power $P_b$ according to

$$
P_{\text{in}} = \gamma I_b m_e c^2 = I_b E_b,$$

$$
P_{\text{sat}} \approx 3\gamma \rho_{\text{FEL}} P_b \exp(-0.82A^2),\tag{30}
$$

$$
P_{\text{in}} \approx 3\sqrt{4\pi \rho_{\text{FEL}}} P_b (N_{\lambda_X} \ln(N_{\lambda_X}/\rho_{\text{FEL}}))^{-1/2},$$

where $N_{\lambda_X}$ is the number of electrons per wavelength given by $N_{\lambda_X} = I_b \lambda_X/(ec)$.

Table 2 summarizes design examples for high-repetition rate, high-average power laser, such as the coherent combining fiber-based chirped pulse amplification (CPA) laser, driven laser plasma accelerator-based kW-level FEL EUV radiation source at 13.5 nm (Case A) and 6.7 nm (Case B) wavelengths using the undulator with the period of 15 mm and the gap of 3 mm, assuming a FWHM electron bunch duration of $\sim$10 fs, a relative energy spread of $\Delta E/E_0 \sim 1\%$.

**All-optical Gamma beam source.** A high-quality Gamma-beam generated from inverse Compton scattering off relativistic electron beams interacting with an intense laser pulse arouses interest in photonuclear physics and nuclear astrophysics research, characterization of nuclear materials or radioactive waste and so on. Here, we present a table-top all-optical laser plasma accelerator-based Gamma beam source comprising a high power laser.

| Case | A | B |
|------|---|---|
| Drive laser | | |
| Wavelength [nm] | 13.5 | 6.7 |
| Average laser power [MW] | 1.19 | 2.60 |
| Repetition rate [MHz] | 0.315 | 0.473 |
| Laser energy per pulse [J] | 3.79 | 5.51 |
| Peak power [TW] | 59 | 75 |
| Pulse duration [fs] | 65 | 73 |
| Matched spot radius [µm] | 27 | 30 |
| Laser plasma accelerator | | |
| Electron beam energy [MeV] | 659 | 935 |
| Plasma density [10^{17} \text{ cm}^{-3}] | 4.2 | 3.2 |
| Accelerator length [mm] | 51 | 74 |
| Charge per bunch [nC] | 0.5 | 0.5 |
| Bunch duration [fs] | 10 | 10 |
| Energy spread [%] | $\sim$1.6 | $\sim$1.1 |
| Transverse beam size [µm] | 25 | 25 |
| Peak current [kA] | 50 | 50 |
| Average beam power [kW] | 104 | 221 |
| Free Electron Laser | | |
| Undulator period (Gap) [mm] | 15 (3) | 15 (3) |
| Radiation wavelength [nm] | 13.5 | 6.7 |
| Peak magnetic field [T] | 1.425 | 1.425 |
| Undulator parameter $K_u$ | 2.0 | 2.0 |
| Pierce parameter [%] | 1.60 | 1.125 |
| Gain length [mm] | 86 | 123 |
| Saturation length [cm] | 102 | 144 |
| Number of periods | 68 | 96 |
| Spectral bandwidth [%] | 1.5 | 10 |
| Saturated power [GW] | 317 | 317 |
| Duration of EUV pulse [fs] | 10 | 10 |
| Average EUV power [kW] | 1 | 1.5 |
system with synchronous dual outputs, a GeV-class laser plasma accelerator, and a scatter optics whereby the laser pulse is focused onto the electron beam to generate a Gamma-beam via inverse Compton scattering with photon energy of 2–20 MeV.

**Laser Compton scattering.** In Compton scattering of a laser photon with energy $\hbar \omega_L$ (eV) $= 1.240/\lambda_L$ [nm] for laser wavelength $\lambda_L$ [nm] off a beam electron, the maximum energy of scattered photon is given by $E_\gamma = 4\gamma_e^2 \hbar \omega_L$, where $\gamma_e = E_e/m_e c^2$ is the relativistic factor of the electron beam energy $E_e$ with the electron rest mass $m_e c^2 \approx 0.511$ MeV, and the factor $a = [1 + 4\gamma_e (\hbar \omega_L/m_e c^2)]^{-1}$. In the laboratory frame, the differential cross section of Compton scattering $^{(35)}$ is given by

$$\frac{d\sigma}{d\kappa} = 2\pi a e^2 \left\{ 1 + \kappa^2 (1-a)^2 \left[ 1 - \kappa (1+a) \right] + \left[ 1 - \kappa (1-a) \right]^2 \right\},$$

where $\kappa = E_e/E_{\gamma\text{max}}$ is energy of a scattered photon normalized by the maximum photon energy and $r_e^2 \approx 79.4$ mb (1 barn $= 10^{-24}$ cm$^2$) with the classical electron radius $r_e$. In the laboratory frame, the scattering angle $\theta$ of photon is given by $\tan\theta = \gamma_e^{-1}[(1-\kappa)/a]^1/2$. Integrating the differential cross section over $0 \leq \kappa \leq 1$, the total cross section of Compton scattering becomes

$$\sigma_{\text{total}} = \pi r_e^2 a \left[ \frac{2a^2 + 12a + 2}{(1-a)^2} \right] + a - 1 + \frac{6a^2 + 12a - 2}{(1-a)^3} \ln a. \tag{31}$$

This total cross section leads to the cross section of Thomson scattering $\sigma_{\text{Thomson}} = 8\pi r_e^2/3 = 665$ mb for the electron beam energy $E_e \rightarrow 0$. The fractional cross section for the photon energy range $E_{\gamma\text{max}} - \Delta E_e \leq E_e \leq E_{\gamma\text{max}}$ is given by

$$\Delta \sigma \approx 2\pi a r_e^2 \Delta \kappa \left[ \frac{1 + a}{1 - a} \right]^2 + \frac{4}{(1-a)^2} \left( 1 + \frac{1-a}{a} \Delta \kappa \right)^{-1} \left( a - 1 \right) \left( 1 + \frac{1-a}{a} \Delta \kappa \right) + \frac{1-6a-3a^2}{(1-a)^3} \Delta \kappa \ln \left[ 1 + \frac{1-a}{a} \Delta \kappa \right], \tag{33}$$

with $\Delta \kappa = E_e/E_{\gamma\text{max}} \ll 1$. All photons in this energy range are scattered to the forward direction within a half-cone angle $\theta \sim \gamma_e^{-1} \sqrt{\Delta \kappa/\kappa}$. For an electron beam interacting with a laser pulse at an angle of $\alpha_{\text{int}}$ in the horizontal plane ($x$-plane), a luminosity representing the probability of collisions between electron and laser beams per unit cross section per unit time is obtained by $L$ [mb$^{-1}$s$^{-1}$] $\approx N_e \int f_L/(2\pi \Sigma)$, where $N_e$ is the number of electrons contained in an electron bunch, $N_e$ is the number of photons per laser pulse, $f_L$ is a repetition rate of laser pulses and $\Sigma$ is an area where two beams overlap, given by

$$\Sigma = (\sigma_{\text{ex}} + \sigma_{\text{Ly}})^{1/2} \cos^2(\alpha_{\text{int}}/2) (\sigma_{\text{ex}}^2 + \sigma_{\text{Ly}}^2) + \sin^2(\alpha_{\text{int}}/2)(\sigma_{\text{ex}}^2 + \sigma_{\text{Ly}}^2)^{1/2}, \tag{34}$$

where $\sigma_{\text{ex}}$ and $\sigma_{\text{Ly}}$ are the real mean square (r.m.s.) horizontal and vertical sizes of the electron beam, $\gamma_e$ the r.m.s. bunch length of the electron beam, $\sigma_{\text{ex}}$ and $\sigma_{\text{Ly}}$ the r.m.s. horizontal and vertical spot sizes of the laser beam and $\alpha_{\text{int}}$ the r.m.s. pulse length of the laser beam, respectively. For a head-on collision providing the efficient Gamma-beam production, a crossing angle between electron and laser beams is chosen to be $\alpha_{\text{int}} = 0$. Tuning the beam focusing system and the interaction optics so as to be $\sigma_{\text{ex}} \approx \sigma_{\text{Ly}} \approx \sigma_{\text{ex}}$, the luminosity turns out to be $L = N_e N_e f_L(4\pi r_e^2)$, where $r_e$ is a laser spot radius at the interaction point. Using $N_e = 1.6022 \times 10^{10}$ ($Q_e/1$ nC) and $N_e = U_{\ell} = \omega_L = 5.0334 \times 10^{18} U_{\ell} \lambda_L$ [nm], where $Q_e$ is charge of the electron bunch, $U_{\ell} = P_{\ell} \ell_{\ell}$ is energy of the scatter pulse with peak power $P_{\ell}$ and duration $\tau_{\ell}$, the luminosity is calculated as

$$L [\text{mb}^{-1}s^{-1}] = Q_e I_{\ell} \ell_{\ell} \tau_{\ell} / (8e \hbar \omega_L) \approx 1.0 \times 10^{-14} f_L [s^{-1}] Q_e [\text{nC}] \times I_{\ell} [\text{W cm}^{-2}] \tau_{\ell} [\text{fs}] \lambda_L [\mu\text{m}], \tag{35}$$

where $I_{\ell}$ is the focused intensity of the scatter pulse at the interaction point. Thus, the total Gamma-beam flux is given by

$$N_e [s^{-1}] = L \sigma_{\text{tot}} \approx 1 \times 10^{-14} \sigma_{\text{tot}} [\text{mb}] f_L [s^{-1}] Q_e [\text{nC}] \times I_{\ell} [\text{W cm}^{-2}] \tau_{\ell} [\text{fs}] \lambda_L [\mu\text{m}]. \tag{36}$$

A fractional Gamma-beam flux with photon energy spread $\Delta \gamma_e = \Delta E_e/E_{\gamma\text{max}}$ is estimated as

$$\Delta N_e [s^{-1}] = L \Delta \sigma \approx 1 \times 10^{-14} \Delta \sigma [\text{mb}] f_L [s^{-1}] Q_e [\text{nC}] \times I_{\ell} [\text{W cm}^{-2}] \tau_{\ell} [\text{fs}] \lambda_L [\mu\text{m}]. \tag{37}$$

*Detection for nuclear resonance fluorescence.* When a nucleus absorbs photons equal to the excitation energy, the nucleus is excited to the definite state due to resonant excitation, instantaneously followed by decaying mainly to a lower state with a re-emission of the radiation equivalent to the
absorbed energy. This process is referred to as nuclear resonance fluorescence (NRF)\(^{86-88}\) for which the lifetime of the excited nuclear state of the order of 100 ps corresponds to an energy width \(\Gamma \sim 10^{-5}\) eV for the absorption and re-emission at the exact resonance. Since this resonant property of NRF is in unique contrast to other nuclear absorption phenomena such as photonuclear reactions and the giant dipole resonance, involving the continuum states of nuclei with broad absorption spectra, the NRF interrogation is capable of characterizing a nucleus in the nuclear structure and its excited states in terms of their energy, lifetime, angular momentum, and parity. The absorption cross section for a nucleus in the state \(i\) to capture a photon and be directly excited to the state \(j\), taking into account the Doppler broadening due to the thermal motion of the nucleus at the resonance, is given by\(^{86}\)

\[
\sigma_{\text{NRF}}(E_{\text{res}}) = 2.5 \times 10^4 \left[ \frac{1\text{ MeV}}{E_{\text{res}}} \right]^2 \frac{2J_j + 1}{2J_i + 1} \Gamma_0 \Gamma_{\text{thermal}}, \tag{38}
\]

where \(J_i\) denotes spin of the \(i\)-state, \(E_{\text{res}}\) is the excitation energy of the \(i\)-state relative to the \(j\)-state, \(\Gamma_0\) is the intrinsic width of the resonantly excited state to the ground state and \(\Gamma_{\text{thermal}}\) is the Doppler width, defined by \(\Gamma_{\text{thermal}} = E_{\text{res}} (2kT_{\text{eff}}/m_{\text{nucleus}}c^2)^{1/2}\) for the effective temperature \(T_{\text{eff}}\) and the mass \(m_{\text{nucleus}}\) of the nucleus with the Boltzmann constant \(k\). For a typical radioactive nuclide with nuclear mass number \(A = 200\), \(E_{\text{res}} = 1\) MeV and \(T_{\text{eff}} = 300\) K, the Doppler width is \(\Gamma_{\text{thermal}} = 0.5\) eV.

For the NRF interrogation, Gamma-ray sources need to cover the excitation energies of most of the nuclides from 10 keV to 10 MeV. Using such a Gamma-ray source, consider the detection of NRF from a nuclide contained at a concentration level of \(C_{\text{nuc}}\) Bq/g in a material such as concrete when irradiated with Gamma rays at a flux of \(F_{\text{GB}}\) photons/s/keV. The number of NRF photons detected for the measuring time \(T_{\text{measure}}\) by a detection system with the efficiency of \(\varepsilon_{\text{detector}}\) can be estimated as\(^{87}\)

\[
N_{\text{NRF}} = \frac{\varepsilon_{\text{detector}} \sigma_{\text{NRF}} F_{\text{GB}} L_{\text{int}} T_{\text{measure}} d_{\text{material}} C_{\text{nuc}} N_A}{A_i m_A}, \tag{39}
\]

where \(L_{\text{int}}\) is the interaction length, \(d_{\text{material}}\) the density of material, \(N_A = 6.022 \times 10^{23}\) mol\(^{-1}\) the Avogadro’s constant, \(A_i\) the specific activity and \(m_A\) the atomic mass number of the radioactive nucleus. Here \(d_{\text{material}} = d_{\text{material}} C_{\text{nuc}} N_A / (A_i m_A)\) represents the number of radioactive nuclei contained in a unit volume of material. As an example, the number of NRF photons from U-238 with resonance energy \(E_{\text{res}} = 2.17\) MeV, cross section \(\sigma_{\text{NRF}} = 28\text{ mb-keV}\) and specific activity \(A_i = 1.2 \times 10^5\) Bq/g contained at a concentration level \(C_{\text{nuc}} = 1\) Bq/g in concrete with density \(d_{\text{material}} = 2\) g/cm\(^3\), corresponding to \(n_{U-238} \sim 4.2 \times 10^{17}\) cm\(^{-3}\), will be \(N_{\text{NRF}} \sim 1.2 \times 10^{-6}\) \(F_{\text{GB}}\) detected by the detector with the total efficiency \(\varepsilon_{\text{detector}} = 1\%\) for the interaction length \(L_{\text{int}} = 1\) m and the measuring time \(T_{\text{measure}} = 100\) s.

The all-optical laser plasma accelerator-based Gamma-beam source at photon energy of 2.17 MeV for the detection of NRF photons from U-238 can be designed as follows. The maximum photon energy of \(E_{\gamma_{\text{max}}} = 2.17\) MeV is generated from the inverse Compton scattering between a laser of 0.8 µm wavelength and electrons with beam energy of \(E_b = 303.4\) MeV. Using the design formulas Eqs. [17]–[23], an electron beam with energy of 303.4 MeV and charge of 1 nC can be delivered from the laser plasma accelerator driven by a laser pulse with the peak power of 44 TW, duration of 56 fs, and energy of 2.5 J, which is focused on spot radius of 12 µm, corresponding to \(a_0 = 3\), in the entrance of gas cell with length of 3 cm, operated at plasma density of \(1 \times 10^{18}\) cm\(^{-3}\). Provided that the electron beam with radius of 25 µm interacts head-on with a scatter laser pulse with wavelength of 0.8 µm, peak power of 10 TW, duration of 1 ps and energy of 10 J, focused on spot radius of 25 µm, correspondingly at the intensity of \(I_{\text{LINT}} = 10^{18}\) W/cm\(^2\), a total Gamma-beam flux yields \(5.3 \times 10^9\) (5.3 \(\times 10^{12}\)) photons/s at the repetition rate of 10 Hz (1 kHz), while a fractional Gamma-beam flux with the spectral bandwidth of 0.1% results in \(8 \times 10^7\) (8 \(\times 10^9\)) photons/s, corresponding to the gamma ray flux of \(F_{\text{GB}} \sim 3.7 \times 10^7\) (3.7 \(\times 10^9\)) photons/s/keV. Accordingly, the number of NRF photons from U-238 yields \(N_{\text{NRF}} \sim 440\) (440), which will be detected by the detector with the total efficiency of 10% (1%) for the interaction length \(L_{\text{int}} = 1\) m and the measuring time \(T_{\text{measure}} = 100\) s (10 s). Here the values in brackets ( ) correspond to the performance of the Gamma-beam source at the operation of 1 kHz. Figure 3(a) illustrates schematically the Gamma-beam source, generated via laser Compton scattering off electron beams driven by a laser plasma accelerator.

**Table-top colliders for testing photon-photon interactions.** There exist neutral resonance particles coupling to two photons at the different energy scales over three orders of magnitude.\(^{89}\) For well-known
examples, the Higgs-like particles at the 100 GeV mass scale and neutral pion at 100 MeV can couple to two photons via their decay processes. Generally speaking, testing photon-photon interactions provides us with crucial information on particle physics and cosmology.\(^{90}\) In the lower energy range, searches for \(\gamma\gamma \rightarrow \gamma\gamma\) interactions\(^{91}-94\) have been performed in the energy range from sub-eV to keV for attempting to search for dark matter and put the upper limit on the QED photon-photon interaction. Regardless of the perturbative QED’s explicit prediction that the cross section can be maximized at the 1-MeV scale, the elastic scattering with real photon–photon collision has not yet been observed experimentally.

Exploiting two identical all-optical gamma beam sources operated at a reasonable repetition rate, one may conceive to carry out a direct measurement of photon-photon scattering with the maximized cross section at the center-of-mass system energy of \(E_{\text{cms}} = 1.4\) MeV. For the incident photon energy of \(E_{\gamma} = 1\) eV, the total cross section for the unpolarized photon–photon scattering is \(\sigma_{\gamma\gamma\gamma\gamma} \sim 10^{-42}\) barn, i.e., \(\sim 10^{-46}\) cm\(^2\), which is extremely small due to scaling as \(\sigma_{\gamma\gamma\gamma\gamma} \propto (E_{\gamma}/m_{e}c^{2})^{6}\), while for the photon energy of \(E_{\gamma} \sim 0.7\) MeV, the total cross section is maximized up to \(\sigma_{\gamma\gamma\gamma\gamma} \sim 1.6\) pb, i.e., \(\sim 10^{-30}\) cm\(^2\), showing a flat-top character in the region of \(E_{\text{cms}} = 1–2\) MeV. Therefore, in order to verify the perturbative QED cross section, it may be quite reasonable to perform the photon-photon scattering experiment tuned at \(E_{\gamma} \sim 0.7\) MeV, allowing a relatively large energy spread of the order of 10–30%.

For generating the incident photons with energy of 0.7 MeV, at first an electron beam with 175 MeV energy and 1 nC are produced from a two-stage laser wakefield accelerator\(^{84}\) comprising a 4-mm long gas cell filled with 95% helium and 5% nitrogen mixed gas for the injector stage and a 2-cm long variable-length gas cell filled with pure helium for the accelerator stage. Provided that a laser pulse with 30 TW peak power and 70 fs duration is focused on 12 µm spot radius on the entrance of the injector cell operated at plasma density of \(3.5 \times 10^{18}\) cm\(^{-3}\), strong nonlinear wakefields can be generated so that a 1 nC electron bunch could be trapped due to ionization-induced injection and accelerated up to 40 MeV, followed by boosting its energy up to 175 MeV at the length of 1.5 cm in the accelerator cell operated at plasma density of \(1.4 \times 10^{18}\) cm\(^{-3}\). The relative energy spread and emittance of resultant output beams are estimated to be 5% in r.m.s. and 1 mm mrad, respectively.

The luminosity of head-on colliding two-photon bunches with three dimensional Gaussian distributions can be given by

\[
L_{\gamma\gamma} = \frac{N_{\gamma}^{2} f_{L}}{4\pi\sigma_{\gamma}^{2}} = \frac{10^{26}\text{[cm}^{-2}\text{s}^{-1}]}{4\pi} \left( \frac{N_{\gamma}}{10^{9}} \right)^{2} \left( \frac{\sigma_{\gamma}}{1\mu\text{m}} \right)^{-2} \left( \frac{f_{L}}{1\text{Hz}} \right),
\]

where \(N_{\gamma}\) is the number of photons, \(\sigma_{\gamma}\) the rms gamma beam size at the collision point (IP) and \(f_{L}\) the collision frequency, which is equal to the repetition rate of the laser pulse. Provided the IP is
separated at a short distance \( d \), e.g., \( d = 4 \) mm from the Compton scattering point, the gamma beam size at IP is approximately equal to the electron beam size \( \sigma_e \), i.e., \( \sigma_e \approx \sigma_c \). The distance \( d \) is set to be a length that is required for spatially separating counter-propagating electron bunches in the strong magnetic field placed at the IP, e.g., 3 T over the length \( 2d \) in order to reduce electron-electron Møller scatterings. An electron beam from LPA is collimated by a beam focusing system comprising a set of permanent-magnet-based quadrupoles. This transport system can be designed so as to have the transverse r.m.s. electron beam size \( \sigma_e \sim \lambda_L \) at the final focus. Thus, substituting the number of photons \( N \), per shot produced via inverse Compton scattering, Eq. \([40]\) is rewritten as

\[
L_{\gamma \gamma} \approx \frac{2 \ln 2}{\pi} \frac{f_L}{e L} \left( \frac{Q_e}{1 \text{nC}} \right)^2 \left( \frac{\Delta \sigma_{\text{Compton}} I_L}{1 \text{mb}} \right)^2 \left( \frac{\lambda_L}{1 \mu\text{m}} \right)^2 F^{-1},
\]

where \( Q_e \) is the electron beam charge from LPA, \( \Delta \sigma_{\text{Compton}} \) the cross section of inverse Compton scattering integrated over a specific energy spread, \( I_L \) is the laser intensity at focus for generating gamma rays, and \( F \) the form factor determined by the interaction geometries of laser and electron bunch interacting at a crossing angle \( \alpha_{\text{int}} \), given by

\[
F = \frac{\left( \frac{\sigma_e}{\sigma_{L\gamma}} \right)^2}{\left( 1 + \frac{\sigma^2_e}{\sigma^2_{L\gamma}} \right)^2} \cos^2 \left( \frac{\alpha_{\text{int}}}{2} \right) \frac{1 + \sigma^2_e / \sigma^2_{L\gamma}}{1 + \sigma^2_e / \sigma^2_{L\gamma}} \frac{\sigma^2_{L\gamma}}{\sigma^2_e} \tan^2 \left( \frac{\alpha_{\text{int}}}{2} \right),
\]

for the electron bunch with transverse size \( \sigma_e = \sigma_{ex} \) and length \( \sigma_{ez} \), and the laser pulse with focused spot size \( \sigma_{L\gamma} = \sigma_{Lx} = \sigma_{Ly} \) and length \( \sigma_{Lz} \). Assuming that the laser pulse length is set to a Rayleigh length, i.e., \( \tau_L = \frac{\pi r^2_L}{\lambda_L} \), where \( \tau_L = 2(2 \ln 2)^2 \sigma_{Lz} / c \) is the FWHM laser pulse duration and \( r_L = 2 \sigma_L \) the laser spot radius at the \( e^{-2} \) intensity, the approximation of \( \sigma_e \sim \lambda_L \leq \sigma_{Lz} \) results in \( F^{-1} \approx 3.19 \times 10^{18} \text{[cm}^{-2} \text{s}^{-1}] \) and \( F^{-1} \approx 3.19 \times 10^{18} \text{[cm}^{-2} \text{s}^{-1}] \) for nearly head-on interaction, i.e., \( \sigma_{\text{int}} = 0 \), and \( F^{-1} \approx 3.19 \times 10^{18} \text{[cm}^{-2} \text{s}^{-1}] \) for \( \sigma_{\text{int}} \neq 0 \) and the total detector efficiency of 50%. Figure 3(b) shows schematically the photon-photon collider comprising two identical gamma beam sources.

Laser-driven VHE electron beam radiation therapy. This application relates to a new external-beam radiation therapy system using very-high-energy (VHE) electron beams with energy of 50–250 MeV, generated by a centimeter-scale laser plasma accelerator built in a robotic system. Radiation therapy uses high energy radiation such as X-rays, gamma-rays, electrons, protons, heavy ions and neutrons to kill cancer cells by damaging their DNA. Most types of external-beam radiation therapy are delivered outside the body in the form of

\[
L_{\gamma \gamma} = 1.14 \times 10^{19} \text{[cm}^{-2} \text{s}^{-1}] \]

\[
\times \frac{r^4_L}{\sigma^2_e \lambda^2_L} \left( \frac{f_L}{1 \text{Hz}} \right) \left( \frac{Q_e}{1 \text{nC}} \right)^2 \left( \frac{\Delta \sigma_{\text{Compton}} I_L}{1 \text{mb}} \right)^2 \left( \frac{\lambda_L}{1 \mu\text{m}} \right)^2 F^{-1},
\]

and for \( \alpha_{\text{int}} \neq 0 \) as

\[
L_{\gamma \gamma} = 1.6 \times 10^{18} \text{[cm}^{-2} \text{s}^{-1}] \]

\[
\times \frac{r^2_L}{\sigma^2_e} \sin^{-2} \left( \frac{\alpha_{\text{int}}}{2} \right) \left( \frac{f_L}{1 \text{Hz}} \right) \left( \frac{Q_e}{1 \text{nC}} \right)^2 \left( \frac{\Delta \sigma_{\text{Compton}} I_L}{1 \text{mb}} \right)^2 \left( \frac{\lambda_L}{1 \mu\text{m}} \right)^2 F^{-1},
\]

respectively. Since the peak gamma ray energy is given by \( E_\gamma \sim 4 \gamma^2_e \omega_L \), the photon spectrum of Compton scattering off an electron with energy \( m_e c^2 \), nonlinear Compton scattering in which an incident electron absorbs more than one laser photon, i.e., \( e^- + n \omega_L \rightarrow e^-' + \gamma \), should be suppressed by setting the normalized laser field to be \( \alpha_0 \leq 1 \).
photon beams with energies of 6–20 MV from a machine called a medical linear accelerator driven by radio frequency (RF) power amplifiers in conjunction with modern radiation therapy technologies for effective shaping of 3-dimensional dose distributions and spatially accurate dose delivery with imaging verification such as 3-dimensional conformal radiation therapy (3D-CRT), intensity-modulated radiation therapy (IMRT), image guided radiation therapy (IGRT), stereotactic body radiation therapy (SBRT) and hadron therapy. However, the limited penetration depth and low quality of the transverse penumbra at such electron beams delivered from the present RF linear accelerators prevent the implementation of advanced modalities in current cancer treatments. These drawbacks can be overcome if electron energy is increased above 50 MeV, more specifically to the range of 50–250 MeV. The proposed radiation therapy system providing VHE electron beams is composed of a drive laser system, laser plasma accelerator, electron beam focusing system and robotic gantry. The drive laser pulse is guided through a vacuum transport optics and focused onto the laser plasma accelerator, both of which are installed in the robotic gantry.

The requirement of electron beam charge is determined by the radiation therapy treatment plan, for example, a 10 cc lung tumor treatment with 100 MeV electrons to a dose of 10 Gy in 1 second. This treatment requires that a 1 nC charge of 100 MeV electrons should be deposited over a 10 cc tumour volume in 1 second. At a repetition rate of 100 Hz, the laser plasma accelerator should provide an electron bunch with charge $Q_b = 10 \text{ pC}$. The laser plasma accelerator for delivering VHE electron beams with charge of 10 pC and variable energies in the range from 50 MeV to 250 MeV can be designed by exploiting the formulas Eqs. [17]–[23]. A drive laser pulse from the laser system is focused on the entrance of gas cell at the normalized laser field $a_0 = 2$ corresponding to the laser intensity $I = 5.5 \times 10^{19} \text{ W/cm}^2$. Self-guided propagation of such laser pulse in the gas cell requires the group velocity correction factor $\kappa_g = 1.19$ and the matched spot radius $R_m = 3.2$. Taking the wakefield reduction factor $\alpha_c = 0.85$ due to beam loading of charge $Q_b = 10 \text{ pC}$, Fig. 4(a) shows the main parameters of the laser plasma accelerator for delivering the VHE electron beams with variable energies from 50 MeV to 250 MeV, which can be controlled by adjusting laser pulse energy, plasma density and accelerator length.

Figure 4(b) schematically illustrates the gantry head that is a most crucial part of the radiation therapy robotic system, where installed are a final focus optics, electron laser plasma accelerator, and beam focusing system for VHE electron beam therapy. The ultrashort intense laser pulse is focused by a spherical mirror or off-axis parabolic mirror on the entrance of a two-stage gas cell, of which the first cell referred to an injector is filled with a mixed gas, e.g., helium gas mixed with nitrogen, and the second cell referred to as an accelerator is filled with a pure gas, e.g., hydrogen or helium. The gases are fed through a gas flow control system to the two-stage gas cell separately at the different pressures. According to the abovementioned mechanism, in the injector of the gas cell, the laser pulse excites large-amplitude plasma wakefields, of which an accelerating electric field can trap plasma electrons exclusively out of the inner shell electrons and accelerate them.
owing to ionization-induced injection.\textsuperscript{54–56} A pre-accelerated electron beam from the injector is further accelerated to the relativistic energy in the accelerator gas cell, where the laser pulse generates plasma wakefields. A collimated electron beam from the laser plasma accelerator is provided to the target in the patient by the beam focusing system comprising permanent quadrupole magnets.

**Ascent to 100 GeV by laser plasma accelerators.** Recently there is a growing interest in rapid progress on laser-driven plasma-based accelerators by exploiting petawatt-class lasers, whereby high-quality electron beams can be accelerated to multi-GeV energies in a centimeter-scale plasma thanks to laser wakefield acceleration mechanism, as reported so far, e.g. 1.8 GeV driven by 130 TW at SIOM,\textsuperscript{37} 2 GeV driven by 620 TW at TEXAS,\textsuperscript{38} 3 GeV driven by 210 TW at GIST,\textsuperscript{39} and 4.2 GeV driven by 230 TW at LBNL-BELLA.\textsuperscript{40} Endeavors to accelerate further high-energy electron beams beyond 10 GeV are underway worldwide at large-scale laser and particle accelerator facilities. The BELLA (Berkeley Lab Laser Accelerator) project at LBNL is aimed at developing 10 GeV laser wakefield accelerators for high-quality electron beam production in the conventional accelerator paradigm, i.e., staged accelerator comprising an injector and an accelerator driven by 1.5 PW laser at 1 Hz. The FACET (Facility for Accelerator science and Experimental Test Beams) project at SLAC is aimed at accelerating 40 GeV electron beams by plasma wakefield acceleration driven by 20 GeV high-current electron bunches delivered from 2 km SLAC linac.\textsuperscript{97} The PDPWA (Proton-Driven Plasma Wakefield Accelerator) project\textsuperscript{98} at CERN is planned for producing ~GeV-level energy gain of externally injected electron beams by means of plasma wakefield generated by 450 GeV self-modulated proton bunches from CERN-SPS proton synchrotron.

The state-of-the-art of PW-class lasers allows us to study the feasibility of laser plasma accelerators toward 100 GeV in a full scale experiment. The experiments are proposed for implementing the demonstration of a 100 GeV electron beam acceleration by means of a laser plasma accelerator driven with a multi-PW laser capable of delivering 3.5 kJ, 500 fs pulses.\textsuperscript{57} This capability allows us to explore laser plasma acceleration operated in the entire laser wakefield regime from the linear regime to the nonlinear bubble regime. Such a large-scale laser plasma accelerator comprises a gas jet or a short gas cell, which acts as an injector, followed by a long, uniform, low-density plasma or preformed plasma channel (plasma waveguide), which acts as the accelerating medium. Accelerated beams are detected and analyzed using diagnostic system composed of high-resolution spectrometers and beam imaging detectors.

**Design of 100 GeV laser plasma accelerator experiments.** According to the design formulas Eqs. [17]–[23], the parameters for the experiment on laser wakefield acceleration of electron beams up to 100 GeV can be designed by taking the normalized vector potential $a_0 = 3$ and the field reduction factor due to the beam loading $a_r = 0.9$ for the multi-PW laser system with wavelength of 1053 nm and 500 fs pulse duration as follows: the operating plasma density of $1.2 \times 10^{16} \text{ cm}^{-3}$, the dephasing limited accelerator length of 12 m, the laser focused spot radius of 110 µm, the laser peak power of 2.1 PW and the required pulse energy of 1 kJ.

**Injector.** Electron beams can be produced and accelerated in the injector stage driven by the same laser pulse as that in the accelerator stage, relying on the self-injection mechanism such as an expanding bubble self-injection mechanism,\textsuperscript{49} or the ionization-induced injection mechanism\textsuperscript{54–56} with a short mixed gas cell.

**Plasma waveguide.** Preformed plasma density channels for guiding ultra-intense short laser pulses are produced by a number of methods, including laser-induced hydrodynamic expansion, pulsed discharges of an ablative capillary or a gas-filled capillary. However, the length of such a plasma channel has been limited to less than 10 cm and the plasma density has been tuned for $>10^{17} \text{ cm}^{-3}$. An alternative method may be a hollow dielectric capillary tube filled with neutral gas for guiding intense short laser pulses over several meters. Since laser is guided by Fresnel reflection at the inner capillary wall, this method relies on neither laser power nor plasma density. Adjusting the capillary tube radius with respect to the laser spot radius can propagate intense laser pulses with peak intensity of the order of $10^{20} \text{ W/cm}^2$ over a 100-m scale. A design of the neutral gas-filled plasma waveguide for 100 GeV laser plasma accelerators has been presented in Ref. 99).

**Experimental system integrating LPA and diagnostics.** Electron beams from a laser plasma accelerator comprising an injector and a plasma waveguide are deflected through a spectrometer dipole magnet, and detected on imaging plates placed at several positions apart from the spectrometer magnet so that beam
energy can be evaluated precisely by reconstructing a track of the electron beam. In order to hold and align the injector, the plasma waveguide and diagnostic system in the centre of the vacuum target chamber, a structure, called as an inserter, with the function of precisely positioning the experimental setup will be built. Figure 5 illustrates schematically an example of the setup for 100 GeV ascent experiments at the multi-PW laser facility.

4. Summary

We have overviewed electron acceleration on the view of strong laser field-electron interaction in vacuum and plasma, whereby the acceleration mechanism is often referred to as the vacuum- or plasma-based accelerator. Nowadays a breakthrough concept of laser acceleration\(^\text{17}\) has led to great progress on laser-driven plasma-based accelerators combined with ultra-intense lasers that had emerged from chirped pulse amplification technique.\(^\text{100}\) More specifically, the achievements of research on laser plasma accelerators delivering electron beams having multi-GeV energy and high-qualities from a centimeter-scale plasma could inspire various applications in the broad range of sciences and technologies. As shown in Fig. 2, the measured energies of accelerated electron beams obtained from GeV-class laser plasma accelerator experiments are well fit to the energy gain versus plasma density scaling, given by Eq. [10] within a factor of 2, which suggests the nonlinear evolution of the drive laser pulse and plasma wake during propagation in plasma as well as the electron beam dynamics.

Here some of examples have been illustrated by designing the embodiment so as to meet requirements in the practical application, based on the design formulas for laser plasma accelerators, which are deduced from a recent understanding of laser wakefield acceleration and the experimental results. The laser plasma accelerator-based EUV-FEL\(^\text{84}\) is a long outstanding objective that exemplifies advantageous properties of laser plasma accelerators over the conventional accelerator-based system in compactness and high-brightness. The all-optical gamma beam source\(^\text{34}\) based on GeV-class laser plasma accelerators is deemed to be a new promising tool for particle and nuclear physics research\(^\text{89–94}\) the interrogation of nuclear materials\(^\text{86}\) and the assay of radioactive wastes,\(^\text{87,88}\) of which system is planned by exploiting a combination between a conventional electron accelerator and a high-repetition rate laser. As an example of medical applications, the VHE electron beam therapy system driven by a laser plasma accelerator might become a reality in the earliest future because of great interest for medical science.\(^\text{101}\) For these applications, a crucial requirement is the stability in the performance of laser plasma accelerators dominantly attributed to the stability of drive lasers, of which the current limits of a few percent-level stability at the repetition rate of the order of 1 Hz operation would be improved to the 0.1%-level by increasing the repetition rate to

Fig. 5. A schematic view of the setup for 100 GeV ascent experiments at the multi-PW laser facility. A multi-PW laser (blue beamline) is focused on an injector plasma target placed at the center of the vacuum chamber, where a produced electron beam is accelerated by laser wakefields generated in a plasma waveguide (yellow beamline).
1 kHz. Regarding the 100 GeV ascent experiments, it would be feasible to demonstrate electron acceleration up to a 100 GeV level by means of the existing or near term multi-PW class lasers and the long plasma waveguide technologies, although the most critical point is a long-range guiding of the intense laser pulse in the low density plasma of the order of $10^{16}$ cm$^{-3}$.

Recently the vacuum laser acceleration attracts renewed interest in the all-optical concept of the quest for extremely high field-electron interaction. More specifically, the research on nonlinear Compton scattering, radiation reaction effects and the vacuum polarization leading to electron-positron pair production has been pursued worldwide by exploiting the complex system of GeV electron beams from laser plasma accelerators and synchronized PW lasers as the embodiment of “relativistic engineering”.

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Profile

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