Compact laser accelerators for X-ray phase-contrast imaging

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Advances in X-ray imaging techniques have been driven by advances in novel X-ray sources. The latest fourth-generation X-ray sources can boast large photon fluxes at unprecedented brightness. However, the large size of these facilities means that these sources are not available for everyday applications. With advances in laser plasma acceleration, electron beams can now be generated at energies comparable to those used in light sources, but in university-sized laboratories. By making use of the strong transverse focusing of plasma accelerators, bright sources of betatron radiation have been produced. Here, we demonstrate phase-contrast imaging of a biological sample for the first time by radiation generated by GeV electron beams produced by a laser accelerator. The work was performed using a greater than 300 TW laser, which allowed the energy of the synchrotron source to be extended to the 10–100 keV range.
1. Introduction

The use of particle accelerators has revolutionized the creation of high-quality X-ray beams. By using synchrotron radiation produced by the bending or undulating of GeV energy electron beams, intense beams of X-rays can be produced with ever-increasing brightness and versatility. Coupled with attractive properties such as high spatial resolution, high temporal resolution, spatial coherence and even significant temporal coherence, this has made them suitable for ever-demanding novel X-ray imaging techniques. However, these third- [1] and now fourth-generation [2] light sources require particle accelerators that are measured in the hundreds of metres, if not kilometres. This limits the widespread adoption of advanced imaging techniques based on these novel sources.

There has also been an increasingly rapid development in the peak intensity available in modern optical laser systems. These systems possess the ability to focus energy to small spatial scales. Indeed, the electric field at the focus of a laser can far exceed that produced in conventional accelerators. But because this field is transverse and oscillating, it is not particularly useful for controlled acceleration of particles. There are, though, a number of methods of generating more energetic photons from intense laser drivers.

The simplest is to use the high energy density at the focus of a laser beam to heat material to high temperatures. Temperatures can trivially exceed keV (approx. 10^8 K) for intensities \( I > 10^{15} \text{ W cm}^{-2} \) [3]. The recombination of ionized plasma ions, on cooling, leads to a monochromatic \( K_{\alpha} \) feature [4] whose wavelength is dependent on the target material. Owing to the small size of the laser focus (approx. \( \mu \text{m} \)), the X-ray emission is close to a point source, and the brightness of the \( K_{\alpha} \) emission can be high. The small source size makes it ideal for imaging techniques based on point projection too [5]. However, the thermal nature of the emission means that photon emission is uncorrelated, and therefore generally incoherent. Also, though the emission can be short in duration, it is always dominated by thermal cooling rates (\( \sim \text{ps} \)), even for heating with ultrashort laser pulses (\( \tau \ll \text{ps} \)).

High-intensity lasers can also be used to produce high-energy photons through the nonlinear response they elicit in matter. In particular, they can produce harmonics of the laser frequency, with photon energies \( E_p = p \hbar \omega \), where \( p \) is an integer (\( p_{\text{max}} > 100 \)). Harmonics are readily produced in gases at intensities close to the threshold for ionization [6,7]. As the harmonics are synchronized to the main laser beam, they also exhibit spatial and temporal coherence. High harmonic generation (HHG) occurs most readily at the peak of the laser’s intensity both spatially and temporally. Hence, the harmonics possess smaller spatial and temporal dimension than the original pulse, leading to the generation of attosecond harmonic pulses from femtosecond laser pulses [8]. Gas harmonics, though, are limited to a maximum laser intensity before the medium becomes highly ionized and the nonlinear atomic response is lost. Recently, it has been shown that a longer wavelength driver can lead to shorter wavelength HHG owing to the increased nonlinear response at longer wavelength [9]. However, HHG below 1 nm is still a challenge.

HHG can also occur through the nonlinear response of a solid surface at high laser intensity—the so-called relativistic oscillating mirror [10]. This scheme shows promise for scaling to X-ray wavelengths [11], though it imposes strong requirements on the laser system. In particular, it requires very high contrast ratio so that the target does not expand too much before arrival of the main beam. Though X-ray production from solid harmonics has been demonstrated [12], controlling this process is also challenging. Numerous alternative schemes using relativistic scattering of laser photons have also been proposed and demonstrated but usually require additional complication in terms of target arrangement [13–15].

An alternative use of high-intensity lasers in radiation generation is to first convert the energy into a fast particle beam [16]. Intense lasers can generate electric fields inside a plasma which can easily exceed by \( > 10^3 \) times the fields present in conventional accelerators. Consequently, a linear accelerator based on a plasma (at the intensities considered all material is ionized) driven by lasers can be many times smaller than the corresponding conventional accelerator, with the total size usually dependent only on the size of the laser. Recent advances in laser technology have allowed...
Figure 1. Cartoon of a ‘bubble’ accelerator. A region of space is evacuated of electrons (white region) by a high intensity laser creating a force that points inward on an electron (arrows). For a sufficiently large bubble, an electron inside the electron sheath is accelerated forward, as well as gaining transverse momentum, from the wakefield (black trajectory). If the acceleration is sufficient, it can become trapped, performing betatron oscillations of amplitude $r_B$ as it moves forward in the wave frame. At each turn of the oscillation, the acceleration (which points towards the axis) is primarily normal to the particle motion, leading to synchrotron-like radiation in the forward direction (shown by cones). (Online version in colour.)

demonstration of acceleration to the GeV energy scale in a plasma of the order of centimetres [17–19]. This is notable because this is the energy range of accelerators that drive third-generation light sources that are typically based on synchrotron rings of diameter of the order of hundreds of metres. By contrast, the compact plasma-based accelerators are now available in a footprint less than $10 \times 10^4$ m$^2$. Initial results sending a laser wakefield produced electron beam through a conventional insertion device (undulator/wiggler), which is a series of (usually equally) spaced magnetic fields with regularly varying field direction, have demonstrated the compactness of this scheme, though with as yet rather modest photons numbers [20,21].

A laser wakefield accelerator also possesses strong transverse fields that serve to focus the electron beam as it is being accelerated. Indeed, these fields are vital to maintain the electron beam in the small spatial dimensions (approx. 10 $\mu$m) of the wakefield. Any accelerated electron that is initially off the axis of propagation of the accelerating structure will therefore be naturally pulled back towards the axis of the wakefield as demonstrated in figure 1. However, as these electrons have transverse momentum as they arrive on-axis, they will overshoot before being stopped and returned on-axis once more by the electric field. Hence, the electron oscillates around the axis. These oscillations resemble those performed by electron beams in conventional accelerators and are usually called betatron oscillations, because they were first observed in betatron accelerators.

These oscillations are also analogous to those of electron beams in the external fields of an undulator/wiggler, and they will radiate in a similar fashion too. However, the fields associated with the oscillations in the plasma wave are many orders of magnitude greater than those of a typical insertion device, in the same way that the acceleration in a wakefield is greater than in a conventional device. This leads to much smaller oscillation wavelength (approx. 100 $\mu$m), and consequently much greater photon energy for a given electron energy. Hence, X-rays can be produced by electrons of energies of only $E_e \gtrsim 100$ MeV [22]. Even though the electrons do not perform many oscillations in the wakefield owing to the short acceleration length, the strength of the oscillation still leads to an appreciable photon yield.

Synchrotron (betatron) radiation from laser wakefield accelerators was first observed in a regime where the wakefield was driven strongly to enable background plasma electrons to be directly trapped and accelerated in the wakefield [22]. Although accelerated quickly, the
electrons produced in this way also lose energy rapidly, leading to a broad energy spread with only a few reaching the highest energies [23]. Recently, several techniques have been developed for controlling the energy spread of electrons from wakefield accelerators, with particular attention given to accelerating a high charge at high energy [24–26]. This has led to dramatic improvements in the yield of photons from laser wakefield-driven betatron oscillations [27] and has finally allowed demonstration of the use of these sources for advanced applications such as phase-contrast imaging [28].

In the rest of this paper, we outline the principles of laser wakefield acceleration of electrons and their generation of X-ray radiation. We then describe a recent experiment where proof-of-principle phase-contrast imaging has been performed for the first time with electrons of GeV energy scale. This experiment demonstrates the potential of these sources for advanced X-ray imaging applications.

2. Laser wakefield acceleration

Modern high-power laser pulses can be easily focused to intensities $I > 10^{18}$ W cm$^{-2}$. This energy density is vital for plasma accelerators where particles gain a lot of energy in small spatial dimensions, and so the driver must also be able to deliver energy to the same small dimensions. Most laser accelerators use the method of laser wakefield acceleration [16]. In this scheme, a short pulse laser is made to be resonant with an electron plasma wave by choosing its length to be about half the plasma wave wavelength, $\lambda_p = 2\pi c/\omega_p \approx 1.05 \times (10^{21}/n_e \text{[cm}^{-3}] )^{1/2} \mu$m. For a plasma of density $n_e = 10^{18}$ cm$^{-3}$, $\lambda_p \sim 30 \mu$m, implying the need for short laser pulse lengths $\tau \sim \lambda_p/2c \lesssim 50$ fs.

Ideally, the laser pulse is focused to the spot size required for relativistic self-guiding, which is where the laser beam size remains unchanged for propagation over many times its Rayleigh length $z_R$ (the length over which it would normally diverge) owing to the relativistic response of the plasma medium at high intensity [29]. As a result, the plasma wave can also be generated over an extended length without large variation in size. The matched size is found to be approximately $\lambda_p$ and only weakly dependent on intensity. Hence, both laser pulse and plasma wave are then approximately spherical in shape with diameter approximately $\lambda_p$, and consequently this type of plasma accelerator is often called a ‘bubble accelerator’ (figure 1) [30].

The longitudinal electric field associated with the plasma wave is $E \sim a_0mc\omega_p/e \sim a_0 \cdot 0.96 n_e \text{[cm}^{-3}] V \text{cm}^{-1}$ [31], for a peak laser strength parameter $a_0 \simeq 0.89 (I_{18}\lambda_{\mu m})^{1/2} \gtrsim 1$, where the intensity $I_{18}$ is in units of $10^{18}$ W cm$^{-2}$ and wavelength $\lambda_{\mu m}$ is in micrometres. The plasma frequency is dependent on plasma density: $\omega_p \simeq 56.400 (n_e \text{[cm}^{-3}] )^{1/2} \text{s}^{-1}$. Hence for a laser wakefield operating at $n_e \approx 10^{18}$ cm$^{-3}$, electric fields of $\sim 10^8$ V cm$^{-1}$ can be conceived, implying acceleration to GeV energies in only a centimetre. A number of experiments have now demonstrated this level of acceleration [17–19].

It is challenging to inject electrons into the small spatial and temporal scales of the wakefield. Electrons from a conventional accelerator can be injected into the wakefield, but matching the beam properties to the wakefield size is difficult leading to low efficiency of particle trapping [32]. A number of advanced techniques have been proposed and demonstrated that use density modification [33–35], secondary laser beams [36–38] or ionization [39–41] to greatly simplify injection into the wakefield. But, perhaps the easiest way of injecting high charge beams into the wakefield is through the use of self-injection [24–26]. Initially, stationary background electrons are accelerated as the wakefield passes by them. For a large amplitude wakefield, the energy gain can be enough such that the electrons ‘keep up’ with the wakefield. Hence, they obtain a Lorentz factor equivalent to that of the plasma wave, which is equal to that of the laser group velocity $\gamma_{ph} \sim \omega_p/\omega_p \sim 10^{21}/(n_e \text{[cm}^{-3}] )$. For trapping of electrons in this way, the plasma bubble needs to exceed a certain size, which is ensured for $a_0 \gtrsim 4$ [42,43].

The trajectory of the electrons injected in this way is shown in the cartoon in figure 1. For a wakefield size just above threshold, the electrons are turned around towards the rear of the bubble structure, and in this case they feel the largest electric fields and have the longest acceleration
lengths. As the bubble travels at the group velocity of the laser in the plasma ($\gamma_{ph}$), the electrons can quickly start to travel faster than the bubble and be accelerated forward in the frame moving at the velocity of the bubble. Indeed, at some point, they can travel beyond the centre of the bubble to where the electric field is reversed in direction, so that they start to decelerate. The maximum energy gained before this *dephasing* varies as $E_{\text{max}} \propto \gamma_{ph}^2 \propto (\omega_{0}/\omega_p)^2 \propto n_e^{-1}$. Hence, $E_{\text{max}}$ increases with decreasing plasma density (despite reduction in the acceleration), because it takes longer to outrun the faster moving plasma waves at lower density. The maximum energy gain is then $E_{\text{max}} \approx a_0 \gamma_{ph}^2 m c^2 \approx a_0 \cdot (10^{21}/n_e[\text{cm}^{-3}]) \text{MeV}$.

3. X-ray generation

As shown in figure 1, as the electrons originate from relatively large transverse displacements (electrons originally closer to the axis are scattered away by the laser’s ponderomotive force), they also gain transverse momentum from the plasma wave fields. This causes them to repeatedly oscillate around the axis as they accelerate. In the laboratory frame, the wavelength of the oscillation is $\lambda_{\beta} = (2 \gamma_{0})^{1/2} \lambda_p$, where $\gamma_{0}$ is the Lorentz factor associated with the longitudinal motion of the accelerated electron. The amplitude decreases owing to the increased $\gamma_{0}$ of the electron in the longitudinal direction, which causes transverse velocity to decrease for a fixed maximum transverse momentum. This oscillation will cause the electron to radiate strongly in a similar way to electrons in an undulator/wiggler [44]. As for the undulator/wiggler, owing to the relativistic motion of the electrons, this radiation will be primarily beamed in their direction of travel.

For small transverse oscillations, the radiation is the result of a dipole oscillation in the stationary frame of the electron, which because of the relativistic increase in field strengths in the (relativistically) boosted frame is $\gamma_{20}$ times faster. This results in radiation of frequency $\nu_{\beta0} = \omega_{0} / \gamma_{0}$ in the boosted frame, where $\omega_{0} = 2\pi c / \lambda_{\beta} = \omega_p / (2 \gamma_{0})^{1/2}$ is the betatron frequency in the laboratory frame. Transforming the energy of the betatron radiation back to the laboratory frame gives a photon energy $E_{\gamma} = \nu_{\beta0} \hbar \omega_{\beta}$. This is called the undulator regime, and for sufficient interaction lengths (and with tight constraints on spatial and energy spread) can result in coherent feedback leading to lasing [2]. For a typical wakefield accelerated electron of $E_{e} = 100 \text{MeV}$ in a plasma of $n_{e} = 1 \times 10^{19} \text{cm}^{-3}$ ($\lambda_{\beta} \approx 200 \mu\text{m}$), the primary wavelength of this radiation is in the extreme ultraviolet at $\approx 5 \text{nm}$ ($\approx 200 \text{eV}$). For a 1 GeV beam at $n_{e} = 10^{18} \text{cm}^{-3}$ ($\lambda_{\beta} \approx 2 \text{mm}$), the minimum photon energy ($\approx 5 \text{Å}, 2 \text{keV}$) is X-ray radiation.

With increasing oscillation amplitude $r_{\beta}$, the oscillation is no longer purely simple harmonic, owing to an increasing longitudinal component of the oscillation. The result is the production of X-rays at harmonics of the undulator wavelength, with the energy spread increasing as the degree of nonlinearity increases. In the limit of large betatron excursion, the spectrum becomes a continuum that closely resembles the synchrotron spectrum from an electron accelerated in a circular orbit. This is because the radiation is primarily produced at the apex of the electron oscillations (figure 1) at which points the trajectories are approximated by an arc of a circle. This regime of interaction makes up for the loss of monochromaticity by producing higher photon yield and at higher energies and is usually called the wiggler regime.

The two different regimes of radiation are characterized by the parameter $\alpha_{\beta} = \gamma_{20} k_{\beta} r_{\beta}$, where $r_{\beta}$ is the oscillation amplitude, and $k_{\beta} = 2\pi / \lambda_{\beta}$. $\alpha_{\beta}$ is analogous to the $K$ parameter in insertion devices, and so one can expect undulator-like single frequency production for $\alpha_{\beta} \ll 1$ (i.e. small oscillation amplitude) and wiggler-like synchrotron emission for $\alpha_{\beta} \gg 1$ (large amplitude). Note that significant X-ray emission will occur only in the synchrotron limit. Therefore, it can be inferred that most plasma accelerator/wigglers operate in the $\alpha_{\beta} \gg 1$ limit, as will be discussed further in §4. In the synchrotron limit, the emission is broadband with a ‘critical energy’ $E_{c} = 3 \hbar \gamma_{20}^{3} \omega_{p}^{2} r_{\beta} / c$. $E_{c}$ is the photon energy at which half of the integrated power is above and half below this value [44]. The angularly integrated power of emission can be found from the Larmor formula and is given by $P_{s} = (e_{0}^{2} c^{3} / 12 \pi \epsilon_{0}) \gamma_{20}^{2} k_{\beta}^{2} a_{0}^{2}$ [44]. Integrating over the time of emission $N_{\beta} \lambda_{\beta} / c$, where $N_{\beta}$ is the number of oscillations performed, it is possible to obtain a
total emitted energy, which when divided by the mean photon energy allows a calculation of the expected (single shot) brightness of the source. For the parameters given above \((E_p = 100\,\text{MeV}, n_e = 1 \times 10^{19}\,\text{cm}^{-3})\), \(E_c \approx 8\,\text{keV}\) with a brightness in excess of \(10^{23}\,\text{photons mm}^{-2}\,\text{mrad}^{-2}\,\text{s}^{-1}\) per 0.1% of bandwidth for an accelerated charge of approximately 100\,pC. For 1\,GeV, \(n_e = 1 \times 10^{18}\,\text{cm}^{-3}\), these figures become \(E_c \approx 40\,\text{keV}\) with a brightness > \(10^{24}\,\text{photons mm}^{-2}\,\text{mrad}^{-2}\,\text{s}^{-1}\) per 0.1% of bandwidth.

The first measurements of synchrotron radiation from a plasma accelerator were performed in a regime where the accelerator was driven very hard to ensure breaking, and thus trapping and acceleration of the particles. However, this leads to rapid decomposition of the accelerating structure and only allows particles to reach the highest energies (approx. 200\,MeV) for a short time [23]. The energy spread of electrons in this case is therefore very broad. Nevertheless, X-ray brightnesses approaching \(10^{19}\,\text{photons mm}^{-2}\,\text{mrad}^{-2}\,\text{s}^{-1}\) per 0.1% of bandwidth were measured [22]. By choosing laser and plasma parameters more carefully, it has been shown now that wavebreaking can be approached gradually leading to production of high-trapped charges without destroying the plasma accelerator. This leads to modest increase in electron energy but with much more charge at high energy. Plasma accelerators operating in this ‘quasimonoenergetic’ regime of self-injection have produced > \(10^8\) photons with energies > 1\,keV from an electron beam with \(E_{\text{max}} \approx 300\,\text{MeV}\) at \(n_e \approx 6 \times 10^{18}\,\text{cm}^{-3}\), leading to an X-ray brightness in excess of \(10^{22}\,\text{photons mm}^{-2}\,\text{mrad}^{-2}\,\text{s}^{-1}\) per 0.1% of bandwidth [27].

4. Phase-contrast imaging

As noted before, the generated electron beam is localized in space and time by the dimensions of the plasma bubble (though some trapping is often seen in the trailing plasma periods too). Owing to the strong focusing forces, and the fact that the longitudinal acceleration is much greater than the transverse one, the oscillation amplitude is only a small fraction of the bubble size. Kneip et al. [27] made measurements of the source size in the bubble regime, using a cleaved Si crystal as a half-plane which was illuminated by the X-ray beam. For a Gaussian source, one would expect the transmission to follow an error function with slope dependent on the source size. These measurements confirmed that the source size was as small as 1\,\mu m RMS.

Particularly notable though in these measurements was that the X-ray shadow was not a perfect error function. An enhancement of the transmission away from the shadow region indicated phase-contrast enhancement owing to spatial coherence. Note that this happens even though the radiation source is initially incoherent and arises owing to the free-space propagation of the small source size beam. Taking a source size \(w_{\text{rad}} \approx 1 \mu m\) at a distance of \(u \approx 457\,\text{mm}\) from the ‘knife-edge’, the coherence length is \(L = \lambda u / w_{\text{rad}} \approx 70\,\mu m\) for 8\,keV (1.5\,\AA) radiation. Clearly, this is much larger than the source size, and thus also of the resolution of the imaging, and so edge enhancement through phase contrast should be possible [27]. Proof-of-principle imaging of small biological samples (damselflies) was also demonstrated. The free propagation phase-contrast imaging was enhanced by reducing the bandwidth of the source using a combination of the falling CCD detector response (at more than 8\,keV) and a high-energy bandpass (Al) filter blocking less than 2\,keV. A magnification of approximately 4.2 allowed resolution of soft tissue (for example, veins in the flies’ wings) at resolution of the order of approximately 3\,\mu m, which was limited by the CCD pixel size. These initial measurements implied that these laser-generated sources could well be used for phase-contrast imaging of less dense material, such as biological tissue [28].

However, a drawback is at these energies the cross sections for the absorption and phase enhancement are comparable, so that the phase enhancement is accompanied with strong absorption, which can make image processing complicated. The absorption would also limit the ability to use phase enhancement for imaging denser bodies, and increase the dose absorbed in medical applications. With the appropriate detectors, imaging could be done at higher photon energy, but with electrons of \(E_{\text{max}} \approx 300\,\text{MeV}\), the photon yield is rapidly falling for \(E_p > 10\,\text{keV}\).
Advances in high-power lasers have now led to systems featuring pulses with power exceeding 100 TW, such as the Astra Gemini laser at the Rutherford-Appleton Laboratory. Gemini can produce pulses of energy up to 15 J on target in pulse lengths down to 40 fs, resulting in peak laser powers close to 400 TW. The density at which trapping and acceleration of electrons is observed with Gemini has now been reduced to $n_e \sim 2 \times 10^{18} \text{cm}^{-3}$, while leading to a consequent increase in maximum electron energy to beyond $E_{\text{max}} > 1 \text{GeV}$ ($\gamma \sim 2000$) [18]. The strong dependence on $\gamma$ should lead to dramatic increases in radiated power and photon energy that should now approach approximately 50 keV.

A proof-of-principle imaging experiment with this improved photon source was performed. Targets were placed approximately 475 mm from the source, with the detector placed a further 1325 mm behind the imaging target (magnification $M \sim 2.8$). The detector used was a caesium iodide (CsI) scintillator coated onto a fibre optic bundle coupled directly to a large area CCD (Princeton Instrument PIXIS-XF). The radiation generating electron beam was directed off the axis of the X-ray propagation using a 1.0 T, 30 cm long magnet. Electron energies were measured simultaneously by recording the deflection of the electrons using Lanex scintillators imaged with a gated high-resolution CCD. A secondary screen placed behind this one allowed the direction of the beam to be calculated to compensate for pointing errors. Figure 2 features a selected electron spectrum which is characteristic of those taken during the run. There is a large spread in electron energy suggesting continual injection of electrons [18] with $E_{\text{max}} = 1.3 \text{ GeV}$. Though the beams were not very mono-energetic, they still featured relatively high charge at high energy. Electrons propagate freely in the other direction (up–down), showing that electrons of different energies have varying transverse momenta, implying that they are in different phases of a betatron motion, and so radiate incoherently. The X-ray image taken on a CsI scintillator is imaged on a CCD. The shadows in front are created by Al wedges, showing transmission through several millimetres of material. For this particular shot, the beam is centred to the bottom-right of the detector, exemplifying a pointing error greater than 25 mrad, which is comparable with the beam divergence.

Images of the X-ray beam illuminating a half-plane comprising a 1 mm thick cleaved Si crystal showed that the source size is still small in this regime. Fringes owing to phase enhancement were observed not only in the transmissive part of the step radiograph, but also a coherent dark fringe was observed in the obstructed part of the image. The contrast of the light-field fringe was as large as 20% of the beam intensity, whereas on the dark-field side it was as much as 50% of the background light level. The fact that the Si crystal was not completely opaque, but transmitted some of the X-ray beam, implied a significant photon flux with $E_p > 20 \text{ keV}$ (1 mm Si has 50% transmission at 20 keV). Line-outs of this edge detection gave a minimum source size of less than 3 $\mu$m, which was partly limited by the resolution of our CCD chip. (One pixel corresponded to 1.4 $\mu$m at the source.) Even with these small source sizes, $\alpha_{\beta} \gg 1$ owing to the relatively small betatron wavelength in this type of radiation source. This confirms that the radiation source is in the wiggler regime.
Figure 3. Raw (untreated) phase contrast images of a cricket taken with the Gemini betatron source. Distance from source to sample was $u = 475$ mm, and from sample to detector $v = 1325$ mm. Images show minimal absorption, indicative of high flux of photons at energies greater than 20 keV, for which the phase-shift cross section greatly exceeds (more than 100 times) that for absorption. Each image is taken in a single shot of the $\tau \sim 30$ fs source.

We proceeded to test the efficacy of this photon source for imaging biological specimens. With the increased typical photon energy, the coherence length is reduced to $L \simeq 15\, \mu m$. However, this is still far greater than the feature size we are imaging, and so significant phase-contrast enhancement may still be expected. Images of a house cricket (*Acheta domestica*) were taken, as can be seen in figure 3. The images have been taken with different projections of the insect, demonstrating that with sufficient projections of such an object full three-dimensional reconstruction of the object could be possible (this was not performed here owing to time limitations). Each image was taken with a single exposure from the laser-generated X-ray source and an estimate based on the sensitivity of the scintillator suggests that there were more than $10^8$ photons on each of these shots in a typical synchrotron spectrum, with a typical flux of approximately 100 photons per pixel. The beam completely fills our detector which subtends approximately 25 mrad, and so the beam divergence must be larger than this. Though the image contrast has been enhanced to ease viewing, the shot-to-shot reproducibility of photon flux and pointing was much better on these shots, with the total exposure varying by less than 50% and the majority of X-ray beams centred on the optical axis. An electron will typically only emit into a radiation cone of half-angle approximately $1/\gamma z_0$, which is much smaller than the measured divergence. This implies that the electrons being accelerated within the bubble have a large spread in trajectories and that leads to the large divergence. In any case, this means that the relative uniformity of the X-ray emission for our measurements was good, with a well-centred beam having variations in beam intensity less than 10%.

Notable in these images is the greatly reduced absorbed fraction when compared with images taken in previous studies at approximately 8 keV [28]. The reduction of the beam brightness within the specimen is minimal, implying that these are the first pure phase-contrast images taken (i.e. without significant absorption) of a biological sample using a laser-generated betatron source. Although the number of images taken so far is limited owing to the relatively low repetition rate of Astra Gemini (typically one shot every 20 s), comparable commercial systems are already available, which offer similar performance at 1 Hz or even faster. Indeed, the speed at which these images can be taken is only limited by the repetition rate of the laser. A number of studies have now been performed which show the power of phase-contrast imaging for identifying small abnormalities in soft tissues. Indeed, great emphasis has been placed on studying breast cancers, which other methods do not always identify especially in the early stages [45–48]. They have shown that *in vivo* imaging of tumours and other medical features can be possible and diagnosis could take place without invasive and worrying operation and time-consuming histology. These studies were performed with conventional light-sources and the possibility of bringing the light source closer to the patient using compact accelerators would have major benefits in diagnosis and treatment.

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