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All-laser-driven Thomson X-ray sources

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Abstract

We discuss the development of a new generation of accelerator-based hard X-ray sources driven exclusively by laser light. High-intensity laser pulses serve the dual roles: first, accelerating electrons by laser-driven plasma wakefields, and second, generating X-rays by inverse Compton scattering. Such all-laser-driven X-rays have recently been demonstrated to be energetic, tunable, relatively narrow in bandwidth, short pulsed and well collimated. Such characteristics, especially from a compact source, are highly advantageous for numerous advanced X-ray applications—in metrology, biomedicine, materials, ultrafast phenomena, radiology and fundamental physics.

Keywords: laser plasma X-ray; scattering; electron accelerator

1. Introduction

The performance of X-ray sources has steadily improved ever since X-rays were discovered by Röntgen [1]. Along with this performance increase, the size of X-ray sources, at least those used for research, has also steadily increased: from the bench-top size of the original cathode ray tube to kilometer length of current X-ray free-electron lasers, such as the linear coherent light source (LCLS) at SLAC [2]. The large size of the brightest sources stems primarily from the large size of their constituent electron accelerators. This, in turn, stems from fundamental limits on the maximum field strength allowed by dielectric breakdown of the materials used in accelerator cavities. This limitation, however, was recently overcome, by replacing the conventional radiofrequency cavity-based accelerator with a laser–plasma-driven accelerator. Since plasmas are inherently ionized, they do not suffer from the usual dielectric breakdown (i.e. arcing) of solids. Consequently, higher electrostatic field strengths (10^4 times higher) can be used to accelerate electrons and, the high-energy electron accelerators have now shrunk correspondingly.

The performance of lasers has also steadily improved since they were invented [3]. As with X-ray sources, this performance improvement was also accompanied by increased size: from the bench-top of the original ruby laser [4] to the kilometer length of the world's largest laser at the National Ignition Facility (NIF) of LLNL [5]. Not surprisingly, this correlation between power and size stems from a fundamental limit: in this case, optical damage limits on the maximum allowable laser flux. Again, just as with electron accelerators, these limitations have recently been overcome, in this case by means of improvements to

laser system technology and design. These include novel amplification techniques (e.g. chirped-pulse amplification [6]), broadband amplification media (e.g. titanium sapphire [7]) and novel mode-locking techniques (e.g. Kerr-lens mode locking [8]). Consequently, lasers are now capable of generating petawatt peak power levels, comparable to that of the NIF laser, but with a table-top-sized device. Additionally, compact high-power lasers now operate at high repetition rates (0.1–10 Hz) [9–11], as compared with the single-shot-per-day rate of the NIF laser.

This combination of recent developments—compact high-peak-power lasers and compact laser-driven electron accelerators—has recently led to a dramatic reduction in the size of bright high-energy X-ray sources. In fact, laser-driven X-ray sources are now small enough to fit in a university or hospital laboratory (one example is shown in Figures 1–3). Despite this compact footprint, these laser-driven X-ray sources have achieved peak brightness levels rivalling those of stadium-sized storage ring X-ray synchrotrons (one example is shown in Figure 4). Such compact light sources can enable widespread application of techniques that were formerly available at only a few national research facilities worldwide.

The most recent milestones achieved in the development of all-laser-driven X-ray sources include demonstrations of micron source size [13,14], narrow X-ray bandwidth [15] and wide photon energy tunability [15]. These characteristics are highly advantageous for advanced X-ray applications—in research, industry, defense, security and biomedicine. For instance, narrow bandwidth can enable spatially resolved metrology of nanometer structures [16, 17], and radiography with low radiation dose and

high image contrast [18]. Large photon energy tunability can facilitate the study and application of X-ray photo-interactions spanning the entire range from the atomic to the nuclear domain. Femtosecond pulse duration can enable time-lapse imaging of ultrafast photo-induced changes in atomic structure [19], or chemical reactions [20]. It can also enable “diffraction before destruction,” that is, molecular structure determination before the onset of catastrophic radiation damage [21]. This is particularly relevant to certain proteins that are difficult to crystallize and thus cannot be characterized with conventional long-pulse-duration X-ray sources.

With the greater availability of high-power lasers, there is a wide variety of laser-driven X-ray sources now under development. We specialize the present discussion to laser-driven accelerator-based X-ray sources, and in particular, to laser-driven X-ray sources that use laser light as a driver for both accelerator and undulator. Specifically, we cover X-ray sources that use laser light for both of these

essential roles: (1) to accelerate electrons to highly relativistic velocity via wakefield plasma waves, and (2) to generate X-rays via scattering from the relativistic electrons.

Lasers are used to drive X-rays through a wide variety of mechanisms, too many to cover in a single review. Following is a list of other types of laser-driven X-ray sources that we are unable to cover here, but have been reviewed elsewhere [22–24]: (1) X-ray lasers based on population inversions in ionic media; (2) radioactive decay of photo-activated nuclei; (3) radiation from betatron oscillations in plasma channels; (4) Thomson scattering sources with conventional RF cavity accelerators; (5) laser-driven plasma accelerators with conventional magnetic undulators; (6) high-harmonic generation, from gases, neutral solids, plasmas or solid-density plasmas; and (7) free-electron lasers.

In this review, we first introduce the underlying physics of Thomson scattering with relativistic electrons, also known as inverse Compton scattering (ICS). We then

Figure 1. Photograph of the Diocles laser system. Photo courtesy of University of Nebraska–Lincoln. Reproduced with permission. All rights reserved.

Figure 2. Close-up photograph of one of the power amplifiers in the Diocles laser system. Photo courtesy of University of Nebraska–Lincoln. Reproduced with permission. All rights reserved.

Figure 3. Photograph taken through vacuum port of the UNL all-laser-driven X-ray source. Photo courtesy of University of Nebraska–Lincoln Office of Research and Economic Development. Reproduced with permission. All rights reserved.

Figure 4. Soleil synchrotron light source near Paris. Copyright © Synchrotron Soleil, used with permission.

highlight the physics of laser-driven electron acceleration. Next, we discuss recent experimental progress in the development of X-ray light sources that are based on these concepts. Last, we conclude with the outlook for further progress in their development and their potential applications.

2. X-rays from scattering laser light with relativistic electrons

2.1. Basic concepts

The theory of laser light scattering with relativistic electrons is well established [25, 26] and presented in detail in most graduate-level textbooks on classical electrodynamics [27, 28]. Here, we review a few of the major highlights.

2.1.1. Electron motion in an electromagnetic wave

Light propagating in vacuum takes the form of a transverse oscillating electromagnetic wave, which obeys the wave equation:

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}\right) u(\mathbf{r}, t) = 0 \quad (1)$$

where $u(\mathbf{r}, t)$ is either the electric or magnetic field, E or B , respectively, and c is the speed of light. Each field component is directed orthogonal to the other, and to the direction of wave propagation, $\hat{\mathbf{k}}$, where $\mathbf{k}$ is the wave vector. For instance, when $\hat{\mathbf{E}}$ points in the vertical direction, $\hat{\mathbf{B}}$ points out of the page, and $\hat{\mathbf{k}}$ points right. The solution of Equation (1) is an infinite plane wave, $u = \tilde{u} \exp[i(\mathbf{k} \cdot \mathbf{r} - \omega t)]$, where ω is the oscillation frequency, and $\omega/k = c$. The direction of the fields reverse twice during each optical cycle, $2\pi/\omega$.

In the presence of electric and magnetic fields, charged particles are subject to the Lorentz force:

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = q[\mathbf{E} + \mathbf{v} \times \mathbf{B}] \quad (2)$$

where $\mathbf{p}$ is the electron momentum and q is the charge. The normalized vector potential is defined as $a_0 = eE_0/m\omega_0 c$, where E_0 is the electric field amplitude. In a low-field-strength light wave $a_0 \ll 1$, an electron simply oscillates along the wave's electric field, reversing direction with the field twice during each optical cycle, $2\pi/\omega$.

It can be seen from Equation (2) that in high-field-strength waves $a_0 \sim 1$, an electron initially at rest will gain from the field an amount of kinetic energy equal to its rest mass, and quiver relativistically $v \simeq c$ during each half optical cycle.

For this reason, the intensity level ($I = \epsilon_0 c E^2$) leading to this relativistic electron motion is often termed as “relativistic intensity.” Since the normalized vector potential scales with laser wavelength (λ) and intensity (I) as

$$a_0 = 0.85 \left(\frac{\lambda}{1 \mu\text{m}} \right) \left(\frac{I}{10^{22} \text{W/m}^2} \right)^{1/2} \quad (3)$$

it can be seen from Equation (3) that relativistic intensity ($a_0 \sim 1$) for 1- μm wavelength light corresponds to $I \sim 10^{22} \text{W/m}^2$, which can be attained at the focus of a multi-terawatt-power optical laser.

At relativistic intensity $a_0 \simeq 1$, the $\mathbf{v} \times \mathbf{B}$ term of Equation (2) becomes comparable to the $\mathbf{E}$ term. Since the transverse electron motion along the electric field is also transverse to the wave's magnetic field, the electron oscillates longitudinally, along $\hat{\mathbf{k}}$ as well as along $\mathbf{E}$. If $\hat{\mathbf{E}}$ is along the vertical direction, and $\hat{\mathbf{k}}$ points towards the right side of the page, then the resulting electron trajectory resembles the shape of the number eight.

2.1.2. Radiation from an oscillating electron in an electromagnetic wave

Thus far, we have been discussing how electrons are accelerated by electromagnetic waves. However, accelerating electrons also radiate electromagnetic waves.

The Larmor equation [29] gives the instantaneous power radiated by an accelerating point charge. When the acceleration is parallel to the velocity, this can be expressed as [28] (Equation 10.142, p. 497):

$$P = \frac{dW}{dt} = \frac{q^2}{6\pi\epsilon_0 m^2 c^3} \left| \frac{d\mathbf{p}}{dt} \right|^2 \quad (4)$$

In a low-field-strength electromagnetic wave, an electron simply oscillates along the wave's oscillating electric field, and thus, the acceleration is parallel to the velocity. The emitted radiation pattern is the same as that from a simple dipole or linear antenna, and the radiated power is given by Equation (4). This is referred to as linear Thomson scattering. The angular power radiated is given by the differential scattering cross-section [28] (Equation 10.197, p. 507):

$$\frac{dP}{d\Omega} = \frac{d\sigma_T}{d\Omega} S \quad (5)$$

where S is the magnitude of the Poynting vector and the incident energy flux per unit area per unit time, that is, the intensity. The Poynting vector is defined as:

$$\mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} = \epsilon_0 c E^2 \hat{\mathbf{k}}_0 \quad (6)$$

The Thomson cross-section is

$$\sigma_T = \frac{8\pi}{3} r_c^2 = \frac{q^4}{6\pi\epsilon_0^2 m^2 c^4} \quad (7)$$

where r_c is the classical radius of the particle. For electrons, the cross-section is $\sigma_T = 6.65 \times 10^{-29} \text{ m}^2$. Integrating over all solid angles, the total scattered power is

$$P = \sigma_T S \quad (8)$$

In higher field-strength electromagnetic waves $a_0 \simeq 1$, the Figure 8 motion causes the electron to radiate into multipole patterns with harmonic content, often referred to as relativistic nonlinear Thomson scattering [30].

2.1.3. Inverse Compton scattering

If the electron is initially highly relativistic, prior to scattering with a light wave, then the scattering is commonly referred to as ICS. Since, in the moving frame of the electron, ICS is simply Thomson scattering, the two names are often used interchangeably. This is not to be confused with the original Compton scattering [31], in which a portion of the energy of a photon is transferred to a recoiling electron. The Compton effect is almost negligible for practically all current accelerator-based X-ray sources, since they operate in the limit of low photon energy ($\hbar\omega \ll m_e c^2$) in the center-of-momentum frame. Equivalently, the photon momentum is much less than the electron momentum ($\hbar\omega \ll m_e c^2$), or the photon wavelength is much greater than the Compton wavelength ($\lambda \gg \lambda_C$). The term “inverse” in ICS originates from the fact that it is the electron’s energy that is transferred to the recoiling photon in this case. ICS is an important process in astrophysics because highly relativistic electron beams occur naturally. For artificial X-ray light sources, relativistic electrons are generated with electron accelerators.

ICS is analogous to synchrotron radiation, as both mechanisms produce X-rays as a result of the oscillating acceleration of electrons in high fields. They differ by virtue of the fact that the undulator in ICS is an electromagnetic wave, whereas in the case of synchrotron radiation, it is instead a fixed, alternating array of magnets. In both cases, the electron oscillation is periodic, and the acceleration is perpendicular to the velocity. However, in ICS, the acceleration is due to the electric field in the Lorentz force, Equation (2), whereas in the case of synchrotron radiation, it is the magnetic field that is responsible for the acceleration. Given the equivalence of these components of the force at relativistic velocities, it is unsurprising that the scaling laws for ICS are found to be identical to those of synchrotron radiation, including even the equation coefficients. However, there are important differences, particularly in terms of undulator wavelength.

2.1.4. Scaling of X-ray photon energy

Although ICS is identical to Thomson scattering in the frame moving of the electron, and thus described by the formulae discussed in Section 2.1.2, the electron’s initial relativistic motion in the case of ICS strongly affects the frequency, power and directionality of the emitted X-rays. The relativistic kinetic energy is given by $(\gamma - 1)m_0 c^2$, where $\gamma = 1/(1 - \beta^2)^{1/2}$ is the Lorentz factor. In the case of backscattering, in which a highly relativistic electron and a laser photon are counterpropagating ($\theta \sim \pi$), the maximum ICS-generated X-ray photon energy is given by [25,26]

$$\omega_{\max} = \omega_0 \gamma^2 (1 + \beta)^2 \approx 4\gamma^2 \omega_0 \quad (9)$$

where ω_0 is the laser frequency. Thus, the X-ray photon energy $\hbar\omega$ scales linearly with laser photon energy $\hbar\omega_0$, and quadratically with the electron energy ($\sim \gamma m_0 c^2$). The quadratic dependence in (9) stems physically from double relativistic Doppler shifts [25, 26], due to Lorentz transformations of distance and frequency—from Einstein’s theory of special relativity—between the laboratory rest frame and the moving frame of a relativistic electron. The first factor of γ arises when the wavelength of light is Doppler-shifted to shorter wavelength in the moving frame of a highly relativistic electron. The second γ factor arises because light emitted by the electron, in its moving frame, is once again Doppler-shifted to shorter wavelength through Lorentz transformation to the laboratory frame of a stationary observer. This hand-waving argument is confirmed by exact treatments [25, 26]. The relative X-ray energy spread is simply proportional to the relative electron energy spread, $\Delta\omega/\omega \approx 2\Delta\gamma/\gamma$, which is found by differentiating both sides of Equation (9).

Since the wavelength of laser light $2\pi c/\omega_0$ is much shorter than the wavelength of a magnetic undulator (micron, instead of centimeter), Equation (9) indicates that, for a given electron energy γ , the X-rays generated by ICS can have correspondingly higher photon energy $\omega_{\max}$ than the X-rays generated by synchrotrons. Since photon energies as high as 10–100 MeV range can be generated by ICS sources, they have typically been used for photo-nuclear research—ever since they were developed in the 1960s [32].

However, ICS can also be advantageous for producing the lower energy X-rays used in atomic materials and biomedical research. Here again, since the wavelength of ICS laser light is much shorter than the minimum achievable wavelength of a magnetic undulator, the electron energy required to generate X-rays of given photon energy is much reduced, which greatly reduces the maximum required accelerator length, and results in a far more

compact X-ray light source. This advantage can greatly expand the range of applications for bright X-ray sources.

2.1.5. Scaling of X-ray beam divergence

The simple dipole radiation pattern of Thomson scattering in the moving frame of a relativistic electron (discussed in Section 2.1.2) becomes—after Lorentz transformation—strongly peaked in the direction of relativistic electron beam propagation in the laboratory frame. The angle of X-ray beam divergence scales inversely with electron energy as $\theta \approx \gamma^{-1} \ll 1$, and all photons emitted in the forward hemisphere in the moving frame will be emitted inside a cone of solid angle $\Delta\Omega \approx \pi/\gamma^2$ in the laboratory frame.

2.1.6. Scaling with laser intensity: undulator versus wiggler

As can be seen from Equation (10), the total radiated fluence scales linearly with laser intensity, a_0^2 . In the linear case, $a_0 \ll 1$, the theoretically predicted X-ray spectrum is peaked and has a relatively narrow bandwidth, as shown in Figure 5. In synchrotrons, this is comparable to the undulator case, $K \ll 1$, where K is the magnetic field strength parameter comparable to a_0 . For $a_0 \geq 1$, although the total amount of radiated energy increases, the X-ray spectrum will also become broader and contain harmonic content, as demonstrated experimentally [30,33], and illustrated theoretically in Figure 5 (dashed line); this is comparable to the “wiggler” case for synchrotrons. This limit is commonly referred to as relativistic nonlinear Thomson scattering [30, 34–41]. Since harmonic generation can be interpreted quantum mechanically as a

Figure 5. “Normalized on-axis spectrum as a function of normalized photon energy y [$y = \omega'/(4\gamma^2\omega_0)$] for different laser pulse amplitudes: (1) $a_0 = 0.2$ (black dashed line); (2) $a_0 = 0.1$ (green solid line); (3) $a_0 = 0.05$ (red solid line); (4) $a_0 = 0.035$ (blue solid line).” (Reprinted from [47].) © IOP Publishing. Reproduced with permission. All rights reserved.

multi-photon scattering event, it is understandable why harmonics are generated when the intensity of incident photons is high $a_0 \geq 1$. For the nonlinear case, the radiated power scales as a_0^{-1} ; whereas for the linear case, it scales as a_0^2 [37].

2.1.7. Scaling of X-ray spectral fluence

Several models for the radiated X-ray power from ICS have been discussed [42–47]. The total angular spectral fluence for the fundamental W_1 at line center in the forward direction is given by [28] (Equation 10.335, p. 530)

$$\frac{d^2 W_1}{d\omega d\Omega} \approx \frac{q^2 N^2 \gamma^2}{2\pi\epsilon_0 c} \frac{a_0^2}{(1 + a_0^2)^2} \quad (10)$$

where N is the number of oscillations per scattering pulse. From Equations (9) and (10), it can be seen that synchrotrons and ICS both require highly relativistic beams to efficiently generate high-energy X-rays, as their X-ray photon energy and the X-ray angular spectral fluence scale as γ^2 . For scattering from a beam of electrons, assuming incoherent emission, the fluence is simply the product of Equation (10) and the total number of electrons in the beam N_e .

3. Principles and modeling of laser wakefield acceleration

This topic alone has been the subject of several recent reviews [48–50]. The basic idea was developed theoretically in 1979 [51], which was over a decade before development of the high-peak-power lasers required to demonstrate the concept experimentally.

Let us begin with the following simple conceptual explanation of laser wakefield acceleration. When laser light is focused to high intensity in plasma, light pressure can drive a “wake” behind the laser pulse. The wake takes the form of an electron density rarefaction, which creates an electrostatic potential, or wakefield plasma wave. If the plasma is highly underdense, then the light pulse and the wakefield will both propagate at just below the speed of light.¹ This can be close to same velocity as a beam of relativistic electrons. Thus, if the relativistic electrons are injected into the wave in just the right phase, at the peak of the potential, then they can gain energy from the wave.²

For maximum energy gain, the electrons should be extracted from the plasma before either of two conditions are met: (1) dephasing occurs, because the electrons eventually outrun electrostatic potential, or (2) the laser pump energy becomes depleted. For $a_0^2 \ll 1$, the dephasing length is given by $L_d \approx \lambda_p^3/2\lambda^2$, and the pump depletion length by $L_{pd} \approx 2\lambda_p^3/a_0^2 \lambda^2$ [48].

Figure 6. Laser wakefield electron-density profile from a particle-in-cell-code simulation [55]. Blue circle shows position of laser pulse. Since the region in the wake of the laser pulse (white area on left side, above, below, and inside the blue circle) is completely evacuated of electrons, it is often referred to as the “blowout region.” Reprinted with permission from S. Y. Kalmykov.

Current experiments operate in a nonlinear regime, $a_0^2 \geq 1$, where the rarefaction region behind the laser pulse becomes completely evacuated of electrons, forming a “bubble.” This is often referred to as the “blowout” regime [52–54]. Figure 6 shows density blowout from a particle-in-cell simulation [55]. A matching condition—on the laser intensity and plasma density—for optimal blow-out was derived analytically, by balancing the laser ponderomotive force on a single electron with the ion channel force [54]; both numerical simulation [54] and experiment [56] support the analysis.

Another condition that must be met in order for electrons to gain the maximum amount of energy from a single stage of a laser wakefield accelerator is that the laser light pulse must somehow be guided, or propagate without increase in beam diameter, and thus decrease in intensity, over an extended distance. This stems from the fact that in order to reach the high intensities required to drive a wakefield, with the parameters of current high-power lasers, the vacuum diffraction distance (the Rayleigh range) is typically on the order of 100 μm , which, to achieve the above-mentioned matching condition, is much less than either L_d or L_{pd} (mm–cm range). Fortunately, if the laser power exceeds a certain threshold value, then the laser light pulse will be relativistically self-guided over distances exceeding many Rayleigh ranges [57,58]. There are also several methods for externally guiding high-intensity light, such as the use of capillaries and preformed plasma channels [59–61].

Significant strides have been made in developing new theoretical approaches, and benchmarking them against experimental results [54,62]. One of the major recent challenges has been the development of numerical models that

capture all features of actual experiments. Due to computational limitations, compromises were needed in order to follow the fields and plasma dynamics over the mm–cm-sized region of laser propagation. These approximations have been accompanied by a commensurate compromise in the accuracy of the results. More computationally efficient numerical models are under development [63, 64]. Numerical codes based on the particle-in-cell algorithm have also recently been adapted to run on large and inexpensive clusters of graphic processing units (GPUs) [65, 66]. Also, new algorithms have been developed to solve the fields and dynamics in the boosted frame of the wakefield, and transform back to the laboratory frame through Lorentz transformations [67]. Also, improved handling of collisions and ionization in particle-in-cell codes have been discussed [68].

4. Recent experimental progress

4.1. Compact and repetitive high-power lasers

The standard laser system used for this type of research has an all-solid-state architecture. It is usually based on the technique of chirped-pulse amplification [6], broadband amplification media (e.g. titanium sapphire [7] and an oscillator with Kerr-lens mode locking [8]). Most modern repetitive high-peak-power systems [9–11] are composed of the same basic design elements, as shown in Table 1. Typical operating parameters are shown in Table 2.

4.2. Laser wakefield electron accelerators

Several comprehensive reviews have been published recently on this broad topic [48–50]. Thus, only some brief historical perspectives will be reviewed here, from the particular perspective that progress in laser wakefield research and development has been correlated with advances in high-peak-power laser technology.

For instance, experimental demonstrations of laser wakefield electron acceleration [57, 69, 70] had to await development of terawatt-peak-power laser systems. The light from these chirped-pulse-amplification systems [6] could be focused to relativistic intensity levels ($a_0 \sim 1$), one of the primary requirements for driving a laser wakefield plasma wave. Terawatt-power light pulses also exceeded the threshold for relativistic self-guiding, allowing laser light to propagate for the first time at relativistic intensity over distances exceeding a Rayleigh range [57, 58]. However, because these early high-power lasers were based on Nd:glass amplifiers, their relatively narrow bandwidth limited the minimum achievable pulse duration to the sub-picosecond range. This combination of relativistic intensity, but sub-picosecond pulse duration,

Table 1. Features of modern high-peak-power laser systems.

Component sub-system	Features
Oscillator	• Gain medium: Ti:sapphire crystal • Kerr-lens mode-locked • Laser-pumped: by a diode-pumped and frequency-doubled YLF laser
Stretcher	• All-reflective aberration-free
Spectral phase modulator	• Acoustic-optical
Multi-pass power amplifiers	• Gain medium: Ti:sapphire crystals • Laser-pumped: by flashlamp-pumped and frequency-doubled YAG lasers
Pulse compressor	• Holographic-etched gold-coated gratings
Deformable mirror	• Feedback control with laser beam spatial phase profile measurements

Table 2. Typical high-peak-power laser parameters.

Parameter	Value
Peak power	100 TW
Repetition rate	10 Hz
Wavelength	805 nm
Duration	<30 fs
Energy	3 J
Energy stability	<1% (rms)
Energy contrast	10 ⁷ at 100 ps

meant that the self-modulation of the laser pulse during propagation in the plasma was required in order to drive a plasma wave. This drives the plasma wave through the mechanism of stimulated Raman forward scattering, and also breaks the long-duration pulse into a train of shorter resonant pulses. However, since the trapping of electrons was uncontrolled and continuous, due to plasma-wave wavebreaking, the accelerated electron beams had large energy spreads; their spectra exhibited the features similar to high-temperature Maxwellian distributions.

It was not until Ti:sapphire was adopted as the laser gain medium—with its much wider gain bandwidth—that femtosecond-duration, multi-ten-terawatt-peak-power, laser pulses could be produced. This combination of shorter pulse and higher intensity, without the need of self-modulation, enabled laser wakefield accelerators to operate in the blowout regime [52–54], shown in Figure 6. In this case, it first became possible to limit the region over which self-injection of electrons occurred, and thus produce quasi-monoenergetic electron beams [59, 71, 72].

Improvements in laser beam quality, in terms of energy contrast, enabled further reduction of the electron energy spread of self-injected electrons [73]. The availability of multiple pulses from a single laser system enabled further

Table 3. Laser wakefield electron beam parameters.

Electron beam parameter	Measured value
Field gradient	100 GeV/m
Divergence angle	2 mrad
Energy spread	10%
Emittance	1 mm-mrad (RMS)

reduction of the electron energy spread by means of controlled optical injection of electrons [74–76]. Control of laser stability and laser–plasma parameters has enabled electron energy tunability [73, 77, 78]. The recent availability of lasers capable of producing petawatt-level peak powers has enabled peak accelerated electron energies to reach the multi-GeV level [79,80].

As discussed in Section 4.3, accelerators producing electron beams with sub-GeV peak energy are sufficient to generate—by means of all-laser-driven X-ray sources—the maximum X-ray photon energy needed for X-ray applications. Such accelerators are driven by lasers that operate at sub-PW peak power level and at 10-Hz repetition rate, with the nominal set of laser parameters shown in Table 2. The required electron energies can be achieved with current laser-driven accelerators, with the nominal parameters shown in Table 3.

Higher average current, better control and stability, and more robust system designs would all serve to improve the practicality of applications of accelerator-driven X-ray sources. Laser–plasma accelerators have also been improved by recent innovations in experimental diagnostics [81] and plasma target designs [78, 82–86]. Both of these research areas continue to be of active interest.

4.3. X-ray light sources based on ICS

X-ray synchrotrons and X-ray free-electron lasers have proven to be transformational technologies for physical and biological sciences. By virtue of its unique characteristics, all-laser-driven Thomson X-ray sources may have similar transformational potential. Not only do their X-ray peak brightness and photon energy rival that of third-generation X-ray synchrotrons, but their femtosecond X-ray pulse duration is comparable to X-ray free-electron lasers. Moreover, the device is small enough to fit in a university laboratory.

In all experimental demonstrations reported thus far, intense light pulses amplified by a single high-power laser system are used. One laser pulse rapidly accelerates electrons (>100 GeV/m) by means of the laser wakefield mechanism; and the other laser pulse Thomson-backscatters from the relativistic electrons. The scattered light Doppler-upshifts relativistically to high photon energy. The canonical experimental set-up is shown in Figure 7.

In the first reported experiment, Schwoerer et al. [43] overlapped the two laser beams inside the plasma used to accelerate the electrons; they reported the emission of soft X-ray (~ 1 -keV) without any beam properties. Later, Ta Phuoc et al. [14] used a single laser pulse first to accelerate the electrons, and then Thomson-backscattered with the same laser pulse, after reflecting it from a mirror (a plasma mirror). In this case, hard X-rays are produced (~ 50 -keV), but the spectrum of the photon number spectral density (photon number per unit energy plotted versus photon energy) is broad and not peaked.³ Chen et al. [13] then used two separate counterpropagating beams overlapped in the vacuum outside the plasma, as in Figure 7, to reach X-ray photon energy of 4 MeV. The electron beam was also well collimated (10-mrad divergence

angle). However, as was the case with Ta Phuoc et al., the X-ray photon spectrum is broad and not peaked. Unlike Ta Phuoc et al., the design used by Chen et al. does not suffer from the risk of several deleterious effects caused by debris contamination and bremsstrahlung background.

More recently, Powers et al. [15] studied all-laser-driven ICS, using the same geometry as used by Chen et al. [13], but employed a laser-accelerated electron beam that had a monoenergetic spectrum. This difference allowed them to report the first demonstration of peaked X-ray photon number spectral density spectrum (Figure 8), as expected from theory (Figure 5). Additionally, they were able to demonstrate, as shown in Figure 9, that the X-ray photon energy could be tuned over an unprecedentedly large range, extending greater than one order of magnitude (from 50 keV to 1 MeV). This was accomplished by tuning the energy of the electron beam (from 50 MeV to 300 MeV) [78]. These results represent the first demonstration of any type of all-laser-driven hard X-ray source with a peaked photon number spectral density spectrum. It is also a demonstration of the widest tuning range of an X-ray source of any type.

Liu et al. [87] used a novel laser system design with two separate independently controllable laser pulse compressors, and second harmonic generation of the scattering laser beam, to reach an X-ray energy of 9 MeV, which—by virtue of exceeding the giant dipole resonance—is sufficient for photo-nuclear active interrogation [88] and shielded radiography [18]. The ability to use two laser pulses with independently variable parameters allows for independent optimization of both the electron acceleration and the scattering, which have very different parameter requirements.

For all of these experiments, the type of target chosen for the accelerator medium was the supersonic gas jet

Figure 7. Schematic configuration for all-laser-driven Thomson X-ray source. Reprinted from [15].

Figure 8. Left: X-ray beam profile [18], reprinted with permission from Elsevier. Right: X-ray spectrum (inset: electron spectrum) [15].

created by a pulsed valve. The primary advantages of gas jet targets are the following: (1) their absence of solid-density walls, which can produce deleterious bremsstrahlung radiation background when struck by laser light or electrons; (2) their immunity to damage, allowing continuous operation at high repetition rate; (3) their lack of ablation debris that can coat optical elements; and (4) their relative insensitivity to misalignment in the transverse location of the laser focus. Because of their ability to guide light beyond a Rayleigh range [61] without the need for relativistic self-guiding, capillaries were used in experiments that achieved multi-GeV electron energies. Capillaries have also been proposed for use in all-laser-driven ICS [47].

Figure 9. X-ray photon energy versus electron beam energy [15].

The latest experimental results on all-laser-driven ICS were achieved with the nominal laser and electron parameters shown in Tables 2 and 3, respectively. Shown in Table 4 are the nominal X-ray parameters that were reported. The parameter region in which all-laser-driven ICS sources operate differs from those of conventional ICS X-ray sources, storage ring synchrotrons or linear X-ray free-electron lasers. All-laser-driven ICS sources currently deliver a relatively high number of X-ray photons per shot, but at a relatively low repetition rate. The measured flux is 10^4 times higher than that reported by several demonstrations of ICS with ultrashort-pulsed lasers and conventional radio-frequency accelerators [89, 90], due to the advantage of all-laser-driven ICS sources in terms of an intrinsically better matching between the scattering laser focal size and the size of the electron beam at the scattering interaction location. In fact, the measured flux is comparable to that produced by advanced ICS-gamma-energy nuclear research facilities [91]. ICS sources that are all-laser-driven are also tunable over an unprecedentedly large photon energy range. As compared with bremsstrahlung sources, they have relatively narrow bandwidth and low intrinsic beam divergence, and, consequently, higher spectral intensity. Due to limitations on the electron beam

Table 4. All-laser-driven X-ray source parameters.

X-ray parameter	Value
Photon number	10^7
Peak energy	10 keV–10 MeV
Energy spread	~50% (FWHM)

emittance presently achievable with laser-driven electron accelerators, the X-ray beam divergence angle of all-laser-driven ICS sources is currently considerably larger than the theoretical limit $\theta \approx \gamma^{-1}$ predicted for single electrons or ideal electron beams.

5. Outlook for the further progress

5.1. Further X-ray source development

5.1.1. Technological improvements

Further improvements in X-ray performance can be expected [47] with advances in laser-plasma accelerator technology and high-peak-power lasers. The X-ray bandwidth will decrease as the e-beam bandwidth decreases. The X-ray beam divergence angle will decrease as electron beam emittance decreases. Control and stability of ICS X-rays will also improve with comparable improvement of accelerator performance. Higher X-ray flux and even more compact ICS sources will result from advances being made in high-power lasers—based on new gain materials, diode pumping and fiber laser pumping.

For applications requiring relatively narrow bandwidth light, operating ICS in wiggler mode ($a_0 \geq 1$) is only practical for increasing the X-ray fluence of low-energy X-rays, since only in this case are dispersive reflective optics available to monochromatize the broad-bandwidth X-rays produced. Unfortunately, no such monochrometers exist for high-energy (gamma-ray-energy) X-rays. As can be seen from scaling of Equation (10), there are several practical alternative approaches to linearly increase the X-ray fluence, by increasing either the charge per pulse of the electron beam N_e , or the number of cycles per incident laser pulse N , but use ICS in the linear, or undulator mode $a_0 < 1$. In order to increase N , the incident laser pulse duration τ needs to be increased, since $N \propto \tau$. However, in order to hold a_0 constant, the energy of the incident scattering laser pulse (U) also needs to be increased proportionally, since $a_0^2 \propto U/\tau$. This strategy only works with two independently controllable laser pulses [87], since optimization of the pulse that drives ICS has a different parameter scaling than the pulse that drives laser wake-field acceleration.

Although an all-laser-driven ICS source has already reached a photon energy of 9 MeV [87], which exceeds the threshold for photo-activation of most materials, the X-ray photon energy $\omega_{\max}$ can be increased even further. As can be seen by Equation (9), this can be accomplished either by increasing the electron energy γ or the scattering laser photon energy ω_0 . The primary

disadvantage of increasing γ , especially for compact X-ray sources, is the commensurate increased device size and weight, associated with the increased sizes of the requisite electron beam-dump and the radiological hazard shield.

5.1.2. Traveling wave amplification

Traveling wave amplification [92, 93] has been proposed theoretically to increase the X-ray flux and brightness by several orders of magnitude. In this geometry, instead of backscattering the scattering laser beam, it is cylindrically focused to a line parallel to the path of the electron beam. This, and use of a tilted wave front, can in principle substantially increase the scattering interaction length. Of course, much higher laser energy is required to provide sufficiently high light intensity over a line focus instead of a round focus.

5.1.3. Electromagnetic undulator free-electron laser

With expected improvements in the emittance of laser-driven accelerators, it may be possible to dramatically increase the ICS X-ray brightness via the free-electron lasing mechanism. Here, electrons in the beam become bunched by the ponderomotive force of the beat wave formed by interference between the incident optical and scattered X-ray photons. Electrons bunched in this way will radiate coherently, scaling as N_e^2 , instead of as N_e , as in ordinary incoherent ICS. X-ray free-electron lasers based on laser-driven electron accelerators were proposed [94–96] and demonstrated with conventional fixed magnet undulators [97]. They are yet to be demonstrated experimentally with electromagnetic undulators.

5.2. Potential for X-ray applications

5.2.1. Ultrafast X-ray science

The new source has advantages for X-ray science in general, and for the study of ultrafast phenomena in particular. Its exceptionally large X-ray-energy tuning range facilitates probing of almost any element's inner-shell atomic structure. Its femtosecond X-ray pulse duration, coupled to high photon energy, enables ultrafast time-resolved studies with atomic-scale spatial and temporal resolutions [19]. Its synchronization with ultra-high-intensity laser light pulses ($\leq 10^{26} \text{ W/m}^2$, $a_0 \sim 100$) can merge ultrafast science with high-field science. For example, ultrafast dynamics of either highly stripped atoms or extreme states of matter can be investigated [98].

5.2.2. Metrology and nondestructive evaluation

The micron source size of all-laser-driven X-rays is small enough to provide the necessary resolution to characterize (via small-angle scattering) the nanometer structures of advanced semiconductor chips. Additionally, the source's high X-ray photon energy can be used to measure cracks and voids in thick materials.

5.2.3. Biomedical and nuclear radiology

Even with their currently demonstrated characteristics, all-laser-driven X-ray sources have the potential to improve medical applications [99], nuclear radiology [100–103] and radiotherapy [104–106]. Their high photon energy, relatively narrow energy spread, wide tunability range as well as micron radiation source size [73, 85, 107, 108] can all serve to increase spatial resolution, image contrast and signal-to-noise level. Moreover, they can do so while also delivering much lower harmful radiation dose than with conventional bremsstrahlung X-ray sources. Also, MeV photon energy, combined with ultrashort pulse duration, may enable exploration of a new research direction, namely ultrafast nuclear science [109, 110]. For instance, Weidenmüller [110] recently investigated theoretically the possibility that “a zeptosecond multi-MeV laser pulse may either excite a ‘plasma’ of strongly interacting nucleons or a collective mode.”

5.2.4. Experimental studies of theoretical models for radiation reaction

The new possibility of combining ultra-high-intensity scattering light ($\leq 10^{26}$ W/m², $a_0 \sim 100$) with ICS can be used to experimentally test the various previously untested theoretical models for the radiation reaction force [111–116]. This fundamental electrodynamical mechanism involves the reaction of an electron to its “self-force” caused by the electromagnetic fields emitted by the electron itself when it is in a strong external electromagnetic field. Predicted observable signatures include modification of the Thomson cross-section, damping of the electron beam and change in the X-ray spectral and angular distributions. Experiments at such high fields may also enable studies of scattering in the quantum regime, including nonlinear Compton scattering, vacuum birefringence or even, eventually, vacuum breakdown.⁴

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Notes

1. A light pulse propagates in plasma at the group velocity, $v_g = c(1 - \omega_p^2/\omega_0^2)^{1/2}$, where ω_p is the plasma frequency, defined by $\omega_p = (n_e q^2/\epsilon_0 m_e)^{1/2}$, and n_e is the plasma density. In highly under-dense plasmas, $v_g \sim c$, since in this case $\omega_p^2 \ll \omega_0^2$, or $n_e \ll n_c$, where n_c is the critical density, the density at which $\omega_0 = \omega_p$.
2. When relativistic electrons, with $v \approx c$, are accelerated, their kinetic energy increases much more rapidly than does their velocity, since the relativistic kinetic energy is $\approx \gamma m_0 c^2$.
3. Photon energy spectral densities, or photon energy per unit bandwidth (MeV/MeV), can be peaked due to the nonuniform photon energy weighting. However, the same spectrum may not be peaked when plotted as photon number spectral density, photon number per unit bandwidth (MeV⁻¹), which has even energy weighting.
4. Several relevant articles were published subsequent to submission of this manuscript: [18, 117, 118].

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