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Originator: Tor Raubenheimer, Accelerator Physics Lead	12/4/19
Approver: Natalia Toro, S30XL Lead Physicist *Email Approval*	12/10/19
Approver: Tom Markiewicz, Accelerator System Manager Thomas W. Markiewicz	12/16/19
Approver: Ludovic Nicolas, Radiation Physicist	Dec 3rd 2019

Revision History

Revision	Date Released	Description of Change
R0	12/16/2019	Original Release.

Table of Contents

1 Scope

S30XL is a beamline that connects the LCLS-II to the End Station A (ESA) beamline. The beamline is constructed in two phases, A and B, where A first verifies the ability to produce the desired beam currents to a dump in Sector 30 or the BSY, and Phase B connects to the A-line and delivers beam to ESA. This document describes the electron beam parameters for the S30XL phases A and B and then possible upgrades to the overall requirements. It also describes the operating modes for Phases A and B as well as estimates of the Maximum Credible Beam and expected beam losses in S30XL and the A-line.

2 Documentation

The S30XL requirements and interface documentation are listed in the Table 1 below. Some documents are limited in scope to Phase A but they will be updated as the complete Phase B requirements are specified.

Table 1. S30XL Physics Requirements Documents

S30XL-PR-001	S30XL Beam Parameters and Operating Modes
S30XL-PR-002	S30XL Beam Containment Requirements and Radiological Concerns
S30XL-PR-003	S30XL DC Magnet Requirements
S30XL-PR-004	S30XL Kicker and Septum Requirements
S30XL-PR-005	S30XL Spoiler/Collimator System and A-line Beam Loss Requirements
S30XL-PR-006	S30XL Machine Protection System Requirements, Phase A
S30XL-PR-007	S30XL Injector Laser System Requirements
S30XL-PR-008	S30XL Diagnostic Requirements
S30XL-PR-009	S30XL Vacuum System Requirements
S30XL-PR-010	S30XL Steering and Vibration Tolerances
S30XL-PR-011	S30XL Stoppers and Beam Dumps, Phase A
S30XL-PR-012	S30XL Beam Stay Clear
S30XL-IC-001	S30XL and LCLS-II Interface Control
S30XL-IC-002	S30XL Accelerator to Controls Interface Control

The S30XL lattice description and MAD8 output files can be found in: http://www.slac.stanford.edu/grp/ad/model/output/lcls2he/mad/latest/. The MAD decks contain both beamline components for LCLS-II as well as S30XL beamlines and are used to develop layouts.

3 Introduction

The Sector 30 Transfer Line (S30XL) delivers a beam for high-energy physics experiments at low cost by exploiting the 4 GeV superconducting RF linear accelerator under construction for the LCLS-II X-ray Free Electron Laser (FEL) [1,2]. The LCLS-II can fill up to every 1400'th 1.3 GHz rf bucket which corresponds to a 929 kHz beam rate. For S30XL, unused RF buckets between the LCLS-II electron bunches are filled with sub-μA current, extracted by a fast kicker in Sector 29, and diverted via a transfer beamline towards End Station A (ESA) as illustrated in Figure 1 and shown schematically in Figure 2. The current for S30XL is a small fraction of the nominal LCLS-II current of 62 μA. Because the S30XL beam is very low current, is out of time with the FEL kickers, and is extracted downstream of the LCLS-II linac-to-undulator beamlines as illustrated in Figures 2 and 3, it should not affect LCLS-II operations.

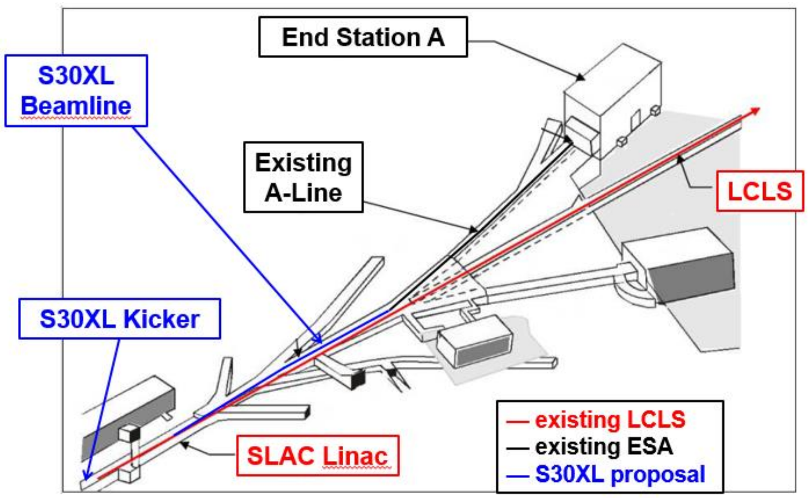

Figure 1. Layout of the S30XL beamline connections to the LCLS-II and the ESA.

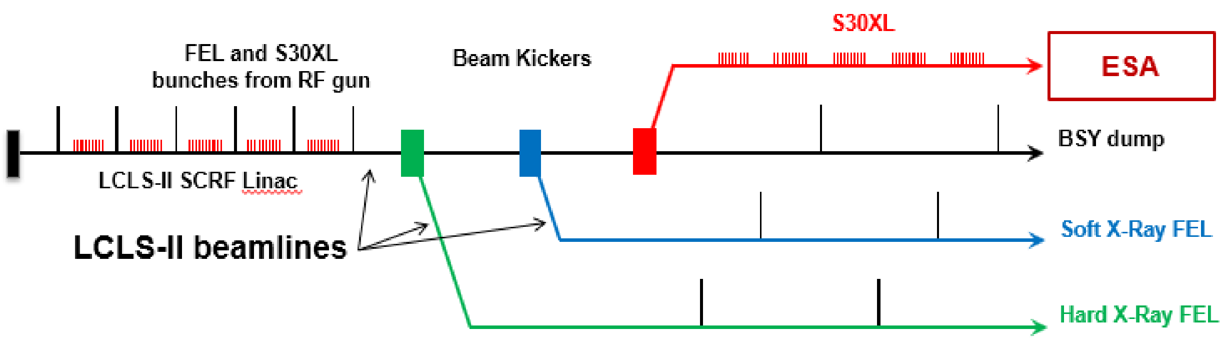

Figure 2. Schematic of S30XL extraction (red) placement and operation relative to LCLS-II SXR (blue) and HXR (green) extraction. Actually, the HXR extraction is in the same direction as the S30XL but the two beamlines do not interfere.

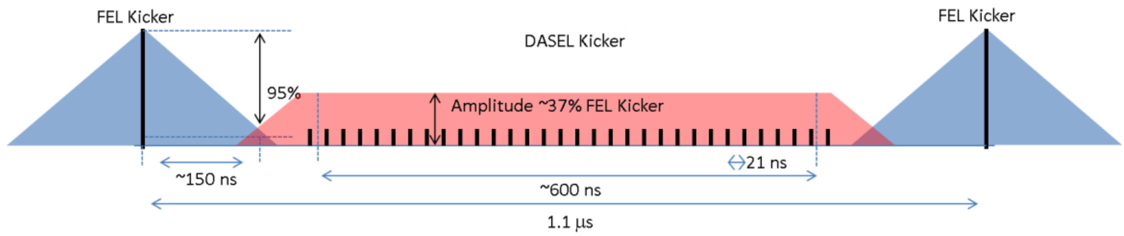

Figure 3. LCLS-II pulse structure showing primary pulses with 4x10^8 e- and dark current bunches from the gun with ~30 e- per bunch. The S30XL beam requires control of the dark current population with a spoiler/collimation system in the A-line and, possibly, with an additional seed laser to deliver final current in the fA to μA range.

The new S30XL system includes two, and possibly three, modifications to the LCLS-II:

- Addition of a long-pulse kicker and septum onto the beamline headed to the BSY dump downstream of the LCLS-II HXR and SXR Beam Spreader kickers in Linac Sectors 29/30;
- An additional 220-meter long beamline extending from Sector 29 through the BSY to connect with the End Station A (ESA) beamline (A-line);
- Possible addition of a low-power photo-cathode laser operating at 46 MHz to augment the natural dark current to a maximum current that is less than 1 uA (described in S30XL-PR-007).

The S30XL beam line is designed to accept beam from the LCLS-II SRF linac and the LCLS-II-HE upgrade. All magnets must be specified to operate over the beam energy range of 2.0 to 8.4 GeV.

The beamline is constructed in two phases, with the first, Phase A, being a 100-meter portion of the beamline to demonstrate the beam properties and extraction system and, Phase B, connecting to the A-line to deliver the current to ESA. In Phase B, the A-line, including the spoiler, collimator, and stopper systems, are used. Minor modifications of the A-line are required to provide the focusing and possible rastering desired at the experiment.

4 S30XL Electron Beam Parameters

In nominal operation, the S30XL kicker extracts as much as 600 ns of bunches between the LCLS-II primary bunches spaced by 1.1 μs, as illustrated in Figures 2 and 3. The nominal operation of the S30XL beamline is with 25 nA current at the 55% duty cycle for an average beam power of 55 W at 4 GeV or 110 W at 8 GeV. The 25 nA beam current is chosen based on the maximum of what is expected from LCLS-II RF gun dark current and the minimum current needed for diagnostic purposes. The maximum operating beam power is set at 220 W in S30XL, the A-line, and ESA, corresponding to 100 nA at 4 GeV. The maximum beam current allowed before tripping the Beam Containment System (BCS) corresponds to 400 W in the A-line or ESA; the BCS requirements are described in S30XL-PR-002. The S30XL Machine Protection System is set at 300 W to trip at a level lower than the BCS trip level; the MPS requirements are described in S30XL-PR-006.

In the case of many experiments such as LDMX [3], the desired electron current in ESA ranges between 100 fA and 150 pA, corresponding to from 1 to approximately 500 electrons per μs, or a maximum of 0.5 Watts of electron beam power at 4 GeV with the 55% duty cycle. In this case, the A-line spoiler/collimator system is used to degrade the incoming beam current of roughly 25 nA; the relatively high incoming beam current is specified to ensure operation of the diagnostics.

The parameters of the S30XL system are listed in Table 2. Table 3 lists the maximum allowed beam power in different configurations. Three categories of parameters are given: beam in the LCLS-II accelerator and the S30XL beamline, beam in the End Station A beamline (A-line) at the spoiler/collimator system, and beam at the experiment in ESA. The primary beamline is designed to meet the LDMX experimental requirements with an ultra-low current beam. This ultra-low current beam has several applications beyond the LDMX experiment, including nuclear structure measurements motivated by the accelerator-based neutrino physics program and test beam experiments. In addition, S30XL could be upgraded to support a future higher-current experiment as is described in Section 8; such an upgrade will likely require a new review from Radiation Physics.

5 S30XL Phase A Beam Parameters

In Phase A, low current beam is transported to a dump in Sector 30 or the BSY; the Phase B and Phase A beamlines are illustrated in Figures 4 and 5, respectively. The primary goal of Phase A is to verify the properties of the dark current, the extraction system, and the diagnostics. The beamline consists of the kicker/septum, the rolled bend, a few quadrupoles, and diagnostics to verify the beam performance. The kicker and septum requirements are described in S30XL-PR-004 while the magnet and diagnostic requirements are described in S30XL-PR-003 and S30XL-PR-008, respectively. In this case, the beam power on the Phase A dump is limited to 4 W by limiting the S30XL kicker repetition rate and/or pulse width. The electron beam parameters for Phase A are listed in the first column of Tables 2 and 3.

Because of the energy collimation in the LCLS-II Bypass Dogleg of +/- 2% [4] and the bunch compression systems at BC1 and BC2, only 'dark current' captured at the RF gun, buncher, or the first one or two accelerating cavities can survive to the BSY. The LCLS-II RF gun specification [5] is that dark current is less than 400 nA at 100 MeV. Measurements of dark current on the APEX RF gun at LBNL are less than 1 nA [6]. Present measurements of the LCLS-II RF gun are also small compared to 400 nA. It is expected that the natural dark current has a large effective emittance and much of it is collimated away at low energy. In particular, if the emission of dark current is uniform across the cathode at the full 400 nA, only 25 nA of dark current makes it to the undulator and DASEL kickers. In Phase A, the maximum beam power to the beam dump is 4 W and this is regulated with the kicker repetition rate and/or flattop pulse width. If the current originates from the edges of the cathode as is more likely, a smaller fraction of the current survives to the BSY, allowing a higher kicker repetition rate.

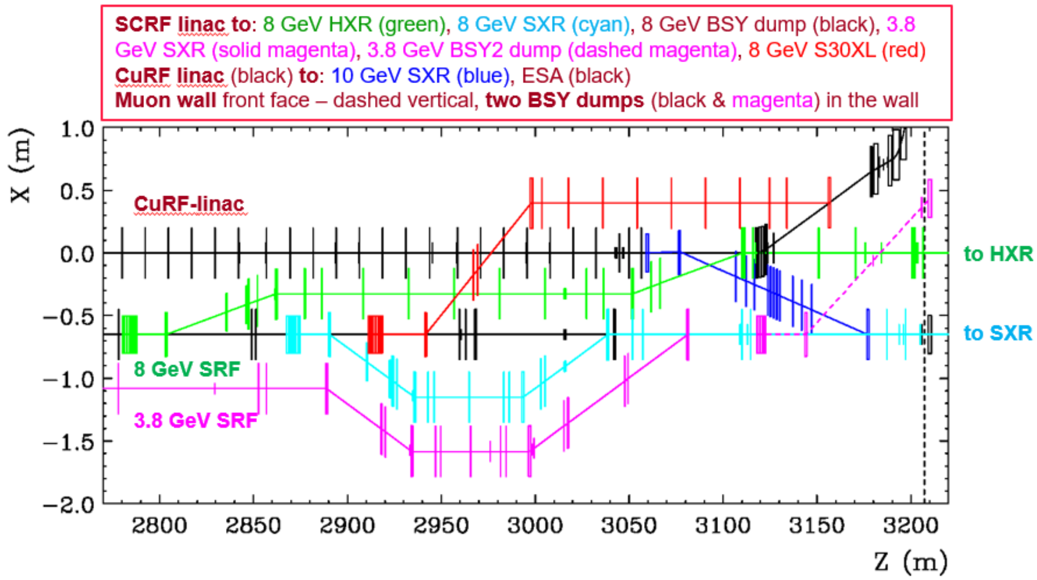

Figure 4. Top view of the S30XL Phase B beamline (red) connecting the LCLS-II BSY Dumpline to the A-line (black)

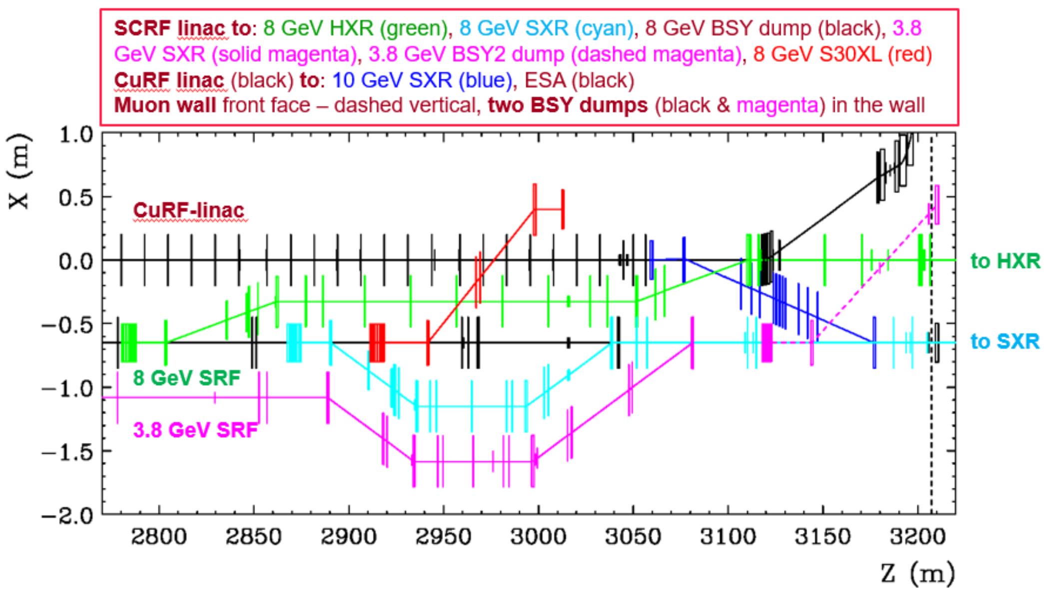

Figure 5. Top view of the S30XL Phase A beamline (red) connecting to the LCLS-II BSY Dumpline and bringing the beam to a dump in Sector 30 or the BSY.

If the measured ‘dark current’ is too low, a separate gun laser can be added at the LCLS-II rf gun for Stage B. This system intentionally populates “dark current” bunches at a sub-harmonic of the gun frequency. These bunches are well separated from the primary beam bunches so they can be extracted by the DASEL kicker downstream. The new gun laser shares the LCLS-II RF gun 46 MHz laser oscillator but has a separate amplifier, UV conversion, and transport, all of which operate at much lower average laser power than the LCLS-II systems [7]. The addition of a second laser is a separate project; the requirements are specified in S30XL-PR-007.

The goals of the initial phase of the S30XL project (Phase A) are to evaluate the dark current transported to the beamline and to enable compact experiments that use single- or few-electron pulses. Currents at the fA to pA scale suffice for many of these objectives.

Table 2. S30XL electron beam parameters for Phase A and Phase B (baseline) as well as a possible upgrade mode motivated by Super-HPS-style experiments.

LCLS-II Accelerator & S30XL Parameters	Phase A	Phase B (low current)	Phase B (high current)
Energy	3.0 - 4.5 GeV	2.0 to 8.4 GeV	2.0 to 8.4 GeV
Bunch spacing	5.4 ns	5.4 to 21.5 ns	5.4 to 21.5 ns
Maximum beam power	4 W	55 W (4 GeV) or 110 W (8 GeV)	220 W
Maximum Duty cycle	55%	55%	55%
Macro pulse beam current	0 – 25 nA	0 – 25 nA	100 nA (4 GeV) 50 nA (8 GeV)
Macro pulse repetition rate	0 – 929 kHz	929 kHz	929 kHz
Beam norm. emittance (rms)	~1μm; < 25 μm	~1μm; < 25 μm	~1μm; < 25 μm
Beam admittance (edge)	<50 nm, defined by LCLS-II collimators	<50 nm, defined by LCLS-II collimators	<50 nm; defined by LCLS-II collimators
Bunch energy spread (FWHM)	<2 %	<2 %	<2 %
Bunch length (rms)	<1 cm	<1 cm	<1 cm
ESA Spoiler Parameters			
Charge/current reduction	N/A	1 – 100,000	1
Emittance increase	N/A	1 - 1000x	1x
Max beam power on spoiler	N/A	220 W	0 W
Spoiler thickness	N/A	0 – 0.5 r.l.	0
ESA Parameters			
Nominal bunch charge	N/A	0.008 – 30 e-	3,000 – 13,000 e-
Nominal macro pulse beam	N/A	<1 nA	50 – 100 nA

LCLS-II Accelerator & S30XL Parameters	Phase A	Phase B (low current)	Phase B (high current)
current			
Beam norm. emittance (rms)		< 1000 μm	< 1000 μm
Bunch energy spread	N/A	<1%	<1%
IP spot size	N/A	4 cm x 4 cm (rastering at 40 MHz could be used)	<250 μm including jitter
Nominal beam power	N/A	< 4 W	220 W

Table 3. Beam power limits for Tuning, Operating, MPS, and BCS.

	Tuning w/ LCLS-II bunches	Nom. Operation	Max. Operation	MPS Trip	BCS Trip
Phase A S30XL Dump	4 W	4 W	4 W	6 W	10 W
Phase B S30XL Beamline	25 W	55 / 110 W	220 W	300 W	400 W
A-line Spoiler	25 W	55 / 110 W	220 W	300 W	400 W
ESA Stopper/Dump	25 W	55 / 110 W	220 W	300 W	400 W

6 S30XL Phase B Electron Beam Parameters

After verifying the electron beam parameters in Phase A, Phase B of the S30XL brings the beam to the A-line which connects to the ESA. The Phase B beamline is illustrated in Figure 4, the electron beam parameters are listed in the second column of Table 2, and beam powers are listed in Table 3.

The nominal beam current into the S30XL beamline is 25 nA in the macropulse which is expected to be sufficient to allow diagnostics for simple tuning and feedback. The 25 nA corresponds to 110 Watts average power at 8 GeV. The maximum beam power is set to be 220 Watts in the S30XL beamline for Phase B. If the dark current is significantly higher than a few nA, it is expected that LCLS-II will further collimate it to prevent unnecessary beam power loss and radiation. However, if the CW dark current is still higher than 100 nA at 4 GeV (50 nA at 8 GeV), S30XL reduces the total current brought into the beamline by narrowing the kicker pulse width and/or reducing the repetition rate to limit the maximum beam power entering the A-line and ESA to 220 W average.

For many experiments that the S30XL can support, the desired beam current is much less than the nominal 25 nA. To maintain diagnostic capability, the S30XL extracts the nominal current and the current reduction is accomplished with spoilers and collimators in the A-line. Past experience with the A-line has shown that a spoiler collimator system can reduce the current by as much as 10^8. The requirements in S30XL vary from 0 to roughly 10^5. The requirements of the ESA spoiler / collimator system are described in S30XL-PR-005.

There are minimal requirements on the beam transverse emittance. The desired beam emittance for many of the experiments is large enough so that the beam can be defocused to a cross-section of roughly 4x4 cm. This emittance is many times (100-1000x) that of the LCLS-II emittance (as well as the LCLS-II admittance, which is determined by the collimation system). This increase may be accomplished using the ESA spoilers with a corresponding degradation of the beam current. A spoiler system increases the beam emittance and the beam energy spread. Assuming an incoming, mono-energetic, 4-GeV beam, a simple 0.1 r.l. spoiler system increases the emittance to more than 300 um, with more than 50% of the current within 0.5% of the incoming energy. In practice, S30XL has spoilers with different thicknesses which, combined with the downstream collimators, are used to control the beam emittance and current in the ESA. The spoiler system has been specified for beam power up to 220 W to allow options for precise control and shaping of the electron beam at the experiment. If the desired beam emittance cannot be achieved with the spoiler system, a rastering system will be added upstream of the experiment to paint the beam across the desired aperture. The dark current beam emittance measured in Phase A will help specify the A-line spoiler/collimator and possible downstream rastering systems.

7 S30XL Beam Steering and Stability Tolerances

The S30XL has relatively loose alignment and steering tolerances. The maximum extent of the beam as defined by the LCLS-II collimation system (65 nm-rad) is +/- 5mm at a 300 m beta function; note the nominal betatron beam size is < 500 um. Steering correctors are specified to compensate alignment and field errors as large as +/- 2 mm and 1.0%, respectively, as noted in the S30XL Steering and Vibration Tolerances PRD and the S30XL DC Magnets PRD. In addition, stability tolerances on magnet and kicker fields and vibration are set to limit beam centroid motion to less than 1 mm rms in the vertical and 1 mm rms in the horizontal at a location with a 300 m beta function as specified in S30XL-PR-010, the S30XL Steering and Vibration Tolerances PRD; the trajectory motion will be as much as 2 times larger in the A-line. Energy stability is determined by LCLS-II but should be significantly better than +/- 0.1%. With the ESA dispersion function of 6-meters, this corresponds to an additional maximum of +/- 6 mm horizontal motion. Tolerances are specified assuming the effects are uncorrelated and add randomly. Incoming effects from LCLS-II, including the ringing of the LCLS-II kicker, need to be accounted as well.

8 S30XL High Power Upgrade Electron Beam Parameters

In the future, experiments in ESA may desire higher current beam. In concept, the S30XL delivery system could operate parasitically to the LCLS-II with currents as high as 1 uA which is still less than 2% of the nominal maximum current in the LCLS-II. Detailed studies by Radiation Physics will be needed to understand potential issues of operating at such high currents and the upgrades required to support such an operating mode. Tentative parameters for such a mode have been developed with a maximum beam power of 3 kW; these are not listed in this document.

9 S30XL Phase A and Phase B Operating Modes

The maximum beam powers for various configurations are listed in Table 3. In Phase A, the primary goal is to quantify the dark current that can be extracted into the S30XL beamline and qualify the kicker/septum extraction system as well as the low current diagnostics. The maximum beam power extracted in normal operations is 4 Watts. This is controlled using the kicker repetition rate and/or the kicker pulse width.

The S30XL kicker performance is quantified by using dedicated LCLS-II 100 pC bunches and deflecting a single bunch into the S30XL beamline at low rate of less than 10 Hz (4 Watt maximum power) while varying the S30XL kicker timing. Diagnostics in the S30XL are used to steer the beam and confirm the initial optics. After the trajectory and optics are established, dark current can be deflected into the beamline and quantified. There are some additional experiments that might be performed using the Phase A beamline. These all require extremely low current (single electron experiments). The current is controlled by adjusting the S30XL kicker pulse length and amplitude to limit the extracted dark current.

In Phase B, there are three modes of operation anticipated: (1) very low current operation with ~150 pA of average beam current in ESA, (2) full current operation with a maximum of 220 Watts in ESA, and (3) tuning, which involves extracting dedicated LCLS-II bunches at 10 to 60 Hz as well as tuning on the dark current beam. Parameters for the operating modes are listed in the second column of Table 2.

As noted previously, the low current in ESA of of ~150 pA in the 1st mode is generated by attenuating the current from S30XL of roughly 25 nA in the A-Line. The beam current of 25 nA in S30XL is chosen to maintain resolution of diagnostics in LCLS-II and S30XL.

The tuning procedure is envisioned to consist of 4 steps: (1) setup of the S30XL kicker system as described above for Phase A, (2) setup of the beam optics through the S30XL and A-line using dedicated bunches from LCLS-II (25 Watt maximum power), (3) setup of dark current beam to ESA, and (4) setup of the spoiler and collimation systems to limit the current to the desired level. If necessary, experiments in ESA have a stopper upstream of them to prevent ‘high’ current beam from possibly damaging the experiment and this stopper is closed for the tuning procedures.

In all cases, the accident scenario involves extracting the full LCLS-II beam power of 250 kW into the S30XL beamline or through the vacuum chamber and into the BSY. During operation, this might occur if the LCLS-II is transporting all 250 kW to the BSY beam dump and the S30XL kicker timing is shifted by >300 ns. During tuning, this might occur if the S30XL kicker timing repetition rate is increased from the maximum tuning rate of 60 Hz towards the full rate of 929 kHz.

The S30XL and the LCLS-II Beam Containment Systems (BCS) must detect and stop such occurrences; the BCS requirements are described in S30XL-PR-002. The S30XL Machine Protection System (MPS) is also designed to detect such occurrences and trip at a lower threshold and faster timescale than the BCS; the MPS requirements are described in S30XL-PR-006. The S30XL MPS trips the S30XL kicker while the LCLS-II and S30XL BCS trips the LCLS-II RF gun.

10 Maximum Credible Beam and Expected Beam Losses

The maximum operating current that could be extracted from LCLS-II or LCLS-II-HE is defined to be <250 kW. The maximum credible beam (MCB) scenario arises when all rf power is fed into the beam. In this case, the LCLS-II Linac could generate a maximum beam power of up to 2 MW at the end of the LINAC [8] and the LCLS-II-HE linac could generate an MCB of 3 MW [9] at the end of the linac. However, for radiation shielding purposes, the MCB for LCLS-II and LCLS-II-HE is set at 250 kW in the LCLS-II Dump line as limited by the 2 LINAC ACMs (near L0 on the main LCLS-II beam line which eventually ends as the Dump line) which are Credited Controls [10]. Since the S30XL beamline is extracted from the Dump line, the same current limitation applies and therefore the MCB for S30XL is 250 kW.

The S30XL beamline is designed with apertures exceeding the S30XL Beam Stay Clear (BSC) as defined in S30XL-PR-012. In summary, the 'dark current' beam that is transported to the BSY has an energy that is defined by the LCLS-II Bypass acceptance and collimators (+/- 3% and +/- 2%, respectively) as well as a transverse phase space that is determined by the Bypass line collimators. The LCLS-II collimation system is a critical component for high power operation of LCLS-II and will always be used to protect the undulators from halo particles. The gaps of the collimators are specified to be +/- 16 times the beam size of a beam with a 1 um-rad normalized emittance at 4 GeV [4]. This corresponds to an admittance of the collimation system of 65 nm-rad. The BSC includes an additional +/- 2 mm for trajectory errors.

The dark current beam has a transverse extent less than +/-3 mm at the S30XL septum which is small compared to the aperture of 15 mm (see S30XL-PR-004). In both the vertical and horizontal, the BSC is usually dominated by the energy spread and dispersion. With a 2% energy spread, the vertical BSC remains smaller than +/- 10 mm throughout the S30XL beam line while the horizontal BSC remains smaller than +/- 20 mm; these are smaller than the vacuum aperture of 45 mm. Thus, after tuning the beam line, the expected losses in the S30XL beamline are <10 W along the length *except* when inserting diagnostics (profile monitors) to measure the beam properties.

When the beam passes through the spoiler in the A-line, there are large losses at the quadrupoles and collimators with essentially all of the beam lost (220 W maximum operating beam power) at those points. Without the spoiler inserted, some losses are still expected at the high dispersion points due to the large energy spread. If necessary additional energy collimation could be made in either the S30XL beamline or the beginning of the A-line to reduce the energy spread. Detailed calculations of the losses in the A-line are described in S30XL-PR-005.

11 References

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