# – Applications of Particle Accelerators and –
# Developments in Miniaturization

Andrew Wang, Shariq Raihan, Justin Poveda

*EST440, Stony Brook University*

## Introduction

This paper is intended to discuss the context and technical background of particle accelerators as well as their major applications to thoroughly evaluate their technological significance. By doing so, we can review the recent developments in miniaturization and what trends they will set for the future. We must first look at the prevalence of particle accelerators in their applied fields before considering their fundamental functions and processes to better understand how they are used. Thus, it is crucial to provide some historical context of the origins of particle accelerators.

In the decades before the 21st century, large accelerator facilities were primarily experimental projects for fundamental investigations, and have been around since the 1950s. Over the last 20 years, however, progressively smaller accelerators have become more common in applied fields such as chemistry, biology, ecology, etc [1]. Figure 1 shows the growth of accelerator use over time, and the total number of accelerators used for science, industry, agriculture, and medicine has grown to approximately 40 thousand as of 2012 [1]. In 2012, accelerators were better known in industry to be small-sized electronic neutron generators (ENGs) for

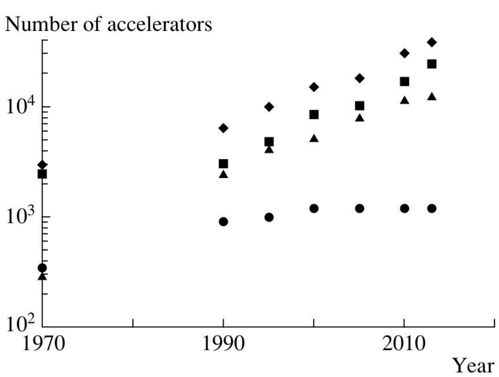



**Fig. 1.** Accelerators in medicine, industry, science, and agriculture: (closed diamonds) total number, (closed boxes) industry and agriculture, (closed triangles) medicine, and (closed circles) fundamental research.

geological analyses in the petroleum business, while other applications included radiography, lab material analyses, organism composition studies, and radiation testing. Over time, those other applications have grown in use as their particle generation capabilities were expanded upon. For example, since accelerators can be operated rather than simply contained like radioisotopes, they offer greater ease of use and oftentimes more utility as well. Furthermore, though ionizing radiation has been used in the food/agriculture industry for about 70 years, accelerators have only recently become more commonly used for this purpose [1]. Radiation is specifically used here to disinfest products, preventing the growth of seeds for long term storage, and is also used to induce new mutations in produce for enhanced properties. It is interesting to note in Table 8 that though many countries in 2009 had setups for radiation-based sterilization for food, China has magnitudes more at a count of 90 compared to the rough average of 2 [1]. These statistics indicate significant exports from China, as well as a probable increase in demand for improved radiation setups. As for the other aforementioned applications, related technologies that have been developed include devices based on cobalt sources, gamma knives, gamma chambers, single-photon emission computer-aided tomography (SPECAT), computer-aided x-ray

**Table 8.** Radiation sterilization of food products in some countries in 2009

| Country | Number of setups for irradiation | Type of irradiated food product |
|---|---|---|
| Australia | 1 | Meat products |
| Algeria | 1 | Potato |
| Argentine | 1 | Spices, spinach, cacao powder |
| Bangladesh | 1 | Potato, onion, stockfish |
| Brazil | 3 | Spices, sublimated vegetables, fruits, vegetables, grain |
| Vietnam | 6 | Onion |
| India | 8 | Spices, onion, potato |
| Indonesia | 2 | Spices, rice |
| Iran | 1 | Spices |
| China | 90 | Spices, lunch meat, garlic, apple, potato, onion, sublimated vegetables, rice, tomatoes, sauces |
| DPRK | 2 | Dried garlic, spices |
| Korea | 1 | Dried garlic, spices |
| Cuba | 1 | Potato, onion, leguminous plants |
| Malaysia | 1 | Fruits, spices |
| Pakistan | 1 | Dried condiments, fruits, spices |
| Thailand | 2 | Spices, sausages, enzymes |
| Ukraine | 1 | Grain |
| Philippines | 1 | Marine products |
| Croatia | 1 | Spices, noodle |
| Czech Republic | 4 | Spices, dried condiments |
| RSA | 4 | Spices, fruits, products of long-term storage |

tomography (CAT), magnetic-resonance tomography (MRT), and positron-emission tomography and scanners (PET) [1].

**Background**

To fully understand the significance of these developments and advances, we must also review the scientific phenomena and the more specific utilizations of accelerators. Particle accelerators operate on energy levels capped at 10 MeV and are sectioned into low, intermediate, and high energy accelerators [1]. Low energy accelerators usually fall within the range of 70-300 KeV and are used for purposes like purification of liquids and gas as well as surface sterilization, while intermediate energy models function at 300 KeV to 5 MeV for applications such as manufacturing radiation-insulated cables and vulcanizing tire components. High energy accelerators work in the remainder of the range at 5 to 10 MeV, and are used to sterilize medical equipment and in customs examination of large objects [1]. The processes that fuel these machines are primarily based upon photon-related reactions and bremsstrahlung radiation (radiation produced by a deflected charged particle by another charged particle) [2]. High energy photons can be used to generate neutrons by reacting with nuclei, while high energy electrons are aimed at materials and cause x-ray radiation to be produced. Linear accelerators, machines that can be designed to deliver target amounts of radiation to a target within a patient, are most often used for generating x-ray radiation [2].

Regarding details on specific applications, we first look at the previously mentioned oil well analyses that employ accelerators. These devices can be used to replace neutron sources like Cf-252, and serve as a strong example for the importance of miniaturizing accelerator sizes. Another major example is the use of accelerators in the field of medicine, which Table 9 displays clearly [1]. In the past, accelerators were used in the field to collect data on a body by measuring the presence and amount of elements in the body, component composition (water, fat, protein, etc.), and bodily processes to allow researchers to better understand the origins of illnesses. More recently, accelerator technology is better known for being used to treat cancer cases. The disease comprises 13% of deaths worldwide and is one of the fastest growing diseases; treatment with radiotherapy is used in more than 60% of cases, and is related to almost half of all recovery cases [3]. As a result, there is considerable interest in improving accelerator technology to expand on what cases are treatable. The treatment works by burning out a tumor with a dose of radiation that is minimally invasive compared to traditional means of removing the mass, in order to avoid a long recovery period.

**Table 9.** Accelerators for medicine in leading countries of the world in 2012

| Country | Number of accelerators, units | Population of country, millions | Population per accelerator, thousands |
|---|---|---|---|
| USA | 3820 | 313.8 | 82 |
| Finland | 45 | 5.3 | 118 |
| Sweden | 69 | 9.1 | 132 |
| France | 476 | 65.6 | 138 |
| Japan | 849 | 127.4 | 150 |
| Germany | 514 | 81.3 | 158 |
| Great Britain | 314 | 63.0 | 201 |
| Czech Republic | 45 | 10.2 | 227 |
| Brazil | 286 | 205.7 | 719 |
| RSA | 65 | 48.8 | 751 |
| Russia | ~125 | 143.1 | 1145 |
| China | 1017 | 1343.2 | 1321 |

Radioisotope usage is also a crucial topic, as they are still the most commonly used source of gamma radiation with approximately 55 thousand active in the US alone [3]. Due to their nature, it is important to lean away from using them to minimize risk of leaks and other accidents, and more compact accelerators could replace them as radiation sources. A major example would be iridium, which is a very useful isotope that is commonly used in industrial radiography to find defects in metal as well as radiotherapy. However, it is also the isotope that is most at risk for being stolen in the U.S., making an alternative very appealing [3]. The main obstacles to size reduction are the power supplies and radiation shielding, which contribute the most to the sheer size of accelerator units. We can reduce the size of components by increasing the frequency of electromagnetic field oscillations to be more energy efficient: "shunt impedance increases as a function of frequency in proportion to $f^{1/2}$, and is defined as ratio of the square of the particle energy increment to power dissipated in the structure ($R_{sh} = V^2 / P$)," [3]. With these considerations in mind, we can discuss the applications of accelerators in certain fields and their specifics.

**Applications**

With the continuous development of particle accelerators, the applications for particle accelerators and its potential uses have been expanding into many different fields of work. Given that particle accelerators are one of the most versatile instruments created by physicists, a wide variety of applications for particle accelerators can include scientific research, applied physics, medicine, industrial processing, search of cleaner greener energy options and our understanding of the universe. One way that accelerators have been commonly used is in geographic data measurement, as previously mentioned.

Measuring underground data with accelerators using traditional means is nearly impossible due to the harsh conditions, and so radioisotopes are more often employed for this purpose. For example, Cs-137 is used in gamma logging of oil wells to determine the surrounding properties, such as composition and structural details. In order to substitute for this kind of application, the design requirements for accelerators are particularly strict and provide only a diameter of 9-10 cm, temperatures of up to 150ºC, a depth of up to 1 km, and vibrations with g-force up to 2g [3]. If a model accelerator were to be developed, however, it would output 2-4 times the gamma energy of a comparable radioisotope, making it very desirable as a replacement. Despite these limitations, researchers have proposed a solution which involves a radio frequency (RF) power source specially designed to handle these conditions [3]. This proposal, though only effective in theory, serves as proof that accelerators can be made to handle multiple scenarios even if some are incredibly demanding.

It is also necessary to evaluate the ecological impacts of using radioisotopes, particularly through a life-cycle analysis (LCA). There are a number of major drawbacks to using radioisotopes, one of which is its vulnerability to shortages. In 2017, the Mo-99 isotope was notable for "suffering shortages in the last decade", with demand increasing gradually over time [6]. Without a new source or clear alternative, accelerator-based means of generating the same radiation is the clear solution. Acquisition and disposal costs involved in preparing and properly discarding isotopes like Mo-99 are also important to consider, as accelerators only have manufacturing costs in comparison. Radioisotopes, as noted above, also run the risk of being stolen and misused for environmental damage or weaponization in certain cases. Perhaps the most appealing aspect of accelerator technology in this field is its potential to have variable beam parameters to output different kinds of radiation with a single model, in contrast to a radioisotope being limited to one kind each.

In order to be a feasible substitute, however, there are still a number of advantages inherent to radioisotopes that must be addressed. Radioisotopes have effectively perfect operational capabilities, while accelerators in comparison are susceptible to failure for a number of reasons at a given moment. They can only function for a few thousand hours before some sort of repair is needed, and also require regular service with some demanding even more if they are a higher particle yield model. In contrast, radioisotopes work without any of those concerns for years or decades before they give out [3]. As such, the requirements for improvements are that the model must be of similar size to a radioisotope, it must have flexible beam parameters to allow it to accomplish multiple tasks with a single design, and it must be more cost effective than a competing radioisotope.

Particle accelerators are not only used in geographic data measurement, but also in the medical field, which can be categorized into two broad main groups: diagnostics and therapeutic. In the medical field, the use of particle accelerators is pivotal to the treatment of patients with cancer and tumors. In addition, it is also "estimated that 25 to 30% of the population of industrial countries will contract cancer in their life-time" [7].

The applications of a particle accelerator can bring many advantages when tackling this challenge, and we must understand the relationship between radiotherapy and particle accelerators. At low doses, radiation is used in x-rays to see inside your body, as with X-rays of your teeth or broken bones," [8]. In terms of therapeutics, "radiotherapy of tumors with particle beams" is the primary method of treating tumors and cancer. The particle accelerator in this case is designed to fire a beam of radiation into the human body. The main problem that arises with this type of method treatment is that it can cause possible "damage to healthy tissues around the tumor due to the uneven distribution of the radiation dose"; however, with the use of a particle accelerator, one would be able to confine the dose to the tumor. This would allow it to shape the radiation dose around the tumor, which would damage the tumor while minimizing any effect on the healthy tissue. This would enable doctors to give patients a treatment with fewer side-effects and better outcomes overall in terms of the treatment. In other words, the particle accelerator “can substantially increase the efficiency of dose delivery to the tumor without damaging the surrounding tissues," [9]. This can lead to the next advancement of tumor and cancer treatment, with the ability to aid many people worldwide.

Currently, there are three popular modes of radiotherapy which function based on beams of photons, electrons, and hadrons (heavy ions and protons). The reason accelerators are appealing as a method of particle delivery is that in theory, they can be made to work with variable beam parameters that allow for better treatment of moving tumors, which are difficult to treat at the moment. This involves synchronizing the ion beam with the scanning beam at a frequency of up to 1 kHz, and if accomplished has “similar efficacy at treating tumors as a 3D printer” [3]. More specifically, hadron therapy is more desirable compared to photon therapy due to what is known as the Bragg effect, where “protons and heavy particles release the majority of their energy at the end of their trajectory” to allow for less damage to surrounding tissues [3]. However, hadron systems cost significantly more to implement than photon systems, sporting a cost of around $100 million compared to a milder $3 million for the latter. The reason hadron therapy costs more is due to how only protons and carbon ions are used in its operations; carbon ions are used since they have the capability to cure radioresistant tumors like inoperable bone and soft tissue sarcomas which are otherwise incurable [3]. The drawback of these capabilities is that it causes the entire accelerator model to be too inflexible, slow and expensive to be more usable. For example, cyclotrons that are used for hadron therapy have fixed beam energy, making it impossible to adjust the penetration depth. Though synchrotrons are capable of this, the adjustment takes too long with 1 second intervals to be able to treat moving tumors, which demands that systems ideally have under a 20 ms energy variability rate to be able to keep up with the tumor scanning system [3].

Since the medical benefits of properly commercializing hadron therapy would enable far less invasive treatment for patients and ideally be more cost effective at some point, research has yielded some progress in recent years. Scientists at CERN have successfully accelerated protons in designs as small as 10 cm, potentially enabling high-power component sizes to be reduced up to a factor of 10, and also managed to increase the frequency capabilities to 750 MHz to allow for further size reduction [3]. These developments allow for the gantry designed around the patient to be much more feasible in terms of size, subsequently lowering costs for this implementation.

While hadron therapy's appeal lies in the Bragg effect, we should still review the potential of photon therapy's application in radiotherapy. Photon therapy's main flaw is its propensity to cause collateral damage to healthy tissue around a tumor; this can be alleviated by "irradiating the patient from a large number of different noncoplanar directions by… rotating the radiation source around the patient within the full 4π solid angle", as seen in Figure 14 [3].

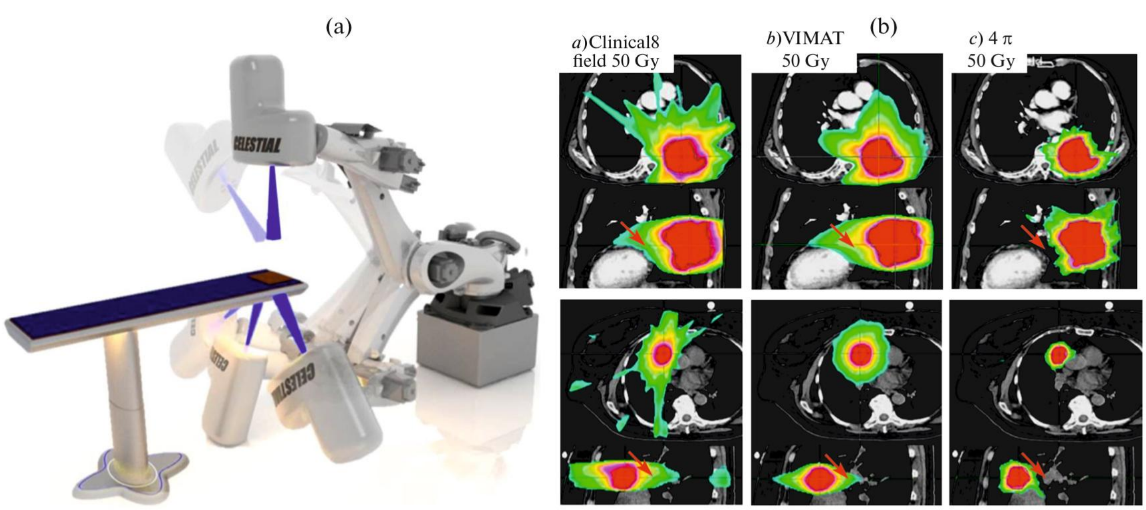
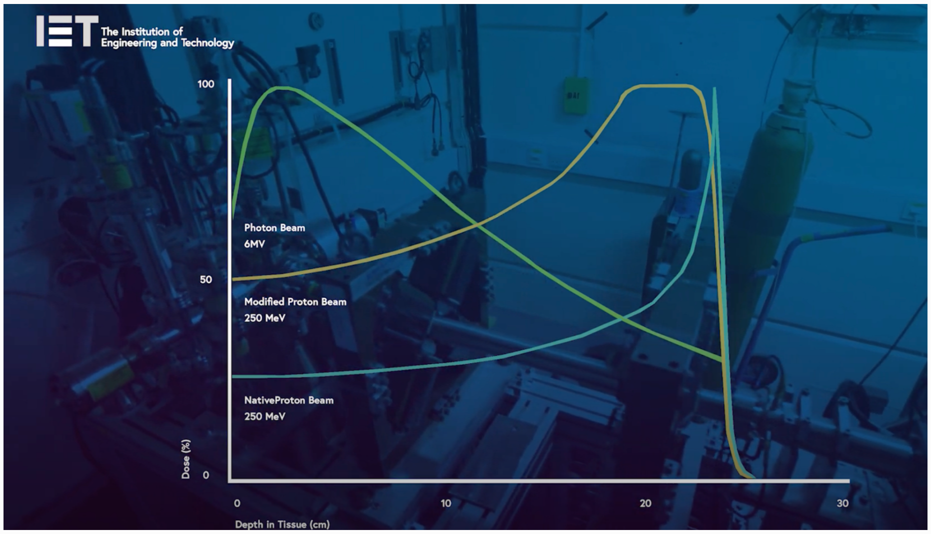



**Fig. 14.** (a) Model of a 4π-therapy unit developed by the University of California Los Angeles in collaboration with RadiaBeam Technologies and (b) comparison of the distribution of a radiation dose around tumors with conventional radiotherapy [364]. The images are from the website of the University of California Los Angeles (https://www.uclahealth.org).

In order to actually utilize this design, however, the accelerator unit must be small enough to fit on the arm. The design and efficacy of 4π-therapy is directly related to the particle source, and traditional sources such as Carm or CyberKnife that are moderately sized rigs cannot use large accelerators. Developments such as the one at CERN indicate that such designs are not far off, though indirectly related.

Though the prices for linear accelerators used in radiotherapy vary wildly depending on what reaction their systems are designed around and what condition they are intended for, it is still prudent to draw a cost-benefit analysis. According to an article from Modern Healthcare, the prices of linear accelerators rose 20% to $2.8 million from April to May in 2013, and by 10% over the last year [4]. This was mainly due to new implementations ordered by the hospitals, however, and according to an article by Healthcare Appraisers, a linear accelerator in 2019 usually cost $3 million [5]. From this, we can conclude that newer technologies will increase the cost somewhat, but the price will stabilize over time without growing much higher. We can also infer that developments in miniaturizing accelerator components and improvements in treatments, such as with hadron therapy, will temporarily raise prices but overall be more cost effective than continuing with current traditional means.

In addition to therapeutics, medical diagnostics such as X-rays benefit as a source for applications of a particle accelerator because X-rays are “energy emitted from a source that is generally referred to as radiation” and involves “Ionizing radiation” which can remove electrons from the atoms, i.e. it can ionize atoms”[10]. According to the United States Environmental Protection Agency there are a number of  particle accelerators that produce ionizing radiation, such as X-rays or neutrons, which can be used to make radioactive materials[11]. This is significant because, x-rays deposit there dose as they come in a broad peak, however with a particle accelerator, one can change the energy so we have what's called a spread out Bragg peak in which the energy is deposited  with protons so you don't have any exit dose, meaning it's great for treating tumors that are close to critical organs.




## Developments in Miniaturization

With the review of accelerator applications and the details of their specific functions in mind, we can discuss the recent developments necessary to make progress and how they work. Among these, new production technologies involving layer-by-layer synthesis and mechanical micromachining aid in minimizing production costs, and new structural design of components, such as split structures or one that enables distributed power to cells allows for overall size reduction (Figure 3) [3]. The distributed power supply design was studied at the Stanford National Accelerator Laboratory (SLAC), and was based on the “absence of electromagnetic coupling between neighboring cells and

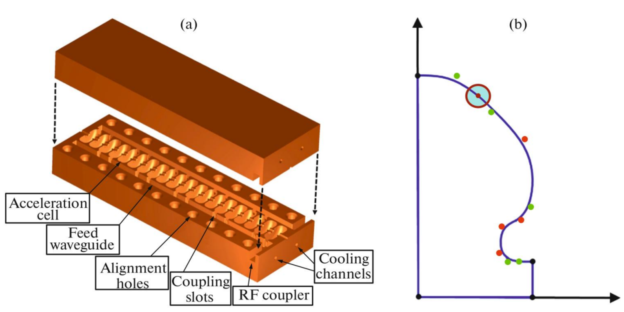
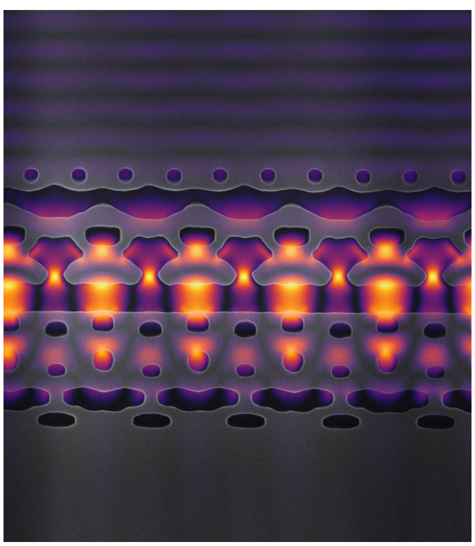



**Fig. 3.** (a) Example of a promising area for the development of accelerating structures: a split accelerating structure with distributed power supply to cells, developed at the Stanford National Accelerator Laboratory. (b) The absence of communication cells makes it possible to implement complex shapes of accelerating cells optimized with use of genetic algorithms. The structure can also be made of novel alloys such as CuAg and welded using electron beam welding technology instead of traditional brazing.

individual power supply, which… [excludes] coupling cells that are necessary for the stable operation of traditional structures… and second… [optimizes] the shape of the cells by means of genetic algorithms," [3]. This ends up improving the shunt impedance compared to traditionally individually powered cells, and allows for continued operation in the event of cell breakdown during high gradient conditions. With split structure technology, accelerators can become compact enough to better replace radioisotopes, as a linear accelerator prototype built by RadiaBeam Technologies demonstrates [3]. Their model is capable of energies up to 180 keV, and is directly comparable to radiation doses from the Co-57 isotope; since it has the inherent ability to provide varying degrees of energy as well, it serves as an appealing alternative and example for other future builds.

Though particle accelerators are crucial tools as proven with previously referenced applications and fields, their high costs and large footprints which range from a few meters to several kilometers, limit their use. The recently proven nanophotonics-based acceleration of charged particles has the potential to drastically lower the cost and size of accelerator designs.



Conventionally known particle accelerators are incredibly large; the Large Hadron Collider, for instance, is 17 miles in circumference. Recently, however, a team of scientists at Stanford have created a silicon chip that can act as a particle accelerator at only 30 micrometers long, about the width of a human hair. A conventional particle accelerator uses a series of metallic cavities powered by microwave energy to continuously accelerate bunches of charged particles traveling through it. Similar to a surfer riding on an ocean wave, particles in the accelerator ride an electromagnetic wave and either gain or lose energy depending on whether they are located at a peak or trough along the radiation's wavelength, which is on the order of 10 cm in conventional accelerators.

Scientists began imagining ways to harness the newly realized power for particle acceleration soon after the first laser was shown at Hughes Research Laboratories in 1960. However, the required technology for laser-driven particle accelerators did not exist in the 1960s. The Laser Electron Acceleration Program (LEAP) was based at Stanford University and SLAC in the early 2000s. LEAP was a laser experiment that led to one of the first demonstrations of laser-driven acceleration. The technique involved shining a laser onto a material boundary, which sat in the path of a high-energy electron beam. The laser's electric field terminated at the boundary on a half cycle, so the truncated laser field gave the particles an accelerating "kick". The design algorithm came up with a chip layout that includes a channel etched out of silicon. Electrons flowing through the channel run a gauntlet of silicon wires that poke through the canyon wall at strategic locations. Each time the laser pulses, which it does 100,000 times a second, a burst of photons hits a bunch of electrons, accelerating them forward. All of this occurs in less than 10 µm on the surface of a vacuum-sealed silicon chip.

For a laser-driven accelerator, the length of each stage is determined by the interaction time of a particle bunch with a laser pulse. To maintain the phase-velocity match of the laser wave and the particle beam over many stages, the laser must be recoupled at each stage and its phase and amplitude carefully controlled. A compact and elegant solution is to couple the laser beam into on-chip photonic waveguides. The design velocity of an optical-scale device such as a particle accelerator must be varied along its length to accommodate the anticipated particle speed at each point along the accelerator. Two parallel methods can address that requirement. One is to vary the periodicity of the accelerator structure itself to match the local wave velocity to the electron speed. The other is to imprint a custom phase profile onto the laser pulse. By simultaneously chirping the laser pulse and tilting the wavefronts using dispersive optics, both phase and group velocities can be matched to achieve high-gradient acceleration and laser-driven focusing over a centimeter-scale interaction length. The result is high- gradient acceleration and laser-driven focus over a centimeter-scale interaction length. Though these developments are not directly transferable to allow for the same kind of energy output as accelerators like the LHC at sizes of a centimeter, they will serve as a guideline for optimizing that kind of output at progressively smaller and more widely useful sizes and costs.

**Conclusion**

From these developments in accelerator technology, we can infer what future trends are for their use and what other potential improvements may be. Proportionately speaking, the number of accelerators used for fundamental science has decreased to a smaller percentage, with more being used for applied tasks [1]. This is due to the specialization of models enabled by more effective and smaller designs, though the ones used in research are still significant since they provide crucial information on the applied particle reaction phenomenon. Their experiments with radio, low-temperature, and solid-state physics will continue to allow for new technologies in industry, medicine, etc. Funding for accelerator research in the medicine field is notably substantial on a global scale, indicating that there is reliable interest in their application to solve existing and nascent problems [1]. In the case of cancer treatment, improvements would increase efficacy in curing more cases, such as moving tumors, as well as potentially cause breakthroughs that help other applications make progress. Particle accelerator chips like the ones created at the

LEAP could very well allow significantly more cost-effective models to be commercially available, lowering the costs and nullifying any new expenses from the new designs. With consideration of these applications of accelerators, their developments, and their trends over time, it is recommended to continue to monitor their technological progress as it has heavy implications for other, more removed fields and their scientific timeline.

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