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Revision History

Revision	Date Released	Description of Change
R2	4/7/2016	Updates to reflect results from 3.9 GHz CM PDR.
R1	9/18/2015	Various updates to reflect design changes.
R0	6/23/2014	Original Release.

1 Purpose

This document describes the physics-driven parameters for the two LCLS-II 3.9 GHz cryomodules (CMs).

2 Scope

Requirements for the 3.9 GHz cryomodules are presented. Additional detail can be found in the LCLS-II 3.9 GHz Cryomodule Functional Requirements Document and the Engineering Specification Document.

3 References

N/A	See the LCLS-II MAD lattice files for beamline details
LCLSII-1.1-GR-0018	Linac Coherent Light Source II Project Requirements
LCLSII-1.1-PR-0133	LCLS-II Parameters PRD
LCLSII-2.4-PR-0041	Linac Requirements PRD
LCLSII-4.1-PR-0098	RF Power and LLRF PRD
LCLSII-4.5-EN-0179	Cryogenic Heat Load
LCLSII-4.1-PR-0146	SCRF 1.3 GHz Cryomodule
LCLSII-1.1-PR-0163	Availability PRD
LCLSII-1.1-TS-0034	LCLS-II Beamline Coordinates

4 Responsibilities

Marc Ross	Cryogenic System Manager
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5 Overview

As described in the Project Requirements Document, the LCLS-II undulators are driven by beams from a superconducting RF (SCRF) linac operating with continuous (CW) RF fields. High level parameters for the LCLS-II are described the LCLS-II Parameters PRD, and the requirements for the linac are described in the Linac Requirements PRD.

The SCRF linac consists of 35, 1.3 GHz, 8-cavity CMs, and two 3.9 GHz, 8-cavity CMs, which are the subject of this document. The 3.9 GHz CMs are located just before BC1 as illustrated in

Figure 1 and are used to 'linearize' the non-linear, sine-wave like energy variation along the bunch induced by the 1.3 GHz rf acceleration. Table 1 summarizes the main parameters of these CMs.

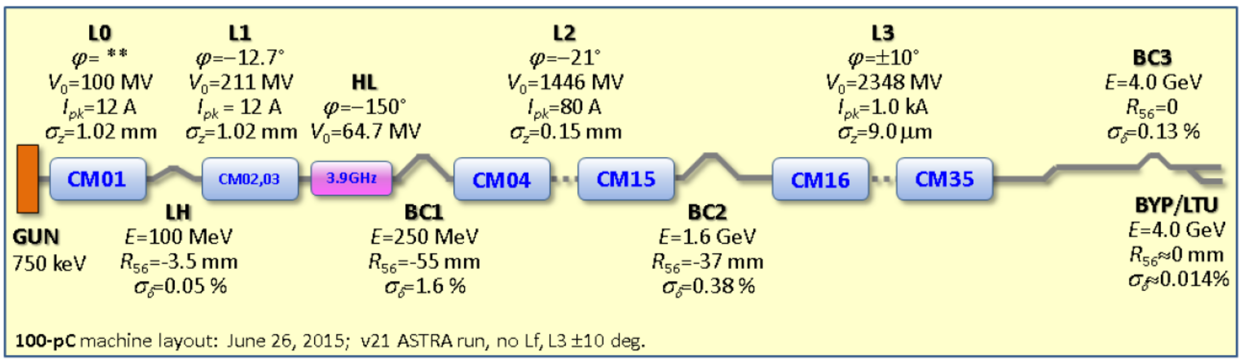

Figure 1. Schematic of the LCLS-II SCRF Linac.

Table 1. Main 3.9 GHz Cryomodule and Cavity Parameters.

	Nominal	Min	Max
Number of CMs	2	-	-
Number of Cavities per CM	8	-	-
Number of Active Cavities	14		16
Operating Temperature	2 °K	-	-
Cavity Average Q_0 and Min Value	2.0×10^9	1.5×10^9	-
Average Operating Gradient with 14 Cavities	13.4 MV/m	-	14.9 MV/m
On Crest, 14 Cavity Voltage	64.7 MV	-	72.0 MV
Nominal Beam to RF Phase	-150°	-90°	-180°
Active Cavity Length (L)	0.346 m	-	-
Cavity R/Q	750 Ω	-	-
Fundamental Mode Coupler Q_{ext} (Fixed)	2.7×10^7		

6 3.9 GHz Cryomodule

Each 3.9 GHz CM contains eight 9-cell cavities, each 0.346 m in active length with a 30 mm minimum aperture. Unlike in the 1.3 GHz CMs, the cavity spacing does not have to be an integer number of half-rf-wavelengths (i.e. bi-directional beam operation is not anticipated in future operation of these cavities). In fact, having integer number of half-wavelengths plus a quarter-wavelength would be helpful to suppress the upstream propagation of dark currents.

The vacuum vessel (cryostat) will be about 6.5 m long, will have same diameter as that for the 1.3 GHz CMs (to keep a similar cryogen transport cross section) and will have the same basic thermal shielding, interconnect and cooling scheme. The beam pipes (bellows and straight sections) will be 38 mm in diameter except between the beam position monitor (BPM) and the gate valve, and in the CM interconnect region, where they will be 78 mm in diameter. All beam pipes will be copper plated on the inside to reduce the heating by HOM and evanescent fundamental mode fields.

To minimize RF kicks from the fundamental and HOM couplers, every other cavity will be rotated 180 degrees about the beam axis. Thus the power couplers will extend out of the CM vessel on both the aisle and wall side. Due to the limited space on the wall side, the waveguide that connects to the coupler ports on this side may have to come preinstalled on the CM.

The CM will not contain a quadrupole magnet nor dipole magnets but will have a BPM. However, there may be a need at a future date for dipoles magnets, so a magnet lead feed-through panel is to be installed on the CM vacuum vessel. The HOM signals will brought out of the CM (although not necessarily extended to the gallery) and can be used to monitor beam position relative to the cavity electrical centers if so desired.

Upstream of the first CM, in the interconnect region, there will be a higher-order mode (HOM) beam line absorber of the EuXFEL design (as is the case for most 1.3 GHz CMs). They provide at least 100 W of power handling capability. There will also be one installed downstream of the first CM, but not after the second CM given that there will be a room temperature section (BC1) that follows it.

For nominal operation, the sum of the on-crest cavity voltages will be about 65 MV but up to 72 MV is requested for other possible operation scenarios. Given the alternating orientations of the cavities to reduce RF kicks, equal numbers of cavities of each orientation should be powered. With two cavities held in reserve (i.e., one of each orientation that is not powered), the remaining 14 would need to operate up to a 14.9 MV/m gradient on average.

The cavities will be cooled to 2 K and are spec'd to have an average Q_0 of 2.0×10^9 at 14.9 MV/m, which is currently achievable without using the doping techniques recently developed to increase Q_0. The corresponding heat loads are discussed in LCLSII-4.5-EN-0179. For 300 μA operation, this includes 13.5 W per CM of beam-induced HOM power above cutoff, with 20% of this being absorbed in the 2 K non-SC beam pipes and 80% in the 55 K beam line absorbers or in the downstream BC section. The HOM power generated due to the 78-to-38 mm transitions is expected to be about 0.5 W per CM for a 300 μA beam – this loss is included in the 13.5 W per CM estimate. For a 100 μA beam, the loss is one third of the 13.5 W per CM value.

Modifications similar to the ones being done to adapt the 1.3 GHz EuXFEL CMs for LCLS-II CW operation will be applied to the pulsed 3.9 GHz CM design used at FLASH. The changes include widening the He 2-phase line and cavity chimneys, improving the cooling of the HOM antennas (without increasing the HOM Q_{ext} values) and modifying to the input coupler to allow higher average power operation (the maximum coupler temperature should not exceed about 450 K). Currently there are no plans to develop higher Q_0 3.9 GHz cavities using N_2 doping.

7 3.9 GHz Cavity Package and Operation

The cavities developed for FLASH operate routinely at 19 MV/m CW. For LCLS-II, they need to be qualified to18 MV/m in vertical tests without quenching, fast Q_0 drop or high (Rad/hr level) radiation emission. At 14.9 MV/m, the captured dark current in each of two CMs should not exceed 1 nA.

Each cavity will include a fundamental mode coupler with a fixed coupling of $2.7\times10^7 \pm 10\%$. This value was chosen to zero the input power required in steady state when running with the full beam current (300 μA) at 14.9 MV/m with the nominal -150° beam-to-RF phase and the cavity detuned by +42.6 Hz (out of a 147 Hz BW) to cancel the out-of-phase loading. However, when running with these parameters, one may want to alter the detuning and increase the input power accordingly to allow better regulation of the cavity fields.

To fill the cavity with the beam off to a gradient of 14.9 MV/m, up to 900 W of 3.9 GHz power is required from the RF source. This allows for a 19% transport loss, a 10% RF overhead, 10% Q_L variation and up to 30 Hz of additional detuning (microphonics), for a maximum of 72.6 Hz detuning. With the beam on and being de-accelerated, the required power will be lower. Although 30 Hz is budgeted for the microphonics, efforts will be made to reduce the source of this detuning and to suppress it with piezo-electric actuators.

With a 300 μA beam current, a 14.9 MV/m gradient and a 180° beam-to-RF phase, the beam loses about 1.54 kW of power in each cavity. With a cavity 30 Hz off resonance, the input power would be about 64 W, so in this case the coupler sees a total equivalent power (in terms of heating) of 1.67 kW. If the RF source is off, the cavity is in tune and the current is 300 μA, the cavity gradient will be 17.2 MV/m and the power to the coupler will be about 1.8 kW. Thus the couplers need to be rated for at least 1.8 kW of average power (in particular, they need to operate below the peak temperature noted above).

The RF sources, waveguide, directional couplers and isolators are to be specified for 300 μA beams for the initial linac operation. That is, the RF source needs to produce at least 900 W at 1 dB compression, and the isolators and directional couplers need to operate with this power at full reflection from the cavities or under the conditions noted above.

The cavities need to have slow tuners with at least a 750 kHz range and fast, piezo-electric actuators with at least a 1 kHz range. The fast tuners need to have a resolution of 1 Hz or better and will be used to suppress microphonics if it is significant.

In operation at FLASH, pulse-to-pulse stabilities of $\leq 2\times10^{-5}$ in gradient and ≤ 0.003° phase have been achieved in the four cavities (when summed) using vector sum feedback. At LCLS-II, each cavity will be powered by a separate RF source and RF feedback will be used to meet the requirements of 0.01% amplitude and 0.01° phase stability on short (seconds) time scales. Other tuning procedures will be used to remove longer term drifts.

Each cavity package will include two HOM couplers that will damp the deleterious trapped monopole and dipole HOMs. The loaded Q levels need to be below about 1×10^6. The maximum HOM power that will be removed by the HOM couplers is expected to be about 4 W.

8 Alignment

The alignment requirements for the CMs are similar to those for the 1.3 GHz CMs and are summarized in Table 2. 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 row specifies the alignment of internal components in the cryomodule, which are assumed to be uncorrelated, while the second row tolerance is for the cryomodule itself.

Table 2. Alignment Tolerances for the 3.9 GHz Cryomodules

Misalignment	**RMS error**	**unit**
Cavity and BPM X,Y misalignments w.r.t. CM	0.5	mm
Cryomodule X,Y misalignments w.r.t. Linac	0.3	mm
Cavity Z misalignments w.r.t. CM	2	mm
Cryomodule Z misalignments w.r.t. Linac	2	mm
Cavity tilt misalignments	0.5	mrad
Cryomodule tilt misalignments	0.1	mrad
Cavity roll misalignments	10	mrad
Cryomodule roll	2	mrad

9 Availability

The LCLS-II should be able to deliver X-rays 95% of the scheduled user time. To ensure the 3.9 GHz linearizer operates as desired, one extra cavity is provided per CM. Detailed availability requirements can be found in the LCLS-II Availability PRD.