MICROCHIP ACCELERATORS

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An international collaboration aims to couple ultrafast lasers with integrated photonics to create chip-scale devices.

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Particle accelerators are among the most important scientific tools of the modern age. Major accelerator facilities, such as the 27-km-circumference Large Hadron Collider in Switzerland, where the Higgs boson was recently discovered, allow scientists to uncover fundamental properties of matter and energy. But the particle energies needed to explore new regimes of physics have increased to the TeV scale and beyond, and accelerator facilities based on conventional technologies are becoming prohibitively large and costly. Even lower-energy, smaller-scale accelerators used in medicine and industry are often cumbersome devices; they can weigh several tons and cost millions of dollars.

Efforts are consequently underway to develop more compact, less expensive accelerator technologies. One approach, a dielectric laser accelerator (DLA), uses an ultrafast IR laser to deliver energy to electrons inside a microchip-scale device. Efficient, ultrafast solid-state lasers and semiconductor fabrication methods developed over the past two decades have enabled a new breed of photonic devices that can sustain accelerating fields one to two orders of magnitude larger than conventional microwave-cavity accelerators.

The approach has the potential to dramatically shrink particle accelerators, thereby enabling ultrafast tabletop electron diffraction and microscopy experiments and tunable x-ray sources. An international effort is now underway to develop a laser-driven accelerator integrated on a silicon photonics platform: an "accelerator on a chip."

Technological evolution

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.

Shortly after the first laser was demonstrated at Hughes Research Laboratories in 1960, scientists began envisioning ways to harness the newly realized power for particle acceleration. The idea was appealing because the corresponding reduction in wavelength by four orders of magnitude—from the RF regime of conventional microwave accelerators to the optical regime of lasers—implied shrinking accelerator structures down to the micron scale.

But the required technology for laser-driven accelerators did not exist in the 1960s. It took several decades for solid-state lasers, optical materials, and nanofabrication to reach the point where researchers could pursue the idea in earnest. Also, metals were the prime candidates for shaping the accelerating fields, but they can't withstand the necessary large optical power levels because they absorb too much. Then, in the 1990s, researchers had the idea to use optically transparent dielectrics. That idea enabled the creation of the Laser Electron Acceleration Program (LEAP), which was based at Stanford University and SLAC in the early 2000s and aimed to realize a fully laser-driven particle accelerator.

LEAP led to one of the first demonstrations of laser-driven acceleration. The scheme used the so-called inverse transition radiation effect, in which a laser was shone onto a material boundary—a thin gold foil—that sat in the path of a high-energy electron beam.[1] 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 interaction distance in the proof-of-principle experiment, however, was limited to one half of an optical cycle, or less than 1 μm.

A key realization from those early experiments was that to make an efficient laser-driven structure, one should take advantage of the high damage threshold and low losses of dielectric and semiconductor materials. The laser in the LEAP experiments had to operate above the damage threshold of the metal surface to produce a measurable electron energy gain, so the gold film was mounted on a reel that refreshed the surface between each laser shot. Transparent dielectrics and semiconductors, on

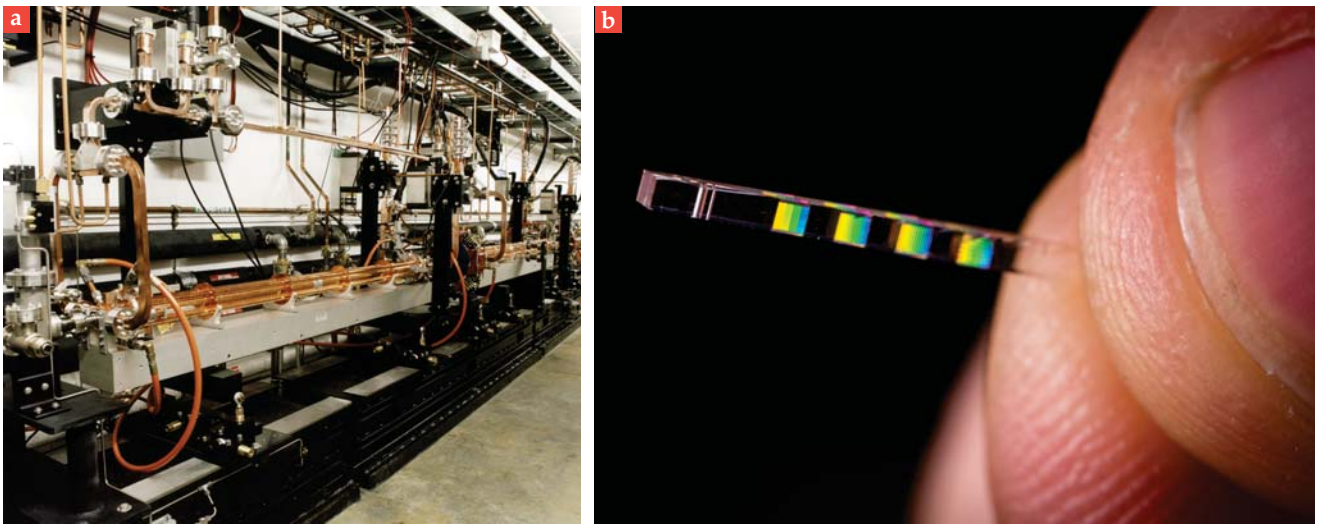

FIGURE 1. THE SIZE CONTRAST between conventional accelerator facilities and chip-based accelerators is dramatic. **(a)** The Next Linear Collider Test Accelerator facility at SLAC was used for early laser-acceleration experiments in 2012–15. (Image courtesy of the Archives and History Office/SLAC National Accelerator Laboratory.) **(b)** The first dielectric laser accelerator chips demonstrated at SLAC were made of fused silica and were each the size of a grain of rice. (Image courtesy of Christopher Smith/SLAC National Accelerator Laboratory.)

the other hand, can sustain accelerating field strengths that greatly exceed those of conventional particle accelerators. Various all-dielectric high-gradient accelerator designs have since been proposed. (For a review of DLA designs, see reference 2.)

In 2011 the authors of this article forged a collaboration with Purdue University and Tech-X, a commercial accelerator code developer in Boulder, Colorado. The program, AXiS (Advanced X Ray Integrated Sources), was a successor of LEAP and was sponsored by the US Defense Advanced Research Projects Agency. It was aimed at developing ultracompact accelerator technologies for portable medical imaging applications. Under the newly formed collaboration, the first high-gradient demonstrations of laser acceleration in nanostructured devices were conducted in parallel experiments at SLAC and at Friedrich–Alexander University (FAU) Erlangen–Nuremberg in Germany in collaboration with the Max Planck Institute of Quantum Optics (MPQ).

A tale of two experiments

Both the SLAC and FAU/MPQ experiments were conducted with fused silica devices. To make the tiny chips work as particle accelerators, periodic features were precisely fabricated along a vacuum channel through which the electrons would propagate. The periodic ridges spatially modulated the incoming laser phase fronts to match the accelerated electrons. Because the wavelength of the near-IR light that generated the force on the electrons was close to 1 μm, the dimensions of the internal structure's features and electron channel had to be around the same size.

A good first step for demonstrating a new acceleration mechanism is to send a test beam of particles through the device and observe the particles' energy distribution, or spectrum, following the interaction. The SLAC experiment used the 60 MeV electron beam provided by a conventional RF accelerator, the Next Linear Collider Test Accelerator, that had been converted into a test bed for developing new concepts. In a David-and-Goliath juxtaposition of size scales, the first DLA trial used a 50-m-long conventional accelerator facility to test some of the smallest particle accelerators ever built (see figure 1).

In late February 2013, two years of preparation finally paid off. As an automated shutter turned a laser on and off, the energy spectrum of the electron beam passing through the device shifted dramatically and unmistakably, thereby indicating the presence of large accelerating fields. Stanford graduate students Edgar Peralta and Ken Soong volunteered to run the

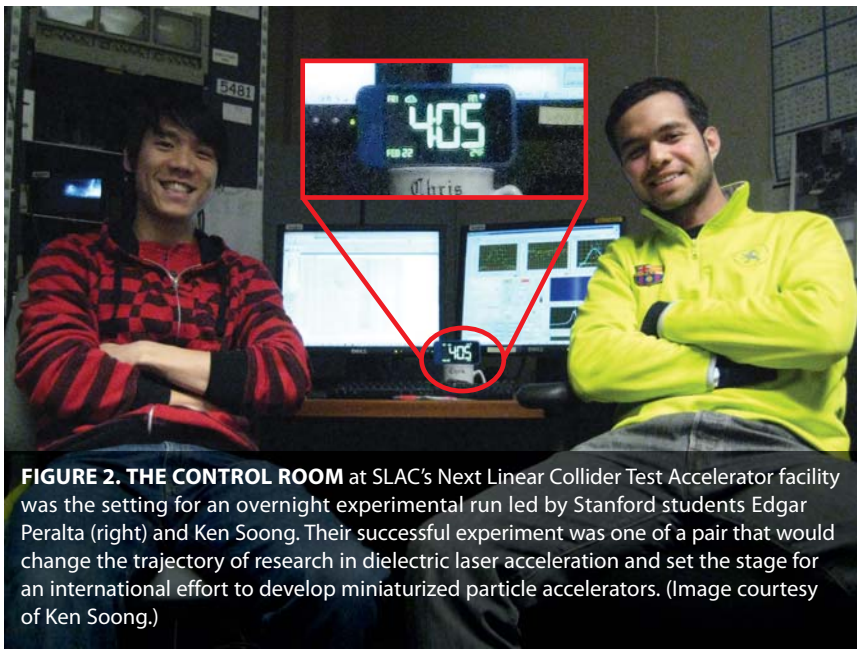

FIGURE 2. THE CONTROL ROOM at SLAC's Next Linear Collider Test Accelerator facility was the setting for an overnight experimental run led by Stanford students Edgar Peralta (right) and Ken Soong. Their successful experiment was one of a pair that would change the trajectory of research in dielectric laser acceleration and set the stage for an international effort to develop miniaturized particle accelerators. (Image courtesy of Ken Soong.)

experiment overnight to collect as much data as possible before the experiment shut down. At 4:05am they took the photograph shown in figure 2. Both were smiling because they knew they had reached an important milestone—and had likely secured enough data to complete their PhDs.

Subsequent analysis of the data showed that the measured variation in the final electron energy corresponded to an accelerating gradient, or energy gain per unit length, in excess of 300 MeV/m, which is about 10 times as high as typical operating gradients in conventional microwave accelerators. A scanning electron micrograph image of the DLA structure and corresponding field pattern are shown in figure 3a.

Around the same time that the experiment at SLAC was taking place, graduate student John Breuer, working with one of us (Hommelhoff) at MPQ, performed a similar experiment. It used a smaller and lower-energy (28 keV) electron source based on a modified electron microscope column. The column came from an old, malfunctioning electron microscope at MPQ and required three years of refurbishment to become an electron source for DLA experiments.

The accelerator structure consisted of an optical grating that was open on one side, as shown in figure 3b. In general, enclosed structures offer better field uniformity and improved coupling of the external laser to the accelerating mode. But the open structure allowed for easier alignment and avoided the difficulties involved in transporting electrons through a narrow channel.

One consequence of using slower electrons was that for a similar laser wavelength, the accelerator's small-scale features—the grating teeth—would have needed to be one-third the size to match the speed of the accelerating wave to the particle velocity. But that challenge was surmountable. The MPQ team acquired custom-made single-sided gratings and used their laser to excite a harmonic mode with triple the frequency to accelerate the particles. Breuer observed a signal of accelerated electrons with 25 MeV/m accelerating gradient, which was comparable to that in conventional accelerators. But the new setup had the potential to significantly improve either by incorporating alternate structure choices or by operating at the fundamental harmonic, where the coupling between the laser field and the structure is stronger.

The SLAC/Stanford and FAU/MPQ demonstrations were both experimental firsts and demonstrated several interrelated concepts: that microstructure-based laser acceleration could be used for both subrelativistic and relativistic particles, that acceleration could be performed using harmonics of the laser wavelength, and that accelerating gradients meeting or exceeding those of conventional accelerators were possible in DLAs. It took about six months to analyze and write up the results, which appeared online in separate journals on the same day.[3,4]

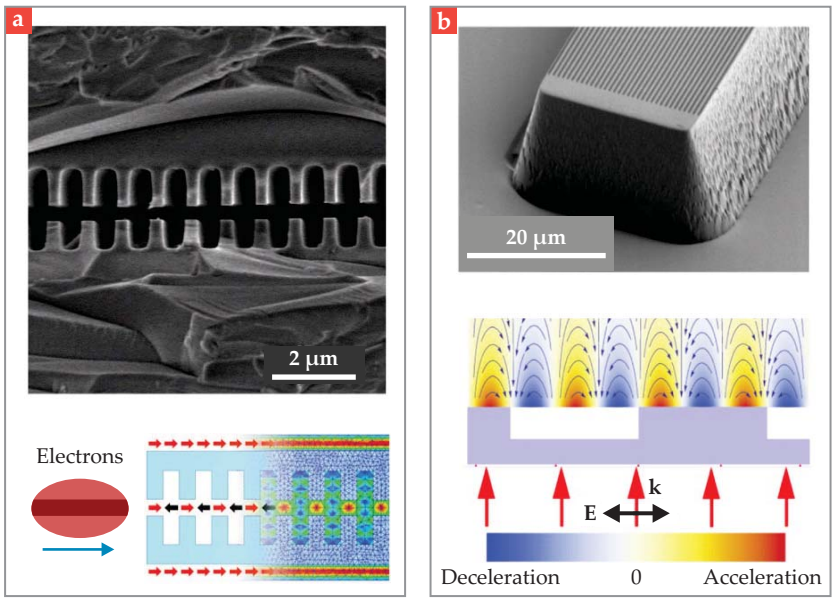

FIGURE 3. CHIP-SCALE ACCELERATORS made from fused silica were employed in two seminal laser-acceleration experiments in 2013. **(a)** The SLAC/Stanford University experiment used a dual-sided structure (top) with a 400-nm-wide channel for uniform field excitation (bottom). (Adapted from ref. 3.) **(b)** The experiment at Friedrich–Alexander University Erlangen–Nuremberg used an open-grating geometry (top) driven at the third harmonic, as illustrated by the contour plot (bottom). The grating's periodicity (purple) corresponds to three periodic repetitions of the longitudinal electric field. (Adapted from ref. 4.) In both experiments, periodic nanofabricated features match the velocity of the accelerating wave to that of the particles.

Collaboration fosters innovation

The initial experiments garnered some attention in the press, and that coverage caused the phrase "accelerator on a chip" to gain traction. Building on the strong collaborations formed under LEAP and AXiS, in 2015 we assembled an international team of scientists and accelerator engineers with an array of expertise spanning accelerator science, photonics, laser technology, materials science, computer simulation, and nanofabrication. The team included six universities (Stanford, FAU, Purdue, UCLA, the Technical University of Darmstadt, and the University of Hamburg), three government labs (SLAC in the US; the German Electron Synchrotron, or DESY, in Hamburg, Germany; and the Paul Scherrer Institute in Switzerland), and one industrial partner (Tech-X). At the invitation of the Gordon and Betty Moore Foundation, the team submitted a proposal to bring laser acceleration from a demonstration of principle to a fully functional feedback-controlled particle acceleration device by the end of 2022. The proposal was reviewed and funded in 2015 for a five-year period.

We named the collaboration Accelerator on a Chip International Program, or ACHIP. The newly formed program was tasked with generating and controlling electron beams with a conceptually new technology and with much stricter tolerances than are required for more conventional approaches. We were proposing a radical change in the entire paradigm of future accelerators. The concrete goals of ACHIP are a 1 MeV particle accelerator on a chip and optical control of so-called transverse effects, which include extreme-UV (XUV) and x-ray photon generation from the wiggled electron beam and optical focusing. The vacuum chamber containing the electron source, electron

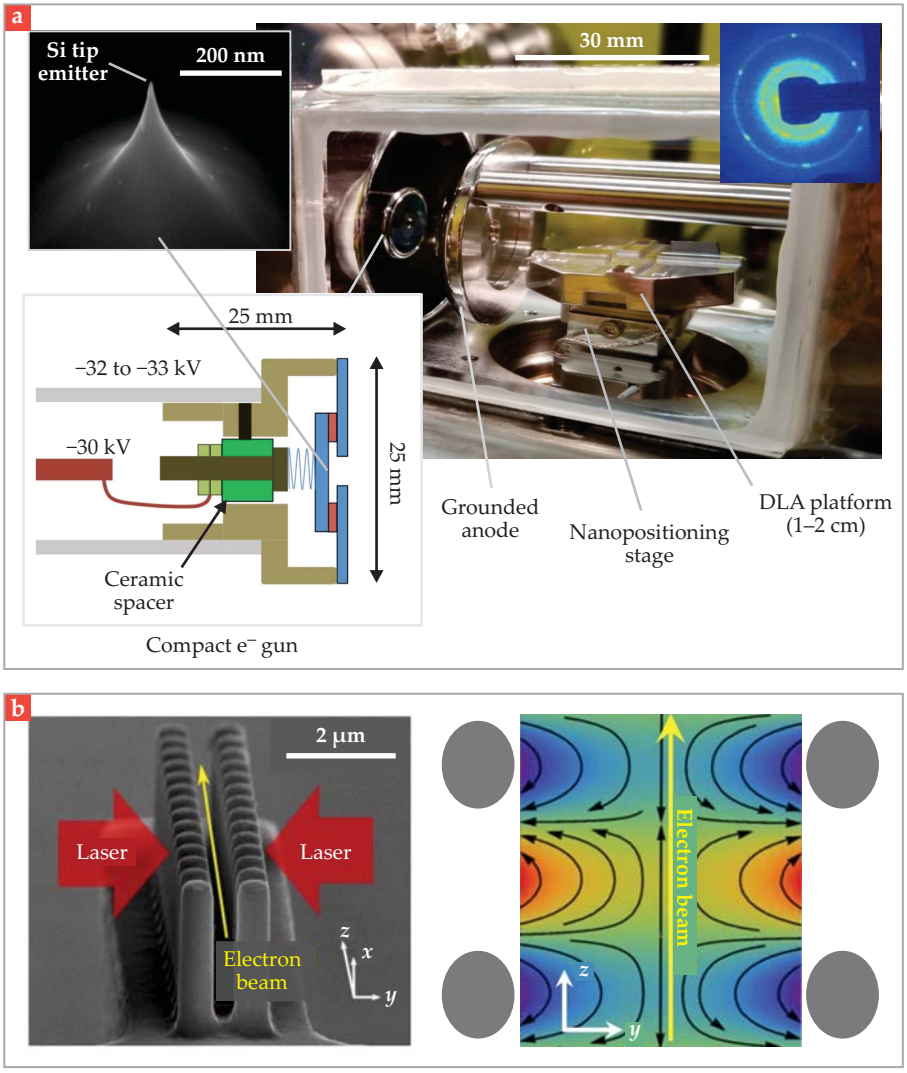

FIGURE 4. SILICON NANOFABRICATION allows for sophisticated structure designs that can be monolithically integrated on a chip. **(a)** A dual-pillar accelerator was incorporated into a 10-cm-long "glass box" test stand that is designed to achieve energy gains of 0.1–1 MeV. The device includes an integrated miniaturized electron gun (lower left) and silicon nanotip emitters (upper left). Such devices could enable ultracompact sources for electron diffraction studies, as illustrated by the diffraction pattern (upper right) obtained with a graphene target and a 57 keV beam. (Schematic adapted from ref. 5; silicon nanotip image courtesy of Andrew Ceballos; glass box and diffraction pattern images courtesy of Kenneth Leedle.) **(b)** The dual-pillar design consists of a colonnade of vertically standing silicon pillars. When driven in phase, two incident laser pulses excite a uniform accelerating mode between the pillars, shown here by simulated contour plots of the axial electric field E_z. (Adapted from ref. 18.)

optics, DLA chip, and detector should be able to fit in a shoebox. Parts of each goal have already been demonstrated, and the collaboration is on track to have a completed device in 2022.

The accelerator components fall into four major categories: the electron source, an injector and buncher that accelerate particles from subrelativistic to relativistic (MeV) energies, on-chip waveguides for controlled laser delivery, and relativistic speed-of-light acceleration. All the elements need to operate together in a final integrated device, which means reinventing them to be compatible with integrated Si photonics and lithographic fabrication. Five years ago that task appeared to be nearly impossible—a prerequisite for any project worth undertaking according to the motto of Edwin Land, inventor of the Polaroid camera.

The electron source must be compact and well suited for coupling to micron-sized devices. Progress there has largely exploited nanotip field-emission sources—tiny metallic or Si needles with tip radii on the order of tens of nanometers, from which electrons are emitted by photoemission excited by an ultrafast laser pulse. Nanotip emission sources have led to the development of centimeter-scale electron guns, which are now being integrated into compact tabletop demonstration accelerators, such as the "glass box" at Stanford,[5] shown in figure 4a.

An important aspect of the electron sources is that because of their tiny size, they have exceptionally high beam brightness—a measure of how small and well-collimated an electron beam can be made. The Si tips employed are quite robust and can last for days or weeks of continuous operation. As a tradeoff for their intense beam brightness, however, nanotip emission sources produce on the order of a few thousand electrons per incident laser pulse, compared with millions or billions of electrons for more conventional sources.

The accelerator naturally divides the electron bunches from the nanotip into smaller, optically spaced microbunches with durations that are less than 1 fs, a fraction of a laser cycle. The particles that successfully transition into a microbunch are "captured." The microbunch spacing is determined by the period of the accelerator—the spacing between grating teeth—and is therefore intrinsic to the design.

The particles naturally form microbunches as they get captured in the potential wells in the electromagnetic wave. The efficiency of the capture process can be enhanced by prebunching the particles. Recently, bunches with durations from 270 to 700 attoseconds have been measured and injected into a subsequent acceleration stage to perform fully on-chip bunching and net acceleration demonstrations.[6,7]

Successfully directing an electron beam through tiny accelerating devices is a major experimental challenge. For a sense of scale, the hollow acceleration channel inside the chip shown in figure 1 is just 400 nm wide and 1 mm long. Electrostatic

lenses are incorporated into the gun to inject the electron beam into an accelerator channel. The lenses can focus the beam down to a submicron spot suitable for coupling into the narrow channel. The electrons are then transported over thousands of optical periods to reach substantial energy gains, from about 100 keV to 1 MeV.

Researchers have explored new innovative designs for accelerator structures, including replacing the grating-like structures used in the earlier experiments with free-standing rows of Si pillars separated by a narrow submicron channel, as shown in figure 4b. The dual-pillar design eliminates unnecessary material that could distort the incident laser pulse. It allows for highly symmetrical fields that can deflect, compress, or accelerate electrons in the channel by adjustment of the incident laser phases.[8]

The structures can focus and confine electrons inside the accelerating channel. They use the inherent laser-driven fields to enable a technique called alternating phase focusing, which was originally used in conventional RF proton accelerators and was reworked for use in photonic devices by researchers at the Technical University of Darmstadt.[9] Simulations of long-distance transport of the electron beam over multiple centimeters have been carried out using that scheme, and it serves as the basis for newly fabricated designs aimed at achieving MeV-scale acceleration in a single on-chip device with minimal particle loss.

Bringing a microaccelerator to light

Any accelerator design based on pulsed particle beams and pulsed electromagnetic energy must rely on a series of sequential acceleration stages. For a laser-driven accelerator, the length of each stage is determined by the interaction time of a particle bunch with a laser pulse. That time is set by their respective durations, typically on the order of 0.1–1 ps.

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 so the laser light can be split and precisely delivered to each successive segment of the accelerator. Photonic waveguides based on Si and silicon nitride materials are well developed and have been shown to support broad-bandwidth femtosecond-class laser pulses with up to 20 nJ per pulse, which are suitable for driving the individual stages of a chip-based accelerator.[10]

Researchers have carried out extensive optimization studies to evaluate the requirements for a complete multistage system based on laser delivery by waveguide.[11] The first integrated accelerator, which was recently demonstrated, coupled an external laser to an on-chip waveguide that fed into a custom-designed accelerator channel.[12] Inverse-design codes were used to optimize the photonic structure's design. The codes produced highly nonintuitive, almost organic-looking geometries (see figure 5) that were tailored to specific optimization parameters such as bandwidth and accelerating field.

Another consequence of accelerating subrelativistic electrons in an optical-scale device is that the particle energy changes along the length of the accelerator. The design velocity of the structure must therefore 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, or chirp, the periodicity of the accelerator structure itself to match the local wave velocity to the electron speed.[13] 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

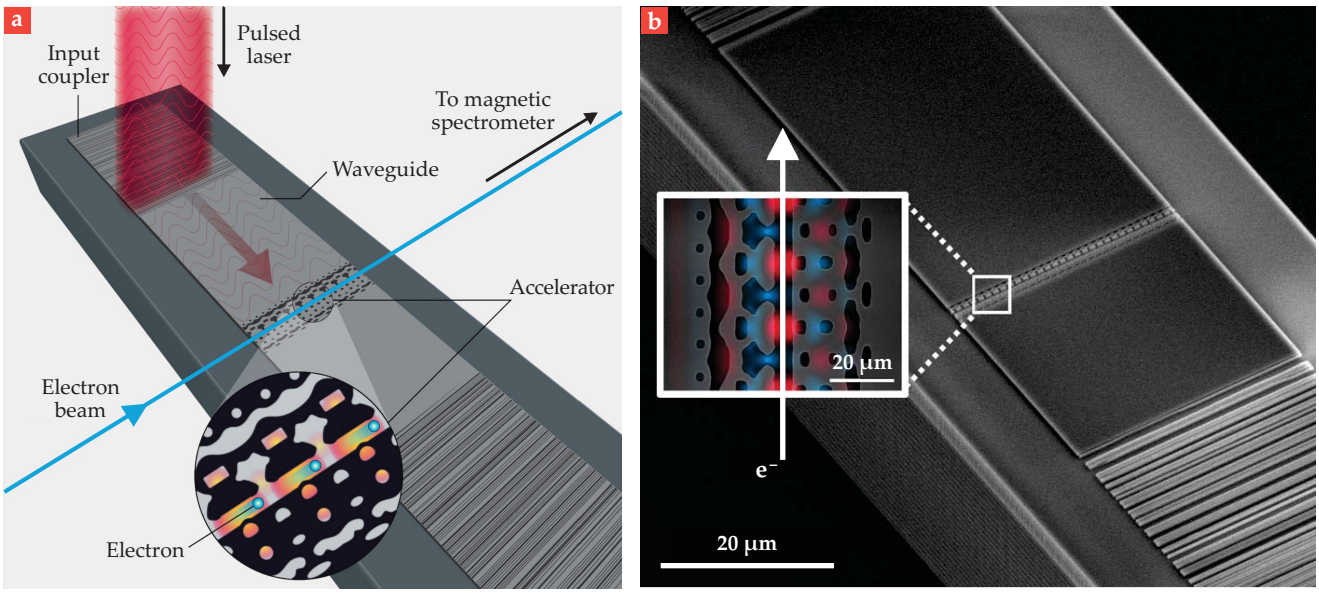

FIGURE 5. INVERSE DESIGN provides a powerful tool for producing highly optimized designs, such as this first demonstration of a single-stage integrated waveguide-coupled accelerator. **(a)** Shown here is a schematic layout of the experiment. **(b)** This electron micrograph image presents the as-built structure. The concept provides a key stepping-stone to future devices with multiple such stages driven by a network of phase-controlled waveguides. (Adapted from ref. 12.)

and laser-driven focusing over a centimeter-scale interaction length. That result illustrates a key aspect of the DLA approach, which is that beam dynamics can be controlled through careful manipulation of the laser phase.[14]

With tabletop integrated accelerator setups in operation, researchers are testing a new generation of structures that incorporate microbunching and laser-driven focusing. Over the next year, a series of planned experiments are expected to incrementally increase the total beam energy up to 1 MeV or higher. Once multi-MeV energies are reached, the particle velocities will become essentially constant at close to the speed of light.

A new set of relativistic-energy experiments are underway at facilities that have access to relativistic test beams. At the UCLA Pegasus Laboratory, moderately relativistic (4–8 MeV) electron beams are probing the limits of accelerating gradients and energy gains in DLA technology. Researchers there have demonstrated axial accelerating-field intensities up to 1.8 GV/m and an energy gain of 0.3 MeV.[14,15]

New facilities are near completion at DESY in Germany and at the SwissFEL in Switzerland to test concepts relevant for beams with larger currents that will carry millions to billions of electrons per pulse and higher particle energies of 100 MeV and 3 GeV, respectively. Through a combination of innovative approaches that leverage the multi-institutional and interdisciplinary capabilities of the research teams, the promising results obtained over the past five years provide a toolbox of technologies to realize fully integrated on-chip accelerators that can be used for scientific, industrial, and medical applications.

FIGURE 6. THE ACHIP COLLABORATION met at the German Electron Synchrotron (DESY) in Hamburg, Germany, on 19 September 2018. (Photo courtesy of Jann Wilken/DESY.)

Revolutionary devices

One of the most promising applications for DLA devices is compact electron sources for ultrafast science and electron diffraction studies. Trains of ultrafast and ultrabright electron bunches with subfemtosecond intrinsic bunch structure could allow resolution of electronic processes in both spatial and temporal domains, thereby enabling new tools for imaging light–matter interactions and for experiments in quantum electrodynamics.

Compact accelerators with target energies in the few-MeV range are attractive near-term candidates for use in medical dosimetry. Electron sources based on laser-driven on-chip accelerators could potentially fit on the end of an optical fiber, be placed on a scanning platform at the surface of a sample, or even get inserted into living tissue. A self-contained multi-MeV electron source based on integrated photonic particle accelerators could enable minimally invasive cancer treatments and adjustable-dose real-time deposition with improved dose control. One could envision an encapsulated micro-accelerator, built onto the end of an optical fiber, being placed at a tumor site using standard endoscopic methods. That could allow a doctor to deliver the same or higher radiation dose compared with what is provided by existing external-beam technologies, but with less damage to surrounding tissue.

The difference in bunch charge and duration for DLA electron beams compared with traditional RF accelerators points to the potential for future DLA-based light sources to generate attosecond pulses of XUV or x-ray radiation. Those pulses could probe matter on even shorter time scales than are possible today. Coherent attosecond radiation could also be produced using the same accelerator-on-a-chip operating principles. Proposed laser-driven dielectric undulators that wiggle the electron beam and produce radiation could be fabricated using photolithographic methods similar to those used to produce current DLA devices.[16]

Although a high-energy particle collider based on DLA technology is admittedly decades away, considerations for physics at the TeV scale indicate that DLAs have the potential to achieve the required luminosities with reasonable power consumption. The highest priority challenges for such future applications

largely pertain to the transport of high average beam currents in the micron-scale apertures of DLA devices. But recent studies of extended structures with laser-driven focusing show promise for improved charge transport, capture efficiency, and preservation of beam quality.[9] They also support the prospect of parallel accelerating channels.[17]

Accelerating toward the future

The idea of laser-driven accelerators was first proposed shortly after the demonstration of the laser. Now ACHIP is a worldwide collaboration (see figure 6) aimed at realizing an integrated laser-driven accelerator on a chip. The program melds the capabilities of universities and government laboratories and therefore has access to the facilities and talent needed to address key challenges in the endeavor. That collaboration enables projects to be handed off to national laboratories in a timely way so that they can handle the more costly engineering of a laser accelerator system. The emerging field of laser accelerators has engaged and trained scientists who can lead the development of new tools that will enable discoveries in areas of physics ranging from atomic and molecular to chemical, biological, and medical.

Fifty years ago the laser was a solution looking for a problem. Today it is a critical "stealth utility" that enables the technology of the modern world. The development of laser-driven attosecond electron sources may bring new capabilities in search of their own problems to solve. Fifty years from now, the DLA may be an essential tool in our lives—and perhaps even a stealth utility itself.

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Endowment of this Fund would sustain an annual lectureship at the Conferences for Undergraduate Women in Physics (CUWiP), provide travel grants for undergraduate women to attend these conferences, and present the first APS scientific Prize named in honor of a woman.

APS was able to offer the first Millie Dresselhaus CUWiP Keynote Lectureship this year, and the goal is to be able to award the inaugural Mildred Dresselhaus Prize in Nanoscience and Nanomaterials next year. Please help us to reach the endowment goal!