Development of a compact fast CCD camera and resonant soft x-ray scattering endstation for time-resolved pump-probe experiments

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The designs of a compact, fast CCD (cFCCD) camera, together with a resonant soft x-ray scattering endstation, are presented. The cFCCD camera consists of a highly parallel, custom, thick, high-resistivity CCD, readout by a custom 16-channel application specific integrated circuit to reach the maximum readout rate of 200 frames per second. The camera is mounted on a virtual-axis flip stage inside the RSXS chamber. When this flip stage is coupled to a differentially pumped rotary seal, the detector assembly can rotate about $100^\circ/360^\circ$ in the vertical/horizontal scattering planes. With a six-degrees-of-freedom cryogenic sample goniometer, this endstation has the capability to detect the superlattice reflections from the electronic orderings showing up in the lower hemisphere. The complete system has been tested at the Advanced Light Source, Lawrence Berkeley National Laboratory, and has been used in multiple experiments at the Linac Coherent Light Source, SLAC National Accelerator Laboratory. © 2011 American Institute of Physics. [doi:10.1063/1.3609862]

I. INTRODUCTION

Strong correlation effects in complex systems can lead to the formation of real space superstructures in different electronic degrees of freedom (charge, spin, and orbital) that can compete and/or cooperate with the electron itinerancy. Such competition/cooperation behavior has been argued as one of the key ingredients for understanding how various emergence phenomena, such as high temperature superconductivity (HTSC) and colossal magnetoresistance effect (CMR), can arise from different ground states.^{1–3} To study the electronic self-assembling effects (called electronic orderings), resonant soft x-ray scattering (RSXS) spectroscopy has been identified as one of the most powerful probes due to its direct coupling to relevant orbitals and the sensitivity to long-range spatial structures.⁴

Although quasi-static electronic orderings in correlated electron systems have been extensively studied with the RSXS spectroscopy at third generation synchrotron facilities, their dynamics remains largely unexplored.^{5–10} It has been suggested that using the pump-probe technique, i.e., perturb the system with the pump beam and probe with an x-ray beam at later time Δt to explore the temporal evolution of these orderings, can yield invaluable insight about their dynamics. However, generating such ultrafast (and bright)

x-ray probe beam has been the major technical challenge that limits the progress in this field. Slicing sources at third generation synchrotron facilities, such as the beamline 6.0 at the Advanced Light Source (ALS), Lawrence Berkeley National Laboratory (LBNL), can produce fast enough x-ray pulses, but their intensity is dramatically reduced by more than six orders of magnitude.¹¹ On the other hand, the newly commissioned Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory is an x-ray free electron laser (XFEL) capable of delivering ultrafast/ultrabright x-ray pulses ($>10^{11}$ photons per pulse with <10 fs temporal resolution),¹² thus it is an ideal source for the aforementioned pump-probe experiments.

The high temporal resolution of the LCLS x-ray pulses can potentially be compromised by fluctuations, such as time jitter and energy fluctuation (it becomes intensity fluctuation after the monochromator), inherent to the free electron laser (FEL) process. To correct these fluctuations, the data acquisition has to be carried out in shot-by-shot mode. The acquired images can then be individually normalized by the incident photon flux and reassigned a new time stamp to eliminate the temporal jitter. This can only be achieved if the imaging detector is capable of reading out the full image between two pulses. Besides the high-speed full-frame readout requirement, the detector also needs to (i) be compact enough to fit inside a reasonable size vacuum chamber, (ii) have sufficient cooling to reduce the thermal noise, and (iii) have single-photon sensitivity in soft x-ray regime (from 0.5 to 1.5 keV).

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FIG. 1. (Color online) Block diagram showing the cFCCD camera system. The camera head with all in-vacuum modules (left) is separated from other components (backend electronics, control I/O, host processor and auxiliary components) by the vacuum-to-air feed-throughs.

In Sec. II, we will present the designs of the compact fast CCD (cFCCD) camera that meets these requirements and the endstation used to carry out time-resolved pump-probe RSXS experiments. In Sec. III, we will also show data taken at ALS and LCLS to demonstrate the capability of this new instrument. Sec. IV concludes this paper.

II. SYSTEM DESIGN

A. Compact fast CCD

The block diagram of the cFCCD camera system is shown in Figure 1. The primary components of this camera include: the camera head with all in-vacuum modules, a vacuum-to-air interface, the backend readout electronics, a host processor unit (typically a personal computer) and auxiliary components like temperature controller, chiller, and power supply for operating this computer.

The cFCCD camera head is based on a custom, thick, fully-depleted, direct detection CCD designed at LBNL.^{13,14} This CCD has an array of 480×480 $30\text{-}\mu\text{m}$ square pixels and can be back illuminated for direct soft x-ray detection. When it is placed at 100 mm away from the sample, the total angular acceptance is approximately 8° in both horizontal and vertical directions. The device is thick ($200\text{ }\mu\text{m}$) and has high detection efficiency for x-rays with energies lower than 8 keV (see Figure 2). It is fully depleted to collect all of the charge and minimize diffusion, thus greatly improving the spatial resolution. This CCD has an “almost column parallel” architecture in which every 10 columns have their own output stage and a total 96 output ports are used to readout top and bottom halves of the CCD.¹⁴ The CCD is read out by a custom 16-channel ADC and signal processing application specific integrated circuit (ASIC) called fast CCD readout IC (FCRIC). Each channel consists of a preamplifier, multi-gain integrator and correlated double sampler, followed by a 13-bit

FIG. 2. Efficiency of a typical $200\text{ }\mu\text{m}$ thick CCD versus x-ray energy.

pipelined ADC. With gains of 1, 2, and 8, a 15-bit range can be spanned (the 16th bit is used to control offsets).

The large number of outputs on the CCD enables the maximum 200 frames per second (fps) operation. Each output has a 12 mW static dissipation, so the total heat generated at the periphery is approximately 1.2 W. This heat load plus limited cooling capacity from commercial Peltier coolers and the requirement of being compact (the entire camera head has to fit inside a $3.5''$ cube) led us to redistribute the electronic circuitries into three sets of circuit boards: top, digitizer, and clock feed-through boards. Figure 3 shows the construction of the top board and the arrangement of various boards in flat and folded-up geometries.

The top board assembly holds the CCD sensor and provides the cooling path for it. The backbone of this assembly is an AlN substrate with an opening for exposing the back side of CCD to the incident x-rays (Figure 3(a)). A Kapton board, embedded with the electrical circuit for the assembly, is placed on top of the AlN substrate and is secured by an adhesive film with same physical dimension. The unmasked

FIG. 3. (Color online) (a) 3D exploded view showing the construction of the cFCCD top board (red arrow indicates the direction of incident x-ray beam). (b) and (c) Arrangement of various boards (top, digitizer and clock feed-through) in folded-up and flat geometries.

region on the AlN substrate is then used to glue the CCD for thermal conduction. To complete the assembly, four connectors are used: two from the CCD to the digitizer boards and two to the clock feed-through boards. These five boards are arranged in the way shown in Figure 3(b) (fold-up) and 3(c) (flat). The top board assembly is attached to the Peltier cooler with four clamp-on copper fingers. During the operation, the CCD is cooled to -25°C to reduce the dark current.

Each digitizer board contains three FCRIC ASICs. Each ASIC has 16 inputs that are AC coupled to the CCD (48 inputs per digitizer board and two boards to handle 96 outputs from CCD). The outputs of groups of four ADCs are multiplexed into one LVDS output. Before the AC coupling, there are bias resistors that provide load current to the CCD source-follower outputs. These resistors are mounted on this digitizer board to minimize the heat load on the top board assembly. The digitizer boards are mechanically secured to the copper cooling block as well.

Digital data is collected by an FPGA-based system designed at Argonne National Laboratory (ANL).¹³ At the ALS, this ANL readout system is used in a stand-alone mode, storing data on a local host processor. At the LCLS, the ANL system has been interfaced to the LCLS experimental data acquisition system.

The clock feed-through boards, which are also mounted on the copper cooling block, transmit the analog clocks and bias voltages generated by the backend electronics in the air side to the CCD. But the long pathway (over 1.2 m in the current system) inevitably leads to higher noise pickup and line inductance. Future designs will move all these functions directly onto the clock feed-through boards and this will greatly reduce the noise. Currently the system noise is 300 eV or 82 e^{-} (with the CCD cooled to -25°C) and it has a sensitivity of 23.7 eV/ADU when the FCRIC is set at its highest gain (8X).

The cooling mechanism of the cFCCD has sufficient flexibility to accommodate the required complex motion. The CAD model and photograph of the actual camera are shown in Figure 4. The CCD is cooled by a three-stage Peltier cooler, which is glued onto the top of a copper block with silver-loaded epoxy. There are three sets of water channels inside the block (Figure 4(a) and 4(b)). When flowing water through these channels, the copper block will reach $\sim 15^{\circ}\text{C}$ and the front side of the Peltier will reach -25°C , sufficiently low for dark current reduction when operating at high frame rates. This copper block also provides the cooling for the digitizer and clock feed-through boards mounted on four sides. The cooling water is delivered from the chiller to the copper block through Teflon tubing, which is separate from high vacuum by the vacuum guard made out of a long edge-welded bellow (see Figure 6).

A metal housing is used to fully enclose the cFCCD assembly for both mechanical protection and holding a visible light blocking filter (Figure 4(c)). Currently, a 250 nm thickness, free-standing Al window (with 15 mm square opening) is used to block out the scattered 800 nm laser beam during the pump-probe experiments at LCLS. The backend of the cFCCD assembly has three anchoring holes for attaching it to the support bracket on the detector flip stage. Four 51-pin

FIG. 4. (Color online) (a) Cross-section view of the cFCCD camera showing the design of the copper cooling block and water channels. (b) Bottom view of the cFCCD showing electronic and water connections. (c) Photographs of the actual cFCCD camera with the mechanical housing removed to reveal its internal construction.

electronic connectors can be accessed through slots on the base plate, which are taped off after connections are made to minimize light-leakage (Figure 4(b)). The detector specifications are summarized in the Table I.

B. RSXS endstation

The RSXS endstation is constructed to house the cFCCD (see Figure 5 for CAD model). It has the following major components: (i) a sample cryostat with an XYZ manipulator, (ii) two differentially pumped rotary seals for sample and detector stages, (iii) an experimental chamber with a large wire-sealed base flange to support the detector assembly (single-channel and cFCCD detectors), (iv) pumping and vacuum monitoring systems for experimental and load-lock chambers, (v) a sample load-lock assembly for quick sample switching, and (vi) a motorized *in situ* alignment system.

In the current design, we have chosen the horizontal scattering configuration and separated out the sample (θ , ϕ ,

TABLE I. Summary of detector specifications.

Specification	Value
Number of pixels	480×480
Pixel pitch	$30 \times 30 \mu\text{m}$
Pixel full well depth	$\sim 900 \text{ k electrons}$
Number of outputs	96
ADC dynamic range	15 bits
ADC precision	12 bits
ADC voltage range	0.5 V
System gain	23.7 eV/ADU @ -25°C
System noise	300 eV or 82 e^{-}

FIG. 5. (Color online) A CAD model showing the major components of the RSXS chamber.

χ) and detector rotations (2θ , γ) (see Figure 6 for angular notions, for six-circle diffractometer, this would be (δ, γ)). Although it is different from the commonly used soft X-ray or multi-cycle hard x-ray diffractometers; nevertheless, similar approach was adopted by other scattering endstations as

FIG. 6. (Color online) Photograph of the detector assembly and the sample cryostat.

well.^{15–26} The disadvantage of using the horizontal scattering configuration is that the angular resolution will be worsened by the larger horizontal beam size on the sample in most soft x-ray beamlines; also separating out the θ and 2θ circles can lead to a larger sphere of confusion that requires post corrections through software. However, the design has the following advantages: (1) the sample cryostat is mounted vertically and has better stability against the gravity, (2) the length of cryostat can be shortened to have better rigidity, (3) the separate 2θ circle simplifies the design of the detector flip (γ circle) and the water cooling mechanism for cFCCD, and (4) it leads to a smaller footprint to allow this roll-up endstation to be used at multiple beamlines that have different spatial constraints. Below we outline the design of each endstation component.

1. Detector assembly

Besides the cFCCD camera, there are different types of single-channel photon detectors installed. Two windowless GaAsP photodiodes, with 4.6 mm square active area (G1127-02, Hamamatsu), are mounted 45° away relative to the cFCCD at the same level. These photodiodes are used for static measurements due to their larger electron-hole pair creation energy (~ 4.58 eV, compare to ~ 3.66 eV for Si) that can give better S/N ratio.²⁷ A 3 mm diameter aperture is used to limit the angular acceptance down to $\sim 1.7^\circ$. The photocurrent is transmitted through a shielded cable (KAP-3, MDC) to the BNC feed-through and then amplified by the low noise DC current amplifier (DDPCA-300, Femto, up to 10^{13} V/A amplification).

To detect the pulse signal, two windowless silicon avalanche photodiodes (SAR3000E1 APDs, Laser Components) are used. They are placed above the cFCCD and at ~ 135 mm away from the sample so their 3 mm diameter active area gives an angular acceptance of $\sim 1.3^\circ$. Each APD is individually biased to approximately -200 V during the operation. The detected pulse signal is transmitted through the $50\ \Omega$ shielded cable (KAP-5, MDC) to the SMA feed-through on the 10'' base flange. The output voltage signal can either be recorded directly by a fast oscilloscope or further amplified by the voltage amplifier (DHPVA-200, Femto). To block out the scattered 800 nm and visible light during the pump-probe experiments, each APD is enclosed inside its own aluminum box. In the back end of this box, layers of graphite-coated copper meshes are used to provide the venting path while offering large surface area for light to scatter. In the front side, a 250 nm thickness Al window is attached and the seams are sealed with carbon tape to achieve light-tight.

To detect the mid-infrared radiation (wavelength up to $17\ \mu\text{m}$) that is used to excite phonons in correlated electron systems, a thermopile detector is installed next to the APDs. This detector has a 6 mm diameter active area (model 6M/HS/RW/AR SI W4/XE, Dexter) and is hermetically sealed with a Ge window to block out the visible light. The large active area is selected to have a good match with the beam size such that the detector can still be sensitive to mid-IR radiation without cooling. When coupled to the scanning pinhole/knife-edge tool mounted underneath the

TABLE II. List of feed-throughs on the 10" base flange.

Feed-through type	Quantity	Purpose
DB25	1	Connector for Princeton MTE detector
Micro-D 51 pin	5	Connector for cFCCD
23-pin type C	1	Power for Peltier cooler, CCD RTD sensor, tilt sensor
BNC	2	Signal from GaASP diodes
SHV	2	High voltage for APDs
SMA	4	Signal from APDs, thermopile
Rotary feed-through	1	For driving the γ circle
Vacuum guard (2 3/4" flange)	1	For supplying the cooling water through Teflon tubing and pumping for the vacuum guard

sample goniometer, these single-channel detectors can be used to measure the photon beam profile (x ray, 800 nm, and mid-IR) for calculating the beam fluence and achieve spatial overlap between pump and probe beams.

The cFCCD camera and these detectors are mounted on a virtual axis flip stage (γ circle) driven by an external stepper motor. They can be rotated by $\sim 100^\circ$ in the vertical scattering plane ($\sim 10^\circ$ above and 90° below the horizontal scattering plane) and the relative angular change is determined by an attached in-vacuum tilt sensor with 0.1° angular resolution (model 84064-02, Applied Geomechanics). The gear mechanism is mounted on a support tube that is attached to a 10" base flange with various feed-throughs (fabricated by SRI Hermetics, see Table II for list of feed-throughs). This flange is attached to a differentially pumped rotary seal, which rotates the detector assembly by 360° in the horizontal scattering plane (2θ circle). The combination of 2θ and γ circles enables the detection of superlattice reflections from the electronic orderings in the lower hemisphere. In the event of the detectors being damaged and needing to be replaced, the assembly is mounted on a rectangular wire-sealed base flange for modular installation.

2. Sample stage and the XYZ manipulator

The open-cycle cryostat and sample goniometer are fabricated at the ALS. On the sample goniometer, there are two rotational degrees of freedom: rotate the sample about its surface normal (azimuthal rotation, ϕ circle) by $>270^\circ$ (maximum 360°) and flip in the vertical plane by $>90^\circ$ (χ circle, facing downward), and these motions are driven by external stepper motors through rotary feed-throughs coupled to worm gears. The goniometer is isolated from the cryostat cold finger with a sapphire disk sandwiched in between to allow the total electron yield (TEY) measurement. A radiation shield is partially wrapped around it to reduce the head load on the sample. A YAG crystal and a pinhole/knife-edge ($300\text{ }\mu\text{m}$ pinhole, Edmund Optics) assembly are attached below the goniometer for alignment purpose. The cryostat has built-in cartridge heaters for temperature control from $\sim 15\text{ K}$ to $\sim 450\text{ K}$, as measured by the Si diodes (DT-470, Lakeshore) attached next to the sample stage. A support tube with 2" OD is used to provide addition rigidity to the cryostat and this tube is directly secured to the top 6" flange. A hydraulic formed bellow connecting the top of the cryostat assembly to the 6" flange can reduce the sample movement during temperature cycle.

The cryostat assembly is mounted on top of the VG Omniax manipulator (with 4" ID Z-stage bellow), providing the three translational degrees of freedom. The manipulator is placed on top of an 8" differentially pumped rotary seal, which rotates the sample in the horizontal plane (θ circle). These combined motions give a total of six degrees of freedom for sample manipulation.

3. Alignment and Motorization

To minimize the sphere of confusion, carefully aligning the centers of θ , 2θ , and γ circles is essential. The centers of θ and 2θ circles are determined by placing the differentially pumped rotary seals under the coordinate measurement machine (CMM) and the measured run-off of the rotational axes is around $50\text{ }\mu\text{m}$. These rotation centers are then registered to the fiducials welded on the seal bodies. When installing both rotary seals onto the experimental chamber, the large through holes (additional 2 mm clearance) on the rectangular base flange provide additional room to maneuver the 2θ circle relative to the θ circle. Limited by the fabrication precision, the centers of θ and 2θ circles are off by approximately $500\text{ }\mu\text{m}$. This offset is registered by four setscrews on the alignment blocks welded to the bottom of experimental chamber for reproducibility. The run-off of the γ circle is about $110\text{ }\mu\text{m}$, which is determined by tracing the track of the detector flip mechanism with CMM and best-fit sections of the trace with circles. Three spring-loaded jacking screws below this flip mechanism are used to move the γ circle in the horizontal plane relative to the 2θ circle. With the help of FARO arm, the centers of γ and 2θ circles are within $125\text{ }\mu\text{m}$. Since ϕ and χ circles are only used to orient the sample so that the superlattice reflections can be detected, their precisions are not considered in the estimate of the sphere of confusion. Based on previous description, the sphere of confusion is around $500\text{ }\mu\text{m}$ if no post software correction is used. The alignment information is tied to fiducials welded on the experimental chamber and is used during the endstation setup at the LCLS.

All motions are motorized by using the IMS smart motors (NEMA 23 and NEMA 34 MDrives, Schneider Electric) with the SLAC-designed circuit protection boards for interfacing with power, communication, limit switches and encoder. The motion precision and encoders are summarized in Table III. These motors are controlled with RS485 communication protocol through DIGI PORTSERVER (TS16-MEI) and LABVIEW

TABLE III. Summary of motorized axes.

Axis	Maximum range of motion	Encoder type	Resolution	Limit switch	Note
x	50 mm	Renishaw RGH24	0.1 μm	mechanical	
y	50 mm	Renishaw RGH24	0.1 μm	mechanical	
z	200 mm	Renishaw RGH24	0.1 μm	mechanical	NEMA34 motor
θ	360°	Rotary encoder on the motor	0.001°	N/A	With 30:1 Parker gear box
ϕ	360°	Rotary encoder on the motor	0.1°	In-vacuum; mechanical	
χ	95°	Rotary encoder on the motor	0.1°	In-vacuum; mechanical	
2θ	360°	Rotary encoder on the motor	0.001°	N/A	With 50:1 Parker gear box
γ	100°	Rotary encoder on the motor; tilt sensor	0.1°	N/A	
Horizontal struts (3EA)	50 mm	Renishaw RGH24	0.1 μm	mechanical	With 30:1 Parker gear box
Vertical struts (3EA)	50 mm	Renishaw RGH24	0.1 μm	mechanical	With 160:1 Harmonic gear box

interface at the ALS or EPICS at the LCLS. The experimental chamber sits on top of a six-strut alignment system. Each strut is attached to a linear translation stage (American Linear) equipped with hard stops, limit switches and encoder. Additional support springs are used inside the translation stage to balance the weight of the endstation such that the load on three vertical stages remains constant. The motorization is done through driving these stages by stepper motors and this capability enables the remote alignment—an essential requirement to perform experiments at the LCLS.

4. Vacuum and Monitoring

The chamber has a nominal outer diameter (OD) of 26'' with several large OD ports (up to 12'') for pumps and viewports. Three 8'' ports in the backside of the chamber are used for the vacuum pumps (Varian V551 and V301 turbo pumps and Titan 200L ion pump from GammaVac). The turbo pumps are backed by a Tri-Scroll pump, which also pumps the vacuum guard of cFCCD and two differentially pumped rotary seals. The rough vacuum is monitored by a Pirani gauge above the scroll pump. To avoid the light contamination from vacuum gauges in the experimental chamber, we have used i-Mag cold cathode gauges (MKS) and the pressure is read by the MKS 937 controller. During the measurements, the chamber pressure can reach $<5 \times 10^{-9}$ torr after few temperature cycles without baking.

There are other instruments used during the pump-probe experiments. For example, the antenna tool for determining the time-zero between the pump and probe beams is installed in the upstream 6'' port. A microscope camera for setting up the spatial overlap of beams and fast video cameras (Uniq, synchronized with FEL pulse) for monitoring the interior of system are mounted on the upstream view ports. The 4 1/2'' viewport below the measurement level is used to view the bottom of the cryostat through a 45° reflection mirror mounted on the detector flip stage. When using the video camera coupled to a telezoom lens, we can position the sample at the center of θ circle to within 200 μm .

5. Load-lock system

A sample load-lock system is constructed to minimize the down time for introducing the samples from air into the measurement chamber. It has a drum-type garage attached to a simple magnetic arm that holds maximum 8 samples. A 24'' stroke magnetic arm, with two sets of magnets that control the opening/closing of the grabber, is used to grab the sample from the garage and transfer it into the sample cryostat. The load-lock chamber is isolated from the experimental chamber with a 4 1/2'' manual VAT valve and has its own vacuum pumping/monitoring system – a Varian V81 turbo pump backed by a scroll pump and i-Mag and Pirani gauges for vacuum monitoring. During operation, the load-lock chamber pressure can reach $<10^{-7}$ torr.

III. EXPERIMENTS

Commissioning of the RSXS endstation and the cFCCD was carried out at the beamline 8.0.1.2 at the ALS, LBNL. Nickelate samples ($\text{La}_{2-x}\text{Sr}_x\text{NiO}_4$) with two different doping levels ($x \sim 25\%$ and 33%) were measured during the commissioning run. The nickelates are isostructural to the high temperature superconducting cuprates ($\text{La,Sr})_2\text{CuO}_4$ and show static electronic orderings in charge and spin degrees of freedom at low temperatures.^{28–35} The charge stripes bear certain similarity to the ones in the cuprates, thus studying them can provide invaluable insight to their roles in the physics of high temperature superconductivity.^{6,36–38}

At low temperature, the patterns of charge and spin stripes are illustrated in Figure 7(a) (example for 33% doping). To first order, in the ionic picture, the excessive holes at Ni^{3+} sites (blue spheres, $S = 1/2$) and spins at Ni^{2+} sites (red arrows, $S = 1$) form one-dimensional stripes extending along the b^* axis and alternating along the a^* axis (in orthorhombic notation), leading to the extended charge (CO) and spin ordering (SO) unit cells represented by the blue and red dashed rectangles. The corresponding ordering vectors are $\mathbf{q}_{\text{CO}} = (2\epsilon, 0, 1)$ and $\mathbf{q}_{\text{SO}} = (1-\epsilon, 0, 0)$ in the $(2\pi/a, 2\pi/b, 2\pi/c)$ units,

FIG. 7. (Color online) (a) Schematic plot showing the spin and charge orderings in 33% doped $(\text{La,Sr})_2\text{NiO}_4$. The blue and red dashed rectangles represent the unit cell for charge (hole) and spin orderings, respectively. (b) Phase diagram of $(\text{La,Sr})_2\text{NiO}_4$ showing the charge (T_{CO}) and spin (T_{N}) ordering transition temperatures with hole concentration. The red represents the doping/temperature where data in panel (d) and (e) were taken (figure reproduced from Ref. 35). (c) Schematic plot illustrating the experimental geometry. (d) The spin-ordering peak recorded at ALS. The incident photon energy was set at Ni L_3 edge (854 eV). The exposure time was 100 ms. (e) The spin ordering peak recorded at LCLS. The image is the sum of 15 (8 ms exposure time) single-shot images. (f) Overlay of the vertical traces taken at $(H,K,L) = (0.723, \delta K, 0)$ ($L = 0$) from ALS and LCLS showing the consistent peak width (correlation length).

where ε is the incommensurability which scales roughly with the doping level.³⁵

These ordering vectors have strong doping and temperature dependence, as seen in the phase diagram in Figure 7(b). The transition temperatures, T_{CO} and T_{N} , show a cusp around 33% doping when SO and CO vectors coincide with each other and decrease when moving away from this doping level. In the studies, we prepared the samples in a following way (we only show the data from 25% doped sample). The nickelate single crystal was grown by float zone method and oriented by the Laue pattern. It was then cut and polished to produce a mirror-like (100) surface. During the measurements, the c axis was in the horizontal scattering plane such that both SO and CO can be accessed by rotating θ and 2θ angles. At Ni L_3 edge around 854 eV, the SO peak was detected at detector angle $2\theta \sim 156^\circ$ and sample angle $\theta \sim 78^\circ$. This corresponds to an ordering vector of $q_{\text{SO}} = (0.723, 0, 0)$ in (H,K,L) unit and the incommensurability ε is 0.277. For detecting the CO peak, the detector angle was set at $2\theta \sim 143^\circ$ and sample angle at $\theta \sim 38^\circ$ to have the proper projection along a^* and c axes.

At the ALS, the beamline resolution was around 0.2 eV and the beam size is approximately $30 \mu\text{m}$ (V) $\times$ $100 \mu\text{m}$ (H). The photon flux on the sample was estimated to be around

10^{13} photons/s. Even under the resonance condition, the ordering peak signal can still be orders of magnitude weaker than the incident photon flux (the reduction is material dependent), thus having a higher incident flux to start with will be beneficial. With such high photon flux, a nice SO peak can be observed at 50 K with 100 ms exposure time (Figure 7(d)). The oval shape of the image suggests that the in-plane correlation length (inverse of the peak width) is much longer than the out-of-plane one and is consistent with the two-dimensional nature of the material.

In Figure 7(e), we show the same SO peak taken at the Soft x-ray (SXR) beamline at the LCLS. With the pulse source, the acquisition was set to the shot-by-shot mode. The exposure time was set to 8 ms, short enough to allow the full image to be read between pulses (60 Hz or 16.67 ms separation). The result in Figure 7(e) is the sum of 15 single-shot background-removed images (total 0.25 s accumulation time). The photon flux on the sample was reduced to $\sim 5 \times 10^9$ photons/shot and the beam size was enlarged to $\sim 300 \mu\text{m} \times 300 \mu\text{m}$ to avoid sample damage. Although the image taken at LCLS is much weaker (roughly 12 times weaker), nevertheless, the SO peak with similar oval shape can be clearly resolved. The in-plane correlation length, derived from the inverse of the peak width in Figure 7(f), is around 230 Å and in agreement with the published results.¹⁰ By comparing the correlation length along the vertical trace at $L = 0$ (along $(0.723, \delta K, 0)$), the agreement between the ALS and LCLS data indicates that the observed SO peak is not disturbed by the FEL pulse during the probing time elapse, even though the incident fluence ($> 5 \times 10^4$ photons/shot- μm^2) is nearly 4 orders of magnitude higher in this case. This finding is very encouraging because it validates the proposed pump-probe experiments at the LCLS such that one can work with very high probe fluence to produce a statistically meaningful image while still preserving the pristine electronic structure during the probe time span (< 10 fs). The consistency also indicates that this cFCCD camera is capable of running at such high full-frame readout speed without degrading the data quality. Some offline tests at 120 fps were also carried out at the ALS and the LCLS using independent trigger signals to test the camera and its readout system performance at this rate. These independent tests also confirm that no degradation in performance is observed with respect to different readout rates.

IV. CONCLUSIONS

A high-speed compact, fast CCD camera (cFCCD) and a new resonant soft x-ray scattering (RSXS) chamber have been designed and constructed. The cFCCD camera is based on two custom ICs (FCCD and FCRIC) designed at LBNL. This new camera together with the new RSXS chamber have been designed to perform laser pump x-ray probe experiments to investigate strong correlation effects in complex systems as explained earlier in this paper. The cFCCD has been used at the LCLS rate (60 Hz) for several experiments, and higher speeds at the ALS. Sample images of the data collected at both facilities have been shown demonstrating the

capability and performance of the system while executing the pump-probe experiments.

Future improvements to this system consist in a new camera, currently under development, with a 1 mega-pixel frame store CCD detector running at similar speeds.

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