Photonic Crystal (PhC)-based Dielectric Laser Accelerator (DLA)

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The possibility to accelerate particles at medium and high energies have enabled great discoveries in fundamental physics and countless industrial and medical applications.
The discussion of such a myriad of applications is, however, limited by the cost and by the footprint of accelerators facilities: conventional accelerating structures are typically big and expensive.
In a long-term vision, we envisage a cost-effective compact dielectric accelerator realized in a tabletop configuration, based on a laser-driven optic-integrated chip [1].
Regardless of the final application, size, cost reduction and achievement of higher accelerating gradient is always desirable for linear accelerators (LINACs).
Due to these requirements, Dielectric Laser Accelerators (DLAs) are very promising candidates able to increase the usual accelerating gradient of radio frequency (RF) electron linear accelerators by several orders of magnitude since the electric field breakdown limit in dielectric structures is significantly higher than in metal ones.
Moreover, cheap and unprecedented high-power laser sources, developed for optical telecommunication and other application, can be incorporated into integrated optics platforms through the use of advanced techniques that allow a stable and precise control of their optical phase.
Miniaturized (nanoscale) accelerating structures are actively investigated and experimental demonstrations of relativistic and sub-relativistic particle acceleration, with promising results, have been carried out [1-3]. **Laser acceleration of electrons with silicon dielectric structures was demonstrated in [2, 3] with accelerating gradients of more than 200 MeV/m.**
Many of the proposed configurations have an intrinsically limited interaction length, because they require a plane wave that impinges laterally throughout the whole structure's length [2, 3]. This requirement spoils the otherwise simple working principle of such interaction gratings, also known as phase-reset gratings.
Moreover, in the Accelerator on a Chip International Program (ACHIP), phase stabilization and on-chip waveguide laser power delivery systems have a very difficult implementation [4].
In order to have both high laser-induced accelerating gradients and adequate interaction length, it could be very helpful to use extended accelerating structures (with possibly co-linear propagation of the accelerating electromagnetic field and the particle to be accelerated [5]).
Photonic Crystals (PhC) based structures such as hollow-core waveguides, seem to be the ideal choice for the realization of a dielectric accelerator: in particular, the waveguide phase velocity can be tuned in order to get synchronous acceleration, the group velocity can be engineered based on the desired interaction length and higher-order modes can be efficiently suppressed.
In our research plan we propose an alternative to transversely illuminated interaction structures consisting in a collinear structure that employees the same path for the accelerating electromagnetic field and for the particle beam.

Preliminary results of hollow-core waveguides based on the "woodpile" photonic crystal have been obtained at scaled frequency: for example, in [6] and [7] characterizations of 3D woodpile waveguide structures, operating in the Ku and millimeter-wave band respectively, are described. In general, hollow-core structures can handle high laser power as compared to solid core ones (i.e. for example compared to a slotted waveguide [8]), thus allowing compact high gradient acceleration stages.
For this reason, dielectric structures based on hollow-core PhC waveguides are actively investigated and proposed in this LoI, since such "interaction structures" can support a suitable synchronous electromagnetic guided mode or resonant mode capable to accelerate charged particles.
In particular, in presence of guided modes or resonant cavity modes, **the interaction can be extended on relatively long distances in order to achieve adequate final energies.**
All the experiment carried so far uses electrons; but according to the study in [9], ultra-low injection energies and long interaction lengths can be achieved by Alternating Phase Focusing (APF).
At optical frequencies, dielectric waveguides for sub-relativistic low β particles are difficult to conceive and realize due to the locally dependence on β of the geometrical features.
Anyway the design of these low- β sections could follow the same design procedures of a conventional Radio Frequency Quadrupole (RFQ) [10], with separate sections of functional blocks that gradually perform the bunching, focusing and acceleration of the considered particles.
The acceleration of sub-relativistic particles up to speed of light can be addressed and solved only with an integrated multi-branched solution based on the innovation of the design of the periodic interaction structure with new concepts and techniques: inverse design of bandgap (EBG) structures to obtain continuously match phase velocity with the velocity of the accelerated particles and an all-electric synchronous focusing system (e .g taper slot waveguides [8]); working at higher harmonics; using a reliable photonic device manufacturing platform; using phased controlled CW laser sources with a proper development of phase control techniques; tailoring and varying the type of interaction structure along the accelerator length in order to follow the particle energy increase with a suitable configuration for each energy regime based on hollow core 2D [11] and 3D EBG structures [6] and [7].
Our proposal is to work at optical frequencies with dielectrics and develop novel interaction structures providing a continuous synchronicity and acceleration for particles from sub-relativistic to relativistic regimes.
This potential change of 6 order of magnitude for the wavelength of the electromagnetic accelerating field will require a precise phase control of the laser source, the employment of innovative dielectric materials, subwavelength geometric features and/or the use at higher harmonics. These requirements are compatible with recent scientific and technological achievements and also with planar manufacturing and mass production techniques.
Such miniaturization will provide unprecedented capability in charged particle acceleration (including sub-relativistic ones).
In order to mitigate current limitations due to the reduced channel cross section an option is to operate with a Continuous wave (CW) electromagnetic field and we could also adopt a multi-channel device which forms a DLAs matrix [12]. For high energy final stages of the accelerator we will take advantage from the virtually lossless nature of the dielectric and from the hollow core wave-guiding system (to be used also for the power distribution and branching): this will allow to operate with continuous wave laser sources and at relatively high power.
The main innovations and departures from classical approach are:
- Continuous wave (CW) laser operation: with a virtually lossless structure we can work in CW
- Dedicated miniaturized electron and ion sources.
- Optical wavelengths.
- All dielectric structures.
- Hollow core structures for high power delivery.
- Different interaction structures for different particle velocity.
In our proposal innovative structures with co-propagating laser light and particle beam will be developed; such structures may have sub-wavelength features for the acceleration of relatively low β particles. This represent an important advancement with respect to the state of the art and is a change of paradigm with respect to the use of diffraction gratings with relatively short interaction length.

REFERENCES

[1] R. J. England et al., *"Dielectric laser accelerators",* Rev. Mod. Phys. 86, 1337 (2014)

[2] K. J. Leedle, R. F. Pease, R. L. Byer, and J. S. Harris, "*Laser acceleration and deflection of 96.3 keV electrons with a silicon dielectric structure*," Optica 2, 158-161 (2015)

[3] E.A. Peralta et al., "*Demonstration of electron acceleration in a laser-driven dielectric microstructure*", Nature, vol. 503, no. 7474, p. 91+, (2013).

[4] Tyler W. Hughes et al., "*On-Chip Laser-Power Delivery System for Dielectric Laser Accelerators"* Phys. Rev. Applied 9, 054017 (2018).

[5] B. Naranjo, A. Valloni, S. Putterman, and J. B. Rosenzweig, "*Stable Charged-Particle Acceleration and Focusing in a Laser Accelerator Using Spatial Harmonics*", Phys. Rev. Lett. 109, 164803 (2012).

[6] G. S. Mauro et al., "*Fabrication and Characterization of Woodpile Waveguides for Microwave Injection in Ion Sources,"* in IEEE Transactions on Microwave Theory and Techniques, vol. 68, no. 5, pp. 1621-1626, (2020).

[7] G. Torrisi et al., "*Design and Characterization of a Silicon W-Band Woodpile Photonic Crystal Waveguide,*" in IEEE Microwave and Wireless Components Letters, vol. 30, no. 4, pp. 347-350, (2020).

[8] Z. Zhao et al., *"Design of a tapered slot waveguide dielectric laser accelerator for sub-relativistic electrons*," Opt. Express 26, 22801-22815 (2018).

[9] U. Niedermayer, T. Egenolf and O. Boine-Frankenheim, *"Threedimensional Alternating-Phase Focusing for Dielectric-Laser Electron Accelerators"* arXiv, (2020).

[10] R. H. Stokes, T. P. Wangler and K. R. Crandall, *"The Radio-Frequency Quadrupole - A New Linear Accelerator",* in IEEE Transactions on Nuclear Science, vol. 28, no. 3, pp. 1999-2003, (1981).

[11] G. Torrisi et al., *"Numerical Study of Photonic-Crystal-Based Dielectric Accelerators"* Journal of Physics: Conference Series, IOP Publishing, vol. 1350, (2019).

[12] Z Zhao et al; *"Design of a multi-channel photonic crystal dielectric laser accelerator",* arXiv 2020.