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IMPLEMENTING PLASMA-DISCHARGE CAPILLARY DESIGN FOR VERY HIGH ENERGY ELECTRON (VHEE) APPLICATIONS AT I-LUCE FACILITY

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Abstract. *Very high-energy electron (VHEE) radiotherapy (RT) has gained significant attention as a viable approach for cancer treatment, offering enhanced dose distribution and deeper penetration (up to 30 cm) compared to traditional photon-based therapies. VHEE RT also supports ultra-high dose-rate (UHDR) irradiation, enabling FLASH radiotherapy (FLASH-RT) to deliver therapeutic doses in milliseconds while minimizing damage to healthy tissues. However, the practical implementation of VHEE has been limited by the lack of hospital-scale accelerators. To overcome this barrier, high-gradient laser-plasma accelerators (LPAs) have emerged as a promising solution, offering cost-effective, compact, table-top accelerators suitable for clinical settings, although the required laser systems may not be as compact. We investigate VHEE applications at the upcoming I-LUCE radiation production facility at INFN-LNS, using a plasma-discharge capillary. Dose delivery estimate for a 200 MeV electron beam is reported through GEANT4 Monte Carlo (MC) simulations, exploring the development of next-generation radiotherapy techniques.*

Keywords: *Very High-Energy Electron, Laser-Plasma Accelerators, Laser Wakefield Acceleration, Plasma-Discharge Capillary, Radiation Therapy, Ultra-high Dose Rate FLASH Radiotherapy*

1. Historical background on VHEE

Since the early days of particle physics in the late 19th and early 20th centuries, accelerating electrons has been a central focus of research, enabling deeper exploration of atomic structures and fundamental physics. The development of linear accelerators (LINACs) [1] and synchrotrons in the mid-20th century, including major facilities like Stanford Linear Accelerator Center (SLAC) and European Council for Nuclear Research (CERN), marked significant milestones in achieving high-energy electron beams. More recently, plasma-based acceleration techniques have emerged, offering compact and efficient alternatives to traditional accelerators [2,3].

Electrons are essential in radiotherapy (RT), where they are typically accelerated to energies between a few MeV and 25 MeV. By the 1980s, attention shifted to very high-energy electrons (VHEEs), with energies ranging from hundreds of MeV to several GeV. These high-energy electrons, particularly those near 250 MeV, offer advantages in precision radiotherapy [4], enabling precise tumor targeting.

The late 20th and early 21st centuries witnessed the rise of innovative acceleration techniques, like laser-plasma wakefield acceleration, which uses an intense laser pulse (LWFA) or an energetic beam (PWFA) to generate electric fields within plasma, facilitating compact and efficient VHEE generation [5,6]. Today, VHEEs are at the forefront of research in both fundamental physics and applied sciences.

Ongoing advancements in acceleration techniques, such as wakefield acceleration, are enabling the production of higher-energy electron beams, leading to novel applications [7]. The historical trajectory highlights the dynamic interplay between technological innovation and scientific discovery, leading to advances in medical studies [8].

2. Acceleration Approaches For VHEEs

The acceleration of VHEEs involves advanced techniques designed to boost electron beams to extremely high energies. Conventional LINACs rely on radiofrequency (RF) cavities to energize electrons over long distances, but with achieving a VHEE beam with this approach requires large and expensive structures, as the accelerating electric field are limited by electrical breakdown ($\approx$ 100 MV/m). In contrast, laser-plasma accelerators (LPAs) [9,10], such as LWFA, offer a compact alternative by driving intense laser pulses through a plasma to generate immense electric fields (100 GV/mm) capable of accelerating electrons over much shorter distances. A high-power laser pulse (i.e., $10^{18}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$) directed into a gas or plasma ($10^{17}-10^{19}\ \mathrm{cm}^{-3}$) creates a wave of ionized particles, enabling electrons to gain substantial energy within millimeters [11]. This technique also offers higher energy gradients, compact setups, and high beam charges, typically ranging from 10 to 400 pC [12,13].

Currently, several facilities are focused on delivering VHEE beams via LPAs. A notable effort is underway at INFN-LNS (Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud) in Catania, Italy, where the development of the I-LUCE (INFN-

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Laser ind**UCE**d Radiation Production) facility is specifically aimed at generating and providing VHEE beams, along with ion beams and neutron production for various applications [14]. Figure 1 presents a 3D rendering of the I-LUCE facility.

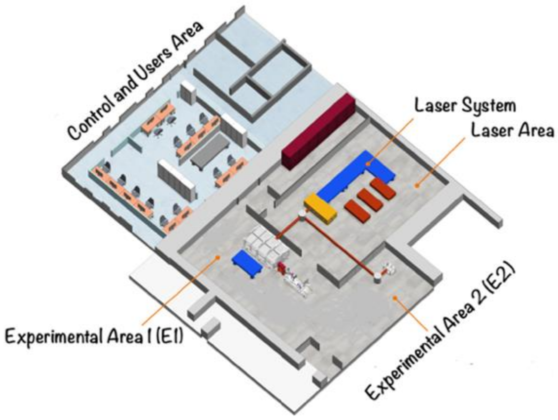

Figure 1. A 3D rendering of the I-LUCE facility at INFN-LNS. The total area of the facility is 407.5 m^2, made up of two sections: one is 19.6 m by 16 m (313 m^2) and the other section measuring 10.5 m by 9 m (94.5 m^2)

This facility represents a European initiative focused on conducting specialized research in radiation production, employing innovative concepts in plasma acceleration and laser technology. The I-LUCE high-power laser system is designed around the THALES LAS QUARK series, an ultrashort pulse femtosecond Titanium-Sapphire (Ti:Sa) laser system. It incorporates a cutting-edge assembly of components, including an oscillator, stretcher, amplifier, and a vacuum-based temporal compressor. Table 1 reports the main characteristics of the I-LUCE laser system. Using these characteristics and a plasma density of 10^{17}-10^{19} cm^{-3}[5-13], we can generate electron beams with energies ranging from 100 Mev to 3 GeV, a beam charge of 30 – 400 pC [5-13], and 10^8 – 10^9 particles per pulse.

Table 1. Main characteristics of I-LUCE laser system

Parameter	Value
Power [TW]	$65 - 320$
Energy Per Pulse [J]	$1.05 - 7.7$
Pulse Duration [fs]	23
Intensity on Target [$\frac{W}{cm^2}$]	$10^{20} - 9 \times 10^{20}$
Repetition Rate [Hz]	$2.5 - 10$

2.1. LWFA Scheme

A distinctive feature of LPAs is their tunability, along with the flexibility of systems to operate at varying repetition rates. Numerous LWFA mechanisms have been developed in recent years, each differing in how electrons are trapped in the accelerating region of the traveling electric field [15-19]. These mechanisms depend on factors such as laser intensity, pulse duration, plasma density, and the type of plasma target (e.g., gas jet, gas cell, capillary) [20-24].

Optimizing these parameters is crucial for achieving electron beams with narrow energy spreads and low divergence. Additionally, beam properties such as energy and charge per bunch can be readily adjusted by modifying the plasma composition, density, and laser settings [15-19], making LPAs suitable for a wide range of applications requiring specific beam characteristics. One promising approach for addressing challenges such as maintaining laser pulse focus over extended distances is the use of plasma-discharge capillaries, ranging from cm-m scales, enabling better control over plasma length and density behavior [25]. These plasma-discharge capillaries provide a control over plasma length and density profiles, thereby stabilizing the wakefield and reducing beam divergence. This stabilization is essential for achieving high beam quality—crucial for applications such as medical radiation therapy, where precision is key. Furthermore, optimizing capillary geometry or using capillaries with controlled density gradients enhances energy transfer efficiency, leading to higher beam charges.

2.2. Plasma-Discharge Capillary

The plasma-discharge capillary is a small, narrow tube designed to generate and confine plasma within a confined structure, enabling its use as an optical waveguide for LWFA. Gas is confined within the capillary, which typically has a small diameter (200-1000 μm) and a length on the order of centimeters. The capillary has one gas inlet to allow controlled gas flow.

Figure 2 presents a CAD design—specifically a technical engineering drawing generated from a CAD model—of the plasma-discharge capillary prototype alongside a photograph of the actual capillary. The capillary is made from a transparent dielectric material, additively manufactured and called VeroClear-RGD810, which mimics the properties of polymethylmethacrylate (PMMA) with a thermal conductivity of 0.2 $W.m^{-1}.K^{-1}$.

The capillary consists of two distinct parts: the inner core, which forms the plasma channel, and the outer core, which serves as the holder. Both components are made from VeroClear, ensuring uniform material properties across the entire structure and contributing to its durability and optical clarity. Using VeroClear offers several advantages, including high transparency, ease of 3D printing, and compatibility with the high precision required for capillary fabrication.

Plasma is formed through an electrical discharge within the capillary [26-30], where a high-voltage pulse ionizes the gas, stripping electrons from atoms or molecules to create a plasma channel. This hybrid approach, utilizing an external high-voltage source for plasma creation can enhance efficiency of plasma generation and stability. This pre-ionization establishes a stable and uniform plasma environment for the main laser pulse, improving the charge and consistency of the accelerated electron beam. The behavior of the plasma depends on parameters such as the current, voltage, gas type, and capillary characteristics. Different regimes of plasma formation can occur, each defined by how the ionization evolves.

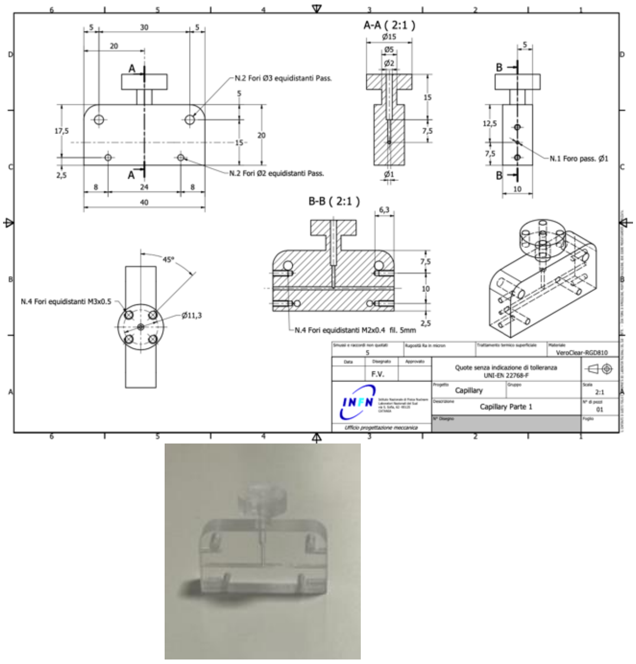

Figure 2. CAD design of the initial prototype (top) and real image (bottom) of the 3D-printed plasma-discharge capillary realized at INFN-LNS

This setup supports more efficient acceleration and enables the generation of VHEE pencil beams in a compact system.

The setup design for plasma discharge, shown in Figure 3, includes a high-voltage source, electric circuit, gas generator, and delay generator. A detection system consisting of a spectrometer and ICCD can be used to measure plasma parameters, including density and temperature, within the capillary.

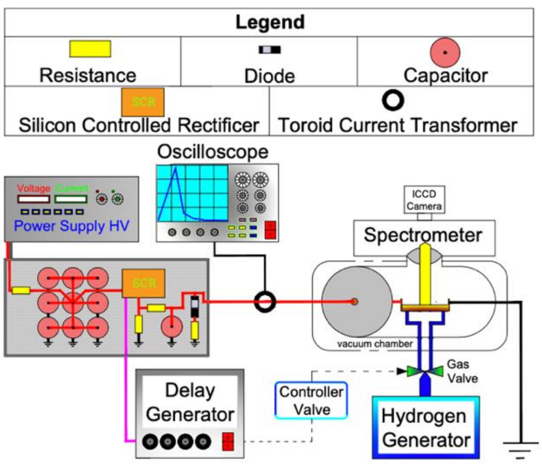

Figure 3. Experimental apparatus for plasma discharge and diagnostics in plasma-discharge capillary

The high-voltage source supplies the necessary voltage, while the circuit controls the current. The gas generator supplies the working gas, which is injected into the capillary through a gas inlet. The delay generator ensures accurate timing for discharge ignition, coordinating the high-voltage pulse with the gas flow to achieve optimal plasma formation. The discharge circuit's main component is a capacitor bank, charged by a high-voltage power supply capable of delivering currents ranging from 100 to 600 A.

The capacitor bank stores the electrical energy ($E_c=0.5 \cdot C_r \cdot V_c^2$), where C_r is the total capacitance and V_c is the voltage (up to maximum of 25 kV). Two planar electrodes, each 1 mm thick, facilitate the plasma discharge within the capillary. The electrodes are secured using small screws. This plasma channel supports efficient electron acceleration by the laser pulse. Figure 4 presents the experimental setup for LWFA using a plasma-discharge capillary. In this setup, a high-intensity laser pulse is injected into the capillary, where it propagates through the plasma and excites a wakefield. The wakefield accelerates electrons, generating an electron beam that exits the capillary.

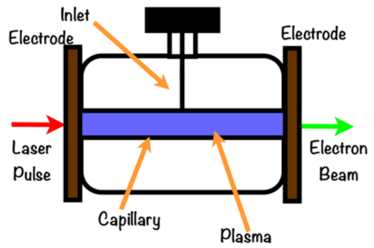

Figure 4. A diagram of an experimental setup for LWFA using a plasma-discharge capillary. Two planar electrodes are mounted at the capillary walls

The typical plasma density profile in plasma-discharge capillary is presented in Figure 5, showing its variation with applied voltage [29] and plasma evolution time [30].

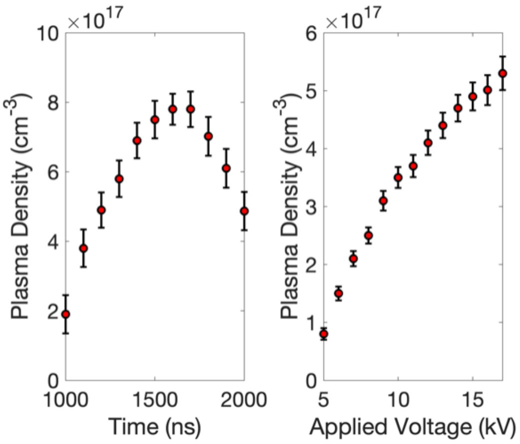

Figure 5. Typical experimentally retrieved plasma density profile in plasma-discharge capillary as a function of plasma recombination time (left) and applied voltage (right)

3. VHEE APPLICATIONS

Building on the capabilities of VHEEs enabled by LWFA, their applications in radiotherapy and cancer therapy are becoming promising [31-36]. With their high energy and low beam divergence, VHEEs are effective in penetrating deep tissues, allowing precise tumor targeting while minimizing damage to surrounding healthy cells [31,32]. These properties make them well-suited for addressing tumors in challenging locations, including lung cancer, prostate cancer, pediatric brain tumors, and head or neck cancers [37].

The precision and penetration capabilities of VHEE aligns with the emerging radiotherapy techniques of FLASH radiotherapy (FLASH-RT) and stereotactic radiotherapy [37]. However, further technological advancements are needed to enhance beam stability, beam charge, and repetition rates to make this widely adopted in clinical practice [38,39].

FLASH-RT delivers ultra-high dose rates (≥10-40 Gy/s) in extremely brief bursts, typically under one second. Unlike conventional radiotherapy (≤0,1 Gy/s), which administers radiation over several minutes per session, FLASH-RT leverages the FLASH effect to destroy tumor cells effectively while sparing healthy tissues. This reduces side effects [40] such as skin burns, fibrosis, and damage to sensitive organs, allowing higher radiation doses to be applied to tumors without increasing toxicity.

Figure 6 depicts the spectrum of the electron beam derived from the plasma-discharge capillary as detailed in [41]. This spectrum forms the basis for the Geant4 simulation shown in the multi-panel Figure 7, where a VHEE beam (~220 MeV, 120 pC), is simulated for potential tumor irradiation in a water tank for treatment [42].

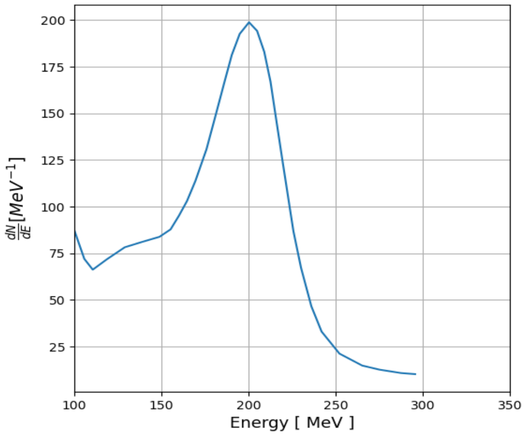

Figure 6. Electron beam spectrum at the entrance of a water phantom used as the source term for a Geant4 simulation

Figure 7 (top panel) shows a parallel-focused VHEE beam entering the water tank. The beam is illustrated in red, representing its trajectory and energy distribution. The water tank mimics the biological tissue surrounding the tumor, and the small rectangular region (5 cm) in the center of the image is labeled *Tumour*. This is the target area that the VHEE beam is meant to irradiate. The red lines diverging outward from the central beam represent the scattering or deflection of secondary electrons or radiation as it passes through the medium (the water). This scattering effect occurs because, as high-energy electrons travel through tissue or water, they interact with the molecules in their path, creating secondary particles and spreading energy in multiple directions. The central beam (red) indicates the primary focus of energy deposition, aimed at the tumor. The spread of red lines around the primary beam shows the broader region where some energy is distributed, which may correspond to dose fall-off in clinical settings.

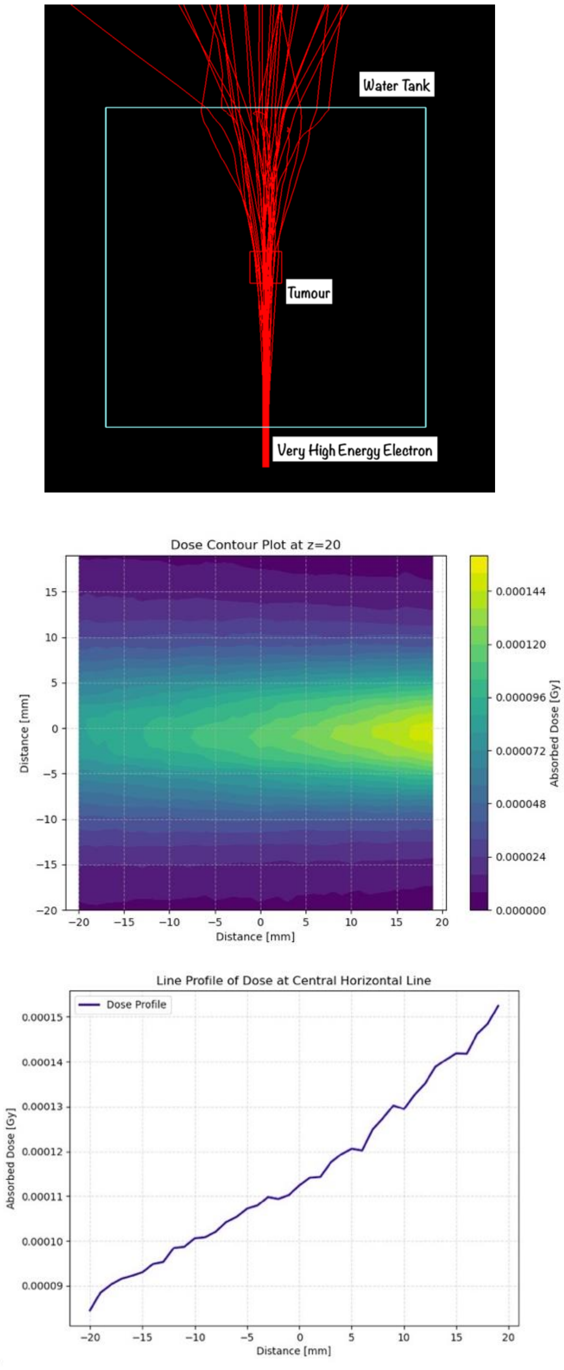

Figure 7. A tumor is modeled as a cubic element located inside the water tank (top panel). Dose counter plot at z = 20 mm within the tank (center panel), along with the line profile (bottom panel)

Figure 7 (center panel), shows a 2D counter plot representing the spatial distribution of absorbed dose within a cross-sectional plane at z = 20 mm. The dose intensity varies, with the highest values concentrated near the central region along the positive x-axis, as observed from the yellow region. The absorbed dose distribution shows a gradual increase from the periphery toward the center, peaking along the positive x-axis. The counters reveal a smooth gradient, which may be attributed to beam focusing or dose deposition.

The symmetric pattern suggests controlled beam propagation with minimal scattering effects. The absorbed dose levels reach approximately 0.000144 Gy, with the dose at the center of 0.00083 Gy, indicating low-dose delivery typical of preliminary studies in plasma waveguides or low-energy setups.

Figure 7 (bottom panel) displays a 1D dose profile extracted along the central horizontal line (y = 0) of the counter plot presented in Figure 7 (center). The profile illustrates the dose variation along the axis, highlighting a gradual increase from – 20 mm to +20 mm. The dose profile reveals a linear upward trend, peaking at the far-right region (x = + 20 mm). The continuous increase suggests either a directional beam propagation or an asymmetric energy deposition process caused by the beam entering the plasma. Such profiles are indicative of non-uniform beam-plasma interactions, where the energy density increases along the propagation axis due to focusing or acceleration effect. The maximum absorbed dose reaches near 0.00015 Gy, consistent with the peak values observed in Figure 7 (center). The absence of sharp fluctuations confirms uniformity in energy deposition, validating the stability of the beam-plasma coupling mechanism.

Therefore, by leveraging the future I-LUCE facility and its laser system, with its characteristics and scaling these results for a beam of 120 pC charge per shot, we can deliver 0.83 Gy/s at 1 Hz and 8.3 Gy/s at 10 Hz. However, the dose deposited at the center remains within low-dose delivery. With an upgrade to the laser system, delivering 83 Gy/s at 100 Hz (which is under consideration in the secondary phase) is possible. These dose rates fall within the ultra-high-rate region characteristic of FLASH-RT, which typically delivers a minimum of 10-40 Gray in under one second.

In addition, emerging kHz systems could potentially deliver this dose fraction in just 100 ms. The development of high-repetition-rate plasma targets is still in its initial stages, and although no fundamental barriers have been identified, reaching kHz repetition rates appears achievable. Some facilities have already demonstrated the viability of kHz systems for high-repetition-rate applications [43,44].

4. Conclusion

In conclusion, LWFA represents a progressive leap in particle acceleration, producing compact, high-quality electron beams for a wide range of applications. As developments continue, its influence is expected to expand into critical areas such as medical treatment—particularly radiotherapy—as well as fundamental physics and materials science, securing its place at the forefront of particle acceleration technologies.

Among its most promising applications is the generation of VHEEs for FLASH-RT, an advanced cancer therapy that delivers ultra-high dose rates within extremely short timeframes. VHEEs offer precise tumor targeting while minimizing damage to surrounding healthy tissue, making them highly suitable for improving radiotherapy techniques.

To fully exploit the potential of laser-driven VHEEs and FLASH radiotherapy, continued advancements in laser technology, diagnostics, and control systems is essential. The upcoming I-LUCE facility at INFN-LNS, set to be fully operational by 2028, will play a pivotal role in this effort. In its second phase, which includes upgrading the I-LUCE facility laser system to a 100 Hz repetition rate and enhancing its beam delivery capabilities, the facility could achieve dose rates of 83 Gy per second, approaching the ultra-high dose range characteristic of FLASH-RT.

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References

1. R. Bingham, R. Trines, "Introduction to plasma accelerators: the basics", *Proceeding of the 2014 CAS-CERN accelerator school: plasma wake acceleration,* vol. 1, 2016, pp. 67-77. https://doi.org/10.5170/CERN-2016-001.67
2. A. Lagzda, "VHEE Radiotherapy Studies at CLARA and CLEAR Facilities", PhD thesis, University of Manchester, Manchester, UK, 2019. https://research.manchester.ac.uk/en/studentTheses/vhee-radiotherapy-studies-at-clara-and-clear-facilities
3. P. Muggli et al., "White paper: AWAKE, plasma wakefield acceleration of electron bunches for near and long-term particle physics application", *arXiv:2203.09198v1*, 2022. https://doi.org/10.48550/arXiv.2203.09198
4. J. Fischer et al., "Very high-energy electrons as radio therapy opportunity", *Eur. Phys. J. Plus,* vol. 139, no. 8, 2024. https://doi.org/10.1140/epjp/s13360-024-05455-x
5. C. Joshi et al., "Plasma-based accelerators: then and now", *Plasma Phys. Control. Fusion*, vol. 61, no. 10, 104001, 2019. https://doi.org/10.1088/1361-6587/ab396a
6. J. Faure et al., "A laser-plasma accelerator producing monoenergetic electron beams", *Nature*, vol. 431, pp. 541-544, 2004. https://doi.org/10.1038/nature02963
7. K. Svendsen et al, "A focused very high energy electron beam for fractionated stereotactic radiotherapy", *Sci. Rep,* vol. 11, no. 5844, 2021. https://doi.org/10.1038/s41598-021-85451-8
8. K.N. Kim et al., "Characteristics of a very high energy electron beam in a laser wakefield accelerator for

cancer therapy", *J. Korean Phys. Soc.*, vol. 77, pp. 399-403, 2020.
https://doi.org/10.3938/jkps.77.399

9. E. Esarey, P. Sprangle, J. Krall and A. Ting, "Overview of plasma-based accelerator concepts", *IEEE Trans. Plasma Sci.*, vol. 24, no. 2, pp. 252-288, 1996.
https://doi.org/10.1109/27.509991
10. W.P. Leemans et al., "The Berkeley lab laser accelerator (BELLA): A 10 GeV laser plasma accelerator", *AIP Conf. Proc*, vol. 1299, 2010, pp. 3-11.
11. K. Nakamura et al., "Analysis of capillary guided laser plasma accelerator experiments at LBNL", *AIP Conf. Proc.*, vol. 1086, 2009, pp. 147-152.
https://doi.org/10.1063/1.3080896
12. H. Lu et al., "Laser wakefield acceleration of electron beams beyond 1 GeV from an ablative capillary discharge waveguide" *Appl. Phys. Lett.*, vol. 99, 091502, 2011.
https://doi.org/10.1063/1.3626042
13. W.P. Leemans et al., "Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime", *Phys. Rev. Lett.*, vol. 113, no. 24, pp. 245002-1-5, 2014.
https://doi.org/10.1103/PhysRevLett.113.245002
14. G.A.P. Cirrone et al., "Ion acceleration by laser-matter interaction: status and perspective with the upcoming I-LUCE facility at INFN-LNS", *in Proc. IPAC'23*, 4386-4388, 2023.
https://doi.org/10.18429/JACoW-IPAC2023-THPA179
15. C. McGuffey et al., "Ionization Induced Trapping in a Laser Wakefield Accelerator", *Phys. Rev. Lett*, vol. 104, no. 2, pp. 025004-1-4, 2010.
https://doi.org/10.1103/PhysRevLett.104.025004
16. C.G.R. Geddes et al. "Plasma-density-gradient injection of low absolute-momentum-spread electron bunches", *Phys. Rev. Lett,* vol. 100, no. 21, pp. 215004-1-4, 2008.
https://doi.org/10.1103/PhysRevLett.100.215004
17. K. Schmid et al., "Density-transition based electron injector for laser driven wakefield accelerators", *Phys. Rev. ST Accel. Beams*, vol. 13, no. 9, pp. 091301-1-5, 2010.
https://doi.org/10.1103/PhysRevSTAB.13.091301
18. C. Thaury et al., "Shock assisted ionization injection in laser-plasma accelerators", *Sci. Rep.*, vol. 5, pp. 16310-1-7, 2015.
https://doi.org/10.1038/srep16310
19. J. Faure et al., "Experiments and simulations of the colliding pulse injection of electrons in plasma wakefields", *IEEE Trans. Plasma Sci*, vol. 36, no. 4, pp. 1751–1759, 2008.
https://doi.org/10.1109/TPS.2008.927430
20. M. Mirzaie et al., "Effect of injection-gas concentration on the electron beam quality from a laser-plasma accelerator", *Phys. Plasmas*, vol. 25, no. 4, 043106, 2018.
https://doi.org/10.1063/1.5008561
21. T. Tajima and J.M. Dawson, "Laser electron accelerator", *Phys. Rev. Lett*, vol. 43, no. 4, pp. 267-270, 1979.
https://doi.org/10.1103/PhysRevLett.43.267
22. E. Esarey et al., "Physics of laser-driven plasma accelerators", *Rev. Mod. Phys*, vol. 81, no. 3, pp. 1229-1285, 2009.
https://doi.org/10.1103/RevModPhys.81.1229
23. W.P. Leemans, E. Esarey, "Laser-driven plasma-wave electron accelerators", *Phys. Today*, vol. 62, no. 3, pp. 44-49, 2009.
https://doi.org/10.1063/1.3099645
24. S.M. Hooker, "Developments in laser-driven plasma accelerators", *Nature Photonics*, vol. 7, no. 10, pp. 775-782, 2013.
https://doi.org/10.1038/nphoton.2013.234
25. M. Hansson et al., "Enhanced stability of laser wakefield acceleration using dielectric capillary tubes", *Phys. Rev. ST Accel. Beams*, vol. 17, 031303, 2014.
https://doi.org/10.1103/PhysRevSTAB.17.031303
26. S. Arjmand et al., "Characterization of plasma sources for plasma-based accelerators", *JINST*, vol. 15, C09055, 2020.
https://doi.org/10.1088/1748-0221/15/09/C09055
27. S. Arjmand et al., "Spectroscopic measurements as diagnostic tool for plasma-filled capillaries", *JACoW.IPAC2022*, WEPOST035, 2022.
https://doi.org/10.18429/JACoW-IPAC2022-WEPOST035
28. S. Arjmand et al., "Spectral line shape for plasma electron density characterization in capillary tubes", *J. Phys. Conf. Ser,* vol. 2439, pp. 012012-1-3, 2023.
https://doi.org/10.1088/1742-6596/2439/1/012012
29. S. Arjmand et al., "Shot-by-shot stability of the discharge produced plasmas in suitably shaped capillaries", *JINST,* vol. 18, C04016, 2023.
https://doi.org/10.1088/1748-0221/18/04/C04016
30. S. Arjmand et al., "Different elements, same results: time-resolved temperature determination by oxygen and nitrogen elements", *JINST,* vol. 18, P08003, 2023.
https://doi.org/10.1088/1748-0221/18/08/P08003
31. M.G. Ronga et al., "Back to the future: Very high-energy electrons (VHEEs) and their potential application in radiation therapy", *Cancers*, vol. 13, no. 19, 4942, 2021.
https://doi.org/10.3390/cancers13194942
32. K. Kokurewicz et al., "Laser-plasma generated very high energy electrons (VHEEs) in radiotherapy", *Proc. SPIE*, 10239, 102390C, 2017.
https://doi.org/10.1117/12.2271183
33. S. Siddique et al., "FLASH radiotherapy and the use of radiation dosimeters", *Cancers*, vol. 15, no. 15, 3883, 2023.
https://doi.org/10.3390/cancers15153883
34. J.C.L Chow et al., "Flash radiotherapy: innovative cancer treatment" *Encyclopedia,* vol. 3(3), 2023.
https://doi.org/10.3390/encyclopedia3030058
35. K. Svendsen et al., "A focused very high energy electron beam for fractionated stereotactic radiotherapy", *Sci. Rep,* vol. 11, 5844, 2021.
https://doi:10.1038/s41598-021-85451-8
36. M.G. Ronga et al., "Back to the future: Very high-energy electrons (VHEEs) and their potential application in radiation therapy", *Cancers*, vol. 13, no. 19, pp. 4942-1-19, 2021.
https://doi.org/10.3390/cancers13194942
37. K. Kokurewicz et al., "Laser-plasma generated very high energy electrons (VHEEs) in radiotherapy", *Proc. SPIE*, 10239, 102390C, 2017.
https://doi.org/10.1117/12.2271183
38. L. Gizzi et al., "Laser–plasma acceleration of electrons for radiobiology and radiation sources", *Nucl. Instrum. Meth. B*, vol. 355, pp. 241–245, 2015.
https://doi.org/10.1016/j.nimb.2015.03.050
39. L. Labate et al., "Toward an effective use of laser-driven very high energy electrons for radiotherapy: Feasibility assessment of multi-field and intensity modulation irradiation schemes", *Sci. Rep*, vol. 10, 17307, 2020.
https://doi.org/10.1038/s41598-020-74256-w
40. V. Favaudon et al. "Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice", *Sci. Transl. Med*, vol. 6, no 245, 245ra93, 2014.
https://doi.org/10.1126/scitranslmed.3008973
41. S. Lee et al., "One-body capillary plasma source for plasma accelerator research at e-LABs", *Appl. Sci*, vol. 13, no. 4, pp. 2564-1-10, 2023.
https://doi.org/10.3390/app13042564

42. GEANT4 Toolkit. https://geant4.web.cern.ch
43. C. M. Lazzarini et al., "Ultrarelativistic electron beams accelerated by terawatt scalable kHz laser", *Phys. Plasmas,* vol. 31, 030703, 2024. https://doi.org/10.1063/5.0189051
44. J. Monzac et al., "Optical ionization effects in kHz laser wakefield acceleration with few-cycle pulses", *Phys. Rev. Research.* vol. 6, 043099, 2024. https://doi.org/10.1103/PhysRevResearch.6.043099