LINAC COHERENT LIGHT SOURCE

40 YEARS

after the Stanford Linear Accelerator Center (now the SLAC National Accelerator Laboratory) developed its two-mile-long linear accelerator (linac), it received approval from the Department of Energy to construct the Linac Coherent Light Source (LCLS), the first free electron laser (FEL) facility that would be able to produce x-rays short and bright enough that individual molecules could be imaged in their natural states.

GENESIS OF THE IDEA

In 1992, Dr. Claudio Pellegrini, a professor at UCLA, first developed a proposal for a facility that would eventually become LCLS. The idea generated interest within the scientific community, and a design study report conducted by SLAC in the late 1990s led to the first funding and collaborative partnerships for the project.

Eight years later, the Department of Energy (DOE) asked SLAC to develop a justification for building the facility that would explain its scientific utility. SLAC held workshops with potential users from around the world and delivered a "First Experiments Report," which focused on the type of research that this light source would be able to perform.

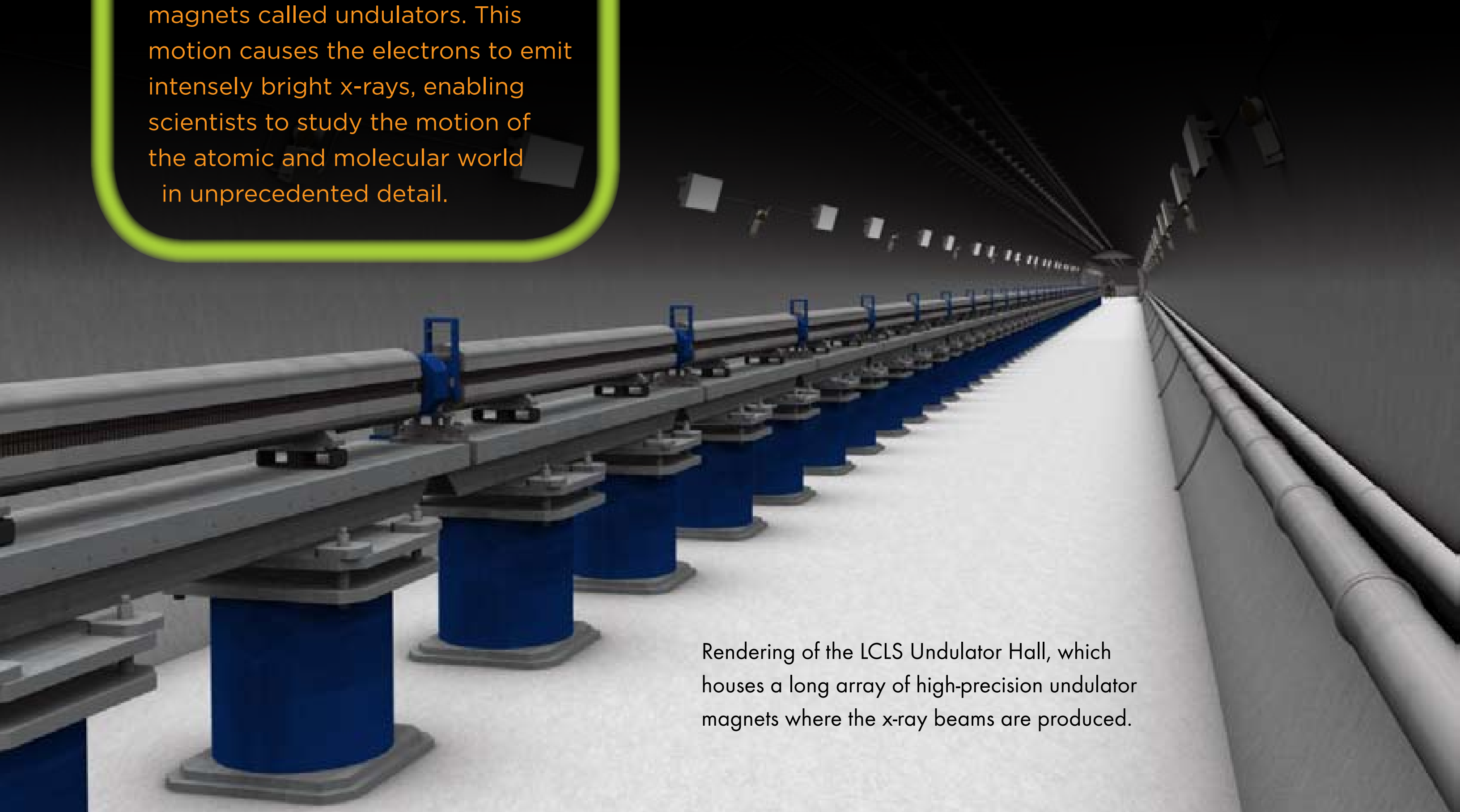
HOW IT WORKS

LCLS takes very short pulses of electrons accelerated by the linac close to the speed of light and injects them into a 100-meter slalom course of alternating magnets called undulators. This motion causes the electrons to emit intensely bright x-rays, enabling scientists to study the motion of the atomic and molecular world in unprecedented detail.

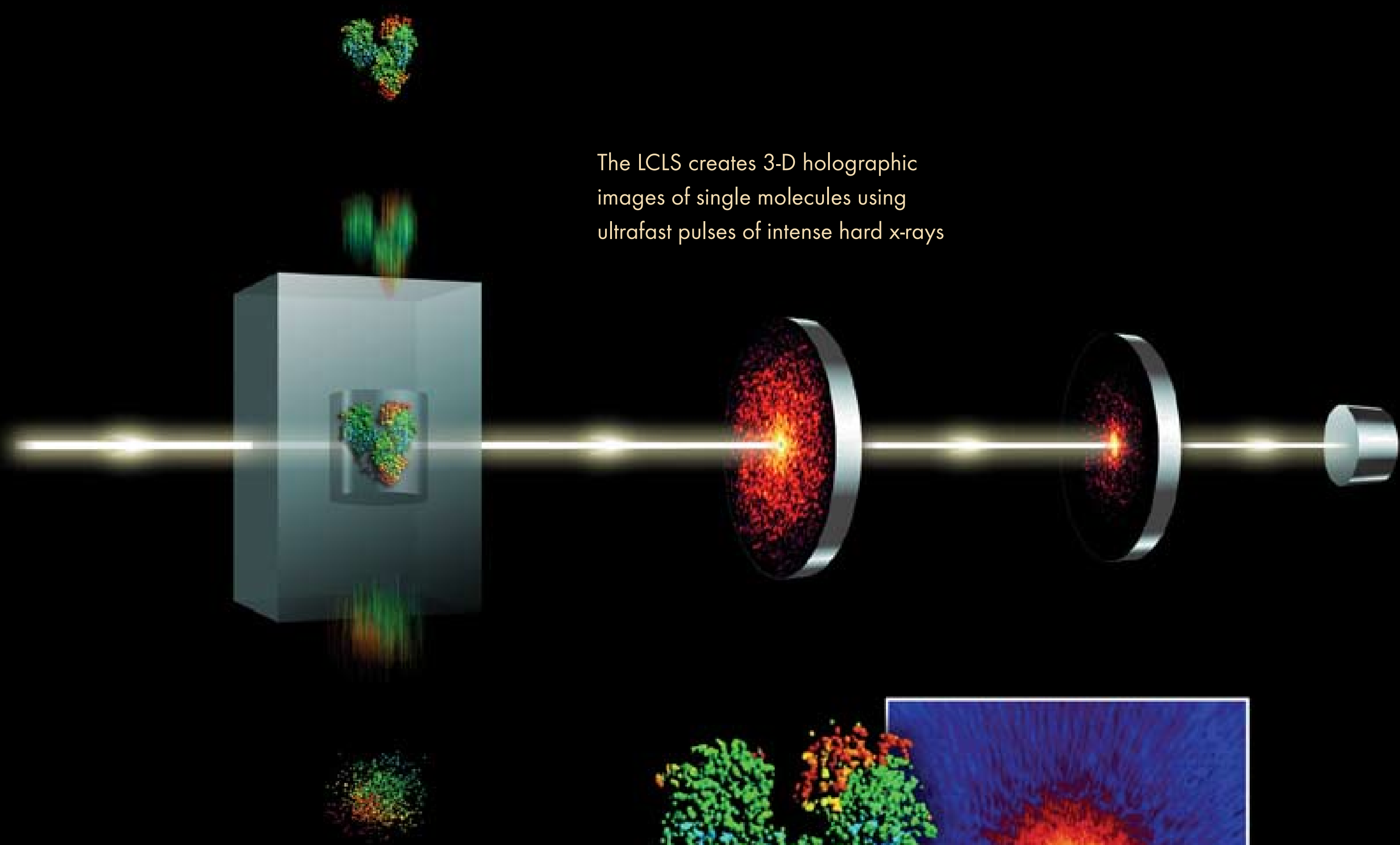
PROJECT INITIATION

In 2001, DOE approved the Critical Decision 0 (CD-0) for LCLS and selected SLAC, the management and operating (M&O) contractor, to construct the facility. The CD-0 document submitted by the Director of the Materials Science and Engineering Division of the Office of Basic Science noted that, "The most significant cost risk is the civil construction," adding, "The San Francisco bay area construction market has been very tight and could well continue so through this project." This would prove to be a more prescient observation than anyone involved with the project could have imagined.

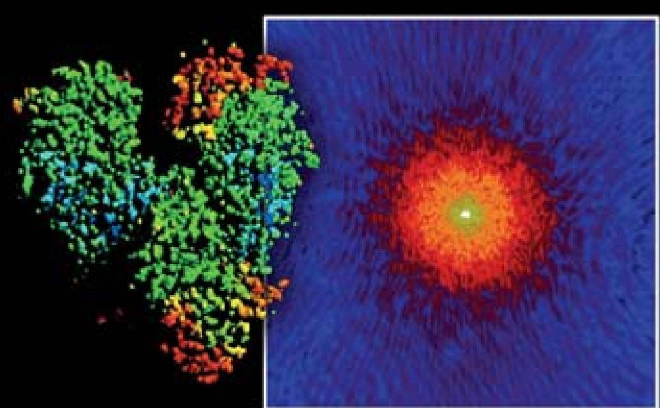
Around that same time, DOE was going through an enterprise-wide process of strengthening its project management practices and requirements. One of the key documents that new projects would now be required to follow was DOE Order 413.3. "We were sort of the first off the boat implementing that order here at SLAC," recalled Hanley Lee, who arrived at SLAC's DOE site office in 1990 and went on to serve as the LCLS Federal Project Director.



Rendering of the LCLS Undulator Hall, which houses a long array of high-precision undulator magnets where the x-ray beams are produced.



The LCLS creates 3-D holographic images of single molecules using ultrafast pulses of intense hard x-rays



INTEGRATING WITH THE EXISTING FACILITY

LCLS would utilize the last one-third of the 2-mile linear accelerator to generate the electrons necessary for the creation of x-rays. Its construction called for roughly a half-mile of new underground tunneling. Integration with the existing system posed a significant challenge because the linac was still being used to operate a high-energy physics facility known as the *B* Factory. Fortunately, the *B* Factory only used the front two-thirds of the accelerator, while the last one-third that LCLS would utilize was essentially not in operation at the time. Even so, great care had to be taken not to disrupt the experimental program underway. The LCLS team also needed a very strong understanding of the facility's infrastructure so that the addition of the new injector would not disrupt the safety system and other key infrastructure systems that ran the length of the accelerator.

"One of the economic attractions to building this thing at SLAC, of course, was the existence of a giant accelerator complex, which would otherwise have to be duplicated even before you began to turn on the free electron laser. That was certainly an incentive to build the LCLS here," said John Galayda, SLAC project director for LCLS. The institutional knowledge base was also important. "A very high level of sophistication had built up in the whole SLAC staff in how you get this thing running, how you keep it aligned, how you do the corrections you need in the undulator, and what strategies you use once you've got this thing going. A lot of that had been tried over the years of operation."

KEY TECHNICAL CHALLENGES: TWO LONG POLES IN THE TENT

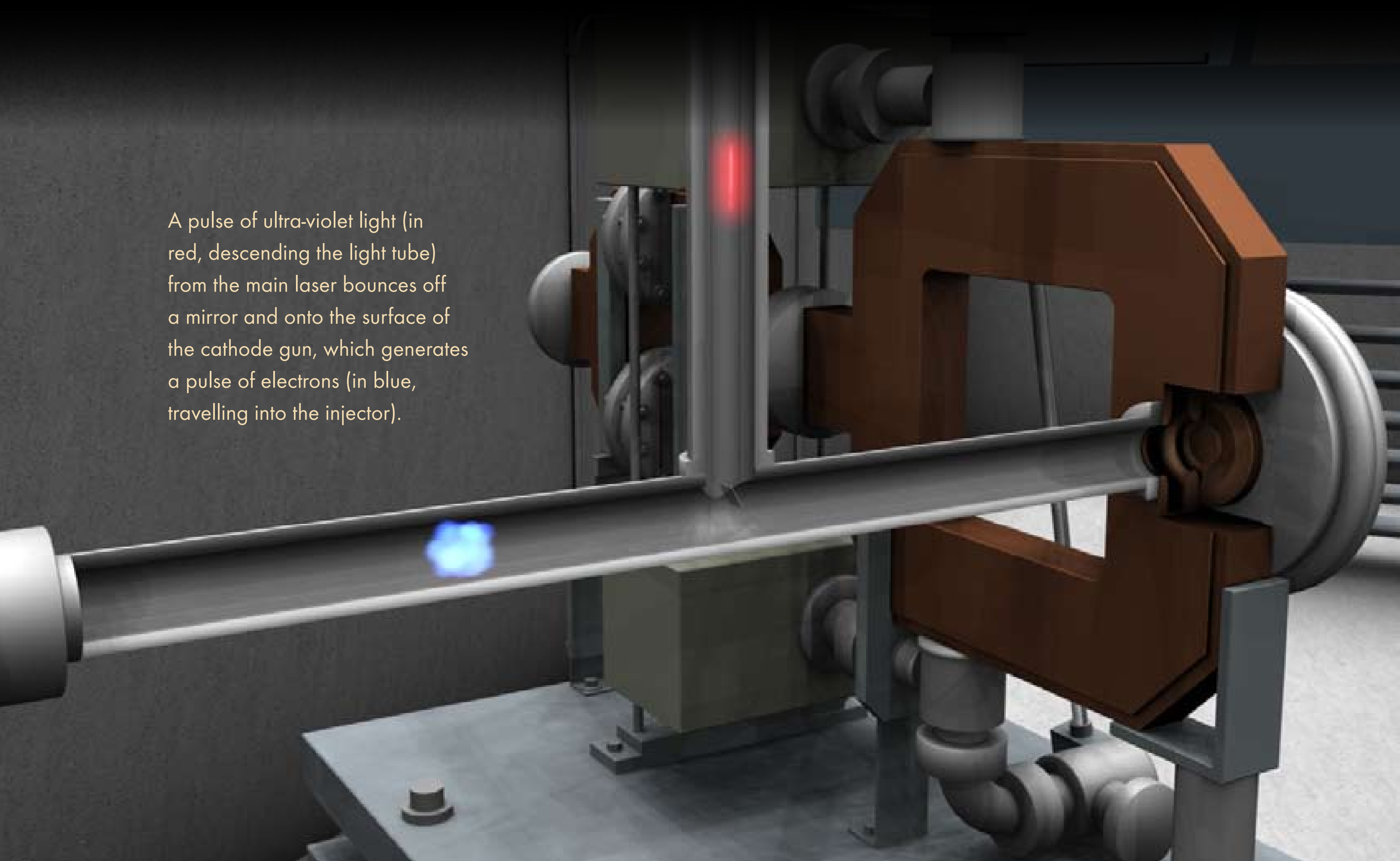
The conceptual design identified two key technical challenges. The first was a state-of-the-art injector (also known as the gun), which would produce electrons in a beam when a laser pulse hit its cathode. Building an injector that could deliver the necessary performance required a significant amount of research and development (R&D) before the procurement process could be initiated. The gun design was inspired by an R&D breakthrough at Los Alamos National Laboratory, one of several laboratories involved in decades of gun design research, during the early phase of the R&D effort.

The team identified the injector as a "long-lead" procurement item; it was not something that could be purchased off the shelf. While the rest of the facility was being built, the injector would be tested and "tuned" so it would provide the electron parameters necessary to deliver x-rays. The quality of the electrons generated by the injector would be critical to the success of the project.

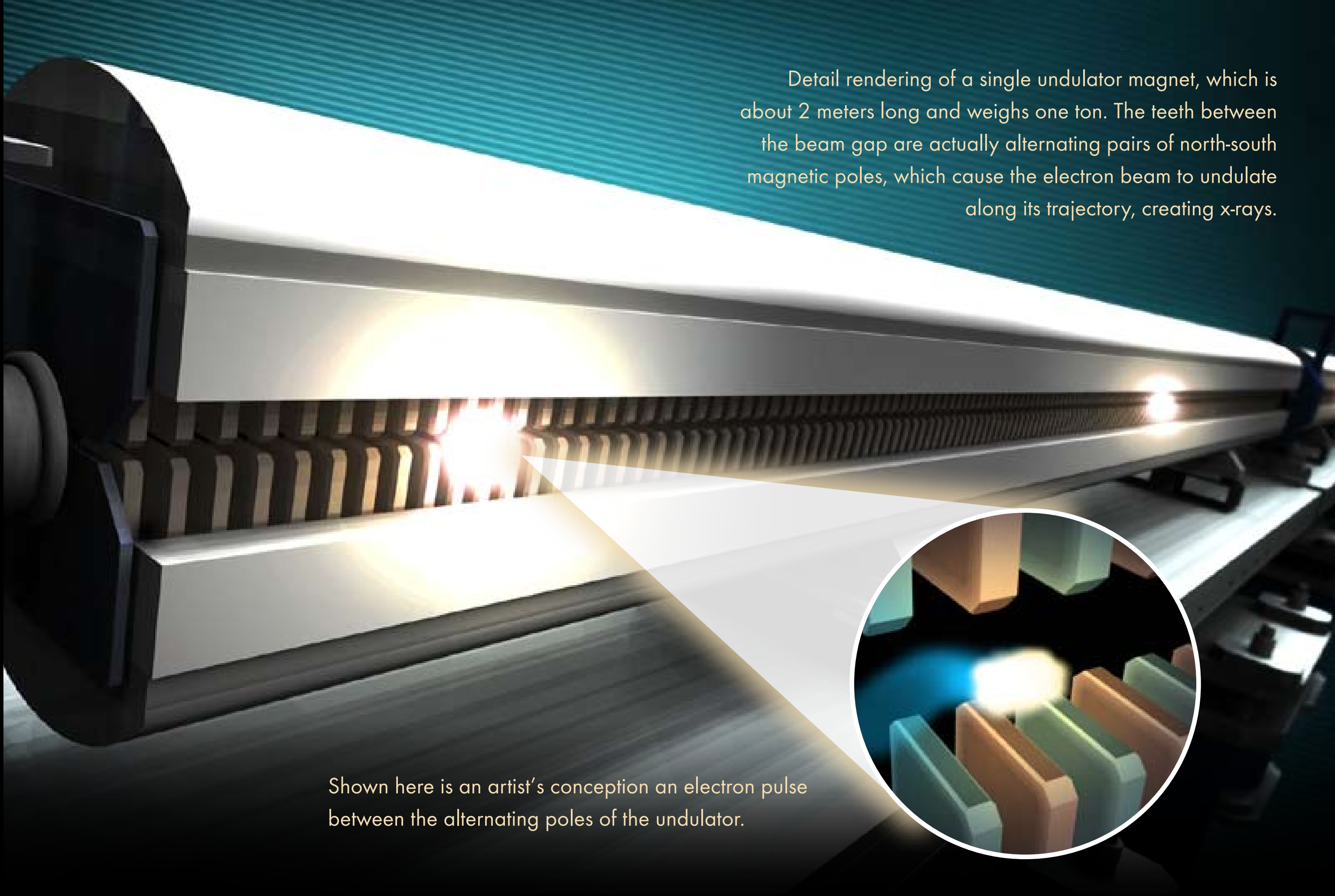
"During the R&D phase, we arrived at a very good design for the source of electrons," said Galayda. "The requirements and the tolerances for the electron beam were very demanding." Research for the injector built on work dated back to the 1980s at a number of facilities around the country, including the Brookhaven National Laboratory, SLAC, UCLA, and Los Alamos. "If the electron beam is in good shape, then all of the other [downstream] tolerances get easier."

A critical insight that emerged during the R&D effort was that the injector would perform better if it delivered a lower charge than originally planned for. "We started realizing that a lower charge might be a better way to run the machine," said Paul Emma, a SLAC physicist responsible for designing the linac portion of LCLS.

"We had been designing the LCLS for high-charge performance," said Galayda. "We had a gun that could do that and achieve the original specs, but work done at UCLA and SLAC



A pulse of ultra-violet light (in red, descending the light tube) from the main laser bounces off a mirror and onto the surface of the cathode gun, which generates a pulse of electrons (in blue, travelling into the injector).



Detail rendering of a single undulator magnet, which is about 2 meters long and weighs one ton. The teeth between the beam gap are actually alternating pairs of north-south magnetic poles, which cause the electron beam to undulate along its trajectory, creating x-rays.

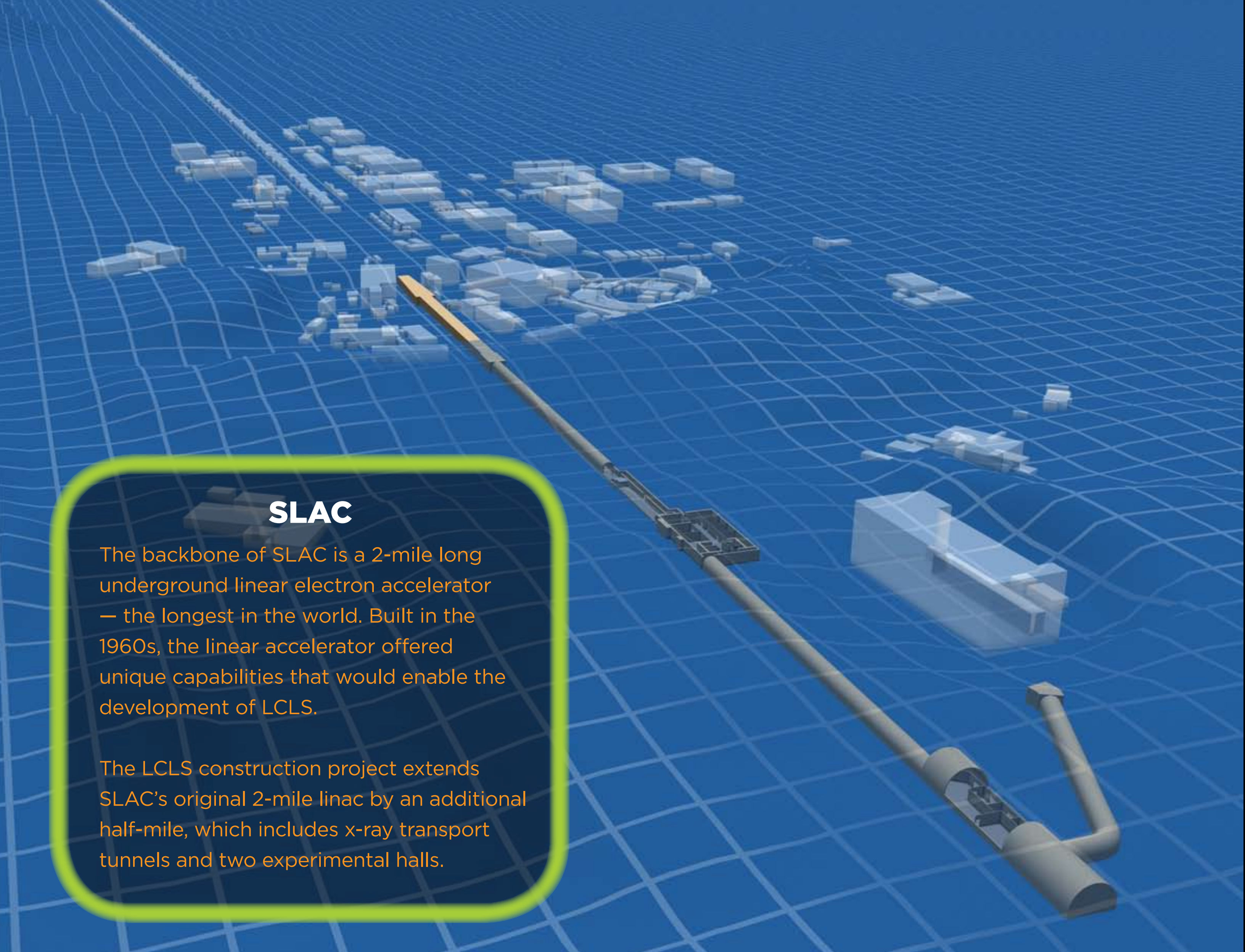
Shown here is an artist's conception an electron pulse between the alternating poles of the undulator.

suggested that if one reduced the charge, the essential characteristics of the electron beam could improve quite significantly." The lower charge would enable the system to function with somewhat relaxed tolerances downstream, and it delivered as many photons as expected from the high-charge design. "It was a pretty significant win," he said.

The other primary technical risk was a 100-meter array of undulators. These consisted of half-inch thick, 2"x 2" square magnets, with alternating north and south poles, arranged in 3.4-meter segments. The magnets would wiggle, or undulate the electrons, which would travel in a sinusoidal path and produce x-rays with enough intensity to perform the experiments that LCLS was designed to carry out. The positioning of the undulators left almost no room for error. "We needed the magnetic field quality to be extremely precise to keep the electron beam going straight," said Galayda. "And we needed the magnets to be identical, we needed the wiggle amplitudes to be perfectly equal, and the alignment tolerances on the electron beam amounted to just a few millionths of a meter."

The undulators covered a longer span than previous systems, and the tight parameters necessary to produce these x-rays had not been attempted before. The project team enlisted Argonne National Laboratory to design and build the undulators because of the laboratory's expertise in this area. The raw materials for the undulator magnets were also identified as long-lead procurement items since an array of this size and complexity had not been built before.

Early identification of the injector and undulator magnets as key challenges and long-lead procurement items ensured that the project team had ample time to learn about each of them. "We had enough experience in using the injector and building the undulator magnets that when we actually got into commissioning the entire facility, it went very smoothly," said Lee. "More smoothly than anyone had expected."



The project team also partnered with Lawrence Livermore National Laboratory (LLNL) for R&D, design, and construction of the x-ray transport, optics, and diagnostics (XTOD) system. LLNL also provided hardware for control of the x-ray beam as well as devices to measure the intensity, spectral content, and size of the beam.

HOT MARKET CONDITIONS

The project team solicited several design and cost estimates, and it brought in tunneling experts who were familiar with the kinds of construction challenges that the project would pose. By the time the LCLS project team was ready to solicit construction bids in 2005-2006, though, the private sector construction market was at an all-time high due to a nationwide real estate boom as well as tremendous demand for construction materials in Asia. To manage the cost risk associated with civil construction, the project team separated the bid packages for the planned office building from those for the linac and experimental halls so that bids for the office building could be solicited later.

Because of the market conditions, the project team got few bids for systems such as HVAC, concrete, plumbing, electrical, and fire protection, and those it did receive were much higher than anticipated. "We experienced a 30-35% increase over what we had estimated," said Lee. "That was an extremely unexpected risk that we encountered. We were totally shocked by the prices that came in."

With its baseline schedule in mind, the project team carefully examined the bids and had the construction manager assess why the bids were so high. "We looked at what we could build versus what we had money for, and we made a conscious decision," said Lee. The tunnels and experimental halls necessary to support the scientific experiments would not be compromised. "We trimmed out as much as we could, and used some contingency (reserve funds) to go ahead and build the experimental facility."

The process took several months, several reviews, and extensive dialogue with the DOE Headquarters program office. "We made sure they understood what we were doing, and would buy off on what we would propose to reduce the scope of the conventional facility so that they would support us when we submitted a baseline change," said Lee. The project team postponed a planned office building for the operational staff, instead using office space in an existing building that was close to the experimental halls. "We were still meeting the mission of the project," said Lee. "We knew we had some operational staff that we had to co-locate. We planned to consolidate the staff in an upgraded existing facility." Eventually, the project team was able to construct a smaller LEED Gold office building because of improved cost performance toward the end of the project.

The project team officially broke ground in October 2006. Construction was completed in less than 3 years.

The LCLS construction site, with views of the near experimental hall (right) and Stanford University's main campus. Hoover Tower and San Francisco Bay are visible in the background.

"What was interesting was that the tunneling [cost] came in within one percent [of the estimate]," said Lee. "That validated our cost estimating methodology. It wasn't the cost estimates—it was just the volatility of the market at the time."

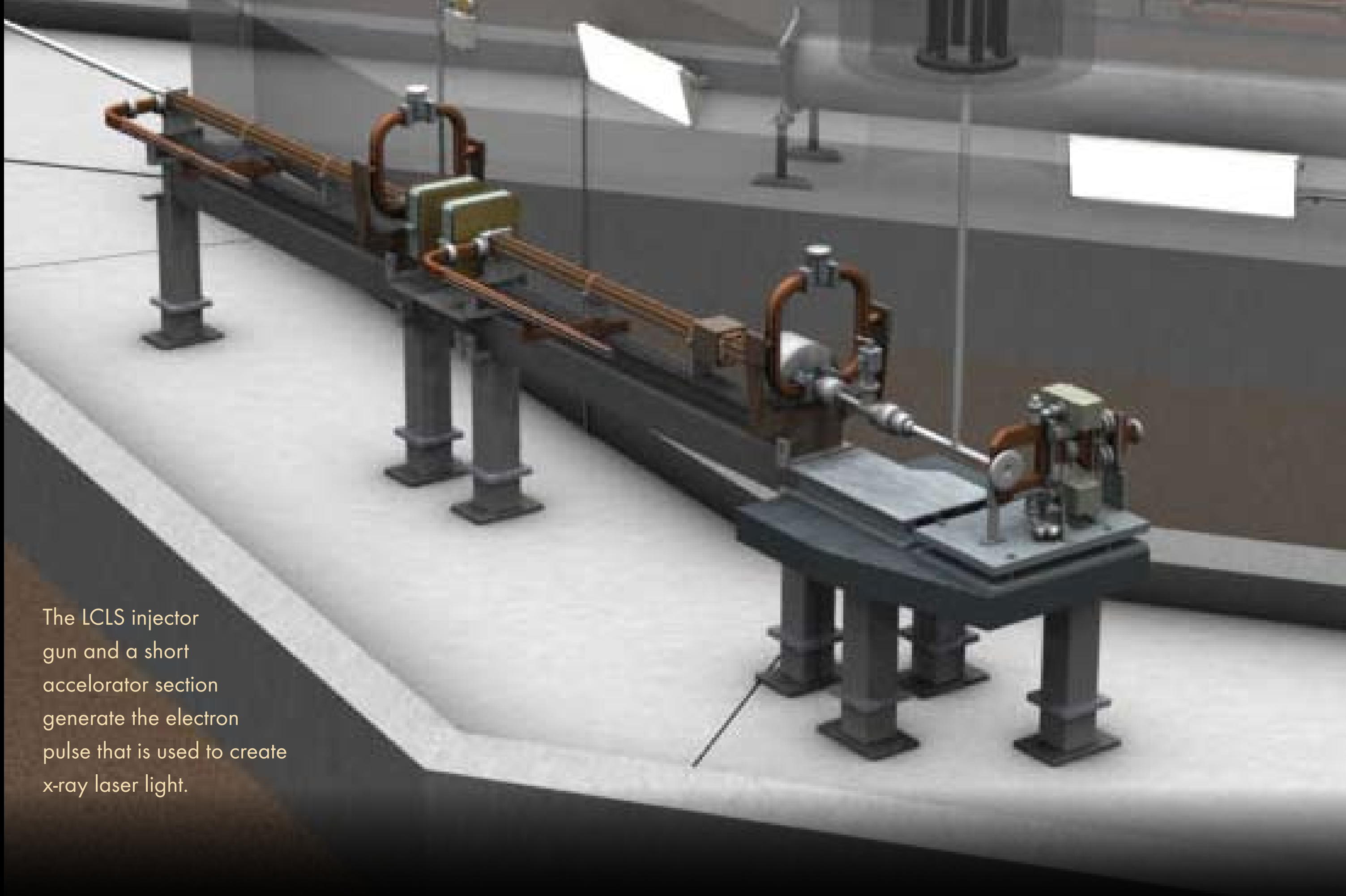
PHASED COMMISSIONING

LCLS employed a phased commissioning process, which meant commissioning subsystems as they became ready. "We conducted phased commissioning throughout the facility so that as one system was completed, we went ahead and commissioned it. This ensured the system was ready when we turned on the downstream systems," said Lee. The commissioning took place over three long phases in 2007, 2008, and 2009 respectively. Between each commissioning phase there was a 3-5 month shutdown, during which other components were installed and inspected.

"From my point of view, it was a matter of risk management. The sooner I found out about problems, the sooner I could do something about them," said Galayda. "Without thorough testing of the subsystems, it becomes nearly impossible to troubleshoot from afar."

Galayda asked Paul Emma to lead the commissioning effort. Emma put together an extensive checkout procedure for each subsystem. "We would do this between the time the construction started and before the first beam went through the machine," Emma said. Each phase consisted of a pre-beam checkout process. "We really knew each component, and could tell that it was performing in a simple way. It was important to make sure we understood the basics before we started relying on the beam to actually behave the way it's supposed to." Once the beam came on, the commissioning continued with a beam-based checkout process. "You can only do so much checkout in a tunnel," he said. "You eventually need the beam to check it more thoroughly."

SLAC engineers measuring and calibrating the LCLS undulator magnets, which were designed and built by LCLS partner Argonne National Laboratory.



The LCLS injector gun and a short accelerator section generate the electron pulse that is used to create x-ray laser light.

Early in the 2007 commissioning phase, Emma's team encountered quality control gaps. "We began finding a lot of problems. Things weren't located where they should be, or switches were not being set up properly," Emma said. The solution was a component-level checkout process. No component could leave the shop unless an engineer, a physicist, and a controls expert signed it out. "That solved quite a lot of the problems," he said. "I was surprised how it really required us to check everything."

After the injector was procured, assembled, and installed, it was first in line for commissioning. "Because that was a self-contained system, we were able to bring in the physicists and the engineers to start playing with that injector while we were constructing and even at times designing some of the downstream systems," Lee said.

After commissioning the injector, which took most of 2007, much of the next year was dedicated to getting a good beam from the injector to the end of the linac. In 2009, once the undulator magnets were installed, an electron beam was injected to see if the undulators would generate x-rays as expected. After the experimental halls were completed, the commissioning process went to the next step by introducing photons to the experimental halls.

"By the time we had the entire facility integrated, the commissioning effort was a lot smoother than we had anticipated," Lee said. The project was able to produce "first light" within a couple work shifts. "Usually bringing a facility like this online can take days, weeks, and possibly months."

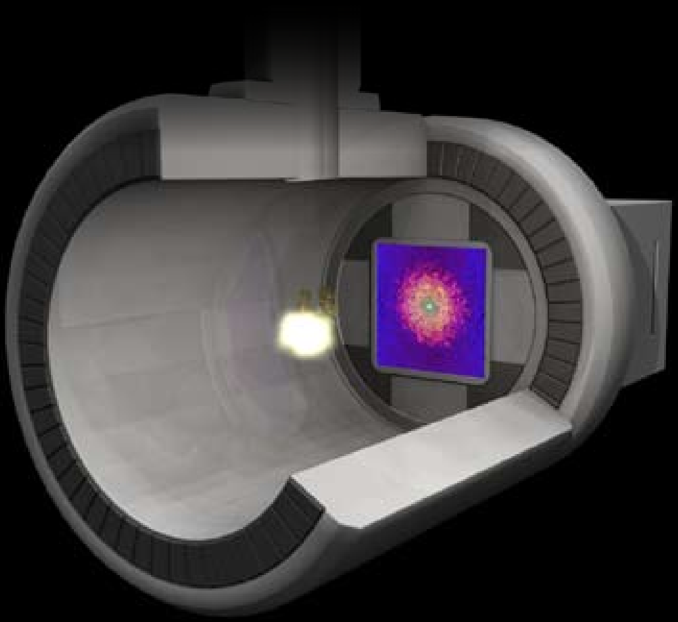
Emma noted that having ample time for commissioning was critical. "We did have a lot of success when we first turned the FEL on. It worked almost immediately, but people forget that we had almost two years of commissioning prior to that to make sure the beam quality from the injector through the linac was all established," said Emma. "Then when we inserted the undulators, and we had success very fast, but it's because we had the time to set up the machine properly. That was two years of work."

Emma also emphasized the importance of having the scientists take a hands-on role in the checkout process. "I became a firm believer that the physicist has to take full responsibility for each component and make sure it meets spec," he said. "The technicians are trying to do their best, the engineers are trying to do their best, but only the physicist knows what it's supposed to do, and he or she better get down there and make sure it's done right."

PROJECT COMPLETION

The project team had a re-baselined total project cost of $420 million, which it was able to reduce to $416 million when it realized it wouldn't use all of its contingency. As of the fall of 2010, Lee expected the final price to come in under $415 million.

The project team received CD-4 approval, which signified project completion, in June 2010. Three instruments were on line as of November 2010, and separate projects to build additional instruments were ongoing. Building on the success of LCLS, an expansion project, LCLS-II, received CD-0 approval in April 2010.



Artist's conception of a device that can take holographic images of single molecules. The x-rays pass through the molecule and leave a distinct pattern of rings and spots on the surface of the detector at the back of the chamber.

LESSON LEARNED: THE IMPORTANCE OF MANAGEMENT SUPPORT

Lee and Galayda both emphasized the role that management support plays in project success.

"You really have to have excellent management in the (M&O) project office," said Lee. "That extends not only to the project office; it also extends to the laboratory. You need managers who will support and do whatever they need to do from the laboratory's perspective to ensure the success of the project." Lee stressed that this was critical when the project team encountered inevitable hiccups during execution. Without the support of the laboratory's management team, he said, "The project wouldn't be able to be successful."

From the M&O project office perspective, John Galayda pointed to the importance of establishing a close working relationship with the Federal Project Director. "It really is very literally a team. [Federal Project Director] Hanley [Lee] understands my role and responsibilities, and lets me do my job, and appeals to me for help when needed. And he is the oversight [for the government]," he said. "Based on the feedback I got from project review process, the situation with LCLS and SLAC was pretty accurately communicated through Hanley and the site office [to DOE Headquarters]." He also pointed to Site Office Manager Paul Golan as an important ally who enabled the project team to complete its civil construction safely and with minimal impact on SLAC operations.

Both also noted the importance of management support in working relationships with partner laboratories. "If there are issues with either delays or performance from the other laboratories, you need the laboratory director to give them a call and say, 'What's going on?'" Lee said. "That's vital on multi-laboratory projects like this."

"We had very dedicated and motivated institutional partners in Argonne and Livermore, and at each lab we also had individuals who were very committed to the project's success," said Galayda.