Ultrafast Imaging and Tracking Instrumentation, Methods and Applications Conference (ULITIMA 2022)

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Book of Abstracts

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Beyond the temporal resolution limit of silicon image sensors

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The temporal resolution limit of silicon image sensors is 11.1 ps as we proved. We defined the super temporal resolution (STR) as the resolution less than this limit, since most image sensors are silicon-based [1]. To achieve the STR, mixing effects along the travel route of signal electrons in a pixel, elongating the temporal resolution, are separately analyzed and the countermeasures are proposed. A branching gate image sensor is proposed with a resistive gate for the center guide gate [2]. It is verified by simulations that the proposed sensor structure can achieve theoretically noiseless imaging at the temporal resolution of 100 ps with an existing 120-nm process. A finer process with a germanium photodiode, in addition, will achieve the STR (<11.1 ps) in the near future [3].
[1] T. G. Etoh., "Toward Super Temporal Resolution by Suppression of Mixing Effects of Electrons", https://imagesensors.org/Past%20Workshops/2021%20Workshop/2021%20Papers/R34.pdf, submitted to IEEE T-ED.
[2] N. Ngo et al., "A Pixel Design of a Branching Ultra-Highspeed Image Sensor", Sensors, 21(7) (2021) (IF:3.6). DOI: 10.3390/s21072506
[3] N. Ngo et al., "Toward the Super Temporal Resolution Image Sensor with a Germanium Photodiode for Visible Light", Sensors, 20(23) (2020) (IF: 3.6). DOI: 10.3390/s20236895

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Effect of nozzle geometry features on the nozzle internal flow and cavitation characteristics based on X-ray dynamic imaging

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Nozzle geometry features directly impact the nozzle internal flow which significantly affects the spray atomization, as well as in-cylinder combustion and fuel economy. In this study, the nozzle internal transient flow was visualized through X-ray phase-contrast imaging technology. The experimental results indicated that the sac-orifice relative positions and the structural asymmetry of the nozzle orifice prominently influence the in-nozzle cavitation strength and distribution. Some nozzle geometry features with general applicability such as inlet normal inclination angle, orifice inlet included angle and orifice conicity angle are defined to better elaborate their effects on the internal flow characteristics. A 3D simulation of the nozzle internal flow demonstrated the relevance between the nozzle geometry and the cavitation characteristics. It is found that the cavitation phenomenon is intensified when the wall inclination angle is positive and will be inhibited when it is negative. The cavitation development is facilitated with smaller orifice inlet included angle. The nozzle orifice conicity, which obviously alters the pressure distribution in the orifice, also has a significant influence on the cavitation characteristics.

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10ps Time-of-Flight PET scanner with a new generation of SiPMs: From Hope to Practice

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The potential of photon detectors to achieve precise timing information is of increasing importance in many domains, e.g. PET and CT scanners in medical imaging and particle physics detectors. The goal to increase by an order of magnitude the sensitivity of PET scanners and to deliver, via time-of-flight (TOF), true space points for each event, requires a further quantum step in time resolution, reaching eventually 10ps in coincidence (CTR) @511keV to be compared to about 200ps obtained with state-of-the-art silicon photomultipliers (SiPM) in the Siemens Biograph Vision PET scanner. The interest is to reduce the radiation dose (currently 5-25 mSv for whole body PET/CT), scan time (currently > 10 minutes), and costs per patient (currently > 1000 € per scan), all by an order of magnitude. To achieve this very ambitious goal it is essential to significantly improve the performance of each component of the detection chain: light production, light transport, photodetection, readout electronics.
Such a 'paradigm' shift must go hand-in-hand with a similar break with traditional methods.
The possibility to reach 10 ps time-of-flight resolution at small energies, as required in PET scanners, although extremely challenging, is not limited by physical barriers.
This talk will show how combining transformation optics light concentrators, hyperbolic metamaterial QE increase, ultra-fast, backside illuminated silicon cell and ultrafast electronics directly integrated in the device will offer new perspectives for the development of new concepts of 3D digital SiPM structures and open the way to new radiation detector concepts with unprecedented performance.
The ultimate goal will be creating a Quantum Silicon Detector (QSD), with close to 100% PDE even with non-collimated light, a few ps Single Photon Time Resolution (SPTR), ultra-high cell density, negligible correlated noise and beyond state-of-the-art primary noise, opening new prospects for the construction of very compact, low power and ultrafast photodetectors with space-time imaging capability.

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An Askaryan effect Calorimeter for the FCC-hh

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Dielectric-loaded waveguide detectors that measure microwave Cherenkov signals can be used to time and characterize high energy particle showers. Beam test results have been used to validate models and produce high-fidelity simulations of timing plane systems which yield picosecond time tags and millimeter spatial coordinates for shower centroids. These timing planes, based on the Askaryan effect in solid dielectrics, are most effective at the high center-of-momentum energies planned for the Future Circular Collider (FCC-hh), and are of particular interest in the forward region due to their high radiation immunity. Beam test results and GEANT4 simulations are used to validate a hybrid microwave detector model, which explores a reference timing plane design for an FCC forward calorimeter. Our results indicate that 0.5-3 ps particle timing is possible for a wide range of collision products in the reference FCC hadron collider detector, even with current technologies.

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TIMEPIX in 65nm, further exploring the sub-ps timing regime.

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We update our sub-picosecond timing studies[1,2], which used a straw-man pixel detector (TIMEMPIX) in which timing information was used to substitute for micron spatial resolution, significantly reducing channel count and data volume. That study considered the 130nm CMOS technology node and we update and contrast the performance and power parameters in the 65nm CMOS technology node.

1. P. Orel, P. Niknejadi, G.S. Varner, "Exploratory study of a novel low occupancy vertex detector architecture based on high precision timing for high luminosity particle colliders," Nucl. Instr. Meth. A857 (2017) 31-41.

2. P. Orel, G.S. Varner, "Femtosecond Resolution Timing in Multi-GS/s Waveform Digitizing ASICs," IEEE Trans. Nucl. Sci. 64 (2017) 1950 - 1962.

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A picosecond avalanche detector in SiGe BiCMOS

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The MONOLITH ERC Advanced project aims at producing a monolithic silicon pixel ASIC with picosecond-level time stamping by using fast SiGe BiCMOS electronics and a novel sensor concept, the Picosecond Avalanche Detector (PicoAD).
The PicoAD uses a multi-PN junction to engineer the electric field and produce a continuous gain layer deep in the sensor volume, generating a thin absorption layer that limits the impact of charge collection noise on the timing performance. The result is an ultra-fast current signal with low intrinsic jitter in a full fill factor highly granular monolithic detector.
In addition to that, the manufacturing process of the PicoAD makes it extremely versatile to enhance the timing capability of existing sensor designs.
A proof-of-concept ASIC prototype not yet optimized for timing confirms that the PicoAD principle works according to simulations. Testbeam measurements show that the prototype is fully efficient and achieves time resolutions down to 24ps.
An optimization of the sensor design and the development of new fast, low-power electronic are the next steps to achieve the picosecond time resolution target.

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Integration and first operation of the Gotthard-II detector at the European XFEL

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Gotthard-II (G-II) is a silicon microstrip hybrid detector developed by Paul Scherrer Institut (PSI) within the framework of a collaboration agreement with the European XFEL (EuXFEL).

The G-II ASIC features a dynamic gain switching (DGS) architecture to cope with the requirements of the single photon sensitivity as well as the large dynamic range at the EuXFEL. In addition, it includes a 12-bit Analog-to-Digital Converter with a sampling/conversion rate of more than 18 MS/s, and a Static Random-Access Memory1 with a depth of 2700 images for temporal on-chip storage in order to match the unique accelerator pulse structure: up to 2700 pulses at 4.5 MHz within one EuXFEL pulse train are generated in a burst2.
Two different sensor designs, with a strip pitch of either 50 μm or 25 μm for a total of 1280 or 2560 output channels, are used in the final detector system. These sensors are able to provide a spectral sensitivity allowing either X-ray detection (optimized in the 5 keV – 20 keV range) or visible light detection.

Its exceptionally good compliance with the EuXFEL beam conditions will make G-II the most widely employed detector across the facility with a total of 29 modules of different flavors installed in several scientific instruments and beam diagnostic setups.

Its usage predominantly in spectroscopic measurement will have a variety of applications, including diffraction/emission/absorption measurements, pulse arrival monitoring (of fundamental importance for pump-and-probe experiments), and beam quality monitoring with the possibility for the detector to generate a veto pattern for the large area pixel detectors such as AGIPD, LPD and DSSC.

In this paper, an overview of this detector technology and its usage at the EuXFEL will be presented; then, detector integration in the EuXFEL control, data acquisition and data correction infrastructure will be described, highlighting its challenges. Finally, an overview of the first results obtained with the EuXFEL beam will be given.

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Move contrast X-ray imaging and its applications in complex systems

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A complex system is usually reflected in several aspects, such as multiple chemical components, entangled spatial structure, aeolotropic relative motion between components, chemical reactions, etc. Extracting the spatial-temporal evolution process of the target component in such a complex system puts forward higher requirements on the spatial resolution, temporal resolution, imaging depth and the invasiveness of the system.
For dynamic complex systems with relative motion between components, a method called move contrast X-ray imaging (MCXI) is introduced, which utilized the different temporal modulation of the incident light field by different moving components to separately image components with different motion modes. Compared with the usual X-ray absorption contrast and phase contrast, move contrast can solve the problem of overlapping of structural information in transmission image caused by high X-ray penetration, and has higher sensitivity and contrast-to-noise ratio for weak signals.
MCXI has been applied in several disparate research fields. In medical radiography, MCXI can reduce the dose of iodic contrast medium to only 10%, while maintaining sufficient signal strength (F.X.

Wang et. el., IUCrJ (2020). 7). In the aspect of plant physiology, MCXI can be used to observe water refilling along microvessels in leaves and thick opaque plant stems resorting to no contrast agents. In electrolytic reactions, transport routes of clustered ions can be depicted with MCXI, which may provide significant support for further electric field research.
In conclusion, owing to the character of high sensitivity and contrast-to-noise ratio for weak signals, MCXI is a promising imaging method in dynamic complex systems of many research fields, where in-vivo and in-operando experiments are in urgent need.

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XIDer: a Novel X-ray Detector for Next-Generation High-Energy Synchrotron Radiation Sources

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The ESRF Extremely Brilliant Source (EBS) is the world's first fourth generation
synchrotron radiation source. Latest generation x-ray sources like the EBS impose increasing demands on sensors and readout electronics. Apart from fast signal processing and high spatial resolution, detectors used at such facilities have to handle a broad dynamic range with fluxes of up to billions of photons per second while still providing single photon sensitivity at low noise levels. Additionally, the targeted high energy range forces detector systems to use less conventional high-Z sensor materials which usually come with additional challenges. As a result, effects like afterglow, sensor leakage and bias- as well as flux-induced leakage have to be handled and corrected for.

The XIDer project aims to build a 2D pixelated hybrid X-ray detector to tackle the aforementioned challenges. It incorporates a novel digital integration readout scheme to combine the high-rate capabilities of charge integration with the noise and leakage suppression of photon counting systems. The final detector is planned to cope with the conditions imposed by the EBS such as fluxes of up to 10^9 ph/px/s, photon energies of up to 100 keV as well as different beam modes ranging from pulsed to near-continuous illumination.

This contribution is meant to introduce the XIDer project, its challenges and the progress that has been made so far. This will be supported by the presentation of first characterisation measurements of the readout ASIC as well as test prototypes equipped with cadmium telluride sensors.

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Photon and minimum ionizing particle detection with ultra fast Geiger mode APDs

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Major advances in silicon pixel detectors, with outstanding timing performance, have recently attracted significant attention in the community. In this work, we present and discuss the use of state-of-the-art Geiger-mode APDs, also known as single-photon avalanche diodes (SPADs), for the

detection of minimum ionizing particles (MIPs) and optical photons with best-in-class timing resolution. The SPADs were implemented in standard CMOS technology and integrated with on-chip quenching and recharge circuitry. By using a femtosecond laser a SPAD in coincidence with a fast photodiode showed a timing resolution of 12 ps FWHM. For the MIPs two SPADs in coincidence allowed to measure the time-of-flight of 180 GeV/c momentum pions with a coincidence time resolution of 22 ps FWHM (9.4 ps Gaussian sigma). This measurement paves the road to a new generation of low-cost beam trackers with extremely high timing and spatial resolution. Radiation hardness measurements are also presented here, highlighting the suitability of this family of devices for a wide range of high-energy physics (HEP) applications.

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Charged-particle tracking with 10ps time resolution using innovative 3D trench-type silicon pixel sensors

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Future collider experiments operating at very high instantaneous luminosity will greatly benefit in using detectors with excellent time resolution to facilitate event reconstruction. For the LHCb Upgrade2, when the experiment will operate at 1.5x1034/cm/s, 2000 tracks from 40 pp interactions will cross the vertex detector (VELO) at each bunch crossing. To properly reconstruct primary vertices and b-hadron decay vertices VELO hit time stamping with 50ps accuracy is required. To achieve this, several technologies are under study and one of the most promising today id the 3D trench silicon pixel, developed by the INFN TimeSPOT collaboration. These 55μmx55μm pixels are built on a 150μm-thick silicon and consist of a 40μm-long planar junction located between two continuous bias junctions, providing charge-carriers drift paths of about 20μm and signals' total durations close to 300ps. Two sensors' batches were produced by FBK in 2019 and 2021. The most recent sensors' beam test was performed at SPS/H8 in 2021. Various test structures were readout by means of low-noise custom electronics boards featuring a two-stage transimpedance amplifier, and the output signals were acquired with an 8GHz 20GS/s oscilloscope. The arrival time of each particle was measured with an accuracy close to 5ps using two 5.5mm-thick quartz window MCP-PMTs. Two 3D trench silicon pixel test structures and the two MCP-PMTs were aligned on the beam line and acquired in coincidence. Signal waveforms were analyzed offline with software algorithms and pixel signal amplitudes, particle time of arrival and efficiencies were measured. A preliminary analysis indicates efficiencies close to 100% for particles impinging at more than 10 degrees with respect to normal incidence, and time resolutions close to 10ps. More up-to-date results, including preliminary measurements on sensors irradiated with neutrons, will be presented at the Conference. 3D trench-type silicon pixels appear to be a promising technology matching the requirements of future vertex detectors operating at very high instantaneous luminosity.

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Induced signals in particle detectors with resistive elements: modelling novel structures.

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Novel detector structures are proposed regularly, mixing old and new ideas, with resistive detectors widening the landscape of possible configurations. In this talk, a universal way of calculating the signals induced in structures with resistive elements is presented. This is done by applying an extended form of the Ramo-Shockley theorem to several different detector configurations using numerical methods. For these, the time dependence of the signals is not solely given by the movement of the charges in the drift medium but also by the time-dependent reaction of the resistive materials. The weighting potential becomes dynamical for these geometries due to the mediums' finite conductivity and can be computed numerically. COMSOL Multiphysics provides these needed time-dependent solutions, which, coupled with Garfield++ and a general-purpose circuit simulation program (e.g., SPICE) to describe the front-end electronics, allows for the targeting of a universal modelling toolkit for the modelling of the signal induction in particle detectors. This study includes a wide range of MicroPattern Gaseous Detector (MPGD) and silicon-based detectors. Particularly for the PICOSEC Micromegas detector and the AC-coupled Low Gain Avalanche Diode (LGAD), the possibility of modelling the time and position response for different readout patterns could provide key insights for the design of new prototypes and application.

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Precise timing PICOSEC Micromegas and rapid imaging with gaseous detectors

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Advances in MicroPattern Gaseous Detector (MPGD) technologies and readout devices allow significant improvements of timing resolution as well as novel imaging approaches. This contribution will focus on PICOSEC Micromegas achieving tens of ps timing precision as well as new developments in the optical readout of gaseous detectors taking advantage of state-of-the-art imaging sensors and fast photon detectors.
PICOSEC Micromegas combine a Cherenkov radiator with a semi-transparent photocathode and Micromegas amplification stage to achieve better than 25ps timing precision for Minimum Ionising Particles (MIPs). The latest developments of this technology towards scalable timing systems include optimisations of multi-pad detector modules for robustness and improved timing uniformity and dedicated readout electronics preserving high bandwidth and timing performance.
Recording scintillation light emitted during avalanche multiplication in MPGDs is a powerful readout approach exploiting high-resolution imaging sensors and the high gain and rate capabilities of gaseous detector technologies. Ultra-fast CMOS sensors offer unprecedented frame rates for rapid imaging and can further enable new approaches for 3D track reconstruction in Time Projection Chambers (TPCs). In addition, hybrid readout approaches and fast photon detectors such as SiPMs offer new possibilities for track reconstruction and fast radiation imaging.

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Timespot1: a Fast-Timing, High-Rate Pixel-Matrix ASIC in CMOS 28-nm technology

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Vertex detectors being conceived for the next generation of collider experiments will have to operate with an increased number of tracks per event. To cope with this problem, it will be mandatory to operate with pixel sensors and electronics having both high space and time resolutions (tens of µm and tens of ps respectively). Furthermore, high radiation resistance is necessary both for the sensors (around 5x10¹⁶ 1 MeV neutron equivalent per cm²) and the electronics side (1-2 Grad). Dedicated development activities have already started in the last years to study possible technical solutions in this respect. The INFN-funded TimeSPOT project aims to produce a small-scale demonstrator, which includes both a pixel sensor with a size of 55×55 µm² and a pixel read-out chip satisfying the above mentioned requirements. This demonstrator includes an ASIC, named Timespot1, which is described in this paper. The chip is being bump-bonded to dedicated 3D silicon sensors, having already shown a time resolution better than 20 ps. Timespot1 is designed in CMOS 28 nm technology. It features a 32×32-pixel matrix with a pitch of 55 µm. The ASIC is conceived to be capable to read-out pixels with timing resolution below 50 ps on the full chain (sensor, amplifier, Time-to-Digital-Converter). Each pixel is endowed with a charge amplifier, a discriminator, and a Time-to-Digital Converter with time resolution around 30 ps and maximum read-out rates of 3 MHz per pixel. The timing performance are obtained keeping the power budget of per pixel lower than 40 µW per channel. The ASIC has been tested in the laboratory in order to characterize its performance in terms of time resolution, power budget and sustainable rates. The ASIC is being hybridized on a matched 32×32 pixel sensor matrix and will be soon tested under laser beam and Minimum Ionizing Particles in the laboratory and at test beams.
In this paper we present a description of the ASIC design, its operation and the results obtained from characterization tests concerning its performance in tracking measurements. A typical time resolution of the order of 30 ps has been achieved. The die size is 2.3x2.6 mm². The ASIC layout has been conceived to be easily scalable in area by design, in such a way to read-out larger pixel matrices with the same pitch. This suggest further developments of this first prototype, which are already under consideration by our collaboration. This item will also be addressed in this paper.

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The DSSC soft X-ray Detectors with Mega-frame Readout Capability for the European XFEL

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The DSSC camera was developed for photon science applications in the energy range 0.25-6 keV at the European XFEL in Germany. The first 1-Megapixel DSSC camera is available and is successfully used for scientific experiments at the "Spectroscopy and Coherent Scattering" and the "Small Quantum System" instruments. The detector is currently the fastest existing 2D camera for soft X-rays.
The camera is based on Si-sensors and is composed of 1024×1024 pixels. 256 ASICs provide full parallel readout, comprising analog filtering, digitization and data storage. In order to cope with the demanding X-ray pulse time structure of the European XFEL, the DSSC provides a peak frame rate of 4.5MHz. The first megapixel camera is equipped with Miniaturized Silicon Drift Detector (MiniSDD) pixels. The intrinsic response of the pixels and the linear readout limit the dynamic range but allow one to achieve noise values of ~60 electrons r.m.s. at 4.5MHz frame rate.
The challenge of providing high-dynamic range (~10⁴ photons/pixel/pulse) and single photon detection simultaneously requires a non-linear system, which will be obtained with the DEPFET active pixels foreseen for the advanced version of the camera. This technology provides lower noise and a non-linear response at the sensor level. The readout ASICs and the camera-head electronics are compatible with both type of sensors.
We will present the architecture of the whole detector system with its key features, focusing on the sensors and the integrated electronics. We will summarize the main experimental results obtained with the MiniSDD-based camera and give a short overview of the performed user experiments.
We will present for the first time the experimental results with complete sub-modules of the DEPFET camera which is in the final stages of assembly. Measurements obtained with full size sensors and the complete readout electronics have shown an unprecedented mean noise of ~10 el. rms with MHz frame rate and a dynamic range more than one order of magnitude higher with respect to the MiniSDD camera.

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Commercializing high rep rate burst mode hCMOS imagers

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Nanosecond scale, burst mode hCMOS imagers developed at Sandia National Laboratories (SNL) have provided revolutionary insight and data to a limited few research facilities. As these High Energy Density Physics research facilities typically operate on a shot-per-hour to shot-per-day timescale, little effort has been devoted to fast replication-rate circuitry for hCMOS image sensors. Advanced hCMOS Systems (AHS) was founded by former DOE laboratory employees who developed the hCMOS image sensor and camera concept; their intention is to make these image sensors available to a broader community. For hCMOS to impact an expansive user base, the replication rate needs to be increased and the Read Out Integrated Circuit design must be migrated from the proprietary SNL CMOS7 foundry process to a commercially available foundry process. hCMOS imagers are single die (non-tiled), high spatial resolution, and large pixel count sensors. This pixel count poses a complicated design problem to read out such a large data stream. Existing sensors have 2.1 megapixels equivalent (1024 x 512 x 4 frames) and typically operate at two Frames-Per-Second (FPS), which translates to 4.19 megapixels/s (the sensor has a theoretical maximum of 8 FPS). AHS plans to increase the rep rate to >120 FPS or 251 megapixels/s for an increase of 60x, while porting the design to a radiation-hardened commercially available foundry process.

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How nanophotonics can speed up detection

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This presentation will present the opportunities offered by nanophotonics to improve the performance of detectors including results obtained from the ATTRACT-Photoquant project [1] that aimed at demonstrating that recent nanophotonics innovations such as metalenses and more generally metamaterials could allow a breakthrough in single-photon time resolution. Silicon photomultipliers are bidimensional arrays of single photo-avalanche diodes (SPADs). Many applications would benefit from a single photon time resolution much lower than what is the current state of the art, ideally 10 ps, or even less. Moreover, a photo-detection efficiency as close as possible to 100% is also required. Simulations and measured results show that, using both a light concentrator and including light trapping features to the device stack, the photo-electron generation can be confined in a region as small as 820×780×500 nm3, which could greatly improve the single-photon time resolution and the sensitivity of the device. A concentrator based on a metatamerial gradient index (MM GRIN) lens was created as a 2D square lattice of holes with different diameters [2]. The focusing effect is generated by the refractive index gradient, with bigger holes in the outer region of the concentrator. A concentration factor of about 8 shows the ability of the MM GRIN lens to concentrate light. Moreover, we have shown thanks to numerical simulations that modified SPAD with a thickness reduction of the Si layer down to 500 nm (usually several µm Silicon thickness) and a grating at the bottom or above of the stack resulted in a photon absorption efficiency of nearly 100% in the Si layer. The societal value of such an achievement will be tremendously high in a plethora of fields, from automotive, medical devices and cancer diagnoses to high energy physics.

1 - https://phase1.attract-eu.com/showroom/project/nano-photonics-applied-to-ultrafast-single-photon-quantum-sensors-photoquant/
2 - Mikheeva, E., et al. (2020). CMOS-compatible all-dielectric metalens for improving pixel photodetector arrays. APL Photonics, 5(11), 116105.

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Calibration Strategy and Experimental Qualification of the Non-Linear Response of the First DEPFET Pixel Sensors of the DSSC Camera

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A novel design of the Depleted P-Channel Field Effect Transistor (DEPFET) with non-linear response is at the heart of the 1 Mpixel DSSC camera (DEPFET Sensor with Signal Compression) currently being developed for ultra-fast imaging of soft X-rays at the European XFEL. The simultaneous requirement of single-photon detection down to 0.5 keV and dynamic range up to 104 photons/pixel/pulse is here solved by introducing a non-linear compression of the DEPFET transistor response while the readout electronics is kept linear. The first full-size sensors produced by PNSensor GmbH have been mounted to give birth to the first ladder (128x512 pixel), one of the 16 independent units forming the DSSC camera.

Now the calibration of a 1 Mpixel DEPFET sensor with signal compression is the key to reach the desired performances but also the major challenge, due to the need to accurately qualify the response

of each pixel in different conditions. The aim of this work is to discuss the general calibration strategy, to present the experimental results of the first calibration campaigns on the DSSC ladder and to discuss the open issues.

X-ray spectra were acquired to assess gain and noise performances in the linear region of the DEPFET response by means of a pulsed X-ray source (PulXar) that can provide trains of X-ray pulses with duration as short as 25 ns at high burst rate (up to 4.5 MHz) which effectively mimics the time structure of the beam at XFEL. The reduced number of ADC bit makes gain calibration from spectra fitting particularly dependent on the fitting model which has been carefully optimized to tailor the specific detector properties.
To qualify the full non-linear response of each pixel, from the linear region to the high intensity end, we conducted a dedicated test at the SQS beam line where we can produce intense shots of monochromatic photons (soft X-rays) with a smooth spatial distribution to allow irradiation of a whole quadrant of the camera. The XFEL beam hits an Aluminum target and the DEPFET ladder is at 90-degree to collect fluorescence photons (Al K⊠ 1.48 keV).

The presentation will focus on the evaluation of the first DEPFET ladder performance with low energy photons and on the measurement techniques, modelling and parametrization of the DEPFET response. The achieved results validate the calibration strategy of the full DSSC camera and show achievement of noise levels below 20 electrons rms and an input range of deposited energy up to several MeV per pixel per pulse.

Application / **21**

Fast timing detectors with applications in cosmic ray physics and medical science

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We first describe the development of a fast readout system of an LGAD detector using the waveform technique. We use this detector to measure the type of particles and their energy in cosmic ray measurements in space in collaboration with NASA. We will show the results of the simulation of the detectors as well as the first tests performed before the launch foreseen by the end of the year. We also describe another application related to the measurement of the dose received by a patient during flash beam treatment of cancer.

Application / **22**

FBK SiPM roadmap for ultimate timing performance

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Optimization of the timing resolution in the scintillation light readout has been one of the most important challenges in the SiPM field since the beginning of their development. Several sensor parameters contribute to the timing performance achieved in the application. The latest iteration of the NUV-HD SiPM technology developed at FBK feature Photon Detection Efficiency (PDE) in excess of 60% at 410 nm, Dark Count Rate around 60 kHz/mm² and Single-photon Time resolution (SPTR) of 90 ps FWHM for a 4x4 mm2 device with 40 μm cells, when coupled to a discrete, high-frequency readout. Thanks to these parameters, it was possible to measure an excellent

Coincidence Resolving Time (CRT) of 58 ps FWHM in the readout of a 2x2x3 mm³ LSO:Ce:Ca coupled to a 4x4 mm² SiPM with 40 μm cells (98 ps FWHM with a 2x2x20 mm³ LSO:Ca:Ce). Ongoing developments include the use of metal-filled deep trench isolation, which allows reducing the optical crosstalk probability to 10% with a PDE of 60% (bare die). On the other hand, photon-starved applications, such as BGO readout with the timing resolution enhanced by the detection of Cherenkov photons, further underline the importance of improving the SPTR of the SiPMs. In the current generation of devices, this parameter is heavily affected by both the output capacitance of the sensor and by the characteristics of the front-end electronics reading it. Considering that incremental improvements between subsequent generations of SiPMs are reaching saturation, a deeper redesign of the device structure is needed. In this context, FBK is working on the development of the next-generation of SiPMs, with a strong focus on 3D integration, such as SiPMs featuring fine-pitch Through Silicon Vias and Backside-illuminated (BSI) devices. A fine segmentation of the sensitive area in separated mini-SiPMs, each one connected to a dedicated readout channel through a low-impedance interconnection, will reduce output capacitance and optimize signal integrity. BSI-SiPMs will potentially bring additional advantages, such as reaching a PDE close to 100%, reduced output capacitance, enhanced radiation hardness, single-cell connection to the readout electronics and a uniform light entrance window, suitable for the most advanced optical stacks. In the presentation, FBK roadmap towards 3D integrated SiPMs and the preliminary result obtained so far will be discussed.

Imaging / 23

Single-pulse multi-frame x-ray imaging with a crystal-based x-ray split-and-delay line

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We developed an x-ray optics solution, called x-ray tomographic-delay-line (XTEL), for studying pico- to nanosecond dynamics of mesoscale materials processes at existing x-ray light sources. This optic lays the groundwork for taking snapshot movies of materials processes with selectable delay times, as well as single-pulse 3D images of materials by recording multiple views simultaneously from different angles. The XTEL has been designed to match the time resolution required to probe materials processes in the pico-second to nano-second range, which is not accessible at existing or soon emerging x-ray light source facilities. It will operate between 5 to 20 keV initially to match LCLS, LCLS-II, the European XFEL, and DCS. In future experiments, the XTEL will enable single-pulse tomographic imaging as well as multi-frame movies created from a single x-ray pulse that enables the user to capture dynamic processes.

We will describe the instrument design choices and initial results from LCLS Run 20 beamtime for a single probe beam. The conceptual design for multiple-probe beams, to be used with the upgraded LCLS MEC facility, will be described.

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Imaging / 24

Observing light-in-flight and MIPs with a 7.5-ps resolution

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Single-photon avalanche diodes (SPADs), also known as Geiger-mode APDs, have emerged as the detctor of choice in many photon-counting and high-performance imaging applications. Recently, CMOS-compatible SPADs and SPAD image sensors have reached unprecedented counting-rate (> 1Gcps) and timing-resolution (< 7.5ps FWHM) capability, while demonstrating high sensitivity to photons in the 400-nm to 950-nm and also to minimum ionizing particles (MIPs), such as 80 GeV/c momentum pions.
CMOS SPADs are scalable and thus suitable for large-format image sensors, where massively-parallel, complex functionality is sought, thanks to their digital nature and low power consumption. In this talk we will look at existing and new applications in many fields of science and engineering, often pushing performance to new heights.

Tracking / 25

The power of gaining and sharing: introducing internal gain and built-in charge sharing in silicon sensors

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In this contribution, I will review the performance improvements that two design innovations, low-gain (LGAD) and resistive read-out (RSD), have brought to silicon sensors. Large signals lead to improved temporal precision, while charge sharing has removed the need for very small pixels to achieve excellent spatial precision. LGAD- and RSD- based silicon sensors are now adopted, or considered, in several future experiments and are the basis for almost every next 4D-trackers. Finally, I will show how the introduction of multiple sampling front-end electronics and reconstruction methods based on machine learning can further improve the performances of future 4D trackers.

Tracking / 26

Advanced silicon tracking detector developments for the future Electron-Ion Collider

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The proposed Electron-Ion Collider (EIC) will operate high-luminosity high-energy electron+proton and electron+nucleus collisions at the collision energies from 20 to 141 GeV to solve several fundamental questions in the high energy and nuclear physics fields. Its instant luminosity can reach $10^{33-34} cm^{-2} s^{-1}$ and the bunching crossing rate is around 10 ns. The EIC project has received CD1 approval from US DOE in 2021 and moves towards the machine design and construction. To realize the proposed high precision particle measurements at the future EIC, a low material budget and high granularity silicon vertex/tracking detector with fine spatial and momentum resolutions and nearly 4π solid angle coverage is desired. The Monolithic Active Pixel Sensor (MAPS) and AC Coupled Low Gain Avalanche Diode (AC-LGAD) stand out of several advanced silicon technologies as the top candidates for the EIC silicon detector subsystems. Latest studies and results for the EIC silicon vertex/tracking detector, which includes the conceptual detector design, performance validations in simulation and ongoing MAPS and AC-LGAD detector R&D will be presented. The EIC detector development plan and schedule will be discussed as well.

Application / **27**

Radiation damage effectgs overvoew of Low Gain Avalache Diodes

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Radiation damage mechanisms in depleted sensors with intrinsic gain (LGADs) are probed via electrical characterization, timing measurements and accceptor removal estimation. An analytical model is developed to prove gain vs field coefficients in proton and neutron irradiated sensors up to 6e15 n_{eq}/cm^2 with an emphasis on the gain layer geometry. The breakdown, efficiency and stability issues are investigated in deeply carbonated substrates as well as for boron and Gallium implanted gain layers. The series is completed by detailed SiMS measurements, process simulations and single event burn-out studies on CNM and FBK produced LGADs. An emphasis is placed on future developments with defect engineering and gain layer compensation studies using indium and Lithium co-implantation with preliminary results on both techniques.

Tracking / **28**

Precision Timing with the CMS MIP Timing Detector

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The Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider (LHC) is undergoing an extensive Phase 2 upgrade program to prepare for the challenging conditions of the High-Luminosity LHC (HL-LHC). A new timing detector in CMS will measure minimum ionizing particles (MIPs) with a time resolution of ~30-40 ps for MIP signals at a rate of 2.5 Mhit/s per channel at the beginning of HL-LHC operation. The precision time information from this MIP timing detector (MTD) will reduce the effects of the high levels of pileup expected at the HL-LHC, bringing new capabilities to the CMS detector. The MTD will be composed of an endcap timing layer (ETL), instrumented with low-gain avalanche diodes, as well as a barrel timing layer (BTL), based on LYSO:Ce crystals coupled to SiPMs. In this talk we present an overview of the MTD design, describe the latest progress towards prototyping and production, and show test beam results demonstrating the achieved target time resolution.

Tracking / **29**

Latest results on timing performance of silicon pixel detectors

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Monolithic active pixel sensors (MAPS) have recently been used as building blocks of charged particles tracking and vertexing detectors because they offer lower material budget, higher granularity as well as a simpler assembly procedure and lower cost compared to the traditional wide spread hybrid technology.

The interest towards monolithic silicon sensors offering both excellent timing and position resolution has increased and different approches are being explored. Traditionally large collection electrodes have been used for precision timing to approach a planar structure with large, uniform fields. However, significant improvement of time resolution and speed of charge collection has recently been demonstrated on MAPS built on 180nm TowerJazz CMOS imaging technology and is currently being further explored on 65nm TowerJazz Panasonic Semiconductor (TPSCo) technology. In parallel, structures with amplification layers like SPADS and LGAD are being studied both in CMOS and BiCMOS technologies.

In this presentation I will report on the latest results obtained in the 65 nm CMOS technology and also give an overview of the other developments.

Tracking / **30**

New Developments in Low Gain Avalanche Diode Fabrication Technology

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In the last few years, Low Gain Avalanche diodes (LGAD) obtained growing attention as radiation sensors due to some important advantages: larger internal signal, potentially higher signal-to-noise ratio, better time resolution, and higher radiation hardness with respect to standard p-i-n sensors. They are currently considered state-of-the-art silicon detectors for timing application in HEP experiments, and more recently they are also being investigated as low-energy x-ray segmented detectors (< 1 keV) for synchrotron applications.
An increasing number of foundries and R&D laboratories started to work on this technology by proposing novel designs, mainly focused on increasing the radiation hardness of LGAD and optimizing the segmentation technology for fine-pixel and high-fill-factor sensor production.
In this presentation, the major ongoing developments on LGAD will be reviewed and discussed, supported by experimental results, and with particular attention to the fabrication process and to the technological challenges.
Among the others, some novel segmentation strategies aimed at increasing the fill-factor of fine-pixelated sensors will be discussed: i) inverted-LGAD (i-LGAD); ii) Resistive AC-coupled Detectors (RSD) and Resistive DC-coupled Detectors (DC-RSD); iii) Trench-Isolated LGAD (TI-LGAD); iv) Deep-Junction LGAD (DJ-LGAD).
In addition, new strategies for the production of LGAD operating at extreme fluences above 5e15 neq/cm^2 will be presented. The ideas behind this radiation tolerance are: i) using ultra-thin substrates, ii) optimizing the doping profile by using doping compensation to make it less sensitive to the acceptor removal effect and iii) including some chemical impurities (like Carbon) to mitigate the effect of radiation-induced effects.

Tracking / **31**

A High-Granularity Timing Detector for the ATLAS Phase-II upgrade

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The increase of the particle flux (pile-up) at the HL-LHC with instantaneous luminosities up to L ⊠ 7.5 × 10^{34} $cm^{-2}s^{-1}$ will have a severe impact on the ATLAS detector reconstruction and trigger performance. The end-cap and forward region where the liquid Argon calorimeter has coarser granularity and the inner tracker has poorer momentum resolution will be particularly affected. A High Granularity Timing Detector (HGTD) will be installed in front of the LAr end-cap calorimeters for pile-up mitigation and luminosity measurements.
The HGTD is a novel detector introduced to augment the new all-silicon Inner Tracker in the pseudo-rapidity range from 2.4 to 4.0, adding the capability to measure charged-particle trajectories in time as well as space. Two silicon-sensor double-sided layers will provide precision timing information for minimum-ionising particles with a resolution as good as 30 ps per track in order to assign each particle to the correct vertex. Individual sensor pads will have a size of 1.3 mm × 1.3 mm, leading to a highly granular detector with 3.7 million individual channels. Low Gain Avalanche Detectors (LGAD) technology has been chosen as it provides enough gain to reach the large signal over noise ratio needed.
The requirements and overall specifications of the HGTD will be presented as well as the technical design and the project status. The on-going R&D effort carried out to study the sensors, the read-out ASIC, and the other components, supported by laboratory and test beam results, will also be presented.

Methods / **32**

Bayesian inferencing and deterministic anisotropy for molecular geometry retrieval in gas phase diffraction experiments

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Ultrafast molecular gas phase diffraction is a vital tool for retrieving time dependent molecular structures. We are limited in the systems we can study as we generally require complex molecular dynamics simulations to interpret the results. We develop an alternative analysis to approximate the molecular geometry distribution $|\Psi(\mathbf{r},t)|^2$ that does not require such complex simulations. We achieve real-space resolutions of 1 pm to 10 fm while uniquely defining the molecular structure. We demonstrate our method's viability by retrieving the ground state geometry distribution $|\Psi(\mathbf{r})|^2$ for

simulated stretched NO_2 and measured N_2O. Our method expands the capabilities of ultrafast molecular gas phase diffraction to measure other variables, like the width of $|\Psi(\mathbf{r},t)|^2$. By not relying on complex simulations and with the order 100 fm resolution, our method has the potential to effectively turn ultrafast molecular gas phase diffraction into a discovery oriented technique, exploring systems that are prohibitively difficult to simulate.

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Tracking / 33

Design characterization of AC-coupled LGADs for high precision 4D tracking

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Low Gain Avalanche Detectors (LGADs) are thin silicon detectors capable of providing measurements of minimum-ionizing particles with time resolution as good as 17 ps. These properties make LGADs the prime candidate technology for achieving 4D tracking in future experiments. Furthermore the fast rise time and short full charge collection time (as low as 1 ns) of LGADs are suitable for high repetition rate measurements in photon science and other fields. Granularity in traditional DC-LGADs is limited to the mm scale due to protection structures preventing breakdown caused by high electric fields at the edge of the segmented implants. The structure, called Junction Termination Extension (JTE), causes a region of 50-100 µm of inactive space in between electrodes.
In this contribution, a set of measurements on AC-coupled LGADs (AC-LGADs, also named Resistive Silicon Detectors, RSD) will be presented. AC-LGADs overcome the granularity limitation of traditional LGADs and have been shown to provide spatial resolution of the order of 10s of µm. This remarkable feature is achieved with an un-segmented (p-type) gain layer and a resistive (n-type) N-layer. An insulating di-electric layer separates the metal readout pads from the N+ resistive layer. Because of the AC-coupled nature of AC-LGADs the pulse is bipolar with a theoretical zero area. The high spatial precision is achieved by using the information from multiple metal pads, exploiting the intrinsic charge sharing capabilities of the AC-LGAD provided by the common resistive N-layer. The following detector parameters have been investigated: sheet resistance (resistivity of the N+ layer), oxide thickness, doping profile of the gain layer, pitch, size and shape of the readout metal pads. The response of non conventional metal structures in AC-LGADs such as crosses and microstrips was also evaluated.
AC-LGADs fabricated at the Fondazione Bruno Kessler (FBK) and at Brookhaven National Laboratories (BNL) were studied extensively with a focused IR-Laser and the result of the studies will be reported in this contribution. Sensors were mounted on fast analog electronic boards (with 1 GHz of bandwidth) and digitized by a fast oscilloscope. Sensors mounted on boards are measured in a laser TCT system using an infrared (IR) 1064 nm laser with a penetration length in silicon of several mm. The IR laser produces linear ionization across its path mimicking the behavior of a minimum ionizing particle (MIP). The laser beam is focused by a lens system that can produce a laser spot of 20-30 µm. The board is placed on micrometer motorized stages to allow to study the response of the sensor as a function of laser position.
A balance between all tunable parameters (comprehending doping concentrations and metal pad geometry) have to be identified for future uses of AC-LGADs. The sensor design can be optimized for each specific application to achieve the desired position and time resolution compromised with the readout channel density. AC-LGADs' exceptional precision make them great candidates for future 4-D trackers and will be utilized in several future high energy and nuclear physics projects. To give an example AC-LGADs are the chosen technology for near-future large-scale application like detectors at the Electron-Ion Collider at BNL or the PIONEER experiment.

Imaging / 34

HEXITEC-MHz: A Spectroscopic X-ray Imaging Camera System with 1 MHz Frame Rate Continuous Readout

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The HEXITEC$_{MHz}$ detector system is the latest generation of the STFC's HEXITEC spectroscopic X-ray imaging detector systems. When coupled to Cd(Zn)Te sensor material the original HEXITEC system was capable of delivering high resolution X-ray spectroscopy (50 electrons RMS) per 250 μm pitch pixel for hard X-rays with energies 2 - 200 keV. The major limitation of this technology is that the combination of a 10 kHz frame rate and the need to identify charge sharing events limits its application to photon fluxes of ~ 10^4 ph s^{-1} mm^{-2}. With many photon light sources currently undergoing major upgrades to diffraction limited storage rings, these expected increases in flux have motivated the development of the next generation of the HEXITEC technology.

The HEXITEC$_{MHz}$ system is targeted at delivering the same high-resolution spectroscopy as the original ASIC but targeting much higher photon fluxes. While the ASIC maintains the same 250 μm pixel pitch, the new integrating architecture delivers a 1 MHz frame rate meaning it is possible to operate the system at ~ 10^6 ph s^{-1} mm^{-2} for spectroscopic X-ray imaging applications at synchrotron light sources. At pulsed sources, a maximum of 30 × 10 keV photons (dynamic range = 300 keV) can be measured in each frame and these are readout at the continuous 1 MHz frame rate. In this paper the first results of Cd(Zn)Te sensors bonded to the ASIC will be presented including an evaluation of the energy resolution of these devices and their linearity at high flux.

Imaging / 35

Development of diamond-based diagnostics for next-generation XFELs

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FELs deliver rapid pulses on the femtosecond scale, and high peak intensities that fluctuate strongly on a pulse-to-pulse basis. The fast drift velocity and high radiation tolerance properties of chemical vapor deposition (CVD) diamonds make these crystals a good candidate material for developing a high frame rate pass-through diagnostic for the next generation of XFELs. We report on two diamond based diagnostic systems being developed by a collaboration of a UC campuses and National Laboratories supported by the University of California and the SLAC National Laboratory.

For the first of these diagnostic systems, we have developed a new approach to the readout of diamond diagnostic sensors designed to facilitate operation as a passthrough detection system for high frame-rate XFEL diagnostics. Making use of the X-ray Pump Probe (XPP) beam at the Linac Coherent Light Source (LCLS), the performance of this new diamond sensor system has been characterized and compared to that of a commercially available system. Limits in the magnitude and speed of signal charge collection are explored as a function of the generated electron-hole plasma density and compared to results from a TCAD simulation.

A leading proposal for improving the efficiency of producing longitudinally coherent FEL pulses is the cavity-based X-ray free electron laser (CBFEL). In this configuration, the FEL pulses are recirculated within an X-ray cavity in such a way that the fresh electron bunches interact with the FEL pulses stored in the cavity over multiple passes. This creates a need for diagnostics that can measure the intensity and centroid of the X-ray beam on every pass around the recirculatory path. For the second of these diagnostic systems, we have created a four-channel, position-sensitive pass-through diagnostic system that can measure the intensity and centroid of the circulating beam with a repetition rate in excess of 20 MHz. The diagnostic makes use of a planar diamond sensor thinned to 43 μm to allow for minimal absorption and wave-front distortion of the circulating beam. We also present results on the response and position sensitivity of the diagnostic, again measured using the LCLS XPP beam.

Methods / 36

Computational X-ray Photon Correlation Spectroscopy to analyze Dynamic Polymer Networks

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Dynamic polymer networks (DPNs) are quickly emerging as attractive materials for future applications due to their robustness, flexibility, and reconfigurable characteristics. Reversible bonding and de-bonding in DPNs can be leveraged broadly for performance advantages, and also give rise to the stress relaxation phenomenon that can be measured experimentally. The goal of this study is to quantify the dependence of the observed macroscopic behavior of stress relaxation on the microscale scale dynamics of the reversible bonds.

Experimentally, the X-ray Photon Correlation Spectroscopy (XPCS) and X-ray Speckle Visibility Spectroscopy (XSVS) experiments are used to probe the internal dynamics of materials at different length and time scales. However, it is very difficult to isolate the contributions from individual bonds or polymer chain segments. The scattering signal comprises interactions from multiple compositional components, which makes it non-trivial to deconvolve the signal obtained from the experimental data. To overcome these difficulties, we present a computational framework to model these experiments by computing the intensity speckles from the atomic positions obtained from molecular dynamics (MD) and coarse-grained molecular dynamics (CGMD) simulations. The interpretation of the dynamics through CGMD enables us to connect the measureable XPCS/XSVS signals with the dynamics of individual crosslinks.

We discuss a fast Fourier transform-based (FFT-based) method that can rapidly compute the XPCS/XSVS signals from MD/CGMD simulations. The FFT-based method has the advantage of being able to compute the speckle intensity simultaneously over all points in the **q**-space. We present the convergence of the FFT-based method to the direct method that computes the speckle intensity at one **q**-point at a time. We show that the computational XPCS/XSVS signals satisfy the known relations (e.g. Siegert relation) in experimental XPCS/XSVS through the test case of liquid Argon.

The efficiency and accuracy of our computational XPCS/XSVS model enable us to analyze the dynamics of DPNs during in-situ stress relaxation. We present the change in material dynamics with the chain length, crosslink density, and crosslink distribution along the polymer backbone. We discuss the crosslinks bonding/de-bonding rates in the presence of a polymer melt, reversible crosslinks and permanent crosslinks, and their effect on the XPCS/XSVS signals. The work is a first step toward connecting the macroscopic stress-relaxation behavior of DPNs, the microscopic bond dynamics, and the XPCS/XSVS signals, through the use of CGMD simulations.

Methods / **37**

Time-resolved Full Field Bragg X-ray Diffraction Imaging of Non-Equilibrium Structural Domain States

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Recent work convincingly demonstrates the existence of novel non-equilibrium structural phases and their evolution in time [1]. However, the observation of spatiotemporal evolution of coexisting phases remains elusive because it is challenging to combine nanoscale and mesoscale spatial resolution with femtosecond temporal resolution. The conventional pump-probe X-ray diffraction is extremely sensitive to minute structural rearrangements; however, it averages over large sample volumes.

We explore the Full field Bragg Diffraction Imaging (FBDI) [2] technique as a pathway to ultrafast imaging with a mesoscale field of view. Using Fresnel Zone plates as x-ray focusing optics,
FBDI combines full field imaging with the lattice sensitivity of diffraction to image the local structure in direct space. As a test case, we show that FBDI at XFELs can be used to image mesoscale twin domains in a Lanthanum Aluminate substrate. In addition, our preliminary results suggest that FBDI is sensitive to ultrafast changes of structural domain states in thin, epitaxial calcium ruthenate films undergoing a metal-to-insulator transition induced by an optical pulse. Our work represents a significant milestone towards using FELs to image structural domain states on the nano and mesoscales with fs resolution.

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[2] N. Laanait et al., Journal of Synchrotron Radiation 21, 1252-1261 (2014)

Imaging / **38**

Extreme Frame Rates for Photon Science

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LCLS II HE will deliver x-ray pulses at a rate approaching a megahertz and will be the brightest x-ray source ever. A program is underway to develop detectors that can record images as fast as the accelerator generates them. An incremental approach is being pursued with multiple systems intended to cover the science relevant portions of the performance parameter space in metrics such as dynamic range, noise, frame rate, spatial resolution, etc. Progress and plans will be presented.

Imaging / **39**

Nanosecond x-ray imaging at LCLS with UXI detectors

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We report on the characterization, application, and future of the four-frame Icarus detector at LCLS. The free electron laser is able to produce intense single femtosecond pulses over a wide range of x-ray energies at 120 Hz (soon to be 10s of kHz) but can also make short trains of pulses down to 350 ps separation. This mode gives us access to a variety of interesting science on these timescales and also allows pumped experiments that are rate limited by the optical laser or that have unique targets to collect multiple frames per shot. The Icarus detector from the UXI collaboration has been characterized at LCLS and used in two experiments. After describing this work we discuss current developments in the UXI program to achieve >4 frames, 350 ps spacing, and higher QE using GaAs sensors. We conclude with prospects for related detectors on the MEC-U timescale.

Imaging / **40**

The FastIC ASIC: A Fast Integrated Circuit for the readout of Fast Detectors with Intrinsic Amplification

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Many applications can benefit from detectors which have the ability of detecting low light intensities with precise timing. Some examples are Time of Flight Positron Emission Tomography (ToF-PET),

High Energy Physics experiments (e.g. RICH detectors), Fluorescence Lifetime Imaging Microscopy (FLIM), Light Detection and Ranging (LIDAR) or Quantum Communications.

The FastIC Application Specific Integrated Circuit (ASIC) is an 8 channel chip to readout the signal from fast detectors with intrinsic amplification, like Micro Channel Plates (MCP), Photomultiplier Tubes (PMT) or Silicon Photomultipliers (SiPM). The chip was developed in an standard CMOS 65nm technology. The ASIC includes an input stage that can be configured to process the signal from positive or negative polarity detectors with a linear energy measurement and a dynamic range from a few microamperes to ~20 mA (in the negative polarity stage) and to ~25 mA (in the positive polarity).

The input stage generates replicas (in current mode) of the input signal that are fed in three different paths. The *Time* path provides an accurate measurement of the particle time of arrival using a precise leading edge discriminator. The *Energy* path generates a digital pulse at its output whose duration is directly proportional to the input signal amplitude. The third path is for *Trigger* purposes and might be used to set its threshold above the first photoelectron, allowing to ignore dark count events from the detector . The *Cluster Trigger* adds the trigger signal from multiple channels before discrimination. This is useful to trigger on detectors in which the signal is shared by different channels (e.g. PET detectors based on monolithic crystals). The chip provides the interface between detectors and Time-to-Digital Converters (TDCs).

The power consumption of the full channel is 12 mW with default settings, although in some applications, the user might choose to use only the Time path and in this case the power consumption of the channel reduces to ~6 mW . The power consumption of the input stage is 3 mW.
A first series of measurements was performed with several photodetectors and standard scintillators. A HPK photomultiplier R5900 producing, according to the manufacturer datasheet, pulses with ~5 ns FWHM duration and 330 ps FWHM transit time spread, was tested using a red-light laser. The measured time jitter was ~340 ps FWHM after Time Walk Correction (TWC). This time jitter corresponds to the time uncertainty of detecting tens of photons. These results show that the FastIC electronics does not degrade the system time response.

The Single Photon Time Resolution (SPTR) was measured to be 176 ± 3 ps FWHM (including laser, sensor and electronics contribution) when using the light from a blue laser and a 3x3 mm^2 SiPM HPK S13360-3050CS at 10.6 V over-voltage. When the FastIC is connected to new SiPM technology HD-NUV Low Field (3.2 × 3.12 mm^2, 40 µm cell) from FBK, the SPTR decreased to 151 ± 3 ps.

The chip was also used to read out the signal generated in a pair of identical LSO:Ce:Ca 0.2% scintillators (2 × 2 × 3 mm^3) coupled to SiPM devices, in a setup to record 511keV coincident gamma photons. The results showed a Coincidence Time Resolution (CTR) of 94 ± 2 ps and 76 ± 2 ps FWHM with HPK and FBK SiPMs respectively. First measurements with the FastIC chip confirm its ability to detect scintillating light (e.g., LSO and BGO) and prompt light emission (e.g. using Cherenkov radiators like TlCl and PbF_2).

In this contribution, further results on ASIC characteristics will be presented.

Imaging / **41**

Pixel detectors with built-in signal processing and bandwidth-efficient data transmission

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A high degree of segmentation in pixel detectors is needed for recording trajectories of charged particles or impacts of X-ray photons with high spatial resolution. The desired granularity imposes severe constraints for the in-pixel processing circuits, signal readout, and power budget. Therefore, most of nowadays high-spatial resolution pixel detectors are limited to detection of deposited energy

or occurrences of the event (location)..
Pixel detectors under development at BNL combine high-resolution amplitude measurements with handling of charge sharing events and zero-suppressed readout at the maximum achievable speed in the event-driven form. The readout circuits are being developed to suite hybridization with pixel sensors made of various materials, i.e., Si, Ge, and CdZnTe, with a variety of finely pixelated segmentations with the largest pitch equal to 150 micrometers, operating at room or cryogenic temperatures, and suitable for operation with X-rays in a broad energy range. As the development of an Application Specific Integrated Circuits (ASICs) is a considerable effort, a universal implementation methodology suitable for reading out pixelated sensors was developed. The methodology allows building the circuital skeleton for the Configuration-Testability-Readout (CRT) management logic and is based on code written in System Verilog hardware description language, fully parametrized to reflect all crucial parameters of the ASIC to be developed. The goal is to maximize the area for the Analog Front-End (AFE) while utilizing minimal resources (routing and area) for scaling to various densities, sizes, and shapes (square or hexagonal) of the pixels. Blocks of the readout chain have also been modularized to adapt efficiently to the polarity and magnitudes of the charge signals. The AFE circuit interfaces to the recently developed event driven readout system, EDWARD, through a Readout Interface (RI) circuit.
The implementation of a high-resolution, in-pixel Analog-to-Digital Conversion (ADC) block that completes the development of the signal processing built into a pixel circuitry is discussed as well. This block adds robustness to interference and distortions due to typical circuit non-linearities, and driving strength needed for fast settling.

Application / **42**

Ultrafast Inorganic Scintillators for future HEP and Imaging Applications

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Heavy inorganic scintillators, such as LYSO:Ce, is currently used to construct the CMS Barrel Timing Layer aiming at 30 ps time resolution for the HL-LHC. Ultrafast inorganic scintillators, such as BAF2:Y, has been proposed for ultrafast calorimeter and GHz hard X-ray imaging. In this investigation, we report temporal response of ultrafast inorganic scintillators with ultrafast decay time, such as BaF2, BaF2:Y, Cs2ZnCl4, Ga2O3, Lu2O3:Yb, YAP:Yb, YAG:Yb and ZnO:Ga etc. Potential application for ultrafast timing, tracking and imaging will also be discussed.

Methods / **43**

AI-in-Pixel: data compression at source

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AI-in-Pixel: data compression at source

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The demand for increasingly higher sensitivity and granularity of pixel detectors has resulted in voluminous data generation. A mega pixel readout Integrated circuit with 10b in-pixel ADC operating at 100 kfps generates upto 1Tbps of data. Most of these detectors still rely on full frame readouts creating an IO bottleneck. While zero suppressed and event driven readouts are extremely useful for sparce data environments, often simulated data with 3% occupancy is often closer to 40% occupancy in noisy experimental conditions.

In order to efficiently utilize data bandwidths and create scalable modular structures we need to master the technique of data processing at the source in extremely resource-constrained environments with stringent area, power and latency budgets.

We present the performance and design implementation of two lossy data compression schemes using in-pixel-principal component analysis (PCA) and in-pixel auto-encoder to enable greater than 50x data compression at source. Highly parallel vector matrix multiplications embedded within the pixel with and without preprocessing of in-pixel ADC data is evaluated.

Tracking / 44

The Silicon Electron Multiplier

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Silicon sensors for the future generation of collider physics experiments will require high performances on spatial ($< 10\ \mu$m) and time resolution (20-50 ps) with a radiation tolerance up to fluences of 10^{17}n$_{eq}$. To meet these challenges, a new silicon sensor architecture has been proposed, enabling internal gain without relying on doping, the Silicon Electron Multiplier (SiEM). The SiEM incorporates a set of metallic electrodes within the silicon substrate which are used to create a high electric field region that provides charge multiplication. Simulations of SiEM configurations with TCAD and Garfield++ show a promising performance with a gain exceeding 10. Metal assisted chemical etching is a process shown to be compatible with the desired geometry, and is used to make a demonstrator. Results from a production comprising pillars with a radius of 500nm and a height of up to 8 μm on a hexagonal grid with a 1.5μm pitch will be presented along with key results from the simulations.

Methods / 45

Measurements and analysis of the single photon timing performance of single and multi-anode MCP-PMTs

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Microchannel plate (MCP) based photomultiplier tubes (MCP-PMT) provide state-of-the-art timing performance for both analog and single photon detection in many fields such as plasma diagnostics, high energy physics, and Time-of-Flight Positron Emission Tomography. While intrinsic properties and limitations of these devices as used in analog mode have been well studied, detailed studies of intrinsic performance and limitations in single photon detection have been lacking. In this paper we present measurements of two MCP-PMTs using two independent test set-ups. The first MCP-PMT is a Photek PMT210 having 10 mm diameter active area, impedance matched single anode, and two 3 µm pore MCPs, with measured single photon transit time spread of 30 ps FWHM using a short pulse laser, a vacuum photodiode timing reference, and a high-speed oscilloscope. The second MCP-PMT is a Photek MAPMT253 having 53 mm × 53 mm active area, a 16 x 16 array of 3.3 mm × 3.3 mm anodes, and two 6 µm pore MCPs, with measured single photon transit time spread of < 60 ps FWHM per anode using the same test set-up as the PMT210. These data are compared with an independent test set-up using a femtosecond laser, a vacuum photo-triode timing reference, and a high-speed oscilloscope. In-depth measurements and analysis of the impact on timing performance of bias voltages, MCP pore size, and readout electronics configuration will be presented.

Imaging / 46

Test and qualification of the UDC: a 10 GSa/s, 16 channel digitizer system on a chip for fast plasma imaging applications

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We describe the design and measurement results of the "UDC" - Ultrafast Pixel Array Camera Digitizer Chip. UDC is a 16-channel waveform digitizing microchip with large buffer length (4096 samples per channel) and high timing performance (10Gsps sampling, <10ps resolution), suitable for applications such as High-Energy Density Plasma Diagnostics. It is designed to work with a variety of fast sensors such as fast photo-diodes and fast xray detectors. We have measured relevant performance metrics such as bandwidth, linearity, power consumption, and trigger rate and will present how such specifications can enable new instruments or measurement techniques for fast imagining.

Imaging / 47

SparkPix: a family of experiment-specific X-ray detectors for LCLS-II

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As the repetition rate of LCLS-II increases up to 1 MHz, novel detectors are needed to match the repetition rate of the machine. SLAC is developing several detectors belonging to the SparkPix family. Each detector is tailored to the specific requirements of each experiments and dedicated information extraction engines are implemented in each SparkPix ASICs to overcome the data challenge and enable frame-rates up to 1 MHz. This contribution will describe the overall philosophy behind the Sparkpix family, as well as the current developments, namely: SparkPix-ED, SparkPix-T and SparkPix-S.

Tracking / 48

Thin monolithic pixel sensors with fast operational amplifier output in a 65 nm imaging technology.

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This work presents results on the Analog Pixel Test Structure (APTS), a 4 x 4 pixel matrix prototype equipped with fast individual OPAMP-based buffering of analog pixel signals to output pads for exploration of pixel timing performance. The work was framed in the ALICE ITS3 upgrade and the CERN-EP R&D on monolithic sensors to explore the TPSCo 65-nm imaging technology. This upgrade will replace the inner layers of the ALICE Inner Tracking System at CERN with ultra-thin flexible wafer-scale monolithic silicon sensors. They will improve the material budget in this region, the tracking precision and the efficiency at low transverse momentum.
The presentation will show the gain of the signal chain in the APTS and its speed as a function of the configuration parameters, including calibration results with a 55Fe source. Two different pixel structures will be compared to demonstrate the possibility of enhancing the performance in terms of timing and charge collection efficiency by implant modifications in the epitaxial layer. Finally test beam results planned at the Super Proton Synchrotron at CERN will provide full spatial and time resolution of the APTS OPAMP structures.

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Accelerating the DBSCAN clustering algorithm for low-latency primary vertex reconstruction

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In this work we present the adaptation of the popular clustering algorithm DBSCAN to reconstruct the primary vertex (PV) at the hardware trigger level in collisions at the High-Luminosity LHC. Nominally, PV reconstruction is performed by a simple histogram-based algorithm. The main challenge in PV reconstruction is that the particle tracks need to be processed in a low-latency environment O(1 µs). To achieve this an accelerated version of the DBSCAN algorithm was developed to in run in a Field Programmable Gate Array (FPGA). A CPU optimized version of DBSCAN was implemented in C++ to serve as a benchmark for comparison. The CPU version of DBSCAN resulted in an average PV reconstruction latency of 93 µs, while the FPGA firmware only had a latency of 0.73 µs resulting in a 127x speedup. The speedup is a result of running all the input tracks in parallel, which ultimately results in high resource consumption, of up to 48.6 % of the available logic. Most

of the logic was attributed to the usage of sorting networks that allows for the parallel processing of the input tracks. To tune the firmware for a specific latency and resource usage constraints, the firmware has been parametrized by the number of input tracks to consider at a time. Moreover, the accelerated DBSCAN method yielded a higher PV reconstruction efficiency when compared to the simpler histogram-based method. As clustering applications are prominent in High Energy Physics, we modified the accelerated DBSCAN firmware for higher-dimensional datasets.

Application / **50**

Optical detection of ultrafast electrons for applications in Positron Emission Tomography (PET)

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Positron Emission Tomography (PET) is a unique medical imaging modality that can detect the specific chemical tracers within the patient body and is used every day in clinics to detect cancers. Recently developed time-of-flight PET uses arrival timings of the annihilation photon pairs to increase the image quality. Conventional scintillation-based detection, however, poses limits to the temporal variance due to the stochastic diffusion of charge carriers that will result in scintillation photons. In our effort to significantly reduce the temporal variance, or coincidence time resolution (CTR), we seek to use an alternative detection of charge-carrier-induced optical properties modulation, without diffusion time. At SLAC's MeV-UED facility, we used the ultrafast electrons with known arrival timing to induce the changes in the complex refractive index and read out the modulation with optical pulses. By using an interferometric detection method utilizing bi-refringent delays, we report our results obtained from the high bandgap material of ZnTe (bandgap at 560nm). The optical probe wavelength was scanned from 560-690nm, and the modulation strength started at 1.7% which increased to a maximum of 12.7% at 630nm. After 630nm, the modulation decreased to 8.7%, indicating the importance of probe wavelength in maximizing the detected optical modulation. Further characterization of the optical modulation induced by ionizing radiation will bring critical insight into the optical modulation-based radiation detection, enabling ultra-precise CTR for applications in PET.

Application / **52**

Real time data acquisition for billion pixel x-ray imaging

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The design of a billion-pixel X-ray camera (BiPC-X) is based on the tiling of several CMOS sensors, each having a few million pixels. Both direct low-energy (< 10 keV) and indirect higher energy detection (> 20 keV) are possible, where the camera can achieve frame rates of 1 MHz and possibly higher depending on the settings [1].

With an image size of a billion pixels, the camera generates a data throughput of 100 GB/s to 100 TB/s, which largely exceeds the capabilities of recent acquisition systems. To handle real-time processing, we require an intelligent compression technique that determines useful information within an image and discards the rest. To achieve this, we propose a multistep solution to reduce the amount of incoming data right at the sensor readout electronics. By combining sparse compression and entropy coding techniques, we are able to decrease the data size for each image by a factor of 10. Furthermore, approximating the resulting code with machine learning [2] has sped up the originally slow sparse compression process by a factor of 100. Ongoing tests leverage the low latency of FPGAs and the fast inference of the optimized ML model to reach even faster compression times. In the presentation, we will discuss the compression strategy and the preliminary results obtained with the FPGA implementation of the ML model.

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[2] Karol Gregor and Yann LeCun. 2010. Learning fast approximations of sparse coding. In Proceedings of the 27th International Conference on International Conference on Machine Learning (ICML'10). Omnipress, Madison, WI, USA, 399–406.

Tracking / 53

Test-beam performance results of the FASTPIX Sub-Nanosecond CMOS Pixel Sensor Demonstrator

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Within the ATTRACT FASTPIX project, a monolithic pixel sensor demonstrator chip has been developed in a modified 180 nm CMOS imaging process technology, targeting sub-nanosecond timing precision for single ionising particles. It features a small collection electrode design on a 25-micron-thick epitaxial layer and contains 32 mini matrices of 68 hexagonal pixels each, with pixel pitches ranging from 8.66 to 20 micron. Four pixels are transmitting an analog output signal and 64 are transmitting binary hit information. Various design variations are explored, aiming at accelerating the charge collection and making the timing of the charge collection more uniform over the pixel area. Signal treatment of the analog waveforms, as well as reconstruction of time and charge information, is carried out off-chip. This contribution introduces the design of the sensor and readout system and presents performance results for various pixel designs achieved in recent test-beam measurements with external tracking and timing reference detectors. A time resolution below 150 ps is obtained at full efficiency for all pixel pitches.

Application / 54

The new monolithic ASIC of the preshower detector for di-photon measurements in the FASER experiment at CERN

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The FASER experiment at the LHC is designed to look for new, long-lived fundamental particles. To extend its discovery potential, a W-Si preshower detector is currently under construction, with the objective of enabling the discrimination of photon pairs with O(TeV) energies and separation down to 200 µm. The detector will be based on a new monolithic silicon pixel sensor in 130nm SiGe BiCMOS technology, featuring a matrix of N-on-P hexagonal pixels of 65 µm sides. The ASIC will integrate SiGe HBT-based fast front-end electronics with O(100) ps time resolution, and will feature an extended dynamic range for the charge measurement. Analog memories inside the pixel area will provide the capability of storing charge information for thousands of pixels per event, allowing for a frame-based event readout with minimum dead area. After a description of the preshower detector and its expected performance, the design of the monolithic ASIC and the test results on the ASIC prototypes will be presented.

Application / **55**

Demonstration of sub-micron UCN position resolution using room-temperature CMOS sensor

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High spatial resolution of ultracold neutron (UCN) measurement is crucial to several experiments using ultracold neutrons, including UCN spectrometers, UCN polarimeters, quantum physics of UCNs, and quantum gravity. Here we describe experimental results to demonstrate sub-micron spatial resolutions for UCN position measurements obtained using a room-temperature CMOS sensor, extending our previous work [1] that demonstrated a position uncertainty of 1.5 microns. We also explore the use of machine learning and the open-source software Allpix Squared to automatically analyze the UCN position. The automated analysis for sub-micron position resolution in UCN detection combined with the fast data rates of current and next generation UCN sources will enable improved precision for all modern UCN studies.

[1] K. Kuk, et. al. "Projection imaging with ultracold neutrons." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol. 1003, 165306 (2021).

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Methods / 56

Inversion and Super-resolution of Ultrafast Scattering

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We introduce a model-free method to directly resolve in real-space ultrafast diffuse scattering signals, below the diffraction limit and recover multiple atomic pair distance motions [1]. The method uses natural scattering kernels, a scattering basis representation that is composed of the measurement parameters and constraints, and the subsequent inversion analysis, and leverages signal priors, such as smoothness and sparsity to deconvolve the spatially transformed signals using convex optimization. We demonstrate super-resolution in real space on simulated and experimental scattering data and discuss the resolution limits vs signal fidelity.

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Imaging / 57

DynamiX: A charge cancellation ASIC for high-rate X-ray measurements using CdZnTe

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The DynamiX project is the development of a 2D pixelated hybrid X-ray detector suitable for the next generation of high-flux synchrotrons such as Diamond II in the UK.
DynamiX incorporates a CdZnTe sensor at a 100μm pitch in a 192x192 array with a 65nm CMOS ASIC operating at 533KHz framerate (one frame per turn of Diamond II) with single photon resolution at 25 keV, 3×10^9 photons/s/pixel. The ASIC features a two-stage direct-to-digital pixel architecture with adjustable charge removal per stage, allowing refinement for different energies or trade-off for maximum amplitude. In normal operation, a highspeed Aurora compliant readout system incorporating an array of 14Gbps CML serializers transmits data from the ASIC at 314.4Gbps. The ASIC operational sequence is SPI configurable and can be tailored to a specific application or instrument with a resolution of 2ns. Furthermore, the number of pixel-rows being measured can be reduced via SPI to boost the framerate past 534KHz. The ASIC uses a scalable architecture incorporating a single sub-design capable of servicing 16 columns and up to 192 pixel-rows. To build the full-size, the sub-design is instantiated 12 times along with basic interconnect routing and simple utility circuitry.
A reduced pixel-row-count sub-design (16x16 array ASIC) is scheduled to be manufactured in a Multi-Project-Wafer run this year. The manufactured ASIC will be bonded to a high-flux grade CdZnTe sensor for performance evaluation. A strong focus will be on evaluating the CdZnTe sensor performance and stability when operating at the very high very high fluxes of ~3×10^11 photons/mm2/s and beyond.
In this contribution, we will present the current state of the project in greater detail and the entire architecture of the detector system.

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Implementation of an ultrafast x-ray imaging camera for imaging shockwave evolution in defect-bearing ablator materials

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The quality of dynamic, nanosecond-scale imaging of micro-voids in ablator materials subjected to laser-driven shock compression is currently limited by low temporal resolution, which is crucial in determining factors that prevent ignition in inertial confinement fusion (ICF) experiments. At the Matter in Extreme Conditions (MEC) instrument at the Linac Coherent Light Source (LCLS), we utilized the XFEL multi-pulse mode, delivering four nanosecond-separated pulses to a single sample impacted by a high-intensity laser shockwave. We exploited the capabilities of an ultrafast x-ray imager (UXI), the Icarus V2, to capture multiple frames of microstructural evolution and void compression in a direct imaging geometry. To account and correct for the low- and high-frequency variations that are introduced into our images because of the stochastic nature of the XFEL and lens induced defects, we incorporated principal component analysis (PCA) and image alignment. Flat-field corrected images generated by the combination of these techniques are used as comparison to 2D radiation hydrodynamic simulations, yielding insights on void-shock response on ICF-relevant time scales. To quantitatively understand how the material structure evolves over several nanoseconds, we also implement a transport-of-intensity (TIE) based method to extract the mass density of our images and confirm that it is quantitatively comparable to hydrodynamic simulations.

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Rapid, online screening of complex phase spaces using Bayesian Optimization for SAXS measurements

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Small-angle x-ray scattering (SAXS) has been widely used to probe the intricate structure of biomolecules and proteins. Owing to its conceptual simplicity, the technique has also been applied to study the cluster formation in nanoparticles and supercritical fluids (SCF). However, due to the complex thermodynamic state space often encountered in SCF, the effective exploration and identification of the relevant conditions of maximal cluster organization and amalgamation is unknown a priori. This, in turn, necessitates a complete scan of the state space—a laborious and time-consuming process. In this work, we employ Bayesian optimization (BO) as a data-driven method to effectively sample such complex state spaces. We show that the BO algorithm, unaided by human intervention, converges on average 35-50% faster than an expert human user. We also demonstrate the robustness of the implementation by testing on several temperature and pressure ranges while incurring minimal losses in accuracy. This establishes the validity of the method, which has potential to be combined with current and future high acquisition rate experiments conducted at the Linear Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center (SLAC).

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Opportunities and challenges with femtosecond XFEL imaging of matter at extremes

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The advent of x-ray free electron lasers (XFELs) has enabled us to peer into dynamic extreme conditions with unprecedented spatial and temporal resolution. Imaging with these sources has enabled movies of femtosecond to nanosecond dynamics in plasma, planetary and shock physics. Additionally, the high spatial and temporal coherence of XFELs can enable reconstruction of areal densities of the samples under dynamic loading conditions. However, the shot to shot noise introduced by the most common operating mode for XFELS, known as self amplification of spontaneous emission or SASE, make tradition areal density retrieval challenging. In this talk, we we review the state of the art in using XFEL pulses to image matter in extremes and highlight some of the challenges and progress towards single shot areal density reconstruction of samples undergoing laser shockwave interactions.

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Recent progress in scattering and imaging experiments at the DiProI CDI end station of the FERMI seeded FEL.

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In this presentation we will report about the recent progress in time resolved scattering and imaging experiments performed at DiProI end-station [1,2], one of the user dedicated instrument of FERMI seeded FEL user facility [3]. In the first part of the talk I will show the possibility, offered by mini-Timer split and delay unit [4], to tomographically illuminate the sample from two different view angles, allowing for stereoscopic imaging of the investigated object [5]. In the second part, I will present the advancements performed at FERMI Free Electron Laser (FEL) user facility in the generation of light beams possessing orbital angular momentum (OAM) either using conventional diffractive optics or directly by means of direct source emission [6]. I will report the results of two recent experiments performed at DiProI beamline using XUV-OAM modes taking advantage of the peculiar features of the FERMI source. More specifically:
• we have studied the interaction of phase spiral beams with spin magnetic vortices, showing that the far field scattering profile encodes the vortex symmetries in a way that depends on the sign and value of ℓ, giving rise to a new kind of magnetic helicoidal dichroism (MHD) [7].
• we have exploited the possibility of achieve super-resolution imaging using OAM in diffraction-based imaging technique at FEL [8], showing how the speckles forming the diffraction pattern encode information on the light orbital angular momentum.
For both experiments the possibility to extend the developed techniques in the time-domain realm to either study the spin topology dynamics and plasmonic excitation in metallic nanostructures will be addressed with preliminary results.

[Fig. 1 (a) Sketch of the experimental setup to generate OAM beam from spiral Zone Plate. (b) – (e) Far field image of the interference pattern between Laguerre-Gaussian OAM beam and planar wave for different ℓ = 0, 1, 2, 3.]

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Precision Structure Tracking for Understanding the Interplay of Hydro- and Thermodynamic Parameters in Ultrafast Multiphase Micro-Sized Flows

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Liquid microjets have found industrial, commercial, and technological applications such as machining, cooling, printing, and additive manufacturing. In internal combustion engines, high-pressure liquid-fuel injection plays the most crucial role in the energy conversion process to improve combustion efficiency and emission. Despite the importance, the liquid-jet dynamics have not been fully understood due to the dearth of experimental methods for interrogating complex turbulent and multiphase flows. We developed an ultrafast x-ray near-field speckle imaging method ideally suitable for visualizing the multiphase turbulent and cavitating flows emanated from direct-injection nozzles with unprecedented spatiotemporal resolution. The ultrafast liquid-fuel dynamics are dominated by injection pressure as well as fuel temperature through cavitation, an important thermodynamic parameter but often difficult to control in engine combustion. The fast near-nozzle dynamics, measured in wide-range operating conditions and with a realistic injection nozzle, are sensitive to the hydrodynamic parameters, such as injection pressure, and surprisingly, their interplay with the fluid temperature, an important thermodynamic parameter. With the most direct and quantitative measurement, we discovered that the near-nozzle fuel-jet dynamics can be perfectly scaled by a single dimensionless parameter, cavitation number. This universal scaling shows that cavitation can be harnessed to elevate the pneumatic-hydraulic to kinetic energy conversion efficiency, critical for promoting fuel atomization and engine combustion performance. This enhancement effect will have even more impact on engine combustion using alternative low-emission fuels with higher saturated vapor pressure. Conversely, the x-ray imaging based high-precision structure tracking method is also ideally suitable for understanding the turbulence in the multiphase flows by quantifying turbulence fluctuation and intensity. The results bring greater impetus to developing realistic models and simulations of multiphase turbulent and cavitating flows to understand how they affect energy conversion in combustion processes.

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Welcome

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Keynote - Imaging at the Speed of Light: Reconstruction-free Imaging of Positron-emitting Radionuclides

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Positron emission tomography (PET) is a widely used medical imaging technique and, like many other tomographic imaging modalities, relies on an image reconstruction step to produce cross-sectional images from projection data. Detection and localization of the back-to-back annihilation photons produced by positron-electron annihilation define the trajectories of these photons, which, when combined with tomographic reconstruction algorithms, permit recovery of the distribution of positron-emitting radionuclides. Time-of-flight information, typically at the level of 200-400 ps in modern PET systems, is used to constrain the reconstruction locations, improving the signal-to-noise ratio.

Once the time-of-flight resolution can be improved by an order of magnitude to around 30 ps, a new regime is encountered where radioactive decay events can be directly localized without the need for tomographic reconstruction. We call this direct positron emission imaging. In this presentation, we show how prompt Cherenkov luminescence, photodetectors with very fast single photon response times and deep-learning based timing pickoff algorithms are combined in an ultra-fast radiation detector to achieve a timing resolution of 32 ps, localizing positron-electron annihilation sites to 4.8 mm. We also show this is sufficient to directly generate a cross-sectional image of positron-emitting radiotracers without reconstruction and without the geometric and sampling constraints that normally present for tomographic imaging systems. Future prospects for scaling up the approach, and technological innovations for addressing detection sensitivity limitations, will also be addressed.

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Keynote - The Multiverse of f-electron Quantum Materials

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New materials will define tomorrow's technologies. They are part of a materials multiverse where every crystal provides a unique framework to define a new state of matter – some more exotic than others. Notions of topology have provided a new paradigm for understanding some of these new phases of matter and have exciting physical consequences, such as protected surface states and magnetic fields in momentum space. By adding electronic correlations, additional states of matter can emerge with novel types of excitations such as composite fermions and non-abelian anyons. f-electron-based materials possess both strong electronic correlations and strong spin-orbit coupling. This combination suggests that f-electron materials are ideal for discovering new topologically non-trivial phases, which arise as a consequence of strong electronic correlations. In this talk, I will introduce how various fascinating physical phenomena, including heavy fermions, unconventional superconductors, spin liquids, topological Kondo insulators, Weyl semimetals, and Majorana fermions, emerge in f-electron materials and the quantum information science technologies - ranging from quantum computing to dark matter detection - that we aim to enable with them.

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Keynote - How to meet the X-ray Photon-Science Detector Challenge?

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X-ray photon sources continue their exponential improvement in source brilliance.

X-ray Free-Electron Lasers (FELs) have revolutionized the field of X-ray photon science. For instance, with their intense and ultra-short X-ray pulses, they opened up the field of time-resolved experiments down to the femtosecond. Another area is the study of materials under extreme conditions. So far, FELs have been either low repetition rate machines (warm accelerators), or burst-mode machines (superconducting accelerators). New developments of the accelerator, however, now permit the construction of high repetition rate machines operating in continuous wave mode, with up to a million pulses per second continuously.
This requires the development of new detectors and detector technologies.

Synchrotron storage rings worldwide are upgrading their accelerators to so-called multi-bend achromats, resulting in a 10 to 100-fold increase in brilliance and up to a 1000-fold increase in coherent flux, especially at higher energies. These Diffraction Limited Storage Rings (DLSR) will make some photon-starved experiments more feasible but, more importantly, open up completely new scientific possibilities. Also here, new detectors and detector technologies are required.

I will give a short overview of the ongoing X-ray source developments and their consequences on the X-ray detector requirements. The main part of the presentation will be dedicated to ongoing developments in the community, with a special focus on DESY.

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Keynote - The Timepix chip family and its latest member, Timepix4

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The Timepix hybrid pixel detector readout chips aim at particle detection and imaging with on-pixel time tagging. Timepix4 is the most recent member of the Timepix family. It can be connected to a sensor with a matrix of 448 x 512 square pixels with a pitch of 55um. Hits are time tagged to within a bin of 200ps. The chip can handle a maximum incoming flux of hits of 3.6 MHz/mm2/s in data-driven mode. It is perhaps the largest hybrid pixel detector readout chip ever produced and is designed such that it can be abutted to neighboring chips on all four sides. This is achieved by a fan-in from a uniform matrix of bump bonding pads to 2 matrices of readout cells with slightly smaller pixel pitch in one direction (51.4um). The space left over accommodates the required control and I/O blocks (at the top, middle, and bottom of the chip), which can be accessed from the rear of the chip using Through Silicon Vias. The presentation will start with a brief review of the Timepix chips and some applications before describing Timepix4, electrical test results, and measurements with radioactive sources and particle beams.

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Keynote - Burning and ignited plasmas at the National Ignition Facility

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Thermonuclear fusion in the laboratory is a scientific grand challenge, a highly compelling problem because the fusion reactions can self-heat the fuel and continue the burn. Predominantly approaches use the fusion of deuterium and tritium nuclei, which generates 17.6 MeV of energy released in a neutron and alpha particle. The alpha particle which carries
1/5 of the energy can heat the plasma. A plasma in which the alpha self-heating is greater than external heating is termed a 'burning plasma', and one in which the self-heating dominates over all loss mechanisms, leading to a run-away increase in temperature, is termed 'ignited'. Inertial confinement fusion (ICF) has pursued these scientific milestones using large laser drivers, notably the National Ignition Facility (NIF) at LLNL. Here we use the laser energy, up to1.9MJ, to generate a hot x ray bath, which creates ablation pressures of hundreds of Mbar at the outer surface of a fuel-containing capsule. The ablation pressure implodes the capsule, with fuel pressures of several hundred GBar generated as the fuel stagnates at the center. The combination of these extreme pressures and inertial confinement times from the surrounding material can lead to burning and ignited plasmas. Recent experiments on NIF in the last year have generated 25x higher fusion yields than previous records, up to 1.3MJ, passing the burning-plasma threshold and Lawson's criterion for ignition. In this regime the plasma conditions evolve rapidly as the burn propagates with significant evolution in less than 100 picoseconds over spatial scales of 10s of μm. Measurements at these temporal and spatial scales are extremely challenging yet are critical to improving our understanding of the burn process, which can now be studied in the laboratory for the first time.

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High-Z sensors for synchrotron sources and FELs

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High-Z compound semiconductors aim to replace silicon as sensor material for X-ray energies above 15 keV thanks to their superior absorption efficiency. However, compared to silicon, high-Z sensors still lack in several aspects such as homogeneity, charge transport properties, charge trapping (leading to polarization and afterglow effects), long ranged fluorescence photons, and others.
The aim of this study is to identify sensor materials that can widen the usable energy range of our detector systems at synchrotron sources and free electron lasers (FELs) towards higher photon energies. Promising results have been obtained using the 75 μm pitch JUNGFRAU charge integrating detector in combination with various high-Z sensors (GaAs:Cr, Ohmic/Schottky type CdTe and CdZnTe). As charge integrating detectors allow the direct measurement of the collected charge of every single

photon with a high spatial resolution, these detectors offer interesting insights into temporal as well as spatial sensor effects which affect the charge collection.
As one of the major challenges of the upcoming 4th generation of synchrotrons or FELs are very intense and potentially pulsed photon beams, the sensor material of choice needs to be able to reliably measure highly intense signals and to have no afterglow phenomena after illumination. We performed a measurement campaign at the Material Science (MS) beamline of the SLS using photon fluxes up to 5×10¹⁰ ph/(mm²·s), specifically focusing on the dynamic behavior (like signal stability, polarization and afterglow effects) of various high-Z sensor materials like GaAs:Cr, Ohmic/Schottky type CdTe and CdZnTe. The presentation will give an overview of the results obtained.