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Author(s): Wang, Zhehui
Stevens, Michael Francis
Gruner, Sol
Denes, Peter

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MaRIE Summer 2016 Workshop Series

Ultrafast and High-Energy X-Ray Imaging Technologies and Applications

August 2-3, 2016
Santa Fe, New Mexico

Los Alamos NATIONAL LABORATORY EST. 1943

NNSA National Nuclear Security Administration

The development of new femtosecond x-ray free electron lasers (XFEL)—such as Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory, SACLA in Japan, and the European XFEL—has enabled groundbreaking discoveries in biology, chemistry, materials science, and physics.

At Los Alamos National Laboratory, the first very hard (42-keV) XFEL, part of the MaRIE (Matter-Radiation Interactions in Extremes) facility, is being developed to study the dynamic properties of materials under extreme conditions for national security science missions.

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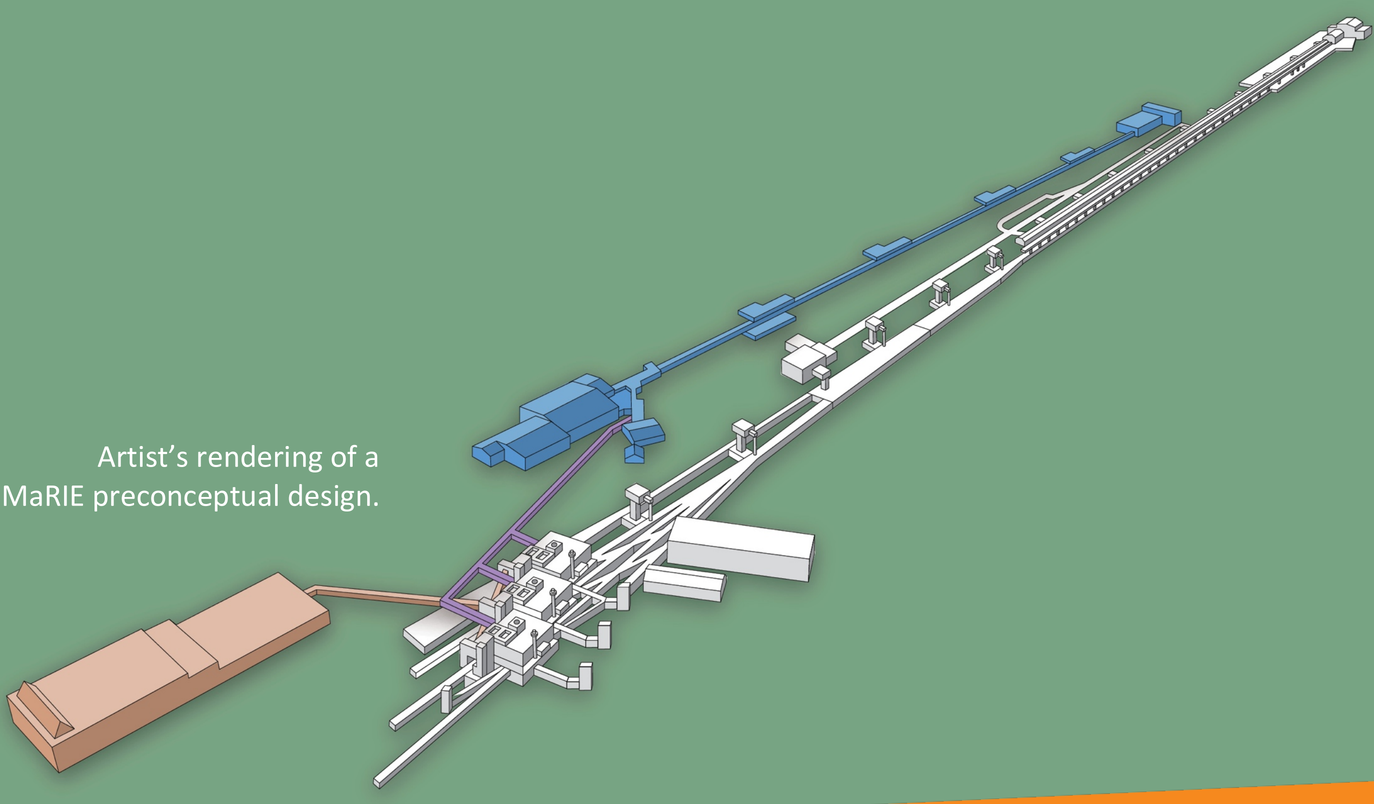

Artist's rendering of a MaRIE preconceptual design.

Ultrafast and High-Energy X-Ray Imaging Technologies & Applications

(August 2-3, 2016; Santa Fe, NM 87506, USA)

Peter Denes (LBNL), Sol Gruner (Cornell), Mike Stevens (LANL) and Zhehui Wang (LANL)

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Executive summary

Three themes are emerging that offer unprecedented opportunities in mesoscopic material discoveries in the coming decade: high-energy X-ray free electron lasers (HEXFELs), ultrafast X-ray imaging technologies, and exascale computing. This workshop, hosted by Los Alamos National Laboratory on August 2-3, 2016, addressed the technological gaps and associated development needs for high-energy (above 30 keV) and high burst frame rate (above 100 MHz frame-rate) X-ray imaging capabilities. Such technologies, although not yet available, will find wide applications at existing synchrotrons, XFELs such as the proposed MaRIE facility, and inertial confinement fusion facilities such as NIF. These applications will range across the discovery sciences, from biology to materials science, and result in new understanding of mesoscale structural dynamics.

Dedicated high-speed imaging technologies have been and are being developed for the existing XFEL sources. Commercial integrating and photon-counting technologies, such as high-speed CCD and CMOS cameras for visible light are often used in conjunction with fast scintillators for many experiments when dedicated imaging technologies are not available. The state-of-the-art X-ray imaging cameras use silicon sensors for direct X-ray detection and have demonstrated a frame-rate around 10 MHz and excellent performance for X-ray imaging at energies below 20 keV.

Possible high-energy ultrafast X-ray imaging technologies can be broken down into two categories with potentially significant advances in performance, albeit with substantially increased challenges from Type I to Type II technologies: Type I technologies, aims at 50% efficiency for 30 keV X-rays, up to 500 MHz frame rate (10 frames of movies in burst mode), pixelated prototype device with 64x64 pixels and a pixel pitch at around 300 μm, will meet the minimum requirements of a Key Performance Parameter (KPP) for MaRIE and will be sufficient for the MaRIE CD2 project milestone; Type II technologies will deliver superior performance for higher X-ray energies (system efficiency no less than 80%, at least 42 keV, up to 126 keV) and a frame-rate in several GHz range. Several innovative ideas and capabilities were presented during the workshop that could allow prototype demonstration of the Type I technologies in the 5-7 year time-frame, including GaAs:Cr sensors for direct detection, BaF_2 scintillators for indirect detection, novel 3D and stacked detector configurations that will permit the continued use of silicon and even diamond or GaN as sensors. New or upgraded Application Specific Integrated Circuit (ASIC) designs can potentially store and pre-process images at a rates of over 500 MHz, and integration techniques beyond bump-bonding can deliver ~ 1 micron pitch over millions of pixels (though perhaps not at the same time. Also, a 1 micron pitch does not imply 1 micron resolution.). Type II imaging technologies will be much more challenging and may require new material properties that may not exist in conventional bulk materials. For example, sensor response time is known to be limited by classical electron drift motion or spontaneous photon emission time in excited states. Stronger ties to nano- and mesoscopic material discoveries and system integration beyond CMOS may present new opportunities for type II technologies. Leveraging the existing resources that have already been used to serve the current and near future needs of synchrotrons, XFELs, high energy physics, and space applications, may be a cost-effective path towards both types of technologies on the MaRIE CD2 time-frame. The participants have also shown strong interests in joint development with LANL.

Introduction

In the 1959 annual American Physical Society meeting, Richard Feynman delivered a talk entitled *There's Plenty of Room at the Bottom*. Feynman's "the bottom" can be translated into "the mesoscale", which bridges the atomic scale where atoms swim to the macroscale that is visible to the human eye. The mesoscale is also the length transition in many materials and structures where quantum effects start to give way to classical observations. Three themes are emerging that offer unprecedented opportunities in mesoscopic material discoveries in the coming decade: X-ray free electron lasers (XFELs), ultrafast X-ray imaging technologies, and exascale computing. Until recently, only nature knows how to manipulate atoms on the mesoscale. Natural self-assembly processes are, however, most typically limited to biomaterials. Humans, in contrast, do this more or less blindly or by trial and error, in no small measure due the fact it is difficult to monitor the progress of the manipulation or manufacture processes on the mesoscale. Visible light, including most lasers, does not penetrate deeply through opaque materials. Charged particles cannot achieve high-resolution and sufficient depth simultaneously due to multiple scattering. The invention of XFELs can help solve the monitoring problem. The proposed MaRIE XFEL would deliver high-energy X-rays of at least 30 keV, which would allow the interrogation of mesoscopic structures formed by higher Z materials, up to and including uranium.

When it comes to attaining high-quality images of mesoscopic structures and their evolution under different forces or loads, the need for high-energy and ultrafast X-ray imaging is just as important as the illumination source. In structural determination, the XFEL plays the role of information generation, imaging detectors the role of information collection, and exascale computing the role of data processing and interpretation (such as structure unfolding). Each of them is indispensable in the chain of information encoding, recording and decoding. Such information, many believe, will be critical to transform material processing and fabrication on the mesoscale and provide the platform for other technological innovations.

Type I & Type II ultrafast and high-energy X-ray imaging technologies

Substantial advances have been made in high-speed imaging technologies, including ones for the full spectrum of X-ray wavelengths. Dedicated high-speed imaging technologies have been developed for the existing and upcoming XFEL sources such as LCLS, European XFEL, SACLA, and SwissFEL. Commercial photon-counting cameras such as Pilatus, x-ray integrating detectors or high-speed visible light CCD and CMOS cameras in conjunction with fast scintillators are used for many experiments when dedicated imaging technologies are not available. State-of-the-art X-ray imaging cameras use silicon sensors for direct X-ray detection and have demonstrated a frame-rate close to 10 MHz and excellent performance for X-ray imaging at energies below 20 keV. Prototype direct detection, high frame rate imaging cameras with high atomic weight sensors have recently been demonstrated.

There exist significant technological gaps between the state-of-the-art high-speed X-ray imaging technology and future high-energy (above 30 keV) and high burst frame rate (above 100 MHz frame-rate) X-ray imaging technologies. An abbreviated summary of desired performance parameters driven by MaRIE high-energy XFEL (HEXFEL), Table 1, were included in the workshop announcement prior to the workshop.

Table 1. Simplified requirements on high-energy X-ray photon imagers for MaRIE-like HEXFEL.

Performance	**Type I imager**	**Type II imager**
X-ray energy	Up to 30 keV	42-126 keV
Frame-rate/inter-frame time	0.5 GHz/2 ns	3 GHz / 300 ps
Number of frames per burst	>= 10	10 - 30
X-ray detection efficiency	above 50%	above 80%
Pixel size/pitch	≤ 300 μm	< 300 μm
Dynamic range	10^3 X-ray photons/pixel/frame	≥ 10^4 X-ray photons/pixel/frame
Pixel format	64 x 64[1] (scalable to 1 Mpix)	1 Mpix

Charges to the workshop

The workshop objective was to address the technological gaps and development paths required for high-energy (above 30 keV) and high burst frame rate (above 100 MHz frame-rate, including burst mode) X-ray imaging technologies. The workshop was also tasked to recognize promising near-term (Type I) & long-term (Type II) concepts, and to discuss time frame and resource requirements. The workshop participants sought to identify existing resources through multi-institutional collaboration, for both kinds of prototype technologies, in light of previous experiences with high-speed X-ray imaging. An ancillary workshop objective was to foster cross-disciplinary dialog among experts in imaging technology development ('integration'), beam-line experiments, data handling, material processing and discovery, ASIC designs, device fabrication, and technology commercialization.

Workshop overview:

The workshop was organized around four themes:

- Experiments & Applications: Scientific questions/applications for ultrafast & high-energy X-ray imaging using accelerator-driven sources;
- The state-of-the-art X-ray imaging detector technologies;

[1] In a sense, 64x64 is an implementation detail for 1 Mpix camera.

- Data software & hardware: Computation/modeling, data collection (ASIC development) and data handling in accelerator-driven ultrafast imaging; and
- New possibilities: Novel approaches to the next-generation high-energy photon imaging technologies (Sensors, on-board data recording/preprocessing, readouts, imaging system integration);

There were 70 registered participants, including workshop organizers and coordinators. The participants came from the DOE complex, academia (including 7 international participants) and US industry (primarily small businesses), as shown in Figure 1.

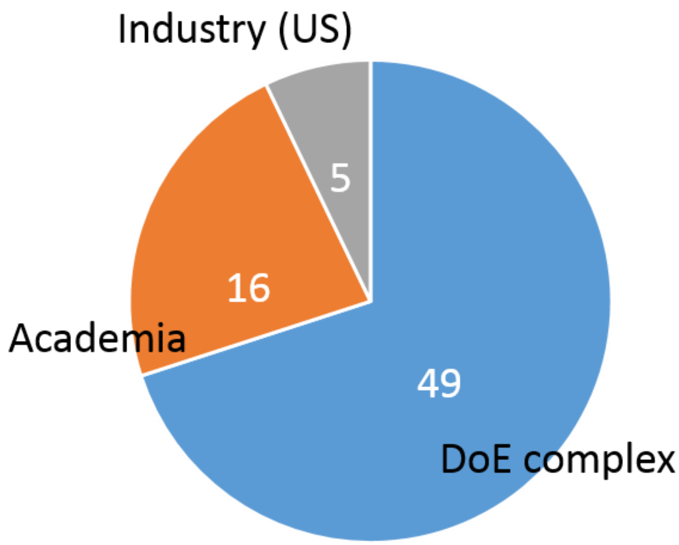

Figure 1. Distribution of the workshop participants. A total of 70 people registered for the workshop.

The workshop received 12 extended 35 minute ‘plenary’ talks on the first day (August 2), and more than 20 short 15 minute talks on the morning of the second day (August 3). The talks were aligned with the four topical areas as listed above. A summary session was held in the afternoon of August 3.

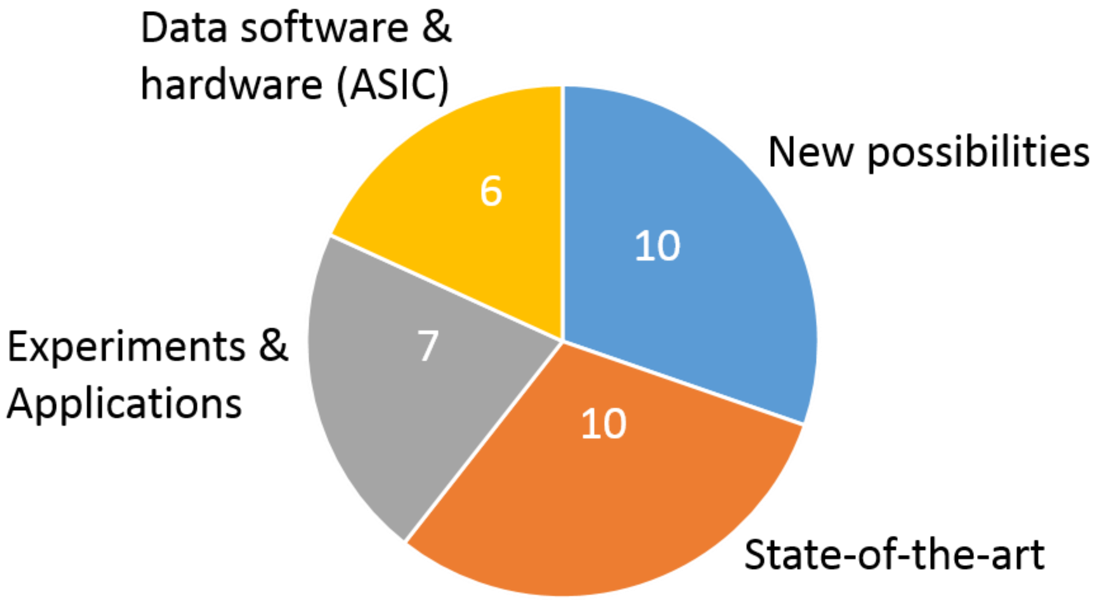

Figure 2. A summary of talk distribution given in the four categories.

Workshop findings

A. The state-of-the art imaging technologies for XFEL and synchrotrons

High-speed ultrafast hard X-ray imaging technologies are X-ray source and application driven. The more advanced technology is therefore not surprisingly associated with XFEL and synchrotron sources. The technologies for lower flux applications such as astronomy and table-top sources are capable of extracting more information than conventional X-ray detection by demonstration of better energy or time resolution (spectroscopy) and even polarization detection, in conjunction with photon counting. A summary of some recent development is given in Table 2.

Table 2. Some recent hard X-ray imaging cameras and their applications.

Detector/ Camera	**Voxel dimension**[2]	**Noise**	**CMOS technol.**	**Pixel Bias**	**Digital clock**	**Frame rate**	**X-ray Source**
	(μm^3)		(μm)	(V)	(MHz)	(MHz)	
CSPAD	110 ×110 × 500	330 e^-	0.25 (TSMC)	190	25	1.2×10^{-4}	LCLS
ePix100a	50 × 50 × 500	50 e^-	0.25 (TSMC)	200	0.1	1.2×10^{-4}	LCLS
Keck-PAD	150 ×150 × 500	1530e^-	0.25 (TSMC)	200	100	6.5	CHESS
AGIPD 1.0	200 ×200 × 500	265e^- (<14.4)	0.13 (IBM)	500	99	6.5	European XFEL
DSSC (DEPFET)	136 (hex) × 450	50 e^-	0.13 (IBM)	150	700	5	European XFEL
pnCCD (CAMP)	75 ×75 × 280	5 e^- (100 ms)	CCD	140 (0.5V/μm)	10	2.5×10^{-4} (5, burst)	Astronomy (XMM-Newton)
LPD	500 ×500 × 500	1000 e^-	0.13 (IBM)	~250	100	4.5	European XFEL
MPCCD[3]	50 × 50 × 50	200 e^-	CCD	~20	5	6×10^{-5}	SACLA
SOPHIAS	30 × 30 × 500	150 e^-	0.2 FD-SOI	~200	25	6×10^{-5}	SACLA
JUNGFRAU[4]	75 × 75 × 450	100 e^-	0.11 (UMC)	220	40	2.4×10^{-3}	SwissFEL
ALPIDE[5] (MAPS[6])	28 × 28 × 50	~ 20 e^-	0.18 (TowerJazz)	<10	40	5.0×10^{-2}	(Charged particles)
FASPAX[7]	100×100 × 500	<1000 e^-	130nm SiGe (IBM)	1000	100	13 (burst)	APS

Each technology listed in Table 2[8] was developed over many years of team effort. Some of them are still being improved over time with inter-disciplinary expertise that covers: materials and characterization, sensor fabrication and bonding, physics and device simulations, engineering design, ASIC design, bench testing and characterization of components and integrated prototypes, storage ring and X-ray free electron lasers testing and characterization of components and integrated prototypes, system integration and assembly, data handling and analysis. Commercial CMOS processes, and more recently FD-SOI and SiGe

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[2] The third dimension is the sensor thickness.

[3] T. Hatsui and H. Graafsma, 'X-ray imaging detectors for synchrotron and XFEL sources.' IUCrJ **2** (2015) 371–383.

[4] J. H. Smith, A. Mozzanica and B. Schmitt, 'JUNGFRAU A dynamic gain switching detector for SwissFEL.' PSI Technical design report (2015).

[5] See the reference [MAG:2016] by M. Mager for ALICE Collaboration and [YAC:2015] by P. Yang et al.

[6] MAPS stands for Monolithic Active Pixel Sensors using standard or VLSI CMOS process.

[7] T. Zimmerman, 'A high-dynamic range pixel readout in a Si-Ge Process.' *10th International Meetingon Front End Electronics (FEE) Conference* (2016).

[8] Based on open literature data. Further check of the parameters with technology owner/developer recommended.

processes, are used in the final products. Several development paths were pursued in parallel for major facilities like LCLS, European XFEL and others.

The following table lists technologies developed or under development for other applications that may also be useful for ultrafast high-energy X-ray imaging.

Table 3. Other X-ray detectors and their applications.

Technology	X-ray induced signals[9]	Existing applications
Pixelated diamond	Electrons/holes (e/h)	Beam monitoring
Picosecond photodetectors	photons	Time-of-flight
CdTe X-ray imagers	e/h	Synchrotrons/storage rings
Ge strip detectors	e/h	Synchrotrons/storage rings
Superconducting detectors	(temperature rise)	Synchrotrons/storage rings
GaN/AlGaN detectors	photons	UV, charged particles, neutrons
GaAs X-ray imagers	e/h	Synchrotrons/XFEL
BaF_2 photodetectors	photons	High-energy physics
3D detectors	e/h	High-energy physics
Optical encoded/gated imagers	photons	Ultrafast science
Streak cameras	photons	1D imaging
Si APD hybrid detectors	e/h	NIF, DoD
Cherenkov detectors	photons	NIF

B. Scientific and LANL mission needs

The topical area of *Experiments & Applications driven by scientific and LANL mission needs* had only limited exposure during the workshop. Meanwhile, other MaRIE-sponsored series of workshops before and after this one, such as "Dynamic Behavior of Materials", "Opportunities for New X-ray Sources to Shed Light on Mesoscale Functional Materials", "Probing Dynamic Processes in Soft Materials Using Advanced Light Sources", "Kinetic Response of Materials at Extreme Conditions", and "Opportunities for In-situ Characterization During Advanced Manufacture", are good resources of information related to MaRIE and LANL mission needs. Broader scientific drivers for ultrafast high-energy X-ray imaging technologies can be found in the regular user meetings hosted by LCLS, European XFEL, APS, CHESS and other light-source facilities, or international conferences such as The International Workshops on Radiation Imaging Detectors (iWoRiD), IEEE, SPIE, International Congress on High-Speed Imaging and Photonics and others. Below, we only list the topics presented during the workshop.

[9] Using X-ray induced electrons as signals is also known as direct detection; using X-ray induced photons as indirect detection. Here and in subsequent tables the word "electrons" is used as a proxy for charge carriers, which may in some cases, be holes.

Table 4. Some of the applications where better imaging technologies will be needed.

Application	**Challenges/ Need**	**Time-frame for development**	**Stakeholders**
Shock-compressed materials	Detector (signal-to-noise, resolution, higher energy photons) Image reconstruction	Near & Long term	LANL/Campaign2 DOE/Fusion Energy Sciences
Ultrafast visualization of phase transformation	Higher frame-rate higher energy photons	Near & Long term	LANL/Campaign2 DOE/FES
Real-time visualization of dynamic damage	Higher energy photons Higher frame rates High detection efficiency	near term	Army ONR Other DoD agencies
Thermal explosion detonation	Higher frame rates Higher energy photons Higher detection efficiency	Near term	LANL/Campaign2
Inertial confinement fusion	More frames Larger area detectors Sub-ns resolution	Near & long term	DoE/NNSA
3D material characterization	Higher energy photons Higher detection efficiency Higher speed	Near & long term	DoE/BES Industry
Microstructure imaging	Higher energy photons Higher detection efficiency Higher speed	Near & long term	DoE/BES Industry
Nuclear engineering materials	Higher energy photons Higher detection efficiency Higher speed	Near & long term	DoE Multiple programs Industry

C. Relations to large data and on-board data processing (ASIC)

In addition to the fact that the computer simulations and Technology Computer-Aided Design (TCAD) software (Synopsis, Cadence, Mentor graphics)[10] are now essential to the development of pixelated imaging technology and the industrial CMOS fabrication of the mega-pixel cameras, ultrafast high-energy XFEL imaging technologies are also tied to the science of big data and computation in two other significant ways. Image data processing and material structure reconstruction depends on iterative algorithms, as well as the quality of the images collected. Ultrafast high-energy imaging technology will likely need new material discoveries for ultrafast X-ray response and data collection. One of the recent MaRIE-sponsored workshop was entitled "Data Science Optimal Learning for Materials

[10] A more extensive list of TCAD can be found at http://www.tcadcentral.com/Software.html.

Discovery”. It is of interest to explore the use of machine learning techniques for materials that will allow ultrafast high-energy X-ray imaging.

Table 5. A list of ~ GHz ASICs for pixelated imagers.

ASIC/Data	No. Chan.	Analog bandwidth (GHz)	digital sampling (GHz)	S/N (dB)	Bit Res.	CMOS technol.
PSEC4	6	1.5	15		10.5	IBM 130 nm
“Hawaii chip”	128[11]	3	20	58 dB/ 1Vpp	9.4	(TSMC 130 nm)
“Cornell Keck GHz”	128x128[12]	0.5				TSMC 180 nm or 130 nm
epixΔ	1M	3			>= 8	TSMC 250 nm

Although most of these ASIC chips are still in the conceptual stage, there is no known technological difficulties to achieve GHz ASICs according to several different groups present in the workshop. Cost is also another important factor in selection of the appropriate commercial CMOS technology. The use of 90 (introduced in 2004 commercially, but yet to be implemented for X-ray imaging technologies) to 130 nm (introduced in 2001, have seen applications in X-ray imaging technologies) CMOS appears to be a reasonable balance between price/device yield and performance for now[13].

D. Emerging sensor materials and device possibilities

Existing X-ray imaging cameras are built around ASICs, which use industrial CMOS processes. FD-SOI and SiGe now also see applications in high-speed imaging technology, probably due to the growth of RF technologies for mobile phones and other consumer applications, which, in turn, lower the cost for R&D applications with increased device reliabilities and functionality. CMOS and related processes are the most successful industrial fabrication methods for data processing on the sub-micron and nanoscale. It is reasonable to believe that CMOS and related family of processes will continue to be used in GHz frame-rate high-energy X-ray imaging. Innovations through 3D Through-Silicon-Via (TSV) and reduced material uses will be welcome and desirable, in particular for new camera architectures other than the extremely successful 2D hybrid. The contributions to the workshop in material and device innovations were mostly focused on X-ray sensors.

There was a consensus among the represented community that high-Z (compared with Z=14 for silicon) sensors will be advantageous for high-energy X-ray imaging. As dominant as silicon is in the existing direct detection imaging cameras, silicon

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[11] Need to verify with the Hawaii group.
[12] Need to verify with the Cornell group.
[13] It is too early to pick a technology node – whose choice should be driven by technical requirements at the time.

sensors have a number of limiting factors for high-speed mesoscopic imaging: lower stopping power for high-energy photons above 30 keV; intrinsic electron and hole mobilities that limit the sensor time-response and frame-rate; Compton scattering that increases with the X-ray photon energy and limits the spatial resolution; and the very thick silicon (~ 1 cm) that would be required for high-detection efficiency.

Table 6. Emerging sensor materials for ultrafast high-energy X-ray imaging

Material	**X-ray-induced signals**	**Desirable features**	**Challenges**[14]	**Demonstrated use?**[15]
GaAs	Electrons/holes (e/h)	High-Z, high mobility	Polarization Plasma effect for high fluxes	Yes
Ge	e/h	High-Z	Small bandgap	Yes
CdTe	e/h	High-Z	Polarization Charge mobility	Yes
LSO,LYSO, $LaBr_3$	photon	High-Z	Decay time > 10 ns	Yes
BaF_2	photon	High-Z, sub-ns response	Low light yield Need ultrafast photodetectors	No
ZnO	e/h, photon	High-Z, ultrafast response	Material processing	No
GaN	e/h, photon	High-Z, ultrafast	May need ultrafast photodetectors	No
Perovskite	e/h	High-Z, New quantum effects	Too thin	No
Plasmonic nanodevices	photon	High-Z	Too thin Need ultrafast photodetectors	No
Rare-Earth doped nanoparticles	photons	High-Z	Too thin Need ultrafast photodetectors	No
2D thin film semiconductors	e/h	High-Z, New quantum effects	Too thin	No

[14] Some of the challenges listed are cross-cutting. For example, Plasma effect could be important to all direct detector concepts. Polarization and deep charge trapping are redundant issues.
[15] All of the demonstrated uses are below 10 MHz frame-rate so far.

Based on the workshop presentations, a few sensor material selection criteria for ultrafast high-energy X-ray imaging is given in Table 7.

Table 7.A few factors that determine the sensor material selection in ultrafast high-energy X-ray imaging

Detector functions	**semiconductors**	**scintillators**
Sensor time response	Carrier mobility, Charge drift distance	Decay time, Light propagation distance
Signal amplitude	No. of electrons per keV	No. of photons per keV
Efficiency	Atomic number (Z), size	Atomic number (Z), size
Resolution	Pixel size, charge sharing, x-ray fluorescence, electron photoemisison	Thickness, emission anisotropy, x-ray fluorescence, electron photoemission
Fill factor	Pixel boundary	Columnar gap
Chemical properties	Oxidation, flammability	Hygroscopicity, flammability
Physical stability	Fragility, temperature sensitivity,	Fragility, Temperature sensitivity,
Noise	Charge trapping, bandgap, Operating temperature	Self-absorption, light scattering loss Operating temperature
Radiation hardness	Defined by crystal structure	Defined by crystal structure
ASIC/CMOS compatibility	Electrical contact, Bonding technology	Refractive index matching, Light coupling QE of photodetectors
Affordability	Cost, device yield	Cost, device yield

At the present, the process flow to make sensors for high-speed high-energy imaging detectors may be characterized as a 'reduction process': silicon wafers are sliced out of silicon ingots, which are grown through the Czochralski process. Additive manufacturing offers new possibilities for imaging sensor fabrication, although such an approach is yet to be seen in practice. Here we list a few other novel fabrication possibilities for sensors. Most of them are yet to be demonstrated for imaging technology.

Table 8. Material assembly processes that are of interest to ultrafast high-energy imaging development.

Material Processes	Features	Application for ultrafast imaging
Reduction process	Wafer available commercially	Yes
Thin film process	novel thin-film properties	Used with reduction process
Additive process	Micro-, nano-grains	Not yet
Microfluidic process	Versatile, nano-particle assembly	Not yet
Polymer-assisted fabrication	Versatile, nano-particle assembly	Not yet
Self-assembly/biological assisted processes	Autonomous	Not yet

E. Near-term & long-term ultrafast imaging technologies for HE-XFEL

CD2 is a major milestone for the MaRIE project, including imaging detector technology, which is currently at Technology Readiness Level (TRL) 2 to TRL 3. It is reasonable for near-term (5-7 years, to align with the current MaRIE CD schedule) imaging detector development to focus on deliverables that will satisfy the MaRIE CD2 milestone requirements. In other words, new imaging capabilities towards achieving TRL 6 or TRL 7 will be demonstrated. Here TRL 6 is defined [16] as *System/subsystem model or prototype demonstration in a relevant environment.* TRL7 refers to *System prototype demonstration in an operational environment*. Since MaRIE HEXFEL is a unique environment itself that cannot be easily reproduced elsewhere, it is only realistic for CD2 to achieve *System prototype demonstration in a relevant environment,* which is literally a TRL 6 level of readiness according to the definition. However, due to the interests and applications in many other existing facilities, see Table 4, new imaging technology can also make useful contributions to existing facilities before MaRIE HEXFEL becomes a reality. For these existing facilities, a MaRIE-relevant imaging technology will be at TRL 7 once successfully demonstrated.

Continuous mode imaging at gigahertz frame rates will be harder than burst mode imaging, which operates at the same frame rate but only for a short period of time. Most fast X-ray imaging techniques take advantage of the burst mode because of the limited bandwidth in real-time data transmission. In continuous mode of imaging, real-time data transmission becomes a bottle neck once the temporary memories/buffers are filled. In burst mode, the images are stored quickly in local, temporary memory. The frame readout can then happen between bursts at a slower rate. In short, the near-term ultrafast imaging technology development can

[16] http://www.ncbi.nlm.nih.gov/books/NBK201356/

use burst mode with frame capacities/burst on the order of 10, where the number is limited by the pixel size.

Nevertheless, ultrafast hard X-ray imaging technology for MaRIE HEXFEL will still require significant advances in both ultrafast X-ray sensing and ultrafast data recording in burst mode. Ultrafast sensor response comes from material properties and structures. Ultrafast data recording requires fabrication and system integration technologies that are compatible with CMOS and related processes, such as Silicon-On-Insulator, SiGe, and others.

A summary of known and candidate materials for ultrafast X-ray sensing is given in Figure 3. The near-term development can use known materials (such as silicon, Ge, GaAs, BaF_2, etc.) and their 'bulk' properties that have been well characterized and tabulated. Examples of such properties are electron/hole mobility, electron-hole production energy, electron/hole life time, light yield, scintillator decay time, etc. These material properties, coupled with circuit models such as SPICE, COMSOL, are currently used to simulate and predict the performance of imaging technology design. Since the bulk material properties are regarded as 'material constants', the innovations to achieve ultrafast imaging will come from fabrication of novel material structures to minimize the time between raw X-ray signal generation and temporary data storage. One example of such an innovation is 3D detector architecture.

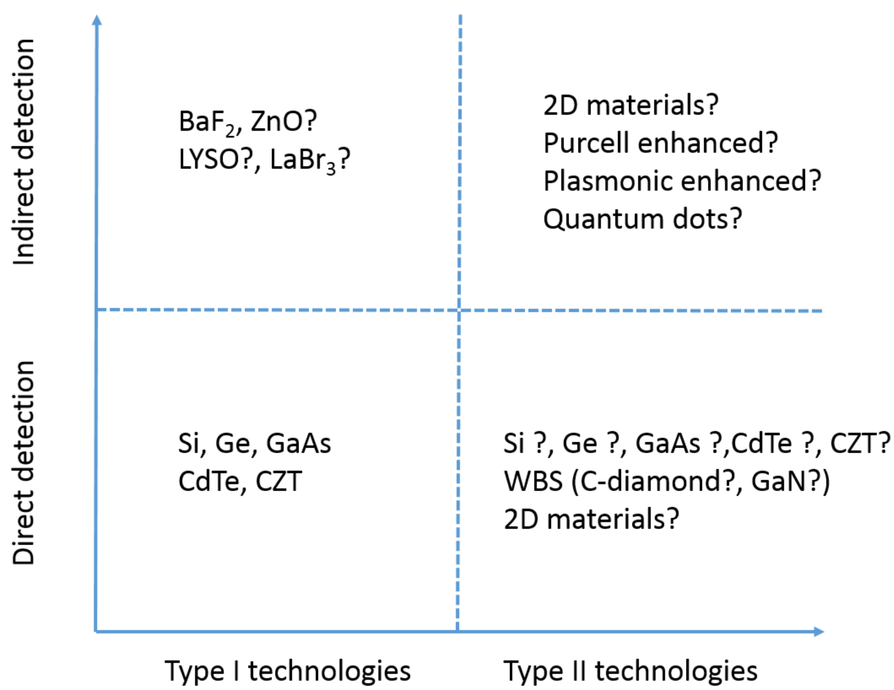

Figure 3. Sensor materials that are used or proposed for ultrafast X-ray imaging.

Modern data processing and temporary storage use ASICs which are also regarded as the 'brain' of the X-ray camera. One of the most successful approaches to X-ray imaging is the so-called 2D hybrid pixelated array detector (PAD). The 2D hybrid PAD architecture allows flexible combination of sensors with ASICs. For example, existing ASICs that have been designed for silicon sensors can also be used for Ge or GaAs sensors. Improvements in an ASIC design will therefore benefit multiple imaging technologies using different sensors. Development of new sensors will, in return, allow different applications through integration with different ASICs (for photon counting, energy/spectroscopy, imaging, timing, flux monitoring, compound direct detection sensors[17], etc.)

It should be mentioned that to achieve high efficiency and high speed together can be mutually exclusive, especially for high-energy photons. For a given sensor material, high efficiency requires thicker sensors as the x-ray energy rises. As mentioned above, the bulk material properties such as electron and hole mobility are fixed. Thicker sensors lead to slower detector response[18]. Therefore, detector architecture innovation is even more important in high-speed high-efficiency high-energy X-ray imaging. Some possible directions of development are summarized in Figure 4. Except for the upper right quadrant, the bulk material properties are assumed.

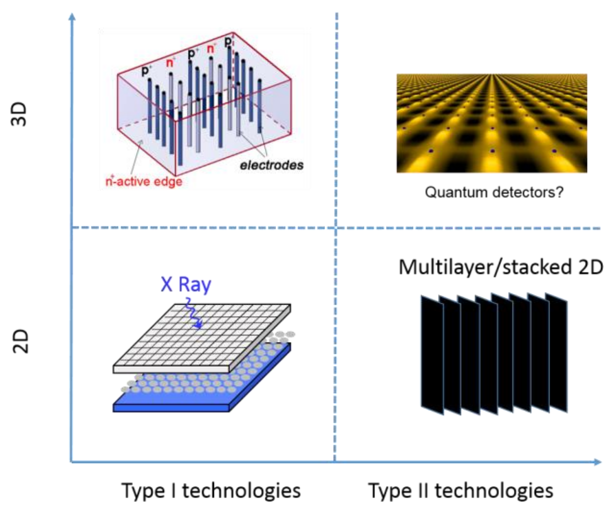

Figure 4. Possible architectures for type I and Type II ultrafast high-energy X-ray imaging technologies. For an overview of 2D hybrid technology, see S. M. Gruner, Physics Today 65 (2012) 29; For 3D imbedded electrode technology, see S. Parker et al, NIMA, 395 (1997) 328. For Multilayer/stacked 2D technology, See Z. Wang, JINST 10 (2015) C12013. Quantum detector concepts have not found applications in X-ray imaging.

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[17] Compound direct detection sensors (GaAs, CdTe, CZT) need lots of R&D. There are very few sources of high quality sensors, and even in those cases, the quality is poor relative to Si. Even so, the best presently available sensors can serve to meet interim benchmarks, provided that there is significant R&D done on characterization. In this regard, see a paper on CdTe in arXiv:1609.03513, soon to appear in JINST.

[18] Technically it is the end of the response, e.g. the photocurrent that takes longer, the speed of the initial response is affect by the thickness only very little. There are technical ways to exploit this, e.g. by using capacitively coupled front ends. (Inputs from Julian Becker, Cornell Univ)

An intriguing question is whether the emergent material properties on the nanoscale can be utilized for ultrafast imaging applications. In contrast to bulk material properties, material properties on the nanoscale are no longer fixed because they can change with the shape, size, and ambient conditions. Some examples include quantum-size effects of electrons that modify the energy levels of electron excitation and electron-hole production, topological insulators that have different electron transport properties from conventional bulk materials for which the classical definition of insulator and conductor seems to be more clear cut, ballistic electron transport that can be significantly faster than bulk electron diffusion, the Purcell effect (which is distinctive from the Smith-Purcell effect) that can reduce the photo-emission time from the spontaneous emission time of an atom, and anisotropic light propagation in photonic crystals as opposed to isotropic light transport in most of bulk materials with more homogeneous structures. The list can go on.

Ironically, the biggest strength of nanomaterials in terms of their material tunability could also become their biggest weakness. This is because many attractive nanoparticle/structure properties tend to change and even get lost subject to their environment and surroundings. Another challenge[19] is in construction of larger structures out of nano-size building blocks. For ultrafast hard X-ray applications structures on the order of mm or even cm are required for efficiency. Constructions based on nano-scale features then require fabrication and assembly methods that span almost six orders of magnitude in length scale, without losing the material properties that may only manifest on the nano-scale. These are not isolated challenges unique to ultrafast high-energy X-ray imaging. Many parallel efforts - a few examples were given during the workshop for energy and solar applications - are taking place. It is reasonable to team up with these on-going efforts to explore nanomaterials for ultrafast imaging applications. This type of development, which will be revolutionary, high risk and have wider impact than the mission needs of MaRIE project will require a visionary, long term R&D.

[19] Here we emphasize 'common challenges' facing nanomaterial-based applications. There are of course also X-ray imaging specific challenges. For example, stability of nanoparticles under X-ray radiation is an open field that have not seen much work. X-rays, as a type of ionizing radiation, are more damaging than visible or even UV photons. What would be X-ray radiation hardness of certain functional nanomaterials? Are there repair mechanisms as in biological systems for functional nano-materials such as X-ray imaging sensors after X-ray-induced damage? Many questions wait for answers.

Recommendations

- Refinement of the Performance Table 1. Additional parameters may be included to expand the table. One example is the specification for read noise, or desired single-photon signal-to-noise ratio. Another example is how to include the expendability of the front end as a requirement for design. The list of performance parameters may also vary with specific applications and also be driven by timescale. The analysis of different measurement techniques and detector and light source requirements for each one would be really useful.
- Previous experience from LCLS, European XFEL, and others reinforce the need for a strategy of “multi-front” or “multiple-thrust” effort to mitigate the risks associated with any single approach.
- It would be very helpful to include a realistic timeline or roadmap (as best as possible) and clarify what might be on-project, off-project, parallel MIE/LDRD project, etc.
- Several existing technologies may be leveraged to meet the KPP requirements of the MaRIE CD2 milestone. Selections of specific concepts for prototype development should be based on peer-reviewed proposal rankings or recommendations from an advisory committee (see below) or strategic decisions for detector development.
- A call for proposals could be based on the refined performance parameter in an expanded Table 1. Tying the technology scope and performance to a range of applications (near-term, mid-term and long-term) could be useful.
- The achievements by the detector community are impressive, and such achievements can be tapped for joint development and collaboration. This is further enhanced by the interest from the detector community.
- Standard planar silicon is unlikely to deliver the performance required for type II detectors.
- Reaching out to other communities such as Inertial Confinement Fusion (ICF) may be mutually beneficial, and it broadens the impact on other LANL, DOE/NNSA programs.
- Opportunities may exist in high-energy ultrafast imaging using 2D materials, scintillator nanomaterial with engineered fast decay.
- Sensor research and development now have a growing number of materials as both direct and indirect sensors. Diamond is a very interesting material, albeit with low stopping power. Pixelated high-speed diamond detectors need further development.
- There is pressing need for R&D on compound direct detection sensors (e.g., CdTe, CZT, GaAs), and pressing need to expand the availability and quality of compound sensors.
- Testing capability, such as fast flashes of photons, will be needed to qualify the prototypes. Facilities like CHESS and APS could be leveraged if beamtime can be allocated for detector developments. For components and some subsystem testing, psec infrared and optical lasers are suitable as

substitutes, as documented in publications by DESY[20] and other groups in the US.

- Establishing an advisory committee for detector development is a common practice for similar project scales. The composition of the committee must properly "morph" over time. In the early stages, the balance between camera technological experts and scientific users (preferably people who understand both the science and technology – and can translate the needs of the former into requirements of the latter) may be tilted towards the latter. In the execution phase, the mix might shift towards the former.

Appendices

Workshop participants & group photo

Workshop agenda

Presentation summaries

Workshop summaries

[20] See for example, J. Becker, D. Eckstein, R. Klanner and G. Steinbrück, *Impact of plasma effects on the performance of silicon sensors at an X-ray FEL*, *Nucl. Instrum. Meth.* **A 615** (2010) 230.

First Name	Last Name	Company
Ghaleb	Abdulla	Lawrence Livermore National Laboratory
Mary-Chris	Arena	Sydor Instruments
Anatoli	Arodzero	RadiaBeam Technologies, LLC
Abul	Azad	Los Alamos National Laboratory
Cris	Barnes	Los Alamos National Laboratory
Laura Robin	Benedetti	Lawrence Livermore National Laboratory
Cindy	Bolme	Los Alamos National Laboratory
Pamela	Bowlan	Los Alamos National Laboratory
Curt	Bronkhorst	Los Alamos National Laboratory
Gabriella	Carini	SLAC National Accelerator Laboratory
CHUN-CHIEH	CHANG	Los Alamos National Laboratory
Aiping	Chen	Los Alamos National Laboratory
Wayne	Chen	Purdue University
Cinzia	Da Via	The University of Manchester, UK
Meyerhofer	David Dietrich	Los Alamos National Laboratory
Marcel	Demarteau	Argonne National Laboratory
Peter	Denes	Lawrence Berkeley National Laboratory
James	Distel	Los Alamos National Laboratory
Angelo	Dragone	SLAC National Accelerator Laboratory
Kamel	Fezzaa	Argonne National Laboratory
Marcus	French	Science and Technology Facilities Council
heinz	Graafsma	DESY
Dominic	Greiffenberg	Paul Scherrer Institut
Sol	Gruner	Cornell University
Gunther	Haller	SLAC National Accelerator Laboratory
Takaki	Hatsui	RIKEN
Bryan	Henson	Los Alamos National Laboratory
Ryan	Herbst	SLAC National Accelerator Laboratory
Mary	Hockaday	Los Alamos National Laboratory
Katherine	Hudspeth	Los Alamos National Laboratory
Li-Wei	Hung	Los Alamos National Laboratory
Ashley	Jadwin	Sydor Instruments
Quanxi	Jia	Los Alamos National Laboratory
Gordon	Keeler	Sandia National Laboratories
Chris	Kenney	SLAC National Accelerator Laboratory
Yongho	Kim	Los Alamos National Laboratory
ianakiev	Kiril	Los Alamos National Laboratory
Alexei	Klimenko	Los Alamos National Laboratory
Alex	Lacerda	Los Alamos National Laboratory
Jonathan	Lind	Lawrence Livermore National Laboratory
XUJIE	LU	Los Alamos National Laboratory
Lucy	Maestas	Los Alamos National Laboratory
Ken	McClellan	Los Alamos National Laboratory
Isar	Mostafanezhad	Nalu Scientific, LLC
Shaul	Mukamel	University of California, Irvine
Rohit	Prasankumar	Los Alamos National Laboratory

Gideon	Robertson	Sandia National Laboratories
Richard	Sandberg	Los Alamos National Laboratory
P James	Schuck	Lawrence Berkeley National Laboratory
Daniel	Schuette	MIT Lincoln Laboratory
paul	seller	Rutherford Appleton Lab
Kate	Shanks	Cornell University
Benjamin	Sims	Los Alamos National Laboratory
Gus	Sinnis	Los Alamos National Laboratory
John	Smedley	Brookhaven National Laboratory
Laura	Smilowitz	Los Alamos National Laboratory
George	Srajer	Argonne National Laboratory
Michael	Stevens	Los Alamos National Laboratory
Ke-Xun	Sun	Univeristy of Nevada Las Vegas
Christine	Sweeney	Los Alamos National Laboratory
Mark	Tate	Cornell University
Sergei	Tretiak	Los Alamos National Laboratory
Anton	Tyazhev	Tomsk State University
Gary	Varner	University of Hawaii
Peggy	Vigil	Los Alamos National Laboratory
Zhehui	Wang	Los Alamos National Laboratory
David	Weitz	Harvard University
Dmitry	Yarotski	Los Alamos National Laboratory
Jinkyoung	Yoo	Los Alamos National Laboratory
Ren-Yuan	Zhu	Caltech

Email Address
abdulla1@llnl.gov
mary-chris.arena@sydortechnologies.com
arodzero@radiabeam.com
aazad@lanl.gov
cbarnes@lanl.gov
benedetti3@llnl.gov
cbolme@lanl.gov
pambowlan@lanl.gov
cabronk@lanl.gov
carini@slac.stanford.edu
CCHANG@LANL.GOV
apchen@lanl.gov
wchen@purdue.edu
cinzia.da.via@cern.ch
dmey@lanl.gov
demarteau@anl.gov
pdenes@lbl.gov
jdistel@lanl.gov
dragone@slac.stanford.edu
fezzaa@aps.anl.gov
marcus.french@stfc.ac.uk
heinz.graafsma@desy.de
dominic.greiffenberg@psi.ch
smg26@cornell.edu
haller@slac.stanford.edu
hatsui@spring8.or.jp
Henson@lanl.gov
rherbst@slac.stanford.edu
mhockaday@lanl.gov
k.hudspeth@lanl.gov
lwhung@lanl.gov
ashley@sydorinstruments.com
qxjia@lanl.gov
gakeele@sandia.gov
kenney@slac.stanford.edu
yhkim@lanl.gov
ianakiev@lanl.gov
klimenko@lanl.gov
lacerda@lanl.gov
lind9@llnl.gov
xujie@lanl.gov
lmaestas@lanl.gov
kmcclellan@lanl.gov
isar@naluscientific.com
smukamel@uci.edu
rpprasan@lanl.gov

garobe@sandia.gov
sandberg@lanl.gov
pjschuck@lbl.gov
drschuette@ll.mit.edu
paul.seller@stfc.ac.uk
ksg52@cornell.edu
bsims@lanl.gov
gus@lanl.gov
smedley@bnl.gov
smilo@lanl.gov
srajerg@aps.anl.gov
mfs@lanl.gov
Ke-Xun.Sun@unlv.edu
cahrens@lanl.gov
mwt5@cornell.edu
serg@lanl.gov
antontyazhev@mail.ru
varner@phys.hawaii.edu
peggysue@lanl.gov
zwang@lanl.gov
weitz@seas.harvard.edu
dzmitry@lanl.gov
jyoo@lanl.gov
zhu@hep.caltech.edu

2016 High-energy and Ultrafast X-Ray Imaging Technologies and Applications
August 1-2, 2016
Buffalo Thunder Convention Center

Los Alamos
NATIONAL LABORATORY
EST. 1943

High-energy and Ultrafast X-Ray Imaging Technologies and Applications

Tuesday, August 2, 2016

7:30 Registration........ Lobby/ Pueblo Ball Room Bay 3

8:10 Welcome........ Mike Stevens

8:20 Introduction .... Gus Sinnis

8:40 Plenary 1: Applications & needs (David Meyerhofer presiding)………… Pueblo Ball Room Bay 2

- Cris Barnes (LANL, 8:40 am -9:15 am)
- Cindy Bolme (LANL, 9:15 am- 9:50 am)
- Shaul Mukamel (UC Irvine, 9:50 am – 10:25 am)

10:25 Coffee/Tea break .... Pueblo Ball Room Bay 3

10:50 Plenary 2: The state-of-the-art (Sol Gruner presiding)........ Pueblo Ball Room Bay 2

- Heinz Graafsma (DESY, 10:50 am -11:25 am)
- Kate Shanks (Cornell, 11:25 am- 12:00 am)
- Takaki Hatsui (RIKEN, 12:00 pm – 12:35 pm)

12:35 Lunch .... On your own

14:35 Plenary 3: Data (Heinz Graafsma presiding)........ Pueblo Ball Room Bay 2

- Chris Kenney (SLAC, 14:35 pm -15:10 pm)
- Wayne Chen (Purdue Univ., 15:10 pm- 15:45 pm)
- GaryVarner (Univ. Hawaii, 15:45 pm – 16:20 pm)

16:20 Coffee/Tea break .... Pueblo Ball Room Bay 3

16:45 Plenary 4: New Possibilities (Peter Denes presiding) .... Pueblo Ball Room Bay 2

- Anton Tyazhev (Tomsk State Univ., 16:45 pm -17:20 pm)
- Sergei Tretiak (LANL, 17:20 pm- 17:55 pm)
- Jim Schuck (LBL, 17:55 pm – 18:30 pm)

18:30 Social half hour .... Cash bar

19:00 Conference Dinner /Keynote speech ....Mike Stevens intro/Quanxi Jia

20:30 Adjourn ....

LOS ALAMOS NATIONAL LABORATORY AGENDA

High-energy and Ultrafast X-Ray Imaging Technologies and Applications

Wednesday, August 3, 2016

7:30 Registration........ Lobby/ Pueblo Ball Room Bay 3

8:30 Breakout sessions (1st half) .... Pueblo Ball Room Bay 2/3

- Electron Session (Session Chairs: Gruner/Yoo)
- Photon Session (Session Chairs: Denes/Sandberg)

10:30 Coffee/Tea break .... Pueblo Ball Room Bay 3

10:50 Workshop photo .... Buffalo Thunder, Lobby

11:00 Breakout sessions (2nd half) .... Pueblo Ball Room Bay 2/3

- Electron Session (Session chairs: Gruner/Yoo)
- Photon Session (Session chairs: Denes/Sandberg)

12:30 Lunch .... On your own

14:30 Summary from the Electron Session (Gruner/Yoo) .... Pueblo Ball Room Bay 2

15:30 Coffee/Tea break .... Pueblo Ball Room Bay 3

16:00 Summary from the Photon Session (Denes/Sandberg) .... Pueblo Ball Room Bay 2
17:00 Closing remarks .... Mary Hockaday
17:30 Workshop ends

Thanks for your participation! Safe travels.

August 3, 2016

ELECTRON breakout session (chairs: Gruner/Yoo) ………………..…. Pueblo 2
(Duration: 12 min talk + 3 min Q&A)

8:30 am **Laura Smilowitz** (Los Alamos National Lab)
Imaging and measuring the evolution of solid density within a thermal explosion
8:45 am **Jinkyoung Yoo** (Los Alamos National Lab)
Ultrafast Dynamics of Three-Dimensional Semiconductor P-N Junctions
9:00 am **George Srajer** (APS/Argonne National Lab)
*Application of High-Energy Synchrotron X-Rays to Studies of Microstructures at the Advanced Photon Source**
9:15 am **Daniel R. Schuette** (MIT Lincoln Lab)
Developments in Image Sensor Detectors at MIT Lincoln Laboratory
9:30 am **Yongho Kim** (Los Alamos National Lab)
Achieving 10 ps Time-Resolution by Coupling Cherenkov Sensor with Pulse-Dilation PMT Technology
9:45 am **Isar Mostafanezhad** (Nalu Scientific)
High Performance, Highly Integrated System-on-Chip Readout Electronics with Future Applications in X-Ray Imaging
10:00 am **Ke-Xun Sun** (Univ Nevada Las Vegas)
GaN Devices as Ultrafast, Radiation Hard Imagers for MaRIE
10:15 am **Ryan Herbst** (SLAC/Stanford Univ)
LCLS-2 Experiment Data Acquisition Design

10:30 am **Coffee/Tea break……………………….Lobby/Pueblo Ball Room 3**
>>>> Group photo <<<<

11:00 am **David A. Weitz** (Harvard)
Formation of amorphous nanoparticles
11:15 am **Aiping Chen** (Los Alamos National Lab)
High quality thin films for hard X-ray detectors
11:30 am **Marcel Demarteau** (Argonne National Lab)
3D Integration and Imaging
11:45 am **Paul Seller** (Rutherford Appleton Lab)
(TBD)
12:00 pm Discussions (if necessary)
12:30 pm Lunch (on your own)

August 3, 2016

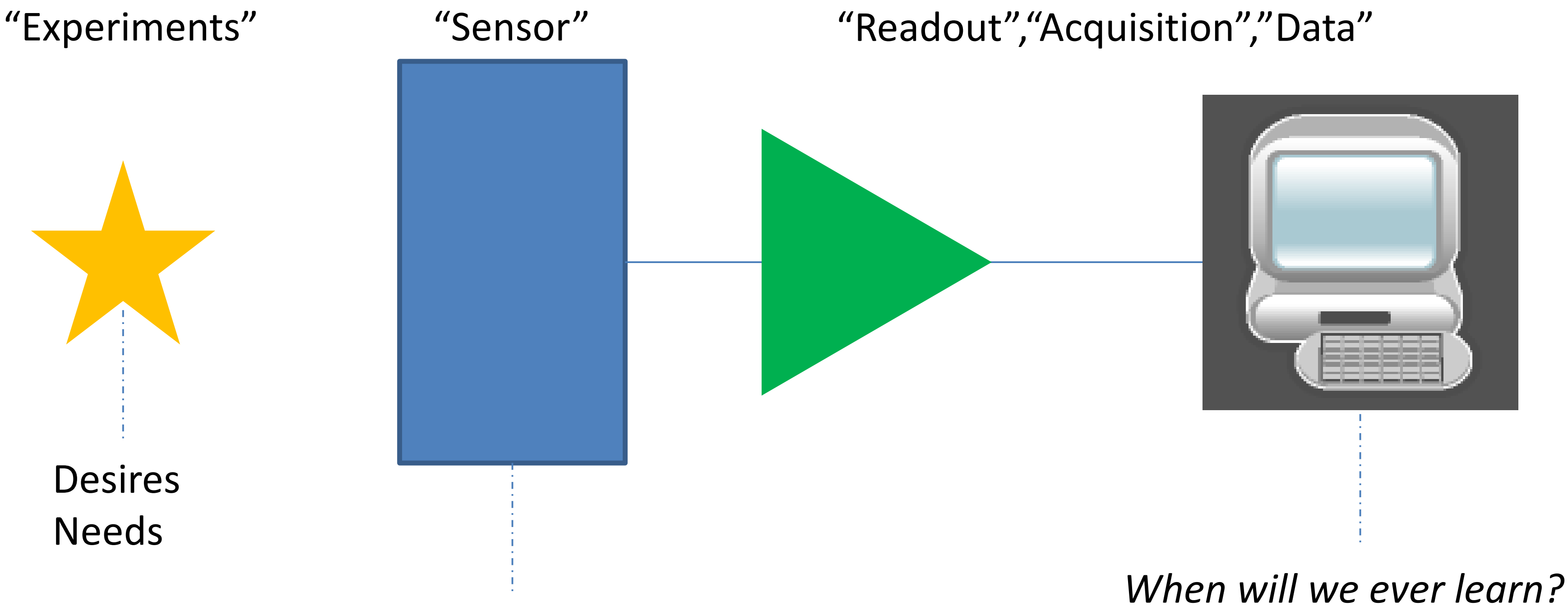
PHOTON breakout session (chairs: Denes/Sandberg) …………….. Pueblo 3
(Duration: 12 min talk + 3 min Q&A)

8:30 am **Mark Tate** (Cornell)
CdTe Sensors on Charge-Integrating Pixel Array Detectors for High-Speed X-ray Imaging
8:45 am **Ren-Yuan Zhu** (Caltech)
Fast Crystal Scintillators for Gigahertz Hard X-ray Imaging
9:00 am **Richard Sandberg** (Los Alamos National Lab)
Revolutions in coherent X-ray sources and needs for detectors to enable mesoscale movies
9:15 am **Dominic Greiffenberg** (Paul Scherrer Institut)
High-Z sensors in combination with charge-integrating FEL detectors
9:30 am **Pamela Bowlan** (Los Alamos National Lab)
Extending ultrashort pulse measurement to the hard x-ray
9:45 am **John Smedley** (Brookhaven National Lab)
Beam Monitoring in the Compton Regime
10:00 am **Christine Sweeney** (Los Alamos National Lab)
Data Handling to Support Efficient and Effective Scientific Discovery at Future XFEL Experimental Facilities
10:15 am **Robin Benedetti** (Lawrence Livermore National Lab)
Detector Needs for Time-Resolved X-Ray Diffraction at NIF

10:30 am **Coffee/Tea break……………………….Lobby/Pueblo Ball Room 3**
>>>> Group photo <<<<

11:00 am **Abul Azad** (Los Alamos National Lab)
Sub-picosecond Optoelectronic Detection of X-rays
11:15 am **Angelo Dragone** (SLAC/Stanford Univ)
Concepts for Ultra-fast Multilayer Distributed Imaging Detectors
11:30 am **Ashley Jadwin** (Sydor Instruments)
(TBD)
11:45 am (Open)
12:00 pm Discussions (if necessary)
12:30 pm Lunch (on your own)

“Electron” Breakout Session



Conventional semiconductors

  direct detection, 3D architecture

Scintillators / Optical detection

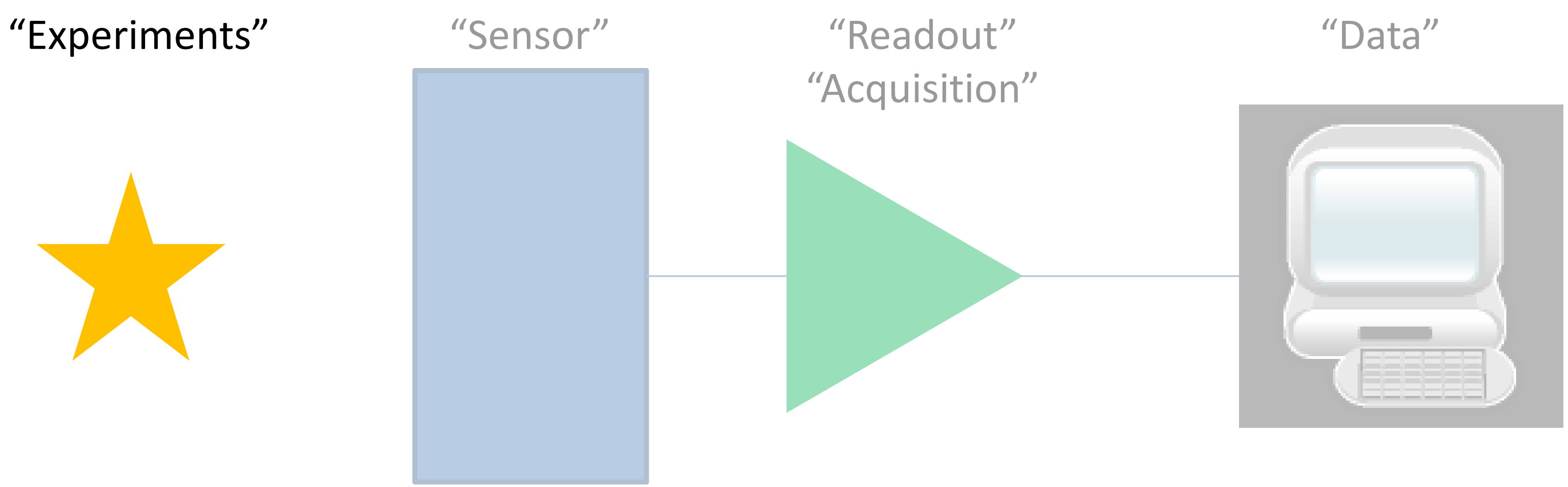
  X-ray to light with new materials

Nano-engineered materials

  both

"Electron" Breakout Session

E	S	R /D	
X			***8:30*** am **Laura Smilowitz** (Los Alamos National Lab) *Imaging and measuring the evolution of solid density within a thermal* explosion
	X		***8:45*** am **Jinkyoung Yoo** (Los Alamos National Lab) *Ultrafast Dynamics of Three-Dimensional Semiconductor P-N Junctions*
X	X		***9:00*** am **George Srajer** (APS/Argonne National Lab) *Application of High-Energy Synchrotron X-Rays to Studies of Microstructures at the Advanced Photon Source**
	X		***9:15*** am **Daniel R. Schuette** (MIT Lincoln Lab) *Developments in Image Sensor Detectors at MIT Lincoln Laboratory*
	X		***9:30*** am **Yongho Kim** (Los Alamos National Lab) *Achieving 10 ps Time-Resolution by Coupling Cherenkov Sensor with Pulse- Dilation PMT Technology*
		X	***9:45*** am **Isar Mostafanezhad** (Nalu Scientific) *High Performance, Highly Integrated System-on-Chip Readout Electronics with Future Applications in X-Ray Imaging*
	X		***10:00*** am **Ke-Xun Sun** (Univ Nevada Las Vegas) *GaN Devices as Ultrafast, Radiation Hard Imagers for MaRIE*
		X	***10:15*** am **Ryan Herbst** (SLAC/Stanford Univ) *LCLS-2 Experiment Data Acquisition Design*
	X		***11:15*** am **Aiping Chen** (Los Alamos National Lab) *High quality thin films for hard X-ray detectors*
	X		***11:30*** am **David A. Weitz** (Harvard) *Formation of amorphous nanoparticles*
	X		***11:45*** am **Marcel Demarteau** (Argonne National Lab) *3D Integration and Imaging*



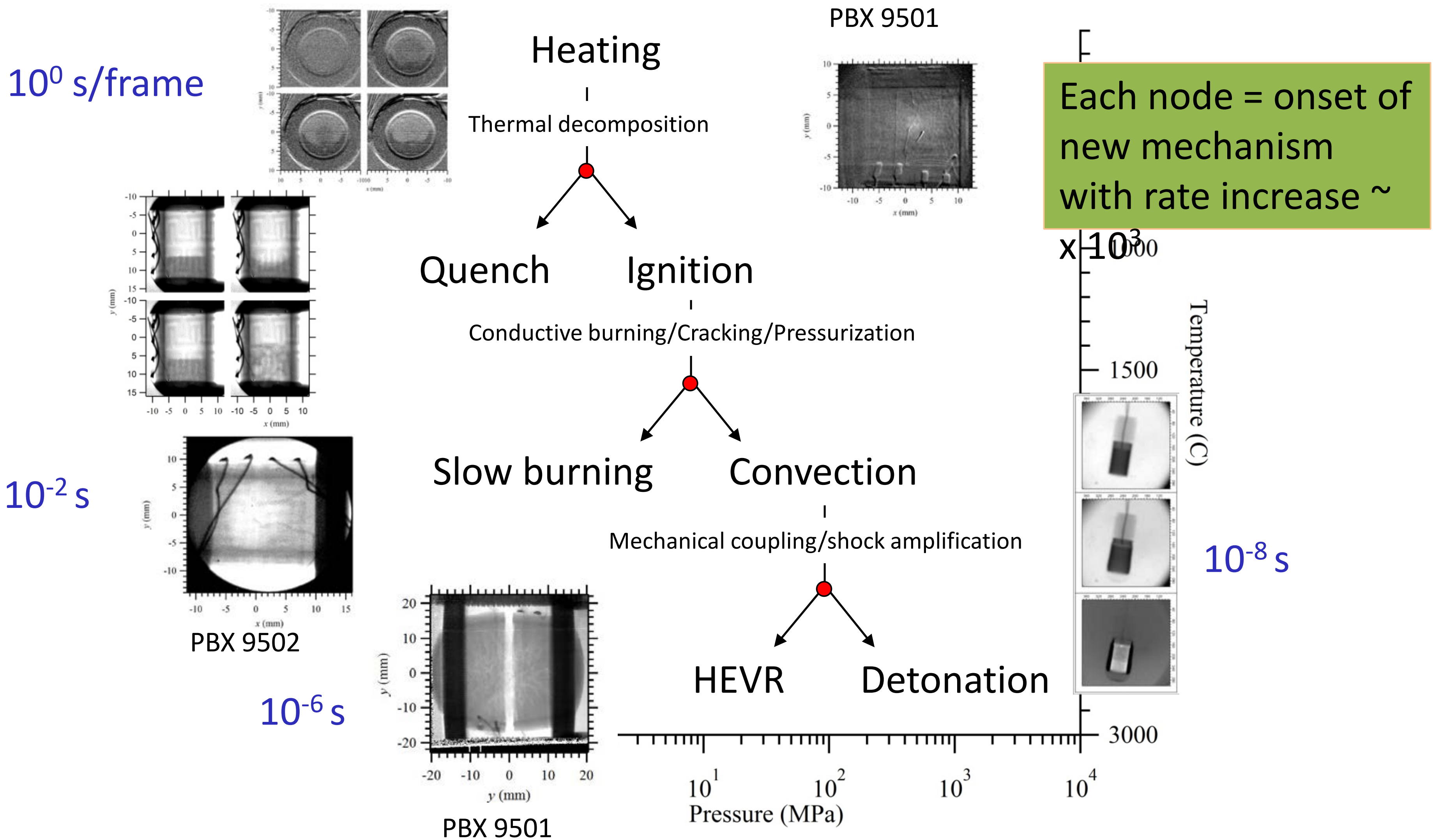
- Laura Smilowitz

  -Coordinating sample spatial/temporal region of interest & X-ray probe is challenging.

- George Srajer

  -High energy X-ray methods are well developed, but detector limited.

Parsing thermal response: Radiographic data
Laura Smilowitz



George Srajer: Group discussion slide

- Applications of high energy x-rays techniques are straightforward to extend to MaRIE's science case
- Transition from storage based sources to XFEL:
  - Increased time resolution - femtoseconds
  - Nanoscale imaging
  - Photon correlation spectroscopy - dynamics of nanoscale objects at nanometer spatial resolution
- Challenges
  - Efficient and fast framing high energy x-ray detectors
  - Integrated data processing and analysis
- Resources for high energy x-ray detectors should be leveraged
  - Significant resources have been already invested

"Sensor (1/2)"

- Jinkyoung Yoo

  - 3D architectures based on nanomaterials provide great opportunity, and some materials can match the requirement of X-ray detector, but still lots of R&D necessary.

- Daniel Schuette

  - Direct x-ray detection with sub-ns time resolution is extremely difficult.

  - Hybrid detector (Fast scintillator and thin semiconductor photodiode) gives us great opportunity.

- Yongho Kim

  -Feasibility study necessary for Cherenkov sensor-based x-ray imagers.

- Ke-Xun Sun

  -Supports needed in order to develop GaN-based x-ray detectors to match MaRIE schedule.

“Sensor (2/2)”

- Aiping Chen

    -Nanostructure detector has potential for MaRIE detector needs.

- David Weitz

    -Microfluidic method can help structural materials from nanoscale to mesoscale.

- Marcel Demarteau

    - 3D technology maturing driven by industry making possible previously unthinkable detector design.

Jinkyoung Yoo

Ultrafast detector based on radial nanoheterostructures

- **Goal**

Ultrafast (<100 ps) radiation detector using three-dimensional (3D) semiconductor heterostructure as active region, in which composition is modulated along radial direction with high detection efficiency

- **Current architecture of radiation detector**

A combination of bulk (for radiation detection) and 3D electrode. Generally, microscale electrodes are inserted in bulk semiconductor material. Current architecture has been evolved from planar structure to improve detection speed by reducing carrier travel distance from excited position to electrode

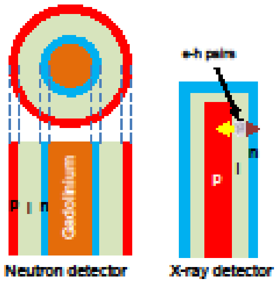
- **Limitations of current radiation detector:**

1) Detector response time (> ns) due to large travel distance of excited carriers (several tens μm)
2) Small signal to noise ratio due to large input capacitance originating from material volume
3) Large power consumption due to high applied bias (several tens~hundreds volts to retain depletion region)

- **Proposed Solution / Innovation**

<u>Vertically aligned radial nanoheterostructure</u>

1) Enhanced absorption of radiation along axial direction (Longer structure, more absorption)
2) Ultrafast carrier extraction along radial direction (several picoseconds ~ several tens picoseconds)
3) Ultrasmall capacitance of nanostructure (Larger signal to noise ratio)
4) Various material combination for wide range of radiation detection
5) Low power consumption: applied bias of several volts or zero bias



- **Why will we succeed?**

- J. Yoo has successfully demonstrated several key technologies for this research as follow:
*Fabrication of tubular and cylindrical nanoheterostructure arrays (Si, Ge, ZnO, GaN)
*Fabrication of electrodes for three-dimensional nanoarchitectures

- **Risks / Possible solutions**

1) Enhanced surface recombination due to large surface to volume ratio
→ Surface passivation
2) Optimized electrode structure to maximize carrier extraction and to minimize screening radiation into detector concurrently
→ Selecting suitable material for electrode and conformal formation
3) Radiation hardness of nanomaterials
→ In-depth study of radiation hardness of nanomaterials and integrative study of electrode architecture mitigating degradation problem in materials during irradiation.

Dan Schuette: Summary

- MIT Lincoln Laboratory is dedicated to novel prototype development and sensors for challenging applications
- Maintains in-house fabrication facilities and special capabilities for developing unique semiconductor sensor structures
  - Silicon image sensor back-illumination
    - Molecular beam epitaxy (MBE)
  - Oxide-bonded 3D-integration
- Expertise in image sensor technology
  - Charge-coupled devices (CCDs)
  - Avalanche Photodiodes (APDs) in multiple materials
  - High performance 3D integrated PiN photodiode sensors

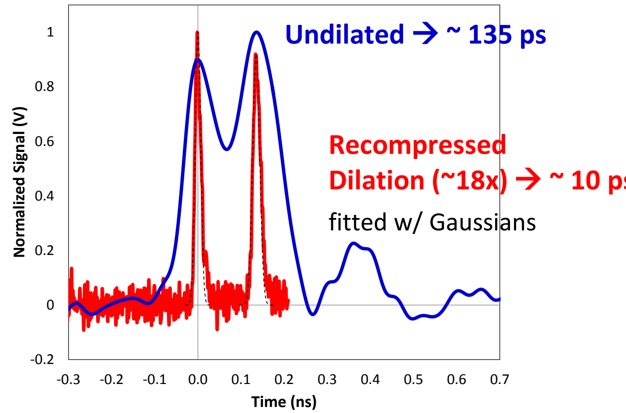
Cherenkov Detector coupled with Pulse-Dilation PMT

Yongho Kim and Hans Herrmann (LANL, P-24)

Summary:

- LANL has extensive experience with Gas Cherenkov Detector (time-resolution ~ 100 ps, energy threshold > 2 MeV)
- Pulse-dilation PMT protype successfully demonstrated ~ 10 ps temporal resolution
- A feasibility study will validate the concept of using Diamond crystal as a Cherenkov source (n = 2.4, energy threshold ~ 50 keV)
- Imaging configuration will be followed by once the feasibility study is successful.

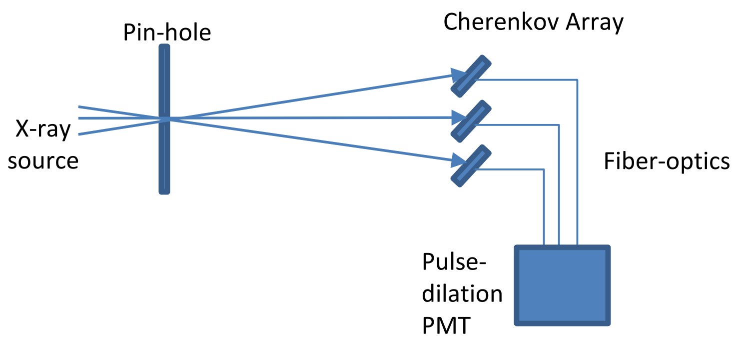
A pulse-dilation PMT prototype demonstrated ~ 10 ps temporal resolution



Key innovations:

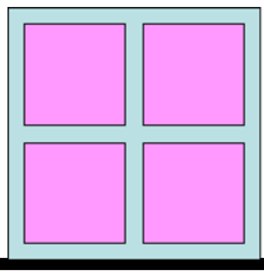
- Demonstrated ~ 10 ps temporal resolution using a pulse-dilation PMT
  - developed by Kentech/Photek (w/ Sydor as US Distributor); funded by LANL and test at AWE
- Diamond crystal may detect 126 keV third harmonic
  - feasibility study is needed

Proposed concept: A diamond crystal Cherenkov detector to be coupled with pulse-dilation PMT



GaN Devices as Ultrafast, Radiation Hard Imagers for MaRIE (Ke-Xun Sun, UNLV/NSTec)

Proposed Idea: Utilizing intrinsic properties of GaN/AlGaN semiconductors, to develop radiation hard (1E16 n/cm^2), ultrafast imagers (>100GHz).



Expected milestones and timescales:

- UNLV MOCVD: 2017-2018
- Ultrafast AlGaN devices generation by LIFE and other meth: 2018-2020
- MaRIE Imager Active Layer: 2021-2022
- MaRIE imager I/O Layer: 2023-2024
- Integrated Diagnostic: 2025-2026
- Acceleration with MaRIE support

Key Innovations

- GaN: high bond strength, wide band gap
- Radiation hardness: Tested with proton and neutron. Flew in space. TRL 9
- Ultrafast: GaN HEMT devices bandwidth >300 GHz (20 GHz commercial)
- Imager active layer
- Imager I/O layer
- Direct radiation sensing (sensitive at MaRIE wavelength)

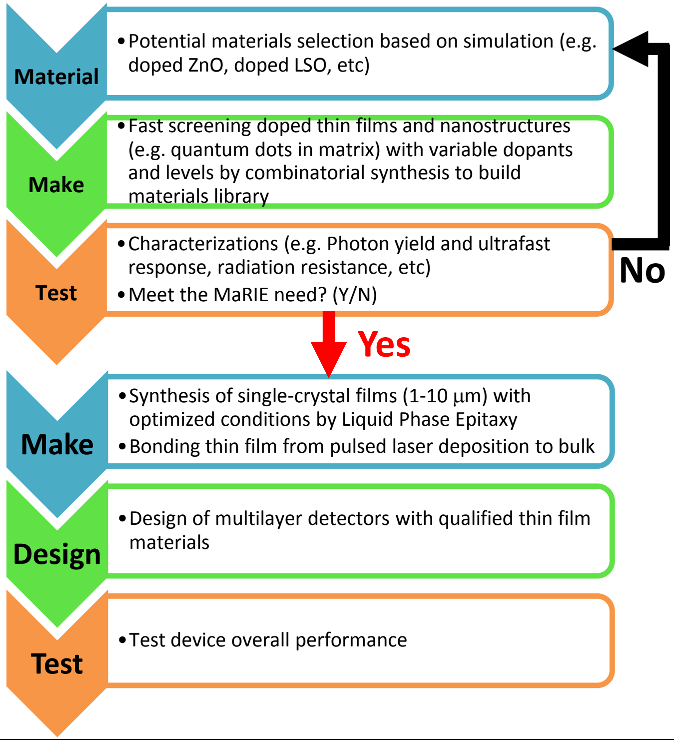
Existing resources leverage

- UNLV GaN labs in progress
- NSTec support
- LANSCE/NIF Radiation hardness tests
- LBNL collaboration in characterization
- Sandia collaboration in device

Exploring oxide films for ultrafast hard x-ray imaging

Aiping Chen, MPA-CINT

Multilayer detector development



key innovations for scintillating type detectors:

1) Using doping in oxide materials such as ZnO and LSO, and doping nanoparticles and quantum dots in nanostructures could dramatically increase the rise time, decay time, photon yield and ultrafast response, which makes GHz frame rate possible.
2) Combinatorial pulsed laser deposition provides a cost and time effective method to optimize/enhance scintillating properties over a large number of dopants and compositions to meet the MaRIE need. It is not available in bulk process.
3) Using the multilayer design to increase the spatial resolution and keep high overall efficiency.

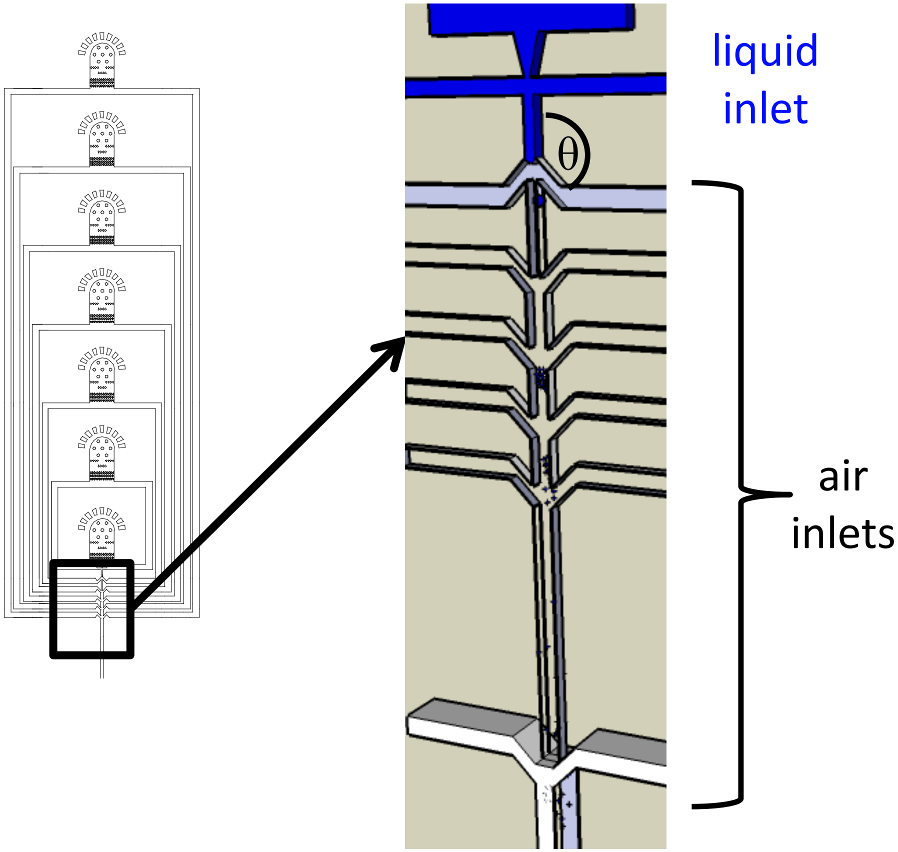
FY	Key Milestones
FY17	1) Potential materials screening from literature and GEANT4 simulations; 2) Combinatorial synthesis of ZnO thin films with different dopants, levels and materials; 3) Synthesis of ZnO nanostructures with adding nanoparticles and quantum dots in different dopants, size, and compositions. 4) Characterization of the luminescence properties and ultrafast response and identify optimized sample conditions.
FY18	1)Synthesis of single-crystal films (1-100 μm) with optimized conditions. 2) Bonding nanostructured ZnO films to thick layers.
FY19	1) Design of multilayer detectors by synthesizing single–crystal and nanostructured ZnO thin films. 2) Test the overall imaging performance.

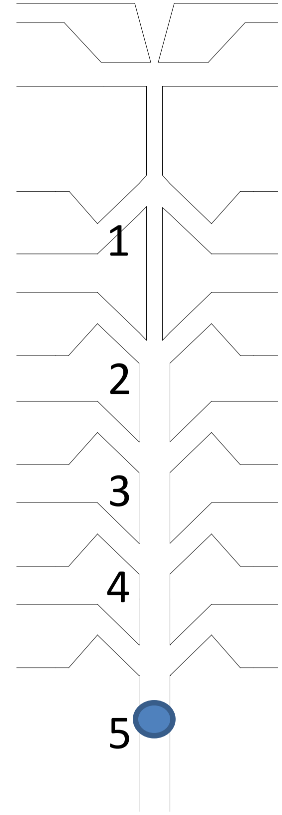
Existing resources/expertise

1) GEANT4 simulation (Jeff Wang)
2) Combinatorial pulsed laser synthesis (Aiping Chen)
3) Basic structural characterization (Aiping Chen)
4) Photoluminescence (Aiping Chen)
5) Ultrafast response (Jeff Wang)
6) Multilayer design and device performance (Jeff Wang)

The microfluidic nebulator
Spray drying amorphous nanoparticles (David Weitz)

Esther Amstad





p_{inlet} = 0.28 MPa

p_1 = 0.27 MPa $v_{air,\,1}$ ≈23 m/s

p_2 = 0.27 MPa $v_{air,\,2}$ ≈26 m/s

p_3 = 0.24 MPa $v_{air,\,3}$ ≈50 m/s

p_4 = 0.24 MPa $v_{air,\,4}$ ≈90 m/s

p_5 = 0.20 MPa $v_{air,\,5}$ ≈740 m/s

p_{outlet} = 0.10 MPa

Gap ~ 1 μm
v ~ 60 km/s
[mach 180!]

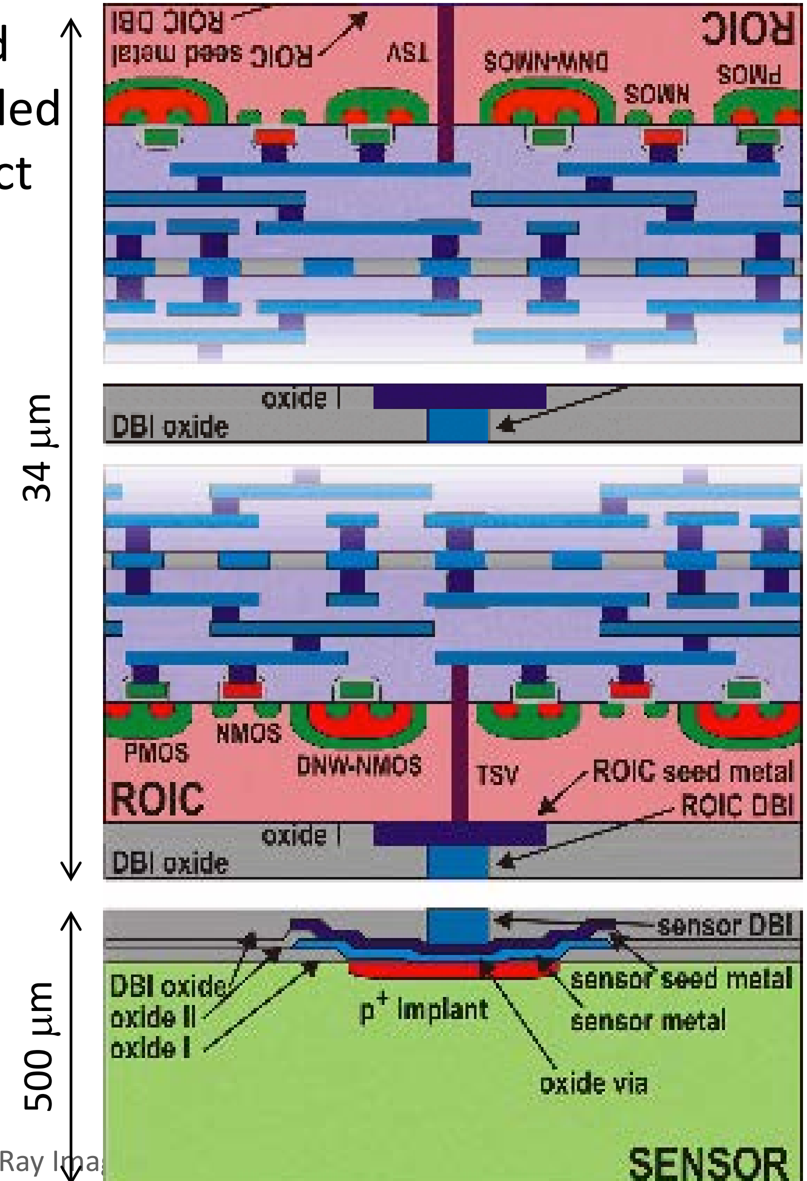
Shear stresses $\frac{\eta v}{l} \sim \frac{\sigma}{r}$ Surface stresses

r ~ 300 nm

Questions:
What produces nanodrops
Can their production be observed
Can formation of amorphous particles be

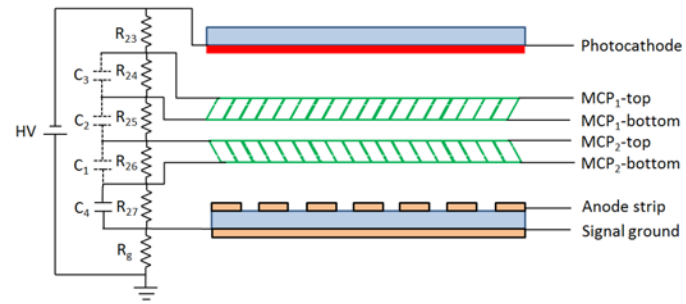
3D Integrated Devices: Marcel Demarteau

- Tiered, integrated devices enables tailored front-end readout – in any process – coupled to sensing medium of choice through direct bond interconnects
  - Deep frame buffers
  - Pixel size and pitch of 50 µm (architecture dependent)
  - High dynamic range possible (QIE) dsad
  - Frame-rate demanding
- Technology being matured
- FASPAX funding limited schedule
- Current developments in HEP community on ASICs and 3D development supported by OHEP and BES, directly applicable to challenge at hand.

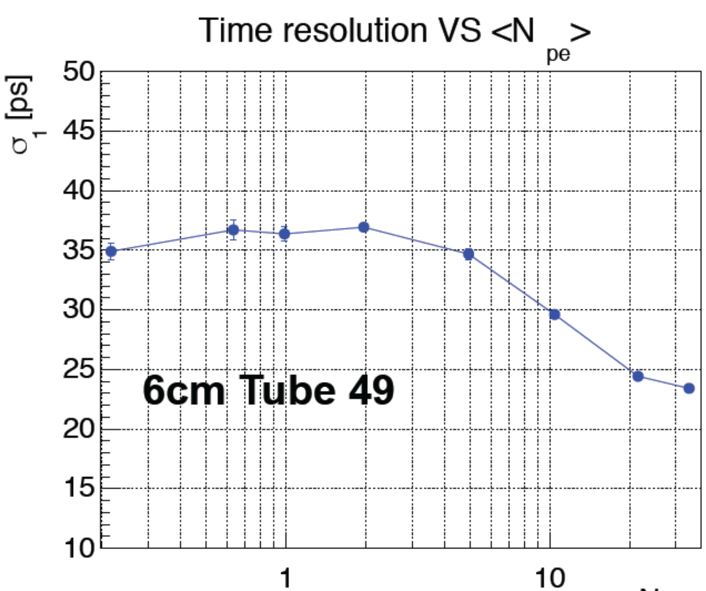


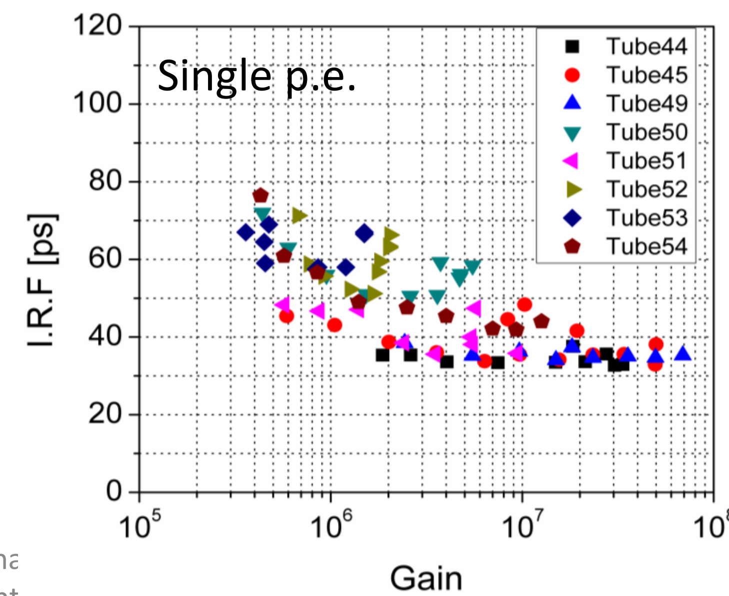
Picosecond Planar Photodetectors

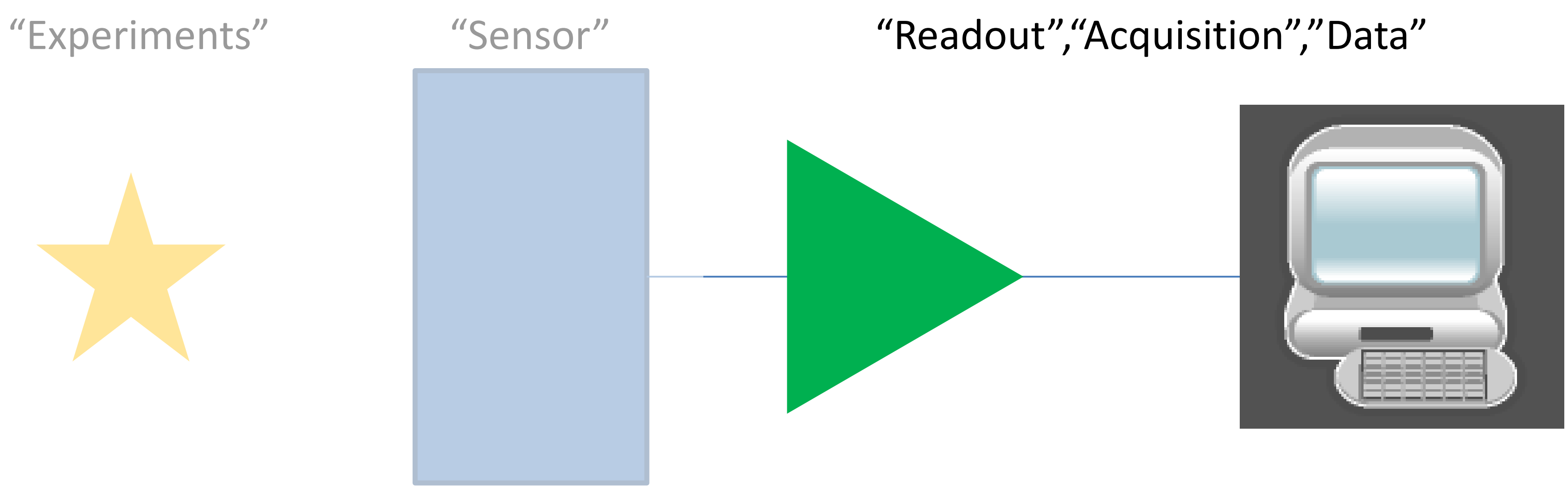
- Micro-channel plate based photodetector (not optimized geometry, 20 micron pores)
- Glass capillaries functionalized through the atomic layer deposition process for resistive and secondary electron emission layer
- Waveform analysis yields timing resolution of 30ps single pe; approaching 5ps for high; significant room for improvement



6cmx6cm







- Isar Mostafanezhad

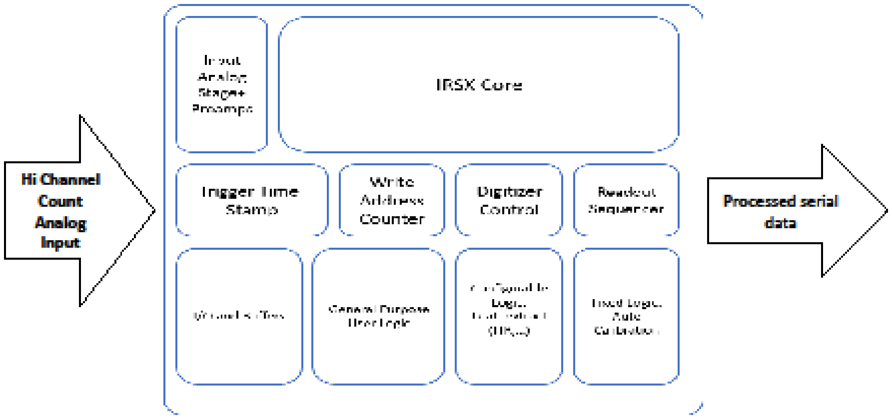
  - Developing compact waveform sampling with 5 G samples/s with built-in processing.

- Ryan Herbst
  - MaRIE’s data flow would be challenging, but building blocks exist to meet the need.

High Performance, Highly Integrated System-on-Chip Readout Electronics with Future Applications in X-Ray Imaging

Isar Mostafanezhad, and Gary Varner

Nalu Scientific, University of Hawaii



Key Contribution:

- High performance digitizer: 4+ Gsa/s
- Highly integrated
- On chip:
    - Analog storage
    - Reconfigurable DSP
    - Calibration

Timeline and milestones

- Previous version of imager installed
- ASIC design in progress
- First article: March ’17
- General testing March-May’17
- Imaging testing pending funds

Resources:

- Funded Phase I SBIR for ASIC design
- Engineers at Nalu Scientific
- Commercial ASIC design license/server
- Lab space available at U. of Hawaii
- Looking to collaborate based on imaging community needs
- Actively seeking SBIRs to develop next generation

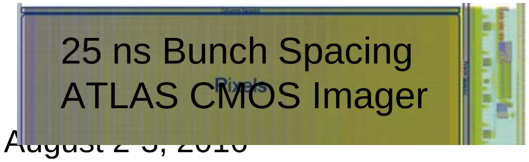
SLAC National Accelerator Laboratory (Ryan Herbst)
Data acquisition, Controls, and Electron Imaging

Proposed Concepts:
- Data Acquisition
  - Facility driven data acquisition with mature run control, online and offline analysis APIs
- Electron Detectors
  - All LCLS photon detectors sense electrons
  - Hybrid single-plane electron trajectory (Kpix+ePix) similar to ePix-Delta
  - Adapt LHC CMOS sensors for MaRIE
- Accelerator Controls
  - Common platform for high performance controls systems (BPM, MPS, LLRF, etc)

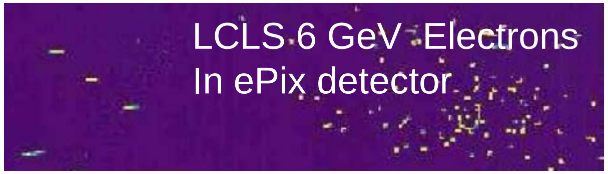
Possible MaRIE Milestones: *
- **Data Acquisition**
  - 2018 Preliminary architecture for combined X-ray, electron, and proton experiments
  - 2019 Preliminary
- **Electron Detectors**
  - 2018 Prototype hybrid KPiix + ePix10k v0.5
  - 2018 Prototype eRAD CMOS sensor v0.5

* Dependent on funding

Critical Advances:
- Evolve MaRIE DAQ from LCLS DAQ
- Incorporate lessons from ATLAS DAQ
- Merge data from eRAD, pRAD, and XFEL detectors
- Combine characteristics of KPix and ePix in optimized eRAD detector for MaRIE



Resources:
- Experienced FEL DAQ team
- Existing LCLS I systems
- Developing LCLS II systems
- Existing designs for KPix and ePix
- Existing designs for LHC CMOS sensors



Needs, Applications

What would be the 1st experiments with MaRIE?

- Any topic struggling to understand materials/systems behaviors at intermediate (meso) scales (spatial, temporal)
- National Security Missions: Explosive (Deflagation − Detonation)

  *Synchronization issue: Event & Imaging
- Energy storage: Operando characterizations under real operation condition.
- In-situ assessment of structural materials.

Current status of imaging detectors

Biggest bottleneck: GHz-frame rate

- Several MHz-frame rate X-ray camera
- Ge strip detector
- Si-based APD-Hybrid detector
- Dilation PMT for high energy radiation detector (5 ps-resolution)

Data handling

How to handle enormous data acquired from X-ray imaging in real-time manner?

- ASICs for fast readout have been developed: (Nalu Scientific, CHESS, SLAC, etc.)

Feedbacks between the fields are essential to realize advanced X-ray imaging science and applications.

Approaches: Materials, Architectures

Current planar Si-based technology has met limit of performances.

- Replacing Si: GaAs:Cr, CdTe, GaN, ZnO, Scintillators (RE doped Lu_xO_y:Eu, BaF_2, etc.)
- Stacked sensors: Thin (<100 um-thick) layers
- Cherenkov sensors with Dilation-PMT technology
- Three-dimensional architecture
- Downsizing: Sub-micrometer scale, nanostructured thin films

User-friendly operation / Production

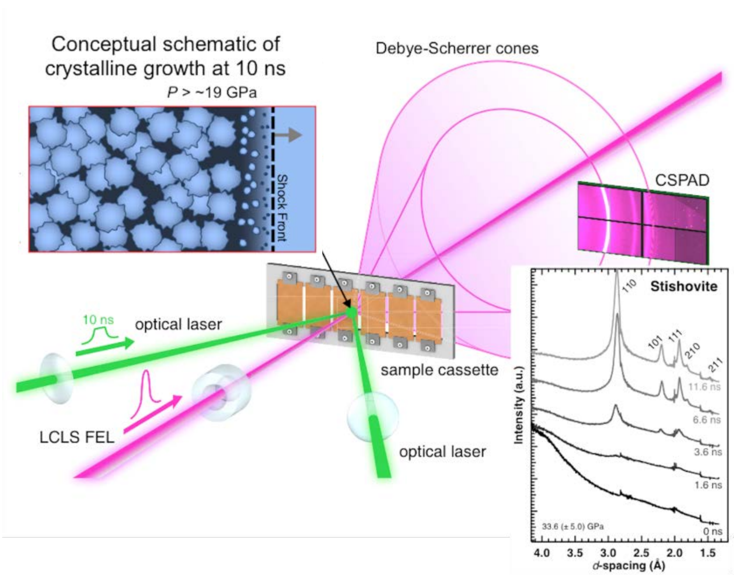
User can damage detectors.

- Front-end parts have to be consumable.

Cindy Bolme *et al.*

Ultrafast Visualization of Phase Transformations in SiO_2

Measuring the kinetics of the non-equilibrium processes by which atoms rearrange advances our understanding of phase transformation pathways and is applicable to many materials.

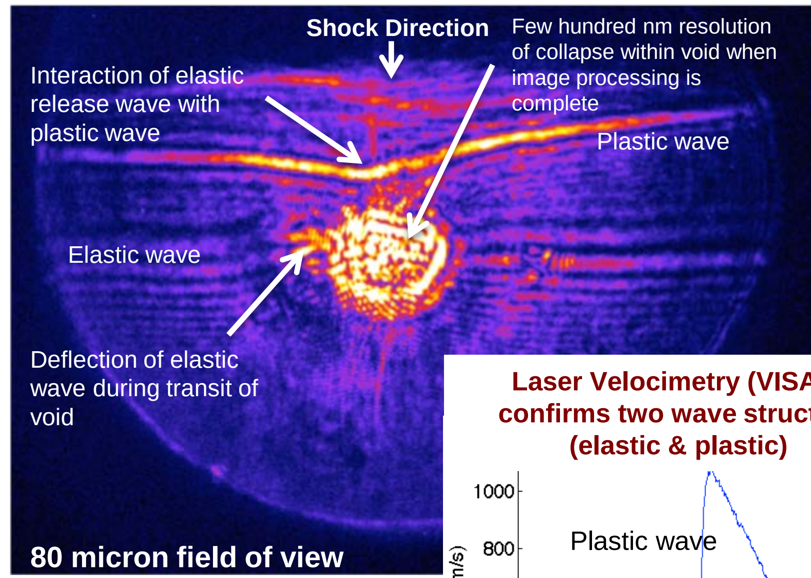


A. Gleason, C. Bolme, H.J. Lee, B. Nagler, E. Galtier, D. Milathianaki, J. Hawreliak, R. Kraus, J. Eggert, D. Fratanduono, G. Collins, R. Sandberg, W. Yang and W. Mao, Nature Communications ***6:8191*** 2015***.***

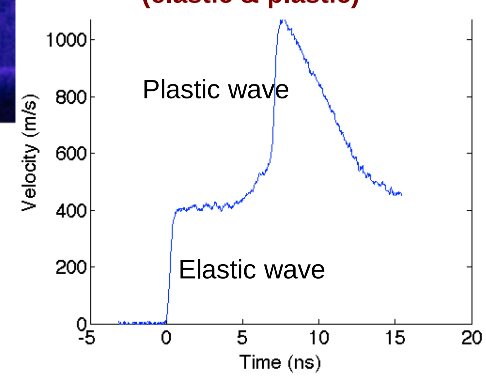
Work was performed at the Linac Coherent Light Source (LCLS), SLAC National Laboratory – Menlo Park, CA

X-ray imaging of void collapse in PETN

X-ray imaging, diffraction, and velocimetry show elastic-plastic response and detailed wave interaction with the collapsing void. Both spatially resolved hydrodynamics and lattice level response were captured during complex loading of void by structured wave.



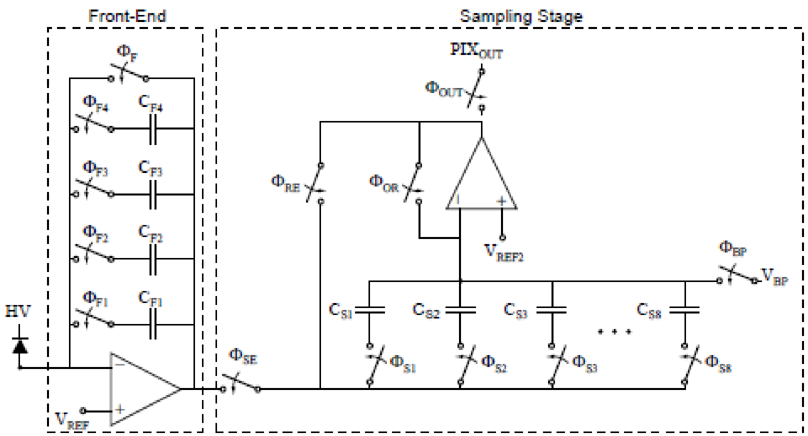
Laser Velocimetry (VISAR) confirms two wave structure (elastic & plastic)

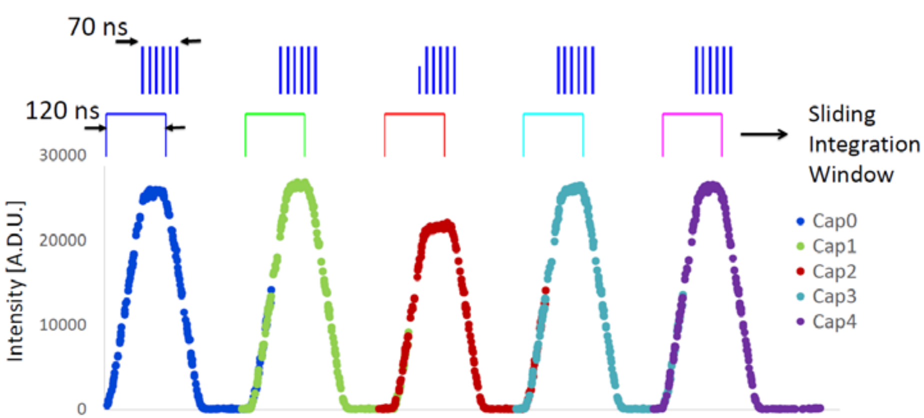


Summary: Designs for Pixel Array Detectors for XFEL and Fast-Bunch Imaging

Present Keck PAD: 10 MHz burst imaging

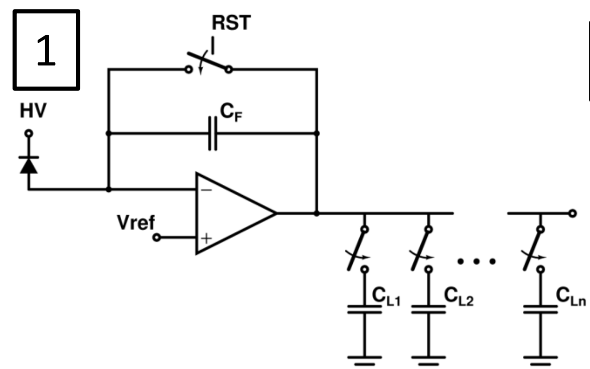
- Sensor: 500 µm Si, 750 µm CdTe
  - GaAs effort has begun
- Excellent performance @ 10 MHz

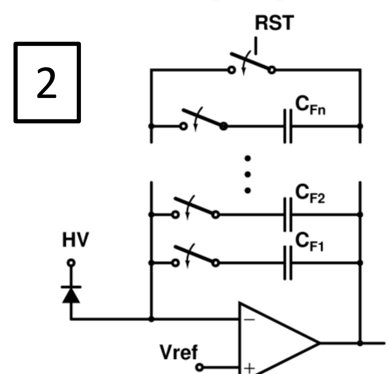


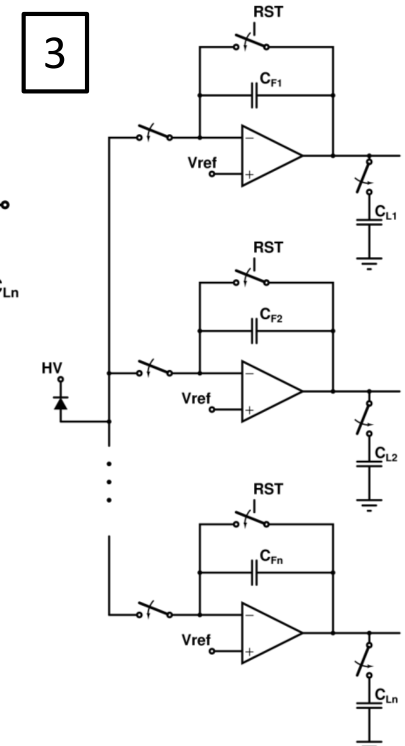


Suggested modifications for use @ MaRIE

- 300 – 500 µm GaAs sensor: few ns signal collection @ reasonable reverse bias
- Re-design pixel for ~500 MHz operation:
  - Explore options for frame storage (1-3)
  - Redesign front-end amp
  - 3-5 years to prototype



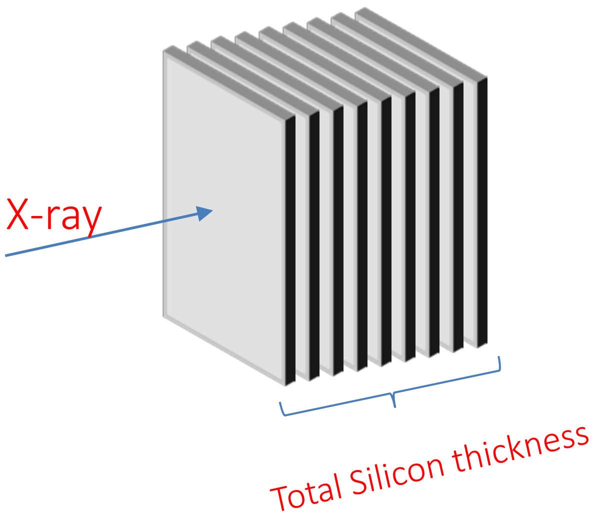




Takaki Hatsui: Stacked Silicon Detector

Concept: Stacked Silicon Sensor

Three Layer Stacking 1) SPring-8 II CDR (2014). 2)T. Hatsui, presented at iWorld (June. 2014).



Key Innovations: SOIPIX process for stacked sensor

Saturation velocity is the limiting factor

	Type I	Type II
Photon Energy	30	42
ΔT	2 ns	300 ps
Pixel Size (um)	80	96
Layer Thickness (um)	60	20
Total Thickness (mm)	3	8
Total Number of Layers	50	400

Charge-Division pixel

- Charge-Division pixel reduces the transient power dissipation by operating each sub pixel independently.

Time Scale (ROM)

3 Yrs: SOIPIX Chip Development
incl. rad. Hard Tr & thinning
3 Yrs: System Development

Existing Resource

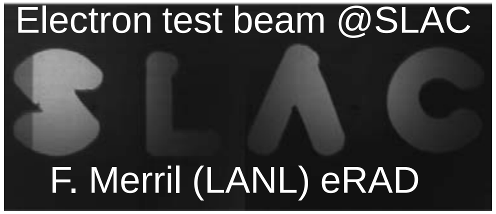
SOIPIX process/ Device Simulation Platform
Ptototype rad. Hard Tr. & Wafer thinning Process

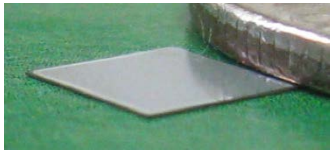
Chris Kenney: Some Take Away Points

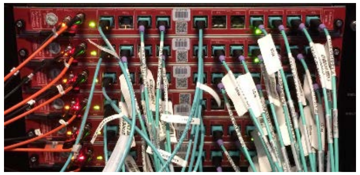
- Options for Photons :
  - Distributed, flash ADC scheme ePixF
  - Fast current signal capture ePixΔ
  - Distributed or stacked thik modules
  - SugarCube side-entrance
- Electrons:
  - Above Photon systems will work for eRAD.
  - Radiation damage may limit detector lifetime
- Detector system manufacturing maybe important

  Due to multiple layers or radiation damage or extreme environment
- Prototypes of above in 2018 *
- Deployable ~ 5 years *

* Depending on funding



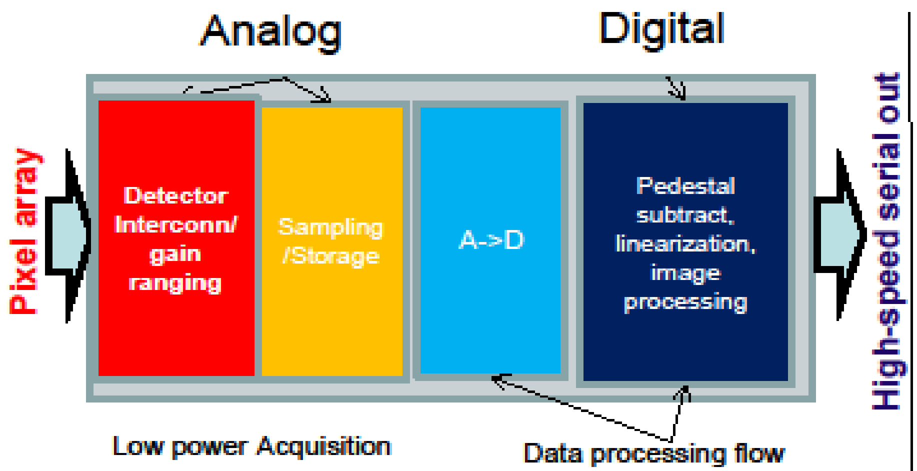




Gary Varner

Exploring the Space-Time Limits in Next Generation X-ray Imaging Readout

University of Hawaii, Nalu Scientific



Relevance and Goals

Technical Challenge –

Custom developed mixed signal ASIC
Noise optimized ASIC assembly
Performance reproducibility and high integration

Performance Targets –

Pico-second or better timing on highly integrated arrays
Optimization of connection and bandwidth
Both Type I and Type II Imager modes

Uniqueness/Transformational Impact –

Compact all-in-one semiconductor detector electronics.
Technology-scalable, rapid-frame rate acquisition

Advantages –

Low power sampling, integrated ADC and signal processing

Technical Approach

Problem Approach –

- Highly compact electronics for finely-pixelated detectors
- Multi-GigaHertz frame rates/precision timing
- On-chip Processing / data reduction

Current Status –

- Optimization studies from pico-second timing ASICs
- Architecture evaluation and downselect
- Integration of control/feature extraction logic

Key challenges –

- Mixed signal ASIC
- Sampling rate, analog bandwidth, processing density

Cost, Schedule, and Team

Milestones/Deliverables – Multi-track:

- Sampling optimization: 9 months
- Initial architecture summary: 12 months

Resources –

- DOE KA-25 (PI: Varner) for analog coupling, dynamic range, storage and conversion optimization
- DOE SBIR Phase I (PI: Mostafenezhad) for System on Chip processing and acquisition control

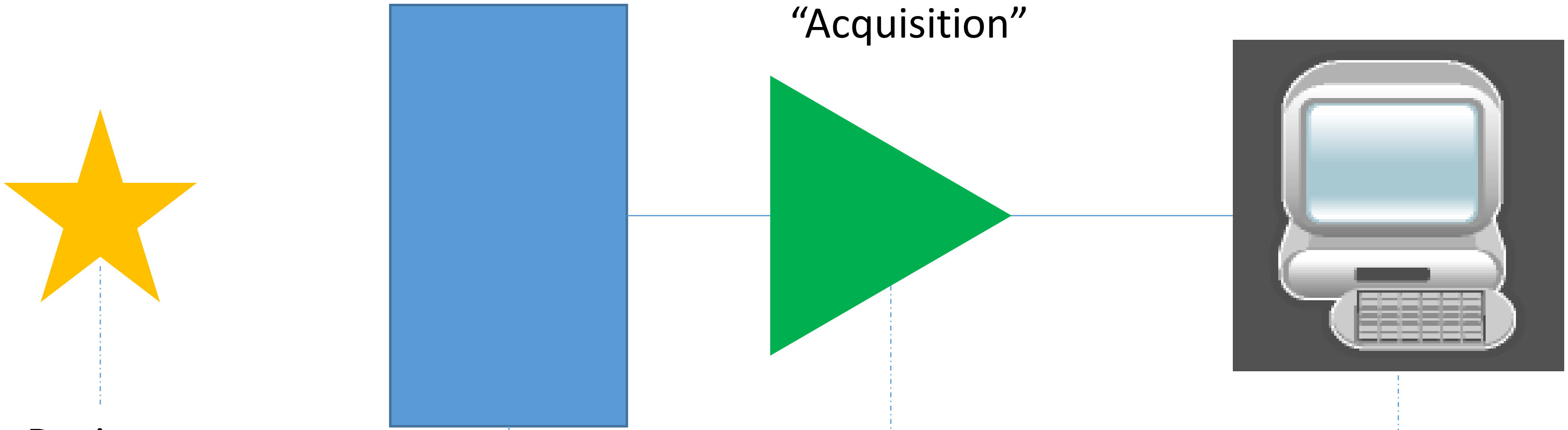
Main team members –

Bronson Edralin (University of Hawaii)
Isar Mostafenezhad (Nalu Scientific)
Peter Orel (University of Hawaii)
Gary Varner (University of Hawaii)

“Photon” Breakout Session

Peter Denes (LBNL) + Richard Sandberg (LANL)

“Experiments” “Sensor” “Readout” “Acquisition” “Data”



Desires
Needs

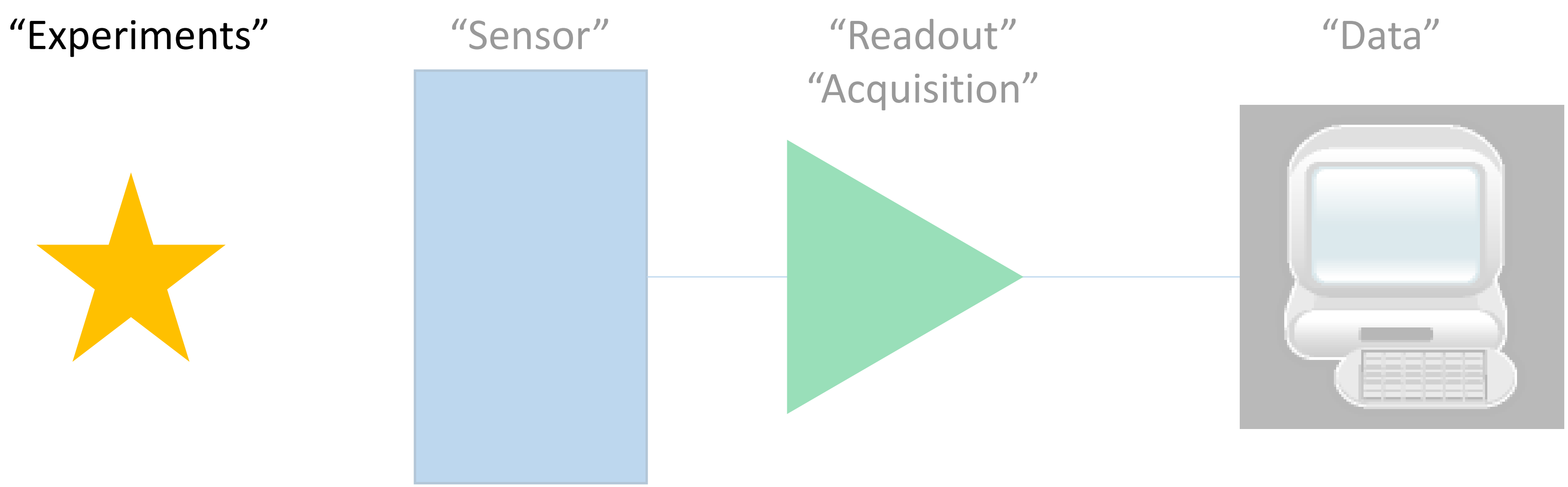
Conventional semiconductors
direct detection
Scintillators / Optical detection
X-ray to light
Nano-engineered materials
both

When will we ever learn?

Expertise in community
Devil is in details

"Photon" Breakout Session

E	S	R	D	Talk
	X	X		***8:30*** **am** **Mark Tate** (Cornell) *CdTe Sensors on Charge-Integrating Pixel Array Detectors for High-Speed X-ray Imaging*
	X			***8:45*** **am** **Ren-Yuan Zhu** (Caltech) *Fast Crystal Scintillators for Gigahertz Hard X-ray Imaging*
X				***9:00*** **am** **Richard Sandberg** (Los Alamos National Lab) *Revolutions in coherent X-ray sources and needs for detectors to enable mesoscale movies*
	X	X		***9:15*** **am** **Dominic Greiffenberg** (Paul Scherrer Institut) *High-Z sensors in combination with charge-integrating FEL detectors*
	X			***9:30*** **am** **Pamela Bowlan** (Los Alamos National Lab) *Extending ultrashort pulse measurement to the hard x-ray*
	X	X		***9:45*** **am** **Paul Seller** (Rutherford Appleton Lab) *High-Z detectors for hard X-ray imaging*
			X	***10:00*** **am** **Christine Sweeney** (Los Alamos National Lab) *Data Handling to Support Efficient and Effective Scientific Discovery at Future XFEL Experimental Facilities*
X				***10:15*** **am** **Robin Benedetti** (Lawrence Livermore National Lab) *Detector Needs for Time-Resolved X-Ray Diffraction at NIF*
	X			***11:00*** **am** **Abul Azad** (Los Alamos National Lab) *Sub-picosecond Optoelectronic Detection of X-rays*
		X		***11:15*** **am** **Angelo Dragone** (SLAC/Stanford Univ) *Concepts for Ultra-fast Multilayer Distributed Imaging Detectors*
				11:30 **am** **Ashley Jadwin** (Sydor Instruments) *Successfully Transitioning Technologies from National Laboratories to the Commercial Marketplace*
			X	**11:45** am **Ghaleb Abdulla** (LLNL) *Application of data mining techniques to exit surface damage growth on fused silica optics*

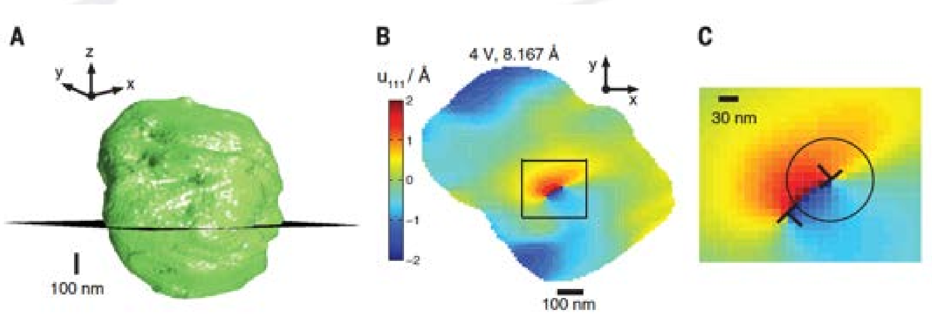


- QE vs. E
- Frame rate
  - Movie duration
- Dynamic range

  - Benedetti: At NIF, we are anxiously awaiting the same advances in high speed, high efficiency X-ray detectors and fast decay scintillators that are needed for MaRIE. (Caveats: slightly different needs, bigger hurry)

Revolutions in coherent X-ray sources and needs for detectors to enable mesoscale movies,

Richard Sandberg, LANL



Ulvestad et al. *Science* **348**, 1344–1347 (2015).

Coherent Diffraction Imaging is revolutionizing the way we can study materials at the nanometer and ultrafast time scale

Key Innovations Needed:

- Mega-pixel detector with ability to tile
- Single photon sensitivity at 42 keV
- High dynamic range (10^3-10^4 photons at 42 keV) per frame
- Smallest pixel possible (<50 microns)?
- GHz repetition rates

Expected Milestones and Timescales:

- Detectors are already a limitation for users (limited dynamic range, pixel size, etc)
- Some work arounds possible to increase dynamic range
- Need higher frame rates for up-coming sources soon (EuXFEL 2017 and LCLS-II 2020)

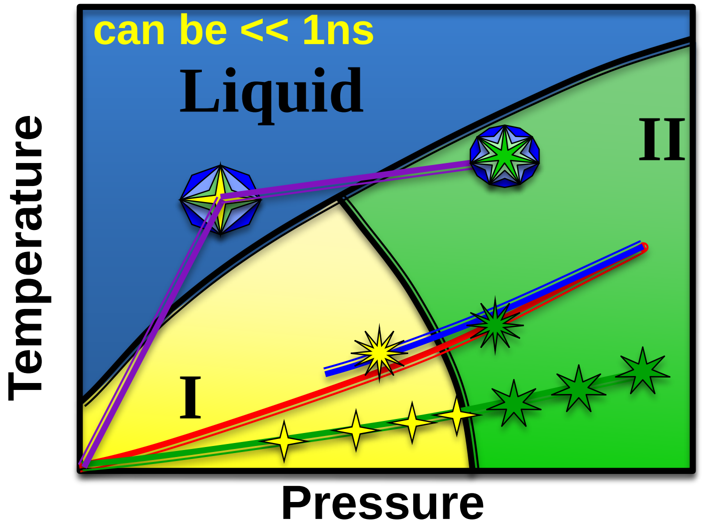
Existing Resources to be Leveraged:

- Field flatteners are possible to increase dynamic range
- ‘Compound’ detectors (PAD + Scintillator) may help in the interim
- Near field techniques can help

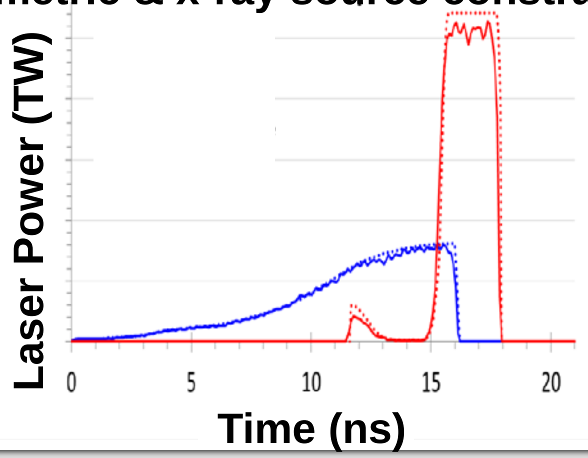
Detector Needs for Time-Resolved X-Ray Diffraction at NIF

L.R. Benedetti J. Eggert, J. R. Rygg, A. Cook, M. Emmons, D. K. Bradley, J. D. Kilkenny

Phase transition timescales



NIF experiments span tens of ns w/ geometric & x-ray source constraints



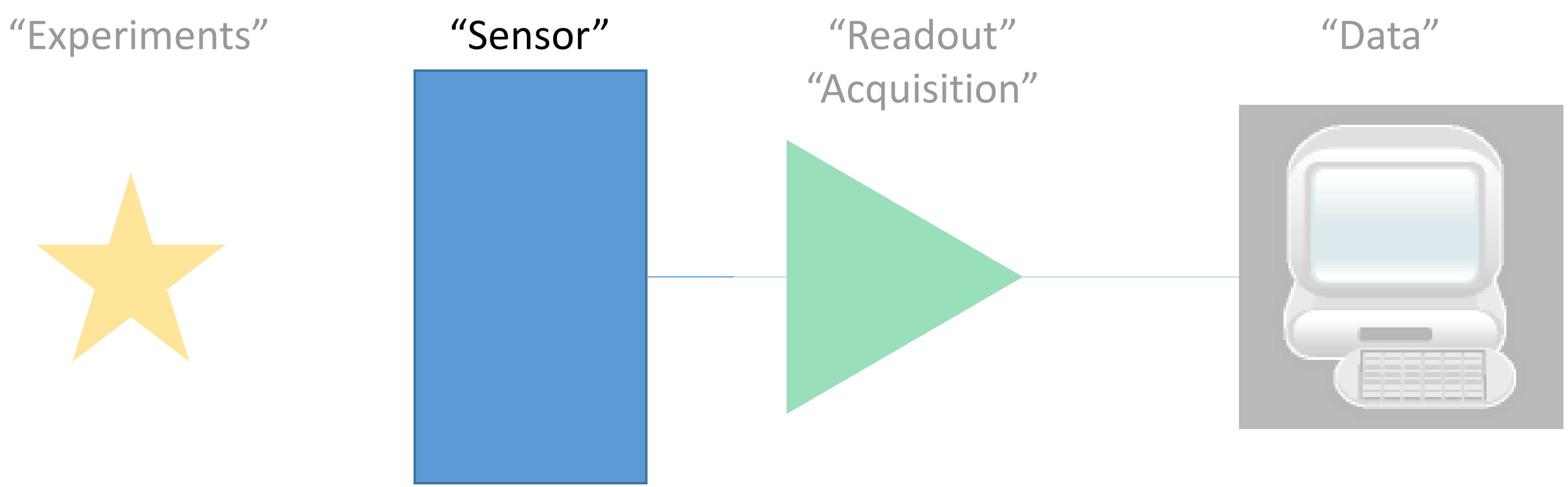
Physics requirements drive imaging detector needs

Concept	Parameter	Desired
Diffraction Quality	**2θ range**	Range 25° - 90°
	2θ resolution	1°
	ϕ range/resolution	Maximize
Diffraction Quantity	**Temporal resolution**	100 ps
	Temporal frequency	100 ps
	Temporal range	20 ns
Photo-metrics	**Energy sensitivity**	8-20 keV
	Photon Sensitivity	1% lines

Our ideal detector …

- **100 ps exposure**
- **Repeats as fast as 100 ps; For up to 10 ns**
- **Imaging area >~ 20 x 20 mm**
- **With QE 2% (or better, 40%!)**
- **For detector AND any relay system**

LLNL-PRES-699132 This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC



- (Conventional) Solid State (GaAs, CdTe, …)
    - Charge collection
    - Tate: GaAs likely successful for Type I detector, but need to study tranient charging which can impact time resolution
    - Greiffenberg: "We have to learn more about the charge distribution in high-Z sensors (in time and space) and how to deal with it to judge its applicability at XFELs."
    - Seller: Materials developments take longer than electronics
- Scintillators
- Non-linear optical techniques
    - Bowlan: Ultrafast phenomena can be measured with slow detectors using nonlinear optics as an instantaneous time-gate
    - Azad: Design, fabrication and characterization of opto-electronic coplanar transmission lines that may enable detection of sub-picosecond X-ray pulses.
- Nano-engineered materials

Development of GaAs:Cr pixel sensor prototypes with 500 and 1000 um active layer thickness

500 um thick GaAs: Cr pixel sensors will have X-ray absorption efficiency more then 50% for X-ray energy up to 50 KeV and 1000 um thick ones will have about 80% efficiency for 50 KeV X-ray energy.

Expected milestones and timescales

Up to the end of 2016

Design of GaAs: Cr pixel sensor prototype layout with pixel pitch within 100 -250 um;
Design and approval of technical specification of GaAs pixel sensor prototypes: dimension of the sensors, thickness, multilayer pixel contact metallization, backside metallization, sensor chip cutting, quantity of the sensors and i.e;
Producing of GaAs: Cr wafers;

Up to the end of Q I, 2017

Producing of GaAs: Cr pixel sensor prototypes with 500 um active layer thickness

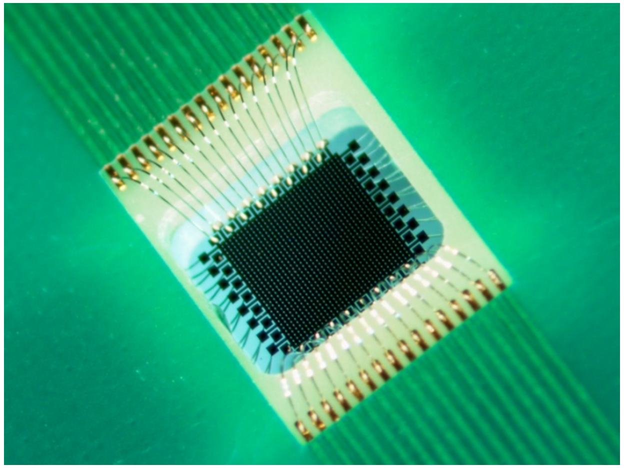
Up to the end of Q II, 2017

Producing of GaAs: Cr pixel sensor prototypes with 1000 um active layer thickness

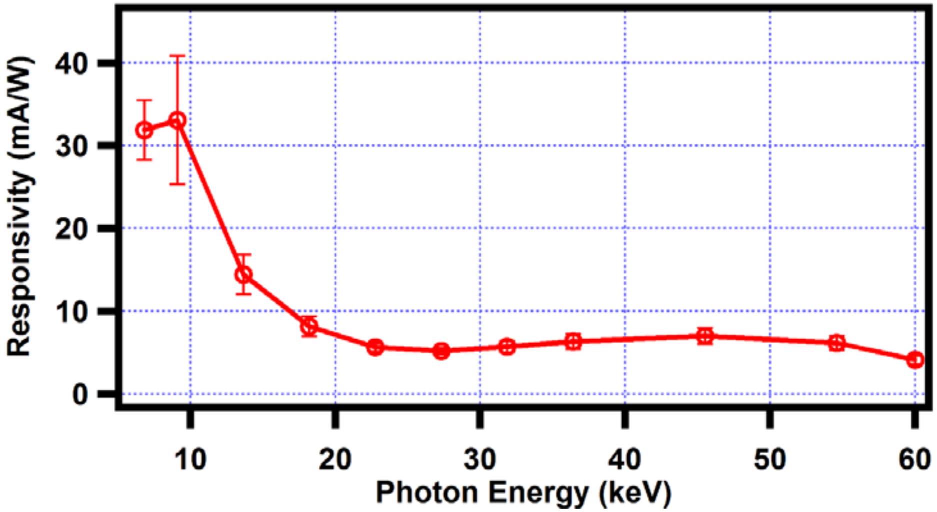
TSU will have to sign appropriate contract or MoU with LANL

Maybe Diamond?

- In Compton Regime, cross section is mostly independent of Z
- Diamond has higher carrier velocities than most other sensor materials – potentially faster response
- 60μm pixels already demonstrated
- Large dynamic range
- Existing beam position monitors and imaging detectors in development
- Commercial interest (Sydor Instruments)



1k Pixel detector with 60 μm pitch



Responsivity of a 0.5 mm thick diamond

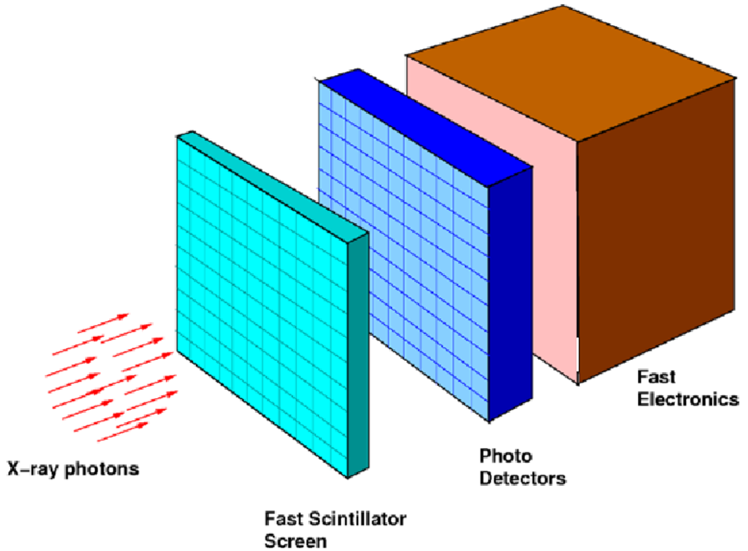
Conclusions

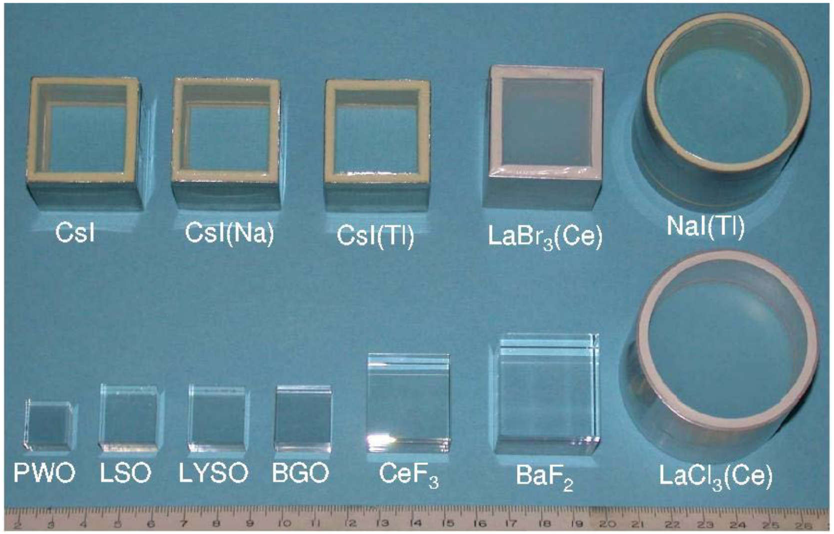
- **Fine pixel detectors certainly possible for fast hard X-ray spectroscopy.**
- **2mm of CdTe efficient for 120keV, GaAs:Cr good at 42keV, but possibly slow and need to look at radiation induced polarisation.**
- **Probably take 8 years and over 10M$ per imaging system.**
- **3DIC and TSVs will be useable for MaRIE detector time scales.**
- **Detector material development takes longer than electronic development.**

MaRIE

Fast Crystal Scintillators for GHz Hard X-ray Imaging

- Crystal scintillators with high light yield in the 1st ns, such as BaF_2, LYSO and $LaBr_3$ may provide fast scintillator based screens for GHz hard X-ray imaging.
- Wide-band semiconductor based scintillators featured with blight and fast light and self-absorption, such as ZnO, PbI_2 , GaAs/ InAs etc., may function as quantum dots in composite scintillators with tunable emission and no afterglow for fast scintillator screens.
- Require matching pixelized photodetector, e.g. SiPM or LAPPD, and fast electronics.
- Type I : BaF_2 based screens: 3 years.
- Type II: Wide-band semiconductor QD based scintillator screens: 5 years.





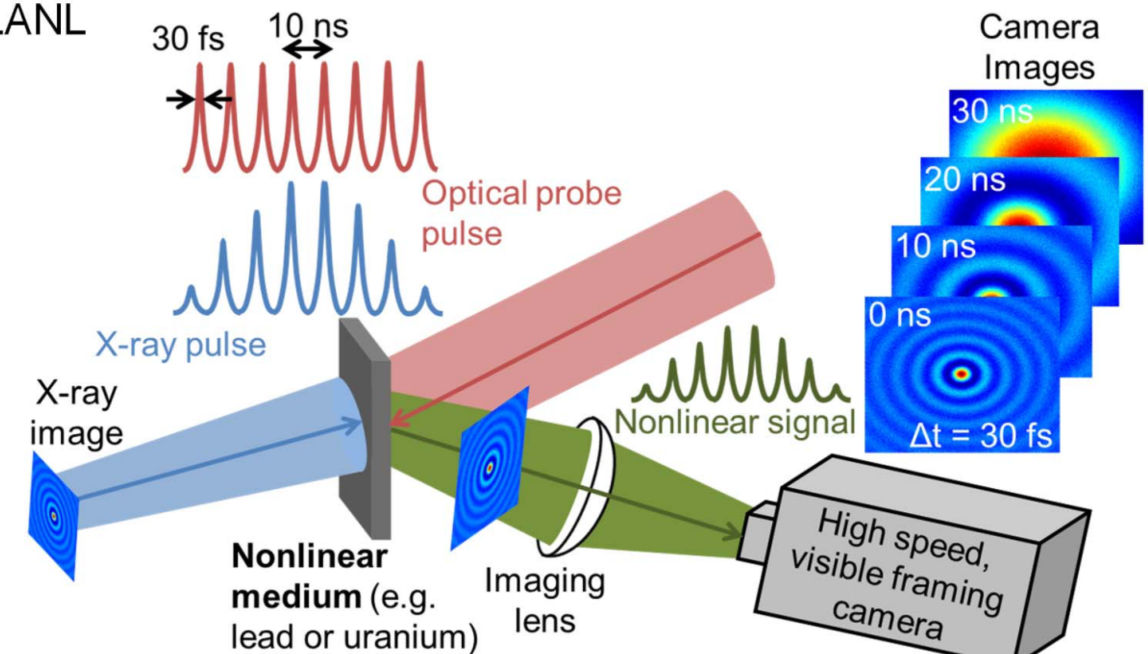
- Caltech HEP crystal lab worked on crystal development for HEP calorimeters, such as L3 BGO, BaBar CsI(Tl) and CMS PWO, and is working on Mu2e CsI as well as LYSO and BaF_2 crystals for future HEP experiments at the energy and intensity frontiers.
- Existing instruments and facilities for crystal characterization and radiation damage tests:
  - Edinburgh Instrument FLS spectrometer.
  - PerkinElmer L950 UV/Vis/NIR spectrophotometer.
  - Hitachi U3210 and F4500 spectrophotometers.
  - 20 GS digital scope and LeCroy QVTs.
  - Nano second OPO laser, excitation sources.
  - Co-60, Cs137 and Cf-252 source facilities.

Ren-Yuan Zhu, HEP Crystal Lab, Caltech, Pasadena CA 91125 (zhu@hep.Caltech.edu)

Encoding ultrafast X-ray images in a visible laser beam using a nonlinear optical interaction.

P. Bowlan[1,2], D. Yarotski[1], R. Prasankumar[1] and others
[1]MPA-CINT & [2]C-PCS, LANL

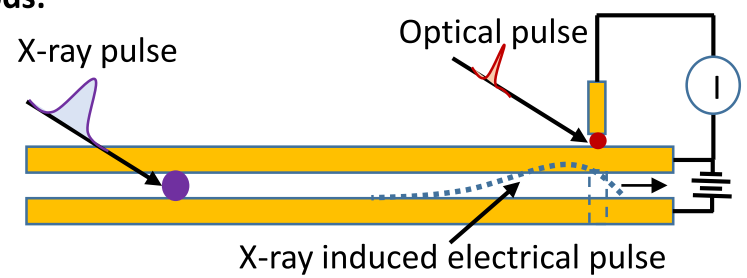
Similar ideas are being developed at the Linear Coherent Light Source (LCSL) at Stanford to characterize 1-10 KeV X-ray pulses. See: Hartmann et. al., Nat. Photon. **8**, (2014) and Bionta et. al., Rev. Sci. Instrum. **85**, (2014).



Since the development of sub-nanosecond laser pulses, nonlinear optics has served as a time-gate for measuring ultrafast phenomena with slow detectors. In the figure above, hard X-ray pulses ionize core electrons in a nonlinear medium, which, following electron-electron scattering (after ~30 fs) changes the reflectivity of an optical probe pulse. Spatially overlapping the two beams, a femtosecond time-slice (Δt) of the X-ray image is transferred to the optical beam which can then be measured with a visible camera. Using existing soft X-ray (up to 100 eV) femtosecond sources at CINT, and through collaboration with the laser group at LCLS, we can immediately begin testing this approach for ultrafast X-ray imaging. Also, with theoretical support from CINT scientists we can determine the best nonlinear medium, and optical probe pulse properties, to optimize the efficiency and speed of this process.

Sub-picosecond optoelectronic Detection of X-rays

Methods:



Schematic diagram of an optoelectronic x-ray detection system. The coplanar transmission lines is fabricated on a semiconductor substrate with ultrafast carrier life time. A DC voltage is applied between transmission lines. The incident x-ray photon will generate a transient electrical pulse, travelling along the lines, which will be detected using an optical sampling methods. The measured current in the sampling gap is a convoluted response of the x-ray pulse and the photo-carrier response time of the semiconductor substrate. The method has been applied to measured the photo-response of synchrotron x-ray with a pulse duration longer than few hundred picoseconds using GaAs substrate.

Appl. Phys. Lett. 102, 051109 (2013)

Innovations:

The temporal resolution of optoelectronic x-ray detector is currently few hundred picoseconds. To increase the temporal resolution it is important to fabricate the photo-conductive transmission lines on a semiconductor substrate that has very short carrier life time. We will identify the suitable materials using x-ray pump and optical probe, and optimize the design of the coplanar transmission line to enable optoelectronic x-ray detector with sub-picosecond temporal resolution.

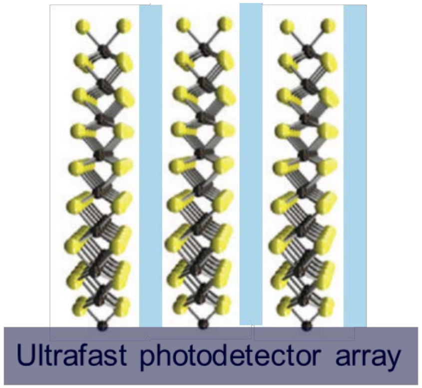
Milestones: (3 years)

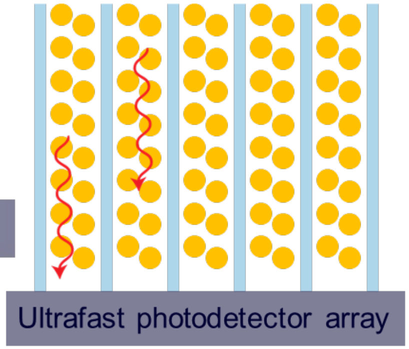
- Investigate the carrier lifetime using x-ray pump optical/terahertz probe (year 1 and year 2).
- Design optimization and fabrication of coplanar transmission line (year 2).
- Detection of x-ray pulses (year 3)

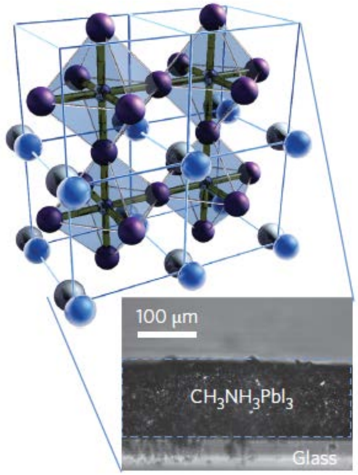
Existing resources:

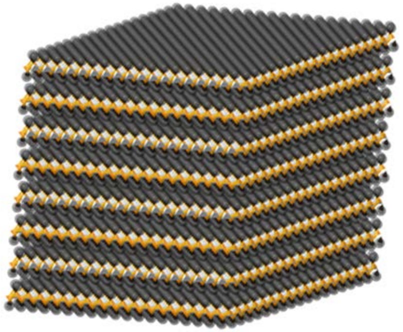
- Multiple ultrafast optical laboratories with pump/probe measurement systems, terahertz systems
- Cleanroom for microelectronic chip fabrication
- Collaboration with UD and UC Santa Barbara material science on ultrafast optoelectronic materials

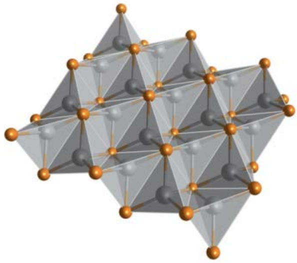
Relevant recent advances in nanomaterials and their growth/synthesis

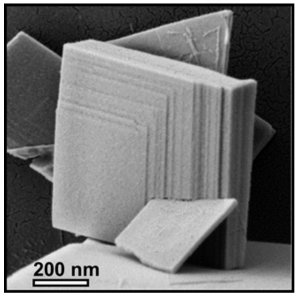












Summary of key innovations

- Recent advances in nanomaterials potentially enable scintillators for Type I and Type II imagers
  - van der Waals 2D semiconductors, novel bulk layered 2D semiconductors, lead-halide perovskites, and metallic nanoantenna arrays all offer exciting properties
- Novel growth and solution-based synthesis approaches enable large area, conformable, thick materials
- Perovskite proof of principle demonstrated; probably best for Type I
- 2D semiconductors are bright, fast, high-z, spectrally matched to photodetectors; possible Type II

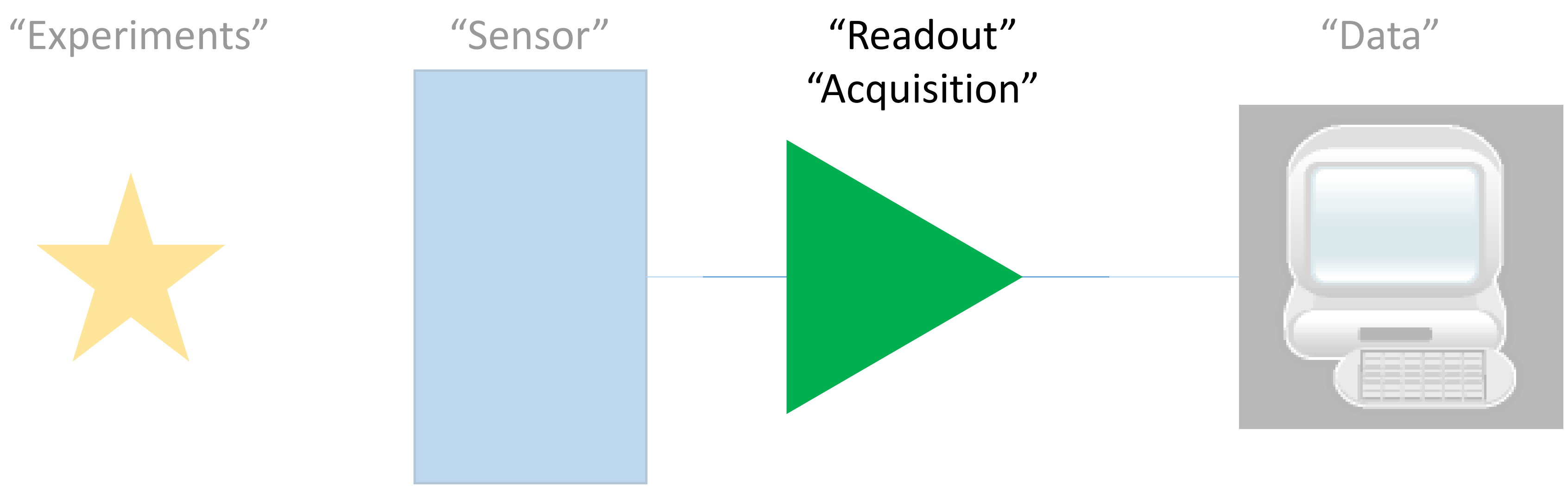
Expected Milestones and timescales

- Demonstration of 2D semiconductors for x-ray detection, establish stability; 1-2 years
- If successful, develop ultrafast prototype to determine readout speed limits; depends on UF photodetector; establish thickness requirements, optimal material composition, and coupling to detector; 5years?

Existing resources that can be leveraged

- Molecular Foundry (and other nanocenters?) for material development; strong ongoing 2D materials program
- LBNL engineering fast CCD detector development; Denes and others

MOLECULAR FOUNDRY



- Existing expertise in several groups
- Type I detector "plausible"
  - 2 ns interframe time
  - Particularly on needed timescale
- Dragone: Different applications might require different detectors and we might have to play tradeoffs between specs, in particular between frame rate and dynamic range. What would be possible ranges of specs and priorities for different experiments?
- Jadwin: Sydor is currently positioned to help transition new detector technology from prototype to robust engineered detectors that can be supported outside the national lab environment and is actively seeking new opportunities for collaboration.

PAUL SCHERRER INSTITUT

Summary slide

Our goals:

- **Investigation** of the **usability of high-Z sensors on our low noise, charge-integrating ASICs (GOTTHARD, JUNGFRAU, MÖNCH)**, which would **enhance the absorption efficiency** at photon energies above 20 keV and would also **reduce the radiation damage of the ASIC**

Research interest:

- Investigate/understand **the distribution of charge in time and space**

Status/Outlook:

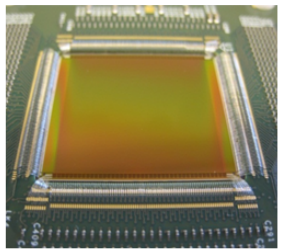
- Sensor Materials:
  CdTe, CdZnTe, GaAs
- Test systems available:
  JUNGFRAU/CdTe (1 mm, ACRORAD)
  GOTTHARD/GaAs (500 µm, TSU)
- Test systems **in preparation (<1 year)**:
  JUNGFRAU/CdTe (1 mm)
  JUNGFRAU/GaAs (500 µm, TSU)
  MÖNCH/GaAs (50x50 µm^2, 500 µm)
- Measurements at **synchrotrons (SLS, ESRF)** and **XFELs (SwissFEL)**

	JUNGFRAU	MÖNCH
Technology	UMC 110 nm	UMC 110 nm
Status	Modules available	(Advanced) Prototyping
Pixel size	**75 x 75 µm^2**	**25 x 25 µm^2**
Maximum system size	16Mpixel (=32 Modules)	Single Chips (=2x3 cm^2)
Noise (r.m.s.)	**<100 e$^-$ ENC <55 e$^-$ ENC (HG)**	**<35 e$^-$ ENC**
Dynamic range	**<1·10^4 x 12.4 keV (3 gain stages)**	<500 x 12.4 keV (2 gain stages)
Maximum frame rate	**2.4 kHz (cont.) <1 MHz (burst/16 frames)**	**6-8 kHz (continuous)**

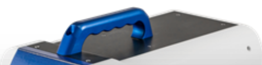
A 5Mfps 180 sample X-ray Camera

STFC Fast Frame Rate Sensor

- Today second generation 5MHz 0.7Mpixel RAL sensor exists:
  - 30 µm pixel
  - Combined high and ultra-high speed operation
  - Burst mode at 5Mfps with 180 memory cells approx. 3.5 Tera-pixel/sec
  - Continuous mode at over 1kfps
  - 10 bit system dynamic range
  - Ethernet based DAQ system with full analogue chain available to buy



RAL Sensor on Kirana Headboard

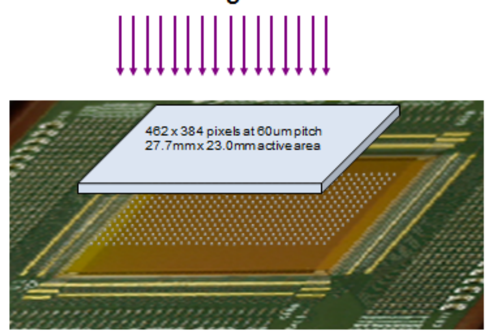


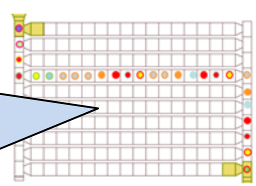
- Today we have an STFC 5MHz visible CMOS sensor with 30um pixel pitch
- Commercially available to buy as a complete system
- Hybrid version with GaAs (Tomsk) is in design for direct detection of X-rays at 5Mfps

For Xray FEL Use GaAs for direct detection

- Use 0.5mm GaAs:Cr material for XFEL use
- Bump bond to customized CMOS ASIC array
- Use fill-spill mechanism to load data to in-chip memory
- In chip frame buffer stores at 5MHz

X ray image





The 2D storage array allows flexible sampling and reset modes with veto/trigger options within each pixel

An in pixel CCD stores 170 samples within the 30um pixel of the current sensor. The X-ray device will use 'Fill Spill' to exploit the same CCD image storage capability

SLAC FEL and HEP Expertise in Support of MaRIE

Proposed Detector Concepts:

- Photons
  - Next-generation, ultra-fast, photon counting in a distributed geometry (ePix-Flash)
  - Ultra-fast analog signal storage in distributed geometry or single layer (ePix-Delta)
  - Above coupled with fast, high QE low-risk sensors and novel interconnects or GaAs / CdTe
- Electrons
  - Hybrid single-plane electron trajectory
  - Adapt LHC CMOS sensors for MaRIE

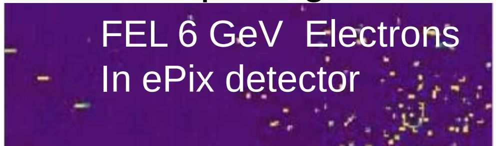
Possible MaRIE Milestones: *

- 2018 Prototype ePix-Flash v0.5
- 2018 Prototype sensors for ePix-Flash
- 2018 Prototype ePix- Delta v 0.5
- 2018 Advanced sensor & interconnects prototypes for ePix-Delta
- 2019 prototype ePix-Flash modules
- 2019 prototype ePix-Delta modules
- 2019 Prototype CMOS imager v0.5
- 2019 DAQ architecture
- 2019 Prototype 42 keV optic elements

* Dependent on funding

Critical Advances:

- Grow ePix-Flash from existing fast CPIx2
- Grow ePix-Delta from Tixel and Kpix
- Advanced sensor developments for LCLS
- Advanced interconnects for LCLS and neuroscience
- LHC (and SSC) CMOS sensor designs and expertise with 25 ns bunch spacing



Resources:

- Large, experienced FEL detector team
  - FEL DAQ team
  - FEL IC design team
  - Advanced sensor and interconnect team
  - TES Quantum sensor team
    - SLAC sensor fab cleanroom
    - Stanford campus fabs
- X-ray optics team
  - X-ray optics ebeam litho fab
- Detector test & assembly cleanroom
- LSST camera cleanroom, Fermi cleanroom, etc.
- FEL electron beam for eRAD development

SLAC Multilayer Distributed Imaging X-ray Detectors for MaRIE

TID-AIR SLAC

Proposed Photon Detector Concepts:

ePixF: Next-generation, ultra-fast, photon counting in a distributed geometry

- Fast synchronous processing
- Multi-threshold discrimination
- Multi-bunch digital storage in pixel

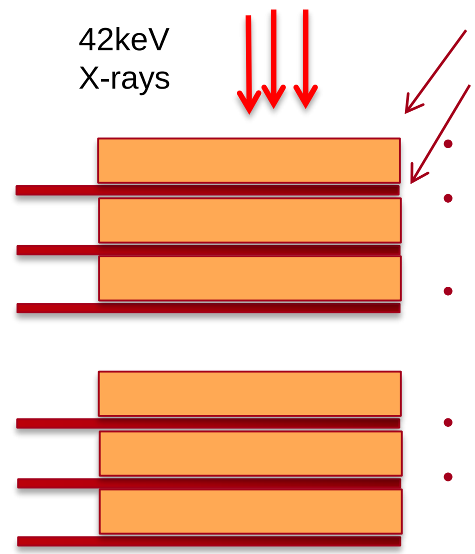
Potential candidate in Turbulence Material Mixing experiments

ePixΔ: Ultra-fast analog signal storage in a distributed geometry

- Ultra-fast signal processing
- Gigahertz burst sampling
- Multi-bunch analog storage in pixel

Potential candidate in Metal Manufacture and Age Aware Performance / HE cert. and qual. experiments

Multilayer Distributed Imaging Approach



Si Sensor ~100µm

ASIC < 50µm

- Thin sensor-IC modules
- Each layer absorbs a few x-rays
- Image distributed across layers and reconstructed in post processing
- Good system-level QE
- Advanced Interconnection and Advanced packaging

Existing Resources and Critical Advances:

- Readout concepts already proposed for LCLS
- Readout concepts re-use the ePix platform and combine features developed in other designs within the family (ePixF is an extension of cPix2, ePixΔ combines tPix and kPix)
- Advanced sensor developments for LCLS (fast, thin)
- Large, experienced FEL detector team (Sensors, ASICs, Interconnections, DAQ)
- Detector test & assembly cleanrooms

Possible MaRIE Milestones: *

- 2018 Prototype (32x32) ePixF
- 2018 Prototype sensors for ePixF
- 2018 Prototype (32x32) ePixΔ
- 2018 Advanced sensor & interconnects prototypes for ePixΔ
- 2019 prototype ePixF modules
- 2019 prototype ePixΔ modules

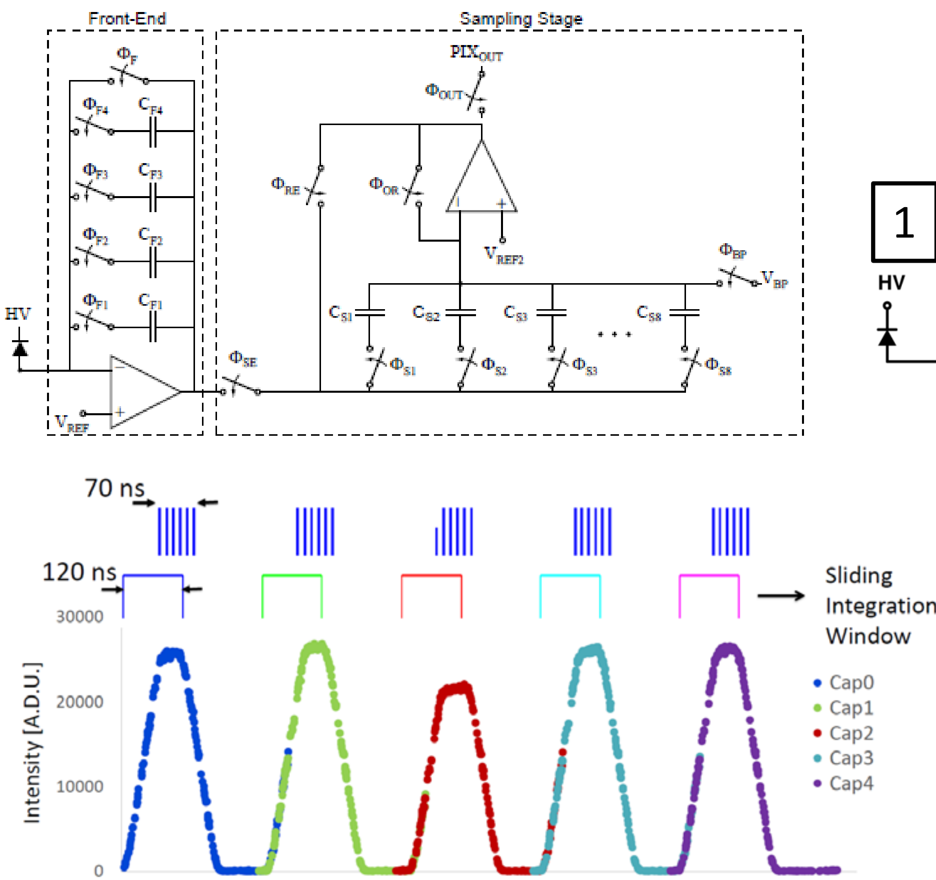
* Dependent on funding

Summary: Designs for Pixel Array Detectors for XFEL and Fast-Bunch Imaging

Katherine Shanks – Cornell University

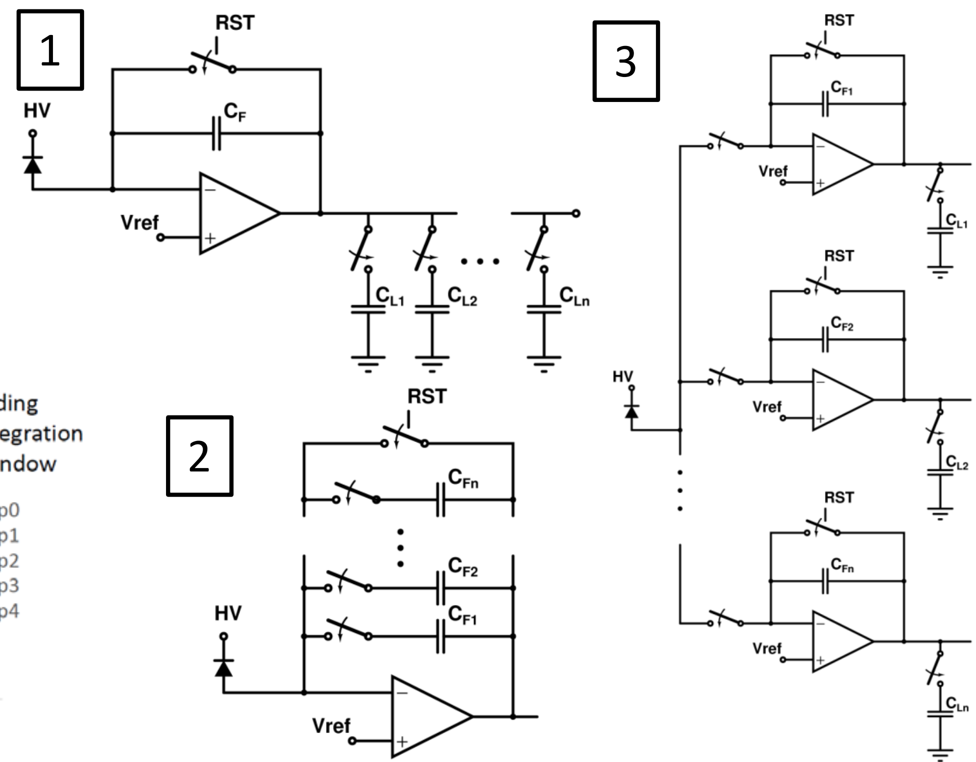
Present Keck PAD: 10 MHz burst imaging

- Sensor: 500 µm Si, 750 µm CdTe
  - GaAs effort has begun
- Excellent performance @ 10 MHz

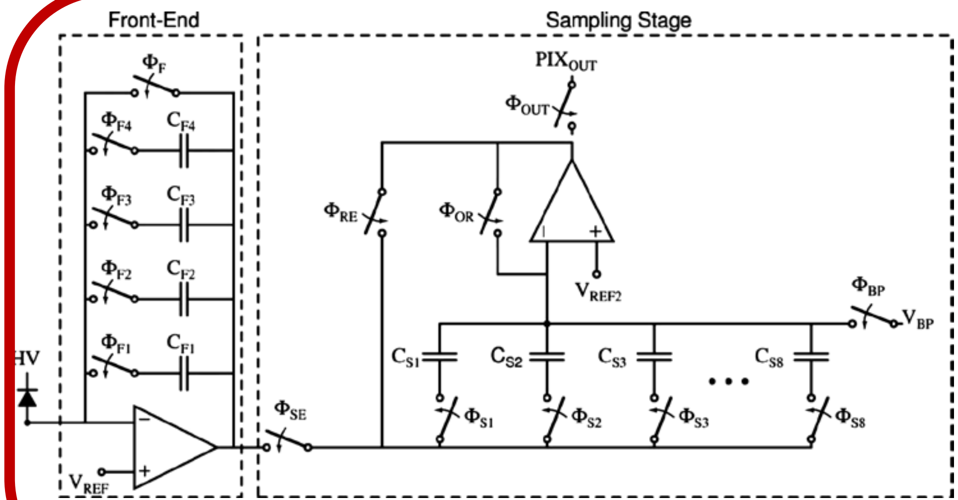


Suggested modifications for use @ MaRIE

- 100 – 300 µm GaAs sensor: few ns signal collection @ reasonable reverse bias
- Re-design pixel for ~500 MHz operation:
  - Explore options for frame storage (1-3)
  - Redesign front-end amp
  - ~3-5 years to prototype



Potential MaRIE detector using 300 μm thick GaAs



Keck-PAD pixel – in-pixel burst mode storage

Existing or in development:

Cornell Keck-PAD detector

Designed for MHz imaging

- 8 frame/pix internal storage
  - 27 frame storage version in works
- 500 μm Si or 750 μm CdTe sensors
  - GaAs version begun

Proposed:

Keck-PAD w/ 300 μm GaAs

Extend Keck architecture to 500MHz

GaAs: max e- drift velocity 200 μm/ns

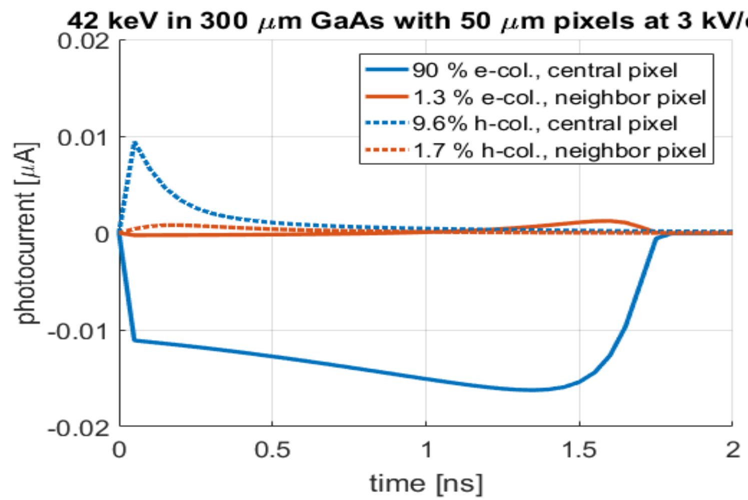
GaAs: absorption @ 300 μm

30keV – 0.88

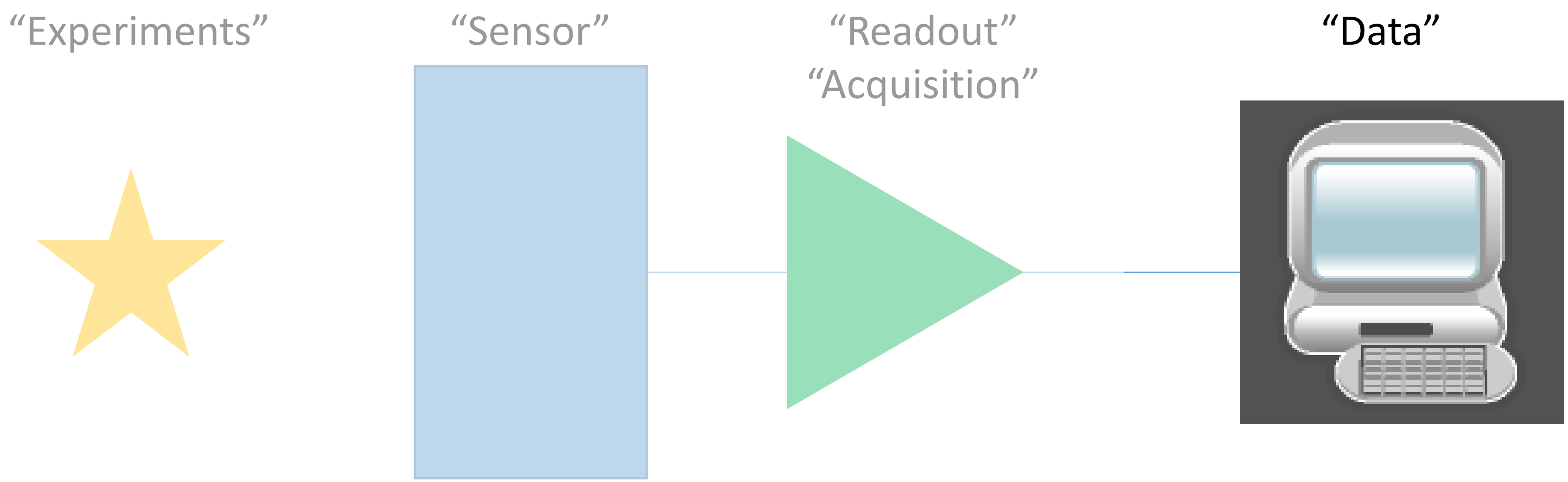
42keV – 0.56

126keV – 0.05

Sensor material available now!



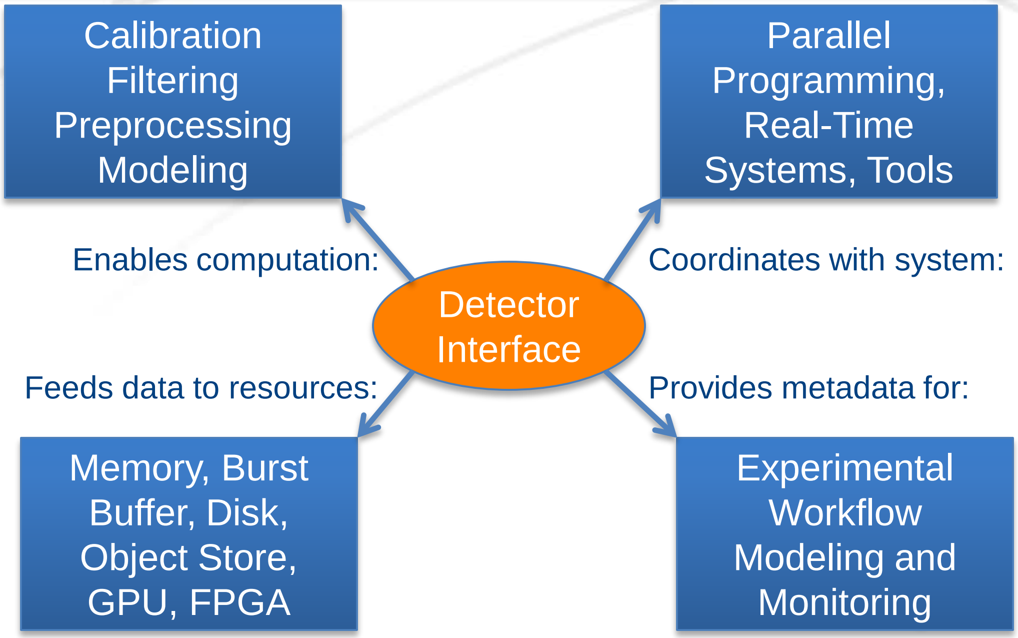
Simulated charge collection pulse



- Not specifically a focus of this workshop
  - As detectors and rates get more complicated, more advantage to considering downstream data path from detector, and interactions of detector properties

  - Abdullah: What are your most important computation and data challenges that you would like to solve to enable your science.

From Detector to Discovery:
Data Handling to Support Efficient and Effective Scientific Discovery at Future XFEL Experimental Facilities, Christine Sweeney, LANL



Key Innovations Needed:

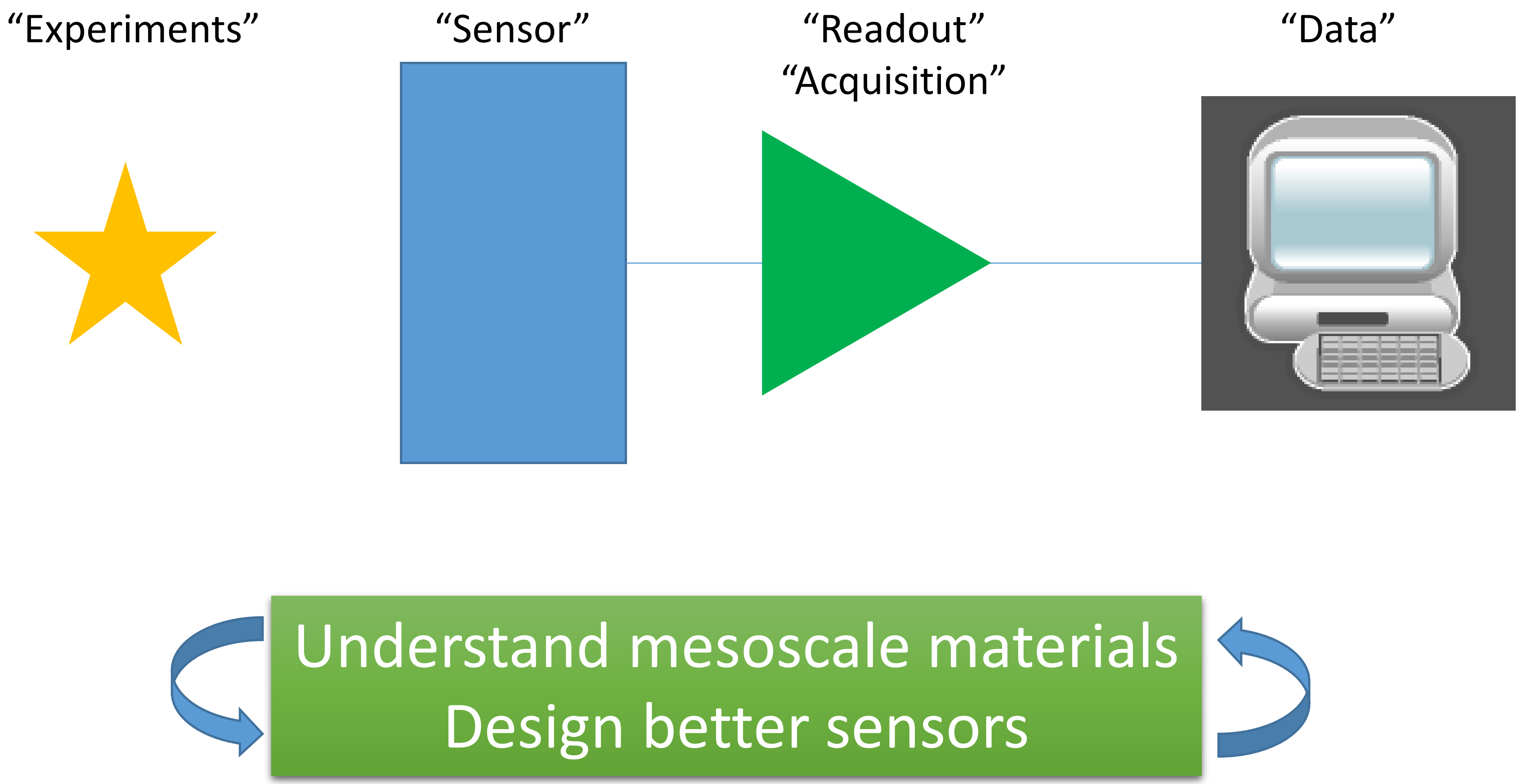
- Flexible detector interface and software frameworks
- Detector integrated with powerful parallel programming, systems, tools
- Detector connected to novel computing hardware and storage
- Better insight into experimental workflows that include detectors

Existing Resources to be Leveraged:

- Experience with current experiments and workflow research
- Parallel programming research
- LANL expertise in burst buffer, GPU, FPGA and storage
- LDRD DR “Real-Time Adaptive Acceleration of Dynamic Experimental Science” starting in FY17

Expected Milestones and Timescales:

- Start software design and development now so ready when facilities are ready. It will take several years.
- Settle on detector knobs that we want to be able to turn fairly early.   These will determine software interfaces and connections to computing resources.


“Experiments”
“Sensor”
“Readout”
“Acquisition”
“Data”
Understand mesoscale materials
Design better sensors