DARK SECTOR EXPERIMENTS AT LCLS-II (DASEL) ACCELERATOR DESIGN *

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Abstract

DASEL (Dark Sector Experiments at LCLS-II) is a new accelerator and detector facility proposed to be built at SLAC. Its primary target is a direct observation of dark matter produced in electron-nuclear fixed-target collisions. DASEL takes advantage of the LCLS-II free electron laser (FEL) under construction at SLAC which will deliver a continuous electron beam from a 4-GeV superconducting linac. DASEL will operate parasitically to the LCLS-II FEL by extracting low intensity unused "dark" current bunches downstream of the FEL kickers. The DASEL key accelerator components include a 46-MHz gun laser system providing controlled intensity and timing of the dark current, a fast (MHz) kicker with 600-ns flat-top, a new transport line connecting the LCLS-II to the existing A-line and to End Station-A, where the experiments will take place, and a spoiler and collimator system in the A-line for final shaping of the DASEL beam. An overview of the DASEL accelerator system is presented.

INTRODUCTION

The identity of dark matter is one of the most important questions in fundamental physics today. The construction of the LCLS-II [1] free electron laser (FEL) at SLAC presents a cost-effective opportunity to enable and host high-impact dark matter and dark force experiments. Continuous electron beams from the LCLS-II 4-GeV superconducting (SC) linac (with a possibility of 8-GeV upgrade) are particularly well suited to these experiments. DASEL (Dark Sector Experiments at LCLS-II) [2] is an accelerator and detector facility proposed to be built to host such experiments. Two experimental proposals, LDMX [3, 4] and SuperHPS [5, 6], are being developed for DASEL, aimed at direct observation of dark matter produced in electron-nuclear fixed-target collisions. These experiments require high-rate beams with very low current.

DASEL is a complimentary program to the LCLS-II; it is designed to not interfere with the LCLS-II beamline components and the FEL operations. DASEL will operate parasitically to the FEL by extracting low-charge unused high-rate "dark" current bunches downstream of the FEL kickers. The key elements of DASEL are the laser system, a long-pulse kicker and septum to extract the beam, a new transfer beamline, the existing A-line with a spoiler/collimator system, and an End Station-A (ESA) experimental area. A description of the DASEL accelerator system is presented.

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OVERVIEW

DASEL uses the LCLS-II to provide a low-current, continuous beam to the experiments. The LCLS-II is an X-ray FEL based on a 4-GeV SC linac; the LCLS facility layout is shown in Fig. 1. DASEL adds the following components to the LCLS-II: 1) a low-power photo-cathode laser operating at 46 MHz to supplement the natural dark current being emitted at 186 MHz; 2) a new fast (MHz) long-pulse (600 ns flat-top) kicker and septum; 3) a new 220-m transfer line to connect with the existing A-line and ESA.

The SC linac operates with an RF frequency of 1.3 GHz and is fed from an RF gun operating at up to 186 MHz. The LCLS-II baseline has a maximum bunch rate of 929 kHz; this corresponds to FEL bunches separated by 1,400 1.3-GHz RF buckets (1.1 μs). Two fast kickers deflect the FEL bunches towards either the soft X-ray (SXR) or hard X-ray (HXR) undulators (see Fig. 1); the unused beam travels to a high-power dump in the Beam Switch Yard (BSY).

A schematic of the LCLS-II beam structure and the kicker pulse is shown in Fig. 2. DASEL takes advantage of the "empty" buckets between the FEL bunches. These buckets are populated with very low dark current from the LCLS-II RF gun at 186 MHz (5.4 ns spacing) or seeded by the 46-MHz laser to produce well-defined, low-charge bunches with 21.5 ns spacing. The DASEL kicker extracts 600 ns of dark current bunches located between the primary FEL bunches into the new transfer line. This operation is parasitic to the FEL beams, since the DASEL beam is low-current (<2 μA compared to 62 μA nominal LCLS-II current) and is deflected downstream of the HXR and SXR kickers as shown schematically in Fig. 3. The actual layout of the LCLS and DASEL beamlines in the beam spreader area is shown in Fig. 4.

The DASEL beamline transfers the beam into the existing A-line. The LDMX experiment requires a very large beam spot size, a very low current, and a relatively small energy spread. The specified beam parameters are obtained using the A-line spoiler and collimator system. Along with the DASEL gun laser, this system provides complete control of the number of electrons and the beam phase space. The beam is finally delivered to the ESA experimental area which has all the support systems for the experimental program.

Beam parameters corresponding to three areas of DASEL are listed in Table 1: the experiment, the A-line with the spoiler/collimator system, and the LCLS-II accelerator. DASEL initial design is based on the LDMX requirements; it can be upgraded for the future SuperHPS experiment.

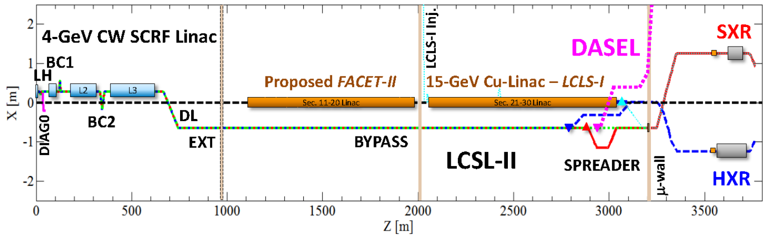

Figure 1: Top view layout of LCLS beamlines, where HXR is dash blue, SXR is solid red, and DASEL is dash pink.

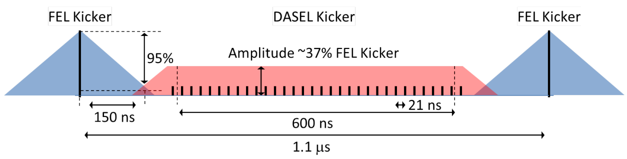

Figure 2: LCLS-II beam structure and kicker pulse. Large bars are FEL bunches, small bars are dark current buckets, blue is FEL kicker pulse, and red is DASEL kicker pulse.

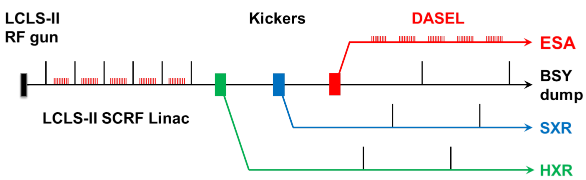

Figure 3: Schematic of the FEL and DASEL kicker system.

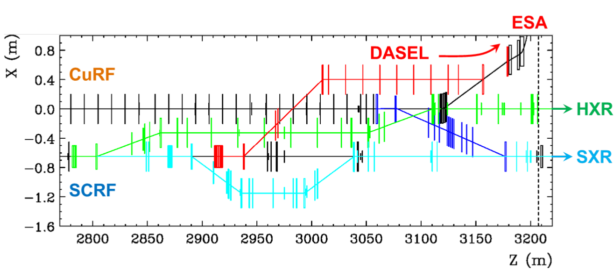

Figure 4: Top view of the spreader area, where the DASEL beamline and components are colored in red. Note that different lines may be at different elevation.

DASEL SYSTEMS

Gun Laser

The LCLS-II photo-injector is based on the APEX RF gun [7]. Measurements on APEX show less than 1 nA of dark current. Due to a large emittance, it is very likely that most of the dark current will be collimated away at low energy, well before it reaches the kickers. To achieve higher currents for DASEL (especially for SuperHPS) and ensure a controlled performance, a separate gun laser is used, which can intentionally fill the dark current buckets between the primary FEL bunches.

The LCLS-II laser system operates with a 46-MHz master oscillator from which pulses are selected at the nominal maximum repetition rate of 929 kHz. The highest beam repetition rate for DASEL is set by the 186-MHz gun frequency.

Table 1: DASEL Parameters

Experiment	**LDMX**	**SuperHPS**
Energy	4 GeV	4 GeV
Bunch spacing	21.5 ns	5.4 ns
Bunch charge	0.02-20 e^-	$7{\cdot}10^5$ e^-
Beam current	0.1-150 pA	2 μA
RMS norm. emittance	~100 μm-rad	~1 μm-rad
Energy spread	<1%	<1%
Spot size	~4 cm	<250 μm
Max. beam power	0.5 W	5 kW
A-line Spoiler		
Charge reduction	0-99.99%	N/A
Emittance growth	×1-1000	N/A
Accelerator		
Beam current	0-25 nA	2 μA
RMS norm. emittance	<25 μm-rad	<25 μm-rad
Admittance	<50 nm-rad	<50 nm-rad
Energy spread (FWHM)	<2%	<2%
RMS bunch length	<1 cm	<1 cm
Max. beam power	55 W	5 kW

However, the cost of such system is relatively high due to the need for an independent laser oscillator and amplifier system, a timing and synchronization system at 186 MHz, and other elements of the control and diagnostic systems. An economical solution for DASEL is to operate at the 46-MHz repetition rate of the LCLS-II laser by splitting the oscillator before the LCLS-II amplifier and adding a separate amplifier and harmonic generation stages for DASEL. This is a relatively simple laser system for DASEL since it operates at much lower average power than the LCLS-II system.

Kicker and Septum

The DASEL fast kicker and two-hole Lambertson septum are used to deflect dark current bunches into the DASEL beamline. The septum magnet is identical to the LCLS-II HXR and SXR septum magnets. The kicker provides a 15-mm vertical deflection at the septum, sending the DASEL beam into a septum hole with strong horizontally bending field. To obtain the kicker field of 87 Gm at 4 GeV while limiting average power, the kicker system includes six 1-m kicker magnets. The kicker operates at the same rate as the FEL kickers but with a longer pulse, lower amplitude, and looser tolerance. Allowing for the kicker rise/fall time, roughly 600 ns of dark current can be extracted between the primary FEL bunches. The kicker field can be doubled for 8

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GeV energy upgrade by proportionally increasing the driver voltage, with a modest development effort to mitigate the power loss in the load and driver transistors.

DASEL Beamline

The DASEL beamline connects the LCLS-II to the existing A-line and the ESA experimental area. Figure 4 shows the beamlines in the LCLS-II beam spreader: the extraction lines to the HXR and SXR undulators; the extraction line to the BSY dump; the LCLS-I CuRF linac; and the DASEL extraction line to ESA. Note that different lines in Fig. 4 may be at different elevation levels. The spreader is a highly congested region with the beamlines sharing a small cross-section. The DASEL line is designed to avoid conflicts with the LCLS-II components and ensure efficient installation.

The DASEL kicker is downstream of the HXR and SXR kickers and septa, at 0.65-cm height relative to the CuRF linac. When the kicker is on, it makes a vertical kick directing the DASEL beam into a hole of the septum magnet with a horizontally deflecting field. When the kicker field is off, the remaining un-deflected primary bunches pass through the other septum hole, with no field, towards the LCLS-II BSY dump. After the septum, the DASEL line makes a horizontal cross-over above the HXR and CuRF linac lines connecting to a rolled DC-bend located 66.4 cm above and 40 cm to the left of the CuRF linac. This magnet directs the beam downward at a shallow angle, parallel to the CuRF linac, towards the second rolled DC-bend which connects DASEL with the A-line. The latter has been recently updated to relocate the A-line pulsed magnets in the BSY. For this reason, a third DC-bend is installed in the A-line downstream of the DASEL line for compatibility with both the DASEL and the ESTB [8] beams. Fourteen quadrupoles in the DASEL beamline provide the beam focusing and dispersion correction. The kicker induced orbit angle is cancelled with a 2.6° roll of the kicker and septum magnets. The DASEL optics is shown in Fig. 5.

For a cost-effective design, DASEL uses existing SLAC dipoles and quadrupoles, and existing LCLS-II designs for the kicker and septum magnets. Magnet aperture is consistent with the LCLS-II collimation and the specified beam admittance and energy spread; the magnet fields are compatible with an 8 GeV upgrade. The magnet parameters are listed in Table 2. The 14 quadrupoles require nine independent power supplies; and the septum and three DC-bends need three power supplies.

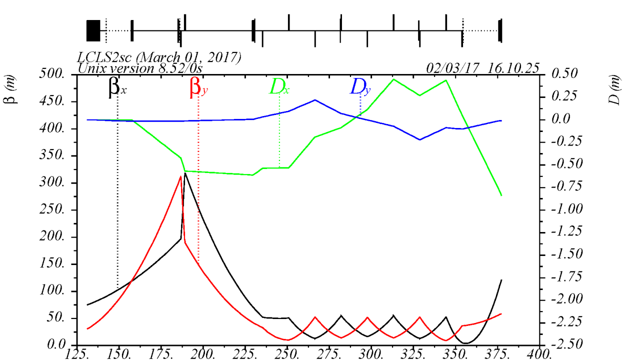

Figure 5: Optics functions in the DASEL beamline.

Table 2: Magnet Parameters at 8 GeV

Magnet	Quantity	Max field	Aperture
Quadrupole	14	22.11 kG	53.8 mm
Kicker	6	29.0 Gm	10 mm
Septum	1	3.89 kGm	15.9 mm
DC-bend (1,2)	2	4.07 kGm	25.4 mm
DC-bend (3)	1	0.62 kGm	50.8 mm

A-line

DASEL takes advantage of the existing A-line spoiler/collimator system for beam shaping and delivery to the experiments. Presently, secondary electron beams are created by steering selected LCLS bunches onto a Cu-target in the BSY. The scattered beam has a wide energy spread, which is then transported through the A-line into ESA. The target thickness and material are chosen to reduce the number of generated hadrons to negligible levels. Additional spoilers (e.g. PR10) are available to further diffuse the electron energy spread without generating a large number of other particles. A-line collimators are used to control the number of electrons per pulse. The momentum slit SL10 reduces the accepted beam energy spread to $<10^{-6}$. The four-jaw collimators C24 and C37 then reduce the geometrical spread of the accepted beam reaching the ESA. The resulting beams are used for the ESTB test beam program [8]. A similar procedure is planned for DASEL, where the individual bunches impinge on a target, and produce a scattered electron beam whose angle and energy spread can be collimated to select an electron spot size and rate as required by the experiment.

Diagnostics

The nominal DASEL bunch charge is too low to measure with standard diagnostics, such as BPMs. The beamline tuning is done with a special tune-up operating mode using low rate (1-10 Hz) of the LCLS-II primary beam. The latter can be extracted on pulses with the SXR and HXR undulator kickers turned off and the DASEL kicker timing shifted by 500 ns. In tune-up mode, the beam is stopped before it reaches the LDMX detector to prevent high charge bunches from damaging the detector electronics. Two BPMs are included in the DASEL beamline to provide a very fast signal to halt the DASEL kicker in case errant high charge bunches are detected. To tune and align the beamline, three profile monitors are appropriately positioned in the DASEL line. They confirm the dispersion, phase advance, and overall match of the DASEL beam before it enters the A-line. Six dipole correctors and two trims on DC-bends together with the profile monitors are used for orbit correction; an additional BPM is used for control of the kicker orbit.

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