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Nanophotonic electron accelerator: A review of particle accelerator technology

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Abstract

Particle accelerators are indispensable tools in various industries, spanning a wide range of research fields such as nuclear and particle physics. They are particularly valuable in the medical sector for applications like medical imaging, radiotherapy and tumor treatment. Currently, the largest and most powerful particle accelerator is the Large Hadron Collider (LHC) at CERN, a 27-kilometer-long ring-shaped tunnel that accelerates particles, such as protons, to near-light speeds and collides them. While the LHC represents the pinnacle of accelerator technology, there is significant interest in developing compact particle accelerators that can fit within buildings, laboratories, or even on tabletops. However, even smaller accelerators often occupy several square meters of valuable space and may suffer from performance limitations. Not all applications require massive machines like the LHC, and more compact solutions could fulfill many needs efficiently.

Furthermore, a breakthrough in this field has been achieved by a team of laser physicists from Friedrich-Alexander University Erlangen-Nürnberg (FAU), who successfully demonstrated the first nanophotonic electron accelerator. This nanoscale device has been used to accelerate electrons, achieving a remarkable energy gain. What makes this development truly exciting is the unprecedented compactness of the nanophotonic accelerator - it is so small that it fits on a one-cent coin, making it the smallest particle accelerator currently available. Often referred to as a "particle accelerator on a chip," this technology holds immense potential, including applications in advanced cancer radiation therapies.

Keywords: Particle accelerator; Nanophotonic electron accelerator (NEA); Large Hadron Collider (LHC); Nanofabrication techniques

1. Introduction

Particle accelerator technology has long been at the forefront of scientific innovation, driving breakthroughs in various fields, from fundamental particle physics to medical diagnostics and treatments. The term 'particle accelerator' will bring to mind the Large Hadron Collider (LHC) in Geneva, an approximately 27 km long ring-shaped tunnel. Large accelerators are used for fundamental research in particle physics. Particle accelerators are complex machines designed to accelerate charged particles, such as electrons, protons, or ions, to high speeds and direct them to collide with other particles or targets. These collisions allow scientists to study the fundamental components of matter and the forces governing their interactions. At the heart of particle accelerators are electric and magnetic fields. Electric fields are used to increase the kinetic energy of charged particles, while magnetic fields are used to steer and focus the particle beams. The main techniques for accelerating particles include linear acceleration, circular acceleration, and synchrotron acceleration [1-2]. But in recent years, a new technological advancement has emerged on the scene, the Nanophotonic electron accelerator (NEA). The field of nanophononics has emerged as a promising solution to the size and cost constraints of conventional electron accelerators. Nanophononics involves the manipulation of light at the nanoscale, allowing for the precise control and confinement of electromagnetic fields. This precise control enables the development

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of compact accelerator structures that can achieve high accelerating gradients, making them much smaller than traditional accelerators.

Moreover, advances in nanofabrication techniques, such as electron beam lithography and focused ion beam milling, have made it possible to create intricate structures on the nanoscale, paving the way for the realization of nanophotonic accelerators. Nanophotonic accelerators require a high-power, short-pulse laser to provide the necessary energy for electron acceleration. The choice of laser wavelength, pulse duration, and other parameters is crucial in optimizing the accelerator's performance. The key to nanophotonic acceleration is the careful design and fabrication of the nanoscale structures that convert the laser energy into the desired accelerating fields. This includes features such as photonic crystals, plasmonic nanostructures, and metasurfaces. Efficiently injecting and capturing the electrons within the accelerating fields is a critical challenge. This may involve the use of specialized electron sources, such as photocathodes or field emission tips, and precise timing and beam shaping techniques [3-4].

Scientists have created the world's first [2] nanophotonic electron accelerator which speeds negatively charged particles with mini laser pulses and is small enough to fit on a coin. However, the idea actually originated in 1960, shortly after the laser was first invented. But at that time the technology did not really exist to actually realize it and again the idea of a nanophotonic electron accelerator was introduced in 2015, but this is the first time scientists have successfully activated and operated it. This technology employs nanophononics principles, a field that deals with the interaction of light and master on the nanoscale, to create ultra–miniaturized accelerators.

As stated earlier, researchers from the Friedrich–Alexander, University of Erlangen Nurnberg (FAU) in Germany used the tiny contraption to accelerate electrons from an energy value of 28.4 kiloelectron volts to 40.7 KeV, which is an increase of about 43%.

The nanophotonic electron accelerator (NEA) consists of a small microchip that houses an even smaller vacuum tube made up of thousands of individual "pillars". The main acceleration tube is approximately 0.02 inches (0.5mm) long, which is 54 million times shorter than the LHC. The inside of the tiny tunnel is only around 225 nanometers wide [4-6].

(Image credit: FAU/Laser Physics, Stefanie Kraus, Julian Litzel)

Figure 1 The Nanophotonic electron accelerator consists of a microchip that houses a tiny acceleration tube that is just millimetres long

The nanophotonic electron accelerators (NEA) creates a magnetic field, but it works by firing light becomes at the pillars in the vacuum tube. This amplifies the energy in just the right way, but the resulting energy field is much weaker. The electrons accelerated by the NEA have only about a millionth of the energy that particles accelerated by the LHC possess. However, the researchers believe they can improve the NEA's design by using alternative materials or stacking multiple tubes next to one another, which could further accelerate the particles [7].

Now, in section 2 we will discuss about the technology/methodology used in this nanophotonic electron accelerator and then we will take an overview of the comparative study of nanophotonic electron accelerator versus traditional particle accelerator and in section 4, we will discuss our findings and finally in section 5, we will highlight the concluding observations.

2. Methodology/Technology Used

The particle accelerators that can use lasers to accelerate electrons to relativistic speed through tiny “nanoscale” structures called “nanophotonic electron accelerators” are cheap and less bulky. Nanophotonic electron accelerators represent a cutting-edge approach to particle acceleration, leveraging the principles of nanophotonics and laser technology to create compact, efficient systems that could revolutionize various fields including medicine, industry, and scientific research.

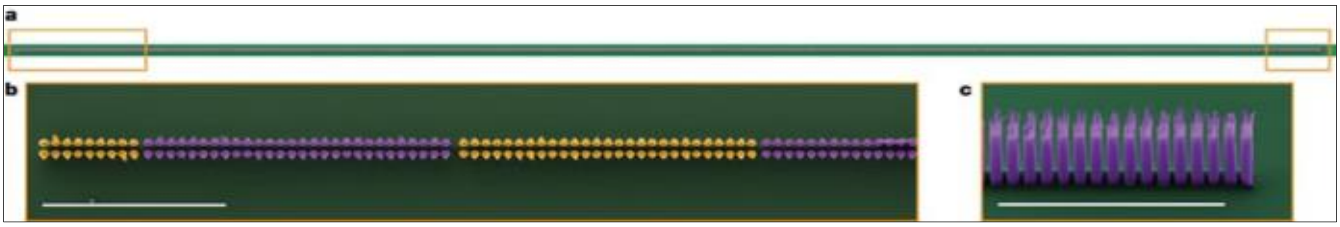
2.1. Principles of Operation

Nanophotonic electron accelerators operate by using laser pulses to accelerate electrons within nanostructured photonic cavities. The core idea is to use laser light to create rapidly oscillating electric fields within the nanostructured cavities. When electrons pass through these fields, they gain energy and accelerate. This process is identical to "surfing" on the electric fields created by the laser pulses. These cavities are designed at a scale smaller than the wavelength of light, allowing precise control over light-matter interactions. The key technology here is dielectric laser acceleration (DLA), where ultrafast laser pulses interact with the photonic structures to impart energy to electrons [3].

2.1.1. Key Components and Mechanisms

- **Photonic Nanostructures:** These are typically made from materials like silicon and are fabricated to include channels just a few hundred nanometers wide. Electrons are accelerated within these channels using high-intensity laser pulses.
- **Laser Pulses**: By firing laser pulses into these nanostructures, alternating electric fields are created, which propel the electrons forward. This method, unlike conventional accelerators does not require large metallic cavities and can achieve high acceleration gradients in much smaller spaces.
- **Alternating Phase Focusing (APF):** This technique helps in maintaining the electron beams focus over longer distances by alternating the direction of the confining forces, thus overcoming the repulsion between electrons in the beam.

Researchers from (FAU) and Stanford University have made significant strides in demonstrating the practical application of these accelerators. For instance, FAU's recent work has shown a 43% energy gain in electrons over a 0.5 mm distance within a 225-nm-wide channel, a substantial achievement for nanophotonic acceleration. This progress was achieved using advanced nanofabrication techniques and by combining the APF method with novel geometrical structures designed to optimize the acceleration and confinement of the electron beam .Researchers aim to further increase the energy gains and electron currents achievable with nanophotonic accelerators. This involves scaling up the nanostructures or integrating multiple acceleration channels to enhance the practical applicability of these devices [4-8].



(Image credit: Nature, volume 622, Oct 19, 2023)

Figure 2 2(a) Coloured scanning electron microscope image of the entire 0.5 mm long structure.

2(b) Top view of the initial part of the accelerator showing individual pillars and guiding channel.

2(c) Side view of the last macrocell of the accelerator.

Using this technique, they now succeeded not only in guiding electrons but also in accelerating them in these nano-fabricated structure over a length of half millimeter. The researchers will now try to increase the amount of energy gained by electrons by a factor of around 100 to make this nanophotonic electron accelerator for medical applications [9].

3. Comparison with Traditional Particle Accelerators

Traditional particle accelerators, such as linear accelerators (linacs), synchrotron and cyclotrons have been widely used for decades. Recently, nanophotonic electron accelerators have emerged as novel technology, leveraging the properties of photonics at the nanoscale to accelerate electrons.

Traditional particle accelerators and nanophotonic electron accelerators each have unique advantages and challenges. Let's take a brief overview:

- Nanophotonic electron accelerators are significantly smaller, often fitting on a chip-sized platform whereas traditional particle accelerators are extremely large, sometimes spanning kilometers (e.g., Large Hadron Collider) [10-12].
- Nanophotonic electron accelerator uses electromagnetic waves, particularly high intense laser pulses, to impart energy to electrons whereas traditional accelerators are use radiofrequency cavities or magnetic fields to accelerate charged particles along a defined path [13].
- Nanophotonic electron accelerators are currently limited to lower energies, suitable for specific applications where as traditional particle accelerators are capable of achieving very high energies suitable for fundamental research.
- Nanophotonic electron accelerators have potentially lower construction and operational costs whereas traditional particle accelerators have high construction and operational costs [13-14].
- Nanophotonic electron accelerators promise to deliver smaller, more affordable and energy-efficient particle acceleration technology. Their compact size and potential for mass production could revolutionize access to high-energy physics research, enabling a wider range of institutions and researchers to participate. While traditional particle accelerator's offer unparalleled collision energies and powerful detection systems that facilitate groundbreaking discoveries in particle physics. Its large scale enables the study of rare events and the exploration of the most fundamental building blocks of the universe [15].
- The high precision and small footprint of nanophotonic accelerators make them ideal for applications where space is limited and precision is critical. This includes potential uses in medical imaging, targeted cancer therapies, and the development of compact X-ray sources. In contrast, traditional particle accelerators provide extremely precise control over particle beams, which is essential for high-energy physics experiments but are less suited for applications requiring miniaturization.
- Nanophotonic electron accelerator is an emerging technology with ongoing research and development whereas traditional particle accelerators are mature technology with established global facilities and collaborations [15-16].

In summary, nanophotonic electron accelerators present exciting opportunities for miniaturized and cost-effective particle acceleration, but they cannot yet replace large scale traditional accelerators like the LHC, which remain crucial for high energy physics research. However, the complementary use of both technologies could lead to new advancements and applications across various fields.

4. Results and Discussion

The successful development of nanophotonic electron accelerators has significant implication for various fields. In medicine, these accelerators could enable more precise and compact radiation therapy systems. This groundbreaking technology promises to revolutionize the field with its compact size, energy efficiency and versatile applications.

One of the key advantages of Nano accelerators is energy efficiency. Traditional particle accelerators consume vast amounts of energy, often requiring dedicated power plants to operate. In contrast, the Nano accelerator operates at significantly lower power levels, making it more sustainable and environmentally friendly. This energy efficiency not only reduces operating costs but also expands the accessibility of particle accelerator technology to a wide range of uses.

The development of nanophotonic electron accelerators has far-reaching implications for a wide range of scientific and industrial applications [16]. Some of the most promising use cases include:

4.1.1. High-Energy Physics

The ability of nanophotonic accelerators to achieve high acceleration gradients in a compact footprint makes them an attractive option for the next generation of particle colliders, enabling more affordable and accessible high-energy physics research.

4.1.2. Medical Imaging and Therapy

Nanophotonic accelerators can be used to generate high-energy electron beams for advanced medical applications, such as targeted cancer treatment and high-resolution electron microscopy for biological imaging [16-17].

4.1.3. Industrial Applications

The compact size and potential cost-effectiveness of nanophotonic accelerators make them suitable for a variety of industrial applications, including materials processing, nondestructive testing, and the production of specialized radioisotopes [18]. While the promise of nanophotonic electron accelerators is significant, several key challenges must still be addressed to fully realize their potential. These include the following:

4.1.4. Scaling to Higher Energies

Achieving higher electron beam energies while maintaining high-gradient acceleration and beam quality is a critical challenge that requires innovative design strategies and further advancements in materials and fabrication.

4.1.5. Reliability and Robustness

Ensuring the long-term reliability and operational stability of nanophotonic accelerator systems, particularly in the face of high-power laser operation and environmental factors, is an important area of ongoing research.

4.1.6. Integrated System Development

Integrating the various components of a nanophotonic electron accelerator, including the laser, beam transport, and diagnostic systems, into a cohesive and user-friendly technology platform is crucial for widespread adoption and real-world applications [18-19].

Despite the limitations, the progress in nanophotonic electron accelerators is promising. Ongoing research aims to increase the energy gain and electron current in nanophotonic accelerators, which will further expand their applications. Enhancements in technology, such as the development of more efficient nanostructures and improved laser systems, are expected to make these accelerators even more powerful and versatile. The collaboration between institutions, including the joint efforts of FAU and Stanford, is accelerating progress in this field moving closer to practical implementations of accelerators on chips [19].

In summary, while nanophotonic electron accelerators offer exciting prospects for miniaturized and cost-effective particle acceleration, they are not yet a replacement for large scale traditional accelerators like the LHC, which remain essential for high energy physics research. However, the complementary use of both technologies could lead to new advancements and applications across various fields.

5. Conclusion

The Nanophotonic electron accelerator (NEA) represents a significant advancement particle accelerator technology, offering unprecedented levels of efficiency, versatility, and portability with its compact size and energy, efficiency. This technology has the potential to provide equal access to particle accelerates capabilities & drive innovation across a wide range of fields. Moreover, the compact size of the nanoaccelerator opens up new possibilities for portable and field deployable systems.

As research and development in this area continues to progress, the nanophotonic electron accelerator (NEA) is poised to lead the way into a new era of scientific discovery and technological advancement. Further research should explore the scalability of nanophotonic electron accelerators. Investigating larger-scale nanophotonic structures and their interaction with high-intensity laser pulses could pave the way for practical applications. Moreover, developing new materials with higher damage thresholds and better thermal properties could further enhance the performance of these accelerators. The development of nanophotonic electron accelerators has the potential to significantly impact a wide range of scientific disciplines, from fundamental physics to materials science and medical research. From high-energy collision experiments to advanced materials characterization and medical imaging, the versatility and scalability of nanophotonic accelerators promise to significantly advance our understanding of the physical world and drive breakthroughs across multiple scientific disciplines.

The collaborative efforts between institutions like FAU and Stanford University, supported by funding from foundations such as the Gordon and Betty Moore Foundation, continue to drive this research forward, pushing the boundaries of what is possible in the realm of particle acceleration.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Chao, Alexander W; Chou, Weiren (2008). Reviews of Accelerator Science and Technology: Volume 1. Singapore: World Scientific. Bibcode:2008rast.book.....C. doi:10.1142/7037. ISBN 978-981-283-520-8.

[2] Livingston, M. S.; Blewett, J. Particle Accelerators. New York: McGraw-Hill. ISBN 978-1-114-44384-6 (1969).

[3] Tomas Choulb, Roy Shiloh, Stefanie Kraus, Leos Bruckner, Julian Litzel, Peter Hommelhoff , Coherent nanophotonic electron accelerator, Nature, volume 622, 18 Oct (2023).

[4] Peralta, E. A., et al. "Demonstration of electron acceleration in a laser-driven dielectric microstructure." Nature, 503(7474), 91-94. (2013)

[5] Particle accelerator on a chip hits penny-size, IEEE spectrum, By Charles Q Choi, 24 Oct (2023)

[6] A big step for little particle accelerators Advanced science news, by Robert Lea, 7 Nov (2023)

[7] Live science, news by Harry Baker, 25 Oct (2023)

[8] Demonstration moves on chip particle accelerators one step closer, Photonics spectra , 0ct (2023)

[9] Xu, J., et al. "Electron acceleration in a laser-driven dielectric structure using a photonic crystal." Physical Review Accelerators and Beams, 23(2), 021302. (2020)

[10] England, R.J., et al. "Dielectric laser accelerators." Reviews of Modern Physics 86, 1337-1389 (2014)

[11] Piggott, A. Y., et al. "Inverse design and demonstration of a compact and broadband on-chip wavelength demultiplexer." Nature Photonics, 9(6), 374-377 (2015)

[12] The Cost of the Large Hadron Collider." Symmetry Magazine, Fermilab/SLAC. Accessed June 26, (2024)

[13] Size Matters: The Scale of Particle Accelerators." Nature. Accessed June 26, (2024)

[14] Breuer, J., & Hommelhoff, P. Laser-based acceleration of nonrelativistic electrons at a dielectric structure. Physical Review Letters, 111(13), 134803. (2013)

[15] Access to Particle Accelerators: Challenges and Opportunities. Science Magazine. Accessed June 26, (2024)

[16] The Future of Particle Accelerators." Physics Today. Accessed June 26, (2024)

[17] Wootton, K. P., Kozák, M., & Leedle, K. J. Dielectric laser acceleration. Nature Photonics, 10(10), 715-721. (2016)

[18] Physics World. "Electrons Accelerated by Firing Lasers into Nanophotonic Cavities."

[19] Photonics Spectra. "Demonstration Moves On-chip Particle Accelerators One Step Closer " Oct (2023)