Using Relativistic Self-Trapping Regime of a High-Intensity Laser Pulse for High-Energy Electron Radiotherapy

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Abstract—Full-3D particle-in-cell Monte Carlo simulation of a new scheme of electron radiotherapy based on electron acceleration by high-power femtosecond laser pulse propagating in plasma of sub-critical density in the relativistic self-trapping regime (V. Yu. Bychenkov et al., Plasma Phys. Control. Fusion 61, 124004 (2019)) was carried out. Based on the results of simulation of distribution of energy deposited by electron bunches accelerated in such high-efficiency regime, it is demonstrated that a laser facility of ≥100 TW class is capable of providing therapy of deep soft-tissue lesions in soft biotissue and this approach has a number of advantages relative to traditional methods of beam therapy.

Keywords: laser acceleration, self-trapping, particle-in-cell simulations, radiotherapy, GEANT4, PIC, VHEE

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1. INTRODUCTION

Acceleration of electrons by means of femtosecond laser pulses of relativistic intensity is studied for more than 20 years since it is considered to be promising for various applications. Studies aiming at application of laser-accelerated electrons for radiation therapy occupy an important place among them. Although these studies were initiated nearly 20 years ago, serious prerequisites for putting laser therapy into practice appeared only recently with development of laser and laser-plasma technologies that ensure sufficient stability of parameters of generated bunches of electrons. In the process, the mechanism of obtaining electrons carrying energy at therapeutic level is related to modern implementation of the wakefield method of particle acceleration proposed long time ago [1].

Quite naturally, the first steps for validation of possibilities of new therapy were made using low-energy (1–2 tens of MeV) laser-accelerated electrons [2, 3], although electrons with this energy level were practically used for intraoperative electron-beam therapy for a long time. This circumstance certainly restrained using the proposed laser-based approach involving low-energy electrons. The situation changes qualitatively in the case of using electrons with energies in the 60–250-MeV range, the so-called very high-energy electrons (VHEE) capable of deeply penetrating soft tissues. This was noted in [4] where the possibility of creation of a source for deep-penetration therapy was predicted based on Monte Carlo simulation of dose distribution from an experimentally obtained 170-MeV electron beam in a water phantom.

Studies on therapeutic application of acceleration of electrons by the wakefield of laser-produced plasma rapidly expanded recently, which can be seen from ever increasing number of publications in this area [5–9], which is largely explained by increased interest to the so-called FLASH radiation therapy (ultrafast dose deposition) based on using traditional sources of radiation, e.g., an electron beam from a linear accelerator [10]. Starting from 1960s [11], a large amount of data was accumulated that demonstrate advantages of rapid dose deposition for reducing damage of health tissues. While achieved rate of dose deposition for traditional sources does not exceed $10^8$ Gy/s, it can be as high as $10^{12}$–$10^{14}$ Gy/s for a laser source. Obviously, this requires studying additional advantages of using such extremely short electron pulses specially.

Wakefield acceleration represents a promising approach to acceleration of electrons to high energies in a laboratory setup for creation of compact sources of nuclear radiation. It is this process that is discussed as a source of VHEEs for electron radiation therapy. To this end, on the one hand, the laser pulse must be channelled on a scale of several Rayleigh lengths in order to ensure long acceleration length required for reaching energies of several tens or hundred MeV required for deep therapy. On the other hand, the laser
pulse must be able to propagate in a relatively dense plasma that allows obtaining maximum possible charge carried by the accelerated electron bunch. Typical experimentally detected charges of electron bunches with an energy of \( E = 100 \text{–} 250 \text{ MeV} \) were so far substantially lower than 1 nC, which restrains practical application of laser-accelerated electron-beam radiation therapy due to the necessity of delivering a therapeutic dose to the target without making the procedure too long. Lasers delivering pulses with energy in the multi-joule range that are unable to operate at a high pulse-repetition rate (the latter is typically limited by \( \sim 1 \text{ Hz} \)) are needed for obtaining electron beams with energy of \( \geqslant 100 \text{ MeV} \). Correspondingly, obtaining electron bunches with a charge at the nC level is needed for performing laser-accelerated electron-beam therapy.

Recently, we proposed such a source of electrons based on wakefield acceleration of electrons by a laser beam propagating in the relativistic self-trapping regime in plasma with sub-critical density of electrons [12–14]. In this approach, accelerating structure represents a cavern of electron density filled by a laser field (a laser bullet) that propagates nearly at a speed of light. The laser bullet stably propagates distances on the order of several Rayleigh lengths even in a relatively dense plasma until laser pulse becomes completely depleted due to losses. In the regime of relativistic self-trapping, diffraction divergence is balanced by relativistic nonlinearity of plasma in such a way that self-focusing on the axis does not occur, and self-consistently established cavern radius remains nearly unchanged during entire time of pulse propagation up to the moment of its depletion. In the process, laser-pulse duration substantially exceeds both the plasma wavelength and its transverse dimension. In fact, such regime of propagation is analogous to self-trapping of weak laser pulses in media exhibiting cubic nonlinearity [15–17] discovered nearly 60 years ago. It is due to this fact that the regime under consideration was referred to as the relativistic self-trapping [12, 13].

In the present work, we carried out full-3D numerical particle-in-cell Monte Carlo simulation of distribution of dose delivered by laser-accelerated electrons in a new scheme of radiation therapy based on using particle acceleration by high-power femtosecond laser pulse propagating in the relativistic self-trapping regime [12–14]. This work does not pretend to be a comprehensive dosimetric investigation of irradiation of a localized area in soft tissues, and, in the absence of special means of controlling the electron beam, aims at proving that the proposed regime of laser acceleration of electrons can be an efficient means of future radiotherapy based on using relatively small laser systems that are already available commercially.

2. SCHEME OF LASER–ELECTRON RADIOTHERAPY

Since investigation of possibility of realization of the method of electron irradiation in radiotherapy by means of available lasers represents the main goal of the present study, we consider using femtosecond laser pulses with power on the order of \( P \sim 100 \text{ TW} \), namely, we analyze two examples: \( P \approx 34 \text{ TW} \) and \( P \approx 135 \text{ TW} \). In both cases, the full width at half-maximum (FWHM) of the laser pulse was assumed to be equal to 30 fs, while the FWHM size of the focal point was assumed to be equal to \( 2R_0 = 4a_0 \), where \( \lambda \) is the laser wavelength. For the sake of definiteness, we assumed that \( \lambda = 1 \mu \text{m} \). Correspondingly, standard dimensionless amplitude \( a_0 \) of the laser pulses under consideration was equal to \( a_0 \approx 12 \) (\( P \approx 34 \text{ TW} \)) and \( a_0 \approx 24 \) (\( P \approx 135 \text{ TW} \)).

Three-dimensional numerical particle-in-cell (PIC) simulation carried out in recent years revealed that stable propagation of a laser pulse of relativistic intensity, i.e., a pulse with dimensionless amplitude \( a_0 \gg 1 \), in a homogeneous plasma by distance much larger than the Rayleigh length requires matching transverse size of propagating cavern to plasma density and laser-pulse intensity [12]. Namely, only under such theoretically substantiated condition of relativistic self-trapping of laser light [13, 18, 19] efficient acceleration of electrons self-injected into the plasma cavern becomes possible along the length of laser-pulse depletion \( L_d \) determined by energy losses of the pulse due to "pushing aside" of electrons of the medium by its leading edge: \( L_d = a_0 (c \tau)n_e/8n_c \), where \( \tau \) is the laser-pulse duration, \( n_e \) is the electron density of the medium, and \( n_c \) is the critical electron density. The condition of laser-plasma matching corresponding to self-trapping regime is expressed in the form \( R = 2(c/\omega_p)\sqrt{a_0 (n_e/n_c)} \), where \( \omega_p \) is the angular frequency of the laser radiation, \( \omega_p \) is the electron plasma frequency, and \( R \) is the self-consistent cavern radius. Hence, only a certain cavern radius corresponds to stable pulse propagation for given intensity and plasma density. In the process, the radius is established "automatically" if radius \( R_c \) of the laser focal spot is chosen close to radius \( R \) corresponding to self-consistency condition due to the effect of attractor of the nonlinear-optical dynamic system that causes it to evolve to a soliton-type structure, or a laser bullet. In the process, the condition of relativistic self-trapping ensures generation of ultrarelativistic electrons with maximum total charge due to stable propagation of the laser pulse up to the point of its complete depletion. It should be noted that the regime of relativistic self-trapping is realized without deterioration of characteristics of laser-accelerated electrons upon focusing of a high-power laser pulse also on a target exhibiting nearly critical density that is naturally characterized by an inho-
mogeneous profile at an interface with vacuum, provided that position of focus of laser light and the size of the focal spot are chosen properly relative to the density profile \([14]\). For this reason, here, similar to studies \([12, 13]\), we limit analysis to the case of a homogeneous medium.

We described acceleration of electrons in the laser-bullet regime by means of 3D PIC simulation based on the VSIm, high-performance relativistic electromagnetic code. A linearly polarized laser pulse was assumed to propagate through plasma characterized by an electron density of \(0.05 n_e\) (for \(a_0 \approx 12\)) or 0.1\(n_e\) (for \(a_0 \approx 24\)), which correspond to self-trapping regime. Simulation was conducted using the moving-window technique with a spatial-grid step size of \(0.02 \lambda \times 0.1 \lambda \times 0.1 \lambda\) in a simulation window of \(X \times Y \times Z = 58 \lambda \times 44 \lambda \times 44 \lambda\). The results of the PIC simulation establishing pulsed spatial characteristics of accelerated bunch of electrons were entered into GEANT4 code for Monte Carlo simulation of its propagation in a therapeutic target. A medium from the GEANT4 library describing soft tissues (model phantom of a biotissue) was chosen as a target. An illustrative design scheme corresponding to conducted PIC-GEANT4 simulation is presented in Fig. 1. We did not use special means of electron-beam collimation/focusing before it was entering the phantom. Rather, we used a model pinhole at the output of the laser target that cut off electrons outside of cone apex angle equal to 7° (Fig. 1). Electrons with energies below 60 MeV do not represent any interest for radiotherapy. Phantom had the shape of a sphere with a diameter of 10 cm for the case of \(a_0 \approx 12\) and 25 cm in the case of \(a_0 \approx 24\). Using irradiation from all directions (for the definiteness sake, in one plane) allowed maximizing absorbed dose in a ~1-cm³ volume when the phantom was placed at a distance of 4 cm.

3. ELECTRON BEAM

3D PIC simulation under the conditions of matching the focal-spot size of the laser beam incident on plasma to laser power and electron density of the medium \([12, 13]\), i.e., in the regime of relativistic self-trapping of laser light, demonstrated efficient generation of high-energy electrons that enter the accelerating cavern from its rare side. Implementation of such regime of relativistic self-trapping in plasma of sufficiently high density ensures obtaining maximum possible charge of the bunch of electrons of therapeutic energies and maximum possible conversion efficiency of the laser-pulse energy to energy of such electrons. Electrons are accelerated by strong electrostatic field of the cavern. In the process, electrons are injected at the accelerating phase of this field by a strong laser field nearly instantly, on a femtosecond time scale, due to extremely high rate of their initial acceleration by the laser field of relativistic intensity (\(a_0 \gg 1\)) \([20]\).

After propagating with acceleration a distance on the order of the laser-pulse depletion length, \(\approx 250 \mu m\) (for \(a_0 \approx 24\)) and \(\approx 130 \mu m\) (for \(a_0 \approx 12\)), an electron bunch leaves the target. At this moment, it has the length on the order of the length of the laser bullet, \(\tau \approx 10\), and the transverse size on the order of the spot of accelerating cavern, \(R \approx 5 \lambda \geq R_1\). High-energy electrons are relatively well collimated and are characterized by emittance of \(\approx 100 \text{ mrad} \mu \text{m}\). Spatial distribution of emerging (in the direction of pulse propagation) electron beam, along with its energy distribution, are illustrated in Fig. 2, while spectra of laser-accelerated electrons are presented in Fig. 3. The spectra reveal characteristic plateau-like distribution with a relatively sharp energy cutoff, \(\approx 200 \text{ MeV}\) (for \(a_0 \approx 24\)) and \(\approx 100 \text{ MeV}\) (for \(a_0 \approx 12\)). Using a pinhole (Fig. 1) for laser-accelerated electron beam allows getting rid of numerous low-energy electrons that propagate predominantly at large angles relative to the axis. Spectra of electrons that exhibit lower divergence after the pinhole and are directed into the “therapeutic” target are illustrated in Fig. 4. As expected from comparison with Fig. 3, loss of electron charge for particles with energies of \(\geq 60 \text{ MeV}\) can be seen. For \(a_0 \approx 12\), the charge decreases by a factor of 2.5 to 0.53 nC, while for \(a_0 \approx 24\) it decreases by a factor of 2.8 to 1.7 nC. For particles carrying the highest energies of \(\geq 120 \text{ MeV}\) (\(a_0 \approx 24\)), the total charge decreases by a factor of 3.5 to 1.3 nC. Nevertheless, the remaining charge turns out to be sufficiently large, at the nC level, and such a reduction is not critical for the laser method. The total charge of electron beams under consideration substantially exceeds that found in \([7, 8]\), which reduces to minimum the number of laser shots needed for achieving the medical dose, thereby providing a real chance of bringing the laser–electron radiotherapy into practice.
4. DOSIMETRIC SIMULATION

Laser-generated electron beam obtained in the PIC calculations was used in the GEANT4 simulation for irradiation of a “therapeutic” target (Fig. 1), which normally should be carried out from several directions in order to reduce exposure of healthy tissues to radiation and simultaneously cover entire affected area. First of all, we studied propagation of a single high-energy electron bunch (VHEE) in a model phantom of a biotissue. Normalized integral depth distribution of absorbed dose along the direction of propagation of an electron beam for the cases of \( a_0 = 24 \) and \( a_0 = 12 \) is illustrated in Fig. 5. Qualitatively, this distribution is similar to the well-studied percentage depth dose distribution for a monoenergetic beam obtained in an accelerator and used for irradiation of a biotissue (see, e.g., [21]). According to Fig. 5, a laser with a power of 135 TW can be used for therapy of deep tumors up to the depth of 15–20 cm, along with lower lying lesions that could be irradiated by means of a 34-TW laser.

The pattern of multilateral irradiation of targeted area with a size of about 10 mm is illustrated in Fig. 6.
In the process, 16 laser shots were used. They delivered a dose into the phantom center by means of identical electron beams that were arranged in a fan-like pattern characterized by even angular spacing in one of the planes in a wide cone apex angle of \( \approx 160^\circ \). Depending on the laser power and the depth of the targeted area, the dose delivered to the latter varied from 3 to 25 Gy. This means that, for a series of several shots, e.g., 10 shots per series, the number of irradiation sessions for obtaining the total characteristic medical dose can be lower than that used in traditional radiation therapy. For example, when using 12 multilateral shots per series for obtaining a medical dose of 50 Gy, a total of 10 sessions of irradiation of the targeted area located at a depth of 120 mm will be required using a 135-TW laser \( (a = 24) \), while 12 sessions of irradiation of the targeted area located at a depth of 60 mm will be required for a 34-TW laser \( (a = 12) \).

Note that, according to Fig. 6, the dose absorbed at the surface of a “therapeutic” target in the examples under consideration turns out to be lower or, at least, does not exceed known safe limit of \( \approx 8 \) Gy that turns out to be even substantially higher for the FLASH regime [10]. To demonstrate detailed longitudinal—transverse profile of the absorbed dose, a scaled-up distribution of the latter in a 24-mm-wide area adjacent to the axis of one of the beams with spectrum corresponding to Fig. 4 \( (a_0 = 24) \) is illustrated in Fig. 7a. For comparison, dose distribution in the case of irradiation by collimated beams of monoenergetic electrons with energy of 120 MeV corresponding to average energy at the plateau in the energy distribution of laser-accelerated electrons is shown in Fig. 7b. Weakly
diverging beams of laser-accelerated electrons were artificially transformed into collimated beams, which implies including a focusing system $f/\infty$ in the design under consideration (Fig. 1). The total charge of the monochromatic beam was chosen equal to the total charge of laser-accelerated particles. According to Fig. 7, non-monochromatic spectrum of electrons does not result in considerable change in spatial distribution of the absorbed dose relative to the case of monochromatic beam characteristic of an electron beam obtained with a classical accelerator. Moreover, note somewhat smaller aureole of absorption in the case of laser-accelerated electrons that can probably be reduced even further by using a system of magnetic

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**Fig. 6.** Distribution of dose absorbed in a model phantom of a biotissue upon irradiation from 16 directions (scale in Gy). Upper row corresponds to a 135-TW irradiating pulse, while the lower row corresponds to a 34-TW pulse. Irradiated area is located at a depth of 120, 80, and 60 mm (left to right). Dimensions are in mm.

**Fig. 7.** An image of distribution of the dose absorbed in a phantom in the region along one of the beams (scale in Gy) in the case of collimated laser-accelerated electron beams ($\alpha_0 = 24$) (a) and analogous irradiation by collimated monochromatic electron beams with energy of 120 MeV (b). The targeted area lies at a depth of 120 mm from the boundary of irradiated target in both cases. Arrows mark the directions of a selected beam and two adjacent ones (16 beams total), while dots mark beam boundaries.
focusing, which is not currently included in out model. Arrows in Fig. 7 mark axes of electron beams. Beam boundaries are shown by dotted lines that allow clearly seeing that the width of the beams is preserved up to the point where they overlap geometrically near the targeted area, which illustrates that the effect of scattering of high-energy particles is low.

5. CONCLUSIONS

Despite being incomplete from the point of view of technical realization, in general, this work shows that development of the method of laser—electron radiotherapy based on relativistic self-trapping of high-intensity light pulse is promising. The study corroborates the possibility of using commercially available femtosecond lasers [22, 23], which simplifies transition from the calculation—theoretical stage of development of the new method of radiation therapy to the experimental and technological stages.

Development of laser—electron therapy of deep regions has objective prerequisites since it demonstrates certain advantages relative to traditional methods, and the number of these advantages can increase with accumulation of new data. For example, the small size of the setup, its much lower and gradually decreasing cost, and the possibility of using commercially available lasers represent important advantages of the laser—electron therapy relative to the hadron one. It should also be noted that these advantages are preserved also relative to traditional electron accelerators of the 100–250-MeV class that enable deep radiotherapy. Demonstrated focussability of a nonmonoeenergetic electron beam by quadruple magnetic lenses [8, 24] indicates the possibility of localization of the absorbed dose for laser-accelerated electrons, which could probably compete with the Bragg peak of protons/ions. The spider-like scheme of parallel splitting of the laser beam would allow treatment of patients in several therapeutic rooms simultaneously thereby reducing occupation time of the irradiation setup per session, which is impossible from practical point of view for charged—particle beams. Evolution of a number of physical processes accompanying propagation of VHEE electron bunch in a tissue also offers several advantages, such as relatively low scattering in air and biotissues determined by factor $E^{-2}$, weak sensitivity to inhomogeneities (regions of bone tissue) [25], dosimetric advantage relative to classical sources related to somewhat lower damage of healthy tissues while retaining therapeutic effect in the affected area, which was noted in a number of studies on dosimetry for short VHEE bunches. Finally, we note that the FLASH effect that ensures orders of magnitude higher rate of dose deposition relative to that achieved so far with traditional sources is guaranteed with a laser source, which can have an impact at the stage of chemical transformations in cells. This does not exclude the possibility of enhancing positive effects of the FLASH phenomenon, although this requires further analysis.

As a final note, we should mention one more possible variant of the laser FLASH radiotherapy. The fact is that, in addition to VHEE, the laser electron source creates much more electrons accelerated to moderate energies in the 5—20-MeV range. Their bremsstrahlung radiation can produce a record flux of photons of therapeutic energies [26]. Estimating the prospects of such a method relative to traditional gamma therapy represents an interesting and important task.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

1. T. Tajima and J. Dawson, Phys. Rev. Lett. 43, 267 (1979). https://doi.org/10.1103/PhysRevLett.43.267
2. K. K. Kainz, K. R. Hogstrom, J. A. Antolak, P. R. Almond, C. D. Bloch, C. Chiu, M. Fomtyksy, F. Raishel, M. Downer, and T. Tajima, Med. Phys. 31, 2053 (2004). https://doi.org/10.1118/1.1690194
3. C. Chiu, M. Fomtyksy, F. Grigsby, and F. Raishel, Med. Phys. 31, 2042 (2004). https://doi.org/10.1118/1.1739301
4. Y. Glinec, J. Faure, V. Malka, T. Fuchs, H. Szymanski, and U. Oelfke, Med. Phys. 33, 155 (2006). https://doi.org/10.1118/1.2140115
5. K. Nakajima, J. Yuan, L. Chen, and Zh. Sheng, Appl. Sci. 5, 1 (2015). https://doi.org/10.3390/app5010001
6. A. Schuller, S. Heinrich, Ch. Fouillade, A. Subiel, L. De Marzi, F. Romano, P. Peier, M. Trachsel, C. Fleita, R. Kranzer, M. Carew, S. Salvador, S. Busold, A. Schonfeld, M. McEwen, et al., Phys. Med. 80, 134 (2020). https://doi.org/10.1016/j.ejmp.2020.09.020

7. L. Labate, D. Palla, D. Panetta, F. Avella, F. Baffigi, F. Brandi, F. Di Martino, L. Fulgentini, A. Giulietti, P. Köster, D. Terzani, P. Tomassini, C. Traino, and L. A. Gizzi, Sci. Rep. 10, 17307 (2020). https://doi.org/10.1038/s41598-020-74256-w

8. K. Svendsen, D. Guénot, J. B. Svensson, K. Petersson, A. Persson, and O. Lundh, Sci. Rep. 11, 5844 (2021). https://doi.org/10.1038/s41598-020-85451-8

9. R. Polanek, N. A. M. Hafz, Zs. Lécz, D. Papp, C. Kamperidis, Sz. Brunner, E. R. Szabó, T. Tőkés, and K. Hideghéty, Nucl. Instrum. Methods Phys. Res., Sect. A 987, 164841 (2021). https://doi.org/10.1016/j.nima.2020.164841

10. V. Favaudon, L. Caplier, V. Monceau, F. Pouzoulet, M. Sayarath, Ch. Fouillade, M. Poupon, I. Brito, Ph. Hupé, J. Bourhis, J. Hall, J.-J. Fontaine, and M.-C. Vozenin, Sci. Transl. Med. 6 (245), 245ra93 (2014). https://doi.org/10.1126/scitranslmed.3008973

11. R. J. Berry, E. J. Hall, D. W. Forster, T. H. Storr, and M. J. Goodman, Br. J. Radiol. 42, 102 (1969). https://doi.org/10.1259/0007-1285-42-494-102

12. V. Yu. Bychenkov, M. Lobok, V. F. Kovalev, and A. V. Brantov, Plasma Phys. Control. Fusion 61, 124004 (2019). https://doi.org/10.1088/1361-6587/ab5142

13. M. G. Lobok, A. V. Brantov, and V. Yu. Bychenkov, Phys. Plasmas 26, 123107 (2019). https://doi.org/10.1063/1.5125968

14. V. Yu. Bychenkov and M. G. Lobok, JETP Lett. 114, 579 (2021). https://doi.org/10.1134/S0021364021220069

15. V. I. Talanov, Izv. VUZov, Radiofiz. 7, 564 (1964).

16. R. Y. Chiao, E. Garmire, and C. Townes, Phys. Rev. Lett. 13, 479 (1964). https://doi.org/10.1103/PhysRevLett.13.479

17. S. A. Akhmanov, A. P. Sukhorukov, and R. V. Khokhlov, Sov. Phys.—JETP 23, 1025 (1966).

18. V. F. Kovalev and V. Yu. Bychenkov, Phys. Rev. E 99, 043201 (2019). https://doi.org/10.1103/PhysRevE.99.043201

19. V. Yu. Bychenkov and V. F. Kovalev, Radiophys. Quantum Electron. 63, 742 (2020). https://doi.org/10.1007/s11141-021-10093-9

20. M. G. Lobok, I. A. Andriyash, O. E. Vais, V. Malka, and V. Yu. Bychenkov, Phys. Rev. E 104, L053201 (2021). https://doi.org/10.1103/PhysRevE.104.L053201

21. M. G. Ronga, M. Cavallone, A. Patriarca, A. M. Leite, P. Loap, V. Favaudon, G. Créhange, and L. De Marzi, Cancers 13, 4942 (2021). https://doi.org/10.3390/cancers13194942

22. Pulsar TW Laser (Amplitude). https://amplitude-laser.com/products/femtosecond-lasers/pulsar-tw/. Cited March 20, 2022.

23. TeraWatt Systems (Thales Group). www.thales-group.com/en/worldwide/group/market-specific-solutions-lasers-science-applications/terawatt-systems. Cited March 20, 2022.

24. L. Whitmore, R. I. Mackay, M. van Herk, J. K. Jones, and R. M. Jones, Sci. Rep. 11, 14013 (2021). https://doi.org/10.1038/s41598-021-93276-8

25. A. Lagzda, R. M. Jones, D. Angal-Kalinin, J. Jones, A. Aitkenhead, K. Kirkby, R. McKay, M. van Herk, W. Farabolini, and S. Zeeshan, in Proceedings of the 8th International Particle Accelerator Conference, Copenhagen, 2017, Paper THPVA139. https://doi.org/10.18429/JACoW-IPAC2017-THPVA139.

26. M. G. Lobok, A. V. Brantov, and V. Yu. Bychenkov, Phys. Plasmas 27, 123103 (2020). https://doi.org/10.1063/5.0028888