SUB-fs RESOLUTION WITH THE ENHANCED OPERATION OF THE X-BAND TRANSVERSE DEFLECTING CAVITY USING AN RF PULSE COMPRESSION SLED CAVITY*

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Abstract

The successful operation of the x-band transverse deflecting cavity (XTCAV) installed downstream of the LCLS undulator has been further enhanced by the recent addition of an RF pulse compression "SLED" cavity that doubles the temporal resolving power of this powerful diagnostic system for measurement of the longitudinal profile of both the electron bunch and the x-ray FEL pulse. RF pulse compression has allowed us to use the existing SLAC X-band klystron with nominal output power of 50 MW and extend the RF pulse length by a factor 4 to give us 4 times the peak power after compression. A new, innovative SLED cavity was designed and built at SLAC to operate efficiently at X-band. The elegant design uses a small spherical cavity combined with a polarizing mode coupler hybrid. We report on the installation, commissioning and beam measurements demonstrating the sub-femtosecond resolution of the XTCAV system.

INTRODUCTION

The X-band RF deflecting structure, commonly referred to as the XTCAV, installed at the SLAC National Accelerator Laboratory Linac Coherent Light Source, LCLS, has been in operation for two years now, serving as a diagnostic for both the electron beam and the x-ray photons[1]. The features setting this device apart from other RF deflecting cavities are the x-band operation together with the placement of the device at the end of the FEL undulator in the electron beam dump line. Operation at X-band has resulted in about a factor 8 greater kick strength than the S-band devices installed in the linac. This allows us to measure and resolve the femtosecond long bunches that we are able to produce in the LCLS. By installing the device downstream of the undulator and viewing the streaked beam on a screen in a region with vertical dispersion we are able to both observe the longitudinal phase space of the electron bunches and witness the time-dependant energy loss within the bunch due to the FEL process. The location of the deflecting structure and observation screen relative to the undulator is shown schematically in Fig. 1. Since these components are downstream of the undulator their operation is non-invasive to normal operation for photon users. There is one caveat to this statement which we will mention when the RF jitter performance is discussed.

* This work was supported by Department of Energy Contract No. DE-AC0276SF00515

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The XTCAV system has allowed a multitude of diagnostics to be performed that characterize the temporal profile of both the electron and photon beams [2]. The temporal profile of the photon beam is reconstructed from the energy loss temporal profile of the electrons, and is recorded on a shot by shot basis by the photon users to correlate with their experiment data. The XTCAV has also enabled exotic setups to be implemented at the LCLS such as twin bunch operation, two-color experiments and slotted spoiler foil operation [3].The XTCAV system is invaluable in this set up since one can observe which slices of the bunch are lasing and at what relative energy.

To make this versatile system even better we have sought to boost the temporal resolution of the measurements by doubling the transverse kick strength of the XTCAV which in turn requires increasing the input RF power by a factor 4.

SLED PRINCIPLE

SLED is an acronym used at SLAC that originally meant *SLAC Linac Energy Doubler*, where RF pulse compression was used to double the accelerating gradient of the SLAC linac by adding RF storage cavities to the output of the klystron. The S-band output power of the klystron could be compressed a factor 4 with two high-Q cavities connected by a hybrid coupler. SLED has since become a generic name for any RF pulse compression cavity scheme. Although a two cylindrical cavity SLED scheme with hybrid coupler could be designed for X-band operation it was considered too complex and costly to implement at this shorter wavelength.

Instead, a new and elegant SLED cavity design was recently conceived, built and tested at SLAC [4] based on a single, compact spherical cavity with a polarizing, mode converting coupler.

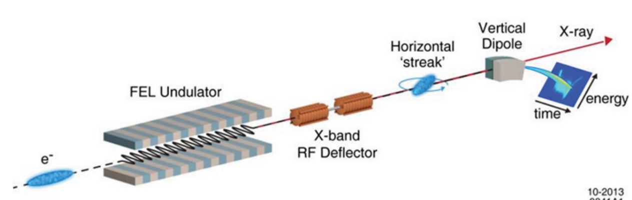

Figure 1: Layout of the X-band RF deflecting structure at the exit of the LCLS undulator where the beam is streaked horizontally and the electrons are bent vertically onto a spectrometer screen.

ISBN 978-3-95450-177-9

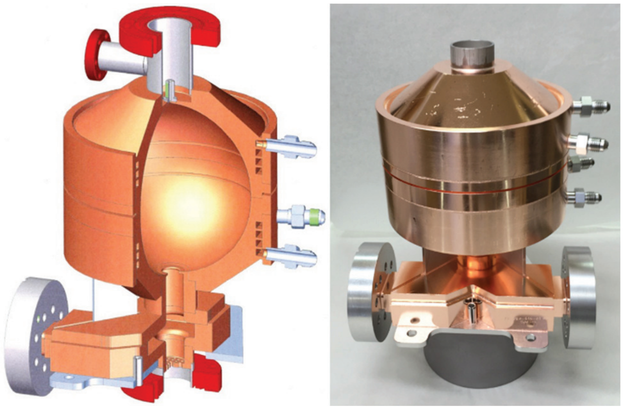

Figure 2: Cut-away view of the X-band SLED cavity together with a photo of the brazed cavity and coupler assembly.

The spherical SLED cavity, shown in Fig. 2, is fabricated from brazed copper and has an internal diameter of less than 12 cm. The quality factor for a perfect sphere depends only on the sphere diameter, a, and the skin depth, δ, and is $Q_0 = \frac{a}{\delta}$, giving Q_0=94,000 for δ=0.61 μm at 11.424 GHz.

The input TE01 mode converts to both TE01 and TE02 modes in a widened rectangular waveguide region, and their magnetic field components will couple to two perpendicular polarized TE11 modes in the circular wave guide. The geometry is adjusted so the phases of the two polarized modes are in quadrature. If the circular waveguide feeds a spherical cavity as shown in Fig. 3, two corresponding polarized spherical modes will act in similar fashion to the two modes from the two cylinders in a traditional S-band SLED system.

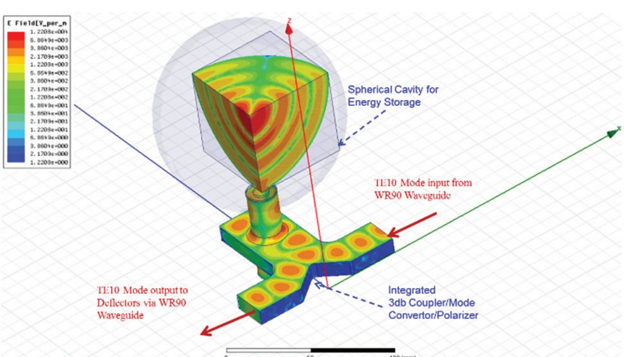

Figure 3: The incoming TE01 waveguide mode converts to two TE11 modes in the circular guide which couples to the two circularly polarized spherical modes in the cavity.

SLED INSTALLATION AT THE XTCAV

The SLED cavity is mounted at the output of the X-band klystron located in the support building above the beam line tunnel. The chosen location is a compromise between accessibility for cooling and instrumentation versus subjecting the long waveguide run to the deflecting structure to the high peak power from the SLED output.

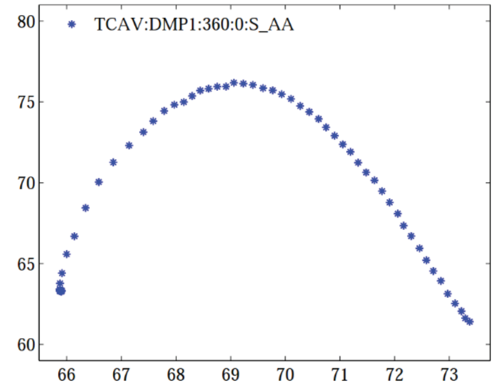

Figure 4: Temperature sensitivity of the SLED cavity is shown when the output power [MW] is plotted versus temperature [deg. F].

The waveguide and waveguide windows had previously seen 50 MW output power from the klystron so we spent several weeks gradually raising the peak power to the new level of around 200 MW in order to RF condition the cavity, waveguide and windows.

The SLED cavity is cooled from a separate chiller system so that its temperature may be set independently to either tune or detune the system. When tuned, the SLED cavity is kept at 69°±0.5°F, as shown in Fig. 4. If it is desired to run the system in non-SLED mode the temperature of the cavity is raised by a nominal 20°F to detune it. In non-SLED operation a klystron pulse of up to 50 MW peak power and 200 ns duration is applied to the deflecting structure, whose fill time is 100 ns. The chosen method of using the temperature to detune the cavity avoids the use of expensive and complex mechanical tuners for the job.

When the system is operated in SLED mode the RF pulse is lengthened to 1 μs and the output phase is flipped 180°in the last 200 ns of the pulse. The fast phase change is implemented by programming the I&Q modulator used in the programmable Phase and Amplitude Controller (PAC) in the low level RF system.

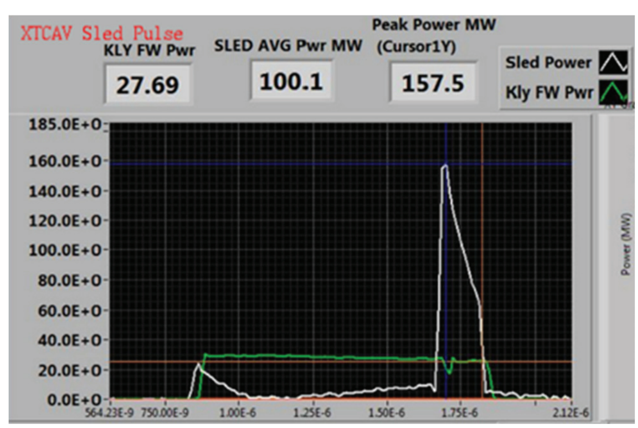

Figure 5: SLED RF output pulse from the SLED cavity (white) peaks rapidly when the phase is reversed and gives 4 times the average power in the last 200 ns compared to the 1 us pulse from the klystron (green).

ISBN 978-3-95450-177-9

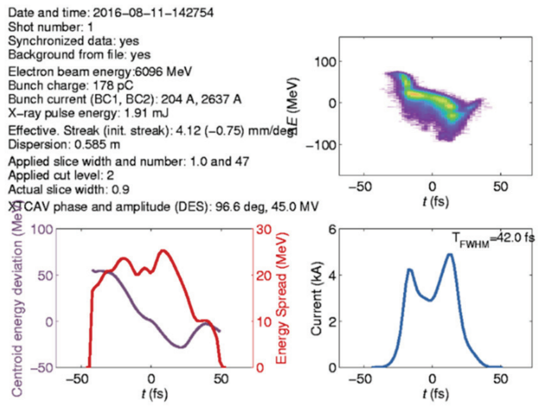

Figure 6: Streaked image (top right), longitudinal charge profile (bottom right) and reconstructed photon profile (bottom left) during non-SLED operation.

The power from the output side of the SLED cavity coupler remains quite low at the beginning of the klystron RF pulse, as shown in Fig. 5. However, when the phase flip occurs in the klystron RF, the output from the SLED cavity rapidly increases producing the characteristic narrow SLED pulse seen in Fig. 5.

The output pulse length from the X-band klystron is increased by a factor 5 in order to operate in SLED mode and this brings with it a new set of challenges. The average output power of the klystron is 5 times higher and this has an impact on the expected peak power performance and expected lifetime of the tube. The X-band klystrons are only manufactured in small quantities at SLAC and limited experience is available in regard to long term performance.

The longer klystron pulse also requires a longer output pulse from the modulator requiring a change in the pulse forming network. The modulator was initially unable to handle the increase in average power which required us to replace the AC power line transformer with a higher rated unit.

BEAM MEASUREMENT

Successful measurement with the XTCAV system requires that the RF be timed to the beam arrival to within 8.4 ns (1 timing clock cycle) and that the RF phase be set to the zero phase crossing within 0.1°X-band. This is done empirically by first observing the steering of the beam by the XTCAV at about 10% of the nominal RF power.

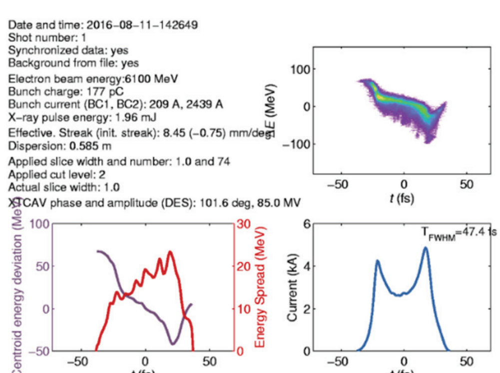

Figure 7: Streaked image (top right), longitudinal charge profile (bottom right) and reconstructed photon profile (bottom left) during SLED operation.

The calibration of the strength of the kick is done by scanning the RF phase about the zero crossing by ±1°X-band, or less, and observing the centroid displacement at the profile monitor screen. The deflection is measured directly in screen pixels and does not rely on an exact knowledge of the screen magnification in pixels per mm. Since LCLS operates over a large range of energies from 4 to 14 GeV the relative deflection strength will vary by a factor up to 3.5.

A software package is used at SLAC (TREX) to perform the XTCAV calibration and record and analyse the streaked image. The longitudinal profile for the electron beam and the photon beam is reconstructed, as shown in Fig. 6 for the nominal non-SLED operating amplitude of 45 MV, and in Fig. 7 for the new SLED operating amplitude of 85 MV. The effective streak is observed to increase from 4.12 mm/°X-band to 8.45 mm/°X-band

The temporal resolution is both a function of the energy-dependant effective streak and the un-streaked beam size. The performance is summarized in Table 1. However, it should be noted that the best resolution of 0.5 fs for the lowest energy electron beam is very difficult to sustain because of RF phase jitter which causes results in deflections large enough to trip beam loss monitors.

Table 1: Comparison of Operating Parameters for Non-SLED and SLED Modes

		Non-SLED	SLED
Klystron power	MW	50	40
Klystron pulse length	μs	0.2	1
XTCAV kick amplitude	MV	45	85
Effective streak at 6 GeV	mm per °X-band	4.12	8.45
Temporal resolution HXR (10kV)	fs	4	2
Temporal resolution SXR (1kV)	fs	1	0.5

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ISBN 978-3-95450-177-9