Impact of pixel detectors on SR experiments

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Outline

- SR Culture
- What is SR?
- Statement of problem
- Examples
- Summary
Culture

- SR and HEP are cultural opposites
  - HEP: teams of hundreds for one experiment, complex detector system
  - SR: teams of <10 usually, simple apparatus.
  - HEP: Experiment takes years
  - SR: Experiment takes hours or days
  - HEP: Detector IS experiment
    - Scientists closely involved in design
  - SR: SAMPLE is experiment: SR and detector a necessary evil
    - Scientists just want the result
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Synchrotron Radiation: the Photon Superprobe

- Covers Infrared to Gamma-like energies: $10^9$ range
  - Unique source in regions not covered by tunable lasers
- Different energy ranges need different instrumentation and different detector technologies
  - IR
  - VUV
  - Soft X-ray
  - Hard X-ray
  - High-energy
SR contd: Unique properties

- Very bright:
  - Very intense
  - Highly collimated
  - Large coherent fraction

- Polarized
  - spin-sensitivity
  - anisotropy sensitive

- Pulsed
  - time-resolved studies

- Has application in most scientific fields.
Wigglers, Undulators and FELs

- Wiggler is series of strong bends alternating in sign
- Undulator is series of weak bends, so light emitted from successive bends has some coherence.
- FEL is very long undulator so radiation field is strong enough to introduce periodic microbunches inside bunch and hence a resonance with undulator.
Wide variety of sources:
- dipole magnets
- wigglers
- undulators

Each have advantages and disadvantages
SRSs worldwide

- 16 in USA
- 23 in Europe
- 25 in Asia
- 1 in Australia
- 1 in South America
SRSs and FELs

- **SRS is quasi-DC source (~10ns bunch spacing)**
  - Electron or positron storage ring
  - No trigger, no 'free time' to dump data.
  - High average brightness, high stability
  - Low peak brightness
  - Fairly broadband source (~1% best case without filtering)

- **FEL is pulsed source (~10ms bunch spacing)**
  - Driven by LINAC / photocathode electron gun (low repetition rate)
  - Pulse width < 1ps
  - Low average brightness
  - Very high peak brightness
  - Quasi-monochromatic (10^-3 SASE, 10^-4 Seeded)
Diamond Light Source (UK)

- Electron Beam Energy 3 GeV
- Circumference 561.6 m
- Number of cells 24 double-bend achromatic
- Straight sections 4 x 8 m, 18 x 5 m
- Beam current 300 mA (500 mA)
- Emittance 2.74 nm rad (horizontal) 0.0274 nm rad (vertical)
- Life time >10 h (20h)
- Max beamline length 40 m
- End-station capacity 30-40
- Phase I beamlines 7 for operation in January 2007
A new 3rd-generation source at BNL

- 3GeV, 800m circumference.
- 30 DBA cells
- 6.6 & 8.6m straights
- <1nm-rad/0.008nm-rad
- Green-field site adjacent to NSLS
- 2014 ops.
Detector challenges: SR

- Dynamic range
  - Photon counting
    - Energy range
    - Rate
    - Energy resolution

- Coverage
  - Area & spatial resolution, Fast readout of 2D detectors

- Multi-dimensionality

- Multiple concurrent methodologies
Absorption length for Si & Ge

- Materials science needs $E > 20\text{keV}$ to penetrate dense materials (alloys, ceramics etc.)

- Biology needs higher $E$ to reduce radiation damage
SR X-ray techniques

- Scattering & diffraction
  - Crystallography
  - Small-angle scattering
  - Diffuse scattering
  - PDF

- Spectroscopy
  - Fluorescence
  - EXAFS & XANES

- Imaging & microscopy
  - Scanning probe microscope
  - Full-field microscope
  - Coherent diffraction & Holography
Crystallography: Sample MUST move

- Complex goniometry
  - to allow sample to have an arbitrary orientation w.r.t. the incident x-ray beam, with minimum blind regions.
Pilatus Module

- 1 Silicon Sensor
- 16 PILATUS CMOS Chips
- 487 x 195 pixels = 94965 pixels
- Active Area 83.8 x 33.6 mm²
- $T_{ro} = 3.6$ ms
- Continuously sensitive: no gaps between chips
- Building Block of all Pilatus Detectors

Hamamatsu Sensor
16 PILATUS II Chips

Mechanical support

Module Control Board (MCB)
Large area detectors

Figure 5: The different multimodule systems. Left PILATUS 6M (5x12 modules). Right: PILATUS 2M (3x8 modules).
Figure 7: Left: Typical diffraction pattern as produced by a protein crystal. The zoom shows an arbitrary pattern with a large amount of reflections where the intensities vary within several orders of magnitudes (right). ©V. Ramakrishnan, MRC Laboratory of Molecular Biology, Cambridge.
Scanning SAXS at beamline X012SA of SLS, F. Pfeiffer et al.

- Automated scans, > 100 x 100 points
- Pilatus 2M used in different acquisition modes:
  - 24 module: full area mode
  - 3x2 module: 2 bank mode
  - 1x3 module: 3 module mode
- Benefit: Higher speed, lower amount of data
bone cartilage interface

> $10^5$ SAXS patterns analyzed (1 TByte of data)

Evaluation of intensity and orientation angle for each pattern & d-spacing >> code into polar

Change of fiber orientation by 90 deg

$d \sim 130\,\text{A}$

$d \sim 690\,\text{A}$
Comparison: Absorption and Phase Contrast Imaging

M. Bech, O. Bunk, C. David, P. Kraft, H. Brönnimann, E.F. Eikenberry and F. Pfeiffer,
X-ray Imaging with the PILATUS 100K detector, Applied Radiation and Isotopes (2007),
doi:10.1016/j.apradiso.2007.10.003
1-D detectors

- The complexity of 2-D detectors is not always needed.
  - liquids
  - polycrystalline solids

- Sometimes the openness of a 2-D device causes reduced signal / background
  - UHV environments
1-D silicon strip arrays

- 4mm x 0.125mm strips in arrays of 384 and 640 strips
- Fully-depleted 0.4mm thick detectors
- Pitch matched to ASIC, so simple bonding to form arrays
- 350eV energy resolution @ 5.9keV
- 1e5 cps per strip maximum counting rate
- Readout of 640 strips in few ms.
- Two example applications
  - GISAXS
  - Powder diffraction pole figures
'HERMES' ASIC channel overview

**INPUT p-MOSFET**
- Optimized for operating region
- NIM A480, p.713

**CONTINUOUS RESET**
- Feedback MOSFET
- Self adaptive 1pA - 100pA
- Low noise < 3.5e⁻ rms @ 1µs
- Highly linear < 0.2% FS
- US patent 5,793,254
- NIM A421, p.322
- TNS 47, p.1458

**HIGH ORDER SHAPER**
- Amplifier with passive feedback
- 5th order complex semigaussian
- 2.6x better resolution vs 2nd order
- TNS 47, p.1857

**BASELINE STABILIZER (BLH)**
- Low-frequency feedback, BGR
- Slew-rate limited follower
- DC and high-rate stabilization
- Dispersion < 3mV rms
- Stability < 2mV rms @ rt×tp<0.1
- TNS 47, p.818

**DISCRIMINATORS**
- Five comparators
- 1 threshold + 2 windows
- Four 6-bit DACs (1.6mV step)
- Dispersion (adj) < 2.5e⁻ rms

**COUNTERS**
- Three (one per discriminator)
- 24-bit each

**POWER**
- ≈ 3 mW
- ≈ 5 mW
Microstrip detector

- Diode array (640 strips) at left of picture
- Custom IC's directly to right of strips
- Peltier coolers and water-cooling channels below
- Power regulators and signal buffers to right.
- Diodes cooled to -35C
First direct *in-situ* observation of oxygen vacancy ordering in (La,Sr)CoO$_3$-d (and LSCF etc.) cathodes using the Si strip detector (Alfred University and ORNL)

Under $10^{-5}$ atm. oxygen

Vacancy-Ordered phase

Vacancy ordering stops ionic conduction
Thermal Evolution of Hafnia

Department of Materials Science and Engineering
University of Illinois at Urbana-Champaign

1369ºC
1508ºC
1249ºC
1100ºC
920ºC
374ºC
1532ºC
25ºC

Intensity(Counts)

1532ºC
1508ºC
1369ºC
1249ºC
1100ºC
920ºC
374ºC
25ºC

×10^3

17 18 19 20 21 22

Two-Theta (deg)

97-002-7313 - HfO₂ - Hafnium Oxide
01-087-0540 - Platinum - Pt

NSLS
BROOKHAVEN NATIONAL LABORATORY
Instrumentation Division
Structure Refinement Using the Powder XRD Data Taken with The Si Stripe Detector

(University of Connecticut, University of Tennessee and BNL Chemistry)

Phase name K$_2$Mn$_8$O$_{16}$ (Cryptomelane)

X-ray wave length 0.73143 Å, Space Group I4/M

a = 9.8480(4), b = 2.8630(1)
In situ synchrotron x-ray diffraction studies on LiFe1/4Mn1/4Co1/4Ni1/4PO4 cathodes for Lithium batteries

(Left) In Situ XRD patterns of C-LiFe1/4Mn1/4Co1/4Ni1/4PO4 during the first charge cycle. Data taken at 17 keV with the $2\theta$ angle converted to the corresponding values of Cu x-ray tube. The numbers marked beside the patterns correspond to the scan numbers marked on the charge curve (right).
we now can fit and subtract large background
First simultaneous pole figures from NSLS linear detector at X20A

C. Detavernier, K. DeKeyser (U. Gent), D.P. Siddons (NSLS), J. Jordan-Sweet, C. Bohnenkamp

NiSi 112
$2\theta = 45.82^\circ$

NiSi 002/011
$2\theta = 31.5^\circ$ (NiSi/Si(001) tiled from 90° phi segments)

NiSi 102/111
$2\theta = 36^\circ$

NiSi 013/020
$2\theta = 56.4^\circ$
Spectrometers for Inelastic X-ray Scattering

Energy resolution: 10 - 1 meV
\[ \delta E \sim 1/E^4 \]

From work of Harald Sinn, Y. Shvydko, APS
Analyzer disk

Dicced and dynamically bent silicon substrate
Inelastic scattering analyzer 'block' dispersion compensation

- Segmented 'spherical analyzer'
- Each 'segment' is mini-Bragg spectrometer
- Can spatially resolve dispersed spectrum from block.
Dispersion compensation

- Image of spot at detector
- Single Medipix + silicon sensor
- Shape of spot is x2 image of silicon block.
- Energy correlated with position in vertical dimension
Direct measurement of dispersion

- Uses high-resolution tuneable monochromator
- Only thing changing is energy of incident beam
- Use of this information provides ~x8 better resolution
- 1-D detector would work as well in this application
GISAXS studies of in-situ surface modification

- NSLS beamline X21 has a new in-situ surface chamber.
- Two examples:
  - Ar-ion bombardment of Si surface seeded with Mo nanodots
  - Ga deposition on sapphire
Grazing-incidence diffraction

- Surface topology on nanometer scale is important: surfaces are different
  - X-rays

- Grazing incidence gives total external reflection
  - No background from substrate

- Linear detector set to measure $q \parallel$
- $q \perp$ by scanning.

- Various surface treatments done under UHV conditions

- 2-D detector has high background
Roughening of a silicon surface under argon-ion bombardment

In 32 steps
GIAXS data from Ga droplets on sapphire
Pad arrays for spectroscopy

- X-ray fluorescence detection for
  - EXAFS
    - Two hardware pulse-height windows on-chip
    - 24-bit counters on-chip
  - elemental mapping (x-ray microprobe)
    - Full-spectrum acquisition from each of hundreds of detectors
    - Modified ASIC
    - Highly-parallel processing electronics
X-ray Fluorescence Microprobe detector

- 96 pads, 1mm x 1mm, wire-bonded to 3 ASICS.
- The long bonds are rather fragile, but this approach provided least parasitic capacitance.
- Each ASIC provides 32 channels of low-noise analog/digital processing.
- ASIC appears to have 100% yield (no bad channels to date).
Avoiding charge-sharing in monolithic pixellated detector

- Charge-sharing near 1mm x 1mm pixel edges significantly degrades peak-valley ratio.
- Molybdenum mask shadows inter-pixel region, restoring good p-v ratio.
- Flood $^{55}$Fe spectrum with inter-pixel mask: 1000:1 P/V.
SCEPTER: The Peak Detector Derandomizer ASIC
(A. Dragone, G. De Geronimo, P. O'Connor)

- New architecture for efficient readout of multichannel detectors
  - Self-triggered and self-sparsifying
  - Simultaneous amplitude, time, and address measurement for 32 input channels
  - Set of 8 peak detectors act as derandomizing analog memory
  - Rate capability improvement over present architectures

- Based on new 2-phase peak detector combined with Quad-mode TAC
  - High absolute accuracy (0.2%) and linearity (0.05%), timing accuracy (5 ns)
  - Accepts pulses down to 30 ns peaking time, 1.6 MHz rate per channel
  - Low power (2 mW per channel)
Time-Over-Threshold Measurement for pile-up rejection

The Pile-Up Rejection Algorithm

Before The Correction

After The Correction
Time-Over-Threshold Measurement for pile-up rejection

Pulse Height Spectra Comparison

Before the correction
After the correction

Normalized Counts

Energy [keV]

5 10 15 20

10^{-4} 10^{-3} 10^{-2} 10^{-1}
Real-time Elemental Imaging...

Event: Detector $N$, Channel $i(E)$, Position $X,Y$

Matrix column

Dynamic Analysis
$\Gamma$ matrix

Energy Cals

Detectors

Instrumentation Division

Synchrotron - Nuclear Microprobe Synergy
Test sample composed of pieces of pure elements, plus GaAs.

Test scan: 3.0 x 2.0 mm²
Demonstration experiment at X27A:
Block diagram of test setup

- HYMOD controls stage and reads detector
- Each photon tagged with energy, XY position and pileup status
- Initial coarse scan generates 'average' spectrum which makes DA matrix
- DA technique then presents elemental map as acquisition proceeds.
Rapid XRF Elemental Mapping
(BNL/CSIRO collaboration)

Fe-Y-Cu RGB composite (1500 x 2624 pixel images, 13 x 21 mm²)

1200 x 2267 (9 x 17 mm²)
5.7 hours (7.5 ms dwell)
7.5 x 7.5 µm² pixels
Rapid XRF Elemental Mapping (BNL/CSIRO collaboration)
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1200 x 2267 (9 x 17 mm²)
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Backscattering geometry for fluorescence microprobe

- Backscattering geometry allows close approach to sample.
- Provides good solid-angle even for small detector area
High-rate multi-element detector for fluorescence measurements

- 384-element silicon pad array (1mm x 1mm) for absorption spectroscopy and/or x-ray microprobes.
- Central hole for incident pump beam to allow close approach to sample.
- Will use 12 BNL HERMES ASICs designed by G. De Geronimo & P. O'Connor.
Assembly
SRSs and FELs

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  - Fully transversely coherent
  - Very high peak brightness
  - Quasi-monochromatic (10^-3 SASE, 10^-4 Seeded)
LCLS

- 16GeV electrons from 1/3 of SLAC
- 1.5 - 15 Angstrom radiation
- 5-6 end stations
- Operational 2009
The XFEL project (DESY)

- 20GeV LINAC
- Remote green field site for end-stations
- Very intense
- 10Hz rep. rate (~1ms macropulse with 200ns sub-period)
- Based on TESLA technology
What is an F.E.L.?

- Undulator radiation spatially modulates electron beam
- Radiation from successive microbunches is coherent
- More radiation makes deeper bunching -> more radiation
Detectors for FELs

- No suitable commercial detectors
  - CCDs?
  - CMOS imagers?

- Both facilities (LCLS and XFEL) have begun a custom development
  - Specifications

- BNL development proposal to LCLS
  - Switch-matrix structure for P-P experiments
  - “Charge-pump” structure for XPCS experiments
  - Readout system
  - Data handling
Specifications

- Source: 100fs pulses at 120Hz -> no photon counting, so need integrating detector.

- Two applications with very different specifications:
  - X-ray Pump-Probe
    - ~100% efficient @ 8keV
    - < 1 photon readout noise
    - $10^4$ photons full-well
    - ms readout time (< 8ms)
    - Extremely challenging spec: >$10^4$ S/N, single-shot, fast readout.
  - X-ray Photon Correlation Spectroscopy
    - 100 photons full-well
    - $<< 1$ photon readout noise, needs different technology
    - ms readout time.
Active-matrix Area Detector

- Fully pixellated hybrid detectors (i.e. Amplifier per pixel, separate sensor array) are complicated and tend to have large pixels.

- Sensor array must be bump-bonded to CMOS circuit
  - 3 separate vendors: CMOS device, sensor array and bonder

- Monolithic devices built on fully-depleted high-resistivity silicon provide simplest structure
  - Large-area devices possible without gaps
  - No bump-bonding
  - Fully depleted wafer -> good efficiency
  - Simplest structure is monolithic active-matrix type
    - Switching mechanism integrated with sensor
    - Small pixels in principle possible (no on-pixel amps)
    - Row-by-row parallel readout by off-sensor amplifiers
    - N readout channels instead of N x N, modular readout from edge of detector by a few (~16) small ASICs

- Need to develop technology to form transistors directly on high-resistivity silicon substrate.
XAMPS for LCLS

- Will be discussed in detail in a later talk (G. Carini, 10:50 today)
Future developments

- Need to provide more functionality on-pixel
  - low-noise spectroscopy (<20e)
  - deep fast time framing / readout
  - time-correlation spectroscopy
- 3D integration?
Process flow for 3D Chip

- 3 tier chip (tier 1 may be CMOS)
  - 0.18 um (all layers)
  - SOI simplifies via formation
- Single vendor processing

1) Fabricate individual tiers

2) Invert, align, and bond wafer 2 to wafer 1

3) Remove handle silicon from wafer 2, etch 3D Vias, deposit and CMP tungsten

4) Invert, align and bond wafer 3 to wafer 2/1 assembly, remove wafer 3 handle wafer, form 3D vias from tier 2 to tier 3
Summary

- SR experiments are slowly learning to use modern detector technology.
- Funding agents are slowly realizing that new sensor technologies can provide improved performance.
- New sources raise new challenges for detector developers.
- 3D integration will certainly play a role in the future.
Collaborators

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