symmetry

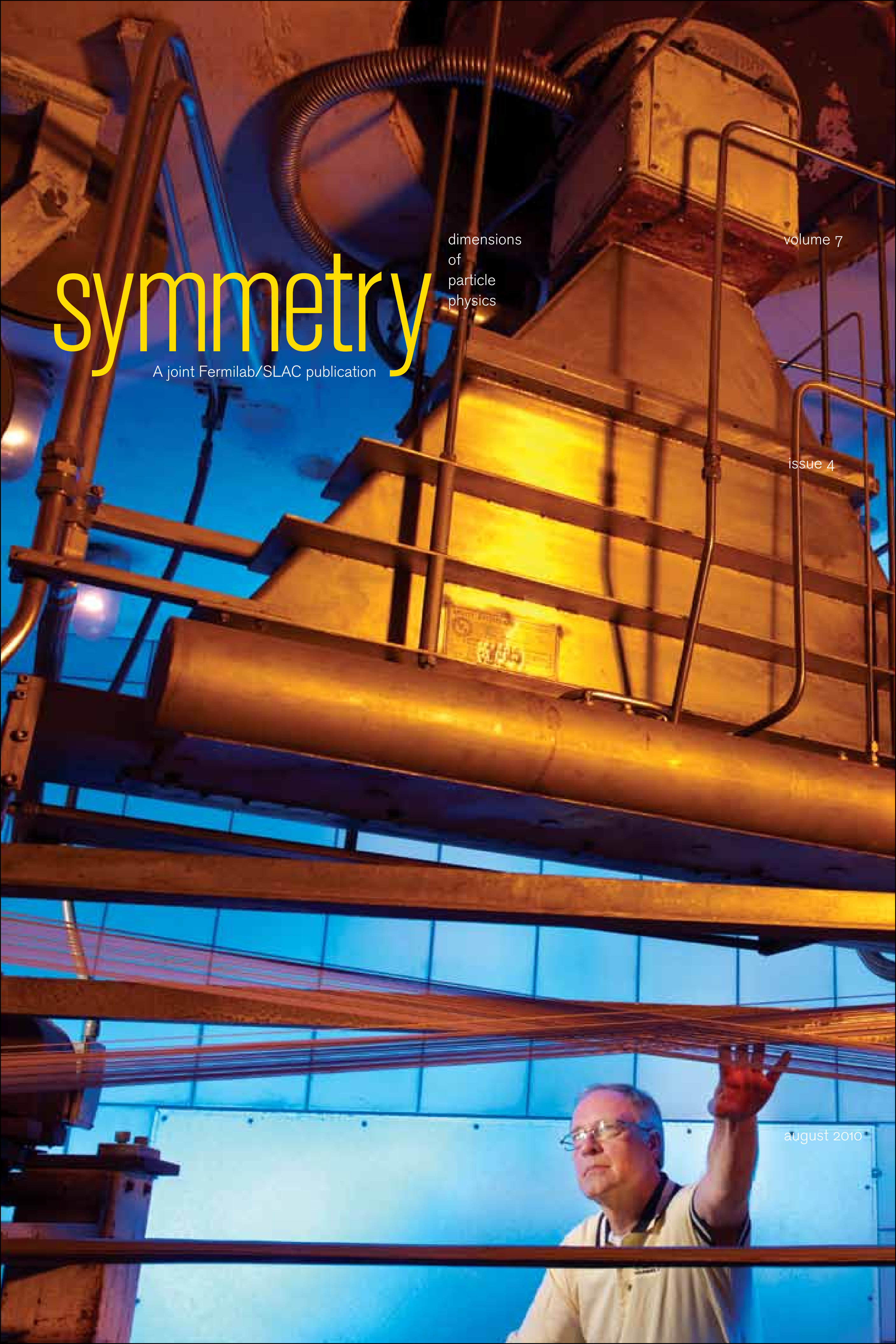
dimensions of particle physics

A joint Fermilab/SLAC publication

volume 7

issue 4

august 2010



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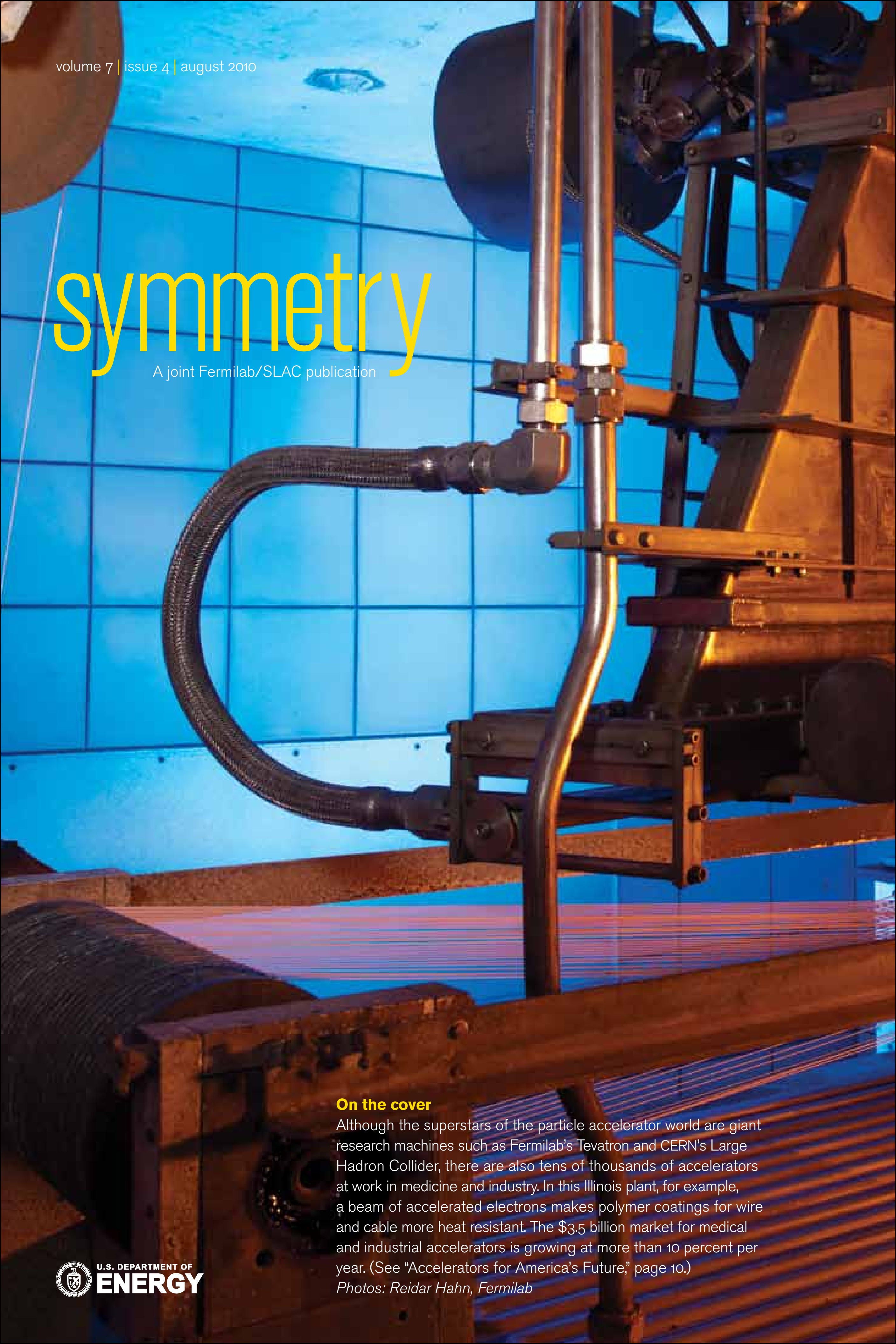

On the cover

Although the superstars of the particle accelerator world are giant research machines such as Fermilab's Tevatron and CERN's Large Hadron Collider, there are also tens of thousands of accelerators at work in medicine and industry. In this Illinois plant, for example, a beam of accelerated electrons makes polymer coatings for wire and cable more heat resistant. The $3.5 billion market for medical and industrial accelerators is growing at more than 10 percent per year. (See "Accelerators for America's Future," page 10.)

Photos: Reidar Hahn, Fermilab

U.S. DEPARTMENT OF ENERGY

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Photo: Reidar Hahn, Fermilab

Accelerators for the future good

With the world economy facing serious challenges and rising pressure to reduce US budget deficits, basic science in the United States looks to be in for some battles during the next few years. Of course, basic science has always been a strong economic driver, but the benefits tend to be further in the future than the next election and so are often trumped by projects with shorter-term payoffs.

In an attempt to help explain the benefits of basic research, scientists, engineers, and industrialists met for the "Accelerators for America's Future" workshop last October. Their goal was to explore and explain how accelerators can be put to practical use in a number of areas, including energy and the environment, medicine, industry, security, and discovery. The report from that meeting has recently been issued and we reprint the introduction on page 10.

While solving everyday problems is not the goal of basic science, it is important to explore potential applications when the opportunities arise. Henry Ford once said, "If I had asked people what they wanted, they would have said faster horses." This quote is often used to illustrate the power of thinking differently, one of the key features of basic research, but it also carries the implication that customers don't know what is best for them. We are living in a more sophisticated world now, and closer ties between suppliers and customers can benefit both. The accelerator workshop brought together the customers (medicine, industry, security) and the suppliers (science, engineering), not to tell science and engineering which way they should go, but to show what a sustained, robust program of accelerator research could produce for the United States.

If scientists just wanted improved medical diagnostics or better packaging materials or more effective cargo scanning, they could probably solve those problems without a full accelerator program. We'd have our faster horses. But we'd miss out on the big leaps of technology that come only from basic research, and we wouldn't have the benefit of all the other applications that come along automatically.

The new report shows that accelerator development has a lot to offer society. However, the United States will reap the benefits only if it invests smartly and sufficiently.

David Harris, *Editor-in-chief*

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symmetry (ISSN 1931-8367) is published six times per year by Fermi National Accelerator Laboratory and SLAC National Accelerator Laboratory, funded by the US Department of Energy Office of Science.

symmetry

Particle physics and America's future

These are extraordinary times for particle physics, remarkable not only for the scientific discoveries that could be in store, but also for the very real opportunities to address critical issues confronting our nation.

We are in the midst of a revolution in the understanding of the very small and the very large. For decades and more, we have been talking about discoveries that may await us when we reach the ultra-high energies of the Terascale. Now we are there. As Fermilab's Tevatron culminates its performance with record luminosities and the Large Hadron Collider begins operations, we have the possibility for discoveries such as extra dimensions and supersymmetry that could fundamentally change our perspective on the universe. If we are fortunate, over the next decade or so we could be in a position to rewrite the textbooks.

We also recognize that future advances will require a new generation of technologies. The detectors and accelerators of tomorrow will need more sensitivity and higher energies, and they must cost less. The quest to develop the tools for future discovery is scarcely less challenging and exciting than the quest for the discoveries themselves.

However, the domain of physicists goes beyond the laboratory and the university. As scientists and citizens, we live in the world and in the midst of recovery from a financial crisis. Economic competitiveness, energy, climate change, and national security are on the front burner for the United States and for countries around the world. In the Department of Energy, the Office of Science has programs positioned to address many of these issues. What is the role of particle physics amid all these challenges?

In fact, the field of particle physics innovates, develops, and drives critical technologies directly applicable to challenges confronting our nation on several fronts. The new Office of Science report, *Accelerators for America's Future* (see page 10), describes many of these applications and lays out the potential for future developments with transformative impacts for energy, the environment, medicine, industry, security and defense, and discovery science.

Although created to serve physics, accelerators are by no means any longer the exclusive province of physics. The report estimates that some 30,000 accelerators are now operating worldwide in industry, medicine, and other realms and that $500 billion worth of products are processed, treated, or inspected by particle beams each year.

Photo: Reidar Hahn, Fermilab

The federal government invests in basic research largely because of the dividends such investments return for the health, wealth, and security of the nation. As particle physicists, we must deliver great science. We must also demonstrate that investment in particle physics drives innovations in technologies that are essential not only for the future of our own and many other fields of science, but for the well-being of the nation as a whole.

Working in partnership with programs across the Office of Science, we in High Energy Physics can play a leadership role in bringing the science and technology of our field to bear on key national issues. The need and the opportunity have never been greater.

Dennis Kovar is associate director for High Energy Physics in the Department of Energy's Office of Science.

Download the *Accelerators for America's Future* report or request a printed copy at www.acceleratorsamerica.org

A flippy way to tell which way is north; a fan and her plushie meet the father of the God Particle; dad-son team mines rock and science; Alan Alda tells scientists to spread the love; a notepad with a peel; letter

Photo: Bradley Plummer, SLAC

Engineers flip for magnets

Forget pocket protectors: Flippy magnets are the low-tech tools that some high-tech engineers won't be caught without.

The plastic hand-held stick topped with a rotating bar magnet the size of an Advil is a quick, easy way to find out if any of the magnets that steer particles through an accelerator is pointed in the wrong direction—a situation that can send particles flying off-course.

At SLAC's Linac Coherent Light Source, for instance, a series of 210 electromagnets steer, compress, and focus a beam of electrons that is used to generate powerful pulses of X-ray laser light. The electron beam can't deviate more than 10 microns as it passes through the magnets, so it's important to get the magnetic fields aligned just right.

Unlike the magnets you have on your fridge, an electromagnet works only when turned on. Its north and south poles are determined by the direction a current flows through a coil to create the magnetic field. Reverse the flow of current and the magnet's poles reverse. So in a special lab, engineers turned on each magnet, carefully measured its magnetic field and marked down how its two power cables should be hooked up to get current flowing in the right direction.

But then the magnets are transported from the measurement lab to the LCLS tunnel; and once there, the power cables, which are hundreds of feet long, may get hooked up the wrong way. To double-check the connections, an engineer walks the tunnel with a flippy magnet. It flips blue for north or red for south.

"It's a nice, quick way of checking the magnets are the right polarity," says Scott Anderson, a SLAC magnet measurements engineer. The magnets-on-sticks can often be found lying around common areas. But lucky are the engineers who get their own. "Not everyone has a flippy magnet," Anderson says.

Marissa Cevallos

Photos courtesy of Annie Callicotte

Fan to Leon: Please sign my Higgs boson

Who would you drive 10½ hours to see? The Grateful Dead? The Dalai Lama?

What about an old, friendly guy who reads a lot and is really good at physics?

Annie Callicotte, a student at the University of Central Missouri, chose the third option: Leon Lederman.

"Why? Because I think he's a wonderful man," she says. "I read his book, *The God Particle*. That is why I went into science."

The trip to see Lederman, a 1988 Nobel Prize winner in physics and former director of Fermilab, was an anniversary present from her boyfriend, Jeff Thomas, who did the driving and manned the camera. Thomas had given her a copy of Lederman's book after getting the particle physics bug himself.

Now Callicotte is leaning toward working on the experimental side of particle physics and has a keen interest in the search for the Higgs boson, aka "The God Particle." In fact, she brought a stuffed plushie version of the Higgs boson for Lederman to autograph at a fundraiser in Aurora, Ill., for the SciTech Hands On Museum, which he helped develop.

Callicotte was beside herself to realize she was also standing in the same room as former Fermilab Director John Peoples, current Director Pier Oddone and several of the accelerator operators who are helping with the Tevatron collider's hunt for the Higgs.

"This is just amazing," she said, beaming, and headed off to shake another hand.

Tona Kunz

Family ties run deep

Mark Hanhardt spent his childhood exploring caverns and watching his dad, who was a miner, come home from work covered in dust. Still, he had no interest in working underground. His dad, Jim, had instilled in him a love of science, and he planned instead to mine the mysteries of the stars and the universe.

But it turns out the mother lode for astrophysics lay deep underground, and not far from his South Dakota home.

Mark is now an astrophysicist working on LUX, an experiment searching for dark matter in the protective depths of the former Homestake gold mine. Jim is a shaft supervisor there. They're one of three father-child pairs at the mine, which is home to Sanford Underground Lab and the proposed site of DUSEL, the world's deepest underground laboratory.

When Mark was a student at the South Dakota School of Mines & Technology, his father was tearing down the lab in the Homestake mine cavern where Ray Davis had made his Nobel Prize-winning detection of neutrinos from the sun in the early 1970s.

"My dad got permission to bring me, a friend, and a professor to see it," Mark says. "That really opened my eyes to the science being done. Then DUSEL fell into place and we both ended up back here."

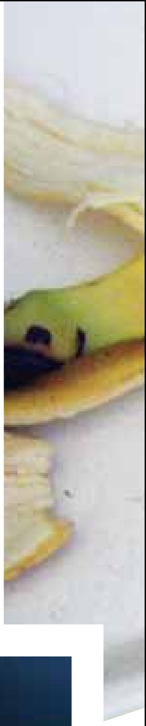
Now it's Mark's turn to teach his dad about the physics being done in the mine. Jim, in turn, fills his mining buddies in on the science, and sometimes they attend physics lectures put on by Sanford Lab.

When Mark surveyed a deep shaft for a place to put magnetometers—instruments that measure the strength and direction of magnetic fields—he turned to his dad for advice. Jim showed him places where the magnetometers would be shielded from iron in the rock, which can interfere with readings.

"I enjoy being associated with a project he's working on," Jim says, "and it was kind of nice that he could come underground."

Tona Kunz

Photo: Steve Babbitt, Black Hills State University



Alan Alda's romance tips for researchers

Are you on a blind date with science? Does talk of protons and prophase make you anxious and stressed? According to actor Alan Alda, most Americans need a little help getting past their first-date jitters and into a meaningful and comfortable relationship with science.

Alda, host of PBS' *Scientific American Frontiers* and star of the TV series *M*A*S*H*, was one of the leading scientists and communicators offering "wooing tips" for researchers during an April workshop sponsored by the Center for Communicating Science.

The center is a collaboration among Brookhaven National Laboratory, Stony Brook University, and Cold Spring Harbor Laboratory. The workshop included sessions on social media, writing for the public, and doing TV interviews, along with improvisational theater games that had scientists mirroring each other's movements and creating things out of imaginary space.

"Don't be afraid to share your excitement about science," Alda said. "Let's tell stories and excite the lust in one another for the curiosity that we have, and let's fall in love with science."

Photo courtesy of Alan Alda

Alda said scientists should court the public through the three stages of falling in love:

- inflame their interest by using engaging body language and tone,
- foster infatuation by telling captivating stories that engage the emotions,
- and win their commitment to learn more.

Everyone has a story to tell about science, Alda said. The goal is tell it so vividly—with all the twists and suspense of a good detective story—that it sticks in the heads of the audience.

Kendra Snyder

LHC detector project a big leap for Pakistan

For most scientists, membership in a Large Hadron Collider experiment is a ticket to research at a frontier of particle physics. For Hafeez Hoorani, it also marked his country's first step toward building a tradition of experimental particle physics research.

Hoorani is director of research for Pakistan's National Center for Physics, Quaid-i-Azam Campus. When he joined the Large Hadron Collider's CMS experiment in 1994, Pakistan had a long tradition in theoretical particle physics but had not collaborated on experiments in the field.

Because it lacked facilities and experience in constructing sophisticated particle detectors, at first it was unclear what Pakistan could offer CMS.

Yet Hoorani's group would go on to build a critical component of the experiment's muon detection system. The resistive plate chambers, or RPCs, record the precise times that muons and other particles pass through the muon detector. They help determine which data from the detector are stored for future study. And their construction played a pivotal role in establishing a new direction for particle physics research in Pakistan.

The chambers were assembled at the National Center for Physics from parts made by Pakistani companies, and tested there for performance and quality. The project cost US$2.5 million, a significant investment for the country. It led to the training of about 50 young scientists and engineers.

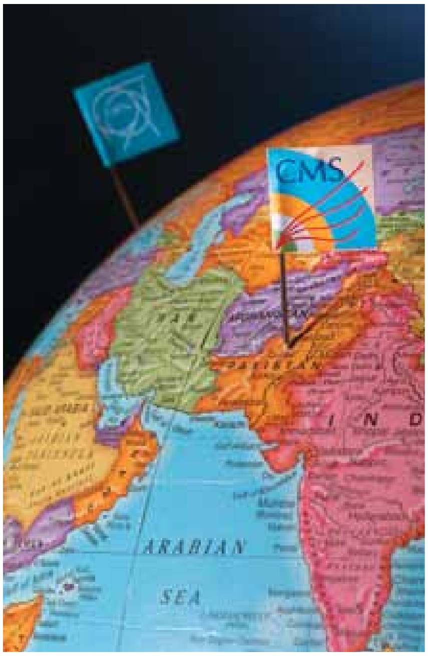
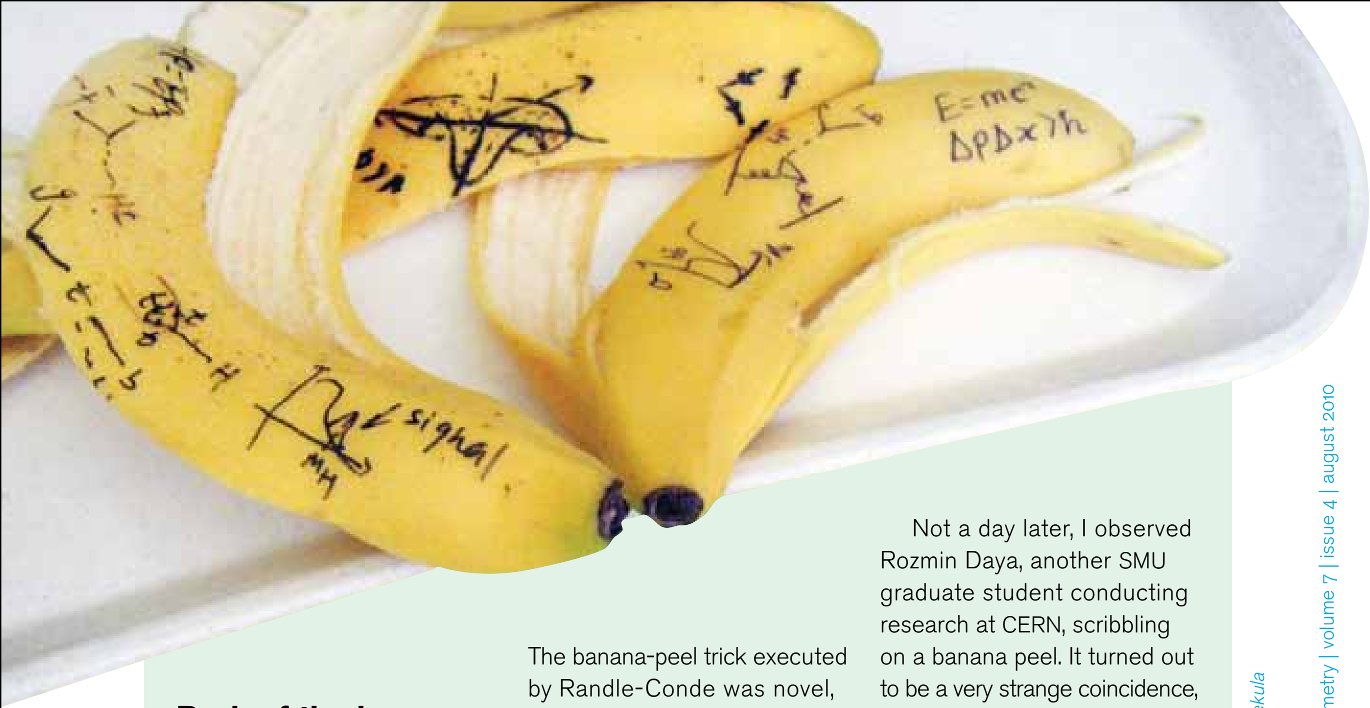


Photo: Reidar Hahn, Fermilab

"We needed to build 320 chambers of the size used in CMS, which required a big engineering enterprise that I had to set up from scratch," Hoorani recalls. "This brought something very new to Pakistan—the concept of quality assurance in building detectors."

The path to participation in CMS hasn't been easy, and Hoorani's 30-member research group still struggles to get funding for research, travel, and computing. Despite these difficulties, the group has eagerly begun searching for the Higgs boson among the very first high-energy collision data from the CMS detector.

Katie Yurkewicz



Back-of-the-banana physics

The lunchtime discussion between grad student Tingting Cao and postdoc Aidan Randle-Conde was already too far under way to stop, and a point needed to be demonstrated.

Normally, a physicist would reach for the nearest envelope and start scribbling, but over mouthfuls of paella and sips of water in the CERN cafeteria the two scientists from Southern Methodist University were nowhere near an envelope. A napkin would do, but they were already used up and crumpled.

So Randle-Conde reached for the nearest thing at hand—a banana peel.

Physicists have a reputation—self-made or otherwise—for discussing physics on any available surface. The most common phrase for a quick, short calculation is a "back-of-the-envelope calculation," implying the nature of the writing surface: whatever you can grab.

The banana-peel trick executed by Randle-Conde was novel, even for a physicist. Still, since a great deal of work at CERN is done over food or coffee in the restaurants, this trick has inherent value.

Not a day later, I observed Rozmin Daya, another SMU graduate student conducting research at CERN, scribbling on a banana peel. It turned out to be a very strange coincidence, but it independently confirmed that the smooth, waxy outer skin of a banana peel makes an *excellent* writing surface.

Stephen Sekula

Photos: Stephen Sekula

letter

Explain it in a dentist's chair

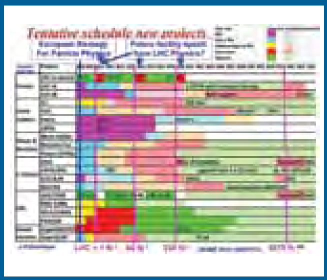
I was having a routine dental cleaning the other day, and of course it's an occupational hazard that people want you to explain what you do in words of one syllable or fewer (which, while you're having your teeth cleaned, is all you can manage anyway.) So I tried the "Explain it in 60 seconds" piece on charged leptons that I wrote for the June 2010 issue of *symmetry*, and by gum (a dental joke there) it worked!

Bob Bernstein, Fermilab

Highlights from our blog

A slide that captures the future(s) of particle physics

July 30, 2010



Of the estimated 10,000 slides shown at the International Conference on High Energy Physics, a few stand out as likely to stick around for a while. One may be the first slide ever that lists all known future projects in high-energy physics around the world, along with their states of readiness.

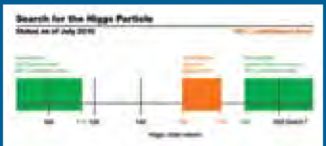
Lighting up the dark universe

July 28, 2010

An experiment doesn't have to be exotic to explore the unexplained. At the International Conference on High Energy Physics, scientists unveiled the first results from the GammeV-CHASE experiment, which used 30 hours' worth of data from a 10-meter-long experiment to place the world's best limits on the existence of dark energy particles.

New limits on Higgs mass announced

July 26, 2010



Scientists at Fermilab's Tevatron collider have ruled out a significant range of possible masses for the Higgs boson, narrowing the search for what is probably the world's most famous particle. The Higgs is thought to give all other particles their masses.

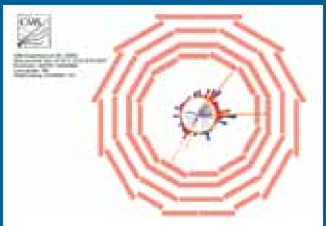
LHC results: Not just the same old thing

July 26, 2010

While the Large Hadron Collider experiments may be measuring particles whose existence has already been proven, they are making those measurements at an energy 3.5 times higher than ever before. This provides new, useful information to the physics community, including input for theoretical models that are continually refined to more accurately reflect the way the universe works and predict where new particles may be hiding.

Europe reaches the top, err, the top reaches Europe

July 23, 2010



It might be a long way to the top, but the LHC experiments are already halfway there: CMS and ATLAS presented their first candidates for the rediscovery of the top quark, the heaviest particle in the Standard Model, which first showed up in Fermilab experiments in 1995.

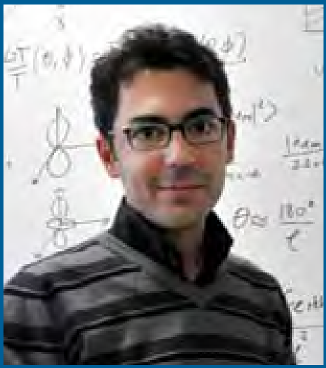
The ILC in one minute flat

July 22, 2010

The folks working on the proposed International Linear Collider have created a one-minute animation that flies you through its 30-kilometer-long tunnel. It has no sound, but the visuals speak for themselves.

People in physics: Listening to the universe with Amedeo Balbi

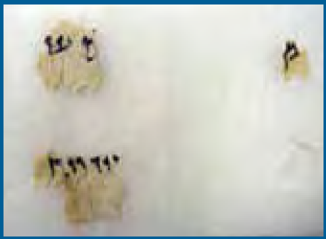
July 12, 2010



Amedeo Balbi, researcher at the University of Rome "Tor Vergata," is one of the rare scientists with a gift for explaining his research to a non-expert public. He studies the Cosmic Microwave Background, the fossil radiation from the big bang.

Protons crack a Dead Sea Scroll secret

July 6, 2010



INFN researchers who probed tiny pieces of a Dead Sea Scroll with protons found that its chemistry matches the chemistry of the water in the area where the ancient document was found, supporting the idea that it was made locally.

Read the full text of these stories and more at www.symmetrymagazine.org/blog/aug2010

SLAC's new X-ray laser peels and cores atoms

July 2, 2010

The first published scientific results from the world's most powerful X-ray laser show its unique ability to control the behaviors of individual electrons within simple atoms and molecules by stripping them away, one by one—in some cases creating hollow atoms.

World Cup fever at CERN

July 2, 2010

During the past few weeks, national pride has hit a high, with the World Cup football (soccer) competition in full swing. Save for the Olympics, it is the only sporting event where everyone at CERN has a home team to cheer for.

CERN opens dazzling new public exhibition

June 30, 2010

It's like stepping into a science fiction film: Eerie blue and green lighting; spherical white chairs with black cushions; touch-operated computer information stations; a full-wall projection of stars and galaxies; and a calming voice coming over a loudspeaker and asking, "Why are we here?"

CMS exotica hotline leads hunt for exotic particles

June 24, 2010

Exotic physics is the physics that breaks rules and defies expectations. This is the domain of the unstable and excited, the string balls, black holes, and extra dimensions. The CMS exotica group is devoted to seeking out these events, and the hotline supports their search.

MiniBooNE results suggest antineutrinos act differently

June 18, 2010

The MiniBooNE experiment has found that antineutrinos, which should follow the same rules as neutrinos, might oscillate in a slightly different way. The results seem to favor a much-debated antineutrino result obtained by the Liquid Scintillator Neutrino Detector experiment in 1990.

Three nerds walk into a bar…

June 15, 2010

Forty-odd Chicagoans gathered in a bar, not to watch the Blackhawks in the Stanley Cup finals but to hear Jason St. John talk about particle colliders, the Standard Model, and how the Large Hadron Collider won't be the end of us all. It was Chicago's inaugural Nerd Nite.

Rewriting textbooks at the LHC

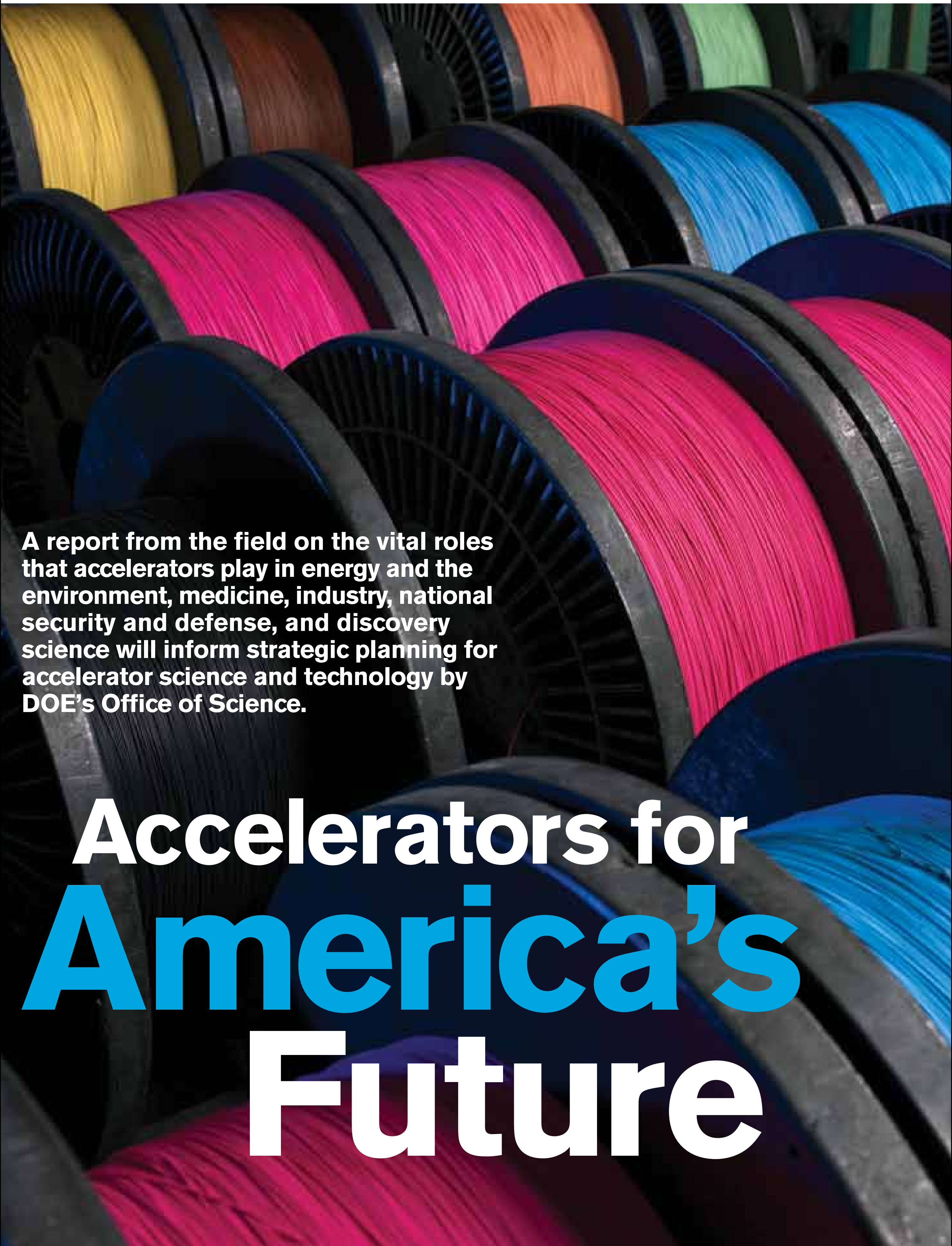
June 14, 2010

During the Physics at LHC conference, textbooks were being rewritten as physicists presented their remeasurements of data contained in the Particle Data Group booklet, which covers all existing and hypothetical particles. One theorist presented his prediction for a page from the 2016 version of the booklet.

Could DZero result point to multiple Higgses?

June 4, 2010

Theorists say the discovery of a significant imbalance between the production of matter and antimatter during particle collisions at the Tevatron points to new physics at work—including the possibility that there may be five types of Higgs boson, rather than just one.

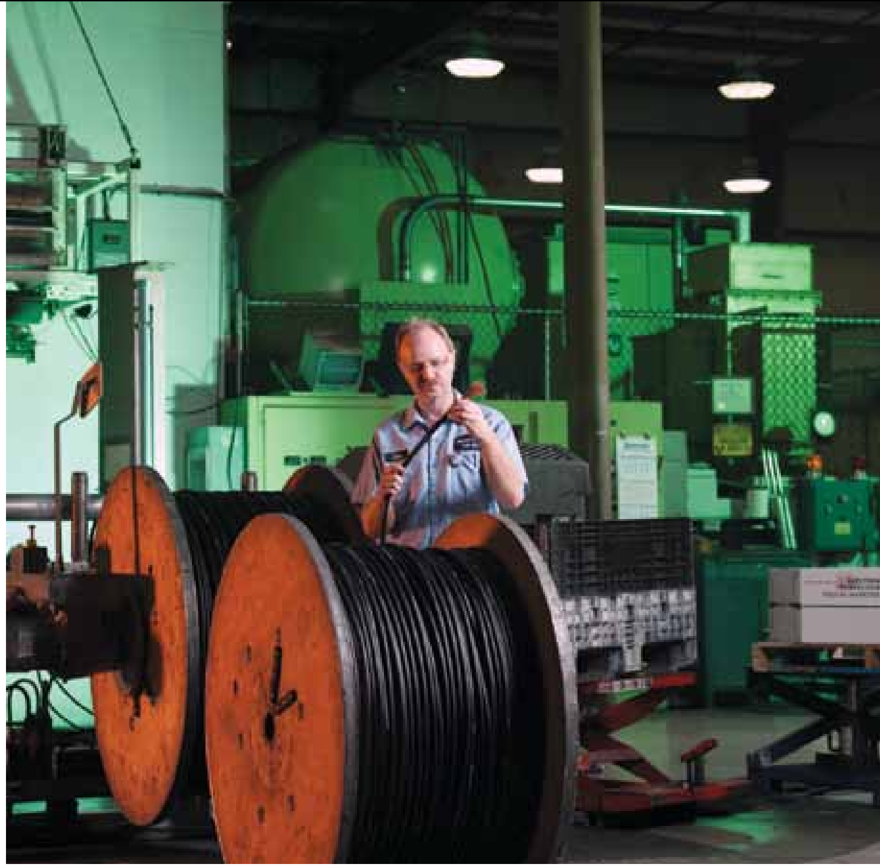


A report from the field on the vital roles that accelerators play in energy and the environment, medicine, industry, national security and defense, and discovery science will inform strategic planning for accelerator science and technology by DOE's Office of Science.

Accelerators for America's Future

Converting metal-coating facilities to electron-beam technology could realize a 95 percent savings in power demand. Coated cables at Electron Beam Technologies, Inc. in Kankakee, Illinois.

Photos: Reidar Hahn, Fermilab



A beam of particles is a very useful tool.

A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey, or discover the secrets of the universe.

Particle beams to meet national challenges

The beams produced by today's particle accelerators address many of the challenges confronting our nation in the 21st century: energy, the environment, good jobs and economic security, health care, national defense, and the war on terror. The next-generation accelerators of tomorrow have the potential to make still greater contributions to the nation's health, wealth, and national security.

Incorporating innovative accelerator technologies into tomorrow's nuclear energy supply, for example, has the potential to make nuclear power safer and cleaner with far less nuclear waste. Electron beams could treat flue gases to make coal-fired plants cleaner and more environmentally friendly. They could detoxify waste water and make municipal water safe to drink.

Advances in beam therapy offer the promise of improving cancer treatment by maximizing the beam energy delivered to a tumor while minimizing the damage to normal tissue. Accelerators could serve as reliable alternative sources of critically needed medical isotopes currently made in nuclear reactors—some no longer produced at all in the United States.

In industry, accelerators represent cheaper, greener alternatives to hundreds of traditional manufacturing processes. For security and defense, compact, rugged, "fieldable" accelerators would have innovative applications from safe and reliable cargo inspection to monitoring international test ban compliance. The continuing development of accelerator technology will give scientists the tools for discovery across a spectrum of science from particle physics to human biology.

For the United States to remain competitive in accelerator science and technology, however, will require a sustained and focused program and changes in national policy.

Practical particles

The marquee superstars of the particle accelerator world are the giant research accelerators like Fermilab's Tevatron, Brookhaven's Relativistic Heavy Ion Collider, and most recently CERN's Large Hadron Collider in Geneva, Switzerland.

Behind the headlines, though, are the tens of thousands of accelerators that are at work every day producing particle beams in hospitals and clinics, in manufacturing plants and industrial laboratories, in ports and printing plants and, literally, on the ships at sea. Adding them all up, some 30,000 particle accelerators operate in the world today in medicine, industry, security and defense, and basic science.

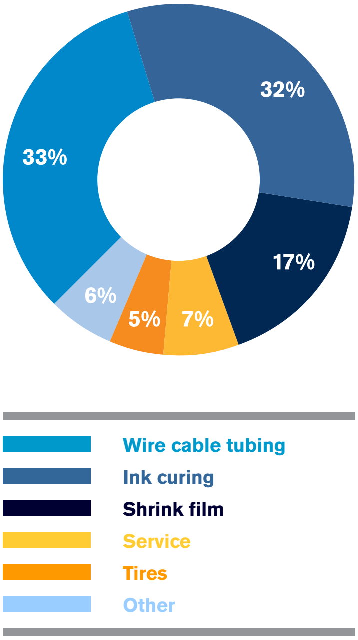
The market for medical and industrial accelerators currently exceeds $3.5 billion a year, and it is growing at more than 10 percent annually. All digital electronics now depend on particle beams for ion implantation, creating a $1.5 billion annual market for ion-beam accelerators. All the products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500 billion.

Other nations have not been slow to recognize the potential for future applications of accelerators. European and Asian nations are already applying next-generation accelerator technology to current-generation challenges.

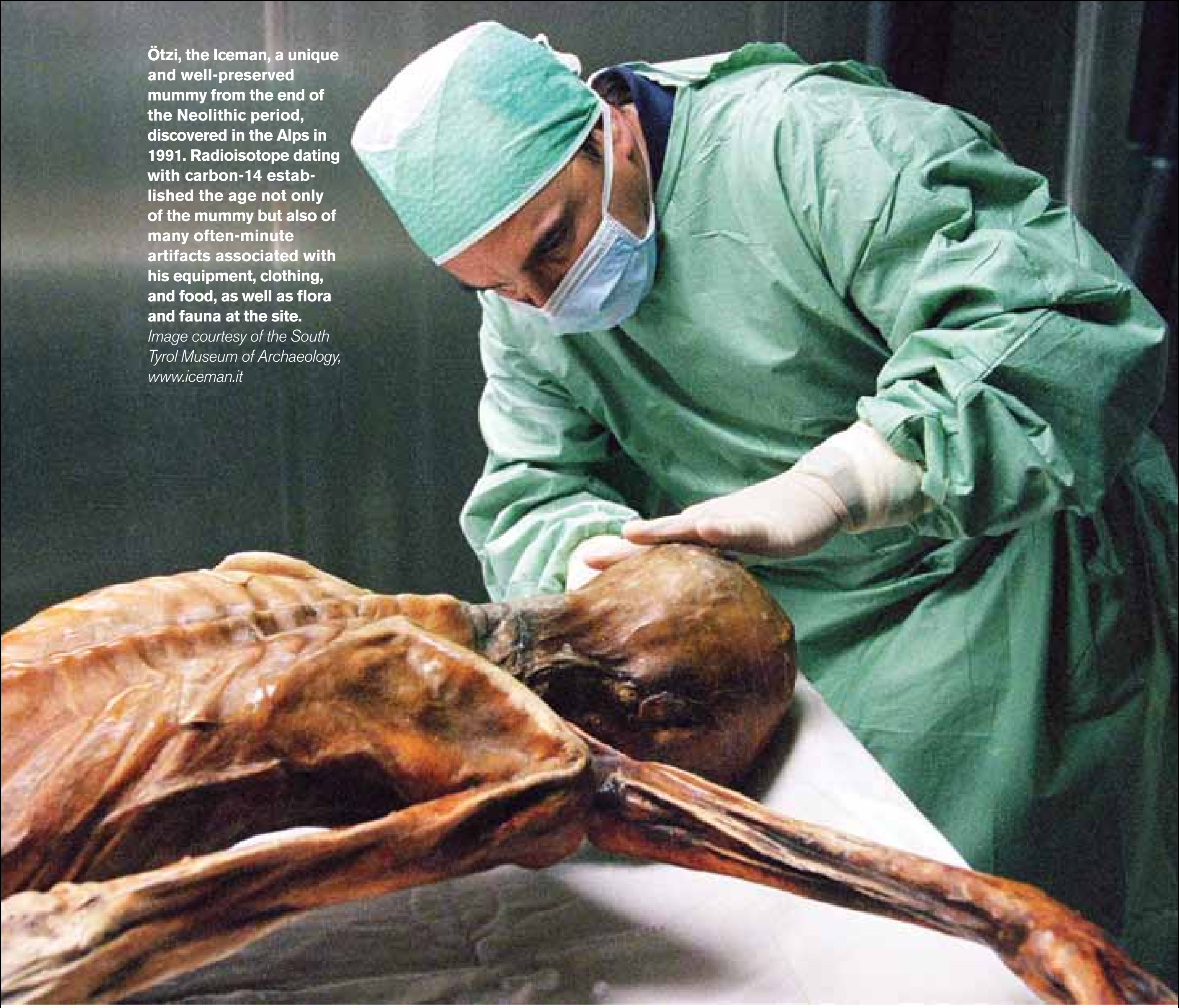
In March 2010, the Belgian government approved $1.3 billion for the MYRRHA project. It will demonstrate an accelerator-driven system for producing nuclear power and transmuting nuclear waste to a form that decays much faster to a stable non-radioactive form. The Belgian government estimates that the project will create 2000 long-term jobs. In China and Poland, accelerators are turning flue gases into fertilizer; and Korea operates an industrial-scale water treatment plant using electron beams. Cancer patients in Japan and Germany can now receive treatment with light-ion beams, and clinical centers with multiple ion beams are coming on line across Europe. US patients don't have these options.

The United States, which has traditionally led the world in the development and application of accelerator technology, now lags behind other nations in many cases, and the gap is growing. To achieve the potential of particle accelerators to address national challenges will require a sustained focus on developing transformative technological opportunities, accompanied by changes in national programs and policy.

Markets for industrial electron beams total $50 billion per year.
Image source: IAEA Working Material on Industrial Electron Beam Processing

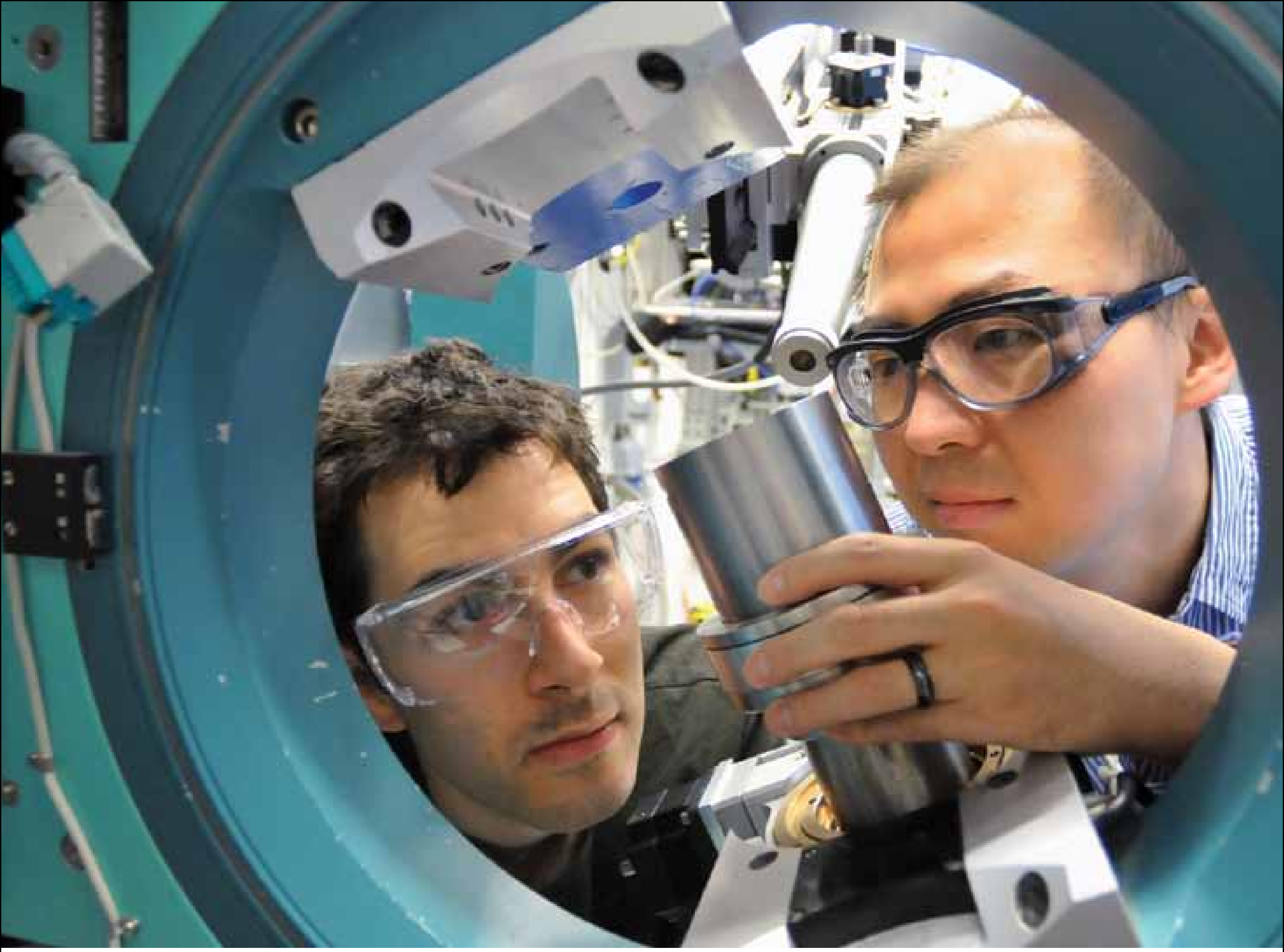


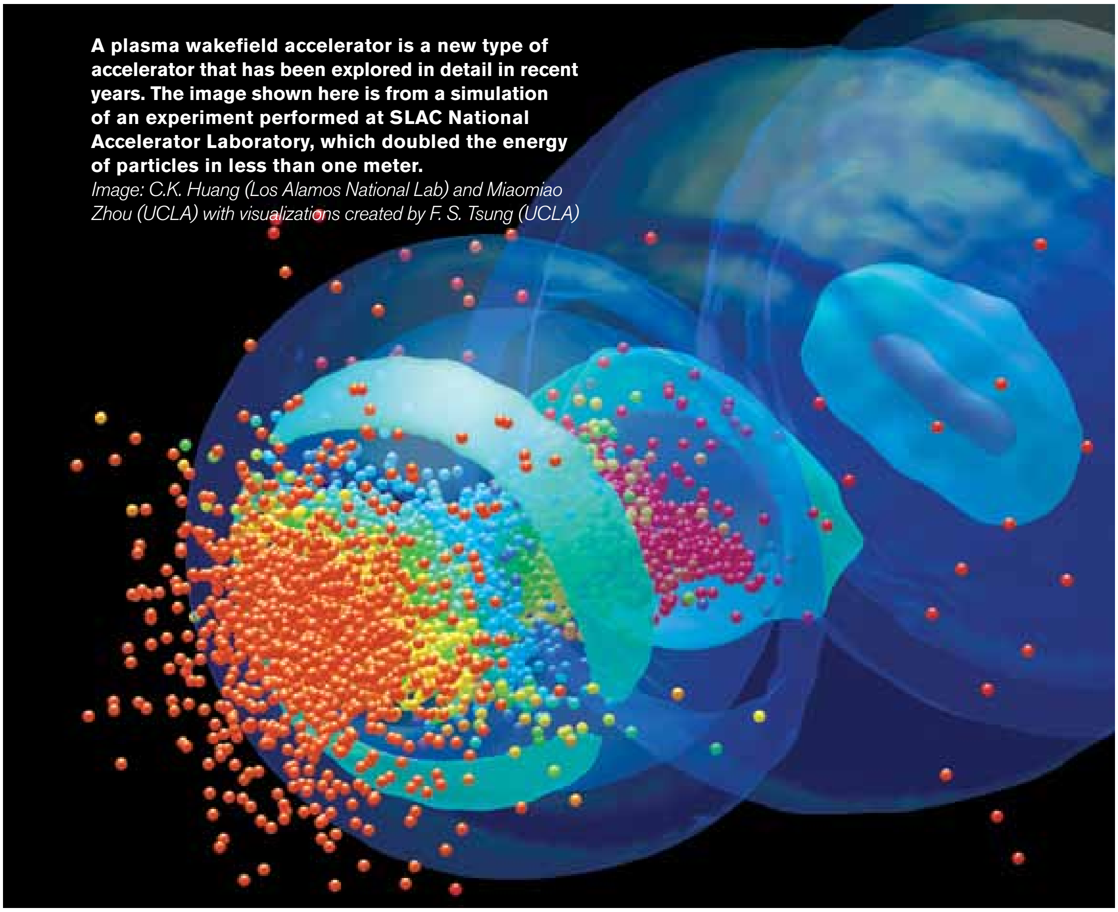
Research has demonstrated the effectiveness of particle accelerators for purifying drinking water, treating waste water, disinfecting sewage sludge, and removing pollutants from flue gases. (Right) Pilot flue-gas treatment plant in Poland.
Photo courtesy of A. Chmielewski, Institute of Nuclear Chemistry and Technology



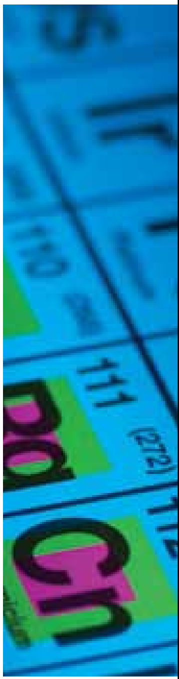
Ötzi, the Iceman, a unique and well-preserved mummy from the end of the Neolithic period, discovered in the Alps in 1991. Radioisotope dating with carbon-14 established the age not only of the mummy but also of many often-minute artifacts associated with his equipment, clothing, and food, as well as flora and fauna at the site.
Image courtesy of the South Tyrol Museum of Archaeology, www.iceman.it

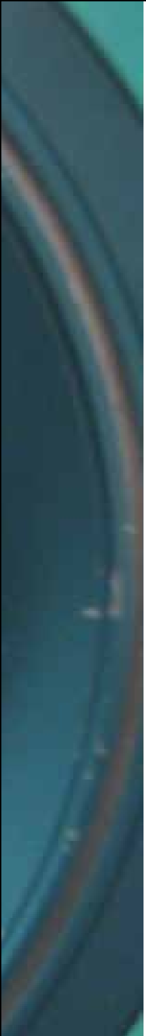
Most of the cereal boxes in the grocery store aisle are printed using electron-beam-cured inks and coatings. Their fast drying times allow for faster web-press printing.
Photo: Reidar Hahn, Fermilab





A plasma wakefield accelerator is a new type of accelerator that has been explored in detail in recent years. The image shown here is from a simulation of an experiment performed at SLAC National Accelerator Laboratory, which doubled the energy of particles in less than one meter.
Image: C.K. Huang (Los Alamos National Lab) and Miaomiao Zhou (UCLA) with visualizations created by F. S. Tsung (UCLA)





University of Chicago scientist Rafael Jaramillo and Argonne scientist Yejun Feng examine the element chromium at the Advanced Photon Source. Studying simple metallic chromium, the joint UC-Argonne team has discovered a pressure-driven quantum critical regime and has achieved the first direct measurement of a "naked" quantum singularity in an elemental magnet.
Photo courtesy of Argonne National Laboratory

From science to society

Historically, breakthroughs in accelerator technology have most often come from the realm of basic science research. The human imperative to discover the laws of nature, from the most fundamental interactions of matter to the behavior of the most complex biological systems, drives the search for ever-more-powerful investigative tools. Writing in 1916, J.J. Thomson, discoverer of the electron, described a famous example of the application of basic science research to immediate practical needs.

"By research in pure science," Thomson wrote, "I mean research made without any idea of application to industrial matters but solely with the view of extending our knowledge of the Laws of Nature. I will give just one example of the 'utility' of this kind of research, one that has been brought into great prominence by the War—I mean the use of X-rays in surgery…

"Now how was this method discovered? It was not the result of a research in applied science to find an improved method of locating bullet wounds. This might have led to improved probes, but we cannot imagine it leading to the discovery of the X-rays. No, this method is due to an investigation in pure science, made with the object of discovering what is the nature of Electricity."

Since the days of cathode ray tubes in the 1890s, particle accelerators have made an extraordinary evolution as tools of basic science. Between Ernest Lawrence's first four-inch-diameter cyclotron, built at Berkeley in the 1930s, and today's most powerful particle accelerator, the 16-mile-circumference Large Hadron Collider, have come dozens of progressively more powerful and precise machines, each incorporating innovations and breakthroughs to advance scientific progress. Each generation of particle accelerators builds on the accomplishments of the previous ones, raising the level of technology ever higher, a thrust that continues today. The National Academy of Engineering lists "to engineer the tools for scientific discovery" among its "Grand Challenges for the 21st Century."

Bridging the valley of death

Just as the investigation of electricity led to the discovery of X-rays, which found immediate use, the future of particle accelerators belongs not just to scientists. The powerful new accelerator technologies created for basic science and developed by industry will produce particle accelerators with the potential to address key economic and societal issues confronting our nation.

A critical challenge is the translation of breakthroughs in accelerator science and technology into applications that benefit the nation's health, wealth, and security. Experts from every field of accelerator science and technology, in the research community and industry alike, agree that making that happen will require bridging the divide often described as the "valley of death" that exists in the United States today between the research laboratory and the marketplace.

On one side of the valley are the innovative accelerator concepts and technologies that emerge, often in government-funded laboratories and universities, for basic research. On the other are industries that could put these new technologies to work to meet national needs—and compete in the global marketplace.

Keeping them apart are a dearth of funding mechanisms for research and development; a lack of national facilities, demonstration projects, and pilot programs to assist with the translation; an aversion to risk; and policies that inhibit coordination and partnership among government entities and between government and industry.

To address the challenge of innovation for national competitiveness in the domain of particle accelerators, the Department of Energy's Office of Science, the nation's major steward of accelerator technology, has inaugurated a program to coordinate basic and applied accelerator R&D. To better understand the direct connection between fundamental accelerator technology and applications, the Office of High Energy Physics sponsored an October 2009 workshop on behalf of the Office of Science to identify the R&D needs of the various users of accelerators who would benefit from future technology R&D initiatives.

Nuclear physics investigates how the fundamental building blocks of the big-bang plasma formed nucleons and nuclei, how astrophysical processes create the chemical elements, and how their interactions power the sun and the stars.
Photo: Reidar Hahn, Fermilab

Accelerator users and experts at the workshop focused on the potential role of accelerators in five key areas: energy and the environment, medicine, industry, national security and defense, and discovery science. They identified the opportunities and research challenges for next-generation accelerators; the most promising avenues for new or enhanced R&D efforts; and a path forward to stronger coordination between basic and applied research.

The accelerator stakeholders articulated the technical challenges and risks involved in achieving their vision for future accelerators and focused on changes in policy that would help to make the vision a reality.

Across the board, all groups strongly advocated the creation of large-scale demonstration and development facilities to help bridge the gap between development and deployment of accelerator technologies. They called for greatly improved interagency, interprogram, and industry-agency coordination.

Because continued innovation in accelerator technology depends on the next generation of accelerator scientists, they emphasized the need to strengthen the training and education of US accelerator scientists and engineers, and to recognize accelerator science as a scientific discipline.

The Office of Science will use the workshop's results, presented in this report, to develop a strategic plan for accelerator technology R&D that recognizes its broad national impacts.

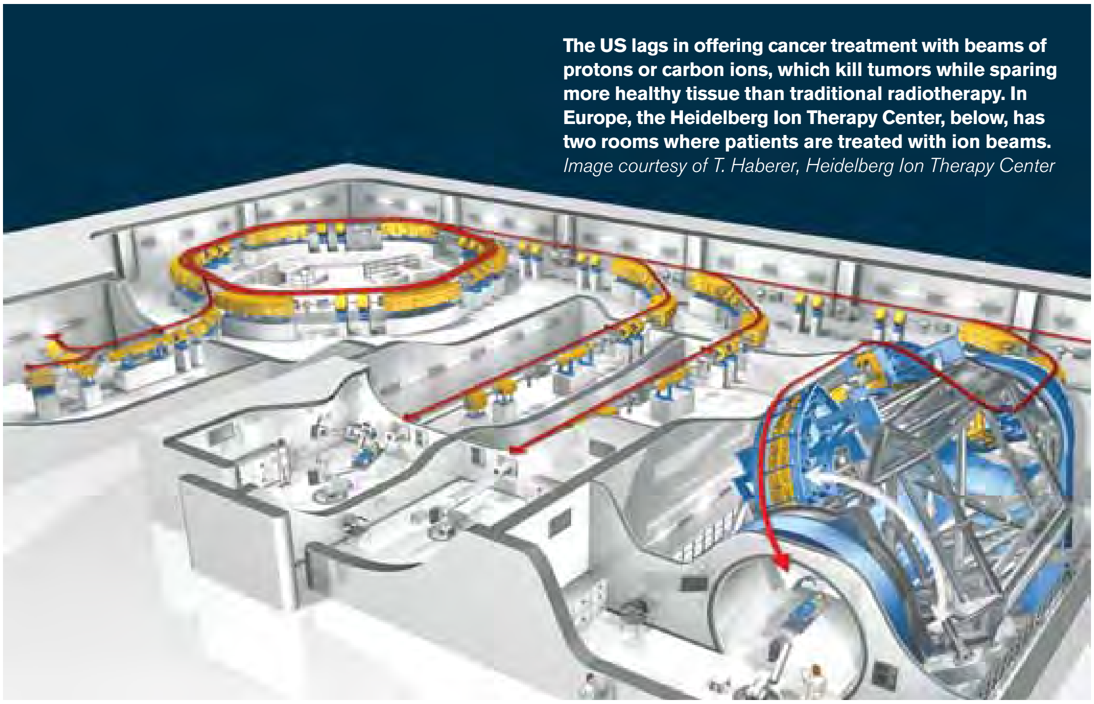
The 2005 National Academies report, *Rising Above the Gathering Storm*, issued a national call to action to address the eroding technological building blocks of future prosperity in the United States.

"This nation must prepare with great urgency to preserve its strategic and economic security," said the report's major finding. "Because other nations have, and probably will continue to have, the competitive advantage of low-wage structure, *the United States must compete by optimizing its knowledge-based resources, particularly in science and technology, and by sustaining the most fertile environment for new and revitalized industries and the well-paying jobs they bring*. (Italics added.) We have already seen that capital, factories, and laboratories readily move wherever they are thought to have the greatest promise of return."

For optimizing knowledge-based resources in science and technology, and for sustaining an environment for new and revitalized industries and the well-paying jobs they bring, a beam of particles is a very useful tool.

This text was excerpted with permission from the Accelerators for America's Future *report, which can be downloaded or requested in print at www.acceleratorsamerica.org*

Only a handful of US universities offer formal training in accelerator science and technology. More than any other factor, the education of the next generation of accelerator scientists and engineers will determine the future of accelerator-based science and technology in the United States.
Photo courtesy of W.A. Barletta



The US lags in offering cancer treatment with beams of protons or carbon ions, which kill tumors while sparing more healthy tissue than traditional radiotherapy. In Europe, the Heidelberg Ion Therapy Center, below, has two rooms where patients are treated with ion beams.
Image courtesy of T. Haberer, Heidelberg Ion Therapy Center

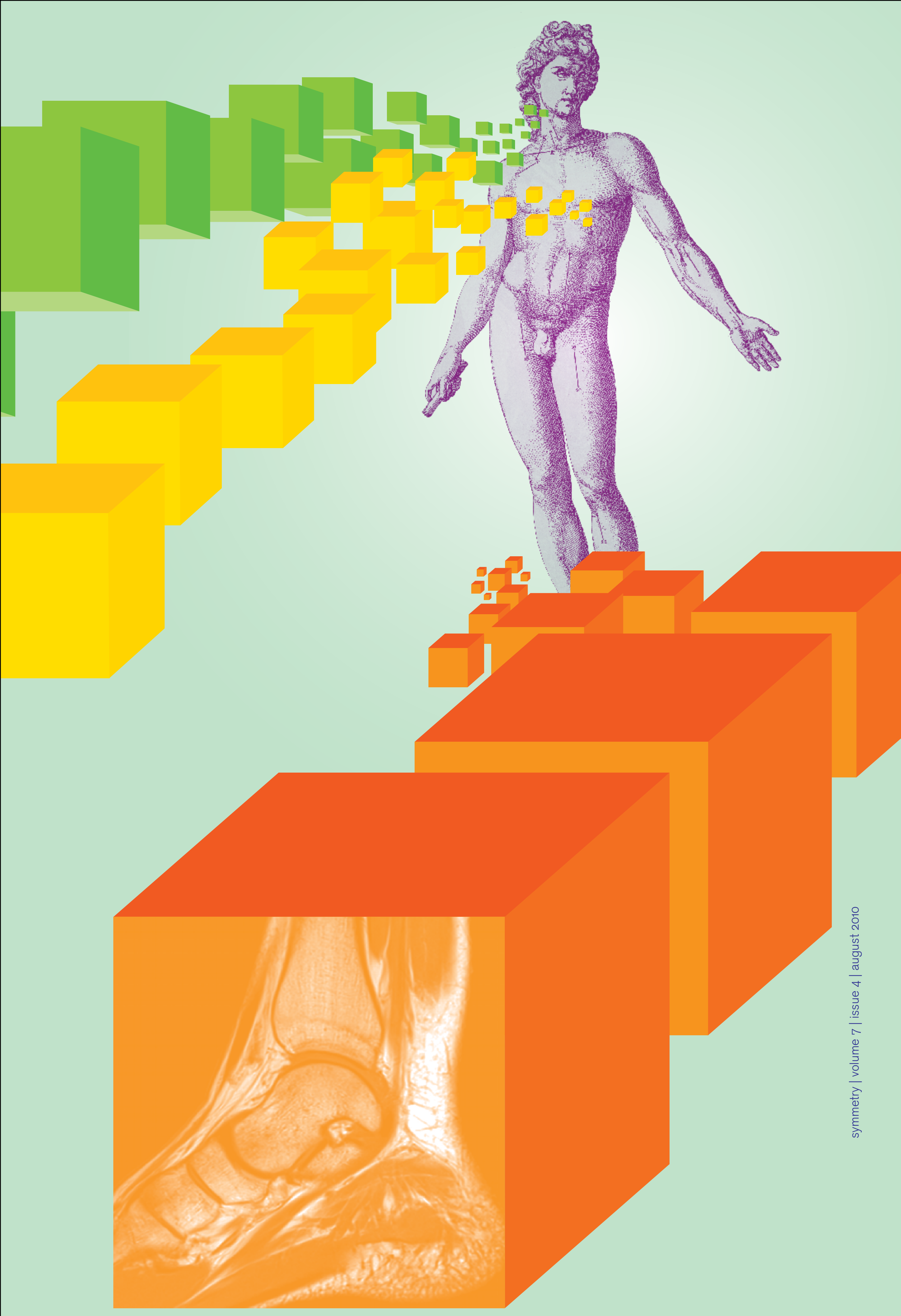
"Accelerators for America's Future," an October 2009 symposium and workshop, brought together stakeholders from across the spectrum of accelerator science and technology. Norman R. Augustine (above), retired chairman and CEO, Lockheed Martin Corporation, delivered the keynote address.

Photos: Reidar Hahn, Fermilab

NEW IMAGING TOOLS FROM THE LHC

Technology developed for the Large Hadron Collider is changing the way we see our bodies.

By Daisy Yuhas



About four years ago, radiologist Anthony Butler was visiting CERN, the European particle physics laboratory, when he saw something that left him, as he put it, "flabbergasted."

Michael Campbell, a CERN engineer, showed Butler a 14-square-millimeter electronic chip, the product of a decade's research. It was derived from other chips that precisely record the charges and locations of individual particles coming into detectors at the Large Hadron Collider.

What Butler was astounded by, however, was not the physics. What surprised Butler was the chip's potential in a *medical* context.

"I was flabbergasted to see this on a physics bench and not in a medical school," Butler says.

This little X-ray imaging chip could find a home in biomedical imaging for more accurate and efficient diagnoses. It could transform the treatment and study of disease. It could be part of the first line of response for seriously injured patients in the emergency room or intensive care unit. And it's just one example of how high-energy physics at the LHC has contributed to a growing revolution in our knowledge of the body.

POTENTIAL-PACKED PIXELS

Every second, the LHC brings billions of particles into high-energy collisions. The collider's four detectors are like super-microscopes that illuminate the infinitesimally small, fleeting particles coming out of those collisions, looking for events that have never been seen before.

At the heart of the ATLAS detector sit 1744 silicon pixel sensors containing a total of 80 million pixels. A pixel is the smallest individual element of a digital image. Just as the millions of pixels in a digital camera capture photons, or particles of light, the ATLAS pixels record information about individual subatomic particles flying out from collisions. But they can just as well record X-rays, which are a form of light more energetic and penetrating than the light we see. That's why scientists are so excited about their potential for medical imaging.

Researchers from the University of Bonn, led by Professor Norbert Wermes, slightly modified the ATLAS pixel sensor to create the Multi Picture Element Counter, or MPEC, in the early 2000s.

They found that MPEC and the follow-up CiX chips created clearer, cleaner X-ray images than conventional technology, while eliminating over- or under-exposure. Doctors get a sharper picture of what's going on inside the body and the patient undergoes fewer examinations.

"The application is virtually a one-to-one transition of ATLAS to X-ray technology," Wermes says. "I've never before in my scientific life seen such a straight spin-off application from fundamental research."

WANDERING SOLUTIONS

The chip that Campbell showed Butler four years ago at CERN was, like MPEC, a pixel detector. In the early 1990s, researchers creating detectors for multiple LHC technologies began testing the quality of their chips by recording X-rays emitted by a radioactive source. They realized in the process that their chip could also be a tool for medical imaging. They dubbed their project Medipix.

What makes Medipix special is its system of embedded electronics, which convert information about the locations and charges of individual particles into a digital format for more robust, efficient imaging. Campbell and his collaborators have created three generations of chips for a variety of non-physics projects, from dentistry to education.

"It's like a solution walking around looking for a problem," physicist Lawrence Pinsky of the University of Houston says of the chip's protean abilities. Pinsky, who works on the LHC's ALICE experiment, is using second-generation Medipix chips in dosimeters that keep track of astronauts' space radiation exposure.

Campbell has been involved with the research since its beginning and is amazed by the diversity of applications.

"What we learned over the years is that bringing people in from other areas of science is not a simple one-plus-one-equals-two sum," Campbell says. "They bring in other ideas and directions. It's been quite an adventure."

In a positron emission tomography (PET) scan, the patient swallows, inhales, or is injected with a radio-active tracer that accumulates in a particular part of the body. A scanner records gamma rays from the tracer and a computer processes the data, revealing oxygen consumption, blood flow, the metabolism of sugar, and other important body functions.
Image courtesy of Radiological Society of North America

PROBLEM FOUND!

Butler, affiliated with New Zealand's University of Canterbury and University of Otago, Christchurch, has a special fluency for translating technologies into the medical field. His research led to MARS, the Medipix All Resolution System CT Scanner.

Doctors use CT (computed tomagraphy) scans to map the body's anatomy and condition. These scans X-ray the body from a number of angles and combine the digital images to get a comprehensive picture. In some cases the patient is given a "contrast agent," such as a solution containing barium or iodine, by injection or mouth to sharpen the view of a particular organ or system.

The MARS scanner is unique in that it can be used with several contrast agents at once. The resulting color images show multiple body systems at the same time, with greater clarity and less total radiation exposure from X-rays. For instance, an iodine contrast agent might light up the vascular system in red, while a barium agent paints a blue image of the liver. Since becoming commercially available in December 2009, the MARS scanner has been used to study cancer, heart disease, and the breakdown of blood vessels.

Someday, doctors could use these scanners in hospitals to monitor, in unprecedented detail, how a patient's body is responding to complicated internal injuries.

IF AT FIRST…

Transferring a technology like Medipix to the commercial sector requires strong support from the group of scientists that developed it. It can be an uphill battle to find funding for research and production.

Sherwood Parker of the University of Hawaii is familiar with these challenges. He was involved in the research and development of pixel detectors for the Superconducting Super Collider, then under construction in Texas, when the mother of one of his graduate students was diagnosed with breast cancer. He became intrigued by the possibility of applying his research to mammography for breast-cancer detection.

Parker's group set about developing an X-ray system for detecting breast cancer. This was 1993, however, and what Parker didn't know was that the ill-fated SSC would soon have its funding cut, and with it the funding for his group's project.

Parker and his group published their research, demonstrating that their X-ray system doubled the resolution of then-conventional technology with 10 times less radiation. However, their study came to a halt when the National Institutes of Health rejected their applications for funding.

THE MOLECULES OF LIFE

The experience could have dissuaded Parker from further attempts to transfer technologies to other fields. However, a few years later Parker found himself on the same committee that had once rejected his proposal. It was there that he met physician and biophysicist Edwin Westbrook, now director of the Molecular Biology Consortium.

At the time, Parker was working on advanced detectors for a future upgrade of the LHC, and he realized that one of these detectors could greatly improve data collection for Westbrook, who was using X-rays to probe the structures of proteins.

"I realized that I was talking to somebody who was writing the raw material for the textbooks of the future," Parker says. "Spin-offs don't only have to be for industry; they can be for basic research, and basic research can be used in the medicine of the future."

The system Parker and Westbrook are developing with Al Thompson of Lawrence Berkeley National Laborataory and Christopher Kenney of SLAC National Accelerator Laboratory is called 3DX. It's designed to aid biologists studying the structures of macromolecules such as proteins and DNA—studies that promise greater insight into the building blocks of life.

SIMPLY SCINTILLATING

At another LHC detector called CMS, physicists measure the energies of particles flying out of collisions with an electromagnetic calorimeter. The calorimeter contains 78,000 crystals that have been grown to very specific parameters so they produce light, or scintillate, when a particle passes. Physicists measure this scintillation to determine the particle's energy.

Developing these crystals for CMS began two decades before the LHC saw its first collisions. In 1990, physicist Paul Lecoq established a research group at CERN, called Crystal Clear, to study scintillating crystals.

"The collaboration was established to answer the requirements of the detector, which are continuously changing, and it continues to respond to new challenges," Lecoq says. "This requires that we maintain the front edge of this science."

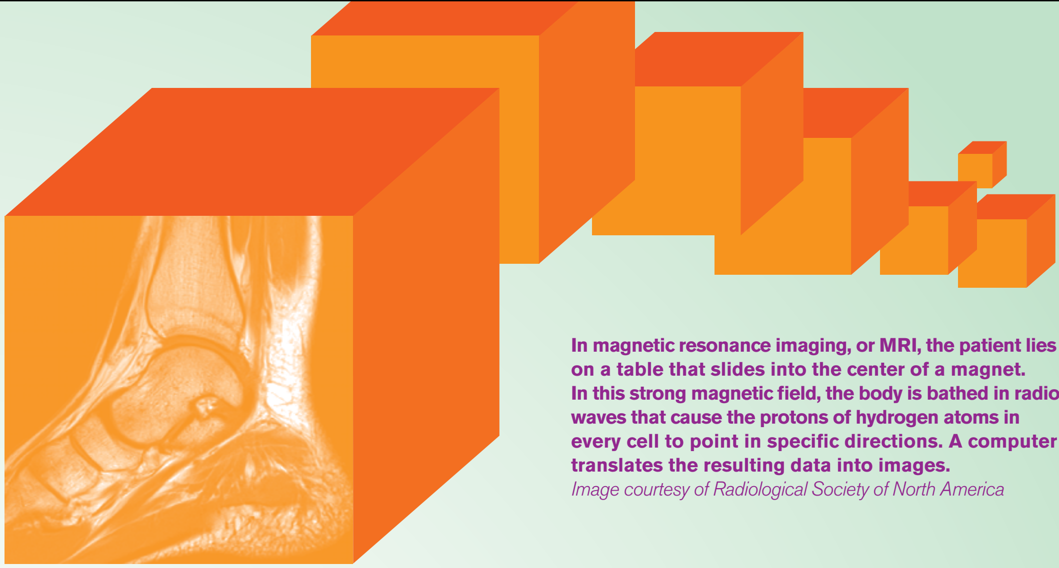
While studying different kinds of crystals, the group became increasingly aware of how their research could benefit other projects. Since Crystal Clear began, they have researched scintillating crystals for use in industry, security applications such as luggage and cargo scanning, biology, and medicine, as well as in high-energy physics.

CLEAR AS CRYSTAL

One of these cross-disciplinary projects was ClearPET, a positron emission tomographic or PET scanner that incorporates scintillating crystals. PET scans reveal the metabolic activity of organs and tissues, providing a window on the body's responses to disease and treatment. ClearPET does the same, but images small test subjects and small areas of the body in higher resolution than a conventional PET scan.

It was this feature that led to the development of a new target for scintillating-crystal research: mammography. Crystal Clear scientists in Portugal are developing what they call ClearPEM, using lessons learned from ClearPET for better breast cancer detection.

Computed tomography (CT) scanners X-ray the body from a number of angles and combine the data to get a comprehensive, 3D picture. In some cases the patient is given a "contrast agent" by mouth or injection to make the image crisper. These contrast agents–solutions of barium or iodide, for example–each light up a particular body organ or system.
Image courtesy of Radiological Society of North America



In magnetic resonance imaging, or MRI, the patient lies on a table that slides into the center of a magnet. In this strong magnetic field, the body is bathed in radio waves that cause the protons of hydrogen atoms in every cell to point in specific directions. A computer translates the resulting data into images.
Image courtesy of Radiological Society of North America

Today, researchers estimate that up to 60 percent of mammograms that show evidence for cancer are false positives. The Crystal Clear research suggests that ClearPEM is more than five times as sensitive and efficient as conventional X-ray mammography and could reduce the number of false positives, eliminating unnecessary biopsies and operations. ClearPET is now commercially available for a range of biological and biomedical studies.

WHAT COMES NEXT?

This successful interplay among fields inspired Lecoq's latest project, the European Center for Research in Medical Imaging (CERIMED), a multi-disciplinary training campus to research and develop new imaging technologies.

Already, participants have designed a ClearPEM with an ultrasound probe and will install the machine at Marseilles Hôpital Nord this autumn.

Dr. John O. Prior, professor and head of nuclear medicine at the Centre Hospitalier Universitaire Vaudois Lausanne, is one of the medical professionals involved with CERIMED. The rapid transfer of detector technologies to a medical setting—what he calls "bench to bedside"—is the focus of his research.

Looking ahead, Prior says, research into endoscopic probes could put radiation detectors inside the human body. Physicians could image tumors from within the body's natural openings or through minute holes in the skin. Recently developed hybrid PET/magnetic resonance scanners give unprecedented information about the brain. These could unlock medical mysteries and help find new drugs for treating neurological diseases, such as Alzheimer's, that are difficult to recognize and treat.

When doctors began using the CT scan in the late 1970s, the new information provided by the scan led physicians to change the course of treatment for their patients in 14 percent of cases. Already, new hybrid PET/CT scan technologies alter treatment in 30 percent of cases by revealing how the body is responding to a given therapy or drug. Advances in medical imaging allow doctors to tailor treatment to a particular tumor, based on its response to therapy.

Prior believes these advances will enable physicians to offer personalized medicine that is better adapted to their patients. Sensitive, low-radiation imaging makes it possible to understand the nuances of each individual.

SEEING THE FUTURE

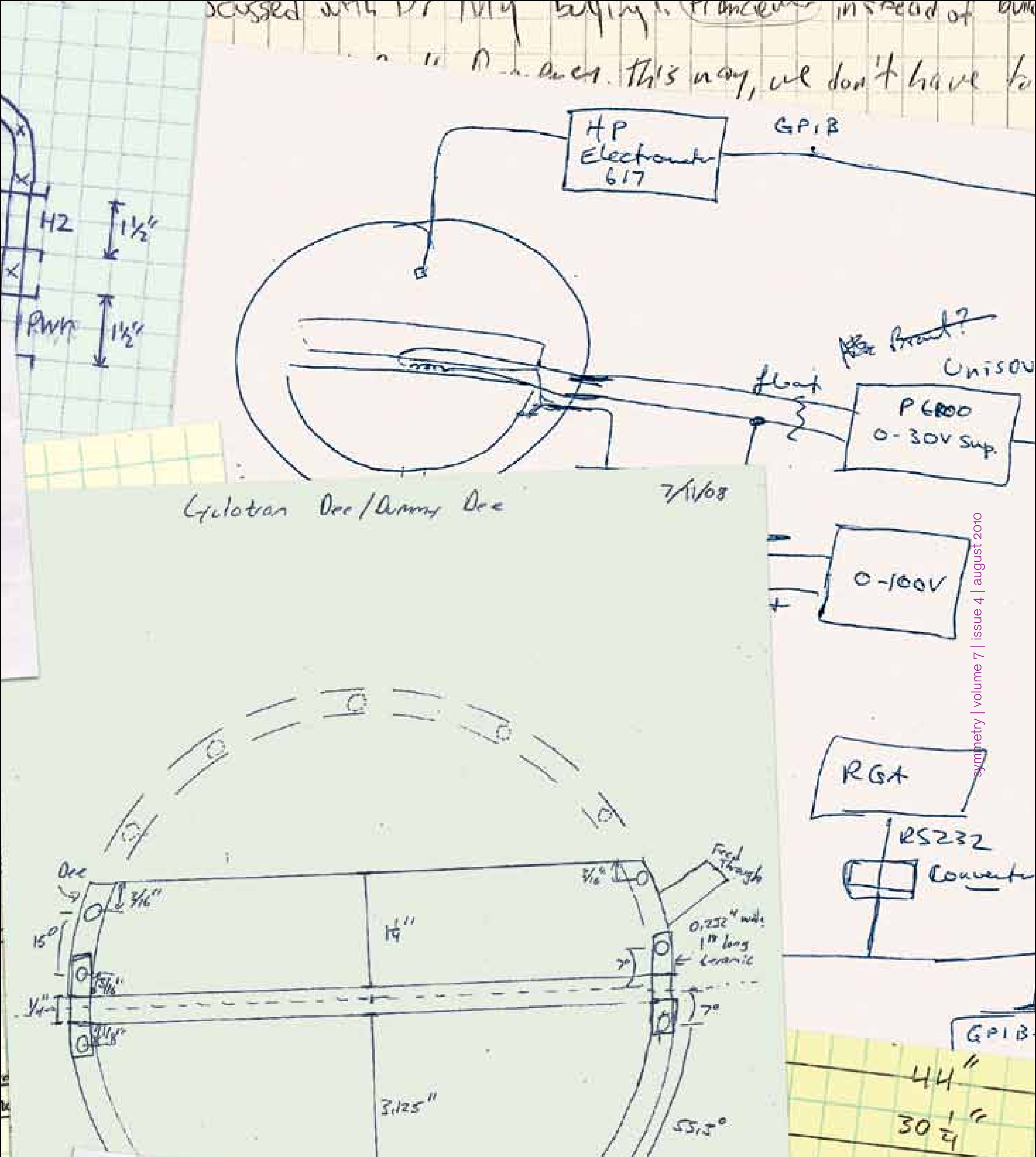
No one knows what the next great advance or discovery will be. If the present pace of research is any indication, breakthrough techniques will exponentially increase through mutually supportive, cross-disciplinary research.

The progress made using LHC technology is an exciting reminder that in the quest to learn more about the universe, we also learn more about ourselves. When scientists and engineers apply complementary technology to medicine, they can improve medical diagnoses, treatment, and care. Technology and research in high-energy physics at the LHC can have a concrete impact on all of us.

We cannot actually see the future, but the future's imaging is getting clearer by the minute.

The do-it-yourself CYCLOTRON

The cyclotroneers at the first amateur cyclotron conference at Houghton College in New York: Fred Niell, Heidi Baumgartner, Tim Koeth, Jeff Smith, Peter Heuer, Mark Yuly, Andrew Loucks, Tim Ponter, Raymond Jimenez, and James Krutzler. *Photo: Tim Koeth*



Amateur cyclotron builders are dedicated, tenacious, and obsessed. Another thing they have in common: The experience changes their lives. By Calla Cofield

If the only thing amateur car builders needed was a ride to work, they wouldn't ever build cars. While it's certainly nice to take the finished product around the block to show the neighbors, there's something more than transportation motivating a hot-rod builder.

That's the analogy Mark Yuly uses for a project he's working on with his undergraduate physics students at Houghton College: building a particle accelerator.

Yuly belongs to a rare breed of people who have a deep fascination—you could even call it an obsession—with cyclotrons. For many of those obsessed, the only way to satiate their hunger for these machines is to build their own. There are no guidebooks or instruction manuals, and if you bought the raw materials off the shelf, it would cost around $125,000. On average, amateur cyclotrons take two to three years to build. And while it would drive some people crazy to build their own car and never drive it, in the 80-year history of amateur cyclotron building, only occasionally have the finished products been used for experiments or in education: Yuly says, "That's not why we build them."

"We" refers to amateur cyclotron builders. And last April, for the first time in history, they held a conference.

First meetings

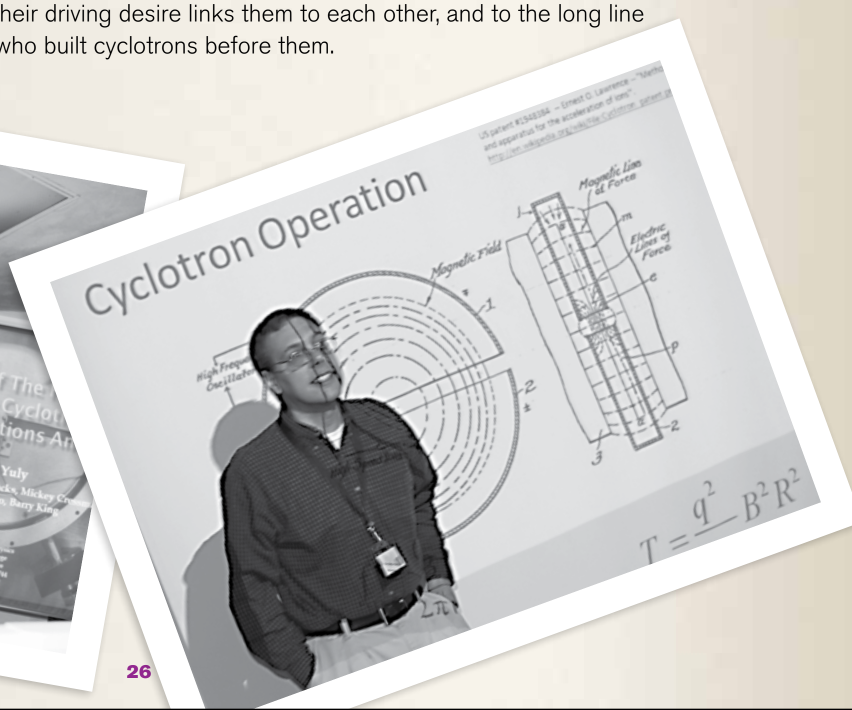
On a chilly but bright Saturday morning, Yuly awaits the arrival of his guests, his boyish smile stretched from ear to ear. He has specific questions for the visitors about some trouble he is having with his own cyclotron, but most of all, he says, "I'm just looking forward to the chance to meet all these people I've been corresponding with over the years."

The Houghton College campus lies more than 300 miles from the closely packed chaos of New York City, and miles from major highways and chain stores. Draped in green farmland and forest, it rests languidly in the middle of nowhere.

Fifteen people from as far away as California, Illinois, and Washington, DC, trickle into the Houghton science building for the Small Cyclotron Conference. Of the four women in attendance, two have come to report on the meeting, while another joined her husband for the ride. The men are in mixed attire from jeans to suits, with a noticeable few who look younger than 30. Not everyone who ever built their own cyclotron is here—there are probably another 10 of them alive in the world—but it's a strong sampling.

The strangers gather in the lobby of the science building, share a spread of coffee and pastries, shake hands, and exchange names. The natural awkwardness of a first meeting dampens the air, but a nervous excitement lifts it up. Most of the builders completed their monumental tasks in isolation. Their driving desire links them to each other, and to the long line of people who built cyclotrons before them.

Below: Conference host Mark Yuly delivers a presentation about the amateur cyclotron he built with his students at Houghton College. Yuly uses the cyclotron as a teaching tool and research project for his undergraduate students.
Photo: James Krutzler



Harder than it sounds

It's actually rather easy to accelerate particles in your own home. When you turn on a fluorescent lamp, the eerie glow comes from electrons accelerating off the filament. With slightly more complex technology, it is also possible to accelerate an entire atom, albeit with some of its electrons stripped away; in this configuration it's called an ion. Put that hardware inside a metal chamber, create a vacuum to get rid of all the other particles in the air, add a magnet to steer the ions in circles, and use radio waves to speed them up, and you've got yourself a cyclotron. Then make a particle detector of your choice-something to shoot the ions at-and you can put your ions to work.

Sound easy?

A commercially built cyclotron can cost anywhere from a few hundred thousand to a few hundred million dollars and take months to build.

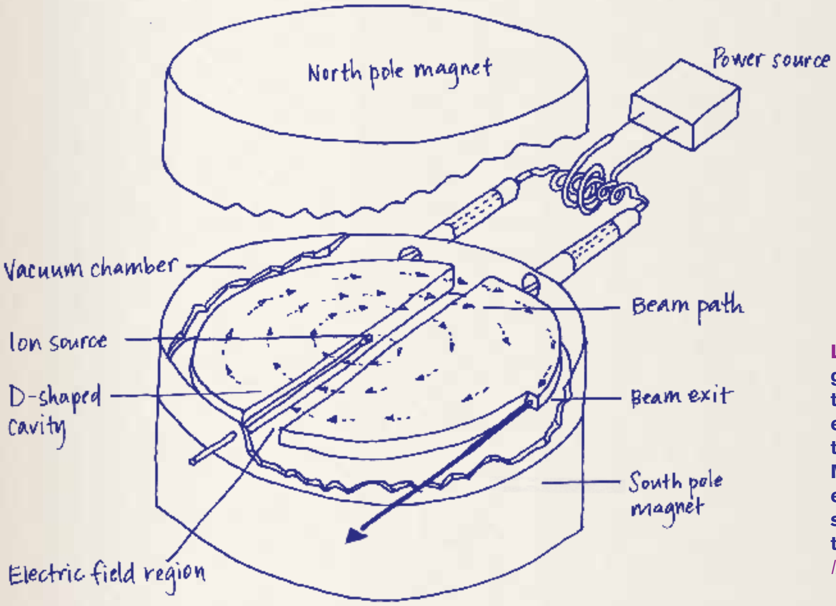
The core of the cyclotron is the chamber: two metal canisters shaped like the letter "D," placed back to back to make a circle. Inside the chamber, the particles spiral around and around. Amateur cyclotron chambers are usually only a few inches to a foot across—small enough to hold in your hand. The very smallest, made by Fermilab employee Chris Olsen, is eight centimeters in diameter. The world's largest cyclotron runs at TRIUMF, Canada's national laboratory for particle and nuclear physics located at the University of British Columbia campus in Vancouver, and is 60 feet in diameter.

From the side of the metal chamber sprout various appendages, giving the impression of a bizarre, circular Swiss army knife. These include, but are not limited to, the filament, which generates the ions; the vacuum pump that removes all other particles from the chamber; a window looking into the chamber, where you can sometimes see a glow as the ions accelerate; and the detector.

The largest piece of a cyclotron is the magnet. Tim Koeth, the conference's lead organizer, designed his cyclotron at Rutgers University while an undergraduate physics student. It has a metal chamber 13 inches in diameter; its magnet is three feet high, four feet wide, and weighs 4600 pounds. A commercially produced magnet of that size might cost more than $10,000, but Koeth and some student helpers had the good fortune to find the magnet, originally manufactured for another cyclotron, going unused at Argonne National Laboratory, which generously donated it to their cause. The ability to track down treasures like these is a necessary skill for amateur cyclotron builders.

Top: **Ions in the Rutgers cyclotron spiral down during a test run.**
Photo: Tim Koeth

Bottom: **A view of the cyclotron's ion source through a vacuum-tight view port.**
Photo: Tim Koeth



Left: **In a cyclotron, ions gain speed every time they cross the alternating electric field created by two D-shaped cavities. Magnets steer the accelerating ions along a spiral path until they exit the cyclotron.**
Illustration: Sandbox Studio

Treasure hunting

Fred Niell built his cyclotron as a high-school student, and with it won the grand prize at the International Science and Engineering Fair: a trip to Sweden to see the Nobel Prize proceedings as a guest of the Swedish Academy of Sciences, where he met the Swedish royal family and danced with Princess Victoria. Now an electrical engineer with his own business, Niell remains up to speed on where to find the equipment to build a cyclotron. He's the one who estimated the cost of all the parts and services needed to build a small cyclotron—not including the builder's time—at about $125,000.

No one at the meeting, even those with sponsors, has anywhere near that much money.

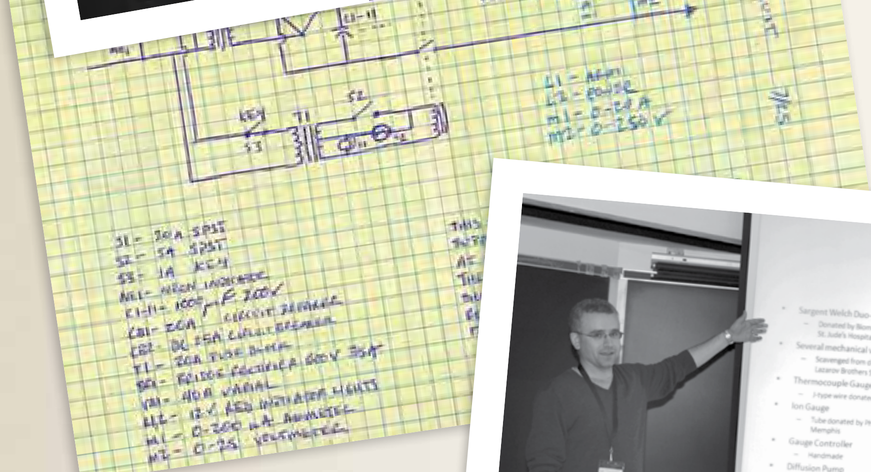
But that's only if you buy everything new. To get stuff cheap or even free, Niell says builders can hunt for materials on websites such as eBay and craigslist (an open classifieds page, more often dedicated to apartment rentals and old furniture), as well as on lesser-known gems, such as a site where the United States government liquidates materials formerly used by the armed forces.

Even more effective, he says, is knocking on doors, calling up shops, and discussing your project with people. The younger and more inexperienced builders have more luck with this, he says, because of the "cuteness factor." Although the vast majority of people would never have the drive or desire to build their own cyclotron, in Niell's experience most people jump at the chance to help out someone who does.

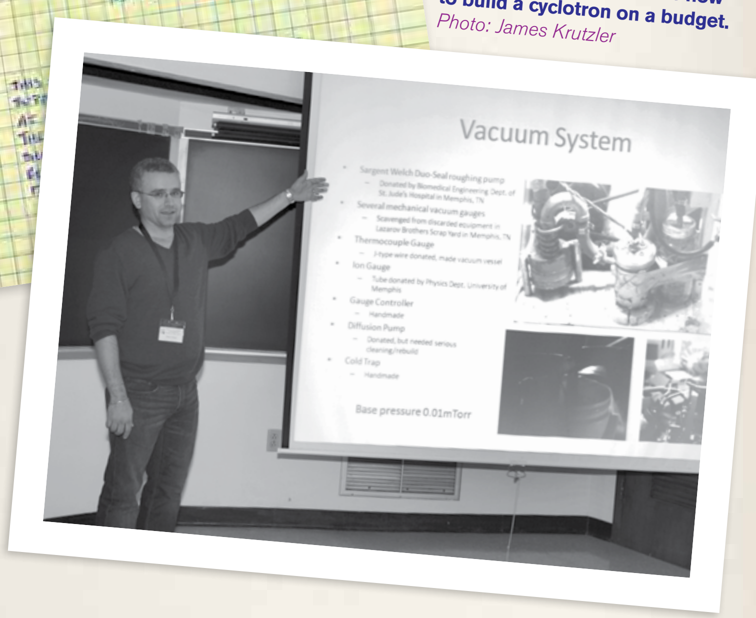
"I've definitely had old scientists or machine-shop guys sort of live vicariously through me," he says.

Top: King Carl XVI Gustaf of Sweden addresses young scientists, including amateur cyclotron builder Fred Niell, who won a trip to the 1994 Nobel Prize ceremony for his amateur cyclotron.

Bottom: The young Niell with Clifford Shull, one of two Physics Nobel Prize recipients that year.
Photos courtesy of Fred Niell



Below: At the Amateur Cyclotron Conference, Niell discusses how to build a cyclotron on a budget.
Photo: James Krutzler



Lots of eager helpers

Every one of the attendees can recount an instance when someone showed them an act of kindness, gave them something for free, or assisted them in some way.

Case in point: when *symmetry* ran a story online about the meeting's two youngest attendees, 17-year-old Heidi Baumgartner and 18-year-old Peter Heuer, a man who worked for a company that makes vacuum pumps contacted them and sent them one free.

"It's such an audacious project," Heuer says. "And I guess people want to donate to things that are inspiring."

Baumgartner and Heuer are building their cyclotron at the Thomas Jefferson National Accelerator Facility, where they have space and a small amount of funding but are left to their own devices to build the machine. The benefit of their location is the population of specialists in their immediate vicinity.

"We usually corner them at lunch and ask if we can talk to them for a few minutes," Baumgartner says. "And then they end up talking to us for two hours."

Above left: Peter Heuer and Heidi Baumgartner, aka The Cyclotron Kids, work on their cyclotron at Thomas Jefferson National Accelerator Facility.
Photo courtesy of Jefferson Lab

Above right: Baumgartner presents a new design for cyclotron "Ds" at the Amateur Cyclotron Conference.
Photo: Tim Koeth

Tools for science and medicine

When you accelerate particles and fire them at a target, the collision reveals properties of the target material much smaller than visual microscopes can see. For a long time cyclotrons were mostly used to study nuclear physics, which focuses on the structures and interactions of the nuclei of different types of atoms. Over the years, linear accelerators and synchrotrons have surpassed cyclotrons in terms of particle energies. Machines like the Large Hadron Collider produce energies much higher than cyclotrons can achieve and bring two particle beams into head-on collision; cyclotrons can only aim beams at fixed targets.

Nonetheless, for many modern applications cyclotrons offer particle beams of sufficient energy while using less space and electricity.

Today, cyclotrons are most widely used in medicine. Cyclotrons generate particles used in medical imaging techniques such as PET, or Positron Emission Tomography, that penetrate skin and muscle and create images of the inside of a patient. Cyclotrons can also produce radioisotopes—unstable nuclei that emit radiation when they decay to a stable form—used in medical imaging and cancer radiation treatment (See "Deconstruction: Isotope production," page 36).

By the mid to late 1950s, laboratories and private companies had commercialized the production of cyclotrons. This eliminated the need for people who could build an entire cyclotron themselves, but it didn't eliminate the desire.

Above: Conference-goers tour the Houghton College cyclotron.
Photos: Tim Koeth

Particles in the basement

In 1947, an article in *Physics Today* featured four teenagers at El Cerrito High School in California who, with the assistance of a teacher, built their own cyclotron. In 1951, three high school boys in Fort Wayne, Indiana, remodeled their high school basement to make room for their cyclotron laboratory. By the time the principal found out, they were already working on the accelerator. The group made another important stride when they decided to keep careful notes, a blueprint for amateur builders to come. Four amateur cyclotrons appeared in the 1950s, including one in Korea, and another in the 1960s. Then the scene went quiet until the 1990s, when five new amateur cyclotrons appeared, including those built by conference organizer Tim Koeth and attendees Jeff Smith and Fred Niell. The other attendees all began building their cyclotrons after 2000.

What strange bug has infected people, decade after decade, with the drive to embark on such a grueling journey?

"It really is a love of this machine," says Jeff Smith, who built his cyclotron in college and now works as an accelerator scientist at SLAC National Accelerator Laboratory. "I think even people who work in the field [of accelerator science] are more interested in the experiment and don't always have this kind of passion for the actual machine."

Some amateur cyclotron builders did perform experiments with their completed projects. Yuly has some specific experiments he'd like to do with the Houghton cyclotron when he and his students get it running at a slightly higher energy. Baumgartner and Heuer have the ambitious goal of using theirs to create antimatter, and then hope to leave it at Jefferson Lab for other students to use.

But that's rare; few amateur builders pursue research with their machines. Niell got his cyclotron working just before he graduated from high school, and left it there when he went to college. He found out later that it had had been dismantled for parts. Smith's is still in the basement of Knox College. He says a student once tried to tinker with it, but didn't follow through.

"I do feel an attachment to it," Smith says. "I don't want to hang it on the wall, but it would be nice to know that someone was getting some use out of it."

A nifty learning tool

The cyclotrons at Rutgers and Houghton have now seen a few generations of students get involved in their construction and design. The impact that the experience has on them varies from minimal to life changing. Yuly says even if the students don't wind up studying accelerator physics, the project is a rich learning tool for undergraduates.

"It involves electric and magnetic fields, nuclear physics, quantum mechanics, electronics, computer programming," he explains. "In almost every course that an undergraduate physics major takes, there are some topics that are directly applied to building a cyclotron."

Tim Ponter started working on the Rutgers cyclotron in the spring of 2009 as part of an undergraduate research class. He had no prior exposure to accelerator physics, but found that building a cyclotron incorporated a number of topics that already interested him. He continued work on the machine after finishing the course, and as a direct result of his work earned a summer internship with an accelerator group at the University of Maryland.

"It didn't take long to become obsessed," Ponter wrote in an email. "Where I would be without the cyclotron project I cannot even begin to imagine."

In searching for common threads among cyclotron builders, it's hard not to notice the frequent appearances of Fermi National Accelerator Laboratory. Two of the Fort Wayne high school students went on to work at Fermilab. Niell worked there for eight years. Fermilab employees Ron Walker and Chris Olsen each built cyclotrons while working there (Olsen actually built three). Olsen then assisted Smith, an undergraduate who had been introduced to cyclotrons at a Fermilab public lecture, in building his own machine. After Koeth built his cyclotron, he went on to do his PhD work at Fermilab. Even one of Fermilab's key founders, Robert Wilson, worked in E.O. Lawrence's Rad Lab in Berkeley in the 1930s and helped build a 37-inch cyclotron. Koeth says it is Fermilab's "you-can-do-it attitude" that seems to attract the kinds of people who join the amateur cyclotron club.

A lifelong achievement

Koeth, who set up a website about the cyclotron he built at Rutgers, gets a handful of emails every year from people, mostly students, who say they want to build their own cyclotron. The students usually inform Koeth that they have one semester and a few hundred dollars. He says he tries not to discourage anyone, but the authors of those emails clearly lack perspective on how much time and money are required. The rare exception was the email he received from Baumgartner and Heuer, which Koeth says came off as more tenacious and definitely better researched than the others. Now the two have set up their own website, and receive the same kinds of emails.

Though few people might understand the obsession that brought these people together, their gifts aren't lost on the rest of the world. The last common thread that the meeting attendees share is the way their cyclotrons have changed their lives. Whether getting them into school or a job, or simply reshaping the job they already had, building a cyclotron has a lot to do with where they are today.

"If you build one in high school, it will get you into college. If you build one in college it will get you into grad school, and so on," Koeth says. "It's a distinction that will never leave you."

Top: Building his own cyclotron at Rutgers, which he used as a teaching tool, prompted Tim Koeth to return to grad school in accelerator physics.
Photo courtesy of Tim Koeth

Bottom: From left: Amateur cyclotron builders Heidi Baumgartner, Tim Koeth, Dan Hoffman, and James Krutzler.
Photo courtesy of James Krutzler

Color by physics

An artist's search for a new way to create color could compel science to ask a few new questions of its own.

By Lauren Rugani

Photo: R. Kaltschmidt, Berkeley Lab

Clad in a white lab coat and safety goggles, Kate Nichols looks no different from the other members of Paul Alivisatos' nanotechnology research group at the University of California, Berkeley. But Nichols is no ordinary grad student. She's the lab's artist in residence.

Like her lab mates, she has spent a great deal of time mastering the art of brewing solutions of nanoparticles—particles so small that their widths might span a few dozen to a few hundred atoms. But while the others are concerned with tweaking the physical and chemical properties of nanomaterials for optical communications, light-emitting diodes, or next-generation transistors, Nichols is exploiting their visual characteristics in the name of art.

"I was thrilled that someone wanted to work at the intersection between art and science," says Alivisatos, a pioneer in the relatively new field of nanotechnology and the director of Lawrence Berkeley National Laboratory. "These are two domains of human activity that are inextricably linked, but often are portrayed as being opposites."

Nichols learned about nanotechnology listening to science programming on National Public Radio, which helped break the silence of her days in the studio where she worked full time as a painter. The concepts brought back to mind an idea she had filed away years earlier: structural color, or the color produced through geometry, architecture, and design rather than by the chemical compositions of pigments. A former professor had introduced Nichols to the wing structures of the *Morpho* butterfly, which demonstrate this effect, and she had sought a way to incorporate the phenomenon into her artwork.

One way to achieve structural color is by constructing thin, multilayered surfaces, much like a Flemish oil-painting technique Nichols used quite often. Carefully overlapping up to 20 or 30 layers in a single painting allows light to briefly permeate and dance among the pigments, bestowing an ethereal quality to her depictions of the human body. But even the thinnest layers of oil paint were orders of magnitude too thick to create true structural color.

"Listening to radio programs about nanotechnology got me thinking about structural color again. I realized that there are people out there with access to architecture small enough to

From top to bottom

Morpho, 2009
18 x 7 inches
Silver nanoparticles, silver halide emulsion, gelatin, glass microscope slides.

Hysteresis, 2009
8 inches x 20 feet
Silver nanoparticles, glass pipettes.

Untitled, 2010
3.5 x 5 inches
Silver nanoprisms, glass capillaries, plywood.

create this kind of color." A casual Internet search led her to Alivisatos; Nichols says she's ashamed to admit she did not realize at the time that he was such a distinguished figure. She sent him a brief email explaining her ideas for using nanotechnology to produce structural color, and asked whether he thought they would work.

Alivisatos was so intrigued by the idea that he invited Nichols to work in his lab and find out for herself, making Nichols a pioneer in her own right. "With nanoparticles, there's a sense of discovery, a sense of mystery," she says. "It's novel. No one has worked with them in this way before.

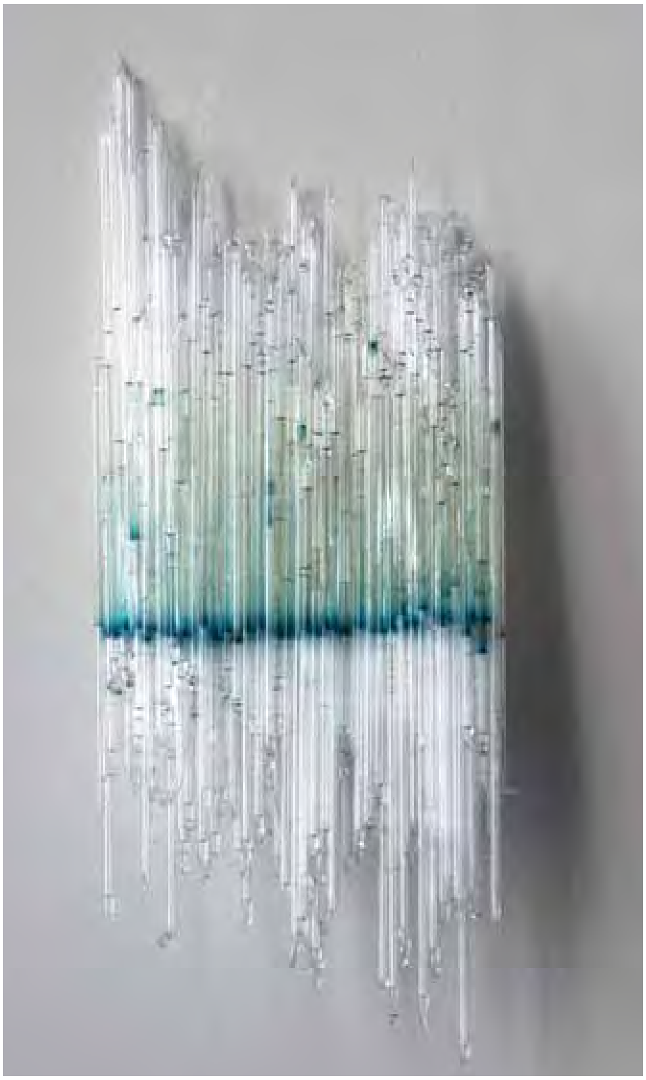
"I did a lot of reading before I joined the lab, but I didn't really know what would prepare me for that experience. I think I focused too much on reading at first," Nichols says. Her biggest breakthroughs came from a tactile, hands-on approach to learning: "It was similar to being a painter's apprentice. It was following around grad students and postdocs and watching what they did, taking notes, repeating things over and over again, making mistakes and learning from them."

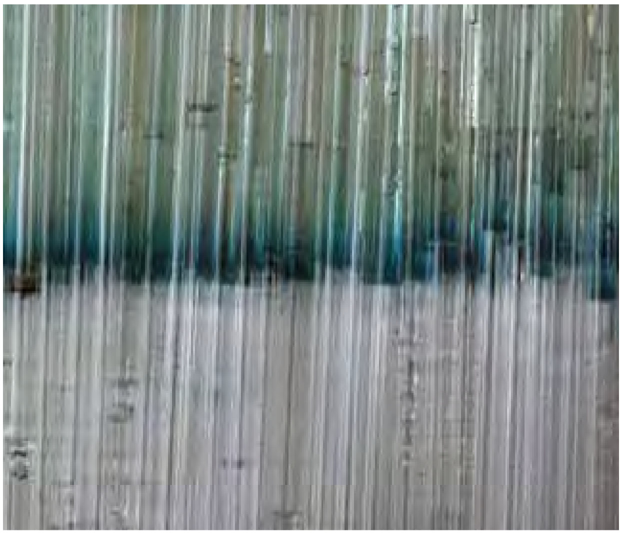
But after a year in the lab, Nichols had little to show for her mistakes; she hadn't created a single piece. What she did have were boxes of nanoparticle-coated microscope slides, vials of muddy-colored solutions, and meticulous notes on what worked and what didn't.

"It was frustrating for me as an artist. I'm used to producing things. But my lab mates told me I had accomplished so much," Nichols says. For someone with almost no science background, she had picked up the chemistry and synthesis techniques quickly, and her lab mates marveled at her genuine curiosity and desire to learn.

Finally, Nichols decided to let the nanoparticles do what they wanted to do naturally. "I had all these nanoparticles in a liquid and started thinking about what liquids are good at, so I played with the fact that liquid finds level," she says. She sucked solutions of nanoparticles into glass capillary tubes and torched the ends, sealing the particles in a vacuum.

At first, triangular silver nanoparticles gave the solution an even, turquoise hue; but molecules





Photos: Kate Nichols

From left to right
Hysteresis: luna, lunar caustic, 2009
17 x 4 inches
Silver nanoparticles inside silver-mirrored glass tubing, wax.

Suspension 3, 2009
8 x 5 inches
Silver nanoprisms, glass capillaries.

Suspension 4, 2010
4.5 x 3 inches
Silver nanoprisms, silver nanospheres, glass capillaries

The first photograph was taken in April, the second in June, and the third is a detail.

in the liquid knocked into the nanoparticles and gradually rounded their corners—much like a river slowly smoothes the edges of a stone. As the nanoparticles transformed from triangles to discs, they turned royal blue and settled to the bottom of the solution.

"After that I don't know," Nichols says. And neither do many scientists, because no one has bothered to keep solutions like these around for very long. Scientists who study these types of nanoparticles generally manufacture them in quantities small enough, and on time scales short enough, to take measurements and images, with little regard for preservation.

Nichols speculates that it's possible the triangular particles could become spheres, which are an energetically favorable shape. Or they could aggregate and become bulk silver, in which case they might look like specks of dust floating in a clear liquid. "Their unpredictability is part of their charm," Nichols says. "These pieces are participating in the science instead of just using the science."

But as a painter, Nichols is also concerned with making her pieces last forever. While the future of the capillary tubes remains to be seen, she has created other pieces out of glass plates that have a better shot at standing the test of time. Nichols coats the plates with silver nanoparticles and then stacks several plates on top of each other, backed by a sheet of mirrored silver. The particles have optical properties that paint pigments don't: While pigments work by reflecting certain wavelengths of light and absorbing others, the silver nanoparticles reflect blue light while transmitting red, orange, and yellow. The transmitted light is in turn reflected back to the viewer, so the dominant color of the piece changes depending on the color of the incoming light, or even on what—or who—is in front of it.

"This opens up a lot of questions about what color really is," Nichols says. "And I think that's really engaging. I hope my work causes more questions than answers."

TRIUMF's new wave of research on medical isotopes

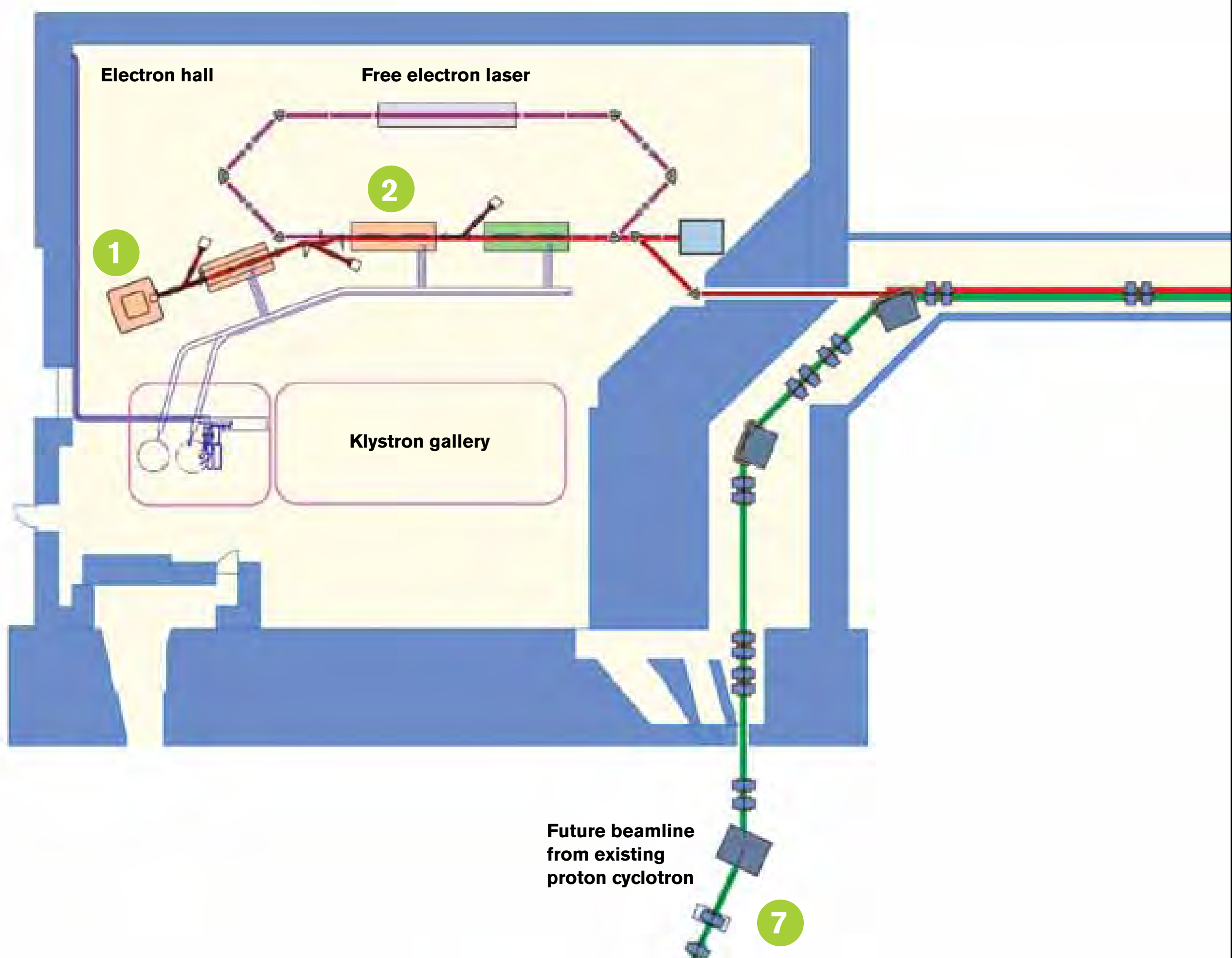
By Daisy Yuhas

Hundreds of thousands of patients around the world depend on medical imaging to reveal injuries, diagnose disease, or learn how a course of treatment such as chemotherapy is affecting their bodies. Physicians use the radioactive isotope technetium-99m in more than 80 percent of medical imaging procedures. But its global supply is in jeopardy.

Scientists at Canada's national laboratory, TRIUMF, are responding to the crisis with a plan to investigate alternative and more efficient ways to produce medical isotopes. The federal and provincial governments are supporting a new C$63-million facility to expand the research and development of isotopes for physics and medicine. The Advanced Rare IsotopE Laboratory, or ARIEL, will triple TRIUMF's current capacity for producing isotopes.

Every chemical element has isotopes that differ only in the number of neutrons in their atomic nuclei. Some isotopes have unstable nuclei that decay over time. When doctors want to study a patient's organs and tissues, they inject, or the patient ingests, short-lived medical isotopes, which then bind to biological molecules in the body. As the isotopes decay, they emit particles that illuminate tissues and blood flow. A scanner detects these particles and produces the desired image.

Most of the isotopes used in medicine are created in nuclear reactors. To get technetium-99m



ARIEL starts with electrons and ends with isotopes. How does it work?

1 First, an electron gun strips electrons from atoms and gives the electrons an initial kick of energy.

2 The electrons proceed to the e-linac, where devices known as superconducting radio-frequency cavities propel them to nearly light speed.

3 Magnets steer the electron beam into an underground target hall, where robotic equipment handles thin slabs of target material.

for medical imaging, for instance, reactors produce the parent isotope molybdenum-99, which decays into technetium-99m.

In the past few years, nuclear reactors in Canada and the Netherlands have unexpectedly had to shut down multiple times for repair. These reactors produce 64 percent of the world's molybdenum-99, and the United States has no facilities that can generate this isotope to make up for the shortage. Though Canada's Nuclear Safety Commission will soon restart the Chalk River reactor, the vast majority of reactors producing medical isotopes are more than 40 years old and more shutdowns can be expected.

At TRIUMF, the world's biggest cyclotron and an array of other particle accelerators have been producing isotopes for more than 30 years. Scientists use those isotopes in both physics and medical research, and send medical isotopes directly to the British Columbia Cancer Agency and University of British Columbia Hospital for use in imaging and treatment.

In addition to developing new technology for producing technetium-99m, ARIEL will research a range of target materials for creating unusual and never-before-studied isotopes for physics and medicine. Then it would be up to industry to turn those isotopes into commercial products.

In the realm of more basic physics, ARIEL physicists aim to understand how unusual nuclei hold together by studying the exotic isotopes they create. Isotopes also provide clues for astrophysicists and cosmologists who want to understand how the elemental byproducts of stars and supernovae became the wide range of elements on our planet today.

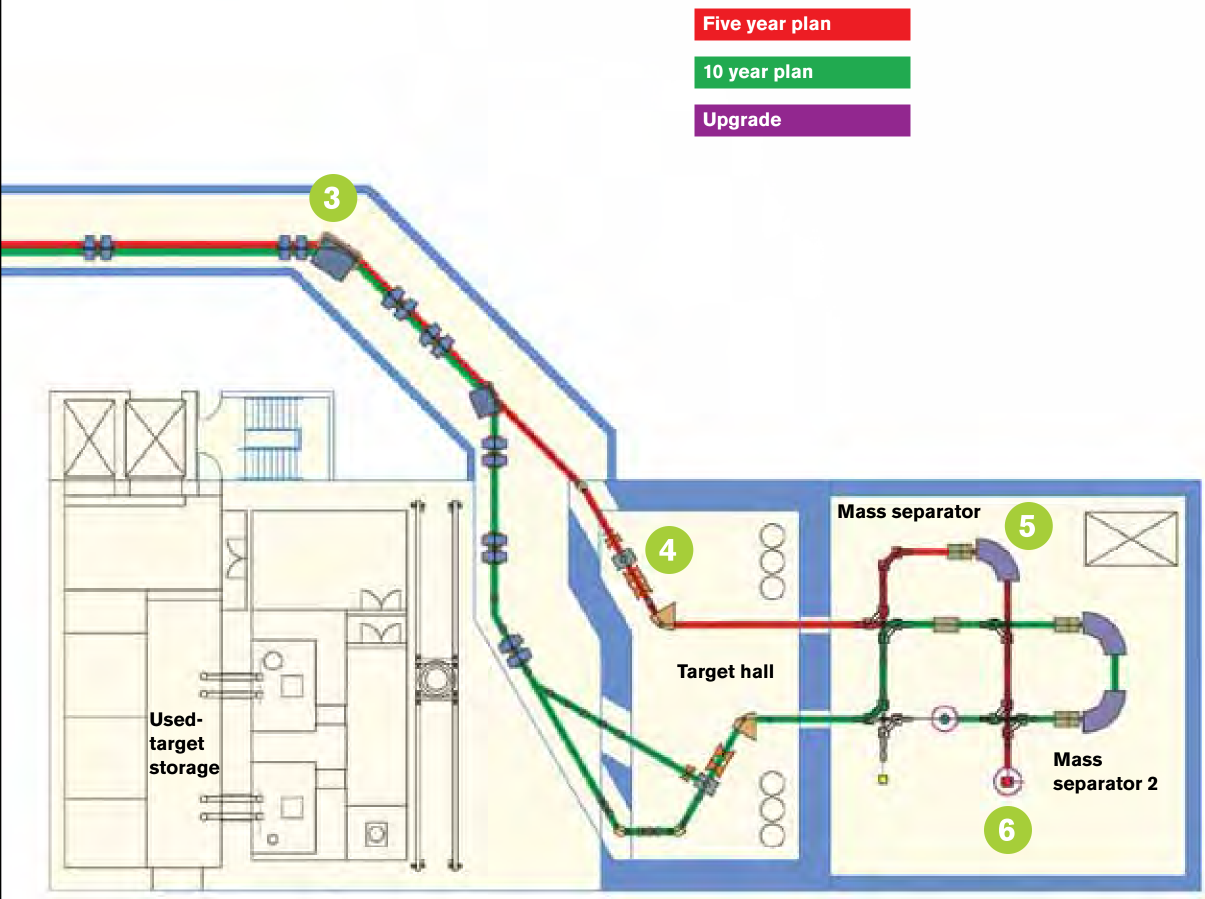


Image courtesy of TRIUMF

4 The beam strikes a target, producing a shower of photons that shatter atomic nuclei in the target material, creating isotopes.

5 The isotopes travel to separator magnets that sort them by charge and mass, according to experimenters' needs.

6 Magnets focus the separated isotopes into particle beams, which travel up one story to the experimental halls.

7 A future beamline will bring protons from TRIUMF's cyclotron, the largest one in the world, into ARIEL to produce isotopes.

High-energy X-rays search containers

More than two billion tons of cargo pass through ports and waterways annually in the United States. Many ports rely on gamma-ray scanners, based on radioactive isotopes such as cobalt-60, to screen cargo for nuclear materials or weapons. But an increasing number are turning to high-energy X-rays generated by particle accelerators to keep ports safe and prevent contraband from entering the country.

X-rays reveal the basic shapes of objects inside a container. The denser the object, the fewer X-rays get through. Scanners that use beams of accelerated electrons to produce the X-rays achieve much higher energies, up to 6 million electronvolts. These high-energy X-rays penetrate deeper and give screeners more information about the nature of the cargo.

Here's how such a system works at a port or border crossing: A truck pulls up to a scanning station that looks like a car wash. The driver gets out of the truck; the scanner moves up and down the container; and a detector on the other side of the truck records the X-rays that have passed through the truck and its cargo, revealing what's inside. Alternatively, a mobile scanning system mounted on a truck can pull right up to cargo that needs to be inspected.

On average, it takes 30 seconds to scan a shipping container. When all 5000 containers on a ship need to be unloaded in a matter of hours, every minute counts. "The flow of commerce is a big concern," says William Reed of Varian, a California-based company that manufactures particle accelerators for national security and medicine. "Ports in the US are very crowded, and the queuing process for scanning is a big logistical issue."

Ports in Africa, Russia, Saudi Arabia, and the United Kingdom have been early adopters of this technology; and as high-energy scanning systems become smaller and more efficient, they are coming to US ports as well.

Meanwhile, scientists at national laboratories, universities, and corporations are exploring other methods for scanning cargo. One system, called "neutron interrogation," is being used to scan trucks entering Idaho National Laboratory. It starts with pulses of neutrons from a particle accelerator.

Neutrons react with the atomic nuclei of materials, which respond by giving off gamma rays. Radioactive materials have their own distinctive gamma-ray signatures. In a neutron scanner, the neutron pulses "interrogate" the container. A detector records the resulting gamma rays, and computer analysis determines if the gamma-ray signatures of materials in the cargo look threatening or benign.

"Neutrons give you a certain level of material specificity that X-rays cannot provide," says Dan Strellis of Rapiscan Laboratories in California, which researches and develops X-ray and neutron-based screening technologies for security applications. "As opposed to looking at shapes and relying on the screener, you can use the physics of the neutron to give you the answer."

Elizabeth Clements

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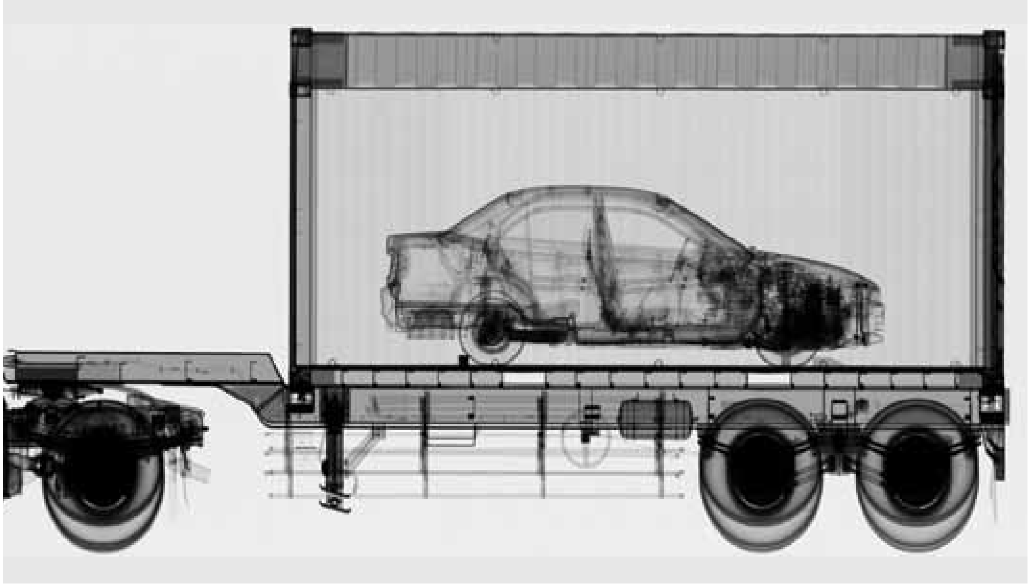
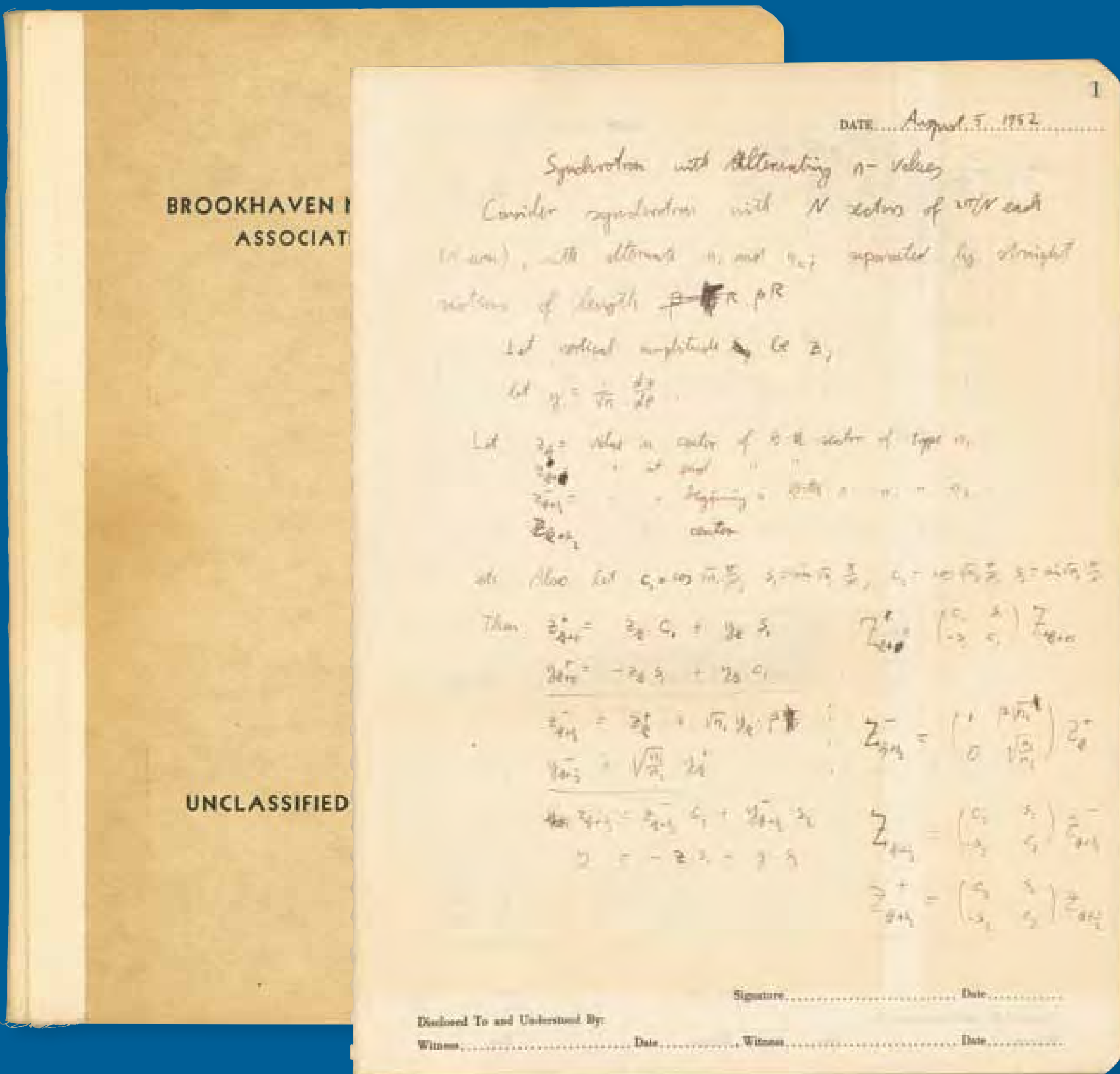


Image courtesy of Varian Medical Systems

logbook: strong focusing



Images courtesy of National Museum of American History, Smithsonian Institution

In the summer of 1952, physicists at Brookhaven National Laboratory's Cosmotron particle accelerator, including Ernest Courant, M. Stanley Livingston, and Hartland Snyder, were preparing for a visit from scientists planning their own, more powerful, accelerator at a new European lab called CERN. Eager to impress their guests, the team began brainstorming ways to improve accelerator design.

Livingston requested some calculations from Courant: What would be the result of physically reversing some of the C-shaped magnets that guided particles around the Cosmotron's circular track in tight beams? The open sides of all the magnets faced outward, allowing each magnet to weakly focus the particles in both the horizontal and vertical directions. But if an individual C's magnetization rose too high, it would focus the beam in one direction while destabilizing it in the other. Would turning some of the magnets to face inward cancel this destabilization?

And so, on August 5, Courant titled the first page of a fresh notebook "Synchrotron with Alternating n-values," and set to work. His calculations demonstrated that flipping some of the magnets would not only focus the beam more strongly, but also allow for more magnetic saturation, and thus, smaller magnets. Without this "strong focusing" effect, multiplying the Cosmotron's power by 10 would have required 100 times more steel for magnets, making them prohibitively expensive.

The Brookhaven team later learned that Nicolas Christofilos, an electrical engineer, had conceived strong focusing in 1949, but his manuscript had not been published because of filing errors. When Christofilos heard about Brookhaven's discovery, he came forward and the lab hired him as work began on a new strong-focusing accelerator, the Alternating Gradient Synchrotron.

Although the AGS design was the first to incorporate strong focusing, CERN's Proton Synchrotron was the first operating accelerator to put Courant's principle to use. Today, as Courant turns 90 and the AGS enters its 50th year of operations, it is strong focusing that puts the current generation of powerful accelerators, like Brookhaven's Relativistic Heavy Ion Collider and CERN's Large Hadron Collider, within practical reach.

Sophie Bushwick, Brookhaven National Laboratory

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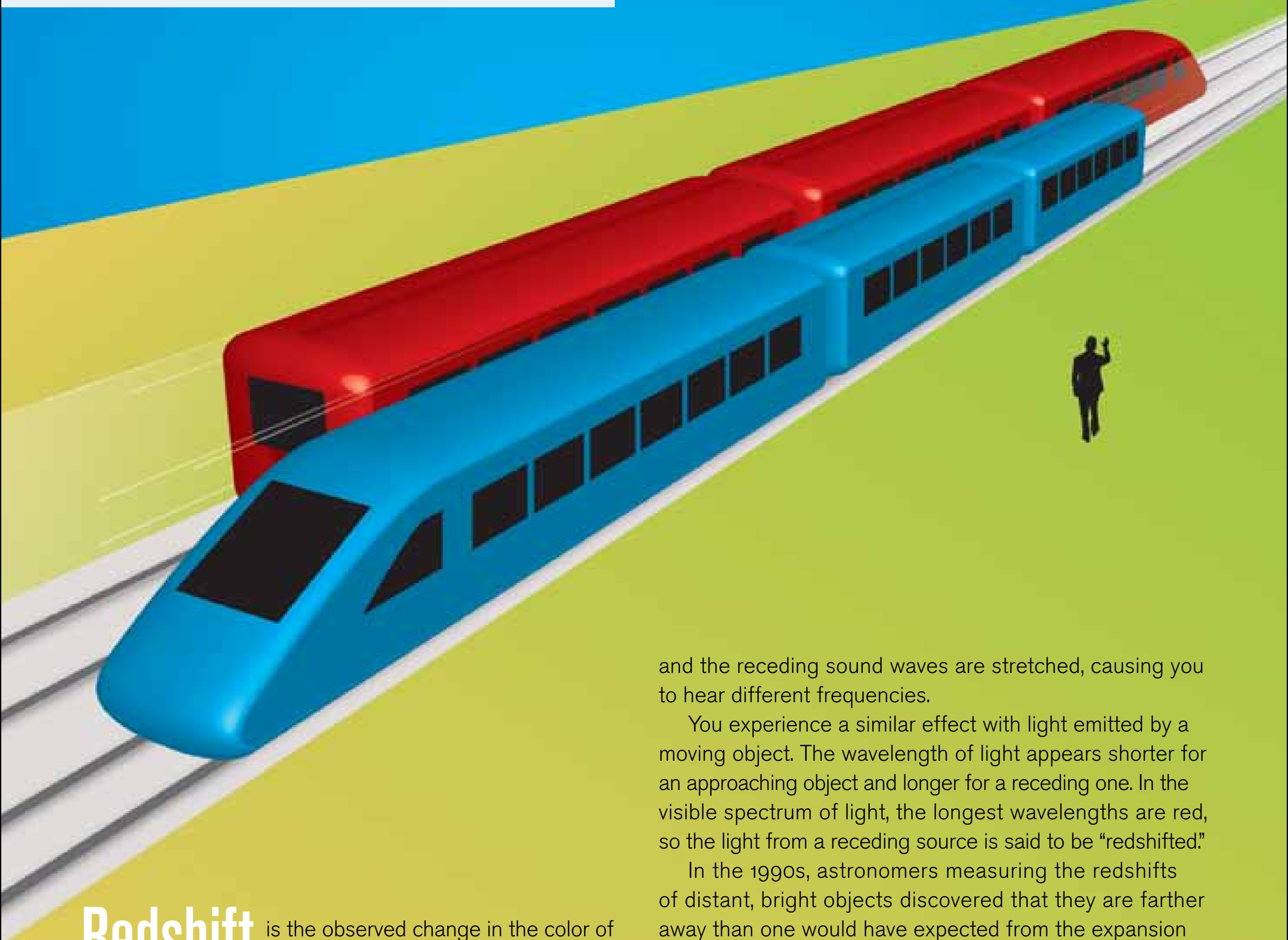

Redshift is the observed change in the color of light emitted by a star or other celestial object that is moving away from Earth.

Light, like sound, travels in waves that are stretched or compressed when the source or the observer is in motion. Imagine a passing train blowing its horn: You hear a high-pitched sound as it approaches and a low-pitched sound as it recedes. The approaching sound waves are compressed and the receding sound waves are stretched, causing you to hear different frequencies.

You experience a similar effect with light emitted by a moving object. The wavelength of light appears shorter for an approaching object and longer for a receding one. In the visible spectrum of light, the longest wavelengths are red, so the light from a receding source is said to be "redshifted."

In the 1990s, astronomers measuring the redshifts of distant, bright objects discovered that they are farther away than one would have expected from the expansion of the universe as influenced by gravity alone. Confirmed by more recent observations, the discovery means that the universe is expanding at an increasing rate. This accelerated expansion is thought to be caused by dark energy, the physical nature of which is one of the most compelling mysteries of modern science.

Joe Bernstein, Argonne National Laboratory