# COMMISSIONING THE NEW LCLS X-BAND TRANSVERSE DEFLECTING CAVITY WITH FEMTOSECOND RESOLUTION*

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*Abstract*

The new X-band transverse deflecting cavity began operation in May 2013 and is installed downstream of the LCLS undulator. It is operated at the full 120 Hz beam rate without interfering with the normal FEL operation for the photon users. The deflected beam is observed on the electron beam dump profile monitor, which acts as an energy spectrometer in the vertical plane. We observe, on a pulse by pulse basis, the time resolved energy profile of the spent electron beam from the undulator. The structure is powered from a 50 MW X-band klystron, giving a 48 MV kick to the beam which yields a 1 fs rms time resolution on the screen. We have measured the longitudinal profile of the electron bunches both with the FEL operating and with the lasing suppressed, allowing reconstruction of both the longitudinal profile of the incoming electron beam and the time-resolved profile of the X-ray pulse generated in the FEL. We are immediately able to see whether the bunch is chirped and which parts of the bunch are lasing, giving us new insight into tuning the machine for peak performance. The performance of the system will be presented along with examples of measurements taken during LCLS operation.

## INTRODUCTION

A new X-band transverse deflecting structure (XTCAV) has been installed at the LCLS at the SLAC National Accelerator Laboratory[1]. It differs from the existing S-band deflecting structures already in operation around the lab[2] with regard to its operating frequency and that it is not installed in the linac, but in an undulator beamline. It provides noninvasive measurement of the temporal profile of the bunch at far greater resolution than was previously achieved. The project took approximately two years to complete at a cost of $5M. The engineering apsects of the project are described in a companion paper at this conference[3].

X-ray Free Electron Lasers such as the Linac Coherent Light Source (LCLS) can produce very short pulses of a few femtoseconds (10-15s) duration [4]. This new application of the deflecting structures was proposed as a means of studying the properties of these very short bunches. [5]. It has given us a unique opportunity to observe the FEL process in the time-resolved energy profile of the beam without interrupting beam to the users. This paper describes the beam commissioning of the system and gives a preliminary survey of the types of measurements that are possible.

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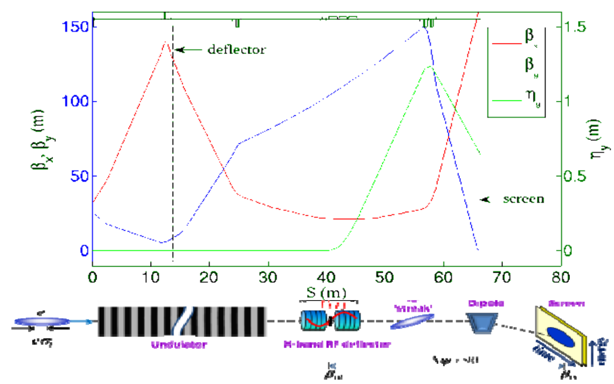

Figure 1: Optics between the XTCAV and the dump profile monitor screen.

## MEASUREMENT CALIBRATION

The transport line between the undulator and the beam dump was reconfigured to give optimal optics for maximising the resolution of the system, given by

$$\sigma_{t,R} = \frac{\sigma_{y0}}{S} = \sqrt{\frac{\varepsilon_{N,y}}{\gamma\beta_d}} \frac{\lambda_{rf} E_e}{2\pi |eV_0 \sin\Delta\psi|} \quad (1)$$

We tested the optics with an orbit response method[6]. The beam was kicked using a corrector before the deflector, and the beam centroid position at the BPMs was measured and compared with the model predictions shown in Fig. 1. The nominal operating RF phase for the deflector is at the zero-crossing so that there is no deflection of the beam centroid at the screen. However, we scan the phase by a few degrees in order to calibrate the deflection in units of image pixels per degree of x-band phase. This is an absolute calibration that is independent of both the camera magnification optics and the beam line betatron optics. In order to be able to move the RF phase by more than a few degrees it is necessary to reduce the amplitude of the RF to a fraction of the nominal maximum power of 50 MW at the klystron output. The deflector is so powerful that a shift in phase of more than degree will move the beam out of the field of view on the screen. The power is therefore reduced to about 10 MW, and the screen calibration is then scaled in the ratio of the RF amplitude. The control system phase and amplitude detectors are calibrated against precision power meters in order to perform this scaling.



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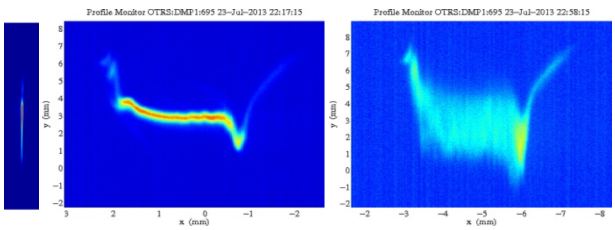


Figure 2: Profile monitor screen images for a 150 pC bunch at 4.7 GeV at the electron beam dump acting as a vertical energy spectrometer. At left the XTCAV is OFF; center image XTACV is ON and FEL is OFF; at right, XTCAV is ON and FEL is ON.

## BASELINE MEASUREMENT

The vertical dispersion at the beam dump screen location allows energy and energy spread of the beam to be measured with a resolution given by

$$\sigma_{E,r} = \frac{E_0}{\eta_{yS}} \sqrt{\frac{\beta_{yS}\varepsilon_n}{\gamma} + \sigma^2_{screen}} \qquad (2)$$

The resolution is in the range between 270 keV at 4.3 GeV beam energy and 704 keV at 13.6 GeV.

When the XTCAV is off we observe a vertical stripe, as in the left-most image in Fig. 2. The extent of the energy spread in the beam is strongly influenced by the FEL lasing process. We can switch the FEL process on and off to quantitatively compare the energy profiles by creating a bump in the trajectory of the beam by steering the beam with a corrector starting at any undulator we choose. If the electron and photon beams do not spatially overlap the FEL process turns off. Another pair of correctors at the end of the undulator steer the beam back on axis so that the beam always remains on the axis of the XTCAV.

In the middle image in Fig. 2 the XTCAV has been turned on to streak the beam while the FEL has been turned off with the trajectory bump method. The energy spread visible in the left hand image in Fig. 2 is now resolved in time, revealing the complete longitudinal phase space of the beam. The head, the tail and the energy chirp along the bunch are clearly visible. This image is used as a baseline with which to compare the FEL-On image shown at the right in Fig. 2.

The ratio of the horizontal width of the unstreaked beam to the streaked beam gives the temporal resolution in each measurement case.

When the beam lases, energy is extracted from the electron beam and its energy spread also increases. The change in energy and energy spread can be used to reconstruct the temporal profile of the x-ray pulse, based on energy conservation, following the method described in reference [5]. The streaked image is divided into temporal slices and, with a knowledge of the total charge in the bunch and the relative intensity in each slice, the peak current in the bunch can be calculated, as shown in the bottom right of Fig. 3. Figure 3 is a screen shot of the

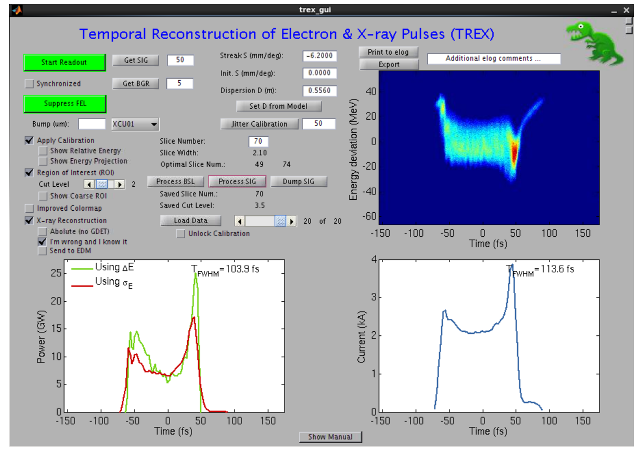


Figure 3: Screen shot of the user interface for analyzing the XTCAV image (top right) and calculating the peak current profile (bottom right) and the reconstructed x-ray temporal profile.

graphical user interface for analysing images from the XTCAV screen and performing the reconstruction. The product of the peak current in a slice with the energy loss due to lasing gives the peak photon power in the slice. The reconstructed x-ray temporal profile using this method is shown in the bottom left of Fig. 3.

## QUALITATIVE VIEW OF SASE EVOLUTION ALONG THE UNDULATOR

The technique of suppressing the FEL process by creating a trajectory bump can be used to view the SASE process along the undulator and generate a gain curve for the photon energy. During this procedure we recorded the XTCAV images to reveal how the reconstructed x-ray temporal profile evolves along the length of the undulator. This is a qualitative view since the images are taken on separate beam pulses and therefore do not take into account the pulse to pulse fluctuations that we also observe. However, it is possible to observe that the energy spread in the bunch increases as the measurement proceeds down the undulator and the gain increases.

The detailed results will be published elsewhere[7], but several interesting features were apparent, such as the band of preferred energy loss at the knee of the gain curve where saturation starts. This band of preferred energy loss is smeared out after saturation in the "taperered" section of the undulator where the K-value of the undulator is nominally matched to the energy loss of the electron bunch. Finally, at the end of the tapered undulator we observed that the temporal structure of the x-ray pulse became more pronounced.

We emphasize that these are qualitative observations only, acquired during the commissioning phase, and are intended to demonstrate that much further study is possible with the XTCAV to study the dynamics of the SASE process and to optimize the taper in the saturated regime.

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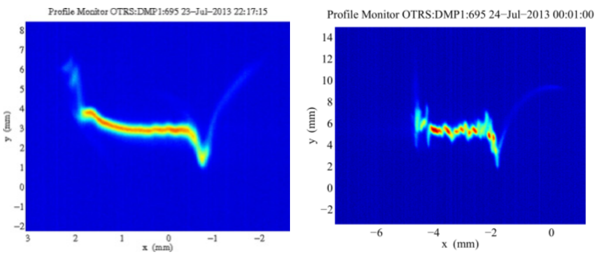


Figure 4: XTCAV images with laser heater on (left) and laser heater off (right), showing the microbunching instability growth.

## MICROBUNCHING INSTABILITY

The extremely high temporal resolving power of the XTCAV system, combined with the energy resolving power at the profile monitor screen makes this an ideal tool for observing the microstructure in the bunch resulting from instabilities. The microbunching instability can be excited by turning off the laser heater at the LCLS injector. Figure 4 shows the microstructure we observe on the XTCAV screen when the laser heater is turned off. The slice energy spread is seen to increase and accounts for the increase in emittance and reduction in FEL power.

## SLOTTED FOIL OPERATION

Slotted foils are installed in the dispersive region of the LCLS bunch compressor to selectively spoil the emittance of a portion of the beam so that only a short portion of the bunch will lase in the FEL[8]. A single slot of variable width can be used, or a pair of slots of variable separation can be used to produce two closely spaced bunches. The effect on the beam is readily observed with the XTCAV, as seen in Fig. 5.

## MULTIBUNCH OPERATION

One mode of operation that is being explored at LCLS is to send two bunches down the linac, closely spaced within the same RF bucket. Two bunches are extracted from the RF photo-injector at the LCLS and pass through the bunch compression stages together. The XTCAV allows us to observe that at under-compression both bunches have an energy chirp. As the linac RF phase upstream of the bunch compressor chicane is adjusted the remaining energy chirp can be removedand the two bunches are separated in energy. These results will be published elsewhere.

This mode of operation is of particular interest since the differing energy of the two bunches implies that they will lase at two distinct wavelengths. This mode will be studied further for two-color experiments at the LCLS[9].

## LOW CHARGE MODE

The shortest bunches produced at the LCLS are done in a special low-charge mode of operation[10]. The collective effects that lead to emittance blowup of the beam during bunch compression become negligible at charges at the pico-Coulomb level, and it becomes possible to fully compress the bunch

We have observed with the XTCAV that a 20 pC bunch at 4.7 GeV is compressed to about 17 fs. However, the XTCAV also reveals that only a small fraction of the bunch is lasing and that the 1 kV x-rays only have a pulse duration of 4.5 fs. These results will be published elsewhere[7].

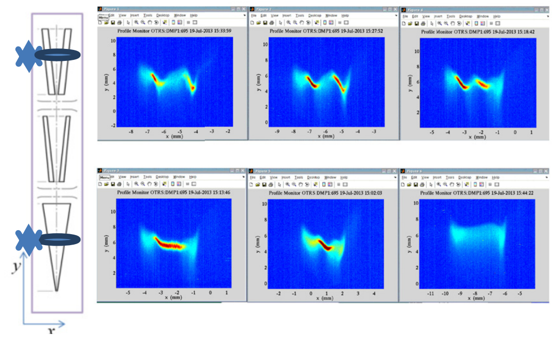

Figure 5: The action of a double slotted foil with varying separation (upper images), and a single foil of varying width (lower images), can be clearly seen with the XTCAV.

## SUMMARY

Several exploratory studies have been done in the first few months of operation of the new x-band transverse deflecting cavity (XTCAV) installed downstream of the LCLS undulator. It has proven to be an invaluable diagnostic that can operate at the full 120 Hz repetition rate of the machine and analyse all pulses non-invasively. These preliminary studies show that there is much to be learnt about the bunch compression dynamics and lasing process in the FEL using this new tool.

We have achieved a temporal resolution as low as 1.3 fs for a 4.7 GeV beam.

Planned upgrades now included a faster camera and data acquisition system so that we can stream the measurements to the photon users to correlate with their experimental data.



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