Electron radiography with different beam parameters using laser plasma accelerator

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An experimental study on the radiography of various metallic and biological plant samples with a minimum resolution of $\sim 75\ \mu\text{m}$ using relativistic electron beams from the laser plasma accelerator is presented. Electron beams were generated from the interaction of Ti:sapphire laser pulses of 120 fs duration with underdense plasma of 4 mm length, created using Ar and He gas jets, with two different parameters, i.e., a maximum energy of $\sim 50\ \text{MeV}$ (broad spectrum) and a quasimonoenergetic beam with a peak energy of $\sim 150\ \text{MeV}$. GEANT4 Monte Carlo simulations were performed to reconstruct the radiographic images and were found to be consistent with the experimental results. Radiography of biological plant samples was also performed, and in this regard penetration depths of two types of electron beams in adipose tissue were estimated through a simulation. The effect of different electron beam parameters on the quality of the radiograph has been discussed.

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I. INTRODUCTION

The laser-driven plasma-based electron accelerator (LPA) has emerged as one of the promising techniques to develop compact and cheap accelerators. The LPA can now routinely generate stable electron beams with an energy ranging from few tens to few hundreds of MeV [1]. Different acceleration mechanisms, such as laser wakefield acceleration (LWFA) [2] and/or direct laser acceleration (DLA) [3–7], responsible for the generation of relativistic electron beams with different laser and plasma parameters, have been investigated in detail. Subsequently, the LPA has become mature enough to be considered for various potential applications such as a compact electron injector for a conventional accelerator and the generation of synchrotron radiation [8–10], which could have further applications in medical, material science, and nuclear fields.

Other potential applications of the LPA being considered are electron beam radiography, interrogation of dense objects, and also radiotherapy [10–13]. The use of photons, neutrons, and charged particle beams (e.g., protons for radiography purposes have been investigated earlier

also [14]), and electron radiography was suggested as a potential alternative [15]. Conventional accelerators based on rf technology are large in size and expensive, and therefore the use of advanced accelerators, particularly the LPA, could be an attractive proposition. Besides being a cheap, compact tabletop source, the unique advantage of laser-driven electron beams over linacs is the generation of very short duration electron bunches (of the order of femtoseconds) [16], which enables delivering a high dose rate [12,13] and also facilitates time-resolved studies.

There are few experimental reports on radiography using electron beams generated from the LPA [17–22]. Mangles *et al.* showed the suitability of 20 MeV electron beams with a broad energy spectrum for radiography of a metal object, although with a poor resolution, and therefore the use of a quasimonoenergetic (QM) electron beam was recommended [17]. In another study, by Ramanathan *et al.*, QM electron beams with an energy $> 100\ \text{MeV}$ was used for a radiographic study of flaws embedded in thick solid objects placed at a distance of 2 m from the source, and submillimeter resolution was demonstrated [19]. Recently, radiography of thin inorganic dense objects and biological samples with a spatial resolution of $\sim 60\ \mu\text{m}$ placed at a distance of $\sim 10\ \text{cm}$ from the source has been reported by Bussolino *et al.* using an electron beam of energy $\sim 2\ \text{MeV}$ with a broad spectrum [20]. Furthermore, an ultrafast electron radiography study of the temporal evolution of the magnetic fields in a high-intensity laser solid interaction has also been reported recently [22].

As stated above, an electron beam has also been used for radiotherapy purposes [10–12]. Mostly, linacs providing

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lower-energy ($\sim 4\text{--}25$ MeV) electron beams are currently being used for the treatment of superficial cancer cells [23], and it has been suggested that, for tumors at larger depths inside the body, very-high-energy electron beams (VHEEs) of $\sim 150\text{--}250$ MeV would be appropriate [24–26]. In this regard, Monte Carlo simulations have been performed for electron beam parameters generated from the LPA [11,12,27–30]. Furthermore, in addition to the several other advantages described above, the LPA has also the advantage of ease and control of dose delivery. Use of the LPA for electron radiography of biological samples has been demonstrated using 2 MeV electron beams [20].

Considering the important applications of electron beams in radiography and radiotherapy, further investigations using advanced accelerators like the LPA are desirable, more so when there are very few reports in this direction. In this paper, we present an investigation on the radiography of different metallic and biological plant samples using relativistic electron beams generated from the interaction of Ti:sapphire laser pulses of ~ 120 fs duration (intensity $\sim 2.2 \times 10^{19}$ W/cm²) with underdense plasma of Ar and He gas targets of 4 mm length. Stable generation of electron beams of a maximum energy ~ 50 MeV with a broad continuous spectrum (divergence $\sim 60\text{--}70$ mrad) was observed from Ar at a plasma density of $\sim 2.4 \times 10^{19}$ cm⁻³. In the case of He, electron beams with a peak energy of ~ 150 MeV and a comparatively narrow energy spread (QM feature) and a divergence

$\sim 5\text{--}7$ mrad were observed at a plasma density of $\sim 6 \times 10^{18}$ cm⁻³. The acceleration of electrons is attributed to the DLA and wakefield mechanisms in the case of Ar and He gas-jet targets, respectively. Radiographs were recorded at a distance of 70 cm from the source, and a minimum resolution of ~ 75 μm was achieved. GEANT4 Monte Carlo simulations [31] were performed, and radiographs of the various samples used were reconstructed to support the experimental observations. The effect of two different electron beam parameters on the quality of radiographs, observed both experimentally and through GEANT4 simulations, is also discussed, particularly its use for radiography of biological samples. In this regard, a GEANT4 simulation was performed to study the penetration depths of two types of electron beams in adipose tissue. Our study demonstrates the use of a compact, tabletop, and stable LPA, with variable electron beam parameters for both industrial and medical applications. Such a detailed comparative study on electron radiography using the LPA has not been reported earlier. Furthermore, it may be pointed out here that electron radiography of biological samples with VHEEs (>100 MeV) has not been studied.

II. EXPERIMENTAL SETUP AND GENERATION OF ELECTRON BEAMS

Figure 1 shows the schematic of the experimental setup. A Ti:sapphire laser pulse of ~ 120 fs duration was focused

FIG. 1. Schematic of the experimental setup. (1) Recording of electron beam profile using phosphor screens 1 and 2. (2) Electron beam energy spectrum measurement using a magnetic spectrograph. (3) Recording of radiographs on image plates.

to a spot of $\sim 6.5 \times 6.5 \mu\text{m}^2$ (radius at $1/e^2$) using an $f/5$ off axis parabolic (OAP) mirror along a 4 mm length of a well-characterized slit nozzle ($1.2 \text{ mm} \times 4 \text{ mm}$) [32]. Considering 38% of the total energy inside the focal spot, the laser power (P) of $\sim 10 \text{ TW}$ and intensity (I) of $\sim 2.2 \times 10^{19} \text{ W/cm}^2$ could be achieved in the laser focus, which corresponds to laser strength parameter $a_0 = 3.2$. Experiments were performed with two different gas targets of He and Ar with a plasma density in the range of $\sim 2 - 30 \times 10^{18} \text{ cm}^{-3}$. The electron beam generated was transported out of the vacuum chamber through a 54- μm -thick Ti foil.

In order to record the electron beam size and its profile at various locations from the source, two phosphor screens [viz. phosphor 1 (Lanex-regular) and phosphor 2 (DRZ-High)] were placed at a distance of 39 and 70 cm, respectively. For measuring the electron beam spectrum, a C-shaped rectangular magnet (dimensions $20 \times 10 \times 10 \text{ cm}^3$, pole gap 15 mm) with a peak magnetic field strength of $\sim 0.9 \text{ T}$ was inserted between the two phosphor screens. Phosphor 2 covered the electron energy spectrum beyond $\sim 80 \text{ MeV}$. In order to cover the lower-energy spectrum, another phosphor 3 (DRZ-high) was also placed in the side direction of the magnet. This covered the lower-energy range of $\sim 15\text{--}80 \text{ MeV}$. The resolution of the spectrograph was $\sim 8\%$ at 100 MeV and $\sim 25\%$ at 300 MeV (for 10 mrad divergence). For the side phosphor, the resolution was $\sim 4.5\%$ at an energy of 25 MeV. In order to estimate the energy of the dispersed electron beams, knowledge of the undeflected path is required, which was obtained from the correlation between the electron beam pointing (recorded without a magnet) on two phosphor screens (phosphor 1 and phosphor 2). The electron beam charge was estimated using standard calibration data available for the various phosphor screens used [33–35].

For electron radiography, samples were kept at a distance of $\sim 70 \text{ cm}$ (i.e., at the location of phosphor 2) from the source, and radiographs were recorded on another detector, i.e., an imaging plate (IP). Samples were kept in contact with the IP to record a one-to-one image. The IP was scanned using a scanner (Dürr Medical, Germany, Model-CR-35 bio 2136-00064), having a 635 nm He-Ne laser. The system provides a true optical resolution of 840 dpi, corresponding to $\sim 30 \mu\text{m}$. The optical density range for the scanner and IP used was estimated to be 3.05.

For generating electron beams with varying beam parameters, two different gases of He and Ar were used separately. The threshold plasma density for generation of electron beams from He and Ar was found to be $\sim 6 \times 10^{18} \text{ cm}^{-3}$ and $\sim 2.4 \times 10^{19} \text{ cm}^{-3}$, respectively. The corresponding plasma density was estimated from the neutral gas densities produced by the nozzle and considering the maximum ionization state achieved for the respective gas at the used laser intensity. For the intensity of $\sim 2.2 \times 10^{19} \text{ W/cm}^2$ used in the present experiment,

He will be completely ionized and generates two electrons per neutral gas atom. However, in the case of Ar, the above intensity is sufficient only for ionization up to the 16^+ state (ionization threshold $\sim 1.1 \times 10^{19} \text{ W/cm}^2$) and the same was used for the estimation of the plasma density. Although in the case of high-Z gas targets refraction induced by ionization is of concern, as it may reduce the laser intensity, the above assumption is consistent with the various other reports using Ar gas targets [21,36]. Furthermore, in the case of the Ar gas-jet target, 16^+ ionization occurring at the peak of the laser pulse would facilitate an ionization-induced injection mechanism [37,38].

In the case of Ar, electron beams with a divergence of $\sim 60\text{--}70 \text{ mrad}$ were generated. The beam size on phosphor 1 and phosphor 2 was found to be $\sim 50\text{--}60 \text{ mm}$ and $\sim 80\text{--}90 \text{ mm}$ (FWHM), respectively [shown in Fig. 2(a), insets (i) and (ii)]. Figure 2(a) shows the electron beam spectrum recorded, showing a broad spectrum with a maximum energy of $\sim 50 \text{ MeV}$. A raw image of the spectrum recorded on phosphor 3 is shown in Fig. 2(a), inset (iii). The electron beam total charge was in the range of 400–550 pC. The pointing variation of electron beams on phosphor 2 in this case was $10 \times 20 \text{ mrad}$.

On the other hand, in the case of the He gas-jet target, the electron beam size on phosphor 1 and phosphor 2 was found to be $\sim 4\text{--}5 \text{ mm}$ and $\sim 10\text{--}15 \text{ mm}$ (FWHM), respectively [shown in Fig. 2(b), insets (i) and (ii)], which is comparatively smaller than the case of the Ar gas-jet target. The electron beam divergence was comparatively smaller and measured to be $\sim 5\text{--}7 \text{ mrad}$. Figure 2(b) shows a typical electron beam spectrum recorded in the case of He. Electron beams with a peak energy of $\sim 150\text{--}170 \text{ MeV}$ and a comparatively narrow energy spread (QM feature) were observed; however, some fraction of a higher-energy component was also present. A raw image of the spectrum recorded on phosphor 2 is shown in Fig. 2(b), inset (iii). The electron beam total charge in the case of He was comparatively lower in the range of 100–200 pC. The pointing variation of electron beams on phosphor 2 was also comparatively lower in this case and found to be $\sim 8 \times 4 \text{ mrad}$.

Thus, through the laser interaction with underdense plasma of two different gas targets of He and Ar, we could generate electron beams with distinct beam properties in terms of divergence, energy, and energy spread. The generation of electron beams, from both He and Ar, in the present experiment was stable and highly reproducible. The characteristics of the electron beams mentioned above have been estimated from 10–12 consecutive shots observed during the experiment.

In the present experimental conditions, the laser pulse length ($L = c\tau$, where c is the velocity of light and τ is the laser pulse duration) is longer than the plasma wavelength (λ_p) and, therefore, falls in the regime where self-modulation of the laser pulse may lead to a wakefield

FIG. 2. (a) For Ar gas: typical electron beam profiles at (i) phosphor 1 and (ii) phosphor 2 and (iii) typical electron energy spectra at phosphor 3. (b) For He gas: typical electron beam profiles at (i) phosphor 1 and (ii) phosphor 2 and (iii) typical electron energy spectrum at phosphor 2.

excitation and acceleration of electrons known as self-modulated laser wakefield acceleration (SM-LWFA) [1, 39–44]. Furthermore, $L > \lambda_p$ would also lead to an overlap of injected electrons with the laser field, and, hence, a contribution of the transverse laser electric field, i.e., DLA, should also be applicable [3–7]. Generally, collimated high-energy QM electron beams are observed from the wakefield mechanism of acceleration [43,44], similar to the case of He in the present experiment. On the other hand, from the DLA mechanism comparatively larger divergence electron beams with broad spectra are observed [3–7] as seen in the case of Ar. The above discussion suggests that in the present case the dominant mechanism could be the wakefield and DLA in the case of He and Ar, respectively. This is also supported by the fact that experimentally observed maximum energy values for He and Ar gas targets match well with the theoretical energy estimations from the

wakefield and DLA, respectively [45,7]. Also, in the case of the Ar gas-jet target, DLA is supported by an ionization-induced injection mechanism, as it provides the initial transverse momentum to the electrons [37,38,46]. Since the main emphasis of the present paper is on the radiography application, a detailed discussion on the mechanisms of acceleration is out of scope and would be a subject of another paper.

III. RADIOGRAPHY USING LPA ELECTRON BEAMS

Radiographs of various metallic and biological samples, kept at a distance of 70 cm from the source, were recorded using two different electron beams generated from He and Ar gas-jet targets. A variety of samples were used [Fig. 3(a)]: (i) a Cu mesh with wire thickness 200 μm and a

FIG. 3. (a) Image of different samples (i) Cu mesh, (ii) Ti circular strip, (iii) IC chip, (iv) Cu wire, (v) aloe vera cross section, (vi) Al disk, (vii) thick leaf, (viii) aloe vera cross section, and (ix) aloe vera cross section. (b) Radiograph of samples recorded using the Ar electron beam. (c) Radiograph of samples recorded using the He electron beam. Lineout of radiograph using Ar electron beams taken across the white line of (d) chip legs (iv) and (e) Ti circular strip (iii). Corresponding derivatives are shown in the insets.

separation of $500\ \mu\text{m}$, (ii) a Ti strip of gap $2.5\ \text{mm}$, strip width $2\ \text{mm}$, and $1\ \text{mm}$ thickness, (iii) an IC chip with leg material of Cu alloy with tin plating and a thickness $300\ \mu\text{m}$, (iv) a Cu wire of $\sim 250\ \mu\text{m}$ thickness, (v) a cross section of aloe vera of $1.1\ \text{cm}$ thickness, (vi) an Al disk of $3\ \text{mm}$ thickness with holes of diameter $1.3\ \text{cm}$ at the center and of diameter $4\ \text{mm}$ at the outer periphery, (vii) a cross section of a thick leaf sample, and (viii), (ix) different cross sections of aloe vera of thickness 0.5 and $1.75\ \text{cm}$, respectively. Figures 3(b) and 3(c) show radiographs of the above samples recorded using electron beams generated from Ar and He, respectively. Since the electron beam size from Ar is much larger than that generated from He, it could cover a larger sample area with better uniformity, and, hence, relatively clear images could be recorded. The resolution of the radiograph recorded using the Ar electron beam was determined by taking lineouts across the edges of the chip legs [Fig. 3(d)] and the Ti strip [Fig. 3(e)] shown by white lines in Fig. 3(b). The lineouts have been fitted by a higher-order Gaussian function [Figs. 3(d) and 3(e)], and the resolutions have been determined from the FWHM width of the derivative of the Gaussian [inset in Figs. 3(d) and 3(e)] and are estimated to be ~ 360 and $150\ \mu\text{m}$, respectively.

The two samples used for estimation of the resolution were made of Cu alloy with tin plating (IC chip legs) and

Ti having densities of 8.2 and $4.5\ \text{g/cc}$, respectively. Although Ti has a lower density, the resolution with the Ti sample is observed comparatively better than that with chip legs. This could be attributed to the difference in the thicknesses of the two samples (Ti strip of $1\ \text{mm}$ thickness vs chip legs of $0.3\ \text{mm}$ thickness) and also, as the two samples were placed at different positions with respect to the electron beam center, the energy of electrons incident on them could be slightly different.

The enlarged images of the IC chip and Cu mesh recorded using Ar and He electron beams are shown in Figs. 4(a)(i), 4(a)(ii), 4(b)(i), and 4(b)(ii), respectively. In the IC chip image, the legs of the chip and inner structure of the electronic circuit are clearly visible. Also, the Cu mesh structure of wire thickness $200\ \mu\text{m}$ and a separation of $500\ \mu\text{m}$ is resolved.

Next, a much thicker sample made of brass, i.e., a 5-cm-thick block dimension ($60\ \text{mm} \times 20\ \text{mm}$) with four grooves ($2\ \text{mm} \times 12\ \text{mm}$) [Fig. 5(a)(i)] and another block of dimension ($50\ \text{mm} \times 20\ \text{mm}$) with five grooves ($2\ \text{mm} \times 12\ \text{mm}$) [Fig. 5(a)(ii)], was used. Figures 5(b)(i) and 5(b)(ii) show the corresponding radiographs recorded using electron beams generated from Ar and He, respectively. As can be seen, the radiograph recorded in the case of He produces a sharper edge of the grooves compared to the case of Ar. This is because of the comparatively lower

FIG. 4. Enlarged image of (i) an IC chip of length 18 mm and (ii) a Cu mesh disk of diameter 30 mm, radiographed with electron beams generated from (a) Ar and (b) He gas-jet targets.

energy range of electrons with a broader spectrum (~ 20 – 50 MeV) used in the case of Ar, and, hence, the scattering of electrons would be significant to cause blurring of the sample edges. Although the two beams

used had different divergences, the blurring effect of beam divergence on the radiographic image can be neglected, as the detector was placed in touch with the samples [47,48]. The resolution of the radiograph recorded using Ar electron

FIG. 5. (a) Image of brass blocks ($60\text{ mm} \times 20\text{ mm}$) with grooves ($2\text{ mm} \times 12\text{ mm}$) with (i) four and (ii) five slits. (b) Experimental radiographs of the blocks using the (i) Ar electron beam and (ii) He electron beam. (c) Lineout of radiograph of the groove taken horizontally and Gaussian fitting of the data points for radiograph using Ar electron beams. The inset shows the derivative of the Gaussian fitting. (d) Image of Al block + key. (e) Radiograph of the key using the He electron beam.

FIG. 6. Magnified radiograph recorded using a lower-energy Ar electron beam of (a) a thick leaf showing inner veins. (b) Aloe vera cross section of 1.75 cm thickness showing a contrast in the outer thick and inner jelly layer. (c) Radiograph of aloe vera cross section using the higher-energy He electron beam.

beams [as shown in Fig. 5(c)] is found to be $\sim 75 \mu\text{m}$. The resolution of the radiograph using the He electron beam could not be retrieved due to saturation of the signal; however, it is expected to be better, as can be seen from the image quality governed by the higher electron energy and lower energy spread. As described above, it may be noted that the detector limited resolution is $\sim 30 \mu\text{m}$.

Next, using the He electron beam, the radiography of a 3-mm-thick stainless steel key kept behind a 6-cm-thick Al block [Fig. 5(d)] was recorded. In the radiograph [Fig. 5(e)], in addition to the intense electron beam (an energy of $\sim 150 \text{ MeV}$ is sufficient to transmit through the 6-cm-thick Al block), the radiograph of the key is also clearly visible. This shows that high-energy electron beams can be used for the interrogation of the interior of thick metallic structures used in various industrial applications such as nuclear vessels, etc., and also for security purposes.

A similar radiography of a key sample using lower-energy electrons of 20 MeV was shown by Mangles *et al.* [17]. A radiography study of voids and cracks embedded in a thick dense steel block using a $>100 \text{ MeV}$ QM electron beam with submillimeter resolution has also been demonstrated [19].

Next, in the present experiment, we have also performed electron radiography of biological samples, e.g., plant tissue of a thick leaf (central vein thickness of 0.5 cm) and various cross sections of aloe vera (thickness of 1.75 cm) [see Figs. 3(b) and 3(c)]. Similar to the case of metallic samples, for this study also, two different electron beams with a lower energy of $\sim 50 \text{ MeV}$ (Ar gas jet) and a higher energy of $\sim 150 \text{ MeV}$ (He gas jet) were used. An enlarged radiographic image of a thick leaf, showing clear finer veins and recorded using a lower-energy electron beam, is shown in Fig. 6(a). Figures 6(b) and 6(c) show enlarged images of the radiographs of cross section of the aloe vera leaf recorded using lower-energy (Ar) and higher-energy (He) electron beams, respectively. For lower-energy electron beams, the outer thick chlorophyll-rich cover layer of the cross section of aloe vera appears darker compared to the inner jelly component [Fig. 6(b)]. However, the contrast produced for higher-energy electrons is comparatively poor [Fig. 6(c)].

IV. RECONSTRUCTION OF RADIOGRAPHS USING GEANT4 SIMULATION

GEANT4 simulations [31] were performed to reconstruct the radiographs. It is a platform for simulating the interaction of particles such as electrons, protons, neutrons, photons, etc., with matter using Monte Carlo methods including facilities for handling the geometry of experiments and tracking of various particles inside materials. As shown in Fig. 7(a), the experimental setup of a laser plasma interaction for electron beam generation and transport (Fig. 1) through 54- μm -thick Ti foil, phosphor 1 (thickness 500 μm), and 36 μm Al foil placed in the electron beam path was simulated. In the simulation setup, a plasma chamber of dimension $60 \times 15 \times 15 \text{ cm}^3$ was considered where a vacuum was set as the environment. The electron beam source, i.e., gas jet, was positioned at the center of the plasma chamber, and electrons were allowed to propagate 30 cm along the z axis [as shown in Fig. 7(a)] before exiting the vacuum chamber through a 54 μm Ti foil. After that, the electron beam was allowed to propagate approximately 40 cm in air and interact with the target samples. In between, phosphor 1 was placed at a distance of 9 cm from the Ti foil with 36 μm of Al foil kept in touch with it. A virtual screen (detector) was placed just behind the samples at a distance of 31 cm from phosphor 1 and 70 cm from the source. Divergences and energy losses by all the above components introduced in the electron beam of given parameters for both the He and Ar cases were estimated to be negligible. Standard modules adopted in GEANT4 for a

FIG. 7. (a) Setup used for GEANT4 simulations. (b) Electron energy input spectra considered for GEANT4 simulations corresponding to the electron beam generated from (i) Ar and (ii) He gas-jet targets. (c) Reconstruction of the image of the Al disk for electron beam parameters (b) (i). (d) Reconstruction of the image of the brass groove (i) and (ii) for two electron beam parameters of (b) (i) and (ii), respectively. (e) Reconstruction of the image of the key with a 1-cm-thick Al block for the electron beam parameters of (b) (ii).

variety of materials were used to reconstruct various samples. In the reconstruction of images, the final exit coordinate positions (at the detector) of transmitted primary electrons only were considered. All the secondary particles including the high-energy bremsstrahlung emission from the sample were not detected.

Next, we discuss the input parameters of the electron beams used in the simulation for the reconstruction of images. Electron beams were constructed considering 10^6 particles defined in a cone shape (with a flat profile) with divergences equal to that observed in experiments for the two different electron beams obtained from Ar and He. For the reconstruction of images recorded using Ar gas-jet beams, the electron beam cone angle was defined such that an electron beam size of ~ 10 cm is achieved at the samples kept at 70 cm from the source as was the case in the experiment. Input electron beam spectra generated in this case were exponential with a maximum energy of ~ 50 MeV and a minimum energy of ~ 1 MeV, keeping the ratio of the number of electrons at a maximum to minimum energy of the order of 10^2 [Fig. 7(b)(i)].

However, this is slightly different than that observed in the experiment, particularly towards the lower-energy side. In the experiment with Ar gas, due to the limitation of our magnetic spectrometer, we could detect only electrons of more than ~ 12 MeV energy, but in actuality the beam contained electrons with energies even below ~ 12 MeV. Direct electron beams used for the radiography study also contained electrons below ~ 12 MeV energy and, hence, justify the used spectrum for the simulation which also has a lower-energy component.

For the reconstruction of images recorded using He gas-jet beams, the divergence of the beam was kept such that an electron beam size of ~ 1.5 cm is achieved at the samples. The electron spectra were generated [Fig. 7(b)(ii)] similar to that observed in the experiment. It has a peak energy of ~ 150 MeV, beyond which the spectrum decreases exponentially to a maximum energy of ~ 250 MeV, and towards the minimum energy side it drastically decreases to ~ 120 MeV.

Figure 7(c) shows the reconstructed Al disk image [Fig. 3(a)(vi)] using the Ar electron beam, which matches

FIG. 8. GEANT4 simulation-generated penetration depth of monoenergetic electron beams in adipose tissue. Red curve, 20 MeV energy; blue curve, 150 MeV energy.

well with the experimentally recorded radiograph on IP [Fig. 3(b)]. However, using the He electron beam, reconstruction of the image was not possible, as the sample thickness and density are much lower compared to the penetration depth of such high-energy electrons. Figures 7(d)(i) and 7(d)(ii) show the reconstructed image of the brass block with four grooves for Ar and He electron beams, respectively. It is clear from the images that the high-energy QM electron beam (He) could produce a sharper image compared to the lower-energy electrons with a broad spectrum (Ar) and is consistent with the experimental observation [Figs. 5(b)(i) and 5(b)(ii)]. This is because lower-energy electrons would diffract more at the sample edges, since the diffraction angle is inversely proportional to the energy of incident electrons, leading to the blurring of the edges [49]. This may lead to an erroneous measurement of the object dimensions due to large blurring. Corresponding to the radiograph of the key recorded using the He electron beam [Fig. 5(e)], reconstruction was done with a 1-cm-thick Al block only. The reconstructed image is shown in Fig. 7(e). A larger thickness of the Al block, as used in the experiment, could not be used in the simulation, due to very large scattering.

V. GEANT4 SIMULATION ON ENERGY DEPOSITION IN ADIPOSE TISSUE

Furthermore, we have simulated the dose deposition rate in adipose tissue using GEANT4 simulations for the experimentally used electron beams parameters, i.e., one with lower energy (~ 20 MeV) and the other with higher energy (~ 150 MeV), both with a monoenergetic spectrum. Dose deposition vs depth is shown in Fig. 8. It shows that the lower-energy (20 MeV) electrons have a maximum dose deposition depth of 5–6 cm in adipose tissue, beyond which the dose deposition decreases rapidly within 10 cm of the length. Similar dose distribution curves for 20 MeV

electrons have also been reported earlier [50]. But for the 150 MeV electron beams the maximum dose deposition length increases to about 20–30 cm, and with further depth the dose decreases to $\sim 50\%$ within 40 cm. A similar observation has also been reported earlier [24]. It is to be noted that an electron beam of a particular energy (e.g., 20 MeV) has a constant dose deposition rate up to a depth of maximum ~ 5 –6 cm, beyond which the dose rate decreases rapidly. For comparison, in the case of photons of similar energy (20 MeV), the dose deposition rate first increases slightly to a maximum at the same depth of ~ 5 –6 cm and falls slowly with further depths [51]. This suggests that photons would deposit a substantial dose to the inner healthier tissues compared to electrons, and for this reason electron beam radiotherapy becomes a better option compared to the photon radiotherapy for the treatment of tissues at a particular depth.

Hence, it is clear that lower-energy electron beams of few tens of MeV can penetrate up to a certain length within biological samples of a thickness of a few centimeters and, hence, can be applicable for the treatment of superficial tissues such as skin, brain, etc. Higher-energy electron beams (~ 150 –200 MeV) would be of use for larger thicknesses and can be applicable for inner deep-seated tissues such as prostate, lungs, etc.

VI. CONCLUSIONS

An experimental investigation on electron radiography of various metallic and biological plant samples using the LPA was performed. A Ti:sapphire laser of 120 fs duration and underdense gas-jet plasma targets of He and Ar were used to generate relativistic electron beams of two different parameters, viz. a maximum energy ~ 50 MeV with a broad continuous spectrum, a divergence of ~ 60 –70 mrad (in the case of Ar), and of a peak energy ~ 150 MeV with QM spectra, a divergence of ~ 5 –7 mrad (in the case of He). Radiographs were recorded at a distance of 70 cm from the source, and a minimum resolution of ~ 75 μm in the case of Ar was demonstrated. Furthermore, GEANT4 Monte Carlo simulations were performed to reconstruct the radiographs which support the experimental results. The role of electron beam parameters for radiography application was elaborated both experimentally and through simulations through a comparative study of the quality of radiographs for two different electron beam properties. Furthermore, the application of both types of electron beams for radiography of plant samples was also explored. The penetration depths of electron beams in human adipose tissue were determined through simulations, which show potential applications of the LPA for radiotherapy. Thus, our study suggests a stable, tunable electron source based on the LPA, generating electron beams in the range of ~ 50 MeV to ~ 200 MeV, suitable for both industrial applications and medical radiography.

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