NSLS-II Beamline Report for SAC Review of Beamlines

Beamline: **Coherent Soft X-ray scattering (CSX*, 23-ID-1*)**
Report Date: **September 12, 2018**

Introduction

The Coherent Soft X-ray (CSX) scattering beamline belongs to the Soft X-ray Scattering and Spectroscopy (SXSS) program. It was design to deliver a bright coherent soft x-ray beam to perform (resonant) scattering experiments in the soft x-ray regime, with the goal of investigating electronic and structural orderings in materials. It is thus perfectly aligned with the BNL laboratory strategic initiatives on "Material Complexity" and the NSLS-II science priority area of "Quantum and Complex Materials". From the instrumentation point of view, the beamline lineout is extremely simple with the goal to preserve the beam coherence and maximize the flux delivered by the specifically designed NSLS-II source. Various focusing options are available allowing the samples to be probed at different length scales. A mid resolution monochromator and an UHV flexible end-station, hosting a stable diffractometer and a fast CCD detector, constitute the experimental setup optimized for exploring electronic dynamics in solids over several orders of magnitudes in time.

The CSX beamline was built during the first phase of the NSLS-II project (fully funded by the DoE, Basic Energy Science). It was the first to receive light from the NSLS-II ring, on October 23rd, 2014. After a very quick initial commissioning, it was also the first one open to general user (GU) operations during 2015-II cycle. By the end of the same year, the sister beamline IOS (23-ID-2) was commissioned and started its activity. Since then, an intensive R&D effort has been produced by the staff of the two beamlines in order to characterize and manage the problem of reciprocal perturbation during operations.

Beamline Overview

The beamline is dedicated to providing a world leading instrument for the investigation of electronic orderings via soft x-ray scattering. The CSX beamline offers the scientific community unique scattering and imaging tools, fully exploiting the exceptional coherent flux delivered by the NSLS-II source at these energies. This is provided though an experimental setup optimized for exploiting soft x-ray resonances in solids, with specific capabilities for studying the electronic and structural correlations, their texture, inhomogeneity and dynamics, across a wide range in both space and time domains. To achieve the challenging purpose, the beamline provides soft x-ray photons over 250 – 2000 eV energy range, with a coherent flux at the sample of up to 2 x 10^{13} photons/s, a typical resolving power of 2 x 10^3 $E/\Delta E$ and a variety of focal spot conditions (~4 orders of magnitude, from few hundreds μm down to sub hundred nm, depending on the optics setup). The beamline and end-station stability, coupled with the novel fast CCD detector, make a perfect match to investigate sample dynamics over a broad interval in the time domain (~6 orders of magnitude, from 10^-4 to 10^2 Hz). The versatile UHV diffractometer geometry can accommodates a wide range of experiments, from forward scattering to reflectivity, from (resonant) diffraction to raster scan imaging.

A layout of the beamline is sketched in Fig. 1, showing its principal optical components together with the sister beamline IOS.

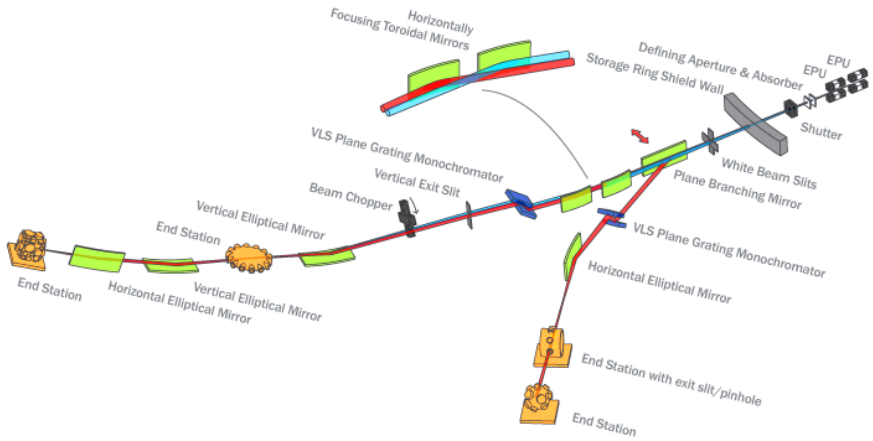


Figure 1. Schematics of the 23-ID beamlines layout. CSX is sketched at the bottom while IOS at the top.

Following the x-ray beam, from right to left, the beamline consists of:

- the source (two EPUs and a canting magnet, CM, in between them, not shown);
- the first outboard bouncing, flat vertical mirror (depicted in position for deflecting the beam down CSX, see red double arrow);
- the variable line spacing plane grating monochromator (VLS-PGM, down-bouncing mirror and up-bouncing grating);
- the third outboard bouncing, meridionally curved vertical mirror;
- a set of pinholes (slits 3) acting both as exit slits (energy selection) and as spatial filter (beam coherence fraction selection);
- the experimental end station (TARDIS);
- a service station (currently populated with standard targets for energy calibration and a rotatable multilayer mirror for polarization measurement).

The EPUs are in-line with the electron beam but the presence of a retractable CM in between them allows the source to be operated in two different modes:

1. straight mode (CM out of the electron trajectory): one x-ray beam is generated and propagated down either CSX (CSX first mirror in) or IOS (CSX first mirror out). Only one beamline operates at a time;
2. canted mode (CM in place, where two X-ray beams are produced): one beam for each branch (CSX first mirror parked on its side position, intercepting half of the photon beam out of the source) or potentially both on IOS (CSX mirror out). The latter configuration was never commissioned.

In theory, the two 23-ID beamlines can be operated simultaneously in the canted mode. Unfortunately, due to reciprocal perturbation issues this was proved to be impossible and the operational time had to be split between the two beamlines (50-50) since the beginning of 2016 (see Appendix A for details).

The simple optical scheme of the beamline is designed to maximize the coherent flux at the sample, to achieve high stability over time and focusing flexibility. The VLS law of the monochromator and the last mirror bender provide vertical and horizontal focusing, respectively. The focal point, typically ~30x30 μm, can be moved from ~1 m upstream (where slits 3 are located) to ~3 m downstream of the current sample position in TARDIS. So, other end stations can be added downstream to the current one for future dedicated experiments. If slits 3 are used for energy selection, a typical beam diameter of 0.1 – 0.3 mm is obtained at the sample position, as a consequence of Airy divergence.

The TARDIS (TARget Diffraction In-Situ) end-station belongs to the Condensed Matter Physics and Material Science Department (CMPMSD) of BNL and it is located on the CSX beamline as part of the current partner user agreement (PU). It was initially commissioned at the NSLS facility, where the very first proof of principle experiments where performed. Prior to operations of the NSLS-II, it was moved to its current floor location during mid-2014. TARDIS hosts a reduced version of a 6-circles diffractometer (z-axis geometry). This geometry was selected for its versatility as it can be operated for scattering experiment in the vertical plane and for surface scattering in a dedicated horizontal configuration, while minimizing the number of movements requiring in vacuum motors (only one). This geometry also offers an easy implementation of the sample cryogenic module, for excellent stability and thermal performance. The experimental station hosts two independent XYZ stage stacks, located just upstream the sample. They are designed for accommodating various optics, like pinholes or Fresnel Zone Plates (ZP) and the related order sorting aperture (OSA). In the former case, a typical beam diameter of 5 to 20 μm is obtained at the sample. In the latter, sub 100 nm have been achieved. A recent development in terms of optics mount and piezo nanopositioners have increased the stages flexibility, in terms of longer motions and a better integration in the scattering geometry.
The sample environment is constituted by a liquid He (LHe) flow cryostat capable of reaching 4K at the sample or 15K if the total electron yield (TEY) has to be measured. The total fluorescence yield (TFY) is collected via a photodiode mounted on the detector arm just aside the main CCD detector and it can also enter the direct beam and be used as a 0D detector. Recently, an energy resolved detector (Vortex) has been added to the chamber for fluorescence collection and analysis at fixed angle (almost backscattering). The counting chain handles all the detectors in parallel.
The samples enter the chamber via a load lock hosting a multi position magazine and is manually actuated. It can be coupled to a simple glove box for some kind of protection in handling moisture-sensitive (and blandly air-sensitive) samples. Options for applying voltages, currents and 4 wire resistivity measurements at the sample are present. Currently, experiments requiring electrical control of the sample environment conditions are quite invasive as the setup is non-compatible with the existing load lock and thus require a very time-consuming venting and pumping cycle of the end-station (~1 day).

The current fast CCD detector was added to the chamber at the beginning of 2015, in the framework of a collaboration between the NSLS-II and LBNL (Berkeley) and SYDOR instruments. Although it granted improved performances (100 Hz maximum frequency compared to tens of second per image of the previous generation detector), it came with essentially no support. Its implementation, commissioning and maintenance represented a major effort completely on the beamline team. The same is true for the beamline diagnostics and feedback systems. The main acquisition software (BlueSky) was initially developed by the DAta MAnagement (DAMA) group on CSX, with a deep involvement of the beamline staff and it is now shared with other DoE facilities across the whole country. In the same way, data acquisition, handling and storing is completely on the beamline side. Although the network group provides basic assistance, the whole data system was set up by the

beamline team. The same is true for the open source python-based software libraries for data retrieving, reduction and analysis, developed in collaboration with DAMA and with some help from PU people (see Impact). The users' data analysis is handled in python as well, via a web interface based on pylab and notebooks, developed and maintained internally by DAMA.

The labor effort supporting CSX has not been constant during the past 3 years. The beamline staff is summarized in the list below (FTE: full-time employee):

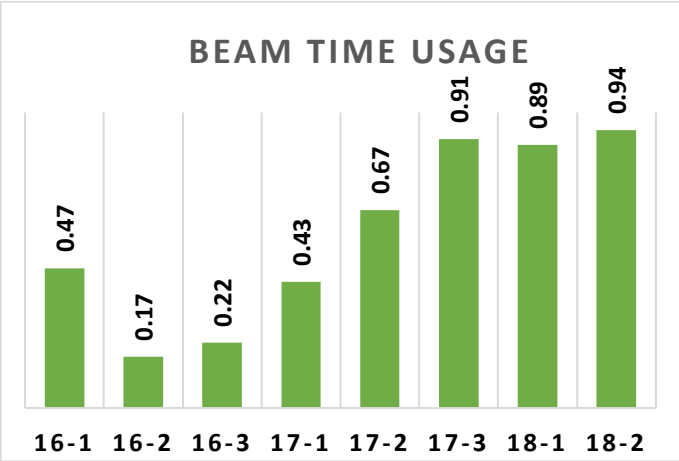
- Stuart Wilkins (various level of support, since 10/2012; lead from 08/2014 to 06/2018; program manager since beginning of 2016);
- Claudio Mazzoli (1 FTE, since 11/2014, lead since 07/2018);
- Wen Hu (1 FTE, since 06/2016);
- Andi Barbour (1 FTE from 07/2015 to 12/2016);
- Felix Büttner (0.5 FTE, shared postdoc with MIT, since 05/2018).

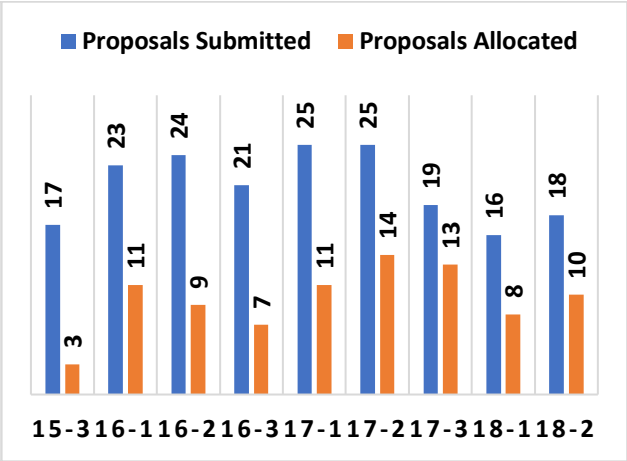
For matrixed support, the CSX beamline receives to date approximately (point of contact):
- 0.2 FTE Mechanical Engineer (Daniel Bacescu);
- 0.2 FTE Controls support (John Sinsheimer), including DAMA;
- 0.25 FTE Mechanical Technician.

The beamline can access one shared users' support lab (1LL04), where delicate setup and sample mount can be performed.

Productivity and Impact

After an initial period of intensive technical commissioning followed by science commissioning (2016), the beamline has delivered beamtime to users for the large majority of its time (see graph below, left panel). The number reported refers to the fraction of beamtime dedicated to user experiments (the reminder to 1 is due to technical commissioning). All the reported periods refer to the 50-50 splitting of beamtime between CSX and IOS (see Beamline Overview).





The number of proposal (see graph above, right panel) is quite constant over the years, with averages of 20 proposal submitted per cycle and 10 allocated, giving and oversubscription factor of 2.0. The cutoff of our proposal is remarkably high (typically 1.5 – 1.6), proving the very high quality and impact of the beamline science.

Up to now the majority of the CSX user community reside in the hard-condensed matter; magnetism and strongly correlated electron systems domains in particular. Recently, it has been a goal of the beamline to diversity the user community, and initial experiments have been undertaken in the areas of material science (ionic pumps and H-storage), organic (liquid crystals) and biominerals ($CaCO_3$ crystalline forms from biological samples). So, the numbers reported are essentially referred to standard beamline capabilities, with a few related to imaging commissioning and reconstruction tests (see Vision below).

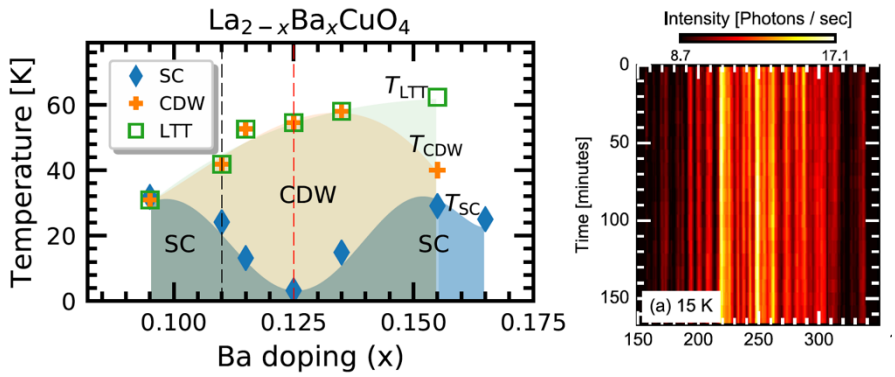
It is worth noticing that CSX had a large users' base supporting its initial call. This is also impressive given that the beamline is producing novel science with novel and almost unique tools. This is clearly shown by the average impact of its scientific production (see Appendix C), but it also accounts for the long average time before publication. Indeed, most of the users have to be familiarized with the technique and exposed to the specific data (information retrieved, acquisition and analysis techniques) before being in the conditions of even conceiving a targeted experiment. For this reason, the beamline staff have worked to create and grow its users' community. In addition to the usual out-reach activities, the beamline team is organizing or has organized 3 dedicated workshops during Users' Meeting (in 2016, 2017 and 2018), 1 international conference to be held in 2019 (REXS2019) and has used the beamline discretionary time (BDT) to work with potential user groups rather than conduct in-house scientific experiments.

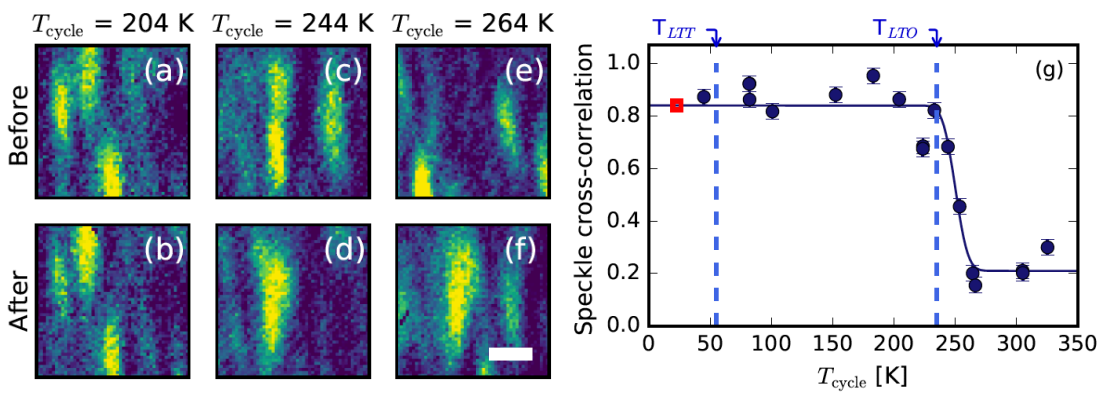
Partner User (PU) agreements: CMPMSD

The TARDIS endstation was contributed to the NSLS-II at the CSX beamline as part of a partner user agreement. In turn for contributing the endstation, available to all users, the CMPMSD team receives 10% of the available user time. The CSX beamline team has enjoyed a fruitful scientific collaboration with the team lead by Mark Dean of CMPMSD. This is evident in the joint publications in high profile journals (see Appendix C).

Selected scientific cases

<u>CDW texture and dynamics in cuprate HTSC (Part of the PU Collaboration)</u>
Since the discovery of the CDW in cuprates HTSC about 25 years ago in the 214 cuprates families, questions have been raised about their relation to superconductivity. In particular it was questioned if CDW fluctuations can provide the explanation for the non-BCS behavior. After the recent discoveries of the ubiquitous presence of CDW in most of the cuprate families, CDW texture and their evolution in temperature across the various phases in these compounds have become of fundamental importance. The high coherent flux of CSX was exploited for dynamics and return point memory measurements on LBCO samples showing unexpected relationship with the lattice transformations.

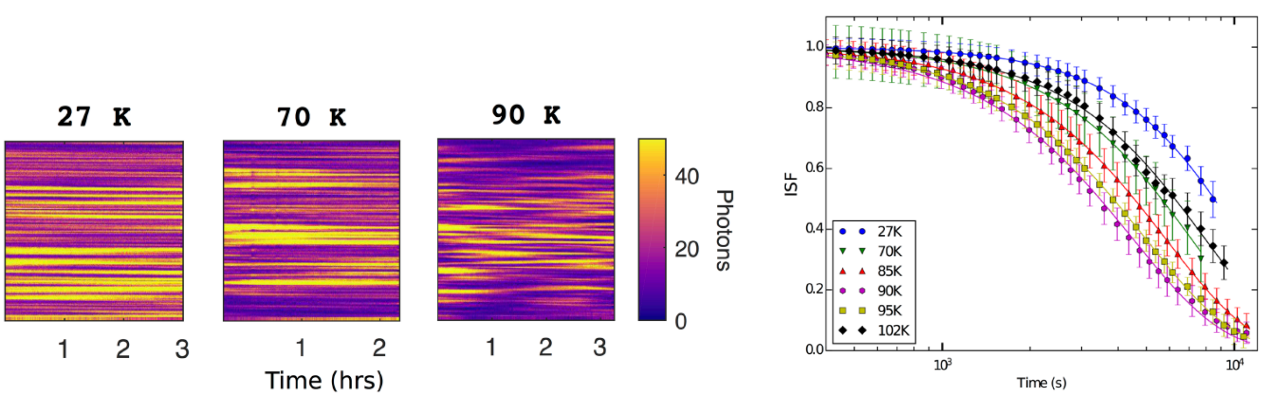




Top panels: the LBCO phase diagram and a kymogram showing perfect stability over long time (up to 3 hours) of the CDW speckles at optimal doping (x = 0.125) and low T (15K). Bottom panels: memory effect on the CDW domains as evidenced by the speckle distribution on the detector and its temperature evolution for x = 0.125.

Orbital domain dynamics in Fe_3O_4

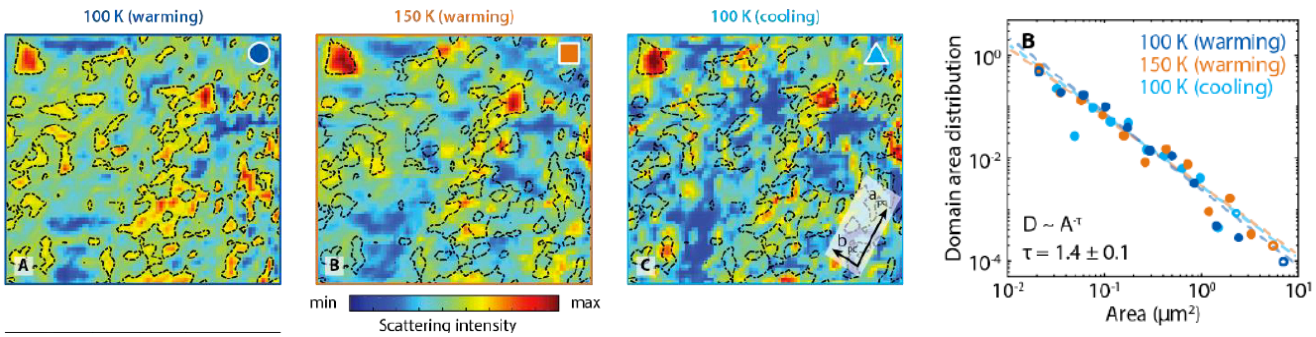
The Verwey transition is a long-standing problem in solid state physics, where the nature and details of the electronic transformation accompanying a sharp increase of electrical resistivity has defeated a complete understanding of the scientific community in Fe_3O_4. On the beamline, the dynamics of orbital reflections associated with insulating domains in the material showed a complex behavior in around the critical temperature, allowing to access unprecedented details of the metal to insulator transition in this compound.



Left panels: kymogram of the orbital reflection speckles at various temperatures. Right panel: intermediate scattering function evolution versus T. Note the non-monotonic behavior (faster dynamic obtained well below T_c).

Scale-invariant magnetic textures in a strongly correlated oxide

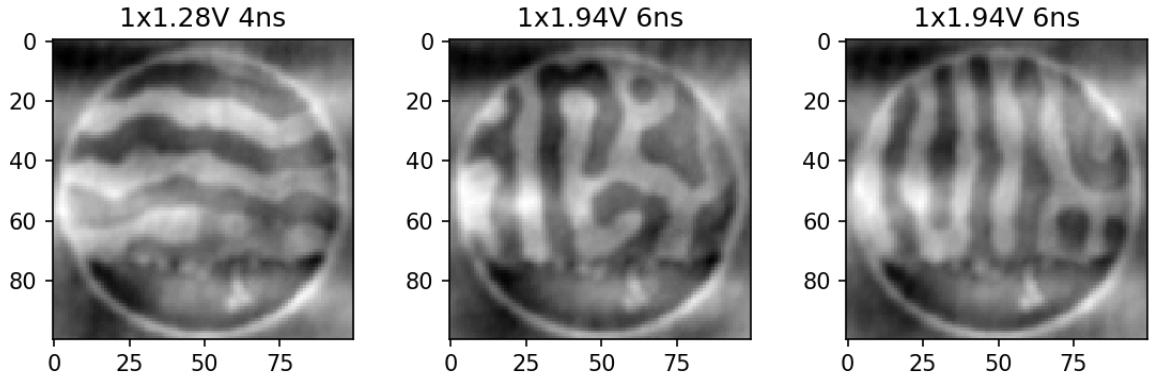
$NdNiO_3$ is well known to present a nanostructured AFM texture. By exploiting the coherence of beamline in a ZP based nanodiffraction experiment, the distribution of magnetic domains and their behavior as a function of the thermal cycle was investigated. This revealed a fractal organization, memory effect and pinning to the lattice as shown below.

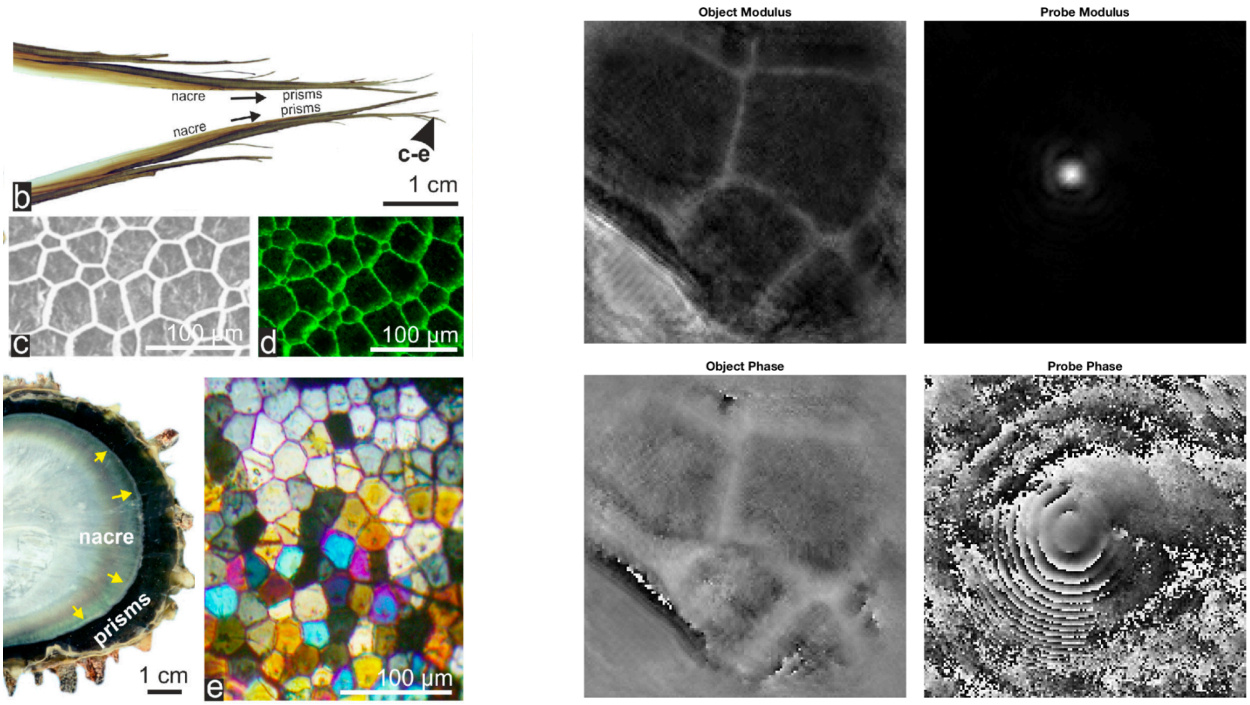


Left panels: distribution of AFM domains as images in the $NdNiO_3$ sample by ZP raster scanning (10 x 10 μm^2). A certain degree of correlation in the domain position is evident and highlighted by the black contours indicating the position of the high intensity domains in the first cooling cycle. Right panel: statistical analysis of the domain area distribution as a function of the thermal cycle, evidencing the reproducibility of the inherent scaling law.

Other relevant examples

As told the main effort is focused on electronic orderings and the determination of their characteristics, thus impacting various examples of Spin Density Waves (SDW) and CDW in a variety of strongly correlated materials (nichelates, cobaltates, CuBr2, tantalates and tellurides, …), AFM domain configurations and fluctuations (manganites, cobaltatites and ferrites), Kondo phase coherence (borates and In5 family), orbital, interface and surface dynamics in transition metal oxides and artificial magnetic structures (spin ice and multilayered structures). On the latter, the holography reconstruction has started to provide interesting results in terms of direct visualization of magnetic domain manipulation by magnetic and electric field (relevant for information storage and quantum computing), shown in the figure below (top panels). As already reported, recently interest has been dedicated to the investigation of biominerals across the Ca K-edge in shells, providing a nice case for reconstructions as shown below (bottom panels).





Top panel: magnetic domain manipulation in magnetic multilayer by application of electric field impulses, as reconstructed via XMCD based holography (the sample diameter is 1 µm). Bottom panel: optical microscopy (right) and ptychographic reconstruction (left, 10 x 10 μm^2) of the prism $CaCO_3$ structure in an oyster shell. The spectroscopic information (not shown here) is expected to provide important insight in the growing process and the impact of environmental conditions on the biomineralization.

Vision for Next Five Years

In forming the 5-year vision, the beamline team have considered the following points:

- financial and technical support (some details are provided in the previous 2 paragraphs);
- beamline staffing level (see previous and following paragraphs);
- level of robustness of control systems (see Beamline Self-Assessment);
- CSX / IOS reciprocal perturbation problem (see Appendix A for details);
- context of other national and international synchrotron sources and beamlines.

In the following we briefly report our current situation and our projected needs and vision for the future.

The CSX staff has invested considerable attention and energies in identifying and developing productive techniques for the beamline (resonant scattering and X-ray Photon Correlation Spectroscopy, XPCS). In addition, new techniques have been investigated (ZP based nanodiffraction, surface diffraction, holography, ptychography, CDI and lens-less imaging). This has been done to provide our scientific community with excellent experimental tools, in line with the beamline mission and covering the interests and the capabilities of the CSX team. In parallel, the beamline requires a continuous technical investment (basic general functioning, reliability and stability) which severely limits our capabilities of following our desired development path (harmonic rejection and sample

environment evolution) and implementation of new ideas (time resolved activities, energy and polarization detection capabilities, various sample environment additions – magnetic field compatible with diffraction experiments, strain control, temperature control with zero thermal expansion, …).

In the short period (1 – 2 years), we need to maintain the user groups support while heavily investing in reliability of routine operations. During this time, we will continue to attract other groups, in the effort of growing and consolidating our user community (see Impact). In parallel, we will concentrate on stabilizing a subset of the techniques currently under development. In particular, the holography chamber should be finalized and turned over for scientific production. Nanodiffraction has been recently opened to general users, although it still suffers some reliability problems. These should definitely be solved, which will require internal support from the in-house experts and capital investments in terms of high-level dedicated piezo stages, controller and encoders.
The lens-less reconstruction is at a very early stage. We aim to develop it by forming a consortium of users to work with the beamline team and the DAMA group specifically focused on soft x-ray needs. We believe that lens-less imaging offers an area where the CSX beamline can make a large impact.
On the reliability issue, investments will be required in order to improve the monochromator and the load lock – sample environment evolution. For the latter we intend to pursue an advanced sample holder design, including electrical contacts compatible with the load lock operation. This will require crucial engineering and design support in order to effectively fulfill quasi in-operando conditions, central for the investigation of materials related to Quantum Information Science, a DOE, BNL and NSLS-II priority.

On a longer scope (2 – 5 years), new synchrotrons or upgrades to existing synchrotrons will become available which may change the relative position of NSLS-II and CSX beamline in the global panorama. In order to maintain the current leading position and keep attracting the best users and science, we will need to carefully choose our technical offer and support. Separation of forward scattering from diffraction experiments should be achieved, granting optimal performances and adequate flexibility to both. Surface diffraction should be kept evolving at its current pace. Lensless reconstruction efforts should produce software packages and resident knowledge in order to serve a user community who are not experts in such x-ray techniques. It is in this area in which we believe that such a consortium can play a key role. Some hardware development at CSX will be necessary (harmonic rejection devices, source evolution, energy – polarization detection capabilities, extension of the space and time domain accessible – in particular toward higher frequencies and smaller length scales, time resolved capabilities, innovative temperature control methods at the sample).

In the above context, we believe that it is critical that a possible change of the source or optical scheme and a relocation of the experimental station and/or beamline should be considered with the upmost urgency. It is critical to address the CSX and IOS reciprocal perturbation. Appendix A reports about this topic. As a first step, the director supported the idea of moving on with the purchasing and installation of a phasing magnet. This would maximize the coherent flux of our straight section. Unfortunately, the whole project is paused due to limited staff bandwidth and the current accelerator division priority list. The availability of the phasing magnet and its use in real experiments on CSX will be crucial to decide the best strategy for dealing with the source on a longer time frame: increasing the canting angle to reduce effects or using two different front ends to eliminate them are the basic options available. Upcoming opportunities of new beamlines and front ends (MIE, DoE funding), the cost, the impact on the beamlines' productivity and their performance should be attentively considered.

Beamline Self-Assessment

Over the last 3 years of operations (2015-II – 2018-I) the CSX beamline has offered unique capabilities in terms of (resonant) coherent scattering and diffraction in the soft x-ray regime. It has shown unprecedented sensitivity and stability in the measurement of electronic ordering, in imaging their texture and inhomogeneity and in capturing their dynamics. We believe that the CSX beamline is starting to be recognized as a world leading instrument capable of providing the scientific community with a unique and complementary perspective on a variety of scientific cases, centered around strongly correlated electron systems. Some other scientific activities have recently (2018-II) been embraced and represent an effective extension of the beamline possibilities scientifically and technically (see Vision).

It is worth noting that the CSX beamline – being the first one to take light –developed several of the technical solutions implemented at NSLS-II on other soft beamlines. During this time, the beamline was also impacted by the ongoing construction activities within the SXSS program (2 NEXT project beamline until 2017-I, 1 NextGen beamline, just aside CSX on the floor with a consequent direct effect on operation during its construction, ended 2018-I).

The problem of reciprocal perturbation with the neighbor beamline (see Appendix A) and the reduced staffing scheme we believe put additional demands onto the already stretched beamline team. To this end, considerable efforts have been produced to find other ways of accessing resources (internal and external collaborations and projects), while performing virtually all the needed technical development in-house (see Beamline Overview). Considered the historic evolution of the beamline, its current staffing level and the various activities present both in terms of techniques and scientific cases (see Vision) the option of PostDocs joining the staff are very welcome and considered appropriate. In the recent past (2016 – 2017) an LDRD PostDoc, shared with CMPMSD and under the local supervision of S. Wilkins, was charged with starting some of the lensless imaging reconstruction activities. She is still currently contributing to the Artificial Spin Ice scientific project started during her tenure at NSLS-II. This activity is expected to produce sound scientific papers soon (two are currently in the pipeline). Very recently another PostDoc has joined our team (through the Director's PostDoc program), in the framework of a scientific collaboration with MIT (G. Beach group). This postdoc is supervised by W. Hu and tasked with the development of the holography setup (one paper is already in the pipeline). Other projects have been submitted in relation with different areas of interest (facility project for laser warming, BNL LDRD for Quantum Computing initiative) and are hopefully bringing fresh and much needed resources to the beamline.

Currently, the beamline (and more generally the program) is dramatically suffering from two main problems: chronical lack of technical resources and diffuse fragility of basic control subsystems. Probably, the two points are interrelated and partially consequent of the tremendous pace at which the facility has been commissioned. However, in order to improve the quality of our performances and the level of support offered to our users, the above points have to be addressed. Otherwise the remarkable technical challenges we are facing (see Vision) will be hard to achieve.

Appendix A
Reciprocal perturbation issues affecting the 23-ID beamlines

The original mission of the IOS beamline was to provide XMCD measurements in a rapid polarization switching fashion. While the beamline was designed for this capability it was never realized. The IOS scientific program moved to chemistry oriented XPS and XAS based measurements. While from the conception of the beamline it was envisaged that the operation at CSX and IOS would nominally be in a mode where both undulators served *one* branch (mode 1), in an attempt to maximize user throughput of both branches the operation defaulted to having a shared mode where both beamlines could operate at the same time (mode 2, see Beamline Overview). During this operation however, insurmountable reciprocal perturbation issues were discovered.

The two principal causes of these issues are:

1) The canting angle: the angular separation of the two beams was set at 0.16 mrad, to allow the fast polarization switching on IOS;
2) The electron beam stability: it is compromised in the canted mode as the electron beam position monitors (eBPM) feedback system was not designed to accommodate two separate canted beams.

In order to resolve these issues, extensive joint studies with the accelerator division were undertaken in order to try to address the second point listed above. About the first point, a joint beamline commissioning was undertaken (2016) to understand and mitigate the consequent thermal instabilities (notably the CSX first mirror, suffering of long drifting times) and the photon beam contamination (cross-talk from one source providing intensity to the neighbor beamline) affecting both CSX and IOS.

The effects listed above impacted very negatively the beamlines' activity. In particular, the first period of operation was extremely hard on the staff, in terms of both R&D for understanding the root cause of the problems and stress for operating the respective users' program while managing and mitigating the situation. From the CSX perspective, the productivity of the beamline was seriously hindered due to the specificities of the techniques used at CSX (extreme sensitivity to the x-ray wave front stability). This was essentially incompatible with the spectroscopy operation of the neighbor beamline (periodical big jump in energy from one edge to another, see thermal perturbation above). During this period, we believe that the CSX beamline suffered the departure of early and promising research groups dissatisfied by the beamline instabilities experienced since the 50-50 sharing.

A working group formed by C. Mazzoli (CSX, chair), I. Waluyo (IOS), J. Dvorak (soft x-ray group optics scientist), D. Bacescu and J. Adams (project manager) was charged by S. Wilkins of analyzing the situation and suggesting possible solutions to these reciprocal perturbation issues. The investigation evidenced that perturbations were particularly severe when the 50-50 splitting was realized on a daily basis, due to the thermal stress induced on CSX optics. Finally, a compromise solution was reached by changing the splitting scheme to a weekly (or multi days) basis. In this way, the beamline designed to control the source (leading) over the period allocates users for several days in a row. In the meanwhile, the other beamline is operated in parasitic mode. Currently, the operation of the source pertaining to the parasitic beamline is allowed only if the leading beamline is not perturbed

(compatible source configuration in terms of EPU settings and/or pauses in the activity of the leading beamline). For CSX, this is virtually incompatible with any user activity and even basic commissioning and testing is tough. However, it is important to keep the optics "ready" to recover a stable situation quickly, as soon as CSX becomes leading. This is particularly important when the swap happens during an operation period (or in case of problems at the other beamline) in order to minimize the thermalization time (better warm and perturbed than starting from cold). As a consequence, rarely our source is operated in mode 1 (see Beamline Overview). Essentially only when special conditions are met (one of the two beamlines is down). In this case CSX can exploit the full beam and the enhanced source stability, a situation typically reserved to particularly delicate experiments (ZP, reconstructions, long XPCS measurements).

Appendix B

Complete list of users

(note that the Users Office did not trace users before cycle 2015-3 although CSX got the first General Users proposals accepted for cycle 2015-2)

Cycle	Last Name	First Name	Affiliation
2015-3			
	Barbour	Andi	Brookhaven National Laboratory
	Boscoboinik	Jorge	Brookhaven National Laboratory
	Bozovic	Ivan	Brookhaven National Laboratory
	Chen	Xiaoqian	Brookhaven National Laboratory
	Dean	Mark	Brookhaven National Laboratory
	Guo	Hongyu	University of Delaware
	Kaznatcheev	Konstantine	Brookhaven National Laboratory
	Langridge	Sean	Rutherford Appleton Lab
	Massey	Jamie	University of Leeds
	Mazzoli	Claudio	Brookhaven National Laboratory
	Morley	Sophie	University of Leeds
	Porro Azpiazu	Jose Maria	Rutherford Appleton Lab
	Sinha	Sunil	University of California @ San Diego
	Song	Jing-Jin	University of California @ San Diego
	Thampy	Vivek	Brookhaven National Laboratory
	Tranquada	John	Brookhaven National Laboratory
	Waluyo	Iradwikanari	Brookhaven National Laboratory
	Wilkins	Stuart	Brookhaven National Laboratory
	Yang	Yi	University of California @ San Diego
2016-1			
	Barbour	Andi	Brookhaven National Laboratory
	Bilgin	Eylul	University of California @ San Diego
	Boscoboinik	Jorge	Brookhaven National Laboratory
	Cao	Yue	Brookhaven National Laboratory
	Chen	Xiaoqian	Brookhaven National Laboratory
	Comin	Riccardo	Massachusetts Institute of Technology (MIT)
	Dean	Mark	Brookhaven National Laboratory

He	Wei	Stanford University
Hua	Nelson	University of California @ San Diego
Kaznatcheev	Konstantine	Brookhaven National Laboratory
Kukreja	Roopali	University of California @ Davis
Langridge	Sean	Rutherford Appleton Lab
Lebert	Blair	University Pierre et Marie Curie
Lee	Young	Stanford University
Mazzoli	Claudio	Brookhaven National Laboratory
Miao	Hu	Brookhaven National Laboratory
Morley	Sophie	University of Leeds
Porro Azpiazu	Jose Maria	Rutherford Appleton Lab
Rotundu	Costel	SLAC National Accelerator Laboratory
Ruby	Joshua	University of California @ San Diego
Shpyrko	Oleg	University of California @ San Diego
Thampy	Vivek	Brookhaven National Laboratory
Tranquada	John	Brookhaven National Laboratory
Waluyo	Iradwikanari	Brookhaven National Laboratory
Wen	Jiajia	Stanford University
Wilkins	Stuart	Brookhaven National Laboratory

2016-2

Barbour	Andi	Brookhaven National Laboratory
Bilgin	Eylul	University of California @ San Diego
Cao	Yue	Brookhaven National Laboratory
Chen	Xiaoqian	Brookhaven National Laboratory
Comin	Riccardo	Massachusetts Institute of Technology (MIT)
Dean	Mark	Brookhaven National Laboratory
Garcia-Fernandez	Mirian	Diamond Light Source Ltd
Gu	Genda	Brookhaven National Laboratory
Hua	Nelson	University of California @ San Diego
Huang	Xiaojing	Brookhaven National Laboratory
Hunt	Adrian	Brookhaven National Laboratory
Kaznatcheev	Konstantine	Brookhaven National Laboratory
Kiryukhin	Valery	Rutgers University
Konik	Robert	Brookhaven National Laboratory
Kukreja	Roopali	University of California @ Davis
Langridge	Sean	Rutherford Appleton Lab
Leo	Naemi	Paul Scherrer Institute
Li	Yuan	Peking University
Luo	Xiangpeng	Peking University
Mazzoli	Claudio	Brookhaven National Laboratory
Miao	Hu	Brookhaven National Laboratory
Morley	Sophie	University of Leeds
Porro Azpiazu	Jose Maria	Rutherford Appleton Lab
Ricci	Alessandro	Deutsche Elektronen-Synchrotron (DESY)
Robinson	Ian	Brookhaven National Laboratory
Ruby	Joshua	University of California @ San Diego

	Ryu	Gihun	Max Planck Institute for Chemical Physics of Solids
	Scagnoli	Valerio	Paul Scherrer Institute
	Sendetskyi	Oles	Paul Scherrer Institute
	Shpyrko	Oleg	University of California @ San Diego
	Thampy	Vivek	Brookhaven National Laboratory
	Tranquada	John	Brookhaven National Laboratory
	Tsvelik	Alexei	Brookhaven National Laboratory
	Waluyo	Iradwikanari	Brookhaven National Laboratory
	Wilkins	Stuart	Brookhaven National Laboratory
2016-3			
	Barbour	Andi	Brookhaven National Laboratory
	Barbour	Andi	Brookhaven National Laboratory
	Bisogni	Valentina	Brookhaven National Laboratory
	Boothroyd	Andrew	University of Oxford
	Boscoboinik	Jorge	Brookhaven National Laboratory
	Cao	Yue	Brookhaven National Laboratory
	Cela	Devin	University of California @ San Diego
	Chen	Xiaoqian	Brookhaven National Laboratory
	Dean	Mark	Brookhaven National Laboratory
	Dvorak	Joseph	Brookhaven National Laboratory
	He	Wei	Stanford University
	Hu	Wen	Brookhaven National Laboratory
	Hua	Nelson	University of California @ San Diego
	Huang	Xiaojing	Brookhaven National Laboratory
	Hunt	Adrian	Brookhaven National Laboratory
	Krick	Alex	Drexel University
	Kukreja	Roopali	University of California @ Davis
	Lee	Young	Stanford University
	Liu	Yihua	Argonne National Laboratory
	May	Steve	Drexel University
	Mazzoli	Claudio	Brookhaven National Laboratory
	Miao	Hu	Brookhaven National Laboratory
	Morley	Sophie	University of Leeds
	Porro Azpiazu	Jose Maria	Rutherford Appleton Lab
	Robinson	Ian	Brookhaven National Laboratory
	Rogge	Paul	Drexel University
	Ruby	Joshua	University of California @ San Diego
	Simonovis Santamaria	Juan	Brookhaven National Laboratory
	Sinha	Sunil	University of California @ San Diego
	Song	Jing-Jin	University of California @ San Diego
	Thampy	Vivek	Brookhaven National Laboratory
	Waluyo	Iradwikanari	Brookhaven National Laboratory
	Wen	Jiajia	Stanford University
	Wilkins	Stuart	Brookhaven National Laboratory
	Yang	Yi	University of California @ San Diego
	You	Hoydoo	Argonne National Laboratory

2017-1

Barbour	Andi	Brookhaven National Laboratory
Barbour	Andi	Brookhaven National Laboratory
Bluschke	Martin	Max Planck Institute for Solid State Research (MPI-FKF)
Boscoboinik	Jorge	Brookhaven National Laboratory
Cao	Yue	Brookhaven National Laboratory
Dean	Mark	Brookhaven National Laboratory
Fernandes Lopes Fabbris	Gilberto	Brookhaven National Laboratory
Frano Pereira	Alex	University of California @ San Diego
Gaina	Roxana	University of Fribourg
Hu	Miao	Brookhaven National Laboratory
Hu	Wen	Brookhaven National Laboratory
Hunt	Adrian	Brookhaven National Laboratory
Kiryukhin	Valery	Rutgers University
Krick	Alex	Drexel University
Li	Jiarui	Massachusetts Institute of Technology (MIT)
Lin	Jiaqi	Institute of Physics, Chinese Academy of Sciences
Liu	Xuerong	Chinese Academy of Sciences, Institute of Physics
May	Steve	Drexel University
Mazzoli	Claudio	Brookhaven National Laboratory
Miao	Hu	Brookhaven National Laboratory
Pelliciari	Jonathan	Massachusetts Institute of Technology (MIT)
Robinson	Ian	Brookhaven National Laboratory
Rogge	Paul	Drexel University
Tao	Jing	Brookhaven National Laboratory
Waluyo	Iradwikanari	Brookhaven National Laboratory
Wilkins	Stuart	Brookhaven National Laboratory
Wilkins	Stuart	Brookhaven National Laboratory
You	Hoydoo	Argonne National Laboratory

2017-2

Barbour	Andi	Brookhaven National Laboratory
Barbour	Andi	Brookhaven National Laboratory
Bhattacharya	Rupak	University of California @ San Diego
Bisogni	Valentina	Brookhaven National Laboratory
Boscoboinik	Jorge	Brookhaven National Laboratory
Bowlan	John	Los Alamos National Laboratory
Chen	Xiaoqian	Lawrence Berkeley National Laboratory
Comin	Riccardo	Massachusetts Institute of Technology (MIT)
Dean	Mark	Brookhaven National Laboratory
Disa	Ankit	Yale University
Fernandes Lopes Fabbris	Gilberto	Brookhaven National Laboratory
Frano Pereira	Alex	University of California @ San Diego
Fuersich	Katrin	Max Planck Institute for Solid State Research (MPI-FKF)
Hastings	Jeffrey	University of Kentucky
He	Wei	Stanford University
Hu	Wen	Brookhaven National Laboratory

Hua	Nelson	University of California @ San Diego
Huang	Lei	Brookhaven National Laboratory
Hunt	Adrian	Brookhaven National Laboratory
Idir	Mourad	Brookhaven National Laboratory
Jiang	Juan	Yale University
Kaznatcheev	Konstantine	Brookhaven National Laboratory
Lee	Sangjae	Yale University
Li	Jianheng	University of California @ Davis
Li	Jiarui	Massachusetts Institute of Technology (MIT)
Li	Yuan	Peking University
Mazzoli	Claudio	Brookhaven National Laboratory
Pelliciari	Jonathan	Massachusetts Institute of Technology (MIT)
Pound	Benjamin	Los Alamos National Laboratory
Robinson	Ian	Brookhaven National Laboratory
Rogge	Paul	Drexel University
Ruby	Joshua	University of California @ San Diego
Sandberg	Richard	Los Alamos National Laboratory
Simonovis Santamaria	Juan	Brookhaven National Laboratory
Song	Jing-Jin	University of California @ San Diego
Walker	Colby	Los Alamos National Laboratory
Walker	Fred	Yale University
Waluyo	Iradwikanari	Brookhaven National Laboratory
Wen	Jiajia	Stanford University
Wilkins	Stuart	Brookhaven National Laboratory
Xue	Shangjie	Peking University
Yue	Li	Massachusetts Institute of Technology (MIT)
Zapf	Vivien	Los Alamos National Laboratory

2017-3

Assefa	Tadesse Abebaw	Brookhaven National Laboratory
Barbour	Andi	Brookhaven National Laboratory
Bisogni	Valentina	Brookhaven National Laboratory
Bluschke	Martin	Max Planck Institute for Solid State Research (MPI-FKF)
Cao	Yue	Brookhaven National Laboratory
Chen	Wenjie	Peking University
Chen	Xiaoqian	Lawrence Berkeley National Laboratory
Chen	Yuan	Lawrence Berkeley National Laboratory
Comin	Riccardo	Massachusetts Institute of Technology (MIT)
Dean	Mark	Brookhaven National Laboratory
Fernandes Lopes Fabbris	Gilberto	Brookhaven National Laboratory
Frano Pereira	Alex	University of California @ San Diego
Fuersich	Katrin	Max Planck Institute for Solid State Research (MPI-FKF)
Hrkac	Stjepan	University of California @ San Diego
Hu	Wen	Brookhaven National Laboratory
Hua	Nelson	University of California @ San Diego
Kim	Min Gyu	Rutgers University
Kiryukhin	Valery	Rutgers University

Le Tacon	Matthieu	Karlsruhe Institute of Technology
Lefrancois	Emilie	Max Planck Institute for Solid State Research (MPI-FKF)
Li	Jianheng	University of California @ Davis
Li	Jiarui	Massachusetts Institute of Technology (MIT)
Mazzoli	Claudio	Brookhaven National Laboratory
Meyers	Derek	Brookhaven National Laboratory
Miao	Hu	Brookhaven National Laboratory
Pelliciari	Jonathan	Massachusetts Institute of Technology (MIT)
Pelliciari	Jonathan	Massachusetts Institute of Technology (MIT)
Robinson	Ian	Brookhaven National Laboratory
Wilkins	Stuart	Brookhaven National Laboratory
Yue	Li	Massachusetts Institute of Technology (MIT)

2018-1

Barbour	Andi	Brookhaven National Laboratory
Bowlan	John	Los Alamos National Laboratory
Cao	Yu	Lawrence Berkeley National Laboratory
Cao	Yue	Brookhaven National Laboratory
Caretta	Lucas	Massachusetts Institute of Technology (MIT)
Chen	Xiaoqian	Lawrence Berkeley National Laboratory
Dean	Mark	Brookhaven National Laboratory
Ding	Xiaxin	Los Alamos National Laboratory
Dr. Buettner	Felix	Massachusetts Institute of Technology (MIT)
Hu	Wen	Brookhaven National Laboratory
Hunt	Adrian	Brookhaven National Laboratory
Jiang	Juan	Yale University
Lee	Sangjae	Yale University
Lemesh	Ivan	Massachusetts Institute of Technology (MIT)
Levitan	Abraham	Massachusetts Institute of Technology (MIT)
Mazzoli	Claudio	Brookhaven National Laboratory
Mazzone	Daniel	Swiss National Science Foundation
Meyers	Derek	Brookhaven National Laboratory
Miao	Hu	Brookhaven National Laboratory
Pelliciari	Jonathan	Massachusetts Institute of Technology (MIT)
Perring	Toby	Rutherford Appleton Laboratory
Pfau	Bastian	Max-Born-Institute
Robinson	Ian	Brookhaven National Laboratory
Sandberg	Richard	Los Alamos National Laboratory
Walker	Fred	Yale University
Waluyo	Iradwikanari	Brookhaven National Laboratory
Wilkins	Stuart	Brookhaven National Laboratory
Zapf	Vivien	Los Alamos National Laboratory
Zhu	Chenhui	Lawrence Berkeley National Laboratory

2018-2

Allain	Marc	Aix Marseille Universite
Barbour	Andi	Brookhaven National Laboratory
Bartell	Jason	Massachusetts Institute of Technology (MIT)

Bhartiya	Archana	University College London
Cao	Yue	Brookhaven National Laboratory
Caretta	Lucas	Massachusetts Institute of Technology (MIT)
Chamard	Virginie	CNRS-Institut Fresnel
Chen	Xiaoqian	Lawrence Berkeley National Laboratory
Dean	Mark	Brookhaven National Laboratory
Dr. Buettner	Felix	Massachusetts Institute of Technology (MIT)
Hu	Wen	Brookhaven National Laboratory
Huang	Mantao	Massachusetts Institute of Technology (MIT)
Hunt	Adrian	Brookhaven National Laboratory
Jiang	Juan	Yale University
Klose	Christopher	Max-Born-Institute
Lee	Sangjae	Yale University
Lemesh	Ivan	Massachusetts Institute of Technology (MIT)
Levitan	Abraham	Massachusetts Institute of Technology (MIT)
Li	Jiarui	Massachusetts Institute of Technology (MIT)
Li	Peng	CNRS-Institut Fresnel
Mazzoli	Claudio	Brookhaven National Laboratory
Mazzone	Daniel	Swiss National Science Foundation
Meyers	Derek	Brookhaven National Laboratory
Miao	Hu	Brookhaven National Laboratory
Pelliciari	Jonathan	Massachusetts Institute of Technology (MIT)
Perring	Toby	Rutherford Appleton Laboratory
Pfau	Bastian	Max-Born-Institute
Pietraszewski	Adam	University College London
Robinson	Ian	Brookhaven National Laboratory
Sandberg	Richard	Los Alamos National Laboratory
Silva Nunes	Daniel	University College London
Tripathi	Ashish	Los Alamos National Laboratory
Walker	Fred	Yale University
Waluyo	Iradwikanari	Brookhaven National Laboratory
Wilkins	Stuart	Brookhaven National Laboratory
Yue	Li	Massachusetts Institute of Technology (MIT)
Zapf	Vivien	Los Alamos National Laboratory

Appendix C
List of Publications

<u>Submitted</u>

- M. Huang, A. J. Tan, F. Büttner, H. Liu, Q. Ruan, S. Wilkins, W. Hu, C. Mazzoli, C. Duan, J. K. W. Yang, G. S. D. Beach. Solid-state electrochemically switchable optics and plasmonics. Submitted to *Nat. Photonics*

- M. G. Kim, H. Miao, B. Gao, S.-W. Cheong, C. Mazzoli, A. M. Barbour, W. Hu, S. B. Wilkins, I. K. Robinson, M. P. M. Dean, V. Kiryukhin. Imaging antiferromagnetic antiphase domain boundaries using magnetic Bragg diffraction phase contrast.
  Submitted to *Nat. Mat.*
- A. J. Tan, M. Huang, C. O. Avci, F. Büttner, M. Mann, S. Wilkins, W. Hu, C. Mazzoli, H. L. Tuller, G. S. D. Beach. Magneto-ionic control of magnetism using a solid-state proton pump.
  Submitted to Nat. Mat.
- J. Li, J. Pelliciari, C. Mazzoli, S. Catalano, F. Simmons, M. Gibert, E. Carlson, J.-M. Triscone, S. Wilkins, R. Comin. Scale-invariant magnetic textures in a strongly correlated oxide.
  Submitted to *Science*
- X. M. Chen, C. Mazzoli, Y. Cao, V. Thampy, A. M. Barbour, W. Hu, M. Lu, T. Assefa, H. Miao, G. Fabbris, G. D. Gu, J. M. Tranquada, M. P. M. Dean, S. B. Wilkins, I. K. Robinson. Persistent charge density wave memory in a cuprate superconductor.
  Submitted to *Phys. Rev. X*
- X. M. Chen, B. Farmer, J. S. Woods, S. Dhuey, W. Hu, C. Mazzoli, S. B. Wilkins, I. K. Robinson, L. E. De. Long, S. Roy, and J. T. Hastings. Nature of spontaneous magnetic superdomain wall fluctuation in an artificial antiferromagnet.
  Submitted to *Phys. Rev. Lett.*

<u>Accepted</u>

- R. Kukreja, N. Hua, J. Ruby, A. M. Barbour, W. Hu, C. Mazzoli, S. B. Wilkins, E. E. Fullerton, O. G. Shpyrko. Orbital domain dynamics in magnetite below the Verwey transition.
  Accepted on *Phys. Rev. Lett.*

<u>Published</u>

2017

1. F. Zuo, P. Panda, M. Kotiuga, J. Li, M. Kang, C. Mazzoli, H. Zhou, A. M. Barbour, S. Wilkins, B. Narayanan, M. Cherukara, Z. Zhang, S. K. R. S. Sankaranarayanan, R. Comin, K. M. Rabe, K. Roy, S. Ramanathan. Habituation based synaptic plasticity and organismic learning in a quantum perovskite, *Nat. Comm.*, 8, 240 (2017). DOI: 10.1038/s41467-017-00248-6
2. V. Thampy, X. M. Chen, Y. Cao, C. Mazzoli, A. M. Barbour, W. Hu, H. Miao, G. Fabbris, R. D. Zhong, G. D. Gu, J. M. Tranquada, I. K. Robinson, S. B. Wilkins, M. P. M. Dean. Static charge-density-wave order in the superconducting state of $La_{2-x}Ba_xCuO_4$, *Phys. Rev. B*, 95, 241111(R) (2017). DOI: 10.1103/PhysRevB.95.241111
3. A. Krick. Controlling the Electronic Properties in La1/3Sr2/3FeO3-d Complex Perovskite Oxides, *Ph.D. Thesis*. Drexel University, Philadelphia (2017).
4. S. Abeykoon, M. Lin, K. Kleese van Dam. Parallelizing x-ray photon correlation spectroscopy software tools using python multiprocessing, *New York Scientific Data Summit*, sponsored by Brookhaven National Laboratory (2017).

2016

5. X. M. Chen, V. Thampy, C. Mazzoli, A. M. Barbour, H. Miao, G. D. Gu, Y. Cao, J. M. Tranquada, M. P. M. Dean, S. B. Wilkins. Remarkable Stability of Charge Density Wave Order in $La_{1.875}Ba_{0.125}CuO_4$, *Phys. Rev. Lett.*, 117, 167001 (2016). DOI: 10.1103/PhysRevLett.117.167001
6. J. Zhong, J. Kestell, I. Waluyo, S. Wilkins, C. Mazzoli, A. Barbour, K. Kaznatcheev, M. Shete, M. Tsapatsis, J. A. Boscoboinik. Oxidation and Reduction under Cover: Chemistry at the Confined Space between Ultrathin Nanoporous Silicates and Ru(0001), *J. Phys. Chem. C*, 120, 8240-8245 (2016). DOI: 10.1021/acs.jpcc.6b02851
7. D. G. Porter, M. S. Senn, D. D. Khalyavin, A. Cortese, N. Waterfield-Price, P. G. Radaelli, P. Manuel, H.-C. zur-Loye, C. Mazzoli, A. Bombardi. Magnetostriction-driven ground-state stabilization in 2H perovskites, *Phys. Rev. B*, 94, 134404 (2016). DOI: 10.1103/PhysRevB.94.134404
8. H. Fernandes, C. Kitegi, D. Harder, .D Hidas, J. Rank, M. Musardo, P. Cappadoro, T. Tanabe. Coherent Soft x-ray EPU Vacuum Chamber Thermal Analysis for Synchrotron Radiation Protection. *MEDSI*, Vol 1, p. 1-3, sponsored by ALBA Light Source (2016).

2015

9. F Willeke, Commissioning of NSLS-II, *Proceedings of IPAC2015*, p. 11-16, sponsored by PAC2015 (2015).