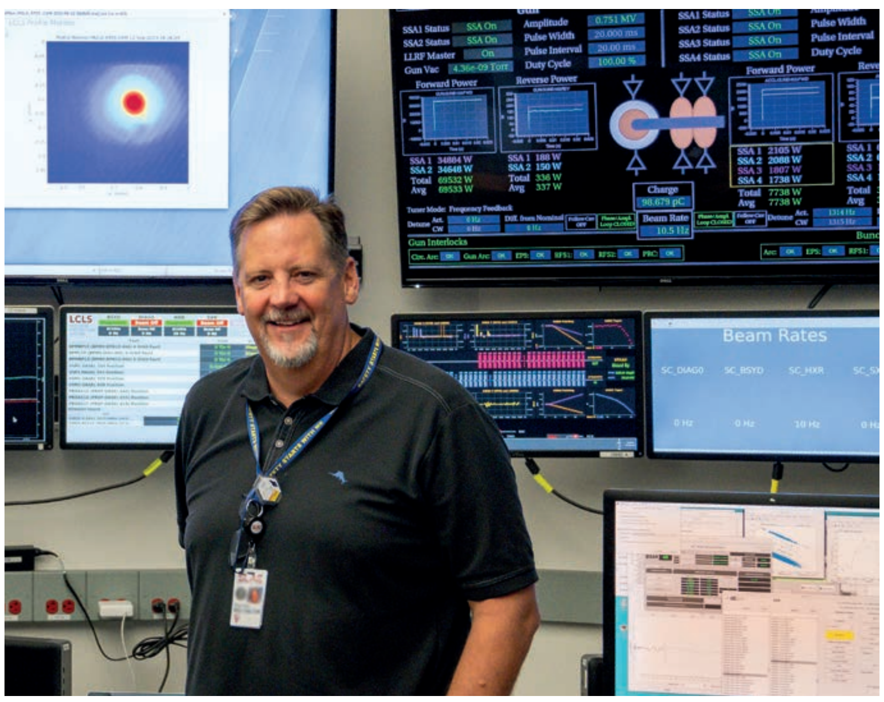
SLAC Fires up the World's Most Powerful X-ray Laser Ushering in a New Era of Science

"LCLS-II is going to drive a revolution across many academic and industrial sectors." ***Mike Dunne***

Scientists from around the world celebrated as the newly upgraded Linac Coherent Light Source (LCLS) X-ray free-electron laser (XFEL) at the Department of Energy's SLAC National Accelerator Laboratory (Menlo Park, California), produced its long-awaited first X-rays on 18th September, 2023.

Researchers have been preparing for years to use LCLS II which, with its ability to produce up to a million X-ray flashes per second - 8,000 times more than its predecessor - is set to transform exploration of atomic-scale, ultrafast phenomena which are key to a broad range of applications, from quantum materials to clean energy technologies and medicine.



Greg Hays LCLS-II Project Director. The spot at the top left is the beam spot of the new X-ray laser. (Credit: Matt Boyes/SLAC National Accelerator Laboratory)

"This achievement marks the culmination of over a decade of work," said Greg Hays, the LCLS-II Project Director. "It shows that all the different elements of LCLS-II are working in harmony to produce X-ray laser light in an entirely new mode of operation."

"This upgrade will keep SLAC and the US at the forefront of X-ray science," added Stephen Streiffer, SLAC's interim Laboratory Director. "It's all thanks to the amazing efforts of all parts of our laboratory in collaboration with the wider project team."

Producing ultra-bright, ultra-short pulses of X-ray light that allow scientists to capture the behaviour of molecules, atoms and electrons, XFELs have been instrumental in many scientific achievements, including the creation of the first 'molecular movie' to study complex chemical processes, watching in real time the way in which plants and algae absorb sunlight to produce all the oxygen we breathe and studying the extreme conditions that drive the evolution of planets and phenomena such as diamond rain.

"The light from SLAC's LCLS-II will illuminate the smallest and fastest phenomena in the universe and lead to big discoveries in disciplines ranging from human health to quantum materials science," said US Secretary of Energy Jennifer M. Granholm. "This upgrade to the most powerful X-ray laser in existence keeps the United States at the forefront of X-ray science, providing a window into how our world works at the atomic level. Congratulations to the incredibly talented engineers and researchers at SLAC who have poured so much into this project over the past several years, all in the pursuit of knowledge."

"The LCLS's history of world-leading science will continue to grow with these upgraded capabilities," said Asmeret Asefaw Berhe, Director of DOE's Office of Science. "I really look forward to the impact of LCLS-II and the user community on national science priorities, ranging from fundamental science research in chemistry, materials, biology and more; application of the science advances for clean energy; and ensuring national security through initiatives like quantum information science."

Folks from the LCLS-II commissioning team gathered in the accelerator control room to celebrate first light through the LCLS-II accelerator. (Matt Boyes/SLAC National Accelerator Laboratory)

Taking X-ray science to new levels

Since the world's first hard XFEL at SLAC emitted x-rays in 2009, the vision for reaching 'first light' on the upgrade began in 2010 and blossomed into a multi-year ($1.1 billion) upgrade project involving thousands of scientists, engineers and technicians across DOE, as well as numerous institutional partners, that enabled achievement of key milestones:

a. Start of construction: 26 March, 2016

b. Accelerator Tunnel Cleared: 21 Nov., 2016

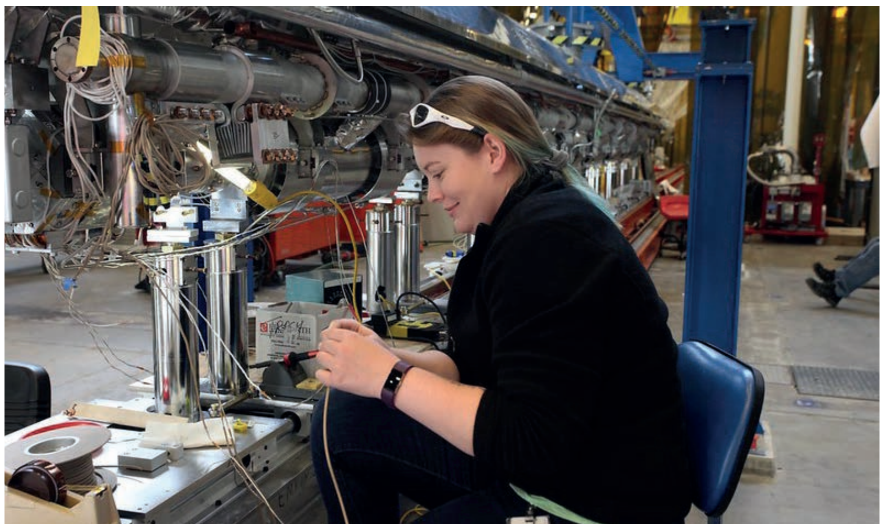
c. Last cryomodule delivered: 23 Oct., 2020

d. First Cool-down of the superconducting accelerator from room temperature to 2K (-456 °F): 5 April, 2022

e. First accelerated electrons in the superconducting linac: 10 Oct., 2022

Asked about some of the major challenges surrounding these developmental stages, Greg Hays told International Labmate: "The project was presented as low risk and shovel-ready because all major technologies had already been demonstrated at other facilities around the world. Indeed, this was true for many of the individual technologies. However, it was also true that minor design changes were required to each of those systems in order to integrate them into the new machine. Therefore, integration became the challenge.

"Another major challenge was the assemblance of five US national laboratories brought together to deliver the new capability. In 2013, SLAC was the world-leading institution in FEL science. However, it had no experience with cryogenics or superconducting RF technology, both of which were key elements of the LCLS-II design. Therefore, SLAC had to partner quickly with four other laboratories to deliver the new machine. Again, integration was the challenge," he said.



Jefferson Lab cryomodule construction and testing. Linked together and chilled to nearly absolute zero, 37 of these cryomodules will accelerate electrons to almost the speed of light. (Credit: Fermi National Accelerator Laboratory)

Partnerships for sophisticated technology

SLAC proudly partnered with experts at four other US national labs – Argonne National Laboratory, Lawrence Berkeley National Laboratory, Fermilab National Accelerator Laboratory and Thomas Jefferson National Accelerator Facility– and Cornell University on planning, design and construction for LCLS-II. Central to LCLS-II's enhanced capabilities is its revolutionary superconducting accelerator, comprising 37 cryogenic modules that are cooled to minus 456 degrees Fahrenheit – colder than outer space – a temperature at which it can boost electrons to high energies with nearly zero energy loss.

Explaining further, Greg Hays said: "Fermilab designed and procured the cryogenic distribution system. They also designed the accelerator cryomodule and assembled half of the accelerator cryomodules. JLab (Thomas Jefferson National Accelerator Facility) assembled the other half of the cryomodules and also designed and procured the two cryoplants.

"The key technology breakthrough was the development and industrialisation of Nitrogen doping in the accelerator cavities. By doping the inner surface of the niobium cavities with nitrogen gas, the superconducting efficiency of the accelerator improved by a factor of 2 over the previous state of the art. The improved efficiency meant 1) the cryogenic heat load would be cut in half, 2) the machine would only require one cryoplant for operation and 3) make available the second cryoplant for a future upgrade."

In addition to a new accelerator, LCLS-II required many other cutting-edge components, including a new electron source, two powerful cryoplants that produce refrigerant for the niobium structures in the cryomodules and two new undulators to generate X-rays from the electron beam, as well as major leaps in laser technology, ultrafast data processing and advanced sensors and detectors.

"ANL (Argonne National Laboratory) designed the hard X-ray undulator and delivered multiple key accelerator components. LBNL (Lawrence Berkeley National Laboratory) designed the soft X-ray undulator and managed the production of both hard and soft. Finally, SLAC, as the host laboratory, acted as the machine architect, delivered the controls system and led the integration and commissioning," Greg Hays added.

Numerous other institutions including vital contributions from researchers across the world have contributed to the realisation of the project, a testimony to its national and international importance and widespread commitment to advancing scientific knowledge.

SLAC's linac at sunrise, looking east. The 2-mile-long particle accelerator has driven a large number of successful research programs in particle physics, accelerator development and X-ray science. (Credit: Olivier Bonin/SLAC National Accelerator Laboratory)

Enabling breakthrough science

The superconducting accelerator fires electrons which travel over a distance of more than two miles during which the 'soft' and 'hard' X-ray undulators produce X-rays with low and high energy, respectively – allowing researchers to tailor their experiments more precisely. These are carried out in experimental hutches where they can capture atomic-scale snapshots of chemical reactions at the attosecond timescale – the scale at which electrons move.

Commenting on the operational readiness of two of the four experimental hutches, LCLS Director Mike Dunne explained further: "The first two areas were tested with the existing LCLS XFEL and so are in an advanced state of readiness. We will spend the first few weeks commissioning with the new LCLS-II X-ray beam and then turn to the first scientific projects. We expect to see the first experiments later this calendar year.

"The first area (called TMO - Time-resolved atomic, Molecular and Optical physics) is focused on the very fastest dynamics in atomic and molecular systems: studying the initiating events of chemistry. LCLS-II will be used to peer into the sub-femtosecond ('attosecond') regime with the ability to watch the electronic motion around individual atoms. This will teach us how energy moves around molecules, which is vital to understand advances in solar energy technologies, ultrafast computing and communications, nanoscience and more.

Mike Dunne LCLS Director. (Credit: Jacqueline Ramseyer Orrell/SLAC National Accelerator Laboratory)

"The second area (called ChemRIXS) is focused on the chemistry of liquid systems, which underpins a wide range of industrial applications based on the role of catalysts that can accelerate chemical reactions. This will open up investigations into the efficient generation of hydrogen and the development of other clean fuels.

"One of the great aspects of DOE 'User Facilities' like LCLS is that scientific access is open to the world and free of charge," Mike Dunne added. "There is an open call every 6 months or so, in which the selection process is via independent peer review (approximately 70 scientists from around the world assess the proposals and rank-order them in terms of scientific merit). Typically we are a factor 4 to 5 over-subscribed, so it's a tough competition! Many experiments are collaborations between multiple groups."

LCLS-II will also provide unprecedented insights into chemical and biological reactions, the flow of energy through complex systems in real time and observation of the internal structure and properties of materials at atomic and molecular scales, predicted to lead to breakthroughs in the design of new materials with unique properties.

"Experiments in each of these areas are set to begin in the coming weeks and months, attracting thousands of researchers from across the nation and around the world," Mike Dunne continued. "LCLS-II is going to drive a revolution across many academic and industrial sectors. I look forward to the onslaught of new ideas – this is the essence of why national labs exist."

Looking to the future

Reflecting on the next stages of development for the LCLS-II and other international XFEL facilities Mike Dunne commented:

"The first generation of XFELs (including LCLS [USA], SACLA [Japan], PAL [Korea], SwissFEL [Switzerland]) use conventional accelerator technologies, delivering X-ray pulses approximately 30 to 120 times per second. More recently, the European XFEL was completed, which can deliver up to 27,000 pulses per second. LCLS-II will be able to deliver up to 1 million pulses per second.

"The next upgrade at SLAC, called LCLS-II-HE ('High Energy') will extend the photon energy reach to much shorter wavelengths, allowing greater atomic precision in the measurements. A similar system is in development in China, called SHINE (in Shanghai).

"The proposed UK XFEL is planning to use the same kind of superconducting technology used in LCLS-II and SHINE and is looking to combine this with other laser sources to create a set of purpose-built instruments to further advance the field. It's worth remembering that we're still teenagers (just 14 years since the first XFEL was demonstrated) and so there's a huge potential for growth and impact in ever more areas."

SLAC is operated by Stanford University for the US Department of Energy's Office of Science. The Office of Science is the single largest supporter of basic research in the physical sciences in the United States and is working to address some of the most pressing challenges of our time.

More information online: ilmt.co/PL/6q5Y