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Revision History

Revision	Date Released	Description of Change
R0	4/30/2014	Original Release.

1 Purpose

This document describes the high level physics-driven parameters for LCLS-II SCRF 1.3 GHz Cryomodule.

2 Scope

Parameters for the LCLS-II SCRF 1.3 GHz Cryomodule are covered. Additional detail can be found in the LCLS-II Cryomodule Functional Requirements Document and the Engineering Specification Documents as well as the PRD's documents for the cryomodule components.

3 Definitions

SCRF linac	Superconducting RF linac installed in Sectors 0-10
CuRF Linac	Copper RF Linac installed in sectors 20-30 = LCLS-I
HXR	Hard X-Ray beamline and undulator located on South-side of LCLS Undulator Hall replacing the existing LCLS Undulator
SXR	Soft X-Ray beamline and undulator located on North-side of LCLS Undulator Hall
MAD	Beam optics code used for designing the LCLS-II beamlines
Spreader	A high repetition vertically deflecting element directing the LCLS-II beam either to the SXR or HXR beamlines or to the BSY dump
BSY	Beam Switch Yard at the end of the SLAC linac

4 References

N/A	See the LCLS-II MAD lattice files for beamline details
PRD# TBD	LCLS-II Global Requirements Document
LCLSII-1.1-PR-0133	LCLS-II Parameters PRD

LCLSII-2.4-PR-0041	LCLS-II Linac Requirements PRD
PRD# TBD	LCLS-II RF Power PRD
LCLSII-2.4-PR-0136	LCLS-II Beam Position Monitor Requirements PRD
LCLSII-2.4-PR-0081	LCLS-II Magnets PRD
LCLSII-2.4-PR-0082	LCLS-II Steering Correctors PRD
PRD# TBD	LCLS-II Availability PRD
PRD# TBD	LCLS-II Coordinate System

5 Responsibilities

N/A

6 Overview

As described in the Global Requirements Document, the LCLS-II will contain a superconducting linac (SCRF) operating with continuous RF fields as well as a Copper linac that is pulsed at 120 Hz. High level parameters for the LCLS-II are described the LCLS-II Parameters PRD. The SCRF linac will consist of 35 1.3 GHz 8-cavity cryomodules along with additional specialized cryomodules for 3.9 GHz cavities and perhaps for special injector cavities. The SCRF linac is broken into 4 segments L0, L1, L2 and L3 which are separated by warm beamline sections. A schematic of the SCRF linac is shown in Figure 1 and the requirements of the linac system are described in the Linac Requirements PRD.

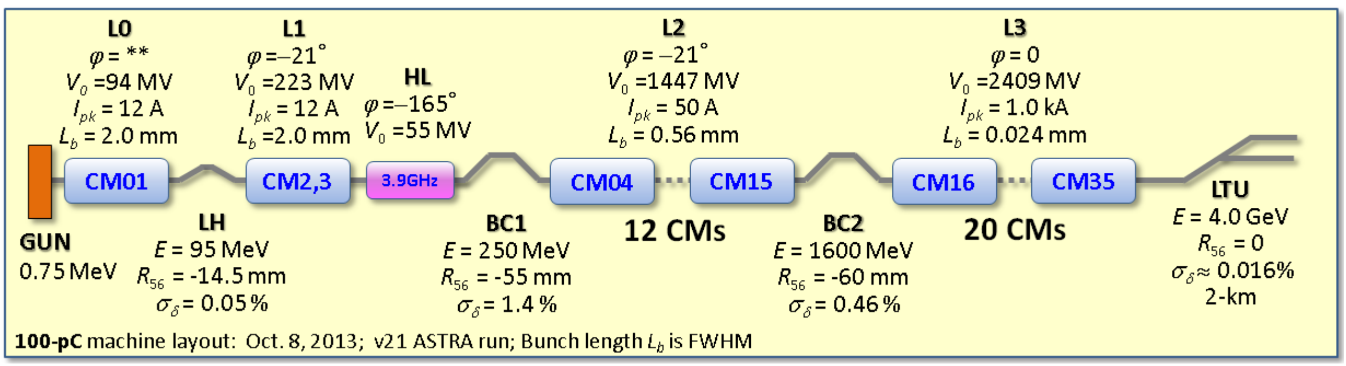

Figure 1. Schematic of SLAC linac tunnel showing some of the regions of the LCLS-II.

This document describes the requirements of the 35 1.3 GHz SCRF cryomodules. The LCLS-II SCRF parameters are also summarized in Table 3 of the LCLS-II parameters list at: https://slacspace.slac.stanford.edu/sites/lcls/lcls-2/ap/parameters/Forms/AllItems.aspx.

7 1.3 GHz Cryomodule

Each 1.3 GHz Cryomodule contains eight 1.3 GHz 9-cell cavities, each roughly 1-meter in length, a quadrupole, a BPM, an X and Y dipole corrector and a beam line Higher-Order Mode (HOM) absorber as illustrated in Figure 2. Each of these components is described in sections below and the summary requirements are listed in

Table 1, Table 2, and Table 3.

The cryomodule cavities will operate at 2K and are speced to operate with an average Q_0 of 2.7e10 at 16 MV/m CW. The dynamic heat load will be ~10W per cavity and there may be additional beam induced heat losses as high as 2 W per cavity. Including the static and dynamic loads, it is estimated that the average heat load per cryomodule will be 110 W at 2K equivalent and the maximum will be less than 140 W at 2K equivalent.

As described in the Linac Requirements PRD, the linac will be designed assuming that roughly 6% of the cavities are unpowered at any one time and thus the total cryopower can be reduced by this factor.

The maximum beam energy in a cryomodule will be 10 GeV and the quadrupoles and dipole correctors are sized accordingly although the power supplies will be sized for the local beam energy. All 35 cryomodules will be identical, except, in the baseline configuration, the first few cavities of the 1st cryomodule (CM01) may be modified for the very low energy injected beams.

Although not a requirement for LCLS-II, to enable future uses of the cryomodules, they are designed to accelerate beams in either direction and thus the cavities are spaced by roughly 35 cm so that the center of each cavity is separated by exactly 6 RF wavelengths. Similarly the cryomodules are designed to be spaced such that the center of the last cavity and the center of the first cavity in the subsequent cryomodule are spaced by 11 RF wavelengths, roughly 2.5 meters. When connected together the length of a cryomodule and interspace region is 12.22 meters and the active acceleration length 8.30 meters.

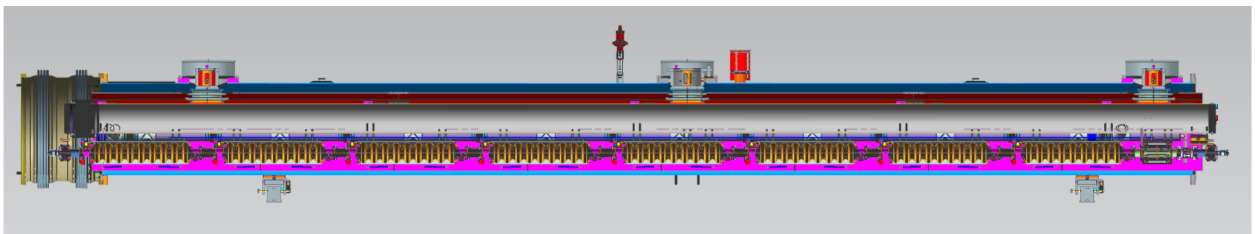

Figure 2. A schematic of a 1.3 GHz cryomodule with 8 cavities, quadrupole, bpm, dipole correctors and HOM absorber.

8 SCRF 1.3 GHz Cavity Package

Each 9-cell cavity package will include a 1.3 GHz 9-cell cavity that is 1.0377 m in active length. The cavities will be capable of operating at 16 MV/m CW with a Q0 = 2.7e10 at 2K. For the cryogenics, the acceptable variation of Q0 is large however, a low Q0 can be an indication of other performance limitations and we will specify Q0 > 1.5e10; it should also be noted that with a large variation, the average Q0 should be slightly higher than 2.7e10 so that the average of 1/Q0 < 1 / 2.7e10.

The individual cavities will be qualified to operate up to a voltage of at least 18 MV/m CW with at most a modest decrease in Q0 from the nominal performance at 16 MV/m. In addition, the cavity field emission current should be less than 25 pA at 16 MV/m which will limit the field emission dark current from a cryomodule to a power of less than 10 mW at the nominal gradient. Ideally, the cavities would be qualified at 25 MV/m with Q0 > 1e10 and maximum emitted dark current less than 2.5 nA; this will ensure the specified field emission currents at the nominal gradient and would provide future upgrade options.

Each cavity will include an adjustable fundamental mode coupler that can change the loaded Qext at least over the range of 1e7 to 5e7 and handle a maximum power of 7 kW CW with full reflection. All fundamental mode couplers will exit the same side of the cryomodule which in the LCLS-II Linac Coordinate System is to the negative X direction or, if looking along the length of the cryomodule toward the quadrupole located at the far end, the couplers all exit on the right side of the cryomodule. The fundamental mode coupler does not need any field symmetrization or modification in the main linac cryomodules; the injector cryomodule, CM01, may require a special fundamental mode coupler. A more detailed specification of the coupler requirements will be specified in the LCLS-II RF Power PRD.

Each cavity package will include a tuner system that is capable of tuning the cavity fundamental mode frequency >+/- 200 kHz with a resolution of 5 Hz and a fast tuner system based on piezo-electrics that can tune the cavity an additional +/- 1 kHz and a resolution better than 1 Hz. A more detailed specification of the tuner requirements will be specified in the LCLS-II RF Power PRD.

The RF cavity phase and amplitude stability tolerances are a function of location along the LCLS-II as specified in the Linac Requirements PRD. The tightest tolerances are in the L0 and L1 linacs. In L1, the tolerances are 0.01% ΔV/V and 0.01 degree at 1.3 GHz integrated through the 8 cavities in the cryomodule, i.e. roughly 0.03% and 0.03 degrees assuming uncorrelated errors between cavities. In L0 (CM01), the tolerances on the 1st cavity are 0.01% ΔV/V and 0.01 degree at 1.3 GHz while the tolerances on the rest of the cavities are similar to those in L1.

Substantial HOM power will be emitted by the beam. A large fraction of this power will be emitted at frequencies above the beam pipe cutoff and will need to be absorbed by a broadband HOM absorber located between cryomodules or in the cryomodules themselves – the absorber is discussed in Section 12.

The trapped HOM's can have an impact on the beam. The dipole HOM's will cause trajectory jitter due to variations in the beam current and will cause transients when changing beam current or the trajectory. The monopole HOM's will cause energy variation along the bunch train and will also induce transients when changing the beam current. Each cavity package will include two HOM couplers that will damp the deleterious trapped monopole and dipole HOM's to have loaded Q's below 1e6. The maximum HOM power that will be absorbed and removed by the HOM couplers is 50 W [1].

Table 1. Main 1.3 GHz Cryomodule and Cavity Parameters.

	Nominal	Min	Max
Number of cryomodules	35	-	-
Number of cavities per CM	8	-	-
Operating temperature	2K	-	-
Cryomodule heat load	110 W @ 2K	10 W @ 2 K	140 W @ 2K
RF frequency	1300 MHz	-	-
Average CW operating gradient	16 MV/m	5 MV/m	25 MV/m
Voltage per cryomodule	133 MV	40 MV	199 MV
Cavity active length (L)	1.0377 m	-	-
Cavity average Q_0	2.7×10^{10}	1.5×10^{10}	
Cavity R/Q	1036 Ω	-	-
Cavity tuner (slow)	-	5 Hz	± 200 kHz
Cavity tuner (fast)	-	1 Hz	± 1 kHz
Fundamental mode coupler Power	4 kW	0 kW	7 kW
Fundamental mode coupler Q_{ext}	4×10^{7}	1×10^{7}	5×10^{7}
Fundamental mode coupler dipole deflection			3×10^{-3}
HOM Monopole R/Q			175 Ω
HOM Dipole R/Q			3×10^{5} Ω/m
HOM damped Q value (monopole and dipole)			$\leq10^{6}$

HOM coupler power extraction	< 1 W		50 W
HOM coupler dipole deflection			3×10^{-3}
Required CM field amplitude stability	0.01% (rms)	-	-
Required CM field phase stability	0.01 deg (rms)	-	-

9 Quadrupoles

Each Cryomodule will include a quadrupole magnet located close to the downstream end of the cryomodule. The beam energy at the quadrupoles can range from 100 MeV to the maximum design energy as higher as 10 GeV. To facilitate matching and possible energy upgrades, the maximum integrated strength of the quadrupole magnet is 20 kG but most quadrupoles will operate at a small fraction of this value. The minimum stable operating integrated strength is 0.5 kG. Each quadrupole will be powered by an independent unipolar power supply.

The field stability requirement is $\Delta K/K < 1e\text{-}4$ rms to limit the focusing variant and the beam jitter due to offsets in the quadrupoles. The heat load of the quadrupole should be estimated assuming a maximum strength of 11 kG, corresponding to a beam energy of 6 GeV. The RF gradient may be reduced if the heat load becomes a limitation at larger excitations.

Although it is likely that not all quadrupoles will be powered, current leads for the quadrupole must be accessible on the outside of the cryomodule and clearly labeled wrt polarity and magnet. When the quadrupole is unpowered, the maximum residual integrated field is 8 G and this field should be less than a few mG at the nearest cavity surface. The aperture of the quadrupole magnet will be equal or larger than the aperture of the SCRF cavities. Additional specifications for the quadrupole magnets can be found in the LCLS-II Magnets PRD.

Table 2. Component specifications for the 1.3 GHz Cryomodules

	Minimum	**Maximum**
Quadrupoles		
Quadrupole integrated gradient	0.5 kG	20 kG
Quadrupole gradient stability ΔK/K, rms		0.01%
Unpowered quadrupole residual field		8 G
Dipole Correctors		
X/Y Dipole corrector integrated field	1 G-m	50 G-m
Dipole corrector field stability Δθ/θ, rms		0.1%
BPM		
Resolution	See BPM PRD	
HOM Absorber		
HOM Absorber frequency range	4 GHz	100 GHz
HOM maximum power absorption	-	50 W

10 Dipole Correctors

Each Cryomodule will include an X and Y dipole corrector magnet located close to the quadrupole magnet. The maximum integrated strength of the dipole correctors is 50 G-m but most will operate at small fractions of this value. At the low energy end of the linac, the peak corrector field will be 1 G-m. The power supplies of the correctors will be matched to the required maximum corrector strength. The field stability requirement is $\Delta G/G < 1e\text{-}3$ rms to limit beam jitter due to the corrector magnets.

Although it is likely that not all dipole correctors will be powered, current leads for each of these must be accessible on the outside of the cryomodule and clearly labeled wrt polarity and magnet. When unpowered, the maximum residual corrector strength should be less than 2 mG-m. The aperture of the dipole correctors will be equal or larger than the aperture of the SCRF cavities. Additional specifications for the dipole correctors can be found in the LCLS-II Steering Correctors PRD.

11 BPM

Each Cryomodule will include a BPM located close to the quadrupole magnet. The aperture of the BPM will be equal or larger than the aperture of the SCRF cavities. The BPM parameters, including bore and resolution requirements are described in greater detail in the LCLS-II Beam Position Monitor Requirements PRD.

12 HOM Absorber

A HOM absorber will be placed at the end of the cryomodule. The average HOM heating is expected to be <20 W [2] but variations along the length of the accelerator could make the local loads higher [3] and the absorber should be designed to handle a maximum of 50 W of HOM power. The absorber aperture may be smaller than that of the SCRF cavities.

13 Alignment

The alignment requirements for the cryomodule as limited by the beam dynamics is listed in Table 3 [4]. The tolerances are assumed to apply to all cryomodules These tolerances are for the alignment of the internal components with respect to the external cryomodule fiducials (when cold) and are expected to be dominated by the internal cryomodule misalignments; the ability to align the external fiducials in the tunnel should be better than 0.1 mm in X and Y and 0.2 mm in Z and will be a small contribution to the resulting misalignments of the internal components.

There are four sets of values: X, Y misalignments, Z misalignments, tilts and rolls. The first two are translations with respect to either the cryomodule fiducials or the linac centerline as noted. A 'tilt' is defined as a rotation about the local X or Y axis generating an X-Z or Y-Z slope and a 'roll' is defined as a rotation about the linac axis. In each alignment category, the first three values specify the alignment of internal components in the cryomodule which are assumed to be uncorrelated while the last tolerance is on the cryomodule itself.

Table 3. Alignment tolerances for the 1.3 GHz Cryomodules

Error Source	RMS error	unit
Cavity X,Y misalignments wrt. CM	0.5	mm
Quadrupole X,Y misalignments wrt. CM	0.5	mm
BPM X,Y misalignments wrt. CM	0.5	mm
Cryomodule X,Y misalignments wrt. Linac	0.3	mm

Cavity Z misalignments wrt. CM	2	mm
Quadrupole Z misalignments wrt. CM	2	mm
BPM Z misalignments wrt. CM	2	mm
Cryomodule Z misalignments wrt. Linac	2	mm
Cavity tilt misalignments	0.5	mrad
Quadrupole tilt misalignments	3	mrad
BPM tilt misalignments	3	mrad
Cryomodule tilt misalignments	0.05	mrad
Cavity roll misalignments	10	mrad
Quadrupole roll misalignments	3	mrad
BPM roll misalignments	3	mrad
Cryomodule roll	2	mrad

14 Availability

The LCLS-II should be able to deliver X-rays 95% of the scheduled user time. This imposes tight constraints on the performance of the SCRF linac. As noted in the Linac Requirements PRD, the SCRF linac has 6% spare cavities in case of RF system failure or a failure of the cavity components. This should ease some of the availability challenge. There are only a few cavities that are absolutely critical for operation such as the 1st few cavities in the Injector cryomodule CM01. Details of the availability requirements are described in the LCLS-II Availability PRD.

15 References

[1] N. Solyak, et al., LCLSII-TN-14-04.
[2] K. Bane, A. Romanenko, and V. Yakovlev, LCLSII-TN-13-04.
[3] K. Bane and P. Emma, Estimates of Power Radiated by the Beam in Bends of LCLS-II, LCLSII-TN-13-03.
[4] A. Saini and N. Solyak, LCLSII-TN-14-03.