Chapter III.10

Dielectric laser accelerators

Benedikt Hermann
Paul Scherrer Institute, Villigen, Switzerland

The concept of a dielectric laser accelerator (DLA) leverages manifold improvements in semiconductor manufacturing and near-infrared laser technology. Energy from a driving laser is transferred to charged particles through the interaction in a sub-micron-scale structure made of glass, silicon, or other dielectrics. Due to high breakdown voltages, acceleration gradients in the order of 1 GV/m are tangible. However, the small aperture of the structure and short bucket length require ultra-high-brightness electron sources for efficient injection into the DLA. Future applications will exploit the compactness, high repetition rate, and most notably the attosecond time structure of a DLA's particle beam.

III.10.1 Introduction to dielectric laser accelerators

The concept of using optical waves to accelerate particles was already conceived shortly after the invention of the laser. In 1962, Koichi Shimoda proposed to use a gas-filled laser cavity with periodic absorption layers on the inner surface as a high gradient accelerator for electrons [1]. Same as for radio-frequency accelerators near-field structures are required to accelerate ultra-relativistic particles. It is impossible to accelerate charged particles by far-field electromagnetic waves of any wavelength. This is formulated by the Lawson-Woodward theorem. A periodic structure is needed to convert the transverse electric field of the laser into a mode that resonantly transfers energy to the charged particles traveling in it. Several decades after Shimoda's concept, thanks to massive improvements in micro- and nano-fabrication technologies driven by enormous investments in the semiconductor industry, building near-field structures at optical wavelengths is now possible. Early demonstrations of dielectric laser accelerators (DLAs) used near-infrared fs-lasers [2–5]. Promising gradients approaching 1 GV/m for relativistic electrons have been achieved [6]. This is already one order of magnitude larger than what is achievable with conventional metallic radio-frequency accelerators. It is possible due to the higher electric breakdown limit of dielectrics, e.g., for fused silica it is in the order of 10 GV/m for waves in the optical spectrum. Not only the high acceleration gradients are an appealing feature of DLAs, but also and maybe even more intriguing is the time structure of optically bunched electrons. The bunch duration reaching into the attosecond regime and the intrinsic phase-lock between the driving laser and electron buckets are appealing features for ultra-fast pump-probe experiments. To miniaturize an accelerator, not only the accelerating structure but also all essential components need to be adapted. This starts at the

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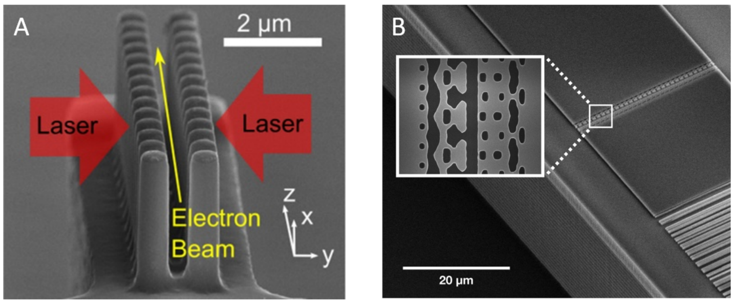

Fig. III.10.1: Pane A: Dielectric laser accelerator made of silicon dual pillars [7], pane B: Accelerator structure optimized with inverse design principles [8].

electron source, continues with efficient injection and bunching schemes, steering and guiding to avoid losses, beam diagnostics, and includes an appropriate radiation generation scheme for applications.

III.10.1.1 Electron sources

Naturally, repelling Coulomb forces limit the number of electrons in a micron-sized bucket, especially at sub-relativistic energies. To efficiently generate a suitable current for applications, a very high-quality electron beam with a controlled phase space distribution is needed. Concerning the injector for a DLA, a pulsed high-rate and high-brightness source is a necessary ingredient for a laser-driven dielectric accelerator. Photo-emission from sharp tips made of tungsten coated with a thin diamond layer produced beams with an excellent normalized of $0.2\,\mathrm{nm\,rad}$ and a normalized peak brightness of $1.2 \times 10^{12}\,\mathrm{Am^{-2}sr^{-1}}$ [9]. Such sources help to reduce losses and enable controlled and efficient injection into the small aperture of a DLA.

III.10.1.2 Transport

Confining particles along the entire length of the accelerator is a particular challenge for DLAs. Alternating phase focusing (APF) is a method where the phase space experiences transverse focusing and defocusing forces in an alternating pattern. This results in a finite beam envelope over long propagation distances. The required phase jumps can be achieved by shifting the structures by half a period. Design optimization and simulations [10] lead to the experimental demonstration confirming enhanced guiding along a DLA using the APF scheme [12]. Controlled beam guiding and transport is essential to develop longer and more powerful DLAs.

III.10.1.3 Diagnostics

Novel diagnostics for DLAs need to be highly sensitive and provide sub-micrometer resolution in transverse and longitudinal dimensions. The longitudinal shape of the electron bunch can be investigated by optical streaking: the longitudinal phase space is probed by a fast-oscillating electric field of a laser. The resulting change to phase space is used to reconstruct the original bunch profile. Two experiments using transverse and longitudinal streaking demonstrated sub-fs electron bunch duration in DLAs [11,13]. Besides longitudinal diagnostics, transverse beam profile characterization with sub-micrometer resolution is required. This can be achieved with small-scale wire scanners. A nano-fabricated metallic wire is scanned across the electron beam. Based on the intensity of the scattered particle shower projections of the particle distribution are obtained. A device with multiple wires oriented at different angles has been developed to characterize the transverse phase space by tomographic methods [14]. Pump-probe experiments of ultrafast phenomena in condensed matter systems would benefit from the short pulse duration and intrinsic synchronization of the driving laser.

III.10.2 Applications and radiation generation with DLAs

Certain accelerator applications make direct use of the accelerated particles, for instance, colliders, tumor therapy or diffraction experiments. Especially ultra-fast electron diffraction would benefit from the sub-fs short electron pulses from a DLA, which are phase stable to the driving laser. This feature is of particular importance for pump-probe experiments in condensed matter. A collider based on DLAs would need to run at very high repetition rates to achieve significant luminosity at a low bunch charge. A beneficial aspect is the reduced energy loss due to beamstrahlung at the interaction point due to low charge densities. Considerations for a DLA-based collider are presented by England *et al.* in Ref. [15]. Other applications require the conversion of energy of the moving charges into electromagnetic radiation ranging from the THz to X-rays and gamma-rays (for inspection, material, and nuclear characterization). Magnetic undulators and active or passive dielectric structures can generate radiation in a wide range of the spectrum. A dielectric structure optimized with inverse design principles was demonstrated to extract narrow-band THz radiation through the Smith–Purcell effect [16] from a 3 GeV electron beam at SwissFEL [17]. Active, laser-driven dielectric undulators are proposed as an alternative to conventional FEL undulators [18, 19].

References

[1] K. Shimoda, Proposal for an electron accelerator using an optical maser, *Appl. Opt.* **1** (1962) 33–35, doi:10.1364/AO.1.000033.

[2] C.M.S. Sears *et al.*, Phase stable net acceleration of electrons from a two-stage optical accelerator, *Phys. Rev. ST Accel. Beams* **11** (2008) 101301, doi:10.1103/PhysRevSTAB.11.101301.

[3] T. Plettner, R.L. Byer and B. Montazeri, Electromagnetic forces in the vacuum region of laser-driven layered grating structures, *J. Mod. Opt.* **58** (2011) 1518–1528, doi:10.1080/09500340.2011.611914.

[4] E.A. Peralta *et al.*, Demonstration of electron acceleration in a laser-driven dielectric microstructure, *Nature* **503** (2013) 91–94, doi:10.1038/nature12664.

[5] J. Breuer and P. Hommelhoff, Laser-based acceleration of nonrelativistic electrons at a dielectric structure, *Phys. Rev. Lett.* **111** (2013) 134803, doi:10.1103/PhysRevLett.111.134803.

[6] D. Cesar *et al.*, High-field nonlinear optical response and phase control in a dielectric laser accelerator, *Commun. Phys.* **1** (2018) 46, doi:10.1038/s42005-018-0047-y.

[7] K.J. Leedle *et al.*, Phase-dependent laser acceleration of electrons with symmetrically driven silicon dual pillar gratings, *Opt. Lett.* **43** (2018) 2181–2184, doi:10.1364/OL.43.002181.

[8] N.V. Sapra *et al.*, On-chip integrated laser-driven particle accelerator, *Science* **367** (2020) 79–83, doi:10.1126/science.aay5734.

[9] A. Tafel *et al.*, Femtosecond laser-induced electron emission from nanodiamond-coated tungsten needle tips, *Phys. Rev. Lett.* **123** (2019) 146802, doi:10.1103/PhysRevLett.123.146802.

[10] U. Niedermayer, T. Egenolf, and O. Boine-Frankenheim, Three dimensional alternating-phase focusing for dielectric-laser electron accelerators, *Phys. Rev. Lett.* **125** (2020) 164801, doi:10.1103/PhysRevLett.125.164801.

[11] N. Schönenberger *et al.*, Generation and characterization of attosecond microbunched electron pulse trains via dielectric laser acceleration, *Phys. Rev. Lett.* **123** (2019) 264803, doi:10.1103/PhysRevLett.123.264803.

[12] R. Shiloh *et al.*, Electron phase-space control in photonic chip-based particle acceleration, *Nature* **597** (2021) 498–502, doi:10.1038/s41586-021-03812-9.

[13] D.S. Black, Net acceleration and direct measurement of attosecond electron pulses in a silicon dielectric laser accelerator, *Phys. Rev. Lett.* **123** (2019) 264802, doi:10.1103/PhysRevLett.123.264802.

[14] B. Hermann *et al.*, Electron beam transverse phase space tomography using nanofabricated wire scanners with submicrometer resolution, *Phys. Rev. Accel. Beams* **24** (2021) 022802, doi:10.1103/PhysRevAccelBeams.24.022802.

[15] R.J. England *et al.*, Considerations for a TeV collider based on dielectric laser accelerators, *JINST* **17** (2022) P05012, doi:10.1088/1748-0221/17/05/P05012.

[16] S.J. Smith and E.M. Purcell, Visible light from localized surface charges moving across a grating, *Phys. Rev.* **92** (1953) 1069, doi:10.1103/PhysRev.92.1069.

[17] B. Hermann *et al.*, Inverse-designed narrowband THz radiator for ultrarelativistic electrons, *ACS Photonics* **9** (2022) 1143–1149, doi:10.1021/acsphotonics.1c01932.

[18] T. Plettner and R.L. Byer, Proposed dielectric-based microstructure laser-driven undulator, *Phys. Rev. ST Accel. Beams* **11** (2008) 030704, doi:10.1103/PhysRevSTAB.11.030704.

[19] S.A. Schmid and U. Niedermayer, Design study of a dielectric laser undulator, *Phys. Rev. Accel. Beams* **25** (2022) 091301, doi:10.1103/PhysRevAccelBeams.25.091301.