The LCLS XTCAV: Manual for Users

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This note discusses using the XTCAV-measured changes of time-sliced longitudinal beam properties to extract the instantaneous FEL power as inspired by [1]. In brief, one can measure the relatively stable properties of the “lasing off” electron bunch by perturbing the orbit in the undulator, thereby disrupting the FEL interaction and effectively recording the initial state of the beam’s longitudinal phase space. Then with an unperturbed orbit, the “lasing on” phase space is recorded.

From the 1D FEL theory, it’s expected that each slice in time will see a net mean energy loss as well as growth in energy spread due primarily to the FEL interaction. Therefore, we can use the changes in the measured phase space to infer the time-resolved FEL pulse power within the resolution of the XTCAV.

This document provides a very broad overview, start to end, on how it’s done. Work is going on daily at SLAC to increase the automation and delivery of information from XTCAV measurements. That should largely mitigate the need for every user needing to process the data from scratch. However, this should still provide an idea of what to expect when using the XTCAV, be a helpful introduction for those working closely on XTCAV tools, and be a starting point when specialized XTCAV analysis is required.

There are three main chapters:

Section I: Basic background for those totally new to the XTCAV.
Section II: Operational considerations when deciding to employ the XTCAV in experiments.
Section III: LCLS-specific, PCSD technical details listing items to record and when.

Specific image analysis codes and proper data structuring are omitted right now. A minimal working example will be published soon to aid in code development.

I. THEORY

The following is a purely conceptual description of how we measure the electron beam's longitudinal phase space using the XTCAV. Then we'll jump to how this information can be used to reconstruct the LCLS xray pulse profile including basic formulas followed by a simulated example using the formulas for xray pulse reconstruction.

A. The XTCAV System

The LCLS X-band Transverse deflecting mode CAVity (XTCAV) diagnostic system is shown in Fig. 1. There are two key elements to the system: the XTCAV and the final dipole magnet.

As shown in Fig. 1, immediately after the undulator is the XTCAV. This generates an effective RF (11.424 GHz) electromagnetic force pointing in the horizontal direction with an amplitude varying sinusoidally in time. Then, as illustrated in Fig. 2a, the electron bunch travels through the cavity with this RF wave at roughly the speed of light. The bunch time of arrival is set so its center coincides with when the amplitude of the RF field is zero. Then the net deflection of the bunch will also be zero.

However, the bunch has a finite length, some-thousand times shorter than the wavelength of the RF. As shown in Fig. 2a, the head sees a small, positive electric field while trailing electrons see a small, negative transverse electric field. The effect is a ~linearly-varying force for different slices of the bunch. The head (tail) gets a transverse momentum kick to the left (right), shearing the bunch into a horizontal streak.

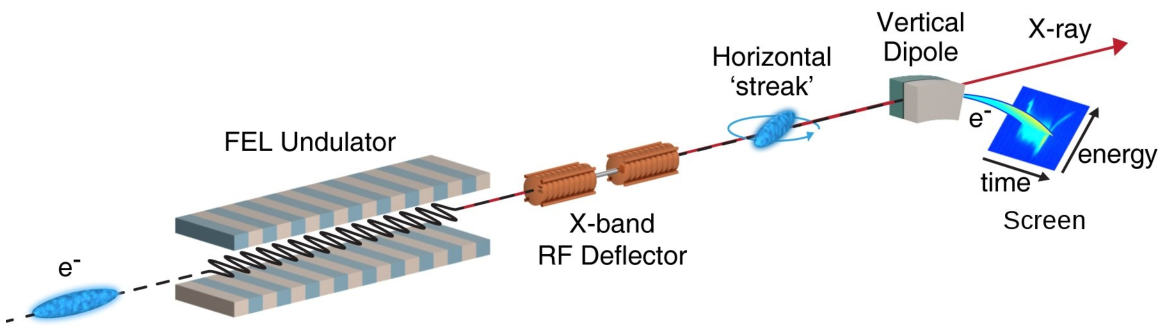

FIG. 1: The LCLS XTCAV diagnostic system, located after the undulator in the LCLS electron dump. The XTCAV imparts a time-dependent transverse momentum kick to the bunch, shearing it horizontally. The dipole magnet separates the beam vertically in energy. The resulting image on the dump screen is the electron bunch's time-energy phase space distribution.

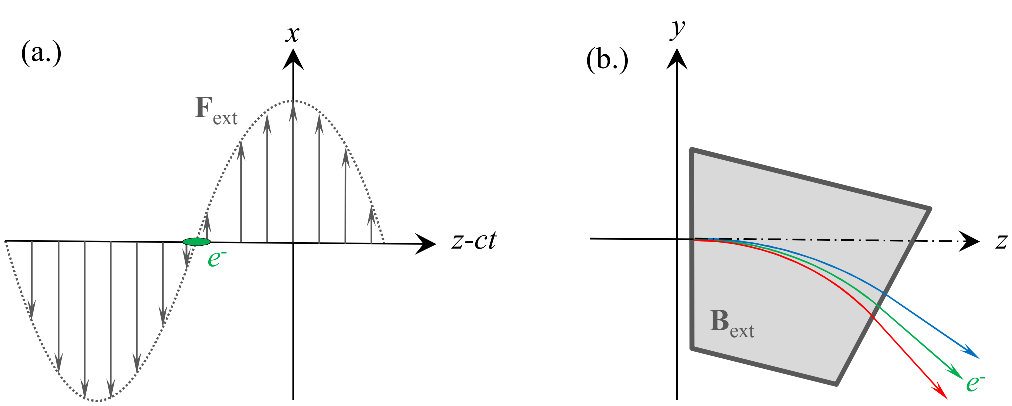

FIG. 2: Illustration of the forces seen by the bunch in the XTCAV diagnostic system. (a) The cavity's effective RF transverse deflecting force $\mathbf{F}_{\text{ext}}$ copropagating with the relativistic electron bunch. (b) The effect of the static magnetic field $\mathbf{B}_{\text{ext}}$ on the beam trajectory for electrons of slightly different energies, indicated by color with blue higher energy, green nominal, and red lower energy.

The bunch then goes through a vertical, static bending magnet, illustrated in Fig. 2b. The Lorentz force for a moving charge in a magnetic field **B** results in a circular arc trajectory with a radius that depends on the velocity(/energy) of the charged particle. Higher energy particles aren't bent as much, following a larger radius of curvature in the field, while lower energy electrons get bent more. In this way the magnet behaves as an electron energy spectrometer, dispersing the electrons in the vertical plane. This is illustrated schematically in Fig. 2 where the different color trajectories correspond to different electron energies.

Finally, combinging these and placing a viewing screen at the end (Fig. 1), the intensity of the image effectively tells us how many electrons we have in two dimensions: time and energy (horizontal and vertical). From this longitudinal phase space image, we can extract significant information about the electrons at different time slices along the bunch.

Most easily we can simply integrate the images over energy to recover the beam current $I(t)$ of the bunch. We can also analyze the energy distribution in each time slice to deduce the mean slice energy $\langle E\rangle(t)$ and RMS slice energy spread $\sigma_E(t)$. This time-resolved energy profile information can then be used to extract very useful information about the FEL behavior.

B. X-Ray Reconstruction Formulas

By conservation of energy, we can relate the change in mean slice energy to instantaneous FEL power [1]. Namely, the average beam energy of each time slice $\langle E\rangle\,(t)$ that's lost is given to the instantaneous power of the co-propagating FEL pulse as

$$P_{\mathrm{FEL}}(t) = \left[\langle E\rangle_{\mathrm{FEL\ off}}\,(t) - \langle E\rangle_{\mathrm{FEL\ on}}\,(t)\right] \times I(t), \tag{1}$$

with FEL power $P_{\mathrm{FEL}}(t)$ [W], time-sliced mean beam energy $\langle E\rangle(t)$ [eV] and macroscopic beam current $I(t)$ [A]. This is assuming all electrons in the slice contribute (and lose), on average, the same energy.

More rigorously, this is also valid in the 1D FEL theory [2] when the slippage (group velocity mismatch) of the electron beam and photon pulse is negligible. This is generally valid up to the saturation point of the FEL, which we'll illustrate later.

The theory also yields the relationship between FEL power and energy spread growth [2, 3]. In high-gain (pre-saturation),

$$P_{\mathrm{FEL}}(t) \propto \left[\sigma^2_{E,\mathrm{FEL\ on}}(t) - \sigma^2_{E,\mathrm{FEL\ off}}(t)\right] \times I^{2/3}(t), \tag{2}$$

where $\sigma_E(t)$ is the RMS slice energy spread. [The 2/3 exponent on the beam current is a small correction due to these formulas scaling with the FEL efficiency (Pierce) parameter ρ which has a 1/3-power dependence on several slice properties of the beam. Beam current is one of them and is known by this measurement.]

These two formulas relate how we analyze most XTCAV images. The basic algorithm is as follows:

1. Disrupt orbit of electrons in undulator to suppress FEL interaction, record many "baseline" images of FEL-off phase space
2. From calibrated images, compute time-sliced first and second moments, $\langle E\rangle_{\mathrm{FEL\ off}}\,(t)$ and $\sigma_{E,\mathrm{FEL\ off}}(t)$
3. Restore orbit, record "signal" images of FEL-on phase space from shot to shot
4. From images, compute current $I(t)$ and the time-sliced first and second moments, $\langle E\rangle_{\mathrm{FEL\ on}}\,(t)$ and $\sigma_{E,\mathrm{FEL\ on}}(t)$
5. Compute $P_{\mathrm{FEL}}(t)$ using Eqs. (1) and (2)

This assumes that the FEL interaction doesn't significantly effect the macroscopic beam current, which is reasonably true. It also expects that the bunch distribution with FEL off is generally stable. That's *kind of* true, but ignore that for now.

Equation (1) we refer to as the "Δ method," as it's related to recovering the FEL power profile using the slice energy *difference*. Similarly Eq. (2) is short-handed as the "σ method" due to its relation to the quadratic difference in *RMS spreads*.

C. Simulated Example

To illustrate how one uses Eq. (1) and (2), next we look at an ideal simulation to get "perfect" longitudinal phase space images to analyze. (See some other excellent examples in [1].) The basic algorithm shown is quite similar as when using XTCAV phase space images. This is also a nice visualization of how the electron phase space is affected by the growing instantaneous xray power profile.

This 1D FEL dynamics simulation is using LCLS "low-charge," short-pulse operation in the soft x-rays. We've used a 40 pC electron bunch with 2 kA flattop peak current, FWHM duration 20 fs, and mean beam energy of 4.7 GeV (980 eV photons). The resulting undulator gain curve is shown in Fig. 3. FEL saturation occurs at $z \approx 35$ m. We mentioned in the previous section that the technique is known to be valid during high-gain, before saturation. So first we look at the phase space at $z = 30$ m.

Reconstruction analysis of the images is shown in Fig. 4. Shown are the ideal on/off phase spaces, as we might expect to retrieve with an almost-perfect XTCAV. Also shown are the energy properties computed as the first moment and RMS width

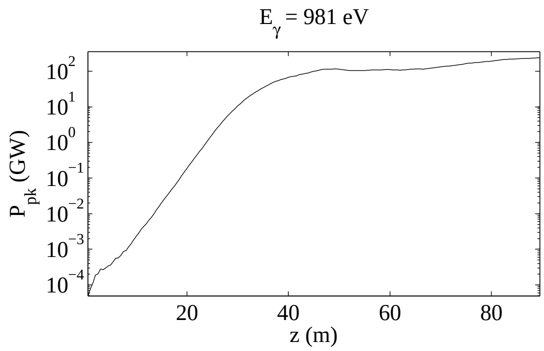

FIG. 3: Undulator gain curve for short-pulse, 980 eV x-ray simulation with 4.7 GeV, 40 pC, 2 kA, 20 fs fwhm electron bunch.

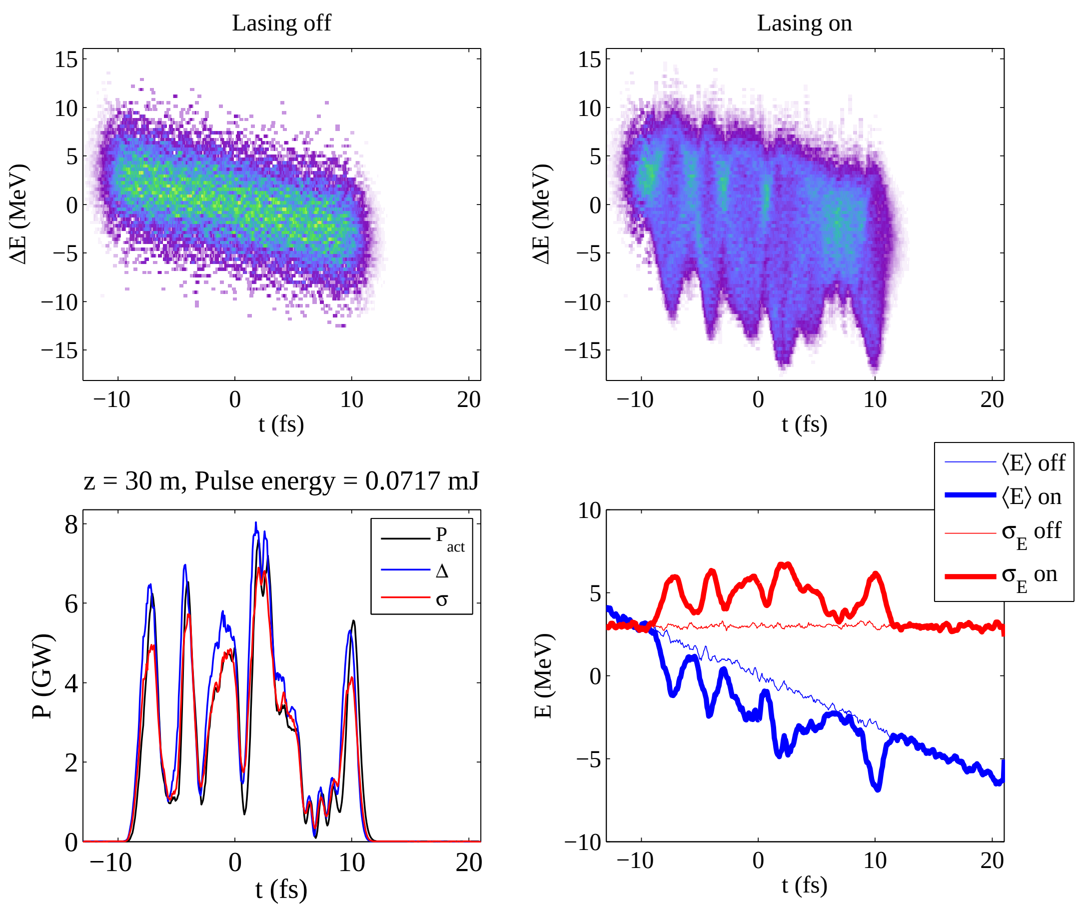

FIG. 4: Low-charge, soft xray LCLS 1D FEL simulation just before saturation (z = 30 m). (*Top-left*): The initial "lasing off" electron phase space. (*Top-right*): The ideal "lasing on" phase space after 30 m of undulator. (*Bottom-right*): The time-sliced energy properties computed from these images. (*Bottom-left*): Actual x-ray power profiles compared to those recovered using both the Δ and σ methods using beam current (not shown) and time-sliced energy properties.

of energy profiles along each time slice of the image. Comparing the blue slice energy curves (Fig. 4, bottom right) with and without lasing, the expected slice energy loss from the FEL interaction is clear. We also see the increase in the slice energy spread (red curves).

Finally, using these curves and the beam current (time-axis projection of image), we have computed $P_{\mathrm{FEL}}(t)$ using the Δ and σ formulas (1) and (2) for comparison with the actual, simulated x-ray power profile P_{act}. As promised, this perfect XTCAV image produces the actual x-ray power profile reasonably well.

So what about well *after* saturation? A more in-depth study has shown that in post-saturation both methods quickly begin to disagree with the exact power profile. The large group velocity mismatch between the e-beam and photon beam after saturation starts to take over: the radiation spikes slip into new parts of the electron bunch. Parts of the e-beam can then extract energy back from the photons and the behavior becomes much more complex.

The usefulness is not completely lost: Deep in saturation, especially for longer bunches with large numbers of longitudinal modes (SASE spikes), this method still gives a reasonable estimation of the overall FEL pulse length. See Fig. 5, taken from the same simulation but at $z = 90$ m. Here we no longer see the spikes in the reconstructed profiles. However we do observe that the entire bunch is lasing and that the (slipping) xray pulse is of similar overall duration. In addition, if only a *part* of a long bunch was lasing and therefore producing a shorter pulse, this feature is typically resolved.

So the slippage spoils the accurate measurement of fine pulse structure. At that point the energy loss and energy spread profiles start to get smeared out.

It's fundamental to note that the Δ and σ methods still remain in good agreement *with each other*. This is true even in deep saturation when they only resemble the power profile in a blurred-out sense. This is an important point: *Applying both techniques provides a data consistency check.* Where the reconstructed profiles of the two approaches don't look at all similar, an issue with either the data acquisition or processing methods is likely.

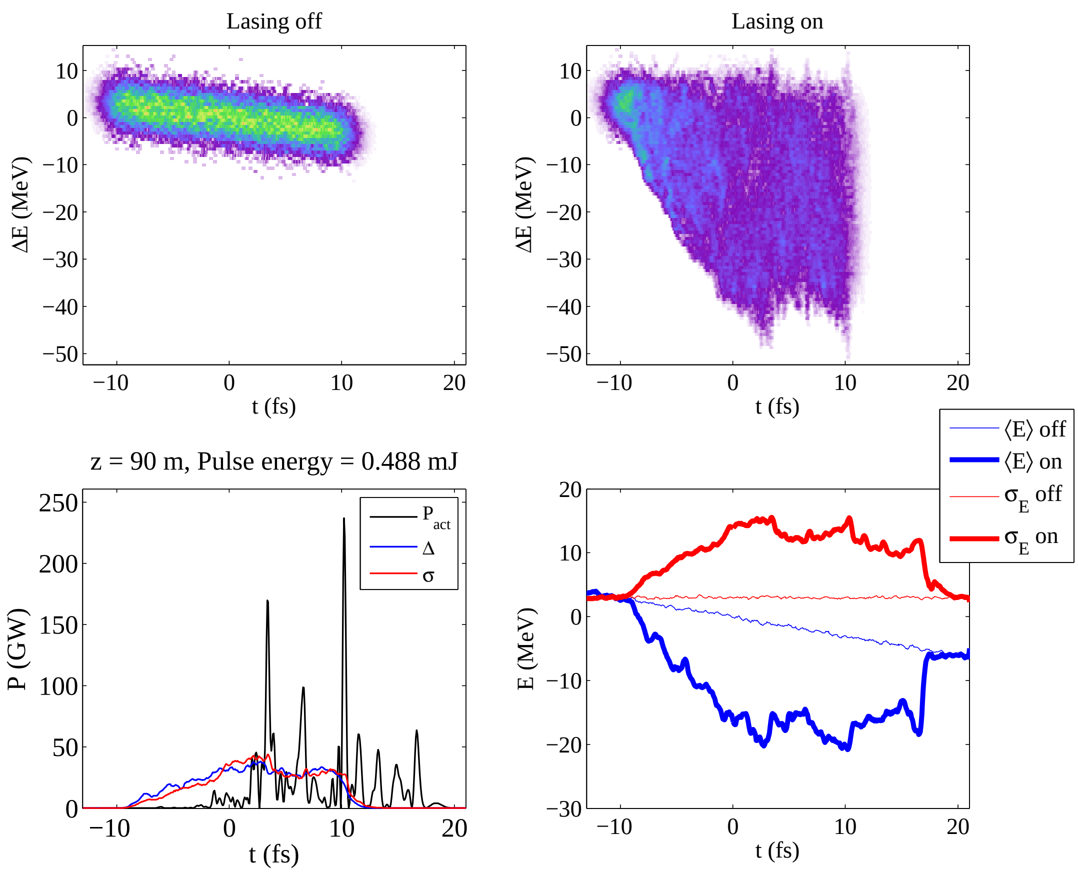

FIG. 5: Low-charge, soft xray LCLS 1D FEL simulation well after saturation (z = 90 m). (*Top-left*): The initial "lasing off" electron phase space. (*Top-right*): The ideal "lasing on" phase space after 90 m of undulator. (*Bottom-right*): The time-sliced energy properties computed from these images. (*Bottom-left*): Actual x-ray power profiles compared to those recovered using both the Δ and σ methods using beam current (not shown) and time-sliced energy properties.

References

[1] Y. Ding et al., Phys. Rev. ST Accel. Beams **14**, 120701 (2011).
[2] K.-J. Kim, Z. Huang, and R. Lindberg, *Synchrotron Radiation and Free Electron Lasers for Bright X-Rays* (Fort Collins, CO, 2013), USPAS Course Notes.
[3] Z. Huang, K. Bane, Y. Cai, A. Chao, R. Hettel, and C. Pellegrini, Nucl. Instrum. Meth. A **593**, 120 (2008).

II. BEFORE XTCAV OPERATION

Before using XTCAV, please understand the following points as pertains to the effectiveness and potential complications introduced by XTCAV operation during an experiment. Questions to ask in advance:

1. Does my time allow for brief, planned interruptions to perform calibration and baseline acquisition when needed?
2. Will the XTCAV provide sufficient time resolution to be interesting?
3. XTCAV operation may cause a slight increase in unexpected beam trips. Can my experiment tolerate this?
4. Am I using a special operating mode (i.e. – not SASE) that requires special analysis?

A. Understanding Limitations

Importantly, some calibration operations necessarily interrupt photon delivery for the acquisition of background images. Usually these interruptions should be very brief (few minutes or less).

As for time resolution and beam trips, other background for the interested: The effective streaking strength of the XTCAV is related to the net electron deflection $\Delta\theta_x \approx \Delta p_x/p_z$. As illustrated in Fig. 6, when operating at much higher beam energies, the same transverse momentum kick $\Delta p_{x,\mathrm{xtcav}}$ is less effective at deflecting the beam.

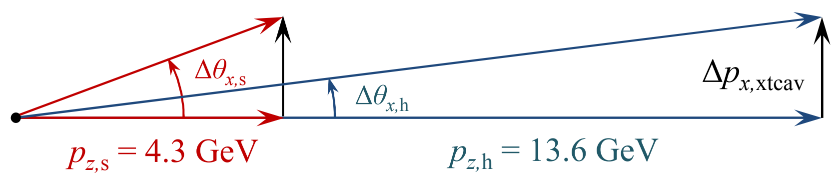

FIG. 6: Illustration of the effectiveness of the transverse momentum kick imparted by the XTCAV at soft and hard xray electron beam energies assuming the same cavity voltage. Note that $\Delta\theta_{x,\mathrm{s}} > \Delta\theta_{x,\mathrm{h}}$.

So assuming XTCAV is always at full voltage, soft xray users will generally get the best time resolution: ∼1 fs RMS for a 4.3 GeV electron beam. In contrast, for hard xray operation at 13.6 GeV, typical time resolution is ∼3 fs. Will you resolve anything of interest at these values?

The other consequence is related to operational stability while XTCAV is running. In Fig. 2, the bunch is shown arriving exactly where the net deflection of the beam will be zero. In practice there is some time of arrival jitter, so the beam can pick up a small overall deflection. If either the beam or XTCAV stability are less than ideal, some shots will get kicked “into the wall” causing momentary loss of beam (machine protection).

When it’s an issue, such trips are worse and more frequent during soft xray delivery. This is again because XTCAV kicks the lower energy beam more effectively. If frequent trips are a problem while the XTCAV is on, the voltage can be reduced to sacrifice XTCAV time resolution for instrument stability. The MCC Operators will adjust according to the users’ needs.

Finally, certain special operating modes such as using the emittance spoiling foil or various two bunch/pulse operating modes may either complicate the analysis or make the relationship between the XTCAV images and FEL pulse highly ambiguous. Please chat with the appropriate LCLS scientists regarding any questions on this.

III. XTCAV DATA ACQUISITION

Note: *If XTCAV support is wanted for an experiment, please notify MCC Operations in advance, ideally when planning the shift. This allows them to be prepared to take the measurements needed, reducing the time of any scheduled interruptions.*

To do experimental xray pulse reconstruction using the XTCAV supporting information is needed. Calibrations must first be performed and, once known, data collection is a matter of acquiring batches of images from the LCLS electron dump camera. The user must also simultaneously record several important shot-to-shot beam measurements whenever capturing images of the electron beam.

Lasing-off (baseline) images are always needed for comparison to the lasing beam (signal) of interest. Whenever changes to the bunch charge, energy or length are made, the baseline properties of the beam will also change and should be resampled before resuming.

Section III A summarizes this overall operating procedure for performing an XTCAV measurement from a user's perspective and when steps need to be repeated or updated. Section III B lists specifics on what should be recorded whenever a burst of beam dump (XTCAV) images is taken. There we also explain which part of the procedure updates each item and, where applicable, brief comments on how the information is later used.

A. General Operating Procedure

Table I lists the order with which to acquire a complete set of data for xray pulse reconstruction from XTCAV images assuming a measurement that "starts from scratch." Points where MCC action is required are noted. Also explained are when various steps must be revisited due to a change of conditions.

When acquiring any sets of images, supporting camera setting information should also be logged. When acquiring any baseline or signal images (images with electron beam on screen), associated electron beamline data must also be recorded. See the next section for the list of process variables.

TABLE I: Procedure overview for LCLS XTCAV xray reconstruction acquisition

	Item	*by*	Action	When to update/repeat
1)	Background/dark images	*User*	Record camera images, no e-beam	ROI is increased or camera optics/exposure changed
2)	XTCAV calibration	*MCC*	TCAV GUI, measure Calib. & BLEN	XTCAV amplitude, major e-beam energy/optics changes
3)	Baseline, lasing off images	*MCC*	Suppress FEL (undulator orbit bump)	XTCAV amplitude, *any* e-beam changes (bunch length, energy, optics, etc)
		User	Record several beam images & data	
		MCC	Restore FEL (close bump)	
4)	Signal, lasing on images	*User*	Record images & data	At will for lasing shots of interest
5)	Process	*User*	Reconstruct xray power profile	With associated preprocessed baseline, reconstruct live or in post

B. Additional Required Data

Table II is a summary of LCLS IOC process variables (PVs) to record. It is assumed the user is familiar with collecting and storing EPICS and Beam Line Data information from the DAQ.

The first table includes various dump camera settings of interest. The second lists PVs that provide information about the most recent calibration factors as well as the electron beam that are critical for xray reconstruction. The final table includes items that provide improved analyses. Information about units and available update frequency are also provided. Detailed information on use of the data follows.

Record as... describes what method to use for DAQ recording of the item. All items requiring beam-synchronous acquisition are now included in the various BLD. Objects labelled "EPICS Data" are slowly updating calibration factors, statuses, etc. These must be added to the list of EPICS Archiver items by the user.

TABLE II: Summary table of process variables (PVs) to record when performing batch image acquisition of the LCLS electron dump camera with the intent of xray pulse reconstruction. (* *120 Hz camera acquisition is possible w/ risks and restrictions. Discuss with OPS if needed.*)

Dump (XTCAV) camera and settings					
Item		**PV**	***Units***	**Updates**	**Record As...**
Camera PV for image acquisition		`OTRS:DMP1:695:Image:ArrayData`	*Counts*	60 Hz *	XTCAV Camera
Screen Region of Interest (ROI) *Note: Append '_RBV' to PVs listed to instead record the read back value, as desired*	X start	`OTRS:DMP1:695:MinX_RBV`	*pix*	slow	EPICS Data
	Y start	`OTRS:DMP1:695:MinY_RBV`	*pix*	slow	EPICS Data
	X length	`OTRS:DMP1:695:SizeX_RBV`	*pix*	slow	EPICS Data
	Y length	`OTRS:DMP1:695:SizeY_RBV`	*pix*	slow	EPICS Data
Calibration: Pixels to screen position coordinate		`OTRS:DMP1:695:RESOLUTION`	*um/pix*	slow	EPICS Data
Camera Attenuator Stats (IN/OUT)	Filter 1 Status (OD 0.5)	`OTRS:DMP1:695:FLT1_PNEU.RVAL`	*Logical*	slow	EPICS Data
	Filter 2 Status (OD 1.0)	`OTRS:DMP1:695:FLT2_PNEU.RVAL`	*Logical*	slow	EPICS Data
Camera Array Rate		`OTRS:DMP1:695:ArrayRate_RBV`	*Hz*	slow	EPICS Data
Camera Acquistion Time		`OTRS:DMP1:695:AcquireTime_RBV`	*s*	slow	EPICS Data
OTRDMP Screen Status		`OTRS:DMP1:695:PNEUMATIC.RVAL`	*Logical*	slow	EPICS Data

Critical beam data and calibrations for reconstruction					
Item		**PV**	***Units***	**Updates**	**Record as...**
XTCAV Operating Status		`KLYS:DMP1:1:MOD.RVAL`	*state num.*	slow	EPICS Data
Calibration: Vertial position to energy (dispersion)		`SIOC:SYS0:ML01:AO216`	*m*	Matlab	EPICS Data
Calibration: Horizontal position to time	Strength parameter S	`OTRS:DMP1:695:TCAL_X`	*um/um*	Matlab	EPICS Data
	XTCAV Amp Des. during calib.	`SIOC:SYS0:ML01:AO214`	*MV*	Matlab	EPICS Data
	XTCAV Phase Des. during calib.	`SIOC:SYS0:ML01:AO215`	*deg*	Matlab	EPICS Data
	sig_x	`SIOC:SYS0:ML01:AO212`	*um*	Matlab	
	sig_z	`OTRS:DMP1:695:BLEN`	*um*	Matlab	EPICS Data
	r_15	`SIOC:SYS0:ML01:AO213`	*unitless*	Matlab	
Beam energy (dump config)		`REFS:DMP1:400:EDES`	*GeV*	slow	EPICS Data
XTCAV Voltage		`TCAV:DMP1:360:ABR`	*MV*	120 Hz	BLD (EBeam v5)
XTCAV Phase		`TCAV:DMP1:360:PBR`	*deg*	120 Hz	BLD (EBeam v5)
Bunch charge in LCLS dump		`BPMS:DMP1:502:TMIT`	*Num. Elec.*	120 Hz	BLD (EBeam v5)
Gas detectors	GDET1	`GDET:FEE1:241:ENRC`	*mJ*	120 Hz	BLD (FEEGasDet)
		`GDET:FEE1:242:ENRC`			
	GDET2	`GDET:FEE1:361:ENRC`			
		`GDET:FEE1:362:ENRC`			
		`GDET:FEE1:363:ENRC`			
		`GDET:FEE1:364:ENRC`			

Extremely useful data for filtering and analysis					
Item		**PV**	***Units***	**Updates**	**Record as...**
BLM1 current		`BLEN:LI21:265:AIMAX`	*Amps*	120 Hz	BLD (EBeam)
BLM2 current		`BLEN:LI24:886:BIMAX`	*Amps*	120 Hz	
Beam Energy (from DL2, can calculate shot-to-shot e beam energy jitter)	DL2, BPM1 (x)	`BPMS:LTU1:250:X`	*mm*	120 Hz	Equivalent Available in BLD (EBeam, LTU Energy)
	DL2, BPM1 (dispersion/E calib.)	`SIOC:SYS0:ML01:AO217`	*m*	Matlab	
	DL2, BPM2 (x)	`BPMS:LTU1:450:X`	*mm*	120 Hz	
	DL2, BPM3 (dispersion/E calib.)	`SIOC:SYS0:ML01:AO218`	*m*	Matlab	

1. Camera Settings

ITEM: Camera image

PV: `OTRS:DMP1:695:Image:ArrayData`

USAGE: LCLS electron beam dump camera (XTCAV) image. Depending on the method of acquisition, may be delivered as a requested number of bytes in 1D array. In this case, requires reshaping to form 2D image based on the presently set camera region of interest (ROI), below.

The camera is listed with physical identifier `XrayTransportDiagnostic-0:Opal1000-00` in the DAQ (not actually an Opal).

ITEM: Screen ROI

PV: `OTRS:DMP1:695:[MinX,MinY,SizeX,SizeY]_RBV`

USAGE: Coordinate (`MinX`, `MinY`) specifies the offset, in pixels, of the (1,1) pixel of the current camera ROI. `SizeX` and `SizeY` specify the horizontal and vertical extent of the current camera ROI.

Used for preserving an absolute camera coordinate system regardless of the user-selected ROI. For example, verifying the same ROI is being used when subtracting a dark image from a signal image. Recorded minimally at start of batch image collection to verify desired ROI has not been altered.

ITEM: Calibration: Pixels to screen position

PV: `OTRS:DMP1:695:RESOLUTION`

USAGE: Screen calibration scale factor R – the physical width of one pixel. Changes with updates to camera system, e.g., magnification.

Use to convert horizontal/vertical image axes from pixel index to physical x/y location on screen.

$$(x\ [\mu\text{m}],\ y\ [\mu\text{m}]) = (x\ [\text{pix}],\ y\ [\text{pix}]) \cdot R\ [\mu\text{m/pix}] \tag{3}$$

Physical $x - y$ coordinates can be converted to $t - E$ using calibrations factors S and ρ_{dump} by using Eqs. (8) and (5) below.

ITEM: Camera attenuator stats

PV: `OTRS:DMP1:695:FLT[1,2]_PNEU.RVAL`

USAGE: (Matter of record.) Indicates whether neutral density optical filters 1 or 2 are in or out, used to attenuate light when camera saturation is observed. These currently have optical densities of OD 0.5 and OD 1.0, respectively.

ITEM: Camera array rate

PV: `OTRS:DMP1:695:ArrayRate_RBV`

USAGE: (Matter of record.) Readback value of the camera triggering rate. May deviate by 1 Hz from actual value. For unrestricted, synchronized running this must be 60 Hz or less. If running at full 120 Hz, there are restrictions on the maximum allowed number of pixels in y to preserve synchronization. If reading back either ~112 or ~44 Hz, the camera likely tripped into free-running mode (not synchronized) and requires reboot.

ITEM: Camera acquisition time

PV: `OTRS:DMP1:695:AcquireTime_RBV`

USAGE: (Matter of record.) Readback value of effective integration time of camera. Should match set value (`OTRS:DMP1:695:AcquireTime`), presently 0.001 s. Known bug: Not always properly restored after reset causing lineout offset (scrambled images) or double images/ghosting.

ITEM: OTRDMP Screen Status

PV: `OTRS:DMP1:695:PNEUMATIC.RVAL`

USAGE: (Matter of record.) Logical 0/1 value, indicates whether or not the OTRDMP (XTCAV) YAG screen is inserted in the electron dump.

ITEM: XTCAV Operating Status

PV: `KLYS:DMP1:1:MOD.RVAL`

USAGE: (Matter of record.) An integer indicating the status of the XTCAV klystron.

1. Accelerating (Active)
2. Standby
3. Offline
4. Maintenance

ITEM: Calibration: Vertical position to energy (dispersion)

PV: `SIOC:SYS0:ML01:AO216`

USAGE: Dump dispersion ρ_{dump} – the change in electron y-offset on the screen per change in incident fractional electron energy offset δ. Weak function of the beam energy. Value in PV automatically updated by `tcav_gui.m` in MCC whenever a new calibration or bunch length measurement is posted.

Used for scaling y image axis values to a true energy axis. The relative energy coordinate δ, absolute energy E, absolute energy offset ΔE and nominal LCLS beam energy E_0 are related by $\delta = \Delta E/E_0 = (E - E_0)/E_0$. Then coordinate y scales to typical electron energy units as

$$\delta\ [none] = \frac{10^{-6}}{\rho_{dump}\ [\mathrm{m}]}\, y\ [\mu\mathrm{m}] \tag{4}$$

$$\Delta E\ [\mathrm{MeV}] = \frac{10^{-3}}{\rho_{dump}\ [\mathrm{m}]}\, y\ [\mu\mathrm{m}]\, E_0\ [\mathrm{GeV}]. \tag{5}$$

ITEM: Calibration: Horizontal position to time, *Strength parameter S*

PV: `OTRS:DMP1:695:TCAL_X`

USAGE: Effective XTCAV streaking strength parameter S – the change in electron x-offset on the screen per relative distance z from the XTCAV zero-crossing phase. Proportional to the XTCAV peak voltage, inversely proportional to beam energy. Value in PV automatically updated by `tcav_gui.m` in MCC whenever a new calibration (XTCAV phase scan) measurement is posted.

Used for scaling x image axis values to z or t coordinate. Coordinate x scales to longitudinal z coordinate in the bunch as

$$z\ [\mu\mathrm{m}] = \frac{1}{S\ [\mu\mathrm{m}/\mu\mathrm{m}]}\, x\ [\mu\mathrm{m}], \tag{6}$$

or directly to t by a factor of speed of light c as

$$t\ [\mathrm{fs}] = \frac{10^9}{c\ [\mathrm{m/s}]}\frac{1}{S\ [\mu\mathrm{m}/\mu\mathrm{m}]}\, x\ [\mu\mathrm{m}] \tag{7}$$

$$t\ [\mathrm{fs}] \approx \frac{1}{0.3\ [\mu\mathrm{m/fs}]}\frac{1}{S\ [\mu\mathrm{m}/\mu\mathrm{m}]}\, x\ [\mu\mathrm{m}]. \tag{8}$$

Note that S is sometimes found provided in units of μm/deg-RF. This can be converted as S [μm/μm] ≈ S [μm/deg] / 72.8954 [μm/deg].

ITEM: Calibration: Horizontal position to time, *XTCAV [Amp./Phase] Desired during calib.*

PV: `SIOC:SYS0:ML01:AO[214,215]`

USAGE: The RF amplitude and phase of the XTCAV during calibration. Value in PV automatically updated by `tcav_gui.m` in MCC whenever a new calibration (XTCAV phase scan) measurement is posted.

This is the XTCAV setting for which the calibration value S is valid. XTCAV amplitude and phase recorded for individual shots should be compared to these values (approximately equal, within RF jitter) to verify time calibration being used is correct. Can also be used to scale S with the shot-to-shot XTCAV amplitude.

ITEM: Calibration: Horizontal position to time, σ_x, σ_z, r_{15}

PV: `SIOC:SYS0:ML01:AO212, OTRS:DMP1:695:BLEN, SIOC:SYS0:ML01:AO213`

USAGE: These values can be used to compute a small effective correction factor C to the strength parameter S due to an initial $x' - z$ correlation of the beam at the XTCAV. PV values automatically updated by `tcav_gui.m` in MCC whenever a new bunch length (BLEN) measurement is posted. [Details on use pending.]

ITEM: Beam energy

PV: `REFS:DMP1:400:EDES`

USAGE: The electron beam energy E_0 right now, based on the currently loaded configuration. Assumed that all signals, baselines and calibrations are for this beam energy.

Also used to scale the energy axis to absolute energy units in Eq. (5).

ITEM: XTCAV [Voltage/Phase]

PV: `TCAV:DMP1:360:[A,P]BR`

USAGE: The actual RF amplitude and phase of the XTCAV right now.

XTCAV amplitude and phase recorded for individual shots should be compared to those set during calibration to verify/scale the time calibration being used. Can also be used to identify momentary XTCAV RF trips/ramps.

ITEM: Gas detectors

PV: `GDET:FEE1:[nnn]:ENRC`

USAGE: Independent shot-to-shot measurement of xray pulse energy.

Used to determine unknown absolute bunch energy offset for Δ reconstruction method and unknown overall scale factor for σ reconstruction method. Also useful in filtering data to intense SASE shots, etc.

ITEM: Bunch charge

PV: `BPMS:DMP1:502:TMIT`

USAGE: Shot-to-shot measurement of the bunch charge Q arriving in the electron dump (typ. in number of electrons $N = Q/e$).

Used to determine the absolute normalization of the single-shot bunch current profile $I(t)$ inferred from the t-projection of the image. (i.e.: to enforce $\int I(t)\,dt = Q$.)

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3. Optional, Very Useful Beam Data

ITEM: BLM1, BLM2

PV: `BLEN:LI21:265:AIMAX, BLEN:LI24:886:BIMAX`

USAGE: Shot-to-shot measurements of the bunch length after LCLS bunch compressors 1 and 2, respectively, determined from the LCLS relative bunch length monitors.

Several nonlinear beam dynamics effects are influenced by the peak current, which can flucutate from shot-to-shot. Filtering data to shots within $\lesssim 1\sigma$ of the nominal peak currents can help select nominal FEL shots.

Similarly, XTCAV image properties will vary with peak current. One advanced strategy for analyzing images for xray reconstruction would therefore use this supporting information to quickly group or match images to shots that have similar peak currents.

ITEM: Beam energy: DL2, BPMs 1 and 3: x positions and associated dispersions

PV: `BPMS:LTU1:[250,450]:X ; SIOC:SYS0:ML01:AO[217,218]`

USAGE: Beam energy before entering the undulator is already recorded in the EBeam BLD as *LTUEnergy*. It is computed by a fast process using the data shown.

Beam matching and lasing dynamics are dependent on beam energy, which can flucutate from shot-to-shot. Filtering data to shots within $\lesssim 1\sigma$ of the nominal beam energy can help select nominal FEL shots.

Similarly, XTCAV images will exhibit properties that depend on beam energy. One advanced strategy for analyzing images for xray reconstruction would therefore use this supporting information to quickly group or match images to shots that have similar beam energies.
