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NEW X-BAND RF DEFLECTOR FOR FEMTOSECOND DIAGNOSTICS OF LCLS-II BEAMS*

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Abstract

An X-band Transverse deflector CAVity (XTCAV) has been successfully developed for femtosecond electron and X-ray pulse temporal diagnostic at the Linear Coherent Light Source (LCLS). The working frequency for the deflector is 11.424 GHz. New free electron laser LCLS-II has two undulator beamlines, one Soft-X-Ray (SXR) and another Hard-X-Ray (HXR). The HXR line deflector is made of two one-meter long XTCAVs. We have designed, built, installed and commissioned another, 1.5 meter long X-band deflector in the Soft-X-Ray beam line. Both HXR and SXR deflectors share one klystron. RF power is transmitted from a 50 MW klystron to a tunnel in an overmoded circular waveguide and then directed to either of the deflectors using a remotely controlled variable RF power splitter. The power split ratio can be changed arbitrarily, and both deflectors can work simultaneously. The system is successfully commissioned and operational. In this article, we provide details on the development and commissioning of the new deflector.

INTRODUCTION

LCLS is the world's first hard X-ray free electron laser. It allows for X-ray snapshots of atoms and molecules at work, providing atomic resolution detail on ultrafast timescales to reveal fundamental processes in materials, technology and living things [1]. One of the most important tools for electron beam diagnostics in LCLS is X-band transverse deflecting structures [2, 3]. XTCAVs are used in the LCLS accelerator for bunch length and beam longitudinal phase space measurements. The high frequency time variation of the deflecting fields streaks the electron bunch while the resulting transverse beam shape measured on a profile monitor represents the absolute bunch length [2, 3]. The LCLS-II is an evolution of the original LCLS with a much higher pulse repetition rate, it is also will benefit from the diagnostic capabilities of the XTCAVs. In LCLS-II there are two X-ray beam lines: HXR line and SXR line. To achieve femtosecond resolution, the XTCAVs are driven by a SLAC 50 MW XL-4 klystron. The klystron and its high voltage modulator are the most expensive components of the system. Rather than purchase a second XL-4 klystron and modulator we chose to use one klystron with a power splitter [4]. This paper will provide details of upgrading the original HXR system with its original two-cavity-deflector, and the addition of a new, simultaneously operated single-cavity deflector on the SXR beamline. The new layout is shown in Fig. 1.

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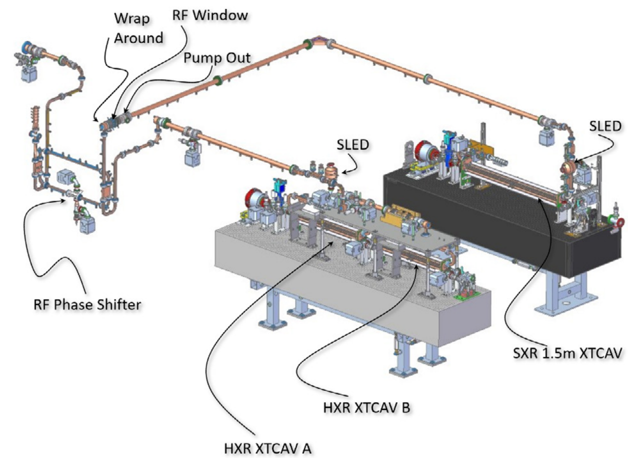

Figure 1: System layout showing the rf deflectors (XTCAVs) of HXR and SXR beam lines. RF power from klystron is coming from the left. LCLS electron beam direction is from the left to right.

Upgrade Goals and Approach

The aim of the modernization was to create a system for measuring the longitudinal phase space of electron beams with a femtosecond resolution, which allows reconstructing the temporal structure of an X-ray pulse in an FEL for alternating operation in two X-ray beams. The goal of the upgrade was to build a system for measuring the longitudinal phase space of electron beams with a femtosecond resolution, which allows reconstructing the temporal structure of FEL X-ray pulse for interleaved operation in two X-ray beamlines, HXR and SXR, at LCLS repetition rate of 120 Hz. To achieve this, we proposed following:

- Build, tune and install a new, longer RF deflector in the Soft X-Ray beamline.
- Build, tune, install a new SLED rf-pulse compressor for operation with new 1.5 m deflector.
- Build, and install a multi-megawatt RF variable power splitter based on a remotely controlled phase shifter.
- Move HXR SLED closer to HXR deflector, install both HXR and SXR SLEDs downstream after the rf power splitter.
- Upgrade the control system for operation with the copper linac, then upgrade it for superconducting linac of LCLS-II.

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NEW HARDWARE

1.5 m Long RF Deflector

The HXR line uses two 1 m long XTCAVs [2] fed from a power divider. The performance of a deflector is ultimately limited by rf breakdowns, which in turn limit input rf power into the deflector. The two-cavity system achieves higher deflecting voltage required for diagnostics of higher energy HXR beams, but is more costly to fabricate. The electron beam in the SXR line has lower energy, so the same temporal resolution as the HXR can be achieved with a single deflector. To compensate some of the lost voltage, we increased the length of the deflector from 1 m to 1.5 m. The deflectors are constant impedance structures and share identical electrical design, with added regular cells for longer deflector. The parameters common for both deflectors are shown in Table 1. The parameters which depend on lengths of the deflectors are shown in Table 2.

Table 1: Common Parameters of both 1 m and 1.5 m 11.424 GHz XTCAVs

Parameter	**Value**
Frequency	11.424 GHz
Beam pipe diameter	10 mm
Phase advance per cell	$2\pi/3$
Kick/m in one cell@20 MW	31 MeV/m
Max. el. field (inp. coupler)	100 MV/m
Max. mag. field (inp. coupler)	405 kA/m
Max. el. field in first cell	115 MV/m
Max. mag. field in first cell	340 kA/m
Peak pulse heating in first cell@110 ns	16 °C@20 MW
Peak pulse heating in coupler@110 ns	23 °C@20 MW
Cell quality factor	6300
Dipole mode frequency separation	100 MHz
Group velocity/speed of light	3.2 %

Table 2: Parameters of 1 m and 1.5 m XTCAVs

Parameter	**1 m**	**1.5 m**
# cells	117	171
Total structure kick@20MW	24 MeV	30 MeV
Total attenuation	0.62 Np	0.90 Np
Dissipated power@20MW	14 MW	16.7 MW
Structure length (with beam pipes)	1.185 m	1.657 m
Fill time	~ 110 ns	~ 160 ns

Variable RF Power Splitter

We have developed an adjustable RF power splitter to enable one klystron to power two RF deflectors with an arbitrary power ratio. Our splitter must meet the following requirements: reliably and reproducibly direct a pre-set power to any of the deflectors, operate at a power of 40-50 MW without faults, and allow a transition to an operating mode in which all the power of the klystron is supplied to any of the deflectors pulse to pulse. The splitter consists of two waveguide hybrids, a remotely controlled phase shifter and auxiliary components such as pumpouts and rf loads. When we started the project we had two previously developed phase-shifters, one designed by Chris Nantista, and more recent one developed by Sami Tantawi and based on a compact high power polarizer [5]. The former was well tested at high power, but the latter is more compact. We adopted the polarizer-based phase-shifter after extensive high-power testing.

MANUFACTURING AND TUNING

1.5 m Deflector

This 1.5 meter long X-band rf deflector is currently the longest of its kind built at SLAC or elsewhere. All cell machining was done at the SLAC Advanced Prototype Fabrication machine shop. Fabrication was completed by diffusion bonding the cells in two half-length structures then joining these and the couplers together with specially designed center coupling cells with high temperature brazing. The bonding and brazing were done in an atmospheric pressure hydrogen retort furnace. Before tuning the completed assembly was straightened to within 200 μm. For preliminary tuning and post-tuning characterization we used the nonresonant perturbation technique, the so-called beadpull [6, 7]. Setup of the final beadpull is shown in Fig. 2. For the tuning of the deflector we used the nodal shift method [8] with a reflective plunger. During the measurements and tuning, the deflector was filled with pure dry nitrogen and its temperature was stabilized to 20 °C ± 0.05 °C.

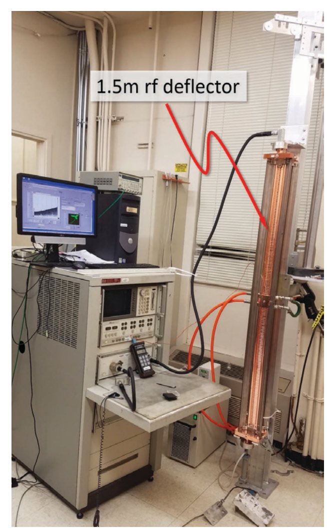

Figure 2: Final beadpull measurements of new 1.5 m rf deflector.

The amplitude and phase of electrical field were obtained by analyzing the reflection from a small ceramic bead moving along the central axis of the deflector. Figure 3(a) shows the measured electrical field amplitude along the central axis.

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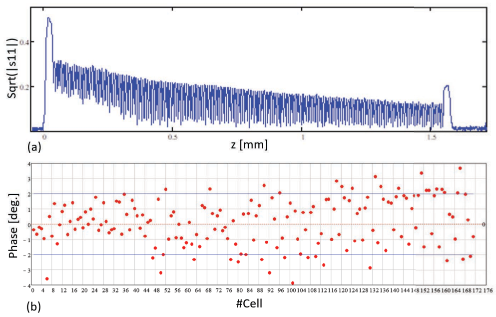

Figure 3: Results of beadpull measurements for the new 1.5 m rf deflector: (a) RF electric field amplitude along the central axis ; (b) Difference between beam synchronous phase and rf phase along the central axis.

This data shows that there is no internal standing wave, this means that the tuning was successful. Figure 3(a) shows the measured rf phase variation from beam-synchronous phase along the central axis of the deflector *vs.* cell number. Random phase variation of ±3 ° has no appreciable effect on deflector operation.

New SLED

The second SLED had the same design as one already feeding HXR XTCAVs [9]. It consists of a compact polarizer [5] and a spherical cavity. The tuning of the cavity was done in two steps. The cavity is build in with a ridge-to-be-cut and a post for deforming the cavity top. The ridge was cut after "before final brazing" cold test to put the frequency in the range of the deformation tuner. The final cold test of the cavity is shown in Fig. 4. The final parameters of the cavity were a good fit for feeding the new deflector.

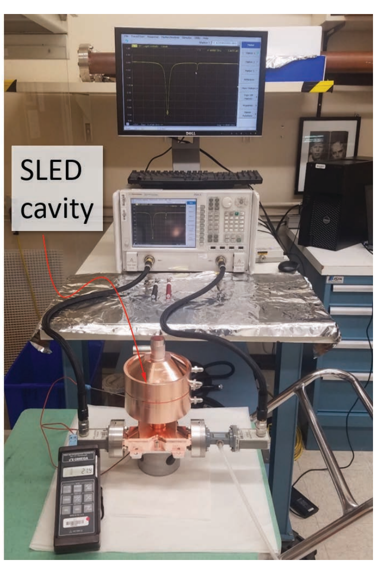

Figure 4: Cold test of new SLED rf pulse compressor.

Variable RF Power Splitter

The rf power splitter was built out of previously developed components such as waveguide hybrids, bends, dry high power rf loads, etc. Again, most of the components were built at SLAC Advanced Prototype Fabrication machine shop. Before installation the splitter was successfully cold tested. The cold test setup is shown in Fig. 5.

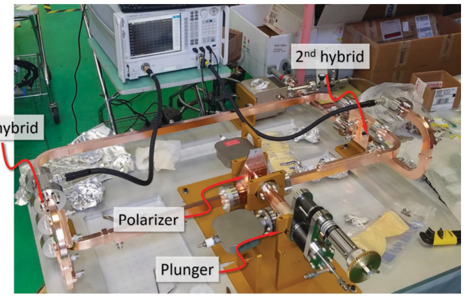

Figure 5: Cold test of variable RF power splitter.

CONTROLS UPGRADES

With the addition of the new SLED and XTCAV in the SXR beamline, several controls upgrades were completed to support the independent and simultaneous operation of two SLEDs and both the XTCAVs in the HXR and SXR beamlines. Some of these upgrades are summarized below

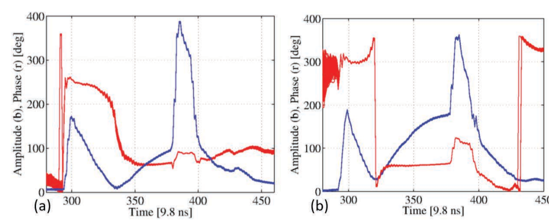

Figure 6: Typical output signals of (a) SXR and (b) HXR SLED RF pulse compressors. Red curves are amplitudes in arbitrary units and blue curves are phases in degrees. The resonant frequencies of the SLED cavities are controlled independently from each other with cooling water temperature.

with brief notes on the main LLRF software upgrades.

- A second *phase and amplitude detector* (PAD) was added to read in the LLRF signals from the SXR XTCAV and the SXR SLED cavity. An example of SLED output signals measured with the PADs is shown in Fig. 6.
- Vacuum controls were upgraded to precisely monitor and control the vacuum in the new RF waveguides and waveguide components.
- As second remotely controlled water chiller for the new SLED and additional temperature sensors were added for temperature monitoring and feedbacks.
- The LLRF Feedback Controls Software was upgraded to support the SXR XTCAV operation.

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Table 3: Summary of Practically Achieved Parameters for HXR and SXR RF Deflectors

Parameter	**HXR**	**SXR**	**Units**
Beam Energy	4-14	4-10	GeV
Beam emittance	0.5	0.5	μm
Structure length (with beam pipes)	2×1.185	1.657	m
Number of regular cells (including joining ring)	2×113	171	
Input power	$70 + 70$	70	MW
On-crest deflecting voltage	80	60	MeV
Resolution achieved	0.5-2	1-4	rms fs
Distance deflector-screen	32	32	m
Beta functions at RF deflector	80@8 GeV	80@8 GeV	m
Beta functions at the screen	63@8 GeV	55@8 Gev	m

The original Software Multiplexer (MUX) for the HXR was split into two virtual MUX-es for independent LLRF Feedback Controls of the two deflectors. This was based on the allocation of the Data Slots corresponding to the two beamlines wherein the two feedbacks are regulated independently of each other. Two different timeslots are used to manage and detect the beam arrival time into HXR and SXR beamlines. The XTCAV LLRF Software is able to support independent LLRF Feedback Controls for the two cavities by setting up and managing two different configurations of these timeslots corresponding to two pairs of data slots. The two data slots have independent settings and read-backs thus allowing the user to configure both the cavities for different rf phase and amplitude values of the klystron output. With these upgrades to the LLRF Feedback Software, deflectors in both beamlines could operative simultaneously, at LCLS rate of 120 Hz, in spite of coupling of the deflectors though the klystron and common rf distribution. This simultaneous operation was a significant milestone for LLRF feedback controls in the LCLS two-beamline (HXR and SXR) operations, and a predecessor for other LLRF stations' feedback controls that are yet to come for future operation with LCLS-II superconducting linac.

OPERATION

The system was installed at the beginning of October 2020 and we started high power processing and commissioning of controls system. A photo of 1.5 m deflector in SXR beamline is shown in Fig. 7. First successful streaking of the SXR beam was done on November 7th 2020. Since then the deflectors are routinely used by LCLS operators to tune the linac and FEL. As an example we show images of the streaked beams in Fig. 8. Typical working parameters of the system are shown in Table 3.

ACKNOWLEDGMENTS

This work is an excellent example of successful and coherent work of multiple SLAC departments: Accelerator Directorate, Technology-Innovation-Directorate, Mechanical Fabrication Department, Facilities and Operation, etc. Together they maintain SLAC competence in high gradient normal conducting accelerators.

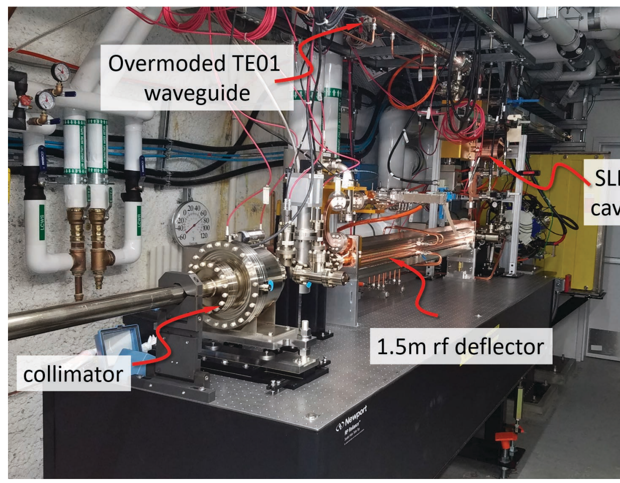

Figure 7: New 1.5 m rf deflector installed in Soft-X-Ray beamline. LCLS beam is coming from the left.

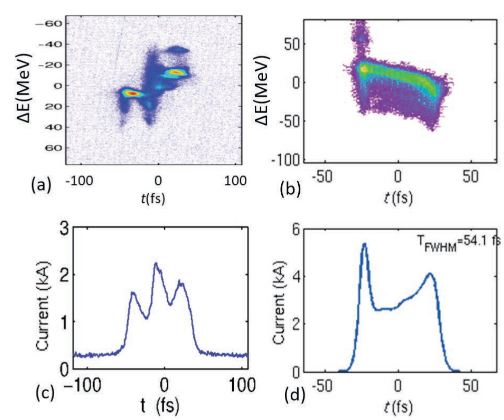

Figure 8: Measurement of lasing LCLS beam's longitudinal phase space using SXR and HXR rf deflectors: (a) image on SXR screen with it current profile in (c); (b) image on HXR screen with it current profile in (d).

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