The Linac Coherent Light Source: Concept Development and Design Considerations

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Contents

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Abstract

The Linac Coherent Light Source (LCLS) is the world's first hard X-ray free-electron laser. First proposed in 1992, the LCLS concept immediately attracted the interest of accelerator physicists in the synchrotron light source community. Interest among x-ray researchers grew slowly until about 1996, when scientists at DESY produced a concept for a large x-ray laser research facility (now the European XFEL). The US Department of Energy (DOE) conducted formal assessments of the science potential of accelerator-based x-ray lasers between 1992 and 2001 when DOE officially acknowledged that such a device should be built. The DOE assessments and their conclusions demonstrate how a young researcher can have a preview, over seven years in advance, of important new science facilities and their capabilities. In 2002, SLAC National Accelerator Laboratory prepared a conceptual design of LCLS. By this time, the LCLS concept had grown from a minimum-cost test to a versatile facility supporting the research of thousands of x-ray experimenters. Groundbreaking for construction of LCLS began in 2006, and first lasing at 8 keV was observed in April 2009. This chapter describes some of the most significant physics and engineering problems and solutions: performance of the electron source, such as the potential deleterious effects of coherent synchrotron radiation instabilities, precision control of magnetic fields in the undulators.

Keywords

inac Coherent Light Source · LCLS · Free-electron laser · X-ray free-electron laser · X-ray FEL

Introduction

The purpose of this chapter is to discuss how several aspects of the overall design of the Linac Coherent Light Source (LCLS) have evolved. The chapter offers the author's personal perspective on the most significant problems identified and subsequently solved in the course of design and construction. Sections "Free-Electron Lasers from Linac to Storage Ring and Back and…" and "Creating the Conditions That Led to the Construction of LCLS" identify some early steps toward an 8-keV free-electron laser. Section "Use of the SLAC Linac" describes the start of planning of the LCLS project.

Section "Growing Interest in LCLS" attempts to identify the transition in attitude of the X-ray research community from skepticism to excitement about an X-ray laser. In some sense, the LCLS project became a coherent effort after starting up from noise. Young researchers should give this section and its references some consideration, as an illustration of the difficulty of predicting which new research tools will prove to be important. Initially, the LCLS did not gain widespread support among X-ray experimenters. Part of the reason for this is that, in the X-ray research community, present-day light sources never really become obsolete; there are almost limitless ideas for new and important experiments to do with them. An idea for a new and unproven facility, even one with capabilities as extreme as an X-ray laser, must therefore compete with the proven and still exciting capabilities of existing light sources in order to attract X-ray researchers' attention. If experienced scientists find it difficult to predict the importance of a new research tool, how might a student or young scientist make a choice?

Section "Growing Interest in LCLS" describes how debate among X-ray scientists was evolved to become a decision by the US government to build the LCLS. The US Department of Energy (DOE) took very specific steps toward this decision, starting in 1997 when DOE requested advice from the Basic Energy Sciences Advisory Committee (BESAC). BESAC is made up of accomplished scientists from a variety of fields whose opinions and recommendations often form the basis of actions taken by the DOE Basic Energy Sciences program (BES). The recommendations of BESAC are generally accompanied by detailed reports explaining the purpose and scientific goals for a new facility. Contributors to these reports include researchers active in the area that will be served by a new facility when it is built. BESAC does not decide where and when the facility is to be built or what it will look like; US national laboratories like SLAC National Accelerator Laboratory (SLAC) submit proposals for new research tools that meet DOE's requirements. SLAC began working on a design for LCLS in 1992, well before DOE committed to building an X-ray laser in 2001. DOE officially accepted SLAC's conceptual design and proposal to build LCLS in 2002. Between 2002 and 2005, the LCLS design, cost, and schedule were defined, and the facility produced first light in 2009. For LCLS and other DOE-funded projects, a student following the DOE decision-making process and information on the "projects" website (DOE Projects 2015) can get 4–5-year advance notice of the first operation of a new research facility and perhaps try to be among the first to make use of its unprecedented capabilities. DOE follows a similar process other fields such as high-energy physics (Science website). In the area of free-electron laser research, no great predictive powers are required to see that research with X-ray free-electron lasers will continue to grow explosively in 2016 and beyond.

Section "Construction and Operation" briefly describes the chronology of LCLS construction. Table 1 reports operating capabilities in 2015. Since LCLS is developing new capabilities every year, Table 1 will not be accurate for very long.

Section "Evolution of Design" describes the rapid transformation of the LCLS concept from the cheapest possible demonstration of lasing at 8 keV to the foundation of a forefront research facility with great potential for growth. This makes an interesting contrast with the TESLA XFEL, which was initially conceived in 1995 as a major international research facility; the 1995 TESLA XFEL concept is easily recognizable in the design of the European XFEL today.

Section "Design Questions and Their Resolution" describes some significant design features of LCLS. They were selected for inclusion in this chapter because they were things that LCLS researchers "worried" about during design and construction. The chapter summarizes how these worries were handled in the final facility design.

Table 1 Typical LCLS performance parameters in 2015

LCLS performance		
Self-amplified spontaneous emission (SASE) operation		
Tuning range	280–12,000 eV	280–10,000 eV is routine
Energy per pulse	1–3 mJ	Dependent on pulse length
Pulse duration, hard X-rays	Up to 300 fs	>1.2 keV
Pulse duration, soft X-rays	Up to 500 fs	Up to ∼1.2 keV
Minimum pulse duration	<3 fs	
Self-seeded operation		
Tuning range	5,500–9,500 eV	Diamond monochromator
Tuning range	500–1,000 eV	Grating monochromator
Pulse energy	0.3 mJ	Typical
Pulse bandwidth	0.4–0.1 eV	

This section also lists some unexpected phenomena that required response as the LCLS design was being finished.

Section "Closing Remarks" is a very brief introduction to the first step in expansion of LCLS, the LCLS-II project. The author will cheerfully forgive the reader who skips all intervening sections and investigates the two references in this section.

Free-Electron Lasers from Linac to Storage Ring and Back and…

In the publication that marks the beginning of FEL research, Madey (1971) anticipated free-electron lasers reaching "the ultraviolet and X-ray regions to beyond 10 keV." The first FEL (Deacon et al. 1977) and many others were based on a linear accelerator. Within a few years, the first operation of an FEL in a storage ring was achieved in the 240-MeV ACO ring at Orsay (Billardon et al. 1983). For decades afterward, the advances in accelerator science and technology of storage ring light sources contributed much to progress toward X-ray FELs. Storage ring light sources provided VUV and X-ray radiation for research in materials science, chemistry, and the life sciences. The innovations in accelerator design that produced brighter synchrotron light sources (Chasman et al. 1975) introduced the community of X-ray experimenters to the virtues of high-brightness electron beams and the challenges of designing X-ray optics for handling very high power. The advent of high-brightness storage ring sources marked the beginning of 40 years of progress toward ever-brighter storage ring designs and the ultimate goal of a "diffraction-limited" source.

Undulator magnets, first used with linacs, became an essential feature of storage ring light sources starting in the 1980s. Much effort was devoted to improving the magnetic field quality of these devices; as a result, the very stringent requirements in field quality for an x-ray FEL were nearly within reach when LCLS was first proposed. Storage ring light sources were used for FEL research because they offered the combination of high average current and electron energies of several hundred MeV appropriate for investigating FEL performance at shorter wavelengths.

FELs producing visible and ultraviolet radiation still operate at electron storage rings (Blau et al. 2014). Storage rings can certainly operate at electron beam energies suitable for a hard X-ray FEL; however, extrapolation of storage ring FELs to shorter wavelengths has been thwarted by basic characteristics of typical storage ring light sources. As the energy of the storage ring increases, the emittance and energy spread of the electron beam tend to grow, so that only a small fraction of the stored electrons can contribute to amplification at shorter wavelengths. Work continues on more advanced storage ring designs incorporating FELs which might offer the advantage of narrower bandwidth than a linac-based FEL (Cai et al. 2013; Adams and Kim 2015).

Creating the Conditions That Led to the Construction of LCLS

Three key ingredients were necessary to make a hard X-ray FEL at SLAC feasible: eliminating the need for a resonant cavity to trap X-rays, developing a high-brightness electron source, and gaining access to a high-energy linac. A fourth key ingredient, buy-in from the scientific community, was necessary to justify its construction.

The first ingredient was made possible through the realization that a resonant cavity to trap X-rays was not necessary to achieve lasing (Derbenev et al. 1982; Bonifacio et al. 1984). Amplification of spontaneous X-ray synchrotron radiation could be achieved with an electron beam of sufficiently small emittance, small energy spread, and high current by means of “self-amplified spontaneous emission” (SASE). The SASE concept inspired efforts by many theorists, leading to a quantitatively accurate prediction that SASE could start up from the “shot noise” of Ångstrom-scale current fluctuations in an electron beam with well-defined properties, though these properties had not been demonstrated at that time. By 1995, the theory of SASE free-electron lasers was quite advanced (see Huang and Kim 2007).

Several research groups worked toward the second ingredient, a high-brightness electron source or electron gun having extremely low emittance and energy spread while producing a high-current electron beam. The necessary performance appeared to be attainable, based on new ideas for high-brightness electron guns developed a few years before the LCLS proposal. Researchers at Los Alamos (Fraser et al. 1987) had developed a promising source design, a 1.3-GHz RF gun that could produce very high peak currents. Electrons were liberated from the gun cathode by laser-induced photoemission. Emittance growth from space-charge effects could be effectively controlled if the electron current density could be held constant in all directions so that space-charge repulsion forces could be tamed by a magnetic solenoid lens (Carlsten 1989).

The Los Alamos gun had been developed as a source of electrons for a longer-wavelength FEL. Researchers at Brookhaven National Lab, UCLA, and SLAC (Batchelor et al. 1988; Palmer 1998) adapted key features of the Los Alamos design to a gun that could be used for an X-ray FEL. The gun operated at 2,856 MHz (Palmer 1998), matching the operating frequency used at SLAC and several other linear accelerators in the U.S. and elsewhere in the world. This gun was installed at the Brookhaven National Labs Accelerator Test Facility, which began operation in 1989 to pursue research in high-brightness electron beams, advanced accelerator concepts and free-electron laser physics. This gun was the electron source for several SASE FEL demonstrations and is frequently called "the collaboration gun." It is very close in design to the gun that was used for the LCLS, which will be described in greater detail later in this chapter.

Use of the SLAC Linac

The third and most expensive ingredient was a high-energy electron linac. This ingredient already existed in the form of the SLAC linac, which had been built to do high-energy physics experiments.

The emittance and fractional energy spread of the electron beam from a linear accelerator tend to scale inversely with increasing electron beam energy. These inherent advantages of a linac are offset by a different impediment, the high cost of a linear accelerator, which was viewed as prohibitive. Luckily, the high-energy physics community and the US Atomic Energy Commission were not deterred by the cost of the "two-mile linac" (Neal 1968), which began operating at the Stanford Linear Accelerator Center (now SLAC National Accelerator Laboratory) in 1966. Originally constructed as a 20-GeV accelerator, it was later upgraded to 50 GeV. The linac was originally constructed in three segments that could be operated together as a single linac or as two or three independently controlled linacs.

In his presentation in the closing session of the 1992 Fourth-Generation Light Sources workshop at SLAC, Claudio Pellegrini described using the two-mile linac to create a 1-Å FEL. The accelerator community responded with great enthusiasm to this proposal to convert the third kilometer of the 3-km electron linear accelerator (Pellegrini 1992; Barletta et al. 1992).

The SLAC linac became the highest energy linac in the world when it was first operated in 1966. The full length of the SLAC linac was committed to high-energy physics research until the Stanford Linear Collider program ended in 1998. SLAC's high-energy physics program then shifted focus to construction and operation of the PEP-II B Factory, a pair of storage rings designed to produce B mesons in electron/positron collisions. The B Factory required the first two kilometers of the SLAC linac as a source of electrons and positrons, leaving the third kilometer of the linac less heavily used. SLAC Director Burton Richter ultimately gave his support to Pellegrini's proposal. This segment of the SLAC linac eventually became available for use in the LCLS; Richter's successor, SLAC Director Jonathan Dorfan, stated that the LCLS would operate during at least 75% of the linac's scheduled running time.

Immediately after the 1992 workshop, Herman Winick organized accelerator experts and X-ray researchers at SLAC and UCLA to develop a more complete concept for the LCLS. By August 1992, a description of a 4-nm "water window" FEL at SLAC was presented at the Free-Electron Laser Conference in Kobe, Japan (Pellegrini et al. 1992, 1993). By November 1992, a study group at SLAC had produced a more complete design concept for review by FEL experts from outside SLAC.

The 4-nm "water window" (between the 2.4-nm oxygen K-absorption edge and the 4.4-nm carbon K-absorption edge) was chosen as the target X-ray wavelength because it could enable single-shot imaging of biological samples. Furthermore, this seemed a safe target for the state-of-the-art undulators and high-brightness electron beams at the time.

Growing Interest in LCLS

The fourth and final essential ingredient for a hard X-ray FEL was convincing scientists to recognize the research capabilities of such a facility. This ingredient was not particularly easy to secure; the prospect of an X-ray FEL did not immediately excite synchrotron radiation researchers and laser physicists, especially in the U.S. A workshop held at SLAC in 1994 (Arthur et al. 1994) did not generate a groundswell of interest in this FEL concept; the proposed X-ray beam properties were perhaps too extreme to attract the interest of biology researchers using storage ring light sources. This prompted the researchers developing the LCLS concept to increase the goal for photon energy to 8 keV to attract attention of researchers who used harder x-rays at storage ring light sources. By 1994, scientific potential of an 8 keV X-ray laser was acknowledged, but uncertainties in feasibility had not yet been resolved in the view of the X-ray research community. A National Academies report (Levy et al. 1994), which addressed the scientific potential of FELs across a wide spectral range, was supportive of research leading to a hard X-ray FEL and acknowledged that such an FEL would be an important research tool. However, the report stated explicitly that construction of a hard X-ray FEL user facility should not be undertaken at that time.

Interest in a linac-based X-ray FEL took tangible form more rapidly in Europe. By 1995, researchers at DESY had already put considerable effort into the development of a 12.4-keV SASE FEL integrated into the TESLA Linear Collider. The DESY strategy included construction of the TESLA Test Facility, which would include a free-electron laser (Edwards 1995; Wiik 1997). The TESLA FEL concept generated much interest when presented in 1996 at the 10th Workshop on Fourth-Generation Light Sources sponsored by the International Committee for Future Accelerators (ICFA). The TESLA FEL offered peak brightness more than 10^{10} times greater than that of contemporary storage ring light sources, with average brightness surpassing storage rings by six orders of magnitude (Laclare

1999). The concept presented at the workshop was a huge facility, utilizing a 20-GeV linac supporting ten X-ray undulator sources, each sending X-rays to two or more X-ray experiment stations. The TESLA FEL was clearly the most ambitious synchrotron light facility ever proposed; yet its juxtaposition next to the TESLA collider made it look rather modest in scale! The European XFEL, which will produce first X-rays in 2016, has remained very close to the TESLA concept.

It is the author's personal opinion that the proposed TESLA FEL prompted a change in attitude toward X-ray FELs in the U.S. A 1997 report submitted to the BESAC strongly recommended support of research leading to coherent X-ray light sources (Birgeneau 1997). In a subsequent report (Leone 1999), a BESAC subcommittee explicitly recommended that research necessary to construct the Linac Coherent Light Source be funded. As envisioned in this report and in the subsequent discussion by the BESAC, LCLS "would not be a next-generation user facility but a step toward such a facility" (O'Hara 2000b).

The DOE view of the purpose of the LCLS evolved in the course of the BESAC meetings in 2000 and 2001. The February 2000 BESAC minutes describe the LCLS as "a testbed for the next generation of light sources" (O'Hara 2000a). By February 2001, "The BES vision for the LCLS is that the LCLS is partly an accelerator/free-electron laser (FEL) R&D project, but it must also be a stand-alone scientific user facility. Previously it was viewed as a testbed for the next-generation XFEL machine, but at this point, BES does not know if that is the case" (O'Hara 2001). The committee reviewed the results of an external peer review of a SLAC report submitted to BES in September 2000 (Stohr and Shenoy 2003). The report described six prototypical experiments proposed for LCLS and evaluated their feasibility and significance. The reviews were favorable, and in June 2001, BES authorized the start of a conceptual design for LCLS.

Construction and Operation

SLAC scientists had already made considerable progress toward a conceptual design, published as a SLAC report (Arthur et al. 1998), before receiving the go-ahead from BES. Also in 1998, the SLAC gun test facility (GTF) began operation for the purpose of demonstrating that LCLS requirements could be met by the "BNL-UCLA-SLAC collaboration" gun. The conceptual design was refined and presented for DOE review and approval in April 2002, along with a schedule for completing construction by 2007.

DOE approval of the conceptual design came in September 2002 (Arthur et al. 2002) with an additional message: if LCLS was configured to be merely a test of SASE and a demonstration of the feasibility of doing X-ray experiments with a FEL, DOE would not approve the final design. This was welcome news at SLAC, leading to an extensive revision of the facility layout to permit future expansion. The redesign of LCLS experiment facilities was carried out in the 2004–2005 time frame. In December 2004, DOE approved the start of construction of the injector. In March 2006, the project was permitted to start construction of the entire facility, with first light forecast in 2009. First electrons were accelerated in the gun by April 2007. By March 2008, electrons were transported to the end of the linac. In December 2008, electrons were first transported through the undulator beam path, with no undulators present. Electron beam tests of the undulator transport line were completed between January and March of 2009. Then the undulators and first X-ray diagnostics were installed. During the evening of April 10, 2009, after careful setup of the electron beam trajectory in the undulator line, undulators were placed on the beam path one at a time. Within 90 min, lasing and near saturation of the SASE X-ray output was observed (Emma 2009, 2010).

The initial LCLS project included only one X-ray experimental station, a soft X-ray high-field physics station for research in atomic, molecular, and optical physics. This station first received LCLS X-rays in August 2009. X-rays were transported to the second experiment hall for the first time in April 2010. Four more X-ray experiment stations were ready for use by July 2011, and the sixth station began operation in January 2012. A seventh station is planned to begin operation in 2016 (White et al. 2015).

Since the start of operation, LCLS performance has exceeded its original design goals by considerable margins and has developed a wide range of operating parameters, listed in Table 1.

Evolution of Design

The LCLS design evolved from a minimal X-ray laser testbed to a much larger facility with great capacity for growth and expansion. The evolution of the facility design kept pace with growing interest from the X-ray research community and DOE, described above. This section describes some of the steps in the evolution of the LCLS concept.

Initial LCLS Concept in 1993

A concept for the LCLS was first published in the proceedings of the 1993 Particle Accelerator Conference (Winick et al. 1993; Bane et al. 1993). The design assumed that about 700 m of the SLAC linac would be available for the LCLS, producing a 7-GeV beam. An invariant emittance of $\gamma\epsilon = 3\,\text{mm} \cdot \text{mr}$ was assumed to compute FEL performance. Two bunch compressors (a “dogleg” compressor and a chicane) were envisioned to form a $\sim$3-kA bunch with duration $\sim$160 fs. An undulator with length 50–75 m was to be installed in the final focus test beam enclosure, located in the research yard at SLAC (Tatchyn and Pianetta 1993). Pulse energy was predicted to be $\sim$3 mJ (Fig. 1).

The electron gun envisioned at this time was a $2^1\!/_2$-cell S-band structure accelerating electrons to 10 MeV.

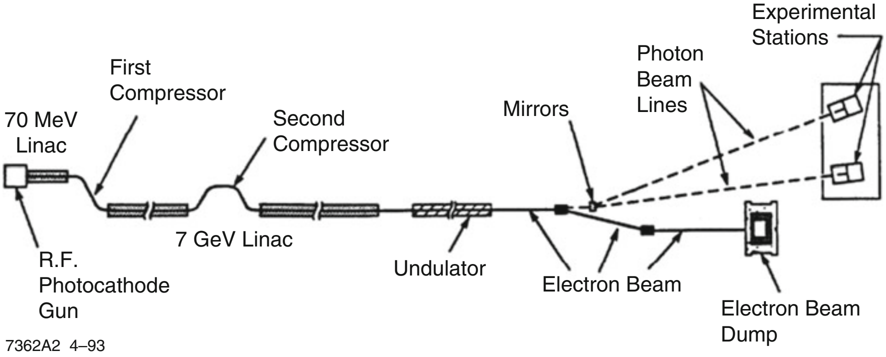

Fig. 1 Schematic diagram of the LCLS accelerator as conceived in 1993 (Winick et al. 1993)

LCLS in 1998

The electron gun to be used at the LCLS was a "1.6-cell" S-band resonator identical to the gun in place at the BNL Accelerator Test Facility. The FEL design was based on this gun, providing a 1-nC pulse with duration 3 ps and normalized emittance $\gamma\epsilon = 1\,\text{mm} \cdot \text{mr}$. The injection accelerator was moved further upstream in the linac, so that the final electron energy would be 15 GeV. The emittance required at the undulator was assumed to be $\gamma\epsilon = 1.5\,\text{mm} \cdot \text{mr}$ (Fig. 2).

Electrons from the gun were accelerated to 150 MeV in an injector linac parallel to the main linac and then brought on the access of the SLAC linac, without compression, using a "dogleg" bend. The SLAC linac was to incorporate a single-chicane bunch compressor at the 280-MeV point and a double-chicane compressor at the 6-GeV point. The double chicane was designed to cancel the effect of coherent synchrotron radiation to avoid dilution of the projected emittance of the electron beam (Bharadwaj et al. 1998) (Fig. 3).

At the time of the design study report (Arthur et al. 1998), a separate building was added directly downstream of the FFTB tunnel, as illustrated in Fig. 4. This was the configuration characterized in the aforementioned 1999 BESAC report as a prototype user facility rather than the "advanced X-ray source" (AXS) that would be comparable to the TESLA XFEL facility.

Enlarging LCLS in 2002

The LCLS conceptual design report, submitted to DOE in April 2002 as required for approval of the start of detailed engineering design, described a significant enlargement of the facility (Arthur et al. 2002) (Fig. 6).

The electron gun and first S-band accelerating sections were no longer to be located within the linac tunnel. Instead, an off-axis injector vault, which had been

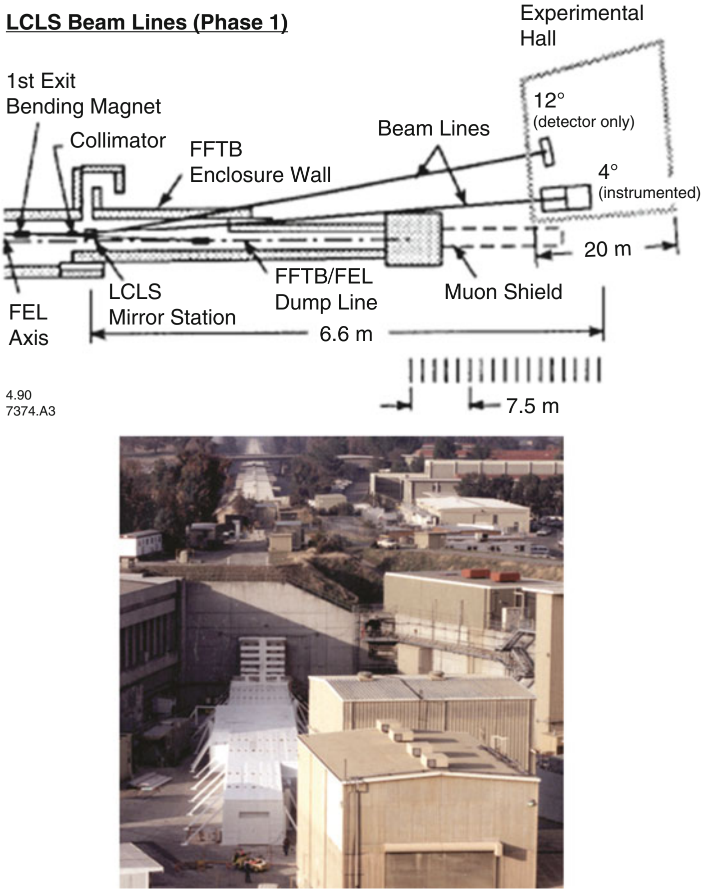

Fig. 2 The X-ray beam path for LCLS, as envisioned in 1993 (Tatchyn and Pianetta 1993). The *top* schematic shows the path of the X-ray beam as it is deflected out of the final focus test beam (FFTB) enclosure. The photograph on the *bottom* shows the FFTB enclosure (*white* concrete block structure with diagonal braces) and utility buildings which might have housed experiment stations to the *bottom*. At the top of the photograph, the SLAC linac klystron gallery is visible, receding into the distance

unused since the construction of the SLAC linac, would house the LCLS injector linac. The vault was not quite long enough, so the injector linac was oriented at an angle to the vault walls to make the best use of existing space. A much larger experiment hall was planned for the research yard, downstream of the FFTB. In addition, a second experiment hall was located further downstream. The laser for the gun was to be installed in an existing building located just above the vault. The basic design features of the LCLS injector and linac are still quite accurately described by the conceptual design report (Fig. 5).

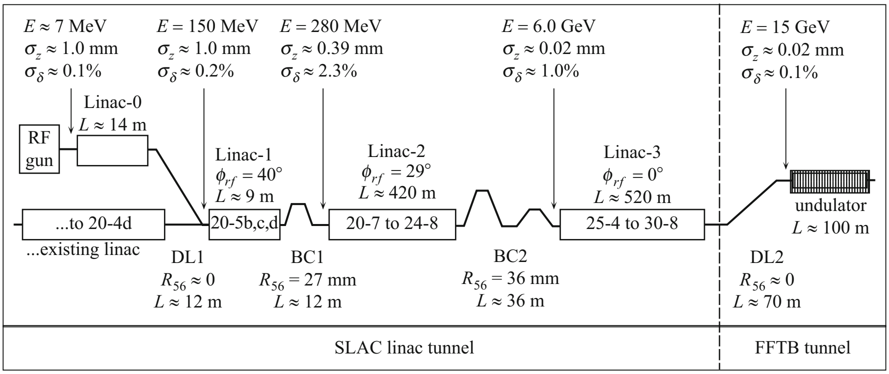

Fig. 3 LCLS linac schematic in 1998. Note the “dogleg” bends connecting the RF gun and “linac-0” to the main linac. The double bunch compressor BC2 was designed to bring about cancelation of coherent synchrotron radiation forces (Bharadwaj et al. 1998)

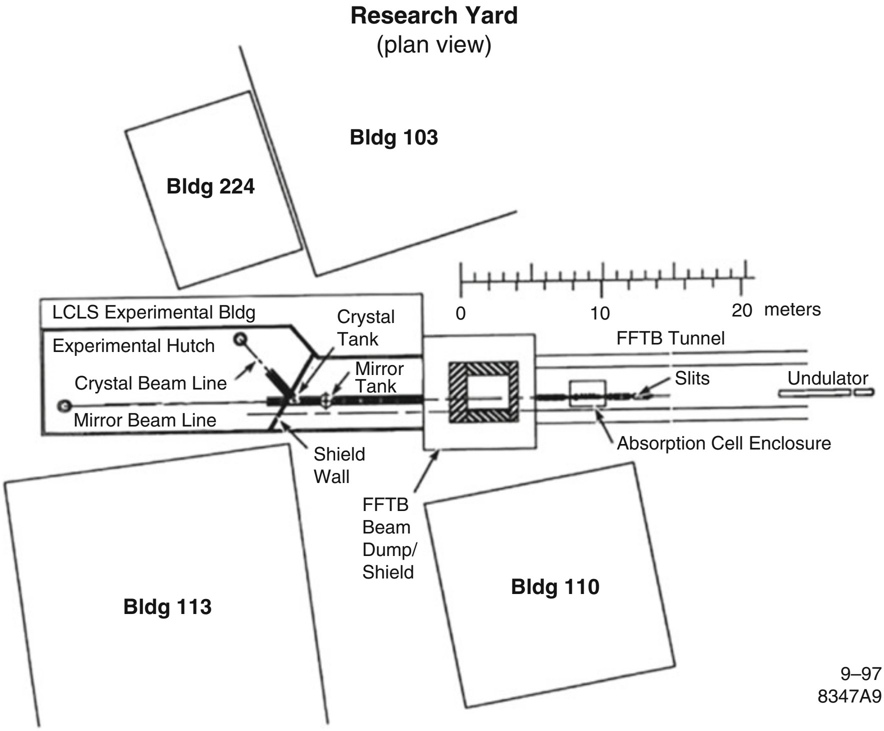

Fig. 4 Experiment hall as envisioned in 1998 (Arthur et al. 1998). A new 10 × 26 m building is shown, positioned directly downstream of the FFTB enclosure. Buildings 113 and 110, shown in this figure, appear to the *right* of the FFTB in Fig. 2

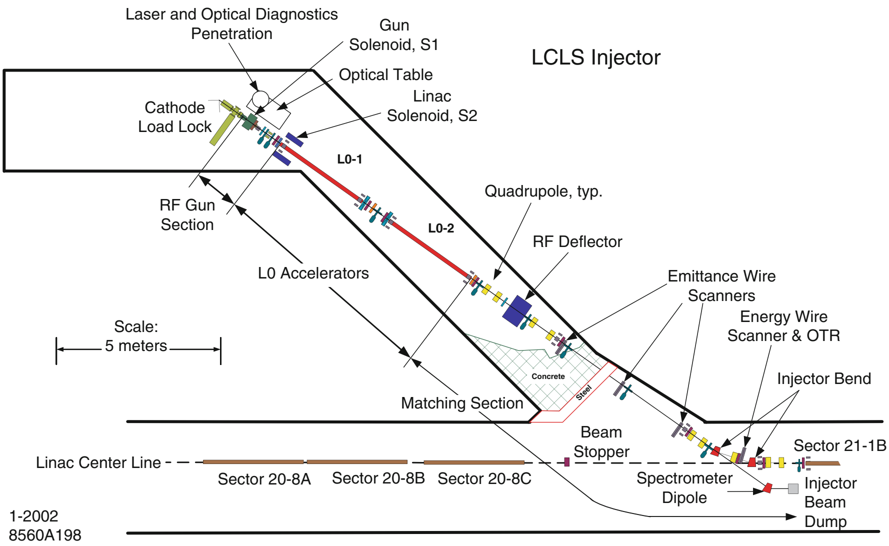

Fig. 5 The LCLS injector, located in the off-axis vault located 1 km from the high-energy end of the SLAC linac (Arthur et al. 2002)

The undulator was to be installed in the final focus test beam (FFTB) enclosure. A much larger experiment hall (30 × 55 m) was envisioned just downstream of the FFTB and 40 m from the end of the undulator. A second, two-story experiment hall was proposed, to be located 322 m from the end of the undulator. The first floor, partially below ground, would house experiment stations. The second floor would provide office and workspace for staff and experimenters. This building was to be 35 × 57 m. These halls were intended to house six experiment stations configured to house the six science programs proposed in the "First Experiments" document (Stohr and Shenoy 2003) (Fig. 7).

Final Facility Design, 2006

The facility design was finalized in 2006. The undulator and experiment halls were moved further away from the linac to make room for gently bending transport lines to additional X-ray sources to be built at some later date. The new layout replaced the FFTB enclosure with a new larger beam transport hall (BTH), a poured concrete enclosure with 1.8-m-thick walls and a 1.2-m-thick roof. It presently houses a single-electron transport line connecting the linac to the undulator. The BTH was designed to enable the installation of at least five more transport lines to new undulators in the future (Fig. 8).

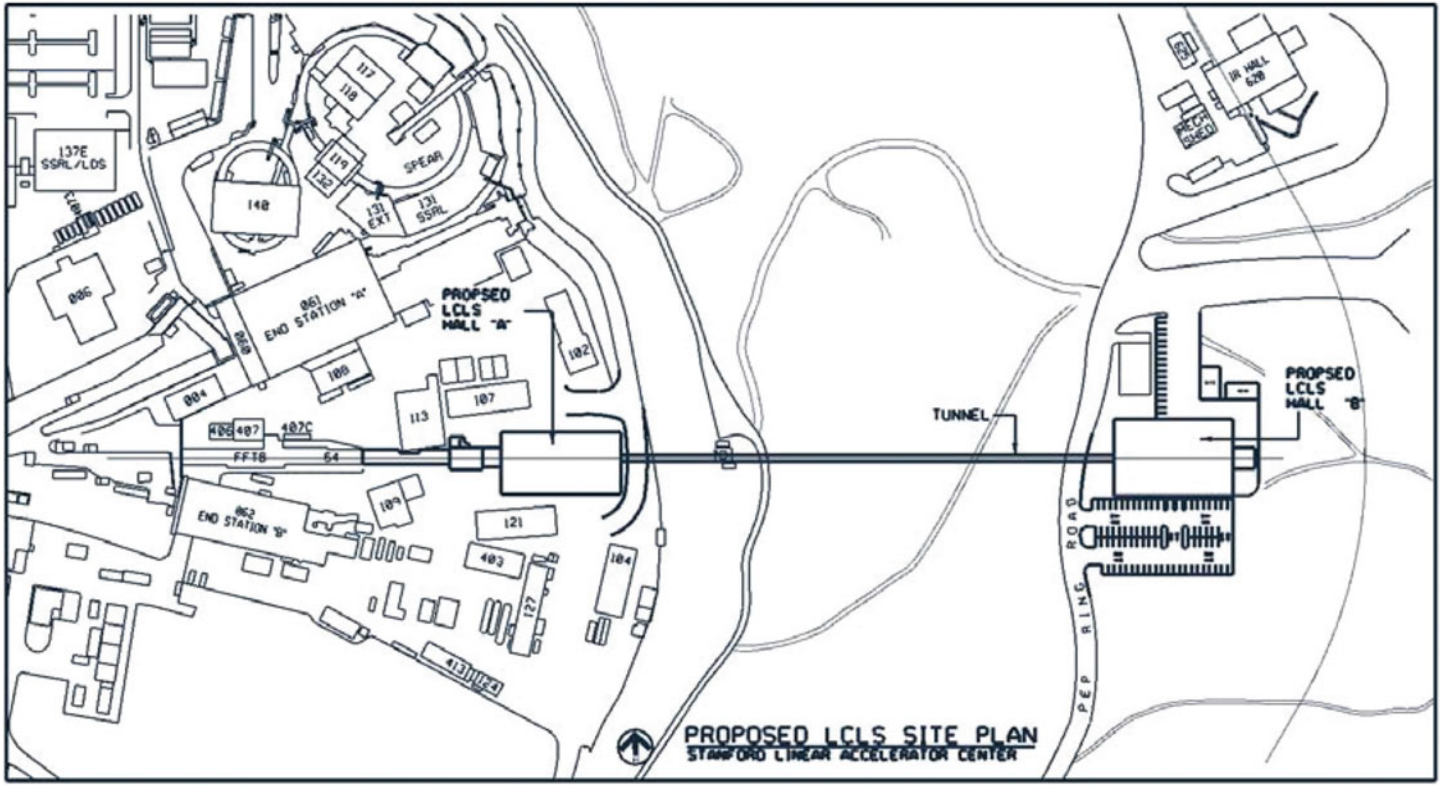

Fig. 6 The experiment halls for LCLS, as envisioned in 2002 (Arthur et al. 2002). "Hall A" is placed immediately downstream of the final focus test beam enclosure, which is shown more clearly in Fig. 2. "Hall B" is shown at the end of a 227-m tunnel, through which the LCLS X-ray beam would drift, bypassing the experiment stations in Hall A

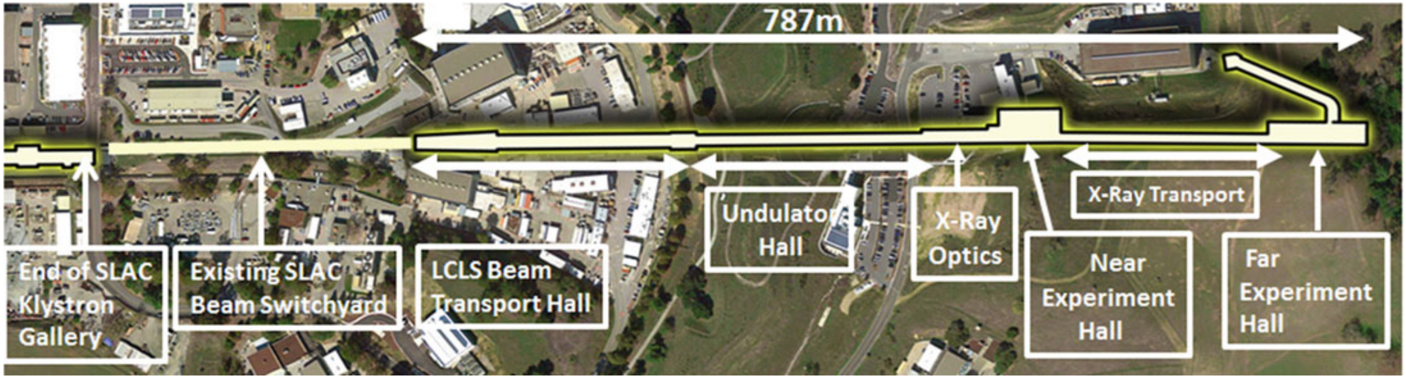

Fig. 7 Linac coherent light source, as constructed 2006–2009 (SLAC archives)

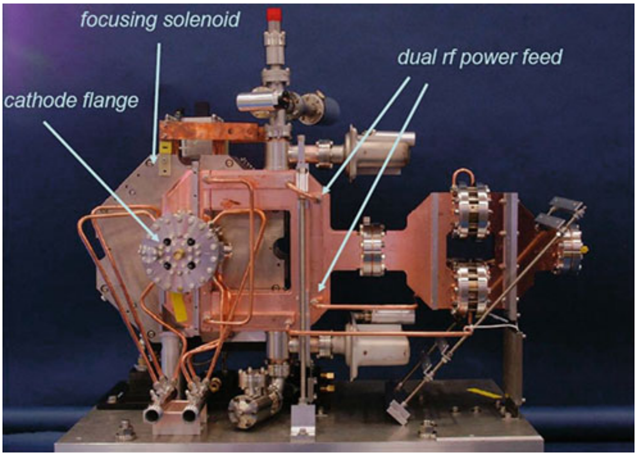

Fig. 8 The LCLS electron gun (SLAC archives). The dual power feeds are fed from a single port, visible in the center of the photograph. To the right of this port is a bolted waveguide extension with two ceramic windows to isolate the gun vacuum from the input waveguide. Two ceramic windows were used due to concern over the high input power for the gun. Operational experience has demonstrated that one window is adequate

Design Questions and Their Resolution

Much progress had been made toward final design of the accelerator by 2001; however, a number of issues needed to be addressed before the design was finalized.

The laser for the photocathode in the gun had performance requirements beyond the commercial state of the art. LCLS required a 120-Hz laser with wavelength 255 nm, providing at least 200 μJ in a 10-ps temporally "square" pulse. The UV pulse was required to have uniform intensity across the transverse dimensions of the pulse. The pulse energy and pulse shape were conflicting requirements, since considerable pulse energy was lost as a result of the UV optics and final collimation required to provide the desired profile.

The electron gun, based on the "BNL-UCLA-SLAC" collaboration gun, had already demonstrated good performance under conditions close to those required by LCLS. However, the LCLS design could tolerate very little degradation of "normalized" emittance anywhere between the gun and the entrance to the undulator system. The LCLS x-ray output would fall precipitously if the normalized electron beam emittance grew larger than 1.5 μm. The challenge was made more difficult by the design goal of producing pulses with 1-nC charge, compressed to 3,400 amperes, at the target repetition rate of 120 Hz.

The "one-pass" effect of coherent synchrotron radiation (CSR) on an electron bunch (Emma and Brinkmann 1997) was considered early in the LCLS design.

Electron transport from the linac to the undulator was designed to bring about partial cancelation of CSR kicks in successive bend magnets in order to minimize emittance growth from this mechanism (Emma 2001). CSR effects were discovered to be a much more serious threat to LCLS in 2001, as a result of the discovery of the CSR microwave instability. This phenomenon is a remarkable example of a beam instability first identified in computer simulations, before it was observed and identified in experiments.

Additionally, several other aspects of the LCLS design posed potential challenges to the success of the project:

- The requirement of straightness and stability of the electron trajectory in the undulator and the challenge of diagnosing and correcting the trajectory
- The field quality of undulator magnets and the diagnostics necessary to verify that the correct value of K and field quality had been achieved
- Adjustment of undulator K (peak field) to account for energy loss in the electron beam due to wake fields and the SASE process itself
- Protection of the undulator from radiation damage
- Diagnostics for the electron beam to enable identification and correction of beam parameters
- Diagnostics for the X-ray beam to detect and optimize the gain of the FEL

The following sections describe some of the technical challenges encountered in LCLS and how they were handled.

The Laser for the Photocathode

As stated earlier, the photocathode laser constituted a serious R&D challenge in 1992. By 2003, a commercial laser meeting LCLS requirements for energy in a pulse became available in time for use by the LCLS project. In commissioning the laser, the LCLS team still struggled to meet all requirements simultaneously (Dowell et al. 2007).

In light of early difficulties in achieving an ideal laser pulse, the accelerator designers began to study LCLS FEL performance with lower-charge bunches (Limborg-Deprey and Emma 2005; Emma et al. 2005). They that very satisfactory FEL performance could be obtained by reducing the laser spot diameter (and hence electron beam emittance) along with reducing charge. Experience has shown that the requirement on transverse uniformity can also be relaxed to some extent; the effect of nonuniform illumination of the cathode has been studied and it has been demonstrated that illumination of the cathode with a truncated Gaussian intensity profile provides better performance than a perfectly flattop profile (Zhou et al. 2012). The LCLS laser system and its upgraded descendants have worked reliably and effectively since 2005.

The Electron Gun

Prior to the start of the LCLS project, SLAC constructed its own gun test facility (GTF) for the purpose of determining whether the “collaboration” gun could meet LCLS design goals. GTF first produced electrons in 1997. Argonne National Lab also set up a “collaboration” gun for its low- energy undulator test line. The longest-running facility, the Brookhaven ATF, had measured emittances comparable to the goals set for LCLS (Palmer et al. 1997), 1.07 μm in a 0.5-nC pulse. The measured performance at 1 nC was 4.7 μm, larger than LCLS specification. The researchers at ANL devoted efforts to study of the SASE process at visible wavelengths, which could be done using a beam with larger emittance (Lewellen and Borland 2001). The GTF group devoted its efforts to achieving the performance required by LCLS parameters. They performed “slice emittance” measurements (Dowell et al. 2003), demonstrating time-dependent focusing and deflection effects in the gun. Based on these measurements, a modification of the “collaboration” gun design was developed for LCLS (Xiao et al. 2005).

In the new design, a second input power coupling port was added to the gun. This eliminated time-dependent deflections of the electron bunch by symmetrizing the accelerating field on axis. The circular shape of the full-length gun cell was changed to a racetrack shape, canceling the quadrupole term created by the dual coupler arrangement. The final change was a dimensional adjustment of the iris between cells. This change increased the frequency separation of the “0” and “π” resonant modes of the 1.6-cell structure, thereby eliminating an undesired transient time-dependent focusing force in the gun.

The LCLS gun was never tested at the GTF; its construction was completed in time for installation in the LCLS and it was operated for the first time in 2007. Luckily, it worked well (Akre et al. 2007). The gun achieved its emittance design goal of $\gamma\epsilon = 1\ \mathrm{mm} \cdot \mathrm{mr}$ for a 1-nC pulse (Akre et al. 2008).

The gun has always been operated with a copper cathode. Reliability has been excellent since first commissioning. The quantum efficiency (QE) is now typically greater than 10^{-4} electrons/photon, twice that assumed during LCLS construction. The QE actually improves with operating time after installation if gun vacuum is maintained at low levels. The gun does not have a load lock for installation of new cathodes, so some time is required after a cathode change to reestablish good performance. Typically, a new cathode requires “laser cleaning” to reach reasonable performance. However, care must be taken to avoid damage to the cathode surface (Brachmann et al. 2011).

Electron Beam Transport and Bunch Compression

The success of the LCLS linac design depended heavily on applying over 40 years of accumulated knowledge of the performance of the SLAC linac and the linear collider. Hundreds of accelerator scientists and engineers spent decades developing techniques for controlling high-current electron beams, studying the detailed shape

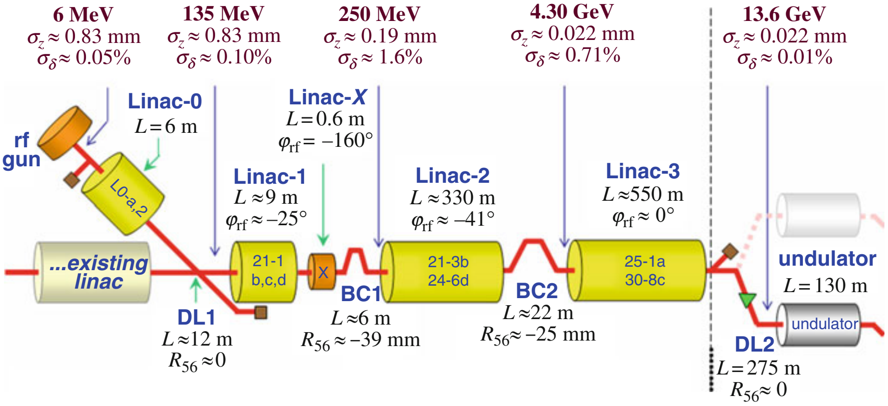

Fig. 9 A schematic of the LCLS linac (Arthur et al. 2002). The *yellow* barrel-shaped icons represent numbered sections of S-band accelerating structures. The figure shows the injector linac (L0) which has two S-band accelerating structures (L0a, L0b) in an alcove adjacent to the linac shown schematically in Fig. 5. "21-3b" refers to sector 21, klystron 3, accelerating structure b, etc. Also illustrated schematically are "dogleg bends" DL1 and DL2 and bunch compressors "BC1" and "BC2." The X-band accelerating structure is shown as an *orange* cylinder labeled "X"

of wake fields that change the energy as a function of bunch current waveform, precision alignment of the beam within magnet components, and use of precision beam diagnostics to establish the desired beam behavior. Chapter 7 of the conceptual design report (Arthur et al. 2002) provides the best description of the myriad considerations that went into the placement of bunch compressors and the degree of compression in each segment of the linac. Figure 9 summarizes the final choices. The "dogleg" bends and two bunch compressors were designed to provide stepped compression that minimizes the effects of transverse wake fields on the low-energy beam while minimizing degradation of emittance from CSR effects. The betatron phase advances from bend to bend were chosen to partially cancel the effects of CSR.

Detailed knowledge of the longitudinal wake fields produced by the linac was used to advantage in the LCLS design. For proper performance of the bunch compressors, the electron beam must enter each compressor with a prescribed "chirp": a linear head-to-tail variation of electron energy. The bunch exits the compressor with reduced length but with same head-to-tail energy variation, which must be removed before the bunch arrives at the undulator. Longitudinal wake fields of the SLAC accelerator are used to partially remove the chirp (Emma 2002). The "Linac-X" accelerating structure shown in Fig. 9 is a short 11.4-GHz accelerating cavity used to cancel the t^2 dependence of electron energy in the bunch current waveform which, if uncorrected, would produce a very undesirable current spike in the waveform of the compressed bunch. After correction, there is still a residual t^3 dependence of energy in the compressed bunch, which produces undesirable current spikes at the head and tail of the electron bunch. Efforts continue to eliminate these spikes and the coherent synchrotron radiation and wake fields they cause.

Coherent Synchrotron Radiation

Michael Borland (Borland 2001; Borland et al. 2002) found that small random fluctuations in electron density would be amplified by the combined effects of coherent synchrotron radiation in a succession of bend magnets, such as compressors, which could produce microbunching instabilities. The phenomenon, now called the CSR instability, was quickly recognized as a potentially serious source of degradation of FEL performance for facilities like the LCLS and the TESLA FEL. Because it is such a rapidly growing instability, double-chicane bunch compressors could not be used to negate its effects; instead they caused greater damage to the beam emittance and energy spread. The double compressors were replaced with single compressors in the LCLS design (Emma 2002) (Fig. 9).

To rapidly assess the threat to FEL performance, DESY and LCLS designers organized a week-long workshop at the DESY-Zeuthen laboratory in Berlin (CSR Workshop 2002). An analytic formulation of the phenomenon emerged within months (Saldin et al. 2002; Heifets et al. 2002; Huang and Kim 2002), along with a recipe for suppression of the instability. Researchers determined that the CSR phenomenon can be suppressed by increasing the energy spread in the electron beam prior to compression, which provides Landau damping for the instability. After considering a superconducting wiggler magnet (Carr et al. 2002), LCLS implemented a "laser heater" (Huang et al. (2004) and references therein). This very compact device, shown schematically in Fig. 10a, was installed between the end of the injector linac and the first bend magnet (i.e., between "Linac-0" and "DL1" in Fig. 1). It induces an energy modulation of the 135-MeV electron beam by superimposing 800-nm laser light on the 135-MeV electron bunch as it passes through a short wiggler magnet tuned to 800 nm. The amplitude of the modulation may be adjusted by changing the intensity of the laser light, as shown in Fig. 10b.

The effect of the laser heater agrees very well with theory, except for one data point showing disproportionately large deviation from theory for heater energy between 1 and 3 μJ. This is not a measurement error; it is evidence of a microbunching phenomenon caused by a small current modulation induced at this setting of the laser power, combined with the weak chicane magnets downstream of the heater undulator. This "trickle" heating phenomenon came as a surprise during tests of the heater.

The Undulator System

The LCLS undulator system was the responsibility of a group of scientists and engineers at the Advanced Photon Source at Argonne National Laboratory. They designed and constructed the undulators, their mechanical supports, precision cam movers for remote alignment, magnetic quadrupoles with built-in steering correctors, cavity resonator beam position monitors, radiation monitors, and electronics

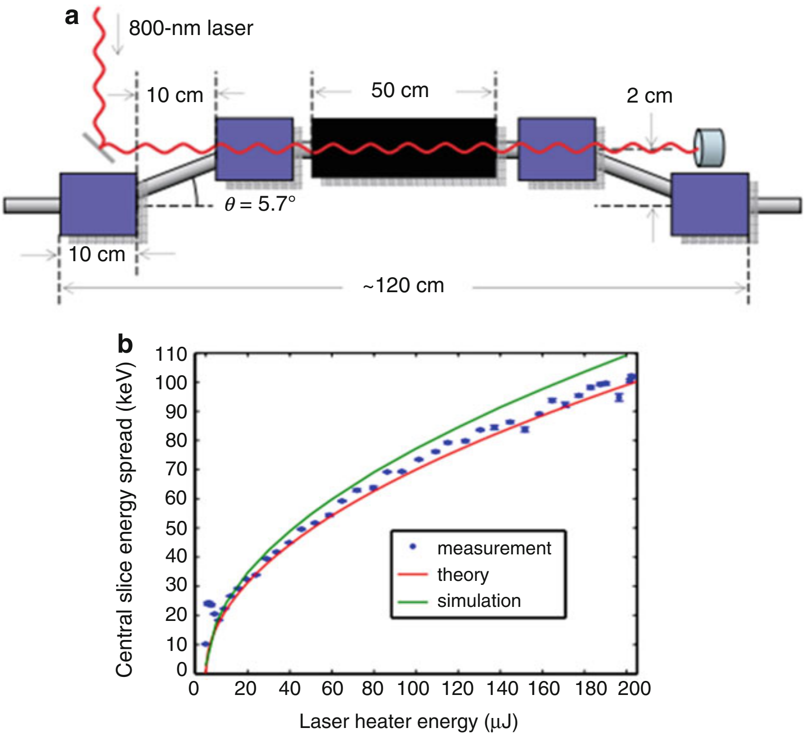

Fig. 10 (**a**) A schematic diagram of the laser heater (Huang et al. 2004). (**b**) Comparison of theoretical and measured heating (Huang et al. 2010)

and controls to operate the items mentioned (Bailey 2008). Engineers at SLAC added a stretched wire system and water leveling system for alignment of undulators. Figure 11 shows one of the 33 undulators installed in LCLS and the diagnostic devices associated with it.

The LCLS undulators themselves are 3.4 m long, with period $\lambda = 3\,\mathrm{cm}$ and $B = 1.25$ T peak field. The nominal K value is therefore

$$K = 0.934^{*}1.25^{*}3 = 3.5$$

Much of the information in the following sections concerning performance of the undulator system can be found in (Nuhn 2009).

Control of the Peak Magnetic Field in the Undulator

During the LCLS design and construction, there was considerable concern over gain reduction due to field errors in the undulator. The concern was such that, from the

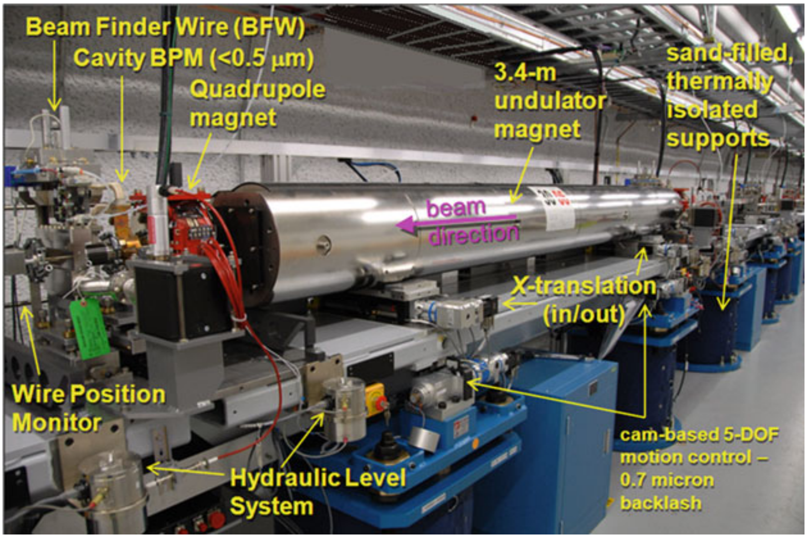

Fig. 11 LCLS undulator assembly. Thirty-three undulators were installed; seven additional spares were built

earliest stages of design, it was decided that the undulator would have a "fixed" gap, and photon energy would be varied by changing the energy of the electron beam. This simplified the undulator design, made inter-undulator phase shifters unnecessary, and eliminated a possible source of field variation that might come from errors in setting the undulator gap. However, this choice seemed to eliminate the possibility of making small corrections to the undulator field to account for energy loss in the electron beam on its way through the undulator. In earlier phases of design, it was decided that a stepwise "taper" or reduction in peak field would be built into the undulator to account for progressive energy loss from wake fields and the SASE process as the electron bunch travels through the undulator. This solution would have placed a very serious constraint on the ability to optimize the FEL (Fig. 12).

Fortunately, this constraint was relieved by implementing a suggestion by DESY scientist Joachim Pflueger (Robinson et al. 2004): the undulator poles have been canted to produce a weak horizontal variation in the undulator K value. Each undulator is mounted on rails that allow horizontal movement over a 1-cm range, so that the K of each undulator can be adjusted remotely by about 0.8%. This has been extremely useful for optimizing the FEL output. The undulators can also be retracted 120 mm from the beam axis so that, after a maintenance period, electrons can be reintroduced to the undulator system without risk of radiation damage.

The temperature-dependent magnetization inherent in the permanent magnet blocks used to build the undulator, unless corrected, would create temperature dependence in the undulator K value. The differing dimensions and thermal expansion coefficients of the aluminum and titanium segments of the undulator

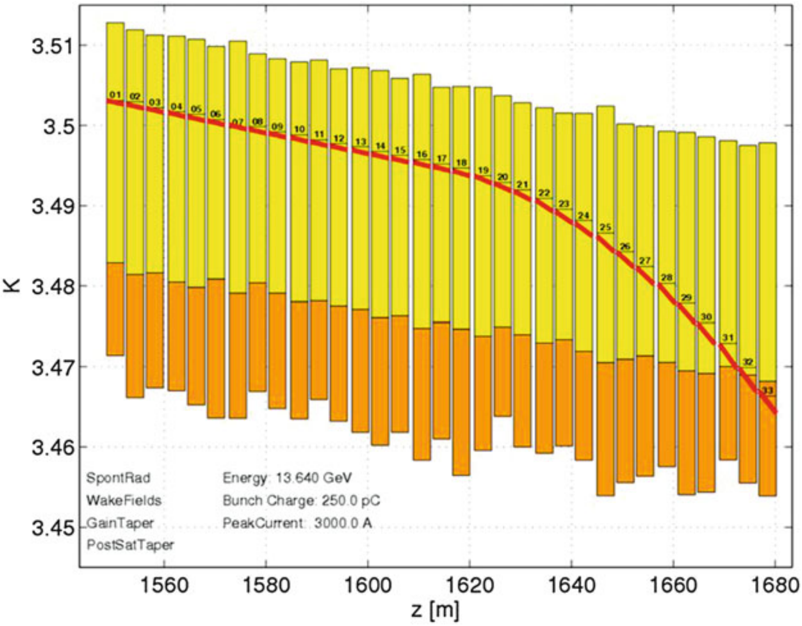

Fig. 12 A plot of the range of variation in K for the LCLS undulators. K is shown on the y axis and distance along the beam path through the undulator is shown on the x axis. Each undulator and its usable (*yellow color*) range of K are illustrated by a two-color *yellow/orange bar*. The *red line* shows what K value was chosen to compensate for energy loss in the electron beam as it travels downstream. The energy loss is caused by both wake fields and the SASE lasing process itself (Nuhn 2009)

mechanical support were chosen to cancel this effect. Another unexpected and undesired temperature dependence was identified in the final design, apparently related to small shifts in the magnet holders. This may be a side effect of the very useful horizontal K variation described in the previous paragraph. This temperature dependence remains in the LCLS undulators. Fortunately, the underground location of the undulator hall ensures that the undulators remain in a safe temperature range even if the air-conditioning system for the hall is turned off. A temperature alarm and interlock system turns off the air conditioner if it malfunctions. When the system is working normally, time variation of the temperature in the undulator hall is only 0.025° over 24 hours during operation (Nuhn 2009).

Wake Fields in the Undulator Beampipe

Wake fields were a source of considerable concern during LCLS design. Wake fields with a range much longer than the electron bunch were not a strong concern;

their effect on the energy of electrons in the bunch would be uniform, so that this change could be accommodated by changing the undulator K value; thus the SASE process could continue. However, very short-range wake fields would cause a progressive and position-dependent change in the energy of electrons within the 200-fs compressed electron bunch as it traveled down the undulator channel, and this could not be compensated by changing undulator K. The magnitude of the effect, taking into account AC resistivity, was predicted to be large enough to disrupt the SASE process for portions of the bunch (Fawley et al. 2005). Some effort was made to choose a chamber material that might minimize the effect. Copper and aluminum were considered; however, at wavelengths comparable to the bunch length (50 μm), data on resistivity were not readily available. Reflectivity measurements were difficult to perform (Bane and Stupakov 2006) and theory indicated some advantage for aluminum when AC resistivity was considered. Aluminum was chosen because it could be extruded with high precision in a "racetrack" cross section, 5 mm high and 12 mm wide, to reduce longitudinal wakes. To minimize the effect of wake fields from surface roughness, the interior of the chamber was polished by pumping an abrasive slurry through the 3.4-m chamber segments. As one might imagine, the slurry would "smooth" the chamber, leaving longitudinal scratches or grooves on its surface. The relevant roughness criterion for these scratches was determined to be the slope of the scratch along the direction of beam motion. Representative samples of the extruded chamber were cut open and measured, confirming that most chambers were smoother than the 20-μrad slope tolerance. The reduced pulse duration routinely used for LCLS operations has no doubt also reduced wake field effects.

Radiation Damage

During the design of LCLS, there was great concern about the risk of ruining the field quality of the undulators if they were hit by a mis-steered electron beam. Several systems of protection were implemented in the form of collimators to stop any electrons on a trajectory that might hit the undulator. These have proven effective. One of the advantages of a copper gun cathode and its low quantum efficiency is the relatively weak "halo" of electrons traveling with the LCLS electron bunch, minimizing the chance of stray electrons reaching the undulator.

Undulators are easily and routinely removed from LCLS for measurement of magnetic field quality and for evidence of degradation of field quality. There was no detectable degradation of field quality in the LCLS undulators since first lasing in 2009; only recently has there been the slightest measurable change in a remeasured undulator, perhaps due to radiation produced in self-seeding tests. An alternative method for checking field quality has also been investigated. This method makes use of a hard X-ray monochromator installed to determine what combination of electron beam energy and undulator K would produce 8.2-keV

X-rays on axis. This device can be used to identify damage to the magnet strength or other misadjustments of an undulator without removing it from the tunnel and will be useful for confirming in situ the K value of variable-gap undulators (Welch et al. 2009).

Setup and Straightness of the Undulator Trajectory

The LCLS design includes an RF beam position monitor (RFBPM) located at the downstream end of each undulator, adjacent to the quadrupole, in order to track the undulator trajectory. Figure 11 shows one of the undulators and associated devices. The undulator and its translation stages, neighboring quadrupole magnet with steering correctors, and beam position monitor and vacuum chamber are all attached to a single steel girder. The position of each girder can be adjusted with submicron resolution using “cam movers” located beneath the steel girder.

The initial setup of the electron trajectory in the undulator system was carried out with undulators retracted. Dispersion-free steering worked well to achieve the required alignment of the undulators. The beam finder wire, indicated in Fig. 11, fulfilled its intended purpose, determining the location of the electron beam in relation to the downstream end of the undulator. The wire could be inserted in a carefully predetermined position within the vacuum chamber. Scanning the wire was accomplished by moving the entire girder and attaching hardware using the cam movers. Since it could be scanned without significant movement of the upstream quadrupole (this could be verified using the RFBPM), the wire could be used to find the centroid and profile of the electron beam. The beam finder wire worked as planned in commissioning but is used infrequently today because the cam movers can be relied upon to make accurate vertical translations of the undulators without causing undesired “pitch” errors.

The straightness of the electron beam trajectory can be established with very high precision, even in the presence of moderate uncertainties and errors in the “zero” position, variations in sensitivity of the electron beam position monitors, and unknown magnetic field errors in the quadrupoles or undulators. In order to accomplish this, the electron beam position monitors must have high sensitivity. Errors in absolute position readout and variation in sensitivity must be stable over time. If these conditions are satisfied, a straight trajectory through the undulator can be identified by making a series of electron beam position measurements for different energy electrons while leaving all magnets at fixed settings. Typically, the LCLS energy is varied from 4 to 14 GeV during this process. The energy dependence at each position can be fit and extrapolated to infinite electron beam energy. It is necessary to correct energy-dependent changes in the incoming beam initial position and angle, but once this is done satisfactorily, it is possible to determine the beam monitor readings that correspond to a straight trajectory. The use and effectiveness of all the undulator diagnostics were reported in detail by H. D. Nuhn at the 2009 FEL conference (Nuhn 2009).

X-Ray Transport, Optics, and Diagnostics

X-ray transport, optics, and diagnostics for the LCLS were designed and fabricated by the Lawrence Livermore National Laboratory. These diagnostics are located downstream of the first X-ray slit approximately 65 m from the undulator. Their most important functions are to contain, control, and steer the X-ray beam (Moeller et al. 2011).

Containment with collimators, slits, and apertures is necessary since so few materials can survive exposure to the LCLS beam without damage. Boron carbide, one of the few materials that can both withstand and stop the LCLS X-ray beam, is placed on the edges of the slit and collimator (Fig. 13).

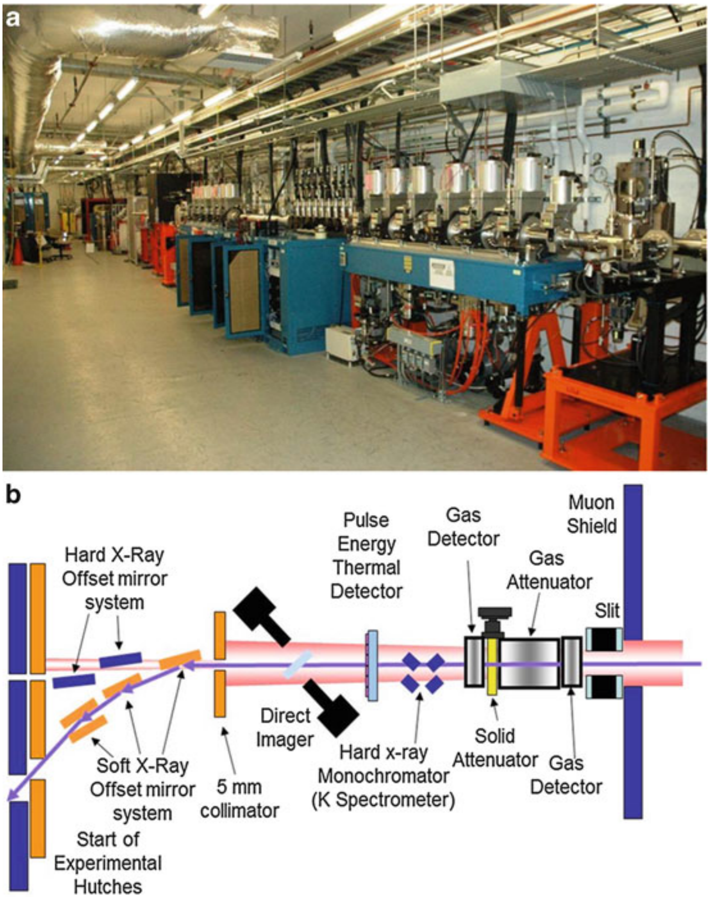

Fig. 13 X-ray diagnostics, designed and constructed at the Lawrence Livermore National Laboratory (SLAC archives). (**a**) Photograph of X-ray diagnostics. (**b**) Schematic of LCLS X-ray diagnostics

The attenuators and gas detectors (Fig. 13b) are in daily use during operation, to set the intensity of the X-ray beam to match the experimenters' needs. The gas detector is a chamber containing low-pressure nitrogen gas which fluoresces in proportion to the pressure and the intensity of the passing X-ray beam. It must be cross-calibrated against a calorimeter. It provides a fast "relative" measure of the X-ray pulse energy by detecting Auger fluorescence. The gas nitrogen pressure in the attenuator can be raised to 12 torr to control the intensity of a soft X-ray beam. These devices are connected to the undulator and accelerator vacuum system through 4mm- diameter holes. Hard X-ray beams can be attenuated in the solid attenuator (Fig. 13b) by insertion of silicon plates of selected thicknesses.

Closing Remarks

Voluminous material has been published about the LCLS design, performance, improvements, and scientific accomplishments, both before and since first light was produced in 2009. The facility continues to expand its capabilities and repertoire of operating modes developing new capabilities unanticipated during construction. In parallel, the design of a major expansion of LCLS is underway, identified by a somewhat understated name: "LCLS-II." This new facility is well on the way to full authorization by DOE and is very likely to produce first light by the end of 2019. The design is quite far advanced now, and acquisition of components has already begun. I feel strongly that LCLS-II will be at least as exciting and revolutionary a research tool as LCLS has been. Young researchers are invited to read about its design (Galayda 2014) and research objectives for this new machine (Schoenlein 2015) and plot their careers accordingly.

Acknowledgments I consider myself extremely fortunate to have had the privilege of working on LCLS with the authors of most of the references listed here. I am grateful beyond words for the opportunity to summarize their work in this chapter. I hope I will be forgiven for any omissions or oversimplifications in this report.

I am very grateful to J. Goldstein for editing this chapter.

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